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Results of High-Harmonic Fast Wave Experiments on NSTX*

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Introduction

NSTX is a small aspect ratio tokamak (R_0 = 0.85 m, a = 0.65 m) in which the plasma has a large dielectric constant (50-100) due to its relatively high density (> 10^{19} m^{-3}) and low magnetic field (usually < 0.45 T at the center) [1]. Under these conditions, high harmonic fast waves (HHFW) with $\omega/\Omega_{ci} = 8 - 16$ are expected to damp on the electrons via Landau damping and transit-time magnetic pumping. Up to 6 MW of power have been delivered to the plasma for short pulses, and routine operation at over 3 MW for pulses up to ~600 ms has been achieved. H-modes were obtained with application of HHFW power alone, with stored energy increasing by a factor of two after the L-H transition. Values of beta poloidal as large as 1 have been obtained, with bootstrap current fractions up to 40%. Preliminary results from current-drive experiments indicate a driven current of order 100 kA (with large uncertainties) for 2 MW of HHFW power.

Description of the ion cyclotron system

The ion cyclotron launching system consists of 12 poloidal strap antennas mounted to the wall of the vacuum vessel, and subtending altogether almost 90°toroidally [2]. The 12 antennas are connected in six resonant loop configurations (Fig. 1), with each loop being driven by an independent rf source.

The phase of the currents in the antennas is feedback-controlled by a new digital system, allowing the phase between adjacent loops to be controlled and changed during a shot. Common phasings used are: slow symmetric phasing ($0\pi0\pi0\pi$), which launches a wave with peaks at $k_{tor} \approx \pm 14$ m^{-1}; fast symmetric phasing ($00\pi\pi00$), co-current drive phasing ($\Delta\phi = -\pi/2$), and counter-current drive phasing ($\Delta\phi = +\pi/2$), all with peaks at ± 7 m^{-1}. Launched k_{tor} spectra for the latter three cases are shown in Fig. 2.

Heating results

The effects of applied HHFW power on total stored energy (from magnetics measurements) and electron temperature and density profiles (from Thomson scattering data) have been measured over a variety of plasma conditions. Generally, the heating effectiveness of the HHFW appears to be the same for He and D plasmas, in agreement with theory [3]. The results are fairly sensitive to the initial discharge conditions, however, and obtaining similar current and temperature profiles prior to applying the HHFW power is not easy. Earlier reports [4] of significant differences between He and D are attributed to this difference. The increase in total stored energy also appears to be relatively independent of the phasing of the antenna array for the four phasing schemes described above.

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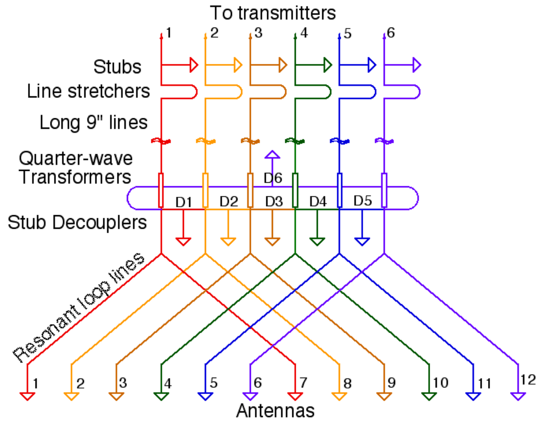

Fig. 1. Circuit schematic

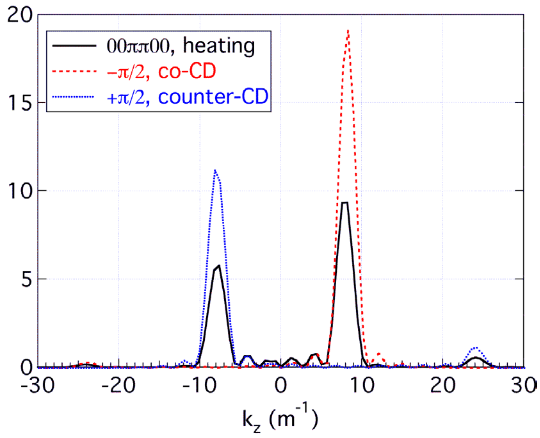

Fig.2. k_{tor} spectra for different phasings

Evidence for a HHFW-generated internal transport barrier is sometimes seen at low plasma density. The electron temperature profiles shown in Fig. 3 exhibit the characteristic behavior of a very high central temperature (3.8 keV) and a large temperature gradient over the inner half of the plasma, obtained with 0π0π0π phasing at 2.6 MW. The internal transport barrier is difficult to maintain and is often destroyed by MHD events, shown in the figure by the collapse of the temperature profile between t = 0.21 and 0.24 s.

High-energy D ions injected by neutral beam heating can absorb a substantial fraction of the HHFW wave energy. A significant high-energy tail with ion energy up to 120 kV can be generated by HHFW. Fig. 4 shows the energy spectrum measured by a neutral-particle analyzer near the end of a 2.4 MW rf pulse 120 ms long, and the spectrum at two times during the decay after the rf was turned off. The tail decay occurs on a collisional time scale. Calculations indicate that over 40% of the injected rf power can be absorbed by the beam ions for these plasma conditions (D plasma, 750 kA, <n> ≈ 2 x 10^{19} m^{-3} and 0π0π0π phasing).

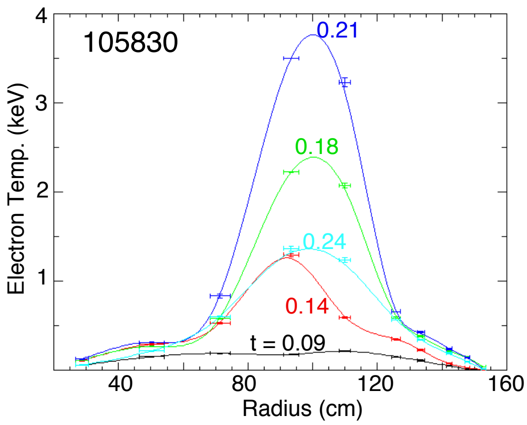

Fig. 3. Te profiles for 0.45T, 0.76 MA diverted plasma shot with internal transport barrier

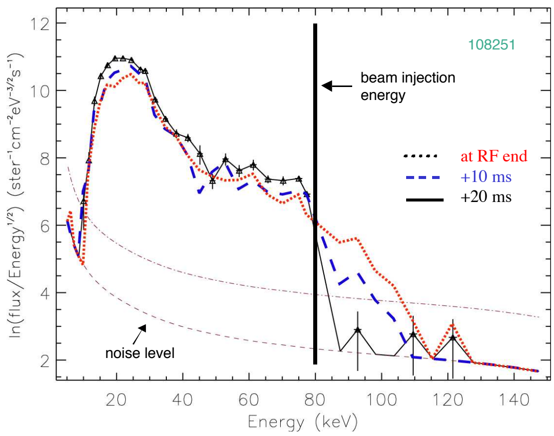

Fig.4. Neutral particle spectra during and after rf pulse

Figure 5 shows stored energy (from magnetics measurements) vs. total input power (ohmic plus HHFW) for a number of shots with I_p ≈ 500 kA, and average densities <n> ≈ 1 x 10^{19} m^{-3}. The behavior with total power is in rough agreement with the ITER 98 H(y,2) H-mode power scaling (dashed curve). There is a tendency of the confinement times for counter-CD phasing to be somewhat above the scaling curve, while the co-CD phasing is usually below. The T_e profiles for the co- and counter-CD shots are similar for r/a ≥ 0.5, but the peak temperature near the center is generally lower in the co-CD case. This may be caused by differences in power deposition (contrary to theory) or by MHD activity enhanced by driven current near r = 0 causing increased radial transport for small r/a.

Phase-dependent loading

We have observed significant asymmetry of loading on the rf system in earlier experiments [5]. This effect is also seen in the current-drive phasings that have been used in this campaign. The results are summarized in Fig. 6, in which the triangles are the average terminating resistance for a 50-Ω line that would give the measured reflection coefficients. For counter-CD phasing, the loading is approximately half that measured for co-CD phasing, with the symmetric 00ππ00 phasing having an intermediate value.

This asymmetry can be understood using impedance matrix (Z-matrix) calculations from the RANT3D full-wave coupling code [6], when used in a coupled-circuit model of the rf system. Measured edge density and magnetic fields are used in the code to compute a 12x12 Z-matrix for the 12 antennas. The asymmetry is introduced by the large pitch angle of the magnetic field lines (25° to 45°) relative to the horizontal. The loading results from this calculation, indicated by the squares in Fig. 6, agree well with the measurements. Conventional coupled-circuit modeling that does not include the asymmetries caused by the large poloidal field gives the same loading for all the phasings shown.

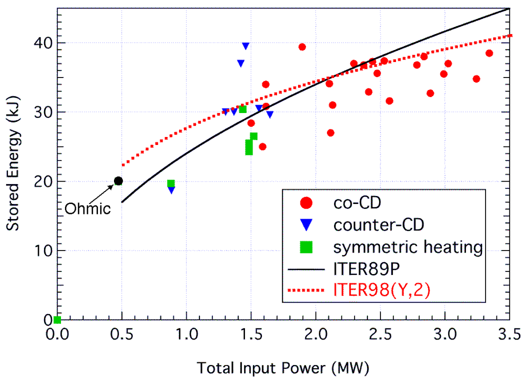

Fig. 5. Stored energy during rf heating

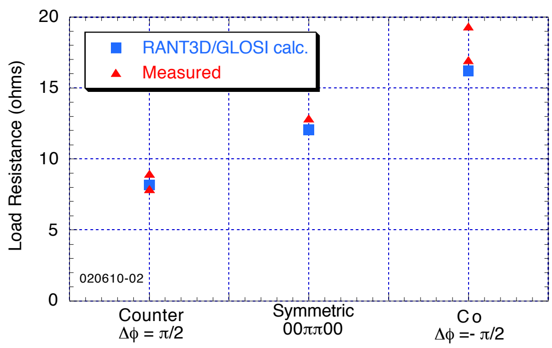

Fig. 6. Loading asymmetry measurements

Results of current-drive experiments

At present, NSTX has no diagnostic to directly measure the current profile. We have carried out current-drive experiments in which we have obtained pairs of plasma discharges with very similar temperature and density profiles, but with the HHFW phasing reversed from co- to counter-CD (-π/2 to +π/2) phasing. Figure 7 shows the loop voltage for two such shots; these are single-null-diverted discharges in D_2, with B_0 = 0.45 T, I_p = 500 kA, and <n> ≈ 0.8 x 10^{19} m^{-3}. The co-CD shot has 2.1 MW of HHFW power, while the counter-CD shot has 1.1 MW, starting at t = 0.22 s. The temperature profiles measured by Thomson scattering are almost identical at 0.4 and 0.5 s in the pulse, as shown in Fig. 8**.**

The loop voltage drops from its ohmic value of ≈ 1.5 V to ≈ 0.6 V as the electrons heat from their ohmic value of $T_e(0)$ ≈ 0.7 keV up to ≈ 1.4 keV during the rf. As can be seen from Fig. 7, there is a difference of ≈ 0.2 V in the loop voltage between the co- and counter CD shots over much of the heating pulse.

The CURRAY ray-tracing code [3] predicts that the HHFW should drive centrally-peaked current, about 150 kA for the co-CD shot and about –80 kA for the counter-CD one. Calculations indicate that it should take about 200 ms for the effects from such a centrally-driven current to equilibrate via current diffusion. Ideally, a steady state should be reached, with constant loop voltage and plasma parameters; however MHD effects later in the pulse tend to flatten out the T_e profiles, particularly for the co-CD shots, so true steady-state operation isn't obtained.

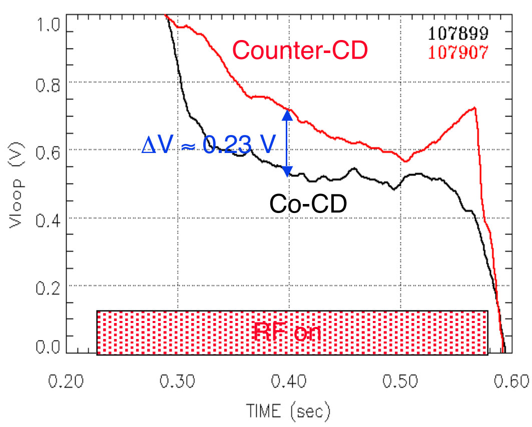

Fig. 7. Loop voltage(t) for a co-CD and counter-CD shot

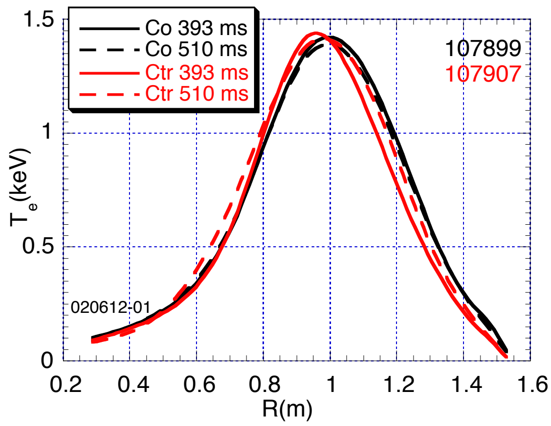

Fig. 8. Te(R) profiles at t = 393 and 510 ms for co- and counter-CD shots

Preliminary estimates of the driven current have been done based on the ΔV shown in Fig. 7 and *assuming*: (1) steady-state conditions have been obtained, (2) $I_{CD} \sim P_{HHFW}$ both for the co- and counter-CD shots, and (3) the discharge conditions are identical. The results give $I_{co\text{-}CD} \approx 100$ kA and $I_{counter\text{-}CD} \approx -50$ kA, about 65% of the CURRAY predictions.

Preliminary analysis using the TRANSP code has also been done, in which the voltage profiles V(r,t) in the plasma are computed using experimental T_e(r,t), n_e(r,t), I_p(t), and V_{loop}(t). Assuming neoclassical resistivity, the difference in current is computed by the integral of σ(r) [V_{ctr}(r) – V_{co}(r)] at a particular time. At t = 0.4 ms, this gives $I_{co} - I_{ctr} \approx 90$ kA.

These results indicate that driven current has been observed, but the magnitude is difficult to determine from the measurements available at present. There are significant uncertainties in these calculations: steady-state has *not* been obtained, and there are slight differences in the temperature and density profiles between the co- and counter-CD shots. More definitive results await the installation and operation of a motional-Stark-effect diagnostic to measure the actual current profile, which should occur within the next year.

Finally, very preliminary current drive studies have been done with different values of Δϕ, including ±60°, ±45°, and ±30°. It is encouraging that all these array phasings appear to heat the plasma and to exhibit non-zero ΔV when co- and counter-CD shots are compared, with the faster waves (±30° and ±45° phasing) causing larger changes in loop voltage than the slower waves. These experiments will be continued in the next operating period.

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