Advances in high harmonic fast wave heating of NSTX H-mode plasmas

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High-harmonic fast wave (HHFW) heating and current drive are being developed in NSTX to provide bulk electron heating and q(0) control during non-inductively sustained H-mode plasmas fuelled by deuterium neutral-beam injection (NBI). In addition, it is used to assist the plasma current ramp-up. A major modification to increase the RF power limit was made in 2009; the original end-grounded, single end-powered current straps of the 12-element array were replaced with center-grounded, double end-powered straps [1]. The motivation for moving the grounds is to reduce the strap peak voltages and electric fields in the vicinity of the plasma/Faraday shield (FS) interface. For a given strap current, the peak voltages on the straps are almost halved, the peak voltage on the vacuum side is reduced by ~30%, and the peak system voltage on the pressurized side remains unchanged. If the system voltage limit in plasma (~15 kV) could be increased to its vacuum limit (~25 kV), the power capability of the HHFW system would almost triple. However, great increases in delivered power were not observed during the brief period of antenna operation at the end of the 2009 experimental campaign. Lithium deposited on the antenna and FS surfaces from the LITER system[2] during the previous months of HHFW inactivity contributed to internal arcing and had to be cleaned away by antenna conditioning into plasma before reliable high power (~4 MW) operation was regained. Figures 1a-c show a typical arc as captured with a fast framing camera (30,000 frames/s). After conditioning, HHFW operation with the new antennas proved to be more reliable and robust in the 2.5 to 3.5 MW range than the previous year's run at the same power. However, there were still significant deposits of Li on the antenna surface at the end of HHFW operations.

Fig 1a. View of the antenna array with the fast framing camera. Illuminating light coming from extinguishing plasma. Figs 1b and 1c have Li-I filter in place to observe excited Li neutrals.

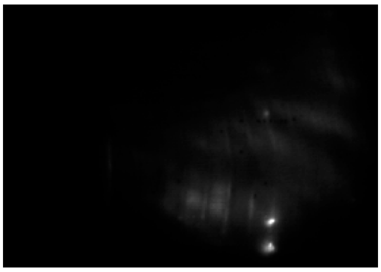

Fig 1b. Arcs between straps 7 and 8 tripped off all rf power due to high reflected power on transmitter 2 (powering strap 7) at t = 161.752 ms.

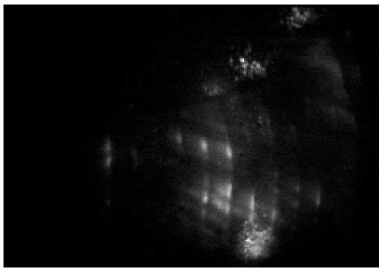

Fig 1c. View 1.0 ms after HHFW power removed (t = 162.752) shows expulsion of Li from the region of the arcs.

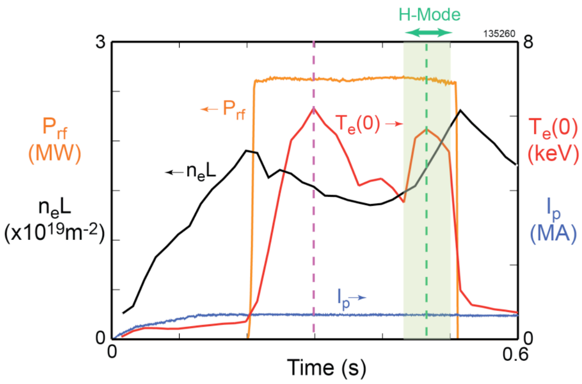

Fig. 2. Ohmic He plasma heated to record $T_e(0)$ in L-mode at 0.3 s and later goes into H-mode with HHFW alone. P_{RF} = 2.6 MW, $k_\phi = -8$ m^{-1}, I_p = 0.65 MA, $B_T(0)$ = 0.55 T.

While L-mode plasmas with record central electron temperatures exceeding 6 keV were produced in He discharges with 2.6 MW of RF power (B_T = 0.55 T, I_p = 0.65 MA, $k_f = -8$ m^{-1}) as shown in Fig. 2, the 2009 HHFW campaign concentrated on RF operation into H-mode plasmas [3]. By setting the trip level of the reflection coefficient to 0.7, the HHFW system was able to maintain power delivery through the transient loads of both the L-H transition and most ELMs without compromising antenna protection (arcs generated reflection coefficients greater than 0.9). Figure 3 shows the transition of an NBI-heated (2 MW) deuterium L-mode plasma (I_p = 0.8 MA, $B_T(0)$ = 0.55 T) to an ELMy H-mode plasma by the addition of 2.7 MW of HHFW at –150° phasing ($k_\phi = -13$ m^{-1}). L-H and H-L transitions in both deuterium and helium were studied with the application of HHFW power to Ohmic plasmas.

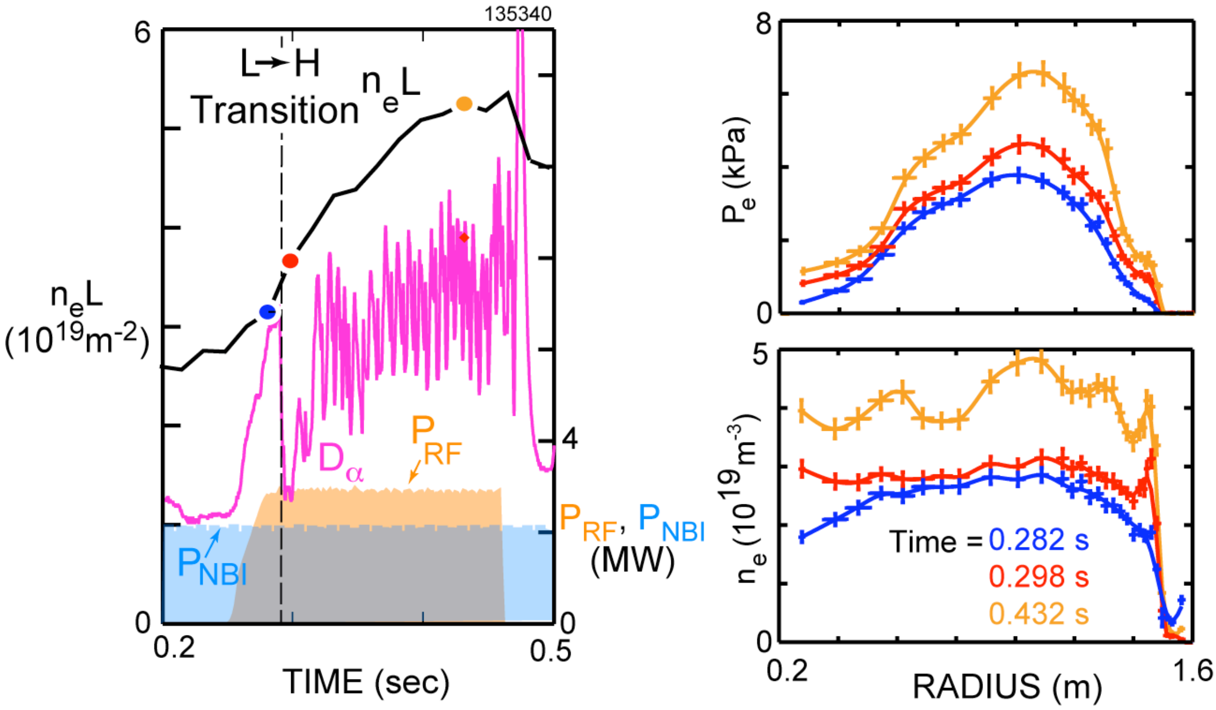

Fig. 3. Addition of 2.7 MW of HHFW at k_ϕ = 13 m^{-1} to an NBI-heated (2 MW) causes a transition to an ELMing H-mode. Also shown are the electron pressure and density profiles just prior to transition, just after transition, and late in the RF pulse.

The lower edge density obtained with Li wall conditioning enabled core electron heating and stored energy increases to be achieved in NBI-driven H-mode deuterium plasmas for all the principal array phasings, including for the first time the long wavelength k_ϕ = 3 m^{-1} (-30° phasing). There is a strong interaction between the RF and the fast ions from neutral beam injection, as evidenced by increases in the measured neutron rate and enhancement of the fast-ion D_α (FIDA) emission profile [4]. Power losses in the scrape-off layer in NBI-driven H-mode plasmas are similar to those in comparable L-mode plasmas. Stored energy time constant analysis of modulated RF pulses gives total power coupling efficiencies of 66% for k_ϕ = –13 m^{-1} and 40% for k_ϕ = –8 m^{-1}; these same phasings give 68% and 44% coupling efficiencies in L-mode plasmas, respectively [5, 6]. Figure 4 shows the modulated 1.8 MW HHFW pulse (k_ϕ = –13 m^{-1}) applied to an H-mode plasma heated by 2 MW of NBI for the –13 m^{-1} case. This same shot was also modeled with the CQL3D Fokker-Planck code [7]; as shown in Fig. 5, the rf power input had to be reduced to 40% of the total antenna power for CQL3D to match the measured neutron rate at the early of 0.353 s [8]. A TORIC-TRANSP analysis [9] of the same shot predicts that the power absorption is equally partitioned between the electrons and fast-ions upon initial RF turn-on. Figure 6 indicates that the power absorption on electrons should increase with time as the electron beta rises and the fast ions thermalize. This analysis does not include a self-consistent treatment of the change in fast-ion population due to the rf acceleration of ions.

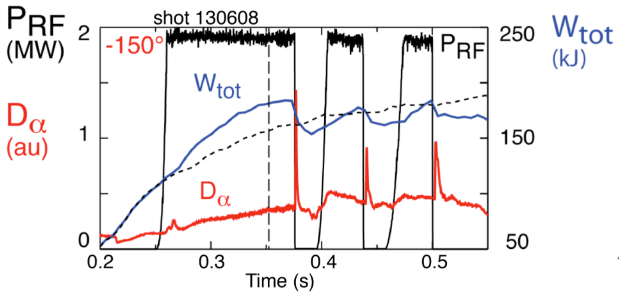

Fig. 4. Modulated HHFW power (–13 m^{-1}), total stored energy, and D_α emission light for an NBI-heated (2 MW) deuterium plasma. I_p = 1 MW, $B_T(0)$ = 0.55 T. Dotted line is stored energy for the subsequent, NBI-only ref shot.

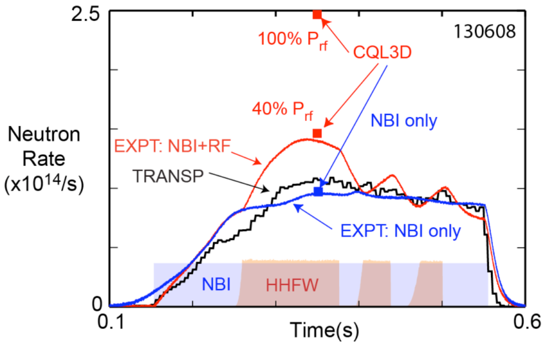

Fig. 5. CQL3D analysis of the shot in Fig. 3 needs HHFW power reduced to 40% of total to match the measured neutron rate.

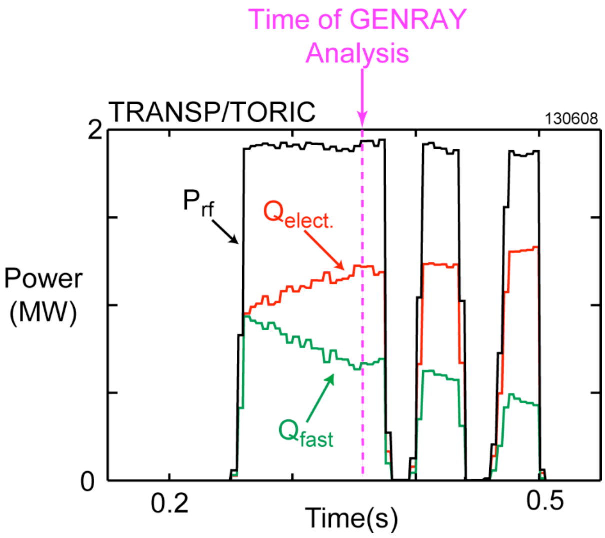

Fig 6. TORIC analysis within the TRANSP code shows power absorption by the electrons increasing with RF on time as the electron beta increases.

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