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The book consists of the abstracts of oral and poster contributions to the XIII International Conference on Physics of Non-Ideal Plasmas (September 13 — 18, 2009, Chernogolovka, Russia). The Conference continues a traditional series of meetings devoted to new theoretical and experimental results on the physics of dense non-ideal plasmas: Martzlow-Garwitz, 1980; Wustrow, 1982; Biesenthal, 1984; Greifswald, 1986; Wustrow, 1988; Gosen, 1991; Markgrafenheide, 1993; Binz, 1995; Rostock, 1998; Greifswald, 2000; Valencia, 2003; Darmstadt, 2006. The following questions are covered: statistical physics and mathematical modeling (including simulation) of strongly coupled Coulomb systems, equilibrium properties and equation of state of dense plasmas, kinetics, transport and optical properties of dense Coulomb systems, dense hydrogen, laser and heavy-ion-produced plasmas, dense astrophysical plasmas, phase transitions in plasmas and fluids, dusty plasmas.

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Contents

1 Statistical physics and mathematical modeling of strongly coupled Coulomb systems

1.1 Mathematical simulation of kinetic processes in the non-ideal nuclear-excited dust plasma of the noble gases

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The present report is devoted to the studying kinetic processes in the nuclear-excited plasma of the noble gases in which are injected the fine uranium (or its chemical compounds) particles.

More than 30 years passed since it was suggested to use such medium containing micro particles for converting of nuclear energy into optical radiation. Recently it has been shown, that application of the uranium nanoclasters or its chemical compounds for this purposes creates the new amplified laser radiation active medium excited by fission fragments of heavy nuclei. The main goal of this investigation is to determine possibilities of creation non-ideals dust plasma, containing nano- and micro-particles, and excited by fission fragments.

A new theoretical model for the mathematical simulation of the kinetic processes in dust plasma of helium gas was developed. System of equation for self-consistent description of the kinetic processes in the dust plasma of noble gas and for calculation properties for nuclear pumped media is derived. The self-consistent mathematical simulation of the kinetic process in the nuclear pump laser medium with the fine uranium particle admixture was performed at the first time.

A new algorithm for mathematical simulation kinetic processes in dust plasma of helium gas was developed. The main goal of the new model is including in consideration both, the multiply charged ions, as well as multiply charged fine particles. It was suggested that fine particles have spherical form with radii from 5 nm up to 0.2 μm. The plasma-chemical reactions with fine particles charged up to 40 electrons were considered.

It was shown that under typical conditions of the nuclear pumping the active laser medium may became non-ideal dust plasma.

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1.2 Diagnosics of dense plasmas via transport and optical properties

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Diagnostics of Coulomb systems in bulk as well as in clusters via transport and optical properties is investigated. In particular, deduction of plasma parameters from experiments on reflectivity, Thomson scattering, inverse Bremsstrahlung, electrical conductivity, and line shapes in the optical as well as in the X-ray regime are discussed.

Within a generalized linear response theory [1], transport and optical properties are described consistently including collision effects. Going beyond RPA for the dielectric function, the concept of the dynamical collision frequency, which is related to auto correlation functions, is applied. Collisions prove to be of relevance in strongly coupled plasmas.

For the evaluation of equilibrium auto-correlation functions at arbitrary coupling strength we apply MD simulation techniques for classical systems. Using pseudopotentials in order to mimic quantum effects, correlation functions are evaluated for bulk systems and finite clusters [2, 3]. We find a more structured frequency spectrum of plasma correlations in clusters indicating several collective modes. Size effects have been found for the damping of plasma oscillations [4, 5].

Alternatively, analytical calculations for quantum systems can be performed in the weak coupling region. The dynamical collision frequency for bulk systems is approximated using Pade approximations taking into account systematically and consistently limiting cases including strong collisions, dynamical screening, electron-electron interactions and effects due to partial ionization in the plasma state [1]. Results are discussed in comparison with MD simulations [2] and kinetic approaches [6] .

In conclusion, improving the RPA dielectric function, collisions prove to be of relevance in strongly coupled plasmas. In the context of the analysis of experiments, those can be seen as diagnostic tools for the free electron density in plasma systems. Further work is necessary for a more consistent description of frequency dependent properties of partially ionized plasmas.

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1.3 Calculation of canonical properties and excited states by path integral numerical methods

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Path integral Monte Carlo method in the expanded ensemble [1] is used for calculation of the ratio of partition functions for different classes of permutations [2] treating the problem of several interacting identical particles (fermions) in an external field. Wang-Landau algorithm is used for adjustment of balancing factors. The complete partition function and average energy is then obtained at finite temperatures down to their low values. Calculations were performed for systems of two and three particles with Coulomb repulsion in 1D and 3D harmonic and 3D Coulomb external fields [3, 4]. For systems consisting of greater number of particles we propose a new variant of our approach which implies calculation of the ratio of positive and negative contributions to the partition function.

Densities and energies of the sequence of excited states starting from the ground state for a system of non interacting quantum particles are calculated in turn, one by one, by means of considering systems with artificially excluded lowest energy levels and further obtaining of the "ground state" of each next system constructed in this way. These artificial systems are constructed with the aid of a recurrent sequence of propagators. It becomes possible to reproduce several tens of energy levels for the harmonic and other 1-dimensional potentials with a small expense of computer time The main advantage of this numerical approach is that it is not constrained to the sign problem for Fermi particles. It can also be extended to 2- and 3-dimensional potentials [5, 6].

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1.4 Investigation formation of charge and of energy spectra of multiply charged ions, generated under the action of laser radiation on the surface of two-element targets Tm_2O_3, Yb_2O_3 and Eu_2O_3

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In continuation of our study of two-element laser-produced plasmas [1] we performed experiments on heavier elements targets (Tm_2O_3, Yb_2O_3, Eu_2O_3). The reason for the choice of these elements is that, although these differ considerably in mass, they have similar thermo physical parameters like conductivity, melting temperature, heat capacity, ionization potential etc. Experiments are carrier out in a laser-mass-spectrometer and we constructed energy spectra of ions on the base of obtained time-of-flight (mass-charge) spectra. Experimental results shows that oxygen ions with charge Z=1, 2 are located in a low energy part of the spectra and Tm, Yb and Eu ions are in larger energy part of the spectra. Energy spectra of Tm ions are shifted to larger energies as compared to energy spectra of Eu ions. We found that characteristics of energy spectra (the maximal energy E_{max}, width of the energy spectra) of light O^{1+} and O^{2+} ions strongly depend on the mass of the second component of the target: for a given intensity of the laser radiation the maximal width (i.e. the maximal energy) of energy spectra of single charged oxygen ions is obtained for the case of Yb_2O_3 and the minimal width is obtained for Tm_2O_3. The maximal energy of O^{2+} ions does not depend on the mass of the heavy component of the target. However, a small dependence of energy distribution of O^{2+} ions on the nature of the target is found in a narrow energy range (60 – 120 eV), where recombination process is dominating. These dependencies vanish at small energy ranges (40 – 60 eV), where ionization process is dominating. Thus, the increase of the second component of the two-element plasma leads to the increased energy exchange between light (O) and heavy (Tm, Yb, Eu) ions and to the expansion of the energy spectra of light ions to larger energies. The mechanisms of formation of energy spectra of ions in two-element laser-produced plasma and experimental outcomes in scientific and applied aspects are discussed.

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1.5 Path integral Monte Carlo simulations of the equation of state of strongly coupled quark–gluon plasma.

[2]**Ivanov Y.B.**, [2]**Skokov V.V.**, *[3]**Filinov V.S.**, [1]**Bonitz M.**, [3]**Levashov P.R.**, [3]**Fortov V.E.**

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We develop a PIMC approach to the strongly coupled QGP which takes the Fermi (Bose) statistics of quarks (gluons) and quantum degeneracy selfconsistently into account. This method has been successfully applied to strongly coupled electrodynamic plasmas before. Examples are partially ionized dense hydrogen plasmas where liquid-like and crystalline behavior was observed. Moreover, also partial ionization effects and pressure ionization could be studied from first principles. The same methods have been applied also to electron-hole plasmas in semiconductors, including excitonic bound states, which have many similarities to the QGP due to the smaller mass differences as compared to electron-ion plasmas.

We present first exploratory PIMC simulations of nonideal quark-gluon plasma. The main goal is to test this approach for ability to reproduce the equation of state known from lattice data. To this end we use the simplest model of a QGP consisting of quarks, antiquarks and gluons interacting via a color Coulomb potential with several approximations for the temperature dependence of the quasiparticle masses. We report surprisingly good agreement with the lattice data for one of the parameter sets, which gives us confidence that the model correctly captures main properties of the nonideal QGP.

1.6 Phase diagram and crystallization in dipolar bosonic systems

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The relevance of strong many-body correlations in dipolar systems appeared in the last several years and considerably enlarged the interesting regimes of many-body physics now accessible with degenerate Bose/Fermi gases. The experimental realizations include tightly bound pairs of electrons and holes in coupled quantum wells, quantum gases of dipolar atoms and molecules.

We focus on the phase diagram and many-body properties of such systems when they consist of bosons. The thermodynamic properties are studied with the grand-canonical path integral Monte Carlo [1].

In the gas phase we analyze the normal-superfluid phase transition and determine the Berezinskii-Kosterlitz-Thouless transition temperature as a function of density. The equation of state, the acoustic phonon-dispersion curve (in the framework of QLCA [2]) and the sound velocity are also analyzed.

By tunning the dipole-dipole interaction we observe the quantum phase transition to a crystalline phase in a full agreement with the previous studies [3]. However, in contrast to a pure dipole crystal we predict melting of a crystal of dipolar excitons at high densities which originates from softening of the short-range part of the inter-exciton interaction due to Coulomb nature of the forces [4].

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1.7 Quantum Potential including Diffraction and Exchange Effects

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An ideal Bose or Fermi gas interacting with an impurity is represented by a classical fluid with effective particle-particle and particle-impurity quantum potentials. The quantum potentials are evaluated at weak coupling, leading to generalizations of the Kelbg potentials to include both diffraction and degeneracy effects [1]. This potential is compared with previous effective pair potentials.

Furthermore, a phenomenological extension to strong coupling is proposed which is based on the "improved Kelbg potential" [2] which is applicable to strongly correlated quantum plasmas via incorporation of exact short range effects. The resulting quantum potential is tested by comparison with Path integral Monte Carlo results as a function of degeneracy.

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1.8 Temperature Dependence of Density Profile for Confined Charges

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Equilibrium density profiles for charges in a harmonic trapping potential are studied, extending earlier work [1, 2] to finite temperatures T (inverse coupling Γ). Density functional theory provides a framework from which approximations are made. Here, correlations are approximated by the direct correlation function for a uniform OCP calculated in the hypernetted chain approximation. The inclusion of correlations yields a shell structure in the density profile at $T < 1$, in semi-quantitative agreement with Monte Carlo calculations and with $T = 0$ molecular dynamics simulations [3]. The characteristics of the shell structure, including size and charge population, are compared for these different approaches for $T \geq 10^{-2}$ and particle number up to $N = 1000$. Several ideas for a more accurate description of correlations in a non-uniform fluid are discussed.

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1.9 Semi-Classical Model of Strongly Correlated Coulomb Systems in Weak Magnetic Field

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The integer and fractional quantum Hall effects are two remarkable macroscopic quantum phenomena occurring in two-dimensional strongly correlated electronic systems at high magnetic fields and low temperatures. Quantization of Hall resistivity indicates the onset of a novel electronic quantum Hall phase of matter that generally stabilizes in the very high magnetic field regime at partial filling of the lowest Landau level. Other interesting phases that differ from the quantum Hall phases take prominence in weaker magnetic fields when many more Landau levels are filled. These states manifest anisotropic magneto-transport properties and, under certain conditions, appear to mimic charge density waves and/or liquid crystalline phases. One way to understand such a behavior has been in terms of effective interaction potentials confined to the highest Landau level partially filled with electrons. In this work we show that, for weak magnetic fields, such a quantum treatment of these strongly correlated Coulomb systems resembles a semi-classical model of rotating electrons in which the time-averaged interaction potential can be expressed solely in terms of guiding center coordinates. We discuss how the features of this semi-classical effective potential may affect the stability of various strongly correlated electronic phases in the weak magnetic field regime.

1.10 Ambipolar diffusion in non-stoichiometric ionic solids

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Non-stoichiometric solids usually contain crystallographic point defects that result in the excess or deficiency of an element. We consider the problem of computer simulation of the high-temperature behaviour of the fluorite-like ionic solids like UO_{2+x} or $Ca(Y)F_{2+x}$ whose elemental composition may deviate from stoichiometry. Since ionic solids are overall electrically neutral, defects are compensated by other ions in the solid, which change their charge (oxidation) state.

The excess charge-lattice coupling causes correlations between the charge position and the local lattice deformation associated to point defects. Such entities in ionic crystals are referred to as "small polarons". At low temperatures polarons have tendency to self-trap themselves in localized states, but at elevated temperatures their hopping became fast enough to affect ionic transport properties. Diffusion of charged anionic defects surrounded by opposite excess charges located on lattice cations is alike ambipolar diffusion of a complex neutral quasi-particle. Molecular dynamics (MD) simulations within ionic model [1] require an adequate formulation of the method, which allows imitation of the electron-phonon (or charge-defect) interaction responsible for the electronic disorder.

Recently we proposed [2] a high-temperature approximation, called "Free Hopping Approximation" (FHA). Within FHA the excess charge in the non-stoichiometric system hop freely from one ion to another, adapting the charge distribution in cationic system to the instant configurations of the anionic defects. In the present work, we propose an improvement of FHA accounting for existence of finite hopping barrier. In contrast to FHA, the improved hopping algorithm allows to instant jumping of the excess electrons/holes into positions of the neighbouring lattice cations, only when the kinetic energy of the initial cation is higher than the height of the hopping barrier and conditions of total energy and momentum conservation are fulfilled during hopping event. Effect of polaron hopping on diffusion was determined by the direct "switching-off" procedure.

Defects clustering and their ambipolar diffusion is studied and compared with existing experimental data in hyper- and hypo-stoichiometric uranium dioxide. We report the results of MD evaluation of the diffusion coefficients from T=1300 K to melting temperature at different stoichiometry and cell sizes ranging from hundreds to several thousands of ions.

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1.11 Interfacial Properties of the Strongly Coupled Imidazolium Ionic Liquids: a Molecular Dynamics Study

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Imidazolium ionic liquids are promising candidates for using in heterogeneous systems such as supercapacitors, fuel cells, solar cells, an operating efficiency of which is greatly influenced by the molecular structure of the electrode/electrolyte interface. However, the interfacial properties of such strongly coupled coulomb systems, composed of asymmetric bulky ions, are not well characterized.

This work reports the results from the molecular dynamics simulation of the ionic liquid [BMIM][PF_6] (with the nonideality parameter in the range of $\Gamma = e^2 n^{1/3}/(kT) \sim 60 \div 80$) on a graphite surface.

For the uncharged surface the temperature dependence ($300 \div 400$ K) of the interface structure and ions dynamics were investigated. It is shown that a near-graphite-surface ionic liquid has a layering structure, extending over ∼2 nm from the surface [1]. In the vicinity of the wall self-diffusion coefficients of ions correlate with the local ion density. From the free energy profiles it is revealed that ions absorption/desorption is a multibarrier activated process. The rate constants of cation and anion absorption/desorption was calculated.

The influence of the surface potential on the distribution of electrolyte ions and their orientation was studied. Increase in the electrode potential induces broadening of the angle distribution of adsorbed imidazolium rings and a shift of the most probable tilt angle towards bigger values.

In addition, the influence of the surface charge ($\pm\sigma$) on the volume charge density and electric potential profiles in the ionic liquid was determined. The differences in the cation and anion molecular structure result in the fact that potential profiles have an asymmetric form when the surface charges are equal in their magnitudes and opposite in sign.

A good agreement of the model predictions with experiments is obtained.

We would like to acknowledge the Joint Supercomputer Center of RAS for the computational resources placed at our disposal.

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1.12 Dynamic local field corrections for two-component plasmas

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The dielectric tensor is a key quantity in the analysis of dense plasmas. It is closely related to the (non-local) reflectivity, the absorption coefficient for electro-magnetic radiation, the generalized non-local collision frequency, and the dynamic structure factor. In non-ideal plasmas, the dielectric tensor has to be treated beyond the random phase approximations. Correlations as well as collisions have to be included. These corrections are known as (dynamic) local field corrections.

Two approaches to the dynamic local field correction are compared with each other. In the first approach we start from the Zubarev approach to linear response theory [1] and use perturbative techniques such as thermodynamic Green's functions to obtain the local field corrections. In this way, a systematic account of collisions as well as dynamical screening is implemented We generalize an one-moment treatment of Reinholz et al. [2] to higher moments including pair distribution functions. Going beyond earlier results, explicit expressions for finite values of the wave vector are presented. Furthermore, we compare to simpler Mermin-like expressions [3, 4]. In a second approach, we start from the recurrence relation technique of Lee [5] and establish an approximation which obeys the first- and third-order sum rules explicitly. Defining a truncation scheme for the continued fractions involved, we set up a non-perturbative approach to dynamic local field corrections of two-component plasmas.

Exploratory calculations are performed for impurity scattering in an electron gas at T=0 as well as a hydrogen plasma in the non-degenerate limit. For the electron gas, static local field corrections due to Farid et al. [6] are used in describing the interacting electron gas in the static limit.

The influence of collisions and correlations on the plasmon dispersion is investigated. With the help of the dynamic local field corrections, the dynamic structure factor of a hydrogen plasma at intermediate coupling and for non-degenerate conditions is determined. Implications for plasma diagnostics are discussed.

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1.13 Specific Features of Spallation Processes in Polymetylmetacrylate under High Strain Rate

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Direct laser interaction and laser-driven thin foils were used for investigation spallation phenomena in polymetylmetacrylate (PMMA) targets in case of high value of strain rates. In experiments the aluminium foils with thickness 8 and 15 μm were used as impactors. The laser-driven foils mass and velocity after laser ablation and acceleration were determined by the method of their deceleration in a gas atmosphere. On the basis of experimental data we measured the position of the spallation plane and the moment at which the spall layer arrived at an additional electrocontact sensor arranged beside of rear side of target. Then, the values of spall strength and strain rate were determined by the using numerical simulations with a hydrodynamic code with a wide-range semi-empirical equation of state of PMMA. As a result of experiments, we found in the first time that in case of strain rate varying from $1.5 \cdot 10^6$ to $6 \cdot 10^6$ 1/s the ultimate spall strength of PMMA (10 kbar) was achieved.

1.14 Transition of Electromagnetic Wave Through a Warm Overdense Plasma

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It is studied a high transparency condition of an overcritical warm plasma layer due to the excitation of the electromagnetic surface modes. This procedure requires evanescent incident waves on the plasma layer which here is prepared by placing two dielectric layer on the both sides of the plasma film. Corresponding consequences for a cold plasma is also discussed and a comparison between cold and warm plasmas is also made.

1.15 Coulomb systems' modeling under consideration of finite instrumental resolution scales

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Traditional description of plasma is based on one-particle kinetic equations for electrons and ions what implies that all coordinates of particle are considered as distinguishable. Long-range Coulomb interaction between particles is modeled by a mean field and collision integral.

Finite instrumental resolution scales restricts observer's ability to distinguish particles coordinates within these scales what results in plasma modeling based on distributions of *joint* probability that particles occupy a probing volume [1]. This *multiparticle* approach produces the description in terms of *fluctuations* of plasma parameters. The generated multiparticle models can be reduced under some assumptions to smaller dimensions but long-range interaction of particles does not allow us to linearize them to one-particle models in difference from the classical statistical theory.

Finite instrumental resolution scales' modeling is discussed in the paper (including Gibbs' paradox and a transition from a classical statistical integral to a quantum statistical sum) and demonstrated in application to solar plasma.

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1.16 Ionization cross section for strongly coupled hydrogen plasma with arbitrary ionization degree

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As it was shown in [1,2], it is very important to take into account the influence of plasma surrounding on the ionization process. The present work is aimed at the generalization of some previous results to the case of arbitrary ionization degree. The ionization cross section is calculated with help of pseudopotential model of plasma particles interaction, which takes into account correlation effects [3].

The electron impact ionization cross section is calculated from phase shifts of scattered and emitted electrons determined within the quantum mechanical approach in Born approximation [4, 5].

Comparison is made with the previous work, experimental data of [6] and suitable results represented in [7].

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1.17 Modeling of Dielectrics Bombardment with Swift Heavy Ions

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The process of nanostructuring as a result of swift heavy ions penetrating a solid or its scattering on a surface has attracted a lot of scientific interest for the last decade. Especially, possible applications of the heavy ion bombardment technique have spawned in IT- and Bio- technologies. The processes of fast energy deposition into the solid and its further dissipation, however, are essentially perturbed with highly excited and nonequilibrium state of both lattice and electron systems. Meanwhile, the precision in treatment of such processes as thermalization of electrons, fast electron heat conduction, and the phase transformation of the overheated solid becomes crucial when considering the mechanism of nanostructures formation. Having several computational techniques to handle the mentioned processes it is nevertheless difficult to describe all of them within a scale of a single physical model.

Our work is aimed on elaboration of the atomistic-continuum computational approach to study the formation of nanohillocks in the experiments on swift heavy ion Xe^{+} bombardment of $SrTiO_3$ [1]. The combined computational approach includes the description of fast ion energy deposition by Density Functional Theory [2], continuum description of the electron heat conduction and the electron-phonon energy transfer with Two Temperature Model [3], and nonequilibrium phase transformation at atomic level with Molecular Dynamics [4]. An advanced Ewald summation method is used to account for long range Coulomb interactions represented by ionic two body potential [5]. The resulted atomistic-continuum model is outlined and applied to study nonequilibrium phase transformations induced by a heavy projectile of high energy.

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1.18 Collective mode dispersion in a two-dimensional quantum dipole system

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Combining path integral Monte Carlo (PIMC) and analytical tools, we have analyzed the collective mode dispersion of a system of two-dimensional (2D) bosonic dipoles in both the normal and superfluid phases. The theoretical approach is based primarily on the extension of the classical quasi-localized charge approximation (QLCA) [1] to quantum systems.

For a normal liquid we propose to use the quantum QLCA [2] to include quantum fluctuation effects. For the pure superfluid phase we use the QLCA with the third-frequency-moment sum rule. The PIMC pair correlation function data constitute an essential ingredient of the theoretical methods.

The dispersion relations are generated both through the Feynman formalism using PIMC structure function data and through the QLCA using PIMC pair correlation functions. At long wavelengths, the two approaches are in good quantitative agreement for the acoustic phase velocity. This allows one to relate the acoustic phase velocity to the thermodynamic sound speed in different temperature and density domains. The results are also compared with the zero temperature quantum Monte Carlo [3] and with classical MD simulation data. The correlational origin of the roton minimum is clearly established and results from classical MD simulations point at its fundamentally classical origin.

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1.19 Classical Molecular Dynamics Model for Coupled Two-Component Plasmas - Ionization Balance and Time Considerations.

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The dynamic properties of ion-electron two-component plasmas (TCP) are studied by using classical molecular dynamics (MD) simulations. There is a variety of time dependent and structural results that MD is able to provide in complement to other methods, e.g., useful micro-field sequences can be generated. The method deals with some specific difficulties: the mass ratio between ions and electrons enforces very small time-steps appropriate to follow electrons motion while, ions must move significantly in order to build, self consistently, their spatial structure. This results in expensive simulations. Electron trajectories are trapped and de-trapped with multiple electron collisions around ions resulting in the occurrence of quasi metastable bound electron states.

An analysis of micro-fields at neutral in a hydrogen plasma reveals the need to consider a complete hierarchy of time scales extended typically over 7 order of magnitude, i.e., from a time-step: $\sim 10^{-18}$ s, to a time required to obtain statistical averages, $\sim 10^{-11}$ s.

In order to extend the MD capabilities in representing real coupled plasmas a classical ionization/recombination process has been implemented allowing to follow the evolution of plasmas involving several ion stages and model the ionization balance. Here again TCP simulations deal with extended time-scale providing information about relaxation of non equilibrium plasma states.

1.20 Ab initio modeling of solids with hot electron subsystem

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The description of the electron-ion relaxation in condensed phase of real substances with excited electrons is currently an actual theoretical problem that has no general methods of solution in the framework of quantum molecular dynamics. As a tool of analysis of the properties of solids with hot electron subsystem the finite-temperature density functional theory is applied. The phonon dispersion and the electron DOS studies are carried out for the two-temperature system. The analysis was performed of the influence of electron temperature on stability of simple and d-metals (Al, Au and Ni) and semiconductors (Si, α-quartz). The results point to the substantial redistribution of electron densities and change of the interionic interaction at electron temperatures above 2-3 eV.

1.21 Experimental and numerical study of distribution of dense non-ideal core and rare corona plasmas in the discharge channel

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Distribution of dense matter of core and rare plasma of corona in the discharge channel upon electrical wire explosion using electrical, optical, and UV diagnostics was studied. Wires of 25 μm diameter and 12 mm length were exploded in vacuum by 10 kA current pulse having a 50 A/ns rate of current rise. It was shown that two-phase vapor-droplets state or non-ideal plasma of the core with density up to 10^{22} cm^{-3} and temperature $T \sim T_{cr}$ and rare radiating corona plasma with density $n << 7 \cdot 10^{18}$ cm^{-3} radiated photons with energy in UV range (10 eV $< \epsilon <$ 180 eV) are formed upon the wire explosion. These dense core and rare corona coexist most of the time in the discharge channel.

The variety of processes during wire explosion was also simulated numerically. The aim of these studies was to examine whether it is possible to obtain good qualitative as well as quantitative description of exploded wire dynamics using the modern wide-range EOS and conductivity models. Two different codes were used for modeling of the wire explosion. The initial stage (before breakdown) was simulated using the conservative numerical technique with accurate accounting of the matter properties. The following simulation was implemented by a Lagrangian-Eulerian RMHD-code RAZRYAD-2.5. By virtue

of this code we simulated the coupled expansion of a wire core and surrounding plasma corona. The simulations show satisfactory evidence of compliance between numerical and experimental results.

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1.22 Approaches to the Simulation of Nonideal Plasmas by the Method of Antisymmetrized Wave Packet Molecular Dynamics

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The method of Molecular Dynamics (MD) is commonly used to study dynamical properties of equilibrium and nonequilibrium nonideal (strongly coupled) electron-ion plasmas where analytical description is difficult or impossible. This method is based on the pseudopotential approach which accounts for quantum effects at short interparticle distances. Nevertheless this approach becomes inaccurate at high plasma densities.

The method of Wave Packet Molecular Dynamics (WPMD) is an extension of MD. It was applied originally in [1] to study the nonideal hydrogen and lithium plasmas. Further implementations [2] extend this approach to warm dense matter. In contrast to the classical Molecular Dynamics, the electrons in WPMD are treated as Gaussian wavepackets (WP). It is expected that this method is more accurate to account for quantum effect of close particle collisions compared to the pseudopotential approach, traditionally used in plasma Molecular Dynamics. There also exist improved WP models with more parameters for the basis wavefunctions or non-Gaussian basis [3]. The most elaborate and computationally demanding version of the method is the antisymmetrized WPMD (AWPMD) [4], where the electron spins are explicitly treated by the single determinant antisymmetrization of the trial wave function. In contrast to the pseudopotentials having adjustable parameters, the WPMD is its original formulation is a fully ab-initio method. On the other side WPMD is expected to be much faster than other quantum MD methods such as time-dependent DFT, etc.

In the present work we develop an alternative nearest image AWPMD scheme, which is close to [4]. The difference is in the way of implementing periodic boundary conditions in the simulation box. The real space treatment of WPs in our work brings more flexibility to the interaction calculation. For example, it permits to treat the particles classically in case of weak interaction.

The results for both antisymmetrized and non-antisymmetrized WPMD, conventional MD and other approaches are compared. Comparison between different models is made with respect to the calculation of the thermodynamical functions such as the interaction energy and pressure, the pair correlation functions and the dynamical conductivity.

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1.23 Formation of the globular defects in fluorite-like ionic crystals

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Self-assembling processes of the defects clusters in hyper-stoichiometric and metastable stoichiometric crystals with fluorite structure was studied by molecular dynamics (MD) method. MD simulation program developed for ionic solids like UO_2 based on partially-ionic model [1] was applied in the study to the relative stability of different types of defects and evolution of the defects concentration in metastable UO_2 solid.

To destroy the less stable anionic sublattice, we applied a method of the thermal shock, i.e. short initial overheating period, which started at the temperature well above the melting temperature, and followed by series of the fast quenching/annealing periods (sudden or step by step temperature drops). To avoid melting of the cationic sublattice, thermal shock period was limited to a few picoseconds. During the whole MD simulation, we monitored the number and type of defects forming in the cell and computed their formation energies. The resulting structure of the relaxed solid was analysed using JMol visualization software. Along with formation of small (Willis) dimers of different types, we observed self-assembling of large regular globular structures.

Such structures in MD simulation can be observed only in a very large MD cells. In our simulation of stoichiometric UO_2 on desktop PC we used the fast method of computing of Coulomb forces proposed earlier [2] what gives us the possibility to use a cell containing 1200 ions ($20 \times 20 \times 20$ unit cells).

It was found that in hyperstoichiometric or thermally shocked stoichiometric solid under conditions when the thermal motion is restricted, the defects interaction leads mainly to the self-assembling of the very stable globular structures, containing 12 or 13 interstitial anions and eight lattice vacancies (cuboctahedral clusters). Such clusters have been found experimentally in hyper-stoichiometric fluorite crystals, but have never been observed at stoichiometric conditions yet.

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2 Equilibrium properties and equation of state of dense plasmas

2.1 Velocity distributions and kinetic equations for plasmas including Levy-type noise

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As known since the pioneering paper of Holtsmark (1919), the distributions of electrical microfields in plasmas are of Levy type. The corresponding distributions of noisy forces due to the stochastic Holtsmark fields have long tails. Correspondingly, several distributions in plasmas and in particular the velocity distributions may show long tails at least in transitory regimes. Further, generalizations of Fokker-Planck and Landau-type equations including the long correlations are required. We present Langevin equations, Fokker-Planck equations, master equations and velocity distributions taking into account Levy-type noise. Several applications to processes in dense exploding Coulomb clusters including fusion rates are given.

2.2 Phase shifts and the second virial coefficient for a partially ionized Hydrogen plasma

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The thermodynamic properties of Coulomb systems can be obtained from the virial expansions. The exact quantum mechanical expression for the second virial coefficient was given by Beth and Uhlenbeck [1]. They showed that the second virial coefficient can be expressed in terms of scattering phase shifts and bound state energies.

A partially ionized dense plasma is investigated, which consists of three components as electrons, ions and Hydrogen atoms. The second virial coefficients for the charged components $e-e$, $e-i$ and $i-i$ was already considered in Refs. [2, 3], but the coefficients for $e-H$ and $H-H$ pairs still present large interest.

The phase shifts for atom-atom scattering were calculated using the wave expansion method. Different pseudopotentials were considered to describe the interaction between atoms.

For the $e - H$ pairs, the second virial coefficient was calculated using experimental and theoretical values for the phase shifts in the singlett and triplett channel. A separable potential was constracted to reproduce these phase shifts. Within a generalized Beth-Uhlenbeck approach, density effects such as Pauli blocking have been incorporated. Thermodynamic and transport properties of partially ionized Hydrogen plasma are considered within our approach.

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2.3 Electrical resistivity in warm dense plasmas beyond the average-atom model

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The exploration of atomic properties of strongly coupled partially degenerate plasmas, also referred to as warm dense matter, is important in astrophysics, since this thermodynamic regime is encountered for instance in Jovian planets' interior. One of the most important issues is the need for accurate equations of state and transport coefficients. The Ziman formula has been widely used for the computation of the static (DC) electrical resistivity. Usually, the calculations are based on the continuum wave-functions computed in the temperature– and density–dependent self-consistent potential of a fictive atom, representing the average ionization state of the plasma (average–atom model). We present calculations of the electrical resistivity of a plasma based on the superconfiguration (SC) formalism. A SC is made of groups of orbitals (namely super-orbitals) with integer electron populations. In this modeling, the contributions of all the electronic configurations are taken into account. It is possible to obtain all the situations between the two limiting cases: detailed configurations (a super-orbital is a single orbital) and detailed ions (all orbitals are gathered in the same super–orbital). The ingredients necessary for the calculation are computed in a self-consistent manner for each SC, using a density-functional description of the electrons. Electron exchange correlation is handled in the local-density approximation. The momentum transfer cross–sections are calculated by using the phase shifts of the continuum electron wave-functions computed, in the potential of each SC, by the Schrödinger equation with relativistic corrections (Pauli approximation). Comparisons with experimental data will also be presented.

2.4 Modeling of Thermodynamic Properties of Dense Multicharged-Ion Plasmas Based on the Chemical-Picture Approach

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Consistent modeling of thermodynamic properties of dense plasmas in the warm-dense-matter domain is still one of the challenging problems to be addressed. Using the chemical-picture representation of plasmas as a mixture of various ions and free electrons [1, 2], a consistent description of thermodynamics of dense multicharged-ion plasmas is being developed that involves: effects of Coulomb non-ideality and degeneracy of plasma electrons; contribution of possible bound ion states (on the base of the superconfiguration approach [3]) that may exist under an appropriate truncation of ion energy spectra due to plasma effects; hard-sphere-model representation of the finite-volume effects of plasma ions [3] with the model parameters (effective ion sizes) corresponding to superconfigurations yielding the greatest contribution to partition functions. We present the calculated data for average ionization, pressure, specific internal energy, and specific heat of aluminum and iron plasmas at temperatures 30 eV - 3 keV and densities 10^{-3} – 10^{-5} of their normal material densities. Calculated shock Hugoniots and thermodynamic functions are compared with other theoretical and experimental data.

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2.5 Ionization equilibrium, thermodynamic and dynamic properties of a dense partially ionized plasma

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In this work ionization equilibrium, thermodynamic and dynamic properties of a dense semiclassical nonideal metal plasma were investigated. Number density is considered in the range of $n = n_e + \sum_{i=1}^{N} n_i + n_a = 10^{18} \div 10^{24} cm^{-3}$; and temperature range is $10^4 \div 10^6 K$. To describe the electron-ion interaction, the pseudopotential was used that takes into account the following effects: charge screening at long distances and quantum effect of diffraction, which occurs in dense systems [1]. The electron-atomic interaction was described by polarization pseudopotential [2], which also takes into account the screening effects and quantum effects of diffraction.

In the first part of this work we studied the ionization equilibrium of hydrogen, tungsten, aluminum and iron plasmas. Nonideal plasma consisting of electrons, ions of different multiplicity and atoms was considered. Within the pseudopotential model the excess of chemical potential of charge particles was calculated. For the investigation of ionization stages we used the Saha equations with corrections to nonideality (lowering of ionization potentials) [3].

In the second part of the work thermodynamic properties (internal energy and equation of state) of dense semiclassical metal plasma were calculated. Results of ionization stages found in the first part was used for the determination of thermodynamic functions.

The last part is devoted to the investigation of effect of runaway electrons in dense partially ionized plasma. We found that the probability of runaway electrons in dense plasma increases in comparison with rarified plasma. This effect is possibly connected with decrease of the collision frequency in nonideal plasma [4] and formation of ordered structures in dense plasma.

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2.6 HNC calculations for the structure of dense multi-component plasmas

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We calculate the static structure factor of dense multi–component plasmas by solving the integral equations for the pair correlation functions within the hypernetted chain (HNC) scheme. For this purpose we derived new effective two-particle quantum potentials for the interactions between the charge carriers from the full two-particle Slater sum by accounting for bound states. Large scale ab initio molecular dynamics simulations are performed in order to cover the region where a consistent quantum treatment for the electrons is inevitable. Comparison to the HNC calculations enables us to determine the short-range behavior of the effective electron–ion quantum potentials. We calculate the static structure factor for dense beryllium plasmas and discuss results for the ion contribution to the X-ray Thomson scattering signal.

2.7 On the metal-nonmetal transition in fluid aluminum

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In a phenomenological way an equation of state of fluid aluminum is constructed for the density range from about 5/6 down to 1/6 of the normal solid density based on the experimental results [1, 2]. Using this equation of state behavior of isotherms and isentropes of fluid aluminum is analyzed to reveal the first order phase transitions present in this density range.

Applying the virial theorem to the system consisting of the valence electrons and the ion cores a thermodynamic criterion for the metal-nonmetal transition is derived. Relation between the present thermodynamic criterion for the characteristic density of the metal-nonmetal transition, the Goldhammer-Herzfeld criterion and that based on the minimum metallic conductivity concept is discussed.

It is demonstrated that on the nonmetallic side of the metal-non-metal transition at the densities 4 to 6 times lower than the normal solid density, fluid aluminum represents a strongly coupled system with the value of the coupling parameter of the order 10.

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2.8 Dielectric catastrophe and insulator-metal transition in AlH_3.

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A study of properties of alane (AlH_3) under multi shock compression has been carried out. The increase in specific conductivity of alane at shock compression up to pressure 100 GPa has been measured. The compression loads the alane sample by multi shock manner up to the pressure $80 - 90$ GPa, heats it to the temperature about $1500 - 2000$ K and lasts 1 microsecond. The conductivity of shocked alane increases in the range up to $60 - 75$ GPa and is about 30 (Om cm)$^{-1}$. In this region the semiconductor regime is true for shocked alane. The conductivity of alane achieves approximately 500 (Om cm)$^{-1}$ at $80 - 90$ GPa. In this region conductivity is interpreted in frames of the conception of the "dielectric catastrophe", using Herzfeld-Goldhammer criterion. According to this criterion, the dielectric-conductor transition takes place when permittivity of a matter begins to rise sharply and amounts to values exceeded unity significantly. In the case of AlH_3 it is necessary to take into account that outer electrons of the Al are transferred to the H atoms and the permittivity is determined by the polarizability of ions Al^{3+} (can be neglected) and H^-. The exchange interaction between electrons of the neighboring ions H^- results in significant decrease of the region occupied by each electron and in decrease of the ion polarizability. Our estimation of the polarizability of the alane molecule in condensed state gave a value equal to 9.6 a.u. With such polarizability the "dielectric catastrophe" and, consequently, dielectric-conductor transition have to begin at $n = 5.6 \cdot 10^{22}$ cm^{-3} or $\rho = 2.8$ g cm^{-3}, what is in agreement with our results and with experiments of Goncharenko *et al.* (2008). Proposed model can be used for estimations of the transition density to the conductive state for other metal hydrides such as MgH_2, NaH, and LiH. Possible mechanism of the alane conductivity is following. At normal conditions valence electrons of aluminum are trapped by hydrogen atoms forming negative ions H^-. The resulting electron energy band is fully occupied and condensed alane is a good insulator. By increasing the temperature a part of the electrons turns to aluminum, neutral atoms of hydrogen appear in the system and migration of electrons from H^- to H becomes possible. Such mechanism of the electron transfer can explain the semiconductor character of the alane conductivity observed in experiment. By increasing the density the permittivity also increases. This results in the decrease in electron binding energy in ion H^- and, consequently, in the decrease in band gap. At high enough density the permittivity becomes infinite, the band gap disappears, and the conductivity gains the metallic character.

2.9 Numerical data for thermodynamics of hydrogen in the Saha regime from exact low-temperature expansions

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At sufficiently low densities and low temperatures, hydrogen behaves almost as an ideal mixture made with hydrogen atoms in their groundstate, ionized protons and ionized electrons. In that regime, the ionization and recombination equilibrium obeys in first approximation to the Saha equation. Even in regimes where deviations to the Saha equation of state caused by interactions among the entities remain typically small (less than 10%), the precise calculation of corrections to Saha theory is of broad interest, in particular in astrophysics where a highly accurate equation of state of hydrogen is necessary to interpret helioseismology measurements.

By performing systematic low-temperature expansions within the physical picture, in which the system is described as a quantum electron–proton plasma interacting via the instantaneous $1/r$ Coulomb potential, we obtained exact formulae for the first five leading corrections to the Saha equation of state [1]. Those corrections account for all effects of interactions and thermal excitations up to order $\exp(E_H/kT)$ included, where $E_H = -13.6$ eV is the ground state energy of a hydrogen atom.

Among the five leading corrections, three are easy to evaluate in terms of closed analytical forms. The remaining ones involve suitably truncated internal partition functions of H_2 molecules and H^- and H_2^+ ions, for which similar expressions are not available because exact results on the three- and four-body problem are very scarce. We currently estimate those partitions functions phenomenologically by using familiar phenomenological values of rotational and vibrational energies. This allows us to compute numerically the leading deviations to the Saha equation of state along several isotherms and isochores, with a good accuracy [2]. The deviations remain small at low densities, but start to grow significantly when the density and temperature approach 0.01 g/cc and 15'000 K respectively. Comparison with data from quantum Monte Carlo simulations [3] performed in this quite dense region showed good agreement. We compare also our results with the numerical OPAL tables calculated within the ACTEX method [4].

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2.10 Use of Pulsed Radiography for Investigation of Equation of States of Substances at Megabar Pressures

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A method of substances densities measurement that are isentropically compressed up to megabar pressures is described in the paper. Measurement results of densities of condensed hydrogen and aluminum isotopes are presented. These results, afterwards, are used for hydrogen isotopes equations of state construction. Experimental x-ray images of the facilities with the hydrogen isotopes, compressed up to several megabars are presented in the paper.

2.11 Multiphase equation of state for iron at high pressures and temperatures

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An equation of state of different materials over a wide range of parameters is necessary for numerical simulations of physical processes in plasmas at high energy densities. Reliability of the calculation results is determined mainly by adequacy of description of thermodynamic properties of a medium. In the present work, a new semiempirical model of thermodynamic potential free energy with taking into account polymorphic phase transitions, melting and evaporation is presented for metals. On the basis of this model, multiphase equation-of-state calculations are carried out for iron at high pressures and temperatures. Obtained results are in a good agreement with available experimental data on shock compression as well as adiabatic and isobaric expansion.

2.12 Hydrofullerene $C_{60}H_{36}$ under high-pressure short-time conditions

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In the previous work [1] the structure of hydrofullerene $C_{60}H_{36}$ has been investigated after shock loadings. It has been shown, that hydrofullerene keeps the molecular structure under the high-pressure short-time conditions. So IR spectra of hydrofullerene samples (in particular the stretching vibrations of C-H bonds) in the initial state and after shock-wave treatment are similar to each other at the maximum pressure of 27 and 42 GPa. X-ray diffractograms of hydrofullerenes $C_{60}H_{36}$ in the initial state and (2, 3) after shock loading to 27 and 42 GPa are close to each other as well.

The purpose of this work was to study the hydrofullerene $C_{60}H_{36}$ under shock-wave loading in situ [2]. The sample in the form of a disk was located

between two copper disk anvils and was loaded by aluminum projectile practically as well as in work [1]. The free surface velocity time profile $W(t)$ of the back anvil was registered with the help of VISAR.

The hydrocode simulation allows to choose the set of fitting parameters for the $C_{60}H_{36}$ hydrofullerene equation of state which give the best calculated profile $W(t)$ coincident with VISAR experimental profile $W(t)$.

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2.13 Low ion-velocity slowing down in a strongly magnetized plasma target

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Ion beam stopping in a dense plasma submitted to an arbitrary large and steady magnetic field B is a recurrent thema encompassing a huge range of practical situations of very timely concern.This range includes ultracold plasmas(UCP), cold electron setups used for ion beam cooling as well as many very dense systems implied in magnetized fusion(MTF),or inertial confinement fusion(ICF). This latter scheme presently advocates a highly regarded fast ignition scenario(FIS) elaborating on femtolaser produced protons or heavier ion beams impinging a precompressed capsule with thermonuclear fuel in it.Then B values up to 10^{10} G may now be observed in the laboratory. Such a topic is also of permanent astrophysical proeminence. Given interaction geometries highlight low ion velocity slowing down(LIVSD) as playing a key role in asserting the confining capabilities and thermonuclear efficiency in dense and strongly magnetized plasma media. Toward these goals, ion projectile stopping at velocity smaller than thermal electron velocity at high B values is investigated within a novel diffusion formulation based on Green-Kubo integrands eveluated in strongly magnetized OCP models, respectively framed on target ions and electrons, as well. Analytic expressions are given for slowing down parallel and orthogonal to B direction, which are free from the usual uncertainties plaguing standard perturbative derivations. B-and temperature-dependences of the resulting LIVSD quantities are thoroughly detailed for dense plasmas of FIS and UCP concern. The present hydrodynamical approach also reproduces the expected $B = 0$ quantities obtained in the usual collision-dielectric formulation.

2.14 Semiempirical equations of state for metals based on Thomas–Fermi model

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For analyzing the physical processes at high energy densities, an adequate description of the thermodynamic properties of matter over a broad region of states including both the condensed phase under normal conditions and plasma at high pressures and temperatures is required. In the present work, a semiempirical equation-of-state model, which is based on Thomas–Fermi theory [1], is proposed. According to this model, the Helmholtz free energy for matter is considered as a sum of three components, $F(V,T) = F_c(V) + F_a(V,T) + F_e(V,T)$, describing the elastic part of interaction at $T = 0$ K (F_c) and the thermal contributions of heavy particles (atoms, ions, nuclei) and electrons (F_a and F_e, respectively). The first and second components are given by interpolation formulae, the third is calculated within the framework of the Thomas–Fermi model [1]. Wide-range equations of state are developed for aluminum and copper. A critical analysis of calculated results in comparison with available experimental data for these metals at high pressures and temperatures is made.

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2.15 Thermodynamic Properties of Gaseous Plasmas in the Zero-Temperature Limit

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Limiting structure of thermodynamic functions of gaseous plasmas is under consideration in the limit of extremely low temperature and density ($T \to 0$;

$n \to 0$). Remarkable tendency, which was claimed previously [1, 2], is carried to extreme. The discussed limit is carried out at fixed value for chemical potential of electrons or atoms or molecules *etc*. In this limit both equations of state (EOS) thermal and caloric one, obtain almost identical stepped structure ("ionization stairs" [2]). The same stepped structure appears in the zerotemperature limit in any molecular gases, for example hydrogen [3]. For rigorous theoretical proof of existing the limit, which is under discussion (Saha-limit) in the case of hydrogen see [4, 5] and references therein. In this zero-temperature limit all thermodynamic differential parameters (heat capacity, compressibility, etc.) obtain their remarkable σ-like structures ("thermodynamic spectrum" [2, 6]). Both kinds of such "spectrum" became apparent: i.e. "emission-like spectrum" for heat capacity and "absorption-like spectrum" for the isentropic exponent [3]. This limiting structure appears within a fixed negative range of μ_{el} ("intrinsic energy scale") [2]. It is bounded below by value of major ionization potential. Binding energies of all possible bound complexes (atomic, molecular, ionic and clustered) in its ground state are the only quantities that manifest itself as location and value of every step. The value depending on the heat of condensation at $T = 0$ supplement this collection. All the "lines" of the "thermodynamic spectrum" are centralized just at the elements of this "intrinsic energy scale". The limiting EOS stepped structure (ionization stairs) of gaseous zero-Kelvin isotherm is generic prototype of well-known "shell oscillations" in EOS of gaseous plasmas at low, but finite temperatures and non-idealities [7]. The gaseous branch of discussed zero-Kelvin isotherm could be naturally conjugated with associated condensed branch. This combination creates complete and totally meaningful non-standard "cold curve" for any substance $\{U_0(\mu)$ instead of $U_0(\rho)\}$ [3]. All present statements about remarkable limiting structure of thermodynamic functions in zero-temperature limit for single substances are valid also in application to the chemical compounds [6].

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3 Kinetics, transport and optical properties of dense Coulomb systems

3.1 Dynamical collision frequency in warm dense matter: Exemplary application to plasma reflectivity

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The dynamical collision frequency is the central quantity for calculating the dielectric function in warm dense matter. In particular, we are interested in static transport properties, e.g. dc-conductivity [1, 2], and optical properties, e.g. reflectivity [3]. The description over a wide parameter region of the plasma's temperature, density, ionization degree, and frequency is subject of current research.

Based on a generalized linear response theory, the dynamical collision frequency has been calculated in different approximations. Within the Gould-deWitt approach, dynamical screening and strong collisions have consistently been taken into account [4, 5].

We apply our expression for the dielectric function to latest experimental data on the reflectivity of a Xe-plasma under oblique incidence [7] in extension to earlier results for the perpendicular case [6].

While the conclusions on the plasma's density profile in the front region [3] are verified, the separate treatment of the s- and p-polarized wave allows for a more detailed examination and further improvement of the profile's description.

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3.2 Magnetotransport properties of dense plasmas

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The Hall coefficient is an important measure of the transport properties of a material in a magnetic field. We investigate whether the relationship of the Hall coefficient to the density of free charge carriers could provide a tool in plasma diagnostics [1]. Correlation effects in dense plasmas require a quantum statistical theory. Linear response theory, as developed within the Zubarev formalism, is a quantum statistical approach for describing systems out of but close to equilibrium, which has been successfully applied to a wide variety of plasmas in an external electric field and/or containing a temperature gradient. We present here an extension of linear response theory to include the effects of an external magnetic field [2]. All relevant transport properties are discussed, in particular the Hall effect and the influence of a magnetic field on the dc electrical conductivity [3]. New low-density limits including electron-electron scattering are presented. Additionally, we compare results from linear response theory with recent experiments in shock wave produced Ar and Xe plasmas [4]. The electrical conductivity and the Hall coefficient have been measured for free electron densities between 10^{14} and 10^{20} cm^{-3} and temperatures in the range 6000 K to 18000 K in a 5 Tesla field.

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3.3 K-line emission profiles of warm dense matter with focus on plasma polarization shift and M-shell satellites

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In recent years K-line spectra in laser-produced solid-density plasmas have become the focus of various experimental and theoretical investigations. As the K-spectra are emitted from a warm and dense plasma, one can determine plasma parameters of the emitting medium by studying the line profiles. Observation of these spectra applying high-resolution X-ray spectroscopy has been performed within a german-israeli collaboration of the Weizmann Institute (Y. Maron et al.), the IOQ Jena (E. Förster et al.) and the University of Rostock. A theoretical treatment of spectral lines using a self-consistent ion sphere model is applied on moderately ionized mid-Z materials. We focus here on the influence of plasma polarization effects on the K-line emission energy and satellite transitions due to M-shell ionization and excitation [1,2]. Titanium and chlorine K_α and K_β spectra have been calculated in order to analyze recent measurements with respect to the plasma parameters of electron heated target regions. Radial temperature profiles, ion and electron densities as well the composition of the created plasmas are inferred. Besides, various competing line broadening mechanisms are considered [3].

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3.4 The calculations of transport coefficients of noble gases under high pressures

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The conductivity, thermal conductivity and thermopower of noble gases have been investigated during last several dozens years (see [1] for references). One of interesting process observed in experiments is the increase of the values of the transport coefficients with respect to their ordinary values under high pressures. This effect is analogous to the phenomena observed in metals in the vicinity of the critical point, which is known as dielectric–metal transition. This transition occurs because of the pressure ionization in both cases. It gives rise to a steep increase in the free electron density, which in turn results in a large increase in the electrical conductivity and other coefficients.

In spite of many theoretical works describing the behaviour of transport coefficients of noble gases there are still open questions. One of them concerns the change ionization degree during compression. Different ionization mechanisms are possible which can give rise to contradictions. For example, recently new experimental data have been obtained [2, 3] by means of shock compression. To describe the results of the measurements there was used two numerical codes, which were created on the basis of the generalized chemical models. But calculated and measured conductivity for the experiments in hand can differ in two times [3].

In present report we try to apply different theories and models to the calculation of transport coefficients of noble gases (argon, xenon, krypton) under wide variation of densities and temperatures. The results of calculation were compared with available experiments and calculations of other authors.

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3.5 Nonlinear Collisional Absorption of Laser Light in Dense Plasmas

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Understanding the laser-matter interaction in strongly coupled plasmas is crucial for the design of the contemporary inertial confinement fusion targets. The conditions imposed by the hydrodynamic instabilities on the spatial symmetry of the laser energy deposition, require the laser absorption to be carefully determined from the early stages of the laser–plasma interaction [1]. In the case of the fast ignition [2] it is important to model the laser absorption starting with the preformed plasma due to the unavoidable nanosecond prepulse. To correctly describe the laser absorption in such regimes, strong electron-ion collisions, the structure of the strongly coupled ion subsystem and degeneracy have to be included. Heretofore no approach been developed that accounts for all these effects as all present models either assume weak electron-ion interactions or weak fields or high laser frequencies.

Here, we present a novel approach bridging between the high– and low–frequency limits where the strong binary and the weak collective interactions are treated simultaneously [3]. This is achieved by solving the Vlasov-Poisson equations in the generalized Kramers-Henneberger frame, determined by the real average velocity of the electron fluid. In contrast to other works, here this frame is not approximated as the rest frame of freely oscillating electrons, but is rather determined as the rest frame of the electrons subjected to the friction force resulting from the binary collisions with the background ions. This friction force is derived from the stopping power calculated using the standard quantum T–matrix approach. Thus, for the first time the stopping power is applied to the calculation of the inverse bremsstrahlung. The results show an excellent agreement with molecular dynamics simulations [4] up to very high coupling strength. Our description is also fully quantum-mechanical which avoids any ad hoc cutoffs.

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3.6 On the replacement of collisional recombination mechanism in nonideal plasma.

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Dependence of collisional recombination mechanism on plasma parameters is considered. Whereas the coefficient C is a constant value in the formula for the collisional recombination rate in ideal plasma $K_e = CZ^3e^{10}m^{-1/2}n_e^2n_iT^{-9/2}$, the dependence of C on the nonideality parameter Γ and ion charge Z should be introduced for nonideal plasma. The boundary value of Γ depends on Z. The coefficient C decreases exponentially with the further increase of Γ for all Z. The following approximate expression is suggested $K_e = K_0\Gamma^{9/2}exp(-a\Gamma)exp(-bZ\Gamma)$, where K_0, a and b are constant values which are found by molecular dynamics simulation.

The change of Γ-dependence of C from the constant to exponentially decreasing function points to the change of recombination mechanism. Analysis of the bound electron-ion pair distributions over binding energies reveals the fact that Fokker-Planck diffusion is blocked for large Γ, isolated strong collisions becoming the predominant recombination mechanism. It is due to the extension of the energy interval of the many-particle fluctuations adjoining the ionization limit with the increase of Γ. The change of the mechanism takes place when the interval value exceeds the thermal energy.

3.7 Energy Relaxation in Dense Two-Temperature Plasmas

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The energy relaxation in strongly coupled plasmas is studied using a quantum kinetic approach. Starting from the quantum version of the BBGKY hierarchy, a balance equation for the total energy is derived which includes a general expression for the energy transfer rate in terms of the correlation function of density fluctuations.

Based on the real time Green's function formalism, different approximations for this correlation function are derived. Well-known approximations for the electron-ion energy transfer such as Fermi golden rule or coupled modes can be reproduced. Furthermore it becomes possible to systematically improve the level of approximation for the energy transfer rates.

For numerical evaluation of specific cases relevant for the warm dense matter regime, we use the coupled modes transfer rates. The response functions are taken in random phase approximation and with additional static local field corrections. Whereas for the required heat capacity of the electron subsystem a perturbation expansion within the Green's function formalism is used, the ion heat capacity is calculated using techniques of classical statistics (HNC).

On this basis, the energy relaxation in dense two-temperature plasmas is then investigated numerically. Special attention is paid on the effects of the correlation energy of the ions and the degeneracy of the electrons on the final temperature and on the relaxation time. The comparison of our results to recent computer simulations and to experiments shows agreement in certain limiting cases but differences in the relaxation process and relaxation time.

3.8 Pressure Broadening of Spectral Lines in Dense Lithium Plasmas

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Pressure broadening of Lyman-lines of hydrogen–like lithium (Li^{2+}) is studied using a quantum statistical approach to the line shape in dense plasmas, for details see [1]. We report line widths (FWHM) and shifts for Lyman-α, -β, and -γ in a wide range of densities ($n_e = 10^{24} - 10^{28}$ m^{-3}) at temperatures relevant for laser-produced lithium plasmas ($T = 10^5$ K). We discuss the effect of different ionic microfield distributions and estimate the influence of ion dynamics. Special care is taken to account for strong collisions by using a microscopic treatment of the three-body T-matrix.

The results are applied to measured spectra of lithium irradiated by a nanosecond laser pulse of moderate intensities ($I \approx 10^{11} - 10^{13}$ W/cm^2), see [2]. By matching synthetic spectra to the experimental ones, density and temperature conditions are inferred assuming the model of a one-dimensional uniform plasma slab. Self-absorption is accounted for and found to be important for Lyman-α. In this way, experimental spectra are overall reproduced.

To describe remaining deviations in the line wings, it is essential to use a multilayer model adapted to density and temperature profiles from hydrodynamic expansion codes.

Alternatively, we need time and space resolved spectra to compare theory and experiments, which are available for He-like lithium (Li^+), see [3]. Therefore, we also calculate the line profile of the Li^+ 1s2p→1s2s transition at 548 nm, using our quantum statistical approach. Implications for the conversion efficiency are drawn.

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3.9 Radiation Hydrodynamics of Laser–induced Plasmas using Dynamic Collision Frequencies

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Radiation Hydrodynamics of laser–induced plasmas is usually treated by well–established hydrodynamic codes such as MEDUSA or MULTI. These codes require transport coefficients, e.g. absorption coefficients or thermal conductivity, as inputs. Typically, Spitzer–Härm–like expressions are used. However, for high densities these expressions can not be applied and have to be replaced by more advanced expressions. In particular, quantum effects and dynamical screening have to be accounted for in a systematic manner, see Reinholz et al. PRE 62, 5648 (2000). Here, we present results of a hydrodynamical calculation including these advanced collision frequencies. We also compare to earlier calculations with Spitzer–Härm–like expressions. In particular, the radiation hydrodynamics for laser-induced Lithium plasmas is studied. Conditions for optimal conversion efficiency are derived.

3.10 S- and P- polarized reflectivities of explosively driven strongly non-ideal xenon plasma

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The interaction of polarized electromagnetic waves of moderate intensity with strongly correlated plasma is of great interest for numerous types of investigations: optical and transport properties of matter under high power action, the validity of the physical models describing the behavior of matter under high temperatures and pressures and so on. The reflectivity of shock-compressed dense xenon plasma using normal incidence has been investigated at wavelengths 1064 nm [1, 2], 694 nm [2–4] and 532 nm [4]. Plasmas created have transitive surfaces with a density profile. The research of transitive layers of explosively driven dense plasmas can be carried out using the technique of inclined probing by polarized electromagnetic waves. Angular dependence of s- and p- polarized reflectivities at several wavelengths can be used in the integration of Maxwell equations to construct the spatial profile of the density of charge carriers. It is necessary to interpret correctly the results of reflectivity measurements because the small changes of layer parameters cause the considerable variations of the total reflectivity of shock-compressed plasma. The results of experiments on reflectivity of polarized light on explosively driven dense xenon plasma are presented. The study of polarized reflectivity properties of plasma was accomplished using laser light of wavelength $\lambda = 1064$ nm and at incident angles up to $\theta = 60^\circ$. During the experiments, the plasma density up to $\rho = 3$ g·cm^{-3}, pressure up to P = 12 GPa and temperature up to T = $3{\cdot}10^4$ K (the nonideality parameter up to $\Gamma \sim 2$) were realized. The calculation of angular dependence of s- and p- polarized reflectivities of dense plasma has been executed for comparison with experimental data.

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3.11 Quantum kinetic approach to time-resolved photoionization of multi-electron atoms

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Recent progress in experiments [1], now often called 'attophysics', allows for time-resolved investigation of electronic processes in atoms and, ultimately also atoms in plasmas. The most prominent examples are the time-resolved measurements of Auger decay [2] and the dynamics of shake-up state population during strong field ionization of atoms [3]. These new fields of ultra-short time physics ('attosecond chronoscopy') require a time-resolved theory of ionization of multi-electron atoms by ultra-short XUV/UV pulses in combination with strong IR fields in pump-probe setups. On the way towards understanding and modeling these phenomena, we present first results of a quantum kinetic theory of ionization of simple few-electron model systems [4]. Approximate many-body approaches, in particular time-dependent Hartree-Fock and Multi-configurational-Hartree-Fock are compared to full solutions of the few-particle time-dependent Schrödinger equation. We further apply the technique of non-equilibrium Greens functions in second Born approximation to systematically account for electronic correlations and their attosecond dynamics in atoms subject to strong electromagnetic radiation.

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3.12 Structure and X-Ray Scattering in Warm Dense Matter

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Inelastic x-ray scattering is one of the few methods to probe high-density systems that are opaque in the visible. The scattering spectrum shows two distinct features: an unshifted peak around the incident wavelength (Rayleigh peak) and a contribution associated with the free electrons. Using different scattering angles, all basic plasma parameters can, in principle, be obtained. However, highly precise data on the structure of the matter probed are needed to use this method as diagnostics. Warm dense matter is particularly difficult to describe as the correlation and the electron Fermi energies are comparable to the temperature making WDM a strongly correlated quantum system.

We apply density functional molecular dynamics (DFT–MD) and more approximate methods to develop an understanding for the ion and electron structure in different materials. By comparing DFT–MD data and results from classical HNC calculations we obtain valuable information on ion structure and can also construct a faster approach based on effective potentials which also take short-range contributions of full shells of bound electrons into account [1]. The obtained model agrees well with measured data [2, 3]. DFT-MD simulations also give electron densities. On the basis of these data, we can calculate the weight of the Rayleigh peak and compare directly with experiments. We found excellent agreement for small angle scattering for warm dense Beryllium [3]. A thorough analysis shows that correlation effects on the bound electrons must be included to get this agreement. More precisely, the deep lying parts of the bound wave functions are unchanged, but the electron densities get blurred for larger distances by correlations in the medium. We finally show how the description of x-ray scattering must be modified to describe materials that contain more than one ion species [5] as they are probed in recent experiments [3, 6].

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3.13 Atomic Database Spectr-W^3 for Plasma Spectroscopy and Other Applications. Current Status and Perspectives

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The Spectr-W^3 information-reference system was developed in 2001–2003 and realized as an online Web resource based on the factual atomic database Spectr–W^3 (`http://spectr-w3.snz.ru`). The information accumulated in the Spectr–W^3 atomic database contains about 450,000 records and includes the experimental and theoretical data on ionization potentials, energy levels, wavelengths, radiation transition probabilities, and oscillator strengths, and the parameters of analytical approximations of electron-collisional cross-sections and rates for atoms and ions. Those data were extracted from publications in physical journals, proceedings of the related conferences, special-purpose publications on atomic data, provided directly by authors and obtained in previous years by the Spectr–W^3 project participants. The information is supplied with references to the original sources and comments, elucidating the details of experimental measurements or calculations. To date, the Spectr–W^3 atomic database is still the largest factual database in the world, containing the information on spectral properties of multicharged ions. In 2007 this collaborative effort was followed by a new project aimed at the creation of a qualitatively updated version of the Spectr–W^3 atomic-data information-reference resource on the Web to provide free access to an essentially extended Spectr-W^3 atomic database. Project activities are also targeted at the creation of facilities for direct submission of new author's atomic data for the follow-on dissemination through the Spectr–W3 resource and downloading the selected data in HTML or XML representation. Updated version of Spectr–W^3 is also supplemented with its fully functional local analog (Spectr–CD) generated for the off-line use and available for downloading from the project website. The results of the project are intended for public and non-profit use. Current status of the project work will be outlined and illustrative results will be presented. The work has been supported in part by the International Science and Technology Center (ISTC) under the project Nr. 3504.

3.14 The kinetic model of laser plasma

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Hydrodynamic modeling of short laser pulse interaction with a solid target requires adequate description of optical and transport properties of the plasma in a wide range of parameters. Model of dielectric function and thermal conductivity of the plasma valid in the range from a solid density degenerate plasma to ideal one is proposed on the basis of Boltzmann equation with collision integral in the relaxation time approximation with a proper choice of ion structure factor.

3.15 The modeling of the continuous absorption spectra of the dense hydrogen plasma on the base of the cut-off Coulomb potential

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The possibilities of the modeling of the continuous absorption spectra of the dense non-ideal plasma by means of the some cut-off Coulomb potentials are examined in this work on the dense hydrogen plasma example. The main aim was the development of the semi-empirical method suitable for the calculations of the spectral absorption coefficients characterizing the processes of the excited hydrogen atom photo-ionization and the electron ion inverse "bremsstrahlung". The corresponded method, presented in this work, was developed on the base of the data obtained in several experiments. The method is tested in the ranges of the electron densities and temperatures $1 \cdot 10^{18}\ cm^{-3} \leq N_e \leq 1.5 \cdot 10^{19}\ cm^{-3}$ and $10000\ K \leq T \leq 25000\ K$. The obtained results can be already used for the interpretation of the experimental results in wide area of the electron densities and temperatures, and they could clearly determine the direction of the further development of the model methods based on cut-off Coulomb potentials.

3.16 Density effects in crossover from bound to free states in plasmas

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The self-consistent joint description of free and weakly bound electron states in equilibrium plasmas is presented. An attempt is done to separate density and temperature effects on restriction of the number of atomic excited states and smooth crossover from bound pair electron-ion excited states to collective excitations of free electrons. The molecular dynamics method is applied since the method is able to distinguish all kinds of fluctuations. The electron-ion interaction is described by the density– and temperature–independent cutoff Coulomb potential. The concept of pair fluctuations elucidates the smooth vanishing of atomic states near the ionization limit. Some examples are discussed. It is shown that the spectrum domain intermediate between low-lying excited atoms and free electron continuous energy levels is defined by the density effects. The influence of temperature is of minor importance. So there is no direct correlation between optical properties and nonideality parameter. Whereas the change of collisional recombination from Fokker–Planck diffusion to one-jump regime takes place at the increase of the nonideality. Both single and multiply ionized plasmas are considered.

3.17 Interparticle interactions effect on behavior of caloric equation of state for plasma of dense metals vapor

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State of the metals changed from the solid to gaseous state at Joule heat, there is occurs metal-nonmetal transition. Many experimental and theoretical papers are devoted to investigation of features of this transition. Pressure, internal energy and conductivity are experimentally measured for rapid heated metal wires and foils. We suggest the 7 components chemical model of dense metals vapor plasma consisting of electrons, atoms, single, double and triple ionized atoms, molecules and molecular ions. The model is used for calculation of caloric and thermal equations of state (EOS) and plasma composition. All kinds of antiparticles interactions (charged-charged, charged-neutral, neutral-neutral) were considered. To take into account free charges interaction the Debye theory in grand canonical ensemble (BD) and nearest neighbor approximation (NNA) were used. Ion-atom interactions are considered in different approximation: second virial coefficient, virial coefficient with Hill correction, Likalter approximation. Electron-atom interaction was taken into account in scattering length approximation. Wigner approximation is used for estimation of scattering length using electron affinity. Pressure dependence on internal energy for isochors of various metals (aluminum, copper, titanium, gold) were calculated. The plasma resistivity in depend on internal energy was calculated using Frost's interpolation formula. The satisfactory agreement with experimental data is received.

3.18 Influence of the correlation effects on the scattering and absorption of the electromagnetic waves in plasma

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On the basis of equation for electron shift caused by the influence of quasielastic restoring force, friction force and force of electromagnetic field, electrical dipole moment of plasma unit volume is obtained as a function of external field frequency, intrinsic frequency and electron-ionic collision frequency, The electron-ion collision frequency is calculated with the aid of pseudopotential taking into account correlation effects at large distances.

Numerical calculations of real and imaginary parts of plasma polarizability shows that correlation effects have essential influence on the absorption and scattering spectrum of electromagnetic waves in plasma.

3.19 Transport coefficients in dense plasmas including ion-ion-structure factor.

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Within linear response theory, a general approach to the thermoelectric transport coefficients has been given. Different approximations for the collision integral are considered. Particular attention is drawn to dynamical screening and the ion-ion structure factor. Results are given for electrical conductivity and thermopower in comparison to earlier approaches as well as experiments.

3.20 Correlation build-up in trapped charged particle systems

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The formation of correlations in non-ideal plasmas and the associated heating or cooling effects have attracted considerable attention in recent years [1–4]. These results were obtained for macroscopic plasmas. Here, we reconsider this question for classical charged particles confined by a spherical trap. Starting from an uncorrelated state we investigate the correlation build–up and the formation of a Coulomb liquid and solid. The method applied is first–principle molecular dynamics. We observe an oscillatory behavior of the potential energy with the signature of a breathing oscillation of the whole cluster and a non-trivial dependence of the transient energy absorption on the choice of the initial density profile. Results are also presented for the time-evolution of the mean density profile and the temperature relaxation to equilibrium.

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3.21 Wigner representation of quantum mechanics and dynamic conductivity of dense hydrogen

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Combining both molecular dynamics and Monte Carlo methods for solving the integral Wigner–Liouville equation we calculate the temporal momentum-momentum correlation functions and their frequency-domain Fourier transforms. Alternatively, at low temperature we use the density functional theory and the Greenwood formula to obtain frequency–dependent electrical conductivity. In the canonical ensemble at finite temperature for weakly coupled plasmas the obtained numerical results agree well with the Drude approximation. The growth of coupling parameter results in strong deviation of the frequency dependent conductivity and permittivity from low density and high temperature approximations. In particular, slowly–damping oscillations on the momentum-momentum temporary correlation functions can be observed, and the transparency window appears on the dependencies of electrical conductivity on frequency.

3.22 Magnetoresistance of Shock-compressed Non-ideal Argon Plasma

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New results of measurements of magnetoresistance of shock-compressed argon plasma in a transverse magnetic field are presented. The plasma was generated behind powerful shock waves in argon at normal initial conditions with the help of linear explosive generators. Magnetic field with induction 17 – 22 Tesla was produced by discharge of a capacitance bank through a solenoid reeled on the generator channel. Magnetoresistance and conductivity of non–ideal ($\Gamma = 0.2 - 0.3$) magnetized ($\omega\tau = 0.2 - 0.3$, ω–electron cyclotron frequency, τ–electron momentum relaxation time) plasma were determined by probe techniques. The influence of non–ideality and magnetic field on magnetoresistance was registered. The obtained results are compared with transport theories of plasma with strong interparticle interaction.

3.23 Uniform Electrical Discharge through Solid Xenon

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The peculiarities of free electron drift in solid xenon dramatically differ from these in xenon gas of the same density; and as a result in a solid the electrons can be accelerated by electrical field up to energy of several eV being sufficient for the matrix electronic excit ation [1]. Basing on this fact we realized the electrical discharge in solid xenon [2] and studied the spectra of the matrix electroluminescence [3]. The discharge in a solid reveals the nature of collective excitation in condensed state by the same way as the gas discharge allows revealing the nature of excitation for individual particles.

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4 Dense hydrogen

4.1 Thermodynamic properties of isentropically compressed hydrogen (deuterium) of megabar range

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The data for three experiments on quasi-isentropic compression of dense hydrogen (deuterium) at megabar pressure range are under discussion and comparison with theoretical predictions. The main statement is claimed and supported that the results on relatively high-temperature compression [1, 2] and new results on relatively low-temperature compression [3], see also this conference) do not contradict nor confirm each other. Hypothetical theoretical explanations of density discontinuity, which were measured at high-temperature isentropic compression, are discussed.

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[2] Fortov et al. PRL **99** (2007).
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4.2 Semiempirical multiphase equation of state of liquid hydrogen

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Semiempirical equations of state for dielectric and plasma phases of liquid hydrogen were constructed. Dielectric phase was modeled as dissociating molecular — atomic mixture. Model reproduces experimental results for single shock compressed hydrogen. Equilibrium line of plasma phase transition was built. For quasi isentropic compression the plasma phase transition occurs at the pressure 130 GPa, according to the current model. Model reproduces experimental results for conductivity of compressed hydrogen under assumption that plasma phase clusters are formed in the dielectric phase of hydrogen.

4.3 Conductivity of multiple shock compressed hydrogen along 135 and 180 GPa isobars

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The results of temperature and conductivity measurements of hydrogen, multiple shock compressed to the pressures 135 and 180 GPa are presented. Explosively driven steel plate with velocity up to 8 km/s was used for shock wave generation. Hydrogen with different initial pressures and temperatures was multiple shock compressed between steel bottom and sapphire window. Brightness temperature of hydrogen was measured by fast optical pyrometer. Electrical resistance of shocked hydrogen was measured simultaneously with optical pyrometer records.

The conductivity of hydrogen decreased from 424 $1/\Omega/cm$ at 2700 K down to 20 $\Omega^{-1}cm^{-1}$ at 6000 K along 135 GPa isobar. The conductivity of hydrogen decreased from 800 $\Omega^{-1}cm^{-1}$ at 5000 K down to 100 $\Omega^{-1}cm^{-1}$ at 6700 K along 180 GPa isobar. Experimental results are compared with different theoretical predictions.

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4.4 Isentropic Compression of Substances Using Ultra-High Magnetic Field: Zero Isotherms of Protium and Deuterium in Pressure Range up to 5 Mbar

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Experiments on isentropic compression of a substance using a high magnetic field pressure are described. Their goal is building of a zero isotherm in a multi-megabar pressures range. A method of the pressure and density determination of the compressed substance based on radiographic data obtained in the experiment is presented. The results of the experiments with solid (in initial state) protium and deuterium are presented. The densities that correspond to more than seventeen-fold compression are reached. Obtained experimental points are compared with extrapolation of a curve that is built

in the experiments using anvil cells and with the results of several ab-initio calculations.

4.5 Dynamic properties of one-component strongly coupled plasmas: the mixed Löwner-Nevanlinna-Pick approach

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The dynamic characteristics of strongly coupled one-component plasmas (the dynamic structure factor, the dynamic local-field correction, the dispersion and decay of collective modes) are studied within the moment approach with local constraints [1,2], similar to that of Schur. The dynamic structure factor is modeled as a rational or non-rational function in a way that its extension onto the upper half-plane of complex frequency is holomorphic with values having nonnegative imaginary part and with a continuous extension to the real axis, by the first three terms of its asymptotic decomposition at infinity and its values at a few points of the real axis.

The results satisfy not only the sum rules and other exact relations automatically, but, also, interpolate between these real frequencies. A quantitative agreement is obtained with simulation data on plasma dynamic properties [3]. The method permits to take into account the energy dissipation processes so that the results of alternative theoretical approaches are included into the moment scheme and are complemented as well.

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4.6 Reflectivity of hydrogen along the Hugoniot curve using QMD simulations

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The reflectivity derived from shock wave experiments is an important measure to probe the equation of state (EOS) and the metal-insulator transition of hydrogen at high pressure. We calculate the EOS of hydrogen and deuterium performing quantum molecular dynamics simulations. Results for the EOS and the Hugoniot curve for different initial conditions are presented. The optical conductivity and reflectivity is obtained evaluating the Kubo-Greenwood-formula and the non-metal-to-metal transition is discussed. We compare with experiments and other theoretical approaches, especially with chemical models as, e.g., the fluid variational theory.

4.7 Equation of State of Shock Compressed Hydrogen

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Experimental results presented more then 10 years ago for deutherium compressed by laser-generated shock waves has attracted attention of researchers to thermodynamics of hydrogen of megabar pressures. Recent experiments provided with Z-mashine in Sandia, new laser results of LLNL and those on shock and isentropic explosively driven compression in Sarov give new important information for development of thermodynamic theory for dense partially ionized hydrogen. Improved model for equation of state (EOS) of warm dense hydrogen is developed in frames of chemical picture. Hydrogen is considered as multi-component strongly interacted mixture of atoms, molecules, ions and electrons. Effects of Coulomb interaction of charged particles, strong repulsion at short distances and degeneracy of free electrons are taken into account. Behaviour of the model is examined by comparison with whole collection of experimental data on compression of pre-compressed gaseous, liquid and solid deuterium. For liquid deuterium this comparison is painted in secondary shock. Additionally, results of calculations are compared with first principle computed data for Hugoniots and double shock. Asymptotics of presented model is studied for very high pressures along Hugoniots of deuterium. This is demonstrated by comparison with first principle calculations and results obtained with asymptotically exact models.

5 Laser and heavy-ion-produced plasmas

5.1 An Overview of Proposed High-Energy-Density Research at the FAIR at Darmstadt: The HEDgeHOB Collaboration

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Substantial progress in the technology of high quality, well focused, strongly bunched, high intensity particle beams has led to the development of a new scheme to study High Energy Density (HED) Physics. This involves generation of samples of HED matter by isochoric and uniform heating of solid targets by the particle beams. These beams can either be generated by traditional accelerators or by high intensity petawatt lasers. Gesellschaft fuer Schwerionenforschung (GSI), Darmstadt is a well known laboratory worldwide due to its unique accelerator facilities that include a heavy ion synchrotron, SIS18, which can deliver intense beams of all stable isotopes from protons up to uranium. The acceleration capabilities of the GSI will be greatly enhanced with the completion of the Facility for Antiprotons and Ion Research (FAIR) which is now entering into construction phase. The beam intensity will increase by a factor of 100 compared to the current level which will lead to a specific energy deposition of 100 kJ/g and a specific power deposition of 2.5 TW/g. These unprecedented beam parameters will allow one to carry out novel and unique experiments in the filed of HED physics.

Extensive theoretical work that includes analytic modeling as well as sophisticated 2D and 3D numerical simulation, has been carried out over the past years to design numerous experiments to study HED physics at the FAIR. One scheme named HIHEX (Heavy Ion Heating and EXpansion), can be used to study the equation-of-state (EOS) properties of different physical states of HED matter that can be generated by isochoric and uniform heating of solid or porous targets followed by isentropic expansion. Another scheme named, LAPLAS (LAboratory PLAnetary Science), that generates a low-entropy compression of a sample material like hydrogen or water in a multi-layered cylindrical target, is suitable to study the interiors of the giant planets. Moreover, in a third type of experimental set up, an intense ion beam can be used to drive a ramp type compression of a solid target. This type of cold shockless compression can be used to study material properties of the sample, like shear modulus and yield strength, under dynamic conditions.

5.2 Ability of plasma to absorb laser radiation depending on the angle of its interaction

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We have conducted experiments in time-of-flight mass-spectrometer connected with electrostatical analyzer to determine the effect of absorbed energy to the charge and energy state of plasma as well as emission of ions. Investigations are conducted in two regimes. In the first case laser radiation with intensity $q = 10^{11}$ W/cm^2 interacted at the angles $\Theta \sim 20^\circ - 70^\circ$ with the targets made of Al, Fe and W and located perpendicular to the axis of the mass-spectrometer. In the second case the same laser interacts at the case angle with the plasma generated previously by the second laser with the same parameters as the first one.

It was found experimentally that, in both cases the laser radiation is more absorbed at small angles $\Theta \leq 23^\circ$. At the same time the charge and energy spectra of ions, as well as their emission increases more effectively in the second case. In both cases with increasing Θ from 20° to 70° the intensity of single charged ions increases while the intensity of highly charged ions decreases.

The analysis of energy spectra of ions in both regimes shows that with increasing Θ the shape of energy spectra for ions with charge $Z \geq 1$ practically does not change, although the maximum of the distribution shifts to lower energies. We also found that the maximum of the energy spectra depends not only on q but also on the mass of the target element A: at small interaction angles larger A leads to larger maximal energy, while for small Θ this dependence is not observed.

We also found that the effect of increased charge and energy state of plasma in the second case can be increased by delaying the laser radiation with $q = 10^{11}$ W/cm^2 relative to the laser with $q = 10^8$ W/cm^2, i.e. to form optimal condition for the consecutive heating of the plasma.

Considerable increase of ions charge in laser-produced plasma, formed in the second regime at small angles can be explained by the resonant absorption of laser radiation on the boundary of gradient of plasma density.

5.3 Resonance penetration of intense femtosecond laser pulses through plasma of ultra-thin foils

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Analytic expression for the transmission coefficient as a function of foil thickness describing penetration of intense femtosecond laser pulse through ultra-thin foils with the thickness of the order of 30 – 100 nm has been derived using the Vlasov-Boltzmann equation.

When an intense femtosecond laser pulse impinges on a thin foil, crystal lattice is destroyed and dense plasma with sharp boundary is produced. In recent experiment of Antici et al, at the irradiation of thin Al foils by the laser pulse with the duration of 300 fs and the peak intensity of $5{\cdot}10^{19}$ W/cm^2 most of free electrons inside the foil had the kinetic energy of about 100 eV. Of course, small amount of electrons are heated up to 100 – 300 keV and more due to inverse induced bremsstrahlung on the critical surface and other mechanisms (so called hot electrons). But their number density is very small, of the order of 10^{19} cm^{-3}. These estimates of the energy of cold electrons are confirmed by the numerical derivations Passoni et al. Typically the ratio of the energies of cold and hot electrons is of about 0.01. It should be noted that atomic ions inside the foil do not move significantly during femtosecond times so that foil surface remains immovable. The energy of bulk electrons in foil of the order of 150 eV was observed also by Chen et al at the peak laser intensity of 10^{18} W/cm^2 and the pulse duration of 60 fs.

It is found that the transmission of laser radiation stops on the skin depth, but sharp and narrow resonances take place when the foil thickness is larger than skin depth, where the transmission coefficient T = 1. Thus, we predict a non-monotonic behavior of the transmission coefficient with maxima and minima as a function of the ultra-thin foil thickness. Unlike known results of Ferrante and Uryupin [1], it can be observed also at isotropic velocity distribution of heated electrons in foil plasma. Our results can be used, for example, for exact determination of thickness of ultra-thin foils based on the measurements of resonant transmission coefficient at the penetration of femtosecond laser pulses, or for determination of the velocity distribution of heated electrons inside the foil plasma. Preliminary results of this work have been published in Refs. [2, 3].

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5.4 Simulations of Shock and Quasi-Isentropic Compression Experiments Driven by Intense Heavy Ion Beams

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In this contribution, the capabilities of the new heavy-ion beam facilities at the Gesellschaft für Schwerionenforschung Germany, Darmstadt to drive laboratory astrophysics (LAPLAS) [1] and ramp wave loading experiments [2] are investigated.

A wide range hydrogen equation of state encompassing solids to high-temperature plasmas was constructed employing experimental data and first principles simulations. These EOS data were then used in our hydrodynamic simulation of LAPLAS targets. In the simulations, the transition of hydrogen from the frozen state at 14 K up to maximum of the melting line and beyond was considered. The results of the hydro-simulations indicate that, using the capabilities of the FAIR, it will be possible to access the regions of solid and fluid molecular hydrogen around the maximum of the melting line as well as the metallic fluid region. By careful tuning of beam parameters it should be possible to determine the hydrogen melting line in the high-pressure region.

Furthermore, a new design for heavy-ion beam driven ramp wave loading is suggested and analyzed. The proposed setup utilizes long stopping ranges and the variable focal spot geometry of the high-energy uranium beams, to produce a planar ramp loading of various samples. In such experiments, the predicted high pressures amplitudes (< 10 Mbar) and short timescales of the compression (< 10 ns) will allow testing the time-dependent material deformation phenomena at unprecedented extreme conditions.

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5.5 Comparison of two theories during self focusing of laser beams in relativistic plasma.

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In the present paper, Self focusing of laser beams in relativistic plasmas is studied by moment theory approach. Equilibrium beam radius of self trapped laser beams is also derived. Results are compared with paraxial ray approximation. It is observed from the analysis that moment theory predicts almost flatter dependence of equilibrium beam radius on intensity than does paraxial ray approximation as intensity of beam increases. This is found to be true on account of saturating nature of relativistic non-linearity. So, the agreement between two theories worsens as the power of beam increases.

5.6 Potential of the Large Hadron Collider at CERN to Study High Energy Density Physics

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Motivation to construct the Large Hadron Collider (LHC) comes from fundamental questions of particle physics. Each of the two beams of this impressive accelerator comprises of 2808 bunches while each bunch is made of $1.15 \cdot 10^{11}$ 7 TeV/c protons. The total energy stored per beam is about 360 MJ that is sufficient to melt 500 kg of copper. Safety of operation is an extremely important issue in the presence of such powerful beams. A rapid loss of even 0.002 % of the 7 TeV/c beam at one spot could already damage a high-Z material like copper. A worst case scenario is the possibility of the full LHC beam being lost at one place. Although the probability of an accident of this magnitude is extremely small, nevertheless it is important to have full knowledge of the consequences if it ever happens. This information is essential in order to design the protection systems of the machine correctly, to set admissible risk

levels, and to determine the inventory of the spare parts needed to possibly replace the damaged equipment.

For this purpose, we carried out numerical simulations of interaction of one LHC beam with a solid copper cylindrical target. First, we calculate the energy loss by 7 TeV/c protons in copper using the FLUKA code [1], which is a fully integrated particle physics and multi-purpose Monte Carlo simulation package capable of simulating all components of the particle cascades in matter up to multi-TeV energies. This data is used as input to a 2D computer code, BIG2 [2] to simulate the hydrodynamic and thermodynamic response of the target. These simulations have shown that the LHC beam will penetrate up to 35 m in solid copper and the target material will be transformed into High Energy Density (HED) matter. This could be an additional, very important application of the LHC.

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5.7 Pump-probe "seismology" of ultrafast two-temperature processes inside a film irradiated by a femtosecond laser pulse

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Report presents new results in theory and experiments concerning short pulse laser – matter interaction. Two terawatt laser sets (Ti:Al_2O_3, 800 nm, $\tau = 10 - 40$ fs and Cr:Mg_2SiO_4, 1240 nm, $\tau = 100$ fs) and pump-probe technique of optical measurements are used. Pump-probe technique allows to observe evolution of a target after pump action with extremely small time steps between successive measurements. The step is defined by probe duration τ. Theory is based on two-temperature (2T) hydrodynamic and molecular dynamic modeling. Measurements and calculations include:

(1) Accurate definition of pump absorption - our calculations start from absorbed fluence F_{abs}, not from incident F_{inc} as in other works. For met-

als reflection is large and F_{abs} is small. Any error in reflection coefficient significantly influences F_{abs} and therefore results;

(2) Early subps-ps probing of irradiated area to obtain data set #1 related to 2T physics. Experiments and simulations point out to the qualitative differences in optical response to pump between simple, noble and transition metals related to their band structures;

(3) Probing at 1–100 ps time interval to obtain data set #2 about rate of propagation and depth into bulk of heated zone at a 2T stage. Also this set contains information describing strength $P_{tns}|_{lim}(T_{nucl}, \dot{V}/V)$ of a melt at different temperatures defined by F_{abs} and at extremely high values of an expansion rate $\dot{V}/V \cong 10^{10} s^{-1}$. Increasing of F_{abs} increases temperature T_{nucl} in nucleation zone and thus decreases strength $P_{tns}|_{lim}$ to resists stretching. At present data about strengths of molten metals are poor;

(4) Plume formation and composition at much more early stage than measured in other works by optical methods at sub μs or by time-of-flight mass-spectrometer many μs later;

(5) Pump-probe micro-interferometry of expansion of a rear-side vacuum boundary in case of thin ($d_f \sim$ sub μm) and moderate ($d_f \sim \mu m$) foils.

Thin foils are used to get 2T data set #3 because rear-side expansion is controlled by a profile of an acoustic wave coming to the rear-side from irradiated frontal side while the wave profile is formed during a short stage of rapid expansion into bulk of a 2T zone. This is a sense of acoustic probing. Moderate foils are necessary for measuring of material strength $P_{tns}|_{lim}$ in solid state. In such foils nucleation starts in crystal lattice near a rear-side which is not affected by the frontal 2T heating and melting. Again rates $\dot{V}/V \cong 10^{10} s^{-1}$ are extremely high in comparison with more ordinary measurements at thicker foils and with at least three order of magnitudes slower (than the pump-probe micro-interferometry) VISAR device. In previous set up peoples try to simplify profile of an acoustic wave. Usually it is a "triangular" shock. They do it to see better kinetic phenomena initiated by wave, e.g., HEL and plastics manifestations, polymorphic transitions, and nucleation of voids. In our approach we do both: $P_{tns}|_{lim}$ measurements for simple acoustic profiles (using foils of moderate d_f) and measurements (with thin foils) of real complicated profiles which carry traces of fast non-equilibrium 2T processes depending on band structure (seismology of the 2T zone).

5.8 Specific features of spallation processes in a Plexiglas (PMM) under high strain rate

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Direct laser interaction and laser-driven thin foils were used for investigation spallation phenomena in a Plexiglas (PMM) targets in case of high value of strain rates. In experiments the aluminium foils with thickness 8 and 15 μm were used as impactors. The laser-driven foils mass and velocity after laser ablation and acceleration were determined by the method of their deceleration in a gas atmosphere. In experiments the 700 μm Plexiglas plates were used as the targets. On the base of experimental data we measured the position of the spallation plane and the moment at which the spall layer arrived at an additional electrocontact sensor arranged beside of rear side of target. The moment of spallation was fixed by means of piezoelectric sensor. Then, the values of spall strength and strain rate were determined by the using numerical simulations with a hydrodynamic code with a wide-range semiempirical equation of state of PMM. As a result of experiments, we found at the first time that in case of strain rate varying from 1.5 to $6 \cdot 10^6$ s^{-1} the ultimate spall strength of PMM (10 kbar) was achieved. This value has been compared to a theoretical estimation.

5.9 Dense Xenon Nanoplasmas in Intense Laser Fields

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The interaction of intense laser fields with xenon clusters is investigated using the nanoplasma model which allows to describe different processes like ionization, heating, and expansion that occur during the laser-cluster interaction by a coupled set of hydrodynamic and rate equations.

The initial plasma in the cluster is created due to tunnel ionization described by the well-known ADK-rates. For the heating rate due to inverse bremsstrahlung, a quantum statistical expression including resonant absorption was used. Furthermore, collisions of electrons with the cluster surface are

included. An important issue of laser-cluster interaction is the creation of a high-density nanoplasma. Here, the influence of correlation effects such as the lowering of the ionization energy on the ionization kinetics is of importance. Using generalized electron impact ionization rates, we found an enhancement of the yield of highly charged ions.

An effective tool to control the plasma dynamics is pulse shaping where phase and amplitude of the laser pulse are simultaneously modulated. In particular, the yield of highly charged ions can be controlled. For an understanding of the underlying physical processes in the dynamics of laser-cluster interaction, a theoretical description using a genetic algorithm and basing on the relatively simple nanoplasma model seems to be promising. In the present approach, the time evolution of the laser intensity has been parametrized. The parameters where optimized with a genetic algorithm to get, e.g, a maximal yield of a specific ion species.

The work was supported by the Deutsche Forschungsgemeinschaft, SFB 652.

5.10 High Energy-Density Physics with Heavy Ion Beams and related Interaction Phenomena

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The experimental programs of the HEDgeHOB collaboration at the upcoming Facility for Antiproton and Ion research (FAIR) in Darmstadt will be introduced. This facility will deliver unprecedented beam intensities of very energetic heavy ions which can be used to create extreme states of matter. This will allow one to study condition as in large astrophysical objects or during inertial confinement fusion.

Ion beam-matter interactions as needed for these experiments have been a subject of very extensive and longstanding experimental and theoretical research. Since the advent of intense proton and light ion beams generated by intense lasers this field has experienced a renaissance. This research is motivated by the application of ion beams for well tailored energy deposition in matter needed for inertial fusion, matter heating and tumour therapy which require a detailed and very precise knowledge of the energy deposition profiles. The target materials are in the plasma-, gas-, liquid- or solid state, also pourous material is of considerable interest. Since the environment influences the energy deposition process, it is necessary to study the underlyinginteraction mechanisms experimentally and theoretically in as much detail as possible. Newexperimental results will be presented and reviewed with respect to experimental programs of the HEDgeHOB collaboration.

5.11 Experimental investigation of femtosecond laser ablation spectral thresholds, condensed matter-dense plasma phase transition dynamics in ambient and vacuum conditions

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The results of femtosecond condensed matter laser ablation opto-thermophysical and radiative gasdynamic processes experimental investigation are presented.

Laser irradiated condensed matter mass flow dynamics is an object of great interest, but is also rather difficult to be experimentally analyzed. While integral ablation rates can be obtained using several methods, data on mass flow dynamics are usually results of numerical simulations. Only two experimental time-resolved methods to investigate ablative mass flow could be rather simple to realize: high-energy photons beam probing and interference microscopy.

Using time-resolved interference microscopy (Michelson interferometer) femtosecond laser ablation spectral thresholds, mass flow integral rate and dynamics have been experimentally investigated for thin film and bulk Ti, Zr, Cu, Mo, Nb, $(CH_2\mathrm{O})_n$, $(C_2F_4)_n$, LiF and fused silica. Targets were irradiated by Ti:Saphhire laser (E/S=0,1-40 J/cm^2 r_0 20μm; τ_{FWHM}=45 fs; λ=266, 400, 800 nm) both in ambient and vacuum ($5 \cdot 10^{-4}$ mbar). Crater and near surface plasma dynamics have been investigated with 300 nm spatial and 100 fs temporal resolution. Mass flow integral rates measured are 10^{-5}-10^{-4} g/J. Ablation thresholds are shown to decrease for shorter wavelength irradiation.

Plume dynamics and macrostructure were analyzed using time-resolved interference (Mach–Zehnder interferometer) and shadow imaging at the same conditions and simultaneously with interference microscopy. Transient density distribution, shockwave (10^3 – 10^5 m/s) and plume velocities have been obtained. Plume average temperature and composition were estimated from emission spectra.

Crater and plume dynamics interconnection is considered and advantages of complex experimentla analysis are discussed. Femtosecond laser ablation performance for different target materials, irradiation wavelengths and ambient conditions is analysed. Presented results are discussed and compared with nanosecond laser ablation.

5.12 Spallative ablation: from metals to dielectrics and from infrared to X-ray lasers

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There is outstanding progress in development of variety of X-rays lasers (XRL) from ones based on transient-collisional and high order harmonic generation schemes to free electron lasers (FEL). Indeed, it is enough to remember extreme parameters of FEL which will be achieved in few years: pulse duration $\tau_L \sim 1$fs, sub-Angstrom wavelengths ($\hbar\omega \sim 20$keV), and intensity up to $\sim 10^{23}$W/cm^2. There are a lot of applications and ablation is one of the most promising. The report presents theory of experiments done on ablation of wide-gap LiF crystal by XRL in Kansai Photon Science Institute with 90 eV soft X-ray photons and $\tau_L = 7$ps. The theory explains why experimental ablation threshold $F_{abl} \approx 10$mJ/cm^2 is drastically small: it is order of magnitude smaller than F_{abl} for XRL with long pulse $\tau_L = 1.7$ns and several orders of magnitude smaller than F_{abl} for dielectrics irradiated by infrared (IR) or visible light lasers with short or long pulses. The explanation is based on **spallative ablation** (SA) mechanism. Previously SA was exclusively attributed to metals and semiconductors irradiated by short laser pulses with optical photons ~ 1eV. Discovery of SA begins from surprising fact of non-monotonous reflection (**Newton rings**, Nr) found in outstanding experiments done by Sokolowski-Tinten et al. [1]. It turns out that the phenomenon of Nr is universal - it was found in all checked metals and semiconductors without any exception. But despite many attempts with similar lasers they *never have been seen in dielectrics*. Explanation of the phenomenon [2] introduces SA into the list of the most important ablation mechanisms.

This report demonstrates that SA takes place in dielectrics if IR or optical lasers are changed to X-ray. Therefore SA becomes very important for future applications of XRL.

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5.13 Transient electron-hole plasma induced in dielectrics by high-intensity laser or particle beams.

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Lasers and ions of sufficiently high intensity or energy, respectively, couple mainly to the electronic system of a solid. Depending on the beam energy, electrons are transferred on a femtosecond timescale from the valence band or inner shells, respectively, to the conduction band. Furtheron, impact ionization leads to an increase of the density of the excited electron-hole plasma.

In this talk we review different aspects of electronic excitation, studied with time-resolved models as the multiple rate equation, Monte Carlo simulation or Boltzmann kinetic approach. We are able to identify the laser-induced dielectric breakdown as a mechanism where two concepts of damage threshold are fullfilled simultaneously: a change of optical parameters leading to an increased photon absorption as well as sufficient energy absorption to melt the lattice. We show the influence of pulse shape on damage threshold due to different dependencies on time and intensity of both absorption processes. For the case of irradiation with ions, we demonstrate that macroscopic nanohillocks originate from spatially discontinous excitation of electrons.

5.14 On the modeling of laser-metal interactions

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On the basis of the kinetic model for laser plasma [1, 2] which permits to include into consideration available phenomenological data on the initial metal state of a target, we develop the numerical model for simulation of laser-metal interaction. This model consistently describes two-temperature effects, thermal conductivity, permittivity, electron-ion energy exchange and ionization. Wide-range semi-empirical models of transport properties describe available experimental findings and permit *ab initio* calculations starting from the room temperature of metal targets in the wide range of laser intensities and pulse durations.

We study numerically the interaction of subpicosecond laser pulses with metal targets of Al, Cu and Au. The intensity range of 10^{13}–10^{18} W/cm^2 achieved in the experiment [3] enables us to verify our numerical model in a wide range of plasma parameters. We find out that correct description of transport and optical properties of the target in wide range of densities and temperatures are extremely important for accurate reproduction of the experimental data.

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5.15 Radiative properties of substances at high energy density and optimizing soft X-ray sources for ICF applications

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Theoretical and experimental studies of radiative properties of substances at high energy density have been carried out depending on the plasma compositions, which are used as soft X-ray sources. Important features of the theoretical model, which can be used for complex materials, are discussed. An optimizing procedure that can determine an effective complex material to produce optically thick plasma by laser interaction with a thick solid target is applied. The efficiency of the resulting material is compared with the efficiency of other composite materials that have previously been evaluated theoretically. It is shown that the optimizing procedure does, in practice, find higher radiation efficiency materials than have been found by previous authors. The optimizing method is also demonstrated for different plasma temperatures and densities. Similar theoretical research is performed for the optically thin plasma produced from exploding wires. Theoretical estimations of radiative efficiency are compared with experimental data that are obtained from measurements of X-pinch radiation energy yield using two exploding wire materials, NiCr and Alloy 188. It is shown that theoretical results agree well with the experimental data [1]. Complex X-pinch, where W and Mo wires are used, is considered. Theoretical explanation of experimental phenomena is discussed basing upon W and Mo radiative spectra.

Keywords: The radiative opacity; Rosseland and Planck mean free paths.

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5.16 Nonideal plasma physics in the ITEP and GSI FAIR team projects

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Knowledge of basic physical properties of matter under extreme conditions of high energy density, and in particular nonideal plasma, such as equation-of-state, static and dynamic electrical conductivity and opacity is of fundamental importance for various branches of basic and applied physics. Intense beams of energetic heavy ions provide a unique capability for the nonideal plasma research compared to traditional drivers . Using intense ion beams, one can heat macroscopic volumes of matter fairly uniformly and generate this way high-density and highentropy states. This new approach permits to explore fascinating areas of the phase diagram that are difficult to access by other means. In this report we discuss various physics and technical issues of the high-energy-density physics (HEDP) research with intense heavy ions beams that is being performed at GSI, as well as that is to be carried out at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt by the HEDgeHOB collaboration. The results of the recent experiments carried out at GSI are presented along with new developments in target and ion-beam diagnostic instruments and methods that are essential for the future experiments at FAIR.

5.17 Non Linear propagation of intense laser beams through collisional plasmas

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In the present paper, Non–linear propagation of intense laser beams through collisional plasma is studied by moment theory approach. As a result of it self focusing happens. Effect of change in absorption coefficient and plasma density on beam width parameter is also analyzed. It is observed from the analysis that increasing the plasma density decreases focusing length due to increase in non–linear part of dielectric constant. Also, due to increase in absorption coefficient, extent of self focusing decreases. This is due to decrease in energy of beam which is equivalent to weakening of non linearity effect.

6 Dense astrophysical plasmas

6.1 Extreme states of matter on Earth and in space

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This report is concerned with the results of studies into the behavior of substances at ultimately high pressures and temperatures obtainable by way of kynetic or electromagnetic energy cumulation in laboratory condition. Also considered are the diversified states of mater and the processes occurring under gravitational forces and thermonuclear energy release.

6.2 High-precision equation-of-state formalisms for solar and stellar modeling

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For solar and stellar modeling, a high-quality equation of state is crucial. In addition, however, helioseismic and asteroseismic observations put constraints on the physical formalisms. Thus they effectively turn the Sun and the stars into laboratories for dense plasmas. Currently, the main astrophysical beneficiary of a good equation of state is the determination of the chemical composition of the solar interior. Here, seismic data have supplemented spectroscopic information. In contrast to the latter, they probe the composition in the interior, but the reliability of the seismic method hinges on the quality of the equation of state. Recently, there has been theoretical progress in the equation of state, thanks to renewed rigorous and phenomenological approaches. At USC, we have adapted, on the one hand, rigorous virial-expansions for stellar modeling. They have the potential of becoming a very accurate equation of state, despite their limited domain of applicability. On the other hand, we have developed phenomenological, parameterized formalisms, which are interesting alternatives to proprietary and pre-computed, table-based efforts. Their enhanced user-friendliness will facilitate implementation in astrophysical applications.

6.3 Thermodynamic functions of dense plasmas: approximations for astrophysical applications

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We briefly review approximations of thermodynamic functions of nonideal plasmas at the conditions typical of white dwarfs and neutron star envelopes. The main focus is on the fully ionized electron-ion plasmas, for which we present several corrections and improvements to previously published formulae and take into account arbitrary magnetic fields.

We also present recent numerical and analytical results for the equation of state of mixtures of different ion species and describe a transition from strong to weak Coulomb coupling for ion mixtures.

The work was supported in part by the Rosnauka Grant NSh-2600.2008.2 and the RFBR Grant 08-02-00837.

6.4 Low-velocity ion stopping in binary ionic mixtures

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Stopping power of thre component plasmas contains carbon an ferrum ions are developed.

6.5 Account of atomic and molecular contributions in the equation-of-state for a weakly non-ideal hydrogen plasmas

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Convergent partition function for atomic and molecular bound states is derived for weakly non-ideal hydrogen plasmas. Corrections due to charged-neutral particles interactions are also described. These contributions were realized in the model equation of state of hydrogen plasmas and the HEOS code. The physical model EOS also includes the Coulomb and diffraction corrections, contributions of the scattering states, electron and ion interactions, and the radiation pressure. The calculated dependences of the adiabatic exponent, sound speed and heat capacity are presented.

6.6 Corrections to linear mixing in binary ionic mixtures and plasma screening at zero separation

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We discuss corrections to the linear mixing rule in strongly coupled binary ionic mixtures. The discussion is based on extensive Monte Carlo simulations. In particular, we analyze the Coulomb energy as well as the plasma screening function at zero separation, $H_{ij}(0)$, for two ions (of types $i = 1, 2$ and j=1,2) in a strongly coupled binary mixture. The function $H_{ij}(0)$ is estimated by two methods: (1) from the difference of Helmholtz free energies at large and zero separations; (2) by fitting the Widom expansion of $H_{ij}(x)$ in powers of interionic distance x to Monte Carlo data on the radial pair distribution function, g(x). Both methods are shown to be in good agreement. For illustration we analyze nuclear burning rates in dense stellar matter.

6.7 Interior structure of Jupiter and Saturn after 40 years of modelling

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Jupiter and Saturn continue to attract attention spurred by advances in various fields. Extrasolar giant planets for instance are classified with respect to solar giant planets; observational constraints for Jupiter and Saturn from Earth-based and space-based instruments are steadily progressing; methods of high-pressure experiments are improving, and the data shape the properties of Jupiter and Saturn's main constituents H and He; finally, the number of coexisting theoretical equations of state is growing, and Jupiter and Saturn are natural laboratories to check them.

Here we review and discuss our understanding of Jupiter's interior (core mass and metalicity) and of Saturn's interior (cooling behavior) with respect to high-pressure equations of state. Special emphasis is given on the method of ab initio molecular dynamics simulations for H and H/He mixtures as well as for H_2O. We discuss the effects of H-He demixing and of the nonmetal-to-metal transition in H on the interior structure of these planets.

6.8 Plasma polarization in massive astrophysical objects

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Macroscopic plasma polarization, which is created by gravitation and other mass-acting (inertial) forces in massive astrophysical objects (MAO) is under discussion. Non-ideality effect due to strong Coulomb interaction of charged particles is introduced into consideration as a new source of such polarization. Simplified situation of totally equilibrium isothermal star without relativistic effects and influence of magnetic field is considered. The study is based on variational formulation of equilibrium statistical mechanics. It leads to conditions of constancy for generalized (electro)chemical potentials and/or conditions of equilibrium for all forces acting on each charged specie. New "non-ideality force" appears in this consideration. Hypothetical sequences of gravitational, inertial and non-ideality polarization on thermo- and hydrodynamics of MAO are under discussion.

7 Phase transitions in plasmas and fluids

7.1 Fluctuation approach to the nonideal plasma equation of state calculation.

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The nonideal plasma equation of state is studied in the frames of the fluctuation approach which provides the self-consistent joint description of free and weakly bound electron states in equilibrium plasmas is presented [1]. The approach avoids a certain peculiarity of the chemical model for which at calculation of value of free energy the account of dependence of the statistical sums $Q_i(T, \varepsilon(\{n_j\}, T))$ from the thermodynamic parameters expressed through variable border of trimming of a spectrum of free particles $\varepsilon(n, T)$ is necessary. Direct result of the account of the given dependence is occurrence of additional corrections to all thermodynamic quantities containing derivatives $\partial Q_i(T, \varepsilon(\{n_j\}, T))/\partial\varepsilon$ [2].

The molecular dynamics method is used. The electron-ion interaction is described by the density- and temperature-independent cutoff Coulomb potential. The range of nonideality parameter $\Gamma = 0.1 \div 2$ is studied. In this region of parameters of nonideality there is an instability, which is characterized according to circular approach by positive value of a derivative of pressure on volume owing to what it is possible to assume occurrence of diphase area [3].

At the analysis of fluctuations of pressure the region of values of Γ in which appreciable difference of function of distribution of pressure from normal distribution is observed has been revealed, and the received results can be approximated by superposition of two Gauss distribution functions. The given fact could be considered as an indirect conformation of existence of diphase area.

Both single and multiply ionized plasmas are considered.

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7.2 LIFT transfer process modeling in ns and fs laser irradiation regimes

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Electron generation and heating in dielectrics is a well known phenomena [1]. The control of the deposited energy in the material allows to predict its behavior when submitted to a femtosecond, ultra-intense laser shot. A self-consistent model is developed that describes ionization process in dielectrics with ultraviolet to infrared laser beams. The energy deposition is described by a full set of Maxwell's equations in the 3D geometry accounting for non-linear propagation in the femtosecond time scale. The calculated energy deposition is transferred to an hydrodynamic code that describes the shock and compression waves expansion in the material.

In untrammeled backgrounds, sub-micron cavities are formed. Comparison to experiments [2] have permitted a good understanding of this process, and parameters of laser energy release and cavity formation are now well known in silica [3].

The above method is now applied to a confined background of water where cavity expansion leads to a jet formation at the interface. The aim is to understand the process of cells transfer via LIFT (Laser-Induced Forward Transfer) technique. Thanks to an hydrodynamic code, simulations have been carried out with nanosecond UV lasers and the jet diameter (10 microns) and velocity (tens of m/s) are comparable to experimental results. In this modeling it is shown that equation of states can have drastic influence. Specific EOS have been built in this low temperature, dense regime of plasma obtained after intense laser irradiation.

A new LIFT technique regime called nanoLIFT has been studied using femtosecond lasers. Jet diameters are found to be much smaller (hundreds of nanometers), allowing the transfer of tiny amount of material like biomolecules. A parametric study is performed in order to predict futur experimental results. Comparison with nanosecond lift has been carried out.

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7.3 Sound velocity measurements behind the shock wave in tin

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In the pressure range of $30 - 138$ GPa by optical method and the method of manganin gauges the sound velocity in shock-compressed tin was measured. The comparison of experimental data and the calculations was conducted. The tin melting range on the principal Hugoniot $(60 - 85)$ GPa was found.

7.4 Experimental and Numerical Study of Isentropic Compression by Laser Irradiation

*[3] **Koenig M.**, [3] **Brambrink E.**, [1] **Vinci T.**, [1] **Mazevet S.**, [2] **Guyot F.**, [2] **Morard G.**, [3] **Wei H.**, [3] **Barbrel B.**, [3] **Benuzzi-Mounaix A.**, [4] **Miyanashi K.**, [4] **Koadama R.**, [4] **Ozaki N.**, [4] **Kimura T.**

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The melting curve and EOS of iron or iron alloys at the inner core boundary (330 GPa, about 5000 K) are still unknown which severally limits current earth modelling. In order to answer partly to these issues, the French National Research Agency supported a program grouping several laboratories including geophysicists. Here we present recent work done within this project. It concerns numerical and experimental studies done on laser generated isentropic compression in iron. The experiments, performed on the LULI2000 laser facility, used two different set-up: indirect reservoir technique and direct ramp-shaped laser pulse irradiation. We will present the experimental data and compared first to numerical simulations done with a radiative-hydrodynamic code (MULTI). Then a second step has been done to couple this simulation with molecular dynamics to reproduce microscopic effects in materials. This is a multi-scale approach to simulate matter in these conditions: the ramp of compression wave of a hydrodynamic simulation is injected as ramp in a pure molecular dynamics simulation (using massive parallel STAMP code) to study the dynamics of the atomic structure of materials on strong stress on the same longitudinal and temporal scales of the experiment (some microns and 1 ns). This a key point to have a complete picture of the experiment since the hydrodynamic approach fails to understand the underlying mechanism of phase changes of the material.

7.5 The Investigation of Phase Changes in Cerium and Titanium by PVDF-gauges

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The phase transitions in shock-compressed samples of cerium and titanium with PVDF-gauges were investigated. In the pressure range of $4 \leq \mathrm{P} < 12$ GPa in cerium a double-wave structure, consisting of head compression wave and the following shock-wave was registered. Such a structure is formed in cerium as a result of isomorphic (γ–α) phase transition. The analysis of shock wave structure and rarefaction shock in the diapason of $(0.6{:}3.0)$ GPa proves that in cerium a rarefaction shock wave is formed in the release phase. In titanium, at the loading pressure of ≈ 21 GPa on the plastic wave profile an anomaly at the pressure of 11.5 GPa, which is associated with the phase $\alpha \rightarrow \omega$ transformation is found out.

7.6 Quasi-entropic compression of Helium in cylindrical devices at pressures of $\approx 100 - 460$ GPa

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The time motion trajectories of steel shells of cylindrical devices, filled with gaseous helium at initial pressure of 120 atm were registered in the series of experiments with two sources of rigid radiation. The minimum radius of helium compression was recorded, and an average gas density in the central part of the chamber was measured. The pressure of compression was obtained from the gas-dynamic calculations of experimental devices taking into account the equation of state of all construction elements. The comparison of the obtained results with the theoretical calculations was conducted.

7.7 Application of Proton Radiography to Non-Ideal Plasma Studies

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Radiographic study of matter using charged particle beams is the unique experimental technique for absolute measurements of important material characteristics of dense objects in superhigh-speed processes. It can give crucial information to a wide range of important issues in the field of HED and WDM physics, including EOS and phase transitions in condensed matter and non-ideal plasma.

The 800-MeV proton radiography facility for HED and WDM studies has been developed at the ITEP Terrawatt Accellerator (TWAC-ITEP). The proton beam intensity of the accelerator is about 10^{10} particles per pulse. A single proton beam bunch with the duration of 800 ns consists of four consequent 70 ± 5 ns long micro bunches with 250 ± 15 ns intervals between them. It potentially enables the registration of up to four proton radiography images of studied processes during a single accelerator cycle. High-speed CCD cameras with the synchronization with a single proton bunch from accelerator were used for this aim.

Static experiments with the variety of test objects were conducted to determine the spatial resolution of the facility. Measured resolution amounted to 300 ± 10 μm in current experimental arrangement. Planned introduction of "proton microscope" magnetic optics system should increase the resolution up to 50 μm.

Dynamic comissioning experiments on the registration of density distribution in detonation wave in pressed TNT charges were conducted. The series of pairs of radiographic images of detonating charges shot for two consecutive proton bunches were obtained. Axial density profiles reconstructed from them show good quantitative agreement with the data on the known parameters and simulation results for detonation of the same TNT charges.

The experiments on density distribution measurements in Ar and Xe non-ideal plasma generated in compact shock tubes are planned for the next stage of the work.

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8 Dusty plasmas

8.1 Compressibility of dusty plasma from observation of compression wave propagation

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A compression wave propagation through the elongated three-dimensional dusty cloud was observed in the PK–4 parabolic flight experiments. The compression wave was excited by a pulse electric action on the cloud in the direct current discharge with 1 kHz alternating polarity. Under experimental conditions the wave velocity was determined mainly by interactions inside a dusty subsystem. Analysis of the wave propagation gives estimation of non ideal dusty plasma adiabatic compressibility. This work was supported by DLR under grant 50 WM 0804, by ESA at the 49th parabolic flight campaign, and by Russian Foundation for Basic Research grant No. 07-02-01464-a.

8.2 Dynamic properties of dusty plasmas with an external ionization source

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Recently, it was established [1] that the screening of the charge of a dust particle absorbing plasma ions and electrons is described, in the presence of an external ionization source, by a superposition of two exponents with different screening lengths. These results are applied to generalize the theory of dust sound, in particular, on the basis of the non-perturbative moment approach [2, 3]. The static correlation functions are calculated corresponding to the above interaction and taking into account the plasma sinking to the dust particles.

The results can be used to study the dielectric and collective properties of dusty plasmas with external ionization sources like, e.g., electric probes, in particular, the stopping power of such systems with respect to heavy ions and fast electrons.

This work is partly supported by the Russian Foundation of Basic Research, project no. 08-02-01212-a and by the Polytechnic University of Valencia, programme PAID-05-08.

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8.3 Effective interaction potential of dust particles on the basis of the Poisson equation and experimental data

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Experimental observation of Coulomb dust crystals, first, in high frequency discharge [1] and, later, in glow discharge [2] introduced a new area in the physics of strongly coupled systems. Despite intensive experimental, theoretical and numerical research devoted to investigation of charged dust grains in plasma environment in the past, several fundamental questions regarding such system remain to be opened. One of the most striking phenomena still requiring further explorations is the nature and the form of attractive forces acting between like-charged dust particles [3–5]. The existence of attractive component in force between dust particles was experimentally studied and verified by several methods in different setups. In the present work, effective interaction potential of dust particles was calculated on the basis of pair correlation functions derived from experiments performed in dc discharge of argon using the Poisson equation. Calculations were performed for two types of boundary conditions: the Coulomb and the Yukawa type potentials. For both cases the interactive potential has an oscillating character in the certain range of system parameters. Existence of attractive component in interaction among dust particles as implied by results of the current paper requires further thorough investigation, both experimental and theoretical, to provide the differentiation between the existing theoretical concepts. For example, one should understand the influence of confinement (trap) potential that may contribute significantly under conditions of experiment. Several generalizing modifications of the presented numerical model are also discussed like the rejection of assumption of weak interparticle interaction in buffer plasma. Within the validity range of the current model, we can confirm existence of the attractive component in the interaction of dust particles. Further investigation is required to get insights into the origin of attraction and non-linearity of Coulomb interaction screening.

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8.4 Ordered structures in nuclear-track dusty plasma for potential and nonpotential forces of interparticle interaction.

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In recent year the stable dust structures and the dynamic instabilities in various types of laboratory dusty plasma are of growing interest, for example in electrode sheath of an high-frequency (hf) discharge, in thermal plasma, in standing strata of a glow discharge and in nuclear-track plasma. The experimental and theoretical studies of dust particles charging, interparticle interaction, interaction with external fields and collective effects are actively carried on. To understand the physical processes leading to the observed phenomena an analysis of the interaction forces between dust particles and an estimations of their charges are needed. The negative charge of a dust particle is estimated as product of its capacity and the floating plasma potential governed by the difference of plasma electron and ion fluxes incident upon a dust particle and essentially depends on high-energy asymptotic behavior of a electron distribution function. It is well known, that the asymptotic behavior of an electron distribution function essentially depends on spatial inhomogeneity of electric fields accelerating electrons and on the local losses due to the ionization of atoms. This is the physical reason of explicit dependence of the particle charge on its location, i.e., on its coordinates: $Q = Q(r)$. According to estimations the dust particle charges $Q(r)$ (in the electron charge units) range from 102 to 106. Below we take $Q = 103$ as a typical value for nuclear-track plasma. Consequently, one of the main components of the interaction of dust particles in a plasma is, in one way or another, the screened Coulomb repulsion. Besides the electrostatic forces associated with the negative charge of dust particles, a number of other physical processes affecting their space arrangement are under investigation in literature. The most notable are the anisotropic forces associated with ion fluxes drifting toward the electrodes of traps and the dust particle conglomerations. The negative charge of the dust particles interacts with ion fluxes and, as a result, the regions with lower and higher ion density are formed in the vicinity of a dust particles. So the background plasma is polarized. The polarization of a dusty plasma is of great interest, as the resulting interparticle forces can not only be repulsive but can be also attractive and can capture the other dust particles. Laboratory experiments have confirmed the existence of Anisotropic interaction forces between dust particles. Numerical calculations based on the quasiparticle method have demonstrated the possibility of the plasma polarization and of there being many ordered equilibrium configurations, with energies depending on both the charge-to-mass ratio of the dust particles and on the number and location of levitating particles. Limitations of this model have, to a significant degree, been overcome by a more realistic three dimensional model considered ion fluxes, plasma particle collisions and charge exchange of ions with atoms of the Neutral gas. The performed calculations showed that the plasma ions not only can be captured by the potential wells of dust particles, but uncaptured ions can be focused and this is leading to the emergence of regions of enhanced spatial positive charge density in the direction of the ion flux. So the forces acting on the dust particles are defined not only by the mechanical forces resulted from changes in the momenta and trajectories of ions but also by the electrical forces associated with the existence of stationary regions with enhanced ion density. To simulate the evolution of the dust particle system we invoke the Brownian dynamic method, which is based on solution of ordinary differential equation with stochastic Langevin force, taking into account random collisions with plasma neutrals. We take into account the gravity, the electric fields of trap and assume that the effective interparticle forces can be potential and non potential. This allow us to analyze the influence of different physical factors on stability of ordered structures of dusty particles in electrostatic traps and formulate some practical prescriptions for stable confinement of dusty particle in electrostatic traps.

8.5 2D Molecular Dynamic Simulations of the Dusty Plasma in the Glowing Discharge.

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The dusty plasma is a modern and important physical object. It is interesting to study it not only because of its fundamental properties as for example tendency to arrangement, also complex plasma emerges in the variety of physical systems, so it has practical applications: TOKAMAK's, atmospheric entry of space vehicles, interplanetary and interstellar clouds.

Actually the dusty plasma is an object that emerges in the different types of plasma discharges, for example glowing discharges. To investigate it properly we have to take into account discharge itself to obtain electric fields, ion and electron concentrations and temperature — the parameters that are important for the dust particle dynamics.

The two dimensional cylindrical computational model of a direct current discharge with a dusty plasma is presented in this work. This model is based on the drift-diffusion model of the glow discharge at pressure 1, 2 tor and EMF 600, 2000 V. Regions of the charged volumes are taken into account. It is assumed that the glow discharge exists in the normal mode. To describe dynamics of the dusty particles inside column of the normal glow discharge a molecular dynamic model is used. In this model each particle is affected by the following forces: gravitational force; electric force, produced by discharge; electric field, produced by all other particles, according to Yukawa potential; drag ion force (collection and orbital parts) and drag neutral force (Epstein expression). Charging model is simplified.

It is shown that initially homogeneous dusty plasma distribution follows to the two dimensional structure of a glow discharge in normal mode. A final configuration of the dusty particles assemble is located inside the column of a glow discharge between cathode and anode charged volumes. It is possible to change dimension of the dusty particle volumes by variation of the total current through the glow discharge in the normal mode.

8.6 Magnetic Tops in Complex Plasmas

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Own rotation of single dust particles (spin) was observed experimentally by means of tracing technique in special discharge chamber and hollow transparent granules.

It was determined experimentally that the own rotation frequency for used particles with $10 - 60$ μm size is some hundreds Hz. The frequency depends on the grain properties and the discharge current. The particles which shape differs from spherical have two axes of rotation. One axis is the top's body axis.

Estimation shows that magnetic moments of tops with uniform surface electric charge are 5 orders higher the Bohr magneton. The gyromagnetic relation of the dust top and the precession frequency in magnetic field are estimated.

Observations in magnetic fields up to 250 Gs show the angular velocity reduction and direction change, which demonstrates paramagnetic properties of dusty plasmas.

8.7 Thermodynamic characteristics of dusty plasma

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There is an essential distinction between physical and chemical properties of electron-ionic plasma and dusty plasma (plasma with macroparticles). This fact causes rapid development of scientific researches in this area of physics of plasma within last decades.

Formation of dust particles in plasma, as a rule, leads to considerable change plasma charging structure. Dust particles are the centres of recombination of plasma electrons and ions. Besides dust particles can be a source of electrons owing to various emission processes (thermionic emission, photoemission, secondary electronic emission) [1].

Debye approach describing ionization equilibrium in dusty plasma is considered. Plasma is considered as a mixture of almost ideal gases (electron-ionic gas and dusty gas). Interaction of these gases is weak. Macroparticles are considered as multiply charged ions. Ionization equilibrium is described by a set of the Sakha equations [2].

The report contains description of method of calculation of thermodynamic characteristics of dusty plasma. This method includes model of ionization chemical equilibrium. Electronic concentration calculations according to Debye approach. The report includes results of numerical experiment for the plasma of polyformaldehyde containing fine-dispersed aluminum particles.

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8.8 Crystallization dynamics of spherically confined dusty plasmas

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In the last few years it has become possible to routinely create 3D dust crystals in experiments [1], where the particles arrange on concentric spherical shells. These so-called Yukawa balls are very similar to confined ions but the interaction between the dust particles is screened [2] due to the ambient plasma. Here we investigate the short-time dynamics of these systems by means of accurate Langevin dynamics simulations which fully include the Coulomb correlations, the confinement and friction with the neutral gas. We start from a weakly correlated initial state using two scenarios: (i) rapid switch of the confinement potential [3], and (ii) a laser-heated initial state followed by a rapid turn-off of the laser power. We analyze the different time-scales in the emergence of the crystal state and the dependence of the dynamics on screening and friction. Our results suggest how to detect the formation of binary correlations in dusty plasma experiments.

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8.9 Kinetic theory of dusty plasmas

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The Kinetic Theory of Dusty Plasmas is derived from Non-Equilibrium Statistical Mechanics based on a generalized Klimontovich formalism, in which the electric charge of the dust particles is introduced as a new phase space variable. As a result the B.B.G.K.Y. hierarchy consists of equations for multiple distribution functions not only of positions and momenta, but also charge. So far this theory is exact. Kinetic equations are derived from the hierarchy equations and Bogolyubov-like boundary conditions, cf. Ref. [1]. An interesting phenomenon discovered is the heating of dust particles to temperatures higher than that of the ambient plasma.

An alternative approach, cf. Ref. [2], is based on a generalized two time master equation. It is a more intuitive than the previous approach. A probability transition function (PTF) plays an essential role. Plausible assumptions regarding the PTF make it possible to derive expressions for diffusion and friction coefficients, which are in good agreement with experimental results and numerical simulations. The method is applicable not only to dusty plasmas, but also to many other systems. It shows interesting phenomena such as anomalous diffusion and in particular circumstances negative friction.

The merits of the two approaches are considered and compared.

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8.10 Experimental study of orientation and dynamical properties of rod-like particles in RF discharge plasma

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In the majority of the experimental and theoretical works deal with researching of properties of strong non-ideal dust plasma, spherical particles were used. Only during the latest time works in which dust particles have the strongly asymmetric form appeared. Using of such particles should lead to occurrence of new states of dusty plasma structures (liquid crystal and crystal phases with various degree orientation and position ordering), those demonstrate a great number of unstuded properties and new phenomena. These phenomena may be studed at the kinetic level. Thus, experimental studying of the dusty plasma structures formed by particles of the asymmetrical form represents significant interest.

The present work deals with the experimental investigation of structural and dynamic properties of dusty plasma with rod-like macroparticles in the high-frequency gas discharge. These plastic particles were 300 μm in length and 15 μm in diameter. A series of experiments were carried out at various pressure in a range of 0.11-0.28 Torr. Movements of particles was recorded by two videocameras. On the basis of experimental data three-dimensional coordinates were obtained. Also dependence of speed of the centre of mass of the particles on time and dependence of speed of their rotation on time were calculated. It should be noted that at low pressure (0.11-0.15 Torr) all particles were orientated in a horizontal plane and changed their orientation with pressure increasing (0.15-0.28 Torr).

8.11 Experimental study of the transition of the dusty structure from monolayer to multilayer state in RF discharge plasma.

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In this paper we report about experimental research of dynamical and structural features of gas rf discharge dusty plasma with spherical melamine-formaldehyde particles 12.74 μm in diameter. We studied a formation of dust plasma structures in near–electrode layer of rf discharge, including an investigation of influence of discharge parameters and sort of gas on quantity of levitated particles in structure. The diagnostics of dusty plasma structures with measuring of basic parameters of dusty component (quantity of particles in a layer, mean interparticle length, particle temperature subject to discharge parameters such as pressure of buffer gas and power consumption) was carried out. Varying a quantity of particles, a conditions of formation a new layer, mechanisms of such a formation, dynamics and structural features of such processes were studied. Using synchronized sistem of video surveillance on horizontal and vertical plane, we measured kinetic temperatures of dust particles on horizontal and vertical sections of dusty plasma structures and made comparative analysis of measurement.

8.12 Abnormal kinetic temperature of charged particles in crystalline dusty plasmas

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A mechanism of an increase of the average kinetic energy of charged dust particles in crystalline plasmas is investigated. The mechanism is based on the phenomenon of a parametric resonance. Possible particle charge variation is the main reason for the parametric resonance appearance. A number of physical factors which could produce particle charge oscillations are analyzed. Mechanisms of energy transfer from an external source to dust particle motion in plasmas are analyzed. The equations of motion of dust particles are derived by the consideration of plasma-dust system using the theory of vibrations with the account of a dust particle charge-variability. The latter is related to fluctuations of plasmas flow falling on the particle and oscillations of dust particle in near-electrode plasmas with sharply changing parameters. Overlapping of frequency intervals of various types of processes in dusty plasmas is analyzed. A range of eigenfrequencies of oscillations in a cluster of dust particles overlaps with a range of eigenfrequencies of particle vertical oscillations in near-electrode plasmas. Due to this overlapping it is possible to propose a parametric resonance model which could explain an anomalously high kinetic temperature of dust particles. Conditions of occurrence of parametric resonance of dust particle oscillations are estimated. It turns out that the conditions of occurrence of the resonance are close to the conditions of abnormal increase heating of dust particle average kinetic energy in plasmas in laboratory experiments.

8.13 Ion heating in two-component dusty plasma of noble gases

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Indication of heavy ion heating in two component weakly ionized plasma of noble gases was reported recently and still requires understanding of underlying mechanisms [1]. Several processes like Penning ionization [2], charge exchange, pre-sheath acceleration [3], etc., are known to play important role under typical conditions of experiment, and, thus, should to be considered in parts or together. In dusty plasma the physical picture can be even more complicated [4, 5]. Therefore, the purpose of our contribution is to consider possible mechanism of heavy ion acceleration and heating to explain existing data. As a result, physical model of ion heating in low pressure dc discharge of helium and argon is formulated and compared to the presented experimental data. In our experiments dc discharge setup for dusty plasma investigation described elsewhere is used [6]. Optical emission spectroscopy (OES) and probe diagnostics are employed as sources of information on the influence of metastable heluim atoms on argon ions. In addition to traditional methods of diagnostics, dust particles of Al_2O_3 with average diameter of 5 μm are used to gain indirect insights into physics of discharge. Obtained data are summarized to provide comparison with theoretical prediction. Importance of metastable helium atoms and pre-sheath acceleration of argon ions in explanation of observed phenomena is revealed.

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8.14 Macroparticle motion in ordered dusty plasma structures

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In this work experimental investigation kinetics of ordered dusty structures is discussed. We studied movement of macroparticles in dusty formation with the help of machine vision system. The research was carried out in DC glow discharge plasma at the pressure P = 80 Pa and current I = 1 mA in Ne, Ar, Xe gases. Polydisperse powder of Al_2O_3 macroparticles was used in the experiment. We calculated, analyzed and compared kinetic characteristics of macroparticles (velocity distribution histogram, mean macroparticle velocity, trajectories of macroparticle movement, diffusion coefficients) in dusty formation in Ne, Ar, Xe plasma at the same discharge current and gas pressure.

8.15 Coulomb clusters of diamagnetic particles levitating in nonuniform magnetic fields

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Strongly coupled Coulomb systems (SCCS) are of considerable fundamental and applied interest. In recent years, dusty plasma structures are frequently considered as a macroscopic physical model of SCCS which can visually be observed. However, charged dust particles in plasma are screened, and the potential of interparticle interaction becomes a Yukawa (Debye) one. Besides, in dusty plasmas, the charge of the dust particles is responsible both for interaction with other particles (and consequently for the formation of a cluster or structure) and for its levitation in electrical fields (of rf or dc discharges). So, changing the interparticle potential, one changes the levitation conditions.

In this communication, we present an alternative way for formation of macroscopic Coulomb systems. We have considered the possibility of the stable levitation of a Coulomb cluster of charged diamagnetic particles in nonuniform magnetic fields. In this case the levitation conditions are independent on the particle charge and depend on the magnetic susceptibility of the particle matter. We present an experimental setup for keeping in a stable state the Coulomb clusters of charged graphite grains in magnetic fields $B \sim 1$ T with $|\nabla B| \sim 10$ T/cm. An analysis of the cluster structure and dynamics is performed. We have developed a simple theoretical model for calculations of the position of equilibrium levitation of the diamagnetic grains and the frequencies of their oscillation. The calculation results are in agreement with the experimental data. We conclude that, using more intensive magnetic fields $B > 10$ T under terrestrial conditions, one can form stable 3D dust crystals and liquids containing several thousands of grains. Less intensive magnetic fields ($B \sim 0.1$ T, $|\nabla B| \sim 0.1$ T/cm) will be required for studying of analogous structures under microgravity conditions onboard a space station.

8.16 Dust Plasma Structures in DC Glow Discharges under Magnetic Field

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Dynamics of dust structures in the striation of dc glow discharges in axial magnetic fields up to 2500 G has been experimentally investigated. Dust structures were formed by monodispersed melamine formaldehyde particles with diameters 5.51 μm. The dependence of rotation frequency of dusty plasma structures as a function of the magnetic field was investigated. As it was observed, with the increase of magnetic field up to 700 G dust particles went from the axial region of the discharge to the discharge periphery with the continuation of the movement around discharge axis. For various magnetic fields kinetic temperatures of the dust particles, diffusion coefficients, and effective coupling coefficient Γ^* have been determined. The bulk dust structures without rotation in the experiments with neon in fields up to 300 G were obtained. It was found that the coupling parameter of the dusty plasma structure was increased with increase of magnetic field. Obtained results are analyzed and compared with theoretical predictions. The investigation of features and development of various type of instabilities of the dust plasma structures in DC glow discharges in magnetic field actions was carried out.

8.17 Binary bilayers in complex plasmas

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Binary bilayers represent a novel type of systems, which can be created by dispersing dielectric microparticles of two different sizes in a gas discharge; the different charge to mass ratios and the spatial variation of the sheath electric field of the discharge result in the formation of two parallel, horizontal layers of particles. Such systems have already been investigated by simulations [1] and have been realized experimentally, too [2]. Here we present preliminary results on a combined theoretical and molecular dynamics simulation study of the structure of and collective excitations in a binary bilayer system [3,4] with a Yukawa interaction. The range of parameters covers the liquid phase of the system as well as the frozen, crystalline phase. Depending on the ratio of the densities of the two species, the latter can form an ordered or a frustrated disordered state, whose collective excitations are of special interest.

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8.18 Influence of Dust Particles Concentration on Plasma Parameters in DC Discharge

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A self-consistent kinetic model of a low pressure DC glow discharge with dust particles based on Boltzmann equation for electron energy distribution function is presented. The influence of dust particles concentration N_d on gas discharge and dust particles parameters was investigated.

It is shown that the increase of N_d leads to the increase of averaged electric field and ion density, and to the decrease of a dust particle charge in the dusty cloud. For dust particle concentrations in the region $N_d r_0 = 10^0$-10^2 cm^{-2} (r_0 is dust particle radius), the charges of dust particles decrease but the Havnes parameter $P_H = Z_d \times N_d/n_e$ increases that means that dusty plasma can be regarded as electron depleted system, (n_e¡n_i). In this region of dust particle concentrations (for different dust particle radii r_0), the electric field is an increasing function of parameter $N_d r_0^2$, and in almost the whole N_d-region the dust particle charge is the function of parameter $N_d r_0$.

The absorption of electrons and ions on the dust particles surface does not lead to the electron energy distribution function depletion due to a self-consistent adjustment of dust particles and discharge parameters. This result is rather unexpected and contradicts the naive conclusion that EEDF should deplete for electron kinetic energy $\epsilon > -\varphi_s(\mathrm{r}_0)$ due to high energy electrons loss in absorption on dust particles ($\varphi_s(\mathrm{r}_0)$ is the potential of dust particle). This fact reflects the self-consistent process of the adjustment of EEDF to a higher electric field in a dusty cloud relative to dust-free conditions in a discharge.

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8.19 Viscoplastic flow of crystal-like dusty plasma structures

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During last years unusual dynamics of dusty plasma flow under the external influence have been demonstrated. It was shown that dusty plasma liquid is nonNewtonian one and its viscoplastic properties depend on shearing force. With aim to explain this behavior of dusty plasma structures at first part of present work we carried out the experimental investigation of dusty plasma liquid without shearing forces. Dusty plasma structures of various order degree were obtained experimentally. On the basis of experimental data was determined the boundary value of coupling parameter. If coupling parameter lower this value then the directions of particle trajectories were chaotic. In other cases trajectories and velocities of the particles were correlated in greater or lesser degree. The sizes of correlated moved particle groups (clusters) depended on coupling parameter. The possible explanation of nonNewtonian behavior of dusty plasma liquid was suggested from these clusters point of view. The second part of present work devoted to the experimental study of viscoplastic flow in the dusty plasma crystal. The coupling parameter values in the experiments were 170 and greater. Under the action of laser beam the dusty structures remain crystal–like and it was for the first time the viscoplastic flow of dusty plasma crystal was obtained. The width of the flow channel was about 0.6 cm. The threshold type of this flow was demonstrated. It was for the first time the mechanism of crystal viscoplastic flow was observed. This mechanism was generation and follow annihilation of boundary misfit dislocations.

8.20 Anomalous diffusion in Yukawa plasmas

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The diffusive behaviour of strongly correlated (Yukawa-)OCP has attracted considerable experimental interest over the last few years, especially in dusty plasma setups [1–6]. In quasi-two-dimensional systems, the diffusive motion of individual particles has been found to behave anomalously, i.e., the mean-squared displacement does not follow the usual Einstein-relation $\langle|\vec{r}(t) - \vec{r}(t_0)|^2\rangle \sim t^\alpha$ with $\alpha = 1$ as is observed in normal Fickian diffusion. Instead, α has been found to be larger than 1, a behaviour which has been termed "superdiffusion".

In the experimental realizations, the particles are typically highly correlated (showing liquid-like behaviour) and are influenced by dissipation. The interesting open questions which we address are the dependence of α on i) the coupling strength, ii) the Debye screening length and iii) the strength of dissipation in the system [7–9].

Through numerical studies by means of molecular and Langevin dynamics simulations we are able to deliver answers to these questions. In addition, we enter into the question of the existence of superdiffusion in systems with finite width, i.e., we consider the 3D-2D transition of strongly correlated Yukawa plasmas through external confinements. We demonstrate how superdiffusion vanishes at the crossover from 2D to 3D [10].

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8.21 Screening a microparticle's charge in a non-equilibrium plasma with two positive ion species

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The study of screening a microparticle's charge in a plasma taking into account electron and ion sinks to the microparticles and net processes of production and loss of charged plasma partcles is reported. The research objective is to investigate the effect of the conversion of the atomic ions Ar^+ to the molecular $Ar_2{}^+$ on character of screening in a plasma with an external ionization source. It is determined that the plasma due to the ion conversion consists of two positive ion species. This circumstance leads to three-exponential charge screening, moreover there exists a region of plasma parameters where all the screening constants have comparable values. Numerical simulation of microparticle's charging on the basis of the drift-diffusion approximation [1–3] and comparision of the obtained data with the analytical results are performed.

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8.22 Influence of neutrals on nano-and microscale particle charging in dusty ionosphere

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Ion-neutral collisions in dust particle charging process in Earth's "dusty" ionosphere are taken into account. These collisions can result in a charge exchange between a fast ion and a slow neutral. The slow neutrals become slow positively charged ions which interact effectively with negatively and positively charged dust grains. As a result a microscopic ion current on the dust grains changes in comparison with the case when ion-neutral collisions are not taken into account in the dust grain charging process. The microscopic ion current on the positively charged dust grains (due to the action of solar radiation) is derived. A condition on neutral density is obtained for which the influence of ion-neutral collisions on dust particle charging process is important both for negative and positive dust particle charges. It is shown that the effect of ion-neutral collisions should be taken into account when considering the charging of nano- and microsize dust grains in Noctilucent Clouds, Polar Mesosphere Summer Echoes, meteoritic dust, active geophysical rocket experiments such as Fluxus 1 and 2. We discuss also the effect of electrons with energies of the order of 1 eV which are produced as a result of photoelectric effect during the charging process, which can result in an increase of the electron temperature in plasmas. The most important effect resulting in cooling of such electrons is that of electron-ion collisions. We found a condition on the neutral density when the electron temperature in Earth's "dusty" ionosphere can become of the order of 1 eV. The importance of this effect for ionospheric plasmas is discussed.

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8.23 Increase of kinetic energy of dusty cluster particles due to parametric instability caused by nanosecond electric pulses

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Influence of high-voltage $2 - 11$ kV pulses of 20 ns duration on charged microparticles levitating in an rf-plasma is studied. A stainless-steel ring with the inner diameter of 8 cm was installed on the bottom electrode to provide radial confinement for the levitating microparticles. A thin copper ring of 4 cm inner diameter was used as a HV electrode. It was mounted coaxially with the stainless steel confinement ring 3 cm above it. The peak amplitude of the resonance increases with voltage of ns pulse from 0.15 mm at 1.5 kV to 0.65 mm at 8.1 kV. Parameters of the experiment are next, gas — argon, pressure 0.31 Pa, dust particles — melamineformaldehyde 7.17 μm diameter, rf peak-to-peak voltage 85 V, self bias on the rf electrode -36 V. Application of repetitive pulses leads to the vertical oscillations of the microparticles. Evolution of the total kinetic energy for the cluster during the instability is investigated. In the initial phase the kinetic energy oscillates around a certain value and its amplitude grows very slowly. At a certain moment it goes into the exponential growth phase and then saturates Flat clusters, consisting of small number of microparticles exhibit parametric instabilities of horizontal modes under the effect of repetitive pulses. It was shown that the parametric instability is caused by the vertical oscillations of the microparticles in the nonuniform electric field environment of the sheath. We suggested next mechanism of action.

1. Heating of plasma electrons by ns HV pulse.
2. Additional charging of dust particles by fast electrons.
3. Disequilibrium in trap due to additional force in vertical direction.
4. Charge relaxation by means of ions flow.
5. Particle disequilibrium in horizontal level as a result of vertical displacement.
6. Instability in horizontal level.

It is possible if the eigenfrequency is the function of height and the dust particle oscillates vertically.

8.24 Formation of dusty layers in linear electrical field: criteria and numerical simulation

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In this work, the conditions of formation of quasi-two-dimensional dusty structures are considered, which are held in the gravity field by the external electric fields. At present, it is common to use the Debye potential as the main approximation of the pair interaction potential of charged grains in plasma. But this approach fits the experimental and numerical simulation data only if the distance between the grains in plasma is small. With increasing of distance between the particles the screening weakens, and the interaction potential can transform into power-law function. The model of the screened Coulomb potential can be inadequate also in the dense dusty cloud or near the walls of laboratory plasma chambers.

In present work, we investigated the power-law pair interaction potentials and also the screened Coulomb potential. For each of the potentials under study, the relations between the radial and the vertical gradients of electric field and the number of grains in the layer were found, that define the criterion of formation of new dusty layer.

The process of formation of quasi-two-dimensional system of dusty grains was studied also numerically. The simulations were carried out for two cases: 1) for the system, restricted radially by the non-zero electrical field, and 2) for the uniform dusty layer in periodical boundary conditions in the horizontal directions (no restricting electrical field). In both cases, the results of numerical simulation agreed well with the analytical criteria of formation of a new layer.

The presented results can be easily adapted to any pair potential, given analytically, and can be used for the passive diagnostics of the interparticle interaction parameters in quasi-two dimensional structures, forming in the near-electrode area of rf- discharge.

8.25 Structure of Dust Particles in Dusty Plasma Confined in Cylinders

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When a dusty plasma, an electrically neutral mixture of dust particles and ambient plasma of ions and electrons, is confined in a cylinder and dust particles are strongly coupled, dust particles form self-organized structures. These structures are obtained by numerical simulations over a wide range of parameters both in the case of one-component dust particles and in the case of binary mixtures. Theoretical analysis is made on the basis of the shell model. We assume that the ambient plasma is uniformly distributed in the cylinder providing the charge-neutralizing background for dust particles. In the potential due to this background, dust particles are organized into concentric shells (thin cylinders).

The structures are summarized as follows.

(1) When we increase the number of dust particles per unit length along the axis, the number of shells increases discontinuously at critical number densities.

(1a) In the case of weak screening, the new shell appears at the central axis.

(1b) In the case of strong screening, the new shell appears on the periphery.

(2) When we have two kinds of dust particles, each species does not mix and takes separated radial distribution.

(2a) In the case of weak screening, dust particles with larger charge form outer shells.

(2b) In the case of intermediate or strong screening, dust particles with larger charge form inner shells contrary to natural expectation.

We apply the shell model [1, 2] developed by authors and try to reproduce the results of simulations. In the weak screening limit (the Coulombic case), these structures have been first obtained by a numerical simulation, reproduced by the shell model, and observed in real experiments in the Penning trap. The experiments under microgravity may provide us with ideal system to observe these structural transitions which will enable us to identify parameters in dusty plasmas.

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8.26 Electrostatic interaction of spherical microparticles in cases of constant charges and constant surface potentials

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The electrostatic interaction of two spherical microparticles in a plasma for the cases of constant charges and constant surface potentials of the microparticles is studied. The investigation of the interaction between a point-like charge and a conducting spherical body in a plasma shows that plasma screening results in decrease a potential barrier as the point charge approaches the likely charged microparticle, the decrease being more pronounced in case that the microparticle radius is comparable with the Debye screening length. The interaction of two conducting spherical microparticles is considered in the bispherical coordinates. The interaction potentials are shown to highly differ in these cases, the electrostatic energy being the interaction potential only in the case of the constant charges independent on the interparticle distance. In the case of the constant surface potentials a work of external sources to sustain surface potentials should be taken into account. By integration of the interaction force calculated using the Maxwell stress tensor, the interaction potential is also defined for the latter case. Approximated analytical expressions for the interaction potential, which are more accurate than the available in the literature, are obtained for both the constant charges and the constant surface potentials.

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8.27 Overview of dusty plasma experiments on the International Space Station

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The research of complex plasmas under microgravity conditions provide new insights and allows to observe phenomena, which are suppressed under gravity conditions on Earth. Briefly, we shall sum up results of the experiments obtained with the help of “Plasma Crystal 3” (PK-3) facility. But the main attention will be given to new experimental results obtained with the help of PK-3 Plus facility. First of all it is the discovery of electrorheological (ER) plasmas which can be formed with the PK-3 Plus laboratory on the ISS. ER fluids are fluids containing colloids which react on external electrical fields changing the viscosity by orders of magnitude. A similar physical process can be investigated in complex plasmas on the most fundamental – the kinetic – level by the use of low frequency fields. At weak fields charged particles form a strongly coupled isotropic fluid phase with typical short-range order. As the field is increased above a certain threshold, particles start to rearrange themselves and become more and more ordered, until eventually well defined particle strings are formed. The transition between isotropic and string fluid states is fully reversible. The other interesting phenomenon is interpenetration of two clouds of different grain sizes. Lane formation is observed in the outer region while the speed of the penetrating grains is high. Besides, we performed a crystallization-melting experiment of the large 3D dusty plasma system.

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8.28 Dusty Plasma and Statistical Theory of Liquid State: Diagnostics, Simulations and Results

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Dusty plasmas are good experimental object for studying the properties of non-ideal systems and for proofing existing empirical models and numerical results, because, owing to their size, dust particles may be videofilmed, which significantly simplifies the use of direct diagnostic methods.

The measurements in dusty plasma were carried out to find the region of validity of approximate relation in statistical theory of liquid states. The superposition approximation was chosen as the objects for investigation. We found that the use of experimental methods of analysis of spatial correlation of dust particles in plasma enables one to answer the question about the range of validity of superposition approximation.

The results of the experimental study of mass-transfer processes are presented for dust systems, forming in a laboratory plasma of a rf capacitive discharge. The validity of the Green-Kubo equations for the description of the dynamics of dusty grains in laboratory plasma is verified. A method for simultaneous determination of dusty plasma parameters, such as the kinetic temperature of the grains, their friction coefficient, and characteristic oscillation frequency, is suggested. The coupling parameter of the system under study and the minimal values of the grain charges are estimated.

Results of experimental study of the dusty plasma kinematic viscosity and the diffusion are presented. The experiments were performed in plasma of a capacitive rf discharge with the particles of different sizes. Experimental examination of the Einstein-Stokes relation between the viscosity and diffusion constants is carried out.

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8.29 Diagnostics of plasma with dust grain induced by electron beam

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Diagnostics of dusty plasma induced by electron beam are of great interest. Investigation of such systems gives the unique opportunities for experimental investigation of strongly coupled systems as well as for developing the new dusty plasma technologies of creating the new composite materials. Presented work deals with the experimental investigation of dust particles charging under direct influence of electron beam.The experiments were carried out with particles of different materials, forms and sizes ($10{-}200$ μm) in the atmosphere of different gases (air, helium) at pressures $\sim 10^{-4}$, 0.2, 0.6 Torr and above.The current of electron beam was varied from 1 to 10 mA; energy of electrons was about 25 keV and electron beam diameter was about 3 mm. Under action of electron beam dust particles became charged. Due to Coulomb interaction these macro particles gained the velocity and spread in the different directions.

Simple technique of particle charge estimation was developed. The changing of particle temperature and time of it charging under experimental conditions were estimated. Role of secondary electronic emission and thermal emission of electrons in processes of macroparticle charging was considered.

The estimations of the 200 μm alumina particle charge was performed. It was about 10^8 elementary charges at pressure $\sim 10^{-4}$ Torr.

8.30 New model of dusty plasma particles interactions

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Pseudopotential model of interaction between structural elements of plasma and conductive dust particles is proposed. This derivation is based on the Bogolyubov hierarchy in the pair correlation approximation [1].

The pure Coulomb potential is taken as a micropotential of interaction between charged particles (electrons and ions). The micropotential of interaction between charged particles and dust grains is simulated by the sum of the pure Coulomb potential due to dusty particles own charge and the potential of interaction between the charged particles (ion or electron) and their images in dusty particle conducting surface [2]. The interaction between two dusty particles is defined by the pure Coulomb potential plus the sum of interactions between dusty particles and infinite number of their images in each other [2].

Numerical calculations of dust-dust interaction potential shows that at high densities of dust particles oscillations are observed on the interaction potential curve and on the radial distribution function as well. This fact evidences the possibility of structure formation in dusty plasmas.

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8.31 Critical Phenomena in Fine Particle (Dusty) Plasmas: Model and Experimental Conditions

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Fine particles in fine particle (dusty) plasmas can be strongly coupled due to their large negative charges. Within some approximate model description of their properties, it is expected that the isothermal compressibility of the whole system (fine particles, ions and electrons) diverges, when the mutual coupling becomes very strong. We then have a phase separation and related critical point [1] accompanied by the enhancement of density fluctuations [2]. It is pointed out that this critical point could be in the solid phase when appropriate conditions are satisfied [1].

In order to observe the critical phenomena, it is necessary to interpret dimensionless theoretical parameters which characterize statistical properties of the system into real experimental conditions. In this respect, it is to be noted that, when the experimental conditions are given, characteristic parameters are readily calculated. The reverse, however, is not straightforward, since each characteristic parameter is related to several experimental conditions of which some are common with other characteristic parameters. We also need to refine the model taking various effects which are neglected there.

In this presentation, we will discuss experimental conditions for observation of critical phenomena in strongly coupled fine particle plasmas and refine our model.

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8.32 Effects of current modulating in complex low temperature plasma

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Work describes effects observed in ordered structures with external modulating of discharge current. Studied the dependencies of size and location of the dusty crystal from the amplitude and frequency of modulation.

Research was carried out in DC glow discharge plasma at different pressures and currents in N_2 and Ar. Polydisperse powder of Al_2O_3 and Zn with particle size range from 5 to 20 micrometers was used for creation of ordered structures. Sinusoidal signal with frequencies from 10 to 100000 Hz was inductively transmitted into discharge circuit at cathode branch with the control of amplitude before and after passing through the glow discharge.

Effects of stretching, compressing, shifting of the structures, stabilizing of unstable structures and resonance movements of the dusty particle were noticed at different frequencies. All the dependencies were graphically built and analyzed for different gas pressures, currents and dusty particles, boarder frequencies and amplitudes for all observed effects determined. All the experiments were performed for Ar and N_2.

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8.33 Recent results from the PK-4 experiments with dusty plasmas under microgravity conditions.

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New results from the recent experiments using the 'Plasma Kristall – 4' onboard of the parabolic flight plane A-300 Zero-G will be presented. These are:

1. The formation of a boundary-free dust cluster due to attractive forces caused by ion fluxes in a bulk plasma region.

2. Structural and dynamics properties of dusty plasma clouds containing elongated dust particles - microrods.

3. Initiation of solitary wave in dusty plasma by electrical manipulative electrode.

4. 3D ordering of dust cloud in pure dc discharge and "alternative" dc discharge.

Physical models of the observed phenomena are discussed.

This work was supported by DLR under grant 50 WM 0804, by ESA at the 49th parabolic flight campaign, and by the Russian Foundation for Basic Research grants No. 07-02-01464-a.

8.34 New technique for analysis of interparticle interaction in non-ideal dissipative systems

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The objective of this study was to develop a new technique for determining of the parameters of laboratory dusty plasma systems (such as the intergrain pair interaction potential, the friction coefficients, and the external confining potential) by solving an inverse problem in which the motion of dust grains is described by a set of Langevin equations. In contrast to the methods used in statistical theory of liquids, the method proposed in this paper requires no additional assumptions on the relationship between the pair correlation function and the pair interaction potential and can be applied to analyzing strongly correlated systems of interacting particles.

A specific feature of the problem under analysis is that Langevin equations are irreversible in the sense that they include the action of random forces. As a result, in order to correctly reconstruct the unknown parameters of the problem, it is insufficient that the number of equations be equal to the number of these parameters. To minimize random errors related to stochastic (thermal) motion of grains, it is necessary that the number of equations be much larger than the number of unknown parameters of the inverse problem. In this paper, the unknown parameters have been determined by fitting the solution of the equations of grain motion to the data on the coordinates and displacements of dust grains. Such data can easily be obtained in numerical and laboratory experiments.

In order for the technique proposed can be used to determine of parameters of dusty plasma systems, it is necessary that the interaction forces between dust grains satisfy the superposition principle (the pair additivity approximation). The accuracy of this approximation for actual systems can be verified by comparing the reconstructed parameters of the system (e.g., the coupling or scaling parameter) with results of reconstructing the same parameters by another methods.

The proposed procedure was tested by numerical simulations in a wide range of the parameters typical for dusty plasma experiments. The first approbation of the technique for analysis of inter-dust interactions in plasma of rf- discharge is presented.

8.35 Numerical Study of Heat Capacity in dissipative two-dimensional Yukawa Systems

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The problems associated with the physical properties of non-ideal dissipative systems are of significant interest in various fields of science and technology (plasma physics, medical industry, physics of polymers, etc.). The best-known model for description of pair interaction of repelling particles in physical kinetics is based on the screened potential of Yukawa type. In this paper we present the results of the numerical study of the heat capacity in non-ideal dissipative two-dimensional Yukawa systems. The calculations were performed in a wide range of parameters typical for the laboratory dusty plasma experiments. The parameters responsible for the heat capacity are determined and investigated. Comparison of obtained coefficients of heat capacity with the existing theoretical model was performed.

This work was partially supported by the Russian Foundation for Fundamental Research (07-08-00290), CRDF (RUP2-2891-MO-07), NWO (047.017.039) and by the Program of the Presidium of RAS.

8.36 Design of a system for cesium coated dust

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In this report, a design of a system for cesium (Cs) coated dust is described. The system comprises of a dust dropper, a Cs coating chamber and a Cs oven. The dust to be used is tungsten powder. The size of the dust grain ranges from 1-12 micron and is maintained with the help of a mesh of appropriate size. Cs vapour comes out from the Cs oven and enters into the Cs coating chamber to coat the dust grains. The Cs coating chamber is designed considering the time scale of monolayer formation of Cs on the surface of the dust grains and the transit time of dust grains in this unit. In the coating chamber, provisions to condensate and collect the unused Cs vapour and stop them from migrating into the plasma chamber are also made. Cs coated dust will act as a surface area having low work-function and influence the effective production of negative ions. The experiment aims to optimize the production of negative ions by using dusts of different size and number density. This work is a part of a project to study a surface assisted volume negative ion source.

8.37 Study of Critical Phenomena with Complex Plasmas

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Research into complex plasmas has opened the way to study strong coupling phenomena in real space and time at the most fundamental kinetic level.The physics of complex plasmas is dominated by the dynamics of slow moving and individually visible microparticles. In contrast to colloidal suspensions,where the fluid background medium results in huge overdamping, the neutral gas background medium in complex plasmas introduces only very little damping so that processes at all relevant time scales can be studied. This is of particular importance for some of the most outstanding questions in the self–organisation of matter and critical phenomena. In this talk we will concentrate on recent advances in these areas. We will describe the discovery of "electrorheological plasmas", including the physics leading to the formation of "string fluids", and the process of phase separation in two–fluid systems — a phenomenon (mathematically) similar to the phase transition at the critical point. We will close with some remarks about the kinetic origin of the observed scale–free and universal properties of thermodynamic quantities in the vicinity of the critical point — where complex plasma research may be able to address this outstanding fundamental issue in physics for the first time.

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9 Acronyms

BMSTU — Bauman Moscow State Technical University
CAU — Institute for Theoretical Physics and Astrophysics
CAZRI — Division of Natural Resources and Environment, Central Arid Zone Research Institute
CEA — Commissariat à l'Energie Atomique
Dept. Appl. Math., C.U. — Department of Applied Mathematics, University of Calcutta
ENSL — Laboratoire de Physique, Ecole Normale Superieure de Lyon
GPI — A.M.Prokhorov General Physics Institute of RAS
GSI — GSI Helmholtzzentrum für Schwerionenforschung GmbH
HU Berlin — Humboldt-University Berlin, Institute of Physics
IAPh-Tashkent — Institute of Applied Physics of National University of Uzbekistan
IEP UB RAS — Institute of Electrophysics, Russian Academy of Sciences
IETP KazNU — IETP, Al Farabi Kazakh National University
IITD — Indian Institute of Technology Delhi
Ioffe Institute — Ioffe Physical Technical Institute of the Russian Academy of Sciences
IoP — Institute of Physics
IPCP RAS — Institute of Problems of Chemical Physics
IPMech — Institute for Problems in Mechanic
ISAN — Institute of Spectroscopy, Russian Academy of Sciences
ITEP — A.I.Alikhanov Institute theoretical and experimental physics
ITP RAS — Landau Institute for Theoretical Physics, Russian Academy of Sciences
IT SB RAS — Institute of Thermophysics SB RAS
IUMP, UPV — Instituto de Matematica Pura y Aplicada, Unioversidad Politecnica de Valencia
JIHT RAS — Joint Institute for High Temperatures
JU — Jadavpur University
LULI — Laboratoire LULI - CNRS
MIPT — Moscow Institute of Physics and Technology (State University)
MTA-SZFKI — Research Institute for Solid State Physics and Optics of the Hungarian Academy of Sciences
NINVAST — National Institute of Vacuum Science & Technology
NIT Jalandhar — Dr. B.R. Ambedkar National Institute Of Technology
OSAR — Odessa State Academy of Refrigeration
OSEU — Odessa State Economics University

PetrSU — Petrozavodsk State University
PVAMU — Prairie View A&M University
RFNC-VNIIEF — Russian Federal Nuclear Center-VNIIEF
RFNC-VNIITF — Russian Federal Nuclear Center All-Russian Scientific Research Institute of Technical Physics
SPbSU — St.Petersburg State University
TRINITI — Troitsk Institute For Innovation & Fusion Research
TSU — Tomsk State University
TUD — Technical University Darmstadt
TUE — Eindhoven University of Technology
TUKL — Technical University of Kaiserslautern
U. Florida — Department of Physics, University of Florida
U. Greifswald — Institute of Physics, University of Greifswald
UParis XI — LPGP Universitè Paris XI
U. Rostock — University of Rostock Institute of Physics
USC — University of Southern California
Warwick — Centre for Fusion, Space and Astrophysics, Department of Physics, University of Warwick

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