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by

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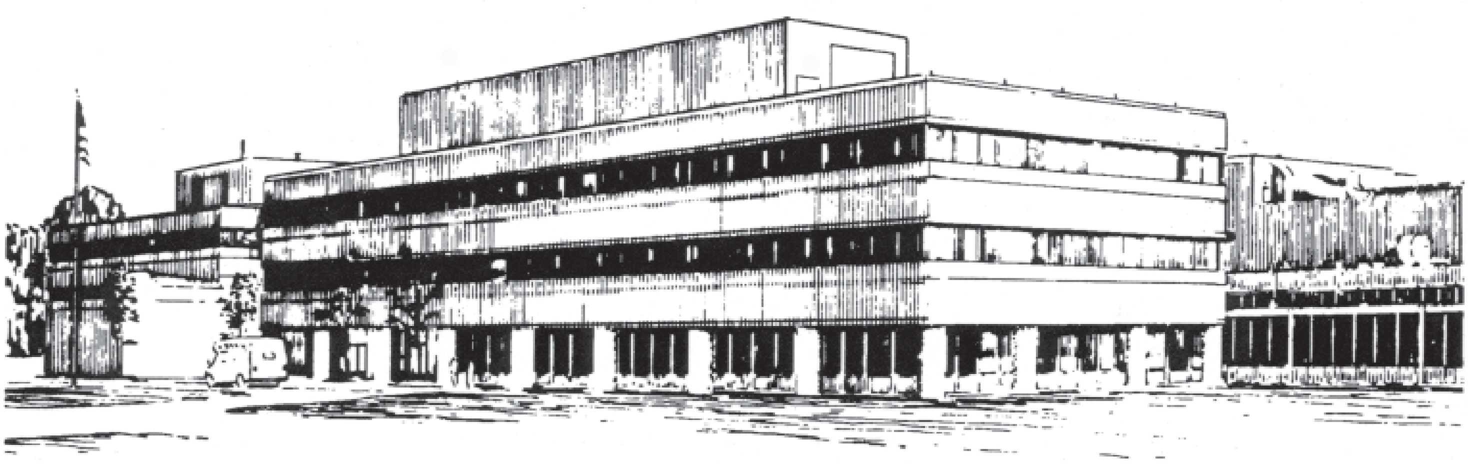

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High-Harmonic Fast Wave Driven H-mode Plasmas on NSTX*

B.P. LeBlanc[a], R.E. Bell[a], S.I. Bernabei[a], K. Indireshkumar[a], S.M. Kaye[a], R. Maingi[b], T.K. Mau[c], D. W. Swain[b], G. Taylor[a], P. M. Ryan[b], J.B Wilgen[b], J.R. Wilson[a]

[a] *Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543*
[b] *Oak Ridge national Laboratory, Oak Ridge, Tennessee 37830*
[c] UCSD, San Diego, California

Abstract. The launch of High-Harmonic Fast Waves (HHFW) routinely provides auxiliary power to NSTX plasmas, where it is used to heat electrons and pursue drive current. H-mode transitions have been observed in deuterium discharges, where only HHFW and ohmic heating, and no neutral beam injection (NBI), were applied to the plasma. The usual H-mode signatures are observed. A drop of the Dα light marks the start of a stored energy increase, which can double the energy content. These H-mode plasmas also have the expected kinetic profile signatures with steep edge density and electron temperature pedestal. Similar to its NBI driven counterpart – also observed on NSTX – the HHFW H mode have density profiles that features "ears" in the peripheral region. These plasmas are likely candidates for long pulse operation because of the combination of bootstrap current, associated with H-mode kinetic profiles, and active current drive, which can be generated with HHFW power.

INTRODUCTION

The application of High Harmonic Fast Wave (HHFW) constitutes an important element of the NSTX research program, where it is used to heat bulk electrons and pursue non-inductive drive current [1,2]. Substantial progress has been achieved over the results presented at the previous meeting of this conference [3], and effective heating has been achieved in helium and deuterium plasmas for different antenna *k//*. In particular electron temperature, T_e, up to 3.9 keV has been measured, with profile behavior suggestive of a thermal electron internal transport barrier [4]. NSTX operates naturally at high beta, with parameters entailing wave physics with dielectric constant $\varepsilon \equiv \omega_{pe}^2/\Omega_\varepsilon^2 \approx$ 50-100, which is large compared to conventional tokamak, where $\varepsilon \approx 1$. For such high ε–value plasmas, an attractive fast-wave window opens in the high harmonic frequency range, $\Omega_i << \omega << \omega_{LH}$, which permits electron heating and current drive [5]. A welcome result has been the observation of H-mode transition during HHFW heating. Such transitions are readily observed when HHFW provides the sole source of auxiliary heating. So far all the H-mode transitions have been observed with lower single null configuration (LSN) and at plasma current lower or equal to 0.5 MA. Attempts made at higher current were not successful, but a systematic study has not been performed to date. In this paper we review some of the parameters of these plasmas and make use of a recent implementation of the ray tracing code CURRAY [6] into the data regression code TRANSP [7] to study the time dependent power deposition under HHFW driven H-mode conditions.

HHFW DRIVEN H-MODE PLASMAS

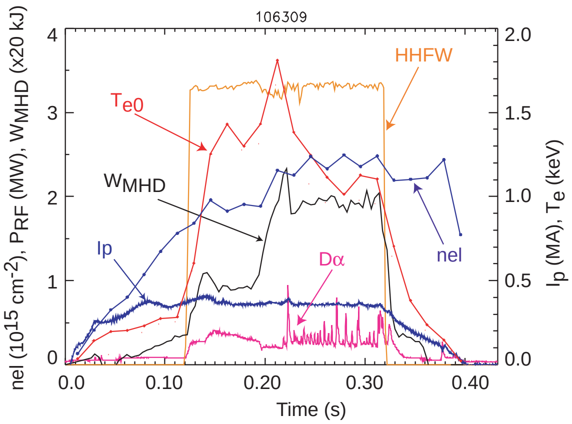

Figure 1. Time evolution of an HHFW driven H-mode discharge. The transition is seen at 0.195 s on the D_ trace; stored energy WMHD doubles. A drop in Te0 occurs during the ELM activity.

The relevant parameters for a HHFW driven H-mode discharge in deuterium are shown in Fig.1. The plasma current is 0.36 MA, and the magnetic field is 0.45 T. HHFW power of 3.3 MW is applied during interval 0.12-0.32 s. The HHFW frequency is 30 MHz with $k_{//}$ = 14 m^{-1}. T_{e0} rapidly responds to the HHFW power by increasing from 0.3 keV to nearly 1.5 keV in 0.05 s. The H transition occurred at 0.195 s and was accompanied by further heating of the electrons and a doubling in the stored energy. The decrease in central electron temperature observed later on could have resulted from power-coupling losses caused by MHD activity or the ELMs (visible on the D_α trace). TRANSP analysis predicts a 40% bootstrap current fraction for this discharge.

Kinetic Documentation

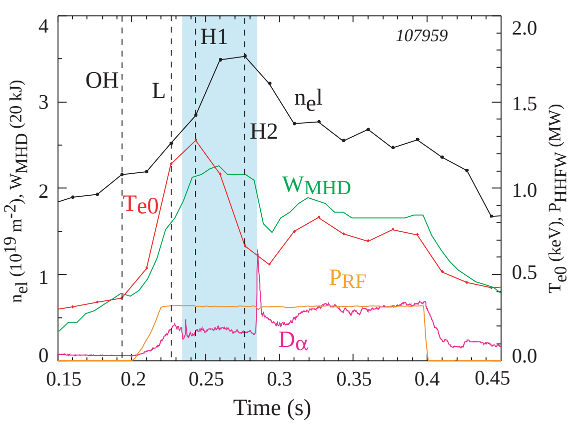

Figure 2. Time evolution of HHFW driven H mode discharge. Time markers OH, L, H1 and H2 shown with dotted lines.

We can see in Fig. 2 a temporal overlay of plasma parameters for a deuterium discharge with plasma current of 0.5 MA and toroidal field of 0.45 T. The HHFW power 3.2 MW pulse is applied from 0.2 to 0. 4 s and is the sole source of auxiliary power. The antenna k// is 14 m^{-1} and the frequency 30 MHz. As a result of the HHFW heating, the central electron temperature T_{e0} increases from ≈ 0.4 keV to ≈ 1.1 keV, before the onset of the H phase occurring during the interval 0.235-0.285 s as can be seen on the D_α trace. Four time points indicated with vertical dotted lines – 0.193, 0.227, 0.243, 0.277 s – correspond respectively to the ohmic phase

(OH), the L phase (L), the early and late H phase (H1 and H2). Also seen in the figure are the line-integrated density, $n_e l$, and the magnetically derived stored energy, W_{MHD}.

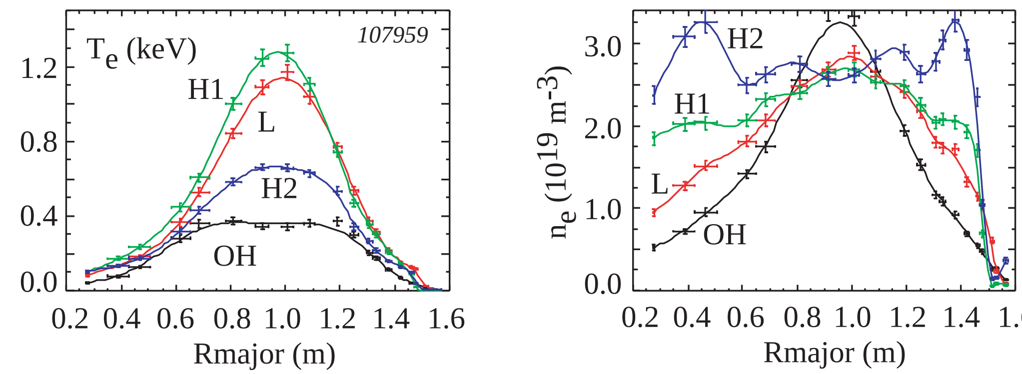

Figure 3. Temporal overlays of $T_e(R)$, and $n_e(R)$ for a HHFW driven H-mode discharge. Four times are shown: ohmic (OH), L-mode (L), early H-mode (H1), late H-mode (H2).

Kinetic profiles of HHFW driven H-mode plasmas show the expected signatures of this high confinement regime. In Fig. 3, we show $T_e(R)$ and $n_e(R)$ profiles for the time points marked OH, L, H1 and H2 in Fig. 2. During the ohmic phase, the T_e profile is flat and limited to 0.3 keV; the density profile is peaked. During the L phase, we observe a T_e increase over the whole profile with the center reaching 1.1 keV; the density profile changes from peaked to triangular shape. There is a hint of a edge profile steepening visible on $T_e(R)$ and $n_e(R)$ outboard data. The early H-mode $n_e(R)$ data show a well established edge gradient. The plasma column has shifted inwards by ≈ 3 cm and the electron temperature is slightly increased. The temperature edge pedestal is ≈ 0.12 keV. During the later H-mode phase, we observe a fully developed edge density gradient with "ears" near the peripheral regions. Meanwhile the central electron temperature has fallen to 0.6 keV.

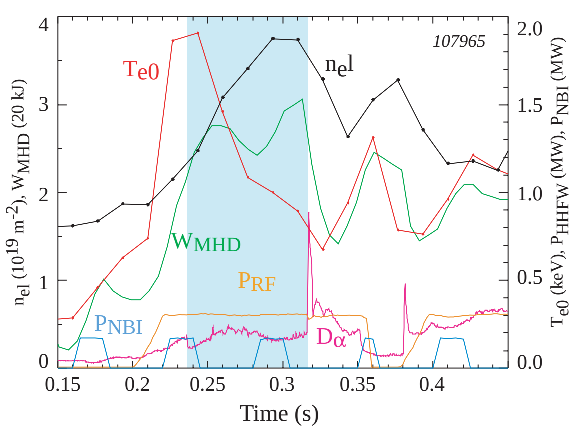

Figure 4. Time evolution of HHFW driven H mode discharge. Short NBI pulses added for T_i measurements

The discharge shown in Fig. 4 has the same nominal parameters as the one just discussed above, but short neutral beam pulses lasting 0.02 s were applied from 0.16 s on to measure the ion temperature profile $T_i(R)$ by charge exchange recombination spectroscopy at 0.06-second intervals. As in the above case, the HHFW power is 3.2 MW. Each beam pulse has a power of 1.7 MW, but TRANSP calculations indicate that only a power level ≈ 0.6 MW contributes to plasma heating. We can see in Fig. 5 plots of the T_i and T_e and n_e profiles during the L and H phases at respectively ≈ 0.230 s and 0.290 s.

Time Dependent Power Deposition with CURRAY

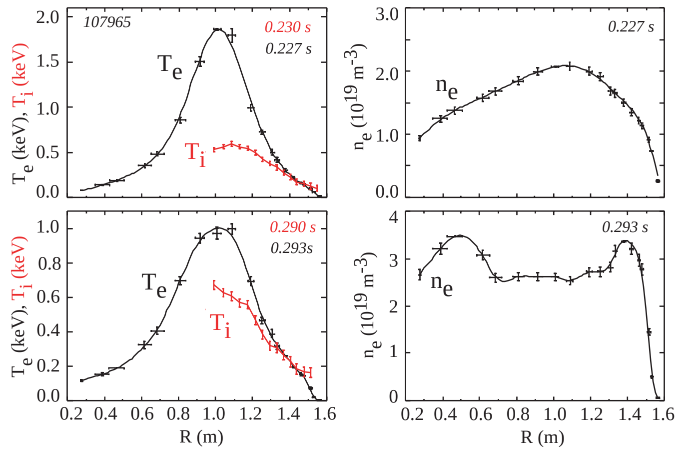

Figure 5. Kinetic profile data at two times near 0.230 s and 0.290 s. T_i from charge exchange recombination spectroscopy. T_e and n_e from Thomson scattering.

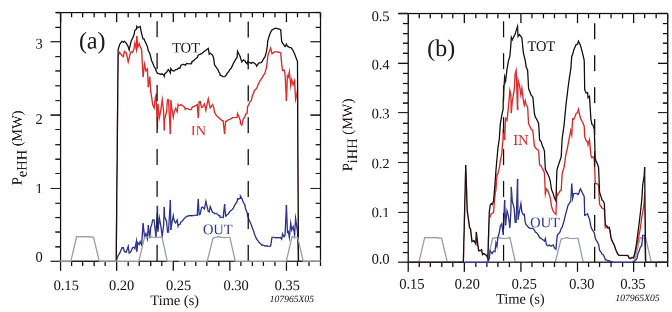

Figure 6. Time evolution of power absorption: (a) power to the electrons; (b) power to the ions. Dotted lines delineate H phase. Neutral beam blips shown for reference.

The ray tracing code CURRAY has recently been incorporated into the TRANSP code and we can see in Fig. 6 some preliminary analysis results. In panel (a) we see the predicted power absorbed by the electrons. Besides the total power, we also show the power absorbed in the inner region and in the outer region. One can see that during the H phase, indicated by dotted lines, more power is absorbed in the outer region as a result of the higher peripheral electron density. There are over 150 time points during the HHFW pulse, which gives true temporal information on the power deposition. For example, the drops in the absorbed power occurring, when neutral-beam pulses are present, are caused by wave absorption by fast particles [8]. Panel (b) show the power absorbed by the ions. Absorption by the fast particle constitutes the dominant term and one can see the ion heating staying in sync with the neutral beam pulses. The quick rise in ion heating at the onset of the HHFW pulse – 0.2 s – comes from the residual fast ions generated by the beam blip at 0.16 s.

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