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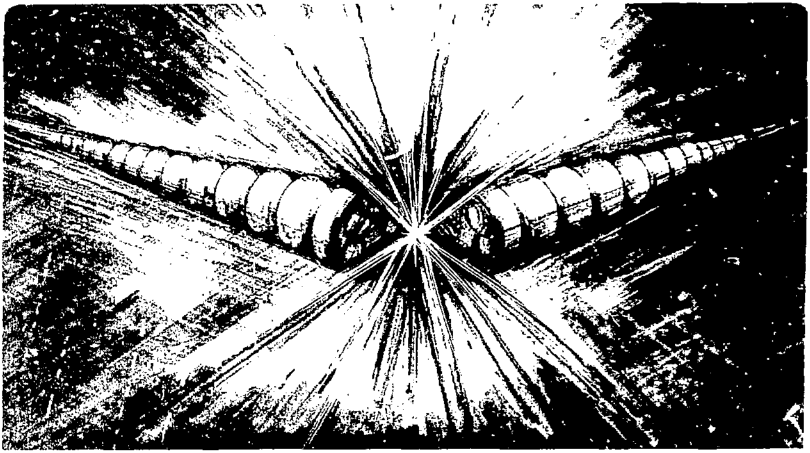

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Plasma Neutralizers for H^- or D^- Beams*

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Abstract

Plasma neutralizers can produce higher conversion efficiencies than are obtainable with gas neutralizers for the production of high-energy neutral beams from negative hydrogen ions. Little attention has been paid to experimental neutralizer studies because of the more critical problems connected with the development of negative-ion sources. With the prospect of accelerating ampere dc beams from extrapolatable ion sources some time next year, we are re-examining plasma neutralizers. Some basic considerations, two introductory experiments, and a next-step experiment are described.

Introduction

The injection of energetic deuterium atoms is a proven technique for heating magnetically confined plasmas in the fusion program. Currently, multi-megawatt hydrogen and deuterium beams with energies up to 50 keV are used, and planned experiments call for about 50 MW of neutral-beam power at energies above 150 keV. At these power levels there is a high premium on maximizing the efficiency for producing neutral beams.

It has been recognized for a long time that the weak electron affinity (0.75eV) of a negative hydrogen or deuterium ion, compared to the binding energy of the electron in a ground-state hydrogen atom (13.6eV), makes efficient conversion of an H^- ion beam to a neutral beam possible even at high energies. In a gas target of optimized thickness the neutralization efficiency can be about 60 percent even for MeV ions.[1]

Riviere and Sweetman[1] showed that the conversion of an H^- or D^- beam to an H^0 or D^0 beam can be considerably more efficient if the target consists of charged particles, i.e., a plasma. A neutralization efficiency, η, of 90% was calculated from cross sections obtained from single-particle interactions in H^-–e^- crossed beam experiments. At Novosibirsk, approximately this conversion efficiency was obtained by shooting lithium and magnesium plasmas from conical plasma guns across a 0.5-to 1.0-MeV H^- beam and measuring the growth and decay of the various charge components.[2,3] Values of η=81% for Li and 80% for magnesium were obtained. We are not aware of any other measurements with plasma targets. Some additional information on this topic was given in a paper by Grossman at the first Symposium in 1977.[4]

If they are to be useful, plasma neutralizers must give substantially higher conversion efficiencies than gas cells; also, they must operate dc and have good electrical and gas efficiencies, as well as suitable geometrical configurations. Neutralizer efficiency has not received much attention in the negative-ion system program because the development of negative-ion sources has been, and continues to be, the critical item. As shown in other papers in this symposium, the progress in source development is quite encouraging, and, as ion sources, accelerators, and neutralizers must be compatible, we are re-examining the plasma-neutralizer topic, including a modest experimental effort in the 200-to-300-keV range.

We are investigating two types of plasma neutralizers with a D^- beam from a small research accelerator: One is a high-density, pulsed hydrogen discharge; the other is a low-density cesium plasma produced in a surface-ionization Q-machine. In this paper we present calculations for the neutralization efficiency expected for partially ionized hydrogen and cesium plasmas. The two plasma targets are described, as is a possible next-step experiment. Neutralization results for the two targets are not yet available.

Computations

We have examined several cases of interest for negative-ion-beam plasma neutralizers. The evolution of the beam fractions is given by equations (1) thru (3).

$$\frac{dI^0}{dX} = I^+\sum_s \sigma^s_{+0} n_s + I^-\sum_s \sigma^s_{-0} n_s - I_0 \sum_s (\sigma^s_{0+} + \sigma^s_{0-}) n_s \qquad (1)$$

$$\frac{dI^+}{dX} = -I^+\sum_s (\sigma^s_{+0} + \sigma^s_{+-}) n_s + I^-\sum_s \sigma^s_{-+} n_s + I^0 \sum_s \sigma^s_{0+} n_s \qquad (2)$$

$$\frac{dI^-}{dX} = I^+\sum_s \sigma^s_{+-} n_s - I^-\sum_s (\sigma^s_{-0} + \sigma^s_{-+}) n_s + I^0 \sum_s \sigma^s_{0-} n_s \qquad (3)$$

Where

$$\sum_s \sigma_{ij}^{s} n_s = \sigma_{ij}^{s} n_e + \sigma_{ij}^{i} n_i + \sigma_{ij}^{g} n_g$$

and $I^- + I^+ + I^0 = 1$

where the subscripts i and j refer to initial and final charge states, respectively, and the superscripts e,i,g refer to electrons, ions, and atoms, respectively. For incident D^-, $I^-(0)=1$.

Not all of the cross sections are known; we present the experimentally known or theoretically estimated cross sections relevant for hydrogen and cesium plasmas in Fig. 1 (Refs. 5-13) and Fig. 2 (Refs. 5-7, 13-16). Excellent review articles covering the cross-section data are in Refs. 17 and 18. At the high energies of interest (E > 200 keV) we assume we can neglect all attachment cross sections.

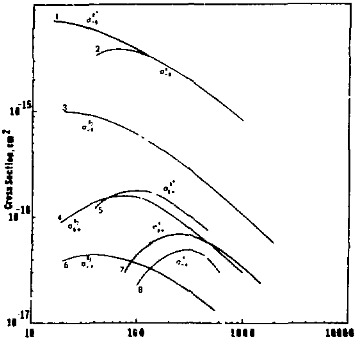

Fig. 1. Cross sections relevant to deuterium plasma neutralizers. Curve 1, Ref. 5; 2, Refs. 6, 7; 3, Ref. 8; 4, Refs. 9, 10; 5, Refs. 11, 12; 6, Ref. 8; 7, Ref. 13; 8, Ref. 14.

We further assume that all target particles are at rest in the laboratory frame. This assumption is valid if the beam velocity is very much greater than electron thermal velocities. For 200 keV D^- this requires that the electron temperature be less than about 5 eV.

For plasma neutralizers we always have $n_e = n_i$. We can then define the degree of ionization as

$$\chi = \frac{n_i}{n_i + n_g}$$

χ equals one for a fully ionized plasma and χ equals zero for a neutral gas target.

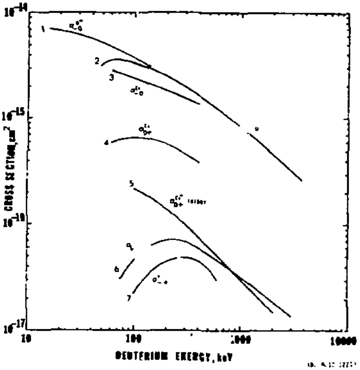

Fig. 2. Cross sections relevant to cesium plasma neutralizers. Curve 1, Ref. 5. (σ^{Cs^+} is taken to be equal σ^{H^+} for the purpose of the computations); 2, Refs. 6, 7; 3, Ref. 15; 4, Ref. 15; 5, Ref. 16; 6, Ref. 13; 7, Ref. 14.

Equations (1) – (3) can be integrated analytically. For a homogeneous plasma containing several constituents the maximum neutralization efficiency is

$$\eta_{max} = \frac{\langle\sigma_{-0}\rangle}{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle} \left(\frac{\langle\sigma_{0+}\rangle}{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle} \right)^{\frac{\langle\sigma_{0+}\rangle}{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle - \langle\sigma_{0+}\rangle}} \qquad (4)$$

The total integrated line density to achieve the maximum neutralization efficiency is

$$\Pi_{opt} = \frac{1}{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle - \langle\sigma_{0+}\rangle} \ln \left(\frac{\langle\sigma_{-0}\rangle + \langle\sigma_{-+}\rangle}{\langle\sigma_{0+}\rangle} \right) \qquad (5)$$

In equations (4) and (5) we have

$\langle\sigma_{ij}\rangle = \sum_s \sigma_{ij}^{s} n_s / n_{tot}$ and $n_{tot} = \sum_s n_s$,

and, the total target thickness is

$$\pi \equiv \sum_s \int_0^{\ell} n_s \, dx.$$

To illustrate the advantage of a plasma target on the neutralization efficiency for D^- beams, we have solved eqs, 1-3 for plasmas with different degrees of ionization for 300 keV D^-. In Fig. 3 we show the neutralization efficiency η (for negative ion beams, $\eta = I^0$) for a deuteruim plasma.

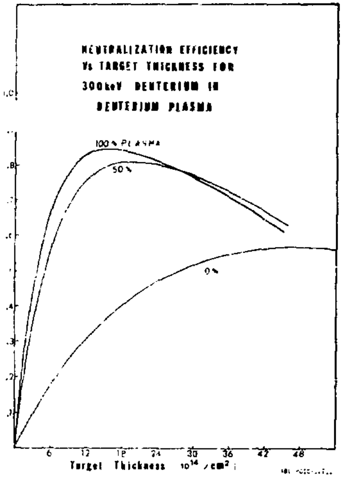

Fig. 3. Neutralization efficiency versus total (electrons and ions and neutrals) target thickness for 300 keV deuterium in a deuerium plasma of various degress of ionization.

We see that the optimum line density (molecules/cm^2) of D_2 gas is about 3 times the optimum line density $(n_e+n_i)\,\ell$, of a fully ionized deuterium plasma. In an actual system there will be some neutral gas in the beamline and the maximum conversion exificiency is expected to be between that for pure gas and pure plasma.

The efficiency for D^- in a cesium plasma is shown in figure 4. It is interesting to note that the optimum line density for cesium vapor is about 50 % less than the optimum line density $(n_i+n_e)\,\ell$ for a fully ionized cesium plasma.

In figure 5 we show the maximum neutralization efficiency as a function of degree of ionization for 300 keV D^- in cesium and deuterium plasmas. We see that the neutralization efficiency for deuterium plasma is fairly high even at low degrees of ionization whereas for cesium plasmas the efficiency rises approximately linearly with the degree of ionization.

Real plasma neutralizers based on deuterium will have a mixture of D^+, D_2^+ and D_3^+. However, we do not have sufficient cross section information to evaluate the effects of molecular ions on neutralizer efficiency.

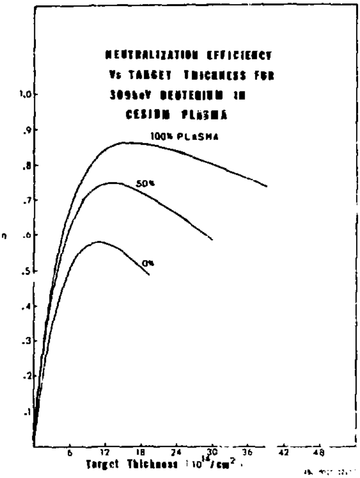

Fig. 4. Neutralization efficiency versus total (electrons and ions and neutrals) target thickness for 300 keV deuterium in a cesium plasma of various degrees of ionization.

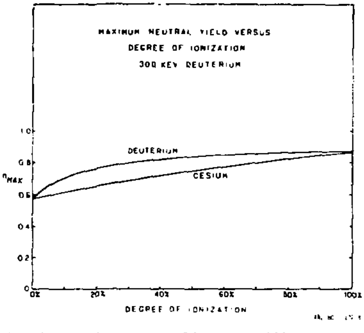

Fig. 5. Maximum neutralization efficiency versus degree of ionization for deuterium and cesium plasmas.

Experimental Program

Hydrogen plasma target

Shown in figure 6 is a plan view of the hydrogen-plasma-target vacuum chamber. D^-

ions from a 300 keV accelerator are steered into the collision chamber and pass through a magnetically confined plasma produced by a hot-cathode (LaB_6) discharge. Gas is pulsed through the anode into the evacuated chamber. The 100 A discharge is pulsed, 1 msec in duration, creating a highly ionized hydrogen plasma, 2 cm X 10 cm in cross section, with a maximum electron line density of 10^{15} cm^{-2} (measured by a movable Langmuir probe and a He-Ne laser interferometer). The measured line density is shown in Fig. 7 as a function of discharge current and magnetic field. The resulting charged and neutral particles then pass between electrostatic analyzing plates and into an analysis chamber. Each charge-state component of the beam is detected and counted separately by an array of diffuse-junction Si detectors and electronic pulse counting equipment. The neutral beam fraction as a function of target thickness is curve fitted to produce an estimate for the maximum neutralization efficiency.

This experiment is operating, but no quotable results have been obtained yet. We also plan to try an atomic-gas, probably argon, target.

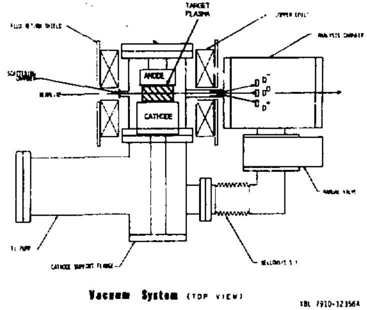

Fig. 6. Experimental arrangement for determination of η_{max} in a hydrogen plasma target.

Cesium plasma target

The cesium plasma target is shown in figure 8. The plasma is a standard Q-Machine plasma originally built for studies of cross sections relevant to heavy-ion fusion. The plasma is formed by spraying cesium vapor on a hot (2700 K) tungsten plate and the contact ionized plasma is confined by an axial magnetic field (B=0.2T). Plasma densities, as measured by Langmuir probes, are variable and are typically 10^{10} cm^{-3}. The diameter of the plasma column is approximately 5 cm. A plasma density profile is shown in Fig. 9. The line density is too small to produce optimum yields and therefore only σ_{-0} and σ_{0+} will be measured. The ambient background pressure is approximately 10^{-6} Torr. Therefore, a plasma chopper is used to separate plasma effects from background gas effects. The vacuum chamber is cooled by liquid nitrogen to keep the cesium atom density below 10^7 cm^{-3}. The incident D^- beam enters the target region and charged beam particles formed in the plasma are charge-state analyzed in the confining magnetic field. The beams then enter the analysis chamber and will be counted to determine the D^-, D^0 and D^+ fractions. Cross sections are determined from the slope of the D^-, D^0 and D^+ fractions as a function of plasma line density.

This experiment will be performed after the present heavy-ion-fusion-related experiment (C_S^+-C_S^+ cross sections) is completed.

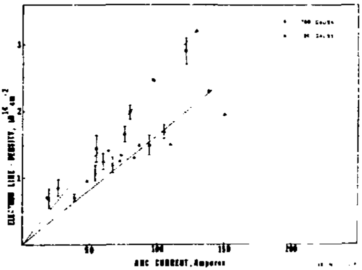

Fig. 7. Electron line density versus arc power for the hydrogen plasma target.

"Practical" plasma target

The experiments described in sections 1 and 2 will yield cross-section information, but the plasma configurations are not suitable for application in practical high-power neutral beam lines. Therefore, our next experimental target will be designed to be compatible with our approach to a multi ampere negative ion accelerator array. We are considering a "magnetic-bucket" arrangement of the general kind described by Ehlers and Leung.[19,20] They have operated a hydrogen discharge in such an arrangement with 10% ionization and ion densities of 2-3x$10^{12}$$cm^{-3}$. Ionization fractions of 0.15-0.20 may be possible.

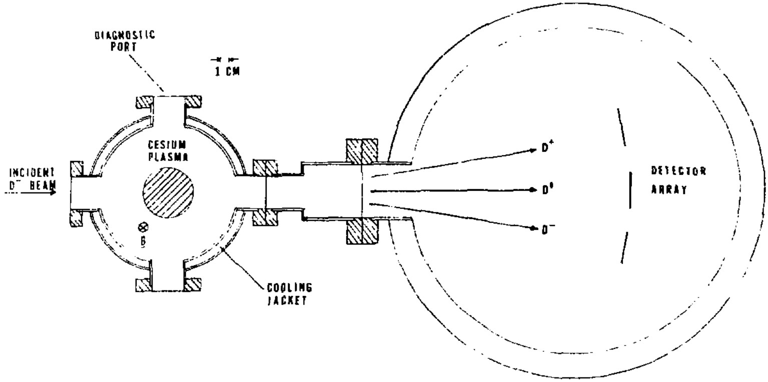

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Fig. 8. Experimental arrangment for determination of σ_{-0} and σ_{0+} in a cesium plasma target.

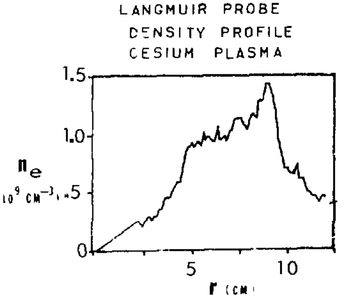

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Fig. 9. Electron density (derived from Langmuir probes) vs position in the cesium plasma target.

The magnetic bucket is essentially magnetic field free in the central region. Beam divergence due to the field of the permanent magnets should be small because of the small distance over which the beam crosses the high field regions.

The beam from an accelerator array[21] would pass between the rows of water-cooled permanent magnets and become partially neutralized (Fig. 10). Calculated beam divergences[21] are small enough that the product beams could emerge from the far side of the array, 50-100 cm downstream.

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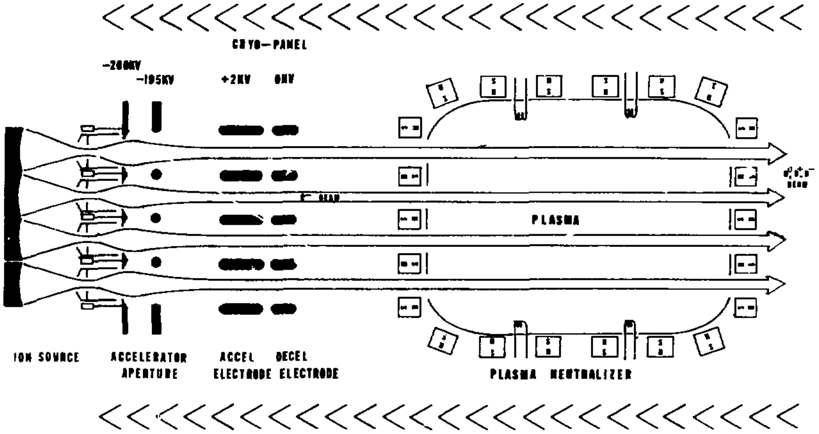

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Fig. 10. Schematic diagram of a proposed pratical plasma neutralizer for a 200 keV neutral beam system using a "magnetic bucket" plasma.

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