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A New Ion Acceleration Mechanism in Z-Pinch Discharges of a Plasma Focus Device

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Abstract

A new mechanism for the acceleration and production of ions in Z-pinch discharges, especially plasma focus is presented. Previously, Yousefi *et al*. [Phys.Plasma **13**, 114506 (2006)] studied the multiple compression and pinch mechanism; they reported that this event can be attributed to the (*m*=0) type instability, while the subsequent ion and neutron acceleration mechanism was not reported. Continuing from previous work, Mizuguchi *et al*. [Phys.Plasma **14**, 032704 (2007)] studied the simulation of high-energy proton production, generated by shock waves in pinch plasma discharge, by use of a 2D relativistic and fully electromagnetic particle-in-cell code. It was found that protons trapped in the electrostatic potential produced near the shock front, can be accelerated to a few Mev by the surfatron acceleration mechanism. On the other hand, the ring-shape of ion bunches, which is in good agreement with the experimental results, were shown. Now we report another acceleration mechanism for subsequent ion production, which differs from the *m*=0 instabilities caused by the surfatron acceleration mechanism.

Introduction

One of the most important phenomena observed in plasma focus devices, is the creation of energetic ions with energies about 100-200 times the charging voltage of the capacitor bank. In this device, the electrical energy of capacitor bank, upon discharge, is initially stored as the magnetic energy behind the moving current sheath, as the sheath is accelerated along the coaxial electrode assembly. A portion of this magnetic energy is then rapidly converted into plasma energy, as the current sheath collapses towards the axis beyond the end of the central electrode. This results in the formation of a short lived, but hot (~1-2 keV) and dense (~10^{25-26} m^{-3}) plasma [1]. The determination of the ion beam characteristics is very important not only to understanding the mechanism of the production of high–energy ions or neutrons, but also for their applications; the energetic ions of the plasma focus device have been used for surface modification [2], for inducing a change of phase in thin films [3-6], for deposition of thin film [7-8] and for ion implantation [9-10]. For neutron production, an initially thermal plasma model was assumed [11-13]. However, results from a different laboratory showed disagreement with this model [14-15]. A beam-target model was introduced in which linearly accelerated deuterons strike stationary ions. In this model ions are accelerated axially by an electric field generated along the neck of each m=0 instability. This model is also unsatisfactory because the duration of neutron production, typically 100ns, is too long for the attributed magnetohydrodynamic instability, and an unrealistically high ion current (greater than 10^6 A) must be assumed. In rejecting this model, Kelly [16] relies on the point, that a beam-target model could not explain the neutron pulse width. Bernstein[17] in 1970 calculated ion trajectories for crossed electric and magnetic fields (E×B) in a z-pinch discharge and showed that ion velocities can be randomly oriented without thermalization. This suggestion inspired the development of new mechanisms for neutron production than those assumed in the beam-target and thermal plasma models. J. H. Lee [18] proposed a converging ion model, in which the neutrons are produced at each instant of time by the three-dimensional convergence of ions, into a small volume centered at the region of collapse. However, in spite of the many challenges, thermonuclear reaction, beam target and gyrating particle models have been proposed as mechanisms for neutron production [19-23]. Different kinds of acceleration mechanisms for charged particles have also been identified; mostly based on induced electromagnetic fields due to fast movements of the plasma column [24-28], or perhaps due to anomalous resistivity [29-31]. Deutsch and Kies on the other hand mentioned that in large plasma focus devices, especially the fast ions and high voltage experiments, neither instabilities nor anomalous resistivity are necessary for fast ions to be created in dynamical pinches, where radial run-away can take place. Therefore another mechanism was formed, based on the ion run-away during the compression stage of the current sheath [32-33]. This implies that, irrespective of the m=0 instability, other acceleration mechanisms may play an important role.

Multiple spike structures of ion and electron pulses were reported (I. F. Belyaeva, 1980; M. Sadowski, 1985; A. Patran, 2005; H.R.Yousefi, 2006) [34-37]. The acceleration mechanisms responsible for the generation of the subsequent ions pulses are more complicated; an electric field connected with anomalous resistivity or a local electric field induced by a fast decay of plasma microstructure [38]. In general, various acceleration mechanisms are probable during the different phases of a plasma focus (PF) discharge, but they cannot be unequivocally identified on the basis of the experimental data collected so far. During the compression phases, rapid local changes in the magnetic flux are the main cause of the strong electric field [39]**.** After maximum compression, the plasma column is extended axially and the plasma inductance slowly increases. But, growth of the (*m*=0 type) instability gradually generates an alternating constricted and extended region along the plasma column axis, which eventually causes the cancellation of the increased inductance. However, it has been shown [40] that the *m*=0 instability does not cause a rapid change in inductance, therefore this type of instability is not connected with neutron production.

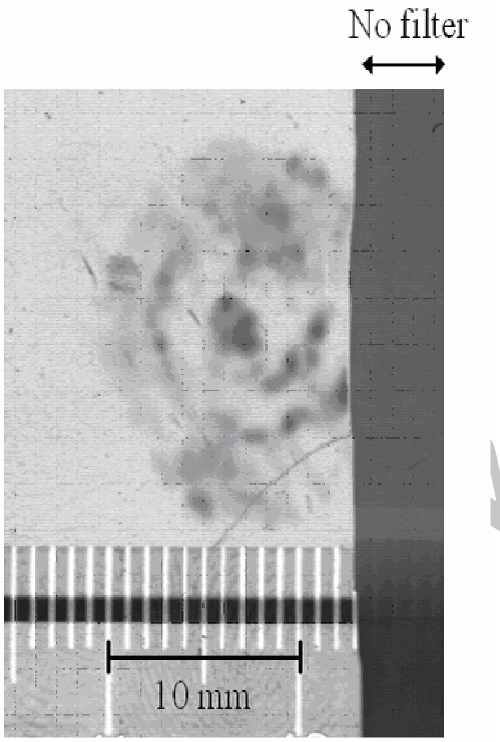

Fig. 1: Particle pinhole image obtained with the aluminum filtered pinhole camera with CR-39 film that shows ring-shape of ion (proton) [45].

Experimental observations using an ion pinhole camera, performed with a different plasma focus device under different conditions [41-44], have shown that the ring-shape of the ion bunches are similar to those obtained in our experiment [45]. Ion angular distribution and ion flux dips have been presented by many groups [38, 46], without any description. However until now, no detailed studies have been carried out to investigate the mechanism of by which the multiple structure of ions, ring-shape of ions and ion flux dip are generated.

Hence, the main aim of this work is to extend previous research on the ion and neutron production mechanism, as well as to investigate the;

(i) Mechanism of subsequent ions production,
(ii) Mechanism of ion flux dip,
(iii) Circumstances of formation of ring shape of the ions.

Result and Disscusion

Recently Haruki *et al*. [47] investigated the high-energy particle production in Z-pinch plasma through sausage and kink instabilities, by using 3-D Particle-In-Cell (PIC) code. In their model, the cylindrical current is driven by an external electric field. The pinched current is unstable against both the sausage and kink instabilities. Two-step acceleration of particles in both sausage and kink phases were found. However in these simulations, protons with MeV, observed in the experiment [45, 48], were not seen. Following this, a 2-D PIC code was used to focus on the shock formation and acceleration during the current pinch phase. In this simulation, fast magnetosonic shock wave production was observed during the pinching phase. It was also shown that after the maximum pinch, the shock wave can be strongly enhanced, and then propagates outwards [49]. We also in our experiment [45] found that the ion pinhole picture shows ring-shaped (tubular) ion bunches, with a concentric circle pattern of many small spots (Fig.1). These experimental results are in good agreement with the simulation results, which show that protons accelerated by surfatron mechanisms near the shock front, have a ring-shaped angular distribution around the z axis (Fig.2). Therefore we could apply the surfatron acceleration mechanism to the proton acceleration observed in pinched plasma discharges. One can concluded that the number of accelerated protons near the Z-axis (X=0) is less than that of the protons outside the z-axis. The reason for this ring-shaped structure is due to the surfatron acceleration becoming strongest after maximum pinching occurs (as seen in Fig.2). This angular proton distribution around the Z-axis is consistent with ion flux dip and the ring shape of ion bunches [38, 44-46], therefore the ion flux dip observed in the experiments and simulations, can be attributed to the surfatron acceleration mechanism. We also propose that the subsequent ion production is due to the surfatron acceleration mechanism. Finally we remark that multiple pinch or compression was attributed to the *m* =0 instability [37], but usually this cannot cause the rapid change in the inductance. Therefore, as we demonstrated in the last report, electric fields that occurred due to the *m*=0 instability do not have sufficient energy to accelerate the ions or produce the neutrons, and they simply appear on the current signal as multiple spikes. Therefore, the proposed mechanism for the multiple compressions is the *m*=0 instability, whereas for multiple ions or neutrons, it is due to the surfatron acceleration mechanism.

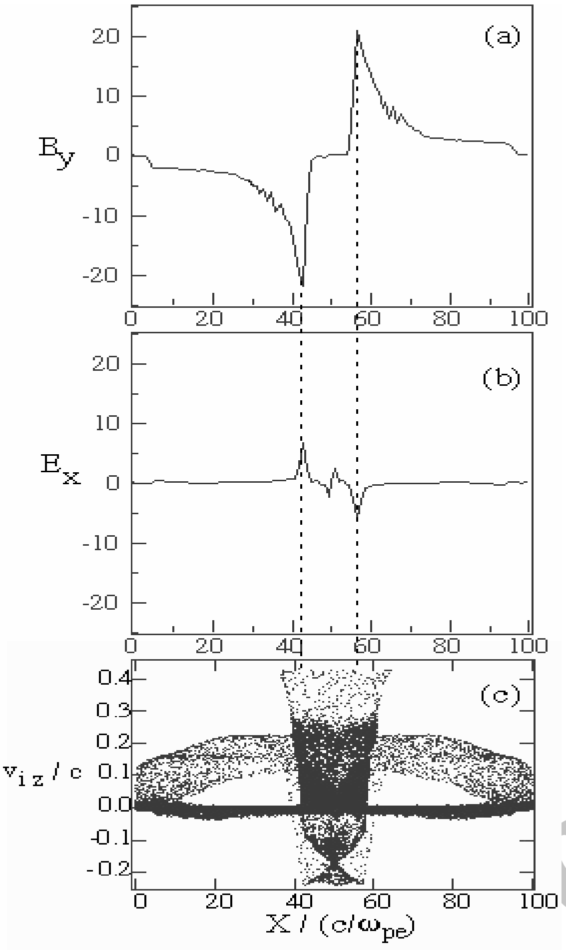

Fig. 2: the ring-shaped angular distribution of proton around the z axis was simulated by PIC code [49].

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