NSTX

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On the Analysis of HHFW Heated Plasmas in NSTX

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51st Annual Meeting of the Division of Plasma Physics
2-6 November 2009, Atlanta, GA

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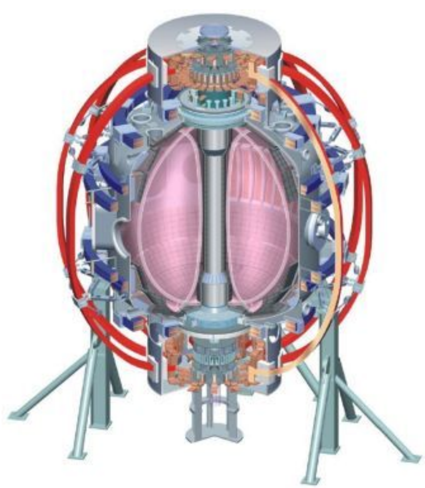

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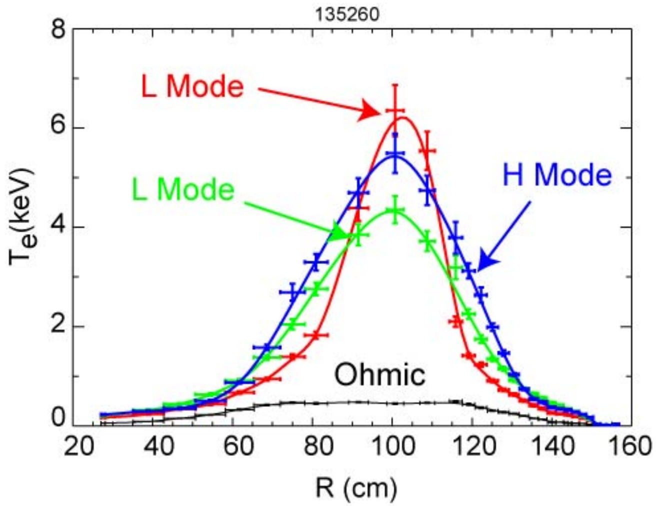
Newer TORIC in TRANSP Provides Improved Analysis Tool
Supplement analysis with CQL3D

- TRANSP makes use of recent version of TORIC, which can compute HHFW propagation and absorption in NSTX
  - M. Brambilla, Plasma Phys. Control. Fusion 44 (2002) 2423-2443
- TORIC calculates power deposition into all species including fast ions
  - But TRANSP RF Monte Carlo Fokker-Planck operator is not ready
  - Self-consistent calculation of fast ions not available for NBI + HHFW plasmas
- Use CQL3D to estimate neutron rate generated by fast ions
- Analyze two cases
  - HHFW generated high-T_e plasmas
  - HHFW heating of NBI-induced H-mode plasmas

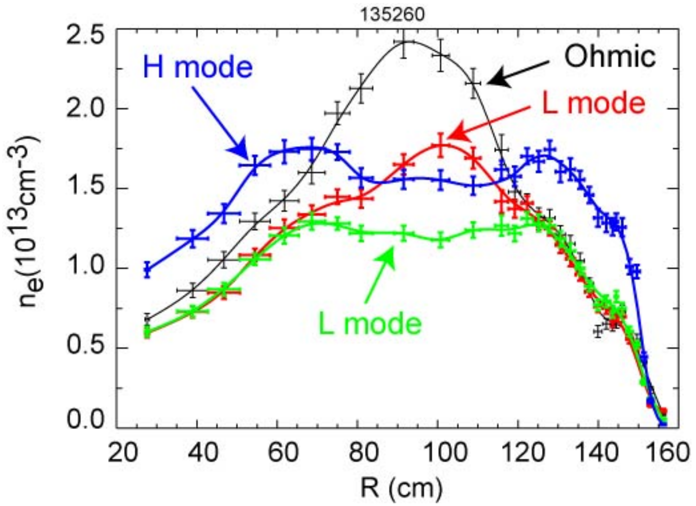
TORIC/TRANSP Calculation Assumptions
Power absorption hypothesis

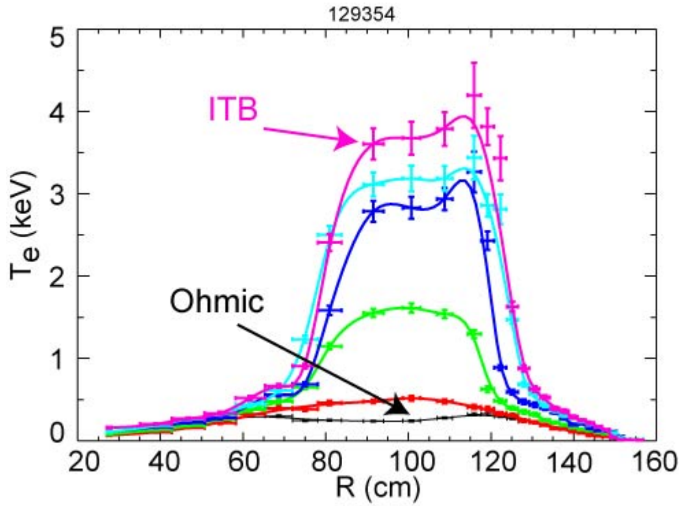
- TRANSP/TORIC assumes that only the fast wave is propagating
  - AORSA calculations show mode-conversion effects small
- Assume that all the antenna power is absorbed
  - This assumption is not met experimentally, but provides a uniform reference
    - Edge/coupling physics effects have been identified: excitation of surface wave and PDI ion heating, which can absorb up to 30% of the power in the plasma periphery
    - J.C Hosea,et al., Physics Plasmas **15** (2008) 056104
    - T. Biewer et al, Physics of Plasmas **12** (2005) 056108
  - Efficiency will be addressed later by comparing with experimental neutron production rate
- Notation
  - Qa = Volint(qa) where qa is the total power density coupled by the antenna
  - Qe = Volint(qe) where qe is the power density coupled to electrons
  - Qf = Volint(qf) where qf is the power density coupled to the fast ions

High T_e Achieved during HHFW Heating in He and D_2 Plasmas

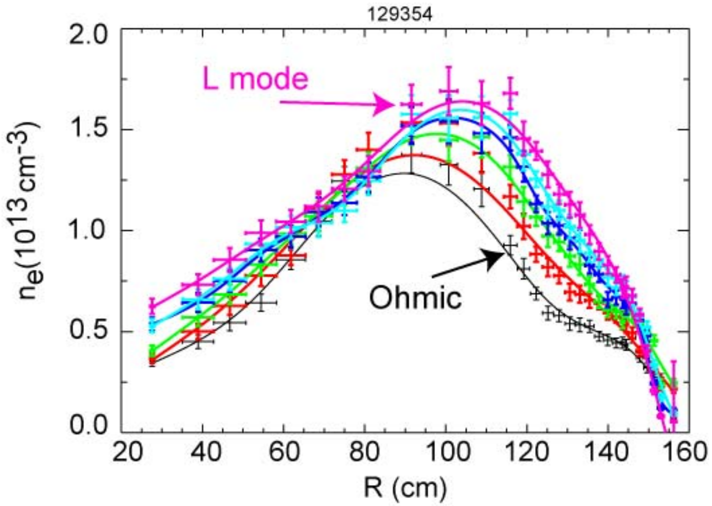


He plasma
k_ϕ=-8/m
2.6 MW





D_2 plasma
k_ϕ=-8/m
3.0 MW



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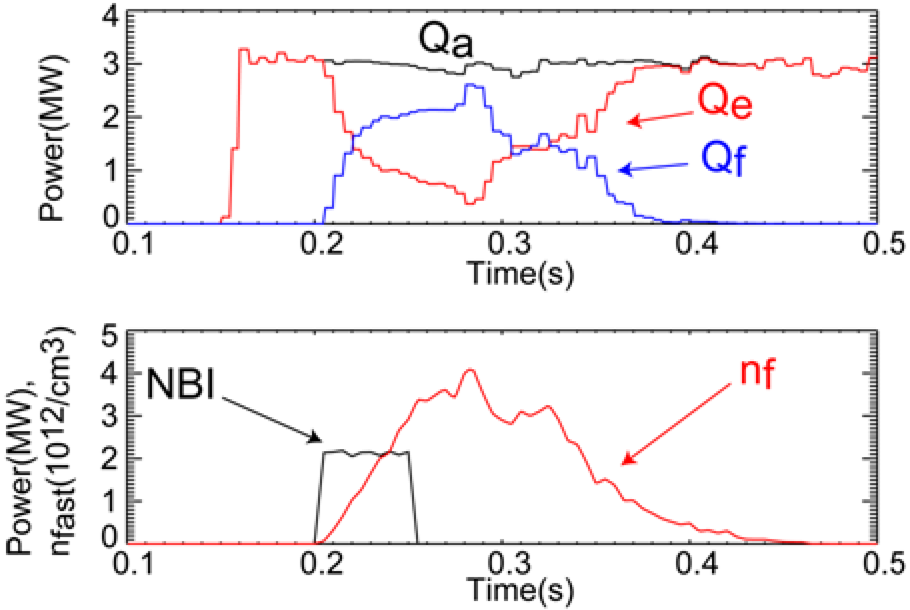
Competition between Electron and Fast-ion Damping
Qe reduced when fast ions are present

- All HHFW power absorbed by electrons prior to NBI pulse starting at 0.2s.

- After NBI onset, the fast-ion population absorbs HHFW power at the expense of the electrons
  - Long lasting effect since the fast-ion density n_f persists beyond 0.4s.
  - TORIC/TRANSP consistent with single time point calculations done with AORSA, GENRAY and TORIC

TORIC/TRANSP RESULTS



Q_a: power delivered by antenna
Q_e: power absorbed by electrons
Q_f: power absorbed by fast ions
n_f: on axis fast-ion density
NBI: NBI power

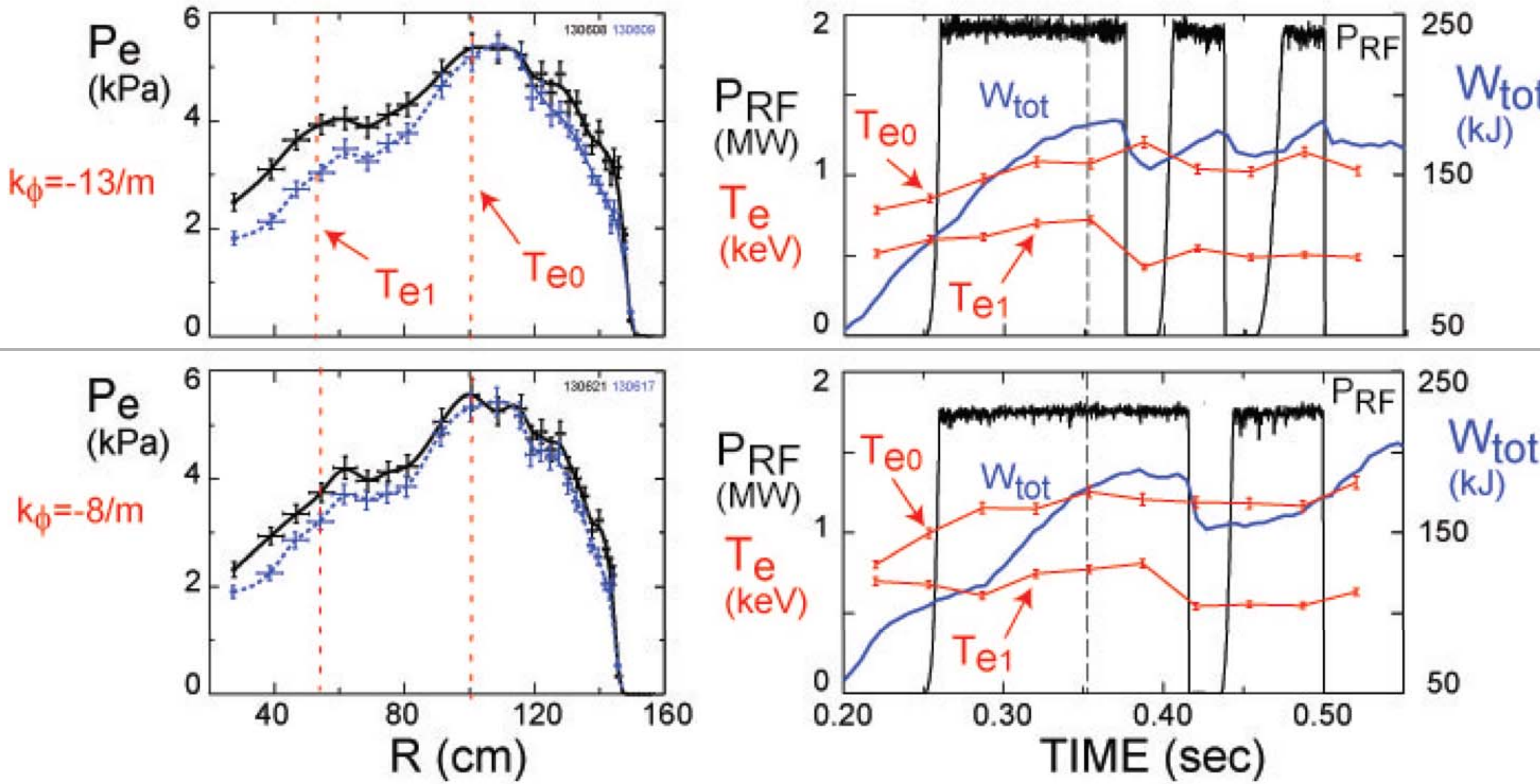
HHFW Heating of NBI-Induced H-mode Plasma Achieved using k_ϕ=-13m^{-1}

- Previous attempts at HHFW heating of NBI-induced H-mode plasmas were unsuccessful[i], but recent application of k_ϕ=13m^{-1} HHFW power resulted in measurable change in the stored energy and kinetic measurements.
- Better understanding of edge effects and attention to the edge density were conducive to this power coupling improvement[ii].

[i] B.P. LeBlanc, 16th RF Conference, AIP Conference Proceedings 787, p.86

- [ii] J.C. Hosea, *et al.*, RF Conference, Ghent, Belgium, 2009

Measured W_{tot} and T_e Increase during HHFW Heating *of NBI-induced H-mode Plasma*



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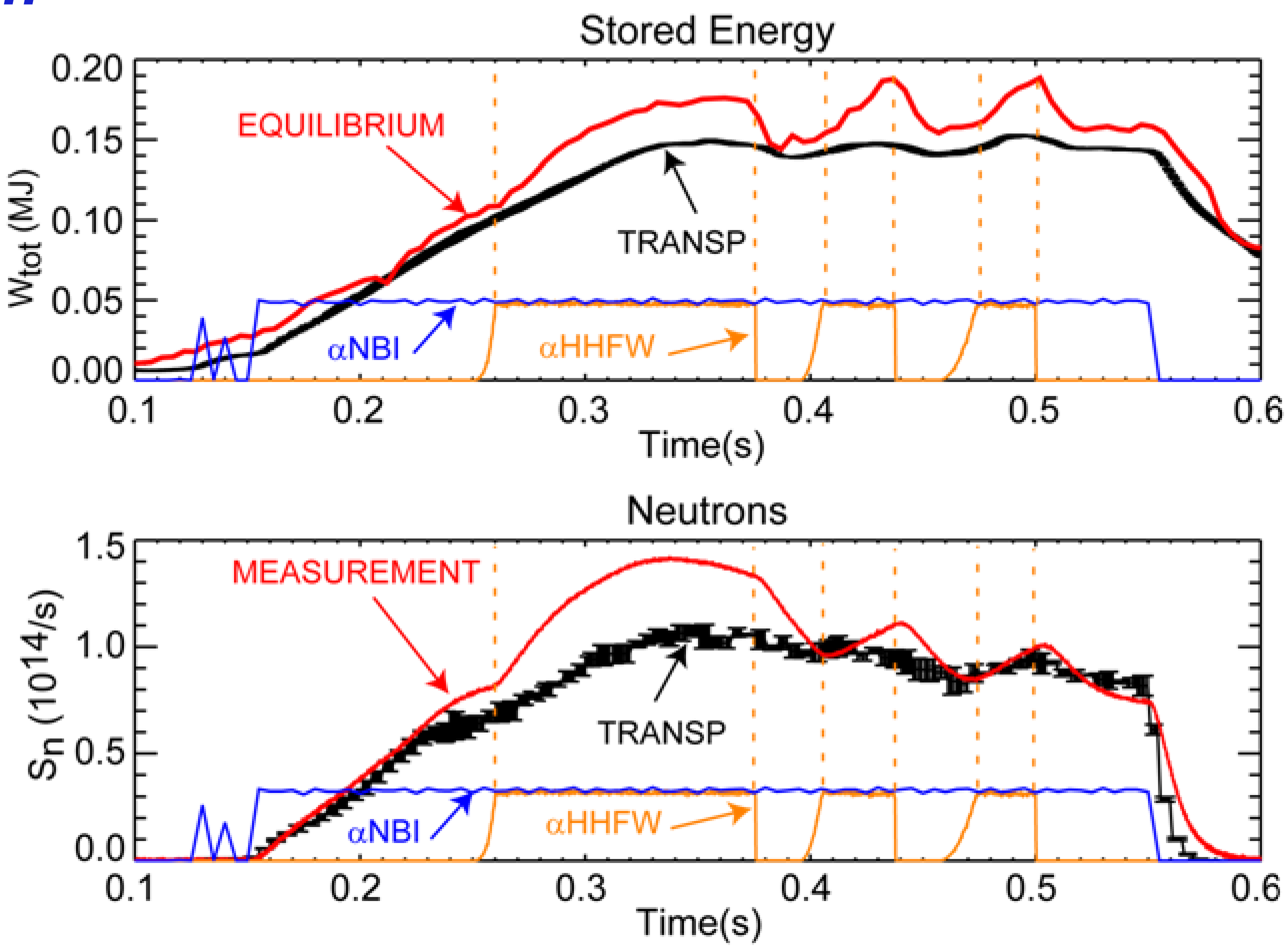
Measured Stored Energy and Neutron Rate Exceed TRANSP Calculations during HHFW Pulses

K_ϕ = -13m^{-1}



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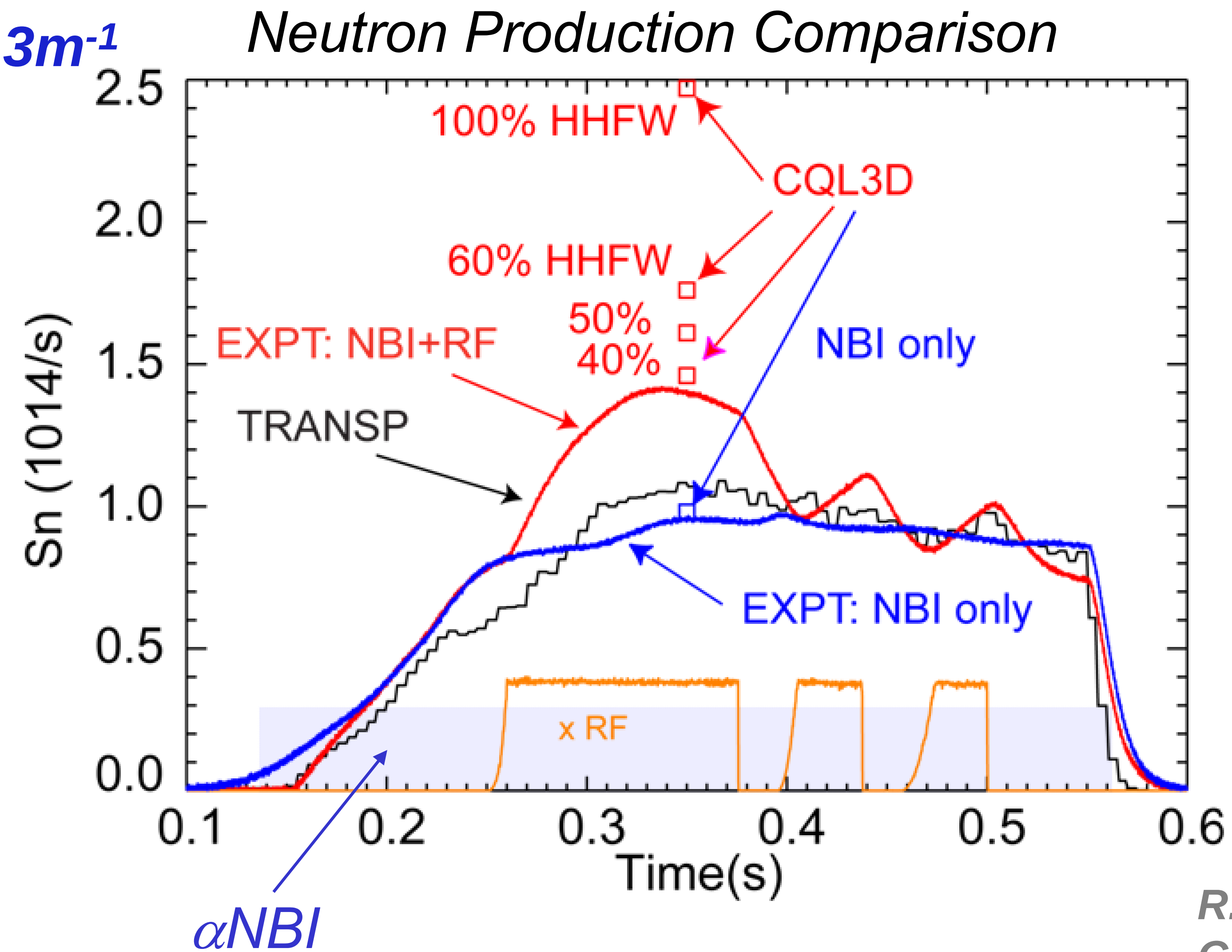
CQL3D Suggests ≈40% of HHFW Power Ultimately Coupled to Plasma Core

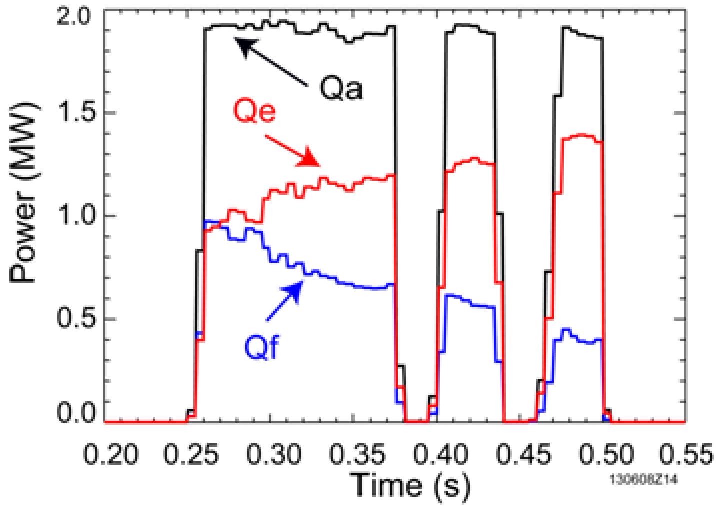
$K_{\phi} = -13m^{-1}$

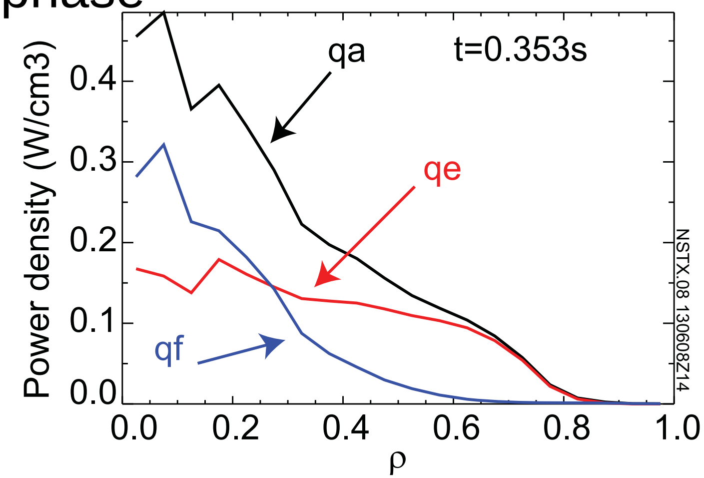


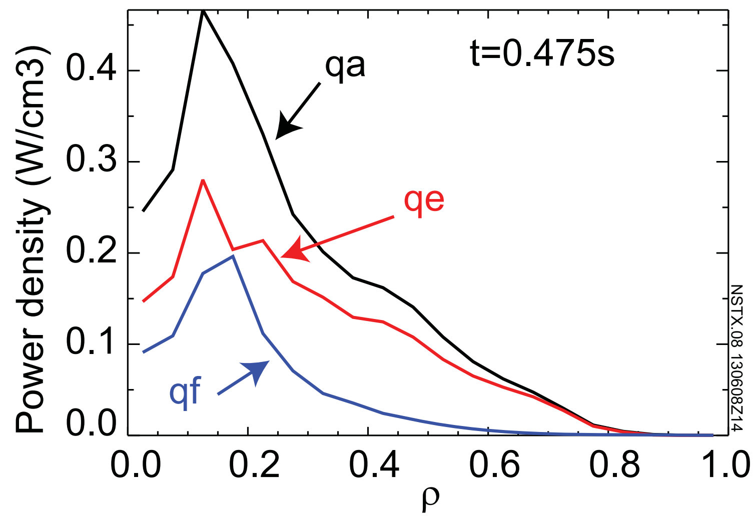
R. Harvey
CompX

TORIC/TRANSP HHFW Power Deposition Results for Heating of NBI-Induced H-mode Plasma, k_{ϕ}=-13m^{-1}

- HHFW power, Qa, is divided between the electrons, Qe, and the fast ions, Qf
- Qf decreases with time as the fast ions thermalize
  - (*e.g.* as fast-ion density decreases)
- Power deposition profiles (qa, qe,qf) become peaked at the end of HHFW phase







TRANSP with TORIC has been used to Estimate HHFW Heating

- The current implementation of TORIC into TRANSP, although not fully consistent for fast ions, provides revealing information about the time and profile evolution of the HHFW power absorbed by plasma species
- TRANSP analysis has been complemented with single time point CQL3D calculation to determine the ultimate HHFW power coupling based on neutron production
- More work needed to continue validating modeling for HHFW heating in NSTX plasmas

TI3.00002: G. Taylor, Advances in High-Harmonics Physics in NSTX

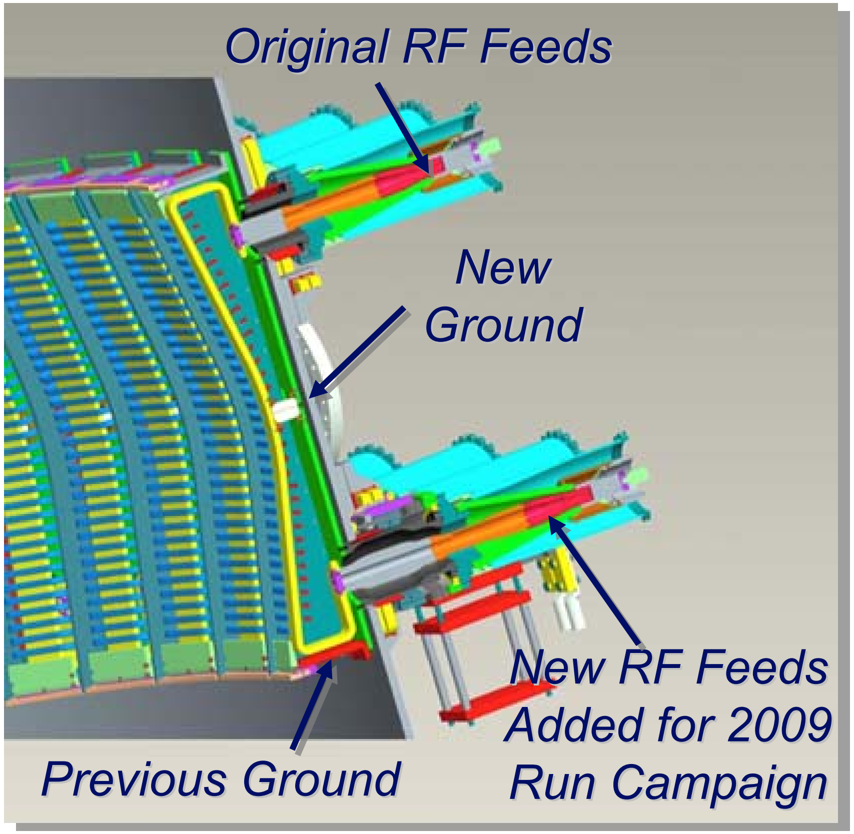
Work supported by US DOE contract no. DE-AC02-09CH11466

EXTRA SLIDES

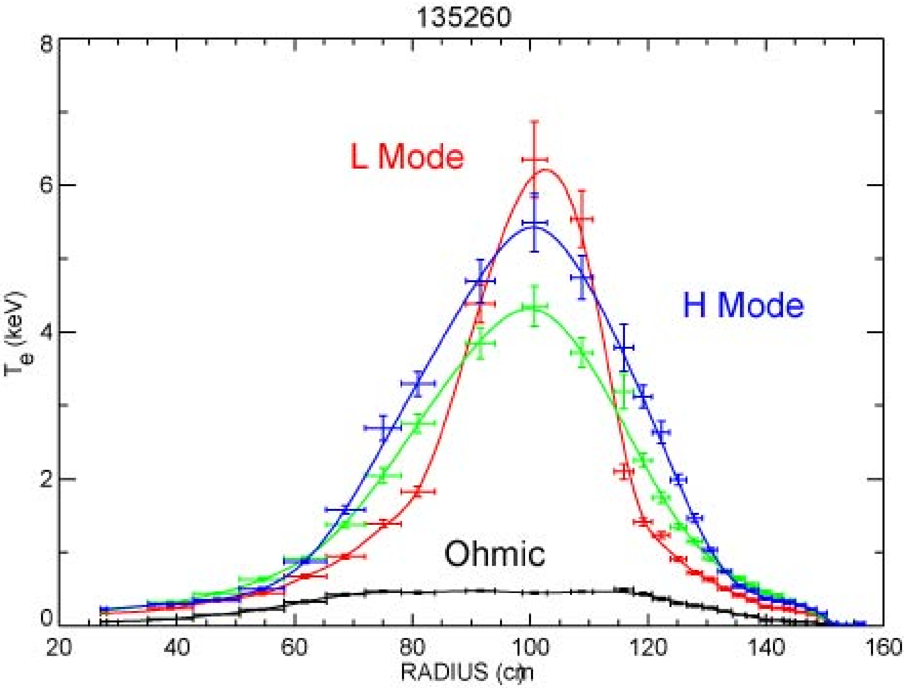
HHFW Progress during 2009 Campaign

TI3.00002: G. Taylor, Advances in High-Harmonics Physics in NSTX

Double End-Fed Upgrade Installed and Commissioned



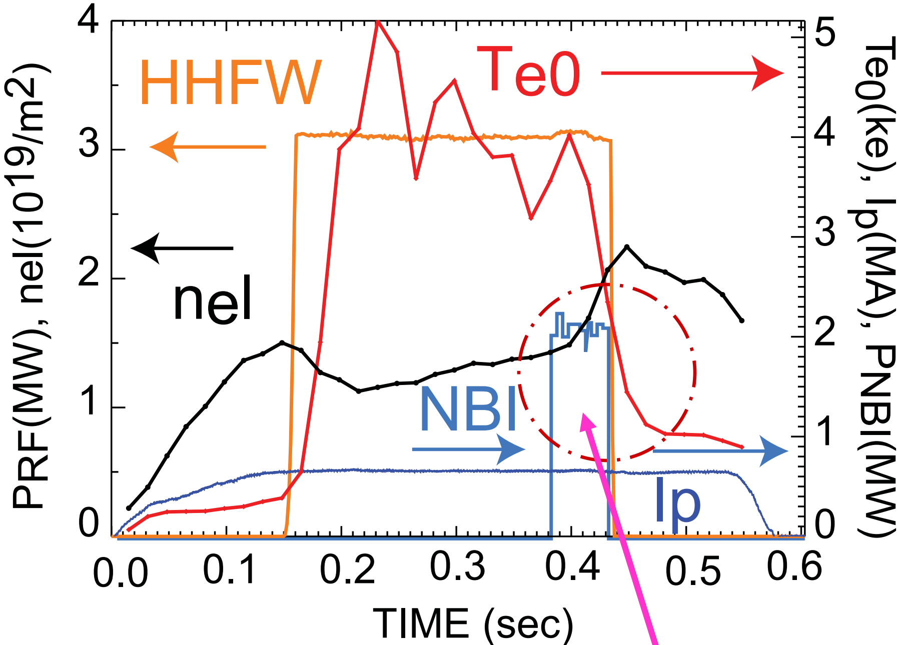
Achieved 2.7 MW for 300 ms resulting in T_e > 6.0 keV

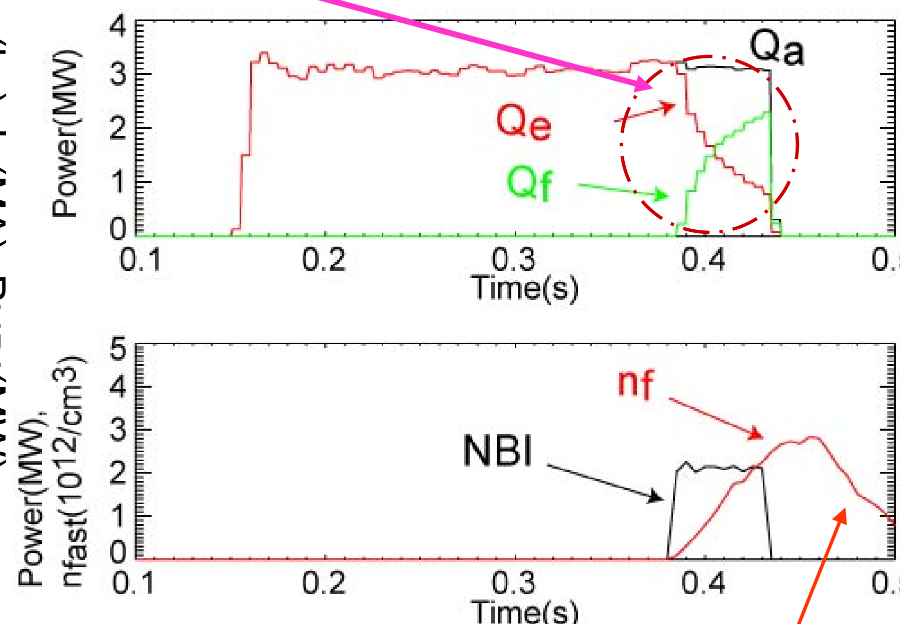


HHFW Power Shifted from Electrons to Fast Ions during NBI

Power channeled away from electrons to fast ions

Q_a: Power at the antenna
Q_e: Power to the electrons
Q_f: Power to the fast ions



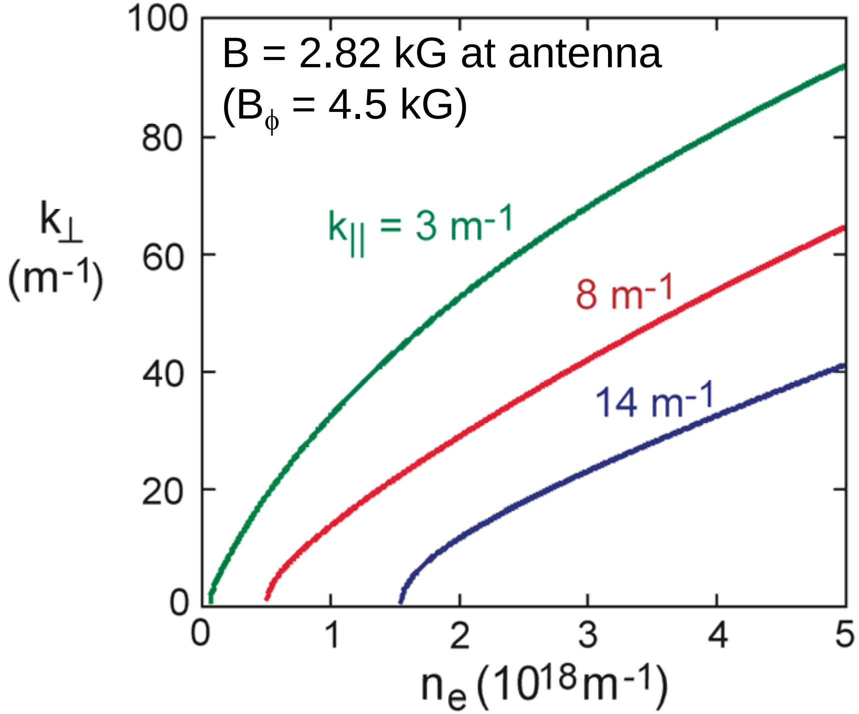


T_{e0} decrease occurs when part of HHFW power is channeled toward the fast ions.

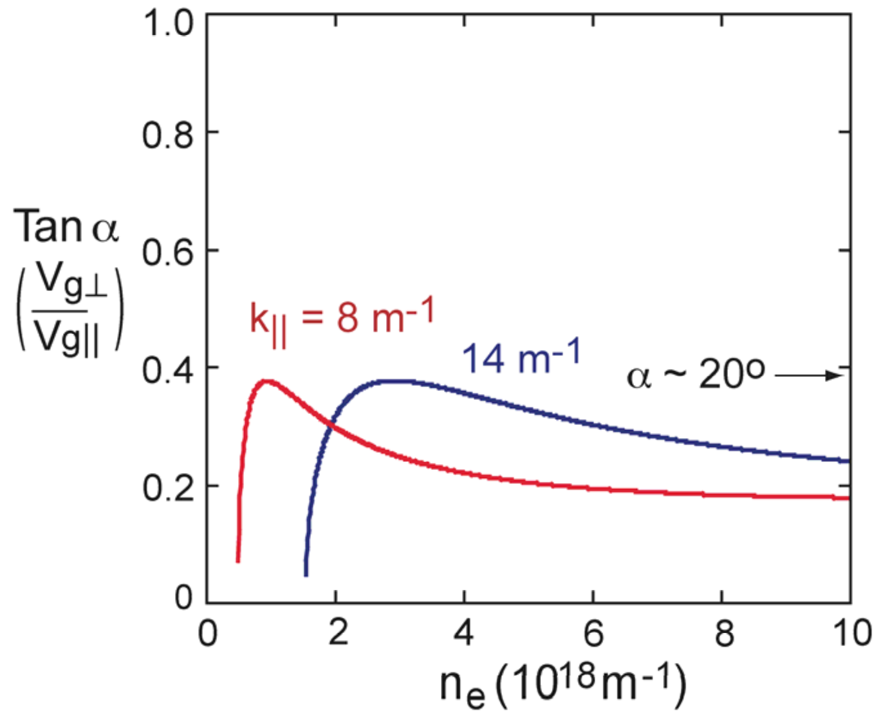
On axis fast-ion density, n_f.

Surface FW Propagation Supports Surface Loss at Lower $k_{||}$

Propagating k$_{|}$ vs. density at antenna B



Angle of ray to B vs. density

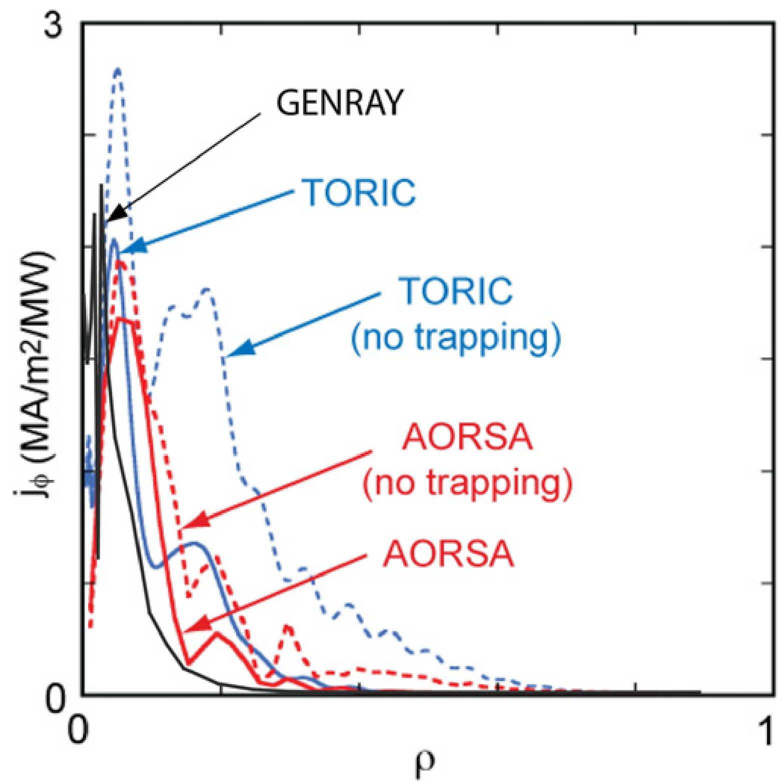


Onset density is $\propto B^*k_{||}^2/\omega$

- Propagation is very close to wall at $k_{||} = 8\ m^{-1}$, on wall at $k_{||} = 3\ m^{-1}$
- Losses in surface should be higher for lower $k_{||}$
- Propagation angle relative to B much less than for lower harmonic case
- Increasing B should move onset farther from antenna, increasing heating

J.C.Hosea

TORIC VERIFICATION
Compare to codes AORSA and GENRAY



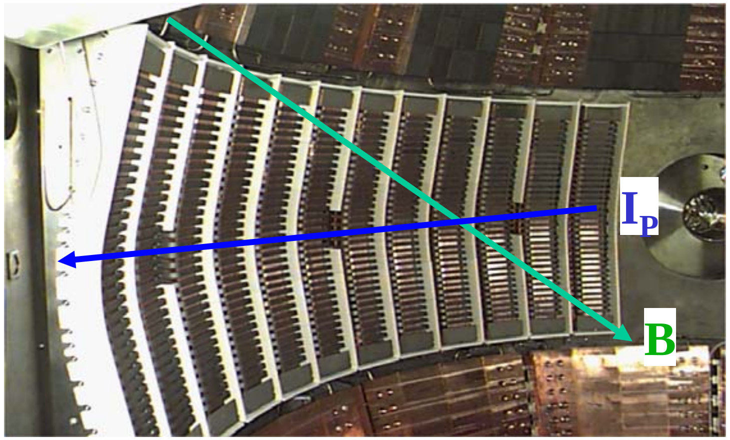
AORSA and TORIC simulations, with and without trapping, and GENRAY, with trapping, of the HHFW-CD for

Nφ = 12.

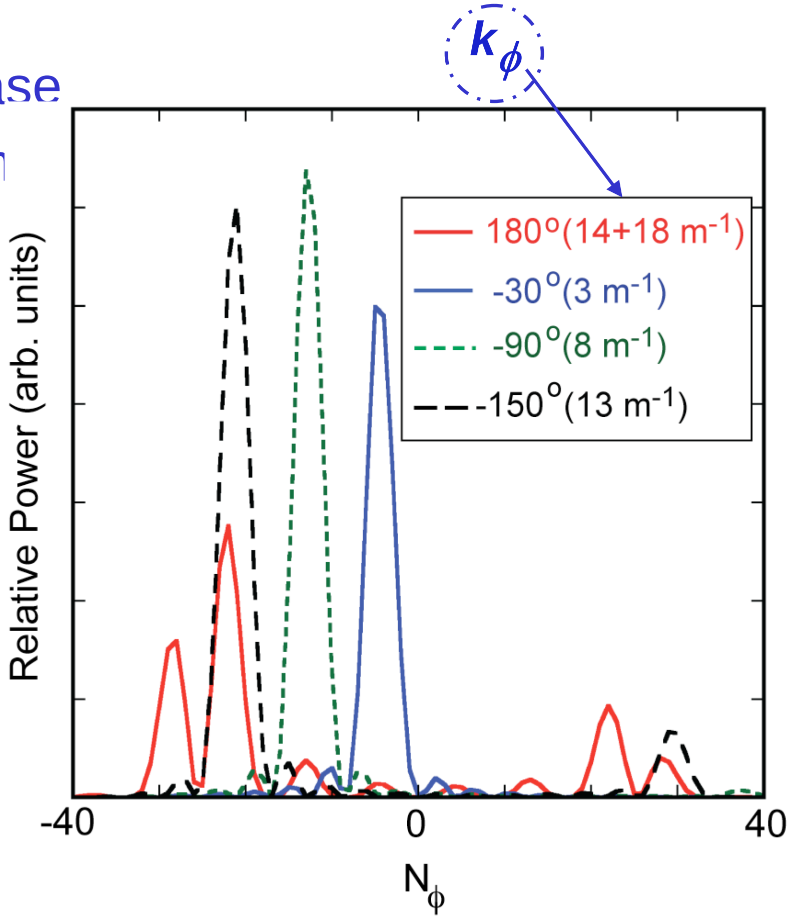
•*C.K. Phillips, Nucl. Fusion 49 (2009) 075015*

NSTX HHFW Heating System
Fixed frequency 30 MHz, variable $|k_\phi| = 3, 8, 13, 14\ m^{-1}$

- System parameters:
  - 12 antenna straps, six sources, decoupling loops, phase shifters, and stubs
  - Digital control of power and phase
  - Automated matching calculation



The double-peak $k_{//}=(14,18)m^{-1}$ spectrum will be referred to as simply $k_{//}=14m^{-1}$.



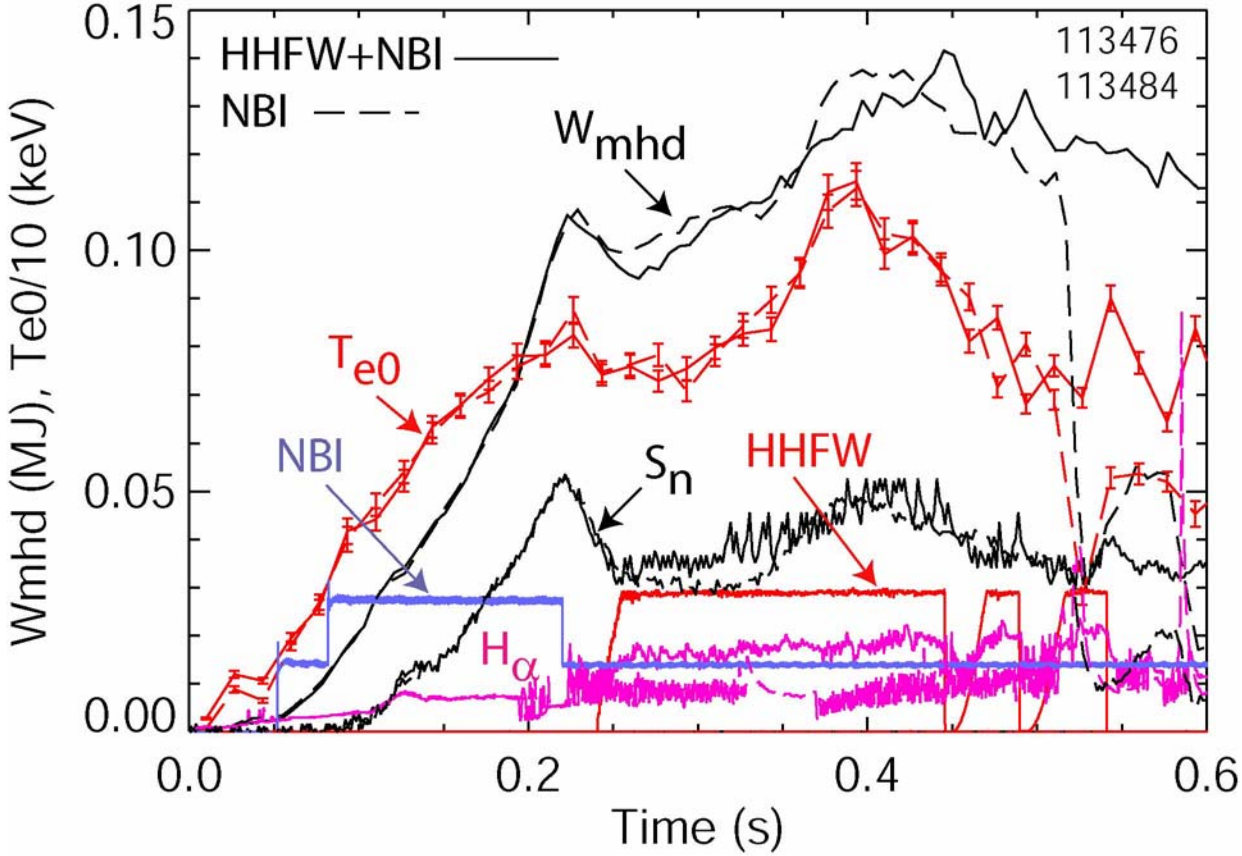
HHFW during NBI Driven H-mode Plasma

W_{mhd} and neutron (S_n) changes are small and reproducible, but appear related to edge effects

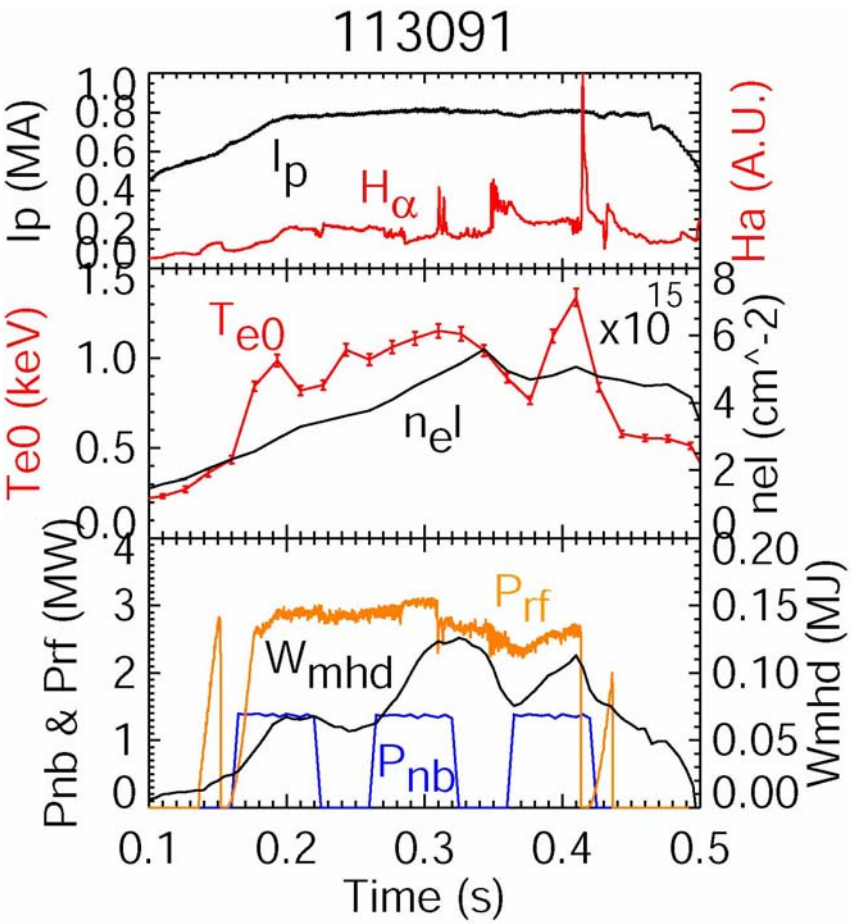
<u>HHFW+NBI (solid)</u>
<u>NBI (dashed)</u>

113476
RF: 3.0 MW
NB: 3.2 MW
$k_{//}$ = 7 m^{-1}

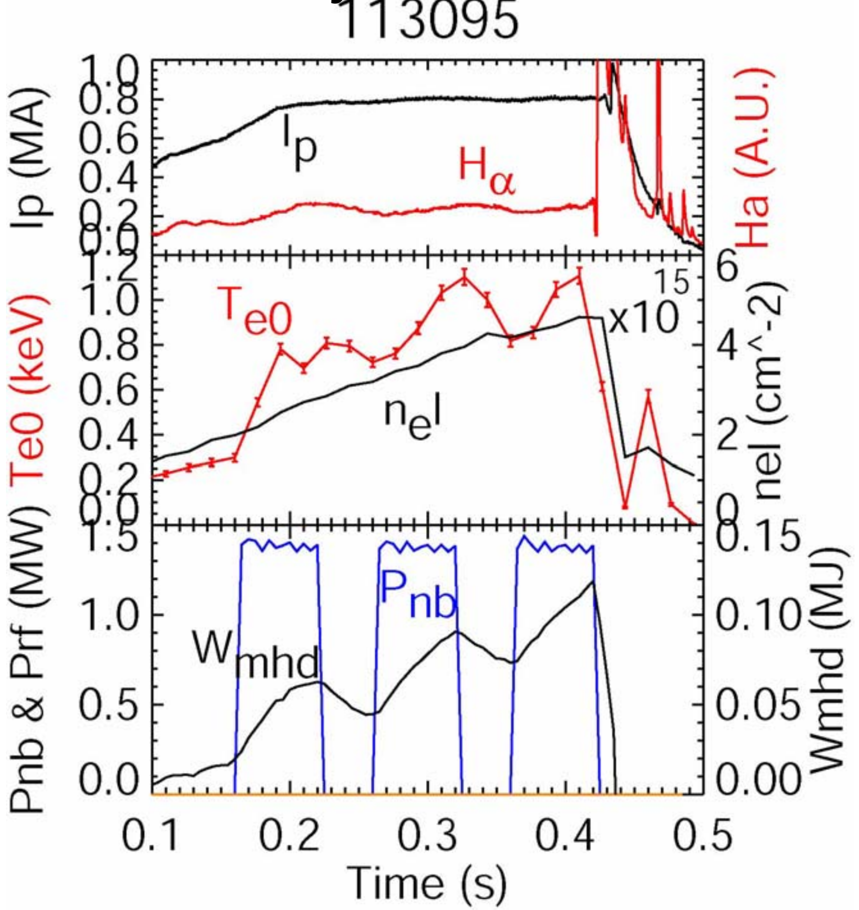
113475
NB: 3.1 MW



NBI + HHFW $k_{//}$=14 m^{-1}



NBI only



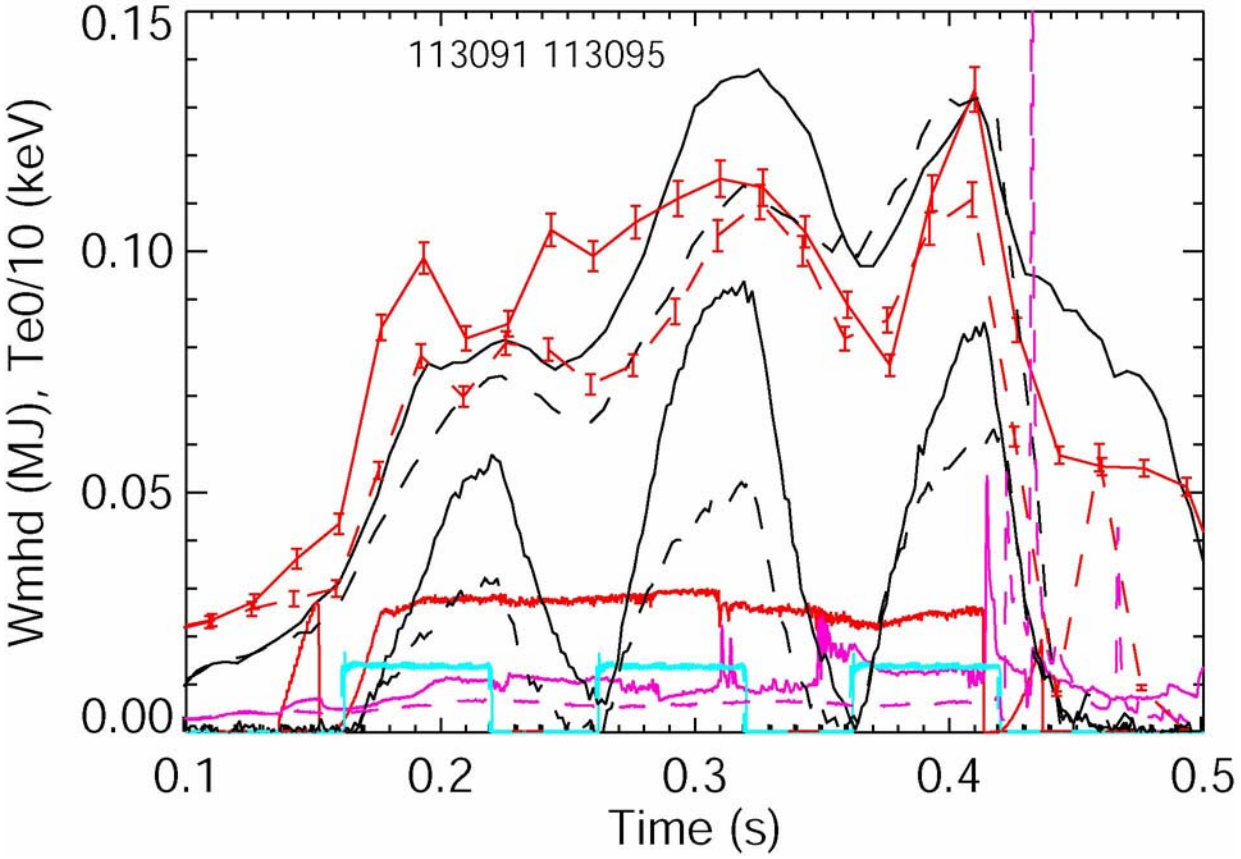
Neutrons (S_n) Double and W_{mhd} Increases

HHFW starts before H-mode onset: three NBI pulses

<u>HHFW+NBI (solid)</u>
<u>NBI (dashed)</u>

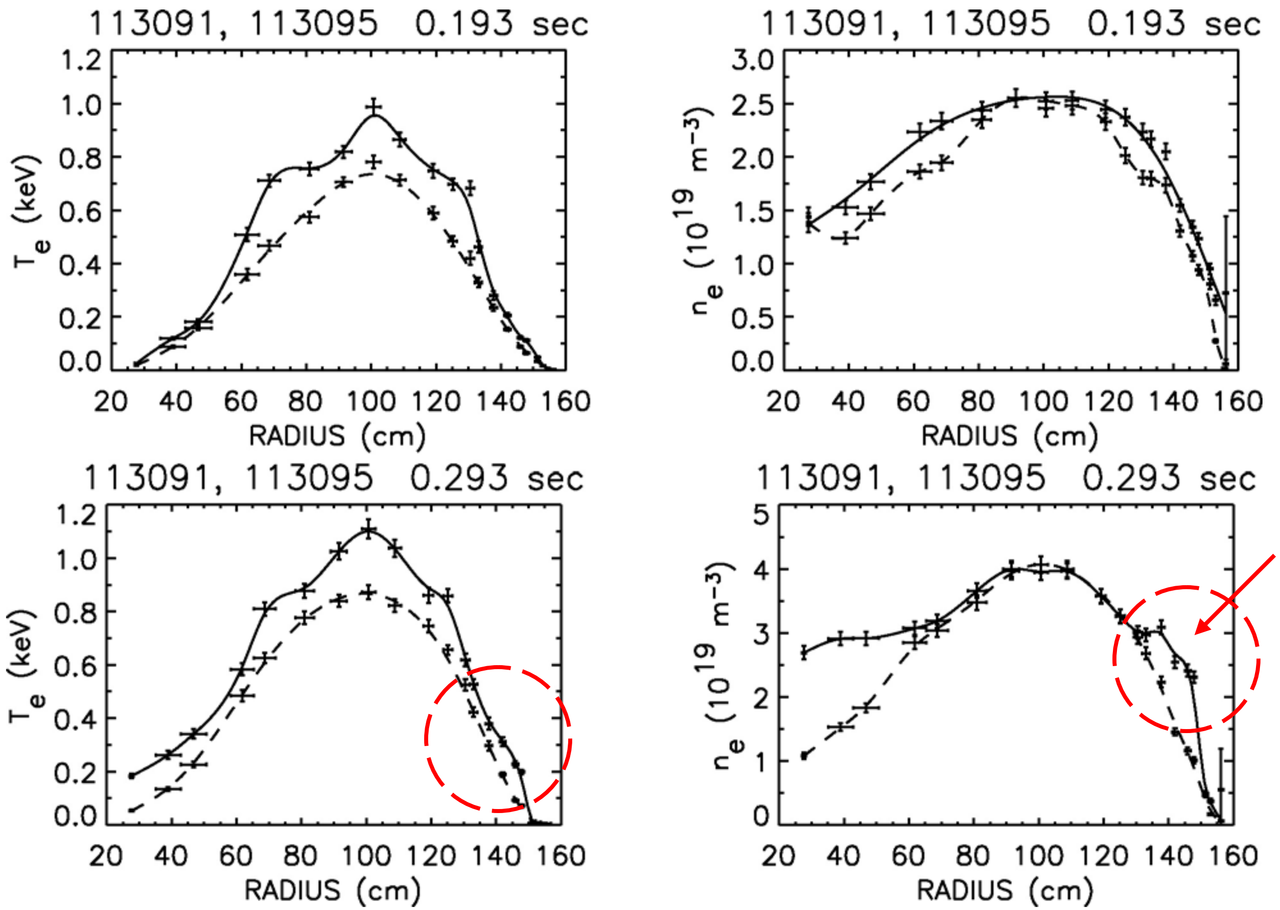
113091
RF: 3.1 MW
$k_{//}$ = 14 m^{-1}
NB: 1.7 MW

113095
NB: 1.7 MW



HHFW Increases Core T_e Compared to NBI-only

Overlay of HHFW+NBI (solid) and NBI (dash) at 0.193 and 0.293 s



Plasma with HHFW enters H mode