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IMPROVED HHFW HEATING AND CURRENT DRIVE AT LONG WAVELENGTHS ON NSTX

P. M. Ryan[1], R. E. Bell[2], L. A. Berry[1], P. T. Bonoli[3], R. W. Harvey[4], J. C. Hosea[2], E. F. Jaeger [1], B. P. LeBlanc[2], C. K. Phillips[2], G. Taylor[2], E. J. Valeo[2], J. B. Wilgen[1], J. R. Wilson[2], J. C. Wright[3], H. Yuh[5], and the NSTX Team

[1] *ORNL, Oak Ridge, TN 37831, USA*

[2] *PPPL, Princeton University, Princeton, NJ 08540, USA*

[3] *PSFC, MIT, Cambridge, MA 02139, USA*

[4] *CompX, Del Mar, CA 92014, USA*

[5] *Nova Photonics, Princeton, NJ 08540, USA*

INTRODUCTION

The High Harmonic Fast Wave (HHFW) system on NSTX is used for plasma (electron) heating and current drive. It consists of twelve current straps powered by six 1-MW transmitters operating at 30 MHz, with straps 1&7, 2&8, ... connected by 2λ of transmission line and oriented to have opposite currents [1]. Thus, straps 1-6 and 7-12 form two phased arrays which are permanently 180º out of phase with each other; the phase shift between transmitters can be rapidly and arbitrarily varied during a pulse. For relative phase shifts of ±30º, ±90º, and ±150º, the launcher operates as a highly directional, 12-element array with spectral peaks at $k_{||} \sim \pm 3, \pm 8, \pm 14\ m^{-1}$ respectively, where $k_{||}$ is equivalent to $n_\phi/(R+a)$.

Operation of NSTX at $B_T(0) = 0.55$ T has increased the HHFW core power deposition and heating efficiency compared to previous $B_T(0) \leq 0.45$ T operation, particularly when launching lower toroidal wavenumbers. This improvement at higher B-field is attributed, in part, to moving the density at which the fast waves begin to propagate in the plasma to a point further from the wall [2]. At this magnetic field strength the HHFW power deposition in helium plasmas at $k_{||} = -8\ m^{-1}$ was comparable to that of $k_{||} = \pm 14\ m^{-1}$, and core heating at $k_{||} = 3\ m^{-1}$ was observed for the first time, albeit at lower efficiency. MSE measurements [3] of the current driven at $k_{||} = -8\ m^{-1}$ in L-mode plasmas yielded ~15 kA for an estimated 1.1 MW delivered to the electrons (1.8 MW transmitter power). For comparison, the TORIC code [4] predicts 34 kA and the AORSA code [5] 31 kA for this case, using a single mode corresponding to $k_{||} = -8\ m^{-1}$. The AORSA CD calculation is reduced to 24 kA when the full toroidal spectrum (101 modes) arising from -90º phasing is considered, in closer agreement with measurements [2].

RECENT HIGH FIELD OPERATION IN DEUTERIUM PLASMAS

Recent operation in deuterium plasmas, where control of density increase is more difficult, duplicated the heating success obtained in He plasmas for B_0 = .55 T. Central electron temperatures of 5 keV have been achieved in both He and D plasmas with the application of 3.1 MW HHFW at -150º phasing. Core electron heating of NBI-driven H-mode plasmas has been observed for 1 MA, 0.55 T operation for $k_{||} = \pm$ 14, 18 m^{-1}; such heating had not been seen at lower toroidal field operation.

A phase scan of the HHFW array was carried out with using a 1.1 MW, 250 ms RF pulse. Fig. 1 shows that the best heating of the central electrons is obtained when the spectrum contains a $k_{||}$ = 14 m^{-1} peak (180º also has a peak at 18 m^{-1} and 120º at 8 m^{-1}). The electron temperature is less peaked for phasings where the dominant peak is at 8 m^{-1}, although the total stored energy remains high for these phasings, as can be seen in Fig. 2. Figs 3 and 4 show that the central electron temperatures are high and the densities low for the 14 m^{-1} cases, while the central density increases for the lower wavenumbers. Little RF power is deposited in the core for $k_{||}$ = 3 m^{-1} (-30º). While the cutoff density at which waves begin to propagate is 2×10^{12} cm^{-3} for 14 m^{-1} and 6×10^{11} cm^{-3} for 8 m^{-1}, it is only 9×10^{10} cm^{-3} for 3 m^{-1} and these waves with low $k_{||}$ can propagate very close to the first wall, increasing edge losses.

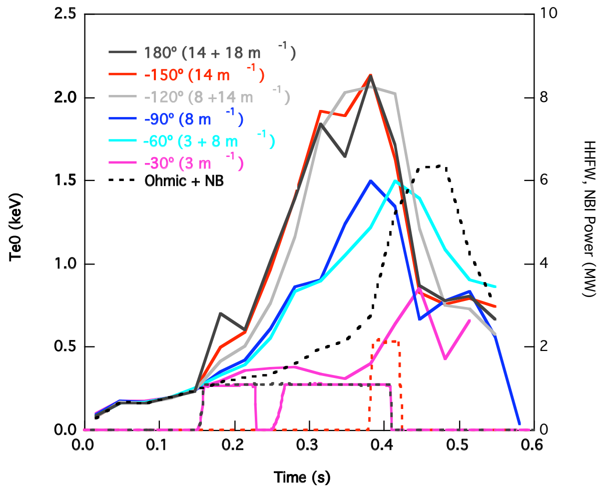

Fig. 1 Central electron heating in D plasma as a function of array phase shift. 1.1 MW HHFW applied from 0.15-0.41 s (RF trip at 0.23 s for -30º phase). 2 MW NBI from 0.38-0.42 s.

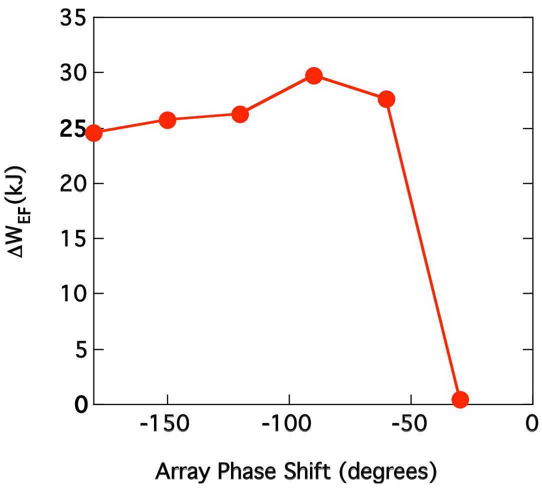

Fig. 2 Change in total stored energy (EFIT calculation) at 0.38 s as a function of array phase shift for 1.1 MW HHFW. Heating efficiency stays fairly constant from -180º to -60º.

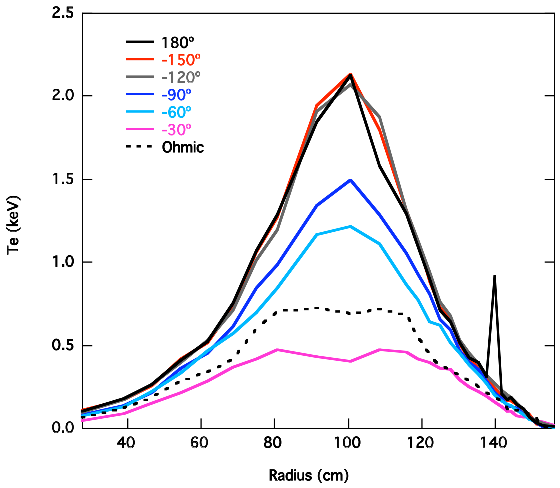

Fig. 3 Electron temperature profiles at 0.38 s shows increased heating at larger phase shifts ($k_{||}$ predominantly 14 m^{-1})

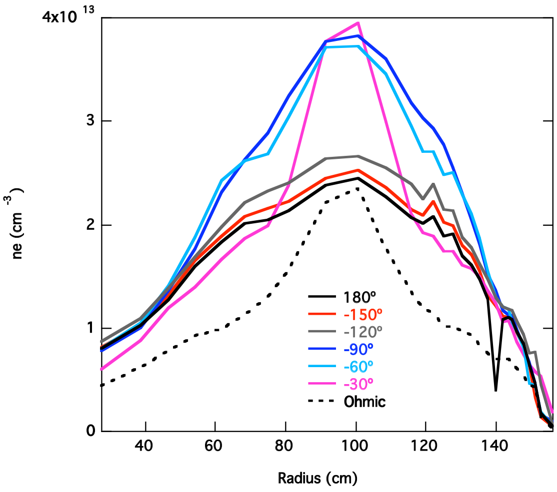

Fig. 4 Density profiles shows broadening for $k_{||}$ predominantly 14 m^{-1} and increased central density for $k_{||}$ predominantly 8 or 3 m^{-1}.

AORSA CALCULATIONS OF DEUTERIUM PLASMA OPERATION

A representative case from the phase scan study (shot 128662, corresponding to the plasma density and temperature conditions of the -90º case in Figs 1-4) was used as the basis for AORSA calculations with plasma conditions fixed as the array phase shift was varied. Figure 5 shows the electric field plotted on toroidal and poloidal slices of the plasma. The toroidal slice is positioned at the poloidal midplane of the plasma, and the poloidal slice bisects the toroidal extent of the HHFW array.

The waves are propagating (and driving electrons) in the direction opposite to the indicated plasma current, thus driving co-currents. The short toroidal wavelength for the -150º case (-13 m^{-1}) can be seen in contrast to the long wavelength for the -30º case (-3 m^{-1}). While the high $k_{||}$ wave fields are localized near the antenna, the low $k_{||}$ fields extend further into the plasma volume and may be making multiple passes through the plasma center. Figure 6 shows greater power deposition outside the rho = 0.2 flux surface for the 3 m^{-1} case.

Figure 7 plots the calculated driven current against the phase shift of an ideal 12-element array; hence the x-axis is the equivalent of $k_{||}$. The red dots are the $k_{||}$ peaks achievable with the present array connecting paired straps. Efficient central electron heating has been seen at 180º and -150º, and now at -90º for high B-field, low edge density operation. While co/cntr-CD operation is possible at ±90º phasing, Fig. 6 indicates that ±30º would be more efficient operating points if we can overcome the edge losses that dominate at the very longest wavelengths. Recent results with lithium wall treatment to reduce the edge density have shown the first increases in electron temperature and stored energy with -30º phasing and this line of investigation will continue. In NSTX, and possibly in ITER, there is a trade off between high efficiency current drive and increased edge losses at low $k_{||}$.

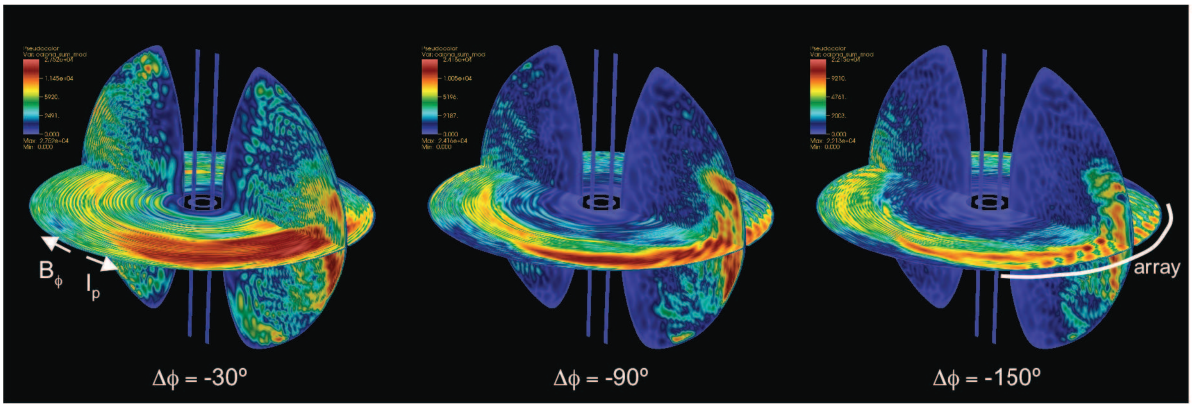

Fig. 5 AORSA E-fields for shot 128662 (1.1 MW, Te(0) ~ 1.5 keV, Ti (0) ~ 800 eV, D with 2% H) for three array phasings

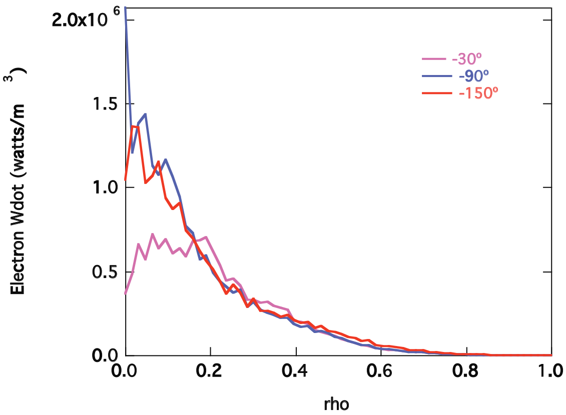

Fig. 6 AORSA electron power deposition profiles for 128662 show less centrally peaked heating for the -30º case. This case also shows some ICH minority heating (~2% of total power).

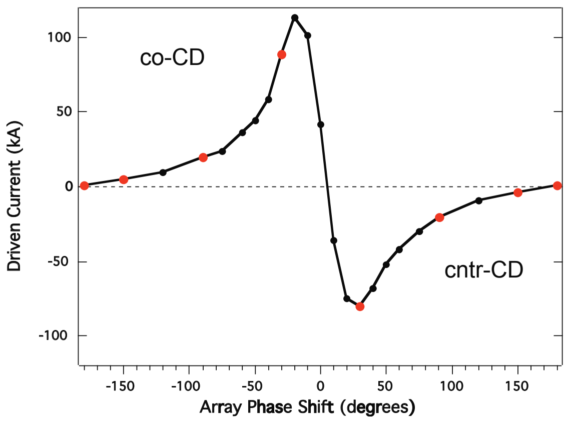

Fig. 7 In the absence of plasma edge losses, AORSA predicts CD efficiency for the Te(0) ~ 1.5 keV plasma to be most efficient for -30º. (Red dots are attainable phasings for the 12-element array as configured).

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