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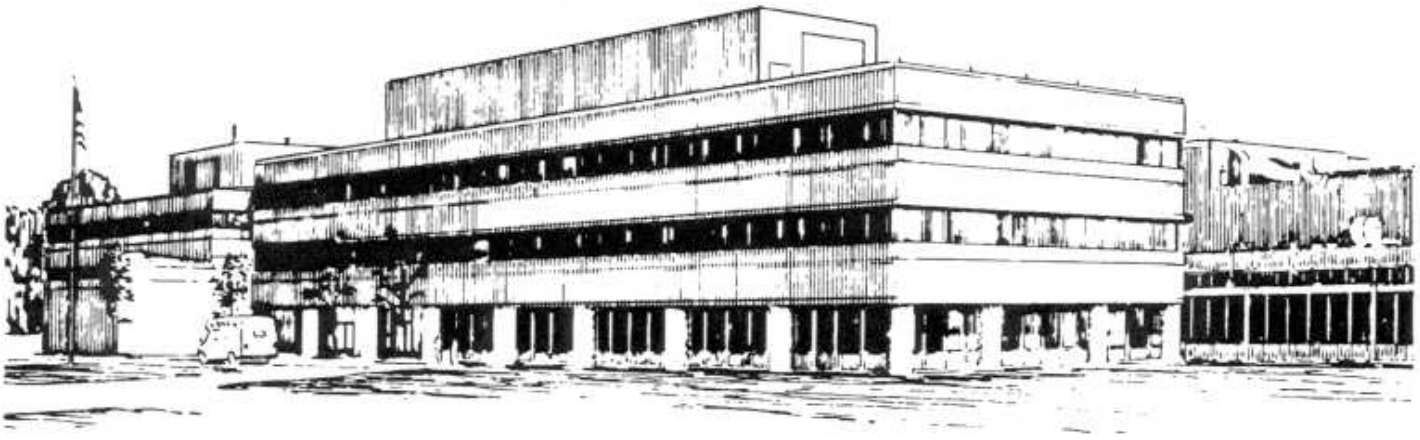

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Results of High Harmonic Fast Wave Heating Experiments on NSTX*

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1. Introduction

The study of high harmonic fast wave (HHFW) heating and current drive is being conducted on the NSTX device to determine the physics of applying RF waves at high harmonics (~ 10-20) of the ion cyclotron frequency in this high β plasma regime and to extend the performance of the NSTX plasma. The magnetic field of this low aspect ratio device is lower (≤ 0.35 T for this work) than that for the typical moderate aspect ratio tokamak regime by about an order of magnitude and the plasma densities achieved are typically in the mid 10^{19} m^{-3} range. Thus, the dielectric constant of the plasma, $\varepsilon \equiv \omega_{pe}^2/\omega_{ce}^2$, is of order ~ 50-100 resulting in wave physics properties which favor electron heating by TTMP and Landau damping [1]. RF power is applied on NSTX at 30 MHz using an antenna array with 12 current straps aligned in the poloidal direction. The antenna can be phased to launch waves with toroidal wave numbers, k_T, between 2 m^{-1} and 14 m^{-1} and can be phased for current drive with peak toroidal directionality at 7 m^{-1}. To date most of the HHFW experiments have been carried out using k_T = 14 m^{-1} with 0–π–0–π–... phasing of the strap currents. The diagnostic complement on NSTX includes a 30-Hz, 10-spatial-channel Thomson scattering (MPTS) system for measuring profiles of electron temperature T_e and density n_e every 33 msec and a charge-exchange recombination spectroscopy (CHERS) system for measuring profiles of the impurity ion temperature T_i and toroidal rotation V_T during a neutral beam blip. Strong electron and ion heating are observed in helium discharges whereas the heating efficiency is noticeably reduced for deuterium discharges. A detailed comparison between helium and deuterium discharge responses at k_T = 14 m^{-1} is presented here. Also, initial results for different RF phasing and start-up assist experiments will be discussed briefly.

2. Helium and Deuterium Heating with k_T = 14 m^{-1}

Electron response: The HHFW heating results reported earlier for helium discharge conditions on NSTX showed very strong electron heating [2]. With P_{RF} = 2.3 MW applied during the current flat top of a discharge with I_P = 0.7 MA, B_T = 0.3 T and $n_e(0) \approx 4 \times 10^{19} m^{-1}$, the central electron temperature, $T_e(0)$, was observed to increase from ~ 400 eV to ~ 900 eV with very little change in plasma density and only ~ 10% power radiated. At somewhat higher RF power, magnetic equilibrium measurements showed values of plasma stored

energy up to 59 kJ as compared with 43 kJ for the ohmic case, corresponding to a toroidal $\beta_T = 10\%$ and a $\beta_N = 2.7$. Noticeably less efficient electron heating was observed for deuterium discharges.

In the earlier results, an m =1/n = 1 MHD instability persisted throughout the flat top of the discharge current. This caused a flattening of the T_e and n_e profiles in both the ohmic and RF heated discharges. This instability effect made it difficult to determine if RF power deposition, which is predicted to peak at ~ 2/3 of the plasma minor radius [3,4,5], is also contributing to the flattening in the RF heated case. More recently, better control of the discharge conditions and operation in a single-null divertor configuration has provided discharges with the m = 1 mode onset pushed to much later in the current flat top phase. Figure 1 demonstrates that prior to the onset of the m = 1 mode, $T_e(0)$ peaks up to ~ 1.15 keV at t = 0.197 sec from the ohmic value of ~ 0.5 keV with P_{RF} = 1.8 MW. The corresponding electron temperature profiles [6] are peaked for the RF case and flat in the core for the ohmic case. The density profile is broadened in the RF case. Outboard RF power deposition may be contributing to the density broadening but the peaking of the temperature profiles suggest a possible pinch effect in the energy transport. Further experimentation and analysis are planned to directly measure the RF deposition profile and to determine the underlying transport properties of the discharge.

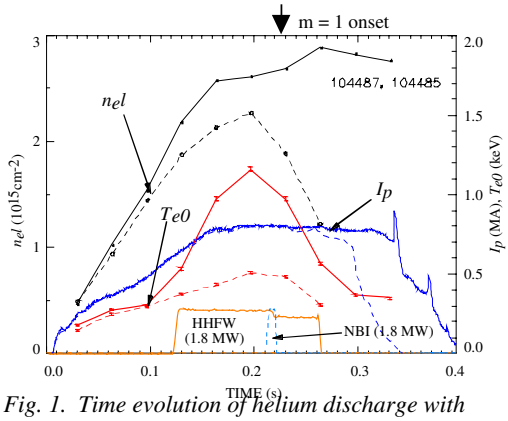

Fig. 1. Time evolution of helium discharge with P_{RF} = 1.8 MW (solid) compared with ohmic-only case (dashed). B_T = 0.35 T, δ_A = 3 cm.

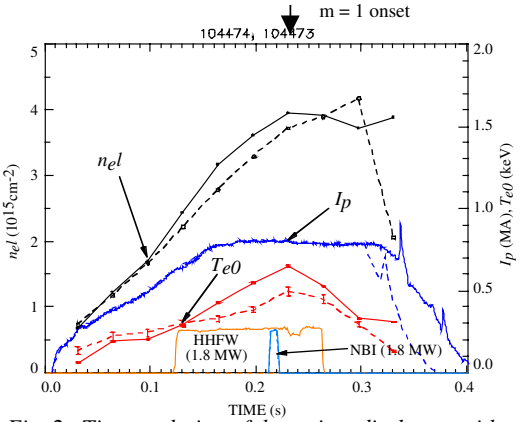

Fig. 2. Time evolution of deuterium discharge with P_{RF} = 1.8 MW (solid) compared with ohmic-only case (dashed). B_T = 0.35 T, δ_A = 4 cm.

The response of the electrons for deuterium discharges in the absence of the m = 1 instability is shown in Fig. 2. The experimental conditions are essentially the same as in the helium case of Fig. 1 except for a somewhat higher density level and a slightly larger antenna gap ($\delta_A \approx 4$ cm). It is clear that the $T_e(0)$ is less for deuterium at the same P_{RF}, peaking up to ~ 0.55 keV from ~ 0.4 keV at t = 0.197 sec. The T_e and n_e profiles in this case [6] are peaked for the ohmic and RF cases but both profiles broaden with the application of RF power. This broadening may indicate more peripheral RF power deposition for deuterium and/or the absence of a strong pinch effect in the electron energy transport.

The kinetic measurements of stored electron energy at t = 0.197 sec show an increase of ~ 11 kJ for helium and 6 kJ for deuterium. Thus, with regard to electron heating, HHFW heating appears to be ~ 2 times as efficient for helium as for deuterium for these results.

Ion response: The CHERS system has come on line and has enabled ion temperature profiles to be measured for the conditions of Figs. 1 and 2 as shown in Fig. 3. (Note that for the helium RF heated case the RF power is reduced from that for Fig. 1 to 1.4 MW.) Short 10 msec neutral beam pulses were injected at t = 0.21 sec to permit these measurements (see Figs. 1 and 2). Due to low carbon levels for the ohmic cases, error bars are large in the plasma periphery so that ohmic T_i values are shown only in the core plasma for comparison to the RFheated cases. A T_i increase comparable to the T_e increase is observed for both helium and deuterium, taking into account that T_e is measured at t = 0.197 sec and T_i at t = 0.21 - 0.22 sec with the beam power added. (The next T_e profile at t = 0.230 sec brackets the T_i profile.) Thus it would appear that the overall plasma stored energy increase measured kinetically is also about a factor of 2 higher for helium.

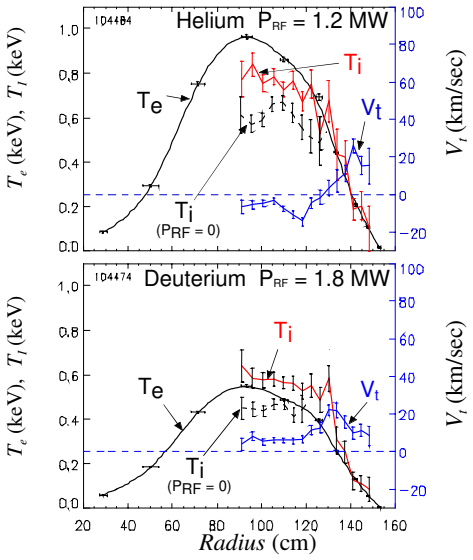

Fig 3. $T_i(R)$ and $V_t(R)$ profiles for t = 0.215 sec for conditions of Figs. 2 and 3. $T_e(R)$ profiles at t = 0.197 sec are shown for comparison.

It is interesting to note that there appears to be a steepening of the T_i profiles in the vicinity of R = 130 cm in Fig. 3 and that toroidal rotation V_T peaks there.

Possible energy loss mechanisms: The reduced stored energy for deuterium relative to that for helium may be due to different confinement properties. However, possible RF effects are also being considered: hydrogen minority ion heating (ω_{CH} ~ 7 x ω), turbulence scattering of the HHFW [7], and possibly surface wave/sheath excitation/damping due to the large magnetic field pitch at the antenna. Future research will be directed toward discerning the dominant mechanism(s) involved.

3. Other Heating Experiments

Heating with a fast wave spectrum k_T = 7 m^{-1} in deuterium: Preliminary kinetic electron and magnetic plasma stored energy results have been obtained for P_{RF} = 2.5 MW applied to a deuterium discharge using a fast spectrum k_T = 7 m^{-1} with symmetrical (heating) phasing and with directed co – CD phasing, and compared with the slow spectrum k_T = 14 m^{-1} heating case. Whereas the magnetic stored energy increase is found to be the same for the three cases, the electron energy increase is significantly larger for the slower toroidal phase velocity case: $T_e(0)$ up to ~ 0.6 keV for k_T = 14 m^{-1} versus ~ 0.5 keV for both the 7 m^{-1} cases. The linear theory predicts strong absorption for all three cases and does not predict strong ion

absorption. Again, further study is required to discern the causes for this difference in electron response.

Heating during I_p ramp-up: HHFW power has been applied during the plasma current ramp-up in an attempt to slow down the current diffusion and improve the MHD properties [8]. It is observed that when the antenna gap is large, δ_A ~ 12 cm, a large increase in the plasma density results with central values reaching NSTX record levels of 8 x 10^{19} m^{-3}. Figure 4 shows the time evolution of such a discharge. As the density increases by a factor of ~ 8, $T_e(0)$ nearly doubles from 130 to 240 eV. The density rise occurs without gas injection. Spectroscopy and x ray measurements indicate that Z_{eff} remains at a value of ~ 1.75 during the RF pulse. The desired effect of slowing the current penetration is observed. The central q remains above 1.4 instead of dropping below 1 and the plasma internal inductance l_i remains at ~ 0.5 instead of increasing with time.

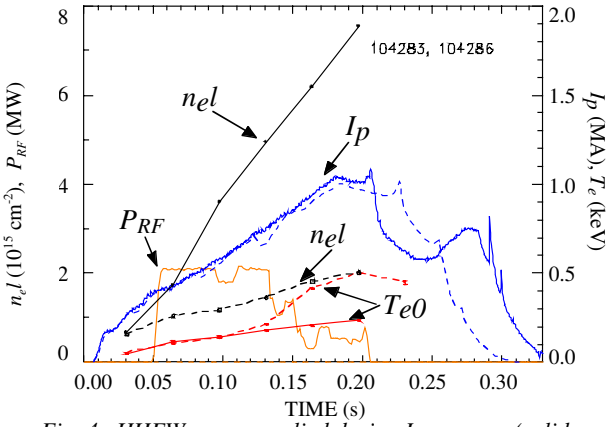

Fig. 4. HHFW power applied during I_p ramp-up (solid line) and reference plasma (dotted line).

4. Summary

Significant HHFW heating has been observed under several conditions on NSTX. The strongest heating has been observed for helium plasmas with the RF antenna phased to launch a slow antenna spectrum k_T = 14 m^{-1}. A peaked T_e profile, with $T_e(0)$ more than doubling to 1.15 keV at $n_e(0)$ = 2.8 x 10^{19} m^{-3}, is obtained at P_{RF} = 1.8 MW when the m = 1 MHD instability is avoided. The lower stored energy increases observed in deuterium suggest the power may be being deposited in the periphery of the plasma in addition to the confinement being generally lower. Heating during the plasma current ramp-up has been used successfully to slow the current penetration and surprisingly to dramatically raise $n_e(0)$ to ~ 8 x 10^{19} m^{-3} while doubling $T_e(0)$ from ~140 eV to 240 eV. Future work will focus on direct experimental determination of the RF power deposition characteristics and comparison with theory/modeling to help separate transport and RF effects on heating, and on studies of HHFW driven plasma current.

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