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FULLY STRIPPED ION BEAMS PRODUCED BY PULSE POWERED PLASMA FOCUS DEVICE*

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Abstract. A new type of plasma focus device is used to produce ion beams of helium, nitrogen and argon. The ion beams are analyzed by a Thomson spectrometer that has as its detector CR-39 plastic, a material which allows high sensitivity and spatial resolution. It is found that virtually all of the helium, nitrogen and argon ions are fully stripped and accelerated to energy per charge of 550 keV/Z. From the same Thomson parabolas, methods of obtaining the energy spectrum and the emittance of beam are discussed.

Introduction

It is now well known that the plasma focus device can be operated so as to produce ions and electron beams of energies up to many times the product of their charge and capacitor-bank charging voltage.[1] Previously we reported the preliminary experimental studies of ion beam generation in pulse powered plasma focus device.[2] It is shown that the ion beams either from gaseous or solid elements can be accelerated and that the normalized beam emittance of helium ions are less than 1 cm-mrad.

In the work reported here, we extend the previous study by using a Thomson spectrometer in which nuclear track detection is used. Also reproducibility is improved by lowering operating voltage and by employing continuous gas injection system. The Thomson parabolas obtained for three ion species, helium, nigrogen and argon are used to analyze energy, charge to mass ratio of the accelerated particles and the emittance of the beams.

Experimental Description

A Marx generator charged Blumlein pulse system[3], modified to produce a pulse with positive polarity, is used to drive a plasma gun as shown in Figure 1. The gun consists of an anode of 5 mm diameter molybdenum rod and planar cathode with a 1.25 cm diameter hole (plenum) on axis. The rate of gas continuously injected into the plenum is adjusted by a needle valve and is monitored using a flowmeter and a thermocouple gauge.

The pulse system is operated at relatively low voltage producing typical output of +300 kV. The gas flow rate of 3 ~ 10 cc/min. which gives pressure range of 2 ~ 25 m Torr at the plenum, provides a condition for ion acceleration. The accelerated ion beam in the forward direction is monitored by a small Faraday cup, which is placed 3.5 cm above the axis of symmetry. The ion beam moving along the axis is analyzed by a compact Thomson spectrometer, which is placed at the end of drift chamber, 100 cm from the cathode plane. As shown in Figure 2, the spectrometer has a field region of 3 cm x 3 cm cross sectional area in which electric field (18 kV/cm) and magnetic field (2.6 kG) are perpendicular to the axis. The aperture plate has three 65 um diameter pinholes at r = 0, and r = $\pm$ 5 mm and is placed downstream of the field region. The target plate, the CR-39 plastic particle track detector[4] is placed 1 cm further downstream of the aperture plate. Three shots are made to complete the exposure of each detector plate. One shot with both electric and magnetic fields forms the parabola; the next with magnetic field only forms the vertical axis; and the last with electric field only forms the horizontal axis. The exposed CR-39 plate is then etched for 120 min. in 6.25 N NaOH solution at 70°C.

Thomson Parabola Analysis

A charged particle passing through the Thomson spectrometer experiences two different types of forces resulting in two different deflections, one in the vertical direction due to magnetic field and the other in the horizontal direction due to electric field when the fields are arranged as in Figure 2. It is shown[5] that the use of deflection angle rather than absolute deflection, not only makes the analysis simpler but also reduces the error sources in data deduction. The two deflection angles are easily found under the assumptions of uniform fields over the length L and small deflection angles, as

$$\Theta_b = \frac{ZeBL}{\sqrt{2AMT}} \tag{1}$$

$$\Theta_e = \frac{ZeEL}{AMT} \tag{2}$$

where Θ_b and Θ_e are magnetic and electric deflection angles in radians, Z is the charge state of the ion, e is the electronic charge, B is the magnetic field, E is the uniform electric field, L is the length of uniform field region, A is the mass number of the ion, M is the unit nucleon mass based on C^{12}, and T is the kinetic energy of the ion. Combining two Equations (1) and (2) eliminating kinetic energy T, we obtain the well known equation of parabola as

$$\Theta_e = \frac{AMEL}{Ze(BL)^2}\,\Theta_b^2 . \tag{3}$$

In the above equations (1), (2) and (3), the term BL which is the product of the constant magnetic field and length assumed in the calculation, is replaced by the first order corrected value $\int B\,dl = 0.0133$ TM, the numerical integration of measured magnetic field distribution along the axis and the term EL is substituted by the field of an ideal parallel plate capacitor with measured voltage, EL = (18 kV/cm) x 3 cm = 5.4×10^4 V. With these measured values and convenient laboratory units, the Equations (1) and (2) are rewritten for the kinetic energy as

$$T_{[\mathrm{MeV}]} = 8.54 \times 10^3 \frac{Z^2}{A\Theta^2_{b[\mathrm{mrad}]}} \tag{1'}$$

$$T_{[\mathrm{MeV}]} = \frac{27\ Z}{A\Theta_{e[\mathrm{mrad}]}} \tag{2'}$$

From these equations the kinetic energy can be deduced from the parabola by measuring either electric or magnetic deflection. Also equation (3) with the measured values becomes

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$$\Theta_e = 3.164 \frac{A}{Z} \Theta_b^2 \quad (3')$$

where the angles are measured in radians. A family of parabolas of possible values of charge to mass ratios for helium, nitrogen and argon ions are displayed in Figures 3, (a), (b) and (c). Notice that EL = 6 x 10^4 V is used for helium case to be compared with experiment where 20 kV biasing voltage is used.

Results

Each CR-39 plate after etching in NaOH solution shows three sets of parabolic patterns of ion tracks corresponding to r = 5 mm, r = 0, and r = - 5 mm respectively. These three sets of parabolic patterns are almost identical implying that the radial dependence of the beam is very weak. One set of parabolas from each plate is enlarged by using an optical microscope and displayed in Figures 4, (a), (b) and (c). An 1 mm full scale is also enlarged together with the parabola, which corresponds to an angle of 100 mrad, since spacing between the aperture and detector plate is 10 mm. These parabolas are compared with the calculated ones in Figure 3 and are found to be in excellent agreement. The ions shown on the upper most parabolas corresponds to charge to mass ratios of 2/4, 7/14, and 18/40, which are fully stripped ions of helium, nitrogen and argon respectively. Thus it is apparent that virtually all of the ions are in the fully stripped charge state. It should be noted here that the ion species are not identified positively by any other independent method. Thus it is not clear at the moment whether the background impurity ions such as singly charged hydrogen molecule H_2^+ or fully stripped heavy ions formed the parabola since their charge to mass ratios are very close. Nevertheless, a parabola of proton, which can be easily distinguished from others, never has been observed throughout the experiment. This fact appears to support the hypothesis that either CR-39 plastic is insensitive to the protons as is the case for many other track detectors or that no hydrogen ions are dominant in the system.

The end of the parabola tracks near the origin of coordinate corresponds to the ions with peak energy. The peak energy is found by measuring either electric or magnetic deflection from equation (1') or (2'). The result is plotted in the Figure 5 as a function of atomic number Z, which is charge number of ions if the ions were fully stripped. Thus as seen in the Figure 5 the peak energy appears to be proportional to the atomic number Z with a constant, energy per charge of T/Z = 550 keV.

In principle, one can construct an energy spectrum by counting the ion track density along a parabola as a function of deflection angle (either Θ_e or Θ_b). Since the deflection angle is a function of energy as given by equation (1) or (2), the energy spectrum, i.e., the particle density per unit energy as a function of energy can be constructed. Unfortunately the track density in the parabolas in Figure 3 are too dense to count the individual tracks. We find qualitatively, however, by careful inspection of the tracks with a microscope that the track density is higher at near the peak energy than lower energy tail. The total number of ions per shot is estimated from the Faraday cup signal and found to be approximately 10^{11} particles per shot.

Also energy-resolved emittance of the beam can be determined from the same parabolic track patterns. Assuming a cylindrically symmetric beam and no aberration, the normalized emittance[6] is approximated[7] as

$$\varepsilon_n = \beta\gamma a r_o' , \quad (4)$$

where a is the radius of the beam, r_o' is the diverging angle, dr/dz at r = 0, and β = v/c and γ is the ratio of relativistic to rest mass. The diverging angle r_o', in principle, can be determined by measuring width of the track density along the parabola as a function of energy. The full width of any parabola shown in Figure 3 are found to be very close to the size of the pinhole used. Thus detailed emittance analysis can not be obtained from present data. As a figure of merit, however, the maximum possible value of emittance is estimated. The largest width among the parabolas in Figures is found at near the peak energy of He^{++} parabola. The full width is measured to be less than 68 μm and the diameter of the pinhole measured by a microscope is 65 $\pm$ 1 μm. Thus taking diverging angle conservatively as $\bar{r}_o'$ = (1/2)(Full width of tracks - dia. of pinhole)/ separation distance = (1/2)(68 μm - 64 μm)/10 mm = 0.2 mrad., and 4 = 10 cm, γ = 1, β = 0.025 for T = 1.1 MeV helium ions, we find the maximum possible value of nomalized emittance of ε_n = 0.05 cm-mrad., which appears to be very attractive value for conventional accelerator applications.

Conclusions

The fully stripped ions of helium, nitrogen and argon are produced by the pulse powered plasma focus device. An empirical scaling law for peak energy of ion is obtained; the peak energies of ions are proportional to the atomic number of ion species, which is the charge number of the ions if the ions were fully stripped. Thus the higher energy is expected for the heavier ion species. The emittance of beams are extremely small and comparable or better than that of beams used in the conventional accelerators.

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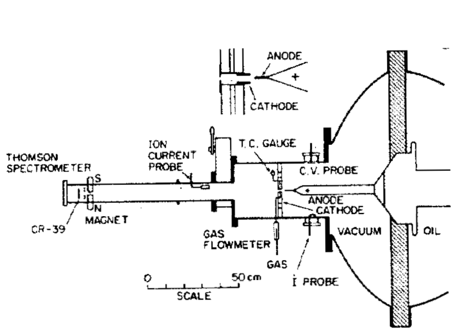


Figure 1. Schematic of experimental configuration.

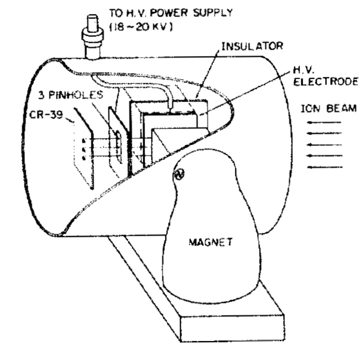
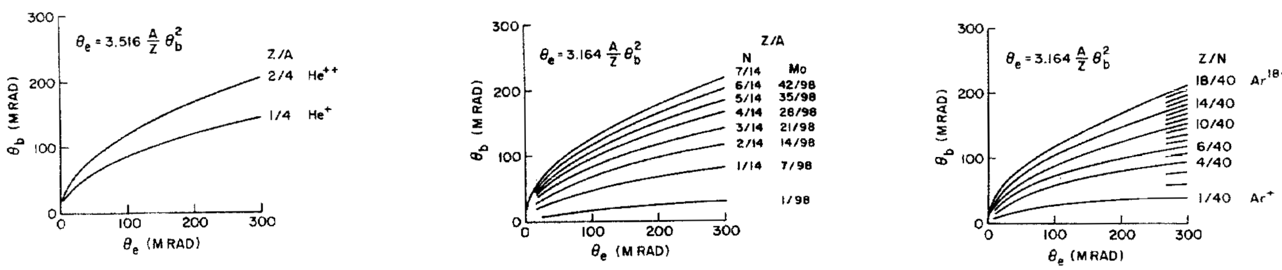
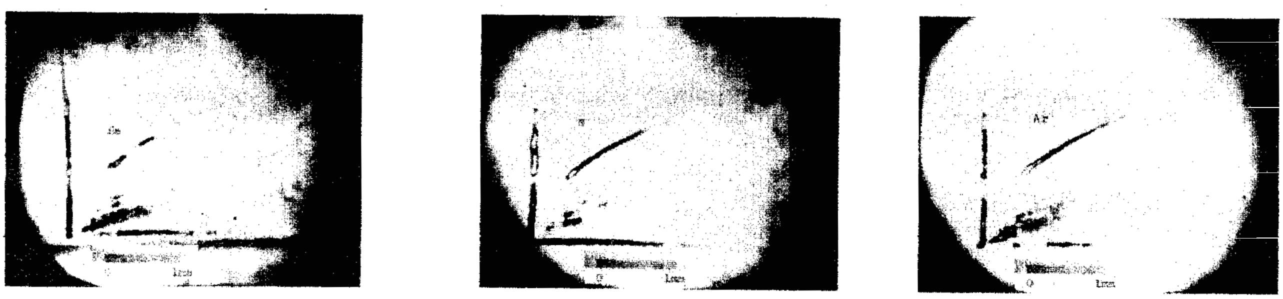


Figure 2. Thomson spectrometer.



(a) (b) (c)

Figure 3. Calculated Thomson parabolas of possible values of Z/A for (a) helium, (b) nitrogen and some of molybdenum (A = 98), and (c) argon ions.



(a) (b) (c)

Figure 4. Enlarged pictures of etched CR-39 plates exposed in the Thomson spectrometer to ion beams of (a) helium, (b) nitrogen, and (c) argon. 1 mm full scale corresponds to 100 mrad.

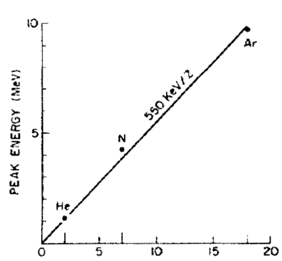


Figure 5. The peak energies measured from the Thomson parabolas, showing an empirical scaling law $T_p = 0.55\ Z$ (MeV).