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hold

6th Workshop on Numerical Modeling in MHD and Plasma Physics: Methods, Tools, and Outcomes

Moscow, Russia
October 11-12, 2023

BOOK OF ABSTRACTS

The conference poster

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6th Workshop on Numerical Modeling in MHD and Plasma Physics: Methods, Tools, and Outcomes

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Investigation of plasma ionization oscillations in SPT

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A number of mathematical problems of the theory of ionization in relation to processes in stationary plasma thrusters (SPT) are solved in this work. Two main one-dimensional mathematical models of ionization are considered – hydrodynamic and kinetic. The main question is the existence of ionization oscillations (breathing modes). On the basis of a hydrodynamic model, a boundary value problem for stationary ionization equations is solved. Its unique solvability and the absence of breathing modes are proved. In the case when the ion velocity in the flow region has a single zero with a positive derivative, it is proved that the stationary boundary value problem has a countable number of solutions, and a necessary and sufficient condition for the existence of breathing modes is formulated. Finally, an analytical solution of the ionization equations is given in the case of constant velocities of atoms and ions, and the formulas obtained are applied to the solution of the Cauchy problem, boundary value and mixed problems in the simplest regions. In the case of the kinetic model of ionization, the existence of breathing modes is numerically shown and the results obtained are compared with the hydrodynamic case.

Using Adaptive Mesh Refinement Technique for Numerical Modeling of Relativistic Jets

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The Relativistic jets are main sources of radio emission in the Universe. Multiscale flows in jets require of using to adaptive mesh technique. In talk will propose original the Patch-Block-Structured Adaptive-Mesh-Refinement technique for multi-scale modeling of relativistic jets. To use this technique, the numerical method was redesigned in a special way. On problem of jet evolution in interstellar medium, the applicability of the developed approach is shown.

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Research of the ionizing gas flows with longitudinal magnetic field in the plasma accelerator channel

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Numerical study of the ionizing gas flows with additional longitudinal magnetic field in the channel of the quasi-stationary plasma accelerator (QSPA) is presented. Two-dimensional axisymmetric flows of an ionizing gas are considered using the transfer equations for multicomponent medium consisting of atoms, ions, and electrons, taking into account electrical conductivity, thermal conductivity, and radiation transport. The equations of magnetic gas dynamics are presented in terms of the vector potential of the magnetic field [1]. To calculate the transport of radiation, the 3D formulation of the problem is used in the multigroup approximation, taking into account the main mechanisms of emission and absorption of photons [2]. The study of the process of ionization and radiation transport was carried out in the approximation of local thermodynamic equilibrium. The longitudinal magnetic field leads to the plasma rotation behind the ionization front, which occurs in the ionizing gas flows. The integral radiation characteristics of the medium are determined. Calculations have shown that the ionization front shifts in the direction of the channel outlet with a decrease in the discharge current in accordance with the available experimental data. This is accompanied by oscillations of the ionization front in the narrowest and expanding part of the nozzle-shaped channel at low discharge currents and leads to the appearance of unstable pulsating flows of ionizing gas [3]. As a result of studying the ionization process in the presence of longitudinal magnetic field, it was found that the flow rotation and thermal conductivity along the magnetic field stabilize the instability of the ionization process in the QSPA installation [4].

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A first application of the turbulent vortex dynamo theory for exact diagnosing the tropical cyclogenesis over the North Indian Ocean

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The contribution crowns a series of the author's presentations in 2019–2022 about how the turbulent vortex dynamo theory and tropical cyclone research were bridging by efforts of Soviet-Russian, American and Indian scientists. This has been done based on researches, which were carried out over nearly the four decades. Finally, our collaborative Russian-American approach for early and exact detection of the birth of a hurricane [1] was successfully applied by Indian colleagues to three observed tropical cyclones [2].

One more recent publication [3] concerns what is happening almost a billion kilometers from the Earth in the Solar system. Based on Juno's mission data, an upscale energy transfer driven by moist convection was found at Jovian high latitudes. This can implicate a universality of the turbulent vortex dynamo as a mechanism for intensifying and sustaining large-scale long-lived vortex structures in rotating stratified moist atmosphere.

This research was supported by the Ministry of Science and Higher Education of the Russian Federation; program "Monitoring", state registration No. 122042500031-8.

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Fast simulation of collisions in the particle-in-cell method for ions of different types*

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The modeling of particle collisions in plasma is a well-known problem [1]. Various methods and algorithms to model particle collisions were proposed, but the full treatment of 3D collisions is a problematic task nowadays. Our article deals with the specialized high-speed algorithm of simulation of pairwise collisions for different types of ions without computing trigonometric functions. This work is based on the development of the ideas described in [2]. The effectiveness of the proposed approach has been shown. The developed algorithm has been compared with other algorithms (previously developed, classical [3] and modern [4] ones).

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Protostellar cores formation for oblate molecular clouds

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The study of the process of formation of stars of the main sequence shows that the cause is often fragmentation of molecular clouds in the early stages of star formation. Clouds often have either an elongated or flattened shape. Radial density profiles have a shape close to Gaussian, while the central density by one to two orders of magnitude exceed the density on the border of the MC [1].

In this paper, we use our own adaptive hydrodynamic code based on the methods of Godunov high order of accuracy for the study of the formation of filament and strongly compressed, gravitational-tied areas that occur during the collision of centrally condensed, elongated clouds with spherical clouds. The main governing equations of our model are the Euler equations of hydrodynamics in three-dimensional space, including the effects of self-gravity, and the Poisson equation for the gravitational potential. The initial mass of the oblate molecular cloud is $M = 10.493\ M_{\odot}$, the length of the big axis of the ellipsoid is $R = 1.679$ parsec. A spherical molecular cloud also has its own distribution of density along the radius. The initial mass of the spherical cloud is $M = 15.214\ M_{\odot}$, the radius is $R = 1.73$ parsec. The barotropic equation of the state is used to represent the transition from isothermal phases with low density to optically thick phases with high density. The initial ratio of thermal energy to the absolute value of gravitational energy is equal to $\alpha \approx 0.24348$.

The calculations of the collision of centrally condensed elongated nuclei of the clouds, on grids with high spatial resolution, were made to assess whether elongated configurations collapse isothermally, forming stellar double and triple systems, or condensed into gravitational structures. In most cases, filaments are formed with maximum densities characteristic of the transition of the isothermal phase to non - thermal. As the filaments become opaque for its own radiation, the increasing forces of internal pressure can slow down the collapse and lead to an increase in disturbances in the density along the length of the filaments, which will ultimately lead to binary or multiple fragmentation.

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An efficient algorithm for calculating the magnetic field in a cylindrical plasma trap*

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In this work, we propose a numerical algorithm for calculating the magnetic field in an open magnetic trap, which is an axisymmetric chamber filled with plasma. The plasma is held in the trap by a special configuration of the external magnetic field generated by current coils located at the ends of the chamber. The problem consists in developing an efficient algorithm for calculating the configuration of the magnetic field, which is determined by a given distribution of the external azimuthal current in the coils. The task is solved in two steps. First, the magnetic field distribution is found from the known arrangement of coils, and then this distribution is scaled so that the magnitude of the field in the center of the chamber and the mirror ratio are equal to the given values. The proposed algorithm can be easily generalized to solve the Poisson equation with Neumann boundary conditions on two opposing boundaries of the computational domain. This allows us to apply the developed method to calculate the potential in nonstationary problems.

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Fully kinetic numerical model of plasma dynamics in an open magnetic trap

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The unique possibility of PIC codes, associated with the use of primary principles in their development, makes it possible to simulate plasma dynamics including the spectrum of possible plasma instabilities without additional assumptions. However, a large difference in the masses of electrons and ions imposes significant restrictions on the size of a spatial step and does not allow even using modern supercomputers to study in detail the dynamics of the ion plasma component on large spatial and time scales. Therefore, in computations an artificial ratio of the ion mass to the electron mass is used and it varies in the range from 10 to 100. A decrease in the mass of ions can affect the dynamics of both the initial phase of the exponential growth of instability and the phase of nonlinear saturation. The paper deals with the description of a new fully kinetic numerical model of plasma based on the PIC method. It is used the real ratio of the ion mass to the electron mass in the proposed new model. The use of a new algorithm for the movement of model particles in the PIC method [Voropaeva E., Vshivkov K., Vshivkova L., Dudnikova G., Efimova A. New motion algorithm in the particle-in-cell method // Journal of Physics: Conference Series, 2021, 2028(1), 012011] makes it possible. Based on the new model, the code in (r-z)-geometry to simulate the dynamics of plasma in an open magnetic trap under the injection of charged particle beams has been developed. The computation results using the fully kinetic numerical model are compared with those of the hybrid numerical model.

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Quantum state and process tomography for a single qubit on cloud quantum computers

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Special quantum circuits make it possible to collect experimental data to study the dynamics of quantum processor qubits [1]. The harmonic inversion method restores a set of eigenvalues that form a diagram qualitatively similar to the full spectrum of the open quantum system Liouvillian [2]. The Lindblad tomography method [3] evaluates initial state preparation and measurement error (SPAM), Kraus operators, non-Markovian measure, Hamiltonian and Lindblad operators describing the evolution of an open quantum system. We estimated SPAM errors, reconstructed the evolution using Kraus operators for discrete times, and estimated the non-Markovianity of the first qubits of the OriginQ Wuyuan 1 (Origin Quantum Cloud) and ibmq_belem (IBM Quantum Computing) quantum computers. The obtained results demonstrate the comparability of the platforms parameters and a low degree of non-Markovian behavior. The nearest future challenges are related to describing the observed processes in the form of the time-independent Lindblad equation along with the experiments involving two-qubit interaction.

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Dispersion and Group Analysis of Dusty Burgers Equations

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We investigate the system of non-stationary one-dimensional equations consisting of a parabolic Burgers equation for the velocity of a viscous gas and a hyperbolic Hopf equation for the velocity of solid particles. The Burgers and Hopf equations are connected into a system due to relaxation terms simulating the momentum transfer between the carrier phase (gas) and the dispersed phase (particles). The momentum transfer intensity is inversely proportional to the relaxation time of the particle velocity to the gas velocity.

A dispersion relation is constructed for this system. A particular solution corresponding to the damping of a low-amplitude sound wave is found. For an infinitely short velocity relaxation time, the effective viscosity of the gas-dust medium is derived, which is determined by the viscosity of the gas and the mass fraction of particles in the mixture.

Symmetries and Lie algebras of symmetries of this system are found. For the defining equations, a detailed course of their solution is described. A code has been developed for the numerical generation of partial solutions of the system corresponding to each of the found symmetries.

The dispersion analysis was funded by the RSF grant 23-11-00142, the group analysis was found by the RSF grant 19-71-30012, the partial solution generator was developed by Yudina N.M. as a part of her bachelor thesis at NSU.

Modelling of the L_1 point jet formation in binary star Her X1

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Observational data from the binary X-ray star system Her X1 indicate that the accretion disk in it is tilted and processes with a period of about 35 days. Precession leads to unbalanced heating of the donor star and, as a consequence, to nonuniform outflow from its surface. A mathematical model has been developed for the outflow of matter from the surface of a star under the action of heating by an accretor, taking into account the shadow from the accretion disk. The model includes a 3D system of equations for the dynamics of an inviscid partially ionized gas, taking into account gravity and radiation effects. The algorithm is adapted to the use of tetrahedral meshes and takes into account the shadow displacement on the donor surface. Calculations have shown that the presence of a shadow leads to a displacement of the gas flow in the vicinity of the Lagrange point L_1. The center of the stream moves up and down, and its shape changes according to the movements of the shadow. Such an effect can lead to a tilt of the accretion disk, which makes the model self-consistent.

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Numerical simulation of the diamagnetic regime of an open magnetic trap*

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The paper presents the results of computational experiments on the injection of high-energy ion beams into an open magnetic trap (probcotron) obtained using an axially symmetric hybrid numerical model PIC-MHD.

In accordance with the data of laboratory experiments, the created numerical model takes into account the dissipation mechanisms associated with the Coulomb conductivity of the plasma. Spatial and temporal characteristics of the process of formation of the displaced magnetic field region (diamagnetic bubble) under continuous axial injection are obtained.

The obtained data were compared with the results of numerical simulation [1], where the frequency of ion-electron collisions was constant. The results of the performed computational experiments were used to clarify the possibility of implementing a diamagnetic plasma confinement regime in open magnetic systems [2].

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Improved vectorization of OpenCV algorithms for RISC-V CPUs

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OpenCV [1] is a widely used open source library of computer vision and machine learning algorithms. It contains high-performance implementation of more than 2500 algorithms and becomes the de facto standard in the development of software for video and image analysis. OpenCV is used in many application areas including computational physics. The methods of computer vision, machine learning and image analysis developed in the library can be employed to visualize the results of numerical simulation [2], to plan and analyze physical experiments [3], to compare the results of numerical simulation with real experiments [4].
Many computer vision and machine learning algorithms are computationally intensive, and their application in computational science requires high-performance computers. However, currently applied x86 and ARM architectures, with all their numerous advantages, are not without shortcomings. For example, the performance of the world's leading supercomputers on the HPCG test, which is based on memory-bound algorithms, is almost two orders of magnitude inferior to the performance on the LINPACK test. Therefore, the development of new architectures is still of interest. The recently emerged free and open instruction set and architecture RISC-V [5] is rapidly developing. In ten years, RISC-V developers have overcome the path from the poof-of-concept stage to publicly available high-performance RISC-V devices, which can already be purchased and tested [6]. In this talk, we continue the work begun in [6] and present our developments in the field of performance analysis and optimization of several OpenCV algorithms for multi-core RISC-V processors with SIMD instruction set extensions. We compare and analyze the performance of available RISC-V devices using image filtering, image resize and other algorithms as benchmarks, and demonstrate how to improve performance using code optimization techniques with a focus on vectorization. The results are publicly available and can be used in scientific research.

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Effect of Temperature Distribution On the Calculation of the thermal current in the Mathematical Model of Pulsed Heating of a Tungsten Plate and a Thin Vapor Layer

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Current distribution model in the tungsten sample and vapor at surface under electron beam heat was considered. The model is based on the solutions of electrodynamic equations and the two-phase Stefan problem in cylindrical coordinates. The two-phase Stefan problem defines the temperature inside a sample area taking into account the evaporation at its surface. A model temperature distribution in a thin layer of evaporated tungsten is used, which repeats the surface temperature. The electrodynamic equation include received temperature values and solved over the whole region. The case of constant values of electrical resistance and thermoemf in gases and metals is considered. The temperature calculations were made considering constant coefficients and temperature dependencies of specific heat capacity, density and thermal conductivity. It is shown that the detail of the coefficients of the Stefan problem has a great influence on the results of solving the electrodynamics equation.

The dependences on the temperature of electrical resistance and thermoemf are presented, based on experimental data and known estimates. The results are compared with the calculations of the problem with constant values of electrical resistance and thermal EMF in gas and metal. The results of the simulation show that the choice of approximation of the material parameters have a great influence on the decision. The model parameters are taken from the experiments on the Beam of Electrons for materials Test Applications (BETA) stand, created at the BINP SB RAS.

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Prediction of the Parameters of the Trap for Plasma Confinement in a Helical Magnetic Field

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The work involves plasma confinement by a magnetic field with helical symmetry as a developmentof the method of multi-mirror confinement [1]. In the frame of reference of a rotating plasma, the motion of magnetic disturbances has a velocity component co-directional with the magnetic field, which makes it possible to transmit momentum to trapped particles. Collisions between passing and trapped particles provide an effective force acting on the plasma as a whole and contributing to the return of ions to the containment area.

The paper presents a method for predicting the parameters of a device for plasma confinement in a helical magnetic field based on mathematical modeling [2]. Plasma confinement is carried out by transmitting a momentum from a magnetic field with helical symmetry to a rotating plasma. Plasma transfer in a helical magnetic field is described in the MHD approximation by a stationary equation of the second order in an axially symmetric formulation [3]. Differences in the motion of trapped andflying ions are considered in the form of an effective friction force depending on the mutual velocityof the components and the fraction of trapped particles. The longitudinal force acting on the plasma arises as a result of the interaction of the radial electric current of trapped ions with the azimuthal component of the helical magnetic field. Plasma diffusion across the magnetic field is considered.

Setting the parameters of the trap allows one to calculate the diffusion coefficient, evaluate the effectof plasma confinement, select the optimal parameters (the depth of the magnetic field corrugation, plasma potential, etc.) The distribution of the concentration of the substance obtained by numerical simulation confirmed the confinement effect obtained in the experiment. For numerical implementation, the method of establishment and a more economical the method of successive over-relaxation are used. The dependences of the integral characteristics of the substance on are obtained. The model was calibrated using new experimental data obtained at the SMOLA trap created at the Budker Institute of Nuclear Physics SB RAS [1].

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Stationary solutions of the Vlasov-Poisson system in a finite cylinder

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We consider the first mixed problem for the two-component Vlasov-Poisson system with non-constant external magnetic field of special structure. For the case of a finite cylinder we construct the stationary solutions which correspond to a two-component plasma confined in a Mirror trap. Distribution functions of constructed solutions satisfy the following property: the supports touch the boundary of the domain only in two small prescribed discs at the top and the bottom of the cylinder.

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Magnetorotational supernova explosions: jets and violated mirror symmetry

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Magnetorotational processes may significantly affect the dynamics of core-collapse supernovae, resulting to magnetically driven jet-like explosions (e.g., [1]). The magnetic field topology of progenitor stellar cores is believed to be quite complex and is not known precisely. Such complex structures may differ substantially from usual dipole or quadrupole field, which may cause to additional anisotropy of magnetorotational explosions. The latter is a result of mirror symmetry violation of the progenitor magnetic field [2]. Here we report the results of two-dimensional MHD modelling of the collapse and further magnetorotational explosion of a rotating magnetized stellar core. We consider the models with different magnetic field configurations with and without mirror symmetry in progenitor magnetic field respectively to equatorial plane. In this work, we study the explosion asymmetry as well as the possibility of protoneutron star kick formation during the explosion phase.

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Calculation of the average ion velocity in a spiral magnetic open trap

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The report presents the results of numerical solution of a system of equations for the components of a vector in three-dimensional space. Spatial distributions in the cylindrical coordinate system of electric and magnetic field potentials, components of the average ion velocity, vector potential of the magnetic field, electric and magnetic fields for three cases are obtained. The calculation of the average ion velocity in a spiral magnetic open trap (resin) is carried out. It is planned to calculate the average ion velocity in a spiral magnetic open trap with an added axisymmetric corrugation field. The model considers Coulomb scattering and recharge on the residual gas. The results of the work will be in demand for predicting the optimal parameters of new multi-test traps.

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Numerical model of diamagnetic plasma confinement in a gas-dynamic trap using a new method for solving the equations of motion

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A 2D numerical model of the diamagnetic regime of an open trap based on the kinetic approximation for the ion components of the plasma and the injected beam and the hydrodynamic approximation for electrons (PIC-MHD) is presented. A new method for solving the equations of motion of charged particles in electromagnetic fields has been used, which makes it possible to accurately calculate the trajectory and velocity of a charged particle. Based on the created model, the basic principles of diamagnetic plasma confinement were tested.

A numerical study of the time integration solver for transient conjugate heat transfer in fluid-solid system

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The present article deals with the numerical study of our innovative time integration solver [1, 2] for transient conjugate heat transfer (CHT) in fluid-solid system. This solver called MCFL (MultiComponent FLows) is intended for numerical simulation of unsteady thermal interaction of fluid flow and solid bodies. As it was announced in [2], here, we present the result of numerical investigation of the known test case [3] of a flow over a heated plate when at the initial time the flow is impulsively accelerated to supersonic velocity. For solids, unsteady heat conduction equation is considered. For fluid-solid interfaces, temperature and normal heat flux are continuous across an interface. For generality, we consider for fluids the extended system of the compressible Navier–Stokes equations supplemented by multicomponent diffusion equations. In this work, we do not consider the phenomena of multicomponent diffusion. The MCFL solver exploits the fluid dynamic simulation framework in which the heat transfer in the fluid flow and in the solid are fully coupled. We use finite-volume discretization of the governing equations and two-layer time integration method with splitting over physical processes. The time step calculation is split into convection diffusion substeps. The Godunov explicit scheme implements the convection substep. The diffusion substep is implemented with the special explicit-iterative Chebyshev scheme. To study performance of the presented method, we have chosen a model problem [3], which is essentially non-stationary, and it is used to evaluate methods for calculating conjugate heat transfer.

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Three-dimensional model for numerical simulation of beam-plasma dynamics in open magnetic trap

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We present the three-dimensional model for numerical simulation of beam-plasma dynamics in open trap. For specific parameters [1] it may be possible to observe a magnetic field push-out by the injecting particles and formation of a configuration required for the plasma confinement (diamagnetic mode). For axially symmetric case in cylindrical coordinates, it was shown that the diamagnetic configuration is possible [2], however the complex nonlinear nature of the processes in the diamagnetic trap and the decisive role of kinetic effects require the use of three-dimensional numerical simulation. Basing on the results of the simulation it will be possible to determine the required conditions for the formation and stability of the diamagnetic configuration. The model includes parallel algorithms for the particles and mesh processing.

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Adaptive time step selection in monotone local iteration and exponential time integration of nonlinear heat conduction problems

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Efficient numerical treatment of nonlinear heat conduction problems is a challenging task, which is caused by the stiffness of the arising differential equation system, a strong nonlinearity of the heat transfer process and necessity to preserve non-negativity of numerical solution. To integrate in time nonlinear heat conduction problems of the form

$$u_t(x,t) = (k(u)u_x)_x,$$

where $k(u)=\kappa u^\sigma$ and initial and boundary conditions are provided, we consider two monotone schemes. The first one is nonlinear local iteration monotone (LI-M) scheme where at each nonlinear iteration a linear initial-value problem is solved by a special monotone explicit scheme based on Chebyshev polynomials. The second scheme is also based on nonlinear iterations. Here a linear initial-value problem arising at each nonlinear iteration is solved by an exponential time integration scheme based on Krylov subspaces. Both schemes possess the monotonicity property, which is a highly desirable feature for this problem class. In this work we extensively compare these two schemes in various numerical tests and, to enhance their efficiency, consider different adaptive time step size selection procedures. It is shown that adaptive time step size selection allows to substantially decrease overall computational costs in both schemes.