NSTX Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

High Harmonic Fast Wave Deposition and Heating Results in NSTX*

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

G. Taylor[1]

P.T. Bonoli[2], M. Choi[3], R.W. Harvey[4], W.W. Heidbrink[5], J.C. Hosea[1], E.F. Jaeger[6], B.P. LeBlanc[1], D. Liu[7], C.K. Phillips[1], M. Podesta[1], P.M. Ryan[6], E.J. Valeo[1], J.R. Wilson[1], and the NSTX Team

[1]Princeton University
[2]Massachusetts Institute of Technology
[3]General Atomics
[4]CompX
[5]University of California - Irvine
[6]Oak Ridge National Laboratory
[7]University of Wisconsin - Madison

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

* Work supported by US DoE contract DE-AC02-09CH11466

US-Japan RF Plasma Physics Workshop
General Atomics, San Diego, California, March 8-10, 2010

Outline

- Role of HHFW in the NSTX Program
- HHFW Heating of Ohmically-Heated Target Plasmas
- HHFW Heating of Deuterium NBI-Fueled Plasmas

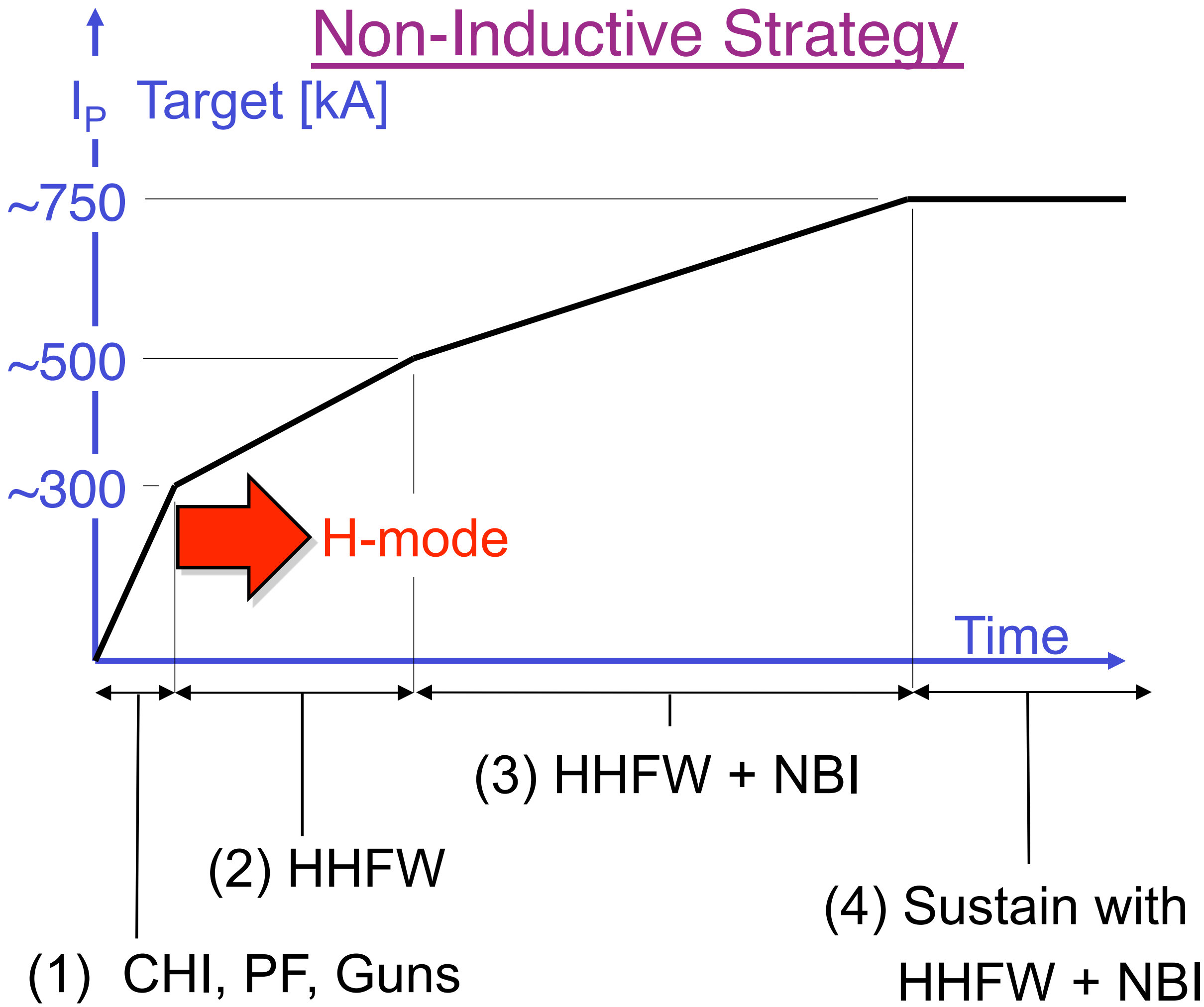
Outline

- Role of HHFW in the NSTX Program
- HHFW Heating of Ohmically-Heated Target Plasmas
- HHFW Heating of Deuterium NBI-Fueled Plasmas

HHFW Heating & Current Drive (CD) Developed for Non-Inductive Ramp-up, Bulk Heating & q(0) Control

- Ultimately Spherical Torus needs to run non-inductively

Non-Inductive Strategy



HHFW Goals

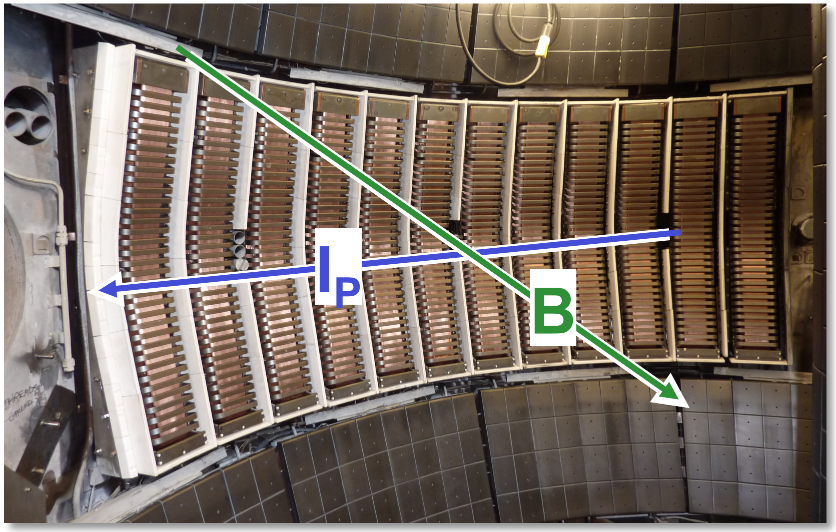
(1) HHFW couples to start-up plasma

(2) HHFW for I_P overdrive through bootstrap & HHFW CD

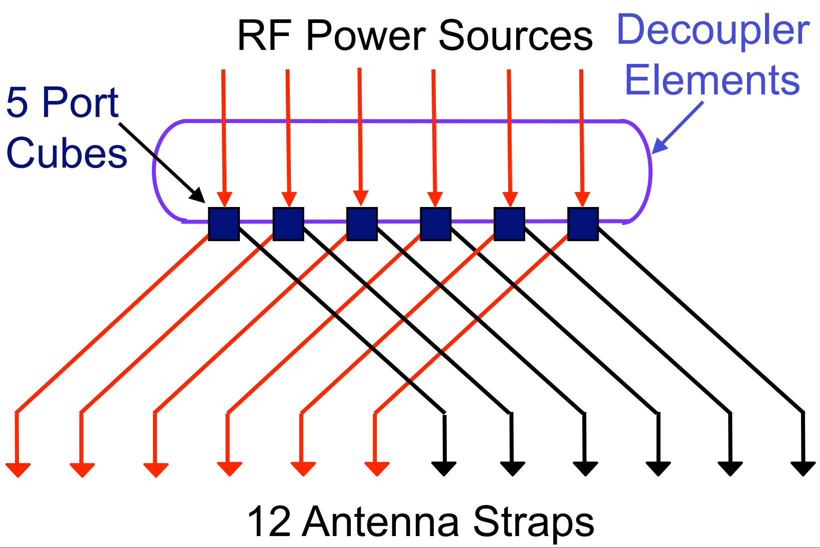
(3) HHFW generates sufficient I_P to confine NBI ions

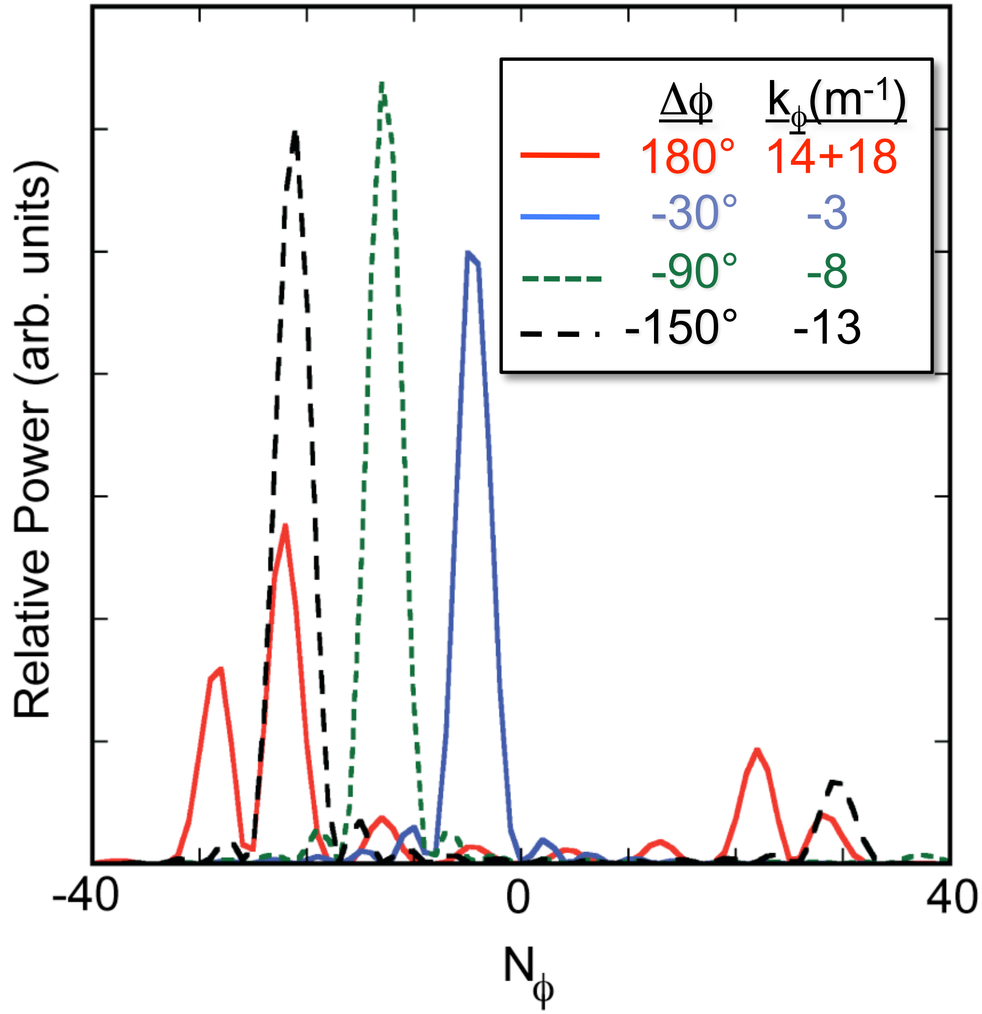
(4) HHFW provides bulk heating & q(0) control in H-mode

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



HHFW antenna extends toroidally 90°





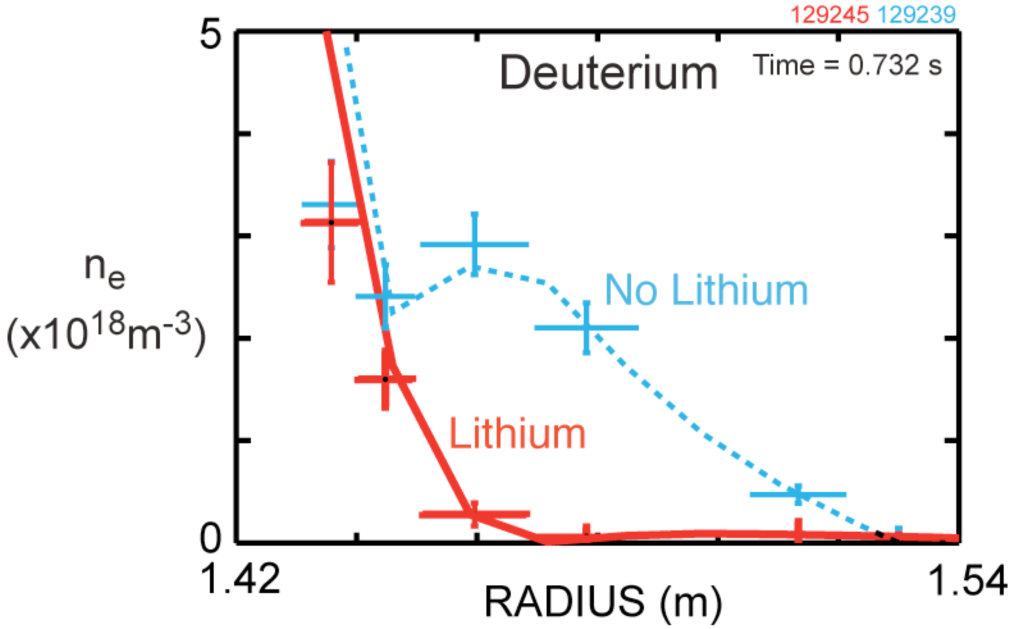
- Phase between adjacent straps ($\Delta\phi$) easily adjusted from 0° to 180°

Outline

- Role of HHFW in the NSTX Program
- HHFW Heating of Ohmically-Heated Target Plasmas
- HHFW Heating of Deuterium NBI-Fueled Plasmas

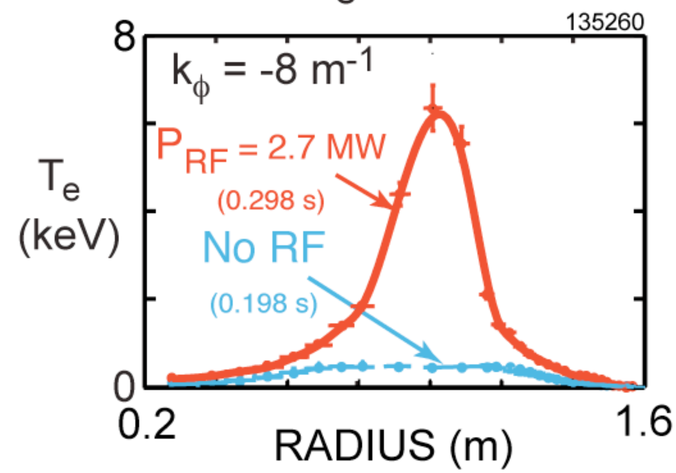
Lithium Wall Conditioning Enabled NSTX Record $T_e(0)$ in He & D_2 in L-Mode with P_{RF}~ 3 MW

$B_T(0)$ = 0.55 T

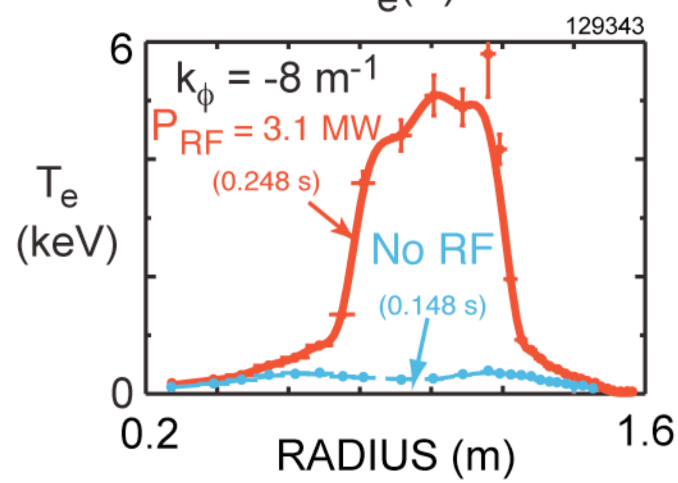


• Lithium reduces edge density – improves core heating efficiency

Helium: $T_e(0)$ = 6.2 keV

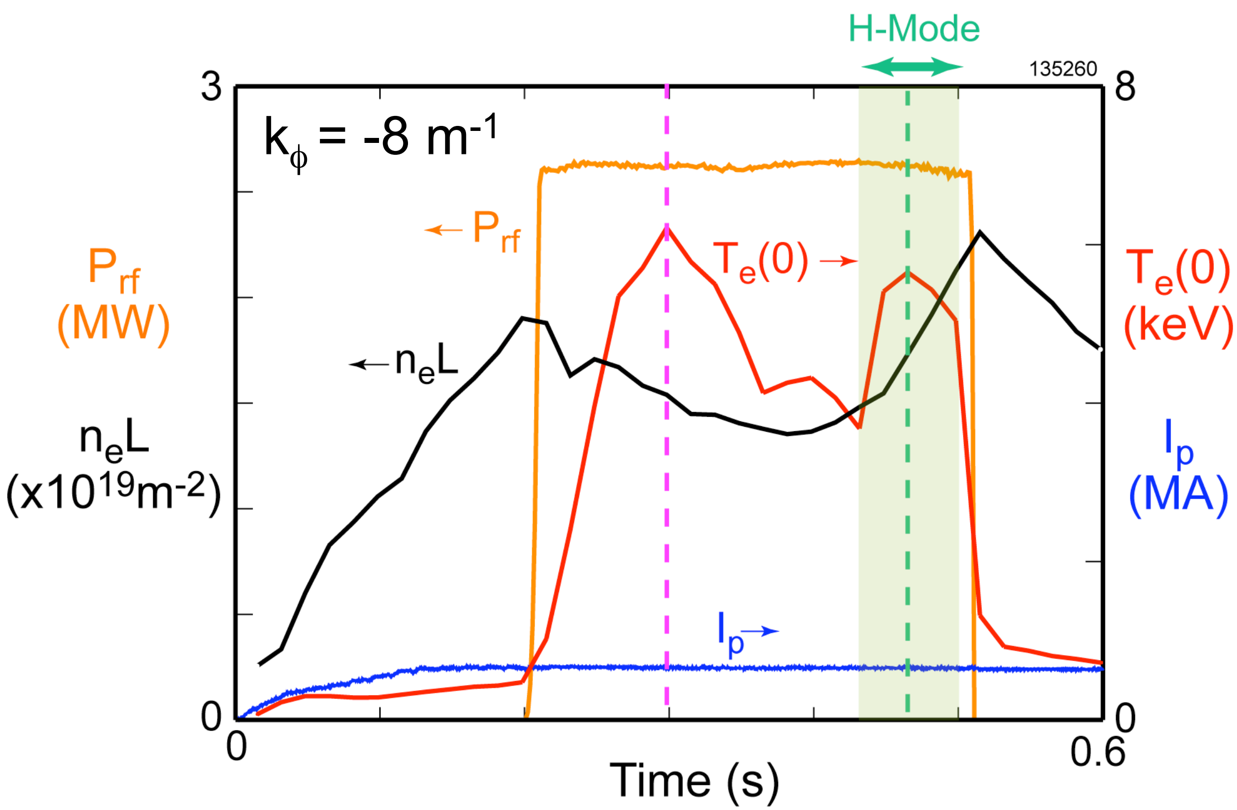


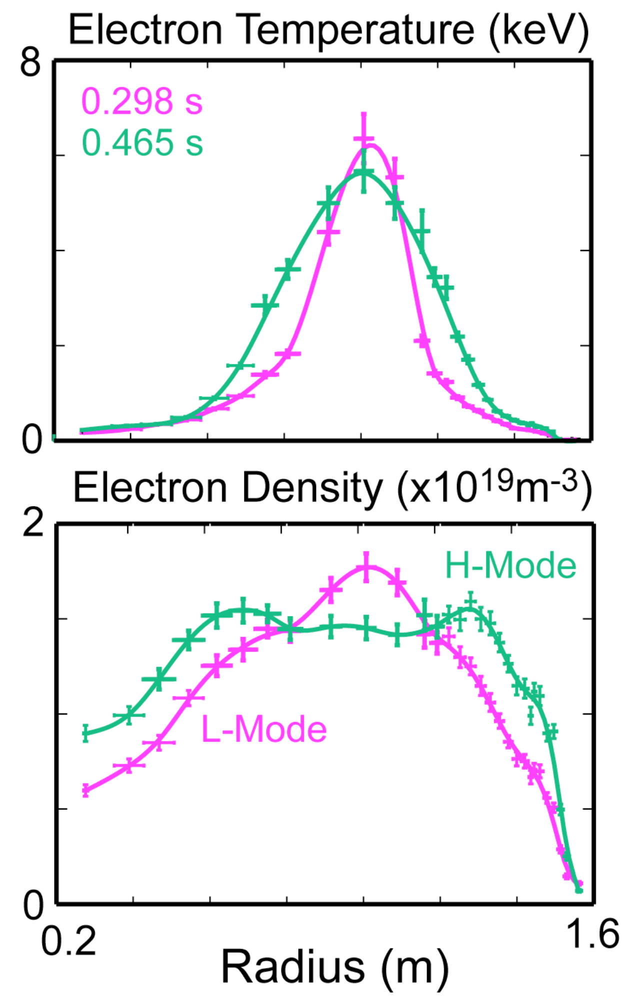
Deuterium: $T_e(0)$ = 5.2 keV



Ohmically-Heated Helium Target Plasma Transitions to H-Mode During 2.6 MW HHFW Pulse

Shot 135260

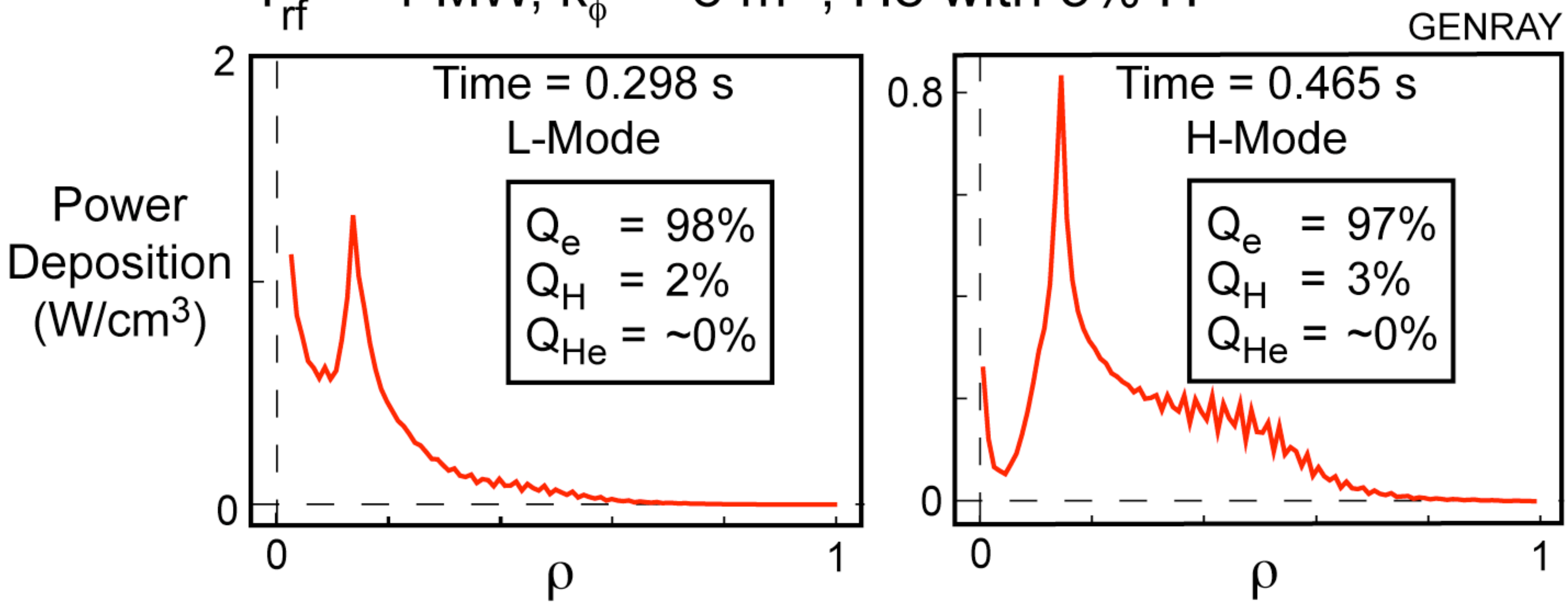




Ray Tracing Simulation Predicts > 90% of RF Power Deposited on Electrons Inside ρ ~ 0.6

Shot 135260

P_{rf} = 1 MW, k_ϕ = -8 m^{-1}, He with 3% H

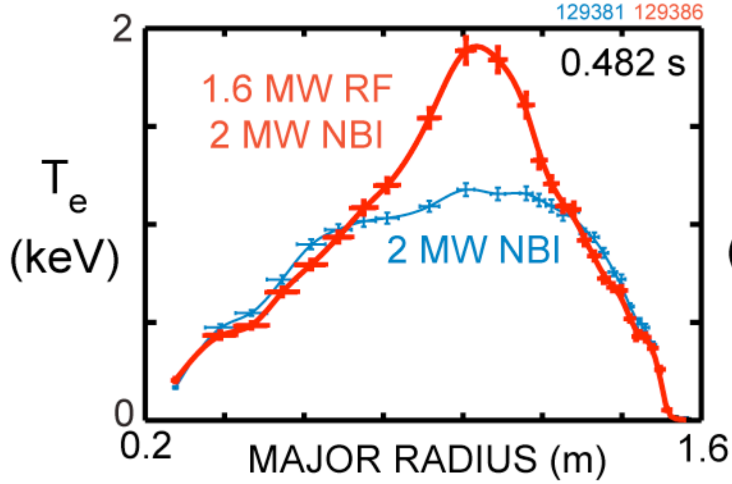


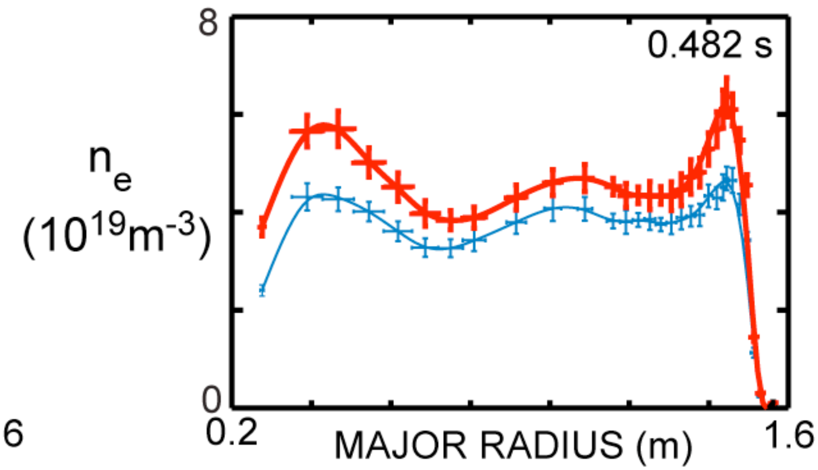
• Broader HHFW power deposition during H-Mode

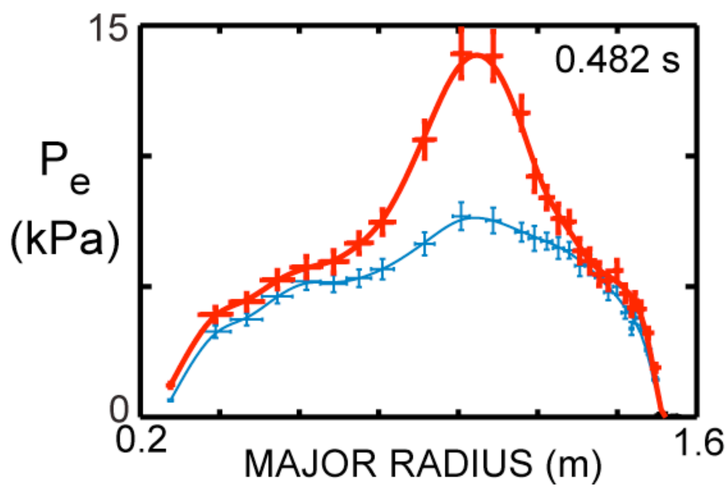
Outline

- Role of HHFW in the NSTX Program
- HHFW Heating of Ohmically-Heated Target Plasmas
- HHFW Heating of Deuterium NBI-Fueled Plasmas

Lithium Enabled Significant k_ϕ = 14+18 m^{-1} Heating of Core Electrons During Some NBI D H-modes







- k_ϕ = 14 & 18 m^{-1}
- $B_T(0)$ = 5.5 kG
- Li Conditioning

RF+NBI Shot 129386

NBI Only Shot 129381

- At $B_T(0)$ = 4.5 kG & without Li, HHFW did not heat core of D NBI-fueled H-mode*

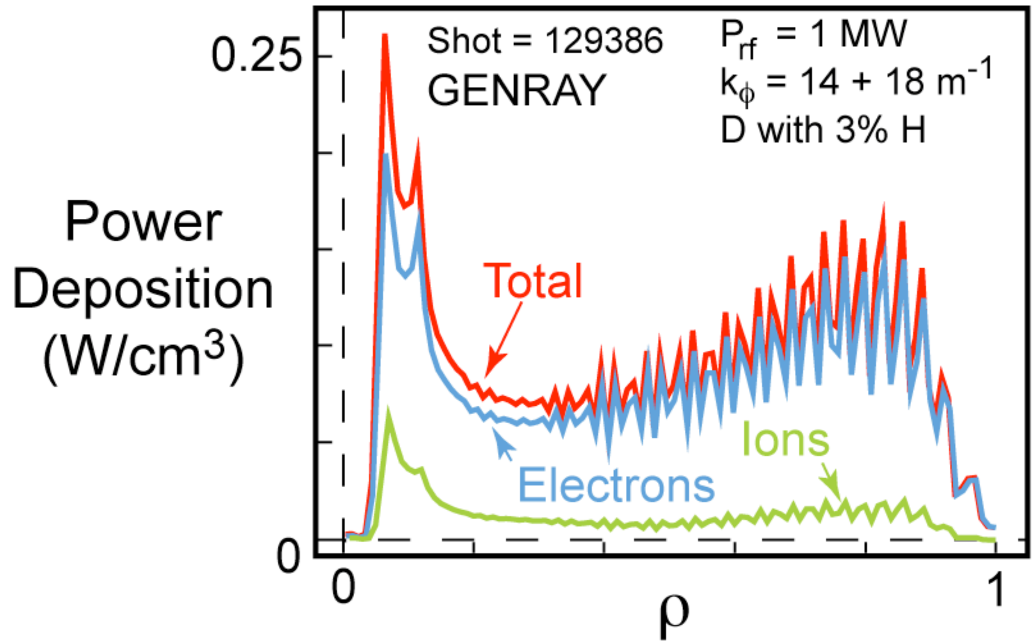
*B. LeBlanc, *et al.*, AIP Conf. Proc. **787**, 86 (2005)

Ray Tracing Predicts ~ 90% RF Absorption by Electrons During RF + NBI H-Mode

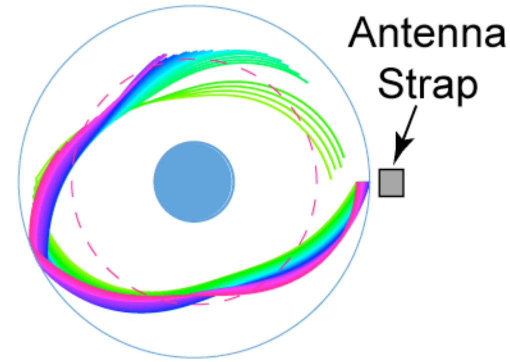
RF+NBI Shot 129386

Q_e = 88%
Q_{fast} = 5%
Q_H = 7%

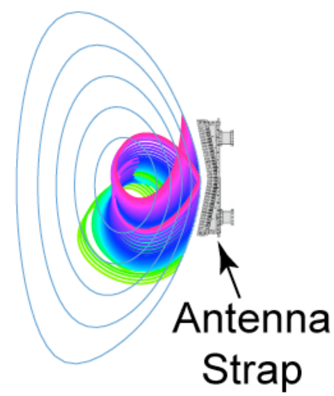
Time = 0.48 s
(End of H-Mode)



Toroidal View*



Poloidal View*

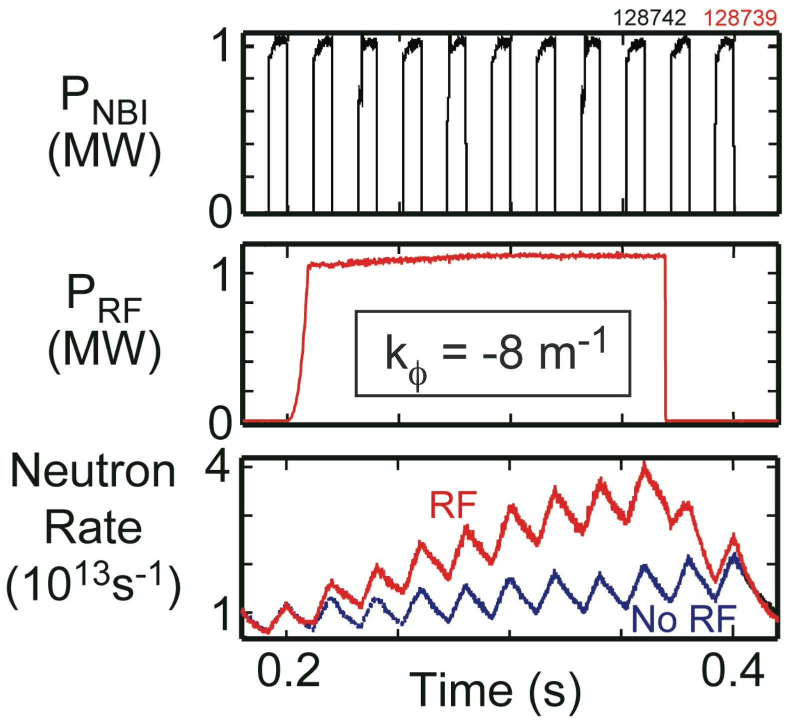


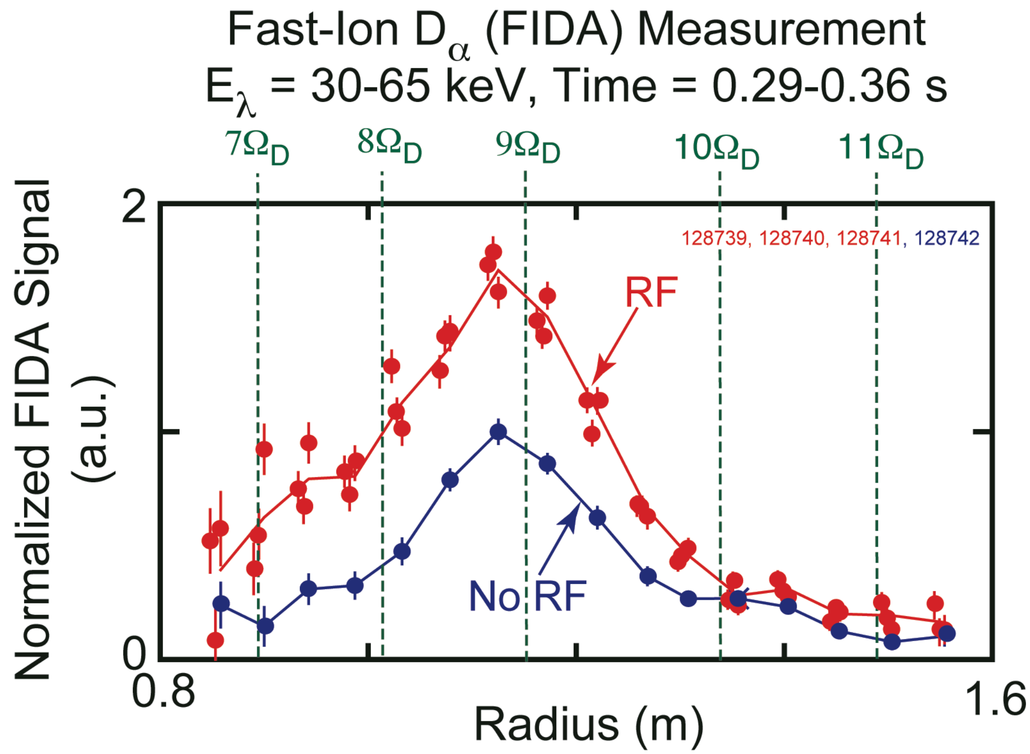
* Rays end when 99.9% of RF power is absorbed

- NBI fast-ion density and effective temperature provided by TRANSP analysis of similar NBI-only H-mode

Significant Interaction Measured Between RF & NBI Fast-Ions Over Multiple Cyclotron Harmonics

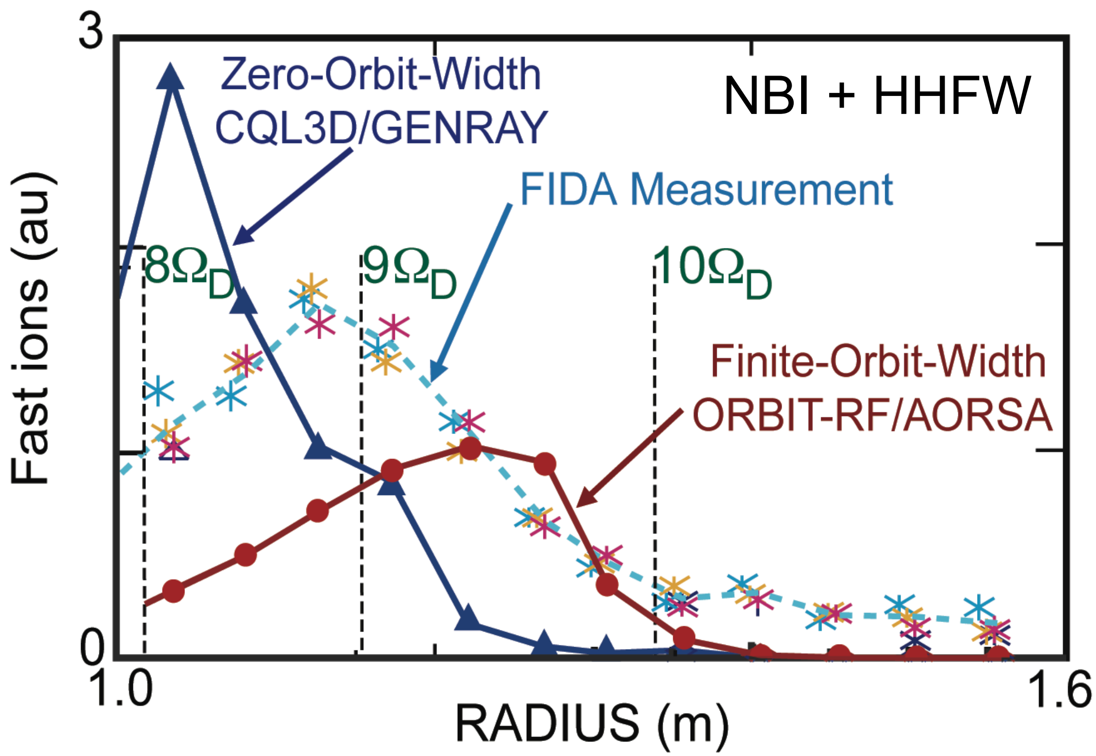
$B_T(0) = 5.5$ kG





- Measured significant enhancement & broadening of NBI fast-ions and large increase in neutron rate when HHFW is applied to NBI plasmas
  - As predicted originally by CQL3D/GENRAY

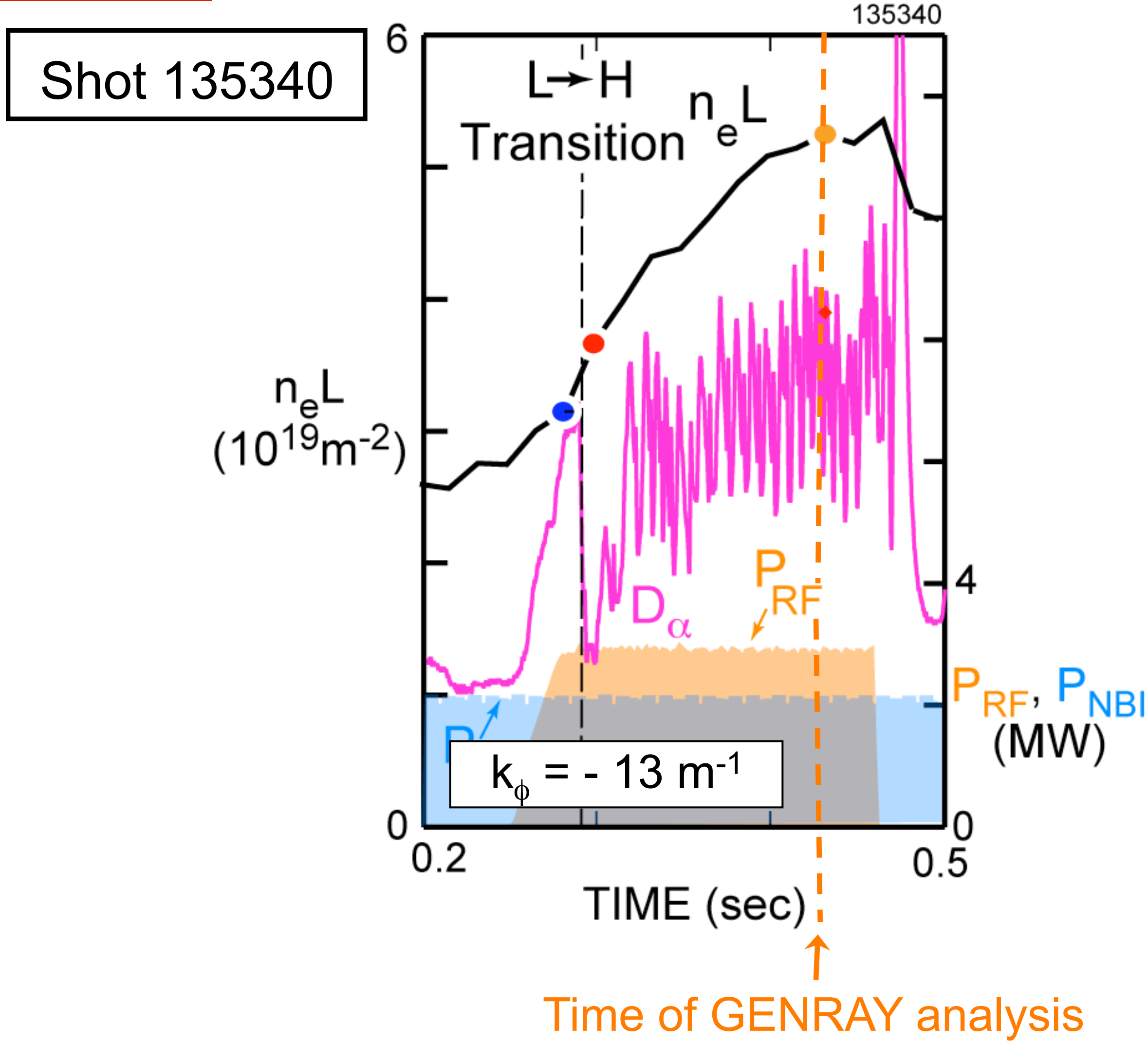
Finite Lamor Radius & Banana-Width Effects Significantly Broaden Fast-Ion Profile in NSTX

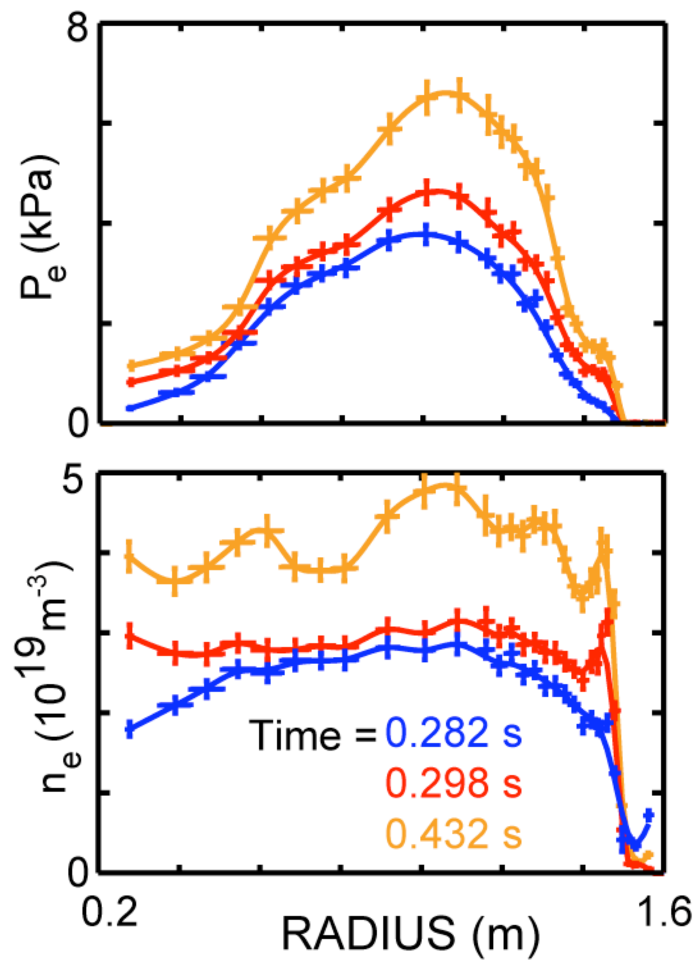


- Zero-orbit-width Fokker-Planck CQL3D/GENRAY ray tracing model predicts fast-ion profile peaks on axis during RF
- Finite-orbit-width Monte-Carlo ORBIT-RF/AORSA 2D full-wave model predicts broader outwardly shifted fast-ion profile

- Differences between ORBIT-RF/AORSA simulation and measurements are being investigated
- CQL3D modeling with first order orbit-width correction in progress this year

H-mode Initiated & Maintained Through ELMs with P_{RF} ~ 2.7 MW During ~ 2 MW D_2 NBI





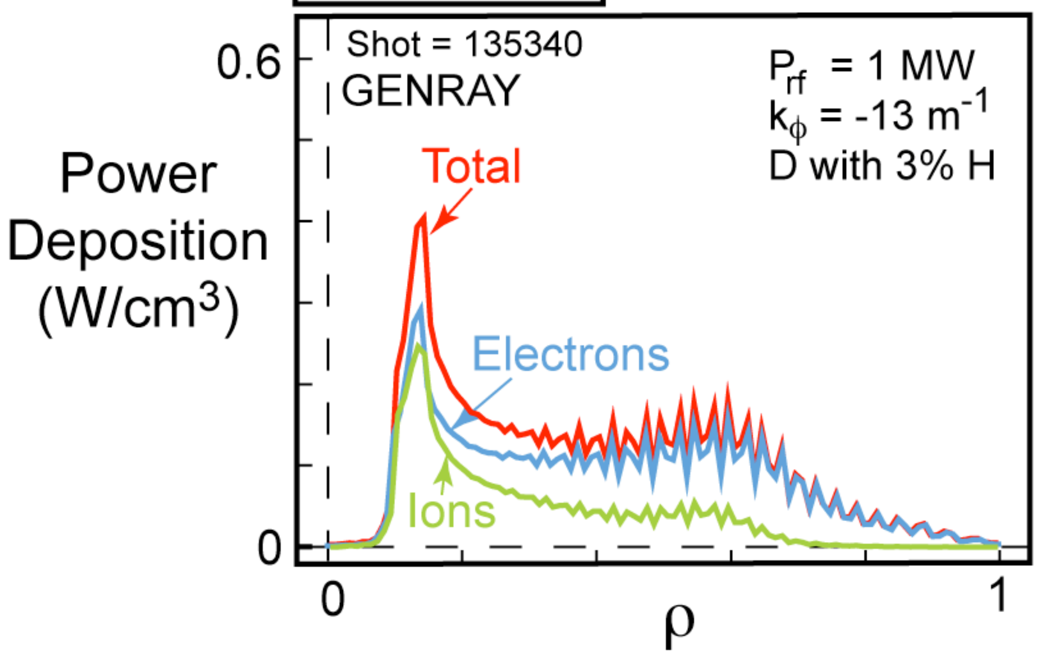
• Transition to H-mode occurs after RF turn on and without RF arc

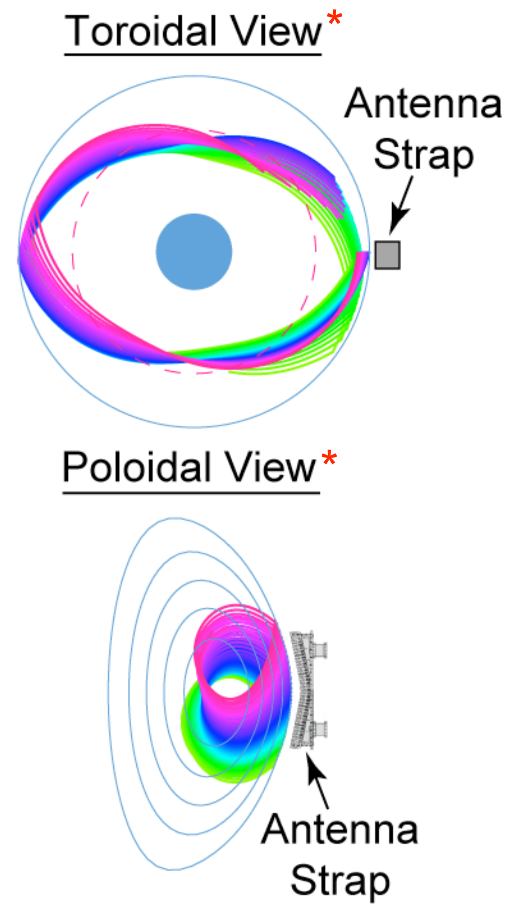
Strong Competition Between RF Heating of Fast-Ions and Electrons Near Axis During Shot 135340

Shot 135340

$Q_e = 84\%$
$Q_{fast} = 13\%$
$Q_H = 3\%$

Time = 0.432 s
(End of H-mode)

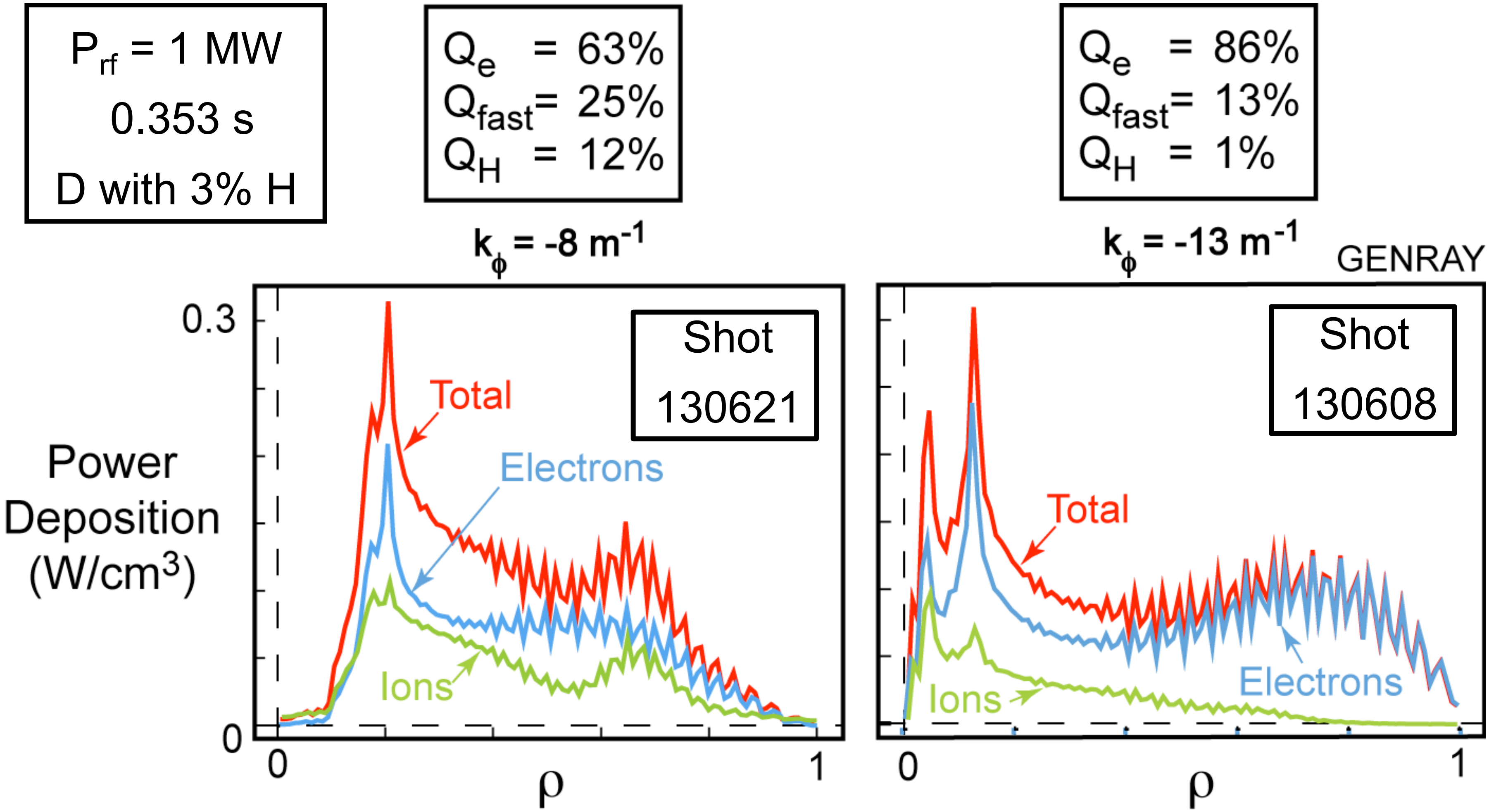




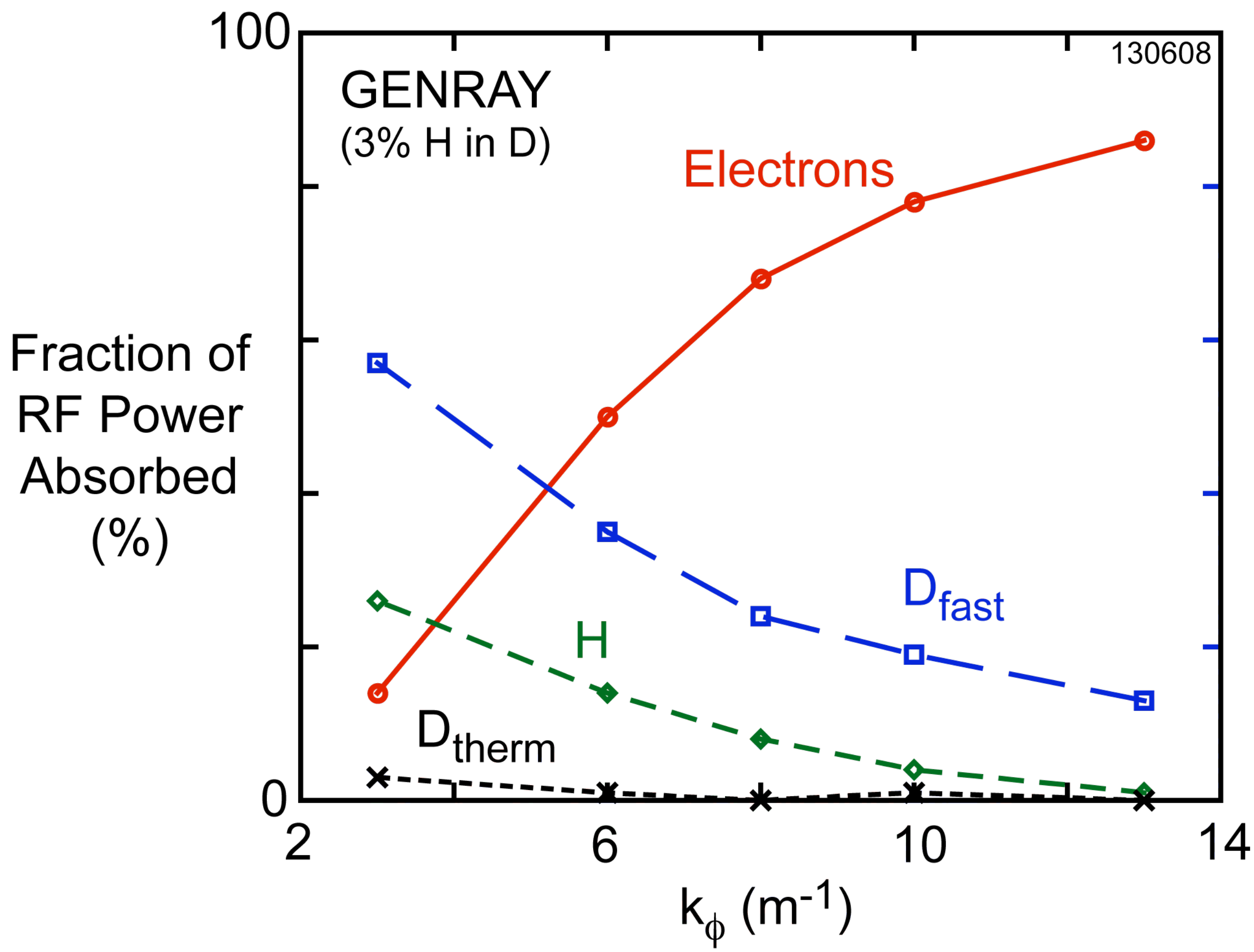
* Rays end when 99.9% of RF power is absorbed

Broader RF Power Deposition at Higher k_ϕ During RF-Heated NBI H-Mode

P_{rf} = 1 MW
0.353 s
D with 3% H



RF Deposition to Ions Increases Significantly at Lower k_ϕ During RF-Heated NBI H-Mode



Recent Version of TORIC Provides New Capability in NSTX TRANSP Analyses

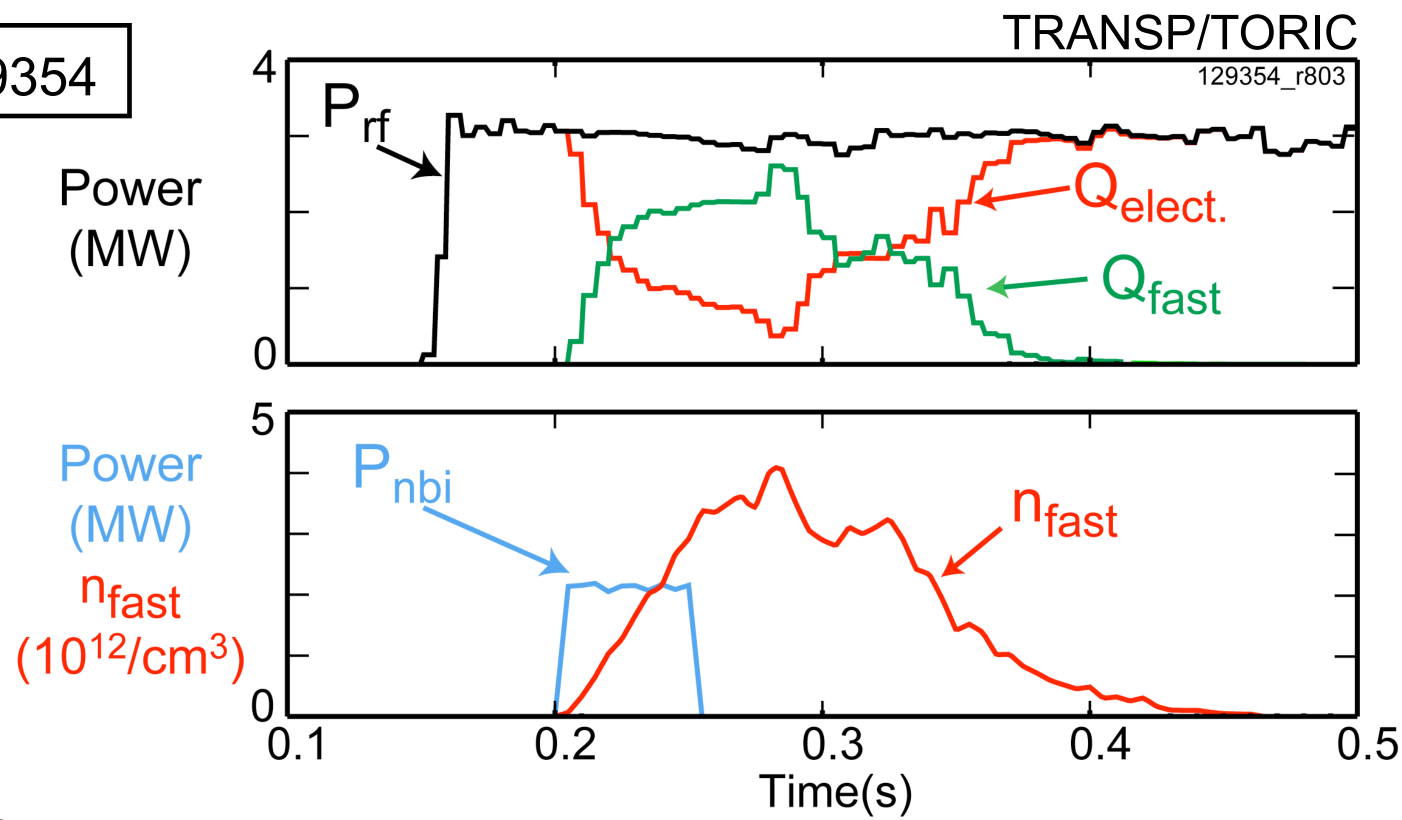
- TORIC* full-wave solver, that can compute HHFW propagation and absorption in NSTX, now included in TRANSP

*M. Brambilla, Plasma Phys. Control. Fusion **44**, 2423 (2002)

- TORIC calculates power deposition into all species, including fast-ions
  - No RF Monte-Carlo Fokker-Planck operator presently in TRANSP
  - Self-consistent calculation of fast-ions not available for RF-heated NBI plasmas
  - Use CQL3D Fokker-Plank code to estimate neutron rate generated by fast-ions

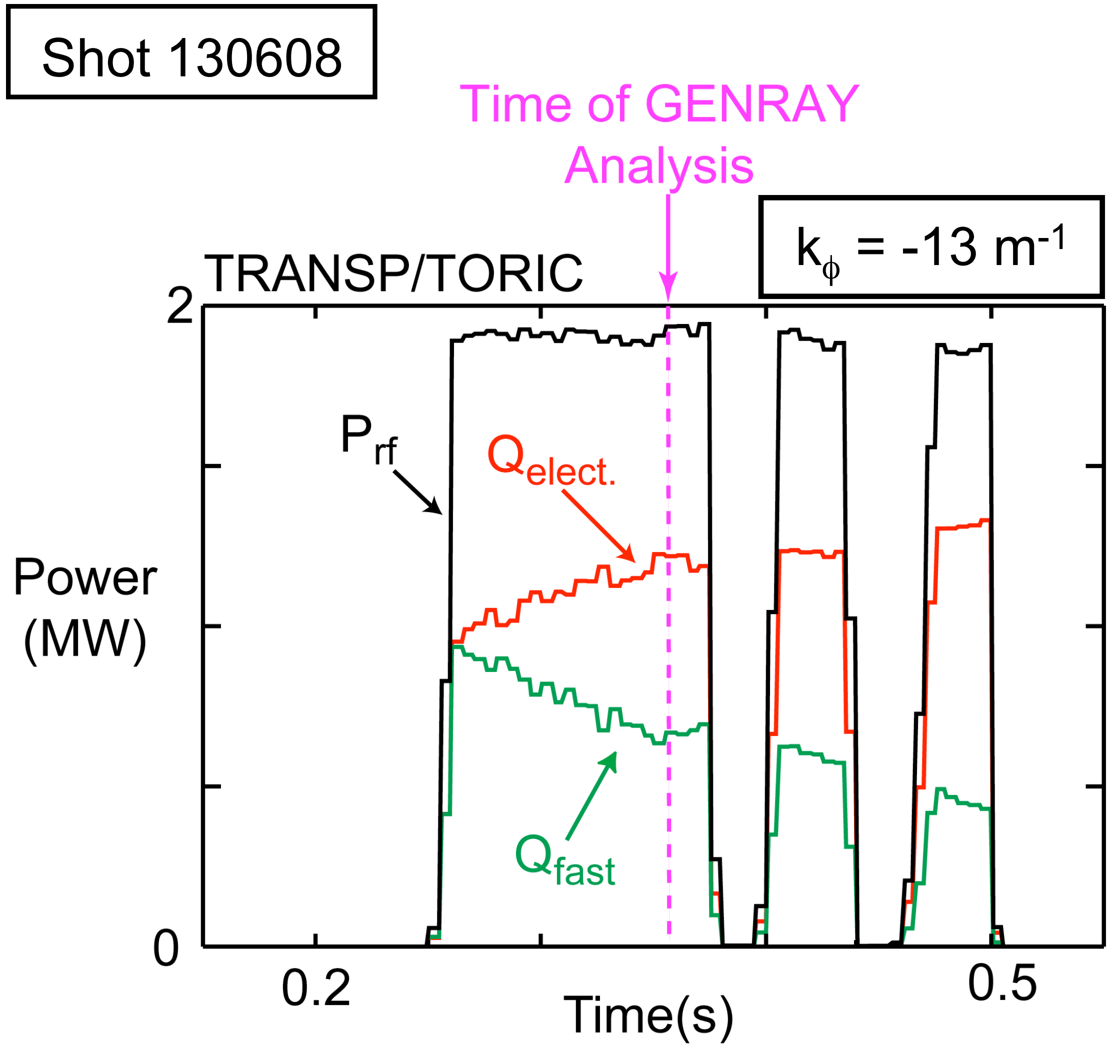
TRANSP/TORIC Modeling Predicts RF Absorption by NBI Fast-Ions Lasts Well After NBI Turn Off

Shot 129354



- All rf power absorbed by electrons prior to NBI pulse
- After NBI turn-on, the fast-ion population absorbs HHFW power at the expense of the electrons
  - ➢ Trend confirmed by single time point calculations with AORSA, GENRAY and TORIC

RF Power Absorption by Fast-Ions Decreases as Fast-Ions Thermalize During RF-Heated NBI H-Mode

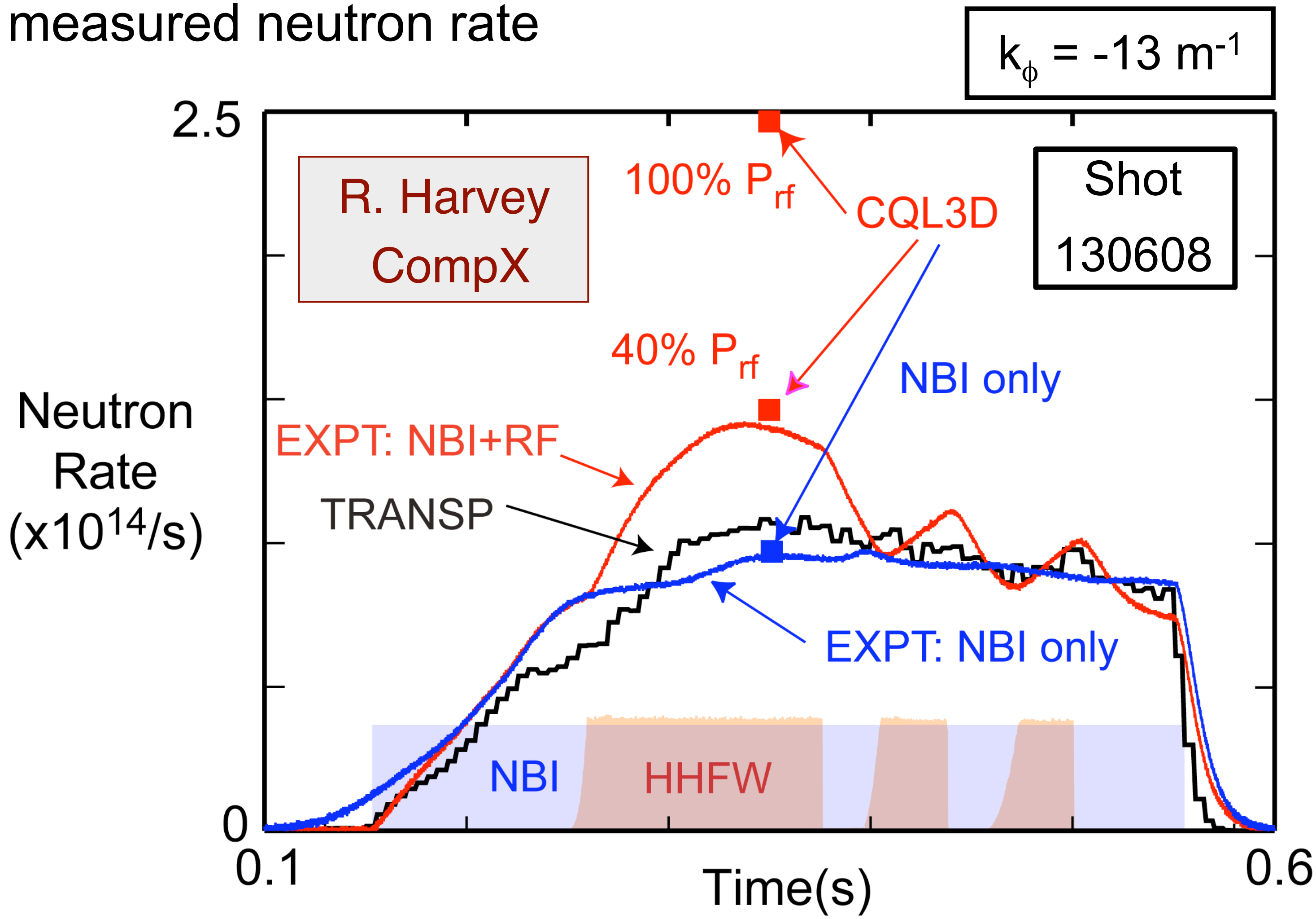


- Electron β increases with time as density rises, increasing RF heating on electrons

- At time of GENRAY analysis (0.355 s), TRANSP/TORIC predicts 66% RF damping on electrons, 33% on fast-ions
  - GENRAY predicts 86% RF damping on electrons, 13% on fast-ions

CQL3D Simulation Predicts ~ 40% of RF Antenna Power Coupled to Plasma for k_ϕ = -13 m^{-1} Heating

- P_{rf} used in CQL3D modeling reduced to match simulated and measured neutron rate



Summary

- NSTX record $T_e(0)$ obtained with P_{rf} ~ 3 MW in Li-conditioned, ohmically-heated plasmas
  - Modeling predicts > 90% of rf deposited on electrons inside ρ ~ 0.6
- Strong interaction measured between RF & NBI fast-ions over multiple ion cyclotron harmonics
- Li conditioning enabled significant k_ϕ = 14+18 m^{-1} heating of core electrons during some NBI D H-modes plasmas
- Modeling predicts significant RF damping on fast-ions near the plasma core during most NBI + RF H-modes studied so far
  - RF deposited on fast-ions increases significantly for lower k_ϕ heating
- CQL3D simulation predicts ~ 40% of RF antenna power heats plasma inside separatrix during k_ϕ = -13 m^{-1} heating