Ion Motion Modelling within Dynamic Filamentary PF-Pinch Column

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Abstract. The paper reports on results of the 3-D modelling of ion motion within the plasma focus (PF) pinch column, which is treated as a filamentary, non-stationary system. Beside magnetic fields also induced electrical fields as well as ion-ion and ion-electron collisions have been included in the equations of ion (deuteron) motion. Obtained results show that filamentary structure influences 3-D ion trajectories and 2-D angular distribution of ions. It has been confirmed that 3-D flower-like filaments can explain some important characteristics of the ion emission from PF discharges.

1. Introduction

Plasma focus operation yields intense bursts of both neutrons and X-rays. In the earliest paper Mather [1] pointed out that high-energy ions are generated in the plasma focus. Several theoretical papers have studied influence of high-energy ions and electrons on neutron and X-ray emissions. Although ion beams have been studied experimentally for many years [2], knowledge about sources and mechanisms of their acceleration is still insufficient. In some theoretical papers [3,4] simple configurations have been adopted to describe ion behaviour inside and in vicinity of the plasma column. Many observations [5,6] show however much more complicated stratified structure of the plasma column (filaments, "hot spots" etc.) that can substantially affect acceleration and motion of ions. The main aim of present study is to investigate motion of deuterons in non-steady flower-like filamentary pinch-column during phase of maximal compression. Induced electric fields and collisions are included in the model. Modelling was carried out for different initial conditions (compact or diffusive sources) and for deuterons in energy range up to several keV.

2. Filamentary Model of PF Pinch Column

In the range of experimental works observations of long, thin filamentary structures in the PF during current sheath acceleration phase as well as collapse phase are reported. Observations show stability of such structures for a long period of time (about 80 ns). We assume that these filaments bear intense electric current with density one order of magnitude higher than that in the remaining part of the pinch and that they are stable enough to neglect their deformations. We have included only radial motion before and after maximum of compression ($\pm$ 50 ns). X-ray observations show the PF pinch column is rather like funnel than cylinder. In this case, we can not use 2D configuration but have to take into account all three co-ordinates. Configuration of filaments used for calculations is presented in Fig. 1.

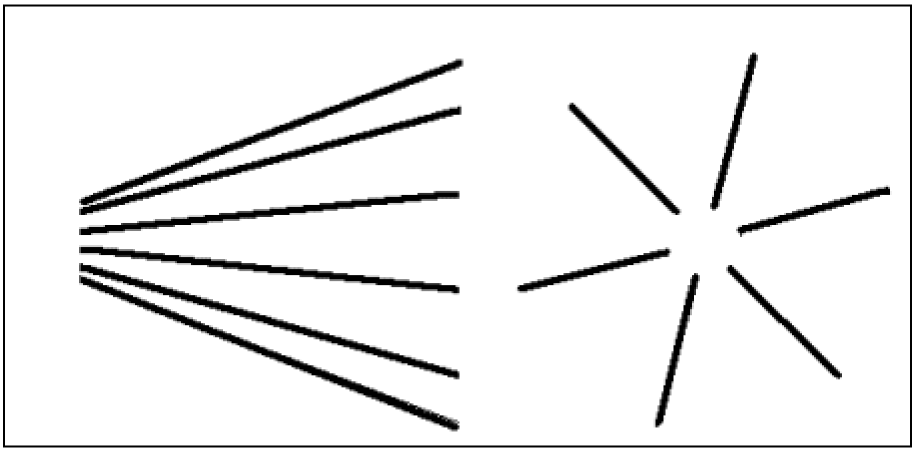

FIG. 1. "Flower-like" configuration of filaments used for modelling.

Magnetic field values for this configuration can be described analytically. Induced electric field have been determined from radial motion toward and outward the axis (Fig. 2). Velocity of compression was taken from experiment.

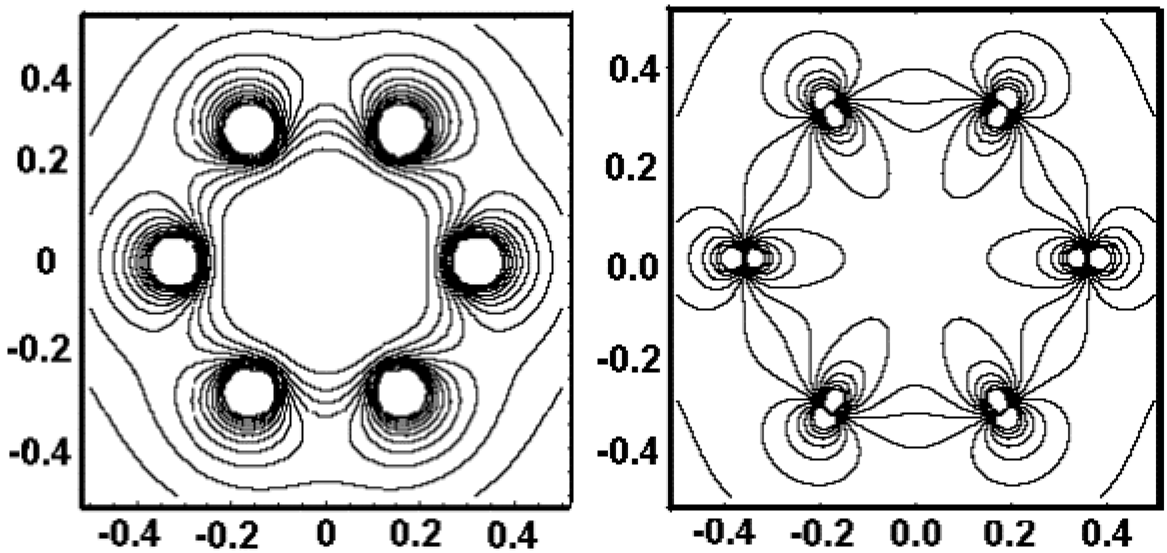

FIG. 2. Configuration of magnetic (left) and induced electrical (right) fields in X-Y plane (all numbers are in cm).

Electric field is negative during the collapse phase and positive during pinch expansion phase. In addition to electric and magnetic fields, ion-ion and ion-electron collisions are included in the model:

$$\nu_{i,e} = 1.7 \times 10^{-4} n_e Z^2 \lambda_{ie} \mu^{1/2} E_k^{-3/2}\,, \tag{1}$$

$$\nu_{i,i'} = 9 \times 10^{-8} n_i Z^2 Z'^2 \lambda_{ii'} (1/\mu + 1/\mu') \mu^{1/2} E_k^{-3/2}\,, \tag{2}$$

where e, i, i' indexes mean electron, ion and other ion, $\mu = m_i/m_p$ where m_p is the proton mass, λ is the Coulomb logarithm, E_k — kinetic energy of an ion, n — concentration of ions, Z is the ion charge state. All calculations were performed for six plasma-current filaments. The equation of deuteron motion is written in the form

$$d\boldsymbol{V}/dt = (e/m_d c)\,[(\boldsymbol{V} \times \boldsymbol{B}) + e\boldsymbol{E}] - \nu_{\text{coll}} \boldsymbol{V}\,, \tag{3}$$

where $\boldsymbol{V} = (V_x, V_y, V_z)$ denotes a particle velocity, e — electrical charge, m_d — mass of the deuteron and $\nu_{\text{coll}} = \nu_{i,e} + \nu_{i,i}$.

3. Results of Modelling

Because of experimental information about sources of accelerated ions are very limited many theoretical approaches were proposed. The mean initial energy distribution of the deuterons in the calculations was $f(Ek) \sim E_k^{-1}$ for $E_k < 100$ keV. We have adopted two different models for deuteron sources: small compact source with strong velocity anisotropy, which is in close relation to the so called "hot spot" region observed in experiment, and large source which has dimension about pinch own size and much more isotropic velocity distribution. The total current for magnetic field determination has been assumed to be about 1 MA. In Fig. 3 and 4 some typical 2D distributions of deuterons with energies up to 100 keV are presented for six filaments configuration. One can see influence of both electric field and collisions on final deuteron distribution.

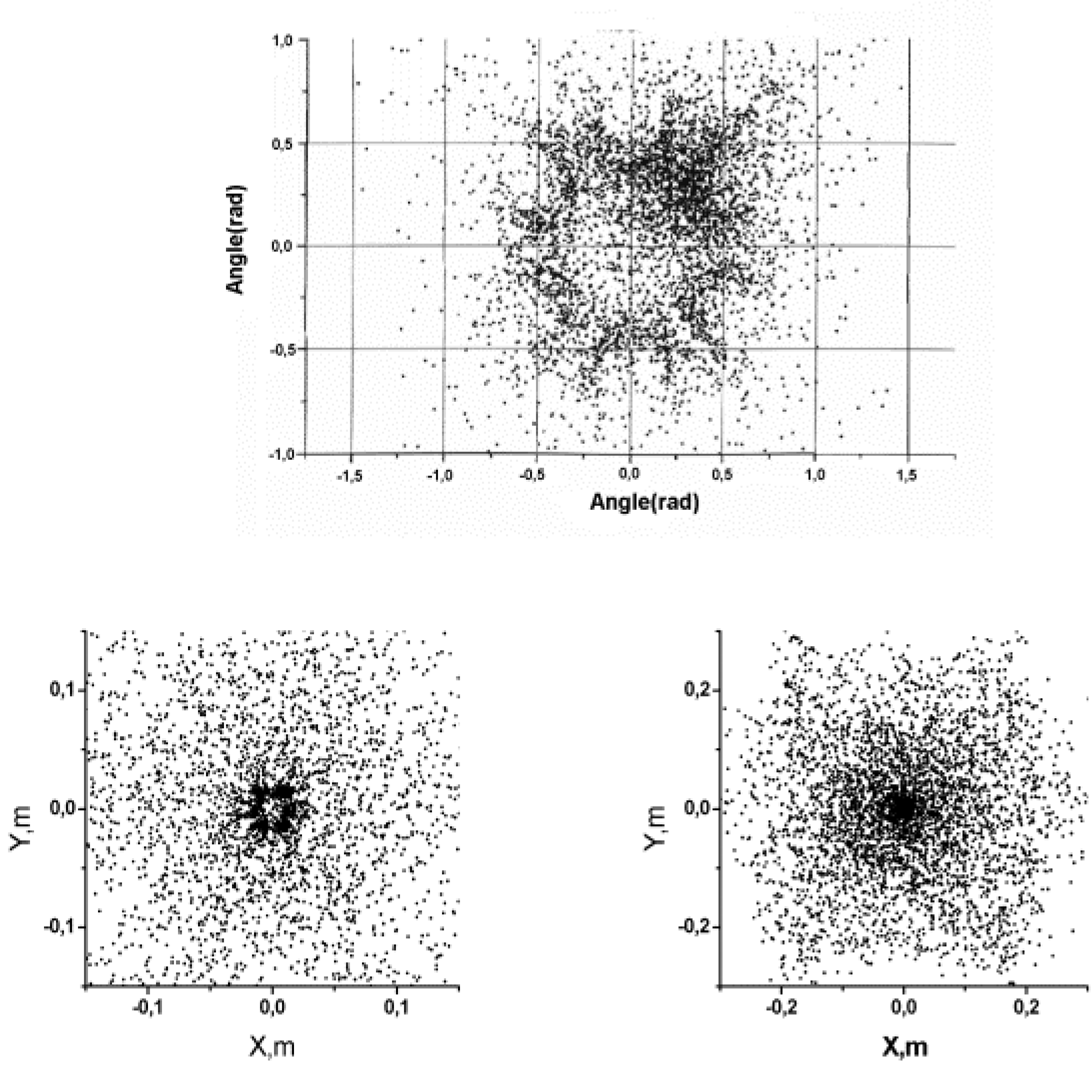

FIG. 3. The three typical spatial distributions of 5000 deuterons under different conditions: above — without induced electric field (a maximum in the right upper corner is caused by non-isotropic distribution of deuteron initial velocity), left — with induced electrical field, right — with high collision rate.

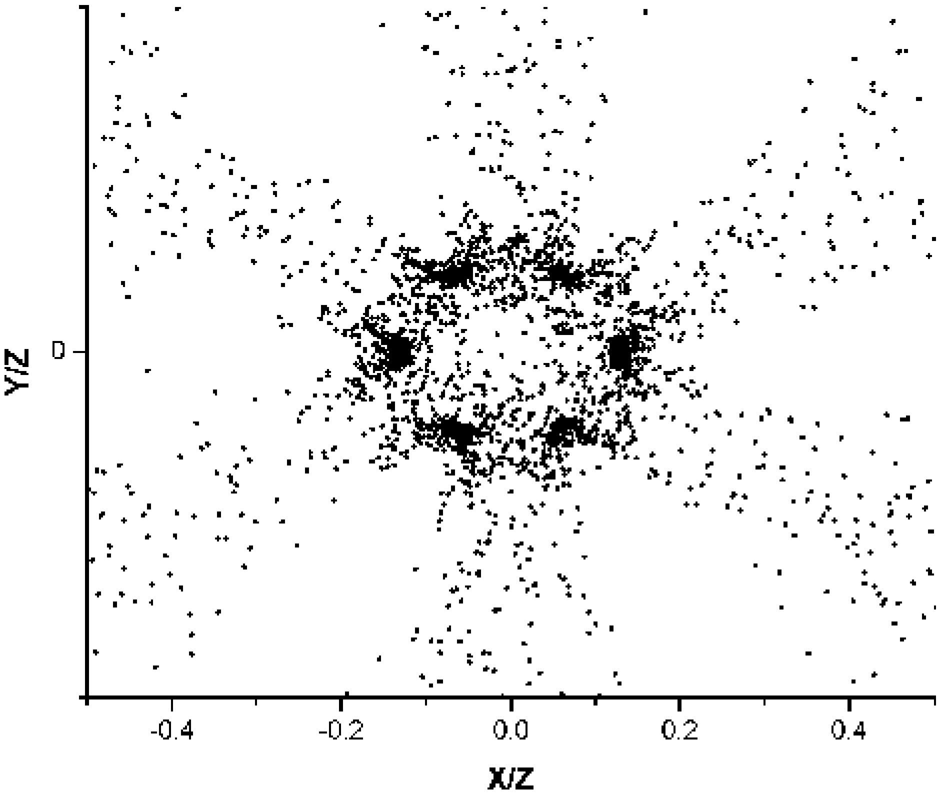

FIG. 4. Angular distribution for six filaments configuration with collisions and inductive electric field (100-200 keV deuterons).

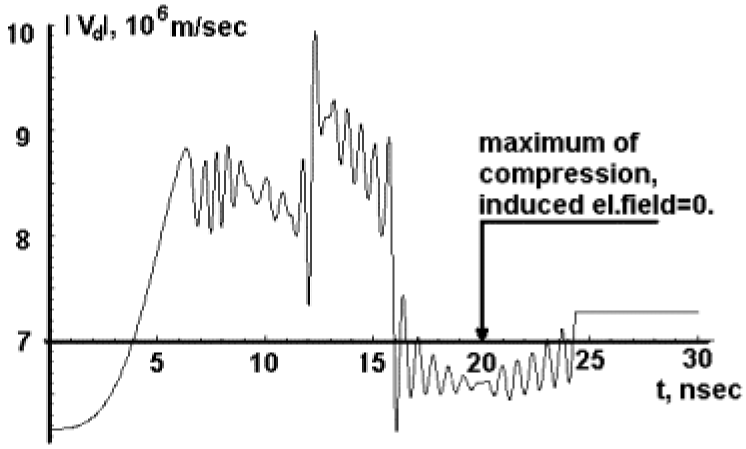

FIG. 5. Time evolution of the deuteron velocity value. Point of maximum compression is shown.After 25 nsec deuteron leaves pinch column.

Moreover, it is important, which model for source of deuterons is used in calculations. Compact source of ions ("hot-spot") creates ring-like distribution, which has its minimum on the axis. Large size source gives well-known distribution with maximum on the axis.

We have also traced ion velocity value. As it is shown in Fig. 5 ion acceleration takes place during compression phase when electric field is maximal. After maximal compression electric field changes its direction and is able only to slow down deuterons. Of course, one important question stays open. This is the question about moment of source appearance in pinch column. According to some time-resolved observations first ion beams are generated before maximum of compression. We have used this assumption. Ion beams can be generated also during expansion phase, but in this case they would have another behaviour and appearance of instabilities should be taken into account.

4. Conclusions

The most important results of this study can be summarised as follows: 3D modelling, which takes into account induced electric field, shows wide range of ion trajectories — from run-away ions to trapped ions. An influence of induced electric field, generated by general pinch column compression, on the ion acceleration can be effective if ion source arises before maximum of compression. The angular distribution of deuterons, emitted from the PF pinch column, is similar to the observed one. It has been shown that filamentary structure of pinch column can explain peculiar ring-like character of deuteron angular distribution under the assumption that ion beam is generated in "hot spot" region.

References

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