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AN INTENSE PULSED NEUTRON AND KILOVOLT X-RAY SOURCE

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by

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Recent generator and diode development work has shown the feasibility of constructing electron beam accelerators with several hundred kilojoules of beam energy (Reference 1). One such design would employ a large annular cathode, a design particularly convenient for collective accelerations of ions. This report describes a technique for plasma heating using collectively accelerated deuterium ions. An important aspect of the scheme is that it utilizes only reported experimental results both for ion production efficiency and plasma parameters. Any optimization of ion fluxes generated by the electron beams would, of course, increase the efficiency of the system. In view of the small effort in this area to date, it is reasonable to assume that further experimental investigations directed toward understanding the collective ion acceleration process will lead to higher efficiencies. This plasma heating technique must ultimately be compared, for practical purposes, with efficiencies of plasma heating using high power CO_2 lasers or the electrons themselves.

A 300 kJ electron beam accelerator, for example, can be used in a low pressure neutral gas mode to accelerate deuterons to energies of 2 MeV. With many small copper pipes emanating from magnetically isolated cathodes, evenly spaced around an annular ring, we can assume generation of 10^{14} deuterons/76 kA with 500 keV electrons or 10^{14} deuterons/100 kA for 1 MeV electrons. These numbers are obtained from published data for ion production using $\nu/\gamma \cong 2$ as the criterion for reproducible deuteron energy from each pipe accelerating channel (Reference 2). Thus, a 1 MeV machine could be expected to produce 1.92 kJ of deuteron energy and a 500 keV machine could produce 5.06 kJ.

We can argue the above experimentally reported deuteron numbers from simple physics, somewhat independently of the acceleration mechanism. The number of acceleration ions, N_i, can be estimated from

$$N_i = n_b \bar{f}_e \pi a_o^2 L \tag{1}$$

where

n_b = electron beam density

$\bar{f}_e$ = fractional electrical neutralization of the ion bunch

a_o = average beam radius

L = bunch length at the start of acceleration

For 2 MeV deuterons, β_L^{ion}, the maximum ion velocity/c is $\approx 4.6 \times 10^{-2}$. During acceleration (in the case where the beam front and ion bunch are coincident), $\beta_L^e \lesssim \beta_L^{ion}$, where β_L^e refers to the electron streaming velocity. From Equation 1,

$$N_{ion} \geqslant 4.5 \times 10^9 \bar{f}_e L I_b \text{ (A)} \tag{2}$$

where

I_b = beam current

If $I_b = 7.8 \times 10^4$, $N_{ion} \geqslant 3.5 \times 10^{14} \bar{f}_e L$. We know that $\bar{f}_e$ exceeds $1/\gamma^2$, let us take $\bar{f}_e \approx 2/\gamma^2$. Then for 500 keV electrons,

$$N_{ion} \gtrsim 1.8 \times 10^{14} L \tag{3}$$

The bunch length, L, should be of the order of the beam radius ($\sim$ 1 cm). The ion number could be doubled if the beam pulse were long enough to accelerate two ion bunches. These simple arguments imply the perhaps obvious conclusion that higher ion numbers are obtainable from higher-current, lower-energy electron beams. Also, the estimate suggests that if desired ion energies are not too high, we can use higher currents per accelerating pipe (and therefore fewer pipes) without degrading the number of accelerated ions. The current value per pipe above was chosen to stay within experimentally verified parameters.

The individual pipes are to be geometrically focused toward the heated plasma region with or without an intermediate transport system such as a linear pinch. The ion bunches and electron beamlets would be transported at first within the pipes until the pipes converged to contact and then would be transported simply in a large tapered drift chamber. A tapered linear pinch could be used for additional focusing as a final stage before plasma injection.

As an example of an application for this intense ion source to plasma heating and neutron production, we consider a readily obtainable plasma which possesses many desirable features for ion injection--the dense plasma focus (DPF). The magnetic field configuration of the DFP increases the ion aperture up to several centimeters, and contains a 10^{19} to $10^{20}/cm^3$ density plasma at a few kiloelectron volts over containment times from 50 to 100 nsec. Some experiments are already underway using electrons to heat the focus plasma, (Reference 3), but there are two serious problems in using electrons rather than ions. Perhaps the main difficulty with electrons is injection. The 2 MG or so magnetic field containing the plasma reflects all but a small fraction of the electrons along the axis if the electrons are directed toward the anode from the exterior. If the electrons are injected through a hole in the anode, the field defocuses the electrons. Secondly, the electron energy deposition range at 1 MeV is $\gtrsim$ 10 meters, and collective enhancement of energy deposition does not appear to be significant with these plasma parameters unless the beam has a very small velocity spread. The velocity spread criterion for electron-electron instability modes (the Singhaus criterion) would refer to transported electrons entering the plasma focus at any one time. In view of the defocusing effect of the DPF magnetic field for anode interior injection, it appears difficult to argue a small velocity spread in the plasma, even if a sufficiently cold beam were injected (Reference 4).*

In contrast to electrons, the 2 MeV deuterons have a range of $\lesssim$ 4 cm in a $10^{20}/cm^3$, 1 to 10 keV plasma, and can be focused by the 2 MG magnetic field if injected through a hole in the anode. (The Larmor radius, ~ 1.4 mm, is the approximate radius of focal plasma.) Thus eight to nine radial oscillations of the deuterons in the (typical) ~ 1.5 cm length of the focal cylinder will deposit all their energy. Both the ion energy and specie can be altered, using this scheme, to achieve complete energy deposition within the plasma region for varying plasma parameters; in fact, the ions themselves can be used as a diagnostic tool to characterize the focal plasma and "tune" the system.

Approximately one-tenth of the injected ion energy, or 190 to 500 joules, will be directly transferred to the plasma

*Collective enhancement of electron energy deposition is suggested as a plausible explanation for observed neutron enhancement with electron beam injection inside the anode.

ions, and if the plasma containment time is ~ 100 nsec, an additional one-third or more of the ion energy can be transferred via electrons. So it does not appear unreasonable to expect that over ~ 60 nsec about a kilojoule or so will be transferred to the ions. A tenfold increase in the ion temperature could be attained with a DPF having a focal plasma energy of 100 joules and the 14 MeV neutron production rate in a DT plasma would be multiplied by a factor of 10^3.

A simpler scheme for X-ray production is, of course, to seed the plasma with higher Z ions to enhance radiation, in which case we can at least expect all of the injected ion energy to be radiated. In this case we could vary the ion pulse width up to 100 nsec or so by small variations in the ion energy, produced by altering the acceleration length in some of the pipes.

Ions from a 300 kJ pulser thus offer the possibility of providing several kilojoules of X-ray energy and an intense neutron source. The estimates above assume a 1 percent electron beam-ion energy transfer which may be improved by a better understanding of the acceleration process. Numerical calculations of the effective ion aperture of the DPF magnetic field are warranted as part of a feasibility study.

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