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The contributions reflect recent progress in physics of strongly coupled plasmas.

Edited by academician Fortov V.E., Iosilevskiy I.L., Levashov P.R.

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THERMODYNAMIC PROPERTIES OF NON-IDEAL PLASMAS

ON THERMODYNAMIC INCONSISTENCY OF EQUATIONS OF STATE IN SESAME LIBRARY

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We have checked the fulfillment of the thermodynamic relation

$$\frac{\partial E}{\partial V} = T\frac{\partial p}{\partial T} - p. \tag{1}$$

for tabular wide-range equations of state presented in SESAME library. For Cu tables in density range of $\rho = 10 \div 1000$ g/cm^3 and temperature range of $T = 1 \div 100$ eV, the inconsistency of left and right parts of (1) has been shown to exceed 30% in gaseous region and 10% in condensed matter region. At the boundary of these regions it is more than 100%.

So, a standard procedure is reasonable to be established for checking of any proposed equations of state on thermodynamic consistency. Any unitized equations of state are reasonable to be constructed via procedure described in [1] which automatically provides their thermodynamic consistency.

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1. N.N. Kalitkin, K. I. Lutskiy // Math. models and comp. simulations. 2015. V. 27. N 4. P. 31–49.

AVERAGE-ATOM MODELS WITH AND WITHOUT ION CORRELATIONS

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Average-atom models disregarding ion-ion and ion-electron Coulomb correlations (Liberman's model [1], neutral Wigner-Seitz sphere model [2], and VAAQP model [2]) are compared with the model of Starrett and Saumon [3] allowing for those correlations. The Liberman's and NWS models are distinguished by the approximations to treat the electron density beyond the Wigner-Seitz sphere: it is assumed to be uniform in the

Liberman's model while the NWS model allows for the nonuniformity of electron density. The VAAQP and NWS models are distinguished by the method to calculate electron chemical potential.

The thermodynamic and transport properties calculated using Liberman's and the NWS models are presented. Distinctions between the relevant equations of state are governed by the contributions due to electrons beyond the Wigner-Seitz sphere.

Ion-correlation models allow for the nonuniformity both of the elecron and ion densities beyond the Wigner-Seitz sphere. The ion density is calculated using the two-component-plasma model based on quantum Ornstein-Zernike equations coupled to the average-atom model. First calculations of average ionization and thermodynamic functions done with fully quantum-mechanical version of the model of Starrett and Saumon are presented. The inclusion of ion correlations leads to the increase of the calculated pressure.

1. D.A. Liberman. // Phys. Rev. B. 1979. V. 20. P. 4981–4989.
2. R. Piron, T. Blenski. // Phys. Rev. E. 2011. V. 83, 026403.
3. C.E. Starrett, D. Saumon. // HEDP. 2014. V. 10. P. 35–42.

EXTENDED AVERAGE-ATOM MODEL WITH SEMICLASSICAL ELECTRONS ALLOWING FOR ION CORRELATIONS

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Warm dense matter (WDM)—a plasma state with a temperature around the Fermi energy and a density below and around normal solid density—is widely met in astrophysical and planetary-science research [1] as well as in various laboratory experiments on high-energy-density physics. Computer modeling of dynamic and radiative properties of the relevant plasma objects therefore suggests that thermodynamic properties of WDM are characterized to an extent to appropriately contribute to the wide-range equations of state (EOS). As the construction of the ionized-matter EOS generally focuses on the electronic subsystem [2], in the WDM state ion-ion Coulomb interaction energy may far exceed average ion kinetic energy, thus resulting in thr formation of the liquid-like microstructure of the ionic subsystem.

We consider a model single-temperature plasma incorporating two subsystems of positively charged classic ions and semi-classical Thomas-Fermi-Dirac electrons. The ionic subsystem charachterized by the ion-ion radial distribution functions (RDF) of a relative probability to find a neighboring ion in the spherically symmetric approximation [3]. Ion-ion RDFs are obtained from the numerical solution of the Ornstein-Zernike equations coupled with the hypernetted-chain closure relations [3]. Self-consistent description of electronic and ionic subsystems is implemented on the base of the model recently formulated by C. E. Starrett and D. Saumon [4].

A close agreement of calculated RDFs is ontained with the data both ab initio molecular dynamic simulations [5] and for X-ray scatternig experiments with melted metals under the atmospheric pressure [6]. The results of recent experimental studies of warm (1.75 eV and 10 eV) compressed ($2.32\rho_0$ and $3\rho_0$) aluminium [7, 8] are explained. Wide-range calculations reveal the areas of $\simeq 5\%$ deviations in average ionization due to ionic nonideality. EOS data tables are generated by the numerical differentiation of free energy incorporating ion-correlation contributions. With EOS data obtained, principal Hugoniots of aluminium and some other chemical elements are analyzed.

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1. H. W. Van Horn. Dense astrophysical plasmas // Science.—1991.—Vol. 252.—Pp. 384–389.
2. A. F. Nikiforov, V. G. Novikov, V. B. Uvarov. Quantum-statistical models of hot dense matter. Methods for computation opacity and equation of state.—Basel: Birkhauser, 2005.
3. Cl. A. Croxton. Liquid state physics—a statistical mechanical introduction.—Cambridge: Cambridge University Press, 1974.
4. C. E. Starrett, D. Saumon. Electronic and ionic structures of warm and hot dense matter // Phys. Rev. E.—2013.—Vol. 87.—P. 013104.
5. K. Wünsch, J. Vorberger, D. O. Gericke. Ion structure in warm dense matter: Benchmarking of the hypernetted-chain equations by first principle simulations // Phys. Rev. E.—2009.—Vol. 79.—P. 010201(R).
6. H. F. Y. Waseda. The structure of non-cristalline materials.— 1980–2014. http://res.tagen.tohoku.ac.jp/waseda/scm/index.html.
7. T. Ma, L. Fletcher, A. Pak et al. Observations of strong ion-ion correlations in dense plasmas // Phys. Plasmas.—2014.—Vol. 21.—P. 056302.
8. L. B. Fletcher, H. J. Lee, T. Döppner et al. Ultrabright X-ray laser scatternig for dynamic warm dense matter physics // Nature Photonics.—2015.—DOI: 10.1038/NPHOTON.2015.41.

SHOCK COMPRESSIBILITY OF SiO_2 CALCULATED IN THE FRAMEWORK OF QUANTUM-STATISTICAL MODELS

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The results of calculations of thermodynamic properties of SiO_2 under shock-compression condition in the framework of Thomas–Fermi, Thomas–Fermi with quantum and exchange corrections and the Hartree–Fock–Slater model [1] are presented. The influence of the thermal motion and the interaction of ions is accounted in the framework of three models: the ideal gas, the one-component plasma and the charged-hard-spheres system. Calculations are performed in the pressure range from 1 to 10^7 GPa. Calculated Hugoniots are compared with available experimental data.

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1. Nikiforov A. F., Novikov V. G., Uvarov V. B. Quantum-Statistical Models of Hot Dense Matter. Methods for Computation Opacity and Equation of State. Birkhauser, Basel, Switzerland, 2005. 428 pages. ISBN 978–3764321833.

REGION OF VALIDITY OF THE THOMAS–FERMI MODEL WITH QUANTUM, EXCHANGE AND SHELL CORRECTIONS

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Thermodynamic properties of nonideal plasma are of high importance in a variety of physical applications such as intensive shock waves, laser ablation and fusion. The equation of state (EoS) which covers a wide range of parameters is possible to construct by using different approaches. The most precise methods are based on the density functional theory (DFT) [1]. However, it is too difficult to perform calculations at low densities and temperatures higher than several tens of eV. Hopefully, the region of validity of the well-known finite temperature Thomas-Fermi model [2] starts from tens of eV at normal densities and expands for higher temperatures and densities [3]. The properties of low density plasma can be also described well with the shell corrections [4]. The region of validity for the model with quantum, exchange and shell corrections is discovered by comparison of EoS calculated by different approaches for non-ideal metallic plasma.

1. Desjarlais M., Graziani F., Redmer R., and Trickey S., Frontiers and Challenges in Warm Dense Matter: Lecture Notes in Computational Science and Engineering, - Springer, 2014
2. Feynman R. P., Metropolis N., Teller E. // Phys. Rev. 1949. V. 75, N. 10. P. 1561–1573.
3. Dyachkov S. A., Levashov P. R. // Physics of Plasmas, 2014. V. 21. P. 052702
4. Shpatakovskaya G. V. // Physics-Uspekhi, 2012. V. 55, N. 5. P. 429–464

SIMULATION OF QUANTUM THERMODYNAMICS IN PHASE SPACE

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Path Integral Monte Carlo methods (PIMC) are widely used in quantum thermodynamics. The most common variety of them a based on representation of partition function in form of path integrals [1]. Such methods are useful in applications to condensed matter [2, 3], plasmas [4], elementary particles [5] and in other fields.

An alternative approach consists of using Wigner function [6]. Wigner function is real (p,x) - representation of density matrix and in many ways is similar to classical distribution function in phase space. Herewith thermodynamical average values of different quantum operators are determined by formulas from classical statistics. Moreover, Wigner formalism opens the way to calculation of transport properties [6], what cannot be achieved by common PIMC methods. However there was not known until this moment any numerical methods for Wigner function at finite temperature. Only pure quantum states was studied [7].

In this work we have developed such numerical method for Wigner function at finite temperature, which is applicable to system of interacting non-relativistic particle. Firstly, we obtained new representation of Wigner function in form of path integral. Secondly, we developed Monte Carlo method for calculations of Wigner function, thermodynamical values of arbitrary quantum operators and wave function of the ground state. Finally, we implemented it in software, tested on some model systems and are going to present some new results for Coulomb systems of particles.

1. Feynman R. P. and Hibbs A. R. Quantum Mechanics and Path Integrals. NY: McGraw-Hill, 1965.

2. Ceperley D. M. Path integrals in the theory of condensed helium. // Rev. Mod. Phys. 1995. No. 67(2). P. 279.
3. Filinov V. S., Fehske H., Bonitz M., Fortov V. E. and Levashov P. R. Coulomb crystal and quantum melting in electron-hole plasmas under high pressure. // physica status solidi (b). 2007. Vol. 244(1). P. 474–479.
4. Filinov V. S., Fortov V. E., Bonitz M. and Levashov P. R. Phase transition in strongly degenerate hydrogen plasma. // JETP Letters. 2001. –Vol. 74(7). P. 422.
5. Filinov V. S., Ivanov Yu. B., Fortov V. E., Bonitz M. and Levashov P. R. Color path integral Monte-Carlo simulations of quark-gluon plasma: Thermodynamic and transport properties. // Phys. Rev. 2013. C87.
6. Wigner E. On the Quantum Correction For Thermodynamic Equilibrium. // Phys. Rev. 1932. 40. 749.
7. Sellier J. M., Dimov I. On the simulation of indistinguishable fermions in the many-body Wigner formalism. // Journal of Computational Physics. 2015. 280. P. 287–294

EQUATION OF STATE AND THERMAL PROPERTIES OF FUSED QUARTZ IN ITS ABNORMAL COMPRESSIBILITY REGION

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Quartz is the basic component of Earth interior and consequently the extensive scientific literature is devoted to research of compressibility and thermal properties of various quartz modifications at high pressures. Fused quartz (silica glass) represents a vitreous form of silicon dioxide which possesses of abnormal compressibility characteristic for glasses. This feature, first of all, is shown in decreasing of the bulk modulus at pressure increasing. For today the representative set of experimental thermal properties of quartz glass exists in the high pressures-high temperatures region. As to quantitative interpretation of these experimental results in terms of equations of state the thermodynamic description of thermal properties of fused quartz in its abnormal compressibility is limited by several empirical relations. In this report the free energy of fused quartz is presented in the form of function of the own variables (volume and temperature) in the silica glass abnormal compressibility. Its volume-temperature dependences thermal properties (bulk module, thermal capacity, thermal expansion coefficient), received by means of partial derivatives of free energy are

presented also. Computed results are compared to available experimental data and the acceptance region is discussed.

ANOMALOUS PHASE DIAGRAM IN SIMPLEST PLASMA MODEL

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The variety of simplest plasma models with a common feature—absence of correlation of charges of opposite sign—is studied. (OCP of ions on the background of ideal fermi-gas of electrons; a superposition of two OCP models of ions and electrons etc.) In all the models the background is considered as uniform and textitcompressible media. It results in: (i) variation of crystal and liquid densities at melting [1]; and (ii) appearance of a new gas-liquid phase transition [2, 3] with properties strongly depending on the value of ionic charge number z.

An anomalous phase diagram is realized in the model at sufficiently high value of ionic charge ($z_1^* \leq z \leq z_2^*$). The only one unified crystal-fluid phase transition exists as continuos superposition of melting and sublimation. The pseudo-critical point exists in both cases $z = z_1^*$ and $z = z_2^*$. The critical isotherm is cubic in this case. Any critical point is absent at intermediate values of charge number z ($z_1^* < z < z_2^*$). A complicated structure of spinodals accompanied the phase diagram discussed. The real calculations have been made for OCP of classical ions on the ideal electron gas background. In this case $z_1^* \approx 35.5$ and $z_2^* \approx 40.0$.

The discussed phase transition may be reproduced, in principle, by means of direct numerical simulation.

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1. Pollock E.L., Hansen J.P. Phys.Rev. A 8, 3110,(1973).
2. Iosilevski I.L. and. Chigvintsev A.Yu, “Physics of Nonideal Plasmas”, /ed. by W.Ebeling, A.Foerster and R.Radtke/, Teubner-Texte zur Physik. B 26, Stuttgart-Leipzig, 1992, p.87.
3. Iosilevski I.L. and. Chigvintsev A.Yu, “Physics of Strongly Coupled Plasmas”, /ed. by W.D. Kraeft and M. Schlanges/, World Scientific, 1996, p. 145.

THERMODYNAMICS OF DYNAMICALLY COMPRESSED GASES AT MEGABAR PRESSURE RANGE

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The thermodynamic properties of hydrogen and noble gases at high pressures and temperatures are of interest because it is widespread in nature and is used in various high energy facilities, as well as because of active investigations of processes inside the giant planets and so called extrasolar planets. The equation of state of hydrogen (deuterium) submegabar and megabar ranges of pressures were experimentally studied with different methods. The thermodynamic properties of hydrogen in the megabar pressure range, where a high density of matter is accompanied by a strong Coulomb interaction (strongly non-ideal plasma) were theoretically described both in frames of the quasichemical concept (free energy minimization method) and within the ab-initio methods involving the direct numerical simulation of system of nuclei and electrons. In spite of experimental and theoretical achievements in this range of parameters further study of dynamically compressed 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 densities three times higher than aluminum density. Last several years new theoretic results in frames of chemical picture and ab-initio methods in a wide range of shock pressures have been presented as well.

Here we present the results of calculation of principal Hugoniots for different initial densities of hydrogen and deuterium together with data for isentropic one. These calculations were carried out with codes implemented the improved SAHA-family models.

The calculations of principal Hugoniots of hydrogen, the same for solid, liquid and pre-compressed gas targets in wide range of thermodynamic parameters together with isentropes are presented. The calculations have shown that in the considered pressure range dynamically compressed gas is in state of strongly coupled, degenerated plasma with density close to condensed matter. The obtained parameters of plasma are discussed together with those obtained in frames of first principal quantum methods.

Results of these calculations are compared with all experimental data on shock and quasi-isentropically compressed hydrogen.

EFFECTIVE INTERACTION POTENTIALS IN PARTIALLY IONIZED DENSE H–He PLASMAS

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In this work the effective interaction potentials of the charged particles with the helium atom and scattering processes in the partially ionized dense plasma consisting of hydrogen and helium atoms are studied. It is important to study the partially ionized dense plasma consisting of hydrogen and helium atoms as these two elements are widespread in the universe and such a plasma is important for understanding of the evolution of giant planets, stars etc.

As it is known, at high densities the manifestation of the quantum effects must be taken account in the effective interaction potential. We construct new interaction model for H-He plasmas taking into account the effect of atom polarization and the effect of partial screening of the nuclear field by the bound electrons [1–3]. Here, the screening effect is taken into account within random phase approximation. The bound electrons of helium are described using the known accurate wave function [1] and the atom polarization effect is taken into account within the multipole expansion approximation. As a result new effective screened potentials for pairs of helium atom-charge, and single ionized helium atom-charge are proposed.

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1. M. Goldberger and K. Watson, Collision Theory Wiley, New York, 1964, p. 750.
2. T. S. Ramazanov, K. N. Dzhumagulova, and M. T. Gabdullin, Phys. Plasmas 17, 042703 (2010)
3. T.S. Ramazanov, K. N. Dzhumagulova, Y.A. Omarbakiyeva, and G. Repke. Contrib. Plasma Phys. 47, 267 (2007).

SCREENED INTERACTION POTENTIALS AND THERMODYNAMIC PROPERTIES OF A NON-IDEAL PLASMA

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This work is devoted to dense electron-ion plasmas in the warm-dense-matter regime where electrons (ions) are weakly (strongly) correlated and electronic quantum effects are relevant. We concentrated on both equilibrium and stationary nonequilibrium states. In stationary nonequilibrium state electrons move relative to the ions—a situation that is ubiquitous in dense plasmas including electron or ion beams, laser accelerated electrons, or ions penetrating a dense quantum plasma or a metal (ion stopping).

To compute the effective screened ion potential a linear response description of the electrons via the Mermin dielectric function is utilized with electron-electron collisions taken into account via a relaxation time approximation [1, 2]. The ion potential strongly deviates from the static Yukawa potential [3, 4] exhibiting the familiar oscillatory structure with attractive minima between ions. The results of the investigation show the importance of finite temperature effects even when the electron thermal energy is lower than the Fermi energy. Also, it is found that the collisions have a strong nonlinear effect on the potential distribution around the ion. Finally, we obtain the minimal electron streaming velocity for which attraction between ions occurs. This velocity turns out to be less than the electron Fermi velocity.

On the basis of the expansion in the long wavelength limit of the dielectric function [4] in random phase approximation the statically screened effective interaction potentials were derived. Using these screened potentials the thermodynamic properties of a dense plasma were investigated. Particularly, the analytical formulas for inner energy and equation of state were obtained [5].

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1. Zhandos Moldabekov, Patrick Ludwig, Michael Bonitz, Tlekkabul Ramazanov Phys .Rev. E 91, 023102 (2015).
2. Zh. A. Moldabekov, P. Ludwig, J.-P. Joost, M. Bonitz, and T. S. Ramazanov, Contrib. Plasma Phys. 55, 186 (2015).
3. T. S. Ramazanov, Zh. A. Moldabekov, M. T. Gabdullin, and T. N. Ismagambetova, Phys. Plasmas 21, 012706 (2014).

4. Zh. A. Moldabekov, T. Schoof, P. Ludwig, M. Bonitz, and T.S. Ramazanov, Phys. Plasmas 22, 102104 (2015).
5. T.S. Ramazanov, Zh. A. Moldabekov, M.T. Gabdullin, Phys. Rev. E 92, 023104 (2015).

ESTIMATES OF THE ELECTRONIC CONTRIBUTION TO THE SPECIFIC HEAT FOR LIQUID ALUMINUM AND LIQUID ZIRCONIUM

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For liquid tungsten the electronic contribution to the constant volume specific heat becomes comparable with that of atoms (ions) already near the boiling point at the atmospheric pressure [1]. Extrapolation of the temperature dependence of the specific heat to the temperatures at which the metal-nonmetal transition was observed in expanded liquid tungsten [2] suggests that in this temperature range the electronic subsystem is degenerate only slightly.

This conclusion, which is very important to elucidate the nature of metal-nonmetal transition, needs to be carefully inspected. In particular, the measurements of the thermal expansion coefficient should be done with sufficient accuracy, as well as the estimates of the electronic contribution to the specific heat should be made for other liquid metals (which are more compressible than tungsten and have a different atomic structure).

In this work such measurements have been carried out for liquid aluminum and liquid zirconium using the pulse Joule heating technique [1]. Dependence of the specific volume on the specific enthalpy and pressure has been measured with accuracy better than 2%. As a result the electronic contribution to the specific heat for these metals has been estimated rather accurately.

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1. Korobenko V. N., Rakhel A. D. // Journal of Physics: Condensed matter 2014. V. 26. P. 045701.
2. Korobenko V. N., Rakhel A. D. // Phys. Rev. B 2013. V. 88. P. 134203.

QUASI-ISENTROPIC COMPRESSIBILITY OF GASEOUS DEUTERIUM AT THE PRESSURES UP TO 5500 GPa

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Experimental results on quasi-isentropic compressibility of gaseous deuterium obtained in the devices of cylindrical and spherical geometry at the pressures up to $P \approx 5500$ GPa are presented. Some data at the pressures up to $P \approx 400$ GPa were presented previously in [1] but, due to limited article volume, some details on experiments and thermodynamic parameters calculation technique hadn't been given. In present work this shortcoming has been removed: parameters of experimental devices, calculation technique, used equations of state (EOS) for the gas and iron, elastoplastic properties of metallic layers are presented. The results of new experiments, including those in the region of registered anomaly in deuterium compressibility at the pressure $P \approx 154$ GPa are given. With recently developed two-stage devices of spherical geometry gaseous deuterium has been compressed up to the density $\rho \approx 6$ g/cm^3 by the pressure $P \approx 5500$ GPa (55 Mbar). Aggregated experimental data in the region of densities from $\rho \approx 0.8$ g/cm^3 to $\rho \approx 6$ g/cm^3 clearly demonstrate a break of the function $P = P(\rho)$ at the pressure $P \approx 154$ GPa, that is consistent with the conclusion of deuterium compressibility anomaly, has made previously in [1].

The trajectories of metallic layers that compress the gas have been registered by means of powerful X-Ray sources with electron boundary energy up to 60 MeV. Average gas density has been calculated using measured magnitude of layer radius at the moment of its "stop" (maximum compression). The pressure of collapsed gas has been obtained from the gas-dynamic calculations that take into account strength properties of every element of experimental devices.

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1. V.E. Fortov, R.I. Ilkaev, V.A. Arinin, V.V. Burtzev, V.A. Golubev, I.L. Iosilevskiy, V.V. Khrustalev, A.L. Mikhailov, M.A. Mochalov, V.Ya. Ternovoi, and M.V. Zhernokletov. Phys. Rev. Lett. 99, 185001 (2007).

WARM DENSE GOLD: EFFECTIVE ION-ION INTERACTION AND IONISATION

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Quantum mechanical description of electrons in condensed phase is a general problem of the highest importance. However the rigorous wavefunctions based theory is very complicated even for ground state ($T_e = 0$), the finite temperature case being much farther from applicability in practice. Only recently accurate quantum Monte Carlo approaches have been developed in this field [1]. That is why the Kohn-Sham density functional theory (KS DFT) method in the finite-temperature (FT) formulation became a tool of choice.

Temperature implies the necessity of the statistical description of the coupled system of electrons and ions. Statistical physics deploys the free energy $\mathcal{F}$ as a starting point for the theory. At the atomistic level one needs to describe the ion dynamics and therefore to know how to calculate forces acting on them. Moreover, in experiments with plasma or WDM electrons and ions frequently are not in thermodynamic equilibrium. These needs (statistical and atomistic description including non-equilibrium phenomena) determine the complexity of building a proper theory.

In our previous work [2] we have presented the results that raised questions about how we should bridge the FT KS DFT description with classical atomistic scale. In this work we present new results for WDM gold that emphasize the need for rethinking the common concepts used in modelling and simulation of WDM at the *ab initio* level.

In this talk we review the free energy models that are deployed in *ab initio* theory of WDM in equilibrium and non-equilibrium cases and provide our novel results on the analysis of the interatomic forces and pressure in WDM gold [3].

The work was supported by the Russian Science Foundation (Grant No. 14-19-01487).

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1. Booth G. H., Grüneis A., Kresse G., Alavi A., Towards an exact description of electronic wavefunctions in real solids // Nature. 2013. V. 493. P. 365.
2. Stegailov V. V., Zhilyaev P. A., Pressure in electronically excited warm dense metals // Contrib. Plasma Phys. 2015. V. 55. No. 2–3. P. 164.
3. Stegailov V. V., Zhilyaev P. A., Warm dense gold: effective ion-ion interaction and ionisation // Molecular Physics (accepted for publication) DOI:10.1080/00268976.2015.1105390

PARTIAL DIELECTRIZATION OF CALCIUM UNDER HIGH PRESSURE: DFT-GGA AND GW CALCULATIONS

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Partial dielectrization of the electronic spectrum of fcc calcium in the pressure range to 20 GPa is studied ab initio using the DFT-GGA approach and GW approximation. The latter method describes experimental electronic spectra very well because it involves a non-local exchange-correlation interaction. We found that a more correct description of many-electron effects given by GW method does not provide significant changes in the behavior of electronic spectrum in comparison with the DFT-GGA approach. Furthermore, the details of calcium's electronic structure are more sensitive to the accuracy of calculations than to the choice of approximation for exchange-correlation functional. The reason for such a sensitivity is a (pseudo)gap in the electronic spectrum at about 20 GPa due to an accidental degeneracy of bands at the Fermi level. Our precise calculation of calcium's band structure shows that this band crossing is removed if the spin-orbit coupling is taken into account.

MOLECULAR DYNAMICS SIMULATIONS OF ELECTRON-ION NONIDEAL PLASMA WITH VARIOUS BOUNDARY CONDITIONS

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Theoretical studies of strongly coupled systems of charged particles such as electron-ion nonideal plasmas often rely on atomistic simulations by the methods of classical Molecular Dynamic (MD) and Monte-Carlo (MC) [1, 2]. For both methods there is a long standing boundary condition problem when modelling an infinite spatially uniform system of particles interacting via the long-ranged Coulomb forces. This problem has solution for crystal-like systems called the Ewald summation, but it fails for disordered plasma as it may introduce artifacts due to unphysical periodicity. A typical choice for the disordered systems is the nearest image method, although some authors prefer reflecting walls [3]. The boundary problem becomes more difficult for the so called Wave Packet Molecular Dynamics (WPMD) [4]. Application of this method to rather dilute nondegenerate

extended systems leads to the problem of unrestricted wave packet spreading [5]. Reflective boundary conditions for simulation box may be used as a method to provide the finiteness of the partition function.

In this work we start with a classical MD and perform a comprehensive study of convergence of thermodynamic quantities with the simulation box size growth for different types of boundary conditions. For the model of extended matter the effect of any boundary conditions should vanish as the system size grows. We study the limiting behavior of various computed quantities and determine the number of particles for which the system size effect is negligible. A special attention is paid to simulations with soft (harmonic) reflecting walls, since they may be applied both for WPMD and classical simulations. Using soft reflecting walls leads to increase of the effective system volume and decrease of the density which affects thermodynamics properties. This can be solved by shifting the walls to correct the mean particle density.

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1. J. P. Hansen and I. R. McDonald Phys. Rev. 1981, A 23, 2041–59
2. I. V. Morozov and G. E. Norman J. Exp. Theor. Phys. 2005, 100, 370–84;
3. S. A. Mayorov, et al. 1994, 37.3, 279–288.
4. D. Klakow, C. Toepffer, P.-G. Reinhard, J. Chem. Phys. 1994, 101, 10766.
5. I. V. Morozov, and I. A. Valuev. J. Phys. A: Math., 2009, 42.21, 214044.

TRANSPORT PROPERTIES OF SOLID AND LIQUID COPPER WITH HOT ELECTRONS

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In order to consider the electron-ion thermalization of heated layer in copper target after femtosecond laser irradiation, two approaches for electron transport coefficients calculations are considered. In the first one the phenomenological model is developed which is based on the analytic model of hot electron thermodynamics and accurate solution of Boltzmann kinetic equation in relaxation time approximation [1]. This model can be used for an investigation of solid and liquid copper transport properties at wide ranges of compression and electron temperature and also at ion temperatures up to critical point. The results of application of Kubo-Greenwood theory in the method of quantum molecular dynamics are essential for the second approach. Using this approach we consider molten copper at different states of compression and heating of electron and ion subsystems. Such states correspond to the conditions obtained in the typical experiments dealt with laser ablation. Different methods were applied to reproduce atomic distributions in molten copper. Also, the effect of parameters used in full electron and pseudopotential calculations for electron structure calculations, is investigated.

In result, we obtained the solutions for electron heat conductivity and electroresistivity as functions of density and electron and ion temperatures by two independent approaches. An improvement of copper transport properties was found using the first method at high electron temperatures in wide ranges of other outer parameters. This improvement is in accordance with the data of the second approach. Using the data of the second approach the relation between electron heat conductivity and electroconductivity was found. This relation can be considered as the extension of Wiedemann-Franz law on the two-temperature state.

1. Petrov Yu. V., Migdal K. P., Inogamov N. A., Zhakhovsky V. V. // Appl. Phys. B. 2015. V. 119. No. 3. P. 401.

SELF-CONSISTENT APPROACH FOR DESCRIPTION OF OPTICAL AND ELECTRONIC PROPERTIES OF WARM DENSE MATTER WITHIN THE FRAMEWORK OF DENSITY FUNCTIONAL THEORY.

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The approach is suggested, which provides self-consistent description of optical and electronic properties of warm dense matter (WDM) arising under shock compression. Following optical properties are considered: reflectivity of WDM either for normal incidence of laser radiation or for incidence at the certain angle. Brewster angles are calculated. The influence of broadening of the shock wave front on the optical properties of WDM is considered. Electronic properties are conductivity, plasma frequency and electronic density of states.

The density functional theory (DFT) is used for computation of the dielectric function (DF). DF is used as the basic value for the calculation of the WDM properties. The core electrons are considered by means of the projector augmented wave (PAW) method potential, which is nonlocal. The Kohn-Sham set of equations with the PAW potential is solved for valent electrons. Due to the nonlocality of the PAW potentials, the longitudinal expression for the imaginary DF [2] is used. The method is suggested to calculate plasma frequency, which is based on the sum rule. The effective free electron number density is also treated.

The first application of the approach is reflectivity of shocked xenon, which is measured in [3, 4]. Most of the experimental data are explained, contrary to all the previous attempts. The influence of the shock front width on the reflectance is analyzed. The widths of the wave front are estimated [4] under assumption of the linear dependence of the DF on distance. These values are much closer to the theoretical estimate of 100 nm obtained in [2], in comparison with earlier works [3, 5, 6], where the Drude formula was used to calculate DF. Dependencies of the plasma frequency and conductivity on density are investigated for warm dense hydrogen as well.

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1. Norman G. E., Saitov I. M., Stegailov V. V., Zhilyaev P. A. // Phys. Rev. E. 2015. V. 91. 023105.
2. Mintsev V. B., Zaporogets Yu. B. // Contrib. Plasma Phys. 1989. V. 29 P. 493.
3. Zaporogets Yu. B. Mintsev V. B., Gryaznov V. K., et al. // J. Phys. A: Math. Gen. 2006. V. 39 P. 4329.
4. Saitov I. // Mol. Phys. 2015. doi: 10.1080/00268976.2015.1078508.
5. Reinholz H., Röpke G., Wierling A., Mintsev V. B., Gryaznov V. K. // Contrib. Plasma Phys. 2003. V. 43 P. 3.
6. Reinholz H., Zaporogets Yu. B., Mintsev V. B., Fortov V. E., Morozov I. V., Röpke G. // Phys. Rev. E. 2003. V. 68 036403.

THE CALCULATION OF TRANSPORT AND OPTICAL PROPERTIES OF DENSE PLASMA BASED ON THE QUANTUM MOLECULAR DYNAMICS AND THE KUBO–GREENWOOD FORMULA

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The information on the matter properties is important for the simulation of various experiments in the physics of extreme matter conditions.

The necessary properties are obtained in this work via the numerical calculation. The method is based on quantum molecular dynamics, density functional theory and the Kubo-Greenwood formula [1].

The dependence of the calculated static electrical conductivity $\sigma_{1_{\mathrm{DC}}}$ on the technical parameters was investigated. This investigation was performed for aluminum at $T = 1273$ K and $\rho = 2.249$ g/cm^3. The estimated error of $\sigma_{1_{\mathrm{DC}}}$ calculation is 23 % [1]. The computational error is mainly due to the dependence on the number of atoms and on the number of **k**-points.

The results are in the good agreement with the calculations of the other authors by the same technique, experimental and reference data [1, 2].

The pratical calculations were performed for the aluminum plasma and the plasma of the effective composition CH_2.

The calculations for aluminum plasma were performed at normal $\rho = 2.70$ g/cm^3 and 3 kK $\leq T_i \leq T_e \leq$ 20 kK [3]. Thus the two-temperature case $T_i \leq T_e$, important for the simulation of femtosecond

laser experiments, was also investigated. The obtained transport and optical properties may be described by the Drude theory with $\tau \propto T_i^{-0.25}$ expression for the relaxation time. So, the Drude theory with the common $\tau \propto T_i^{-1}$ expression is the poor model under the conditions considered.

The most interesting result obtained for CH_2 plasma is the step-like behavior of $\sigma_{1_{DC}}$: it grows rapidly at 5 kK $\leq T \leq$ 10 kK and remains almost constant at 20 kK $\leq T \leq$ 60 kK [4]. The rapid growth of $\sigma_{1_{DC}}$ is explained by the investigation of the electron DOS (density of states).

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1. Knyazev D. V., Levashov P. R. // Comput. Mater. Sci. 2013. V. 79. P. 817.
2. Povarnitsyn M. E., Knyazev D. V, Levashov P. R. Contrib. Plasma Phys. 2012. V. 52. P. 145.
3. Knyazev D. V., Levashov P. R. Phys. Plasmas. 2014. V. 21. P. 073302.
4. Knyazev D. V., Levashov P. R. Phys. Plasmas. 2015. V. 22. P. 053303.

ION RECOMBINATION IN DENSE GASES

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Ion recombination processes in dense gases are considered for different combinations of the gas and ion properties. Three recombination regimes are distinguished which differ by background gas densities and ion-neutral interactions character. The influence of the Coulomb nonideality on the recombination rate constant is calculated for the each of the three regimes. Conditions of the transitions from one regime to another are found depending on the media parameters variation.

The first regime is related to gases of moderate densities. It takes place when ion-neutral interactions are weak to form stable cluster structures. The medium can be described as a system of ions which interact with each other and experience random scattering by medium molecules. Recombination kinetics is similar to that in non-degenerate electron-ion plasmas. Recombination suppression appearance at the transition from weakly to strongly coupled plasmas is due to the formation of multi-particle fluctuation band which separates bound and free electron states.

The second regime is specific for media where complex cluster ions can be formed. The recombination process includes an intermediate stage with the formation of a metastable ion cluster pair and possible inverse disin-

tegration of it before ion recombination. The character of the Coulomb nonideality influence on the ion recombination rate differs from the first regime. It is related to the ion fugacity which influences number densities of the metastable ion cluster pairs. Ion solvation results in recombination suppression even in weakly coupled plasmas.

The third regime is observed in dense gases when the length between strong ion collisions becomes small. The approaching of ions to each other is limited by their mobility. It becomes a process which limits the ion recombination rate. The third regime is a diffusion one. The ion recombination rate is closely connected with the ion diffusion coefficients.

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SOLVATION AND MOBILITY OF IONS FROM MOLECULAR DYNAMICS SIMULATION

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A research of the diffusion of an ion in a liquid is carried out. Dependences of the diffusion coefficient on the ion-molecule potential, ion mass, liquid temperature and density are defined. The results are related to the ion solvation. The classical molecular dynamics method is applied.

The polarization potential $U(r) = \beta/r^{12} - \alpha/r^4$ is used to describe the interaction of the ion with molecules of the liquid. The Lennard-Jones potential is used to describe the intermolecular interactions.

The ion velocity autocorrelation function(VAF) calculated reveals a strong oscillatory character superimposed on the conventional functional liquid-type form. It reflects the oscillations of the ion inside the solvation shell. This is proven by the direct comparison of the cluster natural oscillations frequences and VAF spectrum.

The lifetimes of the cluster molecules are estimated as a function of the ion-molecule distance. For the first five layers of the cluster this times are bigger than oscillation times ($\sim$0.1 ps) and correlation time ($\sim$1 ps, as defined from VAF). Consequently cluster radius could be defined as $R_{clust} = 0.75$ nm.

The model can be described by 5 parameters: α, β, ion mass, liquid temperature and density whereas σ is the unit of length, ε is the unit of energy and liquid molecule mass is the unit of mass. Dependences of the diffusion coefficient on this parameters are defined. Results are compared

with the theoretical model HSK [1]. We have changed this model according to our ion-liquid molecules interaction potential. A rather good agreement between modified HSK model and molecular dynamics calculation of the ion diffusion coefficient is found. Deviations are observed for small solvation shell sizes due to hight temperature, low liquid polarizability and big ion radius.

Results are in good agreement with experimental values of O_2^- [2] and Ar_2^+ [3] ion mobilities.

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1. Hilt O., Schmidt F., Khrapak A. // IEEE Trans. Dielectr. Electr. Insul. 1994. V. 1. P. 604.
2. Henson B. // Phys. Rev. 1964. V.135. P. A1002.
3. Gee N., Floriano M., Wada T et al // J. Appl. Phys. 1985. V.57. P. 1097.

T MATRIX EFFECTS ON THE STATIC CONDUCTIVITY IN WARM DENSE MATTER

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Transport properties of dense plasma are investigated. In the generalized linear response theory, the static conductivity is expressed via correlation functions. The main contribution due to electron-ion collisions is well known. Further relevant interactions have to be considered, e.g. electron-electron collisions. Within Born approximation, this was done in a recent paper [1] for arbitrary degeneracy. Assuming statically screened Coulomb potentials a correction factor is deduced. Additionally, the treatment of strong collisions is necessary in the warm dense matter regime. In [2] the T matrix effects are considered for electron-ion interactions. A new fit formula for the electron-ion transport cross section is proposed in order to reduce the numerical effort in the low density limit.

In reference to experimental results the treatment of electron-electron collisions in different approximations is evaluated and especially the influence strong collisions via T matrix is discussed in more detail.

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1. H. Reinholz, G. Röpke, S. Rosmej, and R. Redmer, Phys. Rev. E **91**, 043105 (2015).
2. S. Rosmej, subm. to Contrib. Plasma Phys.

SCREENING, INHOMOGENITY AND INTERBAND TRANSITIONS EFFECTS IN REFLECTIVITY OF DENSE PLASMAS

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Hot dense plasmas are obtained if solid targets are irradiated with high power short pulse lasers, energetic electron or ion fluxes and in experiments with shock wave compression of gases. We consider different physical processes which influence the optical properties of such hot and dense plasmas.

The screening of Coulomb interactions considerably influences the optical properties determined by free-free transitions. The effect of dynamical screening as well as strong interactions and the restriction of screening in dense strongly coupled plasmas are studied in a wide frequency range.

Simple considerations suggest, that not only *intraband*, but also *interband* transitions can contribute substantially to optical properties of warm dense matter even in the case of optical frequencies below the frequencies of interband transitions. It is shown, that this contribution is especially essential if the real part of the permittivity due to intraband transitions becomes close to zeor. In the case of a homogeneous plasma, comparison of calculations of the absorption coefficient and experimental results permits one to determine numerical coefficients in semi-phenomenological expressions for the interband part of the permittivity ε_{bb}. New expressions for the calculation of both real and imaginary part of ε_{bb} are presented.

For the interpretation of experimental results, possible plasma inhomogeneity effects should be taken into account. The dependence of the absorption coefficient on the ratio of the characteristic length of plasma inhomogeneities near the surface and the skin layer depth as well as the ratio of plasma and laser frequencies is discussed.

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1. M. Veysman, M. Winkel, H. Reinholz, and G. Roepke, Optical conductivity from kinetic and quantum statistical approach in wide frequency range // Phys. Rev. E. (2015), to be submitted

TEMPERATURE DEPENDENCE OF RATE CONSTANTS AND NUMERICAL METHODS FOR KINETICS PROBLEMS

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1. Kinetics problem. Kinetics of reactions is described by a system of ODEs. In case of dual reactions it can be written as follows:

$$dn_j/dt = \sum(\pm)K_{ij}n_in_j, \quad 1 \leqslant i,j, \leqslant J. \tag{1}$$

Here n_j are concentrations, T is temperature, "+" is used for reactions with production of component number j and "−" is for reactions with its consumption; $K(T)$ is rate constant.

There are 2 main difficulties: 1) to find reliable dependencies $K(T)$ because the laws of interaction between colliding particles are usually not known; 2) to solve the system (1) numerically, for the rate constants can vary within several orders of magnitude so the system is superstiff.

2. Rate constants. Chemists use traditional approximations $K(T) = AT^k \exp(-E/T)$. Values of A, K, E given in reference books do not stand any physical critics. We have conducted quantum mechanical derivation of rate constants in the case of neutral gas molecules and obtained

$$K_d(T) = C\sqrt{\frac{\pi}{4}E + T}, \quad K_r(T) = C\sqrt{\frac{m_{b1}m_{b2}}{m_{a1}m_{a2}}}\sqrt{\frac{\pi}{4}E + T}\exp(-E/T) \tag{2}$$

for direct (non-threshold) and reverse (threshold) reactions respectively. Here E is the reverse reaction threshold, m are particles' masses and coefficient C depends on the intermolecular interaction law only.

3. Hydrogen combustion. We have considered hydrogen combustion in oxygen as an example and accounted for components O, H, H_2, O_2, OH, H_2O, HO_2, H_2O_2, O_3, O_4 involved in 24 direct and 24 reverse reactions. These data were processed to the form (2). The resulting tables can be recommended as the most reliable reference data for $T < 10^4$ K.

4. Numerical method. Classical explicit schemes are completely inapplicable for system (1) and implicit schemes are too labor-consuming.

A special chemical scheme was proposed in [1], though its accuracy $O(\tau)$ was not high. Now we have constructed a scheme with better accuracy $O(\tau^2)$ and higher robustness.

1. N.N. Kalitkin, V. Ia. Goldin // Comput. math. and math. phys. 1966. V. 6. N 1. P. 162–163.

ELASTIC AND INELASTIC PROCESSES IN THE NONIDEAL SEMICLASSICAL PLASMA ON THE BASIS OF THE DYNAMIC POTENTIAL

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Collisional characteristics of the electron-atom scattering in the dense semiclassical plasma were calculated within the dynamic model of interaction. This model takes into account the quantum mechanical diffraction effect and dynamic screening which depends on the velocity of the colliding particles. On the basis of the Calogero equation the phase functions and the phase shifts were calculated. Phase shifts and cross sections obtained on the basis of the dynamic potential are larger than those obtained on the basis of the static model and converge with them at small values of the kinetic energy of colliding particles. Excitation of hydrogen atom by the electron impact of dense semiclassical hydrogen plasma were studied on the basis of the effective models of the electron-atom interactions taking into account the effect of screening as well as the quantum mechanical effect of diffraction. The calculations of the excitation cross sections were carried out on the basis of the phase-function method. It was shown that increasing in coupling leads to decrease in excitation cross section. In work [1] an effective interaction of potential of the semiclassical dense plasma particles, taking into account the effects of diffraction and static screening was proposed. However, if the velocities of the colliding particles is larger then the thermal velocity, these fast particles do not have time to polarize the surrounding plasma. So, screening of their charge weakens. Such screening, depending on the velocity of the interacting particles, is called as dynamic screening. It is widely used to study the properties of the strongly coupled plasmas. In work [2, 3] a way of the dynamic screening accounting was proposed. In this method the static Debye length is

replaced by some one, which takes into account the dynamic screening. We applied this screening for the potential from work [1]. On the basis of obtained dynamic model the important characteristics of the elastic and inelastic processes were investigated, for example, the differential, total and transport scattering cross section and excitation cross section.

1. T. S. Ramazanov, K. N. Dzhumagulova, and Y. A. Omarbakiyeva. Effective polarization interaction potential charge-atom for partially ionized dense plasma // Phys. Plasmas 12, 092702 (2005).
2. Kremp D., Schalges M., Kraeft W.-D. Quantum Statistics of Nonideal Plasmas. Springer.Berlin. 2005, Chap.8.
3. R. Redmer. Physical properties of dense, low-temperature plasma // Physics Reports 282, 35–157(1997).

VOLUME-TEMPERATURE DEPENDENCE OF VANADIUM ELECTRORESISTANCE UNDER THE MEGABAR SHOCK COMPRESSION

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Experimental studying of vanadium thermal properties is carried out, since 1970 including at high shock pressures. Throughout these years possibility of electronic transitions at strong shock compression was investigated, as well as influence of pressure on increase in temperature of superconducting transition of vanadium and so on. Last years special attention is given to structural and mechanical properties of this metal in a megabar range of static pressure. This interest is in many respects connected with deformation transition of vanadium at which pressure increase stimulates transition of initial crystal structures to the rhombohedral phase with symmetry fall that is accompanied by strong changes of strength properties in the 40–80 GPa range. The analysis of the current scientific literature on this theme allows to designate area of the phase diagramme of vanadium at 30–120 GPa where deformation transition it is possible to expect at shock compression. Thereupon the experimental research of electrophysical properties of vanadium has been undertaken at high dynamic pressure. Results of this research are presented in the given report and consist in the following. Experimental data on electroresistance of vanadium are received at step shock compression up to megabar pressure and temperatures up to 1000 K. The equations of state with elastic-plastic behaviour of vana-

dium are developed in the megabar range. Mathematical modelling of the experiments is carried out by the hydrocode which supports against the received equations of states. Evolution of vanadium thermal properties is calculated at strong dynamic compression. Volume dependence of electroresistance of vanadium is reconstructed in the megabar shock pressures. As a whole the features of volume-temperature dependence of electroresistance of vanadium is interpreted as consequence of structural transition between vanadium phases provided that electroresistance of each phase is defined by electron-phonon interaction.

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ELECTRICAL CONDUCTIVITY AND STRUCTURAL TRANSFORMATIONS OF TITANIUM IN THE MEGABAR SHOCK PRESSURE RANGE

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The polymorphism of titanium is a subject of extensive scientific literature and it is well known that the titanium at atmospheric pressure exists in two polymorphic modifications: α-Ti at temperatures $<$1155 K and β-Ti at temperatures $>$1155 K. When moving to the megabar region along the room temperature isotherm, titanium suffers other polymorphic transformations: $\alpha \leftrightarrow \omega$ at 9 GPa, $\omega \leftrightarrow \gamma$ at 116 GPa, and $\gamma \leftrightarrow \delta$ at 145 GPa (see [1]). However, it should be noted that high temperature sections of the phase diagram of titanium at high pressures are bounded by relatively low values. A wider range of pressures and temperatures is covered in the research into titanium in shock waves. It is known that the combination of high pressures and temperatures in dynamic loading makes it possible to reach hardly accessible regions of phase diagrams of the substances under study. In this case, one of the experimental methods sensitive to the process of polymorphic transitions in shock-compressed solids is the in situ measurement of their conductivity.

In the present study measured the electrical conductivity of titanium under shock compression up to $\sim$100 GPa It has been shown that, in the phase of compression at a pressure of 83(5) GPa, the resistance of titanium samples stepwise decreases by 30%. In the unloading phase in the same region of dynamic loads, the reverse variation in the electrical resistance of titanium takes place. The observed effect is interpreted as a consequence

of the $\omega \leftrightarrow \gamma$ polymorphic transition in shock-compressed titanium. We discuss two possibilities $\omega \leftrightarrow \gamma$, and $\omega \leftrightarrow \eta$ transition. The magnitude of the calculated values of the transformation temperature (1100 K), allows to give preference to the transition to the not been extensively investigated η-Ti.

1. Akahama Y., Kawamura H., Bihan T. Le // Phys. Rev. Lett. 2001. 87, 275503

POLARIZED REFLECTIVITY PROPERTIES OF DENSE Xe PLASMAS

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Adjustment of the ideal plasma theory in the high density region does not adequately describe the behavior of dense media with strongly interacting particles. Improving the physics of strongly nonideal plasma involves building of a correct model of collision processes, which play a crucial role in such environments. The further development of the theory of strongly non-ideal plasma assumes an obtaining of new data on the transport characteristics for a wide range of variation of the thermodynamic parameters up to extremely high, requiring the use of physical experiments with the powerful shock waves. In this situation, the results of the physical experiments take a particular role, acting as a test of accuracy.

The results of new experiments on reflectivity of polarized light on nonideal xenon plasma are presented. The study of polarized reflectivity properties of plasma was accomplished using laser light at $\nu_{las} = 2.83{\cdot}10^{14}$ s^{-1}, $\nu_{las} = 4.33{\cdot}10^{14}$ s^{-1} and $\nu_{las} = 5.66{\cdot}10^{14}$ s^{-1}.

The thermodynamic parameters and composition of plasma were determined from the measured shock wave velocity with suitable calculations carried out. The plasma composition was calculated within a chemical picture [1]. Working with a grand canonical ensemble, virial corrections have been taken into account due to charge-charge interactions (Debye approximation). Short-range repulsion of heavy particles was considered within the framework of a soft sphere model [1–3]. In the parameter range of the shock wave experiments, the composition was obtained with an error of up to 15%, depending on the approximations for the equation of

state. During the experiments, the plasma density $\rho = 1.8$–2.7 g·cm^{-3}, pressure up to $P = 19$ GPa and temperature up to $T = 32000$ K were realized. Under these conditions, the plasma is non-degenerate. The integration of Maxwell equations are based on an interpolation formula for dc conductivity.

1. Ebeling W., Förster A., Fortov V., Gryaznov V. and Polishchuk A. Thermophysical Properties of Hot Dense Plasmas. Stuttgart: Teubner, 1991.
2. Fortov V. E., Gryaznov V. K., Mintsev V. B., Ternovoi V. Ya., Iosilevski I. L., Zhernokletov M. V. and Mochalov M. A. // Contrib. Plasma Phys. 2001. V. 41. P. 215.
3. Fortov V. E., Ternovoi V. Ya., Zhernokletov M. V. et al. // JETP. 2003. V. 97. N. 2. P. 259–278.

SUPERCONDUCTIVITY OF Al AND Al_2O_3 INTERFACE FORMED IN SHOCK-WAVE CONDITIONS

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A mixture of powdered **Al** and $\mathbf{Al_2O_3}$ has been subjected to a shock-wave pressure of $\approx$ 170 kbar, followed by vacuum-encapsulating and quenching of the product to liquid nitrogen. The starting samples were tablets, 9.6mm in diameter and 0.9mm thick, of bulk 99.99%-pure aluminium disks covered by 0.2mm layer of powdered 5–30μm grain size, 99.99%-pure aluminium 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 170kbar. After the shock-wave pressure treatment, the conservation cell was cut open on a lathe, the samples were extracted and vacuum-encapsulated at residual pressure 1–5 Pa into 5 cm-long quartz ampoules having 0.9 mm-thick walls and 6mm outer diameter, and stored in liquid nitrogen to prevent their degradation. The diffraction patterns of the shock-wave pressure treated Al/Al_2O_3 sample recorded at T$\approx$ 80K and at T$\approx$300K were found essentially the same, to within the thermal expansion factor. All the diffraction rings in the pattern are a superposition of the diffractions from polycrystalline Al/Al_2O_3 and Al crystal structures. Each cycle of T measurements has started from a cool-down of the Al/Al_2O_3 sample to 5.5K at zero magnetic fields H_{ac} and H_{dc}. Quite remarkably, as H_{ac} is applied at constant temperature after

the cool-down, develops to the equilibrium value monotonously in time, t, towards the enlargement of diamagnetism.

The ac magnetic susceptibility measurements of the samples have revealed metastable superconductivity with Tc $\approx$37 K, characterized by glassy dynamics of the shielding currents below Tc. Comparison of the ac susceptibility and the dc magnetization measurements infers that the superconductivity arises within the interfacial granular layer formed between metallic Al and its oxide due to the shock-wave treatment.

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MOTT-HADRON RESONANCE GAS AND LATTICE QCD THERMODYNAMICS

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Based on the Φ derivable approach to a cluster virial expansion in quark-gluon matter we suggest an effective model for QCD thermodynamics. An ansatz for the generic behaviour of hadron masses and phase shifts at finite temperature is suggested which shares basic features with recent developments within the PNJL model for correlations in quark matter.

On this basis we obtain the transition between a hadron resonance gas phase and the quark gluon plasma in the spirit of the generalized Beth-Uhlenbeck approach where the Mott dissociation of hadrons is encoded in the hadronic phase shifts.

We find that the restriction to low-lying hadronic channels is justfied by the rather low chiral transition temperature found in recent lattice QCD thermodynamics results which we excellently reproduce.

THERMODYNAMICS OF YUKAWA SYSTEMS NEAR THE ONE-COMPONENT-PLASMA LIMIT

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The one-component-plasma (OCP) represents an old model with various interdisciplinary applications. In addition, the OCP represents a very important example of classical systems of interacting particles with extremely soft interactions (the limit opposite to hard-sphere interactions) and as such it plays significant role in condensed matter research.

Thermodynamic properties of the OCP (in both 2D and 3D) have been extensively studied over decades and accurate numerical results as well as their fits are available in the literature. Nevertheless, there has also been considerable continuous interest in deriving physically motivated analytical estimates or bounds on the thermodynamic quantities (in particular, internal energy) of the OCP. In this talk we present yet another simple analytical scheme that we have developed recently to estimate the internal energy of the OCP in 3D and 2D. It is based on electrostatic arguments and produces expressions, which reduce to the Debye-Hückel (DH) result at weak coupling and to the Ion Sphere Model (3D) or Ion Disc Model (2D) at strong coupling and provides reasonable interpolation between these limits.

The accuracy of this simple approach is nevertheless insufficient in many cases. For this reason, we investigated in detail the behaviour of the thermal component of the internal energy of 2D and 3D strongly coupled OCP fluids. Of particular significance is the observation that the OCP scaling of the thermal energy component is quasi-universal and applies to other soft repulsive potentials, both in 2D and 3D cases (although the scaling differs considerably between 2D and 3D case). One of direct applications of this observation is accurate estimation of thermodynamic properties of weakly screened Yukawa fluids, both in 2D and 3D. We compare our results with the available and new results from numerical simulations to demonstrate very good accuracy of our approximation. Applications are briefly discussed, mainly in the context of complex (dusty) plasmas.

STATICAL AND DYNAMICAL PROPERTIES OF A TWO-DIMENSIONAL YUKAWA LIQUIDS PERTURBED BY DIPOLE-DIPOLE INTERACTION

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This paper presents the results of molecular dynamics simulation of a 2D charged dust system taking into account the effect of the induced dipole moment of a dust particle. As it is known, in gas discharge the dust particle and ions focused by the dust grain can be considered as a one compound particle with non-zero dipole moment [1, 2]. Such a picture is especially suitable for the description for a 2D dust system as there is no dust grain above the given dust particle which can strongly effect focused ions. Non-symmetric dust particles can also have an induced dipole moment due to charge separation in the external electric field.

The interaction between particles located in the same horizontal layer was taken in the following form [3]:

$$\Phi = \frac{Q^2}{R}\exp(-Rk_S) + \frac{d^2}{R^3}(1 + Rk_S)\exp(-Rk_S), \qquad (1)$$

here k_S is the screening parameter, Q is the dust particle charge, and d is the dipole moment of the dust particle or of the given compound particle. As it is seen the interaction potential (1) gives a stronger repulsion between dust particles than the Yukawa potential.

Using the interaction potential (1) the structural properties and oscillations in the 2D dust system were studied. It was found that the maximum of pair correlation function is higher than that of the Yukawa system.

1. T.S. Ramazanov et al., Phys. Plasmas 18, 103705 (2011).
2. G. I. Sukhinin and A. V. Fedoseev, Phys. Rev. E 81, 016402 (2010).
3. T. S. Ramaznov, Zh. A. Moldabekov, A. Zh. Gabdulin, IEEE Transaction on Plasma Science, DOI: 10.1109/TPS.2015.2490282, (2015).

PROPAGATION OF DUST ACOUSTIC WAVES IN COMPLEX PLASMAS WITH A SIMILARITY PROPERTY

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Dust acoustic waves in the bulk of a dust cloud in complex plasma of low-pressure gas discharge under microgravity conditions are considered. The complex plasma is assumed to conform to the ionization equation of state (IEOS) developed in our previous study [1]. This equation implies the ionization similarity of plasmas. We find singular points of IEOS that determine the behavior of the sound velocity in different regions of the cloud. The fluid approach is utilized to deduce the wave equation that includes the neutral drag term. It is shown that the sound velocity is fully defined by the particle compressibility, which is calculated on the basis of the used IEOS.

The resulting formula for the dust sound velocity has the form [2]

$$c_s = \frac{4}{3}\frac{\Phi(\Phi+1)}{\sqrt{2\pi(3\Phi+4)(\Phi+2)}}\frac{T_e}{e\sqrt{\rho_d a\lambda}},$$

where $\Phi = -Ze^2/aT_e$ is the dimensionless potential of a dust particle carrying the charge Z (in units of the electron charge), e is the elementary electric charge, a is the dust particle radius, T_e is the electron temperature, ρ_d is the particle material density, and λ is the ion mean free path with respect to the collisions against gas atoms.

The calculation of sound velocities and damping rates for different three-dimensional complex plasmas both in ac and dc discharges demonstrates a good correlation with experimental data that are within the limits of validity of the theory. Note that the calculation using well-known formula of Ref. [3] contradicts experimental data. The theory provides interpretation for the observed independence of the sound velocity on the coordinate and for a weak dependence on the particle diameter and gas pressure. Predictive estimates are made for the ongoing PK-4 experiment.

1. Zhukhovitskii D. I., Molotkov V. I., Fortov V. E. // Phys. Plasmas. 2014. V. 21. No. 6. P. 063701.
2. Zhukhovitskii D. I. // Phys. Rev. E. 2015. V. 92. No. 2. P. 023108.
3. Rao N. N., Shukla P. K., Yu M. Y. // Planet. Space Sci. 1990. V. 38. No. 4. P. 543.

MELTING OF SMALL YUKAWA SYSTEMS STUDIED WITH THE HELP OF THE DYNAMIC ENTROPY

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The small systems of interacting particles are actively studied in various fields of science and technology, including nanoengineering and materials design. One of the most interesting and important questions about the properties of small systems is the exploration of their phase states and phase transitions. But the classical thermodynamical approach is inapplicable for this problem.

In this case, methods of analysis of dynamical systems appear to be very effective; in particular, the "dynamic entropy", the concept introduced by Shannon and later developed by Kolmogorov and Sinai. The value of the dynamic entropy decreases when the system orders, and its exploration of the phase space becomes more difficult. In this work we use the simple approach for the estimation of the dynamic entropy, which can be easily applied for the analysis of the experiments and for the numerical simulation – the mean first-passage time, "MFPT dynamic entropy".

In present work, the results of the experimental and numerical study of the dynamics of two-dimensional systems consisting of 7 and 18 particles interacting via the Yukawa potential is presented. Experiments on the melting of quasi-two-dimensional structures of polystyrene dust particles were carried out in RF discharge in argon. To simulate the obtained systems we used the molecular dynamics method with the Langevin thermostat.

We have obtained the dependences of the dynamic entropy for the various values of the kinetic temperature of particles in the simulated systems and for the various magnitudes of the "heating" laser power in experiments. Three phase states of the considered small systems are registered: crystal, liquid and transitional. The mechanism of phase transitions in the systems under study is described.

The suggested technique of the analysis of the system dynamics can be applied to the structures as small as desired.

SOLID-LIQUID PHASE TRANSITIONS IN 2D- AND 3D–YUKAWA SYSTEMS

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Melting of face-centered cubic (fcc), body-centered cubic (bcc), 3D-lattices and the hexagonal primitive (hp) 2D-lattice was studied analytically and numerically for the systems with the Yukawa pair interactions. The Lindemann parameter, the coupling parameter and the density of the thermal fluctuations of pair forces have been obtained near the melting lines of Yukawa systems for a wide range of their parameters. Characteristic frequencies and internal energy densities in crystal lattices were estimated within the framework of the nearest-neighbour approximation, and the amplitudes of the oscillations of particles in the nodes of the lattice were evaluated with the help of Lindemann parameter on the melting lines of the systems under study.

New analytical approaches, taking into account the influence of nonlinearity (anharmonicity) of the pair interaction forces, for the determination of equilibrium melting curves and thermal fluctuations of the electric field, are proposed. It is necessary to emphasize that both the numerical and theoretical data on the density of the thermal fluctuations for pair forces in the Yukawa systems have been received for the first time.

On the basis of the developed theoretical model new analytical approximation for the melting phase curves also has been obtained for solid-liquid transitions in the fcc-, bcc- and hp- lattices for the Yukawa systems. Unlike existing approximations, the proposed approach does not lean upon the empirical fitting of numerical data by an arbitrary polynomial functions and/or on the semi-empirical models, and can be used for the analysis of the melting conditions with the changes of interparticle interactions in a wide range of the screening parameters.

We have to note that the scope of proposed approach is not limited by considered Yukawa systems. The presented model may be easily adapted for a wide range of systems with various isotropic potentials and may be useful for determinations of solid-liquid phase curves in 2D- and 3D-systems and for estimations of fcc-bcc-liquid triple point in 3D, too.

ON FEATURES OF PHASE TRANSITIONS IN MODELS OF DUSTY AND COLLOID PLASMAS

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Some features of melting curves and fluid-crystal phase transitions in dusty and colloid plasmas are under discussion. The base for a consideration is a well-known phase diagram of dusty plasma [1] for an equilibrium charged system with the Yukawa potential in its standard representation in $\Gamma - \kappa$ plane (Γ is the Coulomb non-ideality parameter, κ is the dimensionless Debye screening parameter). This phase diagram is presented for a repulsive one-component Yukawa system in ordinary density–temperature plane. A melting curve is also presented for this system in temperature–pressure plane. There are some density gap estimations. Both of them are based on a hypothesis of similar melting properties in a Yukawa system and a Soft Sphere system. The phase diagram [1] is also plotted for two one-temperature models of complex plasmas in density–temperature plane. Here simplified variants of complex plasmas models are considered as a thermodynamically equilibrium ensemble of classical Coulomb particles: a two-component electroneutral system of macro- and microions ($+Z$, -1) and a three-component electroneutral mixture of macro-ions and two kinds of microions ($+Z$, -1, +1). The phase regions of the three states of the system (fluid vs. bcc and fcc crystals) from the phase diagram are reconstructed in a density–temperature plane [2]. The resulting phase diagram in the logarithmic $\ln n - \ln T$ plane has a form of a linear combination of crystalline and fluid zones separated by the boundaries $\Gamma = \text{const}$. Parameters and locations of these zones are analyzed in dependence on the intrinsic parameter of the model—macroion charge number Z. Questions of thermodynamic stability and an existence of an additional phase transition gas-liquid are also discussed. There are huge negative pressure and negative compressibility areas in the phase diagram [1] if one uses equations of state [1] and [3]. There is also an analytical approximation of an additional splitting of all phase boundaries in the three-component model ($+Z$, -1, +1) because of so-called non-congruence of all phase transitions.

1. Hamaguchi S., Farouki R. T., Dubin, D. // Phys. Rev. E. 1997. V. 56. P. 4671.
2. Martynova I. A., Iosilevskiy I. L. // J. Phys. Conf. Ser. 2015. V. 653. P. 012141.

3. Khrapak S.A., Khrapak A.G., Ivlev A.V., Morfill G.E. // Phys. Rev. E. 2014. V. 89. P. 023102.

DUSTY PLASMA IS UNIQUE OBJECT OF COLLISIONAL PLASMA

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Dusty plasma is an ionized gas containing particles of condensed matter. The dust subsystem can be characterized by different aggregate states - gaseous, liquid and crystal, which allows to explore the processes in the system on the kinetic level. Dusty plasma is widespread in nature and is widely used in the production. The openness and self-consistency of dusty plasma system, inconstancy of dust particles charge and the dependence of the charge on the parameters of the environment, high dissipation and significant influence of stochastic processes, the observed self-organization, as well as easiness of preparation and monitoring of the system in a wide range of parameters and conditions make it a unique object of collisional plasma and open up great opportunities for the study of such complicated self-consistent system. These properties lead to a number of unique phenomena which are observed only in dusty plasmas among examples of collisional low-temperature plasma.

1) The average kinetic energy of dust particles can exceed the electron, ion temperature and neutral gas temperature, and may reach thousands of eV, in particular, the formation of the ordered structure of the dust particles the average kinetic energy can be close to several eV.

2) Dust plasma in vitro is observed in a gas discharge under gravity, resulting in anisotropy and separation into vertical and horizontal subsystems. The average kinetic energy of vertical and horizontal motion can vary significantly, but each of them has normal distribution and may be considered as in partial equilibrium.

3) Application of the thermodynamic approach to the description of dusty plasma properties is severely restricted due to principle of openness, non-equilibrium and anisotropy of dust particles subsystem. The strict limits of applicability of this approach are necessary for a thermodynamic description of the dusty particles subsystem.

4) The anisotropy of the system leads to mechanism of energy transfer between the vertical and horizontal movement of dust particles. This mechanism is based on the phenomenon of parametric resonance. The col-

lisional low-temperature plasma is the first time the appearance of parametric resonance.

5) The fluctuations of the surrounding plasma lead to dust particle charge fluctuations which influence the dynamic properties of the dust subsystem. The dependence of the charge on the distance from the electrode and the position of other charged dust particles results in a strong self-consistency of the system and points to the necessity of taking into account the collective effects. Many-particle interaction potential is dependent on the position of the electrode system by the fluctuating parameters and dust subsystem.

6) The special properties of dusty plasmas are well manifested at cryogenic temperatures, but technological difficulties for a long time hindered the progress of work in this direction. Significant reduction of the screening length due to cryogenic temperatures greatly reduces the distance between the dust particles and leads to a unique structure, such as the formation of dense luminous dust particles structure at a temperature of about 4K.

7) The transport processes in the dust subsystem are affected by the anisotropy of the system and the fluctuations of the particle charge.

These unique phenomena and properties of dusty plasmas are considered in this work with account of dust particle charge fluctuations and features of discharge sheath.

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PARAMETRIC RESONANCE IN DUSTY PLASMA

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Phenomenon and mechanisms of an energy transfer between degrees of freedom of a dusty plasma system are of great interest in the field of dusty plasma. One of such mechanisms is based on parametric resonance [1]. Initial stages of such phenomena can be described by the extended Methieu equation [1]:

$$\ddot{x} + 2\lambda\dot{x} + \omega_0^2\,(1 + h\cos\omega_p t) = \eta(t), \qquad (1)$$

Classical Mathieu equation is studied for $h \ll 1$, $\lambda = 0$ and $\varepsilon = \omega_p - 2\omega_0/n \ll \omega_0$ on the level of the first order of accuracy [2]. Acting by

an analogy with [2] and using averaging over an ensemble of distributions of $eta(t)$, an expression for the growth rate of the amplitude s can be obtained. Resonance occurs near $\omega_0/\omega_p = n/2$ in such case. Results obtained this way are close to ones obtained numerically only for small parameters. This range of parameters is too small to describe standard laboratory dusty plasma experiment.

Using numerical approach resonance regions, growth rate of the amplitude and time of the onset are obtained for a wide range of parameters, corresponding to laboratory experiment. Results obtained this way shows that for $h > 2$ resonance occurs not only when ω_0/ω_p is close to $n/2$, but for almost any $\omega_0/\omega_p > 0.35$. A wide spectrum of dust particles oscillations is also observed in a standard laboratory dusty plasma experiment [3, 4]. Such result shows that a significant part of the spectrum of dust particles oscillations can be involved in the energy transfer between vertical and horizontal motion of dust particles.

Equations describing curves on which growth rate of the amplitude is maximal for each fixed value of h are obtained for various resonance regions.

These results are in agreement with series of experiments [3, 4] and describe energy transfer in dusty plasma more accurate.

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1. Norman G. E., Timofeev A. V. //Phys. Rev. E, 2011. 84, 056401.
2. Landau L. D. and Lifshitz E. M. // Theoretical Physics. Mechanics 1959. London. Pergamon.
3. Vasilyak L.M., Fortov V.E., Morfill G.E. et al. // Contributions to Plasma Physics. 2011. 51. 529–532.
4. Ichiki R., Ivanov Y., Wolter M., Kawai Y. and Melzer A. // Phys. Rev. E. 2004. 70. 066404.

SIMULATION OF PLASMA WITH DUST-VOID IN A NEON DC DISCHARGE

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The parameters of plasma of neon dc discharge with dust-void were numerically simulated. The simulation was based on the drift-diffusion model of the uniform glow discharge positive column in neon with dust

particles [1]. Neon plasma was simulated with regard of stepwise and chemo-ionization processes. The formation, drift, diffusion and losses of electrons, ions and metastable neon atoms were considered in plasma bulk, on the discharge tube walls and on the dust particle surface [2]. The electron temperature and transport coefficients were calculated using the electron Boltzmann equation solver BOLSIG+ [3]. The distribution of dust particles in the discharge was set by a step function with a cavity inside, corresponding to the void radius, and the concentration of dust particles was close to that observed in experiments [4]. The charge of the dust particles was calculated taking into account the ion-atom collisions in the approximation of CEC (collision enhanced collection) [5], and the flow of excited atoms on the dust particles was in the gas-kinetic approximation. The radial distributions of plasma components, the radial and longitudinal components of the electric field are calculated. Calculations were carried out with close to the experimentally obtained [4] values of the discharge parameters corresponding to the transformation of homogeneous dust structure to the structure with dust-void. The significant difference of the discharge parameters with and without dust particles was presented.

1. Vasilyak L. M., Polyakov D. N., and Shumova V. V. // Contrib. Plasma Phys. 2013. V. 53. P. 432.
2. Shumova V. V., Polyakov D. N., and Vasilyak L. M. // Plasma Sources Sci. Technol. 2014. V. 23. 065008.
3. Hagelaar G. J. M., and Pitchford L. C. // Plasma Sources Sci. Tech. 2005. V. 14, 722.
4. Shumova V. V., Polyakov D. N., and Vasilyak L. M. // Prikladnaya Fizika (Applied Physics). 2015. No. 4. P. 27.
5. Dyachkov L. G., et al. // Phys. Plasmas. 2007. V. 14. 042102.

DESCRIPTION OF PARTICLE HEATING IN NONRECIPROCAL SYSTEMS.

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Most of the papers devoted to the analysis of dynamic and structural properties of many-particle systems deal with classical reciprocal pair interactions. There is a variety of cases when the action-reaction symmetry is broken and the interparticle interaction becomes nonreciprocal [1]. The

phenomenon is now widely investigated in colloidal and complex plasma systems.

A laboratory complex plasma is a good experimental model for studying nonreciprocal processes on a kinetic level. Interaction between grains in plasma may be substantially nonreciprocal for grains immersed in streaming plasma (because of the ion focusing effect) [2], and also for grains with the different size or surface temperatures due to the neutral shadowing forces (of Lesage type) [3]. (Note that unlike the case of a reciprocal interaction, Newton-s third law is not satisfied for a nonreciprocal interaction.)

We present a theoretical model for the description of the heating mechanism and the redistribution of kinetic energy in a system of particles with nonreciprocal interactions that occur in disperse systems of different nature [4]. To verify the theory, we carried out the numerical simulation of two-particle systems with a nonreciprocal quasi-dipole-dipole interaction that is similar to the interaction due to the effect of ion focusing in a laboratory complex plasma under experimental conditions. The model allows not only to explain the "anomalous heating " for grains in laboratory RF discharges, but also to predict a difference in kinetic temperature of particles in the system while going down in the direction of ion flow, as well as a uniformity of kinetic energy redistribution between the degrees of freedom.

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1. Ivlev A. V., Bartnick J., Heinen M., Du C. R., Nosenko V. and Lowen H. //Phys. Rev. X. 2015. V. 5. P. 011035.
2. Lampe M., Joyce G. and Ganguli G. //IEEE Trans. Plasma Sci., 2005. V. 33. P. 57.
3. Ignatov A. M. //Phys. Usp. 2001. V. 44. P. 199.
4. Vaulina O. S., Lisina I. I., Lisin E. A. //EPL. 2015. V. 111. P. 50003.

NEW SPACE EXPERIMENT PLASMA KRISTALL-4 ON BOARD THE ISS. FIRST SCIENTIFIC RESULTS

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From 1 to 5 June 2015, the Russian-European scientific apparatus Plasma Kristall-4 (SA PK-4) at the European space laboratory module Columbus of the International Space Station was operated in a test mode

to check their functionality. From 25 to 30 October, the first series of scientific experiments was performed. The experiments have been performed by Russian cosmonauts Gennady Padalka and Oleg Malenchenko. The SA PK-4 is intended for investigation of fundamental properties of strongly coupled dusty plasma under microgravity condition. The apparatus was developed since 2005 in close cooperation between scientists of the Joint Institute for High Temperatures of RAS and scientists of the Max-Planck-Institut fr extraterrestrische Physik in Garching (Germany). In 2013, an agreement between Roscosmos and the European Space Agency on joint operation of the PK-4 laboratory on the ISS has being signed. The first Russian-European Plasma Kristall - 4 space laboratory finally was delivered to the International Space Station (ISS) on October 29 2014 by the transport ship Progress M25-M. In this presentation the next topics will be reported: the goals and objectives of the new space experiment PK-4, the main parameters of the PK-4 equipment, features of the organization of international work scheduling, and main results of the scientific experiments performed in 2015.

PROJECTILE MOTION IN STRONGLY COUPLED BINARY DUSTY PLASMA

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We report on the investigation of a collective phenomena caused by the motion of a large particle (projectile) in a dust cloud in complex plasma of low-pressure gas discharge under microgravity conditions. If two types of particles with different radii are injected into the RF discharge then a binary system is formed. Due to the size dependence of the main forces acting on the particle, the system reveals a tendency toward phase separation. In the steady state, the smaller particles surround a void while the larger ones find themselves at larger distances from the void.

A slowly moving projectile in a dust cloud is situated in the center of a cavity. The radius of a cavity is defined by the relation [1] $R_c = (Z_p^2 e^2/8\pi p_{\rm st})^{1/4}$, where $Z_p = a_p T_e \Phi_p/e^2$ is the projectile charge in units of the electron charge, a_p is the projectile radius, T_e is the electron temperature, $\Phi_p \simeq 2$ is the dimensionless potential of a projectile, e is the elementary electric charge, and $p_{\rm st} = (\pi/32)(en_i\lambda_{in})^2$ is the static pressure of the particles in a dust cloud. Here, n_i is the ion number density and λ_{in} is the ion mean free path with respect to the collisions against

gas atoms. Since R_c is independent of the dust particle radius, its values on both sides of a boundary between the components of a binary system must be equal. For our experiment, $p_{\rm st} = 1.2 \times 10^{-6}$ Pa, which is close to the estimate based on the cavity deformation threshold [2]. For a very large projectile of the radius $a_p = 0.05$ cm, $n_i = 2.2 \times 10^9$ cm^{-3}, and $n_d^{-1/3} = 0.042$ cm (n_d is the dust particles number density) we obtain a theoretical estimate for the cavity radius $R_c = 0.27$ cm, which is close to the experimental value of 0.28 cm on both sides of a boundary.

The work is supported by the program of the Presidium of the RAS "Thermal physics of high energy densities".

1. Zhukhovitskii D. I., Molotkov V. I., Fortov V. E. // Phys. Plasmas. 2014. V. 21. No. 6. P. 063701.
2. Zhukhovitskii D. I., Ivlev A. V., Fortov V. E., Morfill G. E. // Phys. Rev. E. 2013. V. 87. No. 6. P. 063108.

INVESTIGATION ON MICRON-SIZED PARTICLES MANAGEMENT BY THE ALTERNATING ELECTRIC FIELDS

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The paper presents the simulation and experimental results of the control of charged micron sized particles dynamics in the linear Paul traps in stationary gas medium and in the gas flow at atmospheric pressure. For the first time the capture, confinement and removal of charged particles in a linear Paul trap has been experimentally confirmed at atmospheric pressure in gas flows. The regions of the particle, linear Paul trap and gas flow parameters needed for microparticle confinement have been obtained and experimentally tested. Also several non-linear effects were found experimentally: end trap effect of particle locking inside the trap, self generated waves in captured structure of charged particles.

The work was supported by the program of the fundamental research of Presidium RAS 1.13P.

COMPETITION OF ROTATION MECHANISMS OF COMPLEX PLASMA IN THE STRIATION OF GLOW DISCHARGE IN A MAGNETIC FIELD

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Dynamics of the dust structures created in striations in the glow discharge in the magnetic field has the complex character which is shown in inversion of the direction of the movement. The hypothesis of existence of eddy current in the striation which in the magnetic field causes the rotation of dust structures by means of Ampere force in addition to the ion drag force is offered and developed in the recent works of Nedospasov et al and Dyachkov et al.

In the present work the experiment in which eddy current in various phases of striations is registered by means of the probing dust particles under the discharge conditions when the sharp standing striations are exist but ion drag suppressed is carried out. It is shown that for various discharge conditions and various magnetic fields the dragging by the rotating gas and the ion drag are the dominating forces defining the dynamics of dust structures in striations.

INVESTIGATION OF DYNAMICS OF DUST STRUCTURE FORMED IN THE AREA OF NARROWING CURRENT CHANNEL IN THE MAGNETIC FIELD

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In this work we investigate the dust structure, which is levitating in a glow discharge in the area of narrowing of the current channel formed by placing dielectric insert special form that stabilizes discharge, in the discharge tube. In our study we used two types of dielectric inserts and various dust granules, that forming a dust structures. It has been found that the structure has a form of a ring with a center coincident with the axis of the hole in the insert. In the external longitudinal magnetic field the dust particles are rotated with an angular velocity. The magnitude of the angular velocity of each particle depends on the radius at which the particle is located. The dependence of the angular velocity on the magnetic field at a fixed discharge current and the dependence of the angular velocity

on discharge current at a fixed value of the magnetic field are received. Finally, we discuss the possible causes of the rotation of the particles.

FORMATION OF COULOMB CLUSTERS OF DIAMAGNETIC DUST PARTICLES IN CUSP MAGNETIC TRAP UNDER MICROGRAVITY CONDITIONS

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Physical properties of strongly coupled Coulomb systems (SCCS) are of considerable interest in various fields of science and technology. Using SCCS of dust particles, one can investigate the processes of phase transitions, waves, and instabilities on kinetic level. For confinement and investigation of SCCS of dust particles, we propose to use a trap based on the known possibility of the levitation of diamagnetic bodies in a nonuniform steady-state magnetic field. For the investigation of Coulomb systems of diamagnetic (graphite) particles in cusp magnetic field under microgravity conditions the experimental setup with the region of stable levitation about 400 cm^3 and magnetic field gradient of 0.04 T/cm was produced. A cusp magnetic field is generated by two coils placed on the same axis, in which currents circulate in the opposite directions. Experiment "Coulomb crystal" were carried out onboard of International Space Station (ISS) with graphite particles with sizes of 100, 200, 300 and 400 μm. Particles placed in the middle of the replaceable container within a cylindrical glassy cell with a diameter of 52 mm and a height of 40 mm. Glassy cell filled with argon at atmospheric pressure. Charging of the particles was carried out using a central wire electrode of diameter 200 μm that passed along the axis of the cell. For the modifed experimental setup "Coulomb crystal" has developed a new set of four replaceable containers with advanced diagnostics. The maximum electric potential of the central electrode is increased to 150 V. The preliminary analysis of the experiments allowed us to determine the formation of large Coulomb cluster of graphite particles in the magnetic trap. A number of particles in the cluster were about 10^3. Observed the formation of chain-like structures of graphite particles. Chains are formed by the action of the polarization forces. As a result of redistribution electric charge along the chain and accumulate it on a few particles Coulomb explosion occurs, leading to a break of the chain. We performed MD simulation of the clusters in the cusp magnetic trap. Found that

clusters with only a few particles retain a two-dimensional configuration, becoming three-dimensional as the number of particles increases.

EXPERIMENTAL STUDY OF THE ORDER PARAMETER SUSCEPTIBILITY IN TWO-DIMENSIONAL DUSTY PLASMA SYSTEMS

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There are a few standard methods for two-dimensional melting process research, which are commonly used. The most generally employed method is an analysis of the shape of pair and bond-angular correlation functions, which has strict limitations on the number of observed particles and the degree of uniformity of the studied systems. Often in laboratory experiments with dusty plasma, the formation of various irregularities, in particular the so-called domains, is observed, which can significantly affect the melting process in the two-dimensional non-ideal structures. In this regard, the study of global order parameters (translational and orientational) as well as order parameter susceptibility seems promising, since these parameters will vary appreciably even in the real experiments with dusty plasma structures with different structural pertubations, and they are suitable not only for extended monolayer structures, but also for systems with a small number of particles.

In our work we present the results of an experimental study of the global orientational order parameter and order parameter susceptibility as a function of coupling parameter of two-dimensional system, together with the number of free defects, occurring in the system during the melting. The experiments were provided with extended monolayer dusty plasma structures (consisted of 2500–3000 particles), formed in the near electrode area of RF gas discharge.

DUSTY PLASMA STRUCTURES IN DC GLOW DISCHARGE UNDER THE INFLUENCE OF NANOSECOND ELECTRIC PULSES

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Within researching processes of appearance of ordered structures and phase transitions in non-ideal dusty plasma the behavior of dust structures under the influence of nanosecond electric pulses in the DC glow discharge has been studied. The search of resonance effects, stabilization and precipitation of dust structures is carried out. Experiments of influence by nanosecond electric pulses with frequencies from 4 to 300 Hz were carried out. Basing on the analysis of the particle fluctuation amplitude the resonant frequency of 7.1 Hz was found out. The investigation of mechanism of particles fluctuations was of great interest. It was discovered that nanosecond impulses change the background plasma near the particle, and don't get an impact on the displacement of particles. In our previous experiments with the RF discharge a stabilization of particles was observed at a pulsed repetition frequency of 16 Hz. The similar experiment has been made in the DC glow discharge. The stabilization of self-excited fluctuations and waves was observed at frequency of pulses of 200 Hz. Such behavior of particles happens because the imposing of the capacitor nanosecond discharge forms an additional local ionization of plasma and artificial striation in which the dust cloud is stabilized. The further increase of a repetition frequency of nanosecond pulses caused the effect of precipitation of the particles. It was caused by the dusty plasma trap destruction.

The resonant frequency for a dust structure in the glow discharge was discovered experimentally. The effect of stabilization of dusty plasma structure was found out. The frequency at which a stabilization of the dust structure is fixed was defined. The method of separation of particles was offered.

The work is supported by the program of the Presidium of the RAS "Thermal physics of high energy densities".

LASER-INDUCED COULOMB EXPLOSION OF Al NANOCLUSTERS: WAVE PACKET MOLECULAR DYNAMICS

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The interaction of ultrashort laser pulses with nanoclusters has recently become a subject of interest due to efficient laser radiation absorption with an energy capture per atom much higher than for bulk material. In combination with small cluster sizes and low levels of energy losses, it allows to product nanoplasmas and high-energy particles.

Here we apply eFF potential [1] to calculate the properties of electronically exited Al nanoclusters. EFF is based on a simplified solution to the time-dependent Schrödinger equation with a single approximate potential between nuclei and electrons. It provides the combination of molecular dynamics with the methods of wave packet dynamics representing electrons as floating Gaussian wave packets and nuclei as classical particles.

We examine the mechanisms of Al nanoclusters ionization and explosion under different intensities and durations of laser pulse. For system sizes up to several thousand atoms, thresholds for cluster explosion are calculated. For laser intensities below the threshold, rate of electron-ion temperature equilibration in forming nanoplasma and its dependence on laser pulse duration is discussed.

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1. Su J., Goddard W., // Phys Rev Lett 2007. V. 99. No. 18. P. 185003.

HIGH ENERGY DENSITY PHYSICS RELATED TO INERTIAL FUSION WITH INTENSE ION- AND LASER BEAMS AT GSI AND FAIR IN DARMSTADT

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High Energy Density (HED) states in matter can be achieved by pulsed power deposition from intense laser or particle beams. GSI-Darmstadt presently provides the most intense heavy ion beam and a high power laser (PHELIX) for interaction experiments of laser plasma and ion beams. Approximately 200 scientists from 45 institutes and 16 countries worldwide are members of the HEDgeHOB [1] collaboration. They prepare novel experiments at FAIR (Facility for Antiproton and Ion Research) to study thermo-physical, transport, and radiation properties of HED matter, generated by the impact of intense heavy ion- and laser beams on dense targets. Paramount to the success of the research project is the development of cryogenic targets for the beam plasma interaction experiments proposed by the HEDgeHOB collaboration: HIHEX and LAPLAS for the FAIR-start phase. The progress of cryo-target production will be addressed in some detail. For the research topic in general plasma phenomena, phase transitions and equation of state properties of matter are of interest. The proposed experiments will explore the region of the phase diagram which is dominated by strongly coupled plasma and warm dense Matter (WDM). The current status of the FAIR and efforts of the HEDgeHOB collaboration to prepare for the experimental phase at FAIR will be discussed with emphasis on cryo-target development.

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1. HEDgeHOB Collaboration: http://hedgehob.physik.tu-darmstadt.de

NON-IDEAL PLASMAS CREATED IN LASER-MATTER INTERACTION

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Petawatt PHELIX-laser system at the Gesellchaft fur Schwerionenforscung GSI-Darmstadt is an important instrument for creation and investigation of a wide range plasma states, from ideal plasmas of intermediate densities and some keV temperatures up to so called Warm Dense Matter.

In this context, at the GSI, the variety of experiments on the generation of non-ideal plasmas by hohlraum generated X-rays [1], isochoric heating of mass limited solid targets by laser accelerated electrons [2] or creation of WDM using laser generated shocks [3] have been carried out using nanosecond and femtosecond laser pulses. In this research, the GSI-team has a strong experimental and theoretical support of the Russian collaboration [4], [5], [6].

Nowadays, one of the main activities is devoted to the development of secondary laser sources of energetic photons and particles for probing of high energy density (HED) matter. Current experiments on short pulse laser irradiation of nanostructured targets demonstrate up to order of magnitude increase of the soft and hard X-rays yields as well as energy and number of laser accelerated electrons and protons compared to laser irradiated flat foils.

1. Rosmej O. N., Suslov N. V., Martsovenko D. R., et al. // Plasma Physics and Controlled Fusion 2015. V. 57. No. 9. P. 094001.
2. Schoenlein A., et al. // Phys. Rev. Lett. 2015. Submitted.
3. Belikov R. S., et al. // Quantum Electronics 2015. V. 45. No. 5. P. 421.
4. Orlov N, Denisov O. B., Rosmej O. N., Vergunova G. // Journal of Russian Laser Research 2014. V. 35. No. 3. P. 119.
5. Vergunova G. A., Rosanov V. B., Denisov O. B., Orlov N. Yu., Rosmej O. N. // Plasma Physics Reports 2013. V. 39. No. 9. P. 755.
6. Kostenko O. F., Andreev N. E., Rosmej O. N., Schoenlein A. // Physics of Plasmas 2015. Submitted.

EXPERIMENTAL FACILITIES FOR PLASMA PHYSICS EXPERIMENTS AT FAIR

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In my presentation I will give an overview of the experimental facilities that will be available in the APPA cave at FAIR for plasma physics experiments, the current status of the planning of the facilities and the current timeline for their construction and commissioning.

LASER SOURCES OF HIGH ENERGY ELECTRONS AND HARD X-RAYS FOR CREATION AND DIAGNOSTICS OF NON-IDEAL PLASMAS

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Secondary sources of high energy particles and hard radiation, produced by the action of intense short laser pulses on different targets, are widely used for creation and diagnostics of nonideal plasma (Warm Dense Matter, WDM). The scientists of JIHT RAS are participating in the experiments at GSI with petawatt class laser system PHELIX aimed to creation of secondary sources for a preparation phase of the international project FAIR [1–6].

The different mechanisms of generation of the high energy electrons, which can be used as for diagnostics, so for creation of the Warm Dense Matter, are investigated and discussed [5–7].

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1. Kostenko, N.E. Andreev, O.V. Chefonov, A.V. Ovchinnikov, O.N. Rosmej, A. Schoenlein, J. Wiechula, P. Neumayer, and J.Jacoby. Characteristic X-rays from silver foils for backlighting of WDM. GSI reports (2012). p. 375.
2. Kostenko, N.E. Andreev. Simulation of the generation of the characteristic X-ray emission by hot electrons in a foil. Quantum Electronics 43(3) 237–241 (2013).

3. O.F. Kostenko, N. E. Andreev, O. N. Rosmej, and A. Schoenlein. Hot electrons and hard X-rays generation in the intense laser-solid interaction. Phys. of Plasmas (2016) submitted for publication.
4. M.E. Povarnitsyn, N.E. Andreev, P.R. Levashov, K.V. Khishchenko, D.A. Kim, V.G. Novikov and O.N. Rosmej, Laser irradiation of thin films: Effect of energy transformation. Laser and Particle Beams V. 31 (4), pp 663–671 (2013).
5. N. E. Andreev, L. P. Pugachev, M. E. Povarnitsyn, P. R. Levashov, and O. N. Rosmej, Electron acceleration at grazing incidence of an intense laser pulse. Rep. "High Energy Density Phys. with Heavy Ion Laser Beams", p. 49 (2014).
6. N. E. Andreev, L. P. Pugachev, M. E. Povarnitsyn, and P. R. Levashov. Electron acceleration at grazing incidence of a subpicosecond intense laser pulse onto the plane solid target. Laser and Particle Beams (2015) in press.
7. L.P. Pugachev, N.E. Andreev, P.R. Levashov. Generation of intense collimated electron beams under action of the PHELIX laser onto foam targets for diagnostics of WDM. 2nd European Advanced Accelerator Concepts Workshop. La Biodola, Isola d'Elba, September 13–19, 2015.

DIAMOND AND GRAPHITE PHYSICAL PROPERTIES UNDER TENSILE STRESS PRODUCED BY NANO- AND PICOSECOND LASER ACTION

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The experimental studies of spallation phenomena and dynamic mechanical strength of poly and monocrystalline diamonds and graphite at the influence on them of laser pulse with duration 70 ps are presented. It was realized the strain rate up to 10^8 1/s. In these experiments, we used the neodymium glass laser Kamerton-T (A.M. Prokhorov General Physics Institute., Russian Academy of Sciences) and PHELIX (GSI, Darmstadt, Germany) facilities. The basic radiation was transformed to the second harmonic with the wavelength of 0.527 microns and the laser pulse energy of 2.5 J. Irradiated spot on a target surface was of 0.3 to 3.7 mm in diameter. Then the maximum energy density of the laser radiation flux

in the focal area was 10^{14} W/cm2; the ablation pressure was up to 0.7 TPa. Samples polycrystalline diamond plate with a thickness of 140 to 400 microns were synthesized by chemical vapor deposition (CVD) in a microwave discharge (2.45 GHz) in the plasma-chemical reactor UPSA-100 (OOO Optosystems) in mixtures of CH4-H2-O2. It was used also a plate from the synthetic single-crystal diamond of type Ib, obtained by synthesis at high pressures. These polished plate (100) having a thickness of about 300 microns had commercial origin. The spall phenomenon was used to obtain data on the dynamic mechanical strength of the materials under study. In case of diamond it was reached the spall strength of 16.5 GPa. It was reached the value of the spall strength graphite 2.1 GPa, which is almost 20 times greater than the static strength of the graphite. A comparison of the dynamic strength of graphite with dynamic strength synthetic diamond was done. In some cases spallation was observed not only on the back side of the target, but also on its front surface. Morphology of the spall planes, studied using optical and scanning electron microscopes, showed decrease in the size of crystallites over the original diamond polycrystalline. The Raman spectroscopy revealed that in the area of spallation on the back side of the diamond target some of the crystalline substance goes in to graphite phase. In the spall crater for all the graphite samples Raman spectra is showing a very well recrystallized graphitic structure, with little disorder- with a better crystallinity compared to the pristine material.

DETERMINATION OF RECOMBINING LASER PLASMA PARAMETERS USING THE INTENSITIES OF He-LIKE ION RESONANCE LINES

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The invariance of plasma evolution equations under some transformations allows to model plasma jets interaction in astrophysical objects by plasma which is generated by laser systems during irradiation massive solid targets. Ionization state of expanding laser plasma is non-stationary in the most of cases. Such plasma is overcooled so it is recombining one. In this regard, development of the recombining plasma diagnostics methods is one of the directions in laboratory astrophysics.

Intensity ratios of resonance lines of He-like multicharged ions can be used for plasma diagnostics. Mentioned ratios can be calculated in terms of quasi steady-state approximation for the wide range of densities and temperatures. So plasma diagnosing can be held by comparing of ratios obtained from the real plasma spectrum and calculated values.

Calculations were carried out for F VIII ions. Intensity ratios are sensitive to the density in the range of 10^{16}–10^{20} cm^{-3} while the temperature ranges from 10 to 100 eV for ions. With help of them parameters of plasma jets created by nanosecond laser system ELFIE (Ecole Polytechnique, France) for astrophysical phenomenon modelling [1] were determined.

Obtained dependencies are quite universal and can be used for any recombining plasma containing He-like fluorine ions. Spectral lines of another He-like ions also can be used in case of another density range. Probabilities of atomic transitions in He-like ions should be scaled similar to H-like ions along the isoelectronic sequence. So, the method‘s sensitive to temperature and density regions should be shifted proportionally to $(Z_n - 1)^2$ and $(Z_n - 1)^7$ correspondingly.

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1. B. Albertazzi, A. Ciardi, M. Nakatsutsumi, T. Vinci, J. Beard, R. Bonito, J. Billette, M. Borghesi, Z. Burkley, S.N. Chen, T.E. Cowan, T. Herrmannsdorfer, D.P. Higginson, F. Kroll, S.A. Pikuz, K. Naughton, L. Romagnani, C. Riconda, G. Revet, R. Riquier, H.-P. Schlenvoigt, I.Yu. Skobelev, A.Ya. Faenov, A. Soloviev, M. Huarte-Espinosa, A. Frank, O. Portugall, H. Pepin, J. Fuchs // Science 2014. V. 346. P. 325.

PMMA SHOCK COMPRESSION UP TO 0.6 TPa

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The hypervelocity shock in a polymethylmethacrylate (PMMA) cylindrical central body was produced by an impact of a converging conical flyer plate. Unlike in the designs proposed in the 80's, a conical flyer plate was originating from initially cylindrical cavity liner in a cylindrical explosive charge, which was launched by a sliding detonation. Lithium fluoride single crystal window was used for registration of optical light emission during shock compression of PMMA to the pressures of 100–600 GPa. Recorded brightness temperature profiles at near infrared wavelengths were analyzed to evaluate shock compressibility of the investigated PMMA sample and window and to estimate the shocked PMMA temperature and specific heat capacity.

SHOCK COMPRESSION OF COPPER, IRON, ALUMINUM AND TITANIUM UP TO 1–2 TPa BY TWO–STAGE CONICAL EXPLOSIVE DEVICE

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A set of two–stage conical explosive compression generators was developed and realized. To increase the velocity of launching of copper liner, the layered second stage (sloyka) was used. Conical shape of liner was formed dynamically from cylindrical during acceleration by sliding detonation of main charge. Top parameters, achieved in PMMA central body was increased from $D = 21.4$ km/s (typical for one-stage device) up to $D = 29$ km/s. Now the pressures up to 1.2 TPa in Aluminium and 2.2 TPa in Copper is achievable.

Optical baselength technique with fiber-coupled detectors was used to measure time intervals and shock velocities. The first results of shock compressibility measurements for set of metals are presented, along with optical pyrometry data for shock standarts (quartz and sapphire).

HIGH FREQUENCY ELECTRIC FIELDS REGISTRATION IN DENSE LOW TEMPERATURE PLASMA

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Nowadays, experiments on the generation and study of the dynamics of plasma jets at the stand PF-3 (NRC "Kurchatov Institute") are performed. The measurement of their parameters can be useful to elaborate the physical model for astrophysical jets propagating for a giant distances [1]. Temperature and concentration of plasma as functions versus time are measured by electron-optic spectrochronographic method, including analysis of spectral line profile, in a variety of experimental conditions. Distinct dips and picks are observed in the spectroscopic line profile, if short time intervals ($\approx$ 0.1 mcs) from the streak record were extracted. They could be explained as an impress of low- and high-frequency microfields, exited in the plasma [2–4]. Such dips and peaks on the wings of spectroscopic line profile is a clear property of the Langmuir oscillations, that are characterized by a symmetry position from the centre of the line, like this occurs in our experiments. Langmuir oscillation frequency $\omega_{pe}[\mathrm{s}^{-1}] = \sqrt{4\pi N_e e^2/m_e} = 5.64 \cdot 10^4 \sqrt{N_e[\mathrm{cm}^{-3}]}$ is a function of the concentration N_e; here e is an electron charge and m_e is the mass of electron. To understand an origin of observed oscillations, we estimate the electric field level according to method based on the two measured parameters: the dip deviation from the line centre $\Delta\lambda_d$ and the half of dip width, which is calculated to the nearest peak position $\Delta\lambda^d_{1/2}$. For the typical experimental values of HeII 4686Å, namely, $\Delta\lambda_d = 7.7$Å and $\Delta\lambda^d_{1/2} \approx 1.2$Å at $N_e = 10^{16}$ cm^{-3}, the formula $\Delta\lambda^d_{1/2} = (7 \cdot 10^9 E_{HF}/\omega_{pe})\Delta\lambda_d$ from [4] gives the magnitude of HF electric field oscillation equal to $E_{HF} \approx 50$ kV/cm. This formula is valid in the strong HF electric fields exceeding the Holtsmark field, that is $E_{HF} > 2.6|e|N^{2/3} \approx 17$ kV/cm. In plasmas with a few particles in the Debye sphere, HF electric fields with such magnitudes could be a consequence of the common thermal fluctuations of the charged particles concentration. So, the oscillations are an equilibrium process that needs no additional reasons. Energetic level of the thermal noise can be evaluated from the [5] $(E_0^2/4\pi)/N_eT \approx 1/N_D$, where $N_D = N_e \cdot r_D^3 = 4 \cdot 10^8 \sqrt{T^3/N_e}$; r_D is Debye radius in cm, temperature is in eV and concentration—in cm^{-3}. The number of particles is $N_D \approx 50$, and the electric field tension is $E_0 \approx 50$ kV/cm for the plasma jet with elec-

tron temperature of 5 eV and concentration of 10^{16} cm^{-3}. The comparison of E_{HF} and E_0 points to the thermal origin of the Langmuir noise in the investigated plasma. The measurements of the spectroscopic line profile in polarized light, along and transverse to the symmetry axis, reveal the likeness of peaks and dips positions and magnitudes. This fact says about the space isotropy of the HF-noise and quasistatic electric fields in plasma jets, being one more argument of the thermal nature of the observed oscillations. This work was supported in part by the Russian Foundation for Basic Research (project nos. 14–02–00179, 14–29–06085).

1. Krauz V., Myalton V., Vinogradov V. et al. // Physica Scripta T161 (2014) 014036.
2. Griem H.R., Kolb A.C., Shen K.Y. // Phys. Rev. 1959.V.116. N.1. P.4.
3. Sholin G.V. // Dokladi AN USSR. 1970.V.195. P.589.
4. Oks E.A., Rantsev-Kartinov V.A. // Sov. Phys. JETP. 1980.V.52. N.1. P. 50.
5. Shafranov V.D. // Reviews of Plasma Physics. Consultants Bureau, New York, 1967. V.3. P.1.

CONTACT DIAGNOSTICS OF HIGH-CURRENT DISCHARGE CHANNEL IN HIGH PRESSURE GAS

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Diagnostics of high-current discharge in high pressure gas is very difficult task. Basic difficulties of diagnostics are connected to the high density of plasma. High gas pressure, shock waves and plasma radiation add challenging technical problems. Application of standard techniques is very limited.

Original electric and magnetic probes, working in condition of high current high pressure discharge with extreme heat and shock load, was designed and created. Results of experiments in hydrogen for discharge with current amplitude up to $1MA$, current rise rate $\sim 10^{10}A/s$, and at initial pressure up to $30MPa$ are presented. Previous experiment data using magnetic probe diagnostics had been presented in [1, 2].

Discharge was initiated by copper wire explosion. Discharge chamber was designed with axisymmetric geometry. Capacity of energy storage was changed. It was $1.2, 2.4$ or $4.8mF$. Charging voltage was varied from $1kV$ to $15kV$. Energy input was up to $300kJ$. Measurements of current density

and electric field in channel distribution had been carried out. Channel radius (current density) oscillations match electric field oscillations. According to the experiments the current channel radius was reduced with increasing initial gas density.

1. M.E. Pinchuk, A.V. Budin, V.V. Leontev, A.G. Leks, A.A. Bogomaz, Ph.G. Rutberg, and A.A. Pozubenkov. // Izvestija Vysshih Uchebnyh Zavedenij. Fizika, Special Issue High Current Electronics, v57, n12/2, p240, (2014).
2. M.E. Pinchuk, A.A. Bogomaz, A.V. Budin, V.V. Leontev, A.G. Leks, A.A. Pozubenkov and Ph.G. Rutberg. // Journal of Physics: Conference Series (JPCS): XXX International Conference on Interaction of Intense Energy Fluxes with Matter, March 1–6, 2015, Elbrus, Russia, (2015).

HYBRID MODEL FOR SIMULATION OF ULTRASHORT DOUBLE-PULSE LASER ABLATION OF METALS

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For simulation of sub-picosecond double-pulse laser ablation of metals, we develop a hybrid model that combines classical molecular dynamics and an energy equation for free electrons. For the description of the laser energy absorption, we apply the Helmholtz wave equation together with the wide-range coefficients of optical and transport properties of the electron subsystem. This gives possibility to correctly describe the second pulse absorption on an arbitrary profile of the nascent plasma plume produced by the first pulse. In this paper, we demonstrate that the integral absorption of the second pulse drastically increases with the delay between pulses, which varies in the simulation from 0 to 200 ps. As a result, the electron temperature in the plume increases up to three times with the delay variation from 0 to 200 ps. Thus the results of simulation resemble the previous experimental observations of the luminosity increase in the double-pulse irradiation for the delay interval from 100 to 200 ps. Besides, we disclose two mechanisms of suppression of ablation responsible for the monotonic decrease of the ablation crater depth when the delay between pulses increases.

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THEORETICAL AND EXPERIMENTAL STUDIES OF RADIATIVE AND GAS DYNAMIC PROPERTIES OF PLASMA IN EXPERIMENTS WITH LASER AND HEAVY ION BEAMS

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Mathematical modelling of radiative and gas-dynamic processes in substances at high energy density is carried out for experiments, where both laser and heavy ion beams are used. Important features of the theoretical model, known as the ion model (IM), which is used for quantum mechanical calculations of radiative opacity, are discussed. Reliability of (IM) results is tested with experiment, where measurements of X-pinch radiation energy yield for two exploding wire materials, NiCr and Alloy 188 were made. Theoretical estimations of radiative efficiency are compared with experimental results, and (IM) calculations agree well with the experimental data [1]. Subsequently, the theoretical approach was used for temperature diagnostics of CHO plasma target in combined laser - heavy ion beam experiments [2]. Joint radiative and gas-dynamic calculations are performed for comparison with experiment, where hohlraum radiation transmits through the CHO plasma target, and the share of absorbed radiation energy is compared with experiment [3]. Study of radiative properties of CHO plasma with little admixture of gold is carried out as well. A modern method for temperature diagnostics of high-Z element plasma in Z pinch is proposed and discussed.

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1. Orlov, N.Yu., Guskov, S.Yu., Pikuz, S.A., Rozanov, V.B., Shelkovenko, T.A., Zmitrenko, N.V., D. A. Hammer D. A. (2007). Theoretical and experimental studies of the rsdiative properties of hot dense matter for optimizing soft X-ray sources. Laser and Particle Beams. 25, pp. 1–9.
2. Rosmej, O.N., Bagnout, V., Eisenbarth, U., Vatulin, V., Zhidkov, N., Suslov, N., Kunin, A., Pinegin, A., Schafer,D., Nisius, Th., Wilhein, Th., Rienecker, T., Wiechula, J., Zhao, Y., Vergunova, G., Borisenko, N., Orlov, N. (2011). Heating of low density CHO-foam layers by means of soft X-rays. Nuclear Instruments and Methods A 653, p. 52–57
3. G.A. Vergunova, V.B. Rozanov, O.B. Denisov, N.Yu. Orlov, and O.N. Rosmej. Matematical Modeling of Gas Dynamic and Radiative Processes in Experiments with Use of Laser and Heavy Ion Beams. Plasma Physics Reports, 2013, Vol. 39, No. 9, pp, 755–762.

RAPID NON-EQUILIBRIUM CRYSTALLIZATION OF FLYING MOLTEN THIN SHELL CREATED BY FEMTOSECOND LASER ACTION

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Creation of surface nanostructures by an ultrashort laser pulses is used in many applications from nanophotonics (e.g., 2D photon crystals), plasmonics, and SERS to tribology, wetting, and medical applications (e.g., preparation of titanium implants). Created structures are very different depending on materials, pulse fluence, diameter of an illuminated spot, thickness of a film on substrate, and cohesive strength between a film and a substrate. We have developed a procedure to solve the problem using combination of numerical codes and physical approaches. In report the results and comparisons with experiments on gold films are presented. The procedure describes all stages. It starts with absorption of laser energy inside a laser spot. Electron-ion temperature relaxation and expansion of absorbed energy through electron subsystem from skin layer into a film are considered. To solve the two-temperature (2T) problem (initially after pumping electrons are hotter than ions) we need knowledge about 2T equation of state (2T EoS), 2T heat conduction (2T-κ), and coupling parameter. We apply the density functional theory (DFT) and corresponding quantum-mechanical simulation packages together with solutions of the kinetic equations to define these functions, see [1, 2]. Further these functions are used in a 2T one-dimensional (1D) hydrocode to describe response of a film and a substrate to a fast laser heating of an electron subsystem. In experiments the thin films on silica substrate are used as targets. Ultrashort laser pulse is tightly focused [3]. Our model describes separation of a film from substrate, melting, inflation of molten shell, cooling by the conductive heat transfer along a metal film, and recrystallization of a liquid metal as result of this cooling. Strong electron thermal transport in metal is described by a Monte-Carlo subroutine. This is important new achievement. The previous version [4] of the code doesn't include electron cooling. Our model explains many of the previously unclear experimental observations [3] (how the jets are formed, what are the reasons for formation of holes in a film, etc.). In our laser applications the small size of heated objects results in rapid cooling. Therefore we achieve the diffusion limited speed near 100 m/s of a crystallization process. Hydrodynamic ve-

locities are of the same order. Fast cooling and limited solidification speed transfer a crystallization process into highly non-equilibrium state, liquid metal is strongly overcooled (few hundreds degrees below melting temperature). Thus the liquid-solid transition zone is wide. The transition zone exists in conditions of strong inertial stretching of a freezing thin shell. Thus not only break-off in the liquid part of the shell may take place, but break-off of solidified film also takes place. Authors acknowledge support from the Russian Science Foundation (grant RSCF 14–19–01599).

1. Yu. V. Petrov, N. A. Inogamov, K. P. Migdal, JETP Lett. 97, 20 (2013).
2. Yu. V. Petrov, K.P. Migdal, N. A. Inogamov, V. V. Zhakhovsky, Appl. Phys. B 119, 401 (2015).
3. V. I. Emel'yanov, D. A. Zayarniy, A. A. Ionin, I. V. Kiseleva et al., JETP Lett. 99, 518 (2014).
4. N. A. Inogamov, V. V. Zhakhovsky, V. A. Khokhlov, JETP, 120, 15 (2015).

SINGLE PROTON ENERGY RELAXATION IN ELECTRON GAS IN STRONG MAGNETIC FIELD

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In the present paper relaxation of proton energy in ultracold electron gas was studied using molecular dynamics method. Energy relaxation was studied in the presence of strong magnetic field. Magnetic field magnitude was so strong that Lamoure electron radius was smaller than classical distance of minimal approach for charged particles. Calculations were performed for electrons densities of 10^8–10^9 cm^{-3}, magnetic field magnitudes of 1–3 Tesla, electrons temperatures 10–50 K, proton energies 100–300000 K. It was shown that axial and transverse to magnetic field direction proton velocity components are dumping with different rate when proton velocity became less or equal to electrons velocity. Estimation of proton energy in the moment of recombination with electron was made.

RESTORATION OF THE SUBMICROSECOND MEGAAMPERE CURRENT PULSE, FLOWING THROUGH THE TUBE

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In the installations ZR, Angara-5–1, PTS etc. the submicrosecond current pulse, generated in several sections, is transmitted to the coaxial section, containing the load. While transporting electric energy to the load by the magnetically insulated transmission line (MITL), the megaampere current pulse induces in the MITL the processes which lead to the energy losses [1–3]. Experimental measurement of the current flowing just through the load becomes difficult because of many effects which lead to current leakage in the MITL (electron beams, crowbar effects and so on).

To study the transmission properties of the MITL in extreme conditions we have to simulate the process of flowing of submicrosecond current pulse with a linear density of 1–3 MA per cm through the hollow tube with the wall thickness equaled to 1 mm. For closing the mathematical model we need to use the time dependence of the current flowing through the load, so we face the problem of restoration of its waveform. As inputs we use the electric field intensity, measured at the inner surface of the tube.

The problem was solved in [4] for the case when the tube thickness is comparable with the thickness of the skin layer, and assuming temperature and conductivity of material to be constant in time and through the tube thickness. We propose to subdivide the thick (compare with the thickness of the skin layer) tube mentally into the series of thin tubules, and solve the diffusion equation for the magnetic field for each tubule using Laplace transformation. The solutions for neighboring tubules are linking by the boundary conditions. We check the method by the test problems and comparing with experimental data obtained on Angara-5–1.

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1. Grabovskii E V et al. 2006 Plasma Physics Reports, 32 718
2. Bakshaev Yu L et al. 2007 Plasma Physics Reports, 33 259
3. Ananev S S et al. 2008 Plasma Physics Reports 34574
4. Bakshaev Yu L, et al 2004 Plasma Phys. Rep. 30 318

METALLIZATION OF MOLECULAR GASES (H_2, D_2, N_2, O_2) UNDER COMPRESSION AS A RESULT OF THE DISSOCIATIVE-PERCOLATION PHASE TRANSITION

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This work is devoted to research of processes of dissociation and metallization in dense molecular gases. In known experiments on compression of molecular hydrogen, deuterium, nitrogen and oxygen [1, 2], dissociation of molecules at low temperatures and existence of states with high, close to the minimum metal conductivity, caused by pressure are observed. In relation to hydrogen and deuterium we suggested an idea about an important role of the cohesive energy arising in dense gas of the atoms dissociated from molecules [3, 4]. Transition to metallic state has character of the first order phase transition, but essentially new type - dissociative-percolation dielectric-metal phase transition (metallization through dissociation). The calculations of cohesive energy for atomic nitrogen and oxygen have executed for the first time. The data for dense atomic N, O in literature are absent for the reason that this gases do not exist in the nature (as well as H, D considered by us earlier), but in the form of dissociated components can exist. Difficulties of such calculation for nitrogen and oxygen connected with the multivalences of the considered atoms. We used scaling ratios for energy of coupling of atoms of nitrogen, oxygen, etc. with electronic jellium of various density [5]. For calculation of functional connection of density of electronic jellium with a density of atoms well-known approximations of Hartree-Fock orbitals of an isolated atom used. Such approach well proved in embedded atom method. The dependence of cohesive binding energy of atomic nitrogen and oxygen density obtained. Using molecular-atomic model [3, 4], the equations of dissociative balance were solved; isotherms and adiabatic curves of shock-wave compression are calculated. Existence of dissociative-percolation phase transition of the first order in nitrogen and oxygen is convincingly shown. The comparative analysis of adiabatic compression curves for hydrogen, deuterium, nitrogen and oxygen is made. The conclusion about existence of dissociative-percolation phase transition in all considered gases and its influence on shock adiabatic curves is made.

1. Nellis W. J., Weir S. T. and Mitchell A. C. Phys. Rev. B. 1999. V. 59. 3434.
2. Nellis W. J. and Mitchell A. C. J. Chem. Phys. 1980. V. 73. 6137.
3. Khomkin A. L., Shumikhin A. S. JETP. 2012. V. 141. 101.
4. Khomkin A. L., Shumikhin A. S. JETP. 2014. V. 146. 518.
5. Puska M. J., Niemenen R. M. Phys. Rev. B. 1991. V. 43. 12221.

CONDUCTIVITY OF METAL VAPORS IN A CRITICAL POINT AND ITS VICINITY

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A few years ago we suggested a hypothesis that cohesive coupling of atoms remains up to some small, but gas vicinity of the vapor-liquid critical point and therefore the value of cohesive energy can use for thermodynamic calculations of parameters of the critical point. The hypothesis found high-quality confirmation in recent works on a super or near-critical fluid (SCF) - a state of substance near the critical point [1]. It appeared that SCF are inherent many characteristics of liquid and even a solid state (short range ordering). By means of the Helmholtz free energy, based on this hypothesis, critical parameters and binodal were calculated practically for all metals of the periodic table [2]. In this study the problem for calculation of conductivity of metals in a critical point and its vicinity within uniform physical model is considered (in a complex). Let's emphasize that conductivity cannot neither be obtained, nor to estimate by means of traditional thermodynamic approaches, i.e. using numerous laws of similarity, the law of corresponding states, a method of rectilinear diameter, etc. Calculations and the more so experimental data are practically absent (except vapors of alkaline metals and mercury). Being important value in itself, conductivity in a critical point supplements a traditional set of critical parameters and distinguishes vapor-liquid transition in vapors of metals from traditional transitions. The conductivity at the critical point can be called the fourth critical parameter in addition to the critical pressure, density and temperature. For calculation of conductivity it is necessary to know first of all concentration of conductivity electrons, speak about density of electronic jellium. Some ways of its calculation are considered: analytical, with use of scaling ratios [3], and also by direct calculations of electronic density in and out of Wigner-Seitz cell with use of approximations of Hartree-Fock orbitals for electrons of the isolated atom. Conductivity is calculated using

a Ridel-Ioffe formula. Connection of gaseous metal of Likalter and SCF for metals vapors is discussed. This work is performed with financial support of the Program of basic researches of Presidium of the Russian Academy of Sciences "Substance at the high energy density".

1. Brazhkin V. V. et al. // Usp. Phys.Nauk. 2012. V. 182. P. 1137.
2. Khomkin A. L., Shumikhin A. L. // JETP. 2015. V. 148. P. 597.
3. Puska M. J., Niemenen R. M. // Phys. Rev. B. 1991. V. 43. P. 12221.

FLUID-FLUID PHASE TRANSITIONS AT HIGH TEMPERATURES

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Two predictions are introduced in [1, 2]. The first one is "plasma phase transition". Current situation on the problem is discussed in [3]. The second prediction is a fluid-fluid-solid triple point on the melting line at high temperatures. It is discussed in this work. Such a triple point is observed experimentally first for selenium [4]. The nature of the fluid-fluid transition at the triple point is not discussed in [1, 2]. The authors [4] point to the semiconductor-metal transition. A review is presented of the subsequent experimental works where fluid-fluid phase transitions are observed at high temperatures with triple points at the melting line. Both lines of the phase equilibrium and separate points obtained are included. Data are given for different substances as Se, P, Sn, Bi, Te, S [5], Fe [6], Ce [7] and poly(4-methyl-1-pentene) melt [8]. Viscosity drops point to the structural character of the transition, whereas conductivity jumps remind of the plasma nature. The slope of the phase equilibrium dependencies of pressure on temperature and the consequent change of the specific volume, which follows from the Clapeyron-Clausius equation, are discussed. Particular attention is paid to warm dense hydrogen and deuterium, where remarkable contradictions exist between data of different authors [9–12]. $P(V,T)$ surfaces are presented and discussed for the phase transitions considered in the vicinity of the triple points. Particular attention is paid to cases of abnormal $P(T)$ dependencies on lines of phase equilibrium. In particular, a $P(V,T)$ surface is presented when both fluid-fluid and melting $P(T)$ lines are abnormal. Some new calculation results on optical properties of warm dense hydrogen in the region of the phase transition are presented.

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1. G.E.Norman, A.N.Starostin. // High Temp. 1970. V. 8. P. 381-408.
2. G. E. Norman, A. N. Starostin. // J. Appl. Spectr. 1970. V. 13. P 965-967.
3. G. E. Norman, I. M. Saitov, V. V. Stegailov. // Contrib. Plasma Phys. 2015. V.55. P. 215-221.
4. V.V. Brazhkin, R.N. Voloshin, S.V. Popova. // JETP Lett. 1990. V. 50, P. 424-428.
5. V.V.Brazhkin, S.V.Popova, R.N.Voloshin. // High Pres. Res. 1997. V. 15. P. 267-305.
6. V.N. Korobenko, A.D. Rakhel. // Phys. Rev. B. 2012. V. 85, 014208.
7. A. Cadien et al. // Phys. Rev. Lett. 2013. V110, 125503.
8. A. Chiba et al. // Phys. Rev. E. 2012. V. 85, 021807.
9. P. Loubeyre et al. // High Pres. Res. 2004. V. 24. P. 25-31.
10. V.E. Fortov, R.I. Ilkaev, V.A. Arinin, V.V. Burtzev, V.A. Golubev, I.L. Iosilevskiy, V.V.Khrustalev, A.L.Mikhailov, M.A. Mochalov,V.Ya. Ternovoi, M.V. Zhernokletov. // Phys. Rev. Lett. 2007. V. 99, 185001.
11. V. Dzyabura, M. Zaghoo, I.F. Silvera. // PNAS. 2013. V. 110, P. 8040-4.
12. M. D. Knudson et al. // Science. 2015. V. 348. P. 1455-1459.

URANIUM CRITICAL POINT LOCATION PROBLEM

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Great uncertainty (claimed already [1,2,3]) in our knowledge of high-T phase diagram and critical point parameters (CPP) for gas-liquid phase transition in uranium is under discussion. The point is extremely high discrepancy in theoretical estimations for uranium CPP, which are obtained in frames of different widely used variants of high-T extrapolation of known low-T thermodynamic properties for liquid uranium. The descrepancy is so high: Tc $\sim$ 6–14 kK, Pc $\sim$ 0.01–1 GPa that there is *no even one* valid version for uranium EOS theoretical model, which could describe selfconsistently all three empirically known constituents of liquid uranium thermodynamics, namely: thermal EOS (liquid thermal expansion, $\rho(T)$), caloric EOS (joint behavior for gas and liquid enthalpy, $H(T)$) and "entropic" properties (thermal behavior of Gibbs free energy). Possibility for strong violation of one (or more) semiempirical "rules", which are exploited traditionally for extrapolative estimations of CP parameters in metals, namely: (i) – convexity of gas-liquid phase boundary in

$\rho - T$ plane and accompanying "rectilinear diameter rule"; (ii) – linear behavior of saturation curve $Ps(Ts)$ in Arrhenius variables etc. Drastic change in nature and parameters for effective ion-ion interaction potential in liquid uranium on its way from triple to critical point (and further to atomic vapors) is discussed as hypothetical physical reason for such extraordinary violation of standard features for gas-liquid phase boundary in uranium. This strong variability for effective ion-ionic interaction (and subsequent non-ideality corrections) is claimed as fundamental reason for drastic difference in gas–liquid transition features for uranium (and other "bad" metals [2]) in comparison with gas-liquid boundaries in "simple" many-body systems like Lennard-Jones model etc.

1. Iosilevskiy I., in "*Phys. Matter under Extreme Conditions*" / Ed. by V. Fortov, Moscow, (1991) p.106.
2. Iosilevskiy I., Krasnikov Yu., Son E., Fortov V. *Thermodynamics and Transport in Non-Ideal Plasmas*, MIPT, Moscow, 2002, (in Russ); Fizmatlit, Moscow, 2016 (to be published).
3. Iosilevskiy I., Gryaznov V., *J. Nuclear Mater.*, **344**, 30 (2005); arXiv:1312.7584.

THE RESEARCH OF NON-CONGRUENT PHASE TRANSITIONS IN COULOMB SYSTEMS BASED ON THE MODIFIED MODEL OF THE BINARY IONIC MIXTURE

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A model of Coulomb non-congruent phase transition (NCPT) gas-liquid type with an upper critical point in modified model with no associations [1, 2] of a binary ionic mixture (BIM) on a homogeneous compressible ideal background (or non-ideal) electron gas was built in this work /BIM ($\sim$)/. The analytical approximation (EoS) of Potekhin and Chabrier [3] was used for describing the ion-ion correlations. The "linear mixture" approximation (LM—Linear Mixing Rule) was used for mixture properties. Phase equilibrium for the charged components was calculated according to the Gibbs-Guggenheim conditions [1], the equality of generalized electrochemical potentials. The series of calculations have been done for equilibrium values for the above described model. The detail features of the realization of non-congruent equilibrium in comparison with the simpler (standard) forced-congruent evaporation mode were traced.

The phase diagrams were built in $P-T-X$ coordinates with their different cross sections, including two-dimensional ("banana–like") structures of two-phase region $P-T$. The characteristic non-monotonic shape of caloric phase enthalpy-temperature diagram, similar to those obtained previously in the calculations of the non-congruent evaporation of reactive plasma products in high-temperature heating with the uranium-oxygen system [4] was also shown. The parameters of critical points (CT) line were calculated on the entire range of proportions of ions $0 \leqslant X \leqslant 1$ in different equilibrium modes, including two reference values, when CT of non-congruent evaporation coincides with two "end" points on the boundary of the two-phase region - a point of extreme temperature and extreme pressure, X_T and X_P. Remarkable behavior of isotherms within two-phase region have been reproduced for whole temperature range $0 \leqslant T \leqslant T_{max}$.The absence of azeotropic features was also shown in this work, and it is clearly demonstrated the low-temperature property of noncongruent gas-liquid transition—"distillation" , which is weak in chemically reactive plasmas [4, 5], and in contrast, is clearly seen in the exotic realization of noncongruent transition in superdense nuclear matter [6].

1. I. Iosilevskiy, in: Thermodynamics of non-ideal plasmas (Suppl. III-1), edited by A. Starostin and I. Iosilevskiy, Encyclopedia of Low-Temperature Plasma Physics (Fizmatlit, Moscow, 2004), pp. 349–428.
2. Iosilevski I., High Temperature **23**, 807 (1985); arXiv:0901.3535.
3. Ichimaru S., Iyetomi H., and Tanaka S., Phys. Rep. **149**, 91 (1987)
4. I. Iosilevskiy, Hyland G., Yakub E., Ronchi C. Int. Journ. Thermophys. 2001, 22, pp 1253
5. Iosilevskiy I., Gryaznov V., et al. Bulletin Russ. Acad. Sci. (Izvestia RAS), N5, 115 (2011)
6. Hempel M., Dexheimer V., Schramm S., Iosilevskiy I., Phys. Rev.,2013, C **88**, 014906

THE BINODALS CONSTRUCTION AND THE DETERMINATION OF THE CRITICAL POINTS FOR SOME METALS ON THE BASIS OF LOW-TEMPERATURE MEASUREMENTS DATA

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The technique to find the liquid-gas binodals and the critical point (CP) positions is offered. The non-analytical behavior in CP vicinity and the

Claoeyron-Clausius asymptotical behavior at low temperatures are taken into account. Present approach has given good agreement with the data for variety of non-metallic substances as well as for alkali metals and mercury, where the binodals and CPs are known from the measurements. Then the present approach has been applied for a number of metals (Al, Cu, Fe and Zr), where there are only low temperature measurements data are available. In particular, these data are the saturation gas pressures and liquid isobars. The accuracy of results obtained by this approach is acceptable for the measurements in the liquid region and especially for the gas binodal branch, where the density changes in several orders of the magnitude. CP estimates have been obtained as well. These new estimates were compared with the estimates of other researchers, known earlier. It seems that the present CP estimates are the most reliable among the others. The considered approach is simple enough and can be used for the other metals if the experimental data about the low temperature part of the binodals is available.

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