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MEASUREMENTS OF ENERGETIC HELIUM-3 MINORITY DISTRIBUTIONS DURING
ION CYCLOTRON RADIO-FREQUENCY HEATING IN THE PRINCE ON LARGE TORUS

By

G.W. Hammett, R. Kaita and J.R. Wilson

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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MEASUREMENTS OF ENERGETIC HELIUM-3 MINORITY DISTRIBUTIONS
DURING ION CYCLOTRON RADIO-FREQUENCY HEATING IN
THE PRINCETON LARGE TORUS

G.W. Hammett, R. Kaita, and J.R. Wilson

Princeton Plasma Physics Laboratory
Princeton, NJ 08544, USA

ABSTRACT

Ion cyclotron radio-frequency heating experiments were performed with a ^3He minority ion species in a ^4He majority plasma in the Princeton Large Torus. The energetic ^3He ion "tail" was measured directly with a charge exchange neutral analyzer for the first time. Comparisons with bounce-averaged quasi-linear calculations suggest a modestly peaked radio-frequency power deposition profile. The double charge exchange process $^3\text{He}^{++} + ^4\text{He}^0 \rightarrow ^3\text{He}^0 + ^4\text{He}^{++}$ demonstrated in these measurements may be useful as part of an alpha particle diagnostic in a fusion reactor experiment.

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The most successful heating scheme in the ion cyclotron range of frequencies (ICRF) in the Princeton Large Torus (PLT) has been in the ^3He minority, deuterium (D) majority regime[1,2]. With this radio-frequency (RF) heating method, it is difficult to observe the RF-produced ^3He tail using standard charge exchange techniques because most of the neutrals in the plasma are D^0 , which have only one electron and cannot neutralize the $^3\text{He}^{++}$. Fusion product measurements of the $\text{d}(^3\text{He}, \alpha)\text{p}$ reaction have been used previously to study the ^3He tail[3,4]. Post, Grisham, and Medley[5] proposed to neutralize the energetic $^3\text{He}^{++}$ by double charge exchange with $^4\text{He}^0$ from standard neutral beam injectors. A variant of this method using multi-MeV, $Z > 2$ neutral beams has been proposed for detection of 3.5 MeV alpha particles[6]. The double charge exchange process

has a fairly high cross section (only a factor of about 10 less than the usual $\text{H}^+ + \text{H}^0 \rightarrow \text{H}^0 + \text{H}^+$ cross section) because it is a resonant process. A horizontally scanning, mass-resolving charge exchange neutral analyzer (CENA)[7] was used in the present study (Fig. 1). A vertically scanning mass-analyzed charge exchange diagnostic (MACE), also shown in the figure, was used in conjunction with the CENA to determine the relative concentrations of the various ion species during fundamental minority and second harmonic majority ICRF heating[8]. Because the CENA was not oriented to look across the sight-line of the existing neutral beam injectors on PLT, we decided to use a passive charge exchange version of the Post-Grisham-Medley scheme. By making a ^4He majority plasma instead of a D majority plasma (both species having the same charge-to-mass ratio), we were able to get a large enough $^4\text{He}^0$ background to produce a measurable flux of energetic $^3\text{He}^0$ neutrals to our analyzer.

A bounce-averaged Fokker-Planck program (FPPRF)[8] was used to calculate the distribution function $f(E,u,r,t)$, and integrate along a sightline to simulate the charge exchange spectra. It takes into account collisional energy drag, energy diffusion, and pitch-angle scattering, and uses the FRANTIC code[9,10] for calculating neutral density profiles. The cross sections in this part of the program were modified to allow it to calculate the ${}^4\text{He}$ neutral density profile. The ionization cross section included not only electron impact ionization but also single charge exchange ${}^4\text{He}^{++} + {}^4\text{He}^0 \rightarrow {}^4\text{He}^+ + {}^4\text{He}^+$. A bounce-averaged quasilinear operator[8,11] was used to calculate RF-generated energetic ions. This operator is an extension of Stix's work[12] to include properly the preferential heating of some trapped particles and their production by the RF.

The energetic ${}^3\text{He}^0$ must be reionized before it can be analyzed. As suggested by Post, Grisham, and Medley, H_2 was used in the stripping cell instead of the usual He, because it has a higher cross section for ionizing helium. Operation at higher stripping cell pressures than the original design (increasing the gauge reading from 0.5 to 3.5 millitorr, with a gauge factor of 2.0 for hydrogen) also improved the stripping efficiency. Measurements were also made with a 50 Å carbon foil[13], but the count rate was lower than for a gas stripping cell, probably because of larger scattering losses.

It was necessary to run the charge exchange analyzer at very high magnetic fields (approximately 4.7 kilogauss) to measure ${}^3\text{He}$ up to 150 keV, since the analyzer determines the energy of the incident particles by their radius of curvature in a magnetic field, and the gyroradius of the singly charged ${}^3\text{He}^+$ emerging from the stripping cell is larger than that of a proton with the same energy. Obtaining an adequate signal-to-noise ratio for the ${}^3\text{He}$ measurements was difficult, not only because the charge exchange cross section

is a factor of ten less and the stripping efficiencies are slightly worse than for hydrogen, but also because the X-ray background noise was fairly high, perhaps because of the larger breakdown voltages needed to start up a helium plasma. Nonetheless, data were successfully obtained up to 150 keV for several viewing angles (Fig. 2).

The ^3He spectra measured at three different viewing angles are compared in Fig. 2 to the Fokker-Planck code results assuming a peaked RF power profile (E^+ proportional to $(1-r^2/a^2)^{1/2}$), and in Fig. 3 to calculations for a hollow power profile. The total RF power to the ^3He was 2.1 MW after 15% coupling losses. The ^3He concentration ($n_{^3\text{He}}/n_e$) as measured by the density rise during the ^3He gas puff is 6%. Unlike the case of hydrogen minority heating, one might expect this to be a good measurement because the walls are less likely to absorb helium than hydrogen, a conjecture verified by the measurements of Chrien et al.[14]. Other parameters used for these simulations include: $Z_{\text{eff}} = 3.4$, $Z_I = 6.7$ (which may seem low because it includes contributions from the ^3He), $a = 37$ cm, $R = 136$ cm, $B_{\text{tor}} = 31.04$ kilogauss, $R_{\text{res}} = 143.4$ cm, $I_p = 450$ kA, $V_d = 2.3$ V, and $k_{\parallel} = \pm 0.07$ cm $^{-1}$.

Comparing the ^3He spectra of Figs. 2 and 3 to the hydrogen spectra of Fig. 4 (the Fokker-Planck simulations of Figs. 3 and 4 assuming the same hollow RF power profile) leads to a number of interesting observations. In both cases, the largest charge exchange flux is observed not at the most perpendicular angle, but at an intermediate angle between perpendicular and parallel. This is because ion cyclotron heating tends to produce energetic particles whose banana tips are located near the resonance layer[15], an effect that has been termed "resonance localization"[16]. The anisotropy between different viewing angles is not as strong as in the hydrogen case, consistent with the higher pitch angle scattering rate of ^3He . The ^3He tail

is not as energetic as the H tail, and no "negative temperature" is observed at the peak angle. The scatter in the data near 60 keV is thought to be instrumental, due to a change in the sensitivity across adjoining microchannel plates. This problem was corrected after the present measurements were performed. The Fokker-Planck calculations indicate that the fraction of power lost on unconfined orbits is much less for ^3He (about 10%) than for H (about 75%). (These hydrogen minority experiments were done in a low density and low minority concentration regime, which produced an extremely energetic tail that was poorly confined).

The Fokker-Planck calculations ignore radial transport of fast ions, while there are a number of mechanisms (e. g., sawtooth oscillations, ripple, and large banana width neoclassical effects) which may be playing a very important role. Instead, fast ion transport would be seen as a broadening of the RF power profile in the present model, and the shape of this profile is varied to fit the charge exchange neutral spectrum. The peaked power simulation predicts a perpendicular spectrum with a slightly hotter tail than observed, although the calculated peak angle slope is approximately correct. The broad power simulation (Fig. 3) produces the proper perpendicular slope, but the peak slope is much too energetic. The best fit to the ^3He data lies between these two extremes.

While it was necessary to assume a hollow power profile to fit the H spectra (Fig. 4), the ^3He spectra do not seem to require as much broadening. Not only are unconfined orbit losses smaller for the ^3He case, but the radius of the $q = 1$ surface is also smaller (measured to be $r = 9$ cm, from the inversion radius determined by the electron cyclotron emission diagnostic, versus $r = 15$ cm for the H case). This is because the toroidal field is higher while the plasma current is the same. These observations do not

provide solid evidence that the broad hydrogen RF profile is due to sawtooth and edge drag transport, but they are consistent with this interpretation. On the other hand, low power hydrogen spectra [8] seemed to indicate a broad RF power profile in a case of negligible unconfined orbit losses. A more definite conclusion which can be drawn from these data is that ^3He minority heating is more efficient than H minority heating because ^3He is more collisional, transfers more of its energy to ions instead of electrons, and suffers less from unconfined orbit losses.

In conclusion, the utility of charge exchange neutral particle measurements for the study of ^3He minority ICRF heating has been demonstrated through the first direct measurements of the energetic ion tail, and the results show features consistent with previous measurements during H minority ICRF measurements and quasilinear theory. Other diagnostics useful for studying ^3He ICRF heating include radial fusion product measurements (as demonstrated in PLT)[3,4] and charge exchange recombination spectroscopy[17,18]. Although multi-MeV, $Z > 2$ neutral beams are necessary to diagnose 3.5 MeV alpha particles (because of the sharp decrease in the charge exchange cross section for relative energies above 200 keV), the double charge exchange technique we have demonstrated here could use standard neutral beam injectors to measure these particles once they have slowed down to the 50 to 400 keV range.

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Figure Captions

FIG. 1 Top view of the PLT tokamak and the horizontally scanning charge exchange neutral analyzer. The ^3He spectra were obtained at the CENA positions marked PERP (perpendicular), PEAK (angle with peak signal), and PAR (parallel or tangential). (86X0509)

FIG. 2 Measured ^3He spectra compared with predictions assuming a modestly peaked $E^+(r)$ profile. (86X0499)

FIG. 3 Measured ^3He spectra compared with predictions assuming a hollow $E^+(r)$ profile. (86X0500)

FIG. 4 Measured hydrogen spectra compared with predictions assuming the same hollow $E^+(r)$ profile used in Fig. 3. (86X0513)

Vertically Scanning
Mass Analyzed
Charge Exchange
(MACE) Diagnostic

Fig. 1

#86X0499

Fig. 2

86X0500

Fig. 3

#86X0513

Fig. 4

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