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PPPL-4012

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October 2004

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

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

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(Dated: October 6, 2004)

A new spectroscopic diagnostic on the National Spherical Torus Experiment (NSTX) measures the velocity distribution of ions in the plasma edge with both poloidal and toroidal views. An anisotropic ion temperature is measured during the presence of high power High Harmonic Fast Wave (HHFW) Radio Frequency (RF) heating in helium plasmas, with the poloidal ion temperature roughly twice the toroidal ion temperature. Moreover, the measured spectral distribution suggests that two populations are present and have temperatures of 500 eV and 50 eV with rotation velocities of -50 km/s and -10 km/s, respectively. This bi-modal distribution is observed in both the toroidal and poloidal views (in both He^{+} and C^{2+} ions), and is well correlated with the period of RF power application to the plasma. The temperature of the hot edge ions is observed to increase with the applied RF power, which was scanned between 0 and 4.3 MW. The ion heating mechanism is likely to be Ion Bernstein Waves (IBW) from nonlinear decay of the launched HHFW.

Radio frequency (RF) waves are important tools in studying and producing magnetically confined, fusion-grade plasmas such as those in the National Sperical Torus Experiment (NSTX)[1]. Depending on the phase of the launched wave, RF power can be used to tailor either the current-density profile (current drive) or the temperature profile (plasma heating). Moreover, the efficiency of launching waves into the plasma relies on the plasma-antenna coupling. The plasma environment directly in front of the antenna can itself be affected by the input of high power RF waves. The High Harmonic Fast Wave (HHFW) launched by the NSTX antenna is expected (and observed) to heat core electrons, but for the plasma parameters discussed here, the plasma ions should be unaffected[2].

A new spectroscopic diagnostic with both toroidal and poloidal views has been implemented in the edge of the NSTX. This edge rotation diagnostic (ERD)[3] was designed to measure the velocity and temperature of ions. The ERD measures the intrinsic emission of light from the plasma edge. The intersection of the diagnostic sightline 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 $\sim$ 20 cm (toroidally) from the RF antenna, and the toroidal view is $\sim$ 2 m away. The sightlines are nearly tangent to the flux surfaces. The C^{2+} triplet near 4650 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 National Spherical Torus Experiment is a large spherical tokamak[4] 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 considered here are $\simeq$ 600 ms, with an on-axis toroidal magnetic field of $\sim$ 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 $\leq$ 4.3 MW of HHFW RF auxiliary power[5].

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[6]. The distortion is more pronounced in the poloidal view, but it is also present in the toroidal view. Under the influence of RF power, the spectra are clearly non-Maxwellian. Fitting the spectrum with two Gaussians yields a very accurate representation of the measured data, as shown in Fig. 2, 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. In addition to the results presented here, this edge ion heating has been observed at various plasma currents and magnetic field strengths on NSTX; in upper-single, double, and lower-single null configurations; when the antenna is phased for co-current drive, counter-current drive, and heating; at wave numbers of 3.5, 7, and 14 m^{-1}; and in He and D_2 fueled discharges. This heating is not observed without RF application, i.e. in ohmic or neutral beam heated discharges.

Fig. 3 shows the time evolution of NSTX Shot 110144; 4.3 MW of HHFW power is applied from 60 to 460 ms. The effect of the RF heating is apparent in the edge measured brightness, velocity, and rotation. After the RF is applied, $\sim$ 100 ms are needed to establish a new equilibrium rotation, as indicated by the velocity trace. Once an equilibrium is established, however, the plasma is very robust, as indicated by the near constant levels of velocity and temperature. When the RF heating is terminated, the hot component disappears promptly from the plasma.

Fig. 4 shows how the ion temperature and velocity, T_i and v, of the hot and cold components vary with the

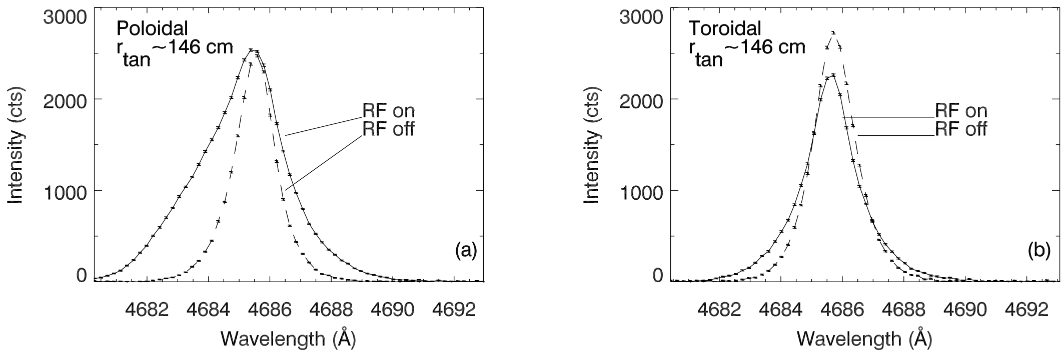

FIG. 1: The He^+ spectrum from Shot 110144 during adjacent 10 ms time slices (centered on 455 and 465 ms), showing the difference in the (a) poloidal view and (b) toroidal view when HHFW RF heating is applied to the plasma. RF heating (4.3 MW) ends at 460 ms. Both views are tangent to the flux surface at $\sim$ 146 cm. Error bars indicate statistical uncertainty.

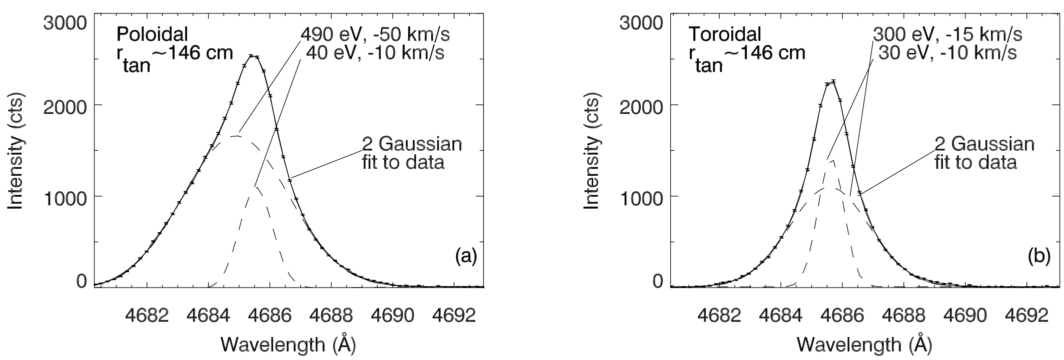

FIG. 2: The He^+ spectrum under the influence of RF heating, fit with two Gaussians, for the (a) poloidal view and (b) toroidal view.

amount of RF power that is applied to the plasma. The ionization potential of He^+ ions is $\sim$54 eV[7]. Hence a reasonable ion temperature for He^+ is on that order. The hot and cold helium poloidal temperatures at the highest RF input power are $\sim$500 eV and $\sim$ 50 eV.

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 $\sim$ 28^o (as calculated by EFIT equilibrium reconstructions[8]), the poloidal and toroidal ERD views are each sensitive to both the parallel and perpendicular (to the field) ion velocity distributions. At this 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 magnetic field pitch angle, $tan\theta_p \sim T_{pol.}/T_{tor.}$.

The observation of the hot 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 thermalization between these two populations of helium ions is $\sim$ 10 ms, which is much longer than the time scale for ionization, $\sim$ 100 μs. The emission time scale is $\sim$ 1 ns, implying that light from both populations (hot and cold) would be readily observed. 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[2]. 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

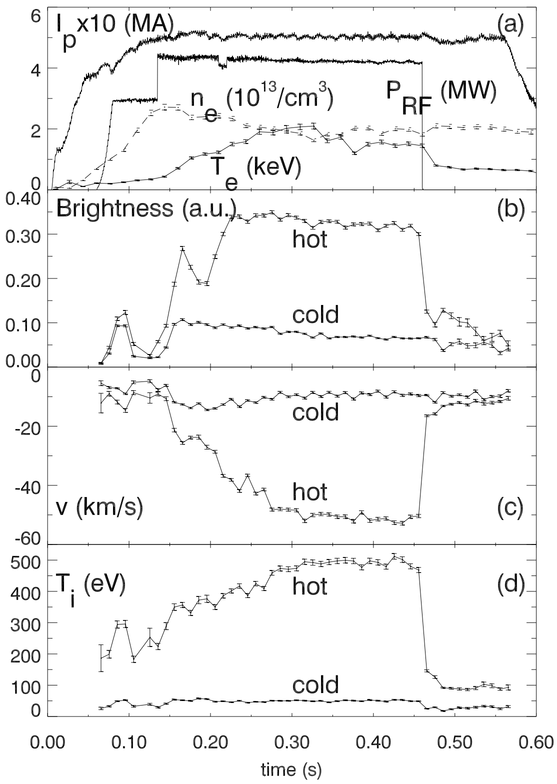

FIG. 3: Time evolution of NSTX Shot 110144, showing (a) I_p, T_e, n_e, and P_{RF} and the hot and cold components of poloidally measured He^+ (b) brightness, (c) velocity, and (d) temperature at a tangency radius of 146 cm. At 100 ms the plasma outer gap increases to 10 cm, reducing the antenna-plasma coupling, but by 200 ms the outer gap is stable at 4 cm.

(IBW) and an ion quasi-mode at the fundamental ion cyclotron resonance[9]. 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 in these plasmas indicates 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+}). In Fig. 5, measurements made with a Langmuir probe in the periphery of the NSTX plasma (2.5 cm outside of the surface bounded by the face of the HHFW antenna) for HHFW power levels in excess of 500 kW show sidebands of the pump HHFW, which are consistent with IBW's[10, 11]. As the launched HHFW power increases the number of side bands also increases, corresponding to higher harmonics of the ion cyclotron quasi-mode resonating at increasing depth in the edge of the plasma.

The observed hot edge ions could be due to charge exchange or recombination or ionization, or some com-

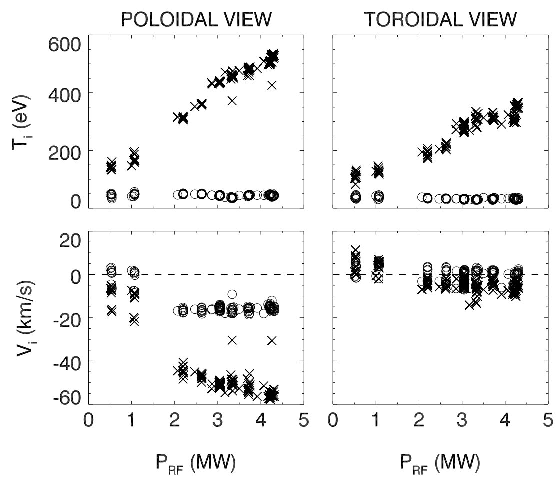

FIG. 4: The temperature of the "hot" component (crosses) scales with P_{RF}, whereas the temperature of the "cold" component (open circles) is not effected by the amount of RF power applied to the plasma. He^+ data from Shots 110133-110145 are shown. In the toroidal view, a + velocity is in the same direction as the plasma current but in the opposite direction to the toroidal magnetic field, while in the poloidal view a + velocity is downward on the outboard midplane, which is in the same direction as the poloidal magnetic field.

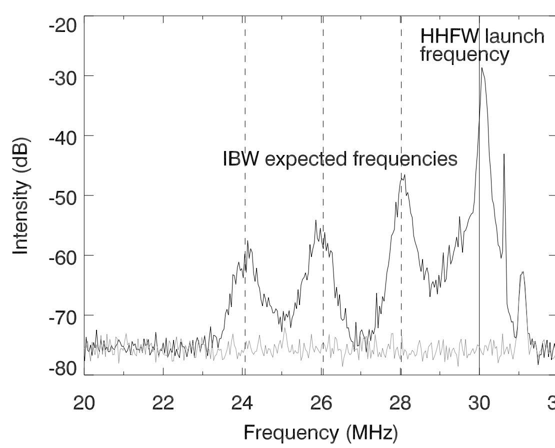

FIG. 5: The frequency spectrum of deuterium shot 112728 (in black) measured by a Langmuir probe near the RF antenna shows the 1 MW launched HHFW (solid vertical line indicates 30 MHz), which has been attenuated with a notch filter by 40 dB, and the detected daughter IBW's (dashed vertical lines indicate the expected IBW frequencies from the first 3 harmonics of the ion cyclotron quasi-mode.) The measured spectrum from shot 112727 (in grey), shows the background level for an ohmic, i.e. no-RF power, discharge. The small peak at 31 MHz is pick-up from a heterodyne network, and is present in both discharges.

bination 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. 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 IBWs. 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, while HHFW RF power is applied to NSTX plasmas, it is observed that the velocity distribution of edge ions is significantly affected. Measured by a new diagnostic, which is sensitive to the intrinsic emission of light toroidally and poloidally from the plasma edge, the He^+ and C^{2+} light from a helium plasma apparently adopts a bi-modal distribution function, with hot and cold components. The cold component is likely representative of the dynamics of intrinsic He^+ ions, and the hot component likely represents a transient state of He^+ ions that have been intensely heated by the RF. This interpretation is consistent with calculations of the thermalization time scale between the two populations as compared to the ionization and emission time scales. The hot ions are ionized before they can reach thermal equilibrium, and both hot and cold ions have sufficient time to emit. The temperature of the hot component scales as P_{RF}, while the cold component temperature remains relatively constant. Under this interpretation, the hot ions are observed to have anisotropic parallel and perpendicular temperatures, for a given RF power input. The anisotropy and edge localization is consistent with parametric decay of the launched HHFW through nonlinear three-wave coupling into an IBW, which has been observed on a Langmuir probe.

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, and Benoit LeBlanc of PPPL for Thomson scattering data. This research was supported by the U.S. D.O.E. under contract: DE-AC02-76CH03073.

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