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PLASMA HEATING WITH MULTI-MeV NEUTRAL IMPURITY BEAMS

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The utility of neutral beams of $A \geq 6$ AMU formed from negative ions, accelerated to ~ 1 MeV/AMU and neutralized, is explored for heating toroidally confined plasmas. Such beams offer the promise of significant advantages relative to conventional neutral beams based upon positive or negative hydrogen ions at 100-200 keV/AMU.

Almost all plans for magnetically confined fusion plasma devices require some form of supplemental heating. The most successful method used to heat current plasmas has been the injection of 20-60 keV beams of hydrogen or deuterium atoms. These beams are formed by electrostatically accelerating protons or deuterons and then neutralizing them by charge exchange with hydrogen. However, the charge exchange cross section drops rapidly above ~ 80 keV/AMU, so only a small fraction of a high energy (≥ 80 keV/AMU) beam is neutralized. On the other hand, a restriction to energies below 80 keV/AMU limits the size and density of plasma that such a beam can penetrate and heat. Further, these beams result in high power densities in the ion source and acceleration grids and need massive liquid helium cryocondensation vacuum pumps. Negative hydrogen ions can be efficiently neutralized at high energies, but producing sufficient currents of H^- has proved difficult. We consider here a novel heating method in which negative ions of $A \geq 6$ AMU are accelerated to ~ 1 MeV/AMU, neutralized, and injected into a plasma. There they are ionized and heat the plasma in the process of slowing down.

Dawson and McKenzie¹ and Grand² have proposed injection of positive ions (He^+ , Ne^+ , etc.) as an alternative to neutral hydrogen injection. Ohkawa³ and Thompson⁴ considered neutral helium beams for current drive and heating. The advantages of the positive ion schemes are that, in principle, there is no inefficiency due to incomplete beam neutralization, and that high current positive ion sources are straightforward to build for a number of elements. The ions are accelerated to ~ 1 MeV/AMU, at which energy the completely ionized nuclei will be as well confined in the plasma as the alpha particles produced by D-T fusion. After reaching the edge of the tokamak, the ions drift into the plasma on unconfined orbits with $\rho_p \propto (A/q)$, where ρ_p is the poloidal gyroradius, A is the atomic mass in AMU, and q is the charge. In the

plasma, the singly charged ion is further ionized until $q = Z$ (Z is the atomic number), while ρ_p shrinks by a factor of $1/Z$, so the fully ionized particle is on a confined orbit. The use of neutral impurity beams retains the advantage of conventional hydrogen neutral injection (which allows easy transport through the tokamak's strong fringing magnetic fields and tangential aiming to achieve centrally peaked heating), while gaining enhanced penetration through the drifting of the (initially) singly charged ion, and allowing injector currents much lower than those required with hydrogen at 100-200 keV/AMU.

We have calculated the heating profiles to be expected from injection of carbon and oxygen neutral atoms using Monte Carlo techniques including orbits, the injector geometry, ionization of the atom by proton or electron impact, subsequent drifting and successive ionization until the atom is fully ionized, and slowing down. The current driven by the beam is averaged over the orbits and slowing down history of the particles. The penetration and heating for a 16 MeV oxygen beam injected into an INTOR-sized⁵ plasma is quite good (Fig. 1). The parameters used were a major radius of 5.2 m, minor radius of 1.3 m, a plasma current of 6 MA, a toroidal field of 55 kG, a central electron temperature of 25 keV, a Z_{eff} of 1.5, a line-averaged density of 10^{14} cm^{-3} , and a plasma elongation of 1.2 (b/a). The initial penetration of the neutral oxygen beam is not fully peaked, but drifting of the not-fully-stripped ions peaks the heating in the plasma core. As shown in Fig. 2, over 80% of the energy of the neutral oxygen beam is deposited inside half the minor radius, or within the inner 1/4 volume. Included for comparison is a Na^+ beam and neutral hydrogen beams made from D^- and D^+ . Only high energy neutral hydrogen beams formed from negative ions approach the central heating efficiency of the oxygen beam. Such a peaked heating profile reduces the injected power required to achieve ignition. The reduction has been shown to be as much as a

factor of two compared with positive ion-based hydrogen neutral injection.⁶

The impurity buildup due to these beams should pose no problems. INTOR is expected to require 50 MW of conventional neutral beam heating. Assuming as a worst case that 50 MW of 12 MeV carbon is required, then the fueling rate for carbon is 0.3% per second and the resulting increase in Z_{eff} is 0.03 per second. A driven $Q = 20$ reactor can tolerate $n_C/n_E \sim 11\%$ since fully stripped carbon does not radiate strongly.⁷ In any event, the carbon ion accumulation rate is less than the helium ion accumulation rate, so the removal of the thermalized carbon is less of a problem than helium ash removal.

The utility of this technique is contingent upon the development of a high current negative ion source of an appropriate element (a total current of ~ 100 mA at a few mA/cm²) and a tractable accelerator. The most straightforward approach to a source is to use a two stage system in which positive ions are extracted from an arc and sent through a transverse supersonic jet of alkali metal vapor, where some portion of the beam is converted to negative ions. In low current experiments⁸ at 5 keV, $\sim 9\%$ of a Li^+ and $\sim 50\%$ of a O^+ beam have been converted to negative ions in a cesium cell, while $\sim 50\%$ conversion of O^+ to O^- was observed with 14 keV O^+ passing through a magnesium cell. Thus, to produce a 100 mA O^- source module should require only ~ 200 mA of O^+ (actually somewhat more to allow for losses due to divergence and scattering). Since oxygen is a gas, such currents should be easily obtainable with a multiaperture duopigatron ion source, smaller than the ones presently used for hydrogen neutral beam injection.⁹ Although producing large currents of Li^+ is more difficult, there is an established technology for doing so. Calutron sources used for isotope separation have produced ~ 1.2 A of Li^+ at ~ 30 mA/cm²,¹⁰ which should be sufficient for a 100 mA Li^- module. Calutron sources have also produced O^+

beams at average current densities of 11.4 mA/cm^2 , using CO_2 or D_2 as a feedstock.¹¹ Thus, at a negative ion conversion efficiency of 50%, only $\sim 10 \text{ cm}^2$ of C^- emitting area would be required for a 100 mA C^- module. These calutron sources, moreover, have operated CW for many days. Accordingly, it appears that the technologies exist to produce sufficient positive ion currents for the two stage source approach to be successful for at least three elements, and there is no reason why the low current conversion results should not scale up with size.

There are, in addition, other approaches which, while less proven than the two stage system, might lead to simpler sources. These include sputtering of negative ions from cesiated surfaces of lithium or carbon, either by cesium beams, as used for H^- production,^{12,13} or by plasma ions accelerated across a sheath in a surface-plasma source similar to one developed for H^- use.¹⁴ Forming Li^- by photodissociating NaLi molecules into Na^+ and Li^- has been suggested,¹⁵ using a laser at 2350-2400 Å.

The other critical component is the accelerator. An electrostatic accelerator is precluded by the combined requirements of high voltage and high current, along with the constraints of having to operate near the tokamak, while conventional magnetically focused RF accelerators do not perform well at low β . However, recent development of RF accelerators with electric quadrupole focusing is ideally suited for this application. These accelerators, the RF Quadrupole (RFQ)¹⁶ and the Meqalac¹⁷ can, because of their velocity-independent strong focusing, accept input beams of low energy ($\sim 50 \text{ keV}$), high space charge density, and high emittance. An RFQ accelerating 100 mA of Li^- per channel to 6 MeV could be 10-11 meters long, while capturing and transmitting 85-90% of the CW input beam.¹⁸ The gross system electrical efficiency of such a RFQ should be at least 34%.¹⁹ Since 100 mA per

channel (with an entrance aperture of 6-7 cm diameter)¹⁸ appears to be a convenient current for a RFQ accelerator, a beam assembly would be composed of a number of RFQ channels, each carrying ~ 100 mA and fed by a negative ion source module with a magnet, lens, and preacceleration stage. After acceleration, the beams would be merged and aimed through a neutralizer into the torus. The power per channel would be very large, so only a few channels would be needed for each beam assembly. The operational simplicity, ruggedness, reliability, and q/m selectivity inherent to RF accelerators make them ideal for assembly into large heating systems.

The simplest choice for a neutralizer is a thin cell of a condensable gas, such as CO₂, which is easily pumped by cryocondensation. Estimates of the neutralization efficiency suggest that 50% or more of the beam might be neutralized. Neutralization of 90% or more of the Li⁻ beam might be feasible by photodetachment with Ga As lasers, depending upon how small the final beam cross section can be made. Since the photodetachment cross section of Li⁻ is similar to that of H⁻,²⁰ the energy economies (increased neutralization efficiency versus laser exciting energy) are similar, but they are more favorable for Li⁻ because of the potentially much higher beam energy density.

If a substantial portion of the beam remains unneutralized, then it will be necessary to deflect and defocus the remaining ions onto cooled dumps. The associated power-handling problems might be severe, but not fundamentally different from such problems with hydrogen neutral beams.

While this heating method can in principle be implemented with any negative ion, practical considerations may limit it to light ions ($A \leq 20$ AMU). Although the current required decreases as the chosen mass increases, the accelerator length required to achieve 1 MeV/AMU becomes excessive for heavier ions. Moreover, the energy per atom carried into the plasma is

proportional to A , which means that it is approximately proportional to Z . However, the energy radiated from the plasma core by the impurity varies as a function stronger than Z^2 . Accordingly, for heavier ions the ratio between energy carried in and energy radiated is less favorable than for lighter ions. In addition, the confinement of the initially partially stripped ion deteriorates as the mass increases.

Neutral impurity beams at 1 MeV/AMU afford more axially peaked heating profiles and easier plasma access than do positive ion impurity beams. Relative to conventional hydrogen neutral beams formed from positive ions at 150-200 keV, neutral impurity beams afford higher neutralization efficiencies and lower injected power requirements due to improved plasma penetration, and they require less ion current to produce the same injected power as a negative-ion based D^0 beam (12 MeV D^0 penetrates as well as 2 MeV D^0). Because the limiting ion energy for confinement is proportional to A , neutral impurity beams can in principle operate at higher power densities than D^0 systems, which should allow smaller access ports through the tokamak blanket (leading to less neutron leakage). With the possible exception of the ion dumps, these systems can in principle operate CW due to relatively low power densities on source and accelerator surfaces.

A major advantage of these heavy beam systems is that they should require much less costly pumping per megawatt than does a deuterium beam. The neutralizer can be a gas, such as CO_2 , which could be cryopumped at the temperature of liquid N_2 (with perhaps some 30°K pumping for any CO or oxygen fragments produced in the cell) which is much cheaper than using liquid He. The source loads are also easier to handle: Li vapor just requires cool plates; oxygen can be cryopumped using helium gas at 30°K, which is less costly and energy intensive than liquid He. Further, since the energy per

atom is much higher than with conventional deuterium beams, the total beam current required to yield a given power is much lower, which means that the gas flow from the sources is also lower. These factors should yield significant savings in capital and operating costs.

Catastrophic impurity effects due to thermalized beam ions are expected to be small for light ions. The unresolved questions involve the choice and development of an optimum ion source, accelerator system, and neutralizer cell, for each of which there exist viable options.

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FIGURE CAPTIONS

Fig. 1. Heating profile for 175 keV D^0 beam using positive ion sources (neutral particle fractions: 0.78 full energy, 0.09 half energy, and 0.13 one-third energy), and a 16 MeV neutral oxygen beam. The $O^0 + O^+$ curve is the profile due to the single ionization of O^0 . The O^{+8} curve is the final heating profile including drifts, subsequent ionization for O^{+1} to O^{+8} , and slowing down.

Fig. 2. Integrated power deposited inside a given radius for four beams: (I) a 175 keV D^0 beam made from D^+ ions (neutral particle fractions: 0.78 full energy, 0.09 half energy and 0.13 one-third energy), (II) a 1 MeV D^0 beam made from D^+ ions, (III) a 20 MeV Na^+ beam, and (IV) a 16 MeV D^0 beam made from D^+ .

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Figure 1.

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Figure 2.