HHFW power absorption in NBI target plasmas*

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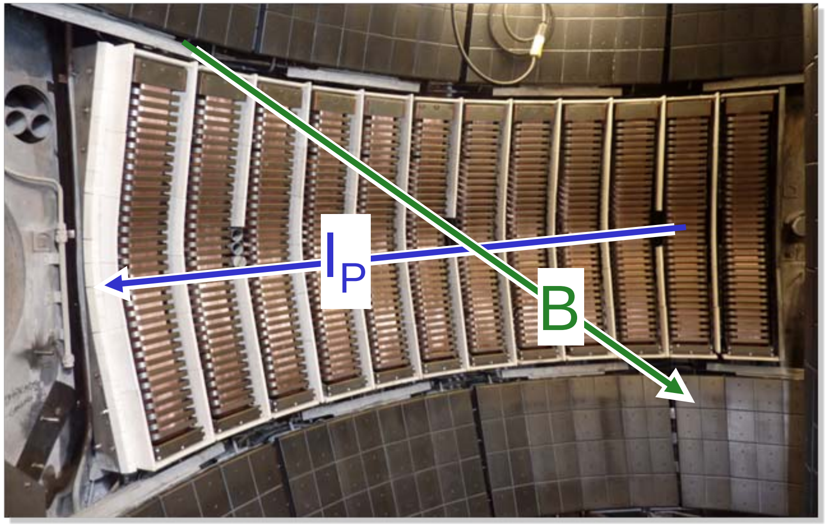
Introduction

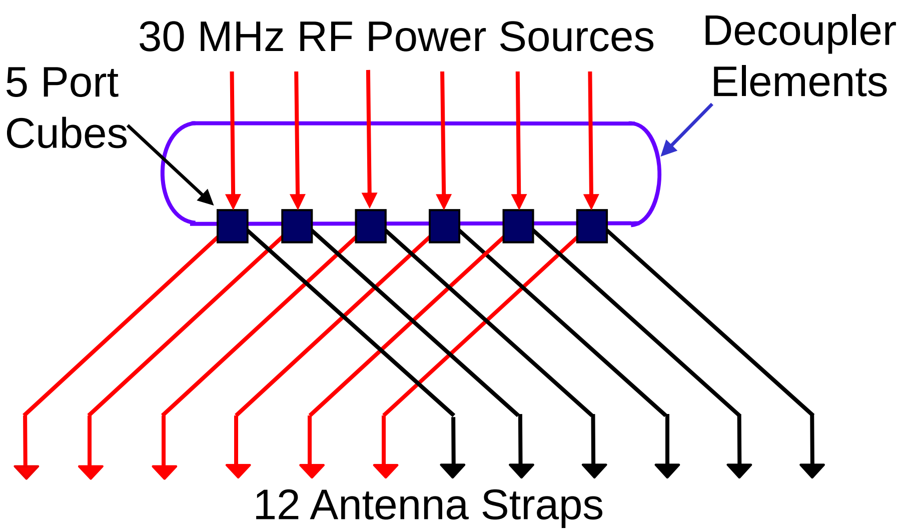
- Goal of High-Harmonic Fast-Wave (HHFW) ion cyclotron range of frequency research on NSTX is to maximize power coupled to plasma:
- Understand and mitigate power loss outside last closed flux surface (LCFS):
  - Relevant to ITER
- NSTX capabilities:
  - Auxiliary heating system includes 7 MW NBI and 6 MW ICRF
  - A complete set of standard diagnostics, and in particular fast-ion diagnostics like fast-ion D-alpha FIDA [1]
- The physics basis of HHFW heating and a review of recent HHFW research are available elsewhere [2], [3]:
  - Typically more than 5 ion-cyclotron resonances present within the plasma in NSTX
- Competition between two dominant absorption mechanisms inside the LCFS:
  - Electron heating via Landau damping and transit-time magnetic pumping,
  - Wave-field acceleration of NBI generated fast ions

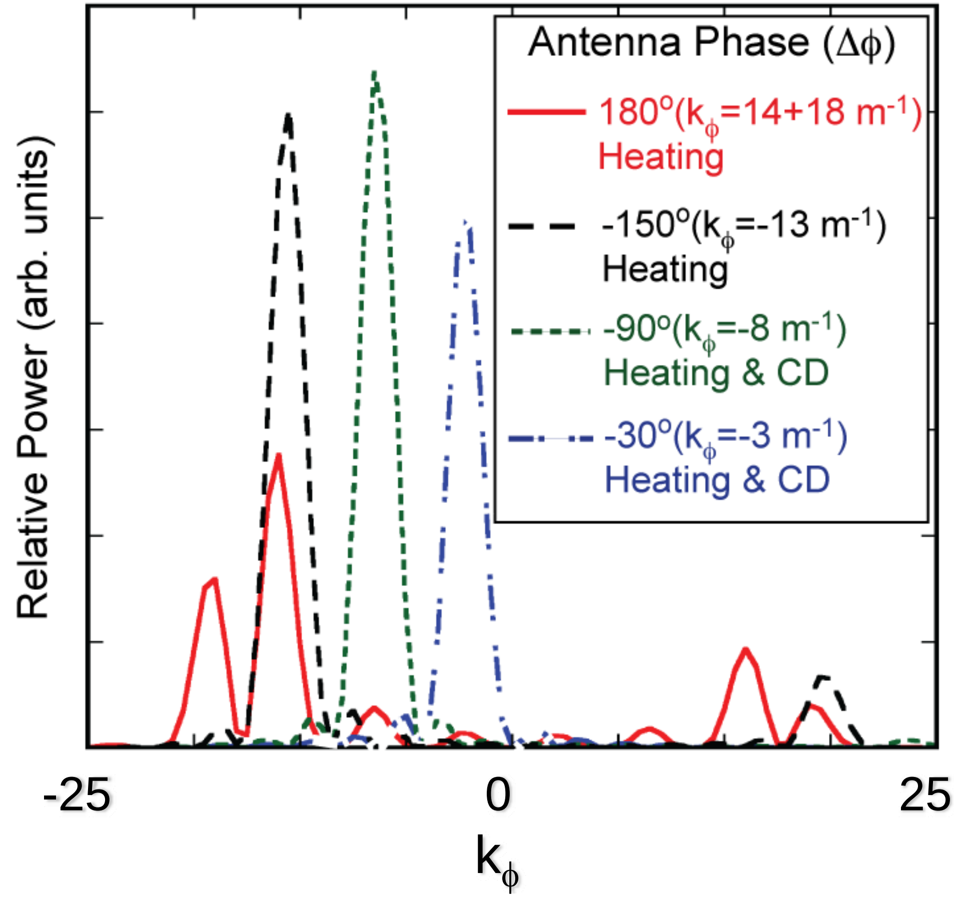
[1] M. PODESTA, et al., Rev. Sci. Instr., 78, 10E521 (2008)
[2] M. ONO, Physics of Plasmas, **2**, (1995) 4075
[3] G. TAYLOR, et al., Physics of Plasmas, Vol. 17 (2010) 05611

HHFW Antenna Has Well Defined Spectrum Ideal for Controlling Deposition, CD Location & Direction



HHFW antenna extends toroidally 90°





- Phase between adjacent straps (Δϕ) easily adjusted from 0° to 180°

Edge Power Absorption and Dispersion

- Propagation onset, power dispersion:
  - Radio–frequency (RF) evanescent wave exits antenna until reaching a region where the local electron density is at the critical level ("onset density") for fast-wave propagation perpendicular to the magnetic field.
  - Propagation onset typically occurs outside of the LCFS, resulting in excitation of surface waves [5]. Such losses can be reduced by having the "onset density" further away from the antenna.
- Edge power absorption:
  - Edge ion heating by parametric decay instability (PDI) is another phenomenon reducing the power reaching the plasma within the LCFS [7]

[4] J.R. WILSON *et al.*, Phys. Plasmas, 10, No. 5, (2003) 1733

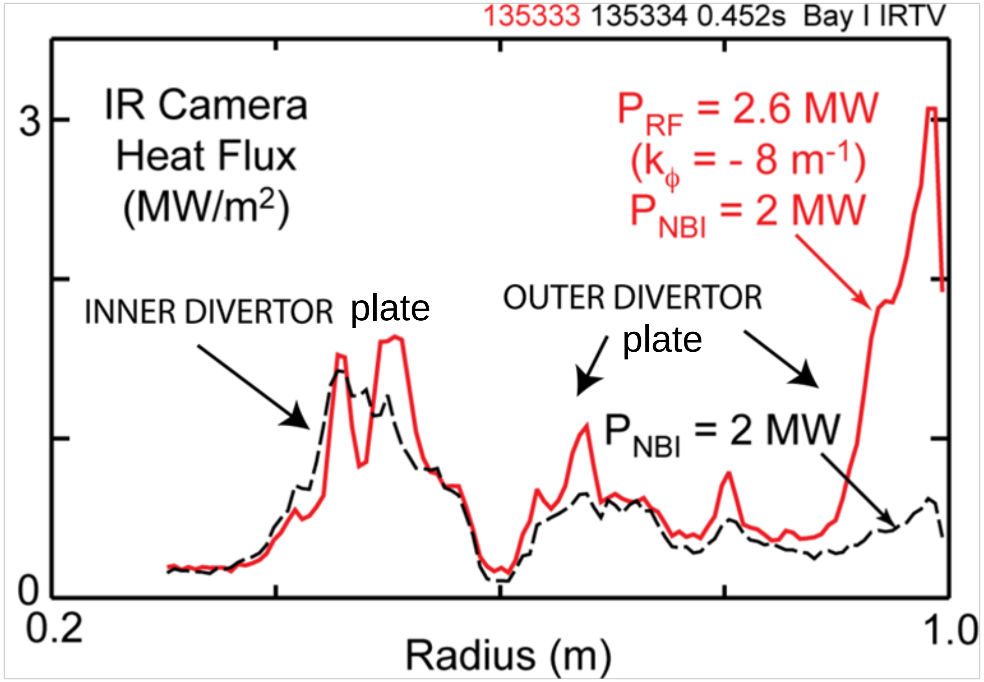
[5] J.C. HOSEA, *et al*., Phys. Plasmas 15 (2008) 056104

[6] D.M. MASTROVITO, et al., Rev. Sci. Instrum. 74 (2003) 5090

[7] T.BIEWER, *et al*, Phys. of Plasmas 12 (2005) 056108

Divertor Power Flux Increase during HHFW Heating

- Infrared measurements [6] indicate a significant amount of the antenna power redirected to divertor
- Heat flux reaching the divertor for two consecutive discharges, both with 2 MW NBI, but with the second having an additional 2.6 MW HHFW heating. In the vicinity of R = 1m, the heat flux increases fivefold with RF power applied

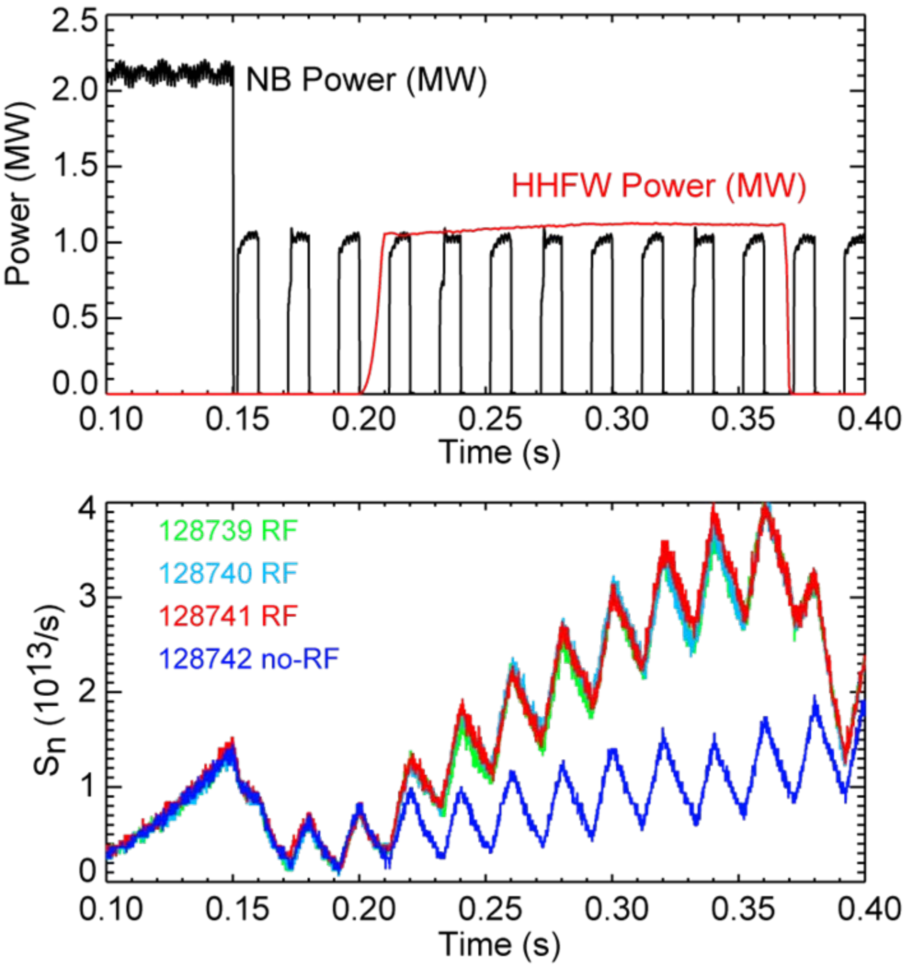


- Divertor heat flux vs. major radius (Preliminary calibration)
- Antenna set to $k_{//}$ = -8 m^{-1}

[6] D.M. Mastrovito, et al., Rev. Sci. Instrum. 74 (2003) 5090

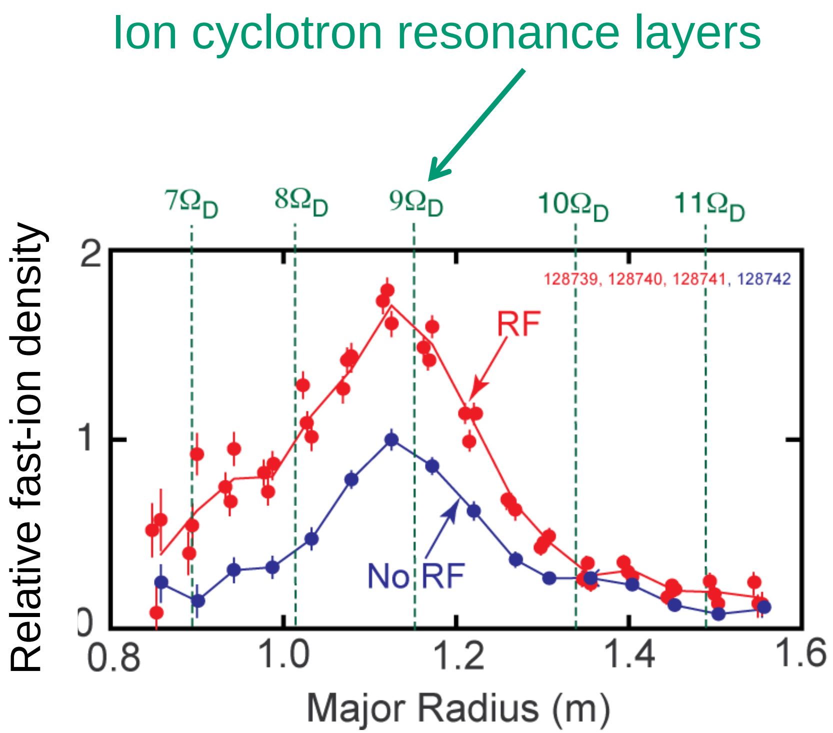
RF Wave Accelerates Fast Ions in L-mode Plasma

- Pulsed 1 MW NBI injection at 65 kV
- Long HHFW 1 MW pulse at $k_{//} = -8\ m^{-1}$
- HHFW power induces a cumulative tripling of neutron production, S_n



Measured Fast-ion Density Increase during HHFW Heating in L-mode Plasma

- Fast-ion D-alpha (FIDA) signal [10]
  - Signal integrated over 30kV-60kV energy range, is proportional to the density of these high-energy fast ions
- Near doubling and broadening of fast-ion density when HHFW is added to NBI [9]



[9] D. LIU, et al. Plasma Physics and Controlled Fusion, Vol. 52 (2010) 025006

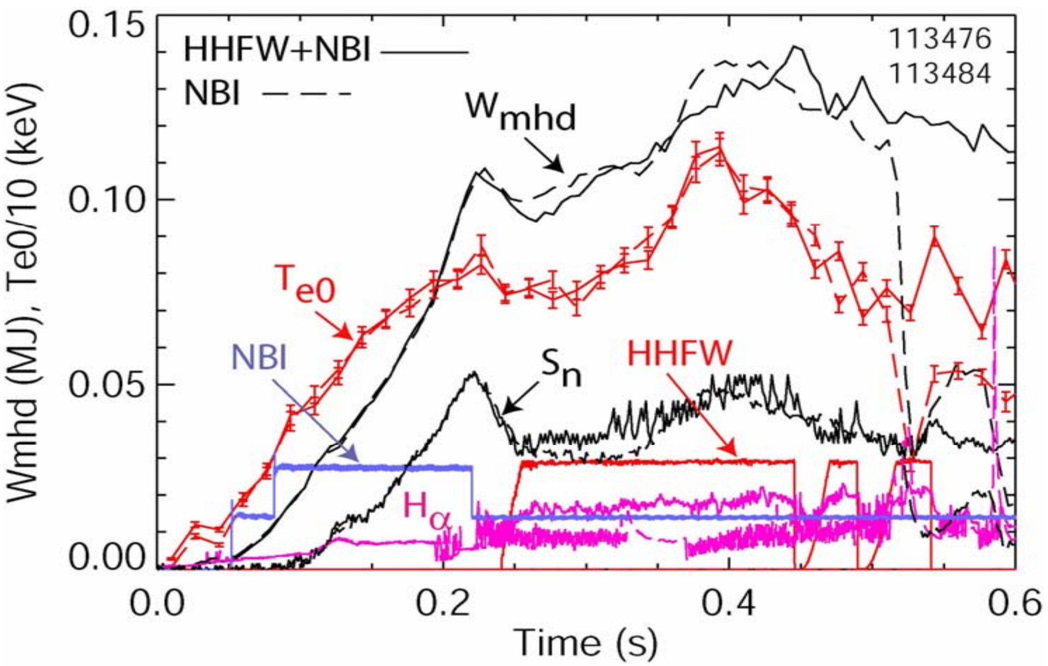
[10] M. PODESTA, et al., Radio Frequency Power in Plasmas, AIP Conf. Proc. 1187 (2009) 69-76

HHFW Heating of NBI-induced H-mode plasma

In the past this task has proved challenging, with essentially no HHFW power reaching the plasma within the LCFS [11]

113476
RF: 2.9 MW
NB: 2.7 MW
$k_{//}$ = 8 m^{-1}

113484
NB: 2.7 MW

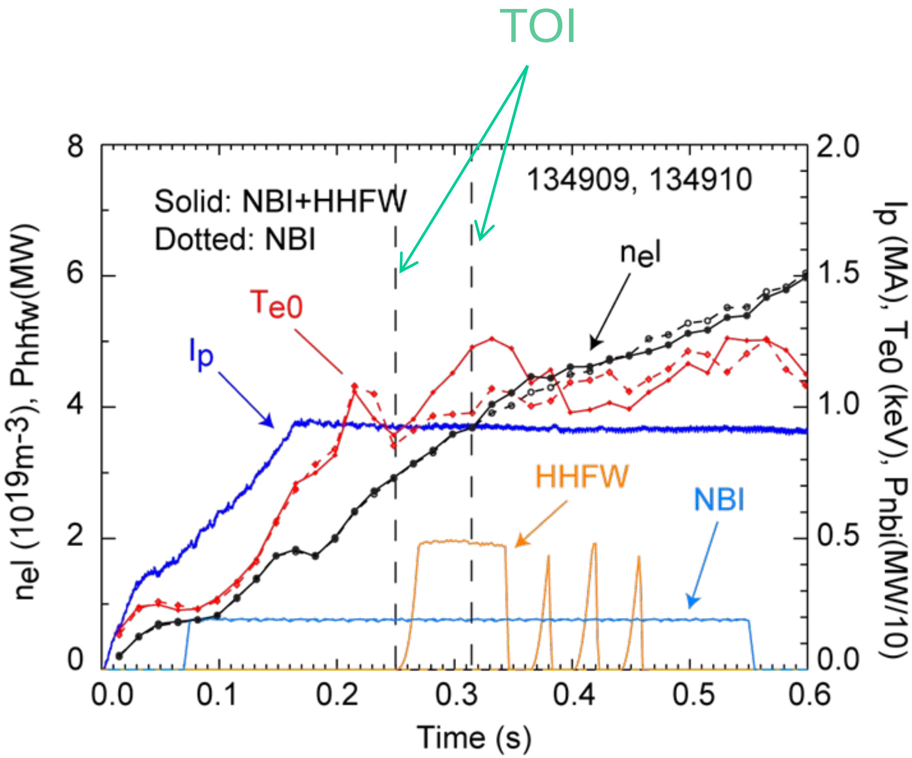


But recently, a sizeable amount of power was coupled to the enclosed plasma, resulting in increase in the T_e, total stored energy and in the neutron rate, as seen in the next slides.

[11] B.P. LEBLANC, *el al*, Radio Frequency Power in Plasmas, AIP Conf. Proc. 787 (2005) 86

Compare Two Matched ELM-free H-mode Discharges NBI+HHFW vs. NBI

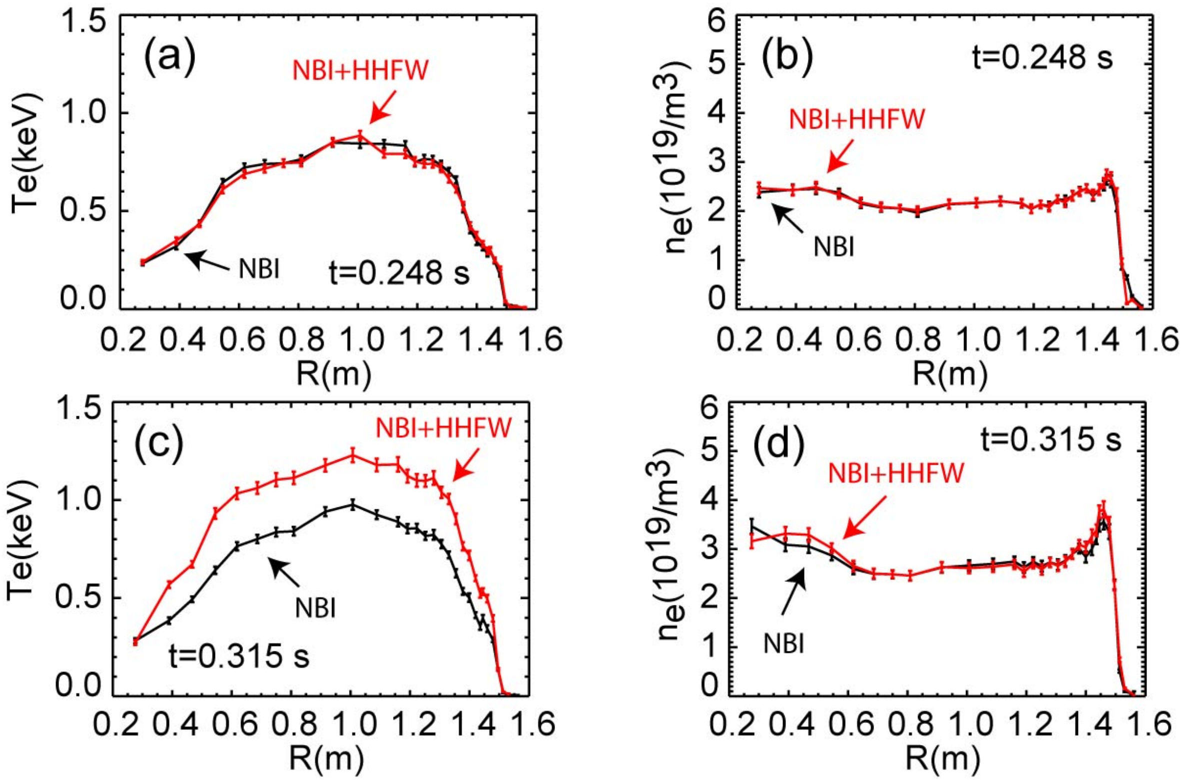
- I_P: 0.9MA, TF: 0.55T
- NBI: 2MW, 90kV
- HHFW: 2MW, $k_{//}$=13m^{-1}
- Benign MHD activity in both plasmas
- Times of interest (TOI) 0.248s and 0.315s



Broad T_e Profile Increase with HHFW Heating of NBI-induced H-mode Plasma

Prior to HHFW Heating

During HHFW Heating

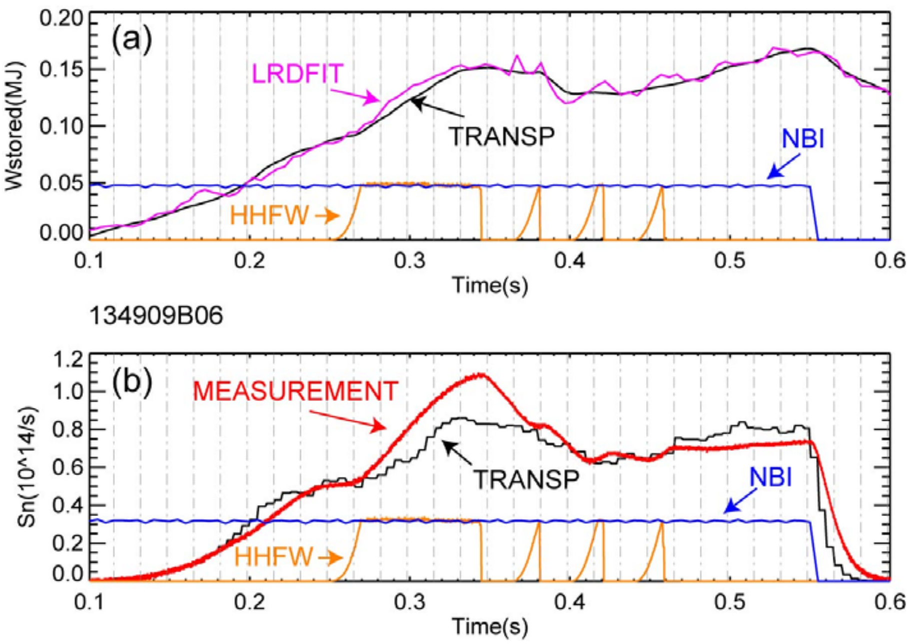


Thomson scattering profiles

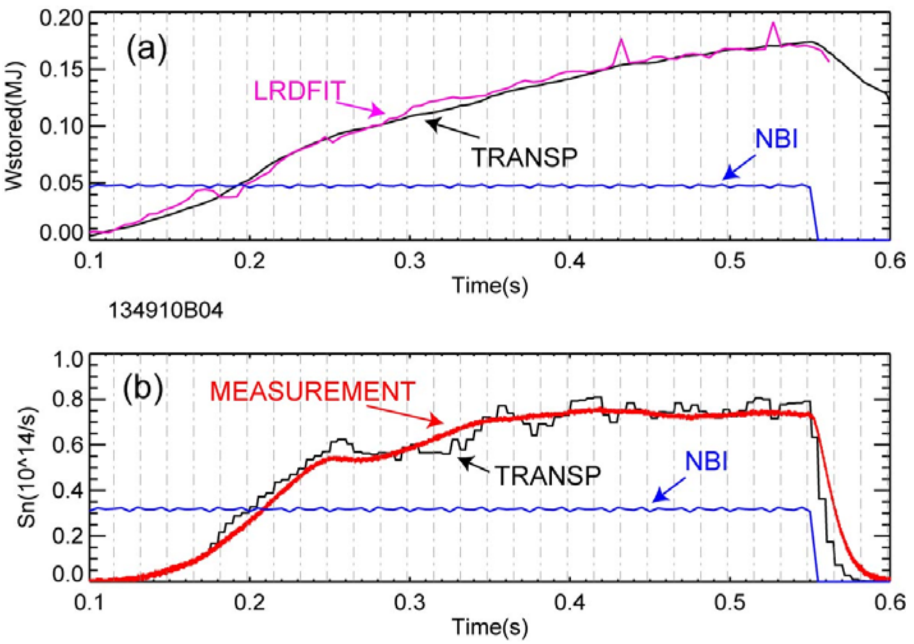
- Identical T_e and n_e H-mode profiles prior to HHFW power onset
- Broad T_e profile increase during HHFW heating, n_e profile remains unchanged. Plasma stayed in the H mode.

TRANSP Analyses of NBI+HHFW and NBI-only ELM-free H-mode Discharges

NBI+HHFW



NBI



- Good match for stored energy, but underestimate neutron production

- Good match for stored energy and neutron production

Estimate HHFW Power Fraction Absorbed within LCFS Based on the Electron Stored Energy

- Three TRANSP calculations of the electron stored energy:
  - (1) Analysis based on the experimental data for combined NBI and HHFW heating
  - (2) Analysis based on the NBI-only experimental data
  - (3) A predictive TRANSP/TORIC calculation
    - Electron thermal diffusivity, χ_e, from the NBI-only reference discharge
    - Assume 100% of antenna power absorbed within LCFS
    - Predict T_e for the NBI+HHFW

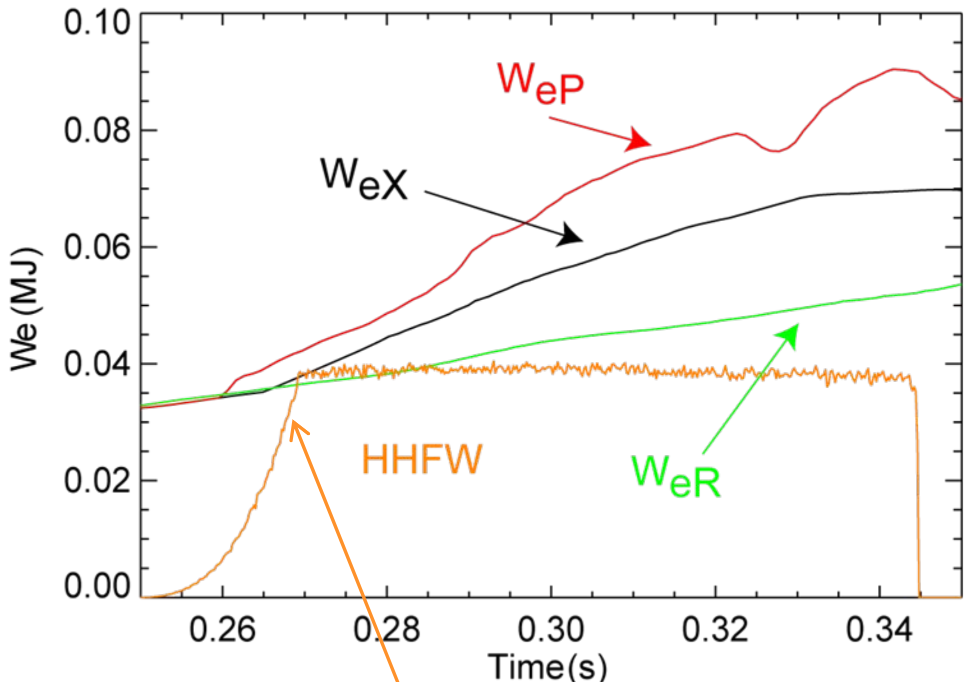
Evolution of Electron Stored Energy Estimates

- W_{eX} is the electron stored energy obtained from the experimental NBI+HHFW TRANSP analysis

- W_{eR} corresponds to the reference NBI-only analysis

- W_{eP} corresponds to the predictive calculation mentioned in previous slide

$W_{eX} < W_{eP}$ implies absorption within LCFS is lower than 100%



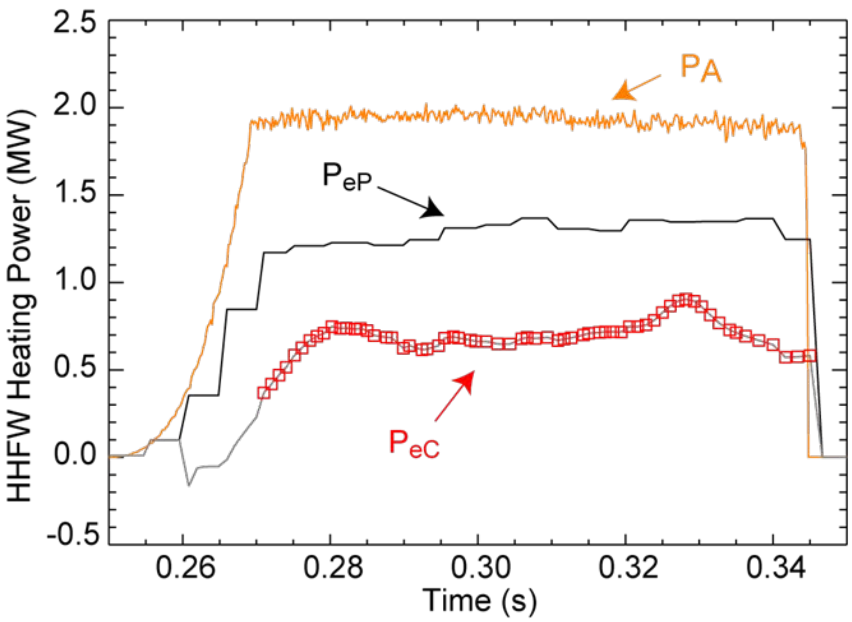
Unscaled HHFW power trace

Coupling to Enclosed Plasma Based on Electron Stored Energy

- Power coupled to the enclosed plasma
- $P_{eC} = f_C \times P_{eP}$, where the fraction, f_C, of the captured antenna defined as

$$f_C=(W_{eX}-W_{eR})/(W_{eP}-W_{eR})$$

- $<f_c>=0.53\pm0.07$
- 1MW absorbed within LCFS
  - 0.7MW by electrons
  - 0.3MW by fast ions



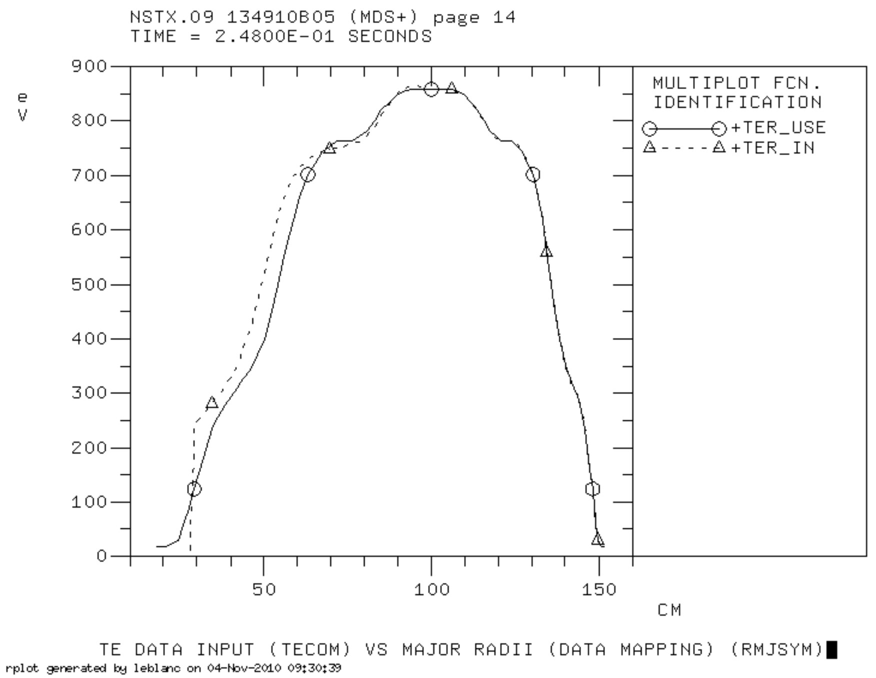
P_A: launched antenna power

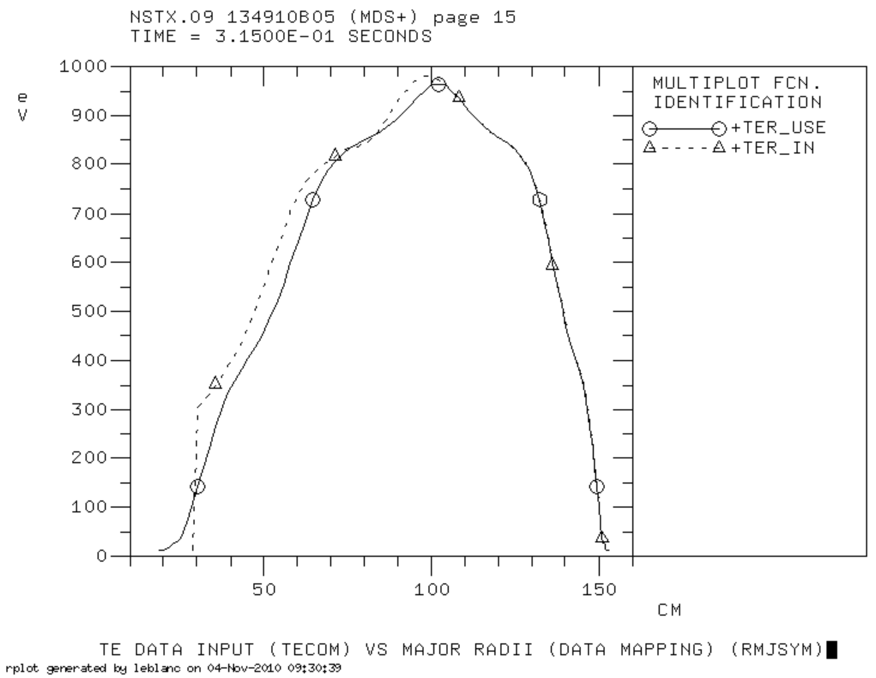
P_{eP}: TORIC calculation of power to electrons assuming 100% capture With LCFS

Using χ_e to Predict T_e

Self consistency check applied to NBI-only plasma

Run TRANSP with experimental Te to determine χ_e
Rerun TRANSP using χ_e to predict Te
Experimental "TER_IN" is reproduced by predicted "TER_USE"





Experimental Te labeled TER_IN
Predicted Te labeled TER_USE

LeBlanc_BP_APS_2010

CQL3D to Estimate Effects of Wave Interaction with Fast Ions

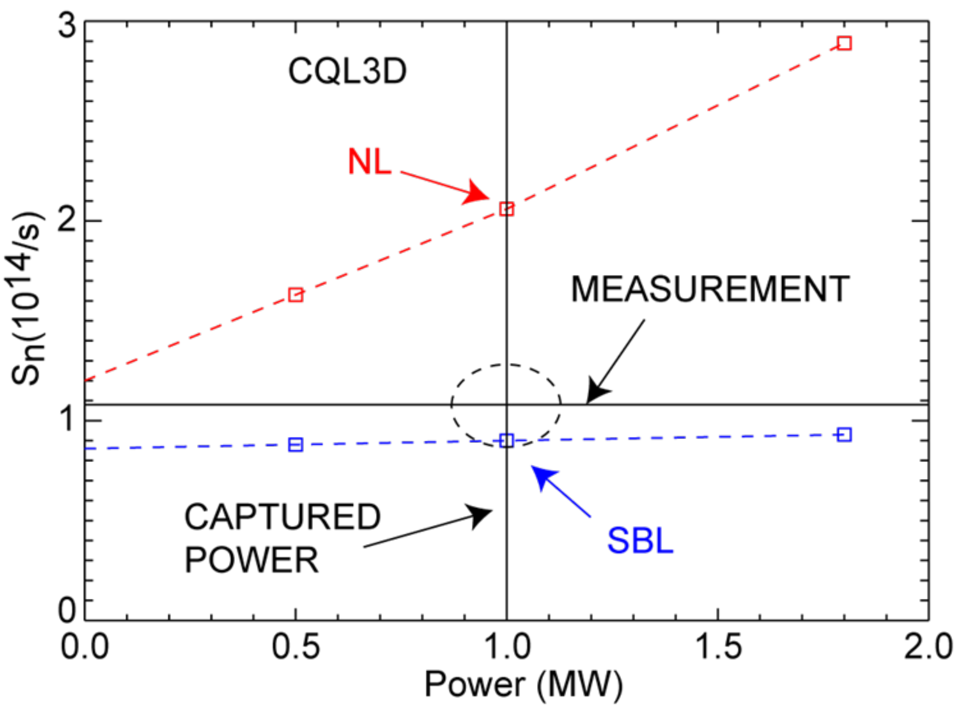
- Currently TRANSP does not include capability to evolve self-consistently the fast-ion energy distribution under the influence of the wave field
- CQL3D is a relativistic collisional, quasi-linear 3D code which solves a bounce-averaged Fokker-Planck equation
- CQL3D can be used to compute the wave effects on the fast ions and neutron production
- Using input data from TRANSP at a particular time of interest, CQL3D is “run to equilibrium” in order to estimate the neutron rate
- CQL3D offers two calculation options:
  - A "no loss" option (NL), which assumes zero banana width orbits
  - A "simple-banana-loss" calculation (SBL)

CQL3D Predicts Significant Fast-ion Losses

Neutron Production (S_n)

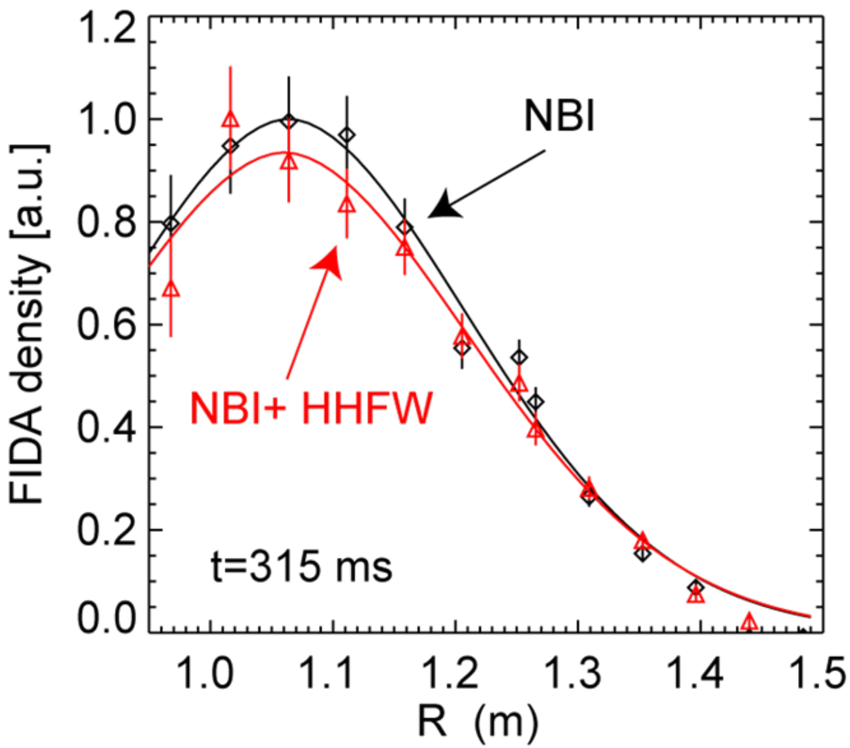
- "no loss" (NL) exceeds S_n measurement
- "simple-banana-loss" (SBL) is at lower limit of measurement error range
  - For 1MW captured within LCFS, about 60% of the power to fast ions is lost compared to NL
- A first-order final-orbit width loss model will be implemented for CQL3D

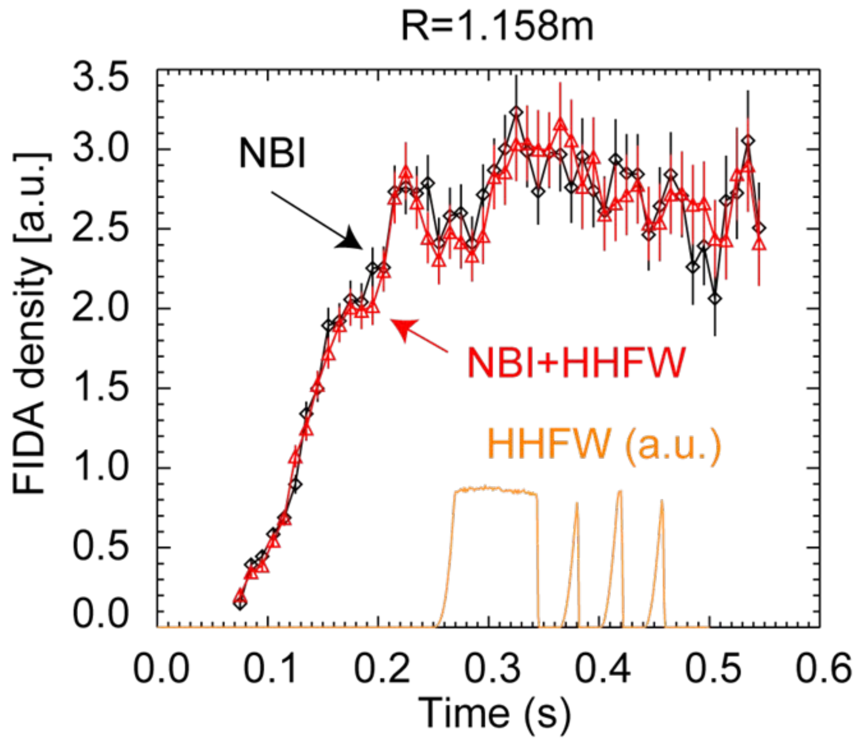
HHFW power scan with CQL3D



FIDA Measurements for NBI+HHFW vs. NBI

No Fast-ion density change observed with HHFW *in this case*



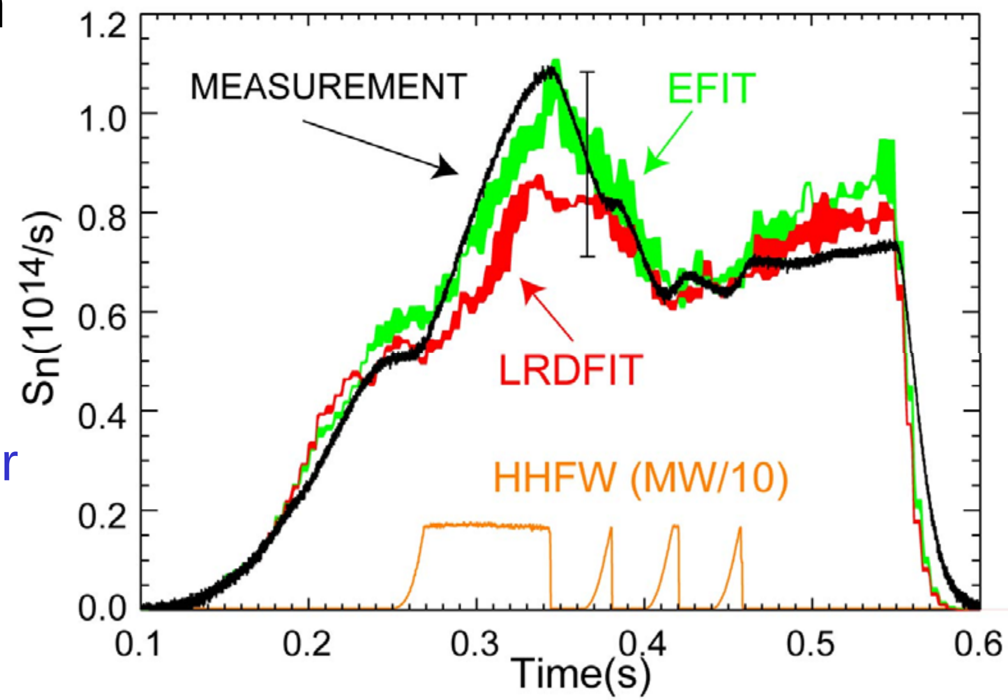


- FIDA density profiles at t=0.315 s for, red, plasma with NBI+HHFW heating and, black, reference NBI-only plasma

- Evolution at R=1.158m of FIDA density for, red, plasma with NBI+HHFW and, black, reference NBI-only plasma

TRANSPORT S_n Estimate Depends on Equilibrium

- Equilibrium solvers LRDFIT and EFIT predict S_n within experimental bar
- EFIT's current profile is more peaked
  - More current in the core region is conducive to better fast-ion confinement and higher neutron production.
- Measurement of q profile (MSE) needed for future experiments



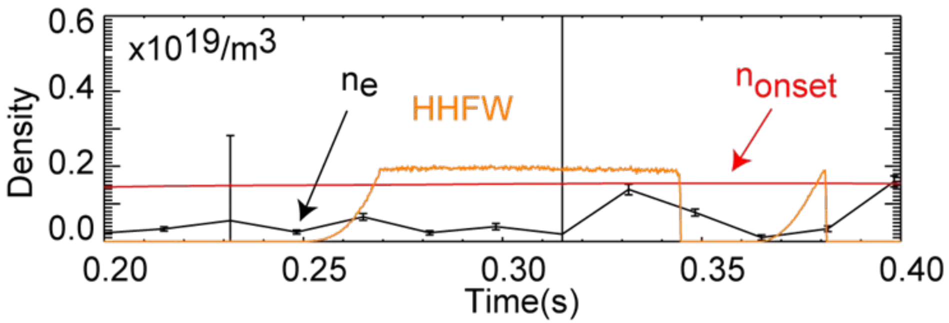
Moving Onset Density Layer away from Antenna Facilitated by Lithium Coating Pumping

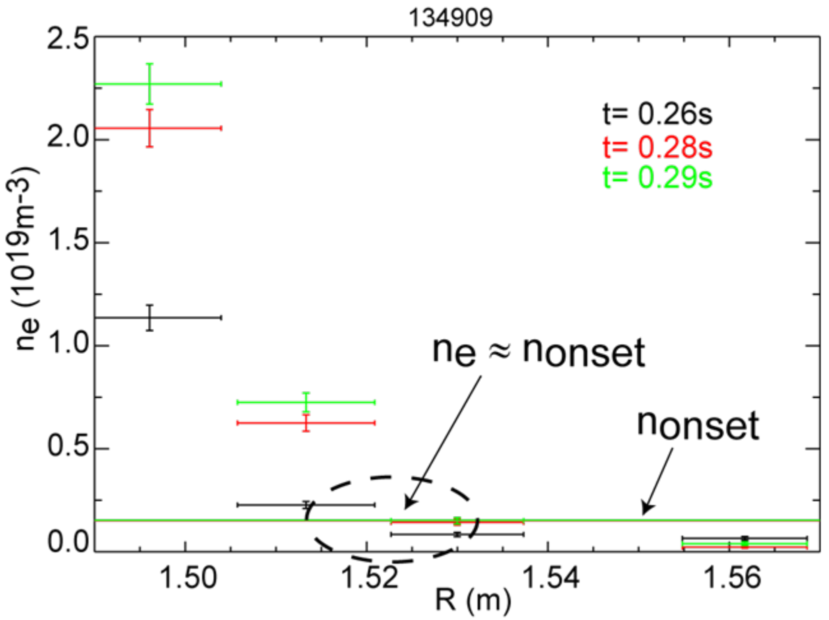
- Onset density, n_{onset}, for perpendicular fast-wave oscillation[5]

$$\longrightarrow n_{onset} \propto B \times k_{//}^{2} / \omega$$

Wave onset occurs where $n_e \approx n_{onset}$, *i.e.* near R=1.52m

n_e near antenna remains below n_{onset} during HHFW pulse





[5] J.C. HOSEA, *et al.*, Phys. Plasmas **15** (2008) 056104

Conclusion

- HHFW Heating of NBI L-mode plasma
  - Near doubling of the density profile of the higher-energy fraction of the fast ions has been measured by FIDA
- HHFW heating of NBI-induced ELM-free H-mode plasma
  - T_e increases over most of the radial profile.
  - 1/2 of antenna power captured with the LCFS
    - 2/3 of power inside LCFS absorbed by electrons
    - 1/3 of power inside LCFS absorbed by fast-ions
  - Fast-ion diagnostics FIDA and NPA observed no changes during HHFW heating
- Edge physics effects
  - Improved core coupling partly attributed to first-wall lithium coating, which keeps the $n_e < n_{onset}$ in front of the antenna
  - Infrared radiation measurements show local power flux on divertor plates reaches ~ 1 MW/m^2 per MW of HHFW heating