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Investigation of HHFW and NBI Combined Heating in NSTX*

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Abstract. A series of experiments was conducted to investigate the combined utilization of HHFW and NBI auxiliary heating in NSTX plasmas. A modest increase of the total stored energy coincident with a near doubling of the neutron production rate is observed when NBI heating is added to HHFW in L-mode plasmas. An increase in the core electron temperature is also observed. On the other hand, essentially no stored energy augmentation nor neutron production rate enhancement is observed when applying HHFW during the “H” phase of NBI driven H-mode plasmas. Spectroscopic measurements of the edge carbon line radiation indicate an unpredicted ion temperature increase, suggesting that edge effects are reducing the amount of HHFW power reaching the plasma core.

Keywords: NSTX HHFW NBI
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INTRODUCTION

High-Harmonic Fast-Wave (HHFW) constitutes an integral component of the NSTX auxiliary heating program, where it complements neutral beam injection (NBI). With a principal goal of current drive[1], HHFW has already demonstrated electron heating when applied to ohmic plasmas[2] and can also induce H-mode operation[3] Details of the 30-MHz rf system can be found elsewhere[4]. In the following, we describe experimental attempts at combining HHFW and NBI heating, done with the goal of expanding NSTX’s operational envelope. The deuterium plasmas discussed here have a toroidal field of 0.44 T at the geometric center and a plasma current of 0.8 MA with a flattop starting at 0.2 s. The outer gap is 3-4 cm and the beam energy has been reduced to 70 keV (from typical 80-90 keV) to prevent strong plasma-antenna interaction. The antenna phasing creates launch spectra with $k_{//} = 14\ m^{-1}$ or $k_{//} = 7\ m^{-1}$.

HHFW IN NBI L-MODE PLASMAS

Figure 1 shows temporal overlays of plasma parameters for two discharges: one using combined HHFW and NBI heating is displayed with solid lines; the other using NBI only is shown with dashed lines. The neutron production rate, S_n, and the heating waveforms are shown with arbitrary scaling. The H_α traces are also shown for reference. A power ramp initiates the HHFW pulse, reaching 2.9-MW flattop approximately 0.1 s before the NBI onset, which has a flattop power of 1.4 MW; the reference NBI-only discharge has the same NBI. Both the central electron temperature, T_{e0}, and the stored energy W_{mhd} respond to HHFW heating prior to NBI. T_e is obtained from Thomson scattering[5] and W_{mhd} from EFIT[6] equilibrium calculations. The NBI-only plasma has a similar rate of rise for T_{e0} and W_{mhd} except for being slightly delayed. There is a higher neutron production when HHFW is combined with NBI: S_n increases by a factor ≈ 2 compared to the NBI-only case. Keeping in mind that the neutron production is dominated by "beam target" nuclear reactions for these "low" temperature plasmas, the near doubling of S_n indicates an interaction between the HHFW and the fast ions of NBI origin[7]. Observation of the H_α traces reveals that both discharges dither into H mode at $t \approx 0.2$ s, before entering longer lasting H phases at $t \approx 0.24$ s.

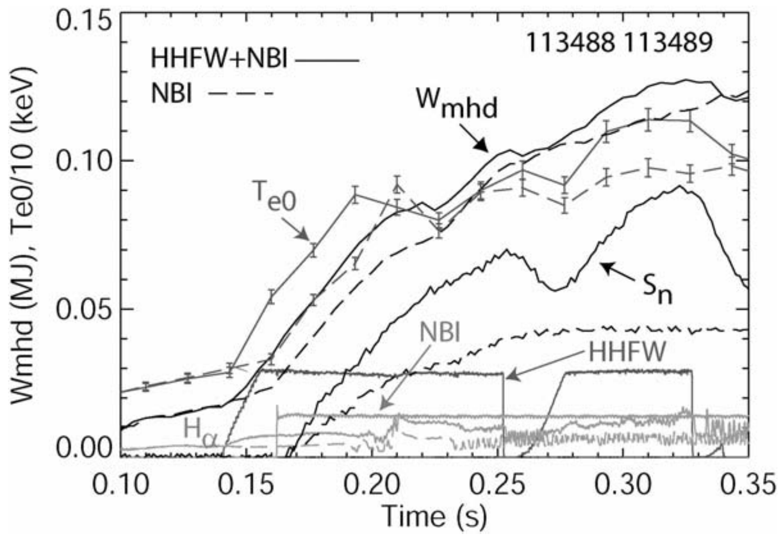

Figure 1. Plasma parameter T_{e0}, W_{mhd}, S_n, H_α and heating powers HHFW, NBI time evolutions: *solid lines*, discharge with combined HHFW and NBI; *dashed lines*, reference NBI-only discharge. $k_{//}$ = 14 m^{-1}.

Figure 2 shows a comparison between the T_e profiles for these two discharges at t = 0.193 s, slightly before the T_{e0} increase saturation. While the profiles overlay well in the edge regions, the core region shows a marked increase for the HHFW heated plasma, with T_{e0} being 0.2 keV above the reference profile. It generates a T_e profile with internal-transport-barrier like ∇T_e as seen at $R \approx 55$ cm and $R \approx 135$ cm.

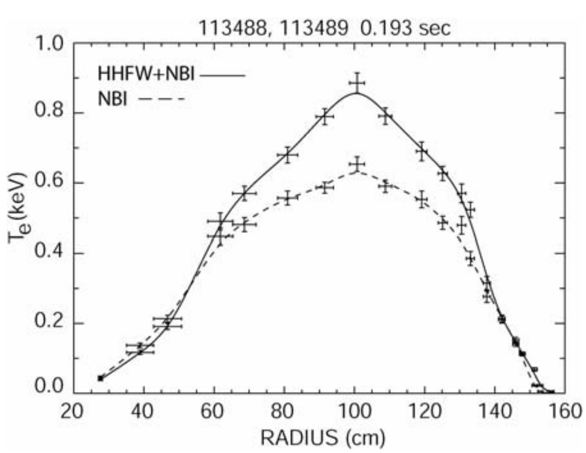

FIGURE 2. T_e profile overlay at t = 0.31 s for combined HHFW and NBI, *solid line*; NBI heating, *dashed line*. $k_{//}$ = 14 m^{-1}.

HHFW IN NBI H-MODE PLASMAS

Figure 3 shows temporal overlays similar to Fig. 1, but for cases where HHFW power is applied after an H-mode transition produced by NBI. $k_{//}$ = 7 m^{-1}. The early NBI heating makes use of two sources to ensure H-mode access. HHFW starts at 0.24 s after the H-mode transition time of ≈ 0.2 s. The maximum NBI and HHFW

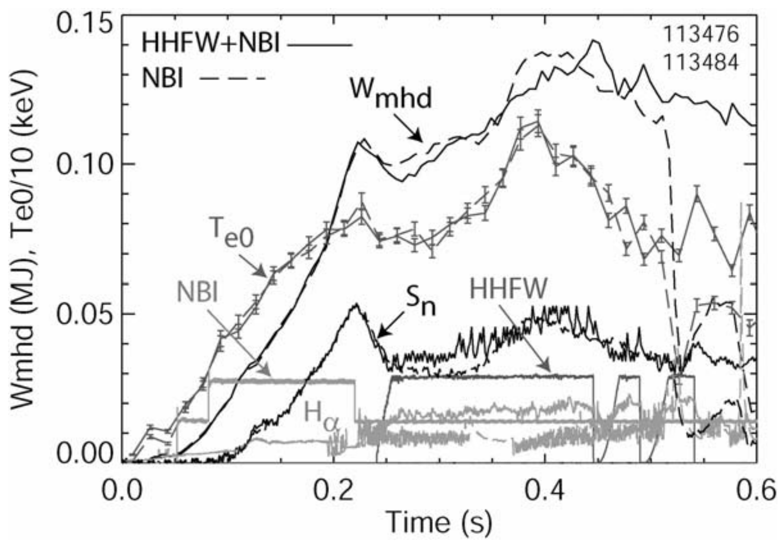

FIGURE 3. Plasma parameter T_{e0}, W_{mhd}, S_n, H_α and heating powers HHFW, NBI time evolutions: *solid lines*, discharge with HHFW applied to a NBI driven H-mode; *dashed lines*, reference NBI-driven H-mode discharge. $k_{//} = 7\text{m}^{-1}$.

powers are ≈ 3.0 MW. One can see that, in contrast to the previous case, parameters of this discharge are essentially not modified by the application of HHFW. The T_e , W_{mhd} and S_n overlay well, suggesting that the HHFW power does not reach the main plasma column. In particular, S_n, which appeared to be a sensitive indicator of HHWF core penetration in the previous case, does not show significant increase, except for times 0.26-0.35 s, when S_n is higher for the HHFW heated discharge.

We can see in Fig. 4 an overlay of T_e profiles taken at t = 0.310 s roughly in the middle of the enhanced neutron production interval. No significant electron heating is observed. While a small amount of HHFW power appears to briefly reach the plasma core causing a modest neutron signal enhancement, no bulk electron heating occurs. Comparisons with other discharges suggest that edge effects, *e.g.* fueling, might be responsible for this small neutron production enhancement.

But edge measurements show HHFW does heat ions. One can see in Fig. 5 a time evolution of T_e and T_i measured at major radius $R \approx 145$ cm. T_i is obtained by edge spectroscopy on the carbon impurity[8]. Similarly solid lines correspond to HHFW combined with NBI, while dashed lines correspond to NBI-only reference plasma. The ion temperature shown here corresponds to a “poloidal” sightline, and is higher than that from a “toroidal” sightline (not shown) during HHFW operation. Parametric decay of the pump wave into IBW has been suggested as a means by which power is delivered to the edge ions. More details can be found elsewhere[9].

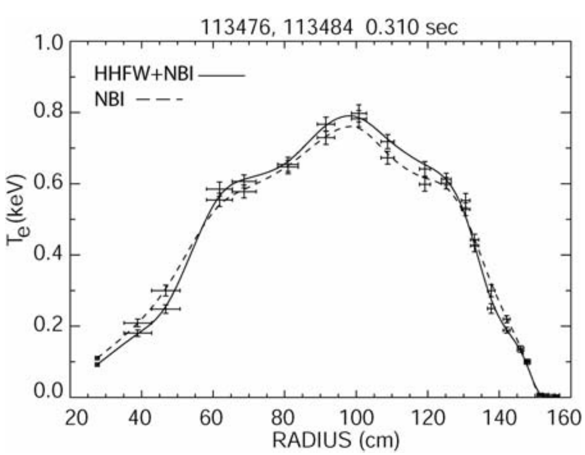

FIGURE 4. T_e profile overlay at t = 0.31 s: *solid line*, combined HHFW and NBI, heating; *dashed line*, NBI heating. $k_{//} = 7\text{m}^{-1}$.

CONCLUSIONS

The combination of HHFW and NBI presents challenges. Depending on

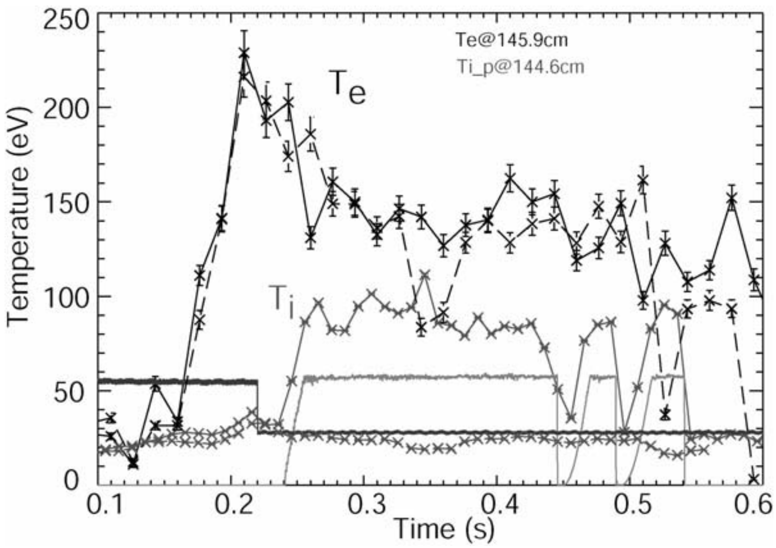

FIGURE 5. T_e and T_i time evolutions at $R \approx 145$ cm: *solid lines*, combined HHFW and NBI heating; *dashed lines*, NBI heating. $k_{//} = 7\mathrm{m}^{-1}$.

condition, a modest or no increase of W_{mhd} is observed although the HHFW power is greater or equal to that of NBI. This result can be partly explained by edge parasitic rf power absorption through parametric decay and the generation of IBW, which deposit power into the edge ions. Based on helium discharges, a few tens of percent of HHFW incident power can be diverted to the low-confinement peripheral region. The presence of NBI generated fast ions creates further hurdles: Fast ions are accelerated by HHFW which, while increasing the neutron production, reduces the power available for direct HHFW electron heating and potential current drive. Furthermore the high NBI energy in relation to the magnetic field strength necessitates special care in order to reduce plasma-antenna interaction. More work is needed before a complete understanding of the physics involved can be obtained, and a strategy is developed to improve on the performance of these plasmas.

ACKNOWLEDGMENTS

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