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A NEW COLLECTIVE EFFECT, HIGH FLUX ION ACCELERATOR

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Summary

A new type of accelerator capable of producing a large flux of medium energy ions is discussed. The accelerator contains a charge neutral plasma in a magnetic field. Electron currents parallel to $\vec{B}$ heat the plasma electrons to an average energy kT_e by the Joule process. The electrons try to escape from the plasma into an adjacent vacuum region along the magnetic field lines. In doing so they create a charge separation electric field which collectively accelerates the ions to energies $\gtrsim 10\ kT_e$. The large resistivity necessary to obtain both the rapid heating and impedance matching to high power sources results from electron streaming instabilities in the plasma. Feasibility is investigated using a one dimensional, time dependent fluid model. In this model a realistic circuit is coupled to the plasma electrons. The resultant plasma heating and expansion are numerically followed in time and space. These calculations seem to imply that present day technology utilizing high voltage Blumlein transmission lines ($Z \approx 1\Omega$) seem capable of creating a 10 MeV proton stream with energy >10 kJ, and equivalent current density $>10\ \mathrm{kA/cm^2}$.

Introduction

We describe here an accelerator concept capable of producing a high flux ($10^4\ \mathrm{A/cm^2}$) of medium energy ions (10^5 to 10^7 eV). The physical principle involved is similar to the electron ring accelerator method of ion acceleration in so much as high velocity electrons are used to accelerate ions to a high energy. In this case though the entire system is charge neutral with equal electron and ion densities, $n \approx 10^{14}\ \mathrm{cm^{-3}}$. In order to understand the acceleration process consider a box containing a plasma with hot electrons having a temperature T_e and cold ions, with charge Z and mass m_i. The box is placed in a vacuum. If one wall of the box is suddenly removed the energetic electrons try to leave first. In doing so they create a charge separation electric field which accelerates the ions and deaccelerates the electrons so that the entire system expands at a few times the ion acoustic speed, $C = \sqrt{ZT_e/m_i}$. A kinetic theory describing the time evolution of the ion velocity distribution function[1] and results of a computer simulation[2] of the basic process have appeared in the literature.

To achieve ion expansion energies of 10 MeV or more the electron temperature must be within an order of magnitude of this value and consequently the plasma in a box scheme is a physical impossibility. The same effect is achieved however by rapidly heating the plasma before it can expand significantly. A unidirectional expansion is obtained with the use of a magnetic guide field. Rapid heating requires high power energy delivery and deposition in the plasma. A schematic diagram of how this may be accomplished is shown in Fig. 1. A high voltage transmission supplies power to a small stabilized Z pinch. The resulting current flow heats the plasma by the Joule process and the hot plasma expands along magnetic field lines through one of the electrodes. Both the impedance matching implicit in high power delivery and the necessary rate of deposition are obtained by exciting microinstabilities in the plasma which increase the plasma resistivity above the stable, equilibrium value.

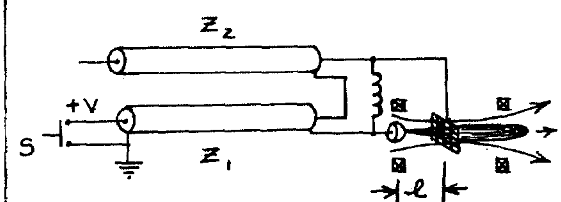

Fig. 1 Schematic electrical diagram of an expanding plasma source energized by a Blumlein circuit. The plasma is shown passing through a grid electrode on the right along a magnetic guide field.

Plasma Instabilities

Streaming Instabilities.

The applied electric field causes the plasma electrons to drift with respect to the ions. If the drift velocity exceeds the electron thermal velocity energy is transferred from the drift motion to electron plasma waves.[3] The wave energy is eventually damped out resulting in heated electrons. The growth rate for this instability is of the order of a percent of the electron plasma frequency; i.e., $\gamma \approx 10^{-2}\omega_{pe}$, where $\omega_{pe} = \sqrt{4\pi ne^2/m_e}$. For our purposes, this is a microscopic time scale. In macroscopic terms the electron drift momentum is dissipated in accordance with the usual concept of Joule heating, although at a higher effective collision frequency. As the electron temperature rises the electron drift velocity may fall below the thermal speed and this instability shuts off. If $T_e >> T_i$ and the drift velocity is greater than the ion acoustic speed $\sqrt{T_e/m_i}$ ion acoustic waves are excited.[4] This is also a rapidly growing instability which heats electrons at the expense of the flow kinetic energy which is driven by the applied electric field. The net result of either instability is to produce a plasma resistivity[5] which falls in the range (CGS units)

$$.01\ \omega_{pe}^{-1} < \eta < 0.1\ \omega_{pe}^{-1}\ . \tag{1}$$

For the temperatures and densities needed here this is orders of magnitude larger than the resistivity of a stable plasma.

Ion acceleration effects also exist as a result of the ion acoustic instability. Some ions may be trapped in the electrostatic potential well of the waves. The effect of this is to produce high energy tails on the ion velocity distribution.[6] The density of these ions would be a small fraction of the total density and hence is not considered here.

Ions may also be accelerated by the applied electric field, i.e., on the IR drop along the plasma column. For the situation considered here the voltage pulse is on for 50 ns and during this time few of the ions leave the accelerator.

MHD Instabilities.

A high current discharge is subject to MHD instabilities.[7] For a cylindrical plasma column the displacement of a fluid element grows as $f(r)\exp(i(\omega t + kz + m\theta))$. If there is no axial magnetic field B_z parallel to the current stream perturbations grow with m=0 (sausage) and m=1 (kink). In the limit that all current flows on the surface of the column it is possible to stabilize these modes for a column of length ℓ and radius r if the ratio of current generated magnetic field B_θ to applied axial field is less than $(B_\theta/B_z) < 2\pi r/\ell$.

Technology

Dielectric properties of useful materials put a limit of about 10^{13} Watts on the high power delivery systems presently employed in pulsed electron accelerators. The highest voltage lines can hold off voltages of about 10 MV and have impedance of about 10 Ω. Lower impedance sources are restricted to lower voltages. A representative number here is 1.0 MV and 1.0 Ω.

Application of a resistivity in the middle of the range implied by equation (1) to a cylindrical plasma column of radius r cm, length ℓ cm and electron density n cm^{-3} gives a plasma resistance of

$$R = 2.5 \times 10^6 (\ell/n^{1/2}r^2)\ \text{Ohms}. \tag{2}$$

A practical high voltage system will have a load inductance L of 50 nH or more. In order to keep the L/Z time sufficiently small (e.g. $\lesssim$50 ns) a lower limit on the useful total resistance is 1 Ω. Maximum power transfer from a given source makes it necessary for the plasma and source impedance to be equal, hence $Z = R \gtrsim 0.5\ \Omega$.

In order to prevent MHD instabilities an axial magnetic field must be applied. An upper limit for this field is about 10 T. For $B_\theta = \mu I/2\pi r \lesssim 10$ T a lower limit is implied for the column radius for a given current or voltage.

Finally for the required microinstability to develop and produce the high resistivity the plasma length should be sufficiently long that an electron does not drift out of the plasma column before the instability has had sufficient time to develop,[8] i.e., $v \lesssim \ell\gamma/5$, where γ is the instability growth rate. Since $I = nev\,\pi r^2$ this can be expressed as (using $\gamma \simeq 10^{-2}\omega_{pe}$)

$$\ell > 1.710^6 I_{AMP}/n^{3/2}r^2\ . \tag{3}$$

All of these conditions can be satisfied for a reasonable range of parameters.

Expansion Calculations

In order for this scheme to work the energy delivery rate, rate of dissipation and the expansion velocities must be such that with realizable parameters the plasma can be heated to sufficient temperatures before most of the plasma expands out of the region between the electrodes. In a first attempt at seeing if this is possible we have performed time dependent calculations on a model in which the plasma is represented by a one dimensional fluid. The fluid equations used are:[9]

the equation of continuity

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nv) = 0\ , \tag{4}$$

the momentum equation

$$nm_i\left(\frac{\partial v}{\partial t} + v\,\frac{\partial v}{\partial x}\right) = -\,\frac{\partial P_e}{\partial x}\ , \tag{5}$$

the heat equation,

$$\frac{3}{2}\,n\left(\frac{\partial T_e}{\partial t} + v\,\frac{\partial T_e}{\partial x}\right) + nT_e\,\frac{\partial v}{\partial x} = j^2\eta \tag{6}$$

and the equation of state

$$P_e = n_e T_e\ . \tag{7}$$

One should be aware that this is really a two fluid model, one for electrons and one for ions. In arriving at equation (5) we have neglected ion pressure, which is consistent with equation (6) where we consider only the electrons to be heated, and in addition we have neglected electron inertia. To see this we could have written the electron fluid momentum equation as

$$nm_e\left(\frac{\partial v}{\partial t} + v\,\frac{\partial v}{\partial x}\right) = -neE - \frac{\partial P_e}{\partial x}\ . \tag{8}$$

In the limit that $m_e \to 0$ one sees that the electric field that accelerates the ions is given by the electron pressure gradient

$$E = -\,\frac{1}{ne}\,\frac{\partial P_e}{\partial x}\ . \tag{9}$$

Equation (5) is then obtained by using this electric field in the ion momentum equation.

The current density $j \equiv I/\pi r^2$ in the energy equation is obtained from a circuit equation

$$V_0 = I(R + Z_0) + L\,\frac{dI}{dt}\ , \tag{10}$$

where V_0 is the source voltage, Z_0 the source impedance, L the load inductance ($\simeq$50 nH) and R is determined by equation (2).

The spatial coordinates are represented by a grid of 100 evenly spaced points. The plasma is initially localized between the two electrodes taken at x=0 and x=ℓ. At t=0 the voltage is turned on and current starts to flow and heat the plasma. The resulting time and space development of equations

(4) - (10) are integrated forward in time using the Flux Corrected Transport algorithm.[10]

The results of some sample calculations are shown in Fig. 2. In these calculations a (Z_0 =) 1 Ω transmission line applies a voltage of 600 kV for 50 ns to a hydrogen plasma. Two different size cylindrical plasma columns are considered, one with ℓ = 20 cm and r = 0.5 cm and another with ℓ = 40 cm and r = 0.71 cm. Initially at t=0 the electron and ion densities are equal to $4 \times 10^{14} cm^{-3}$ from x=0 to x=ℓ. In order to simulate an electrode at x=0 the plasma is maintained at its initial temperature of 10 eV at x=0. In Fig. 2 we show the density profile at t = 100 ns. At this time the current has almost completely decayed away so that no further heating occurs. It is apparent that a much larger density drop has occurred in the 20 cm long plasma than in the 40 cm one. For this set of circuit parameters and electron density an optimum coupling to the plasma takes place for 20 cm < ℓ < 40 cm. For this voltage and density a maximum proton energy of about 4.0 MeV is obtained. Applied voltages of about 1.0 MV seem possible leading to ion energies of about 10 MeV. For different electron densities but otherwise the same conditions the rise of temperature is at a different rate and consequently the expansion velocities are different leading to a different requirement for ℓ. Several different tradeoffs seem possible to shape the output pulse of particles in both particle flux and the energy spectrum.

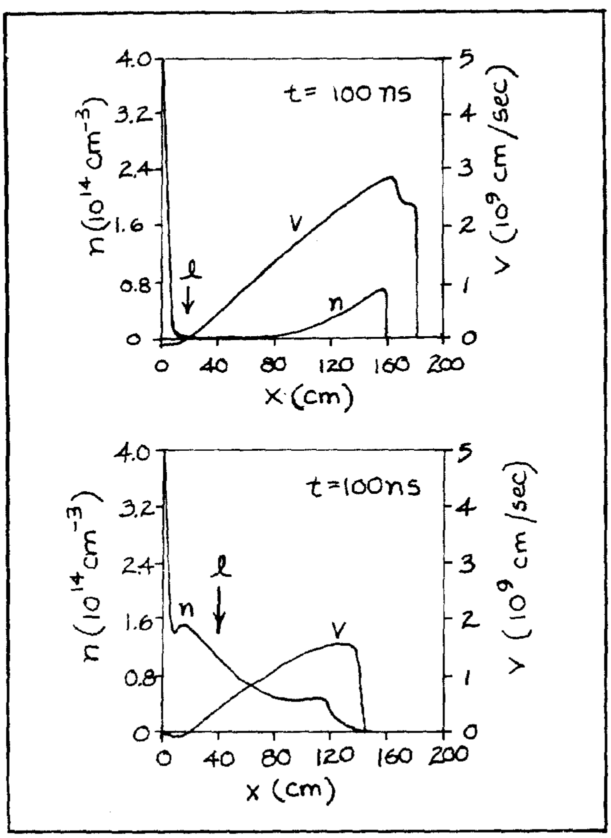

Fig. 2 Hydrogen plasma flow fields at 100 ns that result from applying a 50 ns, 600 kV voltage pulse to a 20 cm long and 0.5 cm radius plasma (top) and to a 40 cm long and 0.71 cm radius (bottom) plasma with a density of $4 \times 10^{14} cm^{-3}$. The source had Z_0= 1Ω and L = 50 nH.

For some applications it may be desirable to produce a lower particle energy pulse than that shown in Fig. 2. Since the resultant flow energy depends on the electron temperature and from equation (6) we see that $\Delta T_e \approx j^2 n\Delta t/n$ there are several possibilities to vary T_e. By simply increasing the particle density by an order of magnitude the flow energy per particle will be reduced by an order of magnitude. This however reduces the skin depth to the point that uniform heating is not guaranteed a priori. A simpler approach is to reduce the applied voltage. In Figure 3 we show results for the same geometry as before but with the applied source voltage maintained at 300 kV. The lower voltage gives peak proton energies of 1 MeV and 320 keV for the 20 cm and 40 cm length plasmas respectively.

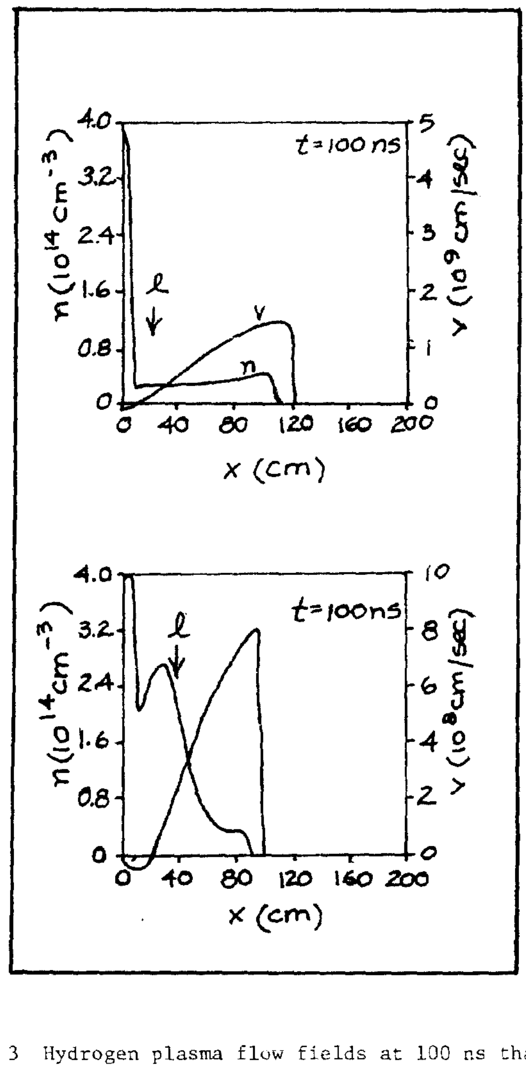

Fig. 3 Hydrogen plasma flow fields at 100 ns that result from applying a 50 ns, 300 kV voltage pulse to a 20 cm long and 0.5 cm radius plasma (top) and to a 40 cm long and 0.71 cm radius (bottom) plasma with a density of $4 \times 10^{14} cm^{-3}$. The source had Z_0 = 1Ω and L = 50 nH.

At the highest particle energies the simple nonrelativistic fluid model presented here probably does not adequately give all the details of the expansion. Other effects such as radial motion, thermal conduction, radiation losses and the magnetic field should all properly be taken into account. The necessity for improvements awaits comparison of this simplified model with experimental results.

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