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8-13 October, Novosibirsk, Russia

Workshop on Numerical Modeling in MHD and Plasma Physics: methods, tools, and outcomes. Honor of academician Anatoly Alekseev's 90th Birthday

October 11-12, 2018, Novosibirsk, Russia

BOOK OF ABSTRACTS

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Topics

Numerical methods for MHD equations
Particle-in-cell method
High performance computing
Computational Fluid Dynamics
Computational Physics of Plasma
Computational Astrophysics

Proceedings

Journal of Physics: Conference Series

Important dates

Abstracts deadline	June, 15
Papers deadline	August, 3
Registration fee deadline	September, 20

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The Talk Schedule

Thursday, October 11

08:30 – 09:00 Registration/Welcome coffee

Session I. Numerical Methods for Hydrodynamics Equations & Poisson Solvers

09:00 – 09:30 **S.K. Godunov**, D.V. Klyuchinskiy *An experimental investigation of discontinuous solutions of a new finite-difference model of fluid dynamics with entropy nondecreasing* INVITED TALK)

09:30 – 10:00 O.B. Feodoritova, M.M. Krasnov, **V.T. Zhukov** *Adaptive technique for Chebyshev-вased solvers for three-dimensional elliptic equations* INVITED TALK)

10:00 – 10:20 **V.A. Protasov**, I.S. Ulyanichev, I.M. Gubaydullin *A new high-order accuracy numerical method for numerical modeling of supernovae explosions*.

10:20 – 10:40 **I.M. Kulikov** *The numerical modeling of the collapse of molecular cloud on adaptive nested mesh*.

10:40 – 10:50 Conference photo

10:50 – 11:30 Coffee break

Session II. Numerical Modeling in Astrophysics

11:30 – 12:00 **B.P. Rybakin**, V.B. Betelin, N.N. Smirnov, S.G. Moiseenko, L.I. Stamov *Computational modeling of density stratification in the process of collision of molecular clouds* INVITED TALK)

12:00 – 12:20 O.P. Stoyanovskaya, V.V. Akimkin, E.I. Vorobyov, **T.A. Glushko**, Ya.N. Pavlyuchenkov, V.N. Snytnikov, N.V. Snytnikov *Methods for computing rapid momentum transfer between gas and dust for supercomputer simulations of planets formation*.

12:20 – 12:40 **E. Lopez** *SS433 jet precession: infrared dispersion Doppler effect*.

12:40 – 13:00 **I.G. Chernykh**, I.M. Kulikov *Numerical modelling of the neutral hydrogen dynamics for astrophysical problems*.

13:00 – 14:30 Lunch

Session III. High Performance Computing in Astrophysics & Physics of Plasma

14:30 – 15:00 M.P. Galanin, **V.V. Lukin**, V.M Chechetkin *3D hydrodynamical simulation of accretion disk in binary star system using RKDG CFD solver* INVITED TALK)

15:00 – 15:30 **A.V. Snytnikov**, A.A. Romanenko *High performance PIC plasma simulation with modern GPUs* INVITED TALK)

15:30 – 15:50 **V.G. Prigarin**, V.A. Protasov, E.A. Berendeev, D.A. Karavaev, A.A. Serenko, V.E. Nenashev, I.S. Ulyanichev, I.M. Kulikov, I.G. Chernykh, A.V. Tutukov *A new Intel Xeon Phi accelerated hydrodynamic code for numerical simulations of interacting galaxies*.

15:50 – 16:30 Coffee break

Session IV. Numerical Modeling in Astrophysics
16:30 – 17:00 **B. Gibson** *To be announced* INVITED TALK)
17:00 – 17:30 **M. Mac Low** *Applications of Adaptive Mesh Refinement Techniques to Models of Star Formation and the Structure of the Interstellar Medium in Galaxies*. INVITED TALK)
17:30 – 17:50 **M. Rubio** *Numerical implementation of ultrarelativistic dissipative fluid theories of divergence type*.
18:00 Conference dinner

Friday, October 12

08:30 – 09:00 Welcome coffee

Session V. Numerical Modeling in Physics of Plasma
09:00 – 09:30 **K.V. Brushlinskii**, E.V. Stepin *Numerical models in applied plasmadynamic andplasmastatic problems*. INVITED TALK)
09:30 – 10:00 **T.V. Liseykina**, S.V. Popruzhenko, A. Macchi *Radiation friction losses in ultraintense laser-plasma interaction* INVITED TALK)
10:00 – 10:20 **G.G. Lazareva**, A.G. Maksimova *Simulation of erosion of fusion reactor wall material under high-power pulsed plasma flow*.
10:20 – 10:40 **I.V. Glazyrin**, A. V. Ershova, N. A. Mikhailov *Record of spontaneous magnetic fields in focus 3D code*.

10:40 – 11:20 Coffee break

Session VI. Particle-in-cell method
11:20 – 11:50 L.V. Vshivkova, **V.A. Vshivkov** *2D problem of electromagnetic waves in the vacuum* INVITED TALK)
11:50 – 12:20 **G.I. Dudnikova**, L.V. Vshivkova *Numerical modeling of the dynamics of the plasma flow interaction in a magnetic field* INVITED TALK)
12:20 – 12:40 **E.A. Genrikh**, E.A. Berendeev, G.I. Dudnikova *3D-PIC simulation of the electron beam interaction with modulated density plasma*.
12:40 – 13:00 **E.A. Berendeev**, V.V. Annenkov *Open boundary conditions for continuous injection of counterstreaming electron beams in PIC-models*.

13:00 – 14:30 Lunch

Session VII. Numerical methods for MHD equations
14:30 – 15:00 **S.G. Moiseenko**, N.V.Ardelyan, G.S.Bisnovatyi-Kogan *Grid functions remapping method for completely conservative lagrangian operator-difference scheme for astrophysical MHD problems* INVITED TALK)
15:00 – 15:30 **A.N. Kozlov**, V.S. Konovalov *3D model of radiation transport in flows of ionising gas and plasma* INVITED TALK)
15:30 – 15:50 **V.A. Kochnev** *Kinematic-gravitational ion model of planetary dynamo*.
15:50 – 16:10 M.B. Gavrikov, **A.A. Taiurskii** *Numerical Analysis of Plasma Column Dynamics in Two-Fluid EMHD*.

16:10 – 16:50 Coffee break
Session VIII. Numerical Modeling in Physics of Plasma
16:50 – 17:20 **I.V. Glazyrin**, O.G. Kotova, K.S. Nazarov *Three-dimensional electrodynamic code focus-EM* INVITED TALK)
17:20 – 17:40 **V.P. Zhukov** *The modeling of interaction of laser femtopulses with a glass. Numerical aperture problem*.
17:40 – 18:00 **M.A. Boronina**, V.A. Vshivkov *Numerical modelling of focused relativistic electron-positron beams, colliding with crossing angle*.
18:00 – 18:20 **B. Dolai**, R.P. Prajapati *The rotating Rayleigh-Taylor instability in a strongly coupled dusty plasma*.

Session IX. Conference summary
18:20 – 18:30 **V.A. Vshivkov** *Conference review talk*

18:30 Drinks & Cheese reception event

OPEN BOUNDARY CONDITIONS FOR CONTINUOUS INJECTION OF COUNTER STREAMING ELECTRON BEAMS IN PIC-MODELS

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The work is devoted to comparison of different boundary conditions for the PIC-model of the problem of injection of two crossed beams with different widths into a magnetized plasma. The 2D3V statement is considered for the problem. A plasma in a rectangular region with the size $Lx \times Ly$ is bounded by a vacuum from both sides in the Y direction and held by a longitudinal magnetic field Bx. Electron beams are continuously injected into the plasma through the boundaries $X = 0$ and $X = Lx$. Each beam swings plasma waves running in opposite directions, due to two-stream instability. It was shown earlier [1] that the electromagnetic radiation can be efficiently generated at a doubled plasma frequency for various transverse profiles of colliding plasma waves. This scheme allows to obtain narrow-band THz radiation of a gigawatt level with using of multi-gigawatt electron beams. It is necessary to ensure the continuous injection of the electron beam into the plasma through the open boundaries of the computational domain for the numerical simulation of such system. Comparison of different realizations of boundary conditions for the PIC model is presented in this work. Numerical parameters that allow ensuring sufficient accuracy of calculations are determined.

The work is supported by the RFBR grant No. 18-32-00107.

References

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THE ROTATING RAYLEIGH-TAYLOR INSTABILITY IN A STRONGLY COUPLED DUSTY PLASMA

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In the presence of density gradient, a dense magnetized electron-ion or complex (dusty) plasma can be subjected to develop the RTI when it is supported against gravity. The problem of RTI prevails great interest to the researchers because of its wide applications. We investigate the linear Rayleigh-Taylor instability (RTI) in a strongly coupled dusty plasma (SCDP) where the dust cloud is rotating uniformly. The electron fluid is assumed to be inertia-less as compared to the other constituents. The strength of the magnetic field is such that the electrons and ions are assumed to be fully magnetized, but the dust particles remain unmagnetized. In the presence of magnetic field the ions experience a rigid rotational force with constant angular velocity and drift along the E×B direction. The strongly correlated dust particles are dragged in the same direction by magnetized ions [1]. The neutral density is supposed to be negligibly small. Thus the dust particles experience a uniform rotational force similar to the Coriolis force [2, 3] mainly due to the drag force of the magnetized ions. The strong correlation between dust particles are considered and hence the dust coupling parameter is much higher than the electron and ion coupling parameters. If any part of the dust cloud experienced a rotational force then the entire dust cloud will rotate rigidly as dust particles are strongly correlated. We formulate single fluid momentum transfer and continuity equation incorporating individual electron, ion and dusty fluid equations [4] for local stability analysis. Normalizing the governing equations for first instance the stability of the system is examined with the small exponentially varying perturbed physical quantities. The slowly varying background density profile make the dusty plasma configuration unstable to the RT mode. The general dispersion relation exhibiting RTI is derived analytically for the considered SCDP and analyzed in the strongly coupled (kinetic) limit. A direct numerical solution is also performed to find the growth rate numerically and the results are compared with analytical results. We use Finite Discretization Method (FDM) to discretize the governing equations in vertical direction and solve the equations to obtain eigenvalues using Octave code. The imaginary part of the eigenvalues represent the instability growth rate. In the presence of both magnetic field and dust-dust strong correlation, the Alfven mode is coupled with the viscoelastic shear mode. The RTI criterion is obtained which is modified due to the presence of shear velocity comprising strong correlation effects, and Alfven velocity. It is found that the presence of the intermediate magnetic field in SCDP, the dust cloud rotation due to drag force of magnetized ions can also stabilize growth of RTI. The influence of dust cloud rotation, magnetic field and strong coupling effects are studied graphically which show the stabilizing effects on the growth rate of linear RTI.

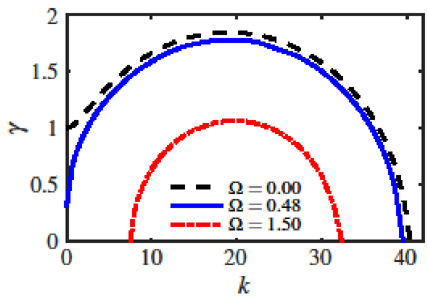

Figure 1: The normalized growth (Analytical) rate of the RTI is plotted against normalized wavenumber for different values of angular frequency.

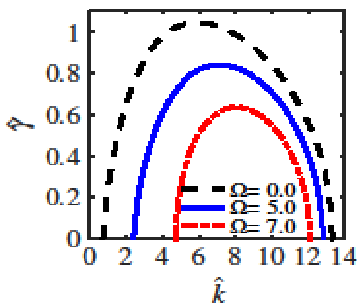

Figure 2: The normalized growth (Numerical) rate of the RTI is plotted against normalized wavenumber for different values of angular frequency.

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NUMERICAL MODELLING OF FOCUSED RELATIVISTIC ELECTRON-POSITRON BEAMS COLLIDING WITH CROSSING ANGLE

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We present a three-dimensional parallel algorithm for numerical modelling of self-consistent colliding beam dynamics in linear supercolliders. The thin ultrarelativistic beams are focused by quadrupole lens field and collide with a crossing angle (~2-25 mrad). The small sizes of the beams are necessary for high luminosity achievement. However, their high density may be critical and the beams may significantly change their shape or even disrupt. The crossing angle between the beams and the non-linear focusing complicate the problem of the beam stability and optimization of the collider parameters.

Our algorithm is based on solution of Vlasov-Liouville and Maxwell's equations in three-dimensional case. We use particle-in-cell method with PIC form-factor and Langdon-Lasinsky scheme on shifted Yee's grids. We combine particle and domain decompositions for the purpose of using 10^9 model particles in the numerical experiments. The beam particle distribution is highly non-linear in space, and the domains with large number of particles are computed with higher number of processors. The algorithm and its components may be applied to different problems in relativistic plasma physics.
The computations were performed on the supercomputer Lomonosov (MSU, Moscow), Polytechnic (SPBSTU, Saint Petersburg) and SSCC cluster (ICM&MG SB RAS, Novosibirsk).

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NUMERICAL MODELS IN APPLIED PLASMADYNAMIC AND PLASMASTATIC PROBLEMS

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The lecture presents a review of mathematical models and computations that became an essential element of problems in the two applied plasma physic projects: elaboration and creation of powerful plasma accelerators and researches of equilibrium plasma configurations being confined by means of the magnetic field in some traps that are of interest in the controlled nuclear fusion programs. The both projects were pioneered by prof. A.I. Morozov and realized in experiments under his direction in some institutes in Moscow, Kharkov and Minsk.

Plasma flows in coaxial channels of accelerators are investigated in the plasmadynamic models. Steady-state transonic flows are obtained after the relaxation in the numerical solving of time-dependent two-dimensional or quasi-one-dimensional magnetogasdynamic problems. Computation results became a part of the de Laval nozzle magnetic analogue theory and promoted to create the quasi-stationary high-current plasma accelerator with record values of the outgoing stream velocity and energy. The recent time works deal with studies of the longitudinal magnetic field influence on the plasma acceleration process in the channels of various geometry.

Equilibrium and quasi-equilibrium magnetoplasma configurations in the traps possessing any symmetry (plane, axial or helical) are researched in plasmastatic models based on the numerical solution of boundary value problems with the Grad-Shafranov equation for the magnetic flux function. As a computation result, the configuration parameters and geometry are investigated for some «galateya»-traps with current carrying conductors immersed into the plasma. Some questions on the configuration stability are related to the general differential equation theory in the models of reaction and diffusion interaction. In the recent time works, configurations in toroidal magnetic traps are studied in comparison with their analogues straightened into the cylinder. Some quantitative estimates are obtained for differences between them.

The references of works discussed above are in the book [1] and in the papers [2, 3].

The works mentioned in this lecture are supported by the Russian Science Foundation (project no. 16-11-10278).

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ADAPTIVE TECHNIQUE FOR CHEBYSHEV-BASED SOLVERS FOR THREE-DIMENSIONAL ELIPPTIC EQUATIONS

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We present an adaptive technique for 3D elliptic PDEs solvers, namely, for the multigrid algorithm [1] and the Chebyshev iterative method [2]. The key elements are self-adaptation of both multigrid and Chebyshev methods. The adaptation provides the estimation of unknown bounds of the spectrum of discrete operators. For Chebyshev method we develop the self-adaptive algorithm which is capable of evaluating an unknown lower bound. For multigrid such algorithm adjusts smoothers for achieving the prescribed rate of multigrid convergence and improves the efficiency of the multigrid. The main features are demonstrated on solving a large system of linear equations $Au = f$, where $u, f \in \mathrm{R}^n$ are vectors and $A \in \mathrm{R}^{n\times n}$ is a self-adjoint positive definite matrix with eigenvalues $\lambda \in [\lambda_{min}; \lambda_{max}]$, $0 < \lambda_{min} < \lambda_{max}$. Such systems usually arise from discretization of Poisson-like equations (computations of the gravitational potential, diffusion, etc). The Chebyshev method can be expressed as $u_{k+1} = u_k + \tau_k\left(f - Au_k\right)$, $k = 0,\dots, p-1$, u_0 is an initial guess, p is a number of iterations, $\{\tau_k\}$ is the optimal set of the parameters. The error propagation operator $F_p\left(A\right)$ of this method is defined by the optimal Chebyshev polynomial $F_p\left(\lambda\right)$ for the interval $\left[\lambda_{min}; \lambda_{max}\right]$. To achieve the specified accuracy ε we need to known λ_{min}, λ_{max}. Estimate λ_{max} is obtained by the Gershgorin theorem. We propose a self-adaptive procedure to find new approximate value λ_{min}, whenever the algorithm has not achieved optimal convergence rate with preceding estimate λ_{min}. The numerical examples are presented to show that the self-adaptive algorithm is effective.

Acknowledgements: This work was supported by Presidium of RAS, Program № 17

References:

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3D HYDRODYNAMICAL SIMULATION OF ACCRETION DISK IN BINARY STAR SYSTEM USING RKDG CFD SOLVER

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The results of 3D hydrodynamical simulations of accretion flow in the eclipsing dwarf nova V1239Her in quiescence are presented. The model [1] contains the optical star filling its Roche lobe, a gas stream emanating from the inner Lagrangian point of the binary system, and the accretion disc structure. The cold hydrogen stream coming from L1 lagrangian point to accretor vicinity is modelled using Euler system of equations for compressible inviscid partially-ionized gas. The Rosche gravitational potential, matter radiative cooling and binary star system rotation are taken into account in mathematical problem formulation.

The numerical scheme for governing equations solution is based on Runge – Kutta Discontinuous Galerkin method written for unstructured tetrahedral meshes. Well-known HLLC numerical flux [2] is adapted for calculations with non-perfect partially-ionized gas. The scheme algorithm is implemented in parallel solver for cluster computational systems. The solver is good scalable up to 500 processor cores.

The light curve of the system is calculated using obtained hydrodynamical solution as the volume emission of optically thin layers along the line of sight up to the optical depth $\tau = 2/3$ calculated using Planck-averaged opacities. The calculated eclipse light curves show good agreement with observations, with the changing shape of pre-eclipse and post-eclipse light curve being explained entirely due to $\sim$ 50% variations in the mass accretion rate through the gas stream.

The work is supported by Russian Foundation for Basic Research (projects 16-02-00656, 18-01-00252).

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NUMERICAL ANALYSIS OF PLASMA COLUMN DYNAMICS IN TWO-FLUID EMHD

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Some important problems in the dynamics of rarefied plasma, as well as plasma with strongly inhomogeneous density, require the use of certain generalizations of MHD equations that take into account electron inertia. Lately, the corresponding systems of equations have been referred to as the *extended MHD* (*EMHD*) *equations* and the *inertial MHD* (*EMHD*) *equations* [1]. An advanced version of the EMHD system, called the *equations of electromagnetic hydrodynamics* (EMHD), was proposed in 1988 [2]. In the present paper, the EMHD equations are used for the investigation of plasma column compression in devices of z-pinch type employed in the early stages of the fusion program. It is assumed that there is a precise geometric plasma-vacuum boundary and the influence of the external electric circuit of the device on compression processes is taken into account. The EMHD equations have the form

$$\begin{aligned}
&(a)\quad \frac{\partial \rho}{\partial t} + \mathrm{div}\rho\mathbf{U} = 0, \quad (b)\quad \frac{\partial \rho\mathbf{U}}{\partial t} + \mathrm{Div}\Pi = 0,\\
&(c)\quad \frac{\partial p_\pm}{\partial t} + \mathbf{U}\cdot\nabla p_\pm + \gamma p_\pm \mathrm{div}\mathbf{U} \pm \lambda_{\mathrm{m}}\rho^{\gamma-1}\mathbf{j}\cdot\nabla\left(\frac{p_\pm}{\rho^\gamma}\right) = (\gamma-1)\frac{m_{\mathrm{m}}}{m_\Sigma}\frac{j^2}{\sigma},\\
&(d)\quad c^{-1}\frac{\partial \mathbf{H}}{\partial t} + \mathrm{rot}\mathbf{E} = 0, \quad (e)\quad \mathrm{div}\mathbf{H} = 0, \qquad (1)\\
&(f)\quad \mathbf{E} + \frac{c^2\lambda_+\lambda_-}{4\pi\rho}\mathrm{rotrot}\mathbf{E} = -c^{-1}[\mathbf{U},\mathbf{H}] + \rho^{-1}\mathrm{Div}\mathrm{W} + \frac{\mathbf{j}}{\sigma},\\
&(g)\quad \mathrm{rot}\mathbf{H} = \frac{4\pi}{c}\mathbf{j},
\end{aligned}$$

where $\lambda_\pm = m_\pm / e_\pm$, $\lambda = \lambda_+ + \lambda_-$, the electrons and ions are assumed to be ideal polytropic gases with a common adiabatic index $\gamma > 1$; Π is the internal stress tensor and W is the electrodynamic state tensor:

$$\begin{aligned}
&\Pi = \Pi^{(h)} + \Pi^{(p)} + \Pi^{(c)},\\
&\mathrm{W}=(\lambda_- - \lambda_+)(\Pi^{(p)} + \Pi^{(c)}) + (\lambda_- p_+ - \lambda_+ \mathrm{p}_-)\mathrm{E}_3 + \lambda_+\lambda_-(\mathbf{jU} + \mathbf{Uj}), \qquad (2)\\
&\Pi^{(h)} = \rho\mathbf{UU} + p_\Sigma \mathrm{E}_3, \Pi^{(p)} = \frac{H^2}{8\pi}\mathrm{E}_3 - \frac{\mathbf{HH}}{4\pi}, \Pi^{(c)} = \lambda_+\lambda_-\frac{\mathbf{jj}}{\rho}.
\end{aligned}$$

In this paper, we propose a difference scheme for finding cylindrically symmetric solutions of the EMHD equations in Lagrangian coordinates. We construct boundary conditions for the generalized Ohm's law (1*f*). This difference scheme is tested on some special solutions of the EMHD equations, the so-called homogeneous deformations found in [3]. Those are cylindrically symmetric solutions for which the radial velocity $U_r(t,r)$ linearly depends on r for any fixed t.

This work has been supported by the Russian Science Foundation (Project 16-11-10278).

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3D-PIC SIMULATION OF THE ELECTRON BEAM INTERACTION WITH MODULATED DENSITY PLASMA[1]

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One of the perspective directions in the terahertz radiation obtaining is the generation of electromagnetic radiation near the plasma frequency in a plasma-beam system. The experiments on the electromagnetic waves generation (0.1-0.5 THz) during the injection of high-current electron beams into the plasma at the GOL-3 facility in the Institute of Nuclear Physics SB RAS showed significant increasing in the radiation efficiency (~ 1%) in the regime when the transverse dimensions of the system comparable with the length of the emitted waves [1]. In the linear theory, the mechanism of a plasma antenna for generating terahertz radiation was proposed [2].

The continuous injection of a beam into a plasma channel with a longitudinal density modulation provides a high efficiency (up to 10%) of the emission at a plasma frequency. It is assumed that the inhomogeneity of the plasma density plays a key role in the conversion of the beam energy into electromagnetic radiation.

The main problem of linear theories is that they do not take into account many factors such as instability which plays an important role in the real plasma. Therefore it is necessary to create a numerical model that takes into account nonlinear effects. In this paper, the three-dimensional numerical model is created for simulation of beam-plasma interaction. It is fully kinetic model based on Particle-In-Cell method. Numerical experiments for different beam and plasma parameters have been performed using computer systems with parallel architecture. Estimates of the radiation efficiency for the initially homogeneous plasma and for longitudinal density modulation are obtained.

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2. *I.V. Timofeev, E.P. Volchok, and V.V. Annenkov* // Physics of Plasmas. 2016. Vol. 23. 083119.

1 This work was supported by the Russian Science Foundation (project 16-11-10028). Simulations are performed at the Siberian Supercomputer Center SB RAS and using computational resources of Novosibirsk State University.

AN EXPERIMENTAL INVESTIGATION OF DISCONTINUOUS SOLUTIONS OF A NEW FINITE-DIFFERENCE MODEL OF FLUID DYNAMICS WITH ENTROPY NONDECREASING

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In this work we introduce a new linearized finite-difference model of fluid dynamics with condition of entropy nondecreasing on discontinuous solutions (shock waves). This model is modern logical development of the canonical work [1]. based on the linearized analogue of the Riemann problem solution from the book [2]. The model has been built by using equations of fluid dynamics 1-3

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(p + \rho u^2)}{\partial x} = 0 \tag{2}$$

$$\frac{\partial H}{\partial t} + \frac{\partial(u(H + p))}{\partial x} = 0, \tag{3}$$

with classical equation of state $E = \frac{p}{(\gamma-1)\rho}$, that represent the conservation laws of mass, impulse and energy. Here in the model $H = \rho\frac{u^2}{2} + \frac{p}{\gamma-1}$ is enthalpy function. The pressure of a gas is determined with formula $p = \sigma(S)\rho^{\gamma}$, where S is entropy variable. The velocity of speed is found as $c = \sqrt{\gamma p/\rho}$. We do not include the conservation law of entropy in our system because the law of entropy nondecreasing is hold automatically due to inner structure of finite-difference model.

The structure of shock waves has been investigated. It was shown the dependence of a width of shock waves and their formation time on the changing of the Courant number. Some tests were performed on different configurations of the Riemann problem to describe the finite-difference features and effects, that can influence on the solution. It was noticed, that arising negative effects come to zero while reducing the grid step. The numerical fulfillment of the law of entropy nondecreasing has been shown here. The problem of an accuracy of the discontinuous solution was mentioned. Performance results of parallel version of the algorithm, implemented through OpenMP and MPI technologies, have been presented.

The work has been supported by the Russian Foundation for Basic Research, grant 18-31-00303.

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RECORD OF SPONTANEOUS MAGNETIC FIELDS IN FOCUS 3D CODE

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Magnetic fields of considerable magnitude were discovered in various experiments on interaction of laser radiation with matter in plasma formed [1, 2]. Spontaneous magnetic fields in matter appear under condition of noncollinearity of pressure and density gradients. The presence of perturbations at the boundary of target and their further development only increase the growth of magnetic fields, which in turn affect the development of instabilities. To study the described processes, Focus 3D code is being developed.

The Focus 3D code uses the finite volume method. Within the framework of the program, the solution of the equations of ideal magnetic gas dynamics in conservation-law form is realized. To approximate the flows in the centers of the cell faces, the HLL scheme is used [3]. To obtain the expression for the numerical flow on the faces of cells, we consider the one-dimensional Riemann problem. The time approximation is carried out according to the two-stage Runge-Kutta scheme. To remove the divergence of the magnetic field, the projection scheme is used [4, 5].

The code was tested by solving the system of equations of the ideal magnetic gas dynamics on one-, two- and three-dimensional problems. The comparison was carried out with the solutions obtained under the FLASH code [6], and the results were shown to be in a good agreement. It is shown that removing the divergence of the magnetic field gives more accurate result.

Test problems having analytic solutions are proposed to verify the correctness of the numerical realization of spontaneous magnetic fields accounting. The second order of approximation is obtained for calculation the gradient of smooth functions by the Gauss theorem for the gradient. The convergence of the solution on refined grids is shown.

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NUMERICAL MODELING OF THE DYNAMICS OF THE PLASMA FLOW INTERACTION IN A MAGNETIC FIELD

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On the base of the numerical modeling there are studied the processes of the generation of whistlers, the Alfven waves and collisionless shock waves under interaction of high-speed plasma flows in a magnetic field. The problem statement refers to the conditions of laboratory experiments using the facility "Space Research - 1" (ILP SB RAS) [1]. The numerical model is based on the kinetic description for ions and the MHD approach for magnetized electrons (the hybrid model) [2]. To solve the kinetic Vlasov equation, the author modification of the particle-in-cell (PIC) method is used. The analysis of the generated perturbation structure, depending on plasma parameters and the magnetic field, has been made. Also, there have been studied the shock wave characteristics for the regimes of multi-flow formation and mechanisms of the ion acceleration on a shock wave front.

This work has been carried out within the framework of the budget project 0315-2016-0009 of ICMMG SB RAS and has been supported by the RFBR under grant 16-01-00209.

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THREE-DIMENSIONAL ELECTRODYNAMIC CODE FOCUS-EM

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The paper is devoted to the description of the three-dimensional Focus-EM code developed in RFNC-VNIITF. This code is intended to simulate the problems of electrodynamics, plasma physics, acceleration of electrons and ions on laser and electrophysical facilities. The code is based on solving the Vlasov kinetic equation and the Maxwell equations system. To solve the Vlasov equations, the method of particles in cells is used [1]. An explicitly finite difference scheme of the second order of accuracy is used to solve the Maxwell equations.

A set of analytical tests (propagation of plane electromagnetic wave in plasma, motion of an electron in electric and magnetic fields, etc.) is given and a good agreement of the numerical solution with them is shown. The order of convergence of the numerical algorithms also determined.

The calculations of the accelerated electrons in plasma wakefield are presented, and the results of comparison with experiment for the parameters for the laser facility of RFNC-VNIITF are demonstrated.

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KINEMATIC-GRAVITATIONAL ION MODEL OF PLANETARY DYNAMO

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In this paper, resulting from solving the inverse problem for the main magnetic field of Earth, it is shown that the global sources of magnetic field are situated in the equatorial region of the Earth's core. The estimates of magnetic moments, volumetric currents and their densities are obtained. The direction of the current flow is determined, which can be explained by the motion of the positively charged core matter under the influence of tidal forces, directed against the basic axial rotation of the Earth. The core is positively charged due to migration of electrons across the core-mantle boundary. For the planets of the Solar system estimates of the tidal forces produced by the Sun and the satellites of the planets are obtained. A close linear relationship is established between the magnitude of tidal forces and the observed magnetic field of the planets. As a result, we arrive to a simple geodynamo mechanism in which the electric current is the motion of weakly positively charged core matter associated with the action of tidal forces.

3D MODEL OF RADIATION TRANSPORT IN FLOWS OF IONISING GAS AND PLASMA

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Research of the axisymmetric ionizing gas flows in the channel of the quasi-steady plasma accelerator (QSPA) is presented. Model is based on the MHD and radiation transport equations. The modified radiation magnetogasdynamics model (RMHD) for a three-component medium consisting of atoms, ions and electrons takes into account the basic mechanisms of the electrical conductivity and heat transport. The three-dimensional model of the radiation transport includes the basic mechanisms of emission and absorption for the different portions of spectrum. Results of the numerical studies of ionization process, plasma flow and radiation transport are received in approximation of the local thermodynamic equilibrium.

Simple plasma accelerators consist of two coaxial electrodes connected to electrical circuit. As a result of the breakdown between electrodes the ionization front corresponding to a phase transition from one state of matter to another is formed in the presence of the main azimuthal component of the magnetic field. The azimuthal field is generated by electric current flowing along the inner electrode. In turn the radial plasma current flowing between electrodes and the azimuthal magnetic field provide the acceleration of plasma due to the Ampere force. The ionization process occurs particularly in first stage of two-stage QSPA [1]. These multifunctional systems are designed for fusion research (see e.g. [1, 2]), technological applications, and are of interest for development of the perspective high-power electro-plasma thrusters (see e.g. [1, 2]).

The problem of the radiation transport in flow should be solved in the 3D formulation. The radiation intensity has to be determined in different directions for the further calculation of the integral values of the radiation energy flux density in any node or cell of the coordinate grid. For this purpose the additional angular grid for each node of coordinate grid is built on the azimuth and polar angle. The ray tracing is carried out in accordance with method of the long characteristics [3] in order to determine the points of the crossing of ray with sides of cells of the 3D coordinate grid and the position of the crossing of ray with one of boundaries of the calculated domain. As a result the intensity is calculated for each node of coordinate grid, for each ray of angular grid and for all portions of spectrum.

The parallel version of program is developed with the help of DVM technology to calculate the plasma flow taking into account the radiation transport based on the RMHD model [4]. This allowed to significantly accelerate the execution of program with respect to the original version using the K-100 computer complex at the Keldysh Institute of Applied Mathematics.

The research was supported by the Russian Science Foundation (Grant No. 16-11-10278).

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GOOPHI: A NEW INTEL XEON PHI – ACCELERATED HYDRODYNAMIC CODE FOR NUMERICAL SIMULATIONS OF ASTROPHYSICAL FLOWS

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In this talk, a new hydrodynamics code gooPhi to simulate astrophysical flows on Intel Xeon Phi processors with KNL architecture is presented. A new vector numerical method implemented in the form of a program code for massively parallel architectures is proposed in details. The details of code verification is described. A detailed description is given and a parallel implementation of the code is made. A performance of 173 gigaflops and 48 speedup are obtained on a single Intel Xeon Phi processor. A 97 per cent scalability is reached with 16 processors.

The research work was supported by the Grant of the President of Russian Federation for the support of young scientists number MK - 1445.2017.9, RFBR grants 18-01-00166 and 18-07-00757.

THE NUMERICAL MODELING OF THE COLLAPSE OF MOLECULAR CLOUD ON ADAPTIVE NESTED MESH

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In this talk, a numerical modeling of the collapse of molecular cloud is presented. The numerical method for solving the equations of hydrodynamics is based on the extension of HLL method for using of nested adaptive mesh technologies. In case of nested meshes, if neighboring cells have the same size as the one considered cell, the Rieman problem is trivial. If the neighboring cell is larger than a considered cell, then a uniform distribution of the parameters over the large cell is assumed. Then a new subcell is allocated in a larger cell corresponding to a size of the cell considered and being adjacent to it, after which the necessary data for a computing. If a neighboring cell is less than a considered cell, then values around a small cell are averaged (in the corresponding octet). The energy behavior of the rotating molecular cloud is in quantitative agreement with the results of other authors before the moment of collapse, and after the moment of collapse. It should be noted that collapse occurs at exactly the same moment in time.

This work was supported by Russian Science Foundation (project no. 18-11-00044).

Radiation friction losses in ultraintense laser-plasma interaction

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We present a self-consistent theory describing the interaction of superintense (with intensities about 10^{23} W/cm^2 and higher) circularly polarized electromagnetic pulses with thick plasmas of overcritical density. In contrast to the case of thin plasma slabs, thick targets are known to provide an interaction regime with extremely high radiation losses, because a high plasma surface density prevents longitudinal acceleration of electrons. Relying on our previous work [1] and on the model suggested by Zeldovich [2], we developed an analytic theory which predicts that the combined effect of the radiation reaction force and of the charge separation in the plasma leads to the self-limited (although high) radiation losses, making a classical picture of radiation fairly accurate up to the intensity 10^{25} W/cm^2, which is currently at the edge of capabilities expected from the Extreme Light Infrastructure pillars [3]. We test our theory comparing its predictions to results of three-dimensional Particle-in-Cells simulations made in the hole boring regime using a code with radiation reaction effects classically included. Although the simulations take into account some important factors which are not covered by the analytic theory, including a spatial inhomogeneity of the laser pulse and its final time duration, a highly inhomogeneous spatial distribution of the electrons during the main stage of the interaction, their results agree qualitatively to the predictions of our model. We expect that at these ultrahigh but nevertheless foreseen in the near future intensities the radiation losses saturated at a roughly 50% energy conversion from the laser pulse to high-energy photons. As a result of this conversion, a quasi-static magnetic field with the magnitude up to 30 gigagauss can be generated.

This research is partially supported by RSF within the project 16-11-10028.

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SS433 JET PRECESSION: INFRARED DISPERSION DOPPLER EFFECT

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In the infrared part of the electromagnetic spectrum, the relativistic dispersion theory is applied to the SS433 jets, to describe its dispersion properties. In particular, we here investigate the dispersion Doppler effect of radiation in the relativistic plasma of this microquasar.
We find that the Doppler line displacement in SS433 is affected by plasma dispersion only in a narrow frequency range in the far IR. As a consequence, although the shift (z) modulation due to precession of the SS433 jets is well described by previous work in the optical range, it has to be corrected by plasma dispersion effects in the far-IR range.

GRID FUNCTIONS REMAPPING METHOD FOR COMPLETELY CONSERVATIVE LAGRANGIAN OPERATOR-DIFFERENCE SCHEME FOR ASTROPHYSICAL MHD PROBLEMS

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The procedure of conservative grid functions remapping for completely conservative Lagrangian operator-difference scheme on a triangular grid of variable structure is suggested. The grid functions remapping procedure based on the conditional minimization of specially constructed functionals is developed. The described procedure is applied to the simulation of MHD astrophysical problems such as magnetorotational supernova explosion.

MOVING MESH CODE FOR ASTROPHYSICAL GASDYNAMICS SIMULATION

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Simulation of gasdynamics is one of the most important stages in modeling of astrophysical processes. Despite the fact that there are a large number of numerical methods in gasdynamics, the development of new and modification of existing ones is actual for today. All methods could be divided into three categories: lagrangian methods, eulerian methods and theirs combinations.

One of the purely lagrangian methods is SPH (Smoothed Particles Hydrodynamics), in which continuous medium is described with system of discrete particles allowing arbitrary connectivity with each other. The doubtless advantage of SPH is simplicity of its algorithmic implementation with a minimum code size. The absence of computational grid allows the method to compute arbitrary rotational and shear fluxes, decay of simply connected and merge of multi-connected computational domains in a natural way. Although it has some disadvantages. Representation of medium with discrete particles leads to the need of using of large number of particles to get acceptable accuracy especially in areas with huge gradients. In addition, it has limited scalability, so we could not solve large-scale problems with using of supercomputers effectively.

Another well-established method is large-particles method by Belotserkovskii-Davydov. It is an eulerian-lagrangian method based on Harlow method, which use discrete particles within eulerian computational grid. Harlow method is numerically unstable because of discrete representation of continuous medium. Also it is difficult to get information about rarefaction areas that leads to the need of increasing of number of particles. Large-particles method does not have these disadvantages because the mass of the entire computational cell is taken into account instead of individual particles. However, the method saves some eulerian characteristics because of using regular computational grid. The main problem of this class of methods is Galilean non-invariance and suppression of complex fluxes that leads to inaccurate reproduction of instabilities important for correct computation of astrophysical processes.

Not so long ago more advanced approach based on moving mesh technology began to be used. It combines advantages of eulerian and lagrangian methods allowing achieving high accuracy of computations. The idea that mesh cells could move with the medium they describe is in the basis of technology. Hence, initially continuous medium is described with continuous approximation as in eulerian methods, but the mesh itself could thickens in the right places, bends and rotates so that medium is described with highest accuracy as in lagrangian methods. Nevertheless, of course it is more complicated in implementation than other methods.

The polygonal unstructured moving mesh method of modeling of gravitational gasdynamics is given. The results of verification and numerical experiments are shown.

NUMERICAL IMPLEMENTATION OF ULTRARELATIVISTIC DISSIPATIVE FLUID THEORIES OF DIVERGENCE TYPE

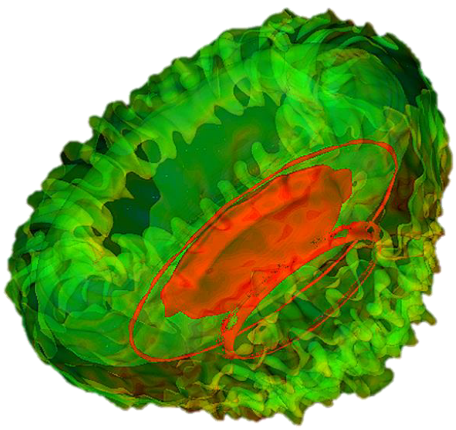
M. Rubio

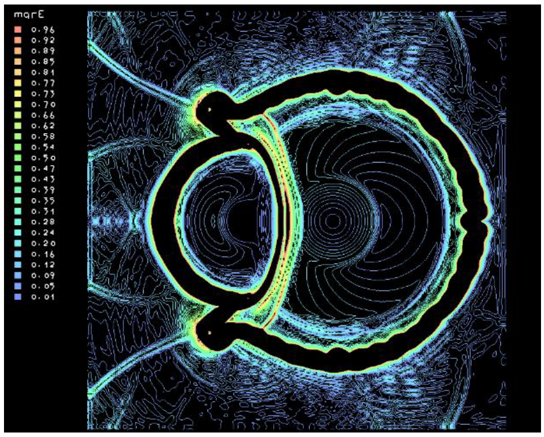
We present a well-posed novel theory of conformal dissipative fluids within the framework of General Relativity, without using Israel-Stewart-like assumptions. The power of the theory is that all the information of its dynamics is encoded in a family of scalar functions parametrized by three free constants. After reviewing the most relevant aspects of it, I will discuss a possible numerical implementation using the algorithm of Kurganov-Tadmor for the treatment of shock waves, as well as show some preliminary simulations.

COMPUTATIONAL MODELING OF DENSITY STRATIFICATION IN THE PROCESS OF COLLISION OF MOLECULAR CLOUDS

Rybakin B.P., Betelin V.B., Smirnov N.N., Moiseenko S.G, Stamov L.I.

The paper presents a mathematical model and a parallel III-d program for modeling the collision process of molecular clouds. The formation of dense clamps that arise as a result of the collision of molecular clouds is a mechanism that allows one to explain the origin of new stars. These clamps are gravitational unstable objects by Jeans and are the precursors of new stars and star clusters. The modeling results of filamentary formations, i.e. concentrated areas with high gas density in molecular clouds (MC), and the non isothermic compression calculation data are discussed. The spatial mesh resolution required for satisfying Jeans conditions in modeling is substantiated. The programming code developed uses dynamic gridding called local adaptive mesh refinement (AMR) at several (up to 10) resolution levels. To provide adequate resolution the meshes are added automatically and dynamically as well as destroyed as needed. The computation paralleling algorithm with OpenMP and CUDA is given. The programming language chosen to compute the problems of gravitational gas dynamics efficiently is justified and substantiated. The practice of applying algorithms for modeling the MC fragmentation after collisions, the filament and protostellar clouds formation, the star formation stages is analyzed.





The penetration of small cloud into more massive GMC can initiate outward explosive shock waves. Cumulative impact has a cavity-like density fragmentation across cloud-cloud conditionally surface. In the case of glancing collision more heave molecular cloud penetrates into more light and friable side of another one. It cuts gas "hollow" in side of another cloud, boundary layers and conditional edges of which begin to roll. Bound of mixing zone becomes film-like with curvilinear profile of their outer surfaces. Density contrast diagrams, shown here indicate a spatial intermittency of supersonic flow, accompanied amplified Kelvin-Helmholtz instability. Compressed density lens-like clumps and rolled rings arise here.

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METHODS FOR COMPUTING RAPID MOMENTUM TRANSFER BETWEEN GAS AND DUST FOR SUPERCOMPUTER SIMULATIONS OF PLANETS FORMATION

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Circumstellar discs, where planets are formed, consist of gas, dust and solids. The dynamics of small dust grains in the disc is stiffly coupled to the gas, while the dynamics of grown solids is decoupled. Moreover in some parts of the disc the concentration of the dust is low (dust to gas mass ratio is about 0.01), while in other parts it can be much higher. These factors place high requirements on the numerical methods for disc simulations. In particular, when gas and dust are simulated with two different fluids, explicit methods require very small timestep (must be less than dust stopping time) to obtain solution, while some implicit methods requires high spatial and temporal resolution to obtain acceptable accuracy. To address these problems we developed fast algorithms based on the ideas of (1) implicit integration of linear (Epstein) drag and (2) exact conservation of local drag momentum. Together with previously described methods [1, 2], where we tested the approach in combination with grid-based piecewise parabolic advection scheme, we also demonstrate how the method works in combination with SPH (smoothed particle hydrodynamics). The developed methods have the following properties:

- applicability for dust and solids of all sizes smaller than the mean free path of the gas molecules,
- possibility of calculating mutual momentum transfer between dust and gas (as an alternative to one-way impulse transfer from gas to dust as considered in many other models),
- possibility to conduct calculations with the time step, that is determined by gas-dynamical parameters (and not the drag force) without sacrificing the accuracy,
- compatibility with parallel high performance algorithms for solving 3D gas-dynamical Euler equations and particle-in-cell methods for collisionless Boltzmann equation representing large solids.

We present results of supercomputer simulations of gas-dust disc dynamics using the proposed approach.

The development of the method for calculating the drag force in SPH method, and parallel SPH-PIC algorithm was supported by the grant of RFBR 16-07-00916. The development of numerical method of momentum transfer between gas and dust in Euler methods, improvement of FEOSAD model [2] and simulation of disc dynamics were done under the support of RNF 17-12-01168. Numerical simulations were done in Siberian supercomputing center (SSCC) and in Vienna scientific clusters VSC-2 and VSC-3.

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TWO-DIMENSIONAL PROBLEM OF ELECTROMAGNETIC WAVES IN THE VACUUM

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In the current work a 3D hybrid numerical model of the interaction of a relativistic electron beam with the stationary plasma to study the generated high-frequency electromagnetic radiation is proposed. Ions are considered in the frame of the hydrodynamics approach and an electron component of plasma is described by the kinetic Vlasov equation. The system of the Maxwell equations is added to these equations as well. At initial time there is the plasma circled by the vacuum in a computational domain. A relativistic electron beam of a small density is injected through the domain boundary and, interacting with the plasma, generates electromagnetic waves. The waves are spread out into the vacuum domain where the wave diagnostics has been carried out.

To find amplitudes and directions of the generated waves the methodology to define directions and amplitudes of all electromagnetic waves, presenting in the domain at a certain time, has been developed. The diagnostics has been made in a 2D case. Also, the tests showing the implementation of the proposed algorithm have been carried out.

The work has been supported by the Russian Science Foundation (RSF) under grant 16-11-10028.

THE MODELING OF INTERACTION OF LASER FEMTOPULSES WITH A GLASS. NUMERICAL APERTURE PROBLEM.

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Femtosecond laser pulses are widely used for microfabrication of materials. To improve the technologies and to explain physical phenomenon taking place in laser-matter interaction the mathematical modeling is effectively used. There are many problems in this modeling. For example, the view of the formulas describing photo- and impact ionizations, recombination, the collision frequencies are not well known. In presented report we pay attention, that usually given in experimental papers value of numerical aperture (NA) concern NA of optic system (objective), but not a laser beam NA, which can be several times smaller. Moreover the presented results of mathematical modeling based on the nonlinear Maxwell equations supplemented by hydrodynamics type equations for the free electron plasma shows that the peak of the absorbed laser energy has unphysical maximum near the threshold. This is typical for many variants of descriptions of physical processes involving into the models and values of the parameters of these models. Such a behavior of the absorption peak corresponds to the situation when residual damage of the glass appears at a certain pulse energy, for larger energy the damage is absent, for more larger one the damage appears again. This not consists with experimental data. Only using smaller numerical aperture in the calculations gives correct monotonic dependence of the peak energy on laser pulse energy.

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Honor of academician
Anatoly Alekseev's 90th Birthday

Anatoly S. Alekseev
October 12, 1928 – February 17, 2007

A.S. Alekseev graduated from the Leningrad University (mathematical-mechanical faculty) with specialization in Mechanics in 1952. He received his Doctorate of Science in 1955 and became Full Professor in 1966 (Geophysics). Prof. Alekseev's thesis was entitled "Direct and inverse problems of seismology". His scientific interests are concentrated on theoretical and computational geophysics.

From 1955 to 1963 he worked in the Leningrad Division of the Mathematical Institute of the USSR Academy of Sciences. Since 1963 he has been working at the Computing Center, SB RAS. Since 1980 A.S. Alekseev has been the Director of the Novosibirsk Computing Center, SB RAS. Prof. Alekseev was awarded a State Prize for the ray method in 1982.

Prof. Alekseev's main results are: ray method theory (1958); study of the problem of identification of explosions and earthquakes (1960-62); statement and solution of inverse dynamic problems of seismics (1962); solution of the two-dimensional inverse kinematic problem of seismics (1967); investigation of the nature of waves in geophysical seismic problems (1961); quantitative statement of combined inverse geophysical problems (1991).