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Recent Improvements in Fast Wave Heating in NSTX

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Abstract. Recent improvements in high-harmonic fast wave (HHFW) core heating in NSTX are attributed to using lithium conditioning, and other wall conditioning techniques, to move the onset density for perpendicular fast wave propagation further from the antenna. This has resulted in the first observation of HHFW core electron heating in deuterium plasma at a launched toroidal wavenumber, k_ϕ = -3 m^{-1}, NSTX record core electron temperatures of 5 keV in helium and deuterium discharges and, for the first time, significant HHFW core electron heating of deuterium neutral-beam-fuelled H-mode plasmas. Also, k_ϕ = -8 m^{-1} heating of the plasma start-up and plasma current ramp-up has resulted in significant core electron heating, even at central electron densities as low as ~ $4x10^{18}$ m^{-3}.

Keywords: Spherical Torus, RF Heating, Electron Energy and Confinement Time
PACS: 52.50.Qt, 52.55.Hc

I. INTRODUCTION

High-harmonic fast wave (HHFW) heating and current drive are being studied in NSTX to provide efficient core electron heating, and q(0) control, during long-pulse H-mode plasmas fuelled by deuterium neutral beam injection (NBI), and to generate bootstrap current overdrive during non-inductive plasma current (I_p) ramp-up [1]. The 12-element HHFW antenna in NSTX provides a well-defined spectrum of directed waves with launched toroidal wavenumbers, k_ϕ = ±13 m^{-1}, ±8 m^{-1} and ±3 m^{-1}, when the phase difference ($\Delta\phi$) between adjacent antenna elements is ±150°, ±90° and ±30°, respectively [2]. Recent significant improvements in HHFW core electron heating are attributed to moving the onset density for perpendicular fast wave propagation farther from the antenna Faraday screen and first wall [3-5]. In deuterium plasmas, lithium wall conditioning [6] has been used to reduce the edge density, and has resulted in first clear observation of k_ϕ = -3 m^{-1} HHFW core electron heating. Also, record NSTX central electron temperatures of 5 keV have been measured with 3.1 MW of k_ϕ = -8 m^{-1} power in both helium and deuterium L-mode discharges. These L-mode results are presented in section II. Significant core electron heating of lithium-conditioned, deuterium NBI-fuelled H-mode plasmas has been measured for the first time and these results are presented in Section III. Finally, as discussed in section IV, k_ϕ = -8 m^{-1} heating of plasma start-up and I_p ramp-up have also benefited from lithium wall conditioning, resulting in HHFW core electron heating even at densities as low as $n_e(0) \sim 4 \times 10^{18}$ m^{-3}.

II. IMPROVED HEATING OF DEUTERIUM L-MODE PLASMAS

Lithium wall conditioning significantly improved HHFW heating efficiency in deuterium L-mode plasmas, especially at longer launched wavelengths. Improvements in core electron heating efficiency at k_ϕ = -8 m^{-1} resulted in NSTX record $T_e(0)$ values of 5 keV when 3.1 MW of RF power was coupled into both helium and deuterium plasmas, as shown in Fig. 1. T_e profiles became very peaked, with the T_e profile being broader in deuterium, with a steeper T_e gradient, probably due to the development of a reversed-shear q profile [7, 8]. Antenna $\Delta\phi$ values with higher k_ϕ spectra resulted in more centrally peaked T_e profiles and faster $T_e(0)$ increases, while antenna $\Delta\phi$ values with lower k_ϕ spectra had increased $n_e(0)$. A degradation in heating efficiency with increased launched wavelength was observed, that was similar to the degradation measured for helium plasmas [4], except that in deuterium no core electron heating was measured at k_ϕ = -3 m^{-1} until 20 mg/min of lithium wall conditioning was used. Wall conditioning reduced the density in front of the antenna sufficiently to allow the first significant k_ϕ = -3 m^{-1} core electron heating to be measured in NSTX deuterium plasmas (Fig. 2). However the heating efficiency at k_ϕ = -3 m^{-1} was still reduced compared to the efficiency obtained at higher k_ϕ since the amount of lithium used was not sufficient to move the fast wave onset density away from the antenna.

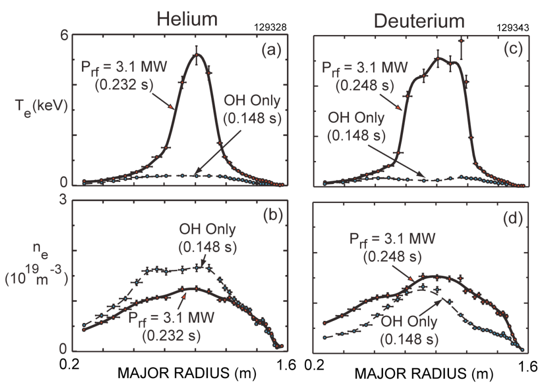

Figure 1. T_e and n_e profiles measured by MPTS during k_ϕ = -8 m^{-1} HHFW heating of helium [(a) and (b)] and deuterium [(c) and (d)] L-mode plasmas show NSTX record $T_e(0)$ = 5 keV. T_e and n_e profiles measured immediately prior to the start of HHFW heating are also plotted for comparison.

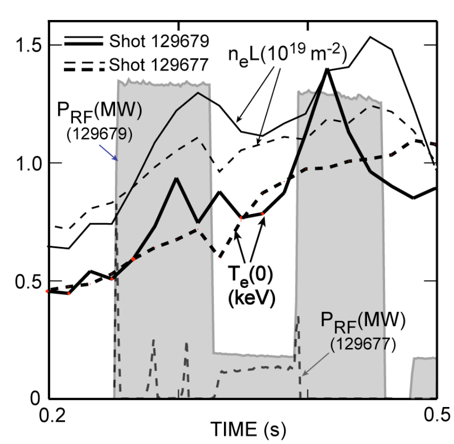

Figure 2. $T_e(0)$ and n_eL evolution measured by multi-point laser Thomson scattering (MPTS) for two similar deuterium L-mode plasmas with 20 mg/min of lithium wall conditioning. Shot 129679 (solid lines) had up to 1.3 MW of k_ϕ = -3 m^{-1} RF power (shaded region). Shot 129677 (dashed lines) had less than 150 kW of RF power.

III. HEATING OF DEUTERIUM NBI H-MODE PLASMAS

Earlier attempts to couple HHFW power into deuterium NBI-fuelled H-mode plasmas in NSTX resulted in edge ion heating, but no core heating [9]. Recently, experiments using lithium conditioning to reduce the scrape-off density in front of the antenna produced the first HHFW-heated deuterium NBI H-mode plasmas that show clear evidence of core electron heating, with $T_e(0)$ increasing from 1.2 to 1.8 keV when 1.8 MW of k_ϕ = 14 m^{-1} + 18 m^{-1} heating was coupled into a plasma fuelled by 2 MW of NBI, as shown in Fig. 3. RF power used in these experiments was limited to 2 MW due to the reduced loading resulting from the need to use a relatively large plasma-antenna gaps (6-7 cm at k_ϕ = -13 m^{-1} and 8-9 cm at -8 m^{-1}) to avoid interaction between fast NBI ions and the antenna at smaller plasma-antenna gaps. Less core electron heating was measured at k_ϕ = -8 m^{-1} than at k_ϕ = -13 m^{-1}, consistent with the heating efficiency results measured in L-mode plasmas. Edge localized modes (ELMs) were more frequently seen during k_ϕ = -8 m^{-1} heating than during k_ϕ = -13 m^{-1} heating, and there is evidence that RF arcs in the antenna may trigger large ELMs [5].

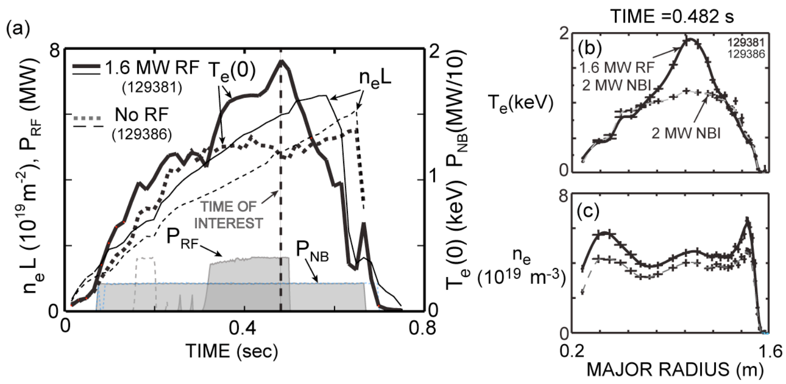

Figure 3. (a) Time evolution of $T_e(0)$ and n_eL, measured by MPTS for two similar plasmas with 2 MW of deuterium NBI. One of the plasmas has 1.8 MW of 14 m^{-1} + 18 m^{-1} ($\Delta\phi$ = 180°) RF power coupled between 0.3 and 0.5 seconds (solid lines). (b) T_e and (c) n_e profiles measured by MPTS at 0.482 seconds.

The RF power deposition calculated by GENRAY [10] for NSTX NBI H-Mode plasmas is much broader than for Ohmically-heated L-mode plasmas, for both k_ϕ = -8 and -13 m^{-1} heating, as shown in Fig. 4. GENRAY predicts about 70-80% of the RF power is damped on electrons with the remaining power deposited on slowing NBI ions. A time-dependent analysis using the TRANSP plasma transport code and a non-self consistent TORIC RF package predicts the fraction of RF power deposited to slowing NBI ions decreases from 50% to 25% during the duration of the RF pulse [11].

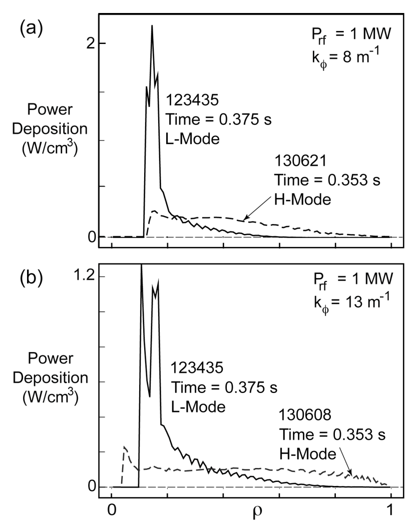

Figure 4. Power deposition profile calculated by GENRAY for an L-mode and H-mode plasma with 1 MW of (a) k_ϕ = -8 m^{-1} and (b) k_ϕ = -13 m^{-1} heating.

A double-feed antenna upgrade installed for the 2009 run campaign should allow higher power coupling to H-mode plasmas and an ELM discrimination and/or resilience upgrade of the HHFW heating system is planned for 2010-11.

IV. HEATING OF START-UP AND RAMP-UP PLASMAS

In solenoid-free scenarios, HHFW-generated bootstrap current I_p ramp-up to over 400 kA is required in order to provide sufficient current to confine NBI ions in NSTX. Recent experiments have successfully coupled $k_\phi = -8\ m^{-1}$ power into lithium-conditioned deuterium plasmas at low $T_e(0)$ and I_p. 550 kW of RF power coupled between 9 and 22 ms during the initiation of a discharge by Coaxial Helicity Injection (CHI) [12] increased $T_e(0)$ from 3 to 15 eV when $n_e(0) \sim 4\times10^{18} m^{-3}$. 550 kW of RF power coupled between 20 and 64 ms after the start of a hollow T_e profile CHI plasma increased $T_e(0)$ from 3 to 33 eV, although the T_e profile remained hollow [Fig. 5(a) and 5(b)]. 1.1 MW of RF power was coupled between 65 and 120 ms, during the Ohmically-heated I_p ramp-up phase, and increased $T_e(0)$ from 140 to 700 eV, at a time when $n_e(0) \sim 6\text{-}9\ \times10^{18} m^{-3}$ [Fig. 5(c) and 5(d)]. With the addition of RF heating the T_e profile went from hollow to very peaked.

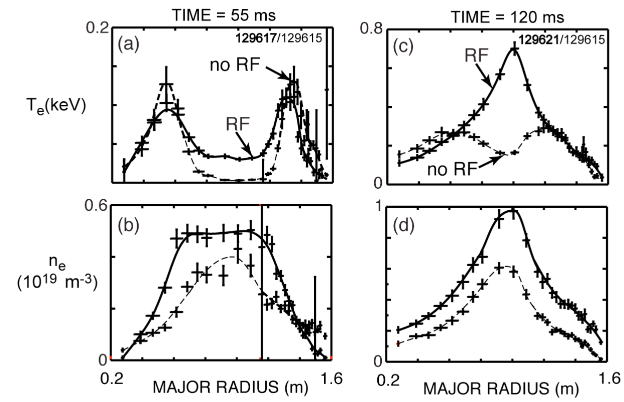

Figure 5. (a) T_e and (b) n_e profiles measured at 55 ms by MPTS when 550 kW of $k_\phi = -8\ m^{-1}$ RF power is coupled into a CHI start-up plasma from 20-64 ms. (c) T_e and (d) n_e profiles at 120 ms after 1.1 MW of $k_\phi = -8\ m^{-1}$ RF power is coupled into a plasma from 65-120 ms, when I_p is ramping from 300 to 500 kA.

ACKNOWLEDGMENTS

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