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POSSIBLE NON-HYDROGEN NEUTRALIZERS
FOR HIGH ENERGY D^+ AND H^+ BEAMS

BY

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POSSIBLE NON-HYDROGEN NEUTRALIZERS FOR HIGH ENERGY D^+ AND H^+ BEAMS

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ABSTRACT

We explore the utility of using a gas other than hydrogen isotopes to neutralize energetic beams of D^+ or H^+ for applications in magnetic confinement fusion. We find that at D^+ energies above 160 keV, helium, relative to hydrogen, offers significant improvements in neutralization efficiency and in enrichment of the full energy component of the beam, and that similar advantages accrue with neon at D^+ energies in excess of 200 keV.

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129

I. INTRODUCTION

Injection of energetic neutral beams of H^0 or D^0 at energies up to 45 keV has been shown to be a highly effective means of heating a tokamak plasma [1]. Unfortunately, at the higher energies required for near-ignition tokamaks and magnetic mirror devices, the achievable neutralization efficiency of beams derived from positive ions declines precipitously. Further, the percentage of the resulting neutral beam which is composed of fractional ($1/2$ and $1/3$) energy atoms is enhanced, because at higher energies the neutral equilibrium fraction, $F_{0\infty}$, is always higher for the fractional energy atoms than for the full energy atoms. These shortcomings have led to the consideration of negative ions, which can be neutralized more efficiently than D^+ ions at energies above ~ 150 keV, and which yield monoenergetic neutral beams. Negative ions of hydrogen are, however, much more difficult to produce than are positive ions, with the consequence that a usable high current D^- source has proven elusive.

Conventional positive-ion-based systems have allowed the gas efflux from the source to flow into a closely-coupled conductance-limiting tube [2]. In the cell thus formed, the ion beam is partially neutralized through charge exchange. Since such a cell is fed by the source gas, augmented as necessary by additional gas introduced directly into the neutralizer, the neutralizers in use on large heating beams have so far used hydrogen isotopes exclusively as the charge exchange gas. In this paper, we investigate the possibility of using a gas or vapor other than hydrogen as the neutralizing medium.

II. EQUILIBRIUM FRACTIONS AND DISCUSSION

Figure 1 displays the neutral equilibrium fractions, $F_{0\infty}$, for a hydrogen beam in a number of gases. The values of $F_{0\infty}$ were taken from Ref. 3, except

for CO_2 and Ne, for which the values were computed from the cross sections in Refs. 4 and 5, respectively. It is apparent that at lower energies, where neutral beam systems have so far operated, hydrogen is indeed the most appropriate neutralizer. However, at beam energies above 80 keV for H^+ (corresponding to 160 keV for D^+), the neutral equilibrium fractions in He, Ne, CO_2 , O_2 , and H_2O begin to exceed the F_{∞} in H_2 . The F_{∞} in N_2 (not shown) varies similarly to, but is slightly smaller than, the F_{∞} in O_2 , while the F_{∞} in Li vapor is significantly lower than that in H_2 at high energies. From the cross sections for other gases given in Ref. 4, we compute that F_{∞} for 100 keV H^+ (or 200 keV D^+) in C_2H_4 and C_2H_{10} is similar to the F_{∞} in H_2 , while the F_{∞} for 100 keV H^+ is somewhat smaller in C_2H_6 , CH_4 , Ar, and Kr than in H_2 . Thus, the gases for which we have displayed the F_{∞} curves appear to afford the best opportunities for improving the efficiency or extending the voltage range of neutral beams based on H^+ or D^+ . Figure 2 shows, as a function of energy, $F_{\infty}^x / F_{\infty}^{\text{H}_2}$, the ratio of F_{∞} for an H beam in each of the neutralizer gases divided by the F_{∞} in H_2 . Accordingly, these ratios indicate the improvement in neutralization efficiency that might be gained by using alternative gases. It is apparent that, with increasing energy, He, Ne, O_2 , CO_2 , and H_2O all provide neutralization superior to that obtainable with H_2 . In fact, for He and Ne the advantage might be even slightly greater than indicated, since F_{∞} in H is declining with increasing energy relative to F_{∞} in H_2 , and some small portion of the gas in an H_2 or D_2 neutralizer may be in the form of atomic hydrogen.

At H^+ energies above 200 keV, such as might be required for H^0 plugging beams for a tandem mirror with a thermal barrier [6,7], any of the gases shown offer major improvements in neutralization relative to H_2 , with neon apparently the best. However, in the important 80-120 keV H^+ range (160-240

keV for a D^+ beam), which is particularly relevant to heating near-ignition tokamaks (present plans for INTOR call for 175 keV D^0 beams [8]), helium offers the greatest neutralization. The superiority of helium as a neutralizer appears to be consequent upon two factors. The electrons of helium, being more tightly bound, have higher orbital velocities than do the electrons of a hydrogen molecule, so the matching for electron transfer to a fast H^+ ion is better. This would also be true for inner electrons in heavier atoms, but helium has the additional advantage that its small geometrical size makes it less effective at ionizing the resulting fast H^0 or D^0 .

III. A HELIUM NEUTRALIZER

Utilizing a non-hydrogen charge exchange medium necessitates decoupling the neutralizer cell from the source, thus allowing the major portion of the emerging hydrogen gas to expand onto pumping surfaces. If required in order to establish space charge neutrality, a very short conductance-limiting duct might be left attached to the source. The main neutralizer, however, would be separated from the source by the hydrogen expansion gap and by a helium pumping system. The presence of helium in the neutralizer introduces a difficulty, since helium cannot be pumped by conventional cryocondensation at 4.2°K. Fortunately, pumps have been developed by Batzer and co-workers [9] which can pump large quantities of helium by entrapment on argon frost, with a sticking probability of 15%, and a pumping speed of ~ 3 liters/cm² for helium at 10^{-5} torr. Ideally, in order to minimize helium migration into the rest of the beam system, one would like to use a directed jet of helium transverse to the beam direction. However, the fact that the sticking probability on the pump is much less than unity appears to preclude the possibility of maintaining a directed flow, at least by a simple pumping configuration where

the jet is pumped by a small surface forming the bottom of the neutralizer duct. A somewhat complicated, but more workable arrangement would be to let the helium jet expand into a large helium pumping region below the neutralizer, where a helium atom would, on the average, impinge upon pumping surfaces several times before having the opportunity to escape back into the neutralizer (Fig. 3).

The most straightforward configuration is to simply introduce helium gas midway along the neutralizer duct, and allow it to diffuse out to argon frost pumps at both ends of the neutralizer (Fig. 4). For a D^+ energy of 200 keV, a helium line density of $\sim 1.9 \times 10^{16} \text{ cm}^{-2}$ would be required to achieve 90% of F_{∞} . If the neutralizer were 2 meters long and 25 cm in diameter, and if the neutralizer duct and the input gas were cooled to LN_2 temperature (77°K), then the required helium throughput would be ~ 22 standard torr-liters sec^{-1} , requiring $\sim 220,000$ liters sec^{-1} of pumping to maintain a system pressure of $\sim 10^{-4}$ torr. Since the speed of the argon frost pumps is ~ 2 liters $\text{sec}^{-1} \text{ cm}^{-2}$ at 10^{-4} torr [9], $\sim 11 \text{ m}^2$ of pumping surface would be required for this example. These requirements could be reduced if it were feasible to keep the neutralizer even colder (the helium mobility would be down by 0.23 at 4.2°K, requiring only $\sim 2.5 \text{ m}^2$ of pumping surface). The helium can easily be introduced to the neutralizer cold (perhaps from the boiloff of the liquid helium cooled pumps), since it does not have to first pass through a warm source, as would be the case for a He^+ source with a closely coupled neutralizer. However, the actual mobility of the helium might be somewhat greater than we have calculated, due to momentum and energy transfers from the hydrogen beam. The use of helium as a neutralizer, while significantly more complicated than using hydrogen, appears feasible in high energy systems where efficiency is critical.

IV. A NEON NEUTRALIZER

Figure 2 shows that in the range 120-150 keV (H^+ energy), neon and helium yield similar values of F_{∞} , while at energies above 150 keV neon offers the greater degree of neutralization. This is presumably due to the fact that the inner electrons have even higher orbital velocities than those of helium or any of the light gases, while neon has a smaller radius than any of the remaining noble gases. Neon is significantly easier to pump than helium. At a temperature of 5.5°K, the vapor pressure of neon is $\sim 10^{-13}$ torr, and at 7.9°K it is only 10^{-7} torr, so the sticking probability must be essentially unity. Accordingly, one should be able to obtain very good confinement of the neon within the neutralizer region, either by spraying a transverse neon jet across the ion beam and onto liquid-helium-cooled condensation surfaces (Fig. 5), or by introducing neon into the middle of the neutralizer duct (which might be LN_2 cooled), and letting it flow to helium-cooled pumping surfaces at the ends of the duct. To obtain 90% of n_{∞} for 200 keV D^+ would require a cell thickness of $\sim 1 \times 10^{16} \text{ cm}^{-2}$. Since the mobility of neon is $\sqrt{5}$ less than that of helium, the gas throughput required for the two meter duct neutralizer discussed in Section IV would be only ~ 5 torr-liters sec^{-1} at 77°K. Alternatively, the use of a transverse jet should allow the duct length to be decreased substantially.

V. CONCLUSION

At high energies (> 150 keV H^+), a number of gases, He, Ne, O_2 , N_2 , CO_2 , and H_2O , appear to afford higher degrees of neutralization than does H_2 . At energies in the range 120-250 keV (D^+ beam) helium offers the greatest degree of neutralization, and should be considered for tokamak applications. At a D^+ energy of 160 keV, F_{∞} in H_2 is 29%, while in helium it is 33.5%. This

difference increases with energy; at a D^+ energy of 200 keV, F_{∞} in H_2 is 19% and in neon it is 23%, while it is 25.4% in helium, which would result in a 30% increase in efficiency for the full energy component. Alternatively, as shown in Table I, a helium neutralizer (or a neon neutralizer at D^+ energies above 200 keV) enables one to obtain a particular degree of neutralization at a higher beam energy than would be possible using H_2 . This permits increased penetration without sacrificing neutralization efficiency. Figure 2 reveals an additional benefit associated with the use of helium or neon (and to a lesser extent the other heavy gases shown) as a neutralizer: since the ratio $F_{\infty}^X / F_{\infty}^{H_2}$ is always larger for the full energy beam component than for the one-half and the one-third energy components, the resulting neutral beam will contain a smaller percentage of its power in the fractional energy components, and correspondingly more in the full energy component, than would be the case with a H_2 neutralizer. This enrichment of the full energy beam component is advantageous, since the fractional energy components deposit their energy in the outer plasma, where it is less effective and even deleterious due to enhanced impurity sputtering and evaporation.

For very high energy mirror applications, such as beam plugging of a tandem mirror with a H^0 beam at ≥ 200 keV [6,7], neon appears to be the best neutralizer, and is far superior to H_2 . At 200 keV, for instance, F_{∞} for a H^+ beam passing through H_2 is 2.4%, while in neon it is 7.2%. For tokamak heating applications, there are three regimes: at D^+ beam energies below ~ 160 keV, the neutralizer of choice is hydrogen, while at D^+ energies between 160 keV and 200 keV helium appears to be the best neutralizer, and at D^+ energies in excess of ~ 200 keV, neon appears to be the most desirable neutralizer. The latter regime arises because neon is much easier to pump than helium, and it offers neutralization which is only slightly inferior to that obtainable with

helium at D^+ energies above 200 keV, and which surpasses helium's neutralization efficiency for D^+ energies above 260-300 keV. Cryogenically pumping gas in quantities sufficient for neutralizer applications appears to be feasible with helium and relatively simple with neon. Our analysis in this paper assumes that the quoted values of F_{∞} are accurate; since the accuracy claimed by Refs. 3 and 5 is $\pm 5\%$, we believe that our major points are at least qualitatively correct, and that they are sufficiently promising that helium and neon should be seriously considered for future applications in high energy neutral beam systems. Confirmation of the relative merits of the best neutralizer gases by remeasuring their equilibrium fractions with extreme accuracy might be desirable prior to designing actual neutralizers.

The final decision on which neutralizer gas to use in a specific application would need to weigh the benefits we have discussed here against the attendant disadvantages of increased beamline length and pumping requirements as well as the enhanced scattering of the beam by neutralizer gases more massive than D_2 .

The use of alternative neutralizer gases probably does not circumvent the eventual need for negative ions, but it offers the possibility of deferring the transition to negative ions to a higher energy by increasing the efficiency and the energy range of neutral beams derived from positive ions.

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TABLE I

Energies Which Yield Equivalent Neutralization in Different Gases

D ⁺ Energy	F _{0∞} in H ₂	D ⁺ Energy in He which gives the same F _{0∞}	D ⁺ Energy in Ne which gives the same F _{0∞}
160	0.29	195	155
200	0.19	245	225
240	0.13	297	300

FIGURE CAPTIONS

- Fig. 1. Equilibrium neutral fraction, F_{∞} , of an H beam in various gases.
- Fig. 2. The ratios, $F_{\infty}^x / F_{\infty}^{H_2}$, of the equilibrium fraction of an H beam in various gases divided by the equilibrium fraction in H_2 .
- Fig. 3. End view of a neutralizer using a transverse jet of helium. The helium is pumped in an enclosed region, whose only opening is from the neutralizer. In this geometry, the chevrons are probably not necessary to prevent escape of the argon. Their removal should somewhat increase the pumping speed.
- Fig. 4. Schematic of a loosely coupled neutralizer at $77^\circ K$ with helium pumping. The pumping area could be decreased by running the neutralizer at $4.2^\circ K$.
- Fig. 5. End view of neutralizer using a transverse jet of neon.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.