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# 3D PIC Model of the Helical Current Filament
# 3D PIC model helikálních proudových vláken

## Summary

A fully three dimensional Particle in Cell model of the plasma fiber had been developed in the Department of Physics of the Faculty of Electrical Engineering, Czech Technical University. The code is written in FORTRAN 95, implementation CVF (Compaq Visual Fortran) under Microsoft Visual Studio user interface. Five particle solvers (Newton, Runge-Kutta, Boris-Buneman, Leap-Frog and Canonical) and two field solvers (FFT and multigrid) are included in the model. The solvers have relativistic and non-relativistic variants. The model can deal both with periodical and non-periodical boundary conditions.

Plasma fiber and its surroundings is generated during the initiation process. The user can influence many parameters of the fiber, such as temperatures of electrons and ions, electric and magnetic fields, perturbations of the shape of the fiber and of the charged particle positions.

The PIC program package simulates the behaviour of the fiber, namely the evolution of magnetic field structures and turbulences.

The numerical solution of the particle motion and calculation of the electric and magnetic fields is the only one small part of the program package. There are many additional routines and collaborating program packages for computer diagnostics, graphical output and other calculations such as radiation, etc.

The field visualization is done via Line Integral Convolution method, the particles are visualized in several ways including fading trace following the particle. The most interesting is the possibility of recording animations of the scene as avi files.

Diagnostic routines enabling to calculate quantities comparable with the experiments are also the integral part of the package.

The program package PIC was developed during five years and several diploma and doctoral students contributed to some parts of the package.

The PIC model developed in our department enables a deep understanding of the processes in the plasma fiber, namely the simulations of the helical mode onset from diocotron instability. It is also very efficient package for simulation of MHD shocks, instabilities, electric double layers, polar cusp and other interesting phenomena. In present time the model was used for plasma fiber simulations but the authors of the package are sure it will be useful for a great number of various plasma simulations in near future.

# Souhrn

Na katedře fyziky FEL ČVUT byl vyvinut plně 3D PIC model plazmových vláken. Kód programu je napsán v programovacím jazyku FORTRAN 95, v implementaci CVF (Compaq Visual Fortran) s uživatelským rozhraním Microsoft Visual Studio. Model zahrnuje pět způsobů řešení pohybů částic (Newtonovo schéma, Rungeovo-Kuttovo schéma, Borisovo-Bunemanovo schéma, Leap-Frog a Kanonické schéma) a dvě možnosti řešení polí (metodami FFT a multigrid). Procedury mají implementovány relativistické i nerelativistické varianty. Model může využívat jak periodické tak neperiodické okrajové podmínky.

Plazmové vlákno je spolu s okolím generováno v iniciačním procesu. Uživatel může nastavit mnoho parametrů vlákna, například teplotu elektronů a iontů, elektrická a magnetická pole, počáteční perturbace tvaru vlákna a poloh nabitých částic.

Programový balík PIC numericky simuluje chování vlákna, zejména vývoj struktur magnetických polí a vývoj turbulencí.

Numerické řešení pohybu nabitých částic a řešení elektrických a magnetických polí tvoří jen malou část programového balíku. Model obsahuje řadu procedur a spolupracuje s dalšími programovými balíky pro počítačovou diagnostiku plazmatu, grafický výstup a další výpočty, například záření plazmatu.

K vizualizaci polí byla použita metoda LIC (Line Integral Convolution), vizualizace částic má řadu možností, včetně mizející kouřové stopy za pohybující se částicí. Užitečná je také možnost nahrávat vývoj scény jako animaci do avi souboru.

Součástí balíku jsou diagnostické procedury, které umožňují výpočet veličin porovnatelných s experimenty.

Celý programový balík byl vyvíjen po dobu pěti let a podílelo se na něm několik diplomantů a doktorských studentů oboru fyzika plazmatu.

PIC model vyvinutý na našem oddělení umožňuje hlubokému porozumění procesům v plazmovém vlákně, zejména pak simulaci nástupu a rozvoje helikálního modu z rozvíjející se diocotronové nestability. PIC programový balík je také užitečný při studiu rázových vln v plazmatu, nestabilit, elektrických dvojvrstev, polárního kaspu a řady dalších jevů. V současnosti je model využíván zejména pro simulace plazmového vlákna, ale autoři jsou si jisti, že bude užitečný v řadě dalších simulací plazmatu v blízké budoucnosti. .

**Keywords:**

plasma physics, plasma simulations, Particle in Cell, fiber, pinch, helicity, Fast Fourier Transform, multigrid, Line Integral Convolution, Runge-Kutta method, Leap-frog method, Boris-Buneman scheme, numerical scheme, diocotron instability, helical mode, weighting, Monte Carlo, vortex, periodic boundary conditions

**Klíčová slova:**

fyzika plazmatu, plazmové simulace, Particle in Cell, vlákno, pinč, helicita, rychlá Fourierova transformace, multigrid, Line Integral Convolution, Rungeova-Kuttova metoda, Leap-frog metoda, Borisovo-Bunemanovo schéma, numerické schéma, diocotronová nestabilita, helikální mod, váhování, Monte Carlo, vír, periodické okrajové podmínky

## Contents

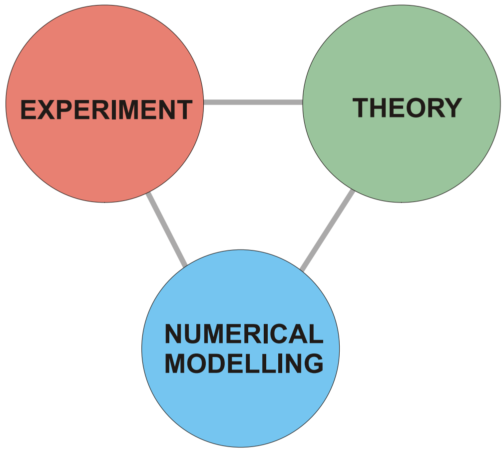
## Introduction

About 99 percent of all the matter in our Universe is in the plasma state. Only on the Earth we luckily live in the one percent of another state. Nevertheless there are a lot of plasma phenomena we can see on the Earth: the lightning channels, ionosphere, auroras and the whole Earth magnetosphere. In the Sun system the plasma is in the solar wind, planet magnetospheres and cometary's tails. In the Jupiter's and Saturn's surroundings the plasma forms giant plasma toruses. And the Sun itself, as well as all the other stars, is a huge plasma ball and the well-known plasma phenomena such as protuberances, sunspots, prominences, spicules are worth of investigating. Not only stars but knock-out most of nebulas in galaxies are wide plasma clouds. In the nebulas we can see typical plasma phenomena: filament structures caused by the presence of electric and magnetic fields, acceleration of charged particles and radiation of various origins. In the vicinity of the Galaxy centre there are extensive plasma filaments with length about 250 light years perpendicular to the Galaxy disk. In other galaxies similar shapes are observed, especially in the so called Active Galaxy Nuclei (AGN). Neighboring galaxies are interconnected through hydrogen plasma bridges (e.g. our Galaxy and Magellan clouds). Typical quasar and AGN jets are plasma formations and the characteristic double radio spots have origin in the related plasma phenomena. In this decade numerical simulations validated that plasma phenomena could be responsible for the star creation from protostar nebulas and enable to form the original globules without achievement of the Jeans criterion values and even without initial shock wave generated by neighboring supernovae. Furthermore it seems that galaxy spirals could be formed both by electromagnetic and gravitational forces. High energy particles in cosmic rays were accelerated in plasma filaments and double layers. Today we come to somewhat different picture of our universe: it is not only gravitation which is responsible for the phenomena in our world, electromagnetic interaction and its properties contribute by equal role to the structures of our universe

In the Department of Physics of the CTU the plasma filaments are investigated for many years. The experimental background is oriented on diagnostic methods including schlieren photography, Quadro camera diagnostics, X - ray and VUV diagnostics, interferometry measurements, etc. In 1997 spirals surrounding the pinch were detected. This phenomenon seems to have the same nature as structures observed in space.

The theoretical research formally orientated on the pure *z*-pinch. The model was based on the equilibrium equation, Ampere law, energy balance equation and Ohm law. The radiative processes were included in the energy balance equation. Later the helical structures and conditions of their onset were investigated. Calculations of the helical equilibrium states were done in [10].

In parallel with the experimental and theoretical endeavor a PIC program package simulating the onset of helical states [6] in plasma filaments was developed. Description of this PIC package is the main topic of this lecture.

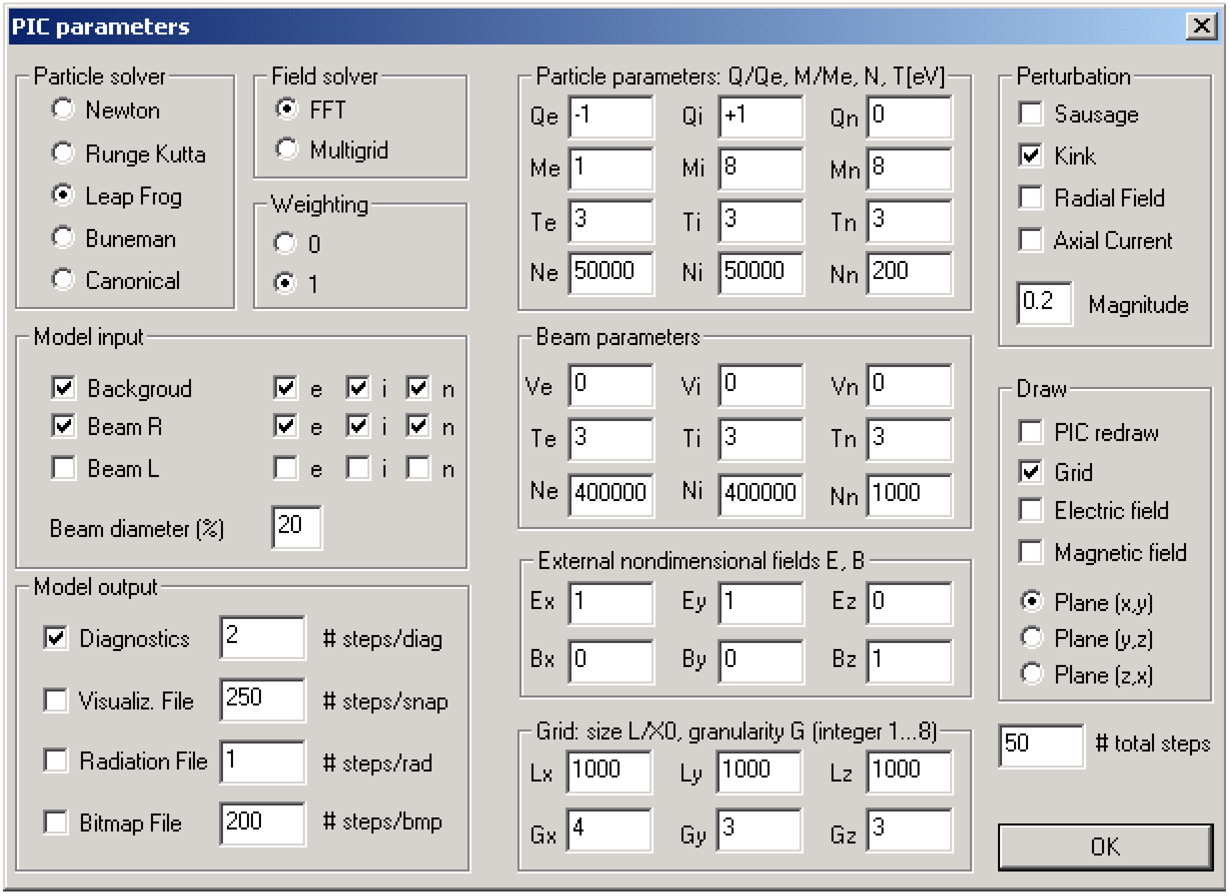



## PIC simulations

Very good model for the description of filament structures is the PM (Particle Mesh) model [1]. Particles move freely through the mesh and fields are located in the mesh points only. The fields are calculated from the Maxwell equations via some suitable field solver. As the particles are located anywhere in the computational area and the fields are located in the mesh points, some weighting procedure of the particles to the mesh points and of the fields to the particles must be implemented in the model. Our endeavor in search of fast and efficient particle and field solvers as well as field display technique and diagnostics of the numerical experiment is the main topic of this dissertation. Detailed description of the model and its results can be found in papers [14-21].

Program code was written in FORTRAN 95, free-style (without compulsory columns). FORTRAN compiler and linker were used from Compaq Visual FORTRAN 6.6 A embedded in the Microsoft Development studio GUI.

Fully three-dimensional code with periodical boundary conditions was developed. The fields are solved via either FFT solver or Multigrid solver [8, 2]. There are implemented five particle solvers in the PIC package (Newton-Euler, Boris-Buneman, Leap-Frog, Runge-Kutta and Canonical). A special graphical package based on the OpenGL Library was developed for visualization of the particles and fields [7, 22]. The field visualization method is based on LIC (Line Integral Convolution) algorithm [3, 4]. Another package was developed for calculation of the filament radiation processes [11].



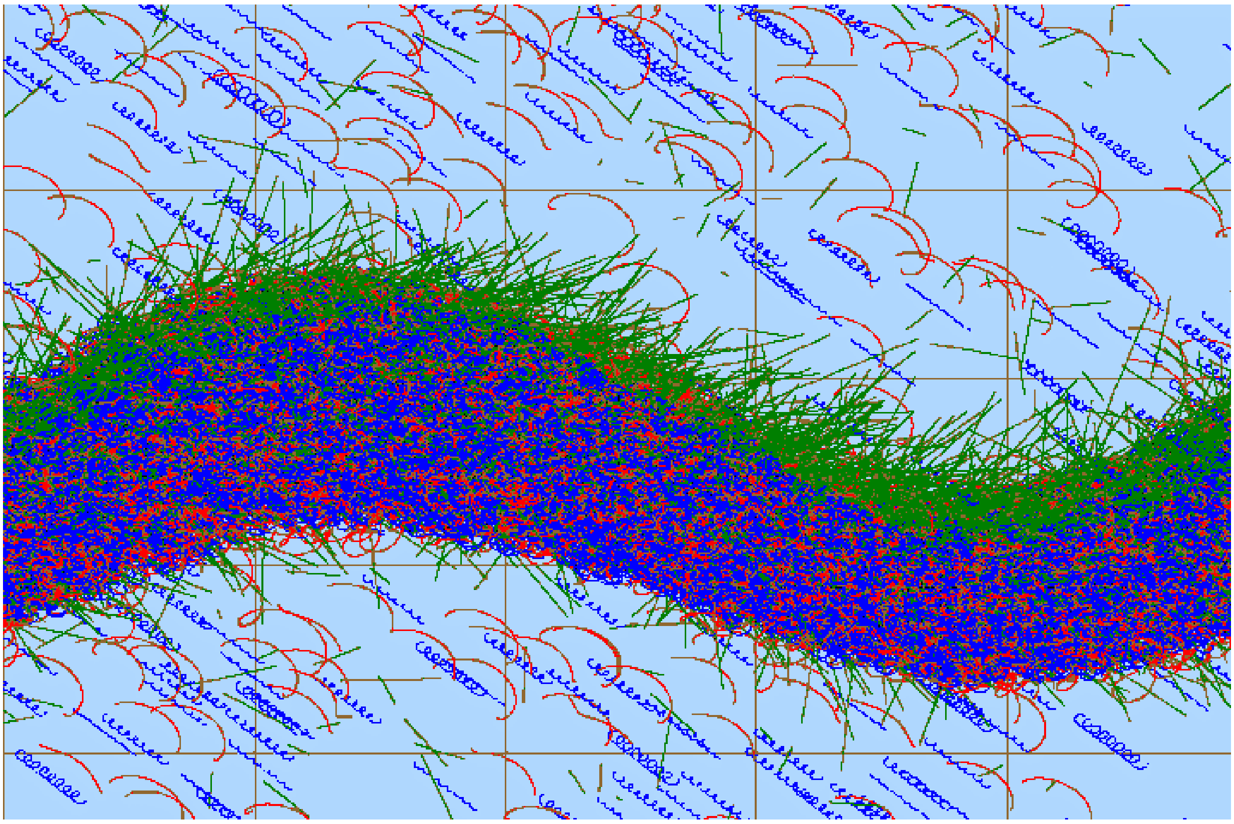

GUI for PIC program package

There are three types of particles included, which may vary by their charge and mass (usually electrons, ions and neutrals). The particles are localized in three-dimensional rectangular parallelepiped with periodical boundary conditions. These conditions can be applied for particle's motion and internal fields. They cannot be used for potentials of external fields (e.g. homogeneous electric field has linear potential $\phi$ dependence which must have discontinuity on the boundary).

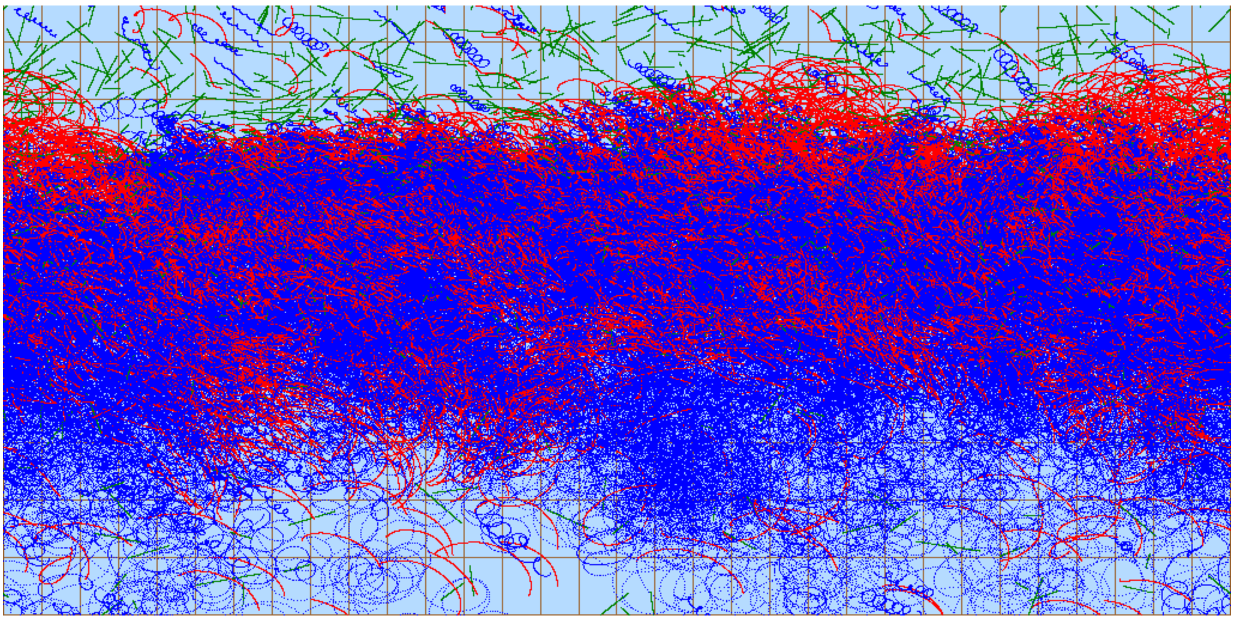
Initial coordinates of the particles are generated randomly. In the computational area two beams and surrounding particles are present. The beam's radius and particles' velocity and temperature can be chosen.

The initial particle velocity has two components: The beam (ordered) and the random one. The beam velocity can be assigned to the beam particles, the chaotic component is entered as temperature of the particles and corresponding Gaussian distribution.

Various initial perturbations of the beam shape can be performed: sausage, kink, small radial displacement of the electrons or ions (radial electric field perturbation), and axial current perturbation. Magnitude of the perturbations can be adjusted from the initial dialog window.



Tests of the model. E×B drift motions, early stage, 10 000 particles.
Non-drifting neutrals remained in the top area.



Tests of the model. E×B drift motions, later stage, 10 000 particles.
Non-drifting neutrals remained in the top area.

In all physical models nondimensional variables play exceptionally important role. In all the branches of science similar phenomena exist in very different dimensions. After introducing the nondimensional variables (if it is possible) we can treat plasma filaments in nebulas as well as in laboratory by the same model. The real dimensions are hidden in the transformation equations and some combinations of concentration, length, magnetic field, temperature and other plasma parameters yield the same solutions. In the PIC package the nondimensional variables are naturally introduced into the model.

There are four main steps in the PIC model:

#### 1. Particle motion

There are implemented several particle solvers in the model:

- Newton-Euler solver
- Leapfrog solver
- Runge-Kutta 4th order solver
- Boris-Buneman solver
- Canonical solver

Newton-Euler solver is very fast but doesn't follow theoretical solution (E×B drifts and other motions were tested) sufficiently exactly. In collision dominated plasma this needn't lead to serious problems because only small parts of Larmor orbits are realized. Other solvers follow the theoretical trajectory and no deviations were observed. The "canonical" scheme proposed in our department seems to be the fastest in the tests performed.

Both non-relativistic and relativistic variants are incorporated in the model. In case of relativistic velocity of the particle the solver is automatically switched to relativistic one. The relativistic variants of all the schemes (with exception of the canonical one) were developed in frame of the Dan Škandera Diploma Thesis. Details can be found in [13]. Stability and convergence of the schemes were investigated as well.

In tests with 50 000 electrons and ions in external electric and magnetic fields the CPU time for 200 differential steps was (PC, Celeron 333 MHz):

| Scheme | Nonrelativistic CPU time [s] | Relativistic CPU time [s] |
|---|---|---|
| Newton-Euler | 14.8 | 33.5 |
| Leapfrog | 38.5 | 92.0 |
| Runge-Kutta 4$^{th}$ order | 25.6 | 44.7 |
| Boris-Buneman | 21.5 | 45.7 |
| Canonical | 17.4 | 42.1 |

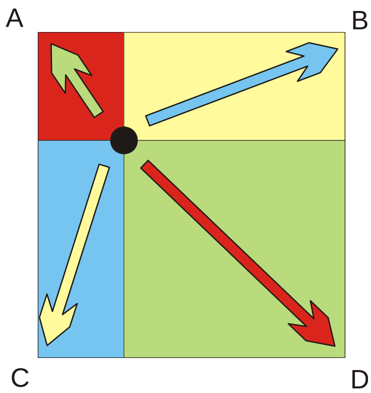
In the table only time of numerical calculations was included. With the exception of the first order Newton-Euler scheme the fastest is the Canonical scheme. The relativistic variants are approximately twice slower than nonrelativistic ones.

### 2. Weighting particles

Particle positions and velocities must be weighted into the grid points, where they represent source terms of the Maxwell equations for the electric and magnetic fields. After the weighting, charge and current densities must be known in all grid points. Zero and first order weighting had been implemented in the model:

Zero order weighting represents standard PIC (Particle in Cell) or NGP (Nearest Grid Point) method. The particle attribute - charge or velocity - is assigned to the nearest grid point. This scheme is very fast, but passage of the particle near the grid point is discontinuous and may cause some numerical problems.

First order weighting is mostly referred as CIC (Cloud in Cell). Particles are weighted to the 8 nearest cell points (4 in 2D) according to the "opposite" volumes (areas in 2D). The passage of the particle near a grid point is continuous (but not the first derivative) and particle behaves like a cloud of particles of the same sign. This type of weighting is used very often because numerical problems connected with discontinuities are eliminated and it is fast enough in comparison with higher order types of the weighting.




I higher order weighting procedure the passage of the particle near a grid point is smooth, but the computational time required is enormous. That is why the higher order weighting have not been implemented into the model. Weighting fields from the grid points to the particles must have the same order as weighting particles to the grid. In other case numerical problems could occur.

### 3. Field computation

There are implemented two field solvers in the model nowadays. The time evolution is treated as explicit via methods based on similar considerations as in the Boris-Buneman particle scheme. Electric and magnetic fields are calculated separately from Laplace–Poisson equations. In the same manner can be treated gravitational filed acting on dust particles. Subsequently time field step follows.

The FFT solver for the Laplace-Poisson equation was developed by Radim Dejmek (FEE CTU student) in frame of his diploma thesis [8]. It is based on standard libraries modified to our purposes. Finite properties of the grid are involved in the Laplace differential operator in the **k** space.

The algorithm consists from five basic steps:

1. Discretization of the Laplace-Poisson equation,
2. Discrete Fourier transform of the equation,
3. Algebraic solution of the equation in **k** space,
4. Inverse DFT, retrieval of the potential,
5. Calculations of the fields in the grid points from the potentials.

The alternative algorithm to the FFT in the PIC package is the Multigrid one. Multigrid iteration combines classical iterative techniques, such as Gauss-Seidel line or point relaxation, with adaptive multilevel grid structure and subgrid refinement procedures to yield a method superior to the iterative techniques alone. By iterating and transferring approximations and corrections at subgrid levels, a good initial guess and rapid convergence at the fine grid level can be achieved. Multigrid iteration requires less storage and computation than direct methods for nonseparable elliptic partial differential equations and is competitive with direct methods such as cyclic reduction for separable equations. In particular, three-dimensional problems can often be handled at reasonable computational cost.

The multigrid solver package MUDPACK 5 developed in the UCAR (University Corporation for Atmospheric Research) was used. It can be obtained on the URL: http://www.scd.ucar.edu/css/software/mudpack. The solver is very fast, was written in FORTRAN 90 and it was without serious problems adapted to our needs. Author of the package is John C. Adams (National Center for Atmospheric Research, e-mail: johnad@ucar.edu) [2].

#### 4. Weighting fields

The fields are weighted to the particle positions in the same manner as in step 2. After the procedure the filed values in the particle positions are known and new positions vcan be calculated using some particle solver (step 1).

# PIC Package Add-ins

### 1. Program package VISUAL

A special program package based on Qt and OpenGl libraries was developed for the particle and field visualization in frame of O. Novak Diploma Thesis [7]. The program is easily portable and can be compiled both on Microsoft Windows and Linux systems.

The Qt library is developed by the Norwegian Company TrollTex. This multiplatform library is designated for working with Graphical User Interface (GUI) of operational systems. The library is offered as freeware for noncommercial usage on the LINUX platform and as a paid professional version for MS Windows platform. The Qt library gives unified programmer's interface based on C++ language, which is completely portable between both platforms. The communication between objects is based on unique signal/slot mechanism (this mechanism distinguishes this library form other similar libraries).

The OpenGL library was developed by Silicon Graphics Company. From 1992 it is an open standard independent on hardware environment. OpenGL represents integrated layer between the programmer and the display hardware. The display hardware is required to have frame buffer. The application interface includes about 120 commands for creating objects and manipulating them. The basic functions are: display of the line, triangle and polygon (3D); 2D image manipulation; work with textures; work with light including lighting the scene; creation of the mist; calculation of the objects visibility; work with the alpha channel; graphical transformations.

The vector field (electric or magnetic) is visualized in cross section planes parallel with coordinate lattice. That means two-dimensional vectors located on the two-dimensional grid have to be visualized.

The cross section can be realized in arbitrary place of the rectangular parallelepiped. The vector values in the grid points are calculated by linear interpolation from neighboring grid planes:

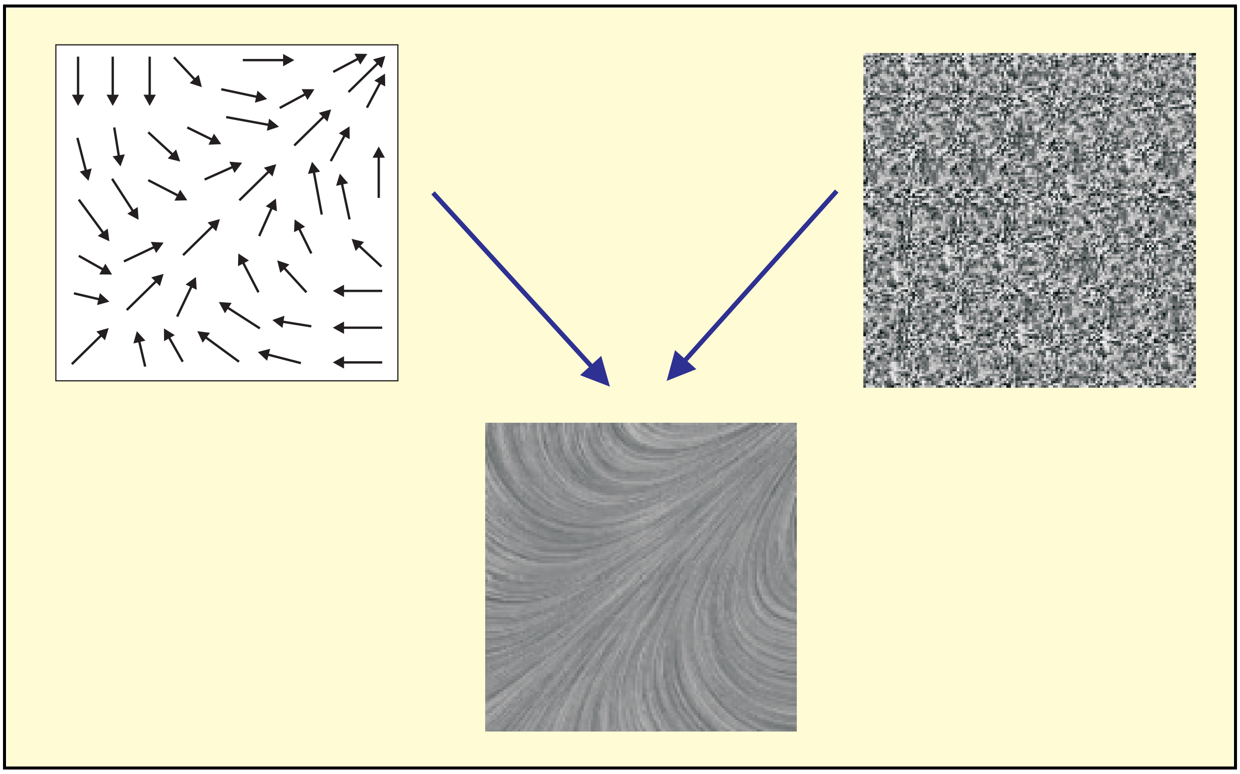
$$\mathbf{F} = \mathbf{F}_A + (\mathbf{F}_B - \mathbf{F}_A)\, t\,; \qquad t = \frac{s(X) - s(A)}{s(B) - s(A)}\,,$$

where s denotes the location of the point in the calculated coordinate (x, y, z).

For the field line calculation we have to know the vector value in arbitrary location of the two-dimensional grid in the cross section plane. It is determined by bilinear interpolation algorithm (two consequent linear interpolations). The field line itself is calculated by Runge-Kutta numerical integrator of the fourth order. The step of the integration is dynamically changed to ensure preservation of small details inside homogeneous areas.

The LIC (Line Integral Convolution) method of the field visualization reminiscent the well-known experiment with permanent magnet and iron filings. After shaking, the fillings form itself along the magnetic field lines.

The LIC method has two inputs: the vector field $\mathbf{F}:\mathbf{R}^2 \to \mathbf{R}^2$ and noise texture represented by noise function $T$. The noise texture is locally blurred along the field lines and the resulting output picture matches the structure of the field.



The principle of the LIC method. The vector field lines are convoluted with the noise texture.

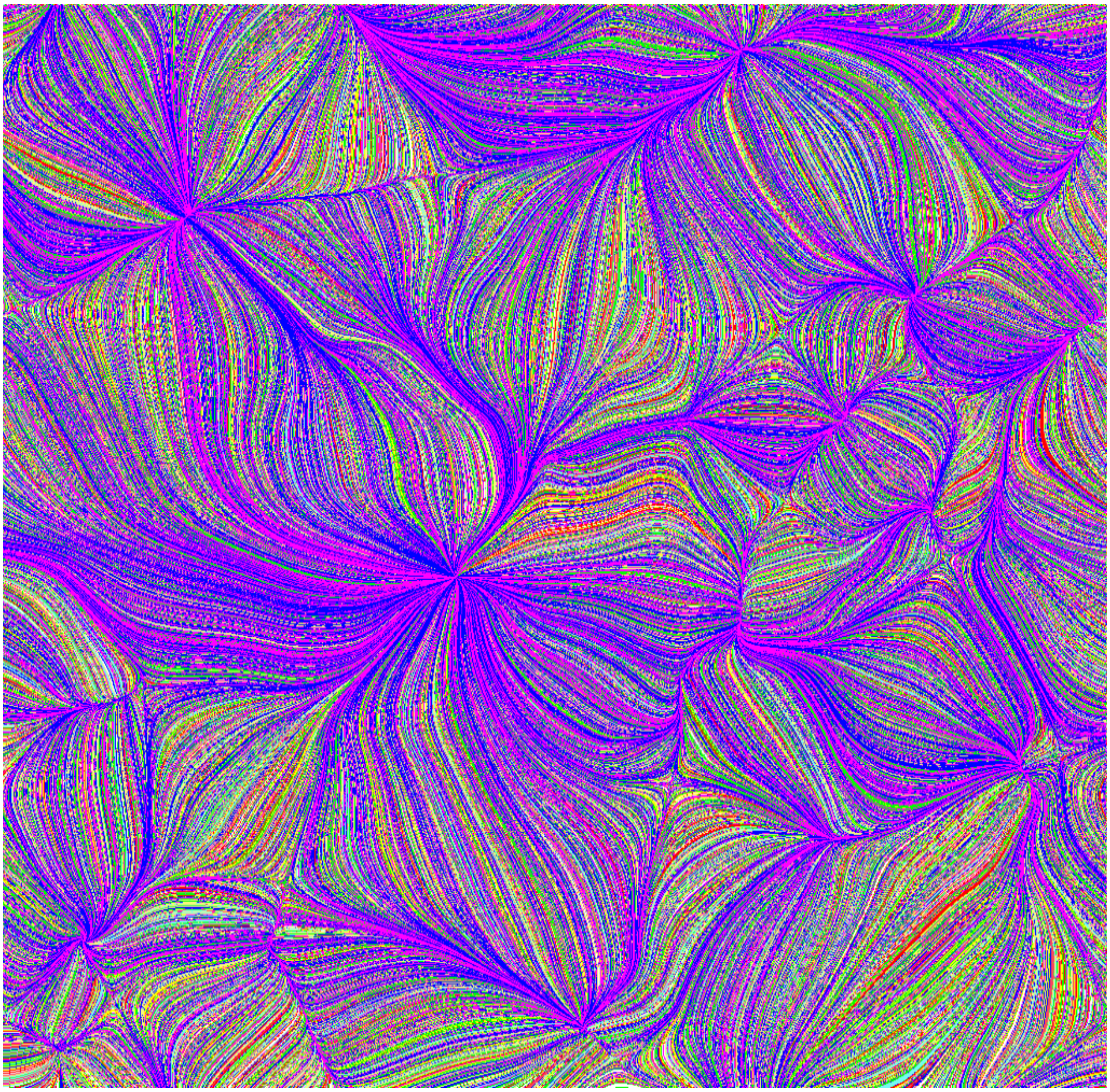
From the mathematical point of view the procedure of the blurring is implementation of the convolution integral

$$I(x_0) = \int_{s_0-L}^{s_0+L} k(s-s_0)T(\sigma(s))\,ds\,.$$

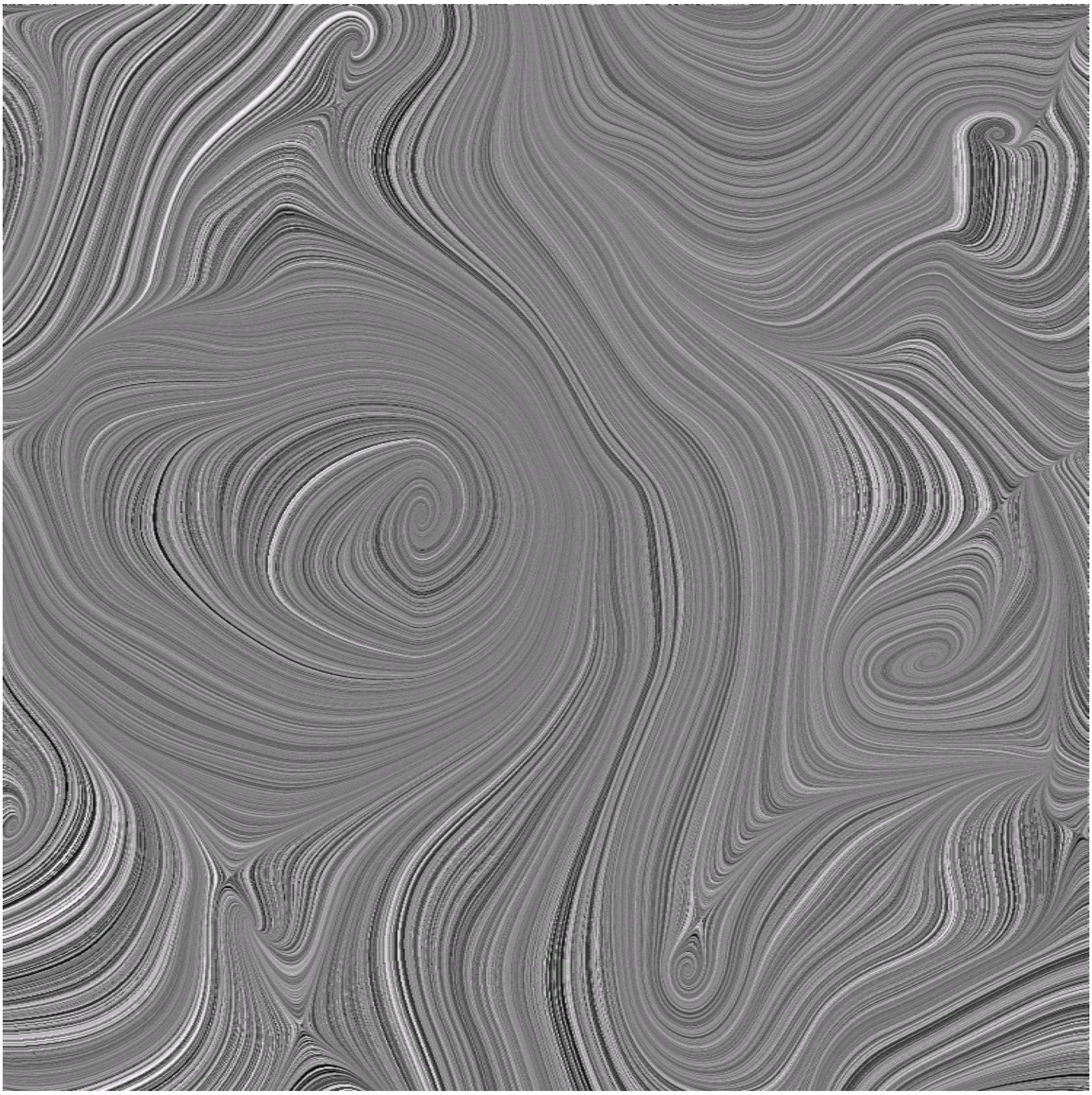
In the integral $I(x_0)$ is the intensity of the point $x_0 = \sigma(s_0)$, where $\sigma(s)$ is the field line parameterized by its length $s$. The convolution kernel $k$ is one-dimensional and has length $2L$. The kernel is normalized to 1.

The convolution procedure creates highly correlated pixels along the field line, while the pixels in perpendicular direction are not correlated. The convolution integral has to be calculated for each pixel at least once. Some enhancement of the method published Hedge and Stalling. As the coherence is sufficient on long distances along the line, it is possible to calculate the convolution integral only for the first point of the field line and for subsequent pixels only changes of the integral can be calculated. This method was named Fast LIC [3].

In the implemented LIC method the algorithm of generating the RGB colors was modified. As the colors have no physical meaning, the field evolution animations are done in grayscale.



LIC visualization of the electric field lines. If the charged particle is nearby the cross section, local Coulomb field can be seen.



LIC visualization of the magnetic field lines. The cross section plane was perpendicular to the filament. Field evolution was treated in this test. The field evolution is best seen in the grayscale. The color output of the LIC method is to a certain extent random and cannot be used for animation or field evolution tracking purposes.

**2. Diagnostics**

Computer plasma diagnostics is very useful both for debugging the program package and for the correspondence with lab and space experiments. Usually the mean values of particle veloci-ties and fields are tracked through the computation. Especially valuable are the mean square values and variances for their relation with measurable physical quantities such as temperature, thermal and electrical conductivity, specific heat, electric and magnetic susceptibility, etc.

First of all very useful are simple average values of many quantities ($n$ is indexing particles, $\alpha$ kinds of particles, $i, j, k$ the grid points):

$$\langle \mathbf{v}_\alpha \rangle = \frac{1}{N_\alpha} \sum_{n=1}^{N_\alpha} \mathbf{v}_{\alpha,n} \; ; \qquad \alpha = \mathrm{e,i,n} \, ,$$

$$\langle \mathbf{j} \rangle = \frac{1}{V} \sum_\alpha \left( Q_\alpha \sum_{n=1}^{N_\alpha} \mathbf{v}_{\alpha,n} \right),$$

$$\langle \mathbf{P} \rangle = \frac{1}{V} \sum_\alpha \left( Q_\alpha \sum_{n=1}^{N_\alpha} \mathbf{r}_{\alpha,n} \right),$$

$$\langle \mathbf{M} \rangle = \frac{1}{V} \sum_\alpha \left( \frac{1}{2} Q_\alpha \sum_{n=1}^{N_\alpha} \mathbf{r}_{\alpha,n} \times \mathbf{v}_{\alpha,n} \right),$$

$$\langle \mathbf{E} \rangle = \frac{1}{N_x N_y N_z} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \sum_{k=1}^{N_z} \mathbf{E}_{ijk} \, ,$$

$$\langle \mathbf{B} \rangle = \frac{1}{N_x N_y N_z} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \sum_{k=1}^{N_z} \mathbf{B}_{ijk} \, .$$

The quantities defined in prevoious equations are subsequently: average velocity of $\alpha$-kind particles, total current density, polarization, magnetization, electric and magnetic fields. Averaging proceeds either over all particles or over all the grid points. Knowing polarization and magnetization the electric induction and magnetic intensity vectors can be obtained:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \, ; \qquad \mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M} \, .$$

Under the assumption of diagonal conductivity, permittivity and permeability tensors, they can be "measured" as

$$\sigma_k = j_k / E_k \, ; \qquad \varepsilon_k = D_k / E_k \, ; \qquad \mu_k = B_k / H_k \, .$$

The quadratic averaging is also of great importance, especially variances of some quantities, which are related to experimentally measured quantities such as temperature, heat capacity, susceptibility, etc.:

$$\left\langle v^2 \right\rangle - \left\langle v \right\rangle^2 = \frac{kT}{m}(3 - 8/\pi);$$

$$\left\langle v^4 \right\rangle - \left\langle v^2 \right\rangle^2 = 6\left(kT/m\right)^2;$$

$$\left\langle W^2 \right\rangle - \left\langle W \right\rangle^2 = kT^2 C_V;$$

$$\left\langle \mathbf{M}^2 \right\rangle - \left\langle \mathbf{M} \right\rangle^2 = \frac{1}{\mu_0}\frac{kT}{V}\chi.$$

The averaged particle quantities are saved separately for electrons, ions and neutrals, so electron and ion components of currents density are known as well as temperatures of relevant sub-fluids.

Another interesting and valuable diagnostics can offer a plot of the particles in phase space (velocity versus coordinates). Some instabilities can be detected from characteristic patterns.

### 3. Collisions

In 2001-2002, collisions of the neutrals with electrons and ions were included in the model, as well as ionization and recombination processes. The collisions are calculated via known cross sections by Monte Carlo method. This module of the PIC package created Dan Škandera in frame of his Diploma Thesis [5, 9, 15].

The pair interaction of charged particles is fully solved in PP (Particle-Particle) codes, which are very time consuming. The PIC code naturally bypasses this problem and instead of collisions introduces interaction with global field generated by the particles. Simple versions of PIC simulation do not need additional collisions for physically correct results. Nevertheless PIC simulations cannot describe interaction of charged particles with neutrals. These types of collisions have to be introduced into the model from “outside”.

There are several possibilities how to add collisions with neutrals into PIC code. If we do not want to permit enormous slowing-down of the model due to the collisions, we have to compute the collisions only statistically (e.g. by Monte Carlo method) with simplified cross section dependence.  This is the way we set forward in our department. The whole algorithm how to implement collisions into PIC model consists from six basic steps:

1. Does the collision occur?
2. What kind of collision will happen?
3. Determination of relative velocity magnitude after the collision.
4. Transformation into new coordinate system.
5. Monte Carlo generation of new particle velocity direction (angles).
6. Transformation of new velocity back into the lab coordinate system.

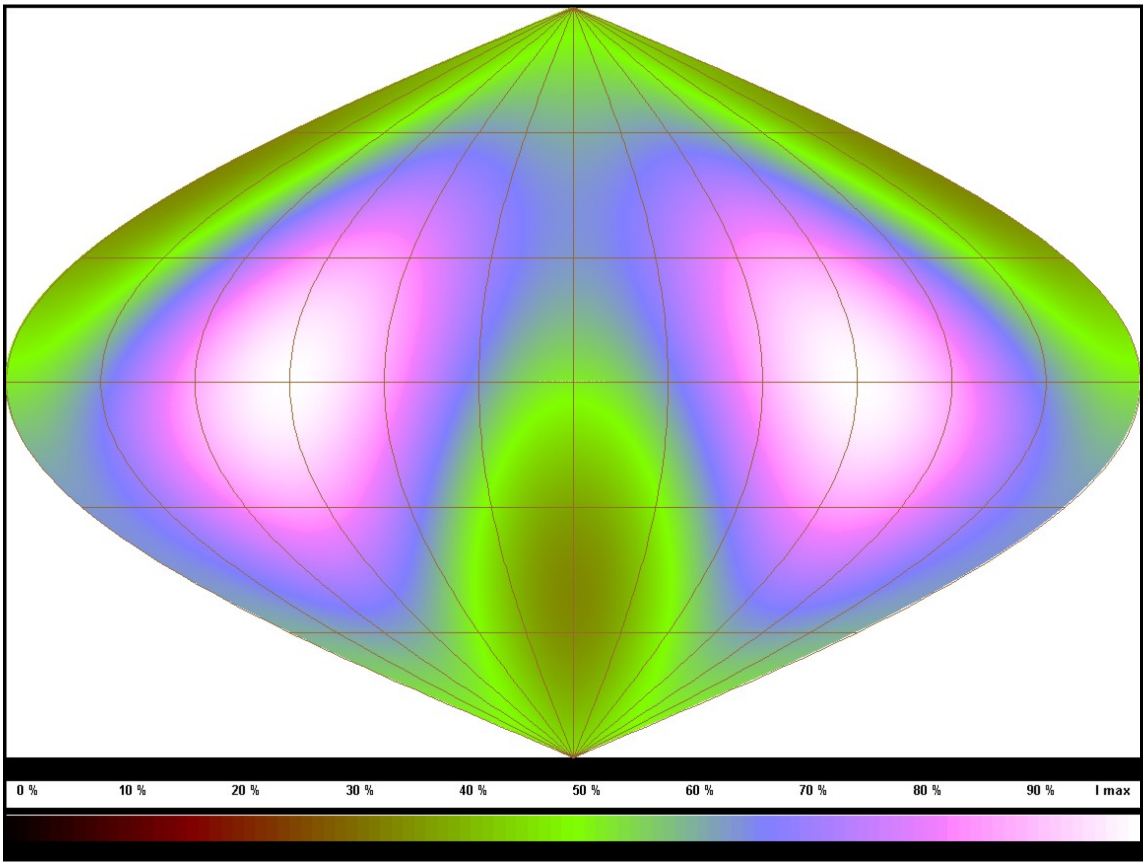
There are two types of interactions to be added into the model: Interaction of electrons with neutrals and interaction of ions with neutrals. Due to different mass of the electron and ion the two types of collisions have different cross section area dependence. Following six types of collisions were implemented into the model:

| | |
|---|---|
| e–n | elastic |
| e–n | excitation |
| e–n | ionization |
| i–n | elastic |
| i–n | charge exchange |

#### 4. Radiation

A very important way of energy losses is radiation. There are several important radiation channels, but the magnitude of most of them can be only estimated from some global considerations. The only one exception is bremsstrahlung radiation and synchrotron radiation. The intensity of this radiation can be calculated directly from positions, velocities and acceleration of individual particles.

Parallely with the PIC package is nowadays developed package RADIATION by David Břeň in frame of his PhD studies. Data from the PIC program (particle velocities and positions) are written to data file rad.dpc and transferred to the RADIATION package. We have to save positions and velocities of the particles from former times to be able to calculate radiation fields from retarded potentials. This is time and memory consuming and it can be done only for several thousands of particles. Nevertheless it can be important for investigation of characteristic behavior of the radiating filament. From the robust PIC model some “representative” particles have to be chosen.



Projection of intensity on a far sphere. Fiber oriented vertically (50 particles).

**5. Role of the Dust**

Dust particles in plasma can influence plasma behavior dominantly. For example dust particles completely change conditions during radiation, the dust particles can radiate in continuum. This phenomenon can be cardinal for large plasma formations such as space nebulas. The dust can be responsible for sufficient exhaust of energy during creation of the stars. In large systems the charged dust particles interact not only via electromagnetic forces but also via gravitational ones. And gravitational interaction fetches in a wide new class of phenomena, new kinds of instabilities, which can for example cause star formation (Jeans criterion). But in lab plasma the presence of dust particles can completely change the plasma behavior as well. In the dust palsma, there are three typical plasma frequencies

$$\omega_{pe} = \sqrt{\frac{n_e Q_e^2}{m_e \varepsilon_0}}\,; \qquad \omega_{pi} = \sqrt{\frac{n_i Q_i^2}{m_i \varepsilon_0}}\,; \qquad \omega_{pd} = \sqrt{\frac{n_d Q_d^2}{m_d \varepsilon_0}}$$

The dust grains are responsible for ultra low frequency wave modes [12], ions for magnetoacoustic modes and electrons dominantly modify the propagation of electromagnetic waves through the plasma. The dust grains can be charged both positively and negatively.

How to treat dust grains in PIC or PIC-like models? We have not only to add next type of heavy charged particles into the model but in most cases also gravitational interaction.

The basic interactions are described by scalar and vector potential of the electromagnetic force and by the gravitational potential. For low frequency modes the Laplace–Poisson equations for the potentials

$$\Delta\varphi = -\frac{\rho_e}{\varepsilon_0}; \qquad \Delta\mathbf{A} = -\mu_0\,\mathbf{j}; \qquad \Delta\varphi_g = 4\pi G\rho_m$$

have to be solved by some field solver. It is fortunate that the gravitational equation is in our approximation of the same type as the other two and the same solver can be used.

At the first glance it seems that adding dust particles into the PIC code need not to be a serious problem: one more type of particles and one more equation for gravitational potential. The equation of motion have to be slightly modified, the gravitational term must be introduced for dust particles

$$\frac{d}{dt}\left(m_a\mathbf{v}_a\right) = Q_a\left(\mathbf{E} + \mathbf{v}_a \times \mathbf{B}\right) - m_a\nabla\varphi_g\,.$$

The generalization of our PIC package in the sense sketched out above will be the motive of our endeavor in near future.

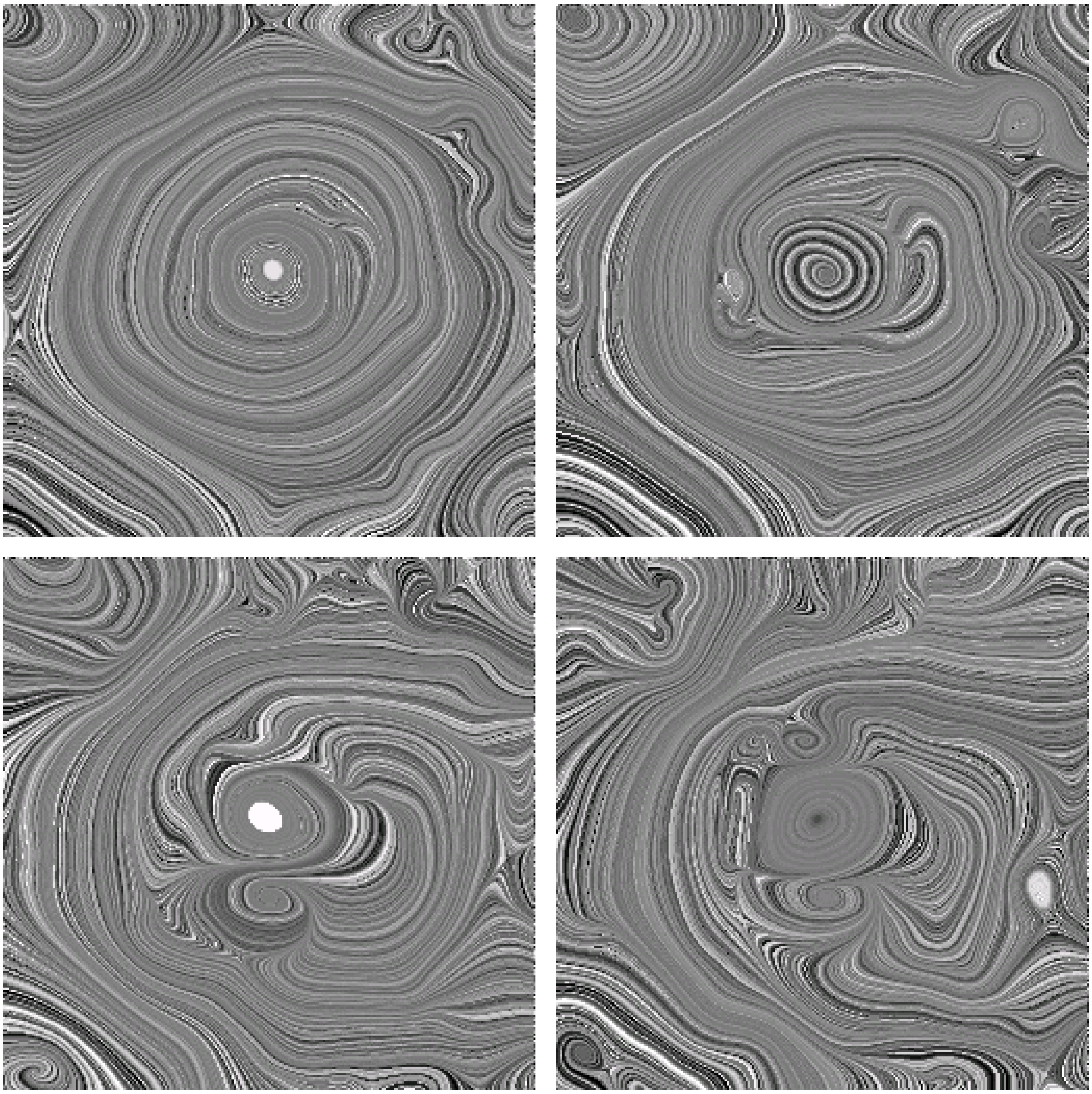
### 6. Animations

Very attractive outputs of our PIC model are various animations. We can animate the time evolution of the plasma fiber shape, the time evolution of fields in some cross sections, evolution of phase diagrams, radiation from the fiber, etc. These parts of our work are beyond the possibilities of printed material and beyond the scope of this dissertation. One can familiarize with it on our server www.aldebaran.cz.

## Some Results

### 1. Surface turbulences and helical structure onset

In the numerical simulations it had been proved, that surface turbulent phenomena can hang together with radial electric field perturbations. The perturbed field along with axial magnetic field causes azimuthal drift and the succeeding diocotron instability forms vortices evolving into structures with non-zero helicity:

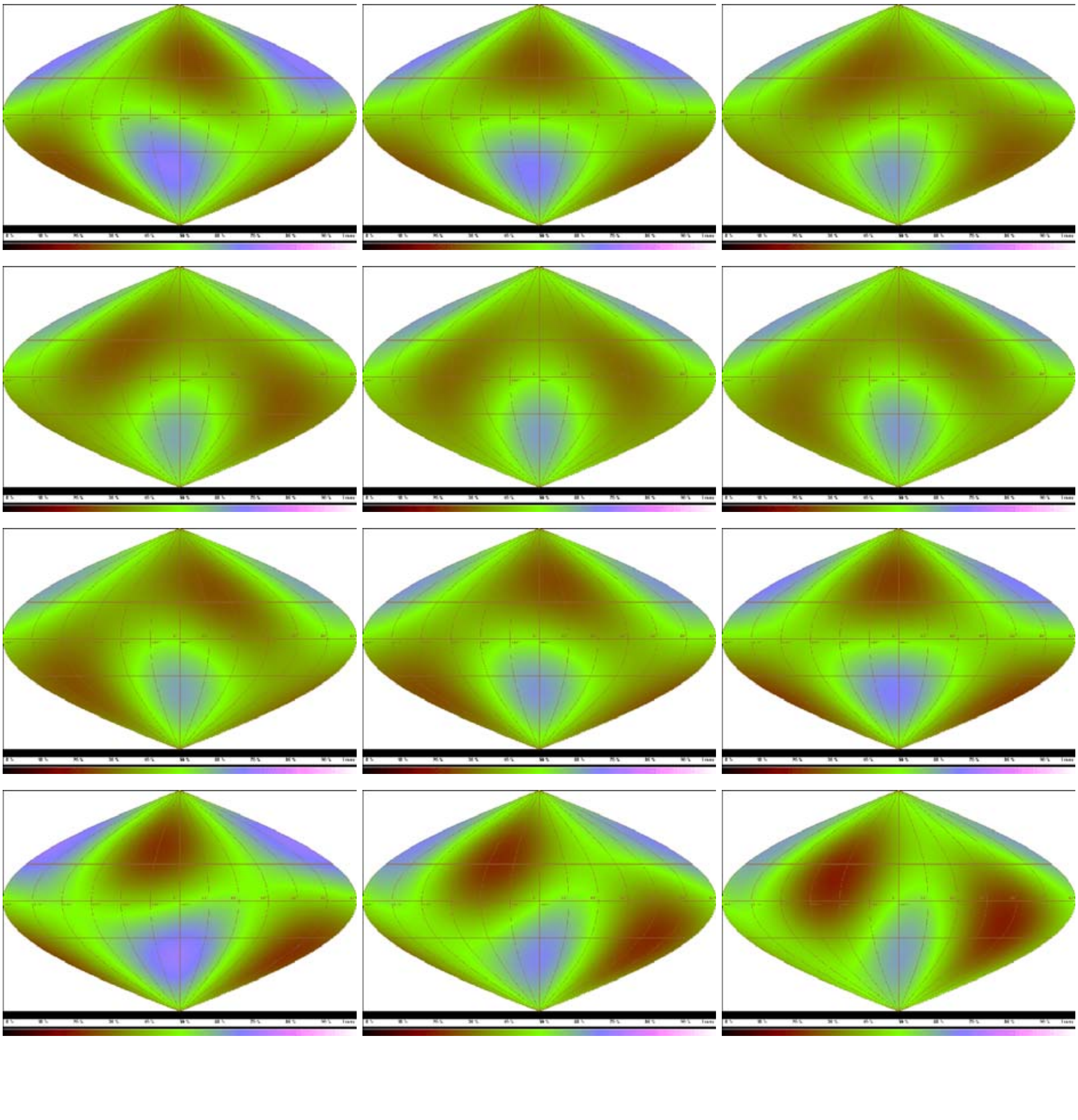


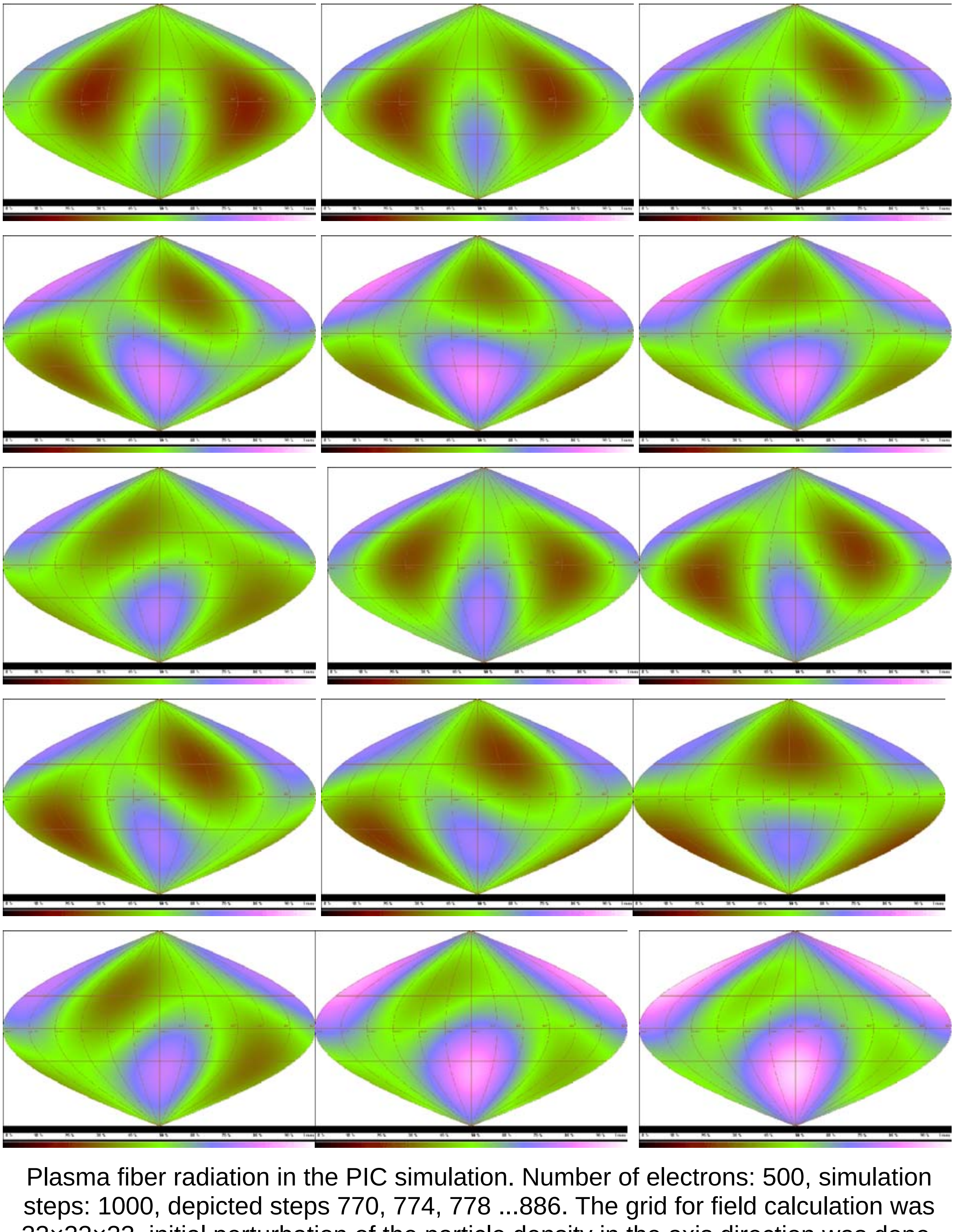
PIC simulation of the surface turbulent structures. Magnetic field lines in the cross section plane perpendicular to the filament. Number of particles: 600 000, steps 1000, 1200, 1400 and 1600. Radial electric field perturbation: 5%, initial temperature 3 eV both fiber and surroundings. The filament diameter: 30 % of the computational parallelepiped width.

## 2. Radiation of the fiber

Bremsstrahlung and synchrotron radiation from the moving charged particles was calculated in the module RADIATION. The radiative intensity is projected on a far sphere. The directional dependence of the radiation during the fiber evolution was calculated. The program package RADIATION was developed for the PIC calculations, but we had used it in other models, for example for treating the radiation of plasma cluster penetrating through the electric double layer, MHD and compress magnetic bow shock and through the polar cusp of the Earth magnetosphere.

In next figure there can be seen the plasma fiber radiation evolution during the simulation. The number of radiating particles must be very low as the calculation of the radiation with retarded time is very time consuming, for 500 particles typically 1 day on 3 GHz processor.

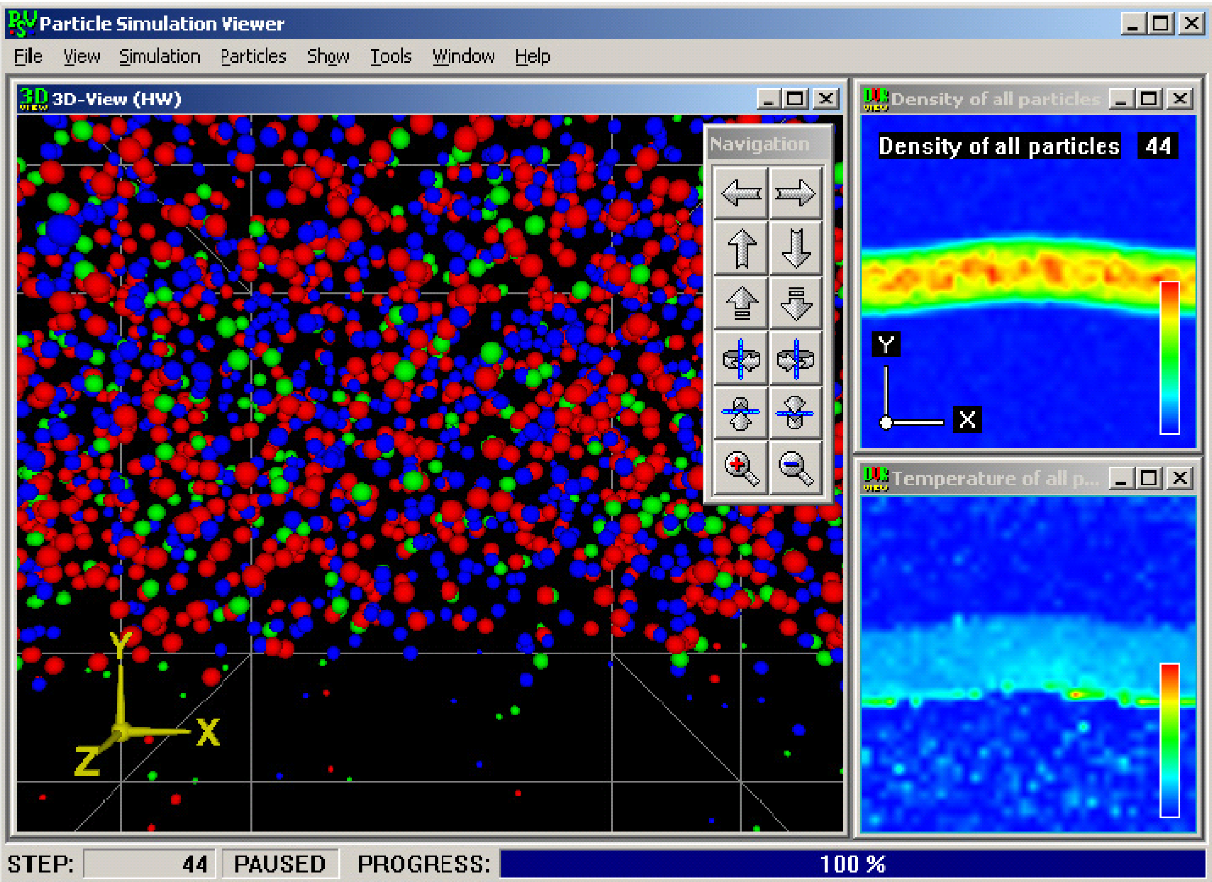




Plasma fiber radiation in the PIC simulation. Number of electrons: 500, simulation steps: 1000, depicted steps 770, 774, 778 ...886. The grid for field calculation was 33×33×33, initial perturbation of the particle density in the axis direction was done, non-zero electric field along the fiber axis was applied.

### 3. New visualization techniques

A great number of visualization routines was developed in frame of the PIC program package. Visualized can be both particle motion and field development. The scene can be rotated, zoomed or shifted during the simulation. Well arranged and transparent Graphic User Interface enables to use particle and field filters, method of visualization or the possibility of recording the animation to avi file. The developed GUI for visualization procedures can be seen in next figure.




Developed GUI for  vizualization procedures

## 4. Current decomposition

In parallel with the numerical simulations a theoretical analysis of the plasma fiber behaviour was performed. It was shown that current density in the plasma fiber can be decomposed into three parts: The first component is caused by the different gradient B drift of the electrons and ions, the second component is caused by the different curvature drift of the electrons and ions and the last component is a contribution from a charged system of particles rotating along magnetic field lines in non homogeneous field.

### 5. Radiative pinch

A simple theoretical model of the radiating pinch was suggested. The radiative intensity is a power function of temperature. Such a course can treat bremsstrahlung, synchrotron radiation and recombination radiation in one formula. The density, pressure and magnetic field profiles of radiative pinch were calculated. A polytrophic behaviour of the plasma was proved and polytrophic coefficients were found for all the types of radiation.

### 6. Authors of the PIC model

| **PART** | **PURPOSE** | **AUTHOR** |
|---|---|---|
| PIC | Basic part of the code | P. Kulhánek |
| INIT | Fiber initiation | P. Kulhánek |
| PS | Particle solver nonrelativistic | P. Kulhánek |
| PSR | Particle solver relativistic | D. Škandera |
| FFT | FFT field solver | R. Dejmek |
| MUDPACK | Multigrid Package field solver | C. A. John, NCAR, USA |
| MC | Monte Carlo collisions of the neutrals | D. Škandera |
| DIAG | Diagnostic routines | P. Kulhánek |
| LIC | Line Integral Convolution field visualization | O. Novák |
| VISUAL | Particle visualization and animations | M. Smetana |
| RADIATION | Radiation program package | D. Břeň, P. Kulhánek |
| DUST | Charged dust particles | V. Kaizr |

## References


[1] Birdsall C. K.: *Particle in Cell Charged - Particle Simulations, Plus Monte Carlo Collisions with Neutral Atoms*, *PIC-MCC*. IEEE Trans. on Plasma Science **19** (1991) 65.

[2] Adams J. C.: *Multigrid package MUDPACK 5.0*. National Center for Atmospheric Research; http://www.scd.ucar.edu/css/software/mudpack; e-mail: johnad@ucar.edu, 1999.

[3] Stalling D., Hedge H. C.: *Fast and Resolution Independent LIC*, SIGGRAPH 95 Conference Proceedings, pp. 249-256, ACM SIGGRAPH, 1996.

[4] Risquet C. P.: Visualizing 2D flows: Integrate and Draw. http://www.informatic.uni-rostock.de/~carlos/FlowVisualization/IntegrateDraw.html

[5] Břeň D., Kulhánek P. Škandera D.: *Monte Carlo Simulations of the Systems with Many Particles*. In: Modelling Collective Phenomena in Complex Systems. Eindhoven: European Physical Society, 1998, vol. 22F, p. 182-183.

[6] Encyclopedia of Astronomy and Astrophysics: *Magnetic Helicity*, Nature Publishing Group, 2001

[7] Novák O.: *Vizualizace plazmového vlákna*, Diploma Thesis, FEE CTU 2000 (in Czech).

[8] Dejmek R.: *Simulace jevů v plazmatu metodami PM*, Diploma Thesis, FEE CTU 2001 (in Czech).

[9] Škandera D.: *Tvorba modulů pro programový balík PIC*, Diploma Thesis, FEE CTU 2002 (in Czech).

[10] Stránský M.: *Zkoumání podmínek vzniku a udržení helikálních struktur v plazmatu*, Diploma Thesis, FEE CTU 2002 (in Czech).

[11] Břeň D.: *Numerical modeling of energy losses in z-pinches*, Proc. 20$^{th}$ SPPT, Czechoslovak Journal of Physics, **52 D** (2002) 226-230.

[12] Kaizr V.: *Low frequency waves in plasma fibers with gravitational field*, Proc. 20$^{th}$ SPPT, Czechoslovak Journal of Physics, **52 D** (2002) 231-234.

[13] Škandera D.: *Relativistic particle solvers in PIC model*, Proc. 20$^{th}$ SPPT, Czechoslovak Journal of Physics, 52 D (2002) 240-245.

[14] Pašek J.: *Particle to particle in cell simulations of the plasma*, Proc. 20$^{th}$ SPPT, Czechoslovak Journal of Physics, **52 D** (2002) 246-250.

[15] Škandera D.: *Charged-Particle Collisions with Neutral Atoms in PIC-MCC Model*, CTU Workshop 2002, 112-113.

[16] Břeň D., Kulhánek P.: *PIC Simulations of the Plasma z-pinch Column*. In: Proceedings Contributed Papers XXIV ICPIG. Warsaw: IPPLM, 1999, vol. 3, p. 109-110.

[17] Kulhánek P.: *3D PIC Model of Helical Current Filament*. In: Proceedings of 6th Granada Seminar on Computational Physics. Granada: Universidad de Granada, 2000, p. 297-306.

[18] Kulhánek P.: *Particle and Field Solvers in PM Models*, Czechoslovak Journal of Physics, Vol. 50 (2000), Suppl. S3, pp 231-244.

[19] Kulhánek P.: *Present State of PIC Simulations*. In: Proceedings of Workshop 2001. Prague: CTU, 2001, vol. A, p. 64-65. ISBN 80-01-02335-4.

[20] Kulhánek P.: *Particle in cell simulation of helical structure onset in plasma fiber with dust grains*, Proc. 20$^{th}$ SPPT, Czechoslovak Journal of Physics, **52 D** (2002) 221-225.

[21] Kulhánek P., Břeň D., Kaizr V., Pašek J.: *Particle in Cell Simulation of Helical Structure Onset in Plasma Fiber with Dust Grains*, in Proceedings „3rd International Conference on the Physics of Dusty Plasmas ", Durban, 2002

[22] Kulhánek P. Smetana M.: *Visualization techniques in plasma numerical simulations*; Czechoslovak Journal of Physics Vol. 54, 123-128, (2004) (2,5 b.)

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Petr Kulhanek was born in Prague on January 9, 1959. Both father and mother were employed in chemistry. He has two daughters, Lucie (*1994) and Zuzana (*1995).

Dr. Kulhanek studied mathematical physics on the Charles University during 1978−1983. He had finished the study with distinction and became RNDr. After the university studies he worked at the Czech Technical University and have finished Ph.D. study (CSc.) in 1987. He became an associate professor in applied physics in 1996.

In the early years he simulated, in frame of his diploma thesis, phase transitions in two-dimensional grid spin models by Monte Carlo methods (Potts and other models). Later he became interested in plasma physics. He did many calculations concerning plasma rail accelerators and afterwards plasma fibers. In last years he coordinates the development of fully three dimensional "Particle in Cell" numerical models of plasma filaments. On a long term basis he is interested in astronomy.

During the university study Petr Kulhánek shortly worked in Tashkent University (Uzbekistan), in 1992 he was on a stay in the Leicester University (UK, ionosphere plasma) and organized scientific expeditions in 1999 (total Sun eclipse, Hungary), 2001 (total Sun eclipse, Zambia) and 2002 (study of aurora structures, Norway).

At present time he is a member of the advisory board of following journals: Astropis, Essentia, Czechoslovak Journal of Physics and a chairman of the Aldebaran Bulletin editorial board. He is a member of the organizing committee of the Symposium on Plasma Physics and Technology international conference for the period of six years. He is a member of the Czech Astronomy Society (CAS) and the president of the Aldebaran Group for Astrophysics (AGA). He was the secretary of the department of Physics of the Czech Technical University from 2003 till 2004.

Petr Kulhánek is the author or co-author of more than 100 scientific papers in the area of plasma physics and he took an active role in many conferences and symposia all over the world. Many years he read lectures in bachelor, master and doctoral courses (e.g. the Ph.D. course in theoretical physics) and he is an author of corresponding textbooks. Four of his Ph.D. students successfully finished the doctoral study and another four will probably finish within next year.

Permanently and responsibly he addicts himself to both scientific and educational activities in the Czech Technical University.