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COLLECTIVE ION ACCELERATION PRODUCED BY INJECTING A ROTATING RELATIVISTIC ELECTRON BEAM INTO NEUTRAL HYDROGEN

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The use of relativistic electron beams to collectively trap and accelerate protons has been studied by a number of investigators. While protons with energies significantly greater than the electron beam energy have been observed, the total number of protons per pulse recorded is on the order of 10^{11} to 10^{13}. This paper presents preliminary observations that show up to 10^{14} protons, with energies exceeding 450 keV, can be produced when a rotating relativistic electron beam is injected into a metal tube filled with neutral hydrogen gas. In contrast to the experiments of Roberson,[1] in which a similar rotating beam was also observed to produce an enhanced number of accelerated protons (approximately 10^{13} per pulse), these experiments are performed with no external magnetic field applied in the metal drift tube. The equilibrium of the beam is provided by the self-magnetic fields (both axial and azimuthal) and induced wall currents.[2]

One possible acceleration mechanism that is consistent with the experimental observations is the formation of a large potential well at the beam front, and the subsequent trapping of protons from the beam-formed plasma in this well. The beam front ionizes the background gas, but cannot produce a sufficiently dense plasma on a fast enough time scale, particularly at lower fill pressures, to fully charge-neutralize the beam head. This produces an electrostatic well which can be deep enough, and propagate slowly enough to trap a significant number of protons and transport them with the same velocity and direction as the beam front. This mechanism was first proposed by Rostoker[3] and then developed in detail by Olson.[4] The condition generally associated with the formation of a potential well whose depth is comparable to the electron beam energy is that the injected current exceed the space-charge limiting current.[5]

In these experiments, the maximum number of accelerated protons has been observed when the beam front velocity is approximately 0.04 c, which corresponds to an equivalent proton energy of 750 keV. This is less than the applied beam voltage. However, if the protons are trapped in a potential well, one can envisage schemes to accelerate the beam front after it has been loaded with protons. This concept is discussed at the end of this paper.

The experimental apparatus is shown in Fig. 1. The rotating beam is produced by injecting an annular beam (V = 900 kV, I = 80 kA, τ = 100 nsec) through a "half-cusp" magnetic field. The half cusp is formed by means of a solenoidal coil around the carbon cathode, which contains a 15 cm long ferrite cylinder, and a 1.3 cm thick aluminum plate, placed 0.2 cm from the aluminized Mylar foil anode. The aluminum plate excludes magnetic flux during the 400 μsec rise of the magnetic field. Thus, this geometry ensures the magnetic field lines emanate perpendicular to the cathode emission surface, but are diverted radially outwards in the shortest possible distance from the cathode. Measurements show the magnitude of the axial magnetic field decreases from 90% to 10% in an axial distance less than 2 cm. The beam axial velocity component interacts with the magnetic field radial component to impart angular momentum to the electrons.[6] The resulting rotating beam is injected into a 14.6 cm diameter, 50 cm long stainless steel drift tube containing neutral hydrogen. Because the tube is initially field-free, the net flux must always be zero, and the induced axial fields inside, B_{zi}, and outside, B_{zo}, the beam are in opposite directions. The beam equilibrium radius is given by magnetic force balance;

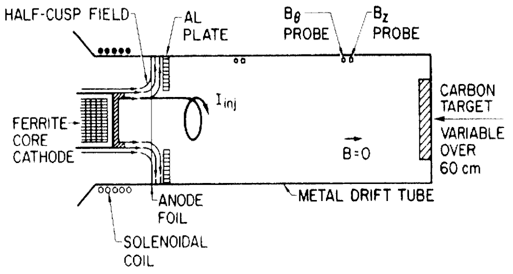

Fig. 1: The experimental apparatus.

$$\frac{B_{zi}^2}{8\pi} = \frac{B_{zo}^2}{8\pi} + \frac{B_\theta^2}{8\pi} \qquad (1)$$

where B_θ is the azimuthal field just outside the beam, and flux conservation;

$$r_b^2 B_{zi} + (r_w^2 - r_b^2) B_{zo} = 0 \ , \qquad (2)$$

where r_b is the beam and r_w the wall radii. (In Eq. 1 the centrifugal force from the beam electrons has been omitted as it has been shown to be unimportant for these high ν/γ beams.[7]) Typically, the injected net current is measured with magnetic probes to be about 75 kA, which is roughly twice the space-charge limiting current (approximately 35 kA) calculated for a hollow beam of these parameters.

The time integrated number of collectively accelerated protons, N_p, is determined from nuclear activation measurements of the $^{12}C(p,\gamma)^{13}N$ reaction.[8] Note that only those protons with energies exceeding 450 kV will be recorded using this technique. N_p is plotted as a function of axial distance from the cusp in Fig. 2, for an initial filling pressure of 150 mT.

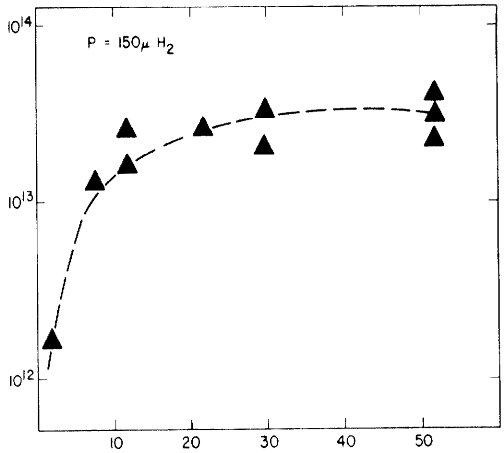

Fig. 2: Time integrated number of protons vs. distance.

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The proton dose increases with distance for the first 15 cm (which is twice the drift tube radius) and then remains constant. The lack of accelerated protons near the cusp indicates that the protons are not being produced in the diode, but rather are generated in the beam-formed plasma. This data is consistent with the notion of a potential well propagating at the beam head, trapping plasma protons until it is insufficiently deep (i.e. the well has "filled up") to overcome the inertia and trap any additional protons swept out by the beam. Measurements show roughly 10% of the accelerated protons are lost radially to the drift tube wall, suggesting that the protons tend to remain localized in the beam channel. The observation of annular beam and plasma profiles with witness plates and framing photography precludes the possibility of a pinched-beam process[9] as the accelerating mechanism, and is again consistent with the picture presented here.

The number of accelerated protons recorded with the target 50 cm from the cusp is shown as a function of fill pressure in Fig. 3a. Proton yields up to 10^{14} are observed at 75 mT fill pressure, whereas an insignificant number was observed at pressures below 25 mT. The beam front velocity, as determined by measuring the difference in the onset of the signal from two B_θ probes separated axially by 50 cm, is shown as a function of pressure in Fig. 3b. At fill pressures below 150 mT, it appears that the axial motion of the beam is retarded electrostatically. The beam cannot propagate further until the plasma density is large enough to overcome a fraction of the beam space-charge, and a large number of beam particles are lost radially outward, as indicated by the observed loss of axial current downstream from the cusp. This lack of space charge-neutralization is anticipated to produce a slow moving, relatively deep potential well, the existence of which is manifested by the relatively large number of protons recorded at these pressures.

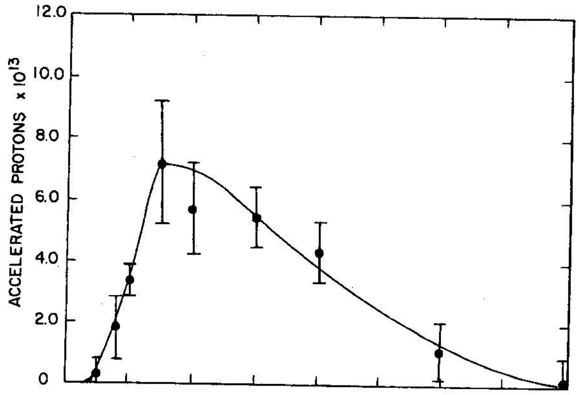

Fig. 3a: (Upper) Time integrated number of protons as a function of fill pressure.

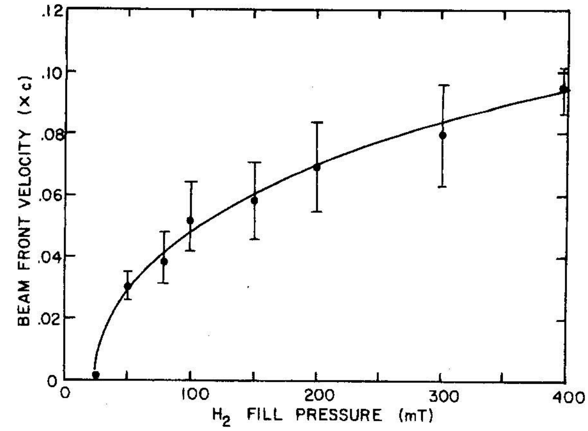

Fig. 3b: (Lower) Beam front velocity as a function of fill pressure.

As the fill pressure is increased, the number of protons decreases. This is to be expected, because at higher fill pressures the plasma density is sufficient to partially charge-neutralize the beam and consequently reduce the depth of the potential well. Furthermore, because of the reduced space charge, the axial motion of the beam is no longer dominated by electrostatic effects. In fact, the axial current is observed to be continuous over the length of the tube. Note that the beam velocity also increases as the pressure is raised. Therefore, it is difficult to say if the reduced number of accelerated protons observed at higher pressures is attributable to the increased beam front velocity, or to the reduced potential well depth, or both.

Preliminary measurements with absorbers placed in front of the carbon target show that, at beam front velocities of 0.04 c (corresponding to proton energies of 750 kV), approximately 60% of the protons have energies between 450 and 700 keV. Copper activation techniques $[^{63}\mathrm{Cu}(p,n)^{63}\mathrm{Zn}]$ under the same conditions show $< 10^{10}$ protons have energies in excess of 4 MeV. These results are consistent with the conjecture that a significant fraction of the total number of observed protons are accelerated to a velocity comparable to that of the beam front.

In Fig. 4, N_p is displayed as a function of the beam front velocity. For reference, the corresponding proton energy is also shown. The vertical line corresponds to the minimum velocity a proton can have in order to exceed the threshold energy necessary to activate the carbon target. This explains the reduction in proton yields at pressures below 75 mT, where $v_b < 0.03$ c (see Fig. 3b). For completeness, note that measurements of N_p for velocities in excess of 0.06 c ($p > 150$ mT) might actually be smaller than indicated due to the enhanced proton yield for carbon activation at energies greater than 1.6 MeV.[8]

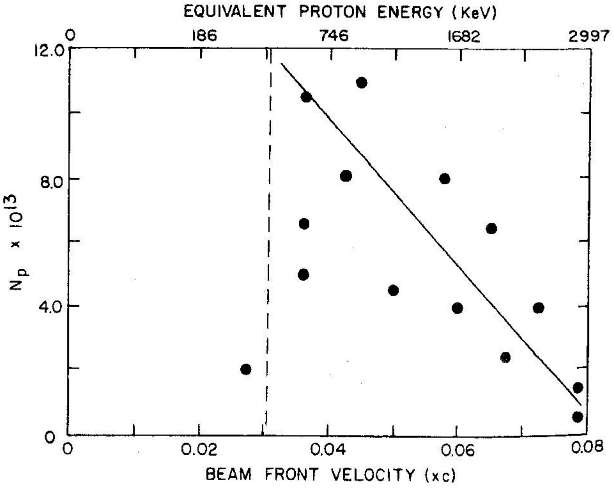

Fig. 4: Proton dose vs. beam front velocity.

It is believed that the relatively large number of accelerated protons observed in this experiment is due primarily to the slow axial velocity of the rotating beam front. If the protons are indeed trapped in a potential well, the velocity of the beam front can, in principle, be increased after the well is "loaded," in order to achieve higher proton energies. The prescription for doing this is provided by a simple model,[7] based on conservation of flux, particles and canonical angular momentum, that describes the propagation of a rotating beam. This model assumes the beam is sufficiently space charge-neutralized ($p > 150$ mT in Fig. 3b) that electrostatic effects are unimportant to the beam dynamics. In this regime, the beam is retarded by the "inductive load" of the induced magnetic fields. By equating the power output of the diode with that necessary to form new magnetic field and beam at a velocity v_b, it has been shown conceptually, and verified experimentally that,

$$v_b \approx \frac{Z}{Lf_m^2}, \qquad (3)$$

where Z is the diode impedance, and f_m is the unneutralized fraction of the diode current ($f_m = 1$ represents net currents equal to the diode current). L is the inductance per unit length of the induced magnetic field configuration, and depends only on the beam current pitch angle, which in turn is a function of the diode current, the magnitude of the cusp magnetic field, and the beam and wall radii. This expression is similar to one obtained by Ecker and Putnam,[10] except that it includes the beam particle energy, and v_b is consequently a factor of two lower. Eq. 3 can be seen to be consistent with Fig. 3b; as the pressure is raised above 150 mT, more of the beam current is neutralized, thereby decreasing f_m and increasing the beam front velocity. The method for accelerating the beam front is suggested by Eq. 3. Assuming this scaling is valid over a broad range of parameters, if a 600 kV, 40 kA, 3.5 cm radius beam produced in a half cusp axial field of 4 kG is injected into a 4.0 cm radius tube, the beam current should acquire a pitch angle of 78°. This corresponds to an inductance per unit length of 14 nh/cm, or from Eq. 3, a beam front velocity of 0.04 c, assuming $f_m = 1$. If the drift tube is allowed to flare out with distance from the cusp to a radius 6 cm (on a sufficiently long scale length so as not to disrupt the potential well) the beam current pitch angle should decrease to 68°. This represents an inductance of $L \sim 5$ nh/cm or a beam front velocity of $v_b \sim 0.11\,c$, corresponding to proton energies in excess of 6 MeV. Such experiments are planned to test this concept.

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References

1) C.W. Roberson, S. Eckhouse, A. Fisher, S. Robertson and N. Rostoker, Phys. Rev. Lett. 36, 1457 (1976).

2) J.D. Sethian, K.A. Gerber, D.N. Spector and A.E. Robson, Phys. Rev. Lett. 36, 1457 (1976).

3) N. Rostoker, Proc. VII Int. Conf. High Energy Accel., Yerevan (1969), p. 509.

4) C. L. Olson, Phys. Fluids 18, 575 (1975).

5) D.C. Straw and R.B. Miller, J. Appl. Phys. 47, 4681 (1976).

6) G. Schmidt, Phys. Fluids 5, 994 (1962).

7) J.D. Sethian, K.A. Gerber, D.N. Spector and A.E. Robson, to be published.

8) F.C. Young, J. Golden, C.A. Kapetanakos, Rev. Sci. Instrum. 48, 432 (1977).

9) S. Putnam, Phys. Rev. Lett. 25, 1129 (1970).

10) B. Ecker and S. Putnam, IEEE Trans. Nucl. Sci. NS-24, p. 1665 (1977).