NUKLEONIKA 2001;46(Supplement 1):S29–S32

Study of deuteron motion in a filamentary Plasma-Focus pinch column for different configurations of filaments

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Abstract The motion of deuterons in dynamical filamentary configurations of a PF pinch column has been studied with a three-dimensional numerical model. Apart from magnetic fields, the motion-induced electrical fields as well as ion-ion and ion-electron collisions have been included in the equations of deuteron motion. Calculations were performed for different numbers of filaments and its spatial distributions under different initial conditions. Energy of ions was assumed to be from 10 keV up to 200 keV. The results obtained have shown many possible modes of ion motion and have demonstrated that the current filaments can cause peculiarities observed in the angular distribution of deuterons emitted from the PF pinch column.

Key words deuterons • filamentary pinch • ion trajectories • numerical modeling • plasma focus

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Received: 23 October 2000, Accepted: 17 January 2001

Introduction

Experimental studies of Dense Plasma Focus (DPF) facilities proved the occurrence of high-energy ion beams, generated within the PF pinch column or its vicinity. Since the DPF phenomena are non-linear, and strongly time-dependent [4], only limited papers have been devoted to theoretical studies of ion beam sources, and to analysis of the influence of high-energy ions and electrons on the neutron and X-ray emission. Although ion beams have been studied experimentally for many years [7], the knowledge about sources and mechanisms of their acceleration is still insufficient. A complex picture of the distribution of ions emitted from the PF pinch region points out on non-uniform and time-dependent character of the appearance of ion beam sources. In several theoretical papers [1, 3, 5] very simple configurations have been adopted to explain ion behavior inside of the plasma column. According to many observations [2, 6], which showed much more complicated structure of the stratified plasma column (e.g. filaments, "hot spots" etc.), such simple configurations seem to be insufficient. Therefore, additional suppositions about the structure of the pinch column should be taken into consideration.

This paper appears to be a continuation of the previous studies [5] and it is based on the known experimental observations [2, 6]. The main aim of the present study was to investigate motion of deuterons in a non-steady 3-D flower-like filamentary pinch-column during the phase of the maximum compression. Induced electric fields and collisions have been included in the model applied. Numerical modelling was carried out by taking into account different parameters, i.e. various numbers and spatial distributions of current filaments, as well as different initial conditions (compact or diffusive sources) for deuterons within an energy range up to several hundreds keV.

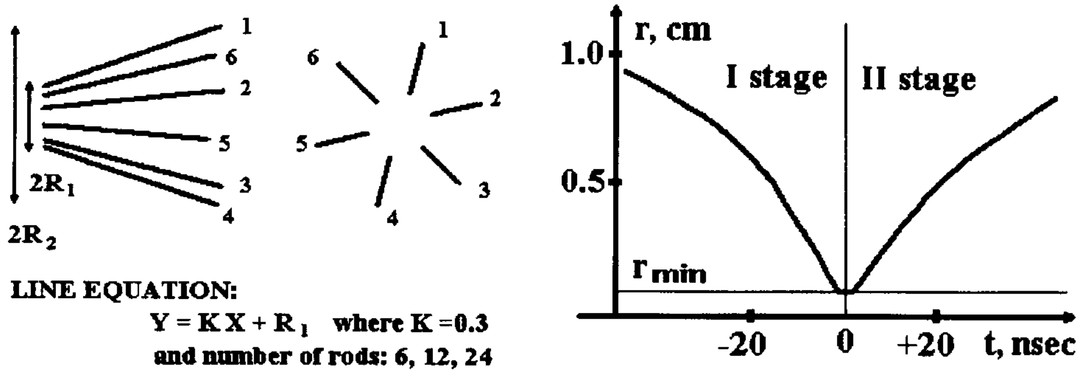


Fig. 1. "Flower-like" configuration of current filaments used for modelling (on the left), and assumed dynamics of the pinch radius (on the right), which was used for calculation of an induced electrical field.

3-D model of a PF pinch column

In many experiments of the DPF type, during different phases of the discharge development, various quasi-axial and spiral filamentary structures were observed [2, 6]. The observations showed relative stability of such structures and their dependence on the initial conditions. We have assumed that such filaments bear electric currents of intensity one order of magnitude higher than that in the remaining part of the pinch column. We have also assumed that they are stable enough to neglect their deformations. During the period considered, we have taken into account only the maximum compression phase of a DPF discharge. Measurements of X-rays showed that the PF pinch column is rather tubular than cylindrical one. In order to calculate magnetic field values analytically, we considered the pinch column as set of rod-like filaments, as presented in Fig. 1.

The considered configuration made it possible to use an analytical expression in order to describe the magnetic field distribution. Induced electric fields have been determined from the Faraday law, where the d**B**/dt term, resulting from the radial motion during the collapse phase, as shown on the right in Fig. 1. Velocities of the compression have been taken from experimental observations.

The spatial distribution of magnetic fields for the two-layer filamentary configuration of the pinch column, as assumed in the applied model, is shown in Fig. 2.

It should be noted that the induced electric field is negative during the collapse phase (see Fig. 3), and it is positive during the pinch expansion phase. To take into account high density of a PF plasma (10^{18}–10^{19} cm^{-3}), the ion-ion and ion-electron collisions were also included in the considered model:

(1) $\nu_{i,e} = 1.7\times10^{-4}\, n_e\, Z^2\, \lambda_{ie}\, \mu^{1/2}\, E_k^{-3/2}$

(2) $\nu_{i,i'} = 9\times10^{-8}\, n_i\, Z^2\, Z'^2\, \lambda_{ii'}\, (1/\mu+1/\mu')/\, \mu^{1/2}\, E_k^{-3/2}$

where: e, i, i' are the indexes denoting mean electron, ion, and another ion, $\mu = m_i/m_p$, m_p is the proton mass, λ is the Coulomb logarithm, E_k is the kinetic energy of an ion, n denotes the concentration of ions, and Z is the ion charge state. During computations of magnetic and electric fields the parameters were varied as follows:
– the number of filaments: six, twelfth, and twenty-four;
– the number of layers: one or two;
– presence of the central filament: yes or no.

The equations of motion were written in the form:

(3) $d\mathbf{v}/dt = (e/mc)\, \mathbf{v} \times \mathbf{B} + e\, \mathbf{E} - \nu_{coll}\, \mathbf{v}$

where $\mathbf{v} = (v_x, v_y, v_z)$ denotes the particle velocity, e is the electrical charge, m is the deuteron mass, and ν_{coll} is the collision rate.

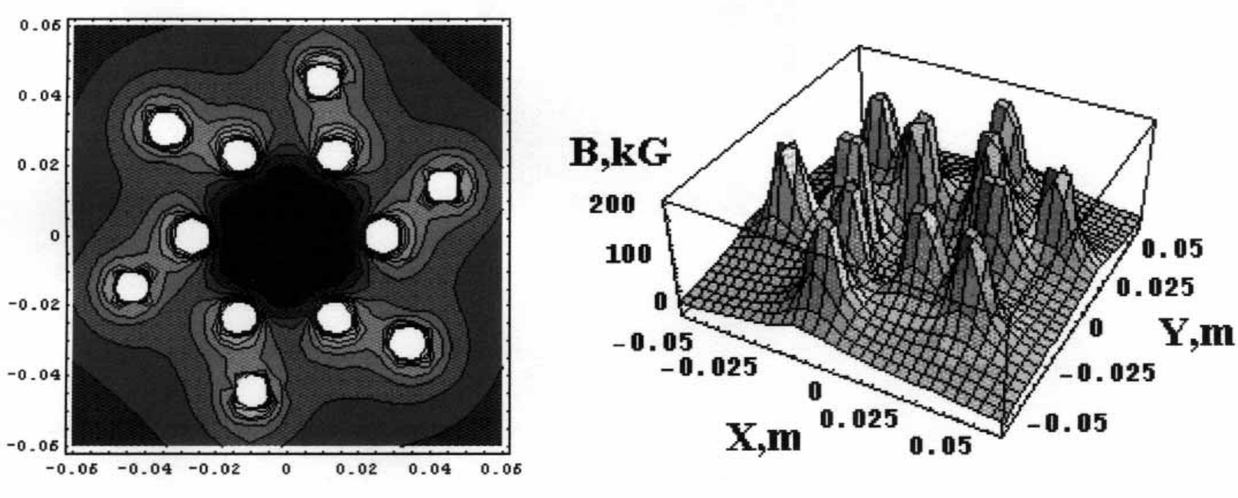


Fig. 2. Distribution of magnetic field for the two-layer configuration, as computed in the z = const. plane (on the left), and the corresponding 2-D model (on the right).

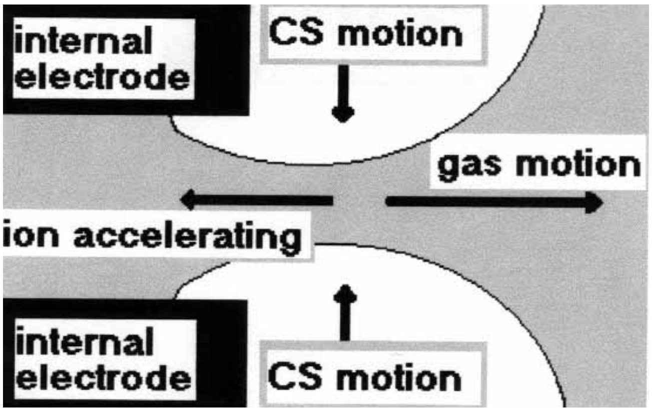


Fig. 3. Scheme used for ion motion modelling during the radial compression phase.

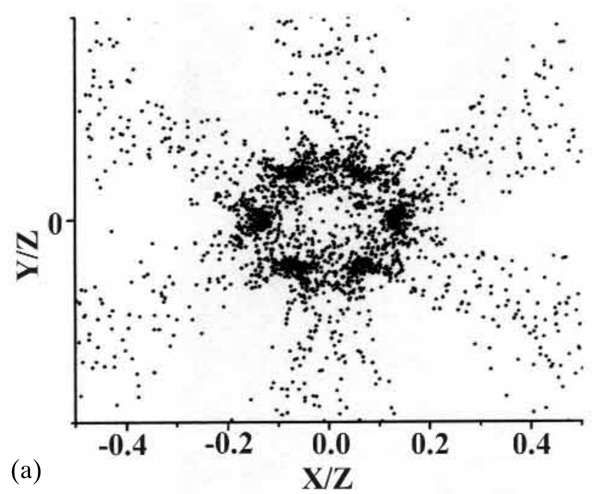
Results of the modeling

Nature of the ion beams emitted from a DPF pinch column is still known rather poorly. Therefore, many theoretical approaches are often discussed. We have included into the modelling some assumptions about sources of non-thermal deuterons. An initial energy distribution of the deuterons in the calculations was chosen as $f(E_k) \sim E_k^{-1}$ for $E_k < 200$ keV. We have also used two different approximations for deuteron beam sources: a miniature (point-like) source with a strong velocity anisotropy, which corresponds to the so-called "hot spot" region, and a large diffuse source which has dimensions of a pinch size and much more isotropic velocity distribution. For the magnetic field determination it has been assumed that the total current is about 500 kA. Some typical 2-D distributions of deuterons with energies up to 100 keV are shown in Fig. 4.

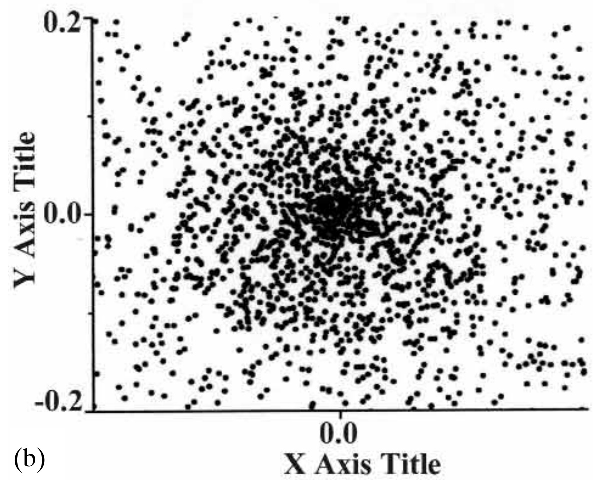
The performed modelling has shown a strong dependence of the final angular distribution on the assumed initial conditions. It has been found that a compact (hot-spot type) source of ions creates the ring-like distribution, which has its minimum on the z-axis. The large diffuse source gives the distribution with a maximum on the z-axis. Moreover, a number of filaments changes the number and size of field-free channels for deuteron escaping in z-direction, but statistics of 5000 events has too low resolution to register differences for six, twelve, and twenty-four filaments.

The appearance of two filamentary layers makes trajectories of deuterons much more complicated, particularly in the zone between the first and second layer, as shown in Fig. 5.

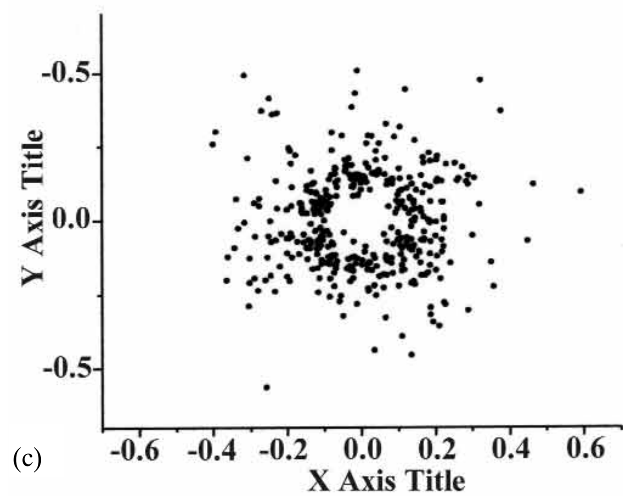
The character of the induced electric field is such that during the compression phase, ions are accelerated in the direction opposite to J_z, and after the maximum compression (when the electric field changes its sign) ions are accelerated in the J_z direction. This effect of the induced electrical field is not important because energy transfer is realized mainly through ion-electron collisions, and directions of their primary motion do not play any role. On the contrary, presence or absence of the central filament changes the angular distribution drastically. When the central filament is taken into consideration the angular distribution has its maximum on the z-axis, as shown in Fig. 4c. Absence of the central filament leads to the ring-like distribution (shown in Fig. 4b). It should be noted that the ion acceleration during the compression phase (if discharge current flows from the internal electrode to the outer one) takes place in the direction opposite to the general flow of gas. It can be an additional source of gas heating within the pinch region (see Fig. 3). There were identified three main types of ions. To the first group belong the so-called run-away ions, which leave the pinch zone very quickly. The second group contains ions staying about 30–50 ns inside the pinch



(a)



(b)



(c)

Fig. 4. Examples of the angular distributions of deuterons emitted under different conditions (projections on the Y-X plane).

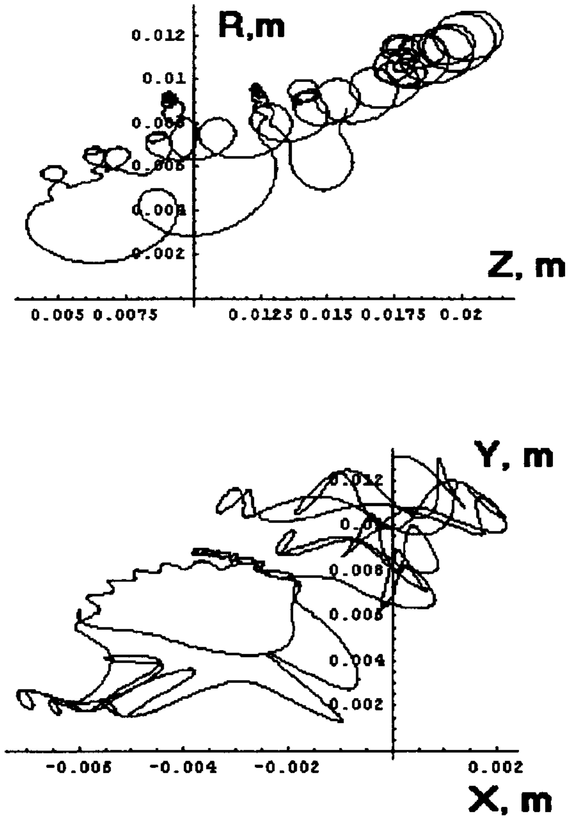


Fig. 5. Projections of the computed deuteron trajectories on the R-Z and Y-X planes.

column (due to electric field and magnetic field action), and after that leaving the pinch zone mainly in the z-direction (or "–z" direction). To the third group belong ions trapped between filaments and staying there longer than a period of validity of the considered model.

Conclusions

The most important results of the theoretical studies reported in this paper can be summarized as follows:

- The 3-D modelling, which takes into account the induced electric fields, shows a wide range of ion trajectories: from the run-away ions to the trapped ions.
- An influence of induced electric field on the ion acceleration can be a source of the additional heating before the maximum compression.
- Presence of the central filament can change considerably the configuration of the magnetic field within the central region, where magnetic fields are usually very weak.
- Under the considered conditions, changes in the angular distributions of deuterons, due to different number of filaments, are negligible. It can, however, be a result of too small statistical resolution, which was limited by CPU ability.

In general, the present model allows magnetic and electrical fields to be described in analytical forms, but it includes the induced electrical fields and filamentary structures. It has been shown that the filamentary structure of a DPF pinch column can explain some peculiarities of the ion angular distribution observed experimentally.

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