INFLUENCE OF AN EXTERNAL MAGNETIC FIELD ON THE VELOCITY PROFILE AND BEAM CURRENT IN A PLASMA FOCUS DEVICE FOR PARTICLE ACCELERATION

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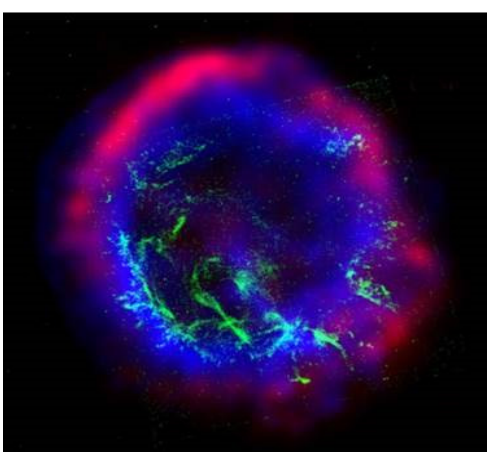
Abstract

Experiments with a plasma focus device (PFD) are being carried out for the understanding of the accelerating mechanisms in collisionless shocks, as a candidate for a new particle accelerating method for beam therapy applications. The current configuration operates under vacuum conditions (0.1Pa) and is capable of achieving high plasma velocities above 40km/s under different electrode configurations. A combination of two external tapered electrodes and two internal electrodes of conical tip, allowed us to evaluate the influence of the inter-electrode area in the accelerating performance of the PFD. The present study evaluates the effect of an external magnetic field on the plasma flow and the resulting beam current profile

INTRODUCTION

Cosmic rays are high energy particles known to reach energies up to 10^{20}eV, which is way much higher than the energies achieved by the particle accelerators created by man [1]. Even since their discovery, scientists have argued upon their origin (supernovas, neutron stars, among other celestial bodies) and accelerating mechanisms. The Fermi acceleration has become increasingly attractive as an explanation for the main accelerating mechanism, by which high energy particles are a natural by-product of the passage of a high Mach number, collisionless shock. Under this circumstance, the shock acceleration is given namely by the reflection of the particles back and forth through shock front by scattering centers (waves), and in the case of a supernova remnant (Fig. 1), they can absorb the kinetic energy of the surrounding blast wave with quite high energy. However, Fermi acceleration processes occur in the relativistic region and the origin of the non-thermal particles required for the initial stage of acceleration, commonly known as the “injection problem”, still remains to be addressed [2]. Furthermore, the examination of the interactions between a fast plasma flow and electromagnetic fields in the non-relativistic region is also required [3].



Credit: NASA/CXC/SAO
http://chandra.harvard.edu/photo/2000/0015multi/

Figure 1: X-ray-optical image of supernova remnant.

The present work aims to the understanding of the above mentioned accelerating mechanism, hereafter referred as shockwave acceleration, by studying the interaction of a high velocity plasma and its interaction with an external magnetic field, under pressures of 0.1Pa in order to guarantee a collisionless environment. The resulting interaction will be interpreted by the interpretation of the beam current.

EXPERIMENTAL SETUP

Figure 2 shows the schematic of the experimental setup.

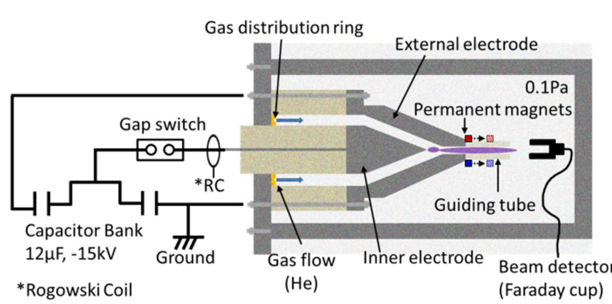


Figure 2: Schematic of the experimental setup.

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A plasma focus device with tapered electrodes is operated under pressures of 0.1Pa or below, with He as the working gas. The input energy is applied by means of a capacitor bank of 12μF (2μF x 6), charged by a negative power supply up to 15kV. The capacitor bank is connected to the electrodes of the plasma focus device through gap switch operating under self-breaking mode. Downstream the tapered electrode, an acrylic guiding tube of 20mm of length and internal diameter of 4mm is placed for the plasma to expand and interact with a perpendicular external magnetic field applied by permanent magnets. The effects of the position of the magnetic field were evaluated by analyzing two different locations (center and inlet of the guiding tube) of the permanent magnets in the guiding tube. For each location, two different magnetic field strengths (25mT and 200mT) were evaluated, for a total of 4 cases.

The discharge current has an oscillatory behavior typical of an underdamped system, with a maximum peak current of 70kA, with characteristic frequency $\omega_L = 4.84^{-5} rad/s$. The stray inductance and resistance were estimated by fitting the discharge current with the ideal waveform, using the least squares method, and with a value of 430nH and 18mΩ, respectively. The discharge current in the present experiment was measured by placing a Rogowski coil as shown in Fig. 2, and the beam current was measured by a Faraday cup placed downstream the guiding tube with a biased voltage of -50V.

Figure 3 shows the inner and external electrodes used for the present work, where Pin (Inlet of guiding tube) and Pc (center of guiding tube) represent the two locations used for placing the permanent magnets.

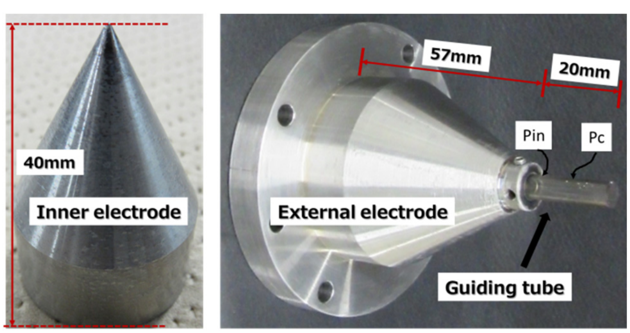

Figure 3: Electrode configuration.

RESULTS AND DISCUSSIONS

Beam current in the absence and presence of a magnetic field

The characteristic discharge and beam currents in the absence and in the presence of an external magnetic field of 25mT (B-field hereafter) are shown in Fig. 4. In the absence of a B-field, the beam current obtained from the Faraday cup will be mainly composed by a mix of electrons and ions. The component labeled as "I" represents the incoming electron flow which arrives faster than their counterpart ions, followed 3μs later by the heavier and hence slower ion flow ("II"). In contrast, as can be seen when placing an external B-field in the guiding tube, two events can be identified. First, the electron component of the current seen in the case without B-field is not present. It is believed that the incoming electron flow was deflected by the effect of the magnetic field, hence making the beam current detected, a completely ion current.

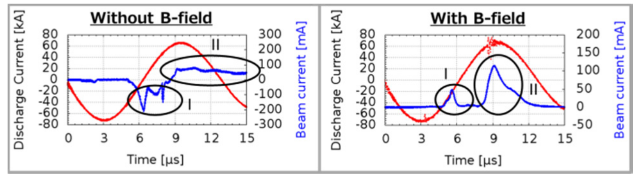

Figure 4: Discharge and Beam current contrast

The second event is represented by the presence of mountain-like components of positive ion current. The first stream labeled as "I" corresponds to the faster ions that were accelerated by the effects of the shockwave acceleration phenomena. A second stream of ions labeled as "II" represents the bulk slower plasma mixed with a component of reflected ions. As can be seen by the magnitudes of both peaks, from the interaction with the magnetic field, a bunch of ions will be accelerated while some others will be decelerated or reflected. As a consequence the first peak although faster, is expected to have a lower amplitude than the second peak.

Numerical results based on a hybrid PIC method reported at [3, 4], suggested that when the dynamic pressure balances with the magnetic pressure, the plasma parameter equals the unity (or surpasses the unity) allowing the plasma to induce changes in the magnetic field lines as shown in Eq. 1. As the magnetic field changes in time, an electric field is induced, directly affecting the ions (accelerating and decelerating effect) in the propagation direction. Furthermore, if one assumes that the velocity of ions in any perpendicular direction of flow is negligible, from Eq. 4 one can notice that the induced electric field in the propagation direction will depend on the gradient of the magnetic field (in our case the gradient of B_z respect to the propagation direction). From the fluctuation of the electric field one can find that part of the ions are accelerated to higher velocities, in our case represented by the first peak in the beam current, while others are reflected and joining the slower incoming bulk plasma, in our case represented by the second peak.

An interesting feature of the obtained beam current profile relies in their mountain-like shape, instead of the typical flat beam profile. More experimental evidence and further analysis are required to fully interpret these results; however, several ideas can be given. For instance, for the shown in Fig. 4, the velocity of the particles "I" is estimated with the TOF to be around 20km/s. Depending on how the magnetic field is fluctuating, the Larmor radius of the particles can reach values higher than the diameter of the guiding tube, and as a consequence some of the particles will be trapped by the magnetic field, eventually being lost to collisions with the wall. On the other hand, other particles might be favored by the accelerating electric fields and hence, will be able to reach the detector. The overall effect being that the beam current reaches a maximum peak and eventually decreases due the trapping of the particles in the magnetic field, and possibly collisions with the wall of the guiding tube and possibly the effect of the reflected particles as well. More evidence is needed to support these last statements and will be left for future works.

In addition, the above interpretation does not include the accelerating effects of the wave-particle interaction in the upstream and downstream of the shock front. This phenomenon must be supported with numerical analysis, also left for future work.

B-field magnitude and position

Figure 5 shows a comparative result of between effects of 25mT and 200mT, both demonstrated at different locations along the guiding tube (Pc and Pin).
We can see two main behaviors from the figure. For the first behavior, in both 25mT and 200mT cases, the peaks tend to reach faster the detector when the magnetic field is placed at the inlet (Pin) of the guiding tube. The second behavior is related to the magnitude and detection time of the first particles when the magnetic field increases in magnitude. For the 200mT, we can see that particles reach the detector 3μs faster than in the 25mT case, with energies of 134eV when the magnets were placed at the center (Pc), and 620eV when the magnets were placed at the inlet of the guiding tube. The magnitude of the beam current on the other hand, decreases in contrast to the 25mT case. From this result one can state that the magnitude of the peak of magnetic field affects the velocity or energy of the accelerated particles, nonetheless, with the consequent trade-off of a reduced beam current. In other words, the higher the magnetic field, the higher the energies of the accelerated particles, however, the higher the particles to be reflected and hence, a reduced ion beam current.

The influence of the magnet position still remains a topic for future work. It is believed that due to the edge effects, as the magnetic field lines permeate inside the plasma focus device, the axial component of the magnetic field lines becomes more significant. The interaction of this parallel component with the incoming plasma might be producing a particle velocity increment more significant than the magnets are located at the center of the guiding tube. The main cause is still to be investigated both experimentally and numerically and left for future work.

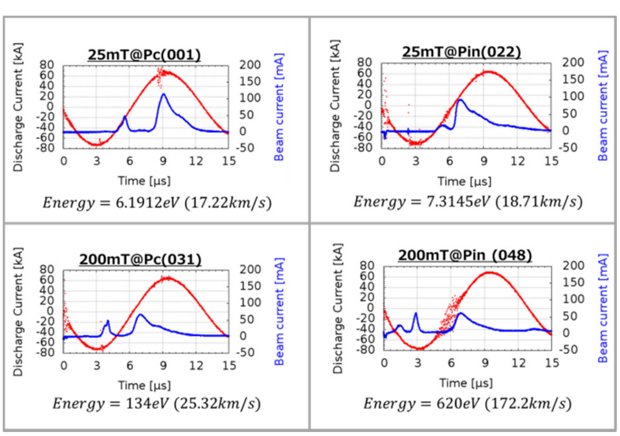

Figure 5: B-field magnitude and position effect contrast.

CONCLUDING REMARKS

- We have evaluated experimentally the effects of an external magnetic field on a high plasma flow under a collisionless environment for the understanding of the accelerating mechanisms in collisionless shocks. Both intensity and relative position of the external magnets respect to the guiding tube were evaluated.
- It was found that the presence of the magnetic field suppresses the incoming electron flow from the quasi-neutral plasma. As a result it was possible to obtain a pure ion beam current extracted from initially quasi-neutral plasma.
- It was also found that the presence of a magnetic field gave rise to two components of the beam current. A fast component composed by fast accelerated ions by means of the induced electric fields. This acceleration is evidence of the changes in the magnetic field produced by a plasma flow in which its dynamic pressure balances with the magnetic pressure. A second component of the ion current was also present mainly composed by the bulk plasma and the reflected ions due to the effects of the fluctuating induced electric field.
- The position of the magnetic field influenced the arrival time of the particles into the detector, however, more numerical and experimental evidence is require to properly explain the meaning of this change.
- The magnitude of the peak of the magnetic field was found to be proportional to the energy of the particles and inversely proportional to the intensity of the beam current. A trade-off is found between beam current and intensity of the field. The increase of the initial plasma velocity can also improve the intensity of the beam but further numerical and experimental studies are required to confirm this statement.

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