*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.198 (2004)*

Observations of Anisotropic Ion Temperature in the NSTX Edge during RF Heating

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A new spectroscopic diagnostic with both toroidal and poloidal views has been implemented in the edge of the National Spherical Torus Experiment (NSTX)[1]. This edge rotation diagnostic (ERD)[2] was designed to measure the velocity and temperature of ions. The intersection of the diagnostic sightlines with the intrinsic emission shell provides the localization of the measurement. There are 7 toroidally directed views and 6 poloidally directed views of the outboard plasma edge. The poloidal view is ~20 cm (toroidally) from the RF antenna, and the toroidal view is ~2 m away. The sightlines are nearly tangent to the flux surfaces. The C^{2+} triplet near 4651 Å and the He^{+} line at 4685 Å are measured. In the results presented here, helium is the bulk, "working" ion of the discharge.

The NSTX is a large spherical tokamak[3] with a major radius of 0.85 m and a minor radius of 0.65 m. The outer walls and center-stack are lined with protective carbon tiles. Pulse lengths for these NSTX discharges are ~600 ms, with an on-axis toroidal magnetic field of ~0.3 T. The plasma current is 500 kA. The on-axis electron temperature and density are ≤2 keV and $\sim 2\times10^{19}$ m^{-3}, respectively with ≤4.3 MW of High Harmonic Fast Wave (HHFW) Radio Frequency (RF) auxiliary heating.[4]

Observations

During the application of 30 MHz RF power, phased to drive current at a wave number of 7 m^{-1}, distortions to the spectra of both He^{+} (as shown in Fig. 1) and C^{2+} are observed. The distortion is more pronounced in the poloidal view, which is nearer to the antenna, but it is also present in the toroidal view. Under the influence of RF power, the spectra are clearly non-Maxwellian. Fitting the spectra with two Gaussians yields a very accurate representation of the measured data, suggesting that "hot" and "cold" thermal components are present in the distribution. Spatially inverting the data indicates that both populations reside at the same radial location, within a few cm of the plasma edge. The ionization potential of He^{+} ions is ~54 eV.[5] Hence a reasonable ion temperature for He^{+} intrinsic emission is on that order. The hot and cold helium poloidal temperatures at the highest RF input power are ~500 eV and ~50 eV. Fig. 2 shows how the ion temperature and velocity of the hot and cold components vary with the amount of RF power that is applied to the plasma.

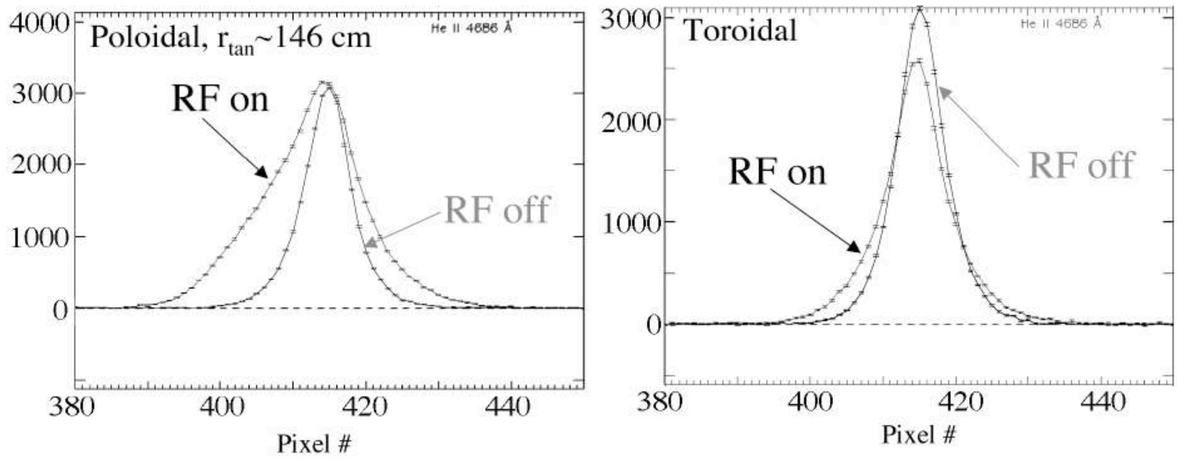

Figure 1: He^+ spectra, fit with two Gaussians, from Shot 110144 during adjacent 10 ms time slices showing the difference in the (a) poloidal view and (b) toroidal view when HHFW RF power is applied.

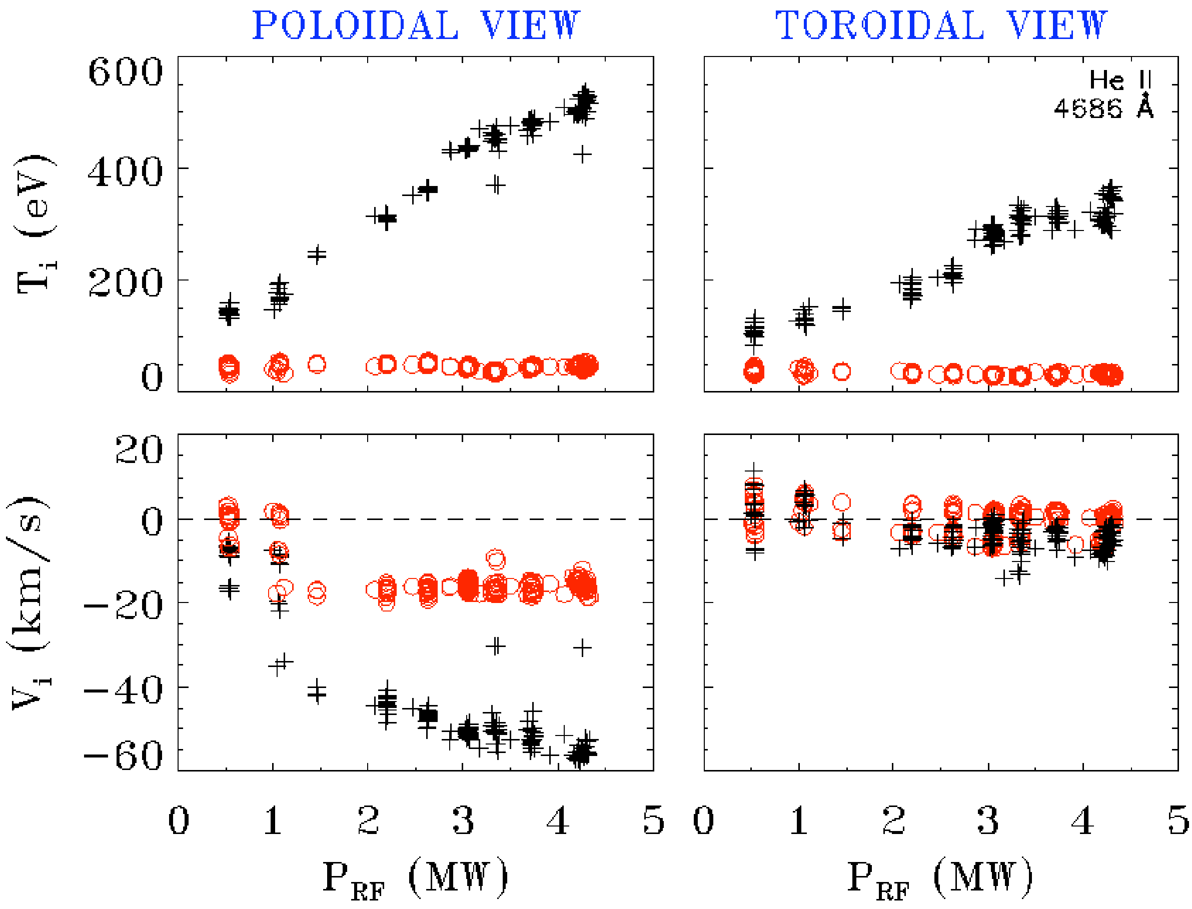

Figure 2: The temperature of the hot component (crosses) scales with P_{RF}, whereas the temperature of the cold component (open circles) is not strongly affected by the amount of RF power applied to the plasma. He^+ data from Shots 110133-110145 are shown.

It is noteworthy that the poloidally and toroidally measured hot components do not have the same ion temperature for a given RF input power. The observed anisotropic temperature is consistent with hot ions having a larger perpendicular energy content. Since the magnetic field lines in the edge of NSTX have a pitch angle of ~28° (as calculated by EFIT equilibrium reconstructions[6]), the poloidal and toroidal ERD views are each sensitive to both the parallel and perpendicular ion velocity distributions. At this *B*-field pitch angle, the poloidal view is more sensitive to the perpendicular velocity distribution. Indeed, the ratio of the poloidal and toroidal temperatures of the hot He^+ is approximately equal to the tangent of the *B*-field pitch angle.

Discussion

The observation of the hot ion component is well correlated to the application of RF power, and the hot ion temperature scales with RF power. The presence of two apparently disparate populations of He^+ ions can be reconciled by the time scales of relevant processes. The time scale for ionization is ~100 μs. However the emission time scale is ~1 ns, implying that light from both populations (hot and cold) would be readily observed, particularly since the time scale for thermalization between two populations of helium ions (at 50 and 500 eV) is ~10 ms. These time scales allow for the observation of the hot He^+ and hot C^{2+} transient states, which are observed then promptly ionized. Interpretation of the heating mechanism is more difficult, since it must account for both He^+ and C^{2+} heating.

The HHFW launched by the NSTX antenna was not expected to heat edge ions, though the expected core electron heating was observed.[7] Resonant heating at the ion cyclotron frequency (27^{th} sub-harmonic of the launched HHFW for helium, and 41^{st} for carbon) is unlikely. One possibility for edge ion heating is parametric decay of the launched HHFW into an Ion Bernstein Wave (IBW) and an ion cyclotron quasi-mode (ICQM).[8] IBW heating occurs in the perpendicular ion distribution, consistent with the observations of anisotropic temperatures. Nonlinear three-wave coupling provides a conversion mechanism for the HHFW into the IBW. Simulations of IBW propagation indicate that all of the IBW power would be absorbed in the outer 10 cm of the plasma, predominantly by fully stripped ions (He^{2+} or C^{6+}), though power would also be absorbed by non-fully stripped ions (e.g. C^{2+}). Measurements made with a Langmuir probe for power levels in excess of 500 kW show side-bands of the pump HHFW, which are consistent with IBW's.

The observed hot ions could be due to charge exchange or recombination or ionization, or some combination of these. One possibility is that the two components of the distribution of He^{+} ions are due to intrinsic emission of He^{+} ions (cold component) and to emission of formerly fully stripped He^{2+} ions (hot component), which have undergone charge exchange with neutral atoms. If the antenna is sourcing atoms, this influx of neutral carbon, among other atoms, could charge exchange with the hot, fully stripped He^{2+} plasma ions, rendering them observable to the diagnostic. Whereas the cold component maintains an ion temperature that is on the same order as the ionization potential of He^{+}, the hot component could be indicative of the ion temperature of fully stripped He^{2+} in the edge of the plasma, which has been heated by the IBW. Heating of solely the fully stripped ions would not immediately account for the observed, elevated C^{2+} ion temperatures, however. Multiple charge exchange interactions between antenna sourced neutrals and fully striped C^{6+} plasma ions to account for the hot component of C^{2+} emission would be unlikely. A more direct heating of the C^{2+} would be expected, perhaps from IBW's. Alternatively, the observed hot C^{2+} and He^{+} could result from ionization and excitation of carbon and helium as they are heated by the RF waves. The induced IBW would have to pass radially through the C^{2+} shell (possibly depositing energy) before reaching and absorbing on the He^{+} ions.

In summary, edge ion heating is observed when HHFW RF power is applied to NSTX plasmas. Parametric decay of the HHFW into an IBW is a possible candidate for the heating mechanism. Details of the heating mechanism are the subject of ongoing investigations.

Acknowledgements

The authors wish to recognize the many contributions of the NSTX group and collaborators at Oak Ridge National Lab. Thanks also to Steve Sabbagh of Columbia University for providing the EFIT reconstructions. This research was supported by the U.S. D.O.E. under contract: DE-AC02-76CH03073.

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