RF Heating and Current Drive on NSTX with High Harmonic Fast Waves

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Abstract. NSTX is a small aspect ratio tokamak (R = 0.85 m, a = 0.65 m). The High Harmonic Fast Wave (HHFW) system is a 30 MHz, 12-element array capable of launching both symmetric and directional wave spectra for plasma heating and non-inductive current drive. It has delivered up to 6 MW for short pulses and has routinely operated at ~3 MW for 100-400 ms pulses. Results include strong, centrally-peaked electron heating in both D and He plasmas for both high and low phase velocity spectra. H-modes were obtained with application of HHFW power alone, with stored energy doubling after the L-H transition. Beta poloidal as large as unity has been obtained with significant fractions (0.4) of bootstrap current. Differences in the loop voltage are observed depending on whether the array is phased to drive current in the co- or counter-current directions. A fast ion tail with energies extending up to 140 keV has been observed when HHFW interacts with 80 keV neutral beams; neutron rate and lost ion measurements, as well as modeling, indicate significant power absorption by the fast ions. Radial rf power deposition and driven current profiles have been calculated with ray tracing and kinetic full-wave codes and compared with measurements.

1. Introduction

The NSTX is a small aspect ratio tokamak; the plasma has a large dielectric constant at rf frequencies due to relatively high plasma density and low magnetic field ($\varepsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50$-$100$). Under these conditions high harmonic fast waves (HHFW) will readily damp on the electrons via Landau damping and Transit Time Magnetic Pumping (TTMP) [1]. The HHFW system on NSTX provides up to 6 MW of power at 30 MHz (~10-20 ω_{ci}) and is capable of launching both symmetric wave spectra for plasma heating and directional spectra for non-inductive current drive.

2. Description of the HHFW System on NSTX

The HHFW array consists of twelve evenly spaced, identical current strap modules connected in pairs, as shown in Fig. 1 [2]. Each pair is connected as a resonant loop, thus fixing the phase relationship of the strap currents for the loop pairs at 180°. Each loop is powered by a single 1 MW transmitter, allowing arbitrary, rapid phase shift between transmitters to be made for real-time spectral control. Each loop is isolated from its nearest neighbors by a shunt

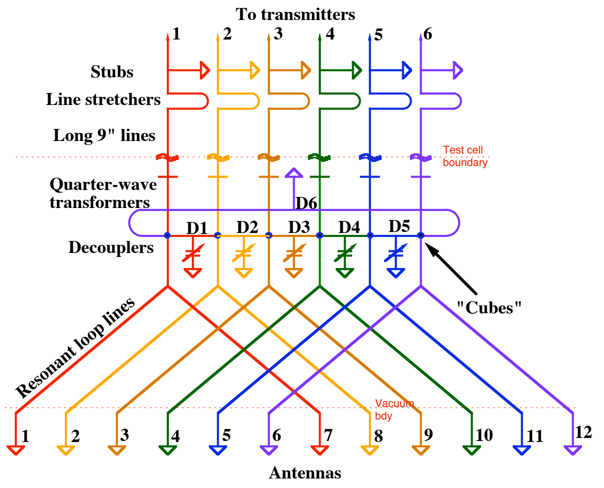

FIG 1. Circuit connecting 12-strap HHFW antenna array to six rf transmitters.

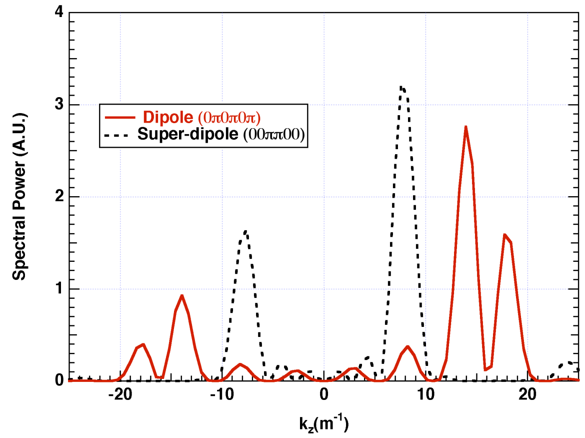

FIG 2. Calculated wave spectra (RANT3D) for symmetric array phasings: dipole (solid) and "super"

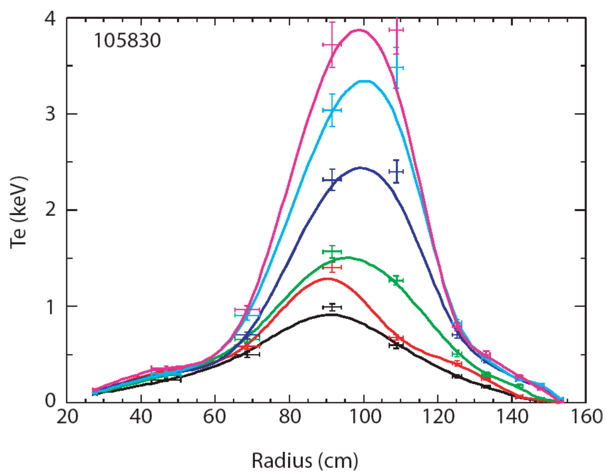

FIG. 3. Strong central heating of electrons and a large temperature gradient develops in the core for low density plasmas. T_e and n_e profiles obtained with Thompson scattering.

decoupling circuit that cancels the mutual inductance between adjacent straps. A new digital system has been implemented that provides active feedback control of the transmitter phase based on phase measurements near the vacuum feedthroughs, allowing full control of the array phase during a shot.

3. Symmetric-Array Operation (Heating)

Up to 6 MW of power has been delivered to the plasma for short pulses; good reliability was obtained for operation at ~3 MW for 100-500 ms pulses. Both D and He majority plasmas have been heated with both high and low phase velocity wave spectra. Strong electron heating was observed over a wide range of plasma conditions: n_e =1-4 x 10^{19} m^{-3}, I_p = 0.3-1.0 MA, B_T = 0.3-0.45 T in either deuterium or helium majority plasmas. One strong advantage of HHFW over conventional ICRF heating is its relative insensitivity to exact plasma parameters.

Two array phasings were employed to excite symmetric wave spectra for heating: *dipole* (0π0π0ππ0π0π0) and *super-dipole* (00ππ00ππ00ππ). Figure 2 shows RANT3D [3] spectra calculations for typical plasma density profiles. Super-dipole phasing produces spectral peaks at $k_{||}$ = ±7.6 m^{-1}, while dipole phasing has dominant peaks at $k_{||}$ = ±14 m^{-1} and secondary peaks at ±18 m^{-1}. The double-peaked spectrum for dipole phasing is a result of the monopole phase relation between straps 6 and 7. The asymmetry in spectral power is caused by the large magnetic field angle (up to 45°) at the antenna. The propagation asymmetries in the direction perpendicular to field lines, arising from radial gradients, are rotated into the toroidal direction. The most effective heating of ohmic plasmas occurred with low phase velocity waves obtained with dipole array phasing. Figure 3 shows $T_e(0)$ increasing to 3.7 keV with 2.7 MW of rf power and dipole phasing (I_p = 800 kA, B_T = 0.45 T, deuterium plasma, $n_e(0)$ =

2×10^{19} m^{-3}). In these discharges the strong central peaking of the central electron temperature was accompanied by a reduction in electron energy transport throughout the plasma but particularly in the inner core. An apparent transport barrier had formed at R ~ 125 cm.

H-mode operation was achieved for diverted plasmas with application of HHFW power alone, for both $k_{||}$ = 7.6 and 14 m^{-1}. The power threshold for H-mode transition was typically 2-2.5 MW for plasma currents from 300 to 800 kA. Both ELM-free and ELMy H-modes were obtained with stored energy increasing by a factor of two after the L-H transition. These discharges provide a valuable target for long-pulse ST scenarios. Values of beta poloidal as large as unity have been obtained with significant (f_{bs} =0.4) fractions of the plasma current being sustained by the bootstrap current.

4. Asymmetric-Array Operation (Current Drive)

Phased array operation to produce directional wave spectra for HHFW current drive (CD) has concentrated primarily on spectra with peaks located at $k_{||}$ = ±7.6 m^{-1} ($\Delta\phi = \pm\pi/2$), with limited operation at higher phase velocities (for example, $k_{||}$ = ±3 m^{-1} for $\Delta\phi = \pm\pi/4$). Figure 4 shows the calculated wave spectra (from equal strap currents) for the various array phasings that were used. The spectral asymmetry in plasma response is reduced for the higher phase velocity waves (lower $k_{||}$), as is the plasma loading. The plasma loading is proportional to the area under the curves; the plasma loading for counter-CD phasing at 7.6 m^{-1} was typically half that for co-CD (8 Ω vs 17 Ω) [4].

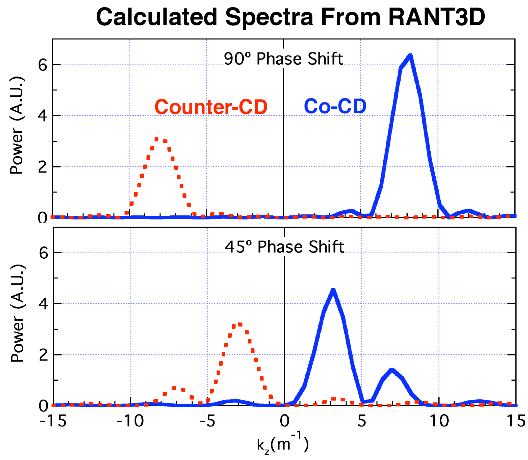

FIG. 4. Calculated wave spectra in plasma as a function of phase shift between transmitters.

The absence of the Motional Stark Effect diagnostic, to be installed at the end of 2002, prevented current density profiles from being measured during our CD experiments. In the absence of this crucial measurement, the HHFW driven current can be estimated by establishing identical plasma conditions for co-CD and counter-CD phasing and assuming:

(1) Steady-state (t > L/R) conditions have been achieved.
(2) The plasma ohmic resistance is the same for both co- and counter-CD phasings.
(3) The HHFW driven current is proportional to the rf power.

Under these assumptions a 0D calculation of the driven current can be made from the measured loop voltage, after subtracting the calculated bootstrap current and compensating for the portion of the loop voltage which drives the changing magnetic stored energy.

Figure 5 shows two comparison shots for $k_{||}$ = ±7.6 m^{-1}, D_2 plasma, $B_T(0)$ = 0.445 T; I_p = 0.5 MA. The HHFW power needed to obtain comparable core density and temperatures was 2.1 MW for co-CD and 1.1 MW for counter-CD; Thomson scattering measured $n_e(0)$ = 1.1×10^{19} m^{-3}, $T_e(0)$ = 1.4 keV. The 0.22 V difference in loop voltage (Fig. 6) for the two cases gives an estimated ΔI = 180 kA (110 kA co-CD, 70 kA counter-CD). However, the assumption of steady-state is not well satisfied; internal MHD activity leads to a decrease in voltage difference with time. A TRANSP analysis that computes E(r), and assumes neoclassical resistivity to get $j_{CD}(r)$, calculates a difference current of 90 kA for this case, half that estimated from the loop voltage difference.

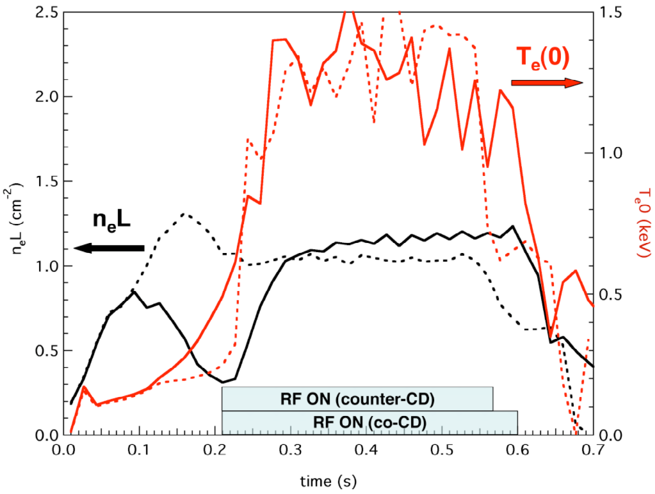

FIG. 5. $T_e(0)$, n_eL, I_p, and P_{RF} vs time for co-CD (solid) and counter-CD (dotted) with $k_{||} = 7.6\ m^{-1}$.

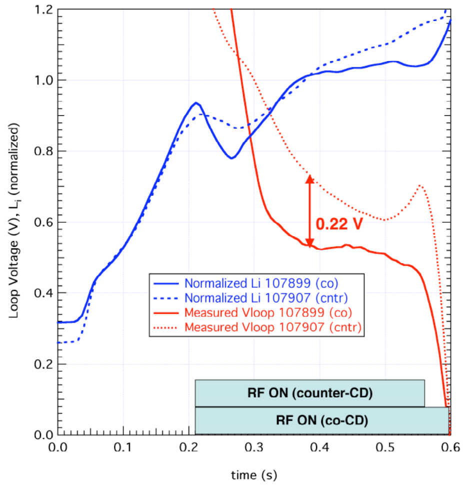

FIG. 6. The calculated internal inductance (EFIT) and measured loop voltage for co/counter-CD cases.

HHFW current drive calculations have been made using the 2D full-wave code TORIC [5] and the ray-tracing code CURRAY[6]; results are shown in Table 1. Both analyses indicate strong central power absorption, negligible damping on the H^+ minority, and a significant decrease in driven current due to rf absorption by trapped electrons (30-40%).

TABLE 1

	Co-CD (kA)	Counter-CD (kA)	Total ΔI (kA)	I_{CD}/P (A/W)
0D Calculation	110	70	180	0.056
TRANSP	–	–	90	0.028
TORIC	96	50	146	0.046
CURRAY	162	79	241	0.075

5. HHFW Interaction With Fast Ions From NBI

A clear fast ion tail has been observed on the neutral particle analyzer (NPA) when HHFW and NBI were active simultaneously. For most shots analyzed, the neutral beam injected deuterium into the plasma at $E_b \approx 80$ keV, $P_b \approx 1.6$MW. Without RF, the energy spectrum observed by the NPA dropped out above ~ 80 keV. With RF, the energy spectrum extended to ~ 140 keV. Furthermore, after RF turnoff with NBI remaining active, the tail decayed to the no-RF spectrum on a time scale comparable to that for decay of a beam-only distribution, as seen in Fig 7. The ZnS and fission neutron detectors also saw a significant signal enhancement with RF, which also began dropping immediately upon RF turnoff. Sets of similar shots with different B_0, I_p, E_b, and launched $k_{||}$ were examined. In agreement with modeling, the tail strength and neutron rate at lower B-field were observed to be less enhanced, likely due to a larger β profile, which promotes greater off-axis absorption where the fast ion population is small. Tail strength also increased with higher beam energy, and a substantial neutron rate enhancement was observed at higher I_p. Though greater ion absorption is predicted with lower $k_{||}$ [7,8], surprisingly little variation in the tail was observed, along with a small neutron enhancement with higher $k_{||}$. Recent data from NSTX's X-Ray Crystal Spectrometer indicates that bulk ion absorption may account for this behavior.

In addition to the NPA and neutron detectors, ion loss probes at R = 163 cm and 166 cm also saw a signal enhancement with RF on in beam shots.

For analysis, the TRANSP transport analysis code was used to calculate fast ion energy and particle density profiles, and this information was used to estimate an effective Maxwellian temperature, T_f, for the fast ion population. This, along with EFIT and Thomson data, was fed into HPRT, a 2-D ray-tracing code which uses the full hot plasma dielectric to compute power deposition profiles along the hot electron/cold ion ray path [7]. As shown in Fig. 8, fast ion absorption was calculated to be quite competitive with electron absorption in sustained neutral beam shots, often taking ~ 40% of the total RF power.

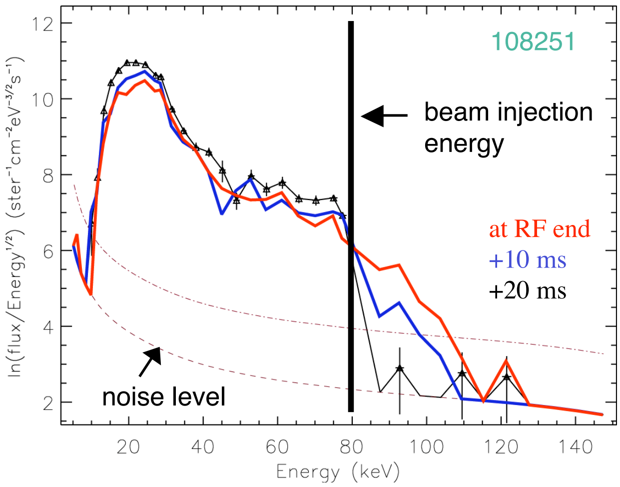

FIG. 7. NPA signals of shot 108251 from 320-340 ms. RF turns off at 320 ms, and signal above the 80 keV injection energy decays to the no-RF spectrum

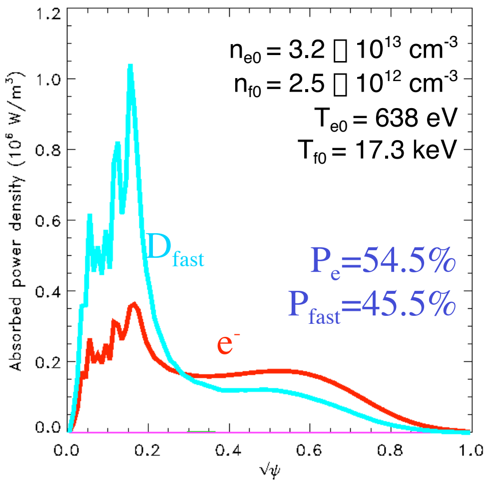

Figure 8: HPRT computed power deposition profiles for NSTX shot 105908, t=195 ms. Significant fast ion absorption is calculated (HPRT) with NBI present.

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