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Analysis of High-T_e Plasmas Heated by HHFW in NSTX

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Abstract. The implementation in TRANSP of a recent version of TORIC capable of calculating power deposition for HHFW conditions is used to analyze NSTX plasma under different operating conditions. The power deposition profile into the electrons is obtained for high-T_e conditions – $T_e \leq$ 5keV – obtained in He and D plasmas with ITB. HHFW heating of NBI-induced H-mode plasmas is discussed. At the RF onset the RF power is divided evenly between the electrons and the fast particles, but as the latter thermalize and the electron density increases, the HHFW power repartition shifts progressively toward the electrons. Power deposition profiles for the electrons and for the fast particles are shown.

Keywords: NSTX HHFW NBI
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INTRODUCTION

High-Harmonics Fast-Wave (HHFW) heating[1] continues supporting NSTX research and significant experimental progress has been achieved. Electron temperatures in the 4-5keV range have been reproducibly obtained in two regimes: one with centrally peaked T_e (R) profile and the other with a T_e internal transport barrier (ITB). These plasmas have been the subjects of turbulence and electron transport studies[2,3]. Further progress has been achieved toward the goal of current drive during the effective coupling and electron heating using a co-current directed $k_{//}$=-8m^{-1} spectrum, but only a small amount of induced current has been measured[4]. Recent experiments conducted with a nominally balanced $k_{//}$=13m^{-1} spectrum have demonstrated increases of the stored energy, T_e and neutron rate during NBI-induced H-mode plasmas. Details of the 30-MHz HHFW system can be found elsewhere[5]. In this paper we take advantage of the implementation into TRANSP of a recent version of the TORIC[6] code with high harmonic fast wave (HHFW) modeling capability[7]. This version of the code utilizes a quasi-local approximation to treat fast wave propagation in the HHFW regime for large values of $k_\perp\rho_i$ but neglects mode conversion to ion Bernstein waves near the cyclotron harmonic layers. Like other 2D rf simulation codes, it has a simplified model for the power coupled into the plasma that ignores edge effects loss mechanisms such as parametric decay instabilities and

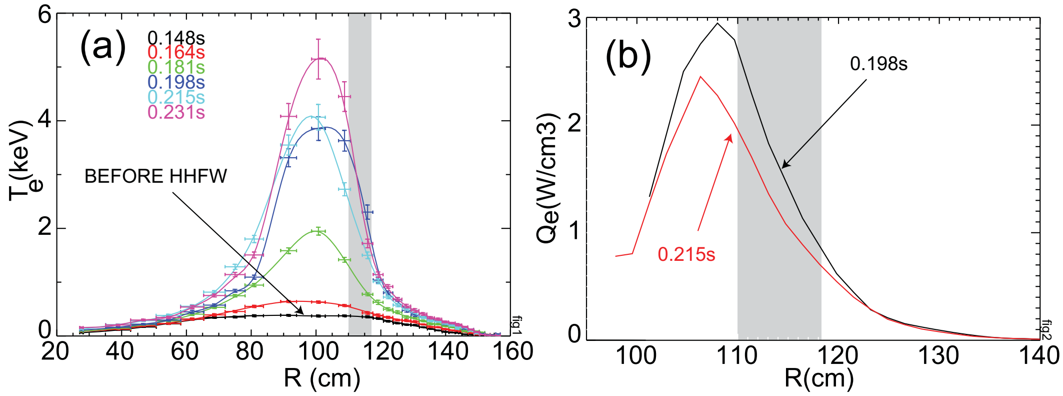

Fig.1 Helium plasma**:** (a) T_e profiles before and during HHFW heating; (b) Q_e profiles for selected times during heating. Gray box marks location of large T_e gradient

sheath effects. TORICS has been validated[4] against other codes for NSTX plasmas. In this paper, the TORIC/TRANSP tool is used to analyze HHFW heated discharges in conditions including high-T_e plasmas and HHFW applied to NBI-induced discharges.

HIGH-TEMPERATURE PLASMAS

We can see in Fig.1(a) a plot of overlays of the $T_e(R)$ at six time points: one just before and five more consecutive times during the application of 3MW HHFW power with $k_{//}$=8m^{-1}. The target is a nominal helium plasma with I_p=65MA and B_T=0.55T. The central electron temperature rises within ≈80ms from 0.4keV at the end of the ohmic phase, to 5.1keV; the plasma maintains a peaked $T_e(R)$ profile; the core profile width reaches ≈30cm. TRANSP analyses indicate that a substantial deuterium density is needed to reproduce neutron production rate and stored energy. This is consistent with the fact that this discharge was generated with a deuterium pre-fill. TORIC calculations show that the power deposition into the electrons, Q_e, accounts essentially for all the HHFW power absorbed. Fig. 1(b) shows the Q_e profile mapped in real space at two times 0.198s and 0.215s. A gray box indicates the region of large T_e gradient. Figure 2(a) shows overlays of the $T_e(R)$ at the same time points for a discharge with

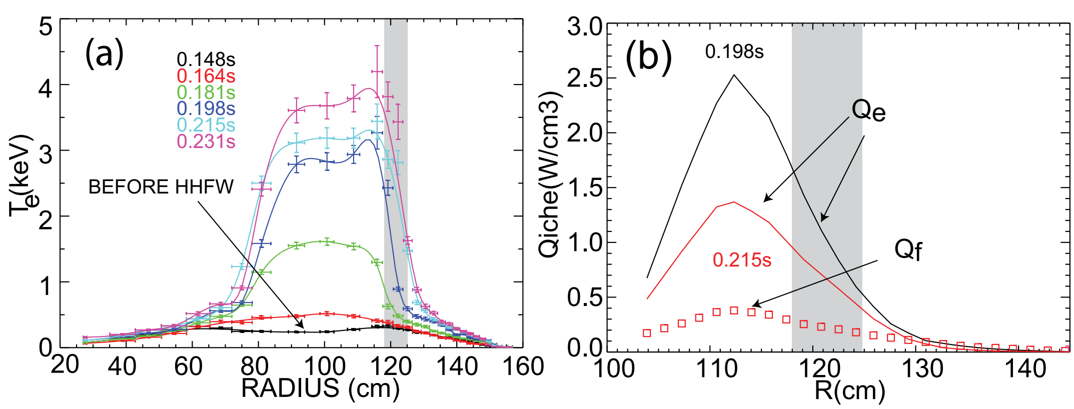

Fig.2 (a)) Deuterium plasma: T_e profiles before and during HHFW heating; (b) Q_e profiles for selected times, *lines;* Q_f during NBI pulse, *boxes*,. Shade marks location of large T_e gradient.

similar operational conditions -- I_p=0.65MA, B_T=0.55T, 3MW of HHFW at $k_{//}$=8m^{-1} -- but for a deuterium plasma, which has NBI power injected during the last two time points for diagnostic purposes. The electron temperature reaches 4keV, but similar plasmas without NBI diagnostic pulse have reached 5keV. Compared to Fig.1(a), one notices that $T_e(R)$ has a steeper gradient and a 50% larger core profile width and presents features of an ITB. On the other hand the power deposition profiles, seen in Fig.2(b) also at 0.198s and 0.215s, are shifted out by 4cm compared to Fig.1(b), while the T_e gradient has moved outside by ≈8cm. The difference in behavior between the H_e and the D_2 plasmas has been attributed to the reversed-shear q profile that has developed in the second case[3]. The later time point 0.215s occurred during the NBI pulse. One notices that Q_e is lower than for the earlier time, namely because of the power absorbed by the fast ions, Q_f ,shown with "box" symbol.

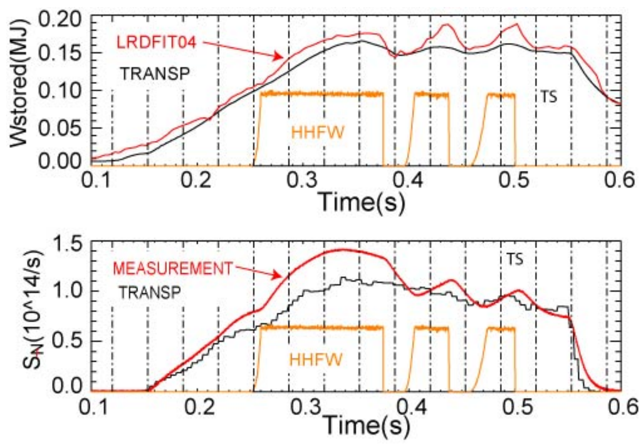

FIGURE 3 *Top panel*: Stored energy measurement and TRANSP; *bottom panel*: Neutron rate: measurement and TRANSP. *Dashed lines*: Thomson scattering times.

HHFW INTO NBI-INDUCED H-MODE PLAMA

While previous attempts at HHFW heating of NBI-induced H-mode plasmas had proven unsuccessful[8], recent application of $k_{//}$=14m^{-1} HHFW power resulted in measurable change in the stored energy and kinetic measurements. Better understanding of edge effects and attention to the edge density were conducive to this power coupling improvement[9]. We can see in Fig.3 temporal overlays of the measured stored energy[10], W_{stored}, and neutron production rate for a deuterium plasma – 0.55T, 1MA – with 2-MW NBI –trace not shown – starting 0.15s as witnessed by the neutron signal S_N. The transition occurs at 0.215s, prior to the beginning of 2-MW HHFW heating at 0.25s. A waveform proportional to the applied RF power is shown for reference. One can see increases in the measured stored energy and neutron production associated with the three HHFW pulses. The neutron rate predicted by TRANPS is noticeably lower than the measured value, perhaps in part because the current version of TRANPS does not include the power deposition to the fast ions calculated by TORIC in the NUBEAM model for the fast ion distribution and damping. Previous work has indicated that HHFW acceleration of the fast ions can

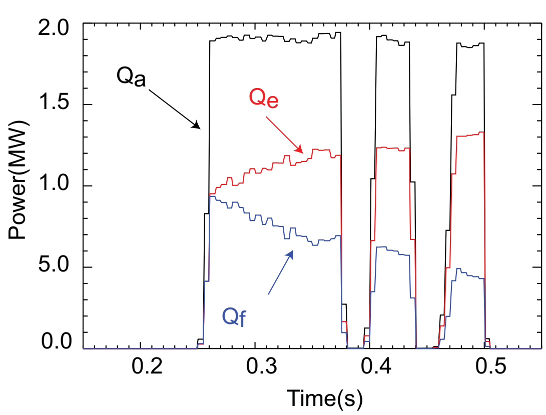

FIGURE 4 Time evolution of Q_a, Qe and Q_f for HHFW into H-mode target

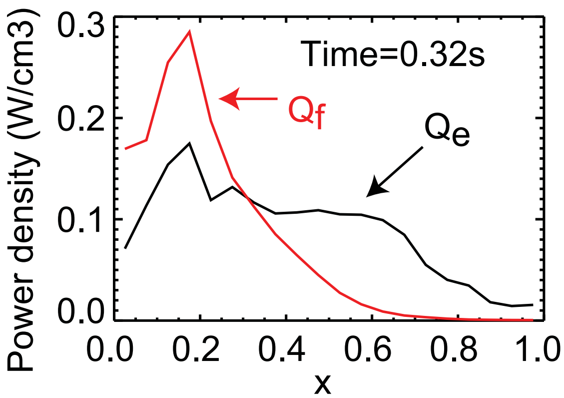

FIGURE 5 Q_e and Q_f against X at time = 0.32s

lead to an enhancement of the neutron rate[11]. Hence, for the time being, the TRANSP output does not reflect the effects of HHFW heating on the fast-ion energy density and the neutrons. The discrepancy between TRANSP and measured W_{stored} stems from the limited Thomson scattering time resolution – dashed lines – and the incomplete fast-ion energy computation just mentioned. But the TRANSP/TORIC output can be used to give us a preliminary estimate of the absorbed HHFW power distribution among plasma species. Outputs from a TRANSP analysis are shown in Fig.4, where Q_a is the antenna launched power. It is noteworthy that a relatively small number of fast ions -- $\leq 0.13 \times ne$ –absorb half of the power at the RF onset. The reduction of Q_f over time coincides with the fast-particle thermalization. Figure 5 shows the Q_e and Q_f profiles against the square root of the normalized toroidal flux, X, at 0.32s. The power deposition profiles peak off axis and $Q_e(X)$ is broad. Corroborating ray-tracing calculations can be seen at this conference.[12]

CONCLUSION

The addition to TRANSP of a recent version of TORIC able to deal with HHFW heating has been used to compute power deposition for different plasma conditions. Although the TORIC implementation is not fully self-consistent when NBI is present, the calculations give insight on the repartition of the HHFW power between the electrons and the fast ions; substantial electron heating can occur in a variety of operational regimes.

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