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CONTENTS

CHAPTER 1. THERMODYNAMIC PROPERTIES AND EQUATION OF STATE OF NON-IDEAL PLASMAS

CHAPTER 2. NON-IDEAL PLASMA IN ASTROPHYSICAL APPLICATIONS

CHAPTER 3. TRANSPORT AND OPTICAL PROPERTIES OF NON-IDEAL PLASMAS

CHAPTER 4. PHYSICS OF DUSTY AND COLLOIDAL PLASMAS

CHAPTER 5. GENERATION AND DIAGNOSTICS OF NON-IDEAL PLASMAS

THERMODYNAMIC PROPERTIES AND EQUATION OF STATE OF NON-IDEAL PLASMAS

QUANTUM FLUID DESCRIPTION OF DENSE PLASMAS

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The development of methods for large-scale simulation of time-dependent features of quantum plasmas is crucial both for fundamental and applied problems. On the other hand, the capabilities of ab initio simulation methods, such as Quantum Monte Carlo, Nonequilibrium Green functions or time-dependent density functional theory (TD-DFT), are typically restricted to the simulation of about a hundred electrons. Therefore, it is important to develop approximate methods which accuratley capture the main features and are able to provide a large-scale simulation. For example, orbital-free DFT allows for a fast calculation of static properties of dense plasmas (warm dense matter) at high temperatures [1]. An extension of this method to the simulation time evolution has also been proposed [2]. With particular additional approximations, this leads to an approach called quantum hydrodynamics (QHD) [2, 3]. However, in the past QHD was often used without strict derivation and outside of its applicability range leading to incorrect results, for a discussion see [3, 4]. Therefore, in this work we present a recently developed method of the fluid description of quantum plasmas [5] which is equivalent to the random phase approximation (RPA) and can even go beyond RPA by employing dynamic local field corrections. As applications, some aspects and peculiarities of the static and dynamic screening of a test charge and of the manifestation of the quantum non-locality are discussed [6–8].

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PLASMA AND SOLID-STATE EFFECTS IN THE PLASMA FLUID OF METALS AND RARE GASES

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Some thermodynamic and transport properties of gases with density of liquid and even a solid state in the presence of processes of thermal ionization are considered. Let us call for brevity such condition of substance a plasma fluid. One of the interesting effects found experimentally in recent years is the metallization of gases at compression. It is fixed in dense vapors of metals [1], at compression of inert [2] and molecular gases (see [3]). Metallization of vapors proves in growth of the conductivity up to minimum metallic. Growth of conductivity is explained in different ways: influence of Coulomb and interatomic nonideality [2], dissociative phase transition [3]. The unusual explanation of effect of metallization of metals vapors was offered in [4] with use of the "3+" chemical model. The conductivity increase at vapors compression was explained by existence of new component – electron jellium (sign "+" in the name of model in addition to traditional electrons, ions and atoms). Jellium arises from tails of the electron density of the ground state wave functions of all atoms lying out of atomic Wigner–Seitz cells. The comparative analysis of a role of jellium, intercharges and interatomic interactions in dense plasma of inert gases and vapors of metals is made. Within the "3+" model, the dense xenon plasma reflectivity is calculated taking into account jellium. Comparison with experiment and *ab initio* calculation [5] is made. The significant role of new component – jellium – is noted. The equation of state, dc and optical conductivity of beryllium plasma are calculated within the "3+" model. Comparison with QMD results [6] is made. The offered simple model of the plasma fluid is rather successfully used in near-critical region of metals vapors and for dense plasma of rare gases. Introduction to model of new component – jellium – allowed to understand and solve a number of problems of the dense plasma physics.

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PRESSURE EFFECT ON STRUCTURAL AND PHYSICAL PROPERTIES OF SODIUM

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At normal pressure and temperature more than temperature of 4 K, sodium has the bcc crystal structure. There are structural transformations at the increase of pressure in sodium, which lead to a more dense packing lattice. Thus Na has the fcc crystal structure at 80 GPa [1]. On a melting curve the anomalies are observed, for example, the maximum at P=28.3 GPa [1]. Structural changes also lead to a change in the kinetic properties and thermo-electrophysical characteristics of the metal. Therefore, the aim of this report is the study of the effect of pressure on structure and physical properties of sodium.

The electronic spectrum of sodium is calculated in the framework of the density functional theory, and phonon spectrum is calculated in the framework of the linear response theory using the package of programs LmtArt-7 [2]. In this package of programs fully potential method of the linear muffin orbitals is realized (FP-LMTO). In our calculations, as a rule, we were taking of 9 orbitals. However, at the compressions $V \leq 0.4V_0$ our calculations are taking into account also all 11 orbitals of sodium and the relativistic corrections. Exchange-correlation potential was considered in the gradient approximation. The calculations were performed by the method of pseudopotential in plane waves expansion. Integration over the Brillouin zone was carried out on the net of 32*32*32 special k-points (Monkhorst-Pack).

In the compressions range from 1 to $V = 0.2V_0$ the electronic band structure and densities of electron and phonon states were calculated for both the bcc lattice with two atoms and the fcc with four atoms in an unit cell (UC). The topological features of the electron density in two projections: for a side and for the main diagonal of the cubic cell, and of the Fermi surface as well as of the first Brillouin zone were investigated A comparison of the Fermi energy, the plasma frequency and the density of states at the Fermi level for bcc and fcc lattices depending on the compressions were carried out. The dependences of phonon specific heat, and the electronic electrical and thermal conductivities of the bcc lattice of sodium in the range from 5 K to the melting temperature at the given compression ratio calculated and constructed.

The data analysis revealed that in case of conserving of the crystal structure type, the lattice deformation leads to the appearance of dielectric properties in the behavior of kinetic coefficients with pressure increase.

The work was performed under state order No. 0389-2014-0006, and at partial financial support of RFBR (project No. 16-08-00466) and Ural Branch of RAS within the framework of fundamental research program "Matter under extreme conditions" (project No. 15-1-2-8).

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THERMODYNAMICS OF LIGHT GASES IN MEGABAR PRESSURE RANGE

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The thermodynamic properties of light gases at high pressures and temperatures are of interest for many years because of their wide spreading in nature to one hand and using in various high energy facilities to the other hand. Equation of state of light gases at submegabar and megabar ranges of pressures and high temperatures were experimentally studied with different methods. At these parameters where a high density of matter is accompanied by a strong Coulomb interaction (strongly non-ideal plasma) thermodynamic properties of gases have been theoretically described both as in frames of the quasichemical approach (free energy model) so with the ab-initio methods involving the direct numerical simulation of system of nuclei and electrons. In spite of achievements of experimental and theoretical methods in this range of parameters further study of dynamically compressed light gases is important. In particular, the problem of the possibility of a phase transitions at high compression degrees is not resolved yet. The experimental data on caloric and thermal equation of state cover pressures of shock and isentropic compression from kilobars to dozen megabars and rather high densities. Last several years new theoretic results in frames of chemical picture and ab-initio methods in a wide range of pressures geenerated with shock and quasiisentropic compression have been presented as well.Here we present the results of calculation of hydrogen isochors in wide range of temperatures, shock adiabats of deuterium and nitrogen and isentropes of deuterium up to megabar pressures. These calculations were carried out with codes implemented the improved SAHA-family models. The calculations have shown that in the considered pressure range dynamically compressed gas is in a state of strongly coupled, degenerated plasma with density close to condensed matter. Results of our calculations are presented in comparison with those obtained in frames of the first principal quantum methods and the data of experiments.

METASTABLE STATES OF WARM DENSE HYDROGEN

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Warm dense hydrogen is investigated by *ab initio* molecular dynamics simulations in the region of fluid-fluid phase transition. The simulation is made in the framework of density functional theory. The hydrogen is observed along 1000 K isotherm at the density interval of 0.880 – 0.975 g/cm^3. The functional PBE is used, since it reproduces experimental pressures and temperatures of phase transition.

The structure changes of warm dense hydrogen are reflected at pair correlation functions (PCF). At lower densities hydrogen is at molecular phase and the PCF has a high peak at $r = 0.74$ Å, that correspond to interatomic distance between atoms in H_2. An important part of phase transition is the destruction of the molecules that leads to a decrease of the height of PCF first peak. Therefore, the shape of the PCF can be used as criteria for determination of the phase of the hydrogen.

Modeling of metastable states is an unexplored problem so far. There are two main points that let us to obtain the metastability: the selection of particular initial configurations (coordinates and velocities of ions) and turning off the thermostat.

We managed to obtain molecular phase far beyond the phase transition. The metastable branch of the isotherm overlaps the equilibrium branch by density at the interval of 0.05 g/cm^3, that is 2.5 times more than density jump at the phase transition. The pressure range of metastabilty studied is more than 300 kBar, while the difference between pressure of the metastable and equilibrium states at the same density is approximately 150 kBar. The pair correlation function conserves its shape along the 1000 K isotherm, that confirms the preservation of the molecular phase.

The existence of the metastability could explain serious discrepancy between different experimental results on the phase transition parameters. The faster is the compression (heating) rate the father from the equilibrium transition and closer to the spinodal is the point of the experimental transition.

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TEFIS DATABASE

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Since the end of 1950-s, in M.V. Keldysh institute of applied mathematics RAS, works on various properties of matter under extreme conditions have been developed. The main efforts were focused on models of thermodynamic properties, electronic and atomic-molecular transfer, and in the latest years, for microfield properties and rates of thermonuclear and chemical reactions.

Currently, basing on these works, we create TEFIS database. The first stage of this database contains thermodynamic functions of elements under extreme conditions constructed from two models: Saha model with finite ion cores volume and statistical Tomas-Fermi model with quantum and exchange corrections. Wide-range equation of state is constructed from these models via interpolation providing rigorous thermodynamic consistency.

Soon, the first stage of this database containing thermodynamic functions of the first 20-30 elements of the periodic table will be placed on the official site of M.V. Keldysh IAM RAS. It is intended to be open-access.

EQUATION OF STATE OF MELT AND MELTING CURVE OF BORONE CARBIDE AT MEGABAR PRESSURES

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The large number of publications are devoted to analysis of the properties of boron carbide in the range of high pressures and temperatures, including extreme conditions of shock compression (see [1–3] and references therein).

Until recently, researchers analyzed the range of shock compression pressures not exceeding 90 GPa. However, comparison of B_4C Hugoniot from [1] for the pressure range 200–800 GPa allows to assume the existence one more clearly manifested kink of B_4C Hugoniot [2] in the shock pressure range 95 GPa–125 GPa. The substantiation and development of this hypothesis is presented in the report.

So the semiempirical description of thermodynamics of shock compression of boron carbide and its melt is given up to megabar pressure. It is shown, the offered thermodynamic description of boron carbide corresponds to experiment at 0–400 GPa within its error. The melting curve of boron carbide is culculated at pressure 0–20 GPa. This curve possesses negative curvature and predicts low temperature melting of boron carbide in the pressure 120 GPa at temperature 700 K. The derived results are compared with modern results of other authors. In particular, the first-principles molecular dynamics calculations [3] in the consent with [2] give the reduction of melting temperature of boron carbide in pressure range up to 40–100 GPa. The calculations of shock temperature of melt and volume dependence of Gruneistn factor of boron carbide melt from [3] and [2] also will be in conformity among themselves.

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NEW DATA ON QUASI-ISENTROPIC COMPRESSIBILITY OF GASES AT MEGABAR PRESSURES

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Given the results of measurements of strongly compressed deuterium and helium plasma properties in the pressure range up to 10^5 GPa and at the compression ratios up to 1500 including the data on their mixtures at the pressures up to 250 GPa. The results were acquired by means of experimental devices of cylindrical and spherical geometry and x-ray diffraction complex consisting of three betatrons and multi-channel optoelectronic system x-ray images recording.

The pressure in the plasma of compressed gases was obtained using gas-dynamic calculations taking into account real thermo-dynamic and strength properties of all elements of experimental devices and their equations of state. The main truth criterion of pressure obtained in the calculations one can consider satisfactory fitting of the whole $R(t)$ trajectory of experimental device shell movement.

QUANTUM-STATISTICAL CALCULATION OF THE RELATIVE COMPRESSIBILITY OF Al AND Cu IN STRONG SHOCK WAVES

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To carry out numerical simulations of different physical processes, in particular, by using the methods of computational fluid dynamics, it is necessary to know the equation of state (EOS) for matter under investigation. EOS is a fundamental characteristic that relates thermodynamic parameters of equilibrium systems with each other, namely, temperature, volume, pressure, internal energy, etc.

In the present report, EOSs for aluminum and copper are constructed in the framework of the Thomas–Fermi model with corrections (TFC) and the Hartree–Fock–Slater model (HFS). The calculated EOSs are used to derive the shock adiabats of investigated substances.

Calculation of shock adiabats is a convenient way to study EOS, because the adiabat expresses the thermodynamic properties of matter in the form of a simple kinematic dependence $D = f(U)$, where U is the mass velocity of matter, D is the wave velocity. In addition, there are experimental data on the shock compressibility of the metals in strong shock waves, where the temperature and density are sufficiently high to apply the approximations of the quantum-statistical approach.

An analysis of the results of experiments on the relative compressibility of aluminum and copper in strong shock waves was carried out. Iron, molybdenum, lead and quartz were chosen as reference substances.

AB INITIO SIMULATION OF LIQUID TUNGSTEN NEAR THE LIQUID-GAS COEXISTENCE CURVE

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We present quantum molecular dynamics calculations of thermodynamic properties of expanded liquid tungsten. We reproduce various shock-compression experiments for porous tungsten and subsequent isentropic expansion into different obstacles. Special attention is paid to available isobaric expansion experimental data and theoretical estimations of critical points. Density on our first-principle isobar of liquid tungsten is slightly higher than in most wire-explosion experiments and the slope of the isobar is more flat. A special Monte Carlo analysis has been applied for the estimation of the liquid–gas coexistence curve and critical point parameters of tungsten. The result is close to an estimation obtained with Likalter's similarity relation.

COULOMB LOGARITHM IN NONIDEAL AND QUANTUM DEGENERATE PLASMAS

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In plasma physics and astrophysics, the long-range character of the Coulomb or gravitational interaction leads to the appearance of various kinds of divergent integrals. To eliminate the divergences, the Coulomb logarithm is introduced into the electron scattering cross section on ions, the determination of which in the case of a nonideal plasma meets with certain difficulties (see, for example, [1, 2] and the literature cited therein).

In this paper, different methods to determine the Coulomb logarithm in kinetic transport theory and different variants for choosing the plasma screening constant (with or without allowance for the contribution of the ion component) and the boundary value of the electron wave vector are considered. To take into account the ion-ion correlations, the Ornstein-Zernike integral equation in the hypernetted chain (HNC) approximation [3] was solved numerically.

The calculated values of the electrical conductivity of a hydrogen plasma are compared with the experimental values measured in a megabar pressure range. It is shown that the Coulomb logarithm values should be much less than one in order to agree with the experimental data. For a more accurate determination of the Coulomb logarithm, it is necessary to carry out special experiments at the gas densities for which the electron scattering by ions predominates over the scattering by neutral atoms and molecules (for hydrogen this density region is above 1 g/cm^3).

The work was supported by the Russian Science Foundation (project No. 16-12-10511).

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INVESTIGATION OF THERMOPHYSICAL PROPERTIES OF DEUTERIUM AT MULTIPLE SHOCK COMPRESSION TO 400 GPa

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Gaseous Deuterium sample at initial temperature of 78 K, pressure 10 and 27 MPa and density 0.06 and 0.12 g/cc, was multiple shock compressed between dielectric sapphire window and sapphire driver plate. High pressure pulse was provided by conical Mach generator of flat shock wave. Optical pyrometer was used to register the brightness temperature of compressed sample at a set of wavelengths and reflection of laser light at 807 nm channel. Fast optical detectors were used to precise measurement of shock velocities in driver plate and sample, allowing to determin the compressibility of Deuterium in a first shock.

APPLICABILITY OF DIFFERENT ATOMISTIC SIMULATION METHODS FOR CALCULATION OF THERMODYNAMIC PROPERTIES OF HYDROGEN PLASMAS

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In this work we report on evaluation of different simulations methods for studying electron-ion non-ideal plasmas and warm dense matter. The internal energy and pressure are calculated using the classical molecular dynamics (MD), the wave packet molecular dynamics (WPMD) and the wave packet Monte-Carlo (WPMC). Constraining boundary conditions with a harmonic wall potential are used for wave packets to prevent wavepacket spreading. The self-consistency of the WPMD with a harmonic wall is discussed.

A combination of Density Functional and Wave Packet Molecular Dynamics methods is proposed to simulate the thermodynamics and the electronic dynamical properties of the nonideal plasma. In this approach we use the non-antisymmetrized single Gaussian wave packets to represent electrons and point-like particles for ions. The kinetic and electrostatic energy contributions for electrons are calculated within the WPMD model, whereas the exchange-correlation energy and its derivatives with respect to the dynamic variables is evaluated on a space mesh.

The second result is concerned with determination of the area of applicability of the classical MD and WPMD-DFT. For this, the equation of state for hydrogen plasma was calculated for a range of densities from $n_e = 10^{21}$ cm^{-3} to 10^{24} cm^{-3} and a range of temperatures form 10^3 K to 10^5 K. The equation of state obtained by different approaches was compared with the ab initio methods such as Path Integral Monte Carlo (PIMC). We show that at certain plasma parameters the MD method fails due to appearance of unphysical ordered structures of particles. This turns out to be the effect of the non-Coulombic pseudopotential (both in electron-electron and ion-electron interactions).

PSEUDO-ATOM MOLECULAR DYNAMIC SIMULATIONS FOR STRUCTURAL AND THERMODYNAMICAL PROPERTIES COMPUTING IN DENSE NON-IDEAL PLASMAS REGIME

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Pseudo-atomic molecular dynamic modeling (PAMD) [1, 2] as an effective tool for structural, thermo-physical and transport characteristics computing in warm and hot dense matter regime (WDM) is a theme of the present report. We may obtain an effective spherically symmetric inter-ionic potential V_{II} in the first approximation as it be done in the model by C. E. Starrett and D. Saumon [3]. Representing WDM as a mixture of neutral pseudoatoms (PA) and semiclassical Thomas-Fermi-Dirac electrons spatial ionic configurations and arrays of PA velocities are obtained. MOLOCH [4] and PALMA codes are used for MD modeling. Ion-correlative energy terms, ionic radial distribution functions (RDFs) and self-diffusion coefficients can be directly calculated from ionic configurations and trajectories.

We compare the WDM equation of state obtained with PAMD method with our previous results in the ion-correlative model TFCS with Ornstein-Zernike (OZ) equations for RDFs determination. EOS data tables in the last model are generated by the numerical differentiation of the Helmholtz free energy incorporating ion-correlation contributions. The area of applicability for the TFSC model may be determined on the base of such comparison. A close agreement of PAMD ionic RDFs is obtained with the data of quantum and orbital free molecular dynamic simulations [3], scatternig experiments with melted metals and laser-driven compressed plasmas. With the help of PAMD method we also can investigate a phase transition from amorphous solid state to ionic liquid in some extremely non-ideal cases.

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THERMODYNAMIC PROPERTIES AND ELECTRICAL CONDUCTIVITY OF COPPER IN THE CRITICAL POINT REGION OF THE LIQUID-VAPOR PHASE TRANSITION

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Isentropes of expanded copper in the critical point region of the liquid-vapor phase transition and metal-nonmetal transition by the method of isentropic expansion of shock-compressed porous samples were obtained.

Plate-samples of porous copper (with porosity $m = \rho_0/\rho \approx 2$–4 ($\rho_0$—normal density, ρ—density of the sample) were studied by isentropic expansion at the different final pressure (from 1 to 10 kbar).

The high-speed pyrometers were used for measuring the temperature and the shock wave velocity. The samples after shock compression expanded in helium medium with different initial pressure (1–150 bars). The shock wave velocity in helium was determined by the optical base length technique. Calculation of the mass velocity and final pressure of expansion of copper was carried out by the equation of state of helium [1].

The electrodes were introduced in the experimental assembly for electrical conductivity measurements. The electrodes (steel wire of ~1 mm in diameter) were mounted on the assembly bottom around windows, through which optical radiation registration was performed from the sample surface. The electrodes are located at a distance of ~2–3 mm from the surface of the sample, and shunted by resistor ~0.5–1.5 Ohm. The bridge circuit was used for measurement of the electrical resistance of samples [2]. The changing resistance of the sample was registered at contact of the sample with the pin-electrodes.

Measuring the time interval at the contact of the sample with pins makes it possible to estimate expanded sample thickness and density, when the initial thickness porosity of the sample is known.

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MODERN UNIFIED EQUATIONS OF STATE FOR NEUTRON STARS

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Models of neutron star plasmas, based on the same microscopic theory for the outer and inner crust and the core of a neutron star, are said to be unified. Such models self-consistently describe the equation of state and composition of plasmas in different phase states, which exist in different parts of a neutron star. Unified neutron-star plasma models evolve with the progress of nuclear and elementary particle theory and with the accumulation and improvement of computational, experimental, and observational data.

I present a family of modern unified neutron-star equations of state, based on the Skyrme effective inter-nucleon potential model and its generalizations. The properties of matter are described by these models in a wide range of densities, which embraces three qualitatively different regions: the outer crust, the inner crust, and the core of a neutron star. In addition, I describe a method of including the effect of superstrong magnetic fields on the magnetar equation of state.

The work has been partially supported by RSF grant 14-12-00316.

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DETECTION OF GRAVITATIONAL WAVES OF MERGING NEUTRON STARS AND FOLLOWING ELECTROMAGNETIC EVENTS

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In mid-October 2017 international collaborations LIGO and VIRGO announced [1] an important scientific discovery: in August 2017, three antennas registered the signal of gravitational waves (GW). This time the signal does not indicate a merger of black holes, but a merger of neutron stars in a close binary system. Since three antennas worked simultaneously, the time delay of the signals allowed to determine the source location – about 100 square degrees on the celestial sphere.

This area is much smaller than obtained by operating only two LIGO antennas. For this localization ground-based telescopes recorded a flash of a weak supernova called the "kilonova" in the galaxy NGC 4993, which is at a distance of 40 megaparsecs. Moreover, the space observatories Fermi and Integral registered a weak short gamma-ray burst in the area of the localization of the source of gravitational waves. It coincides in time with this event (1.7 seconds after the loss of signal of gravity waves).

In connection with this discovery, it is important to emphasize, that the first prediction of this phenomenon of a GRB following a GW signal of merging neutron stars at distance of many megaparsecs was made long ago by S.Blinnikov, I.Novikov, T.Perevodchikova, A.Polnarev [2]. The talk describes the history of the discovery and its consequences for fundamental physics.

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THEORETICAL AND EXPERIMENTAL STUDIES OF RADIATIVE AND GAS DYNAMIC PROPERTIES OF PLASMA FOR COMBINED LASER AND HEAVY ION BEAM EXPERIMENTS

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Theoretical and experimental studies of radiative and gas dynamic properties of plasma is carried out for experiments, where both laser and heavy ion beams are used. A brief review of quantum mechanical models of hot dense plasmas, which can be used to calculate the radiative opacity characteristics, are presented and discussed. Intensive theoretical study in the field of many-body problem in quantum mechanics and the density functional theory have provided development of modern quantum mechanical model, which is known as Ion model of plasma (IM). Important features of this model are considered and discussed. The model is applied to mathematical modeling of radiative and gas dynamic processes in plasma for combined laser and heavy ion beams experiments. As known, the interaction efficiency of heavy ion beam with a target increases if the target is heated to plasma state. The plasma target should keep the fixed temperature and density during further interaction with heavy ion beam. The mathematical modeling was performed to test this requirement realization. Mathematical modeling was also performed for experiment where hohlraum radiation transmits through CHO plasma target during 5 ns., and the share of absorbed energy was calculated and compared with experiment. Calculations of the Rosseland mean free path in dependence of plasma temperature were performed for CHO plasma and for CHO with a little admixture of Au. Theoretical explanation of so called gold doping effect, which can increase efficiency of heavy ion beam interaction with a target, is given, and application of the gold doping effect in the framework of FAIR program is discussed and proposed.

NUMERICAL CALCULATIONS OF MOMENTUM DISTRIBUTION FUNCTIONS IN TWO-COMPONENT STRONGLY COUPLED COULOMB SYSTEM

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In classical statistics at thermodynamic equilibrium all particles are maxwellian regardless of interaction between them. However quantum effects may change form of momentum distribution functions to non-maxwellian by two mechanisms. The first mechanism is exchange interaction between identical particles, which leads to Fermi or Bose distribution. The second mechanism is Heisenberg principle: interaction of some particle with others reduces the available volume, which leads to uncertainty in momentum resulting in increased probability to have higher momentum. This effect was predicted in [1] for two component Coulomb system and has been resulted in additive “tail” to maxwellian distribution function in form $1/p^8$. Recently time this issue have been studied in [2, 3] and formula for the “tail” have been improved.

All these results have been obtained using perturbation theory and are unsuitable for strongly coupled Coulomb systems. However regime of strongly coupling is of the greatest interest, because it covers the most important applications: dense plasmas in astrophysics, electron-hole plasmas in semiconductors, etc. Therefore ab initio non-perturbative methods for calculation of equilibrium distribution functions are needed.

In our work we propose numerical method for calculation of momentum distribution functions for strongly coupled two-component plasma in thermodynamic equilibrium. It is based on Wigner function in the phase space. We study momentum distribution functions of hydrogen plasma with coupling strength Γ from 0.8 to 2.0 and degeneracy of electrons $n_e\lambda_e^3$ from 0.3 to 5. Also we consider the model of “electron-hole plasma” where protons was changed to lighter “holes”.

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SUPERCONDUCTIVITY OF SHOCK-WAVE PRESSURE TREATED Al-Al_2O_3

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It is known that granular films of some superconductors exhibit enhancement of the superconducting transition temperature T_c , compared to that in the bulk, when the grain size is small enough. For example, in aluminum this effect is about a double value of T_c about 1.2 K for the bulk. Moreover, it has been found that the films with comparable grain size evaporated at low temperatures in oxygen-free ambience and at room temperature in oxygen atmosphere demonstrate similar enhancement of the T_c, which led to a conclusion that the aluminum oxide itself does not participate in the T_c-enhancement mechanism. In this paper we report on metastable superconductivity at Tc=37 K of the mixture of Al and Al_2O_3 subjected to shock-wave pressure of 170 kbar. The samples were prepared by means of flat-type shock-wave pressure setup. The starting samples were tablets, 9.6 mm in diameter and 0.9 mm thick, of bulk 99.99 %-pure aluminum disks covered by 0.2 mm layer of powdered pure aluminum oxide Al_2O_3. For preparing the superconducting Al/Al_2O_3 samples, the optimum value of the shock-wave pressure, within a 1 Mbar range, was found 170 kbar. Comparing the *ac* magnetic susceptibility and the *dc* magnetization measurement results, we conclude that the superconductivity arises within the interfacial layer formed between metallic Al and its oxide Al_2O_3. The superconducting Al/Al_2O_3 layer represents a structure of weakly linked superconducting grains.

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OPTICAL PROPERTIES OF PARTIALLY IONIZED STRONGLY CORRELATED DENSE PLASMA

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Improving the physics of strongly nonideal plasma involves building of a correct model of collision processes, which play a crucial role in such environments. This implies an obtaining of new data on the optical and transport characteristics for a wide range of variation of the thermodynamic parameters.

The results of new experiments on reflectivity of polarized light on explosively driven dense xenon plasma are presented. The study of polarized reflectivity properties of plasma was accomplished using laser light of wavelength λ_{laser}=1064 nm at incident angles up to up to $\theta = 60$ degrees. With density $\rho = 1.9$ g/cm^3, pressures P = 10 GPa and temperatures up to T = 30000 K of the investigated plasma, conditions with strong Coulomb interaction (the nonideality parameter up to $\Gamma = 1.5$) were present.

The thermodynamic parameters and composition of plasma were determined from the measured shock wave velocity with suitable calculations carried out. Angular dependence of s- and p-polarized reflectivities at several wavelengths can be used in the integration of Maxwell equations to construct the spatial profile of the density of charge carriers [1].

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DIFFUSION OF CHARGED PARTICLES AND THE CONDUCTIVITY IN AN ULTRACOLD STRONGLY COUPLED PLASMA: CALCULATION BY THE METHOD OF MOLECULAR DYNAMICS

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We present the result of calculation by the method of molecular dynamics (MMD) of electron and ion diffusion and conductivity in an ultracold plasma. We consider a physical model of neutral ultracold plasma in which the charged particles interact via the Coulomb law without any restrictions at large or small distances and without any additional free parameters. The calculations are carried out with a variable time step method. Classical equations of motion are solved for 200—500 electrons and 200—500 ions (protons) contained in the simulation cell using NVE ensemble. To simulate continuous plasma, we applied periodic boundary conditions. The particle density in the calculations was equal to 10^{10} cm^{-3}. The electron temperature is varied between 12 and 15 K, and the temperature of protons between 1 and 2 K. To determine the diffusion coefficients, we calculated the velocity autocorrelation functions (VAF) of the electron and the proton depending on time. In order to calculate the conductivity of the ultracold plasma we included a weak electric field in the equations of motion of particles. The applied electric field is sufficiently small, so that the energy acquired by particles on the mean free path is small in comparison with the temperature. The results of this work are compared with experimental, analytical and numerical data of other authors.

THE EFFECTS OF ION DENSITY ON THE ION RECOMBINATION

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Process of ion recombination in dense gases and liquids is considered with various options for choosing the properties of the medium and the ion itself. The dependence of the ion recombination constant in the gas on coulomb nonideality is established. But this dependence is absents in liquids. Conditions for the position of regions with different regimes of recombination kinetics are obtained.

The dependence of the rate constant of recombination in dense gases on the parameter of the Coulomb nonideality is investigated. The problems of describing ion recombination in both non-parent and parent gas are considered. The process of resonant charge exchange of ions on molecules of the medium is taken into consideration for ions in parent gases. It is established that, in spite of the existing ideas in the literature [1] that there is no dependence of the recombination rate in the diffusion regime on the parameter of the Coulomb nonideality, this dependence actually remains. This dependence can be interpolated in the range of all values of the nonideality parameter of an exponentially decreasing curve. The steepness of the decrease in the rate constant of recombination with an increase in the nonideality parameter decreases with increasing concentration of the background gas. In case of recombination of ions in liquids such dependence of the rate constants of recombination from Coulomb nonideality are not detected. In addition, the dependence of the recombination rate constant on the mass ratio of recombining ions as well as neutral molecules and ions, is studied.

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GALVANIC AND THERMOMAGNETIC PROPERTIES OF A NONIDEAL XENON PLASMA IN THE REGION OF MEGABAR PRESSURES AND MEGAGAUSS MAGNETIC FIELDS

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In [1] the data on thermoelectrophysical properties (the electrical conductivity, Seebeck coefficient and thermal conductivity) of the nonideal hydrogen plasma in a wide range of densities and temperatures, including the region of strong degeneracy of electrons at pressures of megabar range are presented. In the present paper, the same approach is used to calculate the electrical conductivity, thermal emf, and thermal conductivity of a nonideal plasma in a magnetic field from moderate densities to the region of strong electron degeneracy, as in cite StaGFil:2016. In this approach, the quasi-chemical method is used to determine the composition and thermodynamic properties of the plasma, and an interpolation expression is used to describe the components of the thermoelectric power conductivity and the thermal conductivity tensors of a nonideal plasma in a magnetic field in the framework of the τ -approximation (the Lorentz-Bloch model) [1, 2].

Calculations have shown that the thermopower in xenon reaches 3 mV/K, which is slightly lower than in hydrogen or deuterium, and the thermoelectric figure of merit is slightly higher. It is shown for the first time that there exists a density region where the sign of all the components of the thermoelectric power tensor in xenon change sign due to the Ramsauer minimum in the scattering cross section of electrons on neutral atoms in the region of comparable values of the cyclotron and transport frequencies of the electrons.

The work was supported by the Russian Science Foundation (project No. 16-12-10511).

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EXPERIMENTAL DETERMINATION OF THE CONDITIONS OF HOT JUPITER ATMOSPHERE TRANSFORMATION TO THE HIGH CONDUCTING STATE

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The intensity of optical radiation and resistance of a mixture of Hydrogen and Helium layer with He mass fraction 0.24, which corresponds to the composition of the outer layers of Jupiter atmosphere, were simultaneously measured under multiple shock compression up to 400 GPa in plane geometry. The initial pressure and temperature of the mixture were equal to 20MPa and 30 MPa and 77.4 K, respectively, and the velocity of shock wave in sapphire driver plate was equal to about 15 km/s. These conditions provided generation of compressed states, close to the Hot Jupiter atmosphere (HD209458 b) adiabat, according to the models proposed by Guillot et al, 2015. The conditions for appearance of the high conducting phase in the compression process and the achieved level of electrical conductivity were determined. The experimental data were compared with the one-dimensional hydrodynamic simulation of the compression process using the equation of state for the mixture, similar to the one proposed by Pyalling et al, 2004

ANALYTICAL MODEL FOR OPTICAL PROPERTIES OF METALLIC PLASMAS, STIPULATED BY ELECTRON-PHONON INTERACTION

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Optical properties of metals at moderate electron temperatures T (lower than Fermy energy E_F), stipulated by electron-phonon interaction, are described using dielectric function (DF). The expression for DF is derived using quantum statistical approach, long-wavelength approximation and linear response theory, which results in Drude-type expression for DF with complex effective collision frequency $\nu_{\rm ef}$ [1]. In the work [1] this approach was used for study of frequency-dependent DF at relatively high temperatures, $T > E_F$. In the present work similar approach was used for derivation of expressions for frequency-dependent $\nu_{\rm ef}(\omega)$ and DF, stipulated by electron-phonon interaction, which was accounted using the Frohlich Hamiltonian and the first Born approximation [2].

Simple formula for $\nu_{\rm ef}(\omega)$ is obtained for the case of transitions in single zone and with single phonon mode. Besides that, the expressions for correlation functions and $\nu_{\rm ef}(\omega)$ for the case of interband transitions are derived and discussed. The obtained formulas make ones possible to take into account different temperatures of electron and ion systems for the case of metals heated by short (femtosecond) laser radiation and are valid in wide range of radiation frequencies, from infrared to X-ray. The proposed approach opens possibility to spread the derived early wide-range (on radiation frequencies) model of DF, valid for the case $T > E_F$ [1], to the case of lower temperatures.

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NON-LINEAR SCREENING EFFECT ON PHASE STATE OF DUSTY AND COLLOID PLASMA

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Applicability limit of the well-known phase diagram [1] for complex plasma is under discussion. Existence of finite density gap at all phase boundaries at this diagram was claimed earlier [2]. Existence of extensive domains with violation of thermodynamic stability conditions (i.e. with negative isothermal compressibility) was also claimed [2] if one uses well-known non-ideal equation of state corrections [1] and [3]. The present work is devoted to analysis of a range of applicability for basic assumption in the initial phase diagram [1] in κ–Γ plane (Γ is coupling parameter, κ is structural parameter), i.e. linearized (Debye) screening of macroions by microions, which leads to the Yukawa form for effective interactions between macroions. Parameters of non-linear screening for macroions were calculated within direct Poisson–Boltzmann approximation. Two basic effects were revealed as a result of such calculations: (i) – decomposition of all microions onto two subclasses, free and bound ones, and (ii) – significant reduction of "visible" (effective [4]) charge Z^* of initial bare macroion Z under non-linear screening by small high-density envelope of bound ions. This renormalization of initial Z and macroion concentration n at the border of the cell into Z^* and n^* ($Z^* < Z$ and $n^* < n$) leads to corresponding renormalization of initial Γ and κ into Γ^* and κ^* ($\Gamma^* < \Gamma$ and $\kappa^* < \kappa$). The main physical assumption of the present work is that phase state (e.g. solid, fluid etc) of complex plasma under non-linear screening is still the same as in the initial Hamaguchi's diagram, but in κ^*–Γ^* plane instead of κ–Γ one. Corresponding calculated shifts of phase boundaries in the initial phase diagram, i.e. triple point, melting and bcc-fcc boundaries, are discussed and illustrated. The work is supported by the Russian Science Foundation (grant 14-50-00124).

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DUSTY PLASMAS IN THE NARROWING OF A CURRENT CHANNEL IN MAGNETIC FIELD

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Studies of dusty structures formed in the new type of glow-discharge trap are of interest from the standpoint of future experiments with complex plasmas in superstrong magnetic fields in which the dust component is magnetized [1-7]. This work consists of two parts.

In the first part the geometry and dynamics of dust structures in a longitudinal magnetic field is studied experimentally. The structures are formed in a glow-discharge trap created in the double electric layer produced as a result of discharge narrowing by means of a dielectric insert introduced in the discharge tube. Different types of dielectric inserts were used: conical and plane ones with symmetric and asymmetric apertures. Conditions for the existence of stable dust structures are determined for dust grains of different density and different dispersity. According to the experimental results, the angular velocity of dust rotation is $\omega \geq 10 s^{-1}$, which is the fastest type of dust motion for all types of discharges in small magnetic field.

The second part presents the results of a new study of the rotational dynamics of the trapped particles in a large magnetic field, which exceeds the value corresponding to the magnetization of ions. The results show that, up to a value of 10000 G dust structures exist in the trap. They are quite stable. Dynamics of rotational motion of the horizontal dusty sections is presented in the form of graphs on the magnetic induction. The rotation is interpreted by analyzing the dynamics of individual dust grains.

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KINETIC HEATING OF PARTICLES IN THE RADIO-FREQUENCY DISCHARGE UNDER MICROGRAVITY CONDITIONS

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Oscillation of particles of the diameter $2a$ from 2.55 to 3.4 μm in a dust crystal formed in a low-pressure radio-frequency gas discharge under microgravity conditions is studied. Analysis of experimental data obtained previously [1] shows that the oscillations are highly isotropic and nearly homogeneous in the bulk of a dust crystal; oscillations of the neighboring particles are significantly correlated. We demonstrate that the standard deviation of the particle radius-vector δr along with the local particle number density n_d fully define the Coulomb coupling parameter of the particle subsystem $\Gamma = 3(r_d/\delta r)^2$, where $r_d = (3/4\pi n_d)^{1/3}$. The coupling parameter proves to be of the order of 100, which is two orders of magnitude lower than the coupling parameter estimated for the gas temperature, which is close to room temperature. This means significant kinetic overheating of particles under stationary conditions. The particle kinetic temperature $T_d = Z^2e^2/r_d\Gamma$, where Z is the dust particle charge in units of the electron charge and e is the elementary electric charge, ranges from 1.2 to 4.2 eV. A theoretical interpretation of the large oscillation amplitude implies the increase of particle charge fluctuations in the dust crystal. The theoretical estimates are based on the ionization equation of state for the complex plasma and the equation for the plasma perturbation evolution. For the coupling parameter, we obtain $\Gamma = (27/8)(\lambda T_i c_s^2/a\nu v_i e^2)$ [2], where λ is the ion mean free path, T_i and v_i are the ion temperature and thermal velocity, respectively, c_s is the velocity of dust acoustic waves, and ν is the friction coefficient defining the neutral drag. This estimate matches the results of experimental data processing.

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FEATURES OF SPIN MOTION OF DUST PARTICLES IN A MAGNETIC FIELD

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In present work experiments on a research of influence of a magnetic field on spin motion of single dust particles of two types were implemented and data were obtained. Experiments were made in a glow discharge in strata in vertical magnetic field. Dependences of an angular velocity of spin motion of spherical hollow microspheres on the value of the magnetic field were received in different conditions in helium and neon. For nonspherical particles additional rotation around a vertical axis which was interpreted as appearance of a precession under the influence of a driving force of weight was observed.

Data allow to reveal the magnetic properties of dust plasma as the systems of the charged dust tops.

MFPT ENTROPY AND LOCALIZATION AREA OF GRAINS IN EXTENSIVE YUKAWA SYSTEMS

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Nowadays, the knowledge about the processes taking place in open systems gains more and more interest. Dusty plasma of gas discharges is an excellent example of an open system far from equilibrium: for the existence of the discharge (i.e. for the levitation of particles) a constant energy supply is needed; during the experiment this energy dissipates on surrounding plasma particles. To study these systems properly, one should use methods independent of the degree of openness of the system and on the number of particles in it. One of the most natural methods to use is the concept of mean first-passage time dynamic entropy — a simple approximation of Kolmogorov-Sinai entropy [1, 2]. The main idea of this approach is that the change of a phase state is essentially the way from the ordered to the chaotic state and back, and all approaches to the measurement of degree of chaotization of open systems are reduced to the determination of their entropy [3].

In present work, the dynamical entropy of an extensive dissipative system with Yukawa interaction is studied numerically. Two parameters defining the state of a system – the coupling parameter and the scaling parameter – were varied in the wide range (from disordered to highly-ordered state of a system). For each state, the dynamical entropy of a system was calculated, the fractal dimension of grains' trajectories and the size of their localization area was found. Two latter parameters appeared to have critical points in the vicinity of $\Gamma^* = 100$, that complies with the results obtained by the pair correlation function method.

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PHASE TRANSITIONS IN DUST STRUCTURES IN NEON DC DISCHARGE AT TEMPERATURE 77 K

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The dust clouds in plasma can exist in forms analogous to the thermodynamic states of matter [1]. The Coulomb dust structures can be used to simulate nonideal systems in the microworld, including those forming at low and cryogenic gas temperatures. In neon dc discharge at room temperature, the dust structures are formed from individual dust particles. At a temperature of 77 K, the dust structures can be multicomponent [2, 3], i.e. represent a mixture of dust particles and clusters formed by dust particles. In this work, the influence of discharge current on shape, size, composition of complex dust structures consisting of dust clusters, and their phase state, has been studied in neon dc discharge at a pressure of 20 Pa (measured at room temperature) and gas temperature of 77 K.

The experimental setup is described in [2, 4]. At a discharge current of 0.631 mA, the dust structure was in the crystalline state. The dust crystal was formed by cluster chains, which consist of multi-dimensional clusters. An increase in current to 0.633 mA was accompanied by a decrease and disappearance of the symmetry of the dust structure. Thus, the evidence of a second-order phase transition was observed. With increasing current, the complex clusters melted, producing a mixture of components consisting of simple clusters, complex clusters and individual dust particles, which indicated the mesomorphic state of dust mixture. At a discharge current of 0.691 mA, there was an abrupt jump in the dust structure volume, i.e. the density of the dust cloud decreased sharply, which indicated first-order phase transition. Here, the melting of complex dust clusters and partial melting of simple dust clusters were observed. At higher current the dust mixture consisted predominantly of individual dust particles and simple clusters.

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SIMULATION OF DUST-VOID BOUNDARY LINE IN PLASMA OF NEON GLOW DC DISCHARGE

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The diffusion-drift model of the plasma of a positive column of dc glow discharge in neon with microparticles [1] was implemented for the simulation of the boundary of the transition from uniform to hollow dust structures, depending on the gas pressure and the discharge current. Simulations are based on experimental data obtained in a discharge with a diameter of 16.5 mm with dust particles 2.55 and 4.14 μm in diameter [2, 3], in the pressure range from 0.1 to 1.4 Torr. There were considered the heat release of the discharge and the dissipation of the plasma energy on the walls of the discharge tube and microparticles, including the quenching the excited metastable neon atoms. As a criterion for formation of an internal cavity in dust structures, there was accepted the formation of the minimum on the profile of potential energy of dust particle in the net force field, that was a sum of forces of radial electric field, ion drag and thermophoresis. Simulations confirmed the experimentally observed decrease in the discharge current of a transition to hollow structures with increase in gas pressure. It is shown that in the investigated range of discharge parameters and the hollow dust structures formed in it, the magnitude of thermophoretic force is comparable to that of radial electric field and is higher than ion drag force. The value of the thermophoretic force in the investigated range of parameters of the plasma-dust system is determined from the comparison of the simulated position of the hollow dust structure border with the experimental one. The results are relevant for the development of ideas about the fundamental forces acting on microparticles in plasma, and the improvement of plasma technologies.

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ELECTRIC PROBE DIAGNOSTICS OF DUSTY PLASMA PARAMETERS WITH NANOPARTICLES

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This work presents the results regarding the influence of cyclic growth of nanoparticles from the gas phase on the parameters of a low-temperature plasma. The measurements were carried out in an asymmetric RF (13.56 MHz) discharge [1] in mixtures of argon and acetylene gases. The main plasma parameters such as the electron temperature, electron density and plasma potential were determined by the Langmuir probe [2] and compared with the discharge self-bias voltage signal. The contamination problem of the electric probe tip in a reactive plasma due to the sticking of nanoparticles and radicals was solved by applying a rapid "complex" sweep pattern of the probe voltage. Additionally deposits were evaporated by heating the tip with the use of high electron currents and also ion bombardment was applied in order to keep the probe clean. The described "complex" voltage sweep method is based on the oscillation of the probe voltage with a frequency greater than the frequency of dust nanoparticles in the plasma and at the same time a lower frequency than the frequency of electrons and ions. An upper limit for the dust plasma frequency was found by adjusting the probe frequency. The measurement results show a decrease in the electron density during the cyclic growth due to their absorption on the surface of the nanoparticles. On the contrary, the electron temperature and plasma potential increase. The comparison of the results with the self -bias voltage confirms the existence of three main phases of growth of nanoparticles in this low-temperature plasma. The data concerning the influence of nanoparticles on the plasma parameters obtained by the probe method and the applied method itself may be used in further detailed studying of the processes of nanoparticle synthesis in low-temperature plasmas.

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INNER PRESSURE AND ENERGY OF COULOMB SYSTEM IN ELECTRODYNAMIC TRAP

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The results of calculation of thermodynamic functions of strongly coupled Coulomb systems in the linear Paul trap by means of statistical theory of liquid state are presented. Particle motion was simulated by means of Brownian dynamics methods. Evolution of pair correlation functions of Coulomb systems has been studied and using the statistical theory of liquid state the energy of the system, internal pressure and Coulomb coupling parameter Γ were calculated using known interparticle Coulomb potential. The considered system is highly nonideal with coupling parameter of order $\Gamma = 10^{10}$.

HOT COLLOIDAL PLASMA IN SUPERFLUID HELIUM

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Our experiments on laser ablation of tungsten, molybdenum and platinum in superfluid helium have shown that the ensemble of nanoclusters heated substantially above the melting point of the corresponding metal arises during their coagulation in He II. The reason for this is the fact that even the record high thermal conductivity of superfluid helium cannot compete with the enormous heat release developed if the clusters of subnanometer size stuck together. As a result, the liquid helium around a metal particle evaporates, forming bubble of micron size, filled with gas at low pressure, which prevented the heat dissipation. For all metals, the heat such released is sufficient to melt the nanometer cluster, which, due to surface tension, acquires a spherical shape. Coagulation of metal in superfluid helium is anomalously fast, since it occurs inside quantized vortices. The emission spectrum of nanoclusters in the visible region is close to the blackbody spectrum. An ensemble of micron bubbles with a hot nanometer core exists for a relatively long time, which in our experiments was about 10 microseconds; the nanoclusters stuck together in long nanowires after this. Thus, within 10 μs there is a two-temperature system in which the temperature of liquid helium remains equal to 1.5 K, while the cluster and gas temperatures are about 4000 K. Electrons emitted by hot metal cannot leave the parent bubble because of the existence of the 1 eV barrier on its surface. At the same time, electrons embedded into superfluid helium from outside must be captured by bubbles with a large cross section. In this way, dust nanoplasma can be realized (its direct formation is hampered by the smallness of the cross section of electron capture by nanoparticles).

INFLUENCE OF A CHARGE-GRADIENT FORCE ON DUST ACOUSTIC WAVES

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A complex plasma represents an ionized gas containing electrons, ions, neutral atoms or molecules, and massive dust particles. The charged dust particles embedded into plasmas not only change the electron–ion composition and thus affect conventional wave modes (e.g., ion–acoustic waves), but also introduce new low-frequency modes associated with the microparticle motion, alter dissipation rates, give rise to instabilities, etc. Moreover, the particle charges vary in time and space, which results in important qualitative differences between complex plasmas and usual multicomponent plasmas [1]. The focus of this work is on the influence of the plasma background and grain charge variability on linear waves in weakly coupled unmagnetized complex plasmas. In the long-wavelength limit these waves exhibit acousticlike dispersion and are therefore called "dust acoustic waves" (DAWs). The dispersion relation of DAWs for an ideal isotropic complex plasmas was originally derived by Rao, Shukla, and Yu [2].

In complex plasma different forces affect particle dynamics. One of these forces is the so called "polarization" force which was introduced by Hamaguchi and Farouki [3] and comes from the nonuniformity of the plasma background. The grain charge variability may result in the appearance of an additional component of this polarization force. Actually, the energy of an individual test charge Q immersed in an ideal plasma is $U = -Q^2/2\lambda_D$. The total force acting on a small charged grain in a nonuniform plasma with external electric field $\mathbf{E}$ is $\mathbf{F} = Q\mathbf{E} - \nabla U$. The "gradient" force can be written as

$$\mathbf{F}_g = -\nabla U = -\frac{Q^2}{2}\frac{\nabla\lambda_D}{\lambda_D^2} + \frac{Q\nabla Q}{\lambda_D}. \qquad (1)$$

The first item in the RHS of the Eq. (1) corresponds to the conventional polarization force [3], influence of which on the dust acoustic waves was investigated earlier [4]. In this work the charge variation of dust grains are taken into account. In the weakly coupled gaseous plasma only the longitudinal wave mode can be sustained. The dispersion relations of this mode can be written as a sum of the partial susceptibilities of complex plasma components $\varepsilon(\omega, \mathbf{k}) = 1 + \chi_e + \chi_i + \chi_d = 0$, where

$\chi_{i(e)} = \mp 4\pi e k^{-2}\delta n_{i(e)}/\delta\varphi$, $\chi_d = 4\pi k^{-2}\delta(Qn_d)/\delta\varphi$ and φ is the electrostatic potential of the wave. Assuming small perturbations $n_a = n_{a0} + n_{a1}$ $(a = e, i, d)$, $Z = Z_0 + Z_1 (Z = Q/e)$, $\varphi = \varphi_1$ with the $\sim \exp(i\mathbf{kr} - i\omega t)$ dependence we obtain in linear approximation $\chi_{i(e)} = \mp 4\pi e n_{i(e)1}/k^2\varphi_1 = 1/(k\lambda_{Di(e)})^2$ and

$$\chi_d \cong -\frac{\omega_{pd}^2}{\omega^2}\left(1 - \Re - \frac{e^2 I_{i0}}{\lambda_{D_i} T_i \eta}\right) + \frac{I_{i0}}{k^2\lambda_{De}^2\eta}\frac{n_{d0}}{n_{e0}}, \tag{2}$$

where

$$\Re = \frac{e^2 Z_0}{4\lambda_D T_i}\left(1 - \frac{T_i}{T_e}\right) \cong \frac{e^2 Z_0}{4\lambda_{Di} T_i}, \qquad \eta \cong I_{i0}\frac{e^2}{aT_e}\left(1 - \frac{aT_e}{Z_0 e^2}\right).$$

Now assuming $\omega = \omega_r + i\omega_i$ $(\omega_r \gg |\omega_i|)$ one can obtain expression for the real ω_r part of the DAW frequency

$$\frac{\omega_r^2}{k^2}\left(\frac{1 + k^2\lambda_{Di}^2}{\lambda_{Di}^2} - \frac{I_{i0}T_e}{\lambda_{De}^2\eta}\frac{n_{d0}}{n_{e0}}\right) = \omega_{pd}^2\left(1 - \Re - \frac{e^2 I_{i0}}{\lambda_{Di} T_i \eta}\right). \tag{3}$$

A difference from the result obtained in Ref. [4] consists in the appearance of the last terms in the brackets of the both sides of Eq. (3). The equation for ω_i is more cumbersome.

For typical complex plasma parameters in argon gas discharge $a = 1$ μm, $Q = 10^3$ e, $\lambda_D = 10^{-2}$ cm, $T_e = 3$ eV and $T_i = 0.03$ eV, we have $\eta \cong 8.8 \times 10^4$ s^{-1}. Comparison of the polarization and charge gradient terms in RHS of Eq. (3) gives

$$\frac{\Re\lambda_{Di}T_i\eta}{e^2 I_{i0}} \cong \frac{Z_0\eta}{4I_{i0}} \cong 0.33. \tag{4}$$

Thus, the contribution of the charge-gradient force in the dispersion relations of the dust acoustic waves is comparable with the contribution of the polarization force and thus needs to be taken into account.

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STRUCTURAL PROPERTIES OF DUSTY PLASMA CRYSTALS IN A GLOW DISCHARGE

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Experimental data is taken from the work conducted by R.Kh. Amirov's group in JIHT RAS in 2010-2012 [1]. Authors participate in its analysis and complement the classification of dusty structures published in [2]. Structural diagram of dusty plasma in (n,I,T)-coordinates is presented. Inter-particle distance dependence on the temperature of neutrals for the temperature range $4.2 - 300$ K is given and compared with [3].

Theoretical model of dusty plasma is based on the system of N particles with the charge q are in an electrostatic trap with the parameter α in the Langevin thermostat at a necessary temperature. MD modeling of such a system allows to obtain average inter-particle distance dependence on the particle charge, screening length in plasma, trap parameter

$$r(q, \lambda_{scr}, \alpha) = (3.5 \pm 0.2) q^{0.15 \pm 0.01} \lambda^{0.55 \pm 0.01} \alpha^{-0.17 \pm 0.01}$$

and the number of particles in the structure:

$$r(N) = b(q, \lambda_{scr}, \alpha)(1 - 0.25 N^{0.16}).$$

It is shown that accounting of thermophoretical and ion drag forces leads to the increase of the density of dusty particles at cryogenic temperatures. This effect is observed in the experiment [2]. The dependence of maximum density temperature on discharge current and gas concentrations is given. Accounting of periodical strata field in the vertical direction allows to obtain 3D-multilayered structures with properties close to the experimental ones.

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THE GLOW OF THE CORONA IN THE POINT-PLANE SYSTEM

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In previous works, we carried out investigations of the dynamics of charged dust particles in the electrodynamic traps. The corona discharge was used to charge the particles. The magnitude of the charge obtained by the particles in the corona discharge depends on the local electric field strength, which is essentially inhomogeneous in the corona discharge. To reduce the inhomogeneity of the electric field, it is expedient to use a multi-electrode corona discharge. As is known, in the corona discharge, the particles are charged in the unipolar region. Thus in the case of multiple curved electrodes it is necessary that the plasma regions near the adjacent electrodes do not intersect. The purpose of this paper was to determine the size of the plasma region in the point-plane system. It was assumed that the plasma region corresponds to the glow region.

INVESTIGATION OF THE VIBRATIONAL PROPERTIES OF THE DUST TRAP CREATED IN A STANDING STRIATION

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Complex (dusty) plasmas have recently attracted the attention of researchers as systems available for observation at the kinetic level and have been studied in many aspects, such as phase transitions, waves, response to different external influences, and instabilities [1]. The investigation of free and forced oscillations of dust particles is Important for understanding the dynamics of dusty plasma. For example, the investigation of the oscillatory motion of the dust particles can be used to study the phenomena of energy transfer between degrees of freedom in a plasma-dust system [2]. In addition, the experimental investigations of the dust particle oscillations make it possible to determine the charge of a dust particle [3] and to measure the spatial distribution of the electric field [4].

In this paper, the method of the discharge current modulation [5], was used to investigate the vibrational properties of the dust trap in a stratum.

In the pressure range p = 0.06 – 0.66 torr the amplitude-frequency characteristics of the single dust particle oscillations are obtained. The frequency response is investigated with respect to the influence of the form of the modulating signal. The values of the vibrational characteristics of a dust trap such as eigenfrequency, and resonance frequency, Q-factor, damping coefficient are obtained. The calculation of the dust particle charge with the help of the experimentally obtained eigenfrequency is made. The obtained value of the dust particle charge is in good agreement with the literature data for similar discharge conditions [6].

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INFLUENCE OF THE EXTERNAL MAGNETIC FIELD AND BUFFER GAS ON THE PARTICLE LOCALIZATION IN TWO DIMENSIONAL YUKAWA SYSTEM

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In this work, we investigated the influence of a static homogeneous external magnetic field and background medium on the quasi-localization of the particles, which is by the cage correlation functions, in strongly coupled two-dimensional Yukawa systems. We used the Langevin dynamics computer simulation method, with taking into account the Lorentz force acting on dust particles:

$$m\ddot{\mathbf{r}}_i(t) = \sum_{i \neq j} \mathbf{F}_{ij}(r_{ij}) + Q[\mathbf{v}_i \times \mathbf{B}] - \nu\, m\mathbf{v}_i(t) + \mathbf{F}_{\mathrm{Br}},$$

where the first term on the right hand side gives the sum of the interparticle forces, the second one is the Lorentz force, the third term is the friction force (proportional to the particle velocity), caused by the presence of the background gaseous environment, while the fourth term represents an additional randomly fluctuating “Brownian” force that expresses the random kicks of the gas atoms on the dust particles. To integrate the equations of motion, a new numerical scheme was used [1], in which the time step does not depend on the magnitude of the magnetic field. This scheme was obtained similarly to the scheme proposed in Ref. [2], but takes into account the friction force. The obtained results are consistent with the results obtained in [3, 4] in the limiting cases, when the friction force (and random force) or the Lorentz force are zero, respectively.

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A NEW ANALYTICAL APPROACH FOR STUDYING AMPLITUDE INSTABILITIES IN YUKAWA SYSTEM

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The impossibility of a correct use of the linearized equations of motion for a description of nonlinear processes arising with an increase of particles’ temperature (i.e. with a growth of amplitude of their displacements), have led to a wide use of various phenomenological criteria in the theory of solids for determination of the critical parameters of systems near their melting lines, for example, as the ratio of the root-mean-square displacement to the mean inter-particle distance (criterion of Lindeman), the value of first maximum $g_{\rm m}$ of pair correlation function $g(l)$ (Hanssen’s criterion), the changes in $g_{\rm m}$ position, etc. [1]. However, the listed critical parameters may depend considerably on a lattice type, and a use of these criteria for the spatially limited small-sized systems is not possible [2].

In the present work, for the description of the state of a system with a temperature growth, we propose an investigation of its amplitude stability, i.e. stability to any deviations (and not just to small ones) of particles from their equilibrium positions. The presented approach is based on the determination of an inflection point for the potential energy of a system [3].

Study of formation of an amplitude instability for a two-particle system is performed for Yukawa systems with the various screening parameters, friction coefficients, and gradients of external electric field. For the first time, the dynamic of "leaps" of particles (which consists in a spontaneous change of their positions) in the steady two-particle vertical configurations is studied. We found that an increase of grain temperature leads to essential changes of dynamic properties of systems near to the critical coupling parameter $\Gamma = \Gamma_0$. The special features observed close to $\Gamma \approx \Gamma_0$ are caused by the formation of amplitude instabilities in the analyzed two-partials systems (and are similar to those that causes the melting for extended systems).

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THE ALGORITHM FOR STUDY OF ABSOLUTE INSTABILITY IN SPATIALLY NON-ISOTROPIC CLUSTER SYSTEMS

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The investigation of various instabilities development in non-ideal systems is of considerable interest in many fields of science (plasma physics, biology, polymer physics, etc.) [1]. In most cases, empirical relationships are used as the criteria for configurational transitions [2]. Extended chains of particles and monolayers with a large number of particles $N >> 2$ have been studied in many papers (e.g. [3]), and semi-empirical relationships were obtained for configurational instabilities development in systems with a wide range of interparticle interaction potentials. As for analytic relationships, they were proposed only for the case of two interacting particles [3]. The work [4] considers in details various modes of two-dimensional oscillations and stability criteria for two-dimensional systems with respect the displacements of particles in the plane of the system under study. The friction in works mentioned was not taken into account at all (while in the presence of friction a number of modes may be absent).

In this work we consider the conditions of formation and stability criteria for small-sized cluster systems consisting of several particles interacting via an arbitrary isotropic pair potential. Analytical criteria for the development of instabilities in horizontal (quasi-2D) and vertical (chain-like) structures consisting of three, four and five charged particles are proposed. We also propose a simple algorithm for search of such criteria for systems with a larger number of particles. The obtained relations were verified by numerical simulation of the problem for the Yukawa systems.

The work was partially supported by the Russian Foundation for Basic Research (grant 16-08-00594), the Russian Ministry of Education and Science (projects SP-4993.2015.1, MK-2930.2017.8).

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EXPLORING THE WAKE OF A MICROPARTICLE IN A PLASMA BY THE CORRELATIONAL ANALYSIS OF BROWNIAN MOTION OF A TEST PARTICLE

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A general approach to the correlational analysis of Brownian motion of strongly coupled particles in open dissipative systems is described. This approach can be applied to a theoretical description of various non-ideal statistically equilibrium systems (including non-Hamiltonian systems), as well as to analysis of experimental data. In this paper, we consider an application of the correlational approach to the problem of experimental exploring the wake-mediated nonreciprocal interactions in complex plasmas. We derive simple analytic equations, which allows one to calculate the gradients of forces acting on a microparticle due to each of other particles as well as the gradients of external field, knowing only the information on time-averaged correlations of particles displacements and velocities. We show the importance of taking dissipative and random processes into account, without which consideration of a system with a nonreciprocal interparticle interaction as linearly coupled oscillators leads to significant errors in determining the characteristic frequencies in a system. In the examples of numerical simulations, we demonstrate that the proposed original approach could be an effective instrument in exploring the longitudinal wake structure of a microparticle in a plasma. Unlike the previous attempts to study the wake-mediated interactions in complex plasmas, our method does not require any external perturbations and is based on Brownian motion analysis only.

GENERATION AND DIAGNOSTICS OF NON-IDEAL PLASMAS

ANALYSIS OF EFFECTIVENESS OF SUBPICOSECOND MULTI-PULSE LASER ABLATION OF METALS

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Effectiveness of laser ablation is an important issue in processing of materials. Using a hydrodynamic two-temperature model, we simulate single-, double-, and multi-pulse laser ablation of metal targets. Results of modeling demonstrate that the rate of the multi-pulse ablation increases an order of magnitude in comparison to single-pulse regime, while the repetition rate growth up to several GHz because the material surface does not cool down substantially between successive pulses. To prevent the shielding and suppression effects, previously observed in double-pulse laser irradiation [1], the fluence of each pulse in the burst should have a subthreshold value to avoid the generation of slow moving ablated condensed-phase fragments of matter. Obtained results are in very good agreement with recent experimental findings on ablation by ultrafast bursts of subpicosecond pulses [2].

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LASER METHODS OF PROBING IN STUDY OF THE SPARK STAGE OF NANOSECOND AIR DISCHARGE AT ATMOSPHERIC PRESSURE

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Today the lack of information about fast processes of plasma formation during a nanosecond discharge in a mixture of gases or air is associated with the difficulty of diagnosing of these processes. As high rates of plasma formations development as their small-scale (units - tens of microns) impose certain requirements to the spatial and time resolutions of diagnostic complexes applied.

One of solution of the problem is the application of laser probing methods based on multi-channel optical registration systems [1]. These methods allow to trace as local processes of plasma formation with high spatial and temporal resolution as dynamics of its parameters (electron density and it's gradients) along the discharge gap.

Results of application of laser probing methods (interferogram, shadow and schlieren images) for investigation of the spark stage of a nanosecond air discharge at atmospheric pressure are presented. Experiments were carried out using 6-channel 18-frame optical registration system with the spatial resolution of $\sim 2\mu$ m. The exposure time of each frame corresponded to the pulse duration of the laser - 70 ps at a wavelength of 532 nm.

It is shown that at the moment of gap's breakdown (a sharp increase of current through the discharge gap) micron-sized plasma formations with electron density $\sim 10^{19}$ cm^{-3} and rate of propagation $\sim 10^{6}$ cm/s appear firstly on the cathode and then on the anode. Further, cathode and anode plasma clots are closed and formed current channels connecting the electrodes. A complex filamentary microstructure of the plasma objects formed at the stage of cathode and anode plasma closing is found.

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HIGH ENERGY DENSITY SCIENCE EXPERIMENTS AT FAIR

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The Facility for Antiproton and Ion Research (FAIR) will offer unique opportunities in the field of high-energy density (HED) physics and warm dense matter. Using the high-intensity ion beams available at FAIR, macroscopic (mm-sized) samples of warm dense matter can be created. The SIS-100 synchrotron at FAIR will provide 50 ns U^{28+} bunches with energies of up to 2 AGeV and up to $5 \cdot 10^{11}$ ions/bunch for these experiments.

The ion beams can be used to either directly heat a sample to eV temperatures at solid density (HIHEX –Heavy Ion Heating and Expansion) or to indirectly compress samples to Mbar pressures at sub-eV temperatures (LAPLAS – Laboratory Planetary Science). Both methods enable equation-of-state measurements in parameter regions that are important for many applications – e.g. the study of planetary interiors – and are difficult to study with other experimental methods.

In addition, FAIR will also provide high energy proton beams (up to 10 GeV with up to $2.5 \cdot 10^{13}$ protons/bunch), which can be used for proton microscopy measurements of HED samples generated with a secondary driver, such as a light gas gun.

The HED experiments at FAIR will be carried out in the so-called APPA cave, an experimental area with a dedicated beamline for plasma physics experiments. The planning and preparation for HED experiments at FAIR is carried out by the *High Energy Density Science at FAIR* (HED@FAIR) collaboration which has been founded at the beginning of this year.

In my presentation I will give an overview of the experimental facilities that will be available for HED experiments at FAIR, of the planned first-day experiments at FAIR and of the HED@FAIR collaboration.

INTERPRETATION OF DOUBLE LANGMUIR PROBE I-V CHARACTERISTICS AT DIFFERENT IONOSPHERIC PLASMA TEMPERATURES

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A Single Langmuir probe is always connected to an electrode as fixed potential. In cases where such an electrode does not exist or the plasma potential is fluctuating significantly, this method is not relevant. This weakness was overcome by the development of the floating double probe by Johnson and Malter [1]. A distortion of the probe characteristics due to varying potential is eliminated, while the whole probe system is floating. This supports probe operation also in discharges with strongly varying potential.

Double Langmuir probes provide valuable information on the behavior of space plasmas including ionospheres and the interstellar medium.

This research paper focuses on the study of Spherical Double Langmuir Probe I-V characteristics in Maxwellian interstellar plasma. To generate the exact plasma conditions of the experimental testing environments computational procedures is adopted. The investigations address the development of a technique to model Maxwellian plasma. Three different ionospharic plasma temperatures are theoretically taken and its effects on floating potential are studied in this research. The variation of floating potential and ion saturation current due to temperature is clearly depicted. A manifest trail in the I-V curves is the bump that occurs right after the floating potential. This feature in the transition region affects ability to determine the electron temperature, ion saturation current and plasma potential. Symmetric characteristic when both tips are of equal geometry is an important advantage of the double probe. Generally, all surfaces adjacent to plasma become contaminated with deposits, so also does any probe. Here I have also deliver some sense of how one might proceed to use these results in the analysis of experimental I-V curves obtained in space.

GAS TEMPERATURE SPATIAL DISTRIBUTION OF A DC MICRODISCHARGE PLASMA JET IN ATMOSPHERIC AIR

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In recent years, the sources of atmospheric pressure plasma jets (APPJ) have been becoming an object of intensive study, largely, due to the prospects for their use in biomedical applications. An example of such sources are generators of DC air atmospheric plasma jets [1]. In addition to the plasma composition in the case of treatment of living materials the thermal effect on the object is critical. In the study, data on gas temperature distribution in the air APPJ that is driven by glow DC microdischarge have been obtained. A cylindrical quartz tube with an internal diameter of 0.8 cm was used as a discharge cell. A rounded steel cathode was located along the symmetrical axis inside the tube. A flat anode 7 mm in thickness with a central hole 1.5 mm in diameter was fixed at the end of the tube and served as the exit nozzle. The gap between the cathode and anode was 0.7 mm. The gas flow rate of air was varied in the range of 1–5 l/min.

The glow discharge regime was set up at a current of 30 mA. A stationary narrow luminous jet with the length of ~ 1.5 cm and diameter of ~ 1 mm was observed. The temperature field was measured with a thermocouple and compared with the schlieren images [2]. Three separate temperature regions with well-defined boundaries were observed along the diameter of the jet. The first one is a central narrow hot area that corresponds to the area of the visible luminous jet. It has gas temperature of 30 to 120°C depending on the gas flow rate and distance from the anode. It is surrounded by a warm "coat" of diameter of about 1 cm with a temperature of near 50°C. The last region is an ambient air area surrounding the plasma jet and having the room temperature.

The temperature distribution along the jet showed that treatment of surfaces without thermal effects can be carried out at the distance of at least 3 cm from the outlet at studied discharge parameters.

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PROPERTIES OF VOLUME DIELECTRIC BARRIER DISCHARGE IN A FAST AIRFLOW

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The volume dielectric barrier discharge (VDBD) has long been widely used for scientific and practical purposes to create a nonequilibrium low-temperature plasma (NLTP) at atmospheric pressure. Mostly, VDBD studies in air were carried out either without gas flow or under a weak flow through a discharge zone at a maximum of few meters per second. Moreover, the so-called spatial "memory" of microdischarges in VDBD is defined not only by their surface charges, but also by the plasma column created by each of these charges in the interelectrode gap. This is because the plasma created in the previous half-period plays the role of "seeding" during the micro-discharge development at the next half-period. Today, the importance of surface charges and volume plasma in the formation of spatial memory in VDBD microdischarges is still unrevealed. In fact, the contribution of the volume plasma and surface charge mechanisms to the spatial memory of VDBD can be divided if the discharge zone is blown by gas. In this case, the plasma of each microdischarge will be moved by the gas flow along the surface of the electrodes, while the localization of the surface charge remains fixed.

In this work, the authors investigate the effect of air flow on the behavior of microdischarges in VDBD and their spatial memory under atmospheric pressure. The influence of the air flow velocity on the behavior of the microdischarges is also studied. It is established that the spatial localization of microdischarges in the interelectrode gap at a medium flow rate is determined by the volume plasma drifted by the flow, that leads to their movement in the flow direction. Furthermore, at high velocities, intensive flow turbulence results in a sufficient homogeneous mixing of the seed plasma along the gap. Here, (as in the absence of a flow), the spatial localization of microdischarges is determined by surface charges that are not carried by the flow.

TWO PLASMON DECAY INSTABILITY IN INHOMOGENEOUS FEMTOSECOND LASER PLASMA

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Electron acceleration in femtosecond laser plasma with scalelength L lambda is due to nonlinear plasma wave excitation. Optimization of high energy electrons generation requires study of nonlinear laser-plasma interaction and wave excitation. Radiation scattered by waves carries information about their frequencies, wave numbers and space localization.

We made interaction simulations using the fully relativistic 3D3V PIC code Mandor, reduced to the 2D3V within most of the our calculations. The simulation box size was 31 mkm (x) * 14mkm (y), spatial resolution was lambda/100 and total number of particles was 108. Temporal resolution was 3 10-3 fs. The planar foil target consisting of cold ions and electrons. A p-polarized laser pulse with duration of 50 fs (FWHM) and central wavelength of 1 mkm entered the simulation box. Varying the laser pulse intensity, the initial electron density scale length (0.5-10 lambda) incident angle (15-75) and beam waist diameter (2-10 lambda) we found the dependences of the plasmon parameters and optical harmonics yield on these parameters.

Analysis of the electromagnetic fields and electron density spatial and temporal distributions from simulation revealed that hot electrons are generated due to the breaking of plasma waves. At the plasma scale length 1-5 lambda there are two mechanisms of plasma wave excitation in obliquely incident interaction, appropriate for hot electrons generation: two plasmon decay instability (TPD) and charge separation near the turning surface. Both processes lead to generation of the optical harmonics: 3/2 and 1/2 of fundamental.

NON-IDEAL PLASMA AND EARLY EXPERIMENTS AT FAIR

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Early experiments at FAIR in 2018-2022 suggested by the HEDgeHOB collaboration in the field of non-ideal plasma physics are discussed. Specific energies of 5–10 kJ/g, pressures of 1–2 GPa and temperatures of 1–2 eV are expected to be reached in the substance at the first experiments with a U^{+28} beam with the energy of 0.2 AGeV and maximal intensity $3 \cdot 10^{10}$ per impulse. It will provide the possibility to investigate the two phase region including the critical point of several metals in HIHEX (Heavy Ion Heating and EXpantion) experiments with the plane and cylindrical geometry, realizing regimes of quasi-isochoric heating, isentropic expansion and compression when the flow strikes the target.

Comprehensive numerical modeling of HIHEX setups corresponding to ion-beam parameters for FAIR 1st-day experiments has been carried out employing gas-dynamics code using realistic properties of matter and energy deposition by intense beam of ions. According to the evaluations of the critical point parameters based on the multi-phase equation of state for metals, in HED experiment with the highest energy deposition for supercritical states for Pb with complete vaporization in the expansion isentrope will be accessed while the expansion isentrope corresponds to the partial vaporization and is close to the critical point.

OSCILLATING IONS UNDER INERTIAL ELECTROSTATIC CONFINEMENT BASED ON VACUUM DISCHARGE

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Earlier, the yield of DD neutrons in a compact nanosecond vacuum discharge (NVD) of low energy with deuterated Pd anode have been observed [1]. Further, detailed PIC simulation by the electrodynamic code KARAT has recognized [2] that experiment with NVD is the realization of the scheme of inertial electrostatic confinement (IEC) [3]. The goal of this work is to present and discuss in detail the available experimental results on deuteron oscillations in the field of virtual cathode in NVD followed by pulsating DD neutron yield. PIC simulations for some experimental regimes of pulsating neutron yield are shown, and comparison with available scheme of periodical oscillating plasmas spheres (POPS) suggested earlier in Los Alamos for fusion at ICF scheme [4] is given. The requirements needed to achieve a positive energy output for IEC scheme with oscillating ions (analogue of Lawson criterion [5] for breakeven) are discussed also.

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APPLICATION OF THE METHOD OF SMOOTH PERTURBATIONS FOR THE PROCESSING OF INTERFEROGRAMS OBTAINED IN THE STUDY OF SMALL PLASMA OBJECTS

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To study the dynamics of the prebreakdown stage of a gas discharge, laser sounding is used, which allows recording the image of plasma objects in the discharge gap with high spatial and temporal resolution. In this paper, we analyze the effect of diffraction effects on the interference pattern obtained at small plasma objects with characteristic unit sizes and tens of microns. The reconstruction of the electron density from the phase shift of the interference fringes can be obtained by solving the Helmholtz equation for an electromagnetic wave in an inhomogeneous medium, which in general has no analytical solution. In [1], it is proposed to solve the equation in the parabolic approximation, expressions were obtained in [2] with the help of which it is possible to reconstruct the electron density of an axisymmetric object by the phase shift, taking into account the diffraction effects on small structures. In our work, we propose the application of this method to data obtained in the study of the initial stage of the discharge [3]; the necessary assumptions are checked. The method is tested by successively solving a direct problem (obtaining a phase shift in the density of the object) and inverse, and then comparing the obtained data with the original ones. The effect of diffraction effects on the characteristic geometries of an object with a diameter of 5-40 mkm is shown. The data obtained during processing by the indicated method of interferograms obtained at the installation [3] are given.

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STABILITY AND AMBIGUOUS REPRESENTATION OF RELATIVISTIC SHOCK WAVES IN THERMODYNAMICALLY NON-IDEAL MEDIA

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A thermodynamically stable equation of state admitting violation of stability criteria for relativistic shock waves [1–5] is constructed on the basis of the model EOS developed in [6]. The modified equation of state is compatible with relativistic theory (does not produce superluminal speed of sound). The internal energy in units of c^2, where c is the speed of light, is given by

$$e = \xi(1 + k(\xi^{-1}p)^n\rho^{-1} - exp((\xi^{-1}p)^2))(4 - exp(-(4 - \rho^{-1})^2)),$$

where p is pressure, ρ is density; k, ξ, n are adjustable parameters. Model Taub adiabats for this equation of state have segments, in which the shocks are unstable according to linear stability theory of relativistic shock waves. The behavior of shocks in the regions of their ambiguous representation overlapping these segments has been studied numerically in one- and two-dimensional formulation. Calculations at moderate Lorentz factor have shown the both types of solution established previously [7] in the non-relativistic case: splitting with formation of a composite compression wave (in the region of ambiguous representation of the shock-wave discontinuity corresponding to the instability condition $L < -1$) or non-stationary two-dimensional mode characterized by the development of the shock front corrugations ($L > (1 + 2M + v_0v_1)/(1 - v_0v_1)$); where, L is relativistic analog of Dyakov parameter. The work is supported by the Russian Foundation for Basic Research (grant No. 16-02-01179).

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HIGH-CURRENT DISCHARGE CHANNEL PARAMETERS IN HIGH PRESSURE GAS

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Based on experimental data, taken by magneto-probe [1, 2] and X-ray [3, 4] diagnostic methods, electric field strength in the discharge channel and total nearectrode voltage drops for discharge with current rate of rise of $\sim 10^{10}$ A/s were obtaned. At the moment of maximum contraction for the discharge with a current amplitude of 1.2 MA in hydrogen at initial pressure of 5 MPa, calculations on the basis of the measurements give the field strength is 0.89 kV/cm and the sum of the near-electrode drops is 2.87 kV. Depending on initial conditions the parameters of iron plasma in the contracted discharge channel corresponds to temperature of 9–50 eV and concentration of $1.65 \times 10^{19} - -5 \times 1018$ cm^{-3}.

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INVESTIGATION OF THE HALL-EFFECT THRUSTER PLASMA ON DIFFERENT OPERATING MODES BY EMISSION SPECTROSCOPY

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Spectroscopic methods are informative and strong noninvasive tools for plasma research [1].

Nonequilibrium low-temperature xenon plasma of Hall-effect thruster is investigated by emissive spectroscopic measurements in the 250 - 1100 nm range for different discharge parameters such as discharge voltage, mass flow rate and coil current. Non optimal thruster regimes are also studied. Facility and experiment methodology are described in detail in [2] [3].

The state vector [2] as a combination of the excited states distributions of an atom, one charged ion and double charged ion is constructed and studied. More than 60 neutral atom levels, 45 ion levels and 4 double ion levels are explored. The variation of the discharge voltage is found to be the most significant factor contributing to the changes in the excited states distributions.

The correlation between temporal behavior of plasma luminescence and temporal behavior of discharge current is investigated. The oscillation are about 25-35 kilohertz and have different structure for ion emission, neutral emission and thruster current.

Important quantum mechanic processes for hall thruster plasma are discussed.

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NUMERICAL SIMULATION OF PROTON-RADIOGRAPHY FACILITIES AT GEANT4

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The high-energy proton radiography in the investigations of dense dynamic target provides greater penetration depth, spatial resolution, density resolution and dynamic range than conventional X-Ray methods [1], [2]. The high-energy proton microscopy facilities PRIOR-II (2-5 GeV beam energy) [2] will be one of the key diagnostic tool for HEDP experiments at FAIR project, also the scheme of 247 MeV proton microscope (PM) proposed [3] for experiments at INR proton linac (Russia, Troitsk). The ion optics of facilities [4], [5] is designed according to the schemes of proton microscopes with magnifying an image of objects. In this work, using Geant4 code, the full-scale Monte-Carlo numerical simulation of future proton radiography experiments were performed. The virtual model of PRIOR-II facility was developed based on ion optical data described at PRIOR - Proton Microscope for FAIR TDR [5] with energy of the beam - 4GeV. The scheme of 247 MeV proton microscoe was developed by COSY Infinity code. The full-scale numerical simulation for PRIOR-II was performed for static objects (Cu, plexiglas step wedges) and static models of dynamic process, such as Ta-wire in water in the UEWE investigation and investigation of compressibility of Ce. The full-scale numerical simulation for PR proton microscope also was performed for Cu and plexiglas step wedges and for static model of target in the investigation of shock compressed Xe gas (non-ideal plasma) and anomalous compressibility of docosane.

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PLASMA PHYSICS EXPERIMENTS AT HHT-CAVE IN FAIR PHASE-0

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In the FAIR phase-0 heavy-ion beams with unprecedented particle numbers from the SIS18 synchrotron will become available. In the already existing HHT-cave these beams can be focused to mm-sized focal spots and enable homogenous heating of large samples to warm-dense matter conditions. In this talk I will address first HIHEX (Heavy-Ion Heating and Expansion) experiments that can be conducted and show the current planning for the experimental infrastructure at this location.

EFFECT OF THE SDBD PLASMAS BYPRODUCTS ON WINTER RYE SEEDS GERMINATION

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In this work, the reaction of 3-day old seedlings (germination, sprout and root length) of winter rye seeds treated by plasma byproducts of a surface dielectric barrier discharge (SDBD) was considered. The winter rye seeds (*Secale cereal* L., variety Chulpan, crop of 2015 year, seeds are from the collections of The Core Facilities Center "Bioresource Center" SIPPB SB RAS, experiments was carried out in 1-2 quarter of 2016 year) were located on a grounded plane at a distance of 10 mm from the surface of the dielectric barrier. The electrode system consisted of five 1 mm wide aluminum foil strips separated by 4 mm gaps and a buried electrode on the other side of the dielectric. The dielectric barrier was made of 1 mm thick alumina ceramics. A sinusoidal voltage of 2.5 kV (RMS) with a frequency 25 kHz was applied between the strip electrodes and a buried one. Surface of the dielectric barrier was separated from seed by the air gap of about 8 mm. The main factors acting upon the biological materials are known to be the electric field and active particles, the latter supplied to the seed layer by the convective flow induced by the discharge. In the case when the discharge system is not cooled (temperature grow up to saturation on 70°C about 60 sec), the maximum reaction of seedlings is observed after 45-75 seconds of treatment. When the discharge system is actively cooled (temperature 22°C), a linear relationship is observed between the response of seedlings and the treatment time (significant differences at times above 120 seconds). Morphological reaction is associated with humidity (in air and in the filter paper) and does not appear with increased atmospheric humidity. However, seedling response to the discharge treatment is still observed at the level of membrane conductivity (conductivity of seed extract) and enzyme activity (for example activity of peroxidase).

ANOMALOUS THERMODYNAMICS AND FLUID-FLUID PHASE TRANSITION PROBLEM IN COMPRESSED HYDROGEN

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Anomalous properties of hydrogen (deuterium) adiabatically compressed in Megabar pressure range may realized due to existing of anomalous thermodynamic properties of warm dense hydrogen in extended region of its phase diagram. This region always accompanies and includes the so-called *entropic* 1st-order delocalization-driven phase transition. The main analytical feature of such anomalous thermodynamics region (ATR) is simultaneous loss of (usual) positivity by great number of 2nd-order cross derivatives of thermodynamic potential of matter, such as Gruneizen parameter, thermal expansion coefficient etc. (see e.g. Iosilevskiy, NPP-2103; Elbrus-2015 [1] etc.) One of the main manifestation of discussed anomalous thermodynamics is the lost of regular order and mutual crossing and disorderliness of all isolines such as isotherms, isoentropes, Hugoniot adiabats etc. These anomalies lead in turn to corresponding anomalies in hydrodynamics of adiabatic compression and expansion flows.

Mentioned above anomalies in pure hydrogen are complicated additionally by the so-called *non-congruence* of all phase transformations in the case of hydrogen-helium mixtures. Wide number of recent results for experiments (real and "numerical") are under discussions in frames of claimed above anomalous features in thermodynamics of highly compressed hydrogen and helium.

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ANOMALIES IN EQUILIBRIUM CHARGE PROFILES IN NON-UNIFORM IONIC SYSTEMS AND PHASE TRANSITIONS IN HS-OCP MODEL

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Impressive appearance of discontinuities in equilibrium spatial charge profiles in non-uniform Coulomb systems is under discussions in wide number of thermo-electrostatics problems. Such discontinuities are considered as peculiar micro-level manifestation of phase transitions and of intrinsic macro-level non-ideality effects in local equation of state (EOS), which should be used for description of non-ideal ionic subsystem in frames of local-density approximation (LDA or "pseudofluid", or "jellium" etc) [1] [2]. Such discontinuities were discussed already by the authors for electronic subsystems [3]. Special emphasis is made in present paper on the mentioned above non-ideality effects in non-uniform *ionic* subsystems, such as micro-ions profile within screening "cloud" around macro-ion in complex plasmas (dusty, colloid etc), in equilibrium ion distributions in ionic traps or/and in the neighborhood vicinity of "charged wall" etc.

Multyphase EOS for simplified ionic model of classical charged hard spheres on *uniformly compressible* electrostatic compensating background (HS-OCP) was constructed in present work and several illustrative examples of discussed discontinuous ionic profiles were calculated with the use of this EOS in LDA approximation.

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