HHFW Power Deposition in NBI Heated NSTX Plasmas*

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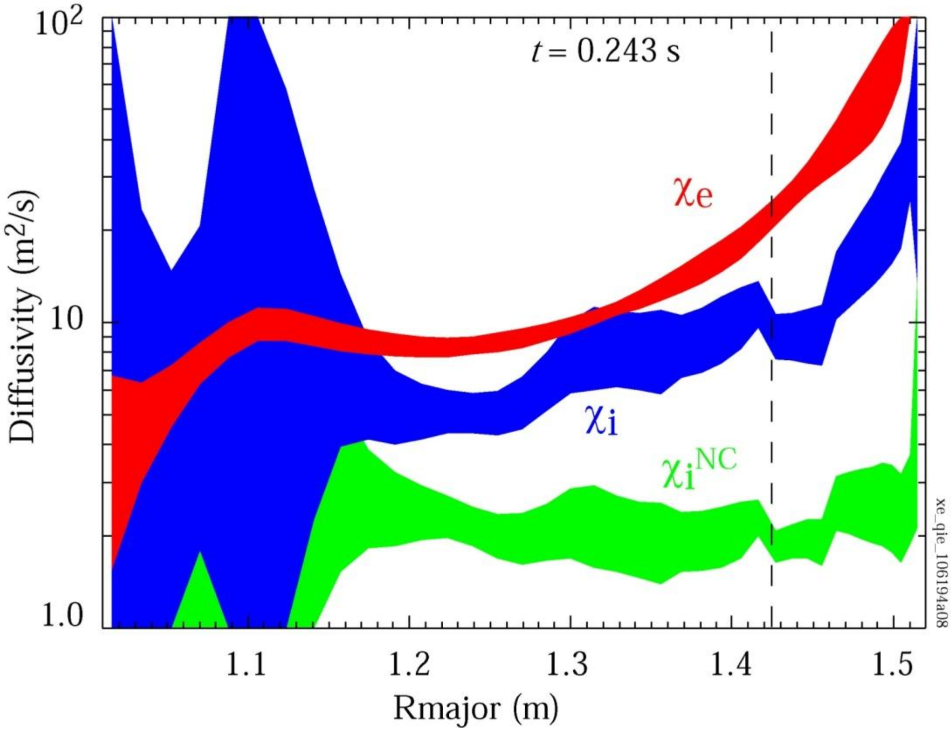
Motivation
Better understanding of thermal transport during HHFW

- Prior to ascertaining thermal transport one needs an accurate estimate of the local power deposition profile
  - This task is notoriously difficult in the case of plasmas auxiliary heated by radio frequency waves

Edge physics effects can deflect power away from the confined plasma i.e. within the last closed flux surface (LCFS)
Resulting in overestimate of the thermal transport when edge



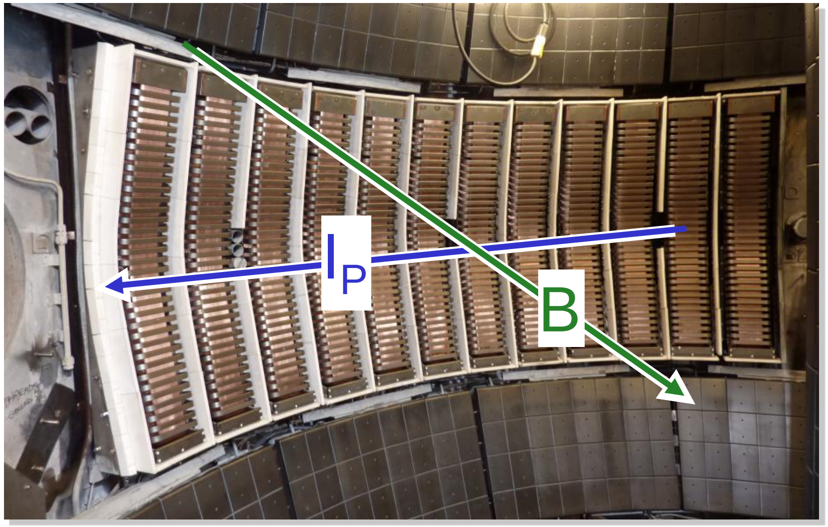
LeBlanc *et al*., Nuclear Fusion, volume 44, (April 2004), pages 513 - 523

Introduction

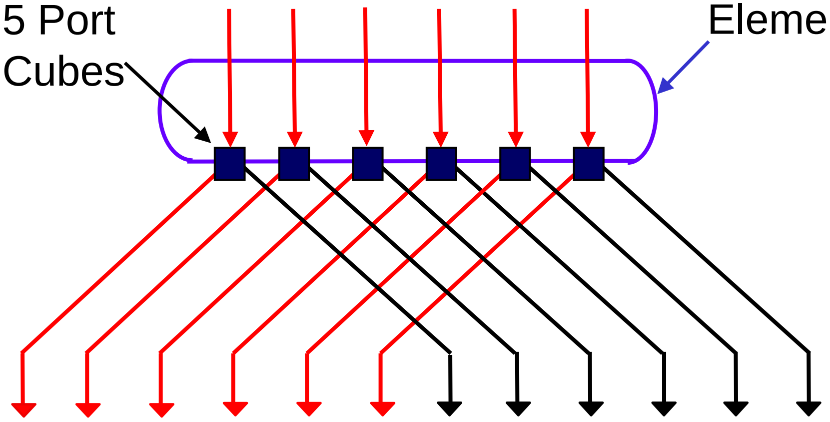
- Goal of High-Harmonic Fast-Wave (HHFW) ion cyclotron range of frequency research on NSTX is to maximize power coupled to plasma:
- Understand and mitigate power loss the LCFS:
  - Relevant to ITER
- NSTX capabilities:
  - Auxiliary heating system includes 7 MW NBI and 6 MW ICRF
  - A complete set of 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°

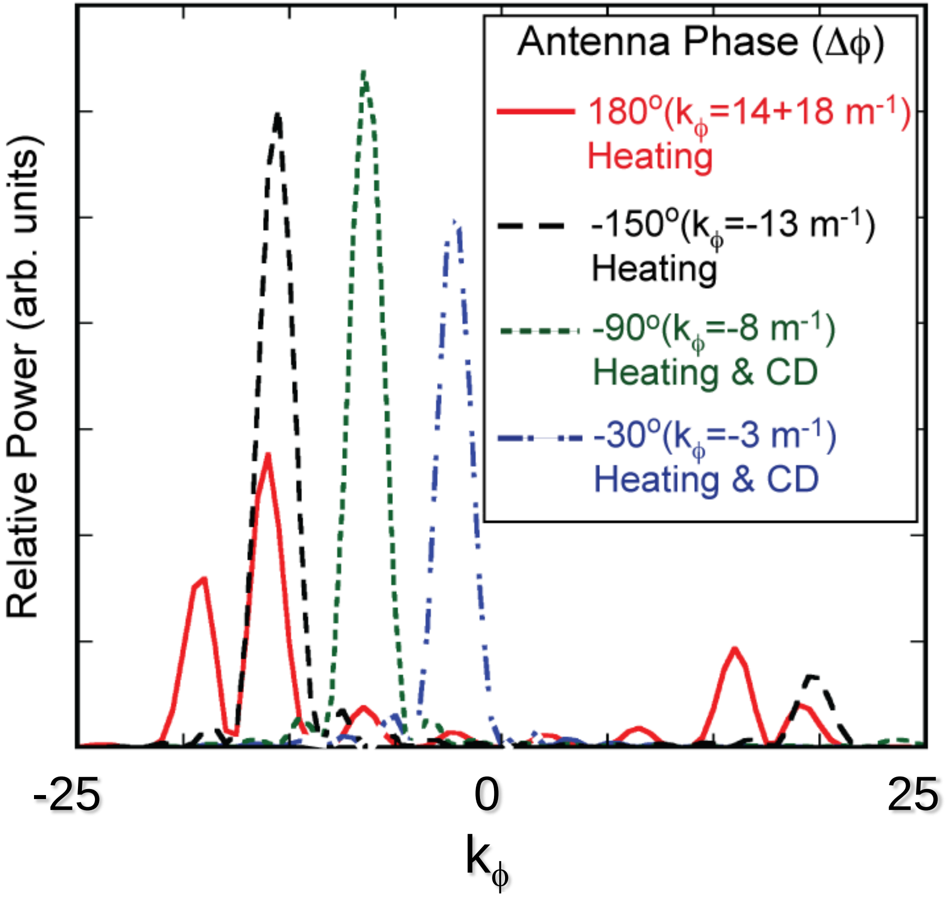


30 MHz RF Power Sources

Decoupler Elements

5 Port Cubes

12 Antenna Straps



- 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” farther 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

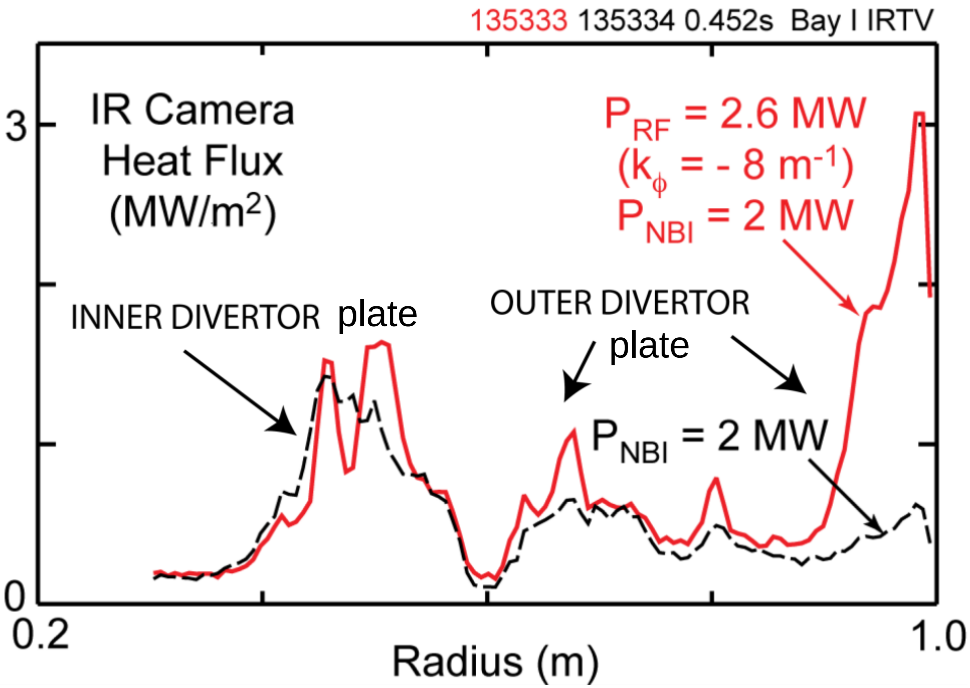
[5] J.C. HOSEA, *et al*., Phys. Plasmas 15 (2008) 056104

[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

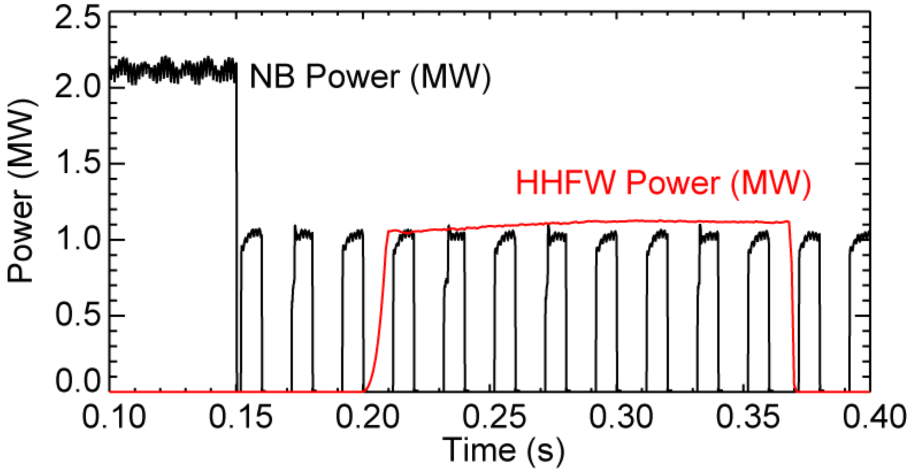


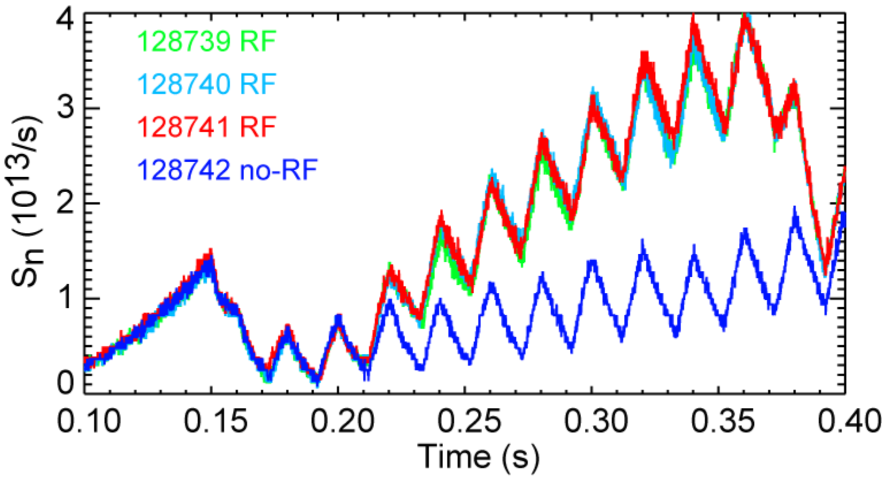
- Divertor heat flux vs. major radius (Preliminary calibration)
- Antenna set to $k_{//} = -8\ m^{-1}$

[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

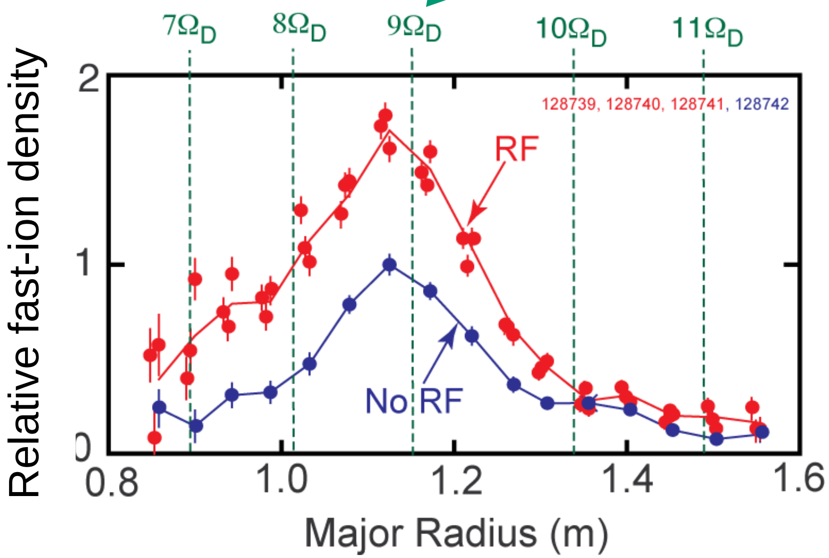




Measured Fast-ion Density Increases during HHFW Heating in L-mode Plasma

- 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]

Ion cyclotron resonance layers



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

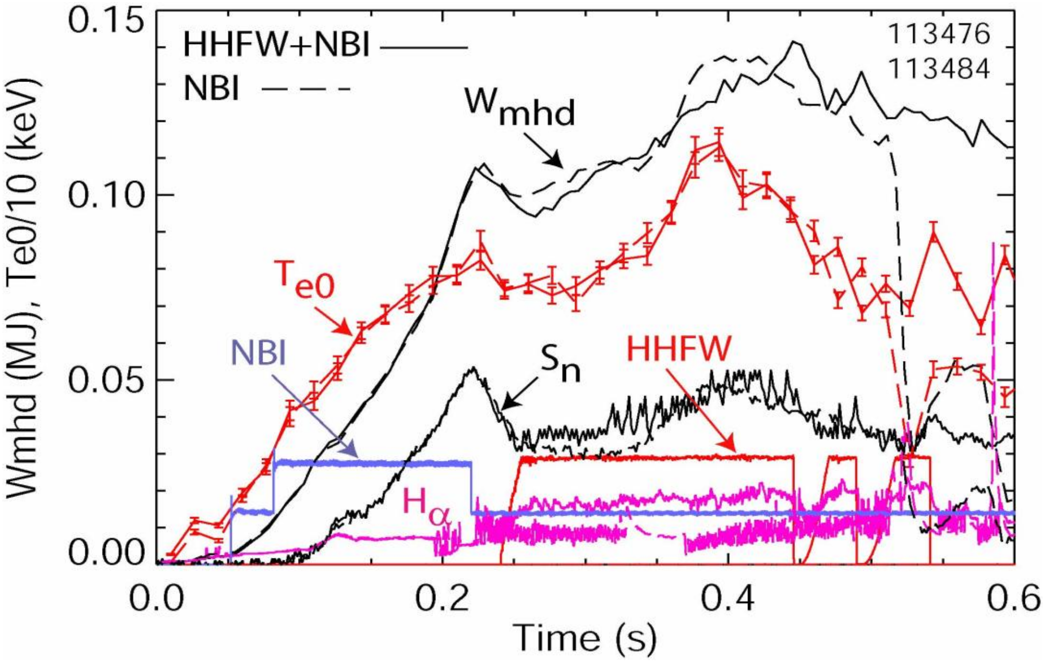
[10] M. PODESTA, et al., Radio Frequency Power in Plasmas, AIP Conf. Proc. 1187 (2009) 69-76

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

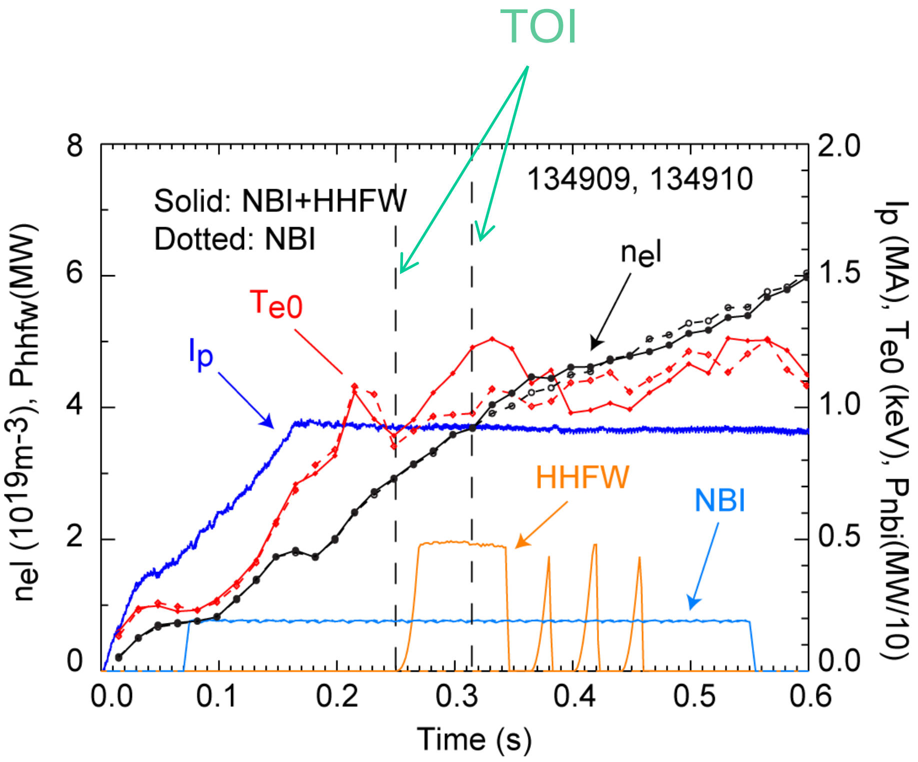


But recently, a sizeable amount of power was coupled to the enclosed plasma, resulting in increase in the T_e, total stored energy and in the neutron rate, as seen in the next slides.

[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

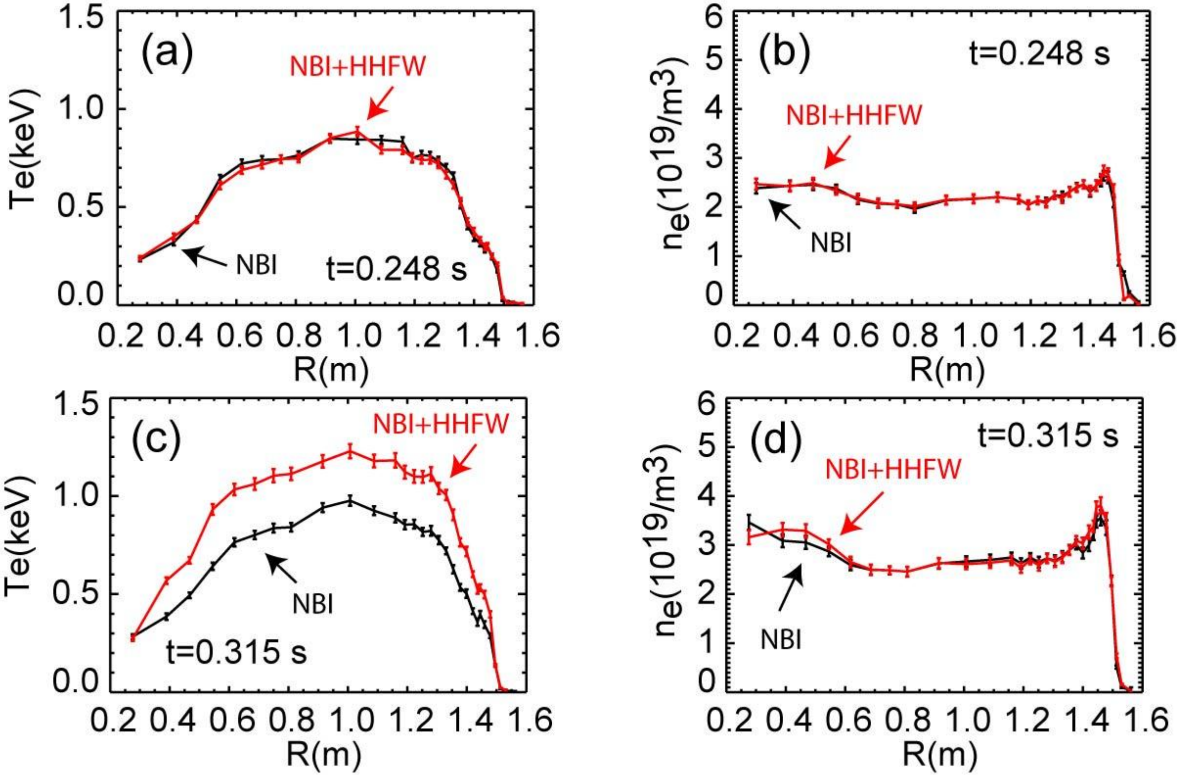
- I_P: 0.9MA, TF: 0.55T
- NBI: 2MW, 90kV
- HHFW: 2MW, $k_{//}$=13m^{-1}
- Benign MHD activity in both plasmas
- Times of interest (TOI) 0.248s and 0.315s



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

Prior to HHFW Heating

During HHFW Heating

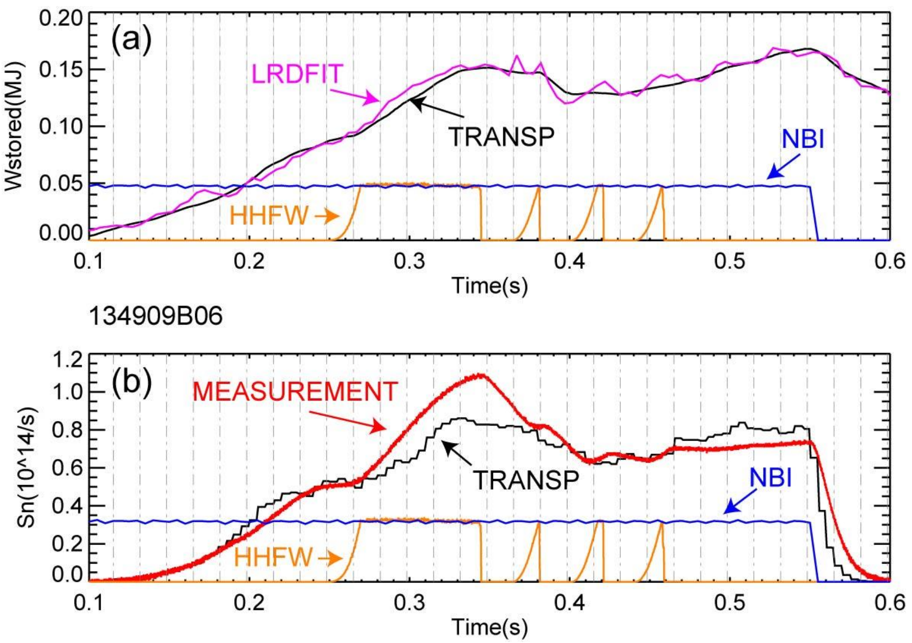


Thomson scattering profiles

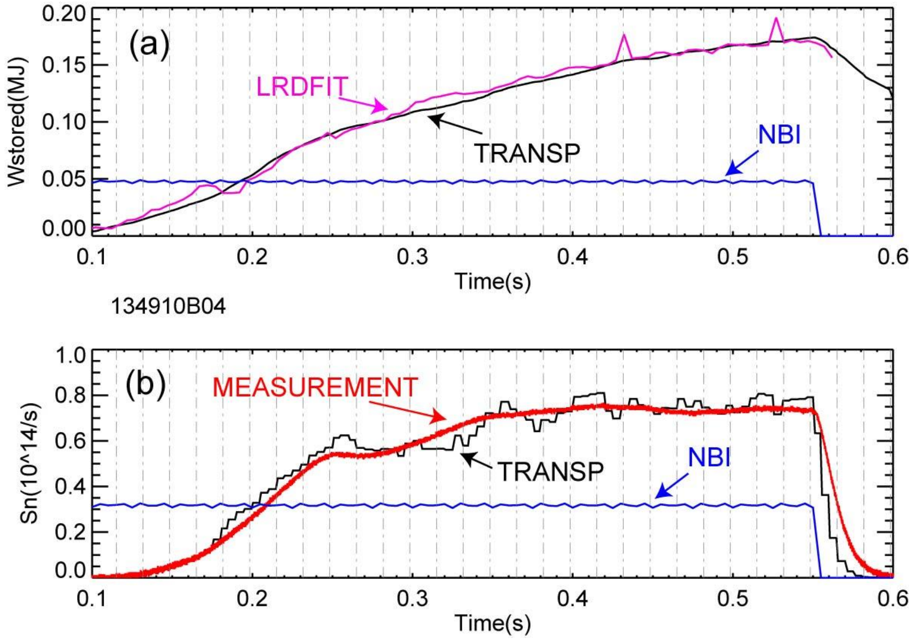
- Identical T_e and n_e H-mode profiles prior to HHFW power onset
- Broad T_e profile increase during HHFW heating, n_e profile remains unchanged. Plasma stayed in the H mode.

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 during HHFW

- Good match for stored energy and neutron production

TRANSP does not include capability to evolve self-consistently the fast-ion energy distribution under the influence of the wave field computed by TORIC

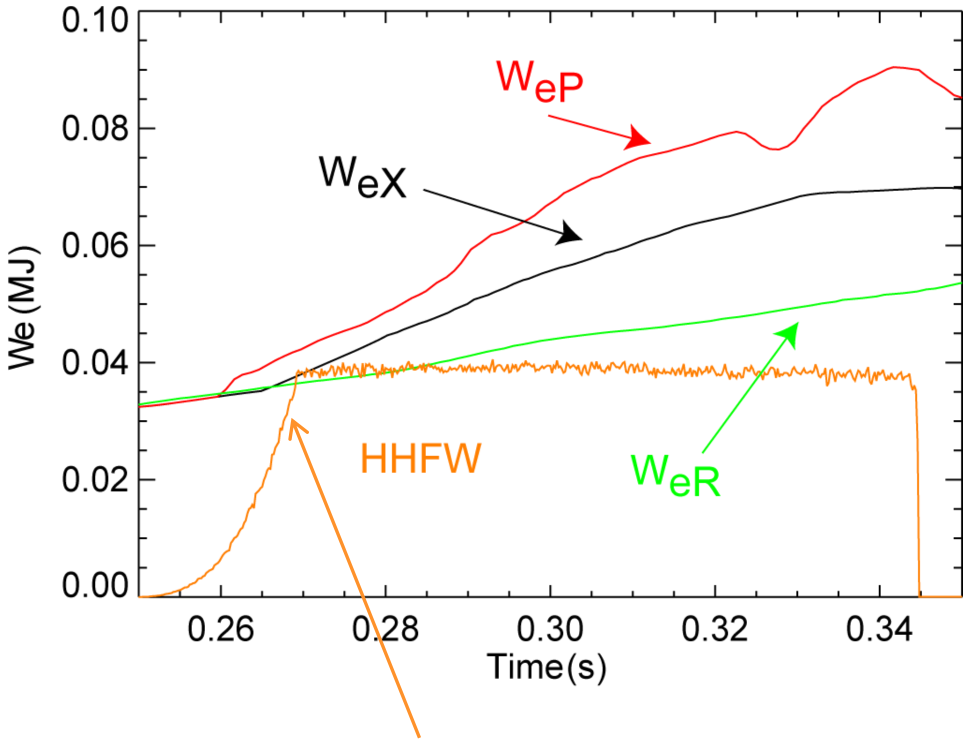
Estimate HHFW Power Fraction Absorbed within LCFS Based on the Electron Stored Energy

- 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

Compare Electron Stored Energy for the Three Cases:
Experimental, no-RF, and assuming 100% absorption

- 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%



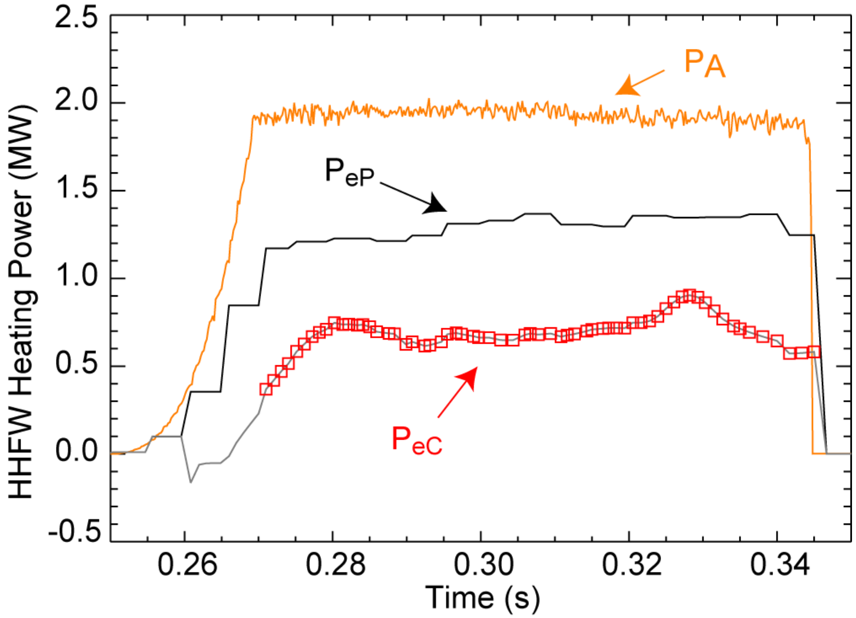
Unscaled HHFW power trace

Coupling to Enclosed Plasma ≥ 53% *Based on Electron Stored Energy*

- P_{eP}: TORIC calculation of power to electrons assuming 100% capture within LCFS
  - 1.3MW out of 2MW at antenna
- The power experimentally captured is $P_{eC} = f_C \times P_{eP}$, where the fraction, f_C, is defined as

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

- $\langle f_c \rangle=0.53\pm0.07$
- Hence ≈1MW out of the applied 2MW is absorbed within LCFS
  - 0.7MW by electrons
  - 0.3MW by fast ions



P_A: launched antenna power

This calculation represents a lower limit of the absorbed power since χ_e is expected to increase under the additional auxiliary heating of HHFW. Increasing χ_e by 50% brings the absorption to near 100%.

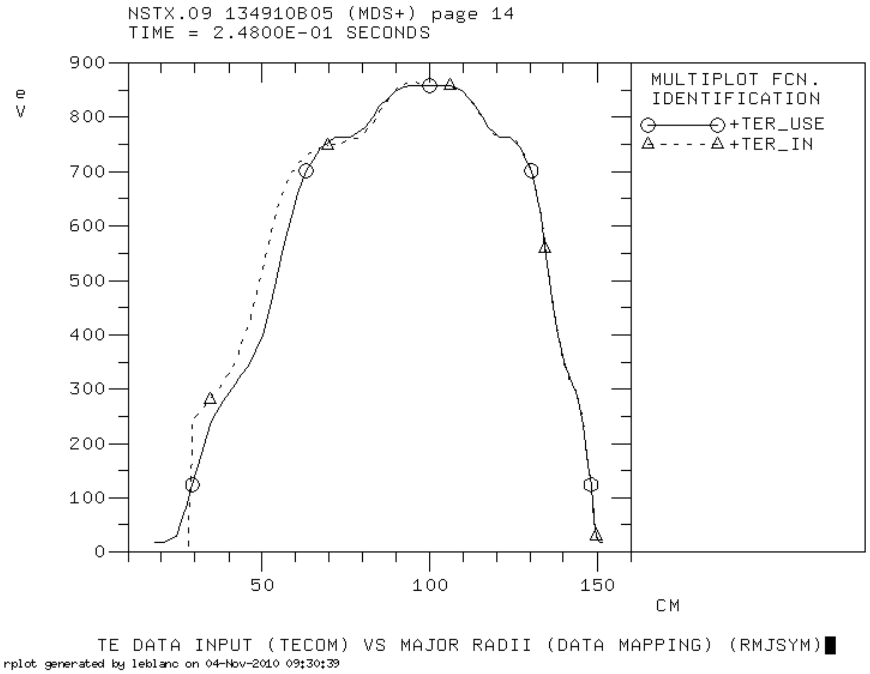
Using χ_e to Predict T_e

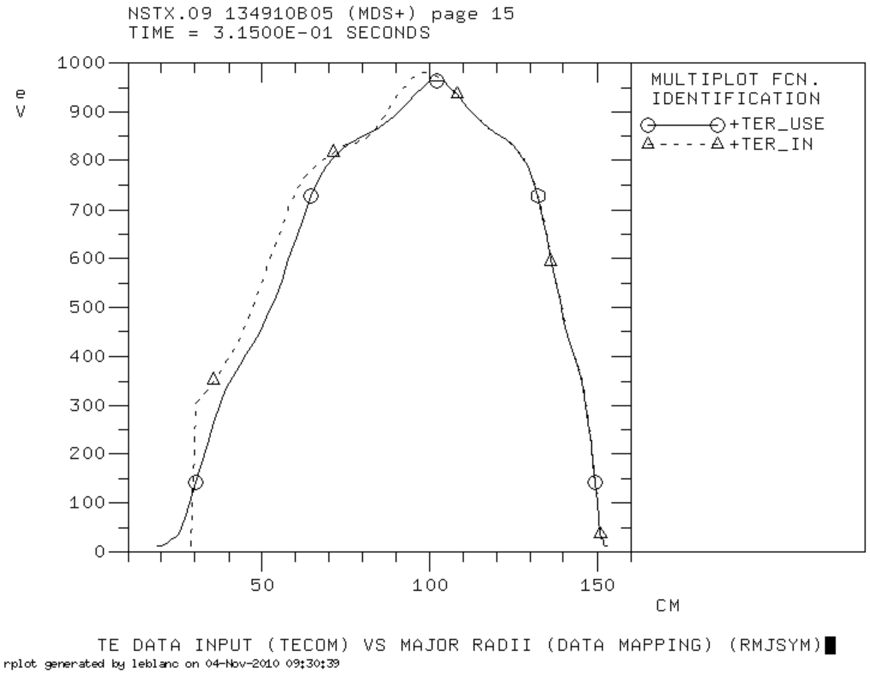
Self consistency check applied to NBI-only plasma

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

CQL3D to Estimate Effects of Wave Interaction with Fast Ions

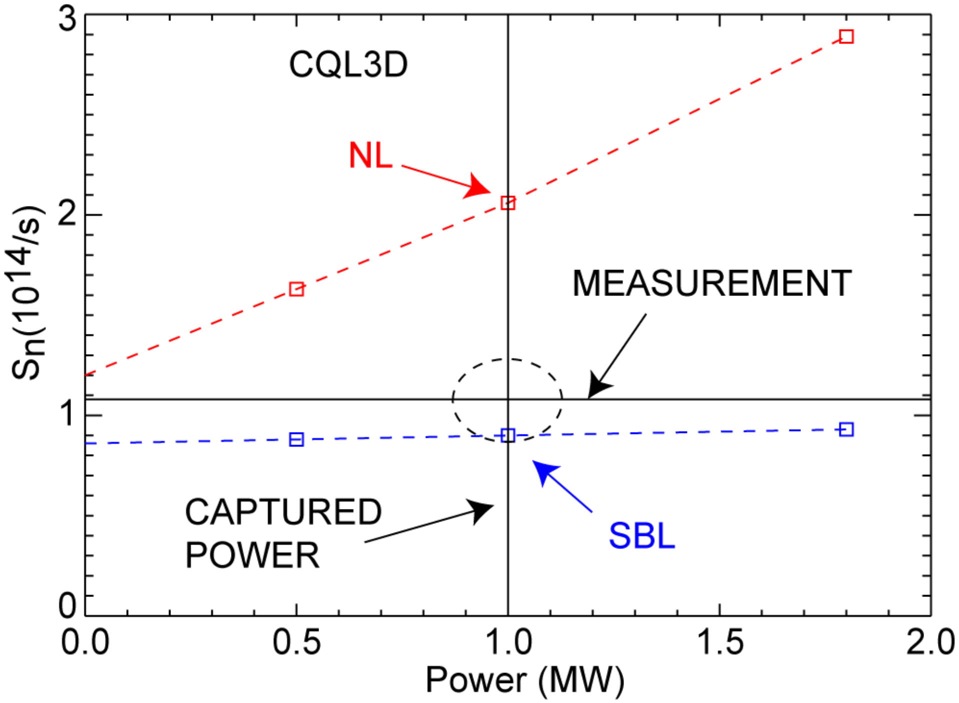
- Currently TRANSP does not include capability to evolve self-consistently the fast-ion energy distribution under the influence of the wave field
- CQL3D is a relativistic collisional, quasi-linear 3D code which solves a bounce-averaged Fokker-Planck equation
- CQL3D can be used to compute the wave effects 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)

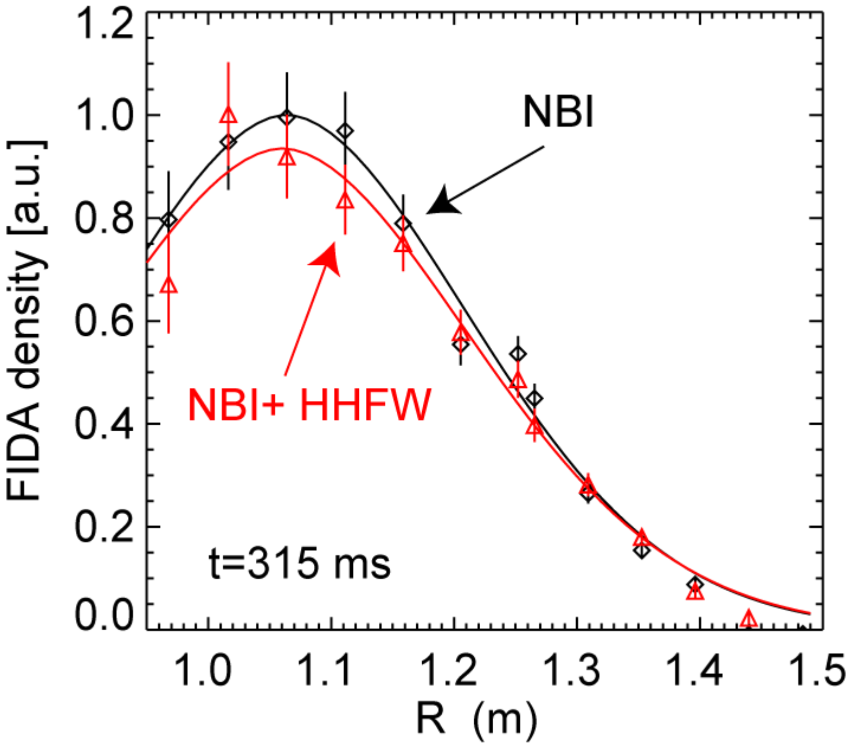
- "no loss" (NL) exceeds S_n measurement
- "simple-banana-loss" (SBL) is at lower limit of measurement error range
  - For 1MW captured within LCFS, about 60% of the power to fast ions is lost compared to NL
- A first-order final-orbit width loss model will be implemented for CQL3D

HHFW power scan with CQL3D

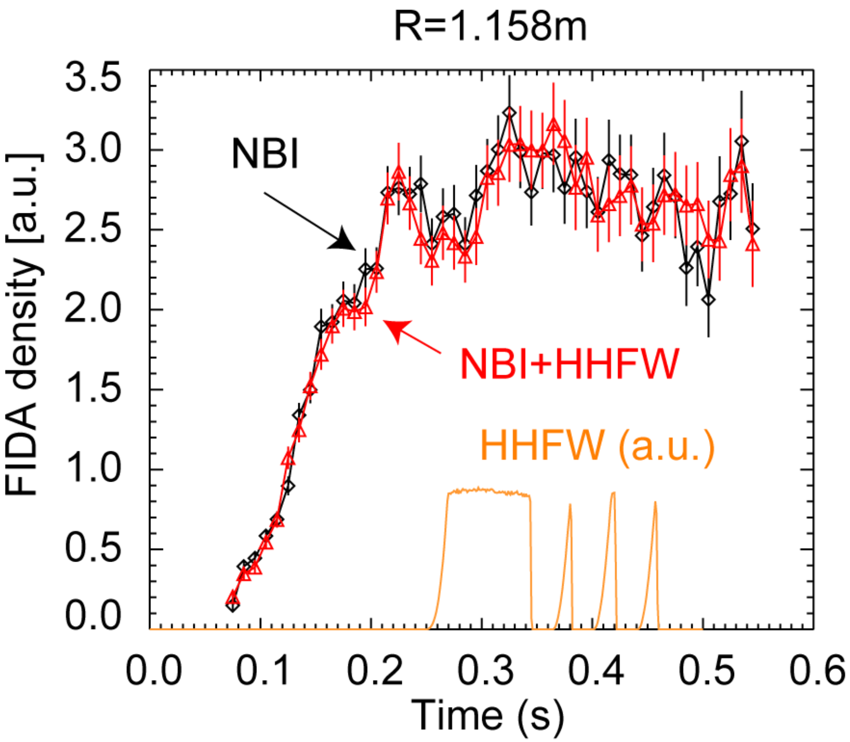


Scan of CQL3D coupled power

FIDA Measurements for NBI+HHFW vs. NBI
No Fast-ion density change observed with HHFW *in this case*



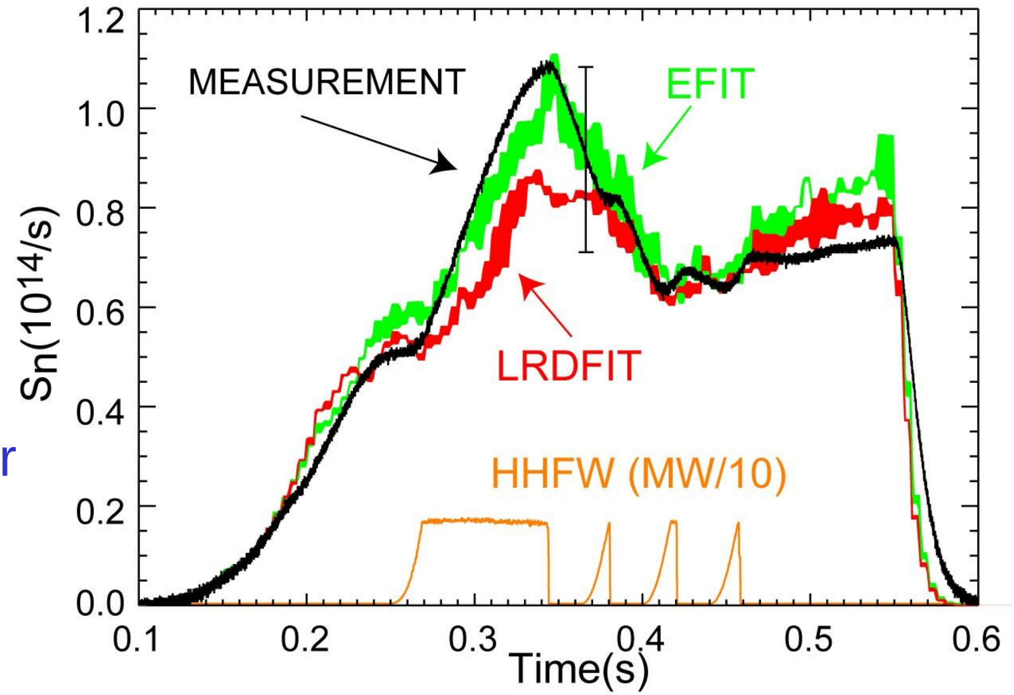
- FIDA density profiles at t=0.315 s for, red, plasma with NBI+HHFW heating and, black, reference NBI-only plasma



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

TRANSP 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

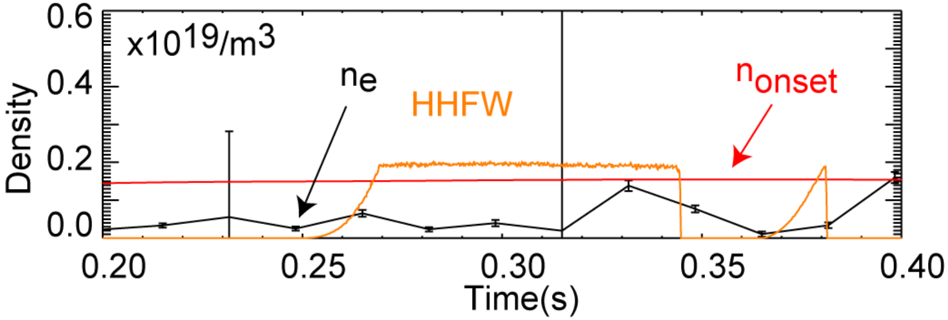


Moving Onset Density Layer away from Antenna Facilitated by Lithium Coating Pumping

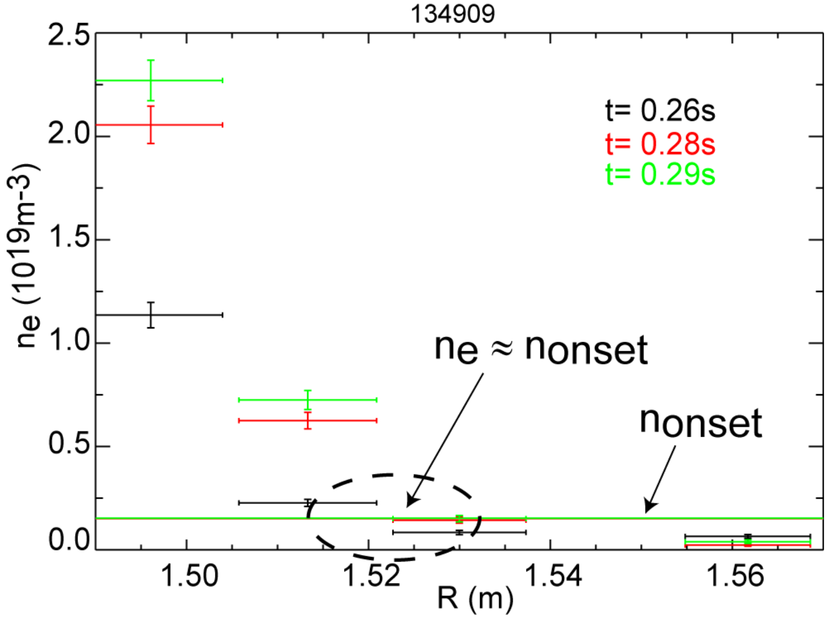
- Onset density, n_{onset}, for perpendicular fast-wave oscillation[5]

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

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



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



[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