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A TECHNIQUE FOR MEASURING THE FAST $^{3}He^{++}$ DISTRIBUTION DURING $^{3}He^{++}$ MINORITY ICRF HEATING

BY

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A TECHNIQUE FOR MEASURING THE FAST $_3He^{++}$ DISTRIBUTION DURING $_3He^{++}$ MINORITY ICRF HEATING

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ABSTRACT

A technique for measuring the fast $_3He^{++}$ distribution during $_3He^{++}$ minority ICRF heating is discussed. The technique involves the use of 10-100 keV neutral helium beams to neutralize the fast $_3He^{++}$ ions by double charge exchange ($_3He^{++} + {}_4He^0 \rightarrow {}_3He^0 + {}_4He^{++}$). The neutralized fast $_3He$ atoms then escape from the plasma and are detected by conventional neutral particle analyzing apparatus. By the use of such a technique, the effectiveness of the coupling of the ion cyclotron waves to the $_3He^{++}$ minority could be measured.

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I. INTRODUCTION

Recent results on TFR [1], DIVA [2], PLT [3], and other tokamaks indicate that ion cyclotron resonance heating is a very promising heating technique for tokamak plasmas. When the waves couple directly to deuterons by either second harmonic heating or protons by fundamental minority heating, measurement of the fast proton or deuteron distribution has been used to assess the effectiveness of the coupling of the waves and the confinement of the fast ions. In particular the penetration of the waves to the plasma center can be established by such a measurement.

Charge exchange between the fast protons or deuterons and neutral hydrogen atoms has allowed the measurement of the fast ion distribution since the confined ions become neutrals which are no longer confined by the magnetic field [4]. The source of neutral atoms is either the background or beam injected neutrals.

On PLT the best heating results with ICRF have been obtained when the waves couple to minority $_3He^{++}$ ions ($\sim$ 5-10% of the plasma density) [3]. The fast $_3He^{++}$ ions then heat the rest of the plasma via coulomb collisions. One advantage of $_3He^{++}$ minority heating is thought to be that the fast ions are not lost due to charge exchange with the background neutrals. This process is a major loss mechanism for proton minority heating [3]. However, there are no direct measurements of the fast $_3He^{++}$ distribution, as there are in the proton minority heating case, to help sort out the questions of how well and where the waves couple to the $_3He^{++}$ ions, and how well the energetic $_3He^{++}$ ions are confined and then heat the plasma.

It may be possible to extend the charge exchange technique to $_3He^{++}$ by using double charge exchange $_4He^o + {_3He^{++}} \rightarrow {_4He^{++}} + {_3He^o}$ to neutralize the $_3He^{++}$. The background neutral helium population would be expected to be small in a large plasma with a $_3He$ minority, since the plasma consists primarily of protons and the charge exchange cross section for $H^o + He^+$ and $H^o + He^{++}$ is small [5], while the ionization rate for He^o is about the same as for H^o. It should be possible to use existing neutral beam technology to make a neutral helium doping beam. This would work in a similar fashion to hydrogen diagnostic beams such as FIDE [6] on PDX. The key questions (Fig. 1) are then (1) production of a neutral $He_4{}^o$ beam, (2) penetration of the $_4He^o$ beam, and (3) production and detection of the $_3He^o$ atoms formed by double charge exchange of $_4He^o$ and $_3He^{++}$.

II. HELIUM NEUTRAL BEAM

Neutral helium beams have been discussed for plasma heating by E. Thompson in a previous letter [7].

A diagnostic neutral helium beam could be made by using a small conventional positive ion source (producing He^+), an electrostatic acceleration system, and a gas cell neutralizer, just as with hydrogen neutral beams. Most conventional ion sources will work with helium as well as hydrogen, except that the extracted currents and gas efficiencies may be somewhat lower than with hydrogen. A number of experiments have been done using existing positive ion hydrogen neutral beam systems with helium substituted for hydrogen [8, 9].

The neutralization of a He^+ beam is feasible using single charge exchange with He^o (Fig. 2). As Thompson points out [7] roughly 70% of a 50 keV He^+ beam could be neutralized. One feature of a He^o beam is that it will have no one-half or one-third energy components since $He_2{}^+$ and $He_3{}^+$ are not common.

The major question is the required pumping of helium, since conventional cryocondensation pumps do not work well for helium. However, small diagnostic beams such as FIDE [6] have only modest pumping requirements which are met using turbo-molecular pumps which work quite well for helium. The conversion of a hydrogen heating beam such as the PLT heating beams [11] to a short pulse helium beam would provide adequate pumping due to the large volume normally occupied by the 300,000 ℓ/sec cryopumps. High current, steady-state helium beams using argon frost pumping have also been proposed [12].

III. HELIUM BEAM PENETRATION

The penetration of a helium neutral beam should be adequate. For energies appropriate to PLT ($\sim$ 40 keV), $\sigma \sim 2 \times 10^{-16} cm^2$, so for $n_e \sim 4 \times 10^{13} cm^{-3}$, λ is $\sim$ 125 cm for He^o, compared to $\lambda \sim 50$ cm for 40 keV H^o (Fig. 3). At 120 keV, D^o and He^o have identical cross sections. Thus the penetration of a helium beam is as good as, or better than, the hydrogen heating beams in use on PLT and TFR and planned for TFTR and D-III [11].

IV. CHARGE EXCHANGE MEASUREMENTS

The existence of a viable signal level for charge exchange diagnostics can be established using simple modeling. Neglecting attenuation and radial profile effects, the detector count rate, S(E), at energy E can be approximated by

$$S(E) = n_b \eta_{He} n_e f(E) \; E\langle\sigma v\rangle \; K(E) ,$$

where η_{He} is the fractional density of ${}_3He^{++}$ in a plasma of electron density $n_e (cm^{-3})$, f(E) is the fast ${}_3He^{++}$ energy distribution, and $\langle\sigma v\rangle$ is the doping beam induced double charge exchange reaction rate. Here the charge exchange production of ${}_3He^o$ on the background neutral density is assumed to be negligible compared with that due to double charge exchange of ${}_3He^{++}$ on the ${}_4He^o$ doping neutral density, $n_b(cm^{-3})$, given by

$$n_b = 1.43 \times 10^{11} j/(E_b/A_b)^{1/2} ,$$

where $j(A/cm^2)$, $E_b(keV)$, and $A_b(AMU)$ are the equivalent neutral current density, energy, and atomic mass number of the beam neutrals respectively. The charge exchange analyzer response function, $K(E)$, includes the analyzer energy resolution and acceptance solid angle, the plasma volume viewed, and the efficiencies of the stripping cell and the detector. Although $K(E)$ depends on the particular experimental arrangement for tokamak applications, the value is typically in the range of $5 \times 10^{-8} - 5 \times 10^{-7} cm^3$steradian. Such values are applicable to the present application as well, provided that H_2 stripping cell gas is used to preserve relatively high stripping efficiencies (~ 0.2) for ${}_3He^o$ above energies of ~ 10 keV, as evidenced by the cross section for ${}_3He^o + H_2 \rightarrow {}_3He^+$ (Fig. 5) compared to ${}_3He^+ + H_2 \rightarrow {}_3He^o$. Using $E = E_b = 50$ keV and reasonable parameter values of

$$n_b \sim 5 \times 10^8 cm^{-3} ,$$

$$\eta_{He} \sim 0.05 ,$$

$$n_e \sim 2 \times 10^{13} cm^{-3} ,$$

$$\langle \sigma v \rangle \sim 3 \times 10^{-8} cm^3 sec^{-1} ,$$

$$K(E) \sim 5 \times 10^{-8} cm^3 \text{ steradian} ,$$

yields

$$S(E) \simeq 7.2 \times 10^5 f(E)\ E \ .$$

Fokker-Planck code modeling of $_3$He minority ICRF heating in PLT indicates that $f(E)\ E \sim 0.1$ is relatively independent of energy in the range $10 \leq E \leq 100$ keV [13]. Thus signal levels of the order of 10^5 counts per second over the noted energy range are envisaged, which are adequate for charge exchange measurements with ~ millisecond time resolution [14].

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FIGURE CAPTIONS

Fig. 1. Schematic diagram of fast $_3He^{++}$ diagnostic.

Fig. 2. Equilibrium fractions for H^+, D^+, and He^+ in H_2, D_2, and He respectively. [10]

Fig. 3. Penetration cross section ($\lambda = 1/n_e\ \sigma_{eff}$) for H^o and He^o beams incident on a proton and electron plasma. [10]

Fig. 4. Double charge-exchange cross section for $_4He^{++}$. [10]

Fig. 5. Ionization cross sections for $_4He^o + H_2 \rightarrow {}_4He^+$ and neutralization cross sections for $_4He^+ + H_2 \rightarrow {}_4He^o$. [10]

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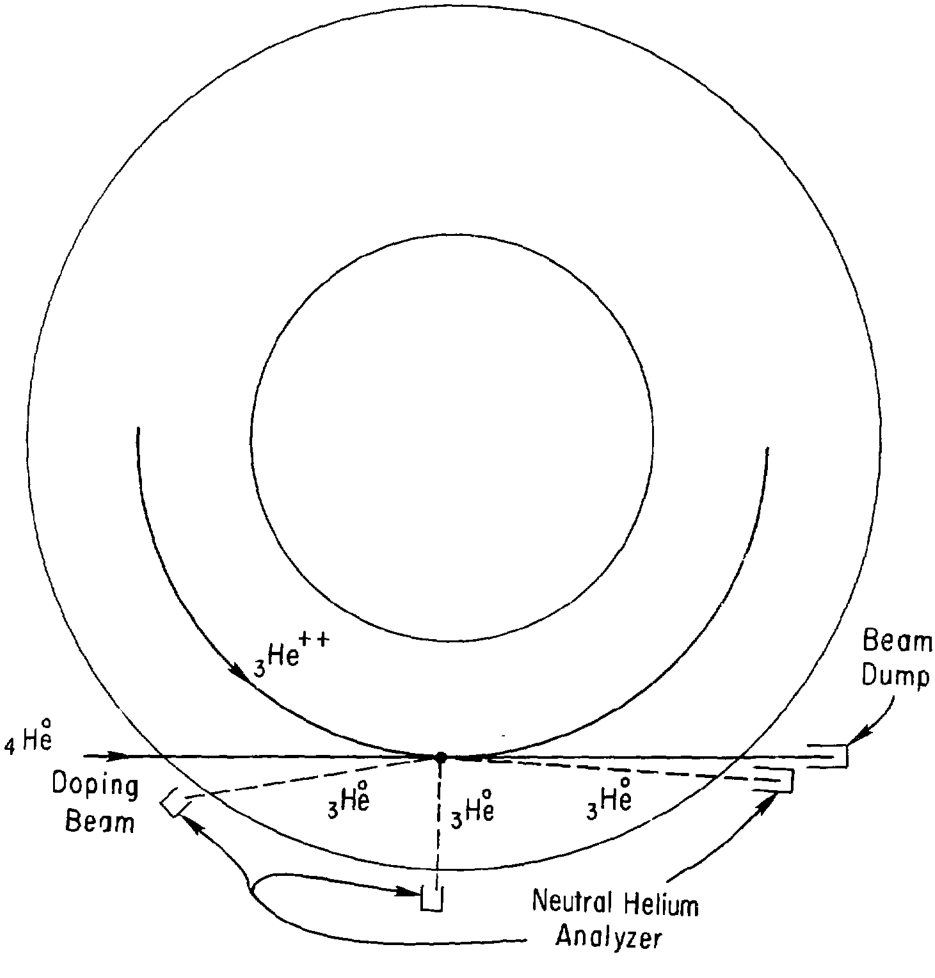

Fig. 1

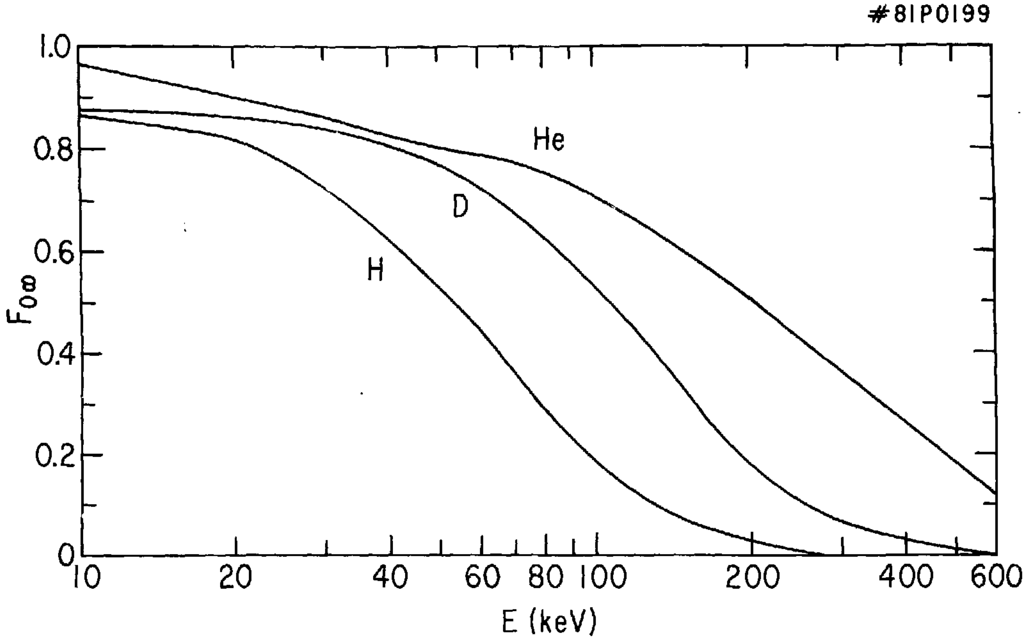
#81P0199
1.0
0.8
0.6
0.4
0.2
0
$F_{0\infty}$
He
D
H
10
20
40
60
80
100
200
400
600
E (keV)

Fig. 2

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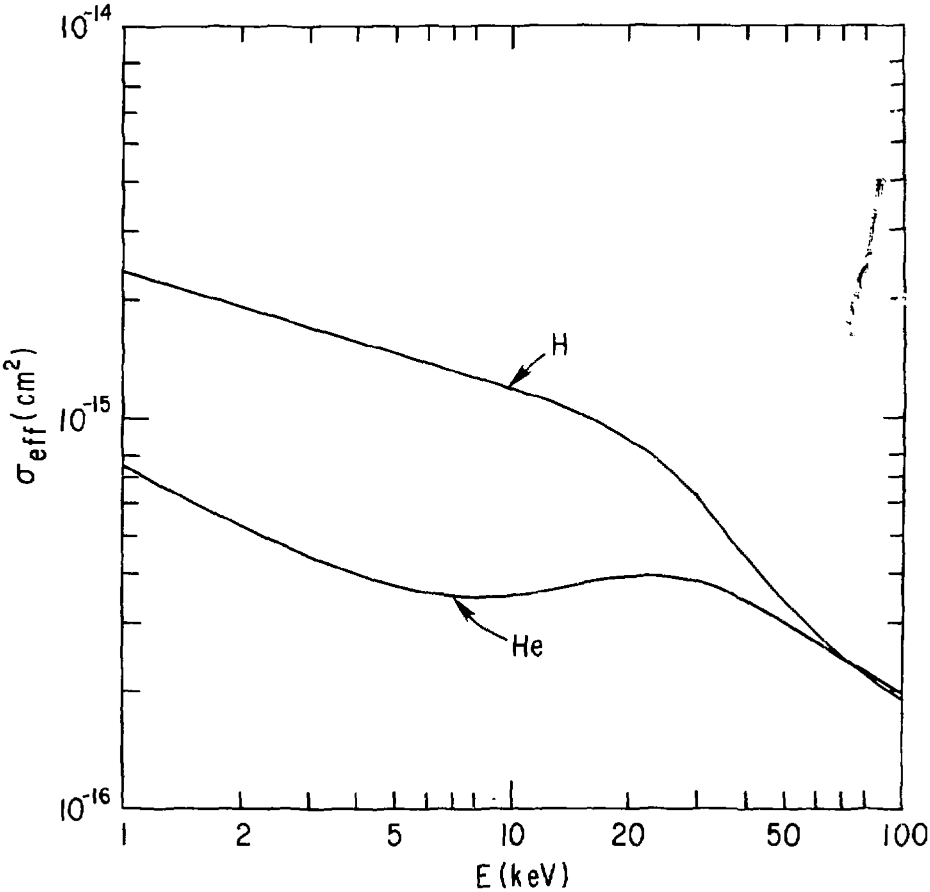

Fig. 3

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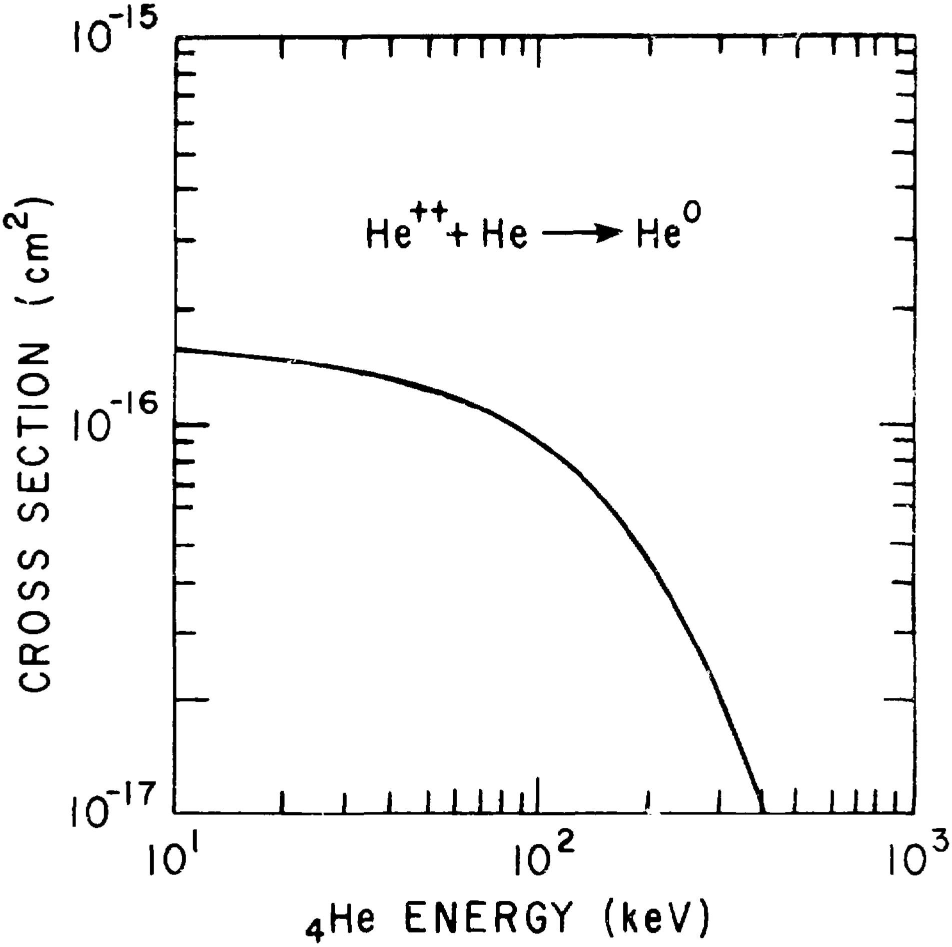

Fig. 4

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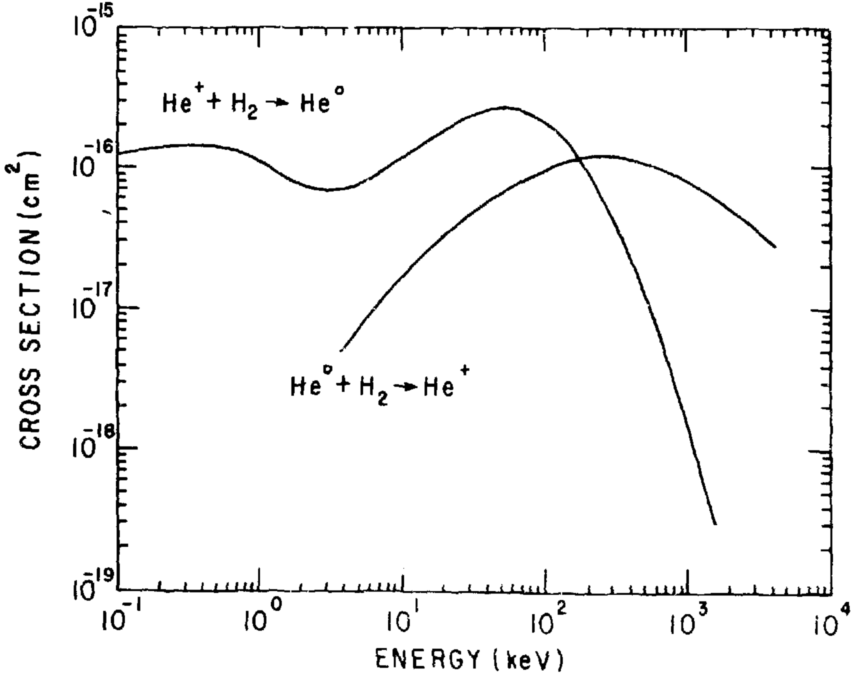

Fig. 5