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Dense Plasmas

I1. The method of effective potentials in the quantum-statistical theory of plasmas

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Effective potentials belong to the most fruitful methods in the modern theory of strongly coupled plasmas. We start with a survey of early pseudo-potential approaches, beginning with pioneering work of Kelbg, Barker, Storer, Norman, Filinov, Zamalin, Zelener and others. These potentials capture the basic quantum diffraction effects and are exact in the low density limit. Using quasiclassical methods, the first approximations of nonideality effects including bound states may be obtained in an exact way. We give a survey of exact results, derived so far. The recently developed new quantum Monte Carlo methods allow applications to strongly coupled plasmas including degeneration and bound state effects. It is shown that the diagonal Kelbg potential may be generalized by including off-diagonal terms. We discuss the accuracy of the existing results for hydrogen, open problems and compare with alternative methods of quantum-statistical theory.

I2. Dense plasma properties from shock wave experiments

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The report presents review of the novel experimental results of investigation of physical properties of the coupled dense plasmas generated as a result of shock compression of metals, H_2, He noble gases up to megabar pressure range. High energy plasma states were generated by single and multiple shock compression and adiabatic expansion of solid, liquid, porous and low-density foam samples. The highly time-resolved diagnostics permit us to measure thermodynamical, electrophysical and optical properties of high pressure condensed plasmas in the broad phase diagram region from the compressed condensed solid state up to the low density gas range, including high pressure evaporation curves with near-critical states of metals, strongly coupled plasma and metal-insulator transition regions. These data demonstrate an ionization rate increase up to ten orders of magnitude as a result of compression of nonideal plasmas at $p \sim 1 - 103$ GPa. The results of experiments on measurements of the Hall resistivity, static conductivity and reflectivity of nonideal plasma of rare gases are considered. The comparison of experimental results with different theoretical models of strongly coupled plasma is carried out.

T1. Direct measurements of the electrical resistivity of dense metal plasmas

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Progress in exploding wire techniques for the measurements of the electrical resistivity of dense metal plasmas is reviewed. It is demonstrated that in general the data on the resistivity obtained by means of quite different techniques give results in good agreement.

Recent results [1] of direct measurements of the resistivity, internal energy and density of tungsten over a wide density and internal energy ranges are presented. Tungsten wires immersed in a water bath were rapidly heated by a pulse current. The voltage across the plasma column formed by an exploding wire, the current through it and the plasma column diameter were measured. Using the measured temporal dependence of the plasma column diameter (from streak camera imaging) as an input function we perform numerical integration of the 1D hydrodynamic equations of motion for water to calculate the pressure at the plasma column boundary and its internal energy (using only a water EOS). Such calculations are independent of the assumption of the radial homogeneity of the plasma, but to determine directly the electrical resistivity and the specific quantities such as specific internal energy and density, the distributions of the physical quantities across the column should be sufficiently homogeneous. In order to specify the parameters of the experiments to approach homogeneity, 1D MHD simulations of the pulse Joule heating dynamics were conducted. As a result, the resistivity of dense tungsten plasma along with the complete set of thermodynamic quantities (pressure, density, and internal energy) without using any EOS model of tungsten was directly measured. The results obtained indicate that the dependence of the resistivity of tungsten on internal energy along isochors is flat at high densities, but acquires a strong negative slope at a density which is 8 to 16 times lower than the normal solid density.

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T2. Frontiers of dense plasma physics with intense beams and accelerator technology

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Intense heavy ion beams from the Gesellschaft für Schwerionenforschung (GSI-Darmstadt) accelerator facilities together with two high energy laser systems (PHELIX: **p**etawatt **h**igh **e**nergy **l**aser for **i**on **e**xperiments, and nhelix: **n**anosecond **h**igh **e**nergy **l**aser for **i**on **e**xperiments) are a unique combination to facilitate pioneering beam-plasma interaction experiments, to generate dense plasma and probe high-energy-density (HED) matter and to address basic physics issues associated with heavy ion driven inertial confinement fusion.

The proposed FAIR facility will even improve the parameter range that can be addressed. In one class of experiments the laser will be used to generate plasma and the ion beam will be used to study the energy loss of energetic ions in ionized matter, and to probe the physical state of the laser-generated plasma. In another class of experiments the intense heavy ion beam will be employed to create a sample of HED matter and the laser beam, together with other diagnostic tools, will be used to explore the properties of these exotic states of matter. The existing heavy ion synchrotron facility, SIS18 delivers an intense uranium beam that deposits about 1 kJ/g specific energy in solid matter. Using this beam, experiments have recently been performed where solid lead foils have been heated and a brightness temperature of the order of 5000 K was measured, using a fast multi-channel pyrometer that has been developed jointly by GSI and IPCP Chernogolovka. It is expected that the future heavy ion facility, FAIR (Facility for Antiprotons and Ion Research) will provide compressed beam pulses with an intensity that exceeds the current beam intensities by three orders of magnitude. This will open up the possibility to explore the thermophysical and transport properties of HED matter in a regime that is very difficult to access using the traditional methods of shock compression. Beam plasma interaction experiments using dense plasmas with a Γ-parameter between 0.5 and 1.5 have also been carried out. This dense Ar-plasma was generated by explosively driven shockwaves and showed enhanced energy loss for Xe and Ar ions in the energy range between 5.9 to 11.4 MeV.

Dense plasmas as in the interior of the sun also display exciting phenomena that can be addressed with present day laser- and accelerator technology. An example will be presented

P1. Reflectivity of non-ideal plasmas

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The results of measurements of the dense xenon plasma reflection coefficient at wavelengthes λ_L = 532 nm, λ_L = 694 nm and λ_L = 1064 nm are presented. The investigation of reflective properties of the plasma was accomplished within the wide range of plasma densities ρ = 0.3–3.4 g/cm^3, pressures P = 4–20 GPa and temperatures up to $T \sim 3.3 \cdot 10^4$ K under conditions with strong Coulomb interaction (the nonideality parameter $\Gamma = (4\pi n_e/3)^{1/3} e^2/(kT) =$ 0.4–2.0 and the degeneracy parameter $\Theta = kT/E_F$ = 1.7–7, E_F is the Fermi energy).

The generation of the plasma was performed by shock wave compression and irreversible heating of the investigated gas. The variation of density and electron concentration of the plasma was achieved by the change of the initial gas pressure (2–5.7 MPa).

To measure the dense xenon plasma reflection coefficient, the pulsed Al_2O_3:Cr^{3+} and $Y_3Al_5O_{12}$:Nd^{3+} + KTP laser system with electro-optical shutter based on DKDP crystal and higher-order mode suppression of the laser radiation was used. The probe pulse of about 25 ns duration was formed by an aspherical optical unit.

For determination of the equilibrium properties of explosively driven plasma appropriate gasdynamics calculations were carried out. The thermodynamic model of the plasma took into account Coulomb interaction in frames of Debye approximation in grand canonical ensemble and the short-range repulsion of heavy particles — within the soft spheres model.

In order to infer plasma parameters from optical reflection coefficient measurements of dense xenon plasma, a finite width of the shock wave front was taken into account. Different forms of profiles $n_e(z)$ have been considered, and the reflectivity can be obtained by solving the wave equation. Our calculations are based on an interpolation formula for dc conductivity, obtained from a systematic quantum statistical treatment of different limiting cases. In particular, the account of the renormalization factor and of strong collisions essential to obtain the correct low-density limit for the dc conductivity. The uncertainty in using the interpolation formula increases for $\Gamma > 1$. Improving this approach by taking a dynamical collision frequency or even nonlocal instead of the static one, only marginal modifications of the reflectivity are expected.

P2. Conductivity of nonideal plasma in relaxation time approximation

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There are known various methods of determination of transport coefficients of plasma [1]. In this work we solved the Boltsman kinetic equation using relaxation time approximation [2] for electrical conductivity calculation. We used Fermi–Dirac distribution to consider the influence of electron degeneration on transport coefficients. This approach is applicable for slightly degenerate plasma. Electron–electron scattering is not essential and was not taken into consideration.

The basic contribution to transport coefficients of partially ionised plasma is determined by electron scattering both on ions and atoms. These processes are characterised by different values of relaxation time, which, in turn, depend on scattering cross-sections and composition of investigated plasma. One usually uses transport cross-sections calculated with the help of Born approximation applicable only at sufficiently high temperatures; this approximation overestimates a conductivity value.

In this work transport cross-sections are calculated by means of a partial waves method [3]. Shrödinger equation with polarization potential (for atom–electron scattering) and Debye potential (for ion–electron scattering) was solved numerically for definition of phase shifts of wave functions at large distances from the scattering center. Phase equations, which are more convenient for numerical calculations were solved instead of finding an asymptotical solution of Shrödinger equation, as it was presented in the work [4].

We calculated electrical conductivity of aluminium plasma with composition computed by V. K. Gryaznov within the framework of chemical plasma model up to density 0.8 g/cm^3 [1]. We also used Thomas–Fermi model with corrections [5, 6] to calculate strongly coupled dense plasma composition. The results were compared with available experimental data and other models.

The authors are grateful to Dr. V.K. Gryaznov for results of his calculations.

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P3. On the electrical conductivity of dense semiclassical plasmas

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Investigation of the kinetic properties of dense plasma is one of the actual problems of plasma physics both in the aspect of the theory development and its practical application.

In this work the subject of study is dense semiclassical plasma where the particles interact due to the pseudopotential which takes into account of local fields and quantum-mechanical effects. As micropotential used Kelbg potential which takes into account quantum-mechanical effects of diffraction [1]. It is well known that local fields play significant role in a dense high-temperature plasma. The Fourier transform of the ion-ion pseudopotential, taking into account local field corrections, quantum-mechanical effects and the electron screening of ions has been derived in the framework of the linear density response formalism [2].

In this work using the semiclassical approach and density response formalism the ion-ion pseudopotential has been derived. This pseudopotential takes account of both local field corrections and quantum-mechanical effects, which as we know play a significant role in dense semiclassical plasma. On the basis of the pseudopotential we have obtained the analytical expressions for the structure factors of dense semiclassical plasma and the numerical values for the Coulomb logarithms.For the calculation of the electrical conductivity coefficients in this work the Chapman-Enskog method in the second Sonine polynomial approximation has been used [3].

The analysis of the mentioned dependences of the electrical conductivity coefficients againts the coupling parameter Γ at fixed value of the density parameter r_s shows that (i) the obtained results for the electrical conductivity on the basis of the considered pseudopotential model of the particle interactions of plasma agree fairly well with the results of other authors. (ii) With an increases of Γ the electrical conductivity first decreases, reaching the minimum at $\Gamma \sim 2$, then it increases with a subsequent growth of coupling parameter.

Hence, we can make a conclusion that our pseudopotential model adequately describes transport processes in dense emiclassical plasma.

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P4. Cross sections and transport coefficients of dense partially ionized semiclassical plasma

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In the present work the phase shifts, cross sections and transport coefficients of dense semiclassical plasma are investigated. It is shown, that taking into account of screening effects at the large distances and quantum effects at short distances leads to decreasing of the probability of scattering, consequently, to increasing of the corresponding transport coefficients. The pseudopotential model taking into account the screening effects and quantum effects of diffraction of dense semiclassical plasma was used [1]. The temperatures and densities change in the following ranges:

$$T = 10^5 \div 10^7\,\mathrm{K}, \quad n = 10^{21} \div 10^{24}\,\mathrm{cm}^{-3}.$$

The object of research is the fully and partially ionized hydrogen plasma. At such parameters the electronic component becomes degenerate. For definition of phase shifts the Calogero equation was solved. The phase shifts at semiclassical approximation were calculated for comparison. The cross sections were determined by phase shifts, and it is compared with the Born approximation and, also with cross sections obtained on the basis of other pseudopotential models.

The transport coefficients were defined by a Chapman-Enskog method. The diffusion, electrical conductivity and thermal conductivity of fully and partially ionized plasma were obtained. At small coupling parameters the curves of the transport coefficients approach to the Spitzer approximation. The comparison with results of Ishimaru, Hansen and other authors was made. There are also a comparison with data of the molecular dynamics (MD) and experiments. The results of presented work are in good agreement with them.

1. T.S. Ramazanov, K.N. Dzhumagulova Phys. Plasmas **9**, 3758 (2002)

P5. DC electrical conductivity of weakly non-ideal plasma in magnetic field: experimental techniques and obtained results

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Experimental results of measuring DC electrical conductivity of weakly non-ideal plasma placed in magnetic field are presented. Plasma generation technique is based on gas compression and heating behind front of shock wave. We used explosively driven linear generators. Magnetic field was produced by discharge of capacitor through solenoid reeled on generator channel. DC electrical conductivity of plasma was determined by two and four contact techniques.

P6. Classical bound states in thermodynamics and optics of non-ideal Coulomb systems and plasma

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Till now the problem of construction of chemical models of non-ideal Coulomb systems, such as plasma, model of the charged spheres and Coulomb model with forepart, is not solved. Chemical models allow to test different theoretical models to account of free charges Coulomb interaction and to use them further at calculations of different properties of real dense plasma. It is necessary to note, that for atomic plasma and charged spheres system a number of chemical models are used in the literature [1, 2], distinguished from each other by a choice of the partition function of the bounded states and doublets. The problem of chemical model for model with forepart was not investigated. In the present work the new concept basic chemical models is introduced. Their distinguishing feature is the exact correspondence of expression for a free energy in chemical model to the results obtained within the physical model for the grand thermodynamic potential [3, 4]. Thus, it turned out possible to formulate, for a first time, the theoretical procedure for matching the calculation of the thermodynamic properties of weakly non-ideal plasma within physical and chemical models. We used the Plank-Larkin approximation (PLA) and the nearest neighbor approximation (NNA) for the calculation of the atomic partition function to derive relations for all thermodynamic functions, equations of state and ionization equilibrium for atomic plasma. Comparison with experiment [5] for cesium, argon and xenon plasma is carried out. Basic chemical models for the charged spheres system and model with forepart are constructed using the theoretical approaches [6]. It is shown that, using the nearest neighbor approximation for calculation of the doublets partition function of the charged spheres system, corrections of free charges interaction differ from the corrections given by Debye theory. For model with forepart the ionization degree as applied to numerical experiments is calculated and comparison with results [7] for internal energy is executed.We calculated thermodynamic and optical properties of hydrogen weakly non-ideal plasma on basis of bound states density analysis.

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P7. Measurements of electron concentration of dense plasma in contracted microwave discharge on surface of dielectric

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We studied electrodeless microwave discharges excited by a pulsed microwave radiation (power up to 2 MW, frequency 2 GHz, pulse duration up to 10^{-5} s) on surfaces of organic glass in vacuum ($P \approx 10^{-4}$ Pa). Different types of electrodeless microwave discharges were observed: (1) secondary-electron-emission microwave discharge, (2) surface microwave breakdown taking the form of a contracted discharge, and (3) plasma-flare microwave discharge. We found that the most intensive optical radiation occurs during the stage of the electrodeless microwave breakdown. The source for this radiation is the dense plasma of the contracted discharge, the typical lifetime of this discharge being $\approx 10^{-7}$ s. The emission spectrum of the contracted discharge consists of hydrogen, carbon and oxygen spectral lines. We obtained that at the stage of a contracted discharge, the halfwidth (FWHM) of the Balmer-alpha line (wavelength is centered at 656.3 nm) of atomic hydrogen reaches 7 nm, whereas at the stage of a plasma-flare discharge the halfwidth of this line does not exceed 1 nm. Under the experimental conditions, the main mechanism for the broadening of the Balmer-alpha line is the Stark effect due to the electric microfields produced by ions and electrons in dense plasma of contracted microwave discharge. Using the experimental profiles of the Balmer-line of atomic hydrogen, we obtained that for the contracted microwave discharge the electron concentration reaches the value of 2×10^{18} cm^{-3}, whereas during the stage of the plasma-flare discharge it does not exceed 5×10^{16} cm^{-3}. The research described in this publication was made possible in part by Award No RU-P1-2594-MO-04 of the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union (CRDF), and by the Russian Foundation for Basic Research (project No 03-02-17140).

P8. Measurement of the electron-ion thermal equilibration rate in a strongly-coupled plasma

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We are conducting a laboratory experiment aimed at measuring the temperature equilibration rate between ions and electrons in a strongly-coupled plasma. Theory indicates that this rate could be significantly (≈ 50 times) lower than that given by the usual weakly coupled model (Landau/Spitzer) due to coupled collective modes present in the dense plasma. The plasma under study is formed by heating a hypersonic SF_6 gas jet with a short pulse (≈ 10 ps) laser, resulting in warm electrons (≈ 100 eV) and cold ions (≈ 5 eV). The electron and ion temperatures of the resulting plasma will be independently measured during and after heating, using collective Thomson scattering for electrons and a high-resolution x-ray spectrometer for the ions (measuring Doppler-broadened absorption lines). Determining how the equilibration rate varies from Landau/Spitzer requires very fast diagnostics, since Landau/Spitzer equilibration would occur within ≈ 100 ps. We will present our most recent experimental results.

P9. X-ray-line plasma satellites of ions in a dense plasma produced by picosecond laser pulse

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The X-ray lines of ions in a solid target interacting with picosecond laser pulses of moderate intensity (2×10^{17} W/cm^2) were measured on the Neodim laser facility [1]. X-ray Lyman-alpha emission spectra of hydrogen-like fluorine ions were observed. Plasma satellite lines were also observed, evidencing the presence of intense electrostatic oscillations. The positions and separation between the satellites allow their assignment to the intense electrostatic oscillations with the frequency of about 7×10^{14} s^{-1} that is noticeably lower than the laser frequency $\omega_{las} \approx 1.8 \times 10^{15}$ s^{-1}. It is suggested that these oscillations may be due to strong plasma turbulence caused by the development of plasma oscillations of the Bernstein-mode type under the action of a strong magnetic field generated in plasma. Using the comparison of experimental profiles of spectral lines of hydrogen-like fluorine ions with a set of theoretically calculated profiles, we deduced typical amplitude of electric field of electrostatic oscillations: $E = (4 - 6) \times 10^8$ V/cm.

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P10. Aluminium plasma excited by Bessel beam

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The extended plasma channels are generated in gases as a result of optical breakdown by diffraction-free laser beams (Bessel beams). The beams are produced when laser radiation is focused with a conic lens (an axicon) and have strongly peaked pump-intensity distribution over long length along propagation axis. The same channels can be formed on surface of a solid state target placed in vacuum. The threads of multi charged plasma obtained contain ions that emit light in vacuum ultraviolet and X-ray range. Hence, the novel technology can be used for gain medium creation. Tight focusing of heating radiation (better than 10 μm) and large extent of focal volume (aspect relation is more than 10^4) are ensured big gain length production and good X-ray output directionality, as expected. Besides, the travelling wave scheme for short pump pulse (running focus regime) is easily realized when an axicon is applied. The higher conversion efficiency of pumping energy in comparison with spherical or cylindrical lens use opens a new approach for table top X-ray laser elaboration.

Experimental observation and numerical analysis have been performed to develop the technology proposed when aluminium plasma was excited by Bessel beam. In the experiments a compact Nd-glass laser (wavelength 1.054 μm) with a telescopic amplifier was used. Its maximum energy amounted 5 J in 6 ns pulse. The pump emission was focused by an axicon on Al target (foil or slab) mounted in vacuum chamber along Bessel beam axis. The inclination angle between heating rays and target surface was 19°. The light intensity in the focal region was 10^{11}-10^{12} W/cm^2. In this case the plasma channels formed were up to 4 cm length. The width of track on the target observed with a microscope after irradiation by laser pulse was about 6-8 μm. The plasma emission spectra in visible and VUV ranges were recorded. Grazing-incidence spectrographs were used in VUV-range. It was founded that neon-like Al ions and other species were presented in this plasma. The shortest wavelength measured belonged to 12.6 nm line of Al V. Some CCD-images of plasma channels were also obtained.

The self-coordinated spreading of Bessel beam in Al gas at 0.1 atm pressure have been simulated by means of mathematical modeling. As a result 2-D distributions of plasma parameters evolution during aluminium ionization by nanosecond laser pulse have been calculated. It was shown the electron temperature was achieved $30 - 40$ eV under pump laser intensity about $5 \cdot 10^{11}$ W/cm^2 near the main field maximum of Bessel beam. This was enough to obtain 3–4 degree of ionization. The calculations based on a radiational-collisional model of quasi-stationary plasma have been carried out that predicted the lasing in neon-like aluminium ions inside $120 - 130$ nm region.

As the investigations show, the extended channel of multi-charged plasma formed by Bessel beam is an intense source of the VUV and XUV radiation. The results will be used to produce X-ray laser based upon fundamentally new technology.

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P11. To the theory of Cherenkov radiation from short laser pulses in a magnetized plasma

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The Cherenkov electromagnetic radiation excited by a short laser pulse propagating along the external magnetic field in underdense plasma is considered. The spectral, angular and power characteristics of emitted waves are studied. It is shown that, the strong radiation is generated by tightly focused laser pulses. This radiation is directed backward and has the frequency near to the upper hybrid frequency, which corresponds to the terahertz range in real conditions.

P12. Strongly coupled thermal plasma with electric current

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Experiments demonstrate that the number density of atoms of alkaline addition agent in the plasma does not vary at small currents. However number density of atoms decreases with intensity of 0.4% on 1 μA at the further magnification of the current. It means magnification of an ion number density as the requirement of maintenance of quantity of an addition agent should be constant. Calculations show that the not perturbing current is restricted to thermal velocity of ions, because the collision frequency in plasma does not vary while the drift velocity of electrons is less than thermal velocity of ions. However magnification of the current gives in diminution of frequency an electron - ionic collisions that entails diminution of the recombination rate. Thus an ionization rate remains invariable in the low-temperature plasma. The solution of the continuity equation allows to obtain the nonequilibrium number density of charge carriers outside of the space charge layer as function of the current. The presented model gives good concurrence of the measurement data and the calculations.

P13. Numerical simulations of two-component model plasmas

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To investigate the properties of two-component ion-electron plasmas (TCP), model plasmas with a regularized Coulomb potential are considered. In these model systems basic quantum diffraction effects are approximated by modifying the Coulomb interaction at short distances. While a real ion-electron plasma requires a quantum treatment the model systems can be treated by classical mechanics. This allows to study these systems by powerful classical methods like molecular dynamics (MD) simulations, which are particularly suited for investigating the dynamic properties of strongly coupled systems and to verify results of analytical treatments.

Recent results of MD simulations of such two-component model plasmas are presented for the dynamic structure factor $S(k,\omega)$, the dynamic conductivity $\sigma(\omega)$ the electric microfield distribution and spectrum, and the pair distribution functions. They are compared to various standard treatments as well as recently developed theoretical approaches like e.g. the RPA, DLFC and Born-Mermin approximation [1] for $S(k,\omega)$ and $\sigma(\omega)$, a modified APEX treatment for the microfield distribution, and numerical solutions of the HNC scheme for the pair distribution functions. To illuminate the role and influence of the attractive ion-electron interaction special attention is paid to the sensitivity of the different observables on a variation of the regularized interaction.

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P14. Thomson scattering using the VUV-FEL at DESY Hamburg

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The scattering of photons in plasmas is an important diagnostic tool. The region of solid-density plasmas can be probed by x-ray Thomson scattering. The scattering cross section is related to the dynamic structure factor $S(k,\omega)$. We improve the standard treatment of the scattering on free electrons within the random phase approximation (RPA) by including collisions. $S(k,\omega)$ is calculated via the dielectric function at finite wavenumbers which can be obtained by using a generalized Mermin ansatz. The dynamic collision frequency is treated in Born and Lenard-Balescu approximation. We show that theoretical description beyond the RPA is crucial to obtain reliable results for the plasma parameters. These results are important for experiments planned at the VUV-FEL at DESY Hamburg.

P15. Effect of runaway electrons in nonideal fully and partially ionized dense plasma

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In investigation properties of plasma under external electric field there are serious problems due to natural phenomenon of runaway electrons in the system; these superthermal electrons determine velocities of ionization and excitation of plasma neutral components in comparison with plasma electrons. In a tokamak plasma runaway electrons are generated above a critical energy due to a decrease in the Coulomb collision frequency with the electron energy. Since these electrons are collisionless in practice, they keep gaining energy from the toroidal electric field until synchrotron radiation losses become sufficiently large. Therefore, high energy runaway beams can be formed that constitute a serious threat to tokamak vessel structures, especially during disruptions. For this reason, a very active field of research has opened up during the last few years on runaway electrons [1, 2]. Mechanism of runaway electron formation in plasma becomes now of particular importance for achieving of subnanosecond electron beams with record current amplitudes at atmospheric pressure [3]. In this connection one needs to analyze the probability of runaway electrons in a system when investigate physical properties of nonideal plasma under external electric field and when run numerical simulations of their properties [4].

In the present work for description of interaction between charged particles we have used the pseudopotential taking into account three-particle correlation in a charged particle system [5], also we used the well-known effective screened polarized Buchingham potential as the model potential of charged–atom particles interaction in partially ionized nonideal plasma.

The paper reports on a study of electron runaway for nonideal plasma in external electric field. Based on pseudopotential models of nonideal fully and partially ionized plasma there are derived the conditions of runaway electrons. The friction force acting on electrons as a function of their energies is determined on basis of Coulomb logarithm. It has been shown that the probability of runaway electrons in partially ionized plasma increases in comparison with fully ionized plasma. The results are compared with data of asymptotic theories.

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P16. Effective polarization interaction potentials of the partially ionized dense plasma

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The knowledge of effective interaction potentials is necessary for the reliable description of processes in plasma. It is necessary to take into consideration many particle interactions because of the Coulomb force between charged particles has the long-range character. However, at high densities when average distance between particles becomes comparable with their de Broglie wavelength, it is necessary to consider quantum effects of diffraction and symmetry at short distances too.

In the present work the partially ionized hydrogen plasma ($n_e = 10^{20} - 10^{24}$ cm^{-3}, $T = 10^3 - 10^7$ K is considered. The method of a dielectric function was used for obtaining of the pseudopotentials. The Coulomb and the Kelbg-Deutsch-Yukhnovsky models were taken as micropotentials. The potential similar to the Buckingham potential was obtained by consideration of system of ions and dipoles with the interaction micropotentials of the Coulomb type. In the second case the other interaction pseudopotentials between atom and charge were obtained. They take into account quantum mechanical effects between different sorts of particles: first pseudopotential takes into consideration quantum mechanical effects only between charges, second pseudopotential – also between atom and charge.

$$\Psi_{ea}(r) = -\frac{e^2\alpha}{2r^4\left(1-4\lambda\!\!\!^-{}^2/r_D^2\right)}\left(e^{-Br}(1+Br)(1-B^2\lambda\!\!\!^-{}^2) - e^{-Ar}(1+Ar)(1-A^2\lambda\!\!\!^-{}^2)\right)^2$$

$$\Psi_{ea}(r) = -\frac{e^2\alpha}{2r^4(1-4\lambda\!\!\!^{-}{}^2/r_D^2)}\left(e^{-Br}(1+Br) - e^{-Ar}(1+Ar)\right)^2 \quad ,$$

where A, B are coefficients, α is polarizability of atom.

The taking into account of quantum mechanical effects between charge and atom influences considerably on effective interaction potential. The second pseudopotential is finite at short distances similar to the Buckingham potential.

Thus, in this work the effective polarization interaction potentials between charge and neutral are obtained, they take into account screening effects at large distances as well as quantum effects at short distances.

Warm Matter

T3. Shock compression of low density SiO_2 aerogel and equation of state for silica at high pressures and temperatures

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Thermodynamic properties of shock-compressed dense strongly coupled plasma are interesting for analysis of physical processes under extreme conditions of high energy densities as well as for development of fundamental knowledge on characteristics of matter over a broad region of phase diagram. In this work experimentally investigated is compression of low density silica SiO_2 aerogel in shock waves. Strongly coupled plasma states with densities $\rho \approx 0.8$–$0.2\rho_0$, where $\rho_0 = 2.65$ g/cc is normal density of quartz, and temperatures $T \sim 16$ kK are generated by shock compression of aerogel samples of initial densities $\rho_{00} \approx 0.33$, 0.19, 0.15, and 0.08 g/cc up to pressures $P \sim 13$ GPa. We have measured compressibility and temperature of shocked samples. We propose a new semiempirical equation of state for silica with taking into account the melting, evaporation, and ionisation effects. The critical analysis of calculated results in comparison with the newly acquired and available [1–4] at high pressures and temperatures experimental data is made.

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T4. Electrical conductivity and thermodynamic functions of aluminum in the metal-nonmetal transition region

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The pulse Joule heating technique [1] was utilized to study the hot aluminum passing from the liquid to gaseous state at supercritical pressure. Electrical conductivity and a complete set of thermodynamic quantities (characterizing completely thermodynamic state of the sample) were measured in a process when the pressure is maintained at a level of 10–40 kbar and density decreases from the normal solid density down to a density 20–30 times less.

Thin aluminum foil strips tamped by sapphire plates were rapidly heated by means of a pulse current. The experimental technique has ensured a sufficiently homogeneous heating and 1D expansion of the foil samples (the sample material moves mainly in the direction perpendicular to the foil). The current through the sample, the voltage drop across its length and the pressure near the sample surface were measured directly during the process. From the measured quantities the electrical conductivity, internal energy, and density were obtained. Density was determined solving a 1D hydrodynamic task describing the movement of a piston when the pressure at the piston position is a known function of time. As the equation of state for sapphire is known with a good precision the displacement of the piston and therefore the density of the sample material can be well determined. The pressure was measured using the ruby luminescence line shift technique [2].

Present results demonstrate the character of the dependence of the electrical conductivity of aluminum on density and internal energy in the metal-nonmetal transition region. The data obtained are compared with recent results of the molecular dynamics simulations based on finite-temperature density functional theory.

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P17. Disordered and self-organized interelectrode complex plasma of vacuum discharge: hard x-rays and DD microfusion neutron yields

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We continue to study the features of random interelectrode dusty-like media in low energy table-top nanosecond vacuum discharges [1]. These complex plasma ensembles of high power density are generated by an intense energy deposition into the cold solid density but very low volume dusty "target" collected specially in interelectrode space (nucleated clusters, nano - and microparticles of different size from anode material). This foam-like erosion "target" could be forming automatically behind of anode flare [2] at the chosen discharge conditions after high voltage applied during the pre-breakdown stage. Current-carrying stage is accompanied by intense emission of hard x-rays from interelectrode complex plasma ensembles. Operations with ensembles of clusters, generation of energetic ions and DD neutrons, trapping and release of fast ions and/or x-rays and self-organization effects are the subjects of our study [3].

The neutrons from collisional DD microfusion, as well as modeling of some interstellar nuclear burning (like oxygen "burning") due to microexplosive nucleosynthesis are discussed. The estimated value of neutron yield from DD fusion at interelectrode space of nanocecond vacuum discharge is variable and amounts to $10^5 - 10^7/4\pi$ per shot (isotropy approximation) under 1 J of total energy deposited to create all discharge processes [3]. In a limiting case of total trapping of fast deuterium ions by the dense "cloud" of clusters under hard x-rays diffusion inside (complex plasma "microreactor"), the neutrons yields may be two order of magnitude higher than for experiments on DD fusion driven by Coulomb explosion of laser irradiated deuterium clusters [4].

Note particular regimes of neutron yields as nanosecond bunches as well as self-organization effects for clusters ensembles themselves. At these diffuse regimes the hard x-ray yield is much lower in spite of higher density of clusters in ensembles. Self-organization effects are accompanied usually by enhanced pulsating yield of neutrons. The nature and reproducibility of these regimes are the subject of present study.

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P18. Analysis of properties of dense non-ideal plasma during the process of recycling centers of explosion emission a cathode spot of vacuum arc

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Non-stationary processes on a cathode and at a near cathode area of a vacuum arc analyzed. Such processes can result in periodicity of occurrence of centers of emission in a cathode spot. This problem is of interest from the point of view of physics of extreme state of matter as an example of transition from condensed state to non-ideal plasma. The interaction of plasma with a surface of the cathode is considered. The phenomenon of a layer of cathode falling is investigated(studied). The density of particle fluxes, momentum and energy shaped in a layer and falling on the cathode are evaluated. Two performances, corpuscular and field will be used. The field performance through tensors of tensions of the Maxwell and vector Umov-Pointing is connected to features of motion of charged particles in a layer. Is displayed, that a major factor is the energy flow from return electrons emitted from plasma in the party of the cathode. The radiation from plasma and Bremsstrahlung of return electrons driving in a layer of cathode falling is taken into account. The model contraction of an electric current in a spot is offered. The conducted analysis allows to evaluate the microcharacteristics of a cathode spots directly which are not observed in experiment, and average macrocharacteristics, which one can be compared to experimental data. The offered model by a natural image explains a phenomenon of a converse motion of a spot in a magnetic field, behaviour of microparticles which are taking off from area of a cathode spot.

P19. Studying of electrical parameters at explosion of micron diameter wire

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Influence of wire material on the wire explosion in the media under nanosecond voltage parameters has been studied and the results are presented in the paper. 25 micron Al, Ni, stainless still, Cu, Mo and W wires were exploded in the air and water using a pulser based on a low inductance capacitor with current rise time 50–200 ns. Discharge parameters (load voltage, load current, current derivative) have been measured under charging voltage of the capacitor varying from 5 to 25 kV. Wire conductivity during discharge was measured and energy deposition in wire was determined. Phase transitions were clearly seen on scope signals and studied. Data about a discharge channel formation in dependence on the wire material and the discharge media have been presented and analyzed.

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P20. Influence of equation of state on interpretation of electrical conductivity measurements in strongly coupled tungsten plasma

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Electrical explosion of metals under the action of powerful current pulse is an effective technique to investigate thermophysical properties of matter at high energy density [1]. We can determine the resistance from experimental oscillograms of current and voltage. Solving the set of 1D hydrodynamic equations under the assumption of sample homogeneous we can obtain temperature and volumetric dependencies for the specific electrical conductivity. It is obvious that in this approach the dependence of electrical conductivity both on temperature and density is determined by the equation of state used in the calculations.

In this work we simulated the heating of tungsten foil squeezed between thick glass or sapphire plates by current pulse (its time dependence can be found in work [2]). We used wide-range multiphase equation of state for tungsten $F(V,T)$ (where F is the Helmholtz free energy, V is the specific volume, and T is the temperature), which described a lot of experimental and theoretical data [3]. We also used simple caloric equation-of-state model $E(V,P)$ [4] (where E is the internal energy, P is the pressure) to describe tungsten properties. The results of calculations differ from those presented in [2]; in particular, electrical resistivity in present work is always higher than that in [2] (by 25% at most). However, it is necessary to mention that available models for the electrical conductivity could not let us reproduce in simulations experimental oscillograms of the current and voltage especially in the region of metal–dielectric transition even qualitatively. The development of an adequate model of the electrical conductivity is one of our aims for future research.

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P21. Pressure measurements for tungsten wire explosion in water

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Results of measurement of pressure generated at electrical explosion of micron-scale wire in water are reported in the current paper. Electrical explosion of tungsten micro-conductors under effect of current pulses with duration 0.1 mks and amplitude of several kA have been studied. Pressure pulse has been measured at the distance of 3 to 15 mm from exploded wire. Piezoceramic pressure sensors were calibrated using stable generator of shock waves lasting for microseconds. Sensors were made with maximum size 3 mm to minimize 2D effects. Experimental data will allow construction of plasma equation of state.

Technique for measurement of pressure pulses generated by electrical explosion of micro-wires in dielectric medium has been developed. Amplitude versus time pressure profiles have been measured for two modes of electrical explosion of tungsten wires in the water having specific resistance minimum 120 $\mathrm{kOhm} \cdot \mathrm{cm}$. Measurements have been made at the distance ranging from 3 to 25 mm. Measurements at smaller distance are complicated by electromagnetic interference. We have observed a strong difference, at least by 300%, in the amplitude and shape of pressure pulse when specific energy put into exploded wire was increased by 60%. The special attention will be paid to measurements of tungsten plasma electric conductivity.

Experiments have been performed for determination of parameters of equation of state for tungsten electrical explosion products.

P22. *Ab initio* study of optical properties of shock compressed Silica and Lithium Fluoride

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The equation of state and the optical properties of shock compressed silica and LiF are investigated using Quantum Molecular Dynamics in a wide range of pressures and temperatures along the principal Hugoniot. For silica, the increase in reflectivity occurs at about 100 GPa and saturates around 40%. For LiF a pressure of 600 GPa is needed to observe a significant reflectivity, but no saturation is observed. Our results are in close agreement with the experimental measurements [1] and can be described using a simple model of thermaly excited electrons across a band gap.

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P23. Temperature of plasma in Silica-based fibers under the action of CW laser radiation

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Although the process of optical discharge propagation through the fiber under the action of laser radiation (also known as fiber fuse effect) was observed for the first time in 1987 [1], only recently the first time-resolved pictures of this process were obtained [2, 3]. High-speed photography of the discharge region showed that the shape of the plasma volume varies essentially with the power of laser radiation in the fiber. Apparently, other parameters of the discharge, such as temperature, also depend on the power of discharge maintaining radiation. The only experimental estimation of the temperature of optical discharge plasma in a fiber (to the best of our knowledge) has been performed so far in [4], where the temperature was estimated by measurement of the discharge plasma radiation spectrum. Although the radiation spectrum was essentially different from that of a blackbody, the blackbody approximation was used to evaluate the temperature, which turned out to be 5400 K.

In this paper, measurements of discharge temperature at laser radiation powers in the range of 2 to 40 W have been carried out. Also the velocities of discharge propagation have been measured under the same conditions. The optical discharge was driven by a CW ytterbium fiber laser with maximum output power of 100 W at the wavelength of 1072 nm. In order to measure temperature of the hottest, head part of optical discharge, we recorded the spectrum of plasma radiation propagating through the optical fiber towards laser source (in the same direction as the optical discharge itself does). In this case the radiation of colder plasma parts is screened by the hot plasma region. In all experiments, throughout the entire range of laser radiation powers, and for both fiber types the radiation of optical discharge plasmas represented a continuous spectrum, with the shape very similar to that of a blackbody.

It has been shown experimentally, that the spectrum of plasma radiation of an optical discharge propagating through a silica-based fiber is close to that of a blackbody. The temperature of the plasma has been measured for various laser radiation powers in the range of 2-40 W (corresponding intensity range: 6-300 MW/cm2) by investigating its spectrum. Plasma temperature increases steadily with the power of laser radiation launched into the fiber, and reaches 10000 K in the fiber with MFD=4 mcm at 40 W laser power. Measured simultaneously with temperatures, the velocities of discharge propagation provide initial data for the analysis of the physical mechanisms of discharge propagation.

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P24. Reflectivity in dense plasmas

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For diagnostics of plasmas, the interaction with radiation is a main tool. Reflection, absorption and emmission as well as inverse bremsstrahlung and stopping power are used to get information about plasma parameters and scattering processes. In dense plasma, many-particle effects which are manifested as correlations and in-medium effects are relevant. A systematic approach for the theoretical description of dielectric and optical properties of dense plasmas is given within linear response theory [1]. The dielectric function is expressed in terms of thermodynamic Green functions, which can be evaluated using perturbation theory. Molecular dynamics simulations are used to check the validity of our results [2]. It is found that for plasma parameters below 1 the approximations used in our analytical approach are justified.

The reflectivity on shock-compressed plasma is calculated and compared with experimental results on Xe [3] which have been observed for three different wavelengths. It is found that the shock wave front has to be considered as a density profile with a spacial extension of about μm. Reflectivity measurments at different wavelengths can provide information about the density profile. Within hydrodynamic considerations [4] and simulations (package MULTI), microscopic processes which lead to a finite shock wave front are discussed.

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P25. Experimental research of combined thermal and laser detonation wave mechanism of plasma generation in vacuum

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The laser ablation phenomenon and strong shock wave technique are widely used for generating of low-temperature plasma with various chemical and ionization compositions for plasmachemistry and spectrochemical analysis, macrostructure modification technology, etc. [1–3]. The results of experimental research and numerical simulation of the efficiency of combined thermal and laser detonation wave mechanism of plasma generation in vacuum using laboratory scale double-stage repetitively pulsed plasma-laser generator of erosion type with two beams solid state laser modulus are presented.

Experimental set up, diagnostic equipment and numerical codes are described. Laser pulsed plasma generator (LPPG) unit: target block, connected with fuel supply system, detonation wave chamber and acceleration/nozzle block with two optical channels of laser radiation input and laser module generated two pulsed beams (I — Nd:glass laser, $E_{L1} \sim (1-2)10^3$ J, $\lambda_{L1} \sim 1.06\ \mu$, $\tau_1 \sim (0.8-1)10^{-3}$ s, $I_{01} \sim (10^5 - 10^9)$ W/cm^2; II - Nd:YAG laser, $E_{L2} \sim (10-50)$ J, $\lambda_{L2} \sim 1.06\ \mu$, $\tau_2 \sim (1.5-5)10^{-7}$ s are characterized. Experimental and theoretical analysis of main successive physical phases of plasma generation is presented (stage I — laser ablation plasma generation and heating; stage II — acceleration of dense plasma flow): ablation to form the initial gas flow (wave of evaporation); ignition of plasma at localized ignition sites (wave of ionization); coalescence of localized plasma to form a single laser supported detonation (LSD) wave; propagation of the LSD wave; expansion and acceleration of plasma flow. The thermodynamic, optical and radiative gasdynamic processes of interaction of laser radiation with solid state (Al, Mo, $(CH_2O)_n$) targets of different forms in quasionedimensional experimental statement have been investigated. The results of research of the macrostructure and dynamics of erosive vapors, LSD - wave and phase transitions (solid - liquid - gas - plasma) are discussed. To evaluate LSD wave (and near sonic radiative wave) maintenance criteria — a computational scheme was developed, which can calculate the structure of steady state waves in various gases and mixtures; to calculate generator performance (I_{sp}/E_{L1}) during the SW acceleration phase. The conditions of optimum laser energy input into target block (first stage) together with solid microparticles and metal drops separation, without plasma screening of laser radiating flow to target, as functions of are determined. Few engineering decisions for supporting of laser induced wave of active surface evaporation are presented. These results have been used for determination of requirements to temporal evolution of laser impulses, pulse laser radiation density distribution for optimal ablated solid consumption rate and effective heat transfer coefficients $K_{HT}(\tau, I_{01})$ on Al, Mo, W, $(CH_2O)_n$ — targets of various forms in laser train of double pulses with frequency repetition.

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P26. Numerical modeling and experimantal research of interaction of ultra-soft X-ray radiation with heterogeneous targets

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Mechanical action of ultra-soft pulse x-ray radiation represents big practical interest [1, 2] and can be used for getting high pressures and temperatures in substance [3]. Magnitude and distribution of pressures and temperatures can be varied both by change of parameters of an influencing radiation pulse and by variation of properties of target material. The big opportunities for variation properties represent modern heterogeneous materials (HM) [4]. The physical processes proceeding in low-temperature plasma, formed at irradiation of HM, are rather various and role of each of them in formation of parameters of radiation mechanical action in details is not investigated. Because of absence of wide range equations of state for HM the construction of adequate numerical model is not possible without carrying out of experimental researches. In the present work the technique of carrying out of such researches on installation Angara-5-1 [3] is offered.

Results of experiments are used for specification of physical model for interaction of ultra-soft radiation with HM and for modernizations of a numerical code [2]. Results of calculations and their comparison with experimental data for heterogeneous coverings with binder made from microspheres covered with tungsten are represented. Influence of various physical processes (enlightenment of plasma, carry of energy by electronic heat conductivity and thermal radiation, difference of electronic temperature from ionic) on parameters of mechanical action is numerically investigated. The special attention is given to studying of influence of gauge film and attenuation of pressure wave in the condensed part of a target on measured parameters.

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P27. The determination of HF dielectrical permeability and the coefficients of refractivity and reflectivity of dense non-ideal plasma in optical spectrum region

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On the basis of existing values of electrical conductivity of dense plasma in the external HF electrical field, here are presented several opticaly measurable parameters of dense plasma in the region of electric concentrations $10^{21} \leq N_e \leq 10^{23}$ cm^{-3}. For such plasma the real and imaginary part of electro-conductivity is used as a initial value for the calculation of the dielectric permeability, refractivity and reflectivity coefficients. The selecte parameters and their form of representation are suitable for experimental verification and further usage. The examined range of frequences cover the IR, visible and near UV region.

P28. The calculation of electronic transport coefficients of metals in the process of transition from liquid to plasma

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The model of calculation of electronic transport coefficients (electrical conductivity, thermal conductivity, thermopower) for non-alkali metals in the process of transition from liquid to plasma is considered. There are a number of successful models in the region of partially ionized plasma ($\rho < 1$ g/cm^3 and $T > 10000$ K), confirmed by up-to-date experimental data [1, 2]. The same statement can be done about liquid region [3], where one can successfully apply Ziman theory for simple metals ($\rho \sim$ normal density and $T < 10000$ K).

But there were no rigorous theoretical models and measurements in the transition region, excluding for *ab initio* calculation [4]. The results of measurements for tungsten and aluminum [5, 6], recently obtained, showed the necessity of transport coefficients calculation in this region.

So, the model for calculation of these transport coefficients is offered on the base of model [7, 8], that was applied to dense liquid and fluid region. The results of these calculations were compared with the results of other theories and measurements.

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P29. Femtosecond laser ablation and Newton rings

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All nontransparent substances in pump-probe experiments show universal behavior with beautiful Newton rings [1]. These interference rings appear in a range of incident fluencies $F^{inc}_{low} < F^{inc} < F^{inc}_{up}$, where F^{inc}_{low} and $F^{inc}_{up} \sim 1$J/cm^2 are lower and upper thresholds. In the pump-probe technique weak probe (diagnostic) pulse follows main, heating or pump pulse with variable delay from $\sim \tau_L$ to several ns. Typical pulse duration τ_L is $\sim$ 100 fs. The interference rings are seen in reflected probe light.

Explanation of this remarkable physical phenomenon has been obtained in [2]. It was shown that probe beam reflects at two sharp (large density gradient) surfaces the bottom of a crater and a spallation shell - and the reflected beams interfere. This is the finest *nanoscale spallation* never seen in previous experiments. The shell is very thin and therefore partially transparent for a probe beam. Its thickness is comparable to a skin depth $\delta_{skin} \sim 10$ nm. In experiments with shocks and more massive objects penetration of light through thick spallation shell is impossible. In the pump-probe experiments the rings play the same role as Doppler shift measurements of velocity in case of more massive objects (e.g., VISAR technique). They allow to measure velocity $u_{shell}(t)$ of the spallation shell.

In the early works [2] a simple case of a homogeneously heated foil has been considered. Here we report the results of much more elaborated calculations. Several hydrodynamics and molecular dynamics numerical codes have been used. New multiprocessor approach to molecular dynamics calculations allows to simulate very large number of particles (up to $4 \cdot 10^7$). A behavior near the lower and upper thresholds is studied. The ratio $F^{inc}_{up}/F^{inc}_{low}$ increases together with the critical to triple temperatures ratio T_{crit}/T_{triple} : larger the temperature ratio - then wider range of fluencies at which the Newton rings exist. Influence of EOS and strength of material is considered. We study absorption of laser light and electron heat wave propagation in metals to define the heating profile. The role of geometry (i) thin foil, (ii) semi-infinite target, (iii) film on a substrate, (iv) thick foil - is studied. Influence of temperature profile (i) the exponential skin layer type v. (ii) Gaussian heat conduction type profiles - is analyzed. The thresholds depend on EOS, material strength, profile and geometry.

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P30. Coulomb explosion in a solid dielectric on medium boundary

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The Coulomb explosion takes place with an output of dense non ideal plasma localized at a head part of the channel of the nanosecond discharge, to the boundary of vacuum, gas and fluid. The plasma contains the ions with a medial degree of ionization $3 \leq Z_{med} \leq 5$ and parameter of non ideality $\Gamma_{ii} \geq 20$. The energy distributions of Coulomb explosion in mediums are explored observationally. The models of Coulomb explosion are offered. The obtained values of density of energy are compared with parameters of dense non ideal plasma.

Astrophysics and Dense Hydrogen

I3. Recent progress in dense astrophysical plasmas: giant planets, White Dwarfs, neutrons stars

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In this review, I will give an overview of recent results in the theory of dense coulombic plasmas in the context of compact astrophysical bodies. The review will address in particular the impact of the equation of state of hydrogen and helium for giant planet interiors, the description of carbon pressure ionization in the envelope of white dwarfs and the effect of magnetic fields on the thermodynamic properties of neutron stars and the consequences on the cooling of these objects.

I4. Monte Carlo simulations of dense quantum plasmas

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Strongly correlated Fermi systems and their equilibrium properties at high pressure are of growing importance in many fields. Among the phenomena of particular current interest are the high-pressure compressibility of deuterium, metallization of hydrogen, Wigner crystallization, plasma phase transition etc., which occur in situations where both *interaction and quantum effects* are relevant and a crossover from a neutral system to full ionization takes place.

The analytical approaches to studies plasmas and the Coulomb systems are mainly applicable at low density and high temperatures as they are usually based on perturbation theories. So numerical quantum path integral Monte Carlo (PIMC) method has been developed for studies of dense plasma systems. Using this concept, the pressure and energy of a degenerate strongly coupled quantum system have been computed as well as the pair distribution functions in the region of partial ionization and dissociation. The results are compared with available theoretical methods. One of the most striking recent results was the observation of droplet formation in dense plasma below $T \lesssim 20,000$ K which confirmed previous chemical picture results about the plasma phase transition.

A theoretical Hugoniot obtained by combining results for the equation of state (EOS) from the PIMC and those from Reaction Ensemble Monte Carlo (REMC) simulations. The resulting Hugoniot is located between the experimental values of Knudson *et al.* and Collins *et al.*.

When electrons in a solid are excited to a higher energy band they leave behind a vacancy in the original band. Such holes behave like positively charged particles. The formation and dissoziation of electron-hole and hole-hole bound states in strongly coupled mass-asymmetric electron-hole plasmas have been investigated by means of PIMC simulations. Density-temperature regions have been found for the existence of excitons, bi-excitons, many-particle clusters, and hole/electron-liquid. The Mott transition to the metallic state is detected. Results are discussed in relation to the excitonic phase diagram of intermediate valent Tm[Se,Te]. It was predicted that holes can spontaneously order into a regular lattice in semiconductors with sufficiently flat valence bands.

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I5. Equation of state of weakly nonideal plasmas and electroneutrality condition

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A detailed independent derivation of hydrogen weakly-nonideal plasma EOS is presented. The impetus to this work was the demand for high accuracy of the EOS of the solar plasma in relation to the problems of modern helioseismology, accuracy sufficient for reproducing the velocity of sound on the Sun from optical measurement results with errors not exceeding 10^{-4}. The existing equations for the second virial coefficient in the expansion of the Helmholtz thermodynamic potential for a system of electrons and protons in powers of activities of these particles involve certain procedures for the removal of the arising divergences that provoke questions and require independent verification.

The analysis of electrical neutrality condition in terms of activities and concentrations is presented. It is shown how to modify the relation between activities and concentrations for removing divergences of Hartree contribution, representing first order correction due to Coulomb interaction in plasma. For the conditions of the Sun trajectory and for brown dwarfs it is shown, that widely used practice of ignoring neutrality condition in terms of activities, taking Hartree contribution into account, gives maximal error for plasmas pressure of the order 10^{-5}.

The suggested EOS is used to qualitatively estimate the accuracy of various physical and chemical models. For the model hydrogen plasmas the values of computed sound velocity and adiabatic exponent along the Sun trajectory are presented. In our computations the relativistic corrections, degeneracy of electrons, radiation pressure in plasma, Coulomb interaction in Debye-Huckel approximation together with diffraction and exchange corrections, and the contribution of bound and scattering states are taken into account.

T5. Impact of impurity sedimentation on cooling of White Dwarfs

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The endpoint of evolution of the vast majority of stars is the white dwarf phase in which nuclear fuel no longer burns, residual energy radiates away, and the star slowly cools. The cooling process in white dwarfs is, not only important for astrophysics, but is also interesting in its own right because it calls for detailed knowledge of thermodynamic and transport properties of dense, strongly-coupled plasmas. Indeed, white dwarfs are made of a dense core of fully ionized mixtures, mainly carbon and oxygen, sustained against gravitational collapse by the pressure of degenerate, relativistic electrons; the core is surrounded by thin surface layers of helium and hydrogen which regulate the energy outflow. Under these extreme conditions,

ions in the core are strongly coupled and constitute the main reservoir of internal energy which evolves as follows. As thermal energy is gradually lost from the star, ion motions lose amplitude and become strongly correlated: the ionic state evolves from a gas to a fluid to a solid, thereby modifying the thermal energy content of the star and delaying or accelerating the cooling evolution. Recently, it has been suggested [1] that, because of a neutron excess, the cooling may be strongly delayed by the gravitational settling of ^{22}Ne impurities in liquid white dwarfs interiors, a mechanism previously overlooked. The uncertainty, however, in the microphysics produces a large uncertainty in the possible impact impurity sedimentation may have on white dwarf evolution. We used particle-particle particle-mesh molecular dynamics simulations to provide the unknown microphysics, in particular the transport properties of highly correlated (quantum) plasmas. Simple models treat the sedimentation of ^{22}Ne as diffusion in a classical, strongly coupled ionic plasma immersed in a uniform neutralizing electron background; such a model suffers from uncertainties in the diffusion coefficient, which cannot be obtained via standard plasma kinetic theory. We first assessed this uncertainty by computing the diffusion coefficient over the entire strongly coupled fluid regime. The calculations also revealed very interesting features of the diffusion across the liquid-solid phase boundary: the diffusion undergoes either a sharp (discontinuous) drop or a smooth (continuous) decrease at the liquid-solid transition depending on whether the system is crystalline or in an amorphous (glassy) state. That allowed us to explore the consequences of white dwarfs interiors not crystallizing but instead undergoing a transition to a glassy state. An analytical model was developed to extend the results into the quantum regime. These results were extended to the more realistic and challenging situation of (dissymmetric) ionic mixtures. These findings and their impact on the cooling process will be discussed.

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T6. The equation of state for the interior of the Sun

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Helioseismology has become the most successful diagnosis of the equation of state for the plasma of stellar interiors. Inside the Sun, the plasma is only weakly coupled and weakly degenerate. However, the great observational accuracy of the helioseismic observations puts nevertheless strong constraints on the nonideal part of the equation of state. For solar and stellar modeling, a high-quality equation of state is crucial. But the inverse is also true: the astrophysical data put constraints on the physical formalisms, making the Sun and the stars novel laboratories for plasma physics. In the 1980s, helioseismology allowed to verify the major nonideal effect (Debye-Hückel screening). Since then, the signature of relativistic electrons, effects of excited states, and details of the pressure-ionization mechanism have become observable, revealing a promising potential for even finer effects.

T7. First principles simulations of dense hydrogen

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A discussion of the high-pressure, low-temperature phase diagram of hydrogen will be presented, based on the results of recent first principles molecular dynamics simulations [1–4] and quantum Monte Carlo calculations [5]. In particular, the discussion will focus on the hydrogen melting line and the appearance of a maximum as a function of pressure [1], on a recently predicted liquid-liquid phase transition, and on the hydrogen and deuterium Hugoniot up to several hundreds GPa [2, 3]. A brief discussion of the influence of strong magnetic fields on the equation of state of hydrogen will also be given [4].

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T8. Path-integral Monte Carlo calculations of helium and hydrogen-helium plasma thermodynamics and deuterium shock Hugoniot

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In this work we present new results of *ab initio* calculations of thermodynamic properties of nonideal Coulomb systems. The calculations were made by path-integral Monte Carlo method in a cubical cell using periodic boundary conditions [1]. To correctly take into account exchange effects at high values of the degeneracy parameter we used a special correcting procedure which considers these effects not only in the main Monte Carlo cell but also in its nearest images. It allowed us to increase significantly the accuracy of computations at relatively high densities. In the work a deuterium shock Hugoniot is calculated by path-integral Monte Carlo method at pressures higher than 1 Mbar. We compare the results with experimental data and calculations by other methods. In this work we also performed modeling of thermodynamic properties of hydrogen-helium plasma with helium concentration corresponding to that in the higher layers of the Jovian atmosphere at temperatures from 10^4 K to $2 \cdot 10^5$ K and electron particle densities from 10^{20} to 10^{24} cm^{-3}. At temperature higher than $5 \cdot 10^4$ K the calculation results are practically coincides with computations by the equation of state based on the chemical plasma model [2]. However at temperatures 10^4 and $2 \cdot 10^4$ K in the density range from 0.5 to 5 g/cm^3 we found a phase transition region positioned in a good agreement with other theories and the experimentally revealed region of the sharp electrical conductivity rise. Along the isotherm 10^4 K in the density range from 0.01 to 0.2 g/cm^3 we found one more region of bad convergence to the equilibrium state; an explanation of this phenomenon is not found yet. We also present first simulation results for helium plasma in comparison with other models and experimental data.

The work is done under financial support of the RAS program No. 17 ”Parallel calculations and multi-processor computational systems” and CRDF grants. The authors are also grateful to the Russian Science support foundation.

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T9. Study of thermodynamic and optical properties of deuterium under shock and quasiisentropic compression

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Experimental data on the shock and quasiisentropic compression, temperature, and absorptivity of gaseous deuterium with an initial density close to its value in the liquid state is represented. In shock experiments strongly compressed states of deuterium were obtained on a spherical explosion shock-wave generator in a pressure range of $80 - 90$ GPa. States in a pressure range of $75 - 300$ GPa were achieved under quasiisentropic compression. The obtained results are compared with the existing experimental and theoretical data, obtained in frames of model the relatively simple compressible covolume and modified plasma chemical model.

T10. Nonideal strongly magnetized plasmas of neutron stars and their electromagnetic radiation

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The neutron stars can be considered as natural laboratories for studying the properties of matter under extreme physical conditions. In their cores the density ρ may exceed 10^{15} g/cm^3. Their thermal emission depends on the properties of the outer envelopes with $\rho < 10^{10}$ g/cm^3 and magnetic field B up to 10^{15} G (most often $B = 10^{12} - 10^{13}$ G). The spectrum of this emission forms at ρ from 0.001 to 10^6 g/cm^3, depending on the chemical composition, B, and temperature T. To produce spectra that can be compared with the observations, one should take into account nonideal plasma properties in neutron-star envelopes, in particular, partial ionization in the atmosphere, and the effects of strong magnetic fields on the properties of the plasma and electromagnetic radiation.

We develop models of neutron-star envelopes that take into account the nonideal plasma effects. The total thermal flux from the surface sensitively depends on chemical composition and in some cases on

the magnetic field [1]. In order to calculate the spectral distribution of this flux, we construct models for the envelopes of strongly magnetized neutron stars in thermodynamic and radiative equilibrium [2–4]. We show that bound-bound and bound-free transitions give an important contribution to the opacities in the outer neutron-star atmosphere layers and may strongly affect the polarization properties of normal waves in specific frequency ranges. Detailed calculations are performed for a model of a partially ionized nonideal hydrogen plasma. In this case, the full account of the coupling of the quantum mechanical structure of the atoms to their center-of-mass motion across the magnetic field is shown to be crucial for the correct evaluation of the polarization properties and opacities of the plasma. It is however possible that the radiation (at least in some spectral ranges) emerges from a liquid or solid phase boundary, which lies below a thin atmosphere. This case is considered in [5], where the spectral flux from condensed, strongly magnetized hydrogen or iron plasma is calculated. Using these results, we calculate the spectra and polarization of thermal radiation for magnetized neutron stars, which can be compared with observations.

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T11. Thermodynamic and transport properties of dense H-He mixtures

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Hydrogen and helium as the most abundant elements in the universe are of special interest for astrophysical studies of, e.g., the interiors of stars and giant planets. Furthermore, using strong shock-waves, hydrogen and deuterium targets are compressed to ultra-high pressures of several megabars in order to demonstrate inertial confinement fusion in the laboratory. Therefore, precise knowlegde of the equation of state (EOS) and of the transport properties is needed for a large domain of densities and temperatures.

We present theoretical results for the EOS and the transport properties of hydrogen-helium mixtures at high pressures. Based on the chemical picture, the EOS of hydrogen and helium is determined within fluid variational theory considering dissociation [1] and ionization processes [2]. We compare with available experimental data and other theoretical predictions. The discussion of the Hugoniot curves derived from shock-wave experiments is of central importance in this context [3]. These results are also used to model interiors of giant planets such as Jupiter.

The composition of the system derived from the EOS serves as input in calculations of transport properties such as the electrical conductivity within linear response theory. The nonmetal-to-metal transition in hydrogen [4] and in noble gases [5] can be explained by pressure ionization. Comparison with experimental data shows good overall agreement.

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P31. Solar plasma. Calculation of thermodynamic functions and equation of state

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On basis of the chemical picture, the SAHA-S equation of state (EOS) of stellar plasma is presented. Thermodynamic functions of solar plasma were calculated in wide ranges of density and temperature. Extended element composition includes hydrogen, helium, carbon, nitrogen, oxygen, neon, silicon and iron. Components of model include atoms, diatomic molecules, electrons and ions with ionization degrees from single to fully ionized species more than 90 components. Using computer code SAHA-S, especially designed for calculations of thermodynamics of multi-components non-ideal plasmas, calculations of components distributions and thermodynamic functions of solar plasma has been performed for densities up to 200 g/cm^3 and temperatures up to $2 \cdot 10^7$ K. Plasma effects were analyzed sequentially to show an influence on the adiabatic compressibility along solar radius from surface to the center of the Sun. Recombination of ions, Coulomb interactions of charged particles with exchange and diffraction corrections, relativistic effects and pressure of radiation were taken into account. Calculated data, alternative EOS-models and new data of helioseismology has been compared. Influence of plasma effects on adiabatic exponent was demonstrated in different parts of solar trajectory. It was shown that reduction of heavy elements abundance could lead to matching of theory data and result of helioseismic inversion.

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P32. Multiparticle statistical approach to solar wind modeling

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The kinetic models of the solar wind are developed on the base of the one- and two-particle distribution functions (e.g. [1], [2]).

The multiparticle statistical approach to modeling of expanding plasma flow is suggested. The method is tested by classical problems (fluctuations in the homogenous ideal gas and Boltzman distribution function).

The developed method is applied to the description of the solar wind as a collisionless steady and spherically symmetrical flow of a quasi-neutral fully ionized plasma. The equilibrium plasma state at the boundary (close to the base of the solar corona) is accepted. The analytical dependences on the heliocentric distance for the statistic moments (number density and flow speed) are derived on the base of the multiparticle distribution functions in the frame of the mentioned assumptions. The dependences obtained for the two-component solar wind coincide with the respective results of the two-particle kinetic model [3] and consist with the observed data [4].

The fluctuation distribution function is also developed on the base of the considered approach. The character of this function depends on the scale applied for averaging the multiparticle distribution function. This can result in qualitative differences of observed particle energy specters because of different space resolving power of measurements or scales of data processing.

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P33. Experimental determination of the conditions of insulator-conductor transition of H_2-He mixtures, modeling the Saturn and Jupiter atmospheres

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The intensity of optical radiation and resistance of a hydrogen-helium mixture layer with He mass fraction $Y = m_{He}/(m_{He} + m_H) = 0.24$, 0.16 which correspond to the composition the outer layers of Jupiter and Saturn atmospheres, were simultaneously measured under multiple shock compression up to 100–164 GPa in plane geometry. The initial pressure was varied from 4 to 8 MPa and temperature was maintained at 77.4 K; the velocity of steel strikers was equal to 4.7, 5.2, and 6.2 km/s. The experimental data were compared with the 1D hydro code simulation of the compression process using the equation of state for the mixture in a model proposed in [1]. The experimental data were also compared with the behavior of pure components under isentropic compression to megabar pressure having the same initial densities as those of mixtures.

This work was supported in part by Russian Fund for Basic Researches Grant # 04-02-16790.

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P34. Simulation of hydrogen plasma with combined multi-range interpolation

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In the present work we use the newly developed Combined Multi-Range Interpolation (CMRI) of interaction potentials to simulate hydrogen plasma using Molecular Dynamics. The scheme combines different interaction models, designed for the description of specific particle configurations in the given distance or connectivity range to automatically produce a single smooth parametric potential suitable for describing reactive systems of arbitrary number of particles. The interpolation is based on variative mixing of atomic cluster connectivity within given atomic system described by coordinates of atoms. It can also be used as a universal switching function between short-ranged bonded and long-ranged non-bonded potentials without interfering into the potentials definition. The CMRI energy $U(\mathbf{R})$ is an ensemble mixture of a set of connectivity configurations S, each having its weight $P(\mathbf{R})$ as a smooth function of particle coordinates:

$$U(\mathbf{R}) = \sum_S P_S(\mathbf{R}) U_S(\mathbf{R}),$$

$$U_S(\mathbf{R}) = \sum_{C_S} U^{N_{C_S}}(\mathbf{R}) + \sum_{C_S^1 \neq C_S^2} \sum_{a \in C_S^1, b \in C_S^2} U^{\mathrm{NB}}(R_{ab}),$$

$$\sum_S P_S(\mathbf{R}) = 1,$$

where $U^N(\mathbf{R})$ and $U^{\mathrm{NB}}(R_{ab})$ are N-particle bonded and pair-additive non bonded potentials respectively.

The use of potential interpolation based on connectivity allows to treat the collisions of small number of particles (up to 2 ions and 3 electrons together) by more accurate empirical models and treat such processes as ionization or molecule formation by means of MD simulation. Note that this is usually not possible by simple pair potentials and inclusion of quantum effects is necessary. The CMRI scheme is used to combine the following interactions into the smooth many-particle potential:

- interaction between 2 protons surrounded by 1 to 3 electrons is described by Morse potentials
- interaction between 1 to 3 electrons with 1 to 2 protons at small distances is described by flat pseudopotentials
- interaction between electrons in the molecule (close to protons) is zero
- interaction between all particles at large distances is desribed by Coulomb potential.

The construction of the scheme and the results of MD simulations are discussed. Comparison between CMRI approach and other simulations and experimental data is performed.

P35. Microscopic and thermodynamic properties of a dense semiclassical partially ionized hydrogen plasma

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In present work the microscopic and thermodynamic properties of dense semiclassical partially ionized hydrogen plasma were investigated. At investigation of the nonideal plasma properties the knowledge of a interaction potential is necessary. We consider the dense semiclassical partially ionized hydrogen plasma consisting of electrons, ions and atoms. Number density is considered in the range of $n = n_e + n_i = 10^{20} - 10^{24} cm^{-3}$, and the temperature domain is $10^5 - 10^7 K$.

The pseudopotential model taking into consideration the quantum-mechanical and screening effects was used for the description of interaction between the charged particles and presents in following form [1]:

$$\Phi(r) = \frac{Ze^2}{\sqrt{1 - 4\lambda\!\!\!^{-}{}^2/r_D^2}} \left(\frac{e^{-Ar}}{r} - \frac{e^{-Br}}{r} \right),$$

where $\lambda\!\!\!^{-} = \hbar/\sqrt{2\pi m k_B T}$ is the thermal de Broglie wave-length, $r_D = \sqrt{k_B T/4\pi n_e e^2}$ is the Debye radius, A and B is coefficients.

The influence of atoms to thermodynamic properties of a partially ionized plasma increases with decreasing of free electrons number density. The Saha equation was solved for obtaining of plasma ionization stages at the different number density and temperature.

The screening version of the Buckingham's potential was chosen as a model potential of charge - atom particles interaction in partially ionized nonideal plasma [2].

Radial distribution functions (RDF) were investigated on the basis of system of the Ornstein-Zernike integral equations. Using this RDF we can calculate the exception of pressure from thermodynamic expressions which is determined as:

$$P = nk_BT - \frac{2}{3}\pi \sum_{a=i,e,n} n_a \sum_{b=i,e,n} n_b \int_0^\infty \frac{\partial \Phi_{a,b}(r)}{\partial R} g_{a,b}(r) r^3 dr.$$

The equation of state results in dependence of coupling $\Gamma = e^2/ak_BT$ and density $r_s = a/a_B$ parameters are presented as the diagrams.

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P36. Pseudopotential approach to ionization equilibrium and equation of state of partially ionized hydrogen plasmas

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Starting from the Bogolyubov hierarchy for the equilibrium distribution functions, a novel approach to the chemical model of partially ionized plasmas is proposed. Unlike the ordinary chemical picture it allows one to determine, in a self consistent manner, both the ionization equilibrium and correlation functions as well. It is shown that the charged and neutral components of the plasma are closely interrelated and, as a consequence, the short-range order formation turns possible.

Radial distribution functions and structure factors are studied in a wide range of plasma parameters. Behavior of the radial distribution functions shows strong evidence of the short-range order formation in the system of interest.

The equation of state of partially ionized hydrogen plasmas is investigated and detailed comparison with an exact quantum-mechanical expansion is made. The approach developed is quite analogous to the Debye theory of weakly coupled fully ionized plasmas and includes it as a limiting case.

P37. Rigorous formulation of nuclear reactions in a plasma

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The powerful methods of quantum field theory are brought to bear on plasma physics. The technology of real-time thermal field theory is employed to reveal the structure of plasma corrections to nuclear reactions. Previous results are recovered in a fashion that clarifies their nature, and new extensions are made. Brown and Yaffe have introduced the modern methods of effective quantum field theory into plasma physics. These methods are used to treat the interesting limiting case of dilute but very highly charged particles reacting in a dilute, one-component plasma background. Although the background plasma is weakly coupled, the highly charged particles are very strongly coupled to this background plasma. The effective field theory methods show that a classical field solution to the Debye-Huckel equation with a point source, an “ion-sphere” model, provides, in field theory language, the tree approximation. The effective field theory proves that this is the dominant effect, with the higher loop corrections making smaller and smaller contributions even though the problem is one that involves the strong coupling limit. Thus, the effective field theory places a physically reasonable model in a rigorous context and shows explicitly that the corrections to this model may be neglected.

P38. Equation of state for dense noble gases and hydrogen — application to planetary interiors

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The knowledge of the equation of state of hydrogen and hydrogen-helium mixtures is important for modeling, e. g., planetary interiors. For this, accurate equation of state data is required for high pressures up to several megabars and temperatures of several thousand Kelvin, also known as warm dense matter. We calculate the equation of state for hydrogen and noble gases (He, Ar, Xe) within fluid variational theory considering dissociation processes self-consistently and ionization in addition. Effective pair potentials are used to describe the interactions between the species. We compare with available simulations and shock-wave experiments.

The results are also used to describe interiors of giant planets as Jupiter within a hydrostatic model considering rotation. The helium abundance and the gravitational moments are used to probe the consistency of the equation of state.

Dusty Plasmas

I6. Complex (dusty) plasmas: theory and experiment

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Complex (or Dusty) Plasmas are a new field of research interesting from an experimental as well as from a theoretical point of view. The charged microparticles, which form the complex plasma with the surrounding electrons and ions, interact strongly and can form crystalline or fluid systems due to their Coulomb interaction. They can be observed on the most fundamental — the kinetic level. This allows the study of processes on the dynamic scale, to identify generic features of complex plasmas and transfer them into other disciplines (e.g. into soft matter, condensed matter, fluid dynamics, cooperative phenomena, quantum physics etc.). In this presentation I will overview the newest experimental and theoretical developments in the field of complex plasmas. As examples I will show the first kinetic measurements of shear flows the development of turbulence, a new non-equilibrium phase transition (two-stream flows), kinetics of crystallisation fronts and the first observations of the onset of cooperative phenomena in fluid flows (nanofluidics). I will discuss these observed processes theoretically and will compare the results with results from numerical simulations.

T12. Two-dimensional Yukawa liquids: structure and collective excitations

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We report a series of Molecular Dynamics (MD) simulations on two-dimensional, strongly-coulped many-particle systems interacting through a Yukawa potential. An effective coupling coefficient $\Gamma^\star$ for the liquid phase is introduced on the basis of observing the constancy of the first peak amplitude of the pair correlation functions. The solid-liquid transition of the system is investigated through the analysis of the bond angular order parameter. The solid-liquid phase boundary - i.e. the dependence of $\Gamma_{\rm m}$, the coupling parameter where melting takes place, on the screening parameter κ of the Yukawa potential - is found to be well approximated by $\Gamma^\star = \Gamma_{\rm m}^{\rm OCP}$, where $\Gamma_{\rm m}^{\rm OCP}$ is the melting-Γ for a Coulomb system [1].

We present thermodynamic properties of the systems: internal energy and pressure (with emphasis on the $\Gamma^\star$ - κ dependence of the correlational contributions). The compressibility is calculated in two independent ways: first, one is making use of the equation-of-state (through taking a derivative of the pressure), second, we analyze the long-wavelength limit of the static structure function $S(k = 0)$ and invoke the compressibility sum rule. Comparising results from the two methods provides an important check on the consistency and accuracy of the computation [2].

Dynamical spectra of density-, and current fluctuations are also provided by the simulation. From these we infer the dispersion for longitudinal (L) and transverse (T) collective modes. A comparison with the predictions of the quasilocalized charge approximation (QLCA) theory [3] shows excellent agreement, except for a finite wavenumber cut-off in the T-mode, which is believed to be a consequence of diffusional-migrational effects that are not included in the QLCA theory. Using the QLCA theory we have calculated longitudinal and transverse sound velocities and Einstein frequencies for the system. The almost perfect fulfillment of the 0-th and 2-nd frequency moment sum rule provides a second independent check on the accuracy of the simulations [1, 4].

The plasma dielectric function and the velocity autocorrelation function give additional information about the collective behavior of 2D Yukawa plasmas [2].

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T13. Structural transition of dusty plasma Coulomb crystal like martensitic transformation

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Three-dimensional duty plasma Coulomb crystals were formed by monodisperse carbon fine particles grown and suspended in a methane/argon plasma. The structures of the crystals were bcc-like and fcc-like. The lattice constants and the structural transition from bcc-like to fcc-like was analyzed by using two CCD video cameras from the top and side. The images of the arrangement of fine particles were taken at the same time.

The bcc-like structure was observed with (110) planes horizontally parallel to an electrode. The ratio of longer to shorter side length of a rectangle formed in a (110) plane was 1.50:1. The ratio of the shorter side to the distance between the lowest and the third lowest layers of (110) planes was 1:1.49. Therefore the bcc-like structure can be regarded as bct (body-centered tetragonal) one. The fcc-like structure was observed with (111) planes horizontally parallel to an electrode. The ratio of the triangle side formed in a (111) plane to the distance between the lowest two layers of (111) planes for the fcc-like structure was 1:0.82. The ratio for fcc one is calculated to be 1:0.816. Therefore the fcc-like structure is regarded as fcc one.

The transition of the bct structure to fcc one was observed by the slip of crystal planes with the (011) planes of bct and the (111) planes of fcc parallel to an electrode. The slip was occurred to the direction of the [011] axis of bct and the [211] axis of fcc. This process of transition between bct and fcc and the relations of the crystal planes and the axes agree with the martensitic transformation of Nishiyama's scheme, which is observed when iron changes the structures between the austenite (fcc) and the martensite (bcc or bct) phases in the process of hardening and tempering. The result suggests that a dusty plasma Coulomb crystal behaves like a metallic crystal and can be a good model for a real atomic crystal.

T14. Structure and transport phenomena in dusty plasma liquid

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The physical properties of nonideal dissipative systems are of significant interest in various fields of science and engineering (hydrodynamics, plasma physics, physics of polymers, medicine, etc.). The major problem encountered in studying such systems is associated with the absence of an analytical theory of liquid that would be capable of explaining its thermodynamic properties, describing the heat and mass transfer, etc. Unlike real liquids, laboratory dusty plasma is a good experimental model for studying the properties of nonideal systems. This plasma is a partly ionized gas with charged particles of the dispersed phase (1-10 μm in size), which may be recorded by a video camera; this enables one to investigate the processes of heat and mass transfer on the kinetic level.

Results are given of experimental investigation of three-particle correlation for liquid plasma-dust structures formed in the electrode layer of a capacitive rf discharge. The obtained three-particle correlation functions for experimental and numerical data are analyzed and compared with the superposition approximation. The forming of clusters of macroparticles in plasma-dust systems being analyzed is revealed. The dynamics of dust vortices was analyzed experimentally. An empirical approximation was obtained for the radial distribution of angular velocities of macroparticles. It was shown that, in the presence of a considerable gravity force, a slight variation of the charge of macroparticles is sufficient for the formation of their vortex motion.

The experiments in heat transfer were performed in plasma of a capacitive radio-frequency (rf) discharge in argon ($P = 20$ Pa) with particles 3 to 5 μm in diameter. The first time the heat-transfer coefficients for liquid dust structures in plasma were measured. The temperature dependence of these coefficients agrees qualitatively with the results of analysis based on the constancy of relations between the basic transfer coefficients. The quantitative difference of the measurement results from the results of numerical calculations performed for monatomic liquids may be caused by the loss of energy of dust particles due to their collisions with neutrals of surrounding gas. The radial distribution functions of quasiliquid dusty plasma in rf discharge has been obtained from videotape recordings of experimental object. With the help of special procedure the parameters of Debye potential between dust particles have been estimated. The calculations of radial distribution functions of dusty plasma with Debye potential with these parameters have been made using hypernetted chain integral equation. The results are in a good agreement with experiment at low coupling parameters. The agreement becomes worse while the coupling parameter increases. This work was supported by by the Russian Foundation for Basic Research (Grants No.03-02-17240 and No.04-02-08150), by CRDF (Grant No.RU-P2-2593-MO-04) and by NWO (Project 047.016.020). Two of authors (O.F. Petrov and O.S. Vaulina) are granted by the Russian Science Support Foundation.

T15. Equilibrium properties of 2D Yukawa plasmas

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In dusty plasmas, we often have purely two-dimensional systems of dust particles which are levitated near the boundary of bulk plasma and the sheath by a balance between the gravity and the electric field. In these systems, dust particles can be regarded as interacting via the repulsive Yukawa potential. By controling the temperature, we are able to realize two-dimensional Yukawa systems with different strengths of mutual coupling.

We have investigated thermodynamic quantities of the uniform (infinite) two-dimesional Yukawa system. In the domain of weak coupling, we apply Mayer's giant cluster expansion. This generalizes the previous analysis for two-dimensional Coulomb system by the author. In the domain of strong coupling, the triangular lattices are formed. In the domain of intermediate coupling, we perform extensive molecular dynamics simulations. The combined results are then expressed in simple interpolation formulas over a wide domain of coupling and screening.

In dusty plasma experiments, the number of dust particles is finite and they are confined by a parabolic potential in directions within their two-dimensional system. At low temperatures, particles are organized into a triangular lattice with many defects. When the number of particles is not small, the structure is characterized only by the distribution function along the radial direction. Based on the result obtained above, we are able to reproduce the structure of these finite two-dimensional Yukawa systems, including the case of finite temperatures. The results are summarized in the form of expressions which give estimations of characteristic parameters of the system from observed structures. Applied to experimental observations, these expressions are shown to be useful.

The dynamic properties of two-dimensional finite and infinite Yukawa systems will also be discussed.

T16. New paradigm for plasma crystal formation

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Three general principles of complex (dusty) plasmas can be formulated as: 1) The sytems are open and non-Hamiltonian with varying charges and with presence of collective attraction of grains. 2) Nonlinearity in grain screening is always large. 3) All complex plasma systems are divided in 2 classes by criterion of their size L being less or larger then the mean free path for ion absorption on grains. Plasma crytals observed in experiments are the structures of the second class. Contrary to usual plasmas where the electrostatic screening is described only by electrostatic field in complex plasmas two field are important - the electrostatic field and the field of plasma flux. In the simplest case the polarization screening is described either by two exponents with different lengths or by an exponent and cos-type term (collective attraction). For non-linear screening the collective attraction is calculated by joining the non-linear screened potential with collective potential. Both the flux and the electrostatic field in the collective part of screenind are determined by the nonlinear screening. The collective potential determines the attraction well which localises the grain positions at distances larger then the non-linear screening distance. This localisation describes the phase transition to a crystal state. The location and deepness of the potential well is callculated in the case of non-linear screening. The coupling constant Γ is derived. The results are in good argeement with existing experiments for formation of plasma crystals in HF discharges, in striations and in dense plasmas at atmospheric pressure. The calculated inter-grain distances are in reasonable agreement with the observed values in plasma crystals. New paradigm of plasma crystal formation is related with violation of strong grain interaction, localization of grains outside the region of strong coupling and strong screening in a potential well due collective non-linear grain attraction. The new paradigm for plasma crystal formation is much simpler then referring to strong interactions with unknown properties and unknown methods of their description. The value of $1/\Gamma$ can serve in future as experimental measure of grain collective attraction.

P39. Dust thermal waves in complex plasmas

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We study waves in complex plasmas with varying kinetic temperature in the solid and liquid states in order to determine how the phonon spectra change. Experiments are performed in a capacitively coupled RF discharge at low Ar gas pressure. We disperse plastic microspheres (of $8.9 \pm 0.1\mu$m diameter) into the plasma to make a monolayer particle suspension. We control the kinetic temperature and the phase state of the particle suspension by adding a small amount of larger particles (they are levitated a few hundred microns

below the main layer and heat it due to an instability). Particle positions viewed by a digital video camera are recorded and traced to calculate their velocities [1]. We use an analytical theory and 2D molecular dynamic simulations to explain the observations.

The wave spectra are computed using Fourier transformation of the particles velocities both in time and space. At lower temperature (strongly coupled plasma), the results match well those measured in [1], [2]. As the temperature increases and the phase state of the plasma changes from solid to liquid, the phonon spectra of both longitudinal and transverse modes broaden (especially at high wave numbers) indicating increased damping. The transverse mode disappears and a thermal (compressional) mode which has been predicted in [3] appears. MD simulations closely reproduce the results of the experiment.

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P40. An experimental investigation of the heat transfer processes in dusty plasma

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The results are given of an experimental investigation of processes of heat transfer in liquid dust structures. The experiments are performed for particles of alumina in plasma of an rf-discharge. Under the experimental conditions, the dust cloud was initially an equilibrium liquid structure consisting of 13–15 dust layers. As a result of minor variation of the working parameters of the discharge (increase in power or decrease in pressure), one of the cloud edges was heated rapidly. The boundaries of the heated region expand during 10 s after thermal perturbation. Then, the dust system assumed a new equilibrium state and represented a liquid two-phase medium with a clearly defined interface between the low-temperature and high-temperature phases. The nonuniform distribution of the temperature of dust particles in plasma (including a highly non-isotropic distribution) is observed quite frequently. This phenomenon may be explained by nonlinear spatial variation of charges of macroparticles, which provides for the formation of internal heat sources in a dust structure. The results of analysis of steady-state and unsteady-state heat transfer are used to obtain the coefficients of thermal conductivity and thermal diffusivity. The temperature dependence of these coefficients is obtained, which agrees qualitatively with the results of numerical simulation for simple monatomic liquids. The quantitative difference of the measurement results from the results of numerical calculations may be caused by the loss of energy of dust particles due to their collisions with neutrals of surrounding gas. The main difference between the properties of simple liquids and plasma-dust systems is associated with the presence of dissipation of the energy of dust particles due to these collisions. No experimental or numerical data have been available heretofore on the effect of the friction forces on the processes of heat transfer in non-ideal systems. The relations between the shear viscosity, thermal conductivity, and diffusion constants were investigated for dissipative non-ideal systems. The analytical approximation for thermal conductivity coefficients in strongly correlated dust structures was proposed.

P41. Friction and diffusion for grains in Coulomb and neutral systems

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A self-consistent and universal description of friction and diffusion for Brownian particles (grains) in different systems, as a dusty plasma with ion absorption by grains, a gas with Boltzmann collisions and active particles (e.g. cells in biological systems) is considered on basis of the appropriate Fokker-Planck equation. Restrictions for the application of the Fokker-Planck equation to the problem of velocity dependent friction and diffusion coefficients are found. A general description of these coefficients is formulated on basis of the master equation. A relation between the diffusion coefficients in the coordinate and velocity spaces is found for active, i.e. capable of momentum transfer to ambient media, and passive particles in the framework of the Fokker-Planck equation. The problem of normal and anomalous spatial diffusion is formulated on basis of the appropriate probability transition function for diffusion (PTD-function). The method of fractional differentiation is avoided to construct the correct probability distributions for arbitrary distances, which is important for applications to different stochastic problems. A general equation for the time-dependent density distribution function, describing all known and some new mechanisms of normal and anomalous diffusion, is formulated and discussed. The application of this approach to plasmas is considered. The generalized friction in velocity space is determined and applied to describe the friction force itself as well as the drag force in the case of a non-zero driven ion velocity in plasmas. Negative friction (due to ion scattering on grains) exists and can be realized for the appropriate experimental conditions.

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P42. Shift equilibrium distributions in plasma with electric current

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Electron and ion distributions describe by Maxwell-Boltzmann equation which is a basis in the theory of the low-temperature plasma processes. However when electric current proceed through the plasma, in process of the dust particles charging for example, equilibrium distributions are not true for its description. That entails the electron and ion number densities balance breaking. It does not allow using the theory which based on balance in system. In presented report the influence of the electric current on the distribution function is studied. The contribution of drift to kinetic energy was used. On the basis of it, the additional parameter to equilibrium Boltzmann distribution function has been defined. Dependence of additional parameter on the electric current density obtained.

P43. Modelling of grain kinetics in dusty plasmas

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Here, we numerically investigate various kinetic characteristics of micron-sized dust grains in plasmas of gas discharge. We consider two-temperature stationary and moving plasma. For the simulation we employ particle-in cell (PIC) method when a heavy macroparticle is placed in the center of the simulation box and Newton equations are solved for the system involving also plasma particles. We simulate the process of charging of grain absorbing all electrons and ions colliding with its surface and obtain kinetic characteristics of the transitional and stationary regimes. We investigate the statistical properties of the charge fluctuations and their time correlations, the ion drag force and force between grains. The resonance charge exchange collisions are included in our code. The simulations made for two-temperature plasmas of argon and neon with various pressure and temperature of gas. The numerically obtained results allow us to analyze the kinetic characteristics of the charging process of a macroparticle in a plasmas as well as to model processes in laboratory experiments. The developed numerical method allows us to widely investigate the charging and behavior of dust particles for various conditions of a complex plasma. In particular, we obtain temporal characteristics of the particle charging as well as characteristics of the charge fluctuations as functions of the particle size and parameters of the plasma, for the cases of stationary and moving plasmas. These results are important for prediction of phenomena that could be observed in experiments.

P44. Transport coefficients for binary (ionic) Yukawa mixtures: theory and molecular dynamics simulations

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We present the generalization to binary (ionic) Yukawa mixtures of equilibrium molecular-dynamics computations transport coefficients of the Yukawa One-Component Plasma [1–2]. The simulations are performed within periodic boundary conditions and Ewald sums are implemented for the potentials, the forces and for all the currents which enter the Kubo formulas. Results includes shear and bulk viscosities, ionic thermal conductivity, electrical conductivity, diffusion (one component) and interdiffusion coefficients (mixtures). We will present the different coefficients and examples of simulations. We shall also compare our simulation results for large screening parameters with Chapman-Enskog theory.

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P45. Kinetic analysis of dusty component of complex plasma in RF-discharge

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As a rule, kinetic temperature of dusty component of dusty plasma crystal is determined via comparison observed distribution function (of macroparticles throughout velocity) and Maxwell one. In this report we would like to point some peculiarities of obtaining dusty component kinetic temperature. Macroparticles velocities are gained using video filming. In dusty plasma crystal dust grains oscillate near equilibrium position. According to estimations fulfilled frequencies of these oscillations could amount 10–100 Hz. Since picture frequency substantially exceeds dust grains oscillation frequencies we can obtain macroparticles velocities that coincide with their proper ones. Otherwise it can lead us to mistakes in dusty component temperature determining. Mean squared velocity determined experimentally and real mean squared velocity are connected with each other by the relation that includes oscillating frequency characteristic for macroparticles' motion. In the report estimations are represented for errors due to the effect scribed. Typical values of frequencies and amplitudes of macroparticles oscillations in dusty plasma solid structure are obtained.

P46. The measurement of heat-transfer coefficients for dusty plasma structures in RF-Discharge

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This work is devoted to investigation of heat transfer in dusty plasma liquid. Numerical estimations for such parameters as thermal conductivity, thermal diffusivity and thermal capacity coefficients of dust component in liquid state were fulfilled experimentally. In this work we have developed and applied the technique that allowed us measuring thermal capacity, conductivity and diffusivity coefficients of dusty plasma liquid. Thermal capacity dependence on non-ideality in the system concerned was also measured experimentally. The data for thermal conductivity and diffusivity have been obtained from the experiments during which stationary kinetic temperature (of dusty component) spatial distribution has been observed. Heat transfer study was based on kinematical analysis of dust grains (macroparticles) movement and on analysis of spatial distribution of dust concentration. Temperature and concentration distributions were obtained for different moments of time. This allowed studying of the processes taking place during time of the experiment. Stationary temperature distribution observed is characterized by presence of two domains, each domain having its own temperature. Intermediate region has approximately linear temperature distribution and permanent dust grains concentration. The latter allowed estimating thermal conductivity coefficient and thermal diffusivity for dusty component.

P47. Dusty plasma liquid viscosity investigation

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Laminar flow of dusty plasma liquid caused by laser beam pressure has been earlier investigated by us. Measuring of flow velocity profile allowed estimating the internal friction due to interparticles reciprocal action. This profile, obtained experimentally, is trapeziform. However Navier-Stokes equation for approaches with cylindrical symmetry requires essentially different profiles. The distinctions present in central region of flow and near its edges as well. In the central region the flow is piston-like. Parabolic form of velocity profile meets Navier-Stokes equation. The size of domain with moving dust exceeds the diameter of region affected by external action. This indicates the existence of critical shear tension, bellow the value of which there is no flow. This fact is verified experimentally. Since the value of laser beam power is less than 10 mW it is observed no flow in dusty plasma liquid under conditions used. The facts mentioned above tell us about non-newtonian character of dusty plasma medium. Moreover, dusty plasma seems to be the Bingham body. In the report presented theoretical analysis of laminar flow in dusty plasma is shown within the scope of viscoplastic Bingham liquid. In the work it is shown that laminar flow velocity profile for dusty plasma medium is described rather well by this approach. The comparison of theoretical profile with experimental data allowed evaluating the parameters of the approach concerned.

P48. Modelling of dusty plasma properties by computer simulation methods

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The investigation of dusty plasma properties has practical and fundamental interest. As well known the different gas, liquid and crystalline structures can be formed in such plasma. The phase state of such structures is related with diffusion processes of grains.

The applying of computer simulation methods is suitable way for investigation of dynamic properties. The difference between usual molecular dynamics and the Brownian dynamics consists in presentation of forces acting on the particles. Because of the size of dust particles is much larger than size of ion or atom their moving can be considered in hydrodynamics approximation. In this approximation the environment (ions and atoms) is taking into account as continuum. The forces acting on the dust particle are:
the force which is conditioned by interaction with other dust particles$\vec{F}_{int}(r)$;
the friction force appearing at moving of dust particle in homogeneous environment $\vec{F}_{fr}(t)$;
the random force is related with random pushes of plasma particles$\vec{F}_{br}(t)$.

It is known that stochastic random force depends on time step, we suggest to choose the normalize factor in random force on the following basis: at the right value of normalize factor the numerical data have to coincide with theoretical results. In this work the normalize factor was chosen by comparison the diffusion coefficient of system without interaction which was calculated on the basis of the Brownian dynamics with its theoretical formula. After that the interaction between grains was taken into account and different values such as the velocity's autocorrelation function, the diffusion coefficient, radial distribution function were calculated.

The convenient dialog interface of program was developed. Users can set up parameters and choose physical values. Computer graphics gives the opportunity to observe the particles moving and different structures formation in the dusty plasma.

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P49. Brownian dynamics study of grain charge fluctuations in dusty plasmas

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The goal of the work is to study the properties of grain charge fluctuations in dusty plasmas (DP) by means of the microscopic molecular dynamics simulations. As is well known, the steady grain charge experiences fluctuations near its average magnitude associated with the discrete nature of the plasma components. These fluctuations may strongly affect the properties of DP. The aim of the simulations is the basic features of the time autocorrelation function for the charge fluctuations. We consider a single spherical grain of a radius a embedded in a weakly ionized high pressure plasma background with the plasma-neutral collisions playing a major role. It is assumed that there are only two oppositely charged plasma components, e.g., ions and electrons, with the equal temperatures and the charge numbers being equal to ±1. The grain charge emerges as a result of the complete absorption of both types of plasma particles by the grain surface (i.e., due to the plasma currents) and the difference in electron and ion diffusivities. The plasma sources are assumed to be far from the grain (at infinity). The investigation of the grain charge dynamics is based on the Brownian dynamics method of computer simulations, which has been employed earlier (O. Bystrenko, A. Zagorodny, Phys. Rev. E67, 066403 (2003)) to investigate the problem of grain screening. Following this work, we employ the particle-in-cell method of simulations with concentric arrangement of spherical cells which allows for the spherical symmetry of the problem. The simulations have been performed for the following range of parameters: the ratio of electron-to-ion diffusivities $A = 10$; the dimensionless Debye radius. The coupling parameter defined as was within the range 0.1–0.01, and the number of plasma particles in simulations $N =$ 350–3000. In computer simulations, there have been examined the statistical properties of the system (charge variance, correlation time, charge correlator). It is found that these properties are close to the ones typical for systems being in the thermodynamic equilibrium. The simulations evidence that the correlations of fluctuations decrease exponentially with time while the correlation time is proportional to the squared Debye length. Within the accuracy of simulations, the charge variance is found to be equal to the inverse coupling parameter, regardless of the other parameters of the problem.

P50. Three-dimensional spherical dust crystals - theoretical and experimental results

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Spherically symmetric three-dimensional charged particle clusters are analyzed experimentally [1] and theoretically [2]. Based on accurate molecular dynamics simulations ground state configurations and energies for cluster for $N \leq 160$ are presented which correct previous results of Hasse and Avilov [Phys. Rev. A **44**, 4506 (1991)]. Further, the lower metastable states are analyzed for such clusters. Further, the melting temperature of these clusters is investigated for various particle numbers. As a second system, dust crystals produced in a systems with an adaptive electrode system are analyzed experimentally and theoretically.

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P51. Extended Monte Carlo data bases and simple analytical forms of the equation of state and the plasma properties of Yukawa fluids

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Monte Carlo (MC) simulation codes are very efficient for studying the thermodynamical and plasmas properties of a plasma, composed of classical point particles at thermodynamical equilibrium. MC simulations results allow to cover, for laser or astrophysical applications, a wide range of thermodynamical conditions from more dense(and correlated) to less dense ones (where potentials are long ranged type. It is why we developed, for opacity and equation of state applications, two MC codes, PDE and PUCE [1–4]. We shall resume here all issues of our two MC codes and give examples of wide conditions applications. We shall also present analytic fits suitable for large hydrocode or spectroscopic applications.

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P52. Dust crystals in plasma created by proton beam

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The first observations of dust grain crystal formation in plasma generated by slowing-down proton beam have been described. The use of beam obtained at accelerator considerably improved experimental conditions as compared to the nuclear-excited plasma. The experiments have been fulfilled for different gases (He, Ne, Ar, Xe, Kr). The dust grains behavior proved to depend on gas pressure considerably, whereas the dependence on its type was weak.

Electrostatic accelerator EG-2.5 at SSC RF-IPPE has been used for the experiments. Experimental cell had the form of rectangular parallelepiped with the basement of 16×16 cm^2 and height of 12 cm. The cell's side faces were made as glass windows, the dust structure behavior being observed through them using a charge-coupled TV camera. Horizontal proton beam was passed via titanium foil and diaphragm of 8 mm diameter.

Essential results of the experiment are as follows. Near the high-voltage electrode, in the paraxial area of the proton beam, a dense dust grain structure is formed with concentration of 5×10^7 cm^{-3}. The process of dust structure formation in proton beam takes about $2 - 3$ sec. The dust structures have a cylindrical symmetry in equilibrium, the maximum diameter approximately coinciding with the beam diameter. Dust structures were divided into separate areas with different character of dust grain movement. The structures can exist for dozens minutes or more. The structure is destroyed when the proton beam is closed and when the voltage applied to the high-voltage electrode is decreased or turned off.

The process of dust structure formation has a weak dependence on the gas sort, where pressure is below 15 Torr. At gas pressure less than several Torr, at the dust structure face turned to the high-voltage electrode, the dust component is crystallized at the distance of 1 cm from electrode. The crystal being formed has a simple cubical lattice with the distance between particles of 100 μm. Crystal structures have been obtained for all types of gases used in the experiment and for particles of different diameters.

A mathematical model has been developed accounting for the dust grain screening by plasma particles, the dependence of dust grains on their space position, and anisotropy of dust grains interaction associated with the drift ion flux focusing. The calculations have confirmed the possibility of dust grain crystal formation in plasma generated in the slow-down of proton beam obtained at accelerator.

We thank our colleagues for stable work of accelerator EG-2,5. The work is done under financial support of the RAS program No. 17 ”Parallel calculations and multiprocessor computational systems” and by Award No. PZ-013-02 of the U.S. Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF) and of Ministry of Education of Russian Federation.

P53. From interelectrode aerosol media to hard x-rays random lasers

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We create and study the random interelectrode dusty-like media in low energy nanosecond vacuum discharges. The foam-like erosion ”target” (nucleated clusters, nano and microparticles of different size from anode material) is forming automatically at chosen discharge conditions after high voltage applied during the pre-breakdown stage. Current-carrying stage is accompanied by emission of hard x-rays of different intensity from interelectrode complex plasma ensembles. Operations with ensembles of clusters, hard x-ray emission efficiency, generation of energetic ions, trapping and release of fast ions and/or x-rays, laser-like behavior and self-organization effects are the subjects of our study [1].

High power density ensembles of clusters are probable candidates for x-rays lasing media [2]. Partial and essential x-ray trapping by ensembles as well as random laser behavior of potentially amplifying media of interelectrode complex plasma are considered. Last scheme with non-resonant feedback by energy have been suggested much earlier by Letokhov [3]. (Note the increased interest to random lasers during last decade and some realisations at visible spectra [4]). In our case this scheme assumes the diffusion and partial ”random walk” of photons inside of x-ray ”ball” due to multiple scattering and reflecting in disordered media of cold and hot ”grains” of any sizes. When the volume gain if available overcomes the surface losses, hard x-ray burst may take place [3]. The properties of ensembles with observed strong hard x-ray bursts which could be interpreted as ASE regimes [2] or random lasing with non-coherent feedback [3] are analysed. The contrary specifics of particular complex ensembles like manifestation of well defined self-organisation, accompanied by absence of generated hard x-rays release, is considered also. Pulsating regimes of x-rays yields, radiation pressure effects, implications of Casimir like forces and ”laboratory astrophysics” based on interelectrode ”dusty” x-ray media at vacuum discharge are discussed.

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P54. Dusty plasma structures in an impulse magnetic field

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To study dusty plasma structures different kinds of influences, such as laser, electric, gas-dynamic ones, are widely used. Here we present a method and results of experiments on the imposition of an impulse magnetic field on the stratified dc glow discharge with the dusty component. Depending upon discharge parameters, namely, a current density and an electric field as well as a neutral gas pressure, we observe dusty structures with a different degree of the order and a dusty component density. The structures with stationary self-excited oscillations are also present. The characteristic times of a relaxation of such structures are limited by a dust acoustic frequency and are on the order of tens or hundreds of μs. For plasma electrons and ions a relaxation time is determined by the ion plasma frequency. For dc glow discharge conditions this time is in the range of several μs up to tens μs. Thus, if an impulse aperiodic magnetic field with a front duration less than 1 ms will be imposed on the plasma with a dusty component, electrons and ions react to the impulse applied “instantaneously”. But the dusty component is late to a change of plasma conditions. Changing a duration and amplitude of the impulse one can control plasma parameters and, hence, a character of dusty structures’ behaviour. The investigation of an influence of the impulse aperiodic magnetic field on dusty plasma structures has been performed with a help of an installation consisting of a discharge tube with a stratified dc glow discharge in neon. The flat coil is wound on the tube. The battery of high-voltage capacitors discharges into the coil. The discharge current amplitude reaches up to 200 A. The maximum magnetic field is up to 0.06 T. The scheme of the coil current supply allows to impose two successive impulses with a controlled delay between impulses of 10 up to 120 ms. The experimental set-up has been described elsewhere [1]. When the impulse magnetic field is applied to the glow discharge plasma an ambipolar diffusion coefficient sharply decreases and an electron density surplus in comparison to the equilibrium density appears in the vicinity of the coil. Due to a higher electron mobility an ionization wave and, hence, a striation are shifted to a direction of the anode. Dust particles do not manage to respond to a striation movement. Appearing in a region of a weak electric field dust grains start to fall down. The dusty structure is being stretched without losing an ordering. As the current is decreasing the striations are moving backwards and drags the particles. In the process of a movement of the structure to the equilibrium shock waves appear in the dust component. Besides, we observe a sharp increase of the dust grains velocity (up to 50 cm/s) and an interaction of a shock wave with the self excited oscillations. The results of dusty plasma experiments with diamagnetic, paramagnetic, ferromagnetic grains and a different dusty component density are presented.

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P55. Experimental investigation of electron beam influence on dusty plasma structures

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The electron beam is known as convenient instrument that allows one influencing on dusty plasma structures. This influence results in changing of the parameters of plasma within which under gravitational and electrical force dust macroparticles are levitating. By applying an electron beam with changeable sweep frequency one has an opportunity of effecting the whole structure or only part of it as well. This work was devoted to studying the dynamical processes in dusty plasma cloud under the effect of electron beam. The latter while being applied entailed altering of such dusty plasma parameters as interparticle distance, mean macroparticle velocity, and parameter of nonideality. The relaxation processes that took place in the system after electron beam switching of were also studied. It was marked that the characteristic relaxation time (during which the system calms down to its initial state) is much less than the time of system perturbation caused by the electron beam. The relaxation time is estimated about several tens of seconds. The dependencies of macroparticles concentration and the systems parameter of nonideality on time were plotted on the basis of the experimental data. Also the relative temperature altering for the system was estimated.

P56. Large-scaled vortices in dc glow discharge dusty plasma

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At present, occurrence and development of various types of instabilities are of the greatest interest to researchers in the field of dusty plasma physics. Dynamic phenomena in dusty structures (waves, regular or stochastic oscillations) are steady-state distributions of densities of macroparticles moving with nonzero directed velocity, as opposed to mean velocity of particle thermal motion in quasi-stationary dust structures (similar to a liquid or solid). Occurrence of stable dynamical dust structures in viscous medium, such as weakly ionized laboratory plasma, can be possible only due to potential sources which compensate dissipative energy losses. Rotation of dusty particles along the axis of cylindrical system (dusty vortices) was first observed in numerical simulations [1]. In [2] the analytical model was proposed that summarizes analysis of conditions for excitation of instabilities in dusty plasma with gradient of particle charges in nonelectrostatic field. The purpose of this work was experimental investigation of formation of large-scaled dusty vortices in the striations of dc glow discharge. Dust vortices were formed by monodisperse MF particles with diameters $\approx$2 μm in the regions of stable striations. Clouds obtained were of about 1 cm in size and contain $\sim 10^4$ particles each. The discharge was exited in neon in a vertically oriented cylindrical glass tube with cold electrodes. Measurements were conducted at gas pressures 0.4–0.5 Torr and discharge currents 0.4–0.5 mA. Observations were made by means of illuminating dust structure with a sheet of diode laser beam (λ = 532 nm). The scattered light from dust particles was registered by CCD video camera. Structural (correlation functions) and dynamic (kinetic temperatures, rotation frequencies, and velocity spectrum) characteristics of large-scaled dust vortices were measured. Gradient of particle charges in the dust cloud as well as plasma screening length were estimated. It was shown that in the presence of gravity even a small charge gradient (about 1 percent) is an effective source of kinetic energy for dusty vortex motion formation.

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P57. Super dense dust structures in cryogenic DC discharges

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In gas discharge dusty plasmas reducing of the gas temperature down to several kelvins causes a very sizeable decrease of ionic Debye radius that can essentially weaken the mutual repulsion of dust particles. As a result, decreasing of interparticle distance due to boundary effect may yield greatly compressed dust clouds (super dense dust structures) that more than thousands times denser than those at room temperature.

In this work, we present the experimental investigation of dust structures in cryogenic dc glow discharge. The experiments were conducted in a cylindrical symmetric dc glow discharge generated in vertically oriented glass tube placed inside cryostat. The cryostat was cylindrical double glass Dewar system. The outer Dewar was used as a thermal guard and was filled by liquid nitrogen (77 K). The inner Dewar was filled by liquid nitrogen or liquid helium (4.2 K) according to the temperature required. We used particles of two types: polydisperse $\mathrm{Al_2O_3}$ particles with effective diameters $2-6$ μm and monodisperse polystyrene (PS) particles with diameter of about 5.4 μm. In order to illuminate the particles, a diode laser beam ($\lambda = 532$ nm) was introduced into the cryostat via optical fibre. The observations were performed through windows on Dewars by CCD video camera. The discharge was generated in He at pressures $p = 2 - 5$ Torr and currents $I = 0.2 - 1.3$ mA.

We found that, at 4.2 K, in addition to super dense dust structures within discharge striation, qualitatively new dust formations with free boundaries moving through discharge plasma can be formed. In discharge at 77 K super dense clouds of polydisperse particles filling the whole striation volume were observed. In the case of monodisperse particles the correlation functions, kinetic temperatures and diffusion coefficients of dust particles were measured. It was found that, in this case, cooling of the discharge down to 77 K did not affect on dust structure ordering but led to increase of particle thermal motion.

P58. Influence of macroparticle matter on characteristics of ordered dusty plasma structures

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In this experimental work the influence of macroparticles matter on characteristics of ordered dusty plasma structures is discussed.

The experiments were carried out at the following plasma conditions. We used a cylindrical discharge tube with internal diameter $d = 28$ mm. Glow discharge was initiated in Neon, Argon and Helium gases. Ordered structures were observed in the field of glow discharge strata. This field is defined by wall charge of the cylindrical tube, charge of macroparticle structure and field, which is formed by truncated cone inside the discharge tube. In our experiments, we injected dielectric $\mathrm{Al_2O_3}$ and zinc particles into mentioned above plasma gases.

The main subject of these experiments was to study process of dusty structure growth due to dosed successive injections of macroparticles into discharge plasma and determine dependencies on interparticle distances, shape and volume of structures. We tried to establish some correlations between these parameters, macroparticle matters and kind of gases.

The experimental results showed that the mean interparticle distance of concrete dusty system (macroparticle matter, gas) is a constant value during the whole time of dusty structure growth. The quantitative dependences of structure volume on the injection number, volume rate changes on discharge current value and characteristics of interparticle distances are presented as well.

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P59. Stability of dust voids

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Dust voids are frequently observed as dust-free regions in a dusty plasma. Experiments demonstrate a variety of dust void structures such as stable or unstable voids, global ”heartbeat” modes of oscillations of voids, dust voids in the center of the chamber or near its walls. Theory shows that a dust void generally results from the balance of the electrostatic and the plasma (such as the ion drag) forces acting on a dust particle. Here, the stability theory of a void is developed and the void behavior is modeled. It is shown that sequences of stable and unstable void sizes can exist. The dynamics of dust in a plasma follows these stability characteristics leading to various stable and/or unstable dust void structures.

P60. Structure and dynamics of spherical Yukawa clusters

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In the isotropic environment such as the condition of microgravity, dust particles in dusty plasmas form spherical clusters. The interaction between dust particles can be modeled by the repulsive Yukawa potential. The structure and dynamics of these spherical Yukawa clusters are analyzed by molecular dynamic simulations and theoretical methods.

This system has three independent dimensionless parameters: the system size N, the strength of screening $\xi = a/\lambda$, and the Coulomb coupling $\Gamma = Q^2/ak_BT$, a, λ, and Q being the mean distance, the screening length, and the dust charge, respectively.

When the temperature is low and Γ is sufficiently large, dust particles are organized into spherical shells. The number and positions of shells are determined by the system parameter, N and ξ. It is found, however, that the positions of shells are almost independent of the parameter ξ, when we measure them in the unit of the mean distance a. It is also shown that the behavior of shell number and shell positions as a function of N can be reproduced by a simple model.

With the increase of the temperature, normal modes in these clusters gain kinetic energy and we have a melting transition. At higher temperatures, structures are smeared out and we have a spherical cloud of dust particles. We analyze the nature of this transition by observing various quantities in molecular dynamics simulations.

P61. Theory of dust self-organized convective structures

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Convection of dust particles in a low-temperature gas discharge plasma is a spectacular phenomenon observed for various conditions in dusty plasma experiments such as those in laboratories on Earth (i.e., in the presence of the gravity force effectively acting on dust particles), in parabolic flights (for the micro-gravity conditions), as well as onboard the International Space Station (also in the absence of the gravity force). The first theoretical explanation related the dust convection to the process of dust charging by the ambient plasma particles (electrons and ions) and, consequently, to an inhomogeneity of the grain charge distributions appearing due to different plasma conditions. This distinguishes the dust convection from the common convection in gases and liquids related to the presence of the temperature gradients, such as Rayleigh-Bernard convection.

Here, we develop a theoretical self-consistent model of the dust convection in the case when it is induced by an external modulation of the ionization rate. Since in the recent experiments the dust stationary convection was observed in the cylindrical gas discharge, we consider the cylindrically-symmetric geometry and assume that the external modulation of the ionization rate acts along the axis of a cylindrical dusty plasma. The main idea of the study is to proceed as far as possible with the analytic description of the stationary convection of dust taking into account the self-consistent dust charge distribution.

P62. Dipolar interaction in two-dimensional complex plasmas

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Experiments in complex plasmas or colloidal systems with grains endowed with a polarizable or permanent magnetic moment are now considered feasible. Both the equilibrium configurations of the dipoles and the possible collective modes due to the dipole-dipole interactions in such systems are of interest. We have studied theoretically the ground state configurations and collective excitations of a two-dimensional system of charged particles carrying permanent magnetic dipole moment. The positions of these particles can be fixed on a lattice by the dominant Coulomb interaction, or can be constrained to small excursions from these predetermined positions. The predetermined positions can be the sites of a square, triangle, or other two-dimensional lattice. A series of earlier investigations [1, 2] studied similar systems in the context of thin magnetic films. Building on the results of these studies, we have analyzed the possible anti-ferromagnetic and ferromagnetic configurations of the dipoles. We obtain numerically the ground state energies and estimate the ratio of the magnetic and electrostatic interaction energies that provide guidance to the stability of the lattice structure dictated by the electrostatic interaction.

The magnetic collective modes consist of the wobbling of the dipole moments around their equilibrium orientations. One can distinguish two polarizations: (1) wobbling in the lattice plane or (2) perpendicular to the lattice plane. We determine the dispersion curves for these modes in the different equilibrium configurations and speculate about their observational signature.

In a dusty plasma, the electrons are subject both to the electric and magnetic fields of the grains, which affects the development of the Debye screening and modifies the magnetic interaction. These issues are currently being studied.

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P63. A new model of intergrain interaction in dusty plasmas

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Of interest in the modern plasma physics are the studies of dusty plasmas which are encountered in a variety of applications and natural phenomena as well. Dust grains are known to form a crystalline structure that poses a question of how attractive forces are generated in a particular dusty plasmas.

In this report a new model of intergrain interaction is proposed. It is based on the density-response formalism and includes local-field correction that alllows one to incorporate dynamical screening as well. This new model reveals a possible source of attractive force in dusty plasmas appropriate for the scrape off layer and divertor plasmas.

P64. Effect of ion-neutral collisions on grain-grain coupling in dusty plasmas

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Due to large charges carried by the microparticles immersed in a plasma (typically, $Q \sim 10^3 e$ for a μm-size grain) the strong electrostatic coupling in the dust subsystem can be achieved much more easily than in the electron-ion subsystem. This makes possible the formation of ordered structures of particles – plasma crystals [1].

The coupling is proportional to Q^2, i.e., it is quite sensitive to the particle charge. Theory has shown that ion-neutral collisions in the vicinity of a dust grain can lead to a substantial increase in the collected ion current in the weakly collisional regime for the ions [2,3]. This can considerably suppress the grain charge compared to the results of collisionless OML theory. Recent experiments performed in a bulk dc discharge plasma (with the PK-4 setup) covering a wide range of neutral gas pressures support this conclusion – Q decreases with pressure [4,5]. A simple analytical model accounting for ion-neutral collisions in the regime of weak collisionality is in good agreement with the available experimental and numerical results [5]. On the other hand, in the strongly collisional regime the charge increases with pressure and the electrostatic potential tends to the unscreened Coulomb form [2].

Using these results the dependence of interparticle coupling on neutral gas pressure for typical conditions in laboratory dusty plasmas is estimated. It is shown that coupling has a profound minimum at intermediate pressures. The obtained results can be important for 'engineering' experiments which aim to study phase transitions in dusty plasmas.

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P65. Influence of space charge inhomogenity and charge fluctuations on strongly correlated dusty plasmas

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An effective anisotropic potential is proposed for the interaction between dust particles in a gas-discharge plasma. In addition to the Coulomb repulsion this potential takes into account attraction due to the spatial positive plasma charge originating from focusing of the ionic fluxes by dusty particles. The time evolution of the dust particle kinetic and potential energies from random initial configurations is investigated by the Brownian dynamics method. Results of our simulation show that the attraction between dusty particles can be the main physical reason for formation and decay of classical bound dust particle pairs and many-particle complexes with low potential energy, while the kinetic energy (temperature) of unbound dust particles and particles oscillating in bound complexes may increase by up to three orders of magnitude as is observed in experiments. In the model without dust particle attraction bound complexes are absent and increase of kinetic energy is much less pronounced. The influence of the high-frequency and low-frequency random charge fluctuations on the obtained results has been investigated. The model is also applied to simulations of the recently observed spherical dust crystals

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P66. Surface activity of charged dust in a plasma sheath

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A simple model is developed for the self-consistent charging of a dust layer in an electrode plasma sheath, as well as for the force balance in this layer. The anisotropy of the plasma pressure near the plasma boundary makes it possible to introduce the notion of surface tension. The equilibrium charge, the height at which the dust layer levitates above the electrode, and the plasma surface tension are calculated numerically as functions of the dust density. The presence of dust is shown to increase the plasma surface tension, which indicates that the plasma sheath may become structurally unstable.

P67. Electron and ion fluxes to a dust grain in atmospheric pressure plasma

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We present an approximate expression for the flux of charged plasma particles to a dust grain under the conditions $a << l << D$, where a is the dust grain radius, l is the mean free pass of the charged particle,

and D is the screening length. Such conditions can be realized, for example, in a plasma at atmospheric pressure and temperature $T \sim 0.1$ eV for dust grains of micron or submicron size. In two limiting cases $l << a$, D and $l >> a$, D the expressions for the flux can easily be obtained. In the first case, the approximation of flat surface is valid. In the second one the OML approximation is usually applied.

In order to derive an approximate expression for the flux at the intermediate case, we consider the motion of a charged particle in the spherical layer $a < r < a+l$ as a collisionless one in the Coulomb potential. Then for the particle incoming to the collisionless region with the given velocity $\mathbf{v}$, using the energy and moment conservation lows, we can obtain the minimal distance r_{min} of the particle trajectory from the Coulomb center. Evidently, only the particles, for which $r_{min} \leq a$, reach the dust grain. But knowing the velocity distribution function we can write the flux of the particles incoming to the collisionless region with velocity $\mathbf{v}$. Thus, averaging over the velocity values and directions, we find the flux to the dust grain.

The obtained expression has been used for the derivation of the boundary conditions near the dust grain for the equations describing the electron distribution in thermoionic plasma. We equate the obtained electron flux to the flux of electrons emitted from the dust grain surface and find the electron density at $r = a + l$. For the conditions under consideration we can use the drift-diffusion approximation for $r > a + l$, and we set this number density as the boundary condition for the corresponding equation.

P68. Interactions of charged dust particles in clouds of charges: Debye atom and Debye molecule

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Two charged dust particles inside a cloud of charges are considered as Debye atoms forming a Debye molecule [1]. Cassini coordinates are used for the numerical solution of the Poisson-Boltzmann equation for the charged cloud. The electric force acting on a dust particle by the other dust particle was determined by integrating the electrostatic pressure on the surface of the dust particle. It is shown that attractive forces appear when the following two conditions are satisfied. Firstly, the average distance between dust particles should be approximately equal to two Debye radii. Secondly, attraction takes place when similar charges are concentrated predominantly on the dust particles. If the particles carry a small fraction of total charge of the same polarity, repulsion between the particles takes place at all distances. We apply our results to the experiments with thermoemission plasma and to the experiments with nuclear pumped plasma.

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P69. Thermodynamic instability and critical fluctuations in dusty plasmas

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In the one-component plasma (OCP), either classical or quantal, the pressure decreases with the increase of the coupling parameter. At the same time, the isothermal compressibility increases and, at some critical value of the coupling parameter, we have a divergence of the compressibility. In neutral systems, this corresponds to a thermodynamic instability and critical fluctuations are observed when we approach to this point.

In the case of OCP, however, there always exists the background charge which neutralizes the OCP and the pressure of the latter usually masks the above instability. In this presentation, we show that, in dusty plasmas, we have a possibility to directly observe this instability when appropriate conditions are satisfied.

Starting from the charge neutral system composed of dust particles, electrons, and ions, we first obtain the effective potential acting on dust particles. We then have an approximate expression for thermodynamic quantities related to dust partices and finally derive thermodynamics of the total system. We show the behavior of the density fluctuation spectrum in this system near the critical point. The experimental possibility to observe these critical phenonena under the condition of microgravity will also be discussed.

Non-Neutral and Ultracold Plasmas

I7. Measurement of screening enhancement to nuclear reaction rates using a strongly-magnetized, strongly correlated nonneutral plasma

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In the hot dense interiors of stars and giant planets, nuclear reactions are predicted to occur at rates that are significantly enhanced compared to the low density Gamow rates. As first discussed by Salpeter and others [1], the reason for the enhancement is that the surrounding plasma screens colliding pairs, increasing the probability of the close collisions that are required for nuclear reactions. However, strongly enhanced nuclear reaction rates have never been observed in the laboratory. This talk will discuss experimental tests of strong screening enhancement. The tests can be done at low energy by using an analogy between nuclear reactions and energy equipartition for strongly correlated ions stored in a Penning trap. In the strong magnetic field of the Penning trap the trapped ions execute rapid cyclotron motion. The kinetic energy of this motion is an “adiabatic invariant.” Like nuclear energy, this cyclotron energy is released only through rare close collisions between ions that break the adiabatic invariant [2]. When the plasma is strongly correlated, close collisions are more likely because of plasma screening and the rate of cyclotron energy release is enhanced, in just the same manner as for nuclear reactions [3]. Simulations of this effect will be presented, along with preliminary experimental results with laser-cooled strongly-correlated Be^{+} ions [4]. The experiments have observed a strongly-enhanced release of cyclotron energy (10 orders of magnitude faster than the two-body equipartition rate).

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T17. Ultracold plasma and Rydberg-like state of matter formed by Rydberg atoms.

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Superultracold plasma and Rydberg-like state formed by strong interaction between Rydberg atoms (Rydberg matter) are studied theoretically. A pseudopotential model and density functional theory is considered. The phase transition to condensed state in a system of excited atoms is reviewed. A lifetime, decay processes of both radiation’s transition and Auger effect are analysed. Comparison of theoretical estimations with experimental data is demonstrated. A kinetic model for ultracold, strongly nonideal plasma with gas of Rydberg atoms (Rydberg plasma) is developed. All stages of the generation and decay of such a plasma can be sequentially traced. Calculations show evidence of a significantly decreased recombination rate and, hence, of the possible formation of a metastable structure in the plasma under consideration. A pseudopotential model is suggested to describe the thermodynamics and correlation functions of such the Rydberg plasma. The Monte Carlo method is used to determine the energy, pressure, and correlation functions in the ranges of temperature $T = 0.1 - 10$ K and $n = 10^{-2} - 10^{16}$ cm^{-3}. For a weakly nonideal plasma, the results closely agree with the Debye asymptotic behavior. For a strongly nonideal plasma, many-particle clusters and a spatial order in the arrangement of plasma electrons and ions have been found to be formed.

T18. Ultra-cold plasma temperature oscillations

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Coulomb matter is typically formed at high temperatures and/or densities where significant ionization occurs. It is now possible, however, to create plasmas in the opposite limit of very low densities and very, very low temperatures; such plasmas are referred to as ultracold plasmas. Ultracold plasmas are formed by the rapid ionization of a cold ($\sim$microkelvin) atomic gas. Initially, the plasma is in a highly uncorrelated state characteristic of a gas, but the Coulomb coupling parameter can be as high as several tens of thousands, which is characteristic of a Coulomb crystal. Such a state is highly nonequilibrium since the charged particles will attempt to correlate to be consistent with the Coulomb coupling. It has been established theoretically [M.S. Murillo, Phys. Rev. Lett. 76, 115003 (2001)] that an ultracold plasma will heat as correlations form; this "disorder-induced heating" can be understood simply in terms of energy conservation whereby the initial Coulomb energy is converted into kinetic energy as the system evolves from a random state to a more ordered state. Recently, this prediction has been confirmed experimentally [Y. C. Chen, et al., Phys. Rev. Lett. 93, 265003 (2004)] by observing the Doppler broadening of the ions as they heat. Interestingly, the experimental data have also revealed that the Coulomb to kinetic energy conversion, and in turn the evolution to equilibration, is not monotonic (direct): the ion temperature rapidly increases to a maximum and then displays damped oscillations towards the equilibrium temperature. We have explored the evolution to equilibrium of ultracold plamas both theoretically and with molecular dynamics simulations. Our theoretical models aim to give guidance to the interpretation of the simulation results, which are much more accurate. We use particle-particle particle-mesh molecular dynamics to simulate the rapid ionic heating and temperature oscillations using a Yukawa model, which assumes a fast electron response. We find that the oscillations also appear in the simulations and we have studied their behavior as a function of plasma conditions; good agreement is found in comparison with the experimental results. These detailed experiments, and the use of molecular dynamics to understand them, greatly expands the study of the already interesting and difficult area of equilibrium properties of strongly coupled Coulomb systems to the case of very strongly coupled and highly nonequilibrium systems.

T19. Coulomb crystals in confined systems: self-organization

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A system of classical particles moving in two dimensions and confined by a parabolic trap exhibits a rich variety of different configurations when the inter-particle potential has a long-range repulsive and a short range attractive part. The groundstate configuration depends very much on the interaction range of the short-range attractive potential and the total number of particles: bubbles, stripe phases and ringlike configurations (or combinations of them) are found. Complete phase diagrams are constructed for $N = 2$ up to $N = 6$ particles. General rules are derived for the occurence of different transitions between the different configurations. These rules are tested for the ground state configuration of large systems.

We also studied a binary system of particles with a Coulomb repusive interparticle interaction. The particles not always arrange themselve in a shell structure. We found that the mixing of the particles goes hand in hand with the occurence of a large number of metastable states. As function of the ratio between the charge or mass of the two types of particles a large number of first order and second order structural transitions are found. The melting of such a system was also investigated and we found that the small particles are able to stabilize the ordening of the larger particles.

T20. Relaxation of expanding ultracold neutral plasmas

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In a number of recent experiments ultracold neutral plasmas have been produced by photoionizing laser-cooled atomic ensembles and investigated using a variety of different techniques [1–3]. Due to their very low temperatures and due to the fact that these plasmas are freely expanding, these systems show a complex relaxation behavior and different theoretical pictures have been applied to understand the observed plasma dynamics ([4–6] and [7, 8]).

Based on recently developed theoretical approaches [6], we provide a detailed discussion of the ultracold plasma dynamics, including the formation of highly excited Rydberg atoms, the build up of spatial correlations, an adiabatic cooling during the expansion, etc. We present a consistent picture of the relaxation of the electronic and ionic component as well as the equilibration between both subsystems [9]. Moreover we demonstrate that our calculations are in excellent agreement with current measurements, giving strong arguments for the respective interpretation ofexperimental observations.

Finally, we discuss consequences of the strongly coupled ion motion for the plasma dynamics and its implications for present experiments [10, 11].

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P70. To the theory of recombination Rydberg nonideal plasma.

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Recombination properties at three-body collisions in hydrogenlike plasma have been investigated. We have shown that existing calculation models for three-body recombination (Thomson model, diffusion approximation and modify diffusion approximation) have worked only in high temperature region electron temperature more or equal 1 eV. In case of electron temperature essentially less 1 eV, we have found out strong dependence this process probability from energy of free particle. As a result is a drastic slowdown recombination in region, where three-body recombination is a main recombination mechanism. Other reason of slowdown recombination connects with an increase nonideality parameter. Effect of slowdown recombination at three-body collisions can reduce to situation when thermal equilibrium is set earlier than ionization equilibrium, and to inverse population on Rydberg levels.

P71. Phase diagram of ultracold strongly coupled plasmas

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It was predicted theoretically in the late 1960s [1] that thermodynamically labile and metastable states might exist for strongly coupled plasmas. The idea was analogous to the van der Waals equation. The approach [1] is extended to lower temperatures in the present paper. The diagram (electron temperature T_e – electron number densities n_e) is plotted. The possible ideal gas of atoms presented is neglected. Three areas of the ultracold plasma parameters are distinguished in the $T_e - n_e$ diagram, where plasmas are thermodynamically stable (I), labile (II) or metastable (III). It is shown that the results of the recent experiments [2-4] and simulation [5,6] do not contradict to the prediction. The plasma parameters of the metastable microdroplets with the lifetime about 1s, which were observed in [2], turn out to correspond to the area III where ultracold plasma is expected to be metastable according to our estimates. The unstable plasmas studied in [3,5,6] had initial parameters which correspond to the area II where plasmas are subjected to the spinodal decay according to our estimates. The parameters of the stationary plasmas studied in [4,7] hit the area I where plasmas are thermodynamically stable according to our estimates as well.

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P72. Decoherence of Rydberg-Atoms in a plasma

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Highly excited atomic states loose their pure quantum-mechanical interference properties by interaction with a statistical background. The process of decoherence is generally studied by system-bath models [1]. These models provide estimations of the decoherence timescale using transitions by system-bath interaction on a Born level.

Refering to experiments on ultracold plasmas [2], we study scattering of charged particles at Rydberg atoms that give the most important contribution to the transition rates in these systems. We find that different approaches to decoherence coincide with scattering rates of the Born approximation.

For the calculation of suitable transition rates the Born approximation is generally not sufficient. We consider therefore extensions including strong collisions in Binary Encounter Approximation (BEA) [3] and show how to improve mesoscopic approaches to decoherence [4].

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P73. Strong correlation effects in cold Rydberg gases

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Recent advances in cooling and trapping of atomic ensembles have paved the way towards an experimental creation of highly excited cold gases. Due to the huge polarizability of the Rydberg atoms, these systems exhibit a number of interesting many-body effects [1, 2], and even the formation of ultracold plasmas from these gases has been observed [3, 4].

One prime example is the interaction-induced suppression of the laser excitation itself, which has been observed in recent experiments [1, 2]. We introduce a Monte-Carlo procedure to describe the excitation dynamics of the strongly interacting Rydberg gas. Beside a detailed comparison with present experiments, the differences between a structured and an unstructured atomic environment will be discussed. Thereby we demonstrate that the van der Waals interaction between the Rydberg atoms induces strong spatial correlations, even during the initial process of the laser excitation.

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P74. Electron cooling of highly charged ions and antiprotons in traps

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For recent and planned experiments like the CPT-tests with antihydrogen at CERN (ATHENA, ATRAP) or the QED-tests and various other investigations with slow highly charged ions at GSI (HITRAP), the ions or antiprotons are cooled with electrons or positrons in Penning traps. In many of these applications an efficient and fast cooling is crucial. In particular for electron cooling of highly charged ions, like e.g. of U^{92+} in HITRAP, sufficiently large cooling rates which exceed the ion-electron recombination rate are mandatory in order to avoid ion losses by recombination during the cooling process.

As one essential part of theoretical calculations of cooling times we have investigated the underlying energy transfer in ion-electron collisions in detail. Here the presence of a strong magnetic field presents a theoretical challenge as linearization and perturbation treatments turn out to become questionable and more complete approaches like classical trajectory Monte Carlo calculations (CTMC) or particle-in-cell (PIC) simulations are needed. Employing such methods we find a rather intricate influence of the magnetic field on the ionic energy loss and significant differences between e.g. electron cooling of antiprotons and protons or the cooling of ions by electrons or positrons. These differences can be traced back to the effectively one-dimensional motion of the electrons like beads on a wire along a strong magnetic field. For ion velocities around the thermal velocity of the electrons the energy loss of antiprotons can be more than 50% larger than for protons.

Special attention is paid to the electron cooling of highly charged ions. Based on our energy loss rates we investigated the related cooling times. For that we calculated the time evolution of the ion energy by taking into account the energy transfer to the limited number of trapped electrons and the resulting heating of the electrons. For typical trap conditions (e.g. HITRAP) the cooling times are of the order of a second, but they strongly depend on e.g. the actual electron density and the ratio of the number of highly charged ions and electrons confined in the trap.

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Condensed Matter and Two-Dimensions

I8. Understanding the spin susceptibility of the 2D electron gas in real devices

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It is nowadays possible to fabricate solid-state devices in which electrons are confined at the nanoscale in suitable geometries and move almost freely, suffering very little scattering. Some of these devices are believed to provide a close realization of the so-called two dimensional electron gas (2DEG) model and are being intensely studied in connection with the apparent metal-insulator transition in two dimensions. I shall review the available experimental evidence on the low-temperature spin susceptibility of such systems and demonstrate, with the help of accurate QMC predictions, that the 2DEG appears to indeed provide a good model when details such as thickness, sources of scattering, and valley degeneracy are duly kept into account.

T21. Strongly coupled and strongly correlated electron and electron-hole quantum 2D systems: state of art

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Phase diagram and coherent properties of strongly correlated electron-hole and electron-electron systems in nanostructures, particularly, in quantizing magnetic fields are discussed. The role of reduced dimensionality is analyzed.

Physical systems under consideration are electrons and holes in quantum wells (2D systems), quantum wires (1D systems) and also traps in quantum wells, quantum dots (0D systems) or Bose atoms in strongly anisotropic traps .

Strongly correlated phases, such as mesoscopic supersolid in 2D trap and Tonks-Girardeau regime in quantum wires, liquid and crystal phases are discussed.

For description of slightly inhomogeneous 2D systems the new approach, quasilocal generalization of Kosterlitz-Thouless theory is developed.

The role of disorder in exciton system (problem of "dirty" bosons and superfluid glass transition) will be discussed. The problem of "dirty" magnetoexcitons is mapped to the problem of "dirty" excitons without magnetic field but with effective mass and random field renormalized by magnetic field.

Pairing in composite fermion bilayer will be considered. The problem of BCS instability of compressible unpaired quantum Hall bilayer state at one half + one half total Landau filling fraction is discussed. The effect of marginality of composite fermions on BCS pairing will be analyzed. Superfluidity and Josephson phenomena in the systems are analyzed.

Possible coherent optical phenomena in the systems (in “coherent” phases), particularly, angular correlations of photons originated from electron-hole recombination, laser beam backscattering, nonlinear coherent processes are described. The light backstattering on coherent exciton phase is connected with photoinduced coherent recombination of two Bose-condensed excitons with production of two photons with opposite momenta. Many-photon coherent emission effects governed by coherent recombination of many excitons from Bose-condensate and described by anomalous photon averages not only 2nd but also 3rd etc. order are also considered. Comparison of the results with recent experimental data is discussed.

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T22. Spectroscopy of correlated electron phases in low-dimensional semiconductor quantum structures

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We present resonant inelastic light scattering measurements obtained from from few-electron states in nanofabricated semiconductor quantum dots and from coupled electron bilayers in semiconductor heterostructures under the extreme conditions of low temperature and large magnetic field. The light scattering experiments probe the peculiar low-energy collective excitations of these systems that represent time- and space-dependent oscillations in the charge and/or the orientations of spin.

We demonstrate that these experiments manifest the fundamental interactions that are responsible for electron correlation. We show in particular that the measured energies of the observed spin and charge modes reveal a significant breakdown of the Hartree-Fock description of the systems in the investigated regimes of temperatures, magnetic fields and electron confinement. The results thus indicate the emergence of new highly-correlated many-particle quantum states. We present an analysis of the light scattering data that offer detailed insights on the properties of these novel states.

Work done in collaboration with: S. Luin, C.P. Garcia (NEST- Scuola Normale Superiore, Italy); A. Pinczuk (Columbia University, New York NY and Bell Laboratories, Murray Hill NJ); B.S. Dennis, L.N. Pfeiffer, K.W. West (Bell laboratories, Murray Hill NJ); M. Rontani, G. Goldoni, E. Molinari (S3 and Universita’ di Modena e Reggio Emilia, Italy).

T23. Simulations of bilayer electron liquids: structure and collective modes

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We have performed extensive Molecular Dynamics simulations of strongly coupled, classical, symmetric electronic bilayers, interacting through the Coulomb potential. A study of its structural properties and the diffusion coefficient indicates a unique feature: a phase change from a liquid to a solid-like system and back to a liquid, as the two layers are brought together. We have thus established a solid-liquid phase boundary in the coupling constant-interlayer separation plane. Our investigation of the plasmon modes confirms theoretical results that an energy gap exists for the out-of-phase mode for long wavelengths and small interlayer separations.

T24. Bose-condensation of 2D interwell excitons in coupled quantum wells

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The luminescence of interwell excitons in coupled quantum wells (n-i-n heterostructures) with lateral random potential fluctuations of a large scale has been investigated. The properties of interwell excitons whose photoexcited electrons and holes are spatially separated in the neighboring quantum wells were studied as a function of density, temperature and magnetic field down to 0.5 K within domains on the scale aroumd one micron. For low pumping and low temperature excitons are strongly localized due to potential fluctuations connected with residual impurities, and the corresponding luminescence line is inhomogeneously broadened (arouns 3 meV). As resonant excitation power increases, the very narrow line of delocalized interwell excitons arises in a threshold manner, its intensity sharply superlinearly increases. With increase in temperature, this line disappears from spectrum ($T > 4$ K). The observed phenomenon, which is critical to exciton density and temperature, is attributed to the bose-condensation in laterally confined quasi-two dimensional system of interwell excitons. In studied temperature range (0.5–4 K), the critical exciton density and temperature increase in linear power low manner. Corresponding phase diagram was constructed. The same collective phenomenon was observed under lateral confinement of interwell excitons in a strongly inhomogeneous electric field. It was found that magnetic field strongly reduces the critical temperature of exciton condensation. Kinetics of interwell exciton luminescence spectra and time evolution of collectice exciton phase under pulse laser excitation has been studied. Exhibition of coherent properties of collective exciton phase is discussed.

P75. Longitudinal collective modes in strongly coupled asymmetric charged-particle bilayers

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We have analyzed the dispersion of longitudinal collective modes in strongly coupled asymmetric charged-particle bilayer liquids in the classical regime. The theoretical analysis is based on a dielectric matrix calculated in the quasilocalized charge approximation (QLCA) [1, 2]; dissipative effects are ignored. The matrix elements are expressed as integrals over intralayer and interlayer pair correlation functions. These integrals are calculated with the input of pair correlation function data that we have generated by molecular dynamics (MD) simulations. At the same time, MD simulations of density and current fluctuation spectra are analyzed to infer the collective mode dispersion. These simulations are carried out over a wide range of density ratios and at a coupling strength $\Gamma = 50$ (in layer 1) and layer separation $d = 0.3a$; a is the Wigner-Seitz radius in layer 1. There are two modes (+) and (-), which, however, in contrast to the symmetric bilayer, do not have fixed in-phase and out-of-phase polarizations. As a result, a quasidiagonalization technique for the density fluctuation matrix has been implemented to separate the two peaks corresponding to the two modes. The theoretical calculations predict that the + and dispersion curves, while they can come exceedingly close to touching, in fact, never do. This behavior has yet to be confirmed by the MD simulations that are currently underway.

The long-wavelength finite frequency (energy) gap, brought about by strong interlayer correlations and reported by the authors for strongly coupled symmetric charged-particle bilayer liquids in the classical [2–5] and quantum [6] domains, is an equally prominent feature of asymmetric bilayers as well.

In general, the MD simulated dispersion curves are in good agreement with the results of the QLCA calculations; the energy gap, however, is systematically higher than its theoretically predicted value. This discrepancy is similar to what has been found for the symmetric bilayer [4], and its origin remains to be understood.

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P76. Phonons in Yukawa lattices

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The understanding of the theoretical structure of phonon dispersion in Yukawa lattices and the relationship between these perfect lattice phonons on the one hand, and the excitations in the disordered and liquid state on the other, is an important issue in analyzing experimental and simulational results on plasma crystals. As the first step in this program, we have numerically calculated the full phonon spectrum for Yukawa lattices, both in 2D (triangular) and 3D (bcc) structures, for a wide range of κ (range parameter) values, and along different propagation angles. While to obtain a full information on the frequency spectrum it is sufficient to consider $\mathbf{k}$-values within the first Brillouin zone, it is quite instructive to follow the dispersion for high values of k and study the angle dependence of the periodicity of the $\omega(\mathbf{k})$ curves. We have calculated the frequency spectrum $g(\omega)$, by numerical integration over the angles: $g(\omega)$ is the quantity that can be most directly compared with MD simulations.

Earlier calculations of the excitation spectra of the 2D [1] and 3D [2] Yukawa liquid were based on the quasilocalized charge approximation (QLCA), whose implicit premise is that the spectrum of an average distribution (governed by the isotropic liquid pair correlation function) is a good representation of the actual spectrum. To test this hypothesis we compare the high Γ (near crystallization) QLCA phonon spectra with the angle averaged phonon spectra of the lattice phonons.

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P77. Application of ionic model with interaction of defects to description of the order-disorder transition in non-stoichiometric solid Uranium Dioxide

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Ionic representation was proved to be successful in thermodynamic description of liquid phase and non-congruent gas-liquid coexistence in systems like non-stoichiometric uranium oxides [1, 2]. A new model approach to thermodynamic description of imperfect and non-stoichiometric ionic solids near the pre-melting transition into superionic state is discussed. Along with short- and long-ranged inter-ionic interactions, the model takes into account the formation of Frenkel defects as well as Coulomb and short-range interactions between these defects. Contrary to existing approaches [3, 4] based on ideal-lattice-gas and Debye-Hueckel approximations, we consider the imperfect solid as a highly non-ideal Coulomb system and treat the short-range interactions of Frenkel defects explicitly as interactions of quasi-dipoles.

A simplified analytical EOS for free energy of a perfect anharmonic solid combined with additional contributions from formation and interaction of defects, after fitting of a few numerical constants reproduces the locations of known phase transitions and predicts the variations of thermodynamic properties with temperature, density and stoichiometry. Results are compared with experimental and computer simulation data for solid UO_{2+x}.

The EOS predicts correctly the behaviour of thermodynamic functions, including the pre-melting of the oxygen sub-lattice in UO_{2+x}. When combined with theoretical model for uranium dioxide EOS for fluid state [5] it has been successfully used [6] in prediction of liquid/solid and vapour/solid equilibria.

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P78. Investigation of action features of ultra-short pulses of power electronic and laser radiation on the condensed matter

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Physical processes operating in condensed matter at an irradiation by intensive streams of a various sort of radiations cause a strong interest due to their use for solving of scientific and practical problems of radiating technologies. Typical values of stream power density of corpuscular and electromagnetic radiation and of irradiation duration are equal to $10^7 - 10^9$ W/cm^2 and $10^{-7} - 10^{-6}$ s. As the characteric time of the electron-phonon relaxation ($\sim 10^{-12}$ s) is much less than the irradiation duration, the contribution efficiency of a beam energy in such processes as generation of tension fields and structural transformations in a solid is extremely low. Now there are pulse voltage generators which allow to generate high-power electron beams with sub-nanosecond duration of pulses. Shorter pulses are achieved in generation of power laser radiation. The non-equilibrium solid-state density plasma, where existance of ”cold” ions and ”hot” electrons is typical, is formed by affecting on a solid of ultra-short electronic and laser radiation. A free path length of the hot electrons essentially exceeds average interatomic distance. On the way they deform a lattice and generate not only tensions but also defects such as dislocations.

Our main goal is theoretical investigation of the action features of ultra-short electronic and laser radiation both at a stage of actual radiation absorbsion which duration is equal to pulse duration, and at a longer stage of electron-phonon relaxation. We explore the first stage within framework of the self-consistent model including the kinetic equations for electrons, phonons and Langmuir plasmons, Maxwell equations and the field equations for defects. The kinetic equations consider the possibility of generation of plasmons and phonons and their interaction with electrons and each other. An influence of defects to the generation of plasmons and phonons is considered to be in mean field approximation. Spectra of collective excitations have been obtained and the possibility of the strong Langmuir turbulence formation in non-equilibrium solid-state density plasma has been also discussed by us. The second stage is investigated within the framework of a two-temperature model of the continuous media mechanics including the balance equations of mass and momentum, two equations for phonon and electron energy, a wide-range equation of state, and also kinetic equation for radiation. The numerical researches of stress and deformation fields, influencing on a solid of electron beams with pulse duration smaller than 1 ns, have been made and discussed by us.

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P79. Beam-plasma interaction in strongly coupled plasmas

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The well-known problem of beam-plasma instability acquires new aspects when one or both of the two components (the beam and the plasma) are strongly interacting [1]. We have now theoretically considered the case when the plasma is in the solid phase and forms a lattice. In this situation the inherent anisotropy of the lattice leads to a coupling between the longitudinal and transverse polarizations. One of the novel features of the beam-plasma instability in this scenario is the possible excitation of transverse modes, which should be an experimentally observable signature of the instability.

We have initiated a Molecular Dynamics simulation program for studying various aspects of the penetration of a beam into a plasma lattice. While the beam plasma instability is essentially a 3D phenomenon, we have concentrated on a 2D toy model with the beam lying in the lattice plane. The beam parameters can be adjusted so as to see the effect of an increasing coupling strength within the beam and to be able to distinguish between collective phenomena and scattering of individual particles. When both components are strongly interacting, a number of remarkable phenomena - trapping of beam particles, creation of dislocations, local melting of the lattice - may be observed.

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P80. Photoinduced metal-insulator transitions: critical concentration and coherence length

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Strongly correlated electrons in solids, characterized by a significant ratio of the Coulomb potential energy to the electron kinetic (Fermi) energy, is a special case of strongly coupled Coulomb systems. Strong correlation effects are responsible for the unique properties of such materials as HTSC, CMR-manganites, and materials with metal-insulator transitions (MIT) [1]. MIT itself, in turn, is a problem of considerable interest, being concerned with a wide range of issues [2] in plasma physics, astrophysics, and condensed matter physics. On the other hand, inducing and probing non-thermal phase transitions in solids using femtosecond (fs) laser [3] and X-ray [4] pulses is nowadays a relatively new and rapidly advancing research direction.

In this work we develop an analytical model to describe the photoinduced MIT in compounds with dual transition [5] governed by Mott-Hubbard electron correlations. Expressions for both the coherence length, and for the critical concentration in case of the re-entrant M-to-I transition, are obtained. The latter is shown to be equivalent to the Mott criterion for the direct I-to-M transition. Experimental results concerning the MITs in SmS and VO_2 are discussed. Some recent data on fs structural dynamics [4] in SmS will also be presented.

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P81. Compressibilities in bilayers of charged particles

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The isothermal compressibility plays a central role in determining the characteristics of the static response in plasma systems. In a charged particle bilayer this role is assumed by L_{ij}, the matrix of inverse compressibilities. For weak coupling, the inverse compressibilities of a bilayer of charged particles can be calculated analytically in the Debye limit, from the equation of state [1] through the chemical potential via the free energy. There are two different charging procedures to obtain the latter. We present the results of a rather lengthy analytical calculation, exploring both approaches. The limits of the validity of the Debye description are discussed, and we compare the weak coupling results with L_{ij} values inferred from $S(k{\rightarrow}0)$ through the compressibility sum rule, where $S(k)$ is generated for strong coupling both through molecular dynamics simulations [2] and by HNC calculations [3].

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P82. Binding energies of excitonic complexes in quantum wells influenced by disorder and longitudinal electric field

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The properties of interacting electron-hole pairs in low dimensional semiconductors (e.g. quantum wells (QW) and dots) are strongly affected by external confinement and electro-magnetic fields. Besides, there is an active discussion about the influence of disorder and localization (imperfections on the QW surface) on the binding energies of confined carriers. In the present work we present a comparison of recent experimental measurements of the binding energies of localized trions in GaAs/AlGaAs based quantum dots [1] with our recently developed Path Integral Monte Carlo technique [2]. The simulation results show good quantitative agreement with the experimental data.

We further improve the adiabatic approach used in [2] to a full 3D calculation. This allows us to include an electric field in growth direction of the QW. A systematic investigation of the influence of field strength on internal structure and stability of excitonic complexes (quantum confined Stark effect) are performed. Comparison with available experimental data and theories are presented.

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P83. Experimental observation of a first-order interface delocalization transition in coupled electron plasma of a type-I superconductor

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Theory [1] predicts that the phase diagram of type-I superconductors with surface enhancement of the order parameter takes an unusual shape, closely resembling a wetting phase diagram of adsorbed fluids [2]. In particular, below a characteristic temperature T_w in a parallel magnetic field slightly above H_c, the superconducting/normal interface meets the sample surface under a finite contact angle. This corresponds to partial wetting. At $T \geqslant T_w$ the superconducting phase forms a continuous surface sheath, the thickness of which diverges upon approaching H_c from above. This corresponds to complete wetting. The transition between these two states is called the $interface\, delocalization$ or $wetting$ transition in type-I superconductors. For superconductors with Ginzburg-Landau parameter κ below 0.374, the transition is expected to be discontinuous (first-order wetting). At $T > T_w$ the first-order interface delocalization transition at coexistence is accompanied by a first-order transition off coexistence, similar to the $prewetting$ transition in fluids. Another predicted feature of the superconductors with surface enhancement is the existence of the superconducting sheath $above$ the bulk critical temperature T_c. In this paper we will report direct experimental verification of the interface delocalization transition in the coupled electron plasma of tin. The magnetization and electrical transport of high-purity polycrystalline and single crystal tin samples $with\ surface\ enhancement$ were measured as a function of H and T above and below the bulk critical point. It is shown that the registered first order superconductor transition above the coexistence line occurs on the sample surface. The phase diagram is in accord with theoretical predictions. This research has been supported in part by K.U.Leuven fellowship F/03/066 for V.F.K. and by FWO-Project G.0237.05.

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P84. Heating and ionization of metal cluster by intensive femtosecond laser pulse

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Spatial structure of the electromagnetic field inside and outside of the spherical metallic cluster is taken into account to describe the clusters matter heating and ionization by intensive femtosecond laser pulse. Calculations were carried out with reference to conditions of experiments on interaction of iron clusters jet with femtosecond laser pulses produced by IHED femtosecond laser complex. Dependence of electron temperature on laser pulse intensity and cluster radius is determined. It is shown that at intensity of about 10^{18} W/cm^2 Be- and Li-similar ions of iron are present in clusters plasma at electron temperature about $2-3$ keV. Calculation of continuous spectrum X-ray emission by Bremstrahlung mechanism is carried out. Impact ionization process of ions by fast electrons from deep electron shell is under discussion. A group of fast electrons is implied to be formed in the vicinity of clusters surface in according to model of ”vacuum” heating by Brunel and produces an effective ionization already at rather small laser pulse intensity.

P85. *Ab initio* calculation of cold curves for FCC, BCC and HCP Nickel at ultrahigh pressures

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The paper presents cold curves for a magnetic fcc and three nonmagnetic (fcc, bcc and hcp) structures of Ni to $\sim$ 800 Mbar, obtained from ab initio calculations done with the full-potential scalar-relativistic method of electronic structure calculation FPLMTO [1] with gradient corrections to the exchange-correlation functional. Our calculations confirm the results that were earlier obtained in [2-4] and suggest that nickel dielectrizes at very high pressures. A gap in the energy spectrum of electrons is formed for all the above Ni structures that is also in agreement with the results presented in [4]. By data from [2], the energy gap for fcc Ni exists in the pressure interval 250–1500 Mbar, while in [4] this interval is 340–510 Mbar. Our research suggests that fcc Ni dielectrizes in the pressure interval 302–720 Mbar, and other Ni structures dielecrize in roughly the same interval.

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P86. Ionization potential and nature of charge carriers of fluid hydrogen and deuterium in wide pressure interval

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Resting on the experimental results of the investigation of the exciton absorption spec-trum in condensed H_2 and D_2, a simple model for estimation of the bottom energy of the electron conduction band V_0 and the forbidden gap energy E_g was proposed. Results of the estimation of E_g are in not bad agreement with the experimental values obtained in conductivity measurements of the single-shock compressed hydrogens. It is shown that electrons in fluid hydrogens are localized not in the electron bubbles as it was considered previously but in molecular negative ions surrounded by empty voids radius of about 0.5 nm. The conductivity of fluid hydrogen at not too high pressures is connected with transfer of positively charged clusters and negatively charged bubbles. It has a thermally activated character similar to a semiconducting fluid. With increasing of pressure and density molecular dissociation occurs and electron localization on atomic hydrogen becomes more favorable, also with creation of void around atomic negative ions. At high enough atomic concentration a probability of the tunnel transition of an electron from one atom to another becomes closed to the unity, the energy level of the negative ion degenerates in the conducting band, and the conductivity is caused by the transfer of these quasifree electrons. It is supposed that this mechanism of the charge transfer may play an important role in the region of the fluid hydrogen metallization observed recently in the multiple-shock compression experiments at pressure about 140 GPa and temperature about 2600 K.

Coulomb Liquids

I9. Liquid metals

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Fluid metals are examples of materials whose electronic structure and properties depend on the thermodynamic state of the system. The most striking manifestation of this state dependence is the metal-nonmetal transition which occurs when the dense liquid evaporates to the dilute vapor or when the liquid is expanded by heating to its critical point. This transition has long been a source of fruitful experimental study. Much of this effort has been stimulated by the paper of Landau and Zeldovitch which called attention to the fascinating possibilities raised by the interplay between liquid-vapor and metal-nonmetal transitions in fluid metals. The results show that this transition noticeably influences the electrical, optical, magnetic, thermodynamic, structural, dynamic, and interfacial features of fluid metals. To understand either the metallic or insulating regimes one must elucidate the manner in which these bulk macroscopic states evolve from the progressive agglomeration of their atomic constituents. The main emphasis of the present paper is on recent experimental results related to this question. Renewed interest in this question is motivated by the exciting progress from recent shock experiments in the search for pressure induced ionization in the nominally nonmetallic fluids hydrogen, oxygen, nitrogen, and helium. However, there is no final proof that "plasma phase transitions" exist in these systems. It has so far not been possible to investigate the phase behaviour of these fluids at the high temperatures and pressures prevailing in the shock experiments, or indeed, even to determine the location of the critical point. In light of the unfavorable outlook for measurements in the critical region of the "plasma phase transition" under shock-condition, fluid metals in their experimentally accessible critical regions may serve as models.

T25. Classical ionic fluids with $1/r^6$ pair interactions have power-law electrostatic screening

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Some years ago it was found that the long-range decay of correlations in quantum Coulomb fluids follow power laws, which is very different from classical Coulomb fluids that have correlations with exponential decay. The exponential screening is killed by the quantum fluctuations - essentially the same mechanism that causes the dispersion interaction. In the current work we investigate classical Coulomb fluids where a dispersion interaction is added as an effective $1/r^6$ interaction potential, i.e. in addition to the Coulombic and the short range repulsive potentials (e.g. hard core). Our results from both exact analysis in statistical mechanics and Monte Carlo simulations is that electrostatic screening follows a power-law with the same exponent as in the quantum case. Thus the dispersion and Coulombic interactions are coupled in an intricate manner. The completely symmetric binary electrolyte is a special case. Then the screening has a decay that is faster than any power law and the dispersion and Coulombic interactions are decoupled to all orders.

T26. Problems of EOS of matter at high energy densities

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Physical processes arising under conditions of extreme energy densities, such as hypervelocity impacts, action of powerful energy fluxes on condensed matter and others, are of interest for fundamental investigations and for numerous practical applications. The typical features of these phenomena are complicated character of 3D gas dynamic flow and big gradients of flow parameters. The numerical modeling of processes at extreme conditions supports experimental investigations in this area. On the other hand, it is the only tool for investigating phenomena which can not been carried out at laboratory conditions. The dramatic progress in the computer industry in past 20 years resulted to the development of high-performance computers and efficient numerical schemes as well. The equation of state (EOS) governing the system of gas dynamic equations defines significantly accuracy and reliability of results of numerical modeling. The current state of the problem of a theoretical description of thermodynamic properties of matter at high pressures, high temperatures is given in a set of publications. In spite of a significant progress achieved on construction of EOS in solid, liquid and plasma state with the use of the most sophisticated first-principle theoretical approaches (classic and quantum methods of self-consisted field, diagram technique, computers Monte-Carlo and molecular dynamics methods) the disadvantage of these theories is their regional character. The range of an applicability of each theory is local and, rigorously speaking, no one of them allows to provide for a correct theoretical calculation of thermodynamic properties of matter on the whole phase plane from the cold crystal to liquid and hot plasmas. The principal problem here is the necessity to take into account correctly the strong collective interparticle interaction in disordered media, which meets especial difficulties in the region occupied by dense disordered non-ideal plasmas. In this case experimental data at high pressures, high temperatures are of peculiar significance, because they serve as reference points for theories and semiempirical models. Data obtained with the use of dynamic methods are of the importance from the practical point of view. Shock-wave methods allow to study a broad range of the phase diagram from compressed hot condensed phase to dense strongly coupled plasma and quasigas states. Available experimental data on the shock compression of solid and porous metals as well as isentropic expansion embrace to nine orders with respect to pressure and four to density. The extension of studied range of the phase diagram to greater relative volumes, in comparison with the principal Hugoniot, is achieving in the investigation of the shock compressibility of porous samples. Nevertheless, difficulties of a work with ultradispersive targets and singularities of the heat transfer in multi-phase non-equilibrium media restrict the possibility of an advance on the density scale. The method of isentropic expansion of shocked matter allows, depending on the magnitude of the shock pressure, and, respectively, the entropy provided, to pass in one experiment states from a hot metallic liquid and strongly coupled plasma to two-phase region liquid-gas and Boltzmans weakly ionized plasma and an ideal gas. The complex of available experimental and theoretical information is discussed.

T27. Nucleation mechanism of explosive rupture for small size systems at high energy densities

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We discuss general conditions of phase equilibrium of a substance in a nonuniform potential field of forces. If the force per unit mass is phase dependent, the field may induce a shift of phase equilibrium. In this case chemical potentials of the substance do not coincide at the phase boundary with equal temperatures and pressures for each phase and one phase is in metastable state. Thus the field-induced phase equilibrium becomes impossible for a given geometry, and the system has to change its phase abruptly when one of the phase reaches the limit degree of supersaturation or superheating. An example of such a transition is the case of a liquid current-currying conductor in its own magnetic field turning rapidly to a dispersion state (drop in vapor). In contrast to the explosion of thin wires, the explosion of micropoints occurs in a strong electric field. In this case liquid metal of a micropoint is in the extended metastable state. At a certain degree of superheating, rapidly growing vapor bubbles arise spontaneously in it (vapor cavitation or explosive boiling),leading to the explosion of the micropoint. The resulting mixture of droplets in vapor expands with a high velocity to transform into plasma bunches. Similar phenomena can occur at the sputtering of materials by slow multicharged ions. It is shown that a strong electric field of a slow multicharge ion approaching the surface of a dielectric target leads to the formation of an extended metastable subsurface region. Cavities spontaneously appearing in this region form a percolation cluster leading to the fracture (cavitational electroexplosive erosion) of the target material. Contrary to some theoretical considerations we show that electric field favors the formation of both vapor bubble in superheated liquid and liquid drop in supersaturated gas.

T28. Effective computer simulation of strongly coupled Coulomb fluids

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Monte Carlo or molecular dynamics computer simulation of disordered strongly non-ideal Coulomb systems like ionic fluids, plasmas, amorphous solids, etc., require an accurate account for long-ranged Coulomb forces which determine to the largest extent their dynamics, thermodynamic and transport properties and strongly affect the equilibrium structure. An essential problem in computer simulations of macroscopic systems modeled by a limited number of particles confined within a main cell with periodic boundaries is the accuracy in account of long-ranged Coulomb forces.

The conventional Ewald summation procedure when applied in simulation of disordered Coulomb systems creates an artificial non-isotropic electric field having the cubic symmetry of the crystalline lattice composed of main cells as elementary units and results in an artificial crystalline field effects in spatially uniform Coulomb systems. In addition, the incorporation of the standard Ewald summation procedure over reciprocal lattice extremely increases the processor load what makes accurate simulations possible, as a matter of fact, only on supercomputers.

A new boundary condition in computer simulation of ionic liquids, based on angular averaging of Ewald sums over all orientations of the reciprocal lattice and eliminating these periodicity artifacts was proposed recently [1]. It provides a simple analytical effective electrostatic interaction potential of two particles having range correspondent to the main cell size.

The effectiveness of this approach, which allows accurate simulations of strongly coupled Coulomb systems even on modern PC, was recently demonstrated on simplest model fluids like one-component plasma and primitive ionic model [2]. Possible applications of the new approach and the role of periodicity artifacts in known computations of electrostatic contribution to the energy of disordered dense systems are discussed. The elimination of this contribution is especially important when the number of particles in the cell is small (e.g. in ab initio simulations) as well as near the crystallization line.

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P87. Measurement of electrical conductivity and pressure on the saturation curve of zinc at 0.5 g/cm^3

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We have performed a set of constant volume experiments to measure the vapour pressure of zinc at energy densities up to 9 MJ/kg. A zinc sample is placed in a sealed sapphire tube and is pulse heated. The time dependence of the sample pressure and electrical resistance are measured. Determining the saturation pressure consists in detecting, on the resistance versus pressure curve, the transition point between the two-phase state and the fluid state.

To be accurate, this technique requires reversible change of the system, that is to say equilibrium at any time. In our experiments, divergence to equilibrium, due to density non-homogeneity, is recorded. Nevertheless a peculiar point is detected at 380 MPa. This pressure looks high according to recent measurement of the zinc critical parameters by C.Otter, G.Pottlacher and H.Jäger in 1996.

We will present and discuss our experimental results. So far, two possible interpretations are retained:
1. The detected point is the two-phase to fluid transition point. The critical pressure of zinc is greater than 380 MPa and, probably, the coexistence curve is very flat between 2.6 and 0.5 g/cm^3.
2. This point is not the two-phase to fluid transition point. At 380 MPa, the electrical conductivity is proportional to the density for a density ranging from 0.35 to 1 g/cm^3.

P88. Thermodynamics and phase transitions of electrolytes on lattices with different discretization parameters

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Lattice models are critical for investigation of thermodynamic properties of many chemical, physical and biological systems. We study Lattice Restricted Primitive Model (LRPM) of electrolytes with different discretization parameters in order to understand thermodynamics and the nature of phase transitions in the systems with charged particles. A discretization parameter is defined as a number of lattice sites that can be occupied by each charged particle. It allows to investigate the transition from the discrete picture to the continuum description of ionic fluids. Explicit analytic and numerical calculations are performed using lattice Debye-Hückel approach, that takes into account the formation of dipoles, the dipole-ion interactions and the correct lattice Coulomb potential. The gas-liquid phase separation is found at low densities of charged particles for different types of lattices. The increase in the discretization parameter lowers the critical temperature and critical density, in agreement with Monte Carlo computer simulations results. In the limit of infinitely large discretization our results approach the predictions from the continuum model of electrolytes. However, for the very fine discretization, where each ion can only occupy one lattice site, the gas-liquid phase transitions are suppressed by order-disorder phase transformations.

P89. The pre-breakdown current-voltage and EHD characteristics calculations for liquid insulators

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The liquid insulator under high voltage reveals well-known features of its behavior, that is concluded in deviation of the current - field dependence from Ohm's law [1,2]. In this work we study the pre-breakdown behavior of liquid insulators on the base of our model [3,4]. We suppose that the liquid dielectric is analogous to the weak electrolyte. And the partial dissociation of its molecules takes place. The concentrations of ions $n_{\pm}$ and impurities n_p are supposed to satisfy the following condition.

$$n_{\pm} \ll n_a$$

$$n_p \ll n_a$$

n_a - is the concentration of neutral particles (molecules). The pre-breakdown EHD equation are written under this condition. For the case of sphere under high voltage U there exist only stationary solution for potential space distribution. This distribution is valid outside boundary layers, consisting to the Frenkel conductivity law. This hydrostatic result is in agreement with experiments for high-voltage spherical capacitor. The 1D analytical and numerical hydrostatic solutions of equation, mentioned above, for plane and cylindrical high-voltage capacitors were also obtained. The EHD-instability problem was also studied on the base of general system [3,4] and standard hydrodynamic equations.

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Statistical Theory of SCCS

I10. Charged DNA beyond mean field theory

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Polyelectrolytes are of great importance in different branches of chemistry and biology. DNA is a very good example of a polyelectrolyte of biological relevance. In this lecture, we apply an approach that goes beyond mean-field and describes DNA solutions in the presence of salt and amphiphiles. After thermodynamic equilibrium is reached, the amphiphiles and the electrolyte associate to DNA, leading to the formation of complexes. As the density of amphiphiles increases, we observe charge inversion of DNA complexes at not too high amphiphile densities. The formation of DNA-amphiphile complexes is essential for developing delivery systems in gene therapy, and we see that it is possible to reverse the charge of DNA even in the presence of multivalent salt.

I11. Criticality in ionic systems

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Even in the simplest classical models of ionic fluids consisting of hard spheres of diameters a_σ carrying charge $q_\sigma = z_\sigma q_0$ $(\sigma = 1, 2, \cdots)$ many questions concerning the location and nature of phase separation and criticality remain open or not fully resolved. Recent progress on some of these issues will be reviewed.

For the RPM or restricted primitive model 1:1 electrolyte (with $\sigma = +, -$, $a_+ = a_-$ and $z_\pm = \pm 1$) the critical temperature and density, T_c and ρ_c, have now been accurately determined by simulations [1]. Furthermore, the Ising character of the criticality is confirmed [1, 2] and novel scaling algorithms [2, 3] determine the coexistence curve and the diameter [4] to unprecedented precision. The analysis for the RPM reveals a large Yang-Yang ratio $\mathcal{R}_\mu \simeq 0.26$ (compared with a hard-core square well fluid, $\mathcal{R}_\mu \simeq -0.044$) while the diameter resembles that seen in liquid metals. However, simulations (in progress) for the 2:1 model (with $a_+ = a_-$) are much harder to analyze.

To understand the effects of valency, the previous treatment using Debye-Hückel theory, Bjerrum ion pairing and ion solvation [5], has been extended to 2:1 and 3:1 equisized models by considering larger ion clusters, their dynamics, and their solvation [6]. In contrast to all other theories, the correct trends of $T_c(z)$ and $\rho_c(z)$ (as discovered by simulations) are recovered. In all cases the *neutral* ion clusters predominate near criticality and the trends of T_c and ρ_c with z can be understood semiquantitatively on this basis [7].

At criticality in any fluid the density-density correlation length $\xi_N(T, \rho)$ diverges; but what happens to the charge screening length $\xi_Z(T, \rho)$ (which deviates from the Debye length at finite ρ)? Answers to these and related queries have been found on the basis of *exactly soluble* 1:1 ionic spherical models [8]. The artificial charge symmetry of the RPM can be broken and proves significant. In general, ξ_Z diverges like ξ_N;

furthermore, the Stillinger-Lovett sum rule may fail just *at* criticality. The introduction of additional power-law interactions, $\sim 1/r^{d+\sigma}$, can be handled and yields some insights into quantum-mechanical effects [9].

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T29. Testing Boltzmann's ergodic hypothesis by electron gas models

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Put simply, the ergodic hypothesis says that the time and ensemble averages of a dynamical quantity are the same. As we well know, the hypothesis is central to statistical physics. The standard approach to proving its validity is to do what was suggested first by Boltzmann himself. But it rapidly becomes mired in measure theory, and therewith irreversibility and the thermodynamic limit (TL) seem to go out of the picture.

A more physically based approach is to do the time averages, espoused by Kubo [1]. It has yielded an ergodic condition but it turns out to be incomplete. To do time averaging properly, one must know the time evolution of a dynamical variable say A, by solving the Heisenberg equation of motion $dA(t)/dt = i[H, A(t)]$, where H is the Hamiltonian. The recurrence relations method solves it generally if H is Hermitian [2].

The structure of the solution is defined by the dimensionality d and hypersurface s of the inner product space of A on H. Now d and s measure irreversibility and the TL and connect the energy transfer mechanisms to the ergodicity. More specifically, they yield an ergodic condition W, an infinite product of a set of numbers given by d and s [3]. If W is finite as is Wallis' infinite product, the model is ergodic with respect to A. Ergodicity is denoted through a delocalization of energy. If $W = 0$ or ∞, it is not. If $W = 0$, there is a localization of energy. If $W = \infty$, the energy transfers are ballistic.

The electron gas models are fertile ground for testing ergodicity by our condition W and to draw from it a physical picture that underlies the ergodic hypothesis. A dynamical variable for an interacting electron gas (Coulomb gas) is the density fluctuation operator at a wave vector k. The dynamic density response functions are known exactly in space dimensions $d = 1, 2, 3$ for $k \to 0$ or ∞ [4]. For them, we can calculate W and thus can determine whether the hypothesis holds. In this talk we will present our results of our calculation and conclusions.

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T30. Collisions and plasma waves in nonideal plasmas

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Investigation of properties of the Langmuir and the ion sound waves in nonideal (strongly coupled) plasmas is a long standing problem. Difficulties of analytical treatment arise from the key role of strong collisions in nonideal plasma which affect the wave damping. Computer simulations by the method of molecular dynamics (MD) are widely used in the case [1–3]. In the preset work the MD simulations are applied to study dispersion and damping decrement of the Langmuir waves, high energy bound states, effective collision frequency, frequency-dependent conductivity and temperature relaxation rate in the plasma with the nonideality (coupling) parameter $\Gamma = (4\pi n_e/3)^{1/3} e^2/(k_B T)$ in range $0.1 < \Gamma < 4$, where n_e is the electron number density, T is the temperature.

Both dispersion and damping decrement of the Langmuir waves are obtained from the dynamical structure factor (DSF) $S(\omega, k)$ calculated as the Fourie transformation of the charge autocorrelation function $F_{zz}(\mathbf{k}, t) = \langle \rho(\mathbf{k}, t) \rho^*(\mathbf{k}, 0) \rangle / \langle \rho^2 \rangle$, where $\mathbf{k}$ is a wave vector. It was found in previous studies [2,4] that usage of position of the DSF peak as frequency of the Langmuir waves result in an negative dispersion for $\omega(k)$. In present work explanation of this effect is given. It is shown that because of the strong wave damping the DSF peak no longer corresponds to the solution of the dispersion equation for the dielectric function $\varepsilon(\omega, \mathbf{k}) = 0$ which lies in the complex plane [3]. The damping decrement δ can be found as the halfwidth of the DSF peak. In order to single out the collisional damping δ_c and find the effective collision frequency $\nu = 2\delta_c$, the dependence $\delta(k)$ is fitted using the ideal plasma model [5] where ν is taken as a free parameter. This approach is still valid for $\Gamma < 3$ as the dispersion of the Langmuir waves turns out to be close to that one for the ideal plasma. A byproduct of these calculations is the dynamical conductivity. Another way to obtain both static and frequency-dependent conductivity is based on the linear reaction approach using the Fourier transformation of the current autocorrelation function $K(t) = \langle \mathbf{j}(t)\mathbf{j}(0) \rangle / \langle \mathbf{j}^2 \rangle$.

Simulations of the equilibration of two-temperature electron-ion plasma are performed. Different relaxation stages are observed including the disorder induced heating. The electron-ion equilibration rate is found depending on the mass ratio, the nonideality parameter and the charge of ions. Special attention is given to formation of high energy bound states of electrons and ions depending on the plasma nonideality. The adjacent problem of using of quasiclassical pseudopotentials in MD simulations is discussed.

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T31. Self-consistent statistical approach to electronic properties of hot dense plasmas

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The knowledge of plasma equation of state, photoabsorption and transport coefficients is needed in astrophysics for the calculation of stellar structure and evolution (white dwarfs, outer crust of neutron stars, ...) and requires suitable and realistic models for the description of ions, which have to be considered as species having integer numbers of interacting bound electrons. The number of relevant electronic configurations in hot dense plasmas can be immense (increasing with atomic number Z). In such cases, calculations relying on the superconfiguration approximation appear to be among the best statistical approaches to photoabsorption in plasmas [1, 2]. Furthermore, the superconfiguration approximation enables one to perform rapid calculation of averages over all possible configurations representing excited states of bound electrons. We present a thermodynamically consistent model involving detailed screened ions (described by superconfigurations) in plasmas. The density effects are introduced via the ion-sphere model. In [2, 4], bound electrons were treated quantum-mechanically while free electrons were described within the framework of semi-classical Thomas-Fermi theory. Such a hybrid treatment can lead to discontinuities in the thermodynamic quantities when pressure ionization occurs. In a previous work [4] we have presented an improvement of the thermodynamics of the model proposed in [2] showing how, through the variation of ionic volumes and the equality of electronic pressure at all ion boundaries, the statistics of the superconfigurations can affect the occurrence of resonances accompanying pressure ionization. In the present model we use the same approach as in [4] except that now free electrons are treated quantum-mechanically. Furthermore, resonances are carefully taken into account in the self-consistent calculation of the electronic structure of each superconfiguration. The procedure is different from the one used in the Inferno code developed by D. A. Liberman [3] in the sense that in the latter case the model was an average atom in a jellium while we perform this calculation in the ion-sphere model for each superconfiguration. The model provides the contribution of electrons to the main thermodynamic quantities, together with a better treatment of pressure ionization, and gives a better insight into the electronic properties of hot dense plasmas.

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T32. Bound states in strongly couopled Coulomb systems

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The formation and dissolution of bound states in dense Coulomb systems is an important quantum statistical phenomenon which influences the properties of such many-particle systems essentially. Different concepts are used to describe medium modifications of bound states in dense plasmas. They reflect different aspects, in particular with respect to limiting cases. They concept of a partially ionized plasma is essentially a chemical picture. The components are considered as well-defined quasiparticles moving in a mean field. Dissolution of bound states due to screening is described as Mott effect. The concept of the averaged atom model calculates the shift of bound state energy levels due to the confinement into a Wigner-Seitz sphere, and the Anderson-Hubbard model includes correlations and disorder to describe a correlation gap or mobility edges in the density of states.

A unified description of bound states in strongly coupled Coulomb systems is given within a quantum statistical approach. Instead of quasiparticles, the spectral function and the density of states are evaluated. These concepts are also applicable near the Mott transition. Under certain approximations, the limiting cases given above can be deducted. Consequences for different properties such as the hopping contribution to the conductivity are discussed.

Another important topic is the Bose-Einstein condensation of bosonic bound states at low temperatures. With increasing density, the fermionic character of the constituents of the bound states becomes of importance. We obtain a crossover from BEC to to Cooper pairing within the Bardeen-Cooper-Schrieffer model.

This effect, which is closely related to the Mott effect, is of importance not only for atoms in traps, but also for excitons in semiconductors at low temperatures. Numerical estimates and comparison with experiments in Cu_2O are presented.

P90. Charged particle motion in a highly ionized plasma

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A recently introduced method utilizing dimensional continuation is employed to compute the energy loss rate for a non-relativistic particle moving through a highly ionized plasma. No restriction is made on the charge, mass, or speed of this particle. It is, however, assumed that the plasma is not strongly coupled in the sense that the dimensionless plasma coupling parameter $g = e^2\kappa_D/4\pi T$ is small, where κ_D is the Debye wave number of the plasma. To leading and next-to-leading order in this coupling, dE/dx is of the generic form $g^2 \ln[Cg^2]$. The precise numerical coefficient out in front of the logarithm is well known. We compute the constant C under the logarithm exactly for arbitrary particle speeds. Our exact results differ from approximations given in the literature. The differences are in the range of 20% for cases relevant to inertial confinement fusion experiments. The same method is also employed to compute the rate of momentum loss for a projectile moving in a plasma, and the rate at which two plasmas at different temperatures come into thermal equilibrium. Again these calculations are done precisely to the order given above. The loss rates of energy and momentum uniquely define a Fokker-Planck equation that describes particle motion in the plasma. The coefficients determined in this way are thus well-defined, contain no arbitrary parameters or cutoffs, and are accurate to the order described. This Fokker-Planck equation describes the straggling — the spreading in the longitudinal position of a group of particles with a common initial velocity and position — and the transverse diffusion of a beam of particles. It should be emphasized that our work does not involve a model, but rather it is a precisely defined evaluation of the leading terms in a well-defined perturbation theory.

P91. Electric microfield distribution calculations of a hot chlorine plasma at solid density

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Spectral line shapes are known to provide powerful tool for characterizing strongly coupled plasmas. Line shape calculations require the knowledge of the electric microfield properties at the emitting atom or ion. Although several methods have been developed to obtain such properties, they are often limited to weakly or intermediate coupled plasmas. In the present work, we consider a chlorine plasma in local thermodynamic equilibrium at solid density and various temperature.

By the means of a self-consistent average-atom model [1], the electronic and the ionic structures are determined self-consistently. Several statistical properties can be calculated such as the radial pair distribution of ions which differs from the one obtained by standard classical derivation.

In parallel, semi-classical molecular dynamics simulations based on a regularized potential accounting for ion-electron short distance quantum effects, is used to model a two-component plasma of ions and

electrons [2]. The radial pair distribution function found with this semi-classical method corroborates the above quantum approach.

The electric microfield distribution, necessary to calculate spectral line shapes are deduced from the obtained radial pair distribution functions.

The impact of these different approaches on the various chlorine ion spectral lineshape computations is presented and discussed.

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P92. Nonequilibrium electron-positron plasma created by a laser field of circular polarization

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On a strong non-perturbative dynamical basis, in the framework of the oscillator representation, a quantum kinetic equation of non-Markovian type is derived which describes the vacuum creation of electron-positron pairs (EPP) under the action of a space homogeneous time-dependent electric field of arbitrary polarization (for a preliminary report see [1]). The particular case of a circularly polarized harmonic "laser" field with amplitude E_m and frequency ν is investigated in detail for the characteristic parameters of the Jena Terawatt Ti:saphire laser (pulse intensity $I = 3 \cdot 10^{18}\ \mathrm{W/cm^2}$, $\lambda = 795$ nm, pulse duration $\tau_L = 84$ fs, [2]), that corresponds to rather weak field $E_m = 5 \cdot 10^{-5} E_c$, where $E_c = m^2/e = 1.3 \cdot 10^{16}\ \mathrm{V/cm^3}$ is the Schwinger critical field strength.

Under these conditions, it is shown that:

- during the laser pulse, a nonequilibrium EPP plasma with the density $\sim 10^{18}$ cm^{-3} is generated, which exceeds that for a linearly polarized field of the same intensity [3, 4] by a factor of two;
- residual EPP's are formed with a density depending on the shape of the laser pulse;
- the creation of these EPP could be verified experimentally by detecting photon pairs from the two-photon annihilation process.

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P93. N-Electrons dynamics of heavy atom in strong fields

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The purpose of this work is to describe accurately the dynamical behaviour of a many electrons system interacting with strong fields, and in particular to take into account electron dynamical correlations on high-density energy deposition in high-Z plasmas, for which the probabilities of multiple excitation/ionisation collision processes are high. The two main applications of this work are:

i) The collision of two high-Z atoms at high energy in relation with energy deposition of a high energy heavy ions beam in high-Z matter and with the focussing of high current heavy ion beams in an heavy ion inertial fusion reactor chamber [1]. The beam radius at the focal plane has a strong influence on the nuclear gain that can be achieved. Using a classical calculation, it was found [1] that multi-ionisation processes should have a large effect in the beam dynamic. The classical approximation has a strong influence on e-e correlation, so it is important to validate the classical results within a more exact quantum calculation.

ii) Plasmas created by optical field ionisation (OFI)using high intensity laser. Recent experiments [2] allow for a precise and quantitative comparison between theory and experiment of the X-ray gain evolution in term of several parameters (pressure, target length, focal position). These experiments provide a unique opportunity to analyse the dynamical evolution of hot and dense plasmas in a highly non-equilibrium state. The influence of dynamical correlation among bound electrons has, up to now, received little attention. It is expected however, that in the case of a high-Z atom such as Xe it can play a significant role.

We use an ab initio formalism well adapted to dense plasmas physics: the Wave Packet Molecular Dynamic (WPMD) model [3]. We improve the model of [3] by writing the wave packet as a sum over Hermitte-Gaussian functions. As in [3] the time dependency of the various parameters entering in the definition of one wave packet is determined through a variational method, which leads us to study electrons dynamics in a time dependent semi-classical potential by the evolution of a set of predefined generalized coordinates. Preliminary and encouraging results had already been obtained in the simplest case of one Gaussian wave packet per electron [4]. At the conferences we will present our first results related to the interaction of a high intensity sub-picosecond laser pulse with a high-Z atom. Comparison will be done between WPMD, using various basis functions, the mean field approximation and one electron models.

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P94. The dipole structure of electromagnetic field

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The electric dipole moment of a system of charges is intimately associated with the energy of their Coulomb interaction. The radiation of electromagnetic energy by such a system is always accompanied by the variation of its electric moment. It is shown in my presentation that the electromagnetic field is equivalently described by a system of oriented electric and magnetic dipoles.

It is demonstrated in [1] that the cooled gas of dipole molecules in a strong electric field may form the Bose-Einstein condensate. Given a complete orientation of the dipole moment, the dipole-dipole interaction may bring about the anisotropy of pressure: it is negative in the direction of orientation and positive in the perpendicular direction, $P_{\|} = -\alpha_1 p^2 n^2$, $P_{\perp} = -\alpha_2 p^2 n^2$. Here, $\mathbf{p} = e_0 \mathbf{d}$ is the dipole moment of particles, n is their concentration, and $\alpha_{1,2}$ denotes coefficients of the order of unity. The anisotropy of pressure expressed by these formulas is similar to that in the tensor of tensions of electric field. Maxwell reduced the tensions, which act per unit of an arbitrarily oriented surface element, to the thrust $E^2/8\pi$ in the direction of field $\mathbf{E}$ and to the pressure (negative thrust) $E^2/8\pi$ in the perpendicular direction. The equilibrium of a system of oriented dipoles in an nonuniform electric field leads to the equality $E^2/8\pi = 2\pi(pn)^2$.

In the case of negative longitudinal pressure, the dipole moments are oriented in opposition to the field, and the positivity of energy reflects the electrostatic instability of the system of charges. The displacement current in vacuum regains the meaning of displacement of electric charges $\mathbf{j}_p = -\partial(\mathbf{p}n)/\partial t$.

By analogy with electric field, these results are valid for magnetic dipoles and magnetic field: $H^2/8\pi = 2\pi(mn_1)^2$. Here, m is the magnitude of magnetic dipole moment, and n_1 is the concentration of such dipoles. The obtained results offer a new physical interpretation of the field properties. For instance, the mutual attraction of the plates of a charged capacitor is attributed to the negative pressure between them.

An eddy field acts on an electric dipole with the force

$$-\mathbf{p} \times \text{rot}\mathbf{E} = \frac{\mathbf{p}}{c} \times \frac{\partial \mathbf{H}}{\partial t}, \quad \text{a similar force} \quad -\mathbf{m} \times \text{rot}\mathbf{H} = \frac{\mathbf{m}}{c} \times \frac{\partial \mathbf{E}}{\partial t}.$$

acts on a magnetic dipole. It is these forces that define in the Maxwell equations the known exchange of momentum between the fields $\mathbf{E}$ and $\mathbf{H}$. The flow of electromagnetic energy is transferred by the motion of polarized medium.

This presentation deals with quasi-stationary field; the application of the quantum theory calls for separate treatment.

The physical nature of the revealed dipole structure of electromagnetic field needs to be explained. A hypothesis is suggested for the possible physical content of the obtained results.

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P95. Microfield distributions in strongly coupled two-component plasmas

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The spectral line shapes of a radiator (atom or ion) immersed in a plasma are a valuable and widely used tool for plasma diagnostics [1]. In many cases the observed line shapes are closely related to the electric microfield at the position of the radiator and the problem is thus reduced to determine the distribution of the perturbing electric fields. To this end various theoretical approaches have been derived and employed, among them the pioneering work of Holtsmark [2] for uncorrelated plasmas, the APEX treatment of Ref. [3] for one-component plasmas or the modified APEX approximation applied to an ion embedded in an electron gas studied in Ref. [4]. We have extended these studies to the electric microfield distribution in a two-component electron-ion plasma (TCP) using both molecular dynamics simulations and a theoretical model. This is done in the framework of classical statistical mechanics using an electron-ion Coulomb potential $V_{ei} \propto (1 - e^{-r/\delta})/r$ which is regularized at small distances to take into account quantum diffraction effects. In our theoretical approach we generalized the exponential approximation of the APEX treatment to the classical TCP. But in contrast to the original APEX the involved effective fields are derived in the potential of mean force (PMF) approximation i.e. as a logarithmic derivative of the plasma-particle radiator pair distribution function. The resulting PMFEX approximation automatically satisfies the exact second moment of the microfield distribution $P(E)$ without the use of adjustable parameters. The pair distribution functions needed to calculate the $P(E)$ within the PMFEX approximation are taken from a numerical solution of the hypernetted chain (HNC) equations for the TCP with the regularized V_{ei}. This scheme is checked by comparing both the pair distribution functions and the resulting microfield distribution with the corresponding results obtained from molecular dynamics simulations. A a quite good agreement between the theoretical model and the simulations is found over a wide range of coupling parameters.
This work was supported by the BMBF (06ER128).

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P96. On plasma coupling and turbulence effects in low velocity stopping

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The problem of stopping power (SP) for projectile ions is considered in terms of dielectric function and dynamic collision frequency for moderately dense and strongly coupled plasma (SCP). Discussed is the role of some aspects of determination of stopping power for correlated particle−oscillator systems. Namely, studied are effects of group (few particles) modes, calculation of SCP dynamic collision frequency, transition from positive to negative dispersion, excitation of collective modes up to suprathermal level at dense plasma targets. Quasilinear stopping of dense superthermal (nonlinear) plasma targets at different levels of excited plasma turbulence is calculated. Energy loss functions obtained are compared with other approximations like Mermin or RPA. The additional force acting on the beam ions resulting from suprathermal plasma oscillations is analogous to increased frictional drag. The results obtained show the possibility of increasing of low velocity anomalous (turbulent) stopping compared to losses in equilibrium dense plasma targets. The influence of critical target plasma parameters and synergism (or combination) of different factors to the stopping are discussed. Some of the experimental conditions that could create specific turbulent targets (laser produced plasmas, dense pinched plasmas, isochoric heating of solid density foils by proton beams, etc.) as well as related molecular dynamics simulations data are analyzed.

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P97. Exchange correlation of particles in a non-ideal plasma with polarization

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In order to describe the quantum non-ideal plasma one should take into account not only non-Markovian effect but exchange interaction too. Starting from the quantum BBGKY-hierarchy for the distribution functions, we have solved, the equation for the quantum pair correlation function considering the non-Markovian correction and exchange contribution. Solution of this equation can be expressed in terms of the resolvent of the linearized Hartree - Fock equation. As a result, we obtain a quantum non - Markovian kinetic equation describing the dynamical screening of the interaction potential and exchange interaction in a non-trivial way. In particular, this equation contains the dielectric function of plasma which exactly takes into account exchange scattering in plasma.

P98. Electroconductivity of dense non-ideal plasma in external HF electric field

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In this work the modified version of previously developed method for calculation of HF electroconductivity of dense non-ideal plasma is presented. The calculations were done for plasma within the range of electron densities $10^{21} \leq N_e \leq 10^{23}$ cm^{-3}. The real and imaginary part of HF electroconductivity is presenet in factorized form wit the help of the specialy developed procedure of factorization. In this form the real and imaginary part of electroconductivity are expressed wit the help of several parameters. One of them is the stationary electroconductivity of dense plasma σ_0. The stationary conductivity is calculated wit the help of a modified RPA method, developed in previos works. In the frame of this work the real and imaginary part of electroconductivity were calculated in a range of freqences of the external electrical field that are smaller than the plasma frequency.

P99. Collisional versus collective absorption in dense plasmas

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In former papers we focused on collisional absorption by a plasma in a strong high-frequency field [1–3]. This approach is extended to arbitrary frequencies. We start from the electrical current balance equation which is derived from a kinetic equation. This balance equation has non-linearities. It is possible to introduce a generalized dynamical electron-ion collision frequency. In the linear response regime we get from this known expressions. We will discuss the external and internal conductivities, respectively. Furthermore, we will discuss the influence of collective absorption.

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P100. Collisional absorption of dense plasmas in strong laser fields. Quantum statistical results and simulations

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An important question in almost all experiments with interaction of intense laser pulses with matter is the calculation of the energy deposition and the description of the heating connected with that. If a solid target is irradiated by such an intense laser pulse, dense plasmas can be created relevant for astrophysical research

and for inertial confinement fusion. One of the important mechanisms of energy deposition is collisional absorption usually described in terms of the electron-ion collision frequency.

In this contribution, collisional absorption of dense fully ionized plasmas in strong laser fields is investigated using quantum kinetic theory as well as molecular dynamics simulations. For high-frequency fields, quantum statistical expressions for the electrical current density and the electron-ion collision frequency are presented [1, 2]. The expressions are valid for arbitrary field strength assuming the nonrelativistic case. Strong correlations are taken into account by local field corrections and by the ion-ion structure factor. Their influence on the absorption rate is discussed, and results for the important case of a two-temperature plasma in a laser field are presented. In addition, molecular dynamics simulations were performed to calculate the heating of dense plasma in laser fields [3]. Comparisons with the analytical results for different plasma parameters are given. There are considered the case of isothermal plasmas as well as two-temperature plasmas. Furthermore, results for the velocity distribution function under the influence of intense laser fields are presented which show a different behaviour in comparison to weak fields.

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P101. Equation of state of high density plasmas

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Today there exists a great variety of methods to determine the equation of state (EOS) of nonideal plasmas. Our approach (a perturbation expansion based on exact quantum statistical theory) has several valuable advantages. From a physics point of view, it includes the degeneracy of electrons and ions; from a more technical view, it allows much faster calculations compared to numerical simulations. Due to the first point, our EOS can also serve as benchmark for numerical simulations in the weak coupling limit for all temperatures and densities.

In the framework of Green's function technique, we establish an EOS for dense nonideal plasmas by an expansion in terms of the interaction potential [1]. Starting from electrons, nuclei, and their basic coulomb interaction, it becomes possible to systematically include nonideality effects of different orders. Altough the EOS is calculated for weak coupling only, collective effects, dynamic screening, and self energy corrections are included self consistently [2]. The evaluation of the contributing terms requires no restriction with respect to degeneracy. We show comparisons with advanced numerical simulation techniques and different analytical approaches. We find rather good agreement between all the different methods in the low density regime. With stronger coupling and higher degeneracy deviations up to a factor of 2 can be observed.

The main problem to be solved in the high density region is the complex interplay of correlation and quantum effects. At high densities, the plasma consists of degenerate electrons and strongly coupled ions. In this case, we improve our EOS by including strong correlations in the ionic subsystem. These can be efficiently considered by treating the ions within classical fluid theory (hypernetted chain equation). It is our goal to retain the advantages of both methods: the inclusion of quantum effects in the EOS (for the electrons) and the inclusion of strong ion–ion correlations. For this reason, we sum both contributions and subtract the low density limiting law once to avoid double counting. We demonstrate that this ansatz leads to a better agreement with numerical simulations.

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P102. Path integral method in quantum statistics problems: Generalized ensemble Monte Carlo and density functional approach

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Though the standard Metropolis algorithm [1] remains the principal instrument in Monte Carlo simulations of molecular systems, last decade several new approaches under the name of Generalized ensemble (GE) MC were introduced and proved to be efficient in treatment of systems with rough potential landscapes (low temperatures, high densities, phase transitions) [2, 3].

One of them, the Wang-Landau algorithm [4], is applied here to calculate density of states of a quantum particle system in the framework of the path integral (PI) form of quantum statistics. The density of states is presented by a two-dimensional function which, being calculated, allows to obtain canonical averages (e.g. internal energy) in a wide range of temperatures by a simple 2d integration. For the quantum oscillator exact data were well reproduced [5].

Another GE approach, method of expanded ensembles [6], was applied to calculating the ratio of quantum partition functions for different classes of permutations in treatment the problem of few identical particles (fermions) in harmonic and Coulomb fields.

The main goal of obtaining the quantum partition function and averages within the PI approach can also be achieved by calculating the average density of the corresponding closed paths (“ring polymers”) in external field. Recent developments within a density functional (DF) approach proved to be very successful in application to classical polymer systems [7, 8]. This encouraged us to apply the polymer DF theory (P-DFT) to PI problems. Our first calculations reproduced very accurately the known data for electron distributions and energies in hydrogen and helium atoms in their ground states. Data for the quantum particle in 1D and 3D harmonic fields are also accurately reproduced in a wide range of temperatures. The computer effort within the reported PI-DFT method is extremely small (seconds or minutes).

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P103. Transport and optical properties of a strongly coupled semiclassical plasma by a molecular dynamics simulation

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The non-ideal (strongly coupled) semiclassical plasma exists frequently in nature. For example, the interiors of many-sequence astrophysical objects (white dwarfs, very low mass stars and giant planets etc.)

are astrophysical strongly coupled plasma. The second group of non-ideal plasma is produced in laboratory conditions: plasma in the focus of the inertial confinement fusion research, shock wave compression experiments, pinch discharges, laser inducing. In all given cases the knowledge of plasma transport and optical properties is of great importance.

In the present work we consider a fully ionized, strongly coupled (dense), semiclassical hydrogen plasma with following parameters: The number density of particles is in the range $n = n_e = n_i \cong (10^{22} \div 2 \cdot 10^{26})$ cm^{-3} and plasma temperature domain is $T \cong (5 \cdot 10^4 \div 10^6)$ K. The dimensionless parameters for description of the system are used: coupling parameter is defined by $\Gamma = e^2/ak_BT$, density parameter $r_s = a/a_B$, where a is the average distance between particles and a_B is the Bohr radius. Degeneracy parameter is defined by ratio of thermal energy to Fermi energy: $\Theta = k_BT/E_F \approx 0,54 \cdot r_s/\Gamma$.

The semiclassical effective potential [1] taking into consideration long-range many-particle screening effects [2] and quantum-mechanical diffraction and symmetry effects at short distances is used for describing of interactions between particles. The microscopic functions (coordinates, velocities, autocorrelation functions) are obtained by computer simulation molecular dynamic method. Classical equations of motion are solved numerically by Verlet's algorithm with periodic boundary conditions. The computer simulation of transport properties is performed for wide ranges of the coupling and density parameters. The transport and optical properties (electrical conductivity, generalized susceptibility, absorption coefficients etc.) are calculated on the basis of the Green-Kubo linear response theory and autocorrelation functions of microscopic dynamical variables. The obtained results are compared with available theoretical and experimental data of other authors.

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P104. Quantum Coulomb crystals in a two-component system

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When electrons in a solid are excited to a higher energy band they leave behind a vacancy in the original band. Such holes behave like positively charged particles. We predict that holes can spontaneously order into a regular lattice in semiconductors with sufficiently flat valence bands. The critical hole to electron effective mass ratio required for this phase transition is found to be of the order of 80 in three dimensions and 30 in two dimensions. These hole crystals are intimately related to ion Coulomb crystals in white dwarf and neutron stars as well as to ion crystals produced in the laboratory in ion traps. A unified phase diagram of Coulomb crystals in two-component systems is derived and verified by first-principe path-integral Monte Carlo simulations [1].

This work is done under financial support of the RAS program No. 17 ”Parallel calculations and multiprocessor computational systems”, the grant for talented young researchers of the Science support foundation and the Deutsche Forshungsgemeinschaft under grant BO 1366-2. The research was also partly sponsored by CRDF Awards and the Ministry of Education of Russian Federation.

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P105. Hall conductivity in dense plasmas

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The Hall conductivity is investigated as a to tool for diagnostics in dense plasmas, in particular to get information about plasma parameters and scattering processes. In dense plasmas, many-particle effects are manifested as correlations and in-medium effects are relevant. The Hall conductivity is particularly sensitive and nonideality leads to strong deviation from the standard results for the Hall conductivity.

This poster looks at recent experimental results for the Hall conductivity in partially ionized Argon and Xenon [1]. Different theoretical approaches are discussed and compared [1,2] which strongly depend on the thermodynamic model and the transport cross section.

We present the basis of a consistent approach to the Hall coefficient within the linear response theory. We take advantage of the experiences from describing thermoelectric properties using equilibrium correlations functions [3]. Incorporating the perturbation by an external magnetic field [4], an expression for the Hall coefficient can be derived.

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P106. Relaxation of plasma composition and species temperatures in laser- and shock-produced plasmas

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Dense plasmas are usually created in states far from equilibrium. After a short relaxation these systems can be described as two-temperature plasmas. Often the plasmas have also a nonequilibrium charge state distribution. During the subsequent relaxation process, population kinetics and temperature equilibration do strongly influence each other. Here, we focus on this interplay of the coupled relaxation processes.

First, different models for the energy transfer between electrons and ions are discussed with special focus on strong electron-ion collisions and collective modes. For systems with degenerate electrons, a Spitzer-like formula is derived. The evolution of the charge state distribution is described with a system of rate equations. Finally, the rate equations are solved self-consistently with the corresponding temperature equations. The latter and the rate coefficients include nonideality corrections that originate from quasi-particle shifts.

The results show that the relaxation can be often divided into two stages: first the charge state distribution equilibrates. Due to the release of binding energy in recombining plasmas, the ionization kinetics can also have a large impact on the electron temperature. During the second stage, the energy transfer between the subsystems drives the temperature equilibration while the plasma composition changes only parametrically. This behavior motivates a quasi-stationary treatment of reactions which allows for a large reduction of the numerical effort and, therefore, the possibility to use more advanced schemes for the chemical composition (e.g., better quasi-particle shifts or consideration of excited states). We also demonstrate how the evolution of the species temperatures is modified by nonideality corrections. Typically, one observes a reduction of the ion temperature in the recombination phase and a higher ionization degree for the whole relaxation.

P107. Bremsstrahlung from dense plasmas and the Landau-Pomeranchuk-Migdal effect

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The suppression of the bremsstrahlung cross section due to multiple scattering of the emitting electrons is an important effect in dense media (Landau-Pomeranchuk-Migdal effect). Here, we study the emission from a dense, fully-ionized and non-relativistic hydrogen plasma. Using the dielectric approach, we relate optical properties such as emission and absorption to equilibrium force-force correlation functions, which allow for a systematic perturbative treatment with the help of thermodynamic Green functions. By considering self-energy and vertex corrections, medium modifications such as multiple scattering of the emitting electrons are taken into account. Results are presented for the absorption coefficient as a function of the frequency at various densities. It is shown that the modification of the inverse bremsstrahlung due to medium effects becomes more significant in the low frequency and high density region.

P108. Analyzing of laser-induce C V line Profiles

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Measured X-ray brilliance spectra of a carbon plasma generated by subpicosecond high intensity laser pulses are analyzed (T. Wilhein et al. 1998). The spectra of helium-like carbon are calculated using a microscopic quantum-statistical approach assuming local thermal equilibrium (S. Günter et al. 1991). Self absorption is taken into account by one-dimensional radiation transport equation in a plasma layer (S. Sorge et al. 2000). The calculated synthetic spectra are compared with the experimental results for transitions $1s^2 - 1s2p$ and $1s^2 - 1s3p$ for hot dense laser plasmas at a given electron density and temperature.

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P109. High harmonics generation in a strongly coupled laser plasma

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The non-equilibrium statistical operator for a strongly coupled plasma embedded in an external strong electromagnetic field is constructed. The theory of high-order harmonics generation taking into account plasma electron heating due to inverse bremsstrahlung absorbtion of an intense, high-frequency electromagnetic wave is developed. Under the conditon where the electron quiver energy is generally much larger than the electron thermal one and on the based of the scattering theory, srongly coupled effects as well as the influence of an external strong elecromagnetic field, are taken into account.

P110. Energy transfer and potential energy contributions in dense two-temperature plasmas

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We investigate the relaxation of dense, strongly coupled plasmas with different electron and ion temperatures. In particular, we answer the question how the used approximation for the energy transfer between the electrons and the ions is connected to the description of changes in the excess energy contributions during the relaxation.

Obviously, the well-known Landau-Spitzer approach to temperature relaxation in weakly coupled plasmas considers only the evolution of the kinetic energies; changes in the excess energy are neglected. On the other hand, the Fermi-Golden-Rule (FRG) and coupled mode (CM) expressions derived by Dharma-wardana & Perrot describe changes in the total energy of the electron and ion subsystems. However, it is difficult to define such electron and ion energies in strongly coupled plasmas since it is unclear how to prorate terms due to the electron-ion interaction. Based on the technique of nonequilibrium Green's functions, we show analytically that these electron-ion interacting contributions must be split equally between the electron and ion energies to be consistent with the CM energy transfer rates.

Finally, we show results for the relaxation of nonideal plasmas. Compared to the Landau-Spitzer approach and the FGR expression, the CM description results in strongly reduced energy transfer rates and, therefore, to longer relaxation times. We also demonstrate the influence of the time-dependent excess energies on the relaxation process in strongly coupled plasmas.

High-Energy-Density Matter Generated by Intense Heavy Ion Beams

P111. High energy density physics experiments with intense heavy ion beams at GSI and at FAIR

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Intense beam of energetic heavy ions is an excellent tool to create large volumes of high energy density (HED) matter with fairly uniform physical conditions. We present an overview of the current experimental research that has been done at GSI-Darmstadt in the field of heavy-ion beam generated HED matter. Special attention is given to the most recent experiments at GSI with an emphasis on development of ion-beam and target diagnostic instruments and methods which will be used for the HEDP experiments of the HEDgeHOB collaboration at future FAIR facility.

P112. Electrical resistivity measurements of heavy ion beams generated high energy density Aluminium

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The high intensity heavy ion beams provided by the accelerator facilities of the Gesellschaft für Schwerionenforschung (GSI) Darmstadt are an excellent tool to produce large volumes of high energy density (HED) matter. Thermophysical and transport properties of HED matter states are of interest for fundamental as well as for applied research. During the last few years development of new diagnostic techniques allowed for a series of measurements of the electrical resistivity of heavy ion beam generated HED matter. These experiments provide us with the basis for future measurements in the frame of the HEDgeHOB collaboration.

In this report we present the latest developments and most recent results on electrical resistivity of HED matter obtained at GSI. The targets under investigation consisted of $5\mathrm{mm}$ long, $0.25\mathrm{mm}$ diameter aluminium wires. Uranium beam pulses with durations of a few hundred ns, intensities of about $2 \cdot 10^9$ particles/bunch and an initial ion energy of 350 MeV have been used as a driver. An energy density deposition of about 1 kJ/g has been achieved by focussing the ion beam to less than 1 mm (FWHM) focal spot size.

P113. Shockwave-driven, non-ideal plasmas for interaction experiments with heavy ion beams

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For laboratory astrophysics and basic research in ICF, generally the research field of warm dense matter physics, investigation of the interaction of heavy ions with non-ideal plasmas is of interest. Non-ideal plasmas are characterized by Γ-parameters $\geq$ 1, and it is predicted that the dependency of the energy loss of charged particles in non-ideal plasma is less than Z_{eff}^2, differing from the behaviour in ideal plasmas. But no experimental data-base, describing the interaction processes exists yet.

Non-ideal, strongly-coupled plasmas can be created by shockwaves, where gas is compressed in front of a shock front propagating with several km/s and a homogenous plasma layer with a thickness of several millimeters forms. The driver for the shock-wave is the detonation of a high explosive (for example 55 g RDX). At the UNILAC accelerator at GSI an experimental set-up for conducting interaction experiments of heavy ions in the MeV/u region with shockwave-driven Ar-plasmas exists since 2001.

The plasma targets are optimized to reduce straggling of the beam and inhomogenities of the plasma. Measurement of the shock-wave velocity is done by recording the light emission from the plasma. With shock-wave velocity and initial gas pressure as input parameters the plasma properties can be determined by a code based on spectroscopic data developed at the IPCP in Chernogolovka. Free electron densities between 0.26–1.5$\cdot 10^{20}$ cm^{-3} for initial Argon-pressures between 0.2–3 bar and Γ-parameters between 0.6–1.3 at about 2 eV were determined. The energy loss of C-, Ar-, and Xe-ions at 5.9 MeV/u and 11.4 MeV/u was measured with TOF-methods in the compressed plasma-phase and compared to the energy loss in the cold Ar-gas at the same line density. Besides detecting an influence of the free electron component in the measured energy loss also an influence from enhanced charge states of the ions in the compressed Argon in the plasma phase leading to an enhancement of the energy loss is within the scope of the investigations. Simultaneous measurement of energy loss and charge states of the ions and measurements with already in low-pressure Ar-gas fully stripped C-ions were therefore conducted.

P114. Intense beams of energetic heavy ions as a tool to create high-energy-density states in matter: studies of strongly coupled plasmas at the GSI Darmstadt Accelerator Facilities

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Numerical simulations have shown that an intense heavy ion beam is a very efficient tool to create high-energy-density states in matter including strongly coupled plasmas. This is due to the intrinsic characteristic of heavy ions that they deposit energy over extended volumes of solid matter that leads to production of near solid density, low temperature (tens of eV)plasmas. Gesellschaft fuer Schwerionenforschung (GSI), Darmstadt is a unique laboratory worldwide that has a heavy ion synchrotron, SIS18 that delivers intense beams of heavy ions including uranium. Currently the SIS18 can deliver 4×10^9 uranium ions in a single bunch that is a few hundred ns long. This facility is being upgraded with the aim to achieve an intensity of 2×10^{11} uranium ions with a bunch length of 50 ns. Moreover, the German Government has recently approved construction of a new accelerator facility named FAIR (Facility for Antiprotons and Ion Research) at the GSI that will involve construction of a much more powerful synchrotron, SIS100 that will deliver a beam with an intensity of 2×10^{12} uranium ions per bunch. Detailed numerical simulations and analytic modeling has shown that the intense heavy ion beams that will be availble in future as a result of upgrade of the SIS18 facility and at the future FAIR facility will enable one to study unexplored regions of the phase diagram using the HIHEX technique which allows for an isentropic expansion of an isochorically heated sample material. Using an alternative scheme that involves a multiple shock reflection technique, one may achieve a low entropy compression of hydrogen that would lead to physical conditions that are expected to exist in the interiors of the giant planets. This scheme is named LAPLAS (LAboratory PLanetary Sciences). These two schemes have provided for the basis of a letter of intent (LOI) named HEDgeHOB (High Energy Density Matter Generated by Heavy Ion Beams) that has been written by members of the GSI Plasma Physics Group in connection to the FAIR project.

P115. Investigation of heavy ions tracks energy deposition inside solid media by methods of x-ray spectroscopy.

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The interaction between low current energetic heavy ion beams and solid matter is in the focus of present investigation. Beam energy and charge state distribution as well as excited target conditions were measured by methods of spatially resolved x-ray spectroscopy. The experimental data of aluminum and aerogel quartz media state is presented during its interaction with energetic (11.4–4.7 MeV/amu) Mg and Ni ions. The measuring method consists in observation of radiation transitions to K-shell of multicharged Si atoms of excited matter with spatial resolution along the beam propagation inside the solid. The extremely short time scale and the solid transparency for inner shell x-ray radiation transitions provides main advantages of the used diagnostics. The relative intensities of Ka-satellites lines are in strong correspondence to ionization equilibrium. For data analyses the numerical simulation of ionization states and excited level populations was applied. As a result, values of ions track electron temperature (120–70 eV) on the first tens of femtoseconds after excitation were estimated. To confirm that, hydro dynamical two-dimensional simulation of heavy ion track in the same conditions was carried out which took us a values of 110–60 eV of electron temperature and 2.5–1.0 g/cc of media density on time scale of 1–20 fs after heavy ion flight through. Accordance of these values achieved by different theoretical methods allows to describe the plasma parameters produced by heavy ions in local nanoscale area of their track inside the solids.

P116. Investigation of plasma stream collision produced by thin films irradiated by powerful pulsed electron beam

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Collision of plasma streams with velocities $7 \div 15$ km/s in vacuum was investigated. Plasma was produced by fast heating of parallel thin flat films by the perpendicular powerful pulsed electron beam (electron energy 300 keV, beam current $10 \div 30$ kA, pulse duration 100 ns at FWHM). Thicknes of used films

($10 \div 40\ \mu\mathrm{m}$) was considerable less than the corresponding electron stopping depth. The distance between films varied from 2 up 10 mm. The experiment geometry was chosen to ensure the one-dimensional collision. Interactions of Al, Ti, Cu, Pb and mica-produced streams and their combinations were investigated. Optical diagnostics, including streak camera (FER-7) and two frame cameras (Nanogate, 10 ns frame exposition) were used to record the plasma expansion and interaction processes. Beam voltage and current were recorded using digital oscilloscope.

The characteristic features of this method producing the extreme states of matter are the possibility to vary the deposited energy in wide range and using almost any material, both metals and dielectrics.

Hot plasma stream produced by the film explosion is expanding and freezing and its brighness is decreasing. Collision of such hardly visible streams creates intense optical flash. The obtained extremely hot plasma begins to spread out. The bright flash is attributed to the fast arising of temperature and density due to the streams collision.

Hydrodynamical simulation of the experiments was performed. According to the preliminary results the temperature of the colliding streams was about 40000 K while the maximum temperature of the irradiated films was only 8000 K.

Thus the technique of obtaining the plasma with required density and temperature suitable for the thermophysical investiagtions was developed.

P117. Transportation and focusing of accelerated protons beams by means of dielectric channels

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A number of experiments in which beams interact with a wall of the channel is carried out to last years, and this interaction has self-organizing character if the channel is made of good isolator [1–4]. During the first moments of passage of the charged particles through the dielectric channel the part of ions collides with a wall and it is charged due to issue of electrons and to sedimentation of ions on ither. Then, when the certain distribution of a charge is formed, particles of a beam cease to collide face with walls, and practically all particles pass through a capillary lost-free energy . The present paper gives an experimental and theoretic study of the transmission and focusing process of protons within the 100 keV to 300 keV energy range through cylindrical and conic quartz tubes. It has been established that protons pass through the tube without energy losses. Proton beam goes through the tube even when the tube axis does not coincide with the beam axis. The angular width of the protons transmission via tube probability curve versus angle of incidence makes about 3 degrees. As authors suggest this effect is explained as follows: as beam transmission starts, protons collide with tube wall and charge it due to electron emission. Collisions of particles with the wall continue until surface charge is produced a field deflecting protons from the wall. So, self-organization of a beam wall charge system takes place. In the present work it is shown, that there are, at least, two mechanisms of this effect. Finiteness of length of the channel is essential. On the average on length of a part of the channel the potential of regional forces depends from x. If the length of the channel is not too great, regional effects play a main role in formation of potential and perfectly explain contactless passage of ions through the channel. With growth L the size of a field decreases and at aspect attitude $L/d > 10000$ it is impossible to explain channels focusing action by regional forces. The second mechanism of the phenomena is the next. The charge arising on a wall is distributed not in regular intervals, and fluctuates. Quickly oscillated force working on a particle, results in occurrence of the unidirectional force, i.e. gradient forces (Miller - Gaponov's force) [5] these forces also provide contactless passages of ions through long dielectric channel. The work is executed at support of the Russian Fund of Basic Researches the grant 05-02-16007.

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P118. FST technologies for cylindrical cryogenic targets fabrication to supply plasma physics experiments with heavy ion beams as a driver

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Target supply is an essential technology and science component for ongoing and future target laboratory experiments.

For almost 15 years the Lebedev Physical Institute (LPI) works in the area of cryogenic target science, technology and delivery for the systems of inertial confinement fusion. As a result of these activities, a special class of free-standing target (FST) technologies has been developed and a unique equipment has been created, which makes it possible to fill polymer shells with a fuel gas in the range of 100-to-1000 atm at 300 K, to refreeze the fuel on the inner surface of the shells (thus we have cryogenic targets) and accelerate these targets at 4.2–10 K up to a velocity of 4-to-8 m/sec in the electromagnetic field of a single coil using the cylindrical ferromagnetic sabot.

Based on these advances, the FST technologies are now at the stage of extension on cylindrical targets fabrication for plasma physics experiments with heavy ion beams as a driver. The research work includes the technology development for producing the components of the cylindrical cryogenic target as well as the design and construction of a device for all components assembly and finished targets delivery.

In this report, we discuss the following topics: Technologies of fabrication of target components, namely: (a) cylindrical lead tamper creating (b) method of plasma deposition on to a mandrel followed by the mandrel dissolving, (c) method of solid hydrogen cylinder fabrication using extruding technique. Two design options of the device for solid hydrogen cylinders production, their assembly with hollow plastic or lead cylinders and acceleration with the aim of delivery.

P119. To the criterion for breaking of a nonlinear plasma wakefield

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The perturbations of electron density in a nonlinear plasma wakefield, driven by the short laser pulse or electron bunch, change their form and value while the distance from a driver increases. The electron density can become infinitely high at some point (so-called, wave-breaking). As a result, the size of that region, where the amplitude of the regular wakefield is quite high to be used for acceleration of injected charged particles is limited. In this paper, from numerical solution of relativistic hydrodynamic equations for electrons and Maxwells equations we find location of that electron density singularity, which arises because of the finite radial size of the wakefield. The analytical theory of the wave-breaking is elaborated by extrapolation of the weak nonlinear theory to the case of strong nonlinear wave. The simple analytical criterion for the wave-breaking space position is found. The numerical results are in good agreement with the analytical theory.

P120. The radiative opacity research for inertial confinement fusion applications

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The radiative opacity research can promote progress in the Inertial Confinement Fusion (ICF). The density functional theory is used to review theoretical models of a hot dense plasma, which are usually used for radiative opacity calculations [1]. The general set of self-consistent field equations, that describe the state of the whole ensemble of plasma atoms and ions, is obtained. It is demonstrated the additional physical approximations, which are applied in different models to simplify the general set of equations, restrict the range where the models can be employed. Other way is a solution of general set of self-consistent field equations on the base of the ion model of a hot dense plasma (IM) [2]. This approach is applied to designing complex ablator materials for ICF targets, to optimizing hohlraums, and to optimizing X- and Z-pinch wires. As known, chemical admixtures can considerably influence the frequency-dependent radiative opacity of plasmas. A theoretical method and the corresponding computer code were created to calculate spectral coefficients of X-rays absorption and to search on this base the optimal complex materials for certain physical conditions. Thermal radiation energy yield from optically thick or optically thin plasmas grows with decreasing Rosseland or Plank mean free paths, respectively. By this way a composition of Au and Gd, as a material to create an optically thick plasma of hohlraum wall, was proposed in [3] instead of pure gold. The composition of Au and Gd gives double decrease of the Rosseland mean free path in comparison with pure gold. A more efficient composition of Au, W, Gd, Pr, Ba, Sb was found using the mentioned optimizing code. This composition ensures the Rosseland mean free path decrease by factor three in comparison with pure gold, and provides more high efficiency than the materials proposed in [3] and, some later - in [4]. The complex ablator materials for ICF targets are also discussed in this case. Another application concerns materials of thin wires for X-pinch source [5]. The Rosseland and Planck mean free paths were calculated at the temperature T=1 keV for NiCr and for the composition Alloy 188 (Cr, Ni, Fe, Co, W) at different plasma densities. More high efficiency of Alloy 188 in comparison with NiCr is demonstrated. Thus, the proposed theoretical method is an effective tool to study complex materials for ICF applications.

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P121. Calculations of LTE opacities for ICF-target modeling

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Spectral and Rosseland-mean opacity calculations are presented for LTE plasmas of Cu-doped Be ablators [1, 2] and Au:Gd hohlraum walls [3] of indirect-driven ICF-targets.

The calculations were done on the base of the STA (Superconfiguration Transition Array) approach [4, 5] utilizing electron-orbital atomic data generated with the Hartree-Fock method with relativistic corrections [6].

Opacities of the Cu-doped Be plasmas were calculated in the broad temperature and density ranges in application to the modeling of the proposed indirect-driven targets for future ICF experiments at the NIF and ISKRA-6 laser facilities being built at LLNL and RFNC VNIIEF [7].

Dependence of Rosseland mean opacities of the Be-Cu and Au-Gd mixtures on the fraction of Cu and Gd for typical plasma temperatures and densities is analyzed. Comparisons with experimental and other calculated data are also presented.

Present-day development of the model is outlined that would enable to consistently calculate optical and thermodynamic properties of mid-ionized ($\bar{Z} \simeq Z/2$) dense plasmas of hohlraum walls using the STA approach.

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