THE USE OF ENERGETIC HELIUM ATOMS FOR HEATING TOROIDAL SYSTEMS

by

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ABSTRACT

Some of the advantages and disadvantages of using helium for heating toroidally confined plasmas by energetic neutral injection are examined. We also discuss how the choice of primary ion influences the design and development of neutral injectors.

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My attention has been drawn to two earlier papers relevant to this work:

(1) Neutral Injection Heating of Tokamaks,
J Rand McNally Jr., ORNL-TM-4363, October 1973.

(2) Chauffage d'un Plasma par Injection d'Atomes Rapides d'Hélium,
J R Girard, M Khelladi, D A Marty, EUR-CEA-FC-682, January 1973.

The last report in particular is a very comprehensive study and covers some of the points mentioned in this report in addition to a more detailed discussion of the slowing-down of the H_e^{++} in the plasma.

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The role of energetic neutral injection for heating toroidally confined plasmas to thermonuclear ignition has been discussed by a Culham Study Group [1] and detailed calculations of the energy required to heat a Tokamak discharge to ignition have been published by Girard [2] and by Sweetman [3]. Ion heating has been observed in existing Tokamak experiments which employ energetic neutral injection as an additional heating method [4,5,6]. We examine some of the advantages and disadvantages of using ions other than the plasma ion species [7], in particular helium, for heating by high energy neutral injection and discuss how the choice of primary ion influences the design and development of neutral injectors.

The choice of atom species used for plasma heating is essentially governed by three factors:

(a) the penetration of the fast atoms into the plasma;
(b) the efficiency of production of the fast atoms, and
(c) the impurity introduced by the beam if we use non-plasma ions (density increase if we use plasma ions).

The first two points with regard to reactors were first considered by Riviere [1] but we re-examine these three criteria for next generation experiments with particular reference to He^o.

(a) Penetration

In fig.1 we show how the total cross-section for trapping various fast atoms incident on a hydrogen plasma varies with the atom energy in the range relevant to present and next generation experiments. The total trapping cross-section σ_t, represents the sum of trapping due to charge exchange and ionization by both protons and electrons.

For a large experiment with a plasma radius of ~ 1m and initial density ~ $5 \times 10^{13} cm^{-3}$ we are interested in values of σ_t between 2 & 3×10^{-16} cm^2. This is in order that the radial profile of the power deposited by neutral injection will roughly match that generated by ohmic heating [1,8]. Referring to fig.1 we see that σ_t restricts the use of H^o to between 60 and 90 keV, or 120 to 180 keV for D^o. The curve for He^o however exhibits a broad maximum at 120 keV and better penetration (if required) can be obtained by either increasing or decreasing the injection energy over the range 20 to 250 keV and hence the choice of injection energy can be determined by other factors.

(b) Efficiency of Production of Fast Atoms

In fig.2(a) we plot the ion current needed to produce 1 MW of neutral beam as a function of energy for H^o D^o and He^o. The curves all show a minimum due to decrease in equilibrium fraction $F_{o\infty}$ at high energies and in terms of minimising the total ion beam required, the optimum energy for H^o is 50 - 60 keV and 100 - 120 keV for D^o. The He^o curve minimises at a considerably lower current of 9.8 amps at 200 keV. We also show in fig.2(b) the value of $F_{o\infty}^{-1}$ for the various atomic ions in their parent gas; this quantity represents the ratio of the accelerated ion current to the neutral equivalent current and as such, is a measure of the efficiency of utilization (and hence cost) of the power supply in the absence of direct recovery of the energy in the un-neutralized beam. He^o at 200 keV offers a considerable advantage over H^o or D^o in terms of neutralization efficiency.

(c) Impurity

Clearly the major disadvantages to the use of He^o is the impurity problem and the need to operate at high voltages. Because of the form of the trapping cross-section these questions are somewhat inter related in that the penetration requirement is approximately satisfied over a wide range of energies and allows operation at constant power between 20 and 250 keV.

If it is assumed that the injected ions are completely contained during the heating phase, then one can simply show that the fractional impurity content γ due to injection of ions other than the plasma ion species (density increase if the plasma species is used) is given by

$$\gamma \approx 3\Delta(kT)/E_o$$

for $\gamma \ll 1$ and uniform density and temperature profiles.

$\Delta(kT)$ is the increase in temperature and E_o is the energy of the injected atoms. By considering more realistic radial profiles, Sweetman [3] obtains a value which is 20% lower. The value of $\Delta(kT)$ required to give ignition is a function of both the plasma current and density [2,3] but for illustration we shall somewhat arbitrarily assume $\Delta(kT) = 5$ keV (equivalent to injecting 10 MJ into 10^8 cm^3 of plasma at $5 \times 10^{13} cm^{-3}$). Operation at low injection energies will of course give an unacceptable impurity content but 10 MJ at 200 keV will result in a 7.5% He^{++} (α particle) content with a corresponding $Z_{eff} = 1.14$.

Implication for the Development of Neutral Injectors

In the absence of other constraints it would appear that the use of He^0 at ~ 200 keV offers the advantages of minimising the total extracted ion current for a given power level and in the absence of direct energy recovery, of giving most efficient use of the power supply. For 1 MW of He^0 the required ion current of 10 amperes is comparable to, or less than that presently obtained. Furthermore the neutral atoms will be mono-energetic unlike the situation in present hydrogenic sources where due to molecular ion production, neutral atoms of ½ and ⅓ as well as the full energy are obtained [9,10,11]. Due to their higher trapping cross-section, these lower energy atoms will deposit their energy in the outer regions of the plasma and the presence of molecular ions will certainly complicate the design and construction of a direct energy conversion scheme.

It is also worth noting that the total amount of thermal gas from a He^0 injector would be expected to be considerably lower than from a hydrogen injector. Apart from the 2 or 4 fold reduction in beam current, the target thickness for neutralizing He^+ is also a factor two lower and these reductions in gas load may well offset the additional complication entailed in pumping helium for example by cryo getter techniques.

The use of He^0 however requires almost an order of magnitude increase in voltage and if we are to maintain high current density at these higher energies, places a considerable premium on the development of post acceleration systems [1] in which the beam is extracted at some convenient energy ∿ 20-40 keV and then accelerated to the final energy in one or more subsequent stages. Such systems will of course also be needed for D^0 injectors.

Finally we note that the use of high energy He^0 will enable the behaviour and accumulation of α particles to be studied in the absence of ignition and attendant induced radioactivity in both the torus and the injector. Furthermore with regard to present generation experiments in hydrogen, He^0 may well deliver more energy to the plasma since energy loss of the injected particles by charge exchange is considerably reduced due to the non-resonant nature of the charge transfer cross-section.

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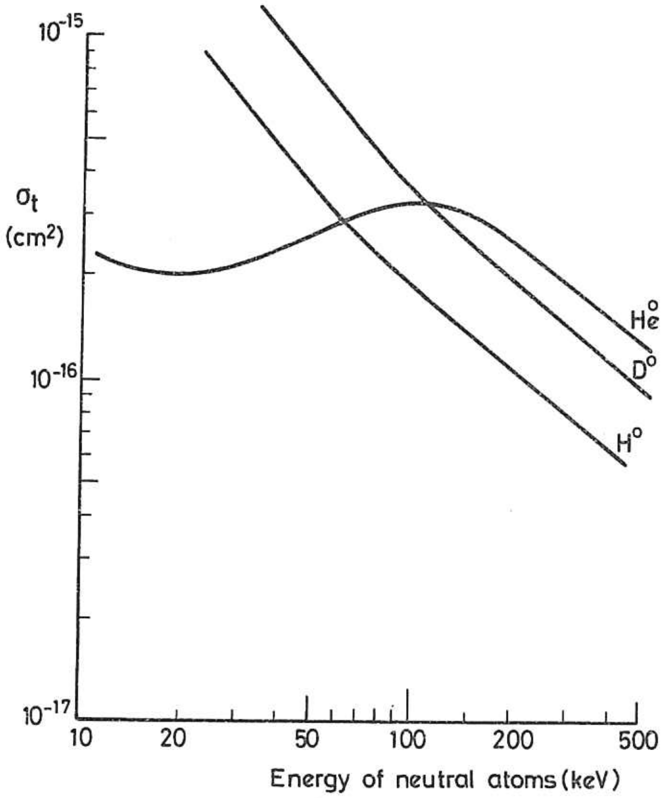
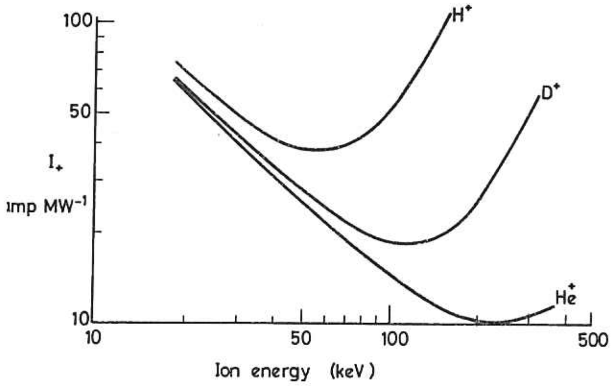


Fig.1. Total trapping cross-section for energetic neutral atoms incident on a $H^o(D^o)$ plasma with an electron temperature of 4 keV.



.2(a). Variation of ion current (amps) uired to produce 1 MW of neutral atoms m the parent atomic ion.

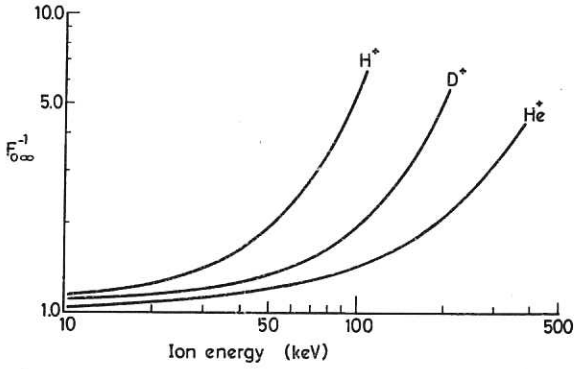


Fig.2(b). Ratio of accelerated ion current to neutral equivalent current for atomic ions in parent gas.