NSTX

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HHFW Heating and Current Drive Modeling Results for NSTX H-Mode Plasmas*

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*Work supported by US DoE contracts DE-AC02-09CH11466 and DE-AC-05-00OR22725

US-Japan RF Plasma Physics Workshop
Toba, Mie Prefecture, Japan, February 8-9, 2011

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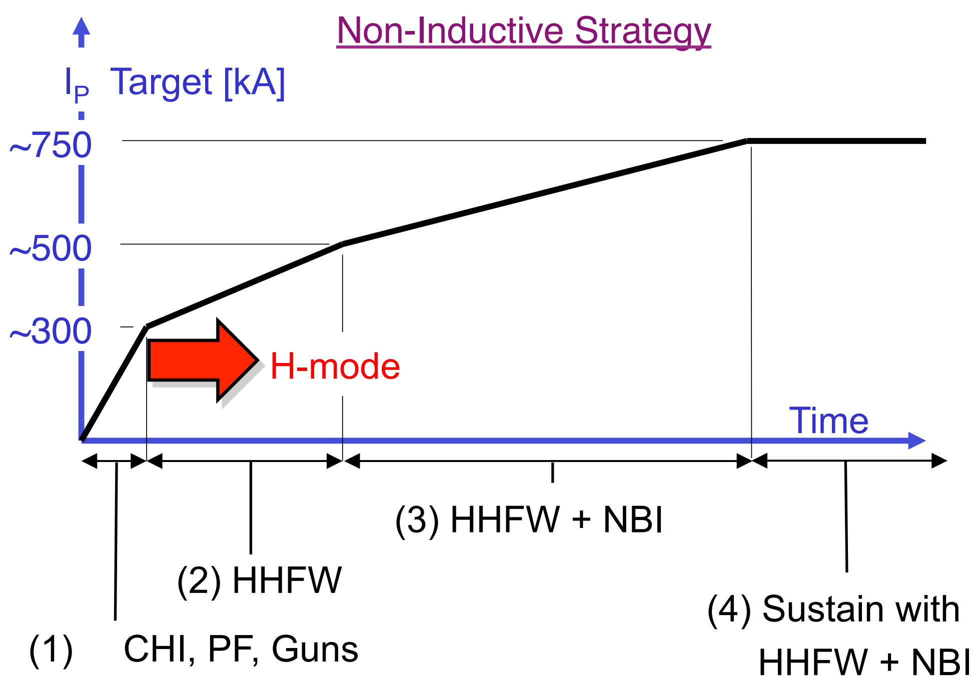
HHFW heating and current drive (CD) are being developed on NSTX for non-inductive ramp-up, bulk heating and q(0) control



HHFW Goals

(1) HHFW couples to start-up plasma

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

(3) HHFW generates sufficient I_P to confine NBI ions

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

- Two major roles for HHFW heating and CD in NSTX:
  - Enable fully non-inductive plasma current (I_p) ramp-up through Bootstrap CD (BSCD) and RFCD generated during early HHFW H-mode
  - Provide bulk electron heating during the I_p flat top, when the discharge is in H-Mode and also heated by neutral-beam injection (NBI)

NSTX HHFW research in 2008-10 was focused on studying HHFW & HHFW+NBI deuterium H-modes at low and high I_p

- Near-term approach to assess HHFW heating during ramp-up has been to heat low I_p ohmic plasmas and access 100% non-inductive CD (f_{NI} ~ 1)

- Experiments at low I_p (~ 300 kA) last year produced sustained HHFW H-mode with f_{NI} ~ 0.65, even though arc-free P_{RF} ≤ 1.4 MW [Phil Ryan's talk]

- Experiments at high I_p (0.7 - 1 MA) in 2008-9 produced significant bulk electron heating when HHFW was coupled to NBI H-mode plasmas:

  - HHFW acceleration of NBI fast-ions produced enhanced fast-ion losses during HHFW heating

  - Conducted extensive studies of HHFW heating and edge power loss mechanisms during high I_p ELMy and ELM-free H-modes [Joel Hosea's talk]

- This talk presents deposition and CD results for H-mode plasmas heated by HHFW and HHFW+NBI at I_p = 300 kA, and HHFW+NBI at I_p = 900 kA

Outline

- RF Modeling Codes
- Low I_p H-mode Modeling Results
- High I_p H-mode Modeling Results
- Summary & 2011-12 Plans

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GENRAY ray tracing code calculates the HHFW power deposition and RF-driven current profile

- GENRAY is an all-waves general ray tracing code for RF wave propagation and absorption in the geometrical optics approximation

- GENRAY outputs ray trajectory and absorption data to other codes

- Recently, an all-frequencies, linear, momentum conserving CD calculation has been added to GENRAY (GENRAY/ADJ-QL)
  - The CD calculation utilizes an adjoint (ADJ) approach based on the relativistic Coulomb Fokker-Planck collision operator and the relativistic quasi-linear (QL) flux

TRANSP-TORIC code provides a time-dependent calculation of the HHFW power deposition and CD profile

- TORIC full-wave RF code has been integrated into the TRANSP plasma transport code
- TORIC solves the kinetic wave equation in a 2-D axisymmetric equilibrium
- Solves for a fixed frequency with a linear plasma response
- Present implementation of TORIC in TRANSP can model HHFW deposition but cannot evolve the fast-ion energy distribution self consistently:
  - As a result, the neutron rate (S_n) calculated by TRANSP-TORIC reflects the beam-target reactions for the NBI fast-ions without HHFW acceleration

CQL3D Fokker-Planck code can predict the RF-driven current and the wave field acceleration of the NBI fast-ions

- CQL3D is a relativistic collisional, quasi-linear, 3-D code which solves a bounced-averaged Fokker Planck equation:
  - Uses the ray trajectories and absorption input from GENRAY to calculate the RF power deposition and CD profile
  - CQL3D also computes wave field effects on the fast-ions & predicts S_n
- Using input data from TRANSP at a particular time-of-interest (TOI), CQL3D can be "run to equilibrium" in order to estimate S_n
- CQL3D currently provides two fast-ion loss calculation options:
  - "No loss" (NL) option, which assumes zero ion gyroradius and banana width
  - "Simple-banana-loss" (SBL) calculation which assumes that any ion which has a gyroradius + banana width > than the distance to the last closed flux surface (LCFS) is promptly lost

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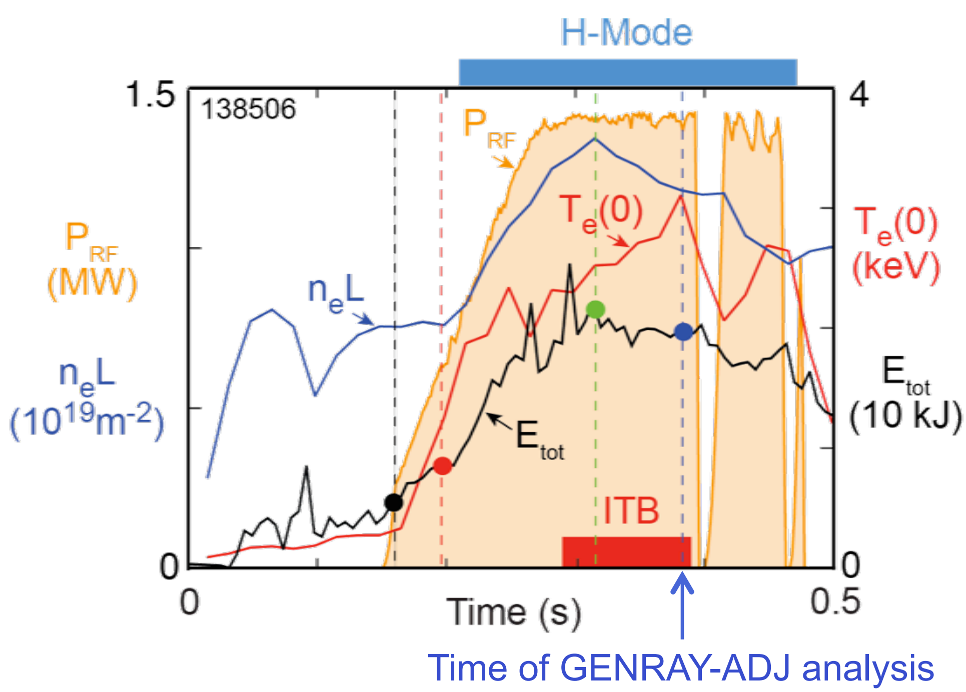
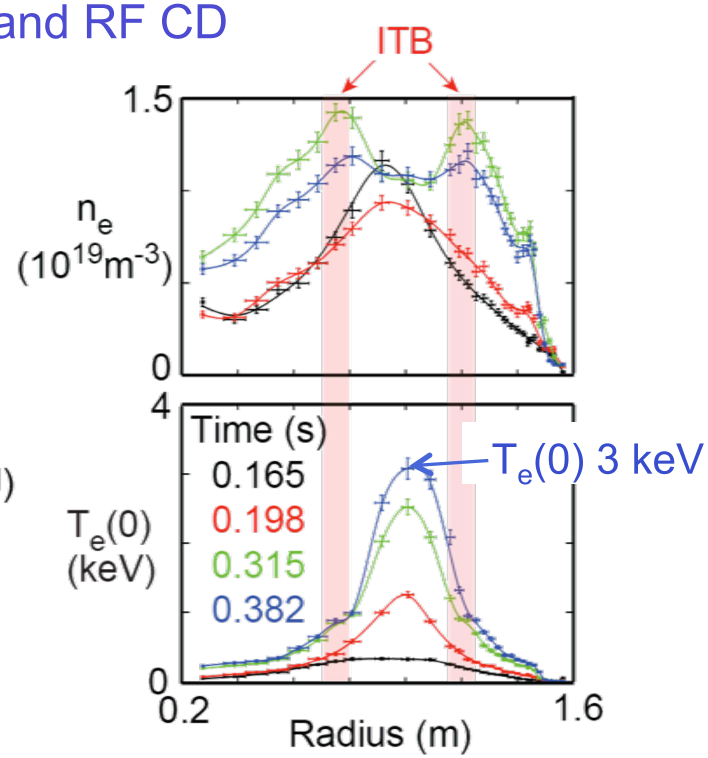
Achieved sustained I_p = 300 kA HHFW H-mode, with internal transport barrier (ITB) and $T_e(0)$ = 3 keV with P_{RF} = 1.4 MW

- Experiments in 2005 did not maintain RF coupling during I_p = 250 kA HHFW H-mode due to poor plasma position control at L-H transitions

- Sustained HHFW H-mode at I_p ~ 300 kA in 2010 made possible by reduced plasma control system latency:
    - ➢ ITB formed during H-mode
    - ➢ Positive feedback between ITB, high $T_e(0)$ and RF CD





GENRAY-ADJ predicts peaked RF deposition on electrons and 115 kA/MW RFCD efficiency, assuming no coupling loss

Shot 138506

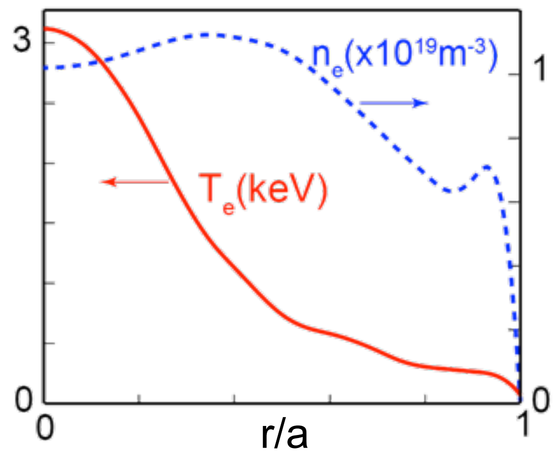
Time = 0.382 s

I_P = 300 kA

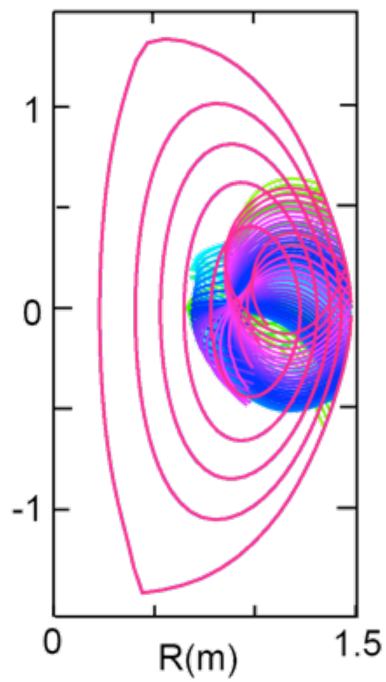
B_T = 5.5 kG

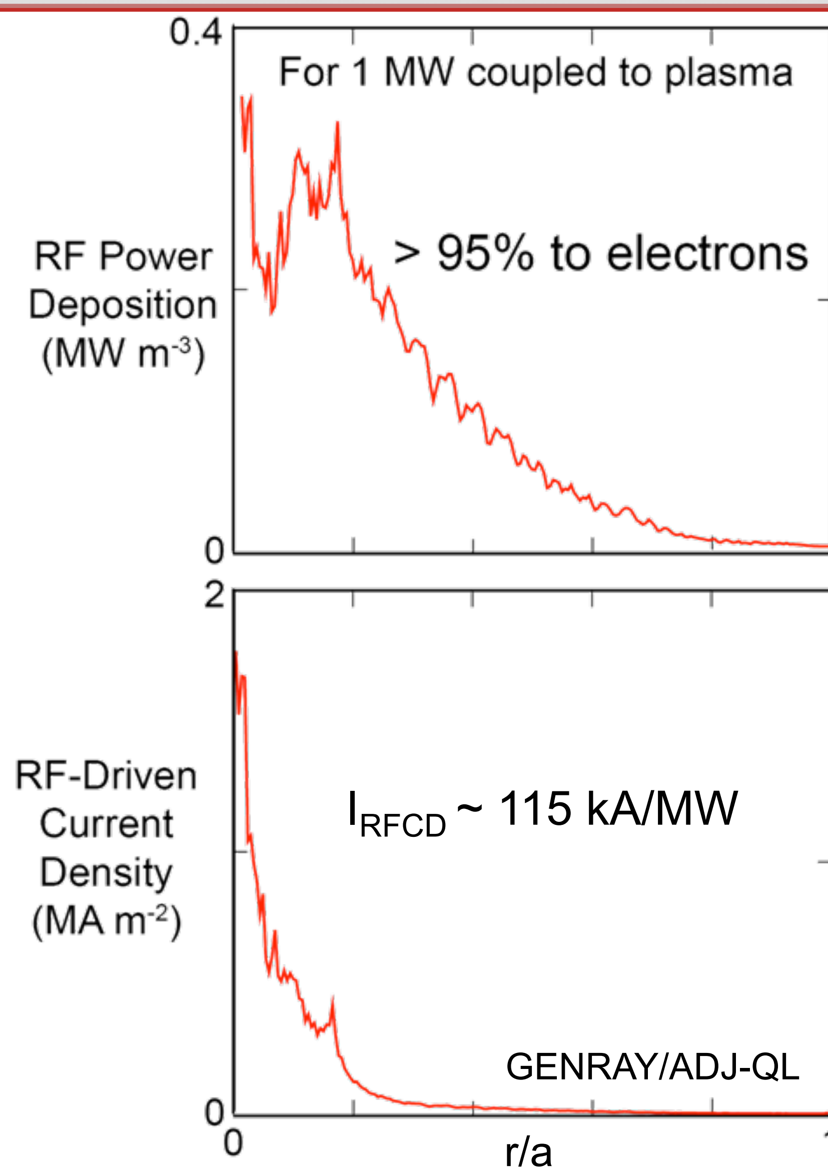
Deuterium

RF H-mode



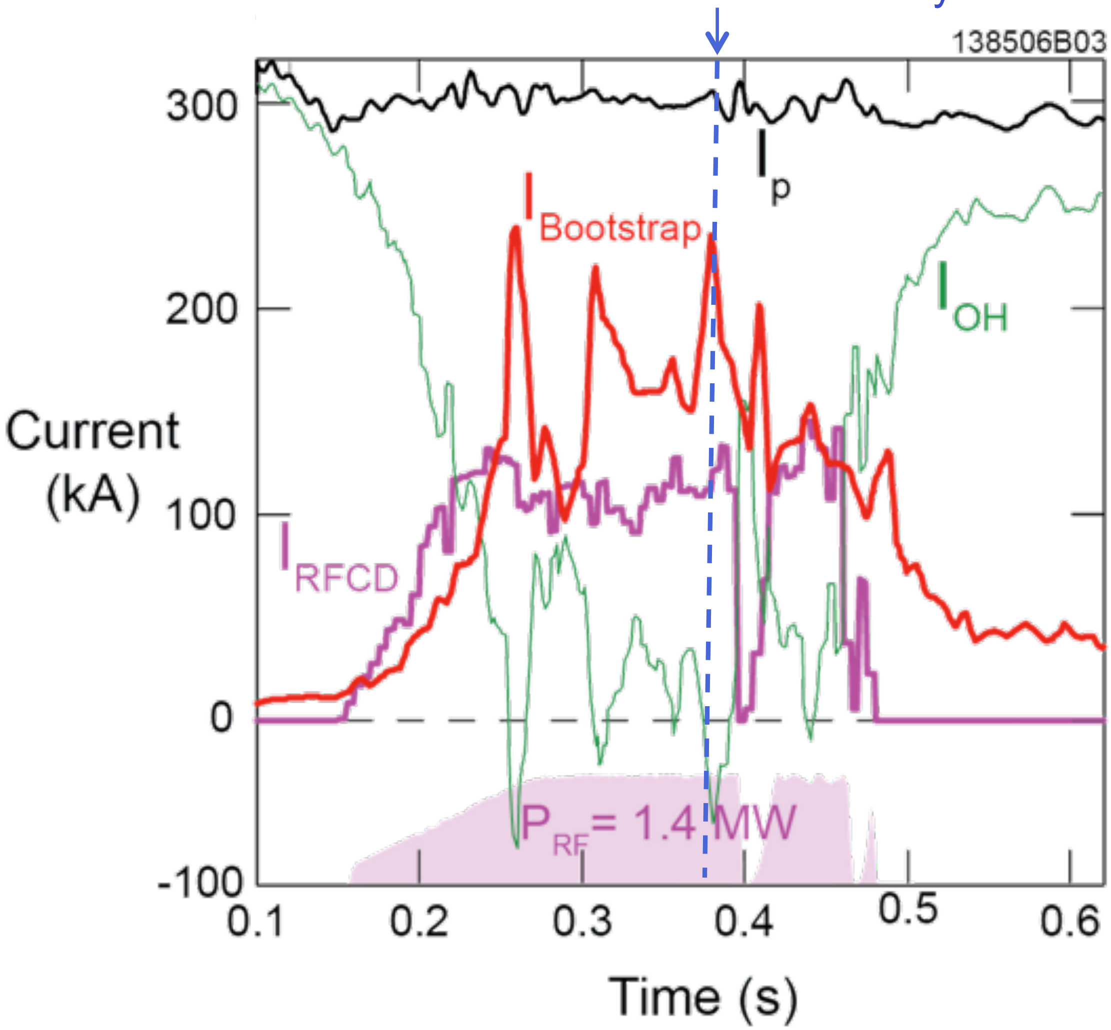
GENRAY
41 Rays
k_ϕ=-8 m^{-1}





TRANSP-TORIC simulation, assuming 100% RF coupling (η_{eff} = 100%), predicts $I_{Bootstrap}$ = 220 kA and I_{RF} = 120 kA

TORIC-TRANSP modeling for η_{eff} = 100%:



- TRANSP-TORIC predicts RFCD efficiency ~ 85 kA/MW at GENRAY analysis time:
  - Compared to GENRAY RFCD efficiency ~ 115 kA/MW
- $\eta_{eff} = \Delta W_T/(\tau * P_{RF})$

  ΔW_T ~ 13 kJ

  τ ~ 15 ms

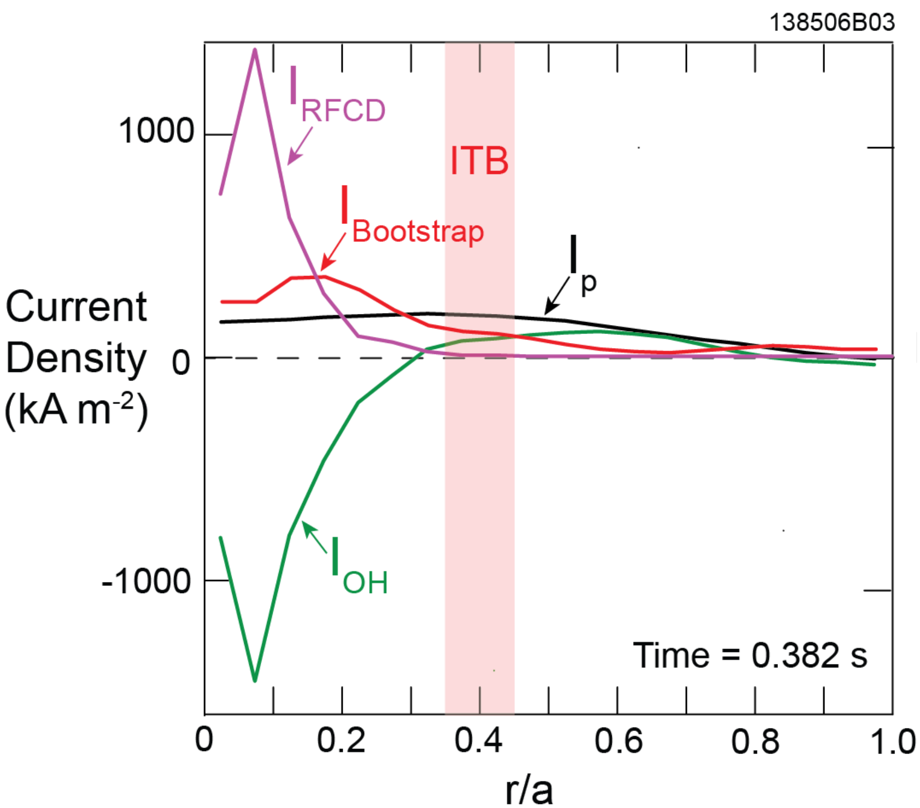
  P_{RF} ~ 1.4 MW

  → η_{eff} ~ 60%

  - $n_{edge} \sim 4\times10^{11}\ m^{-3}$ ($n_{crit} \sim 5\times10^{11}\ m^{-3}$)

80% of the non-inductive current is generated inside the ITB in the I_p = 300 kA HHFW H-mode

TORIC-TRANSP modeling for η_{eff} = 100%:



For η_{eff} = 60%

	HHFW H-Mode
I_{BS} (kA)	130 kA
I_{RF} (kA)	70 kA
f_{NI}	0.65

- Motional Stark Effect – Laser Induced Fluorescence (MSE-LIF) diagnostic will allow current profile measurements during HHFW H-modes in 2011-12

Coupling P_{RF} = 1.4 MW into I_p = 300kA P_{NBI} = 2 MW H-mode resulted in lower f_{NI} than the I_p = 300kA HHFW H-mode

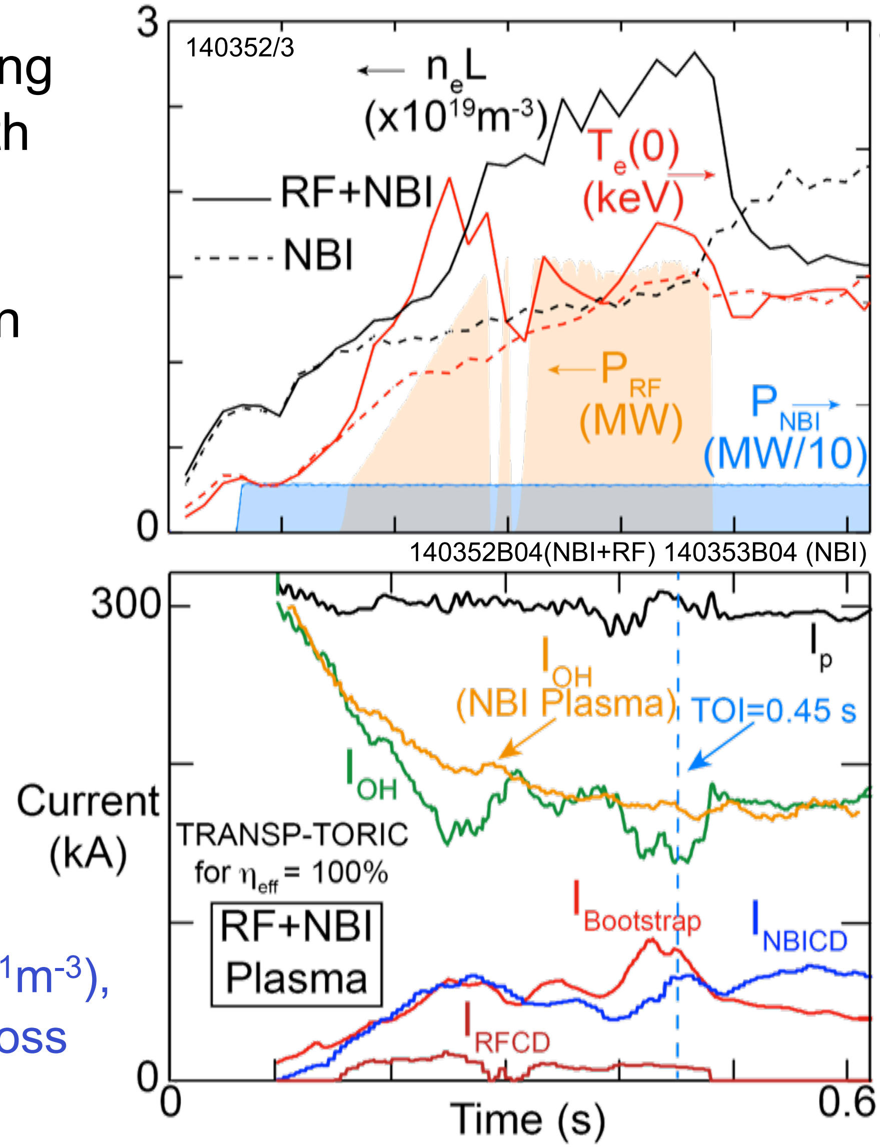
- Density increased during HHFW heating probably due to fast-ion interaction with the antenna

- Much lower $T_e(0)$ and higher $n_e(0)$ than HHFW H-mode resulted in lower → I_{RFCD} ~ 10-20 kA

- 50% of injected NBI fast-ions are promptly lost at this low I_p

- $I_{Bootstrap}$ = 60-90 kA, I_{NBICD} = 50-70 kA

- η_{eff} was only ~ 40%:
  - high n_{edge} ~ 1-2 x10^{12} m^{-3} (n_{crit} ~ 5x$10^{11}$$m^{-3}$), probably caused more surface wave loss



40% of coupled RF power accelerates NBI fast-ions which are then promptly lost from the plasma

Shot 140352

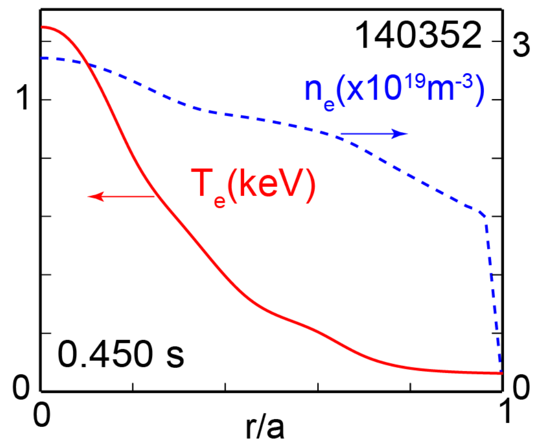
Time = 0.450 s

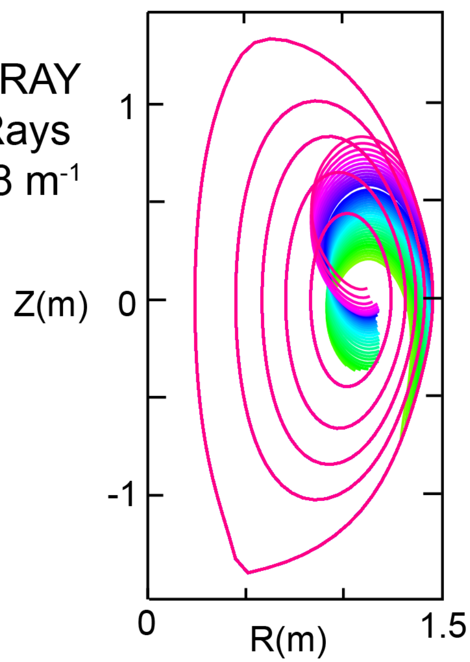
I_P = 300 kA

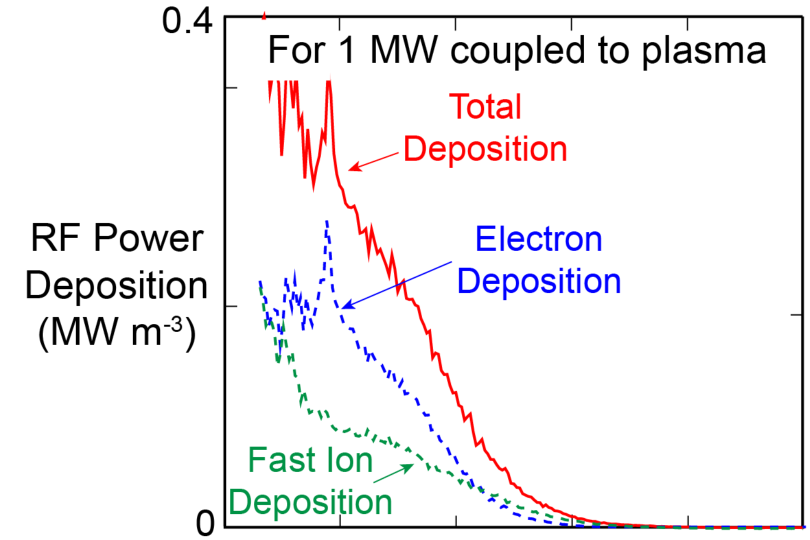
B_T = 0.55 T

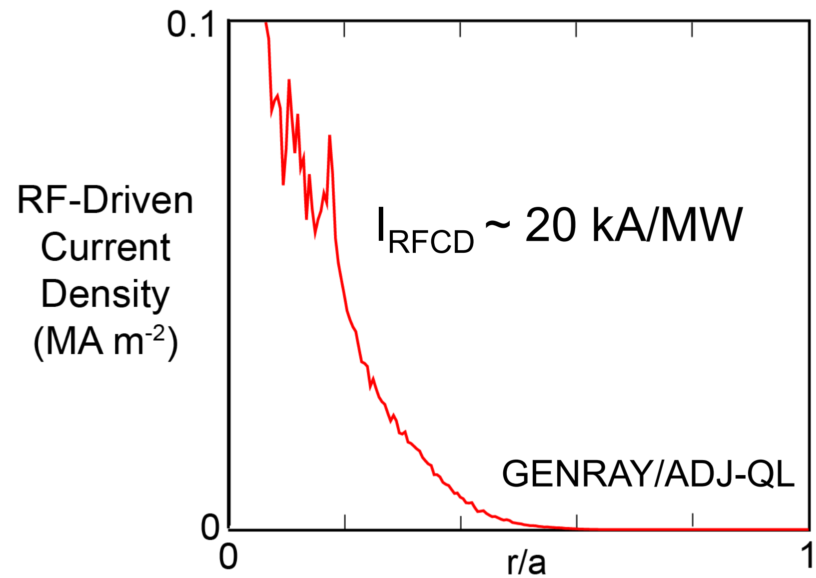
Deuterium

HHFW+NBI H-mode



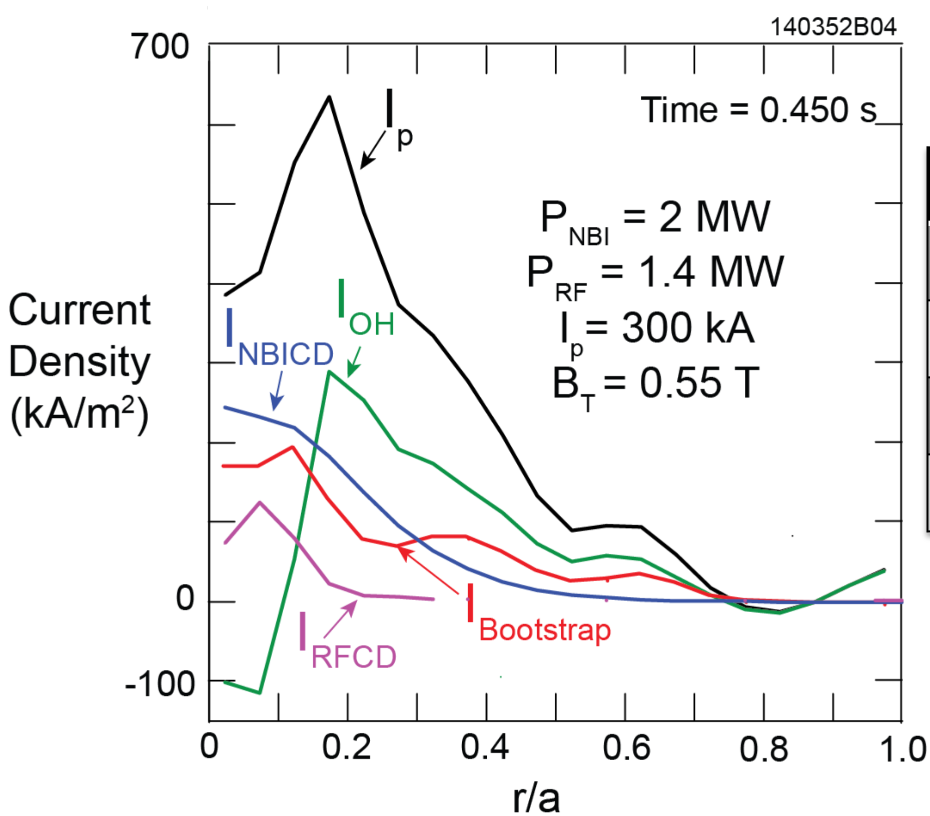






HHFW heating of I_p = 300 kA NBI H-mode produces a small increase in f_{NI}, due to increased $I_{Bootstrap}$

TORIC-TRANSP modeling for η_{eff} = 100%:



For η_{eff} = 40%

	HHFW+NBI	NBI
I_{BS} (kA)	60 kA	40 kA
I_{NBI} (kA)	65 kA	75 kA
I_{RF} (kA)	10 kA	-
f_{NI}	0.45	0.40

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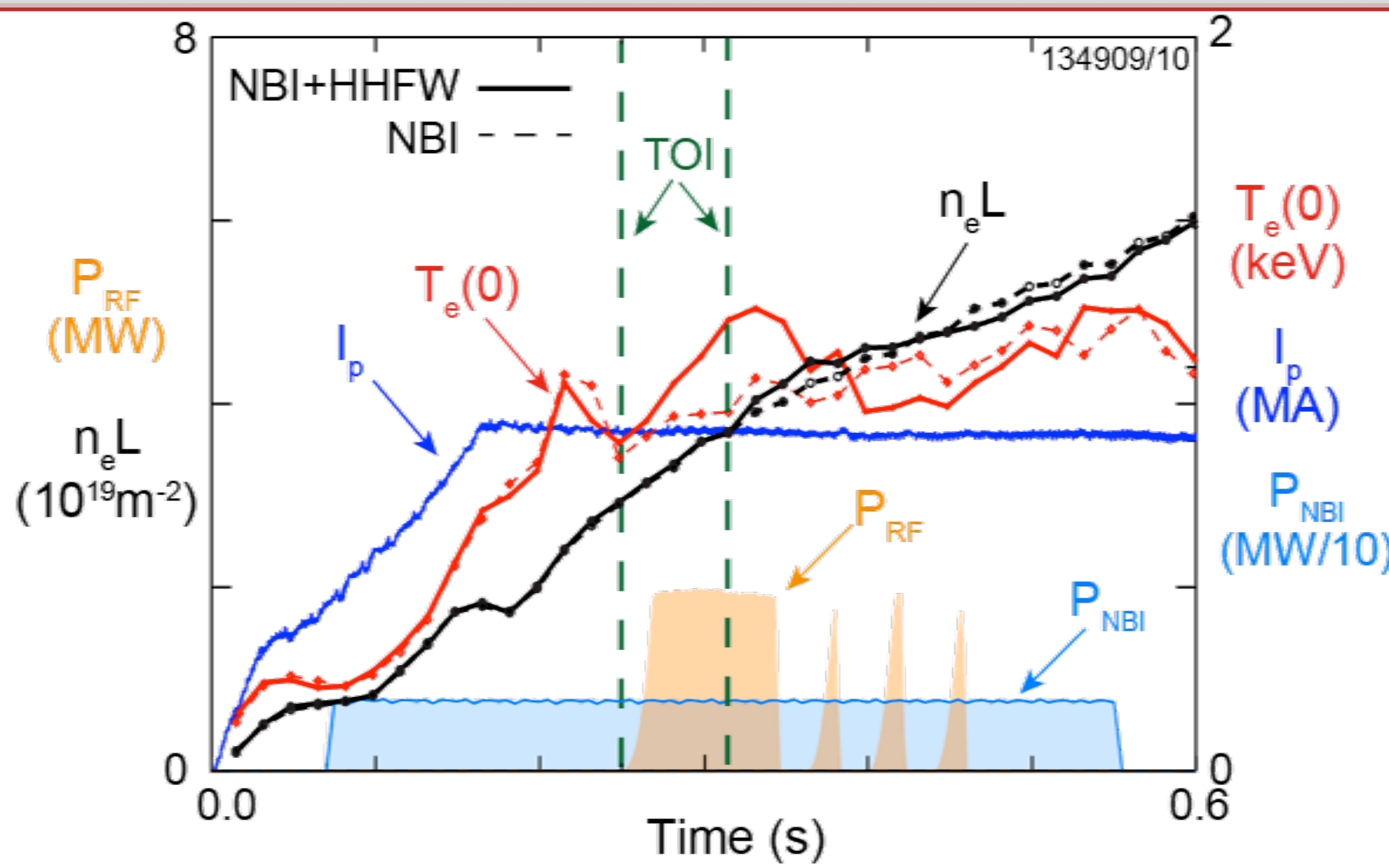
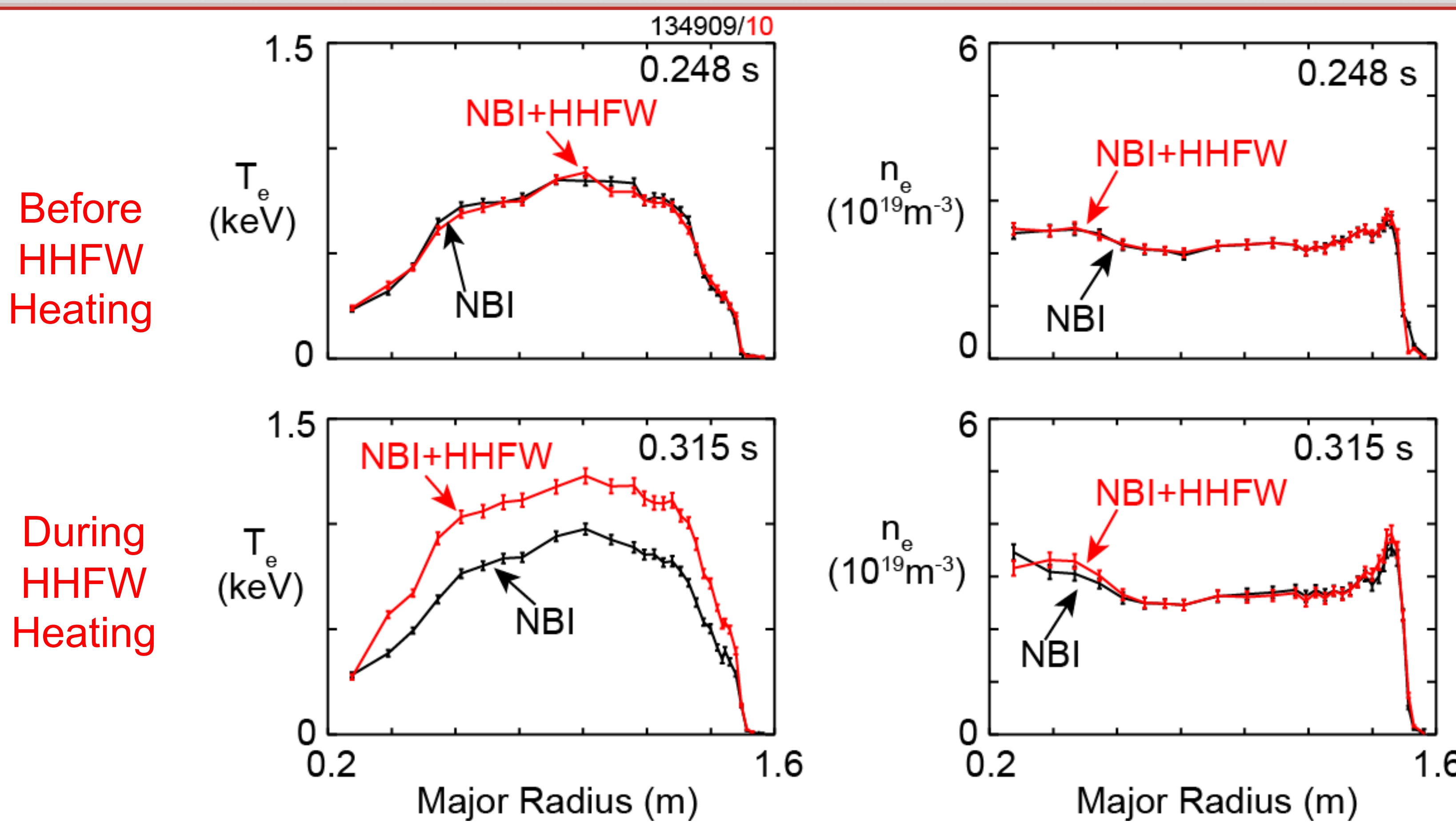
Compare two closely matched I_p = 900 kA ELM-free H-mode plasmas: NBI+HHFW and NBI



- I_P = 900 kA, B_T = 0.55 T, P_{NBI} = 2 MW, P_{RF} = 1.9 MW, $k_{||}$ = 13 m^{-1}
- Benign MHD activity in both plasmas
- MSE q profiles unavailable
- Times-of-interest (TOI) 0.248 s and 0.315 s

Broad T_e profile increase with HHFW heating of NBI H-mode plasma



- Identical T_e and n_e H-mode profiles before HHFW power onset
- Broad T_e profile increase during HHFW heating, n_e profile remains unchanged and plasma stayed in H-mode

TRANSP-TORIC predicts ~ 50% of P_{RF} coupled to I_p = 900 kA ELM-free NBI H-mode absorbed inside LCFS

- Fraction of P_{RF} absorbed within LCFS (f_A) obtained from TRANSP-calculated electron stored energy:

  W_{eX} – from HHFW+NBI H-mode

  W_{eR} – from matched NBI H-mode

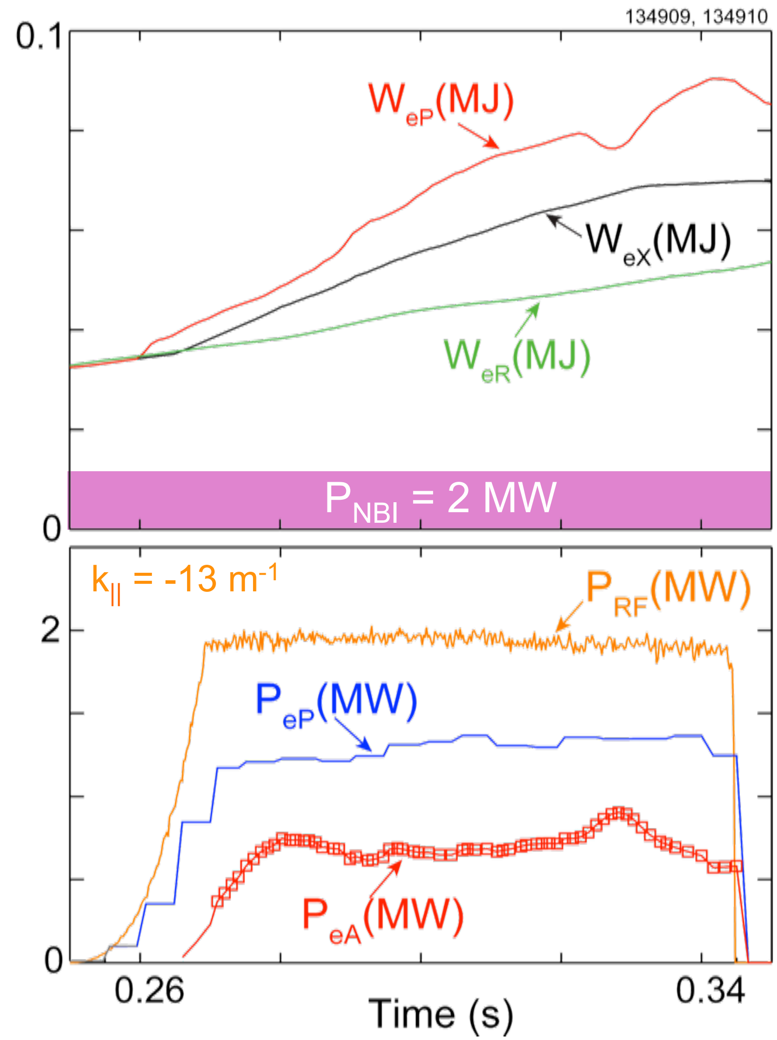
  W_{eP} – using χ_e from NBI H-mode to predict T_e in HHFW+NBI H-mode

- $\eta_{eff} = (W_{eX}-W_{eR})/(W_{eP}-W_{eR}) = 0.53 \pm 0.07$
- TORIC used to calculate the power absorbed by electrons (P_{eP}) assuming 100% RF plasma absorption
- Electron absorption, $P_{eA} = \eta_{eff} \times P_{eP}$

  For P_{RF} = 1.9 MW:

  – 0.7 MW ➡ electrons

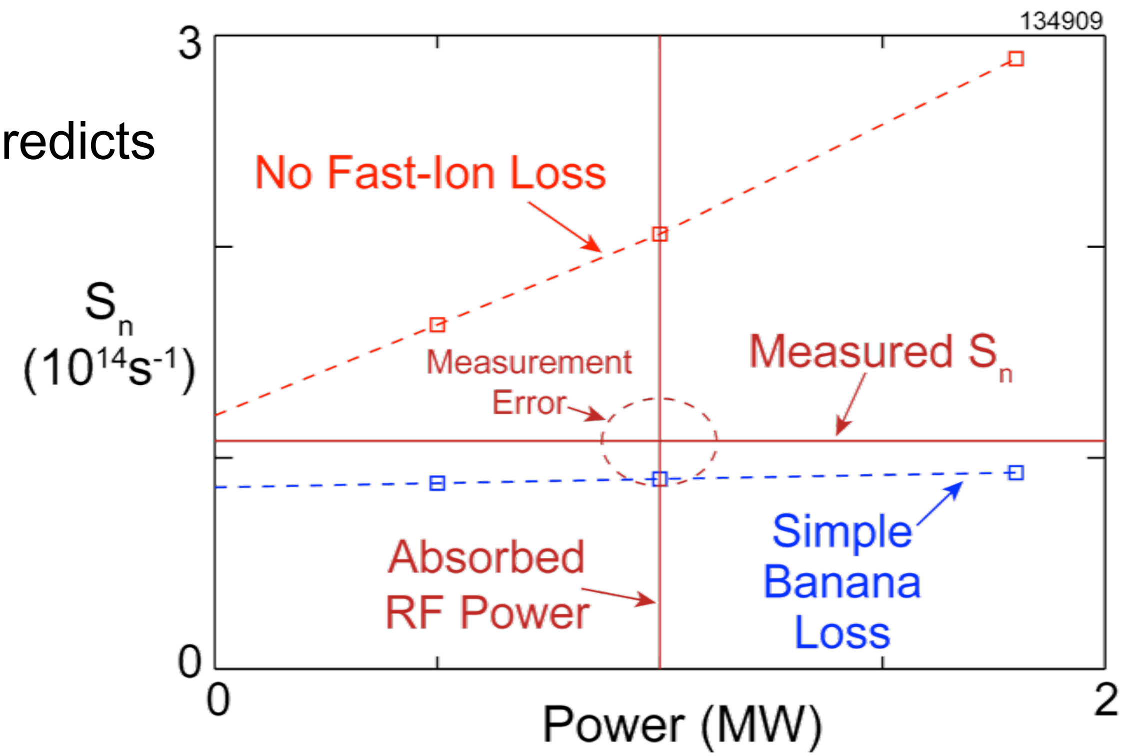
  – 0.3 MW ➡ ions



CQL3D code predicts significant fast-ion losses in I_p = 900 kA ELM-free HHFW+NBI H-modes

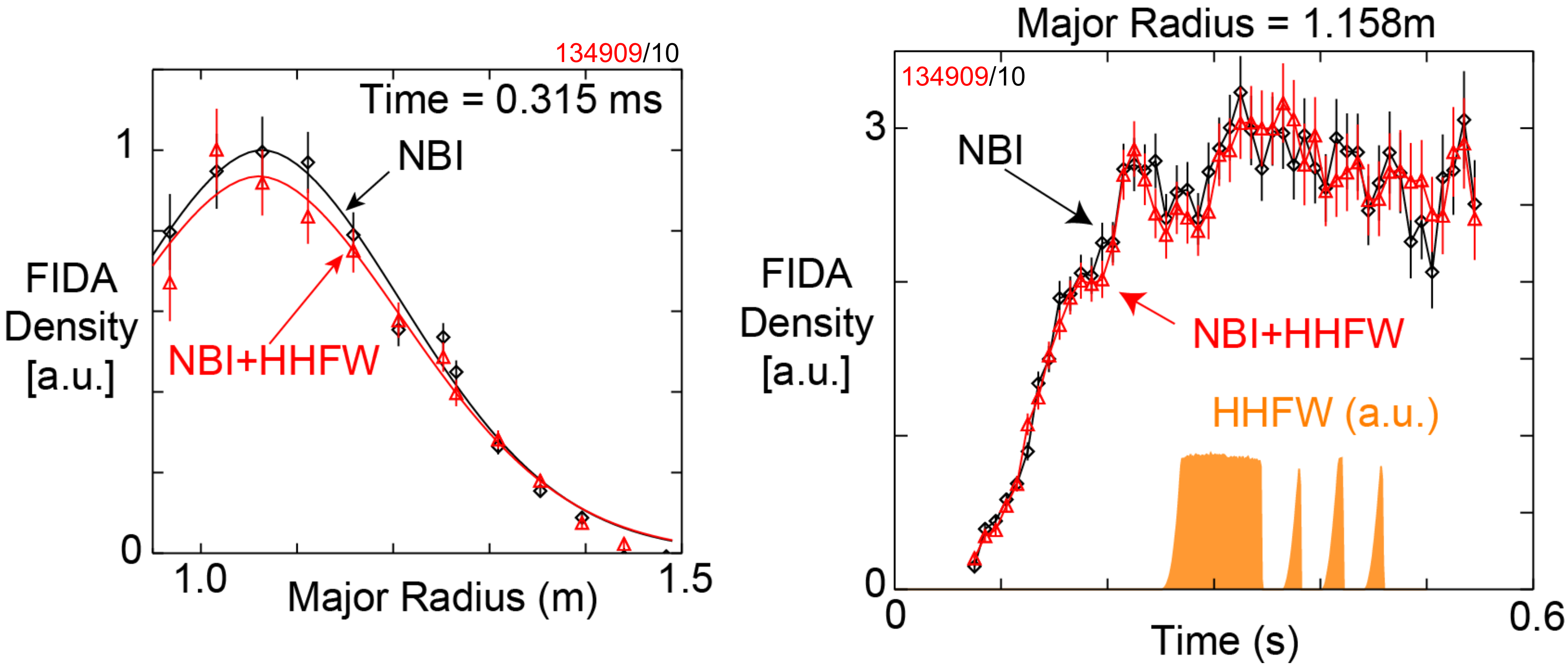
- Without fast-ion loss CQL3D predicts much higher neutron production rate (S_n) than is measured

- Simple-banana-loss model predicts S_n just below measured S_n :
  - Assumes prompt loss of fast-ions with a gyro radius + banana width > distance to LCFS
  - 60% RF power to fast-ions is promptly lost



- f_{NI} ~ 0.3 ($I_{Bootstrap}$ = 180 kA, [I_{RFCD}+I_{NBICD}] = 60 kA)

Fast-ion diagnostic measures no change in fast-ion density during HHFW heating, consistent with CQL3D modeling



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Summary

- Positive feedback between ITB, high $T_e(0)$ and RFCD during I_p = 300 kA HHFW H-mode produced $T_e(0)$ = 3 keV and f_{NI} ~ 0.65 using P_{RF} = 1.4 MW
  - To achieve $f_{NI} \geq 1$ at I_p~ 300kA will require P_{RF} ~ 3 MW, well below minimum arc-free P_{RF} available in 2009

- $T_e(0)$ and f_{NI} in I_p = 300 kA NBI+HHFW H-mode significantly lower than for I_p = 300 kA HHFW H-mode due to fast-ions interacting with antenna

- Modeling results for I_p = 900 kA ELM-free H-modes are consistent with broad T_e profile increase and enhanced fast-ion loss during HHFW:
  - ~ 40% of P_{RF} directly heats bulk electrons
  - ~ 15% of P_{RF} accelerates fast-ions, that are mostly promptly lost
  - ~ 45% of P_{RF} goes to edge losses (surface waves, parametric decay etc.)

Plans for 2011-12 HHFW Research

HHFW Experiments:

- HHFW coupling at low I_p & during I_p ramp-up
  - HHFW heating of low I_p plasma
  - Couple HHFW into CHI-initiated plasma
  - HHFW-assisted I_p ramp-up of an inductively generated discharge to 400kA
- HHFW+NBI high I_p H-modes at P_{nbi} up to 6 MW:
  - Interaction of fast-ions with antenna and antenna heating
  - Study surface waves at maximum available P_{rf} & P_{nbi}
  - Dependence of heating and CD efficiency on $k_{||}$, outer gap, n_{edge}

HHFW Modeling:

- Complete full finite-orbit-width CQL3D (late 2011)
- Benchmark core HHFW CD in HHFW+NBI H-mode against advanced RF codes upgraded to include interactions with fast-ions

New & Upgraded Diagnostics will Aid HHFW Research in 2011-12:

- MSE-LiF will provide q(r) without NBI heating
- Additional Thomson scattering channels will improve RF modeling
- Tangential FIDA will improve the study of RF fast-ion interaction