HHFW Heating and Current Drive Studies of NSTX H-Mode Plasmas*

Gary Taylor[1]

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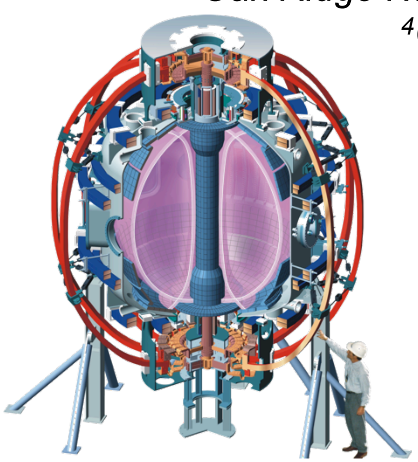

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Outline

- Introduction to HHFW Heating on NSTX

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- HHFW-Generated H-Mode Plasmas

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- HHFW Heating of NBI H-Mode Plasmas

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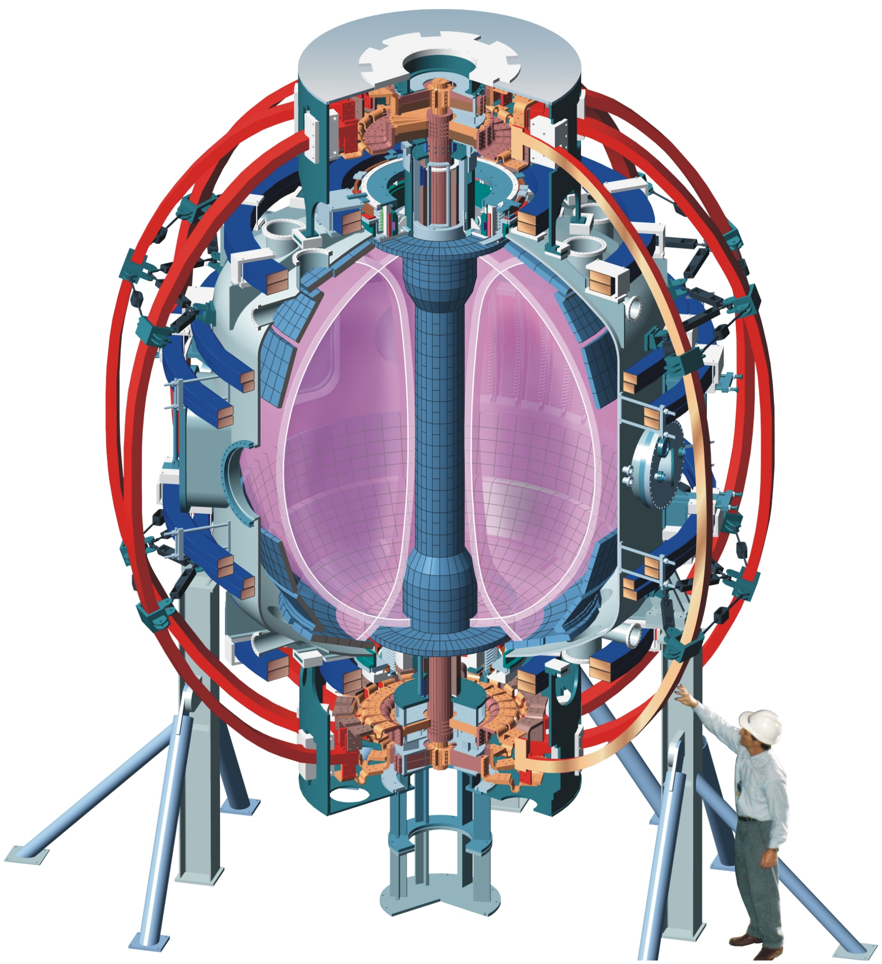
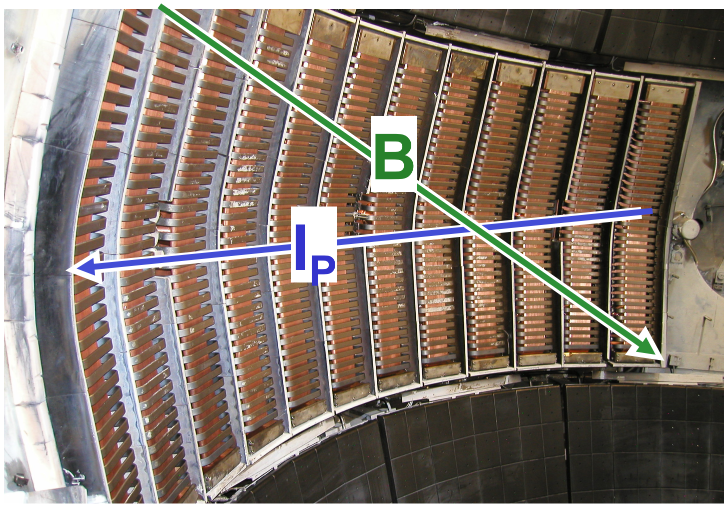
- Summary

NSTX is a high β, low aspect ratio, spherical torus with both 90 keV NBI and 30 MHz HHFW heating

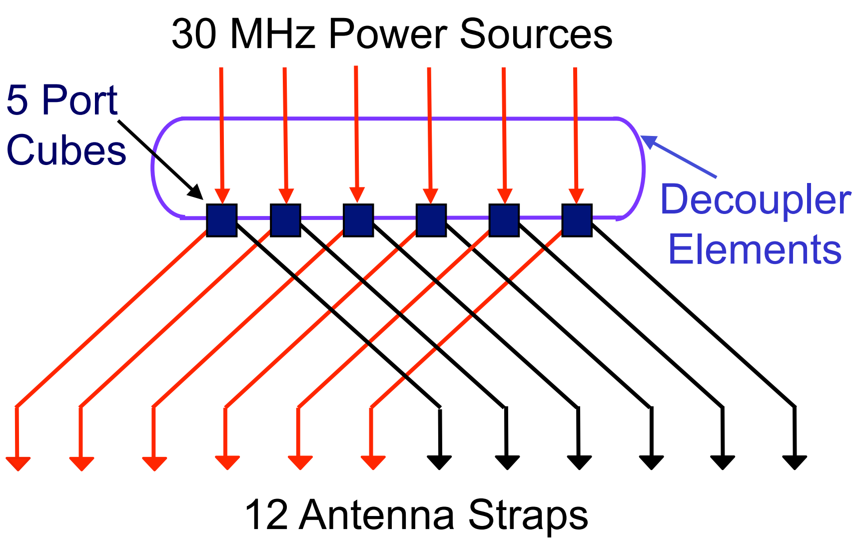


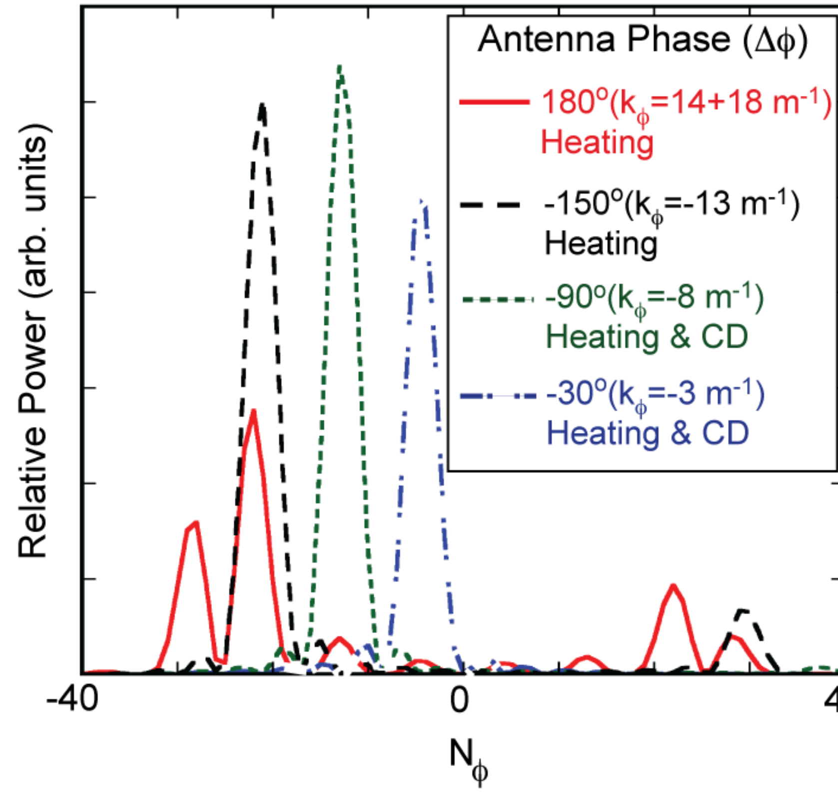
- $R = 0.86$ m
- $A > 1.27$
- $I_p < 1.5$ MA
- $B_t(0) = 0.55$ T
- $\beta_t \leq 40\%$, $\beta_N \leq 7$
- 90 keV D $P_{NBI} \leq 6$ MW
- 30 MHz $P_{RF} \leq 6$ MW
  - Many fast wave ion resonances: 7-11 Ω_D
  - Strong single pass direct absorption on electrons

Well defined antenna spectrum, ideal for studying phase dependence of heating & current drive (CD)



12-strap antenna extends toroidally 90°

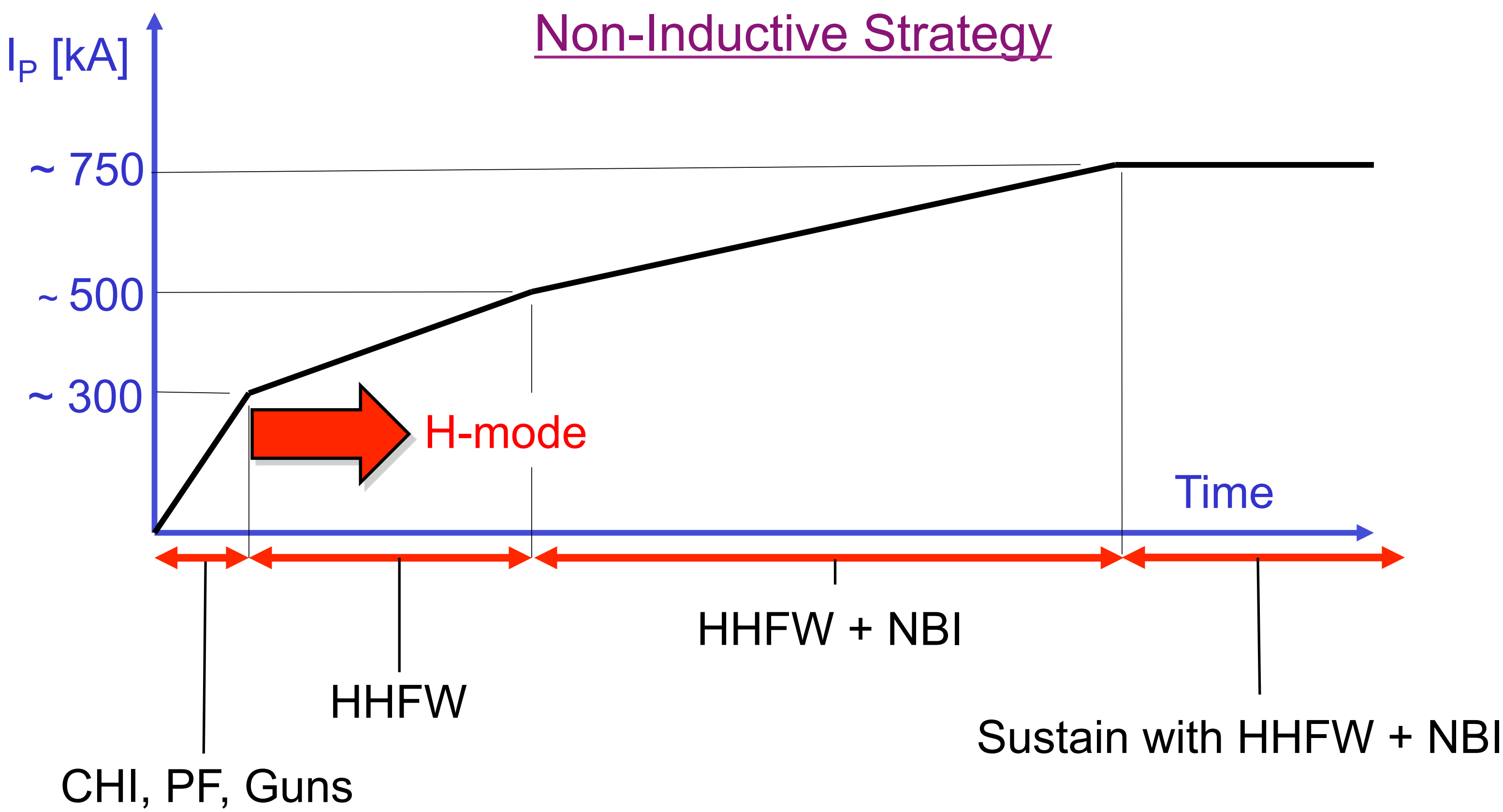




- Upgraded from single to double feed straps, with center grounds, in 2009 to reduce electric fields near Faraday shield ~ 1.5 x for same strap currents

P. M. Ryan, et al., Poster A32

HHFW heating and CD are being developed for non-inductive ramp-up and bulk electron heating



- 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 direct RFCD during early HHFW H-mode
  - Provide bulk electron heating during I_p flat top, during NBI H-Mode

NSTX HHFW research in 2008-10 focused on studying both HHFW-Generated H-Modes & HHFW-Heated NBI H-modes

- Near-term approach to assess HHFW heating during I_p ramp-up has been to heat low I_p ohmic (~ 300 kA) plasmas to access 100% non-inductive CD

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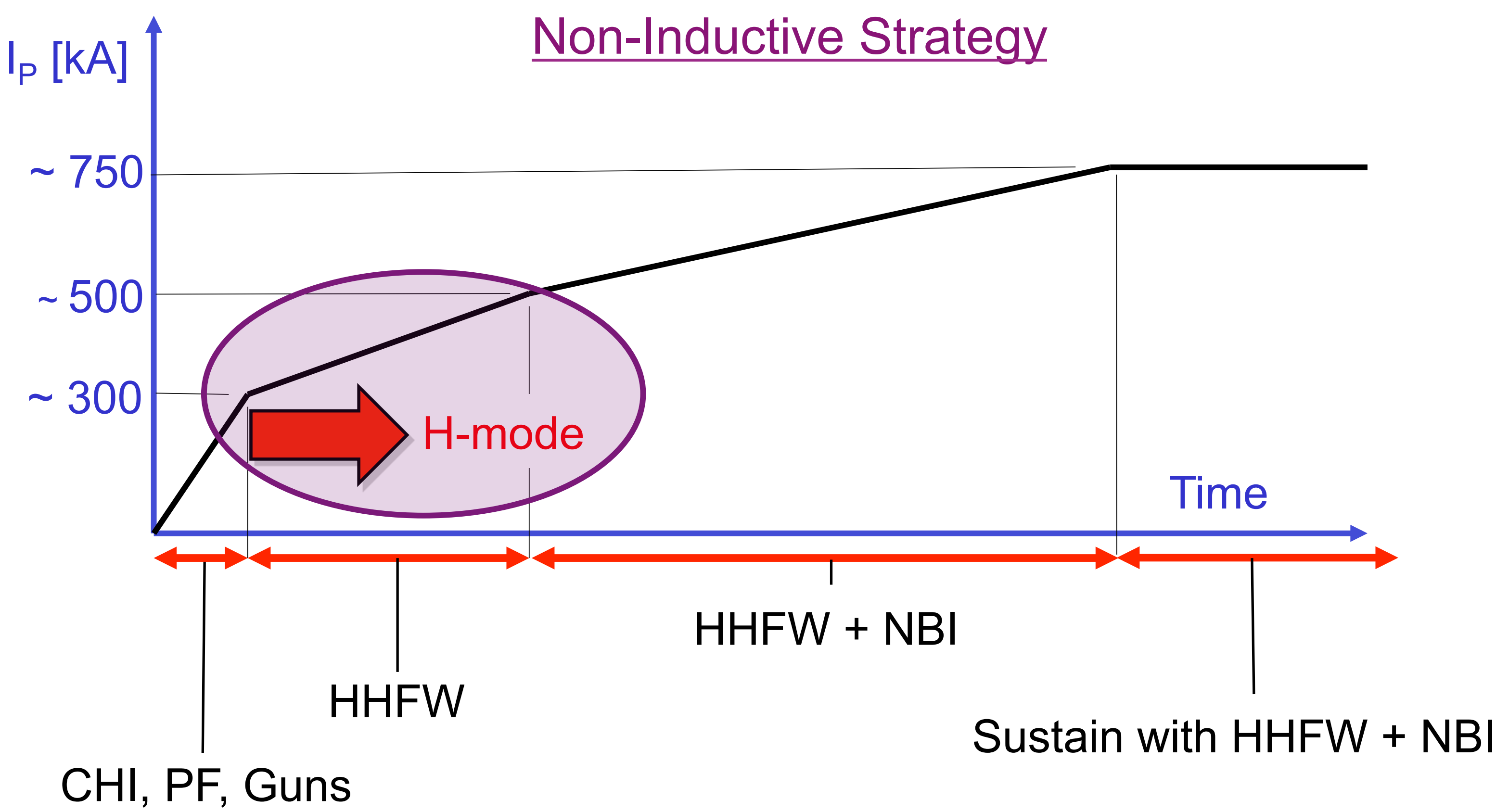
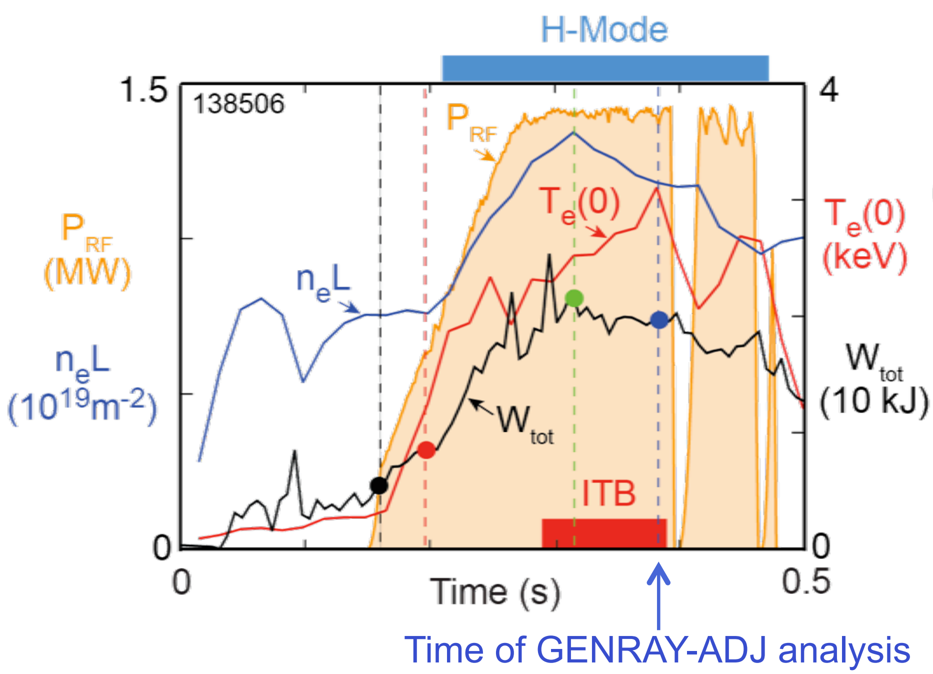
  - However HHFW acceleration of NBI fast-ions produced enhanced fast-ion losses during HHFW heating
  - Conducted extensive studies of HHFW heating and edge power loss mechanisms during both ELMing and ELM-free H-modes

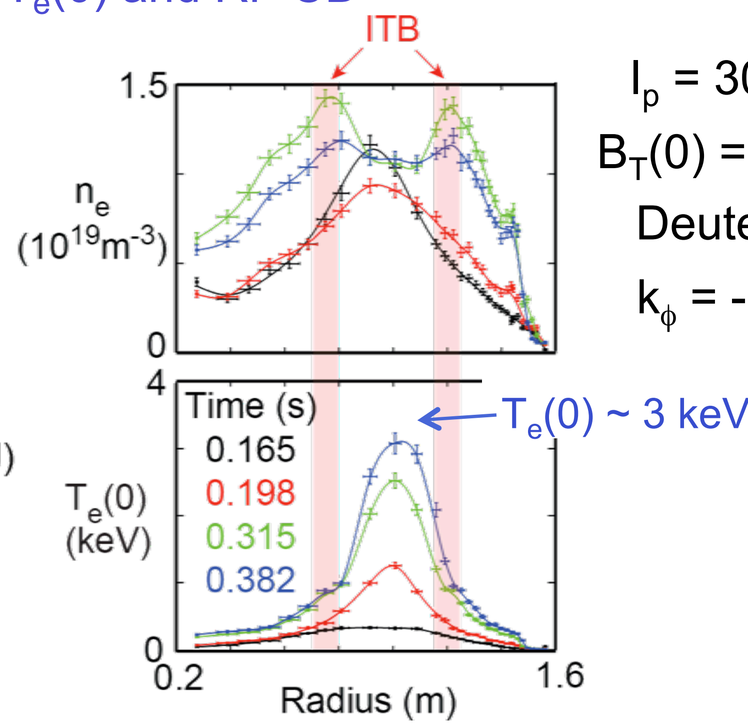
HHFW-Generated H-Mode Plasmas



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

- In 2005 could not maintain RF coupling during I_p = 250 kA HHFW H-mode due to poor plasma position control at L-H transitions
- Reduced plasma control system latency made possible sustained I_p = 300 kA HHFW-generated H-mode in 2010:
  - $T_e(0)$ ~ 3 keV achieved with only P_{RF} = 1.4 MW
  - ITB formed during H-mode
  - Positive feedback between ITB, high $T_e(0)$ and RF CD





I_p = 300 kA

$B_T(0)$ = 0.55 T

Deuterium

k_ϕ = - 8 m^{-1}

GENRAY-ADJ predicts peaked RF deposition on electrons and RF CD efficiency ξ_{CD} ~ 115 kA/MW

Shot 138506

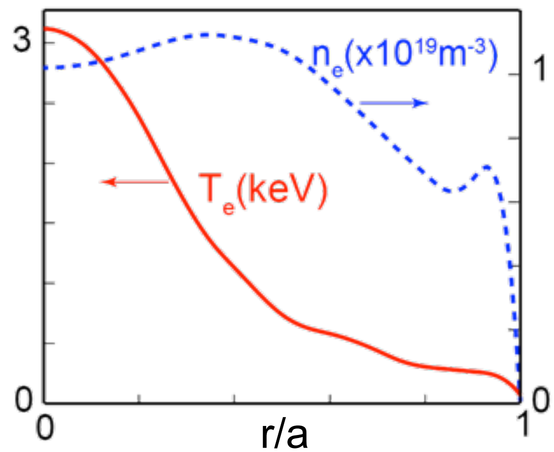
Time = 0.382 s

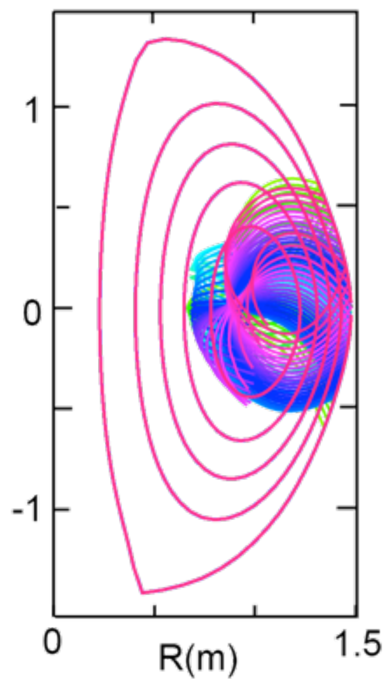
I_P = 300 kA

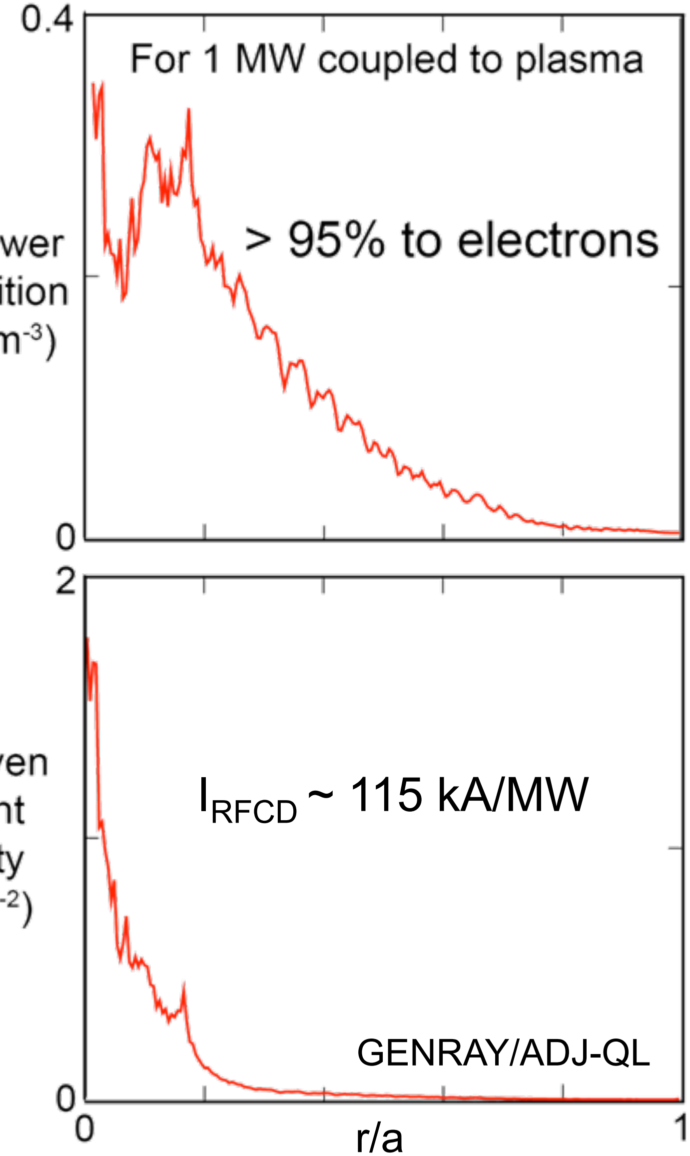
B_T = 5.5 kG

Deuterium

RF H-mode

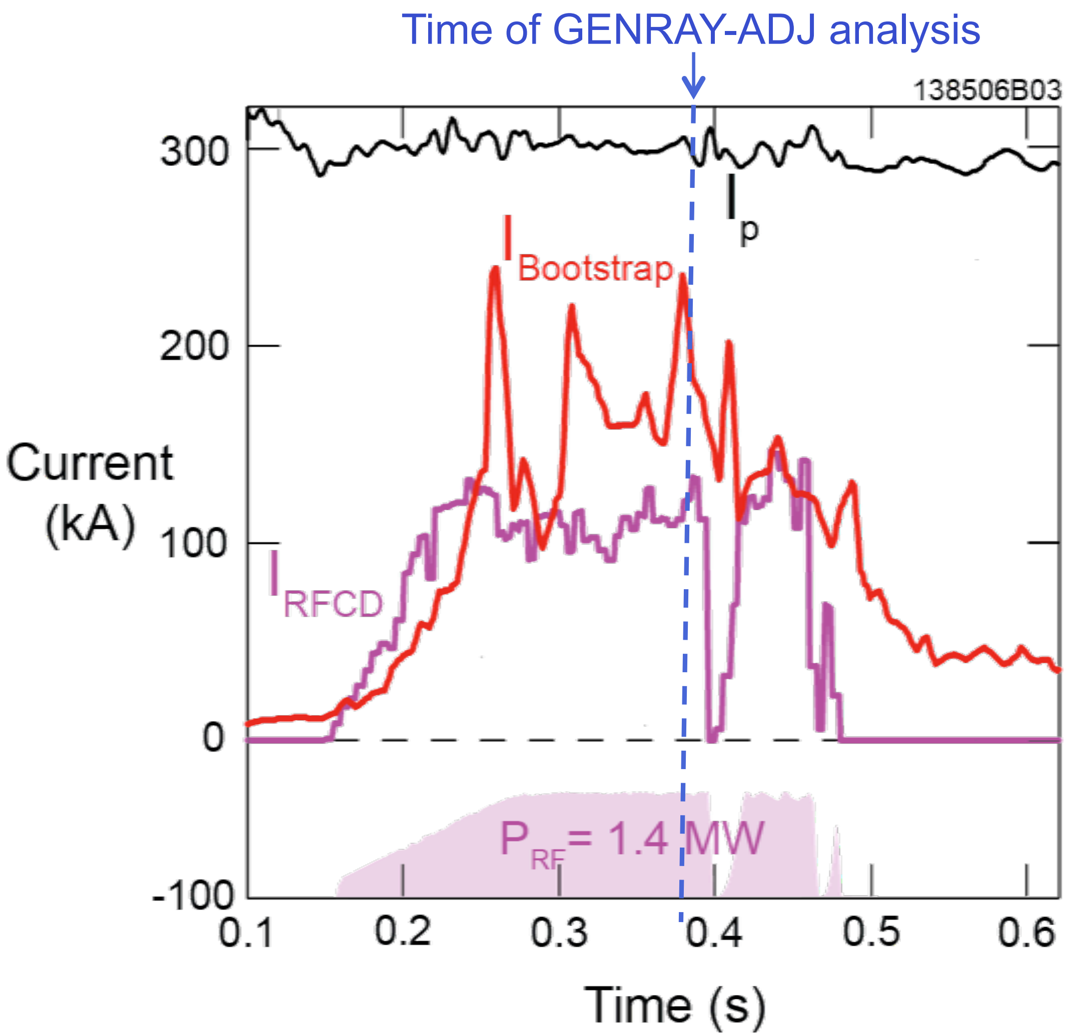






TRANSP-TORIC simulation, assuming 100% RF coupling (η_{eff} = 100%), predicts $I_{Bootstrap}$ = 220 kA and I_{RF} = 120 kA

<u>TORIC-TRANSP modeling for η_{eff} = 100%</u>



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

  ΔW_T ~ 15 kJ

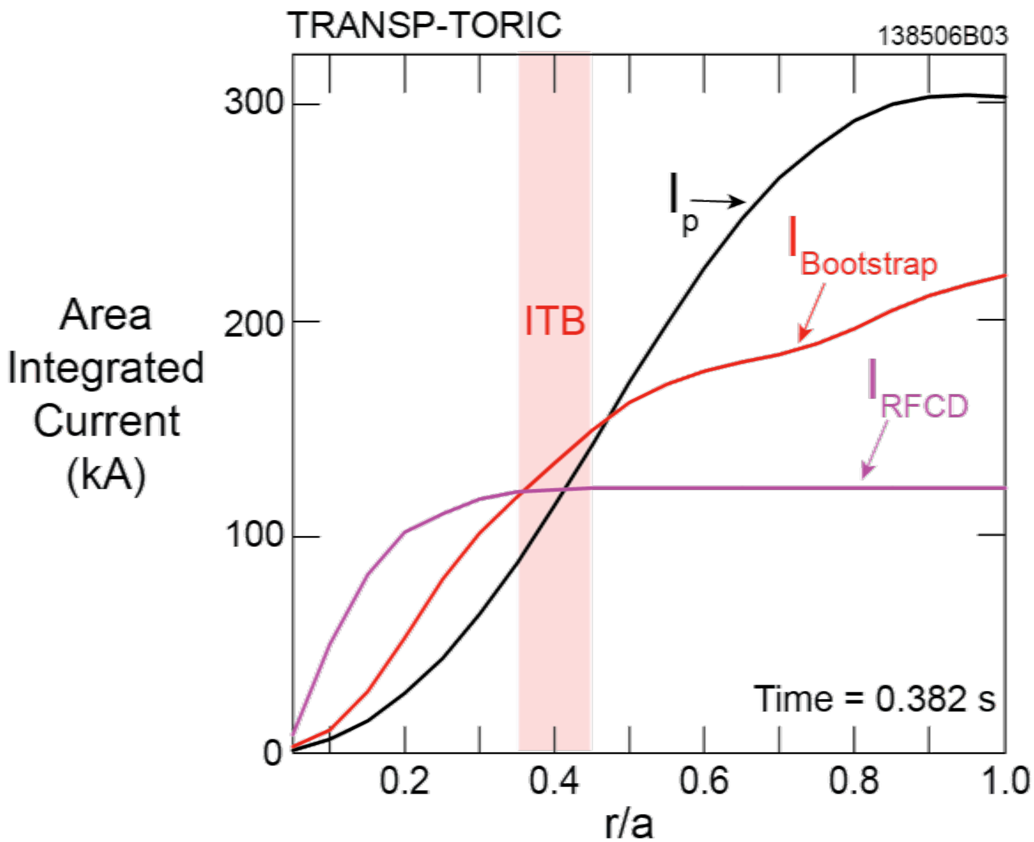
  τ ~ 15 ms

  P_{RF} ~ 1.4 MW

→ η_{eff} ~ 60%

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

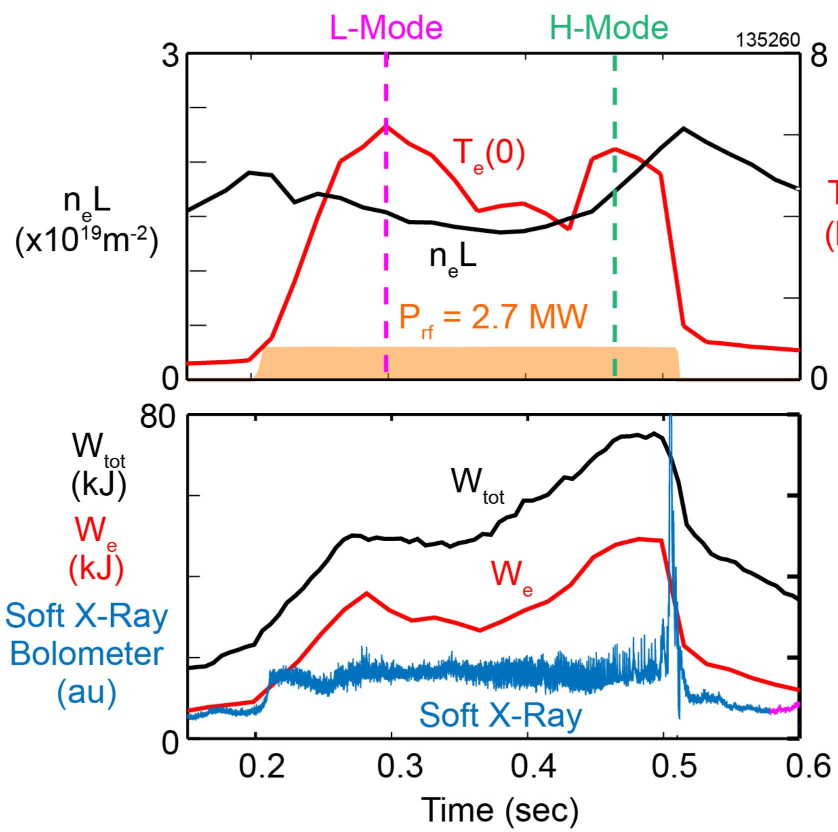
TORIC-TRANSP modeling for η_{eff} = 100%

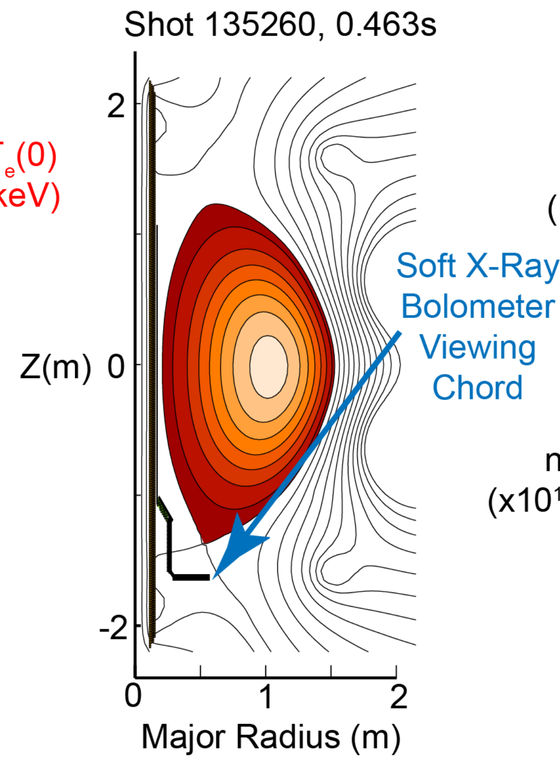


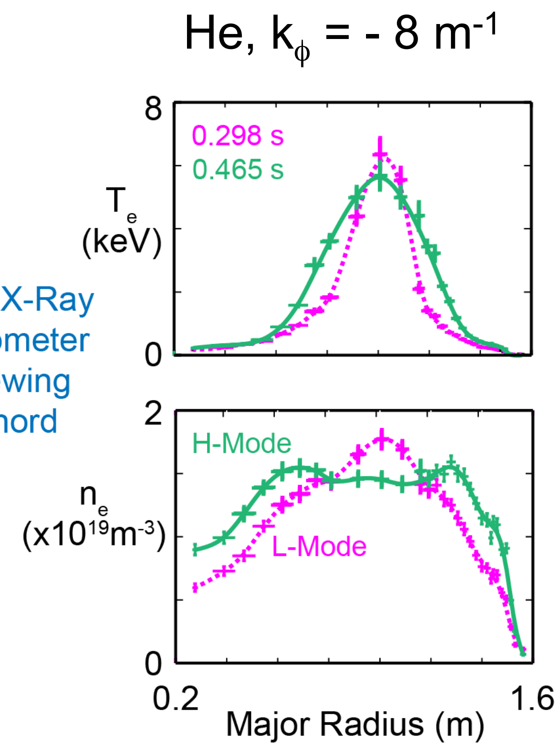
For η_{eff} = 60%

I_{BS}	130 kA
I_{RF}	70 kA
f_{NI}	0.65

Improved antenna conditioning produced ELM-free-like HHFW H-modes at I_p = 650 kA with $P_{RF} \geq 2.5$ MW





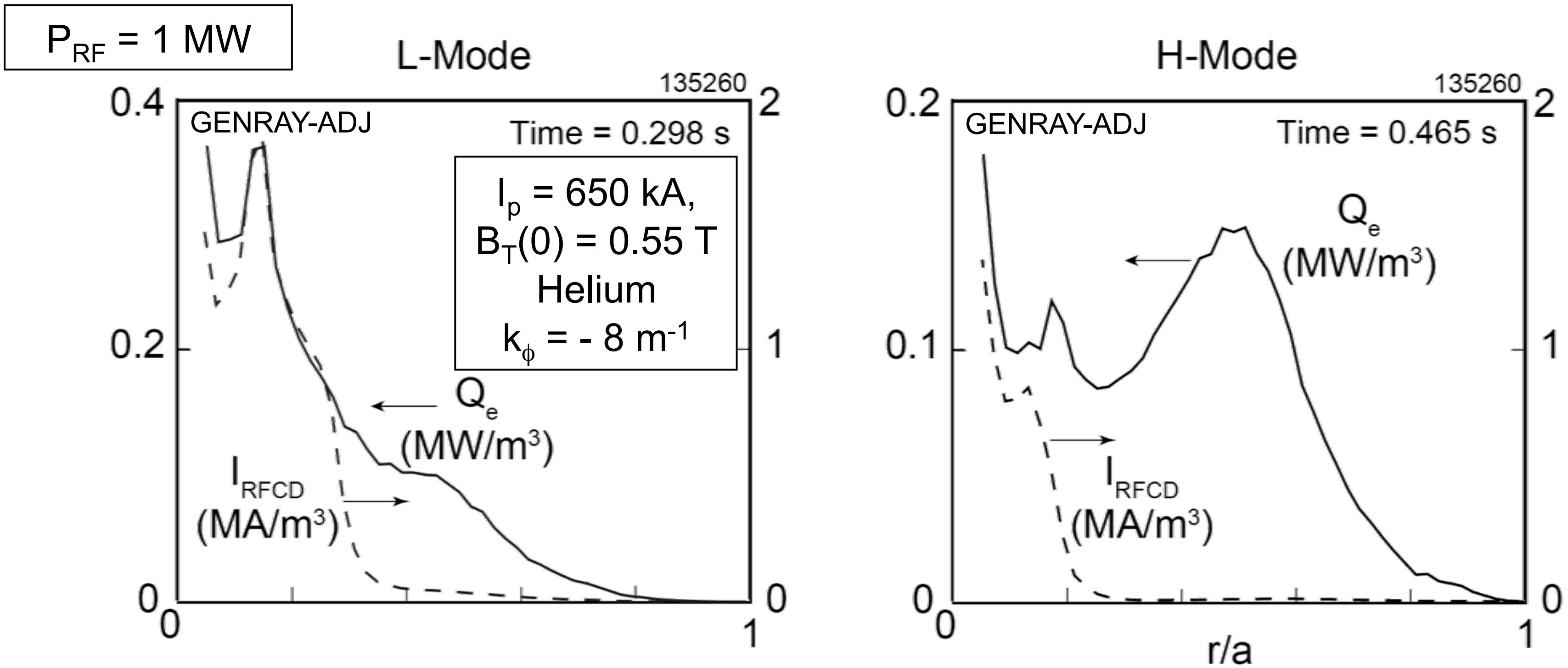


I_p = 650 kA,

$B_T(0)$ = 0.55 T

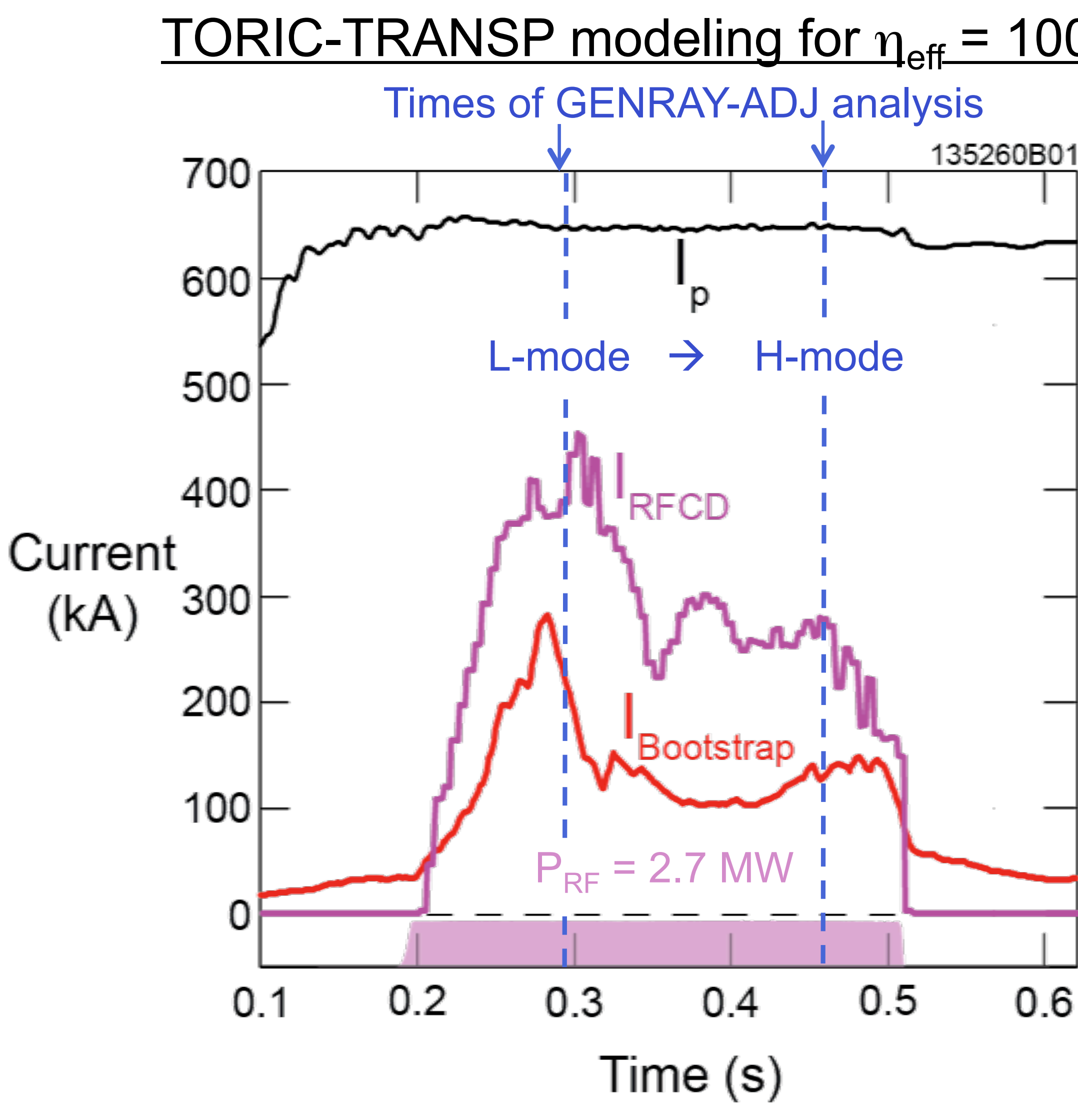
- Substantial increase in stored energy during H-mode
- Stored energy increase is accompanied by edge oscillations and small ELMs
- Sustained $T_e(0)$ = 5 - 6 keV

Very broad RF electron power deposition profile (Q_e) in H-mode; off-axis trapping significantly reduces ξ_D



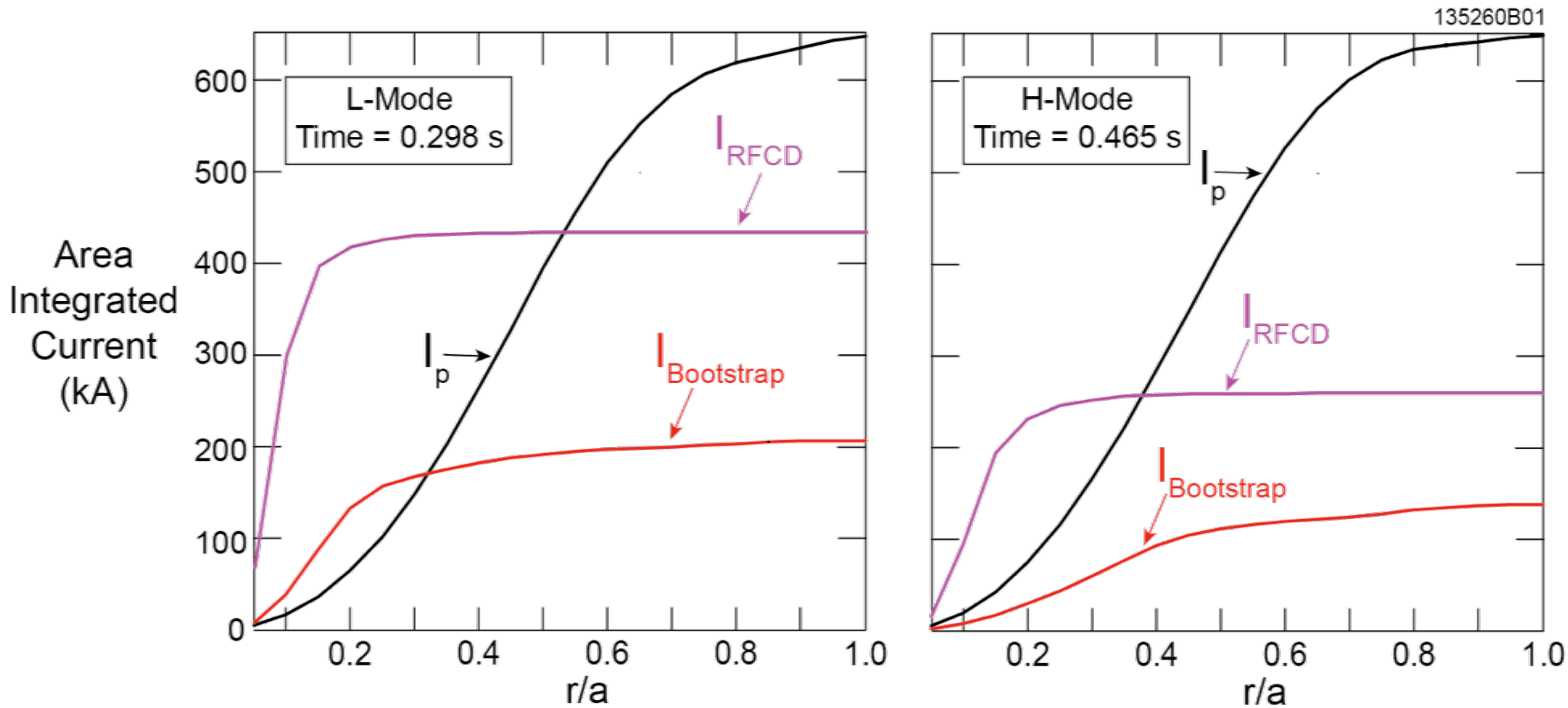
- RF power coupled to plasma directly heats electrons, no ion heating
- ξ_{CD}~ 220 kA/MW in L-Mode, ξ_{CD}~ 130 kA/MW in H-Mode

I_{RFCD} and $I_{Bootstrap}$ decline as the plasma slowly transitions from L-Mode to H-Mode



f_{NI} decreases from ~ 0.5 in L-mode to ~ 0.35 in H-mode as $P_e(R)$ broadens & RF deposition moves more off-axis

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

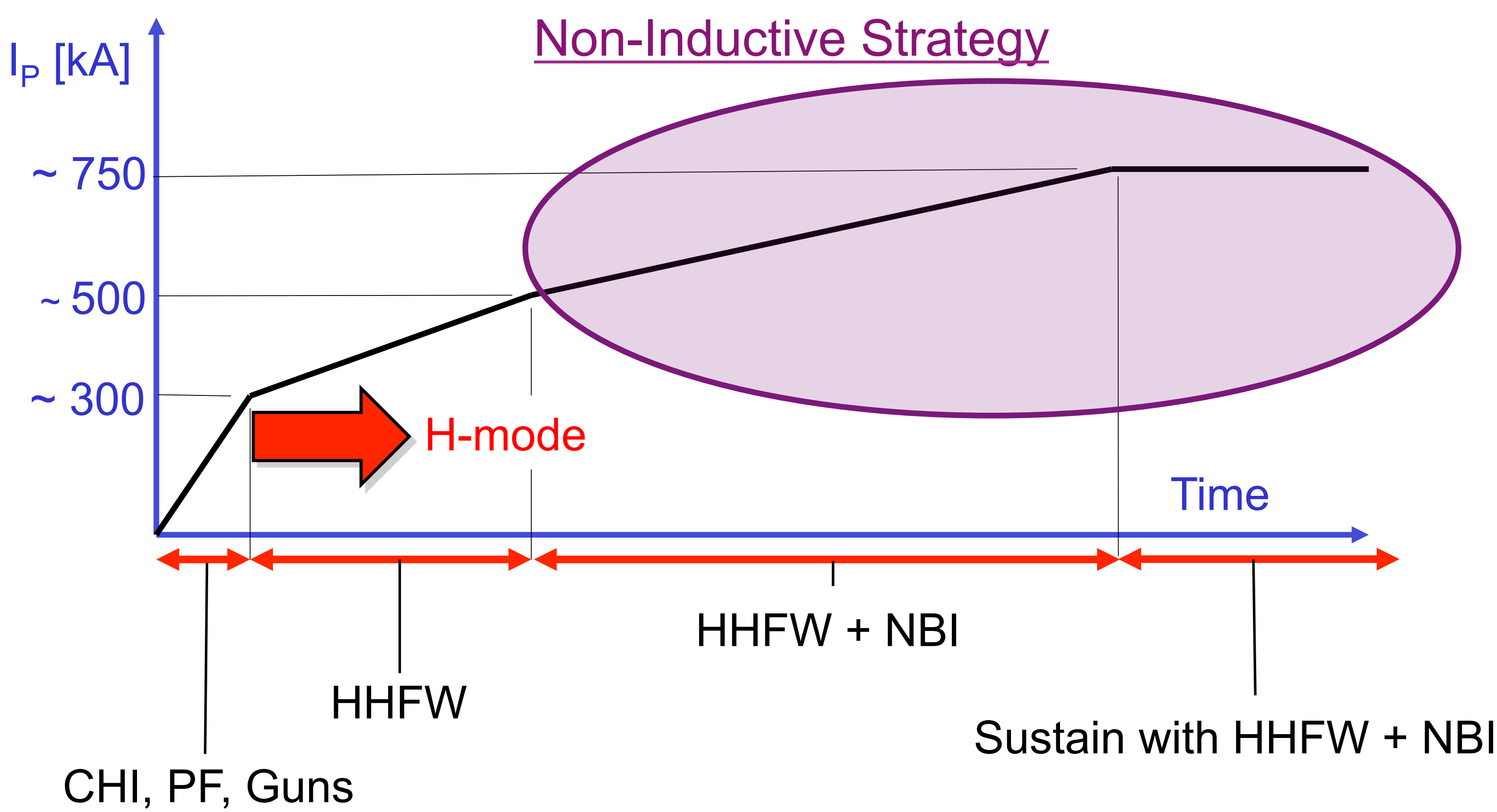


ΔW_T ~ 25 kJ, τ ~ 17 ms → η_{eff} ~ 55%

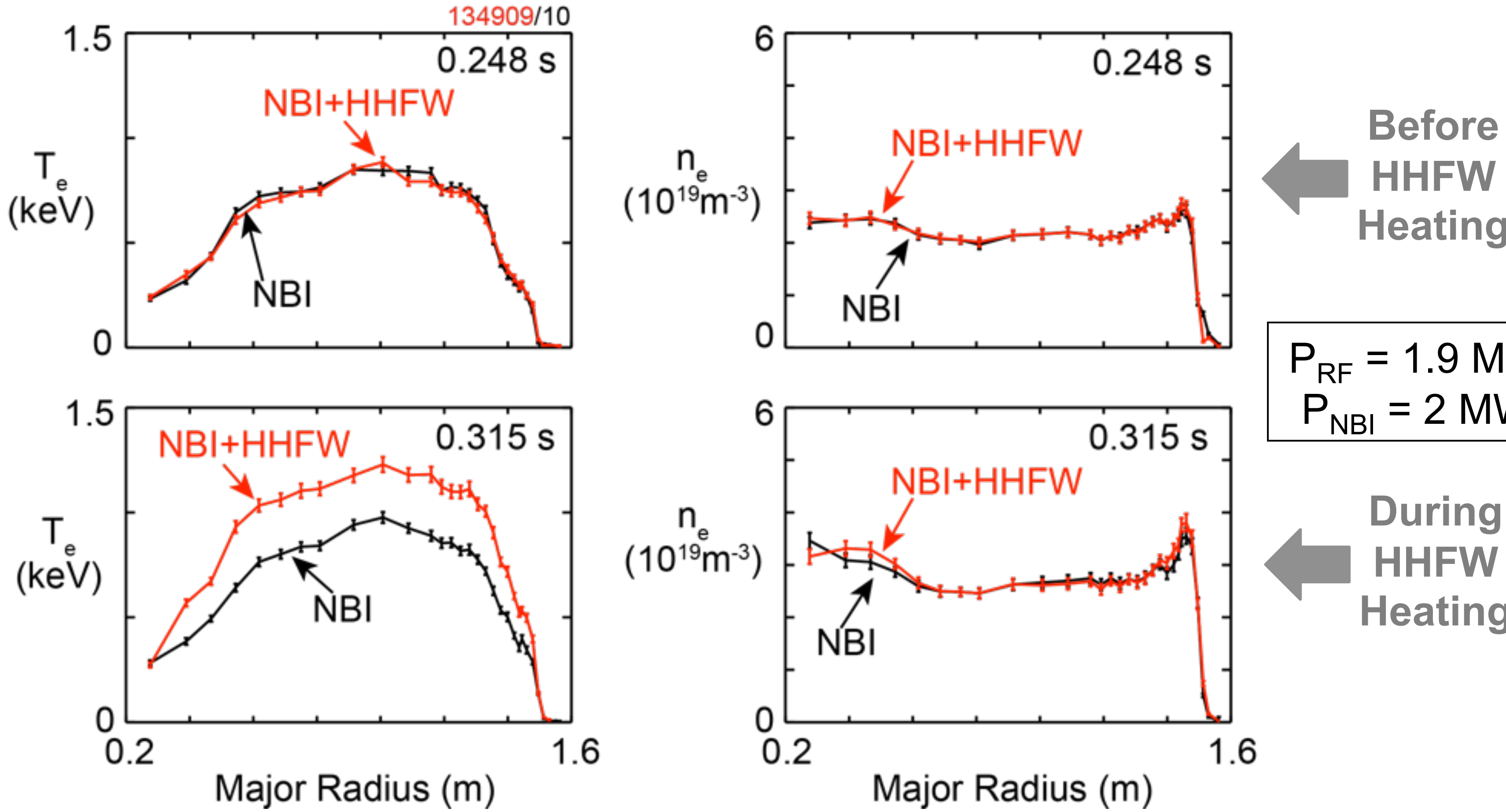
For η_{eff} = 55%→

	L-Mode	H-Mode
$I_{Bootstrap}$	110 kA	80 kA
I_{RFCD}	230 kA	140 kA
f_{NI}	0.5	0.35

HHFW Heating of NBI H-Mode Plasmas



Broad T_e profile increase when k_ϕ = -13 m^{-1} HHFW heats I_p = 900 kA, $B_T(0)$ = 0.55 T, Deuterium NBI H-mode plasma



P_{RF} = 1.9 MW
P_{NBI} = 2 MW

- Identical T_e and n_e H-mode profiles before HHFW power onset
- During HHFW heating, n_e profile remains unchanged and plasma stays in H-mode

TRANSP-TORIC analysis predicts η_{eff} ~ 50% for I_p = 900 kA ELM-free NBI H-mode plasma

- η_{eff} obtained from W_e calculated by TRANSP-TORIC:

  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

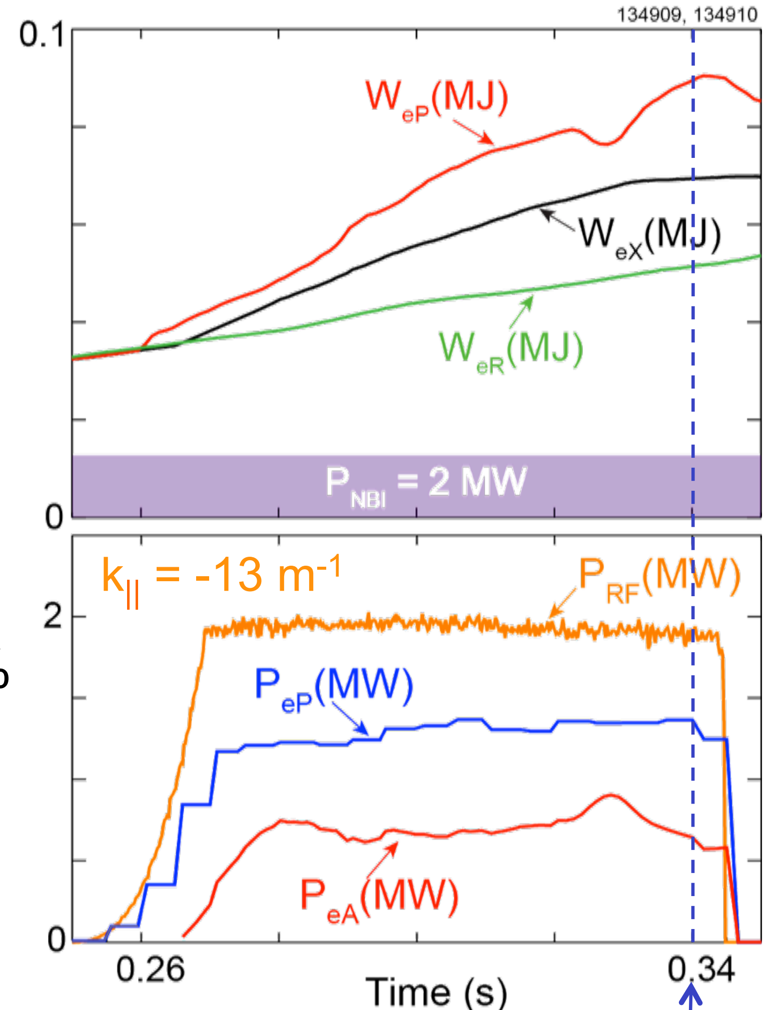
- $\eta_{eff} = (W_{eX}-W_{eR})/(W_{eP}-W_{eR}) = 0.53 \pm 0.07$
- If P_{eP} is the power absorbed by electrons calculated by TORIC assuming η_{eff} = 100%
- Electron RF absorption, $P_{eA} = \eta_{eff} \times P_{eP}$

  For P_{RF} = 1.9 MW:

  – 0.7 MW ➡ electrons

  – 0.3 MW ➡ fast-ions

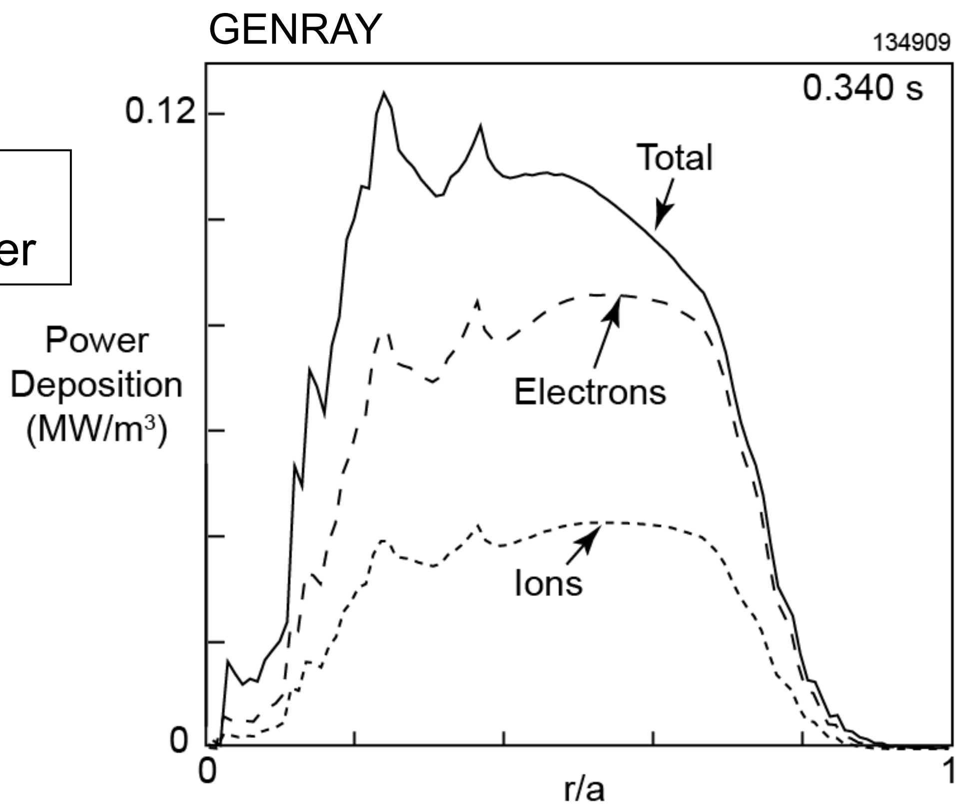
- f_{NI} ~ 0.3 ($I_{Bootstrap}$ = 180 kA, [I_{RFCD}+I_{NBICD}] = 60 kA)



Time of TRANSP-TORIC, GENRAY & CQL3D analysis

GENRAY ray tracing analysis predicts broad deposition, with very little RF power reaching magnetic axis

For 1 MW of Coupled RF Power



Deuterium

k_ϕ = - 13 m^{-1}

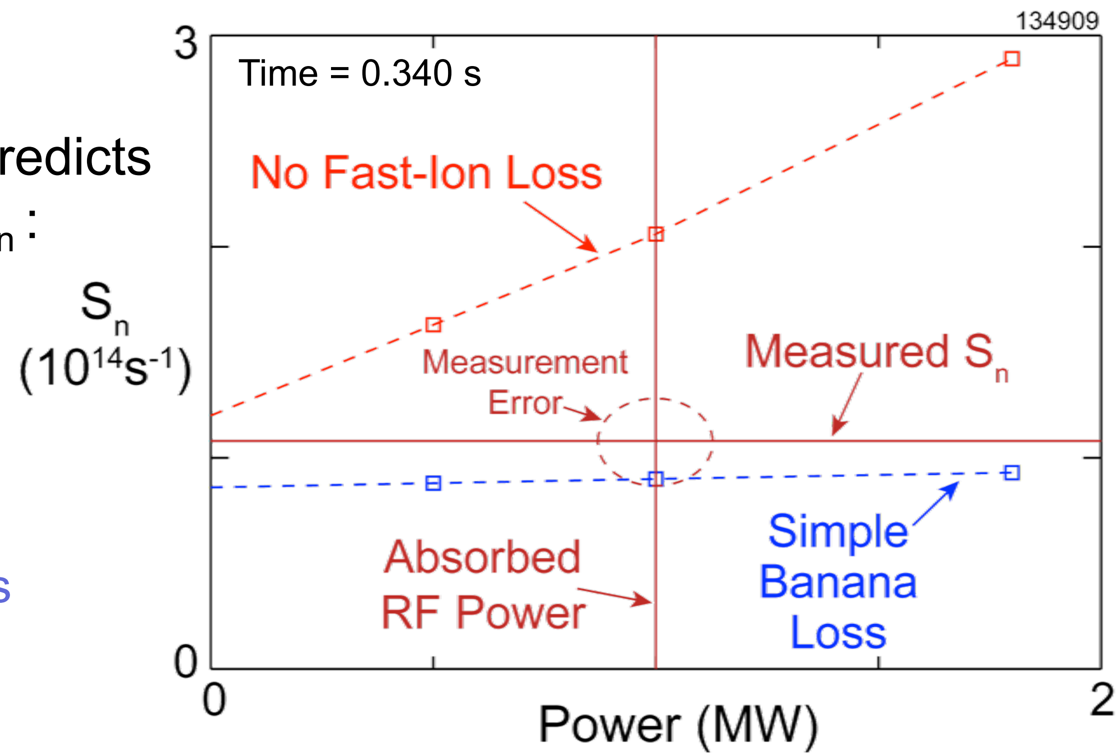
I_p = 900 kA

$B_T(0)$ = 0.55 T

- 75% of RF power directly heats electrons
- 25% of RF power accelerates NBI fast-ions off axis

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

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

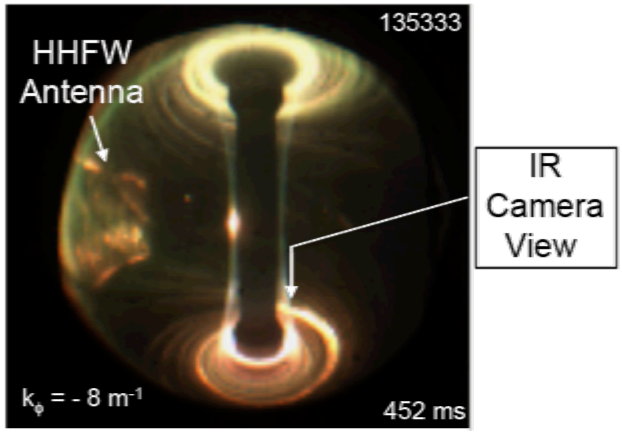


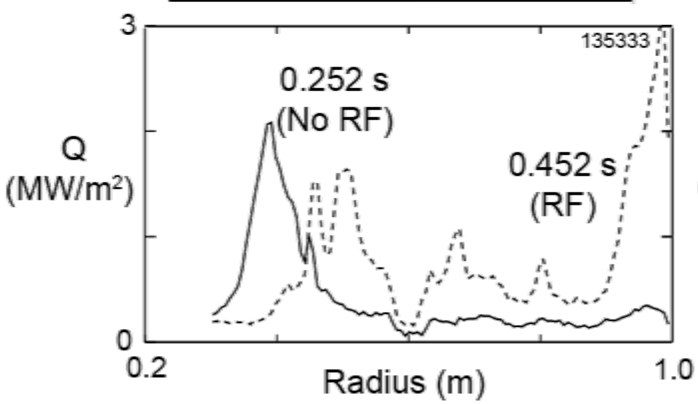
- Simple-banana-loss model predicts S_n ~ 20% below measured S_n :
  - Assumes prompt loss of fast-ions with a gyro radius + banana width > distance to LCFS
  - ~ 60% RF power to fast-ions is promptly lost
- Significant prompt fast-ion loss is due to RF wave-field acceleration occurring predominantly off-axis

HHFW+NBI H-modes can exhibit a significant RF power flow in the scrape-off layer (SOL) to the lower divertor

I_p = 0.8 MA
P_{RF} = 2.6 MW
k_ϕ = - 8 m^{-1}
P_{NBI} = 2 MW

$B_T(0)$ = 0.45 T





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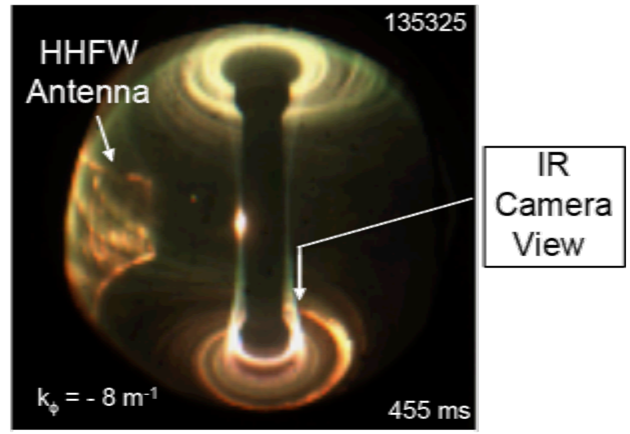
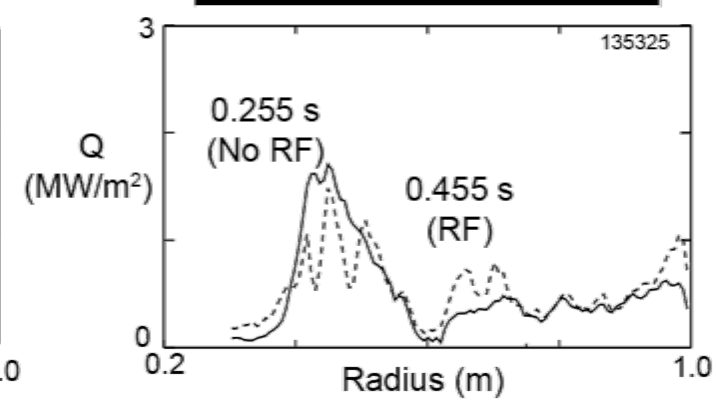
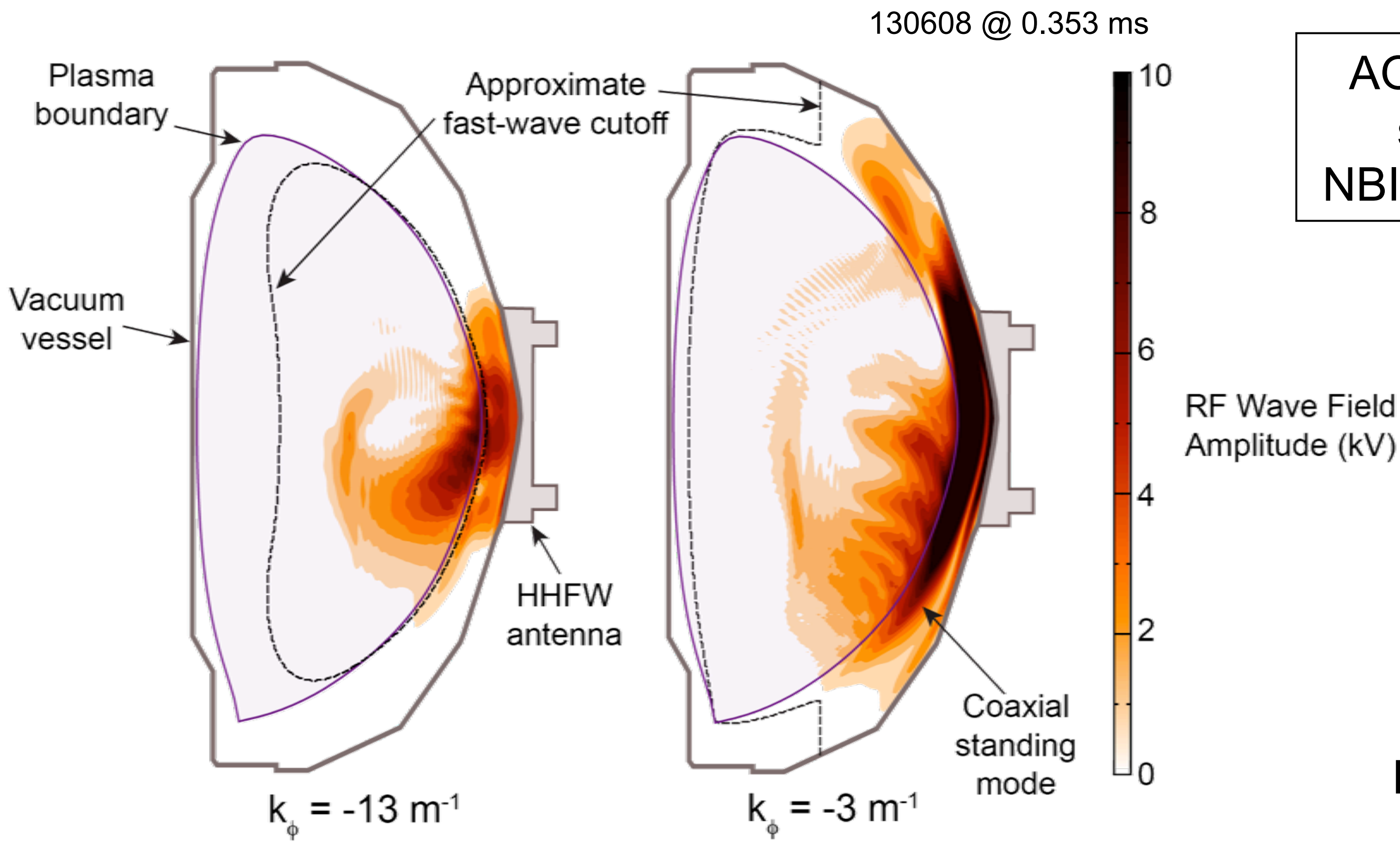




- RF power flow produces local hot region on divertor plate that moves with changes in the magnetic field pitch
- ELMs increase RF power flow to the divertor

J. C. Hosea, et al., Poster A33

AORSA simulations of NBI+HHFW H-modes predict large amplitude coaxial modes at long launch wavelengths



AORSA full wave simulation of NBI+HHFW H-mode

P_{RF}=1.9 MW

P_{NBI} = 2 MW

I_p = 1 MA

$B_T(0)$ = 0.55 T

- Large amplitude, non-propagating coaxial modes form in SOL can dissipate significant RF power if collisionally damped

D. L. Green, et al., Poster A36

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- Generated HHFW-only "ELM-free-like" H-modes that have rising W_{tot}, high $T_e(0)$, f_{NI} up to 0.65, and sometimes ITBs

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Backup Slides

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

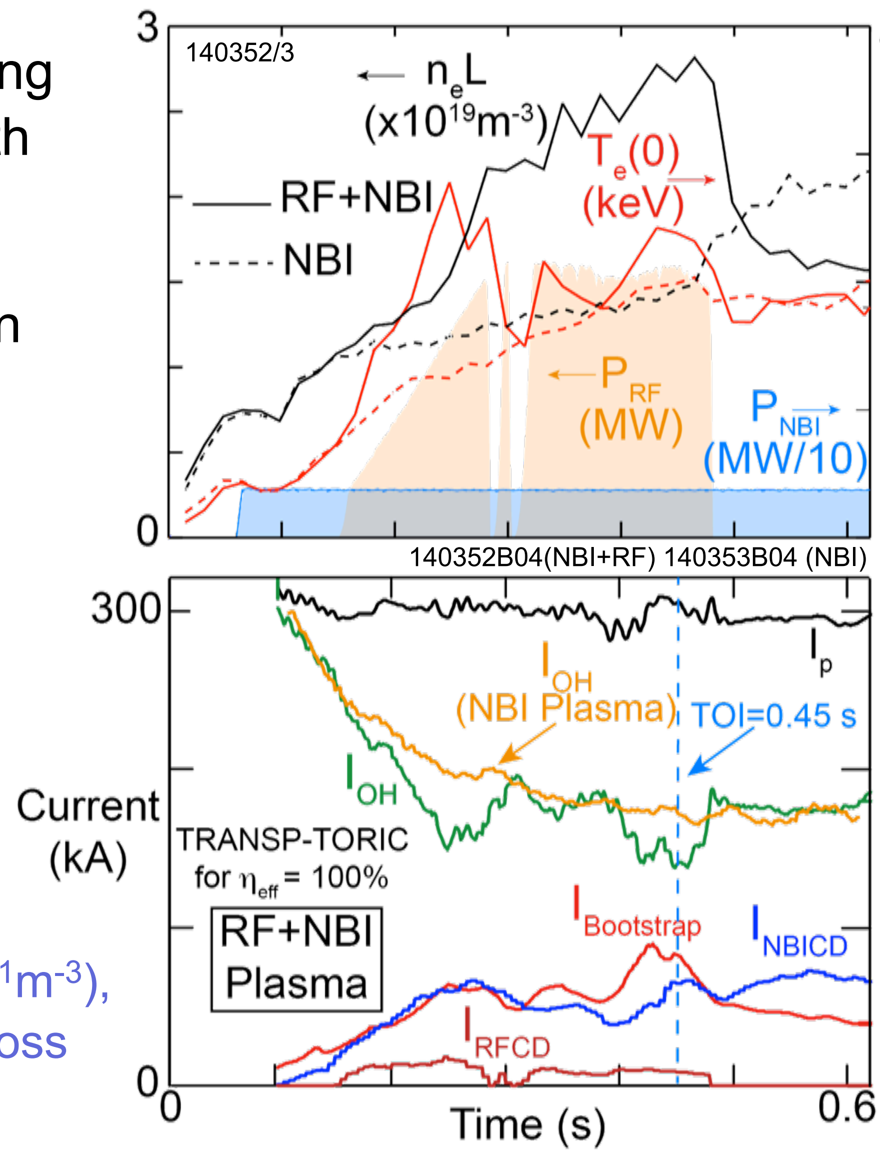
- Present implementation of TORIC in TRANSP can model HHFW deposition but cannot evolve the fast-ion energy distribution self consistently:
  - As a result, the neutron rate (S_n) calculated by TRANSP-TORIC reflects the beam-target reactions for the NBI fast-ions without HHFW acceleration

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

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

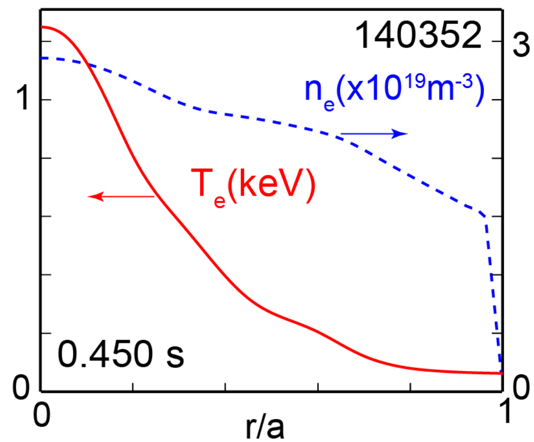
Time = 0.450 s

I_P = 300 kA

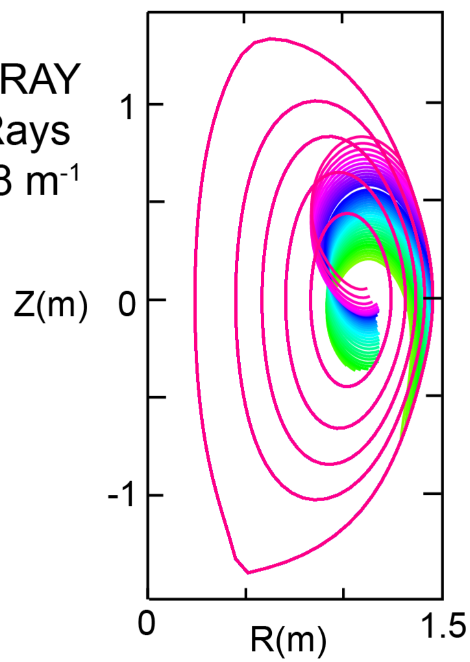
B_T = 0.55 T

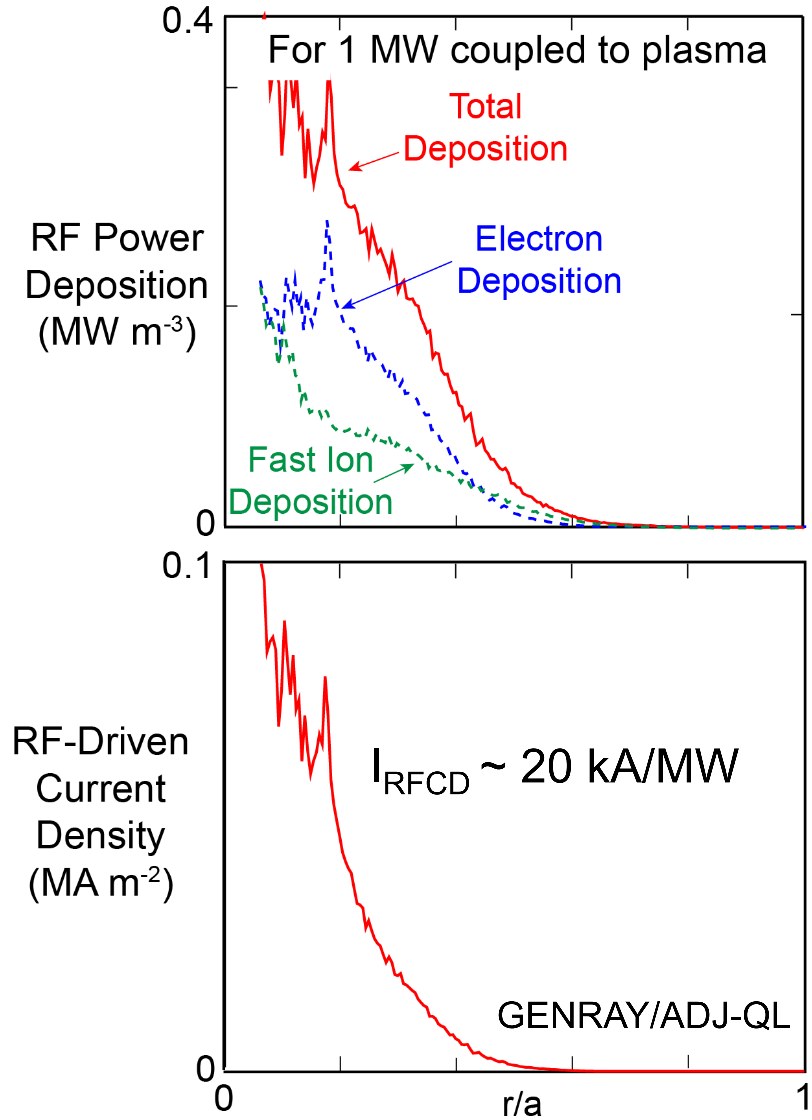
Deuterium

HHFW+NBI H-mode



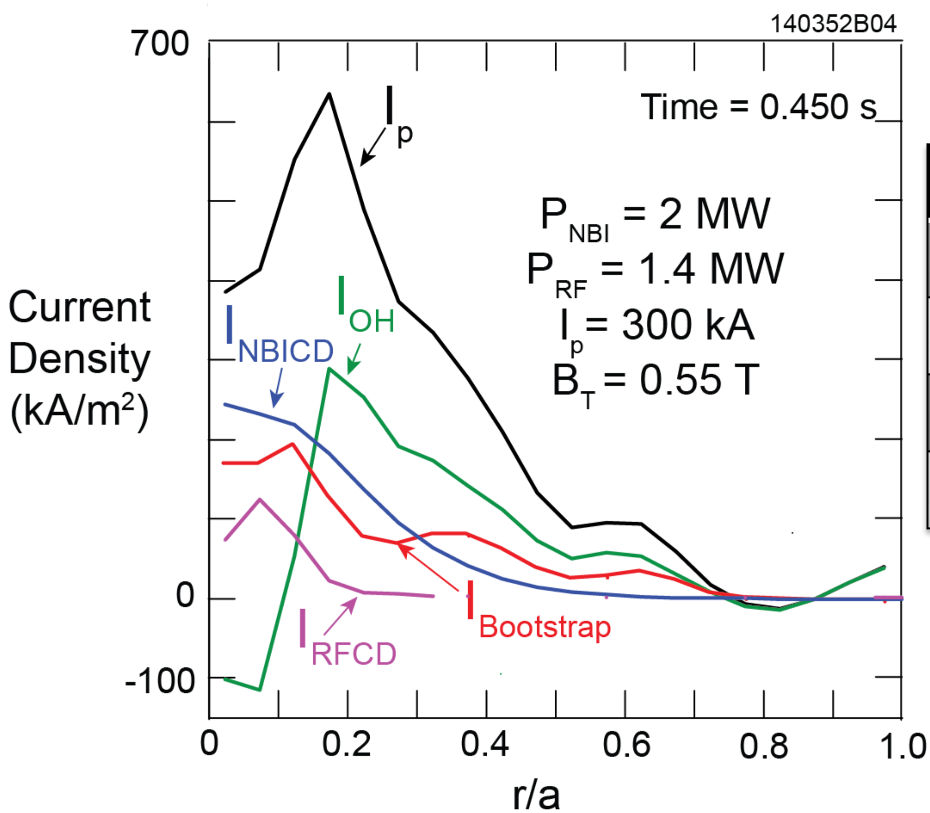
GENRAY
41 Rays
k_ϕ=-8 m^{-1}





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

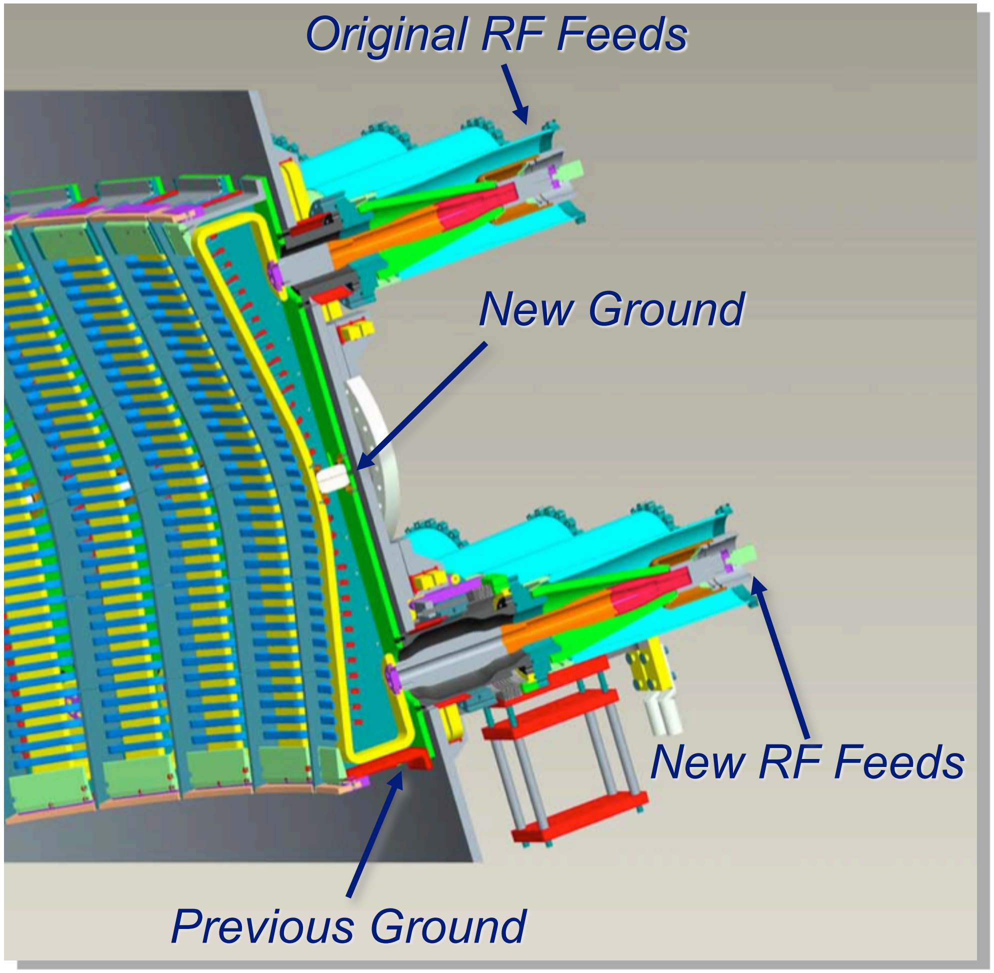
TORIC-TRANSP modeling for η_{eff} = 100%:



For η_{eff} = 40%

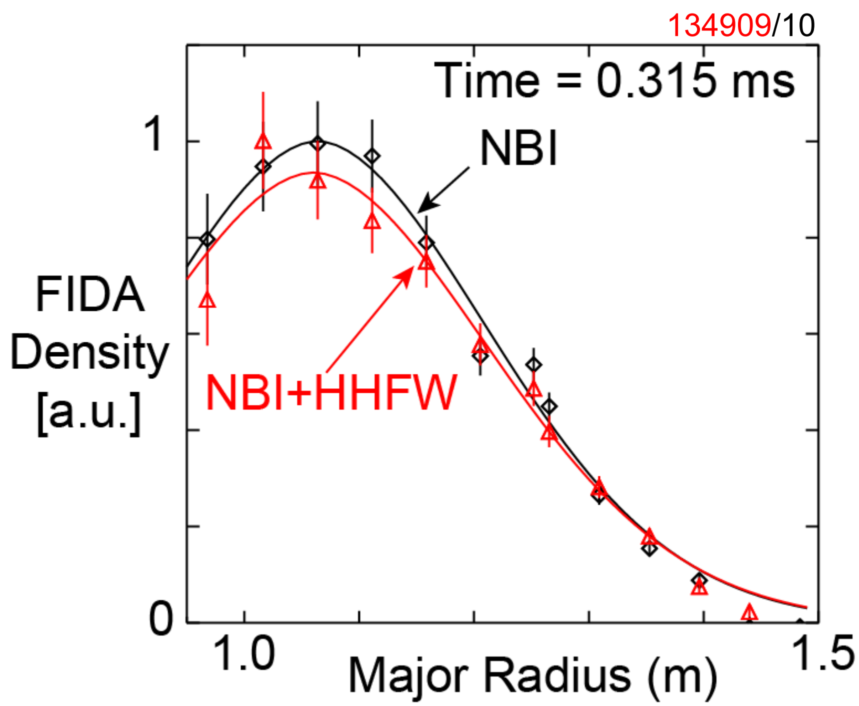
	HHFW+NBI	NBI
I_{BS} (kA)	60 kA	40 kA
I_{NBI} (kA)	65 kA	75 kA
I_{RF} (kA)	10 kA	-
f_{NI}	0.45	0.40

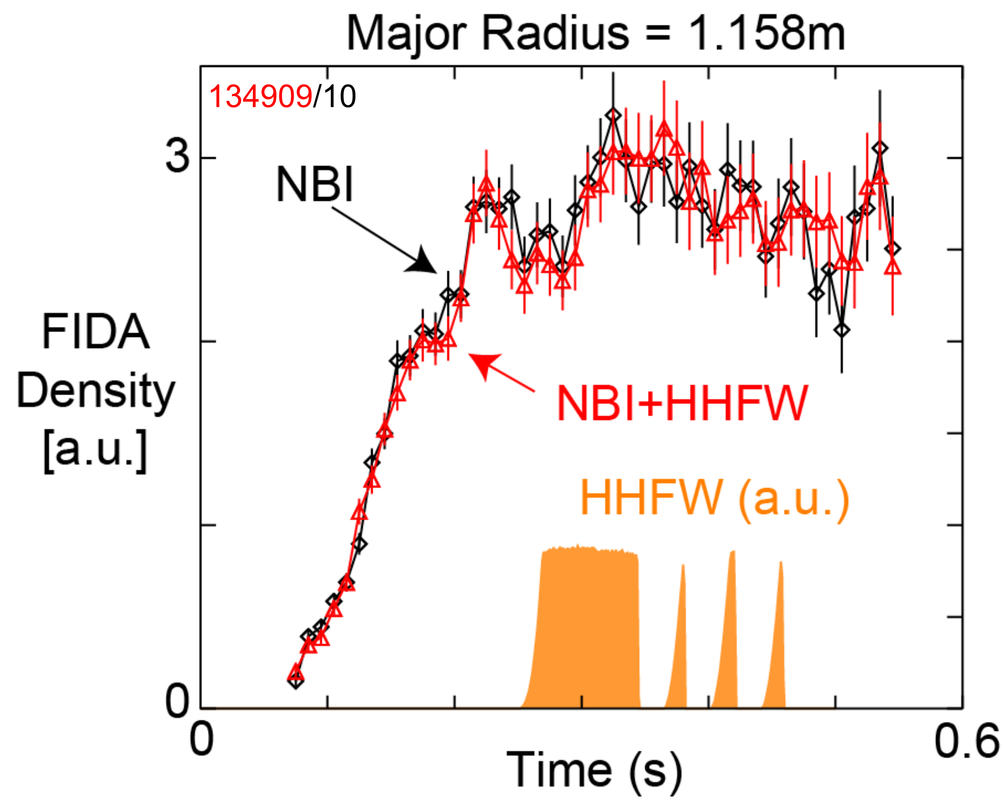
HHFW double end-fed upgrade was installed in 2009, shifted ground from end to strap center to increase maximum P_{RF}



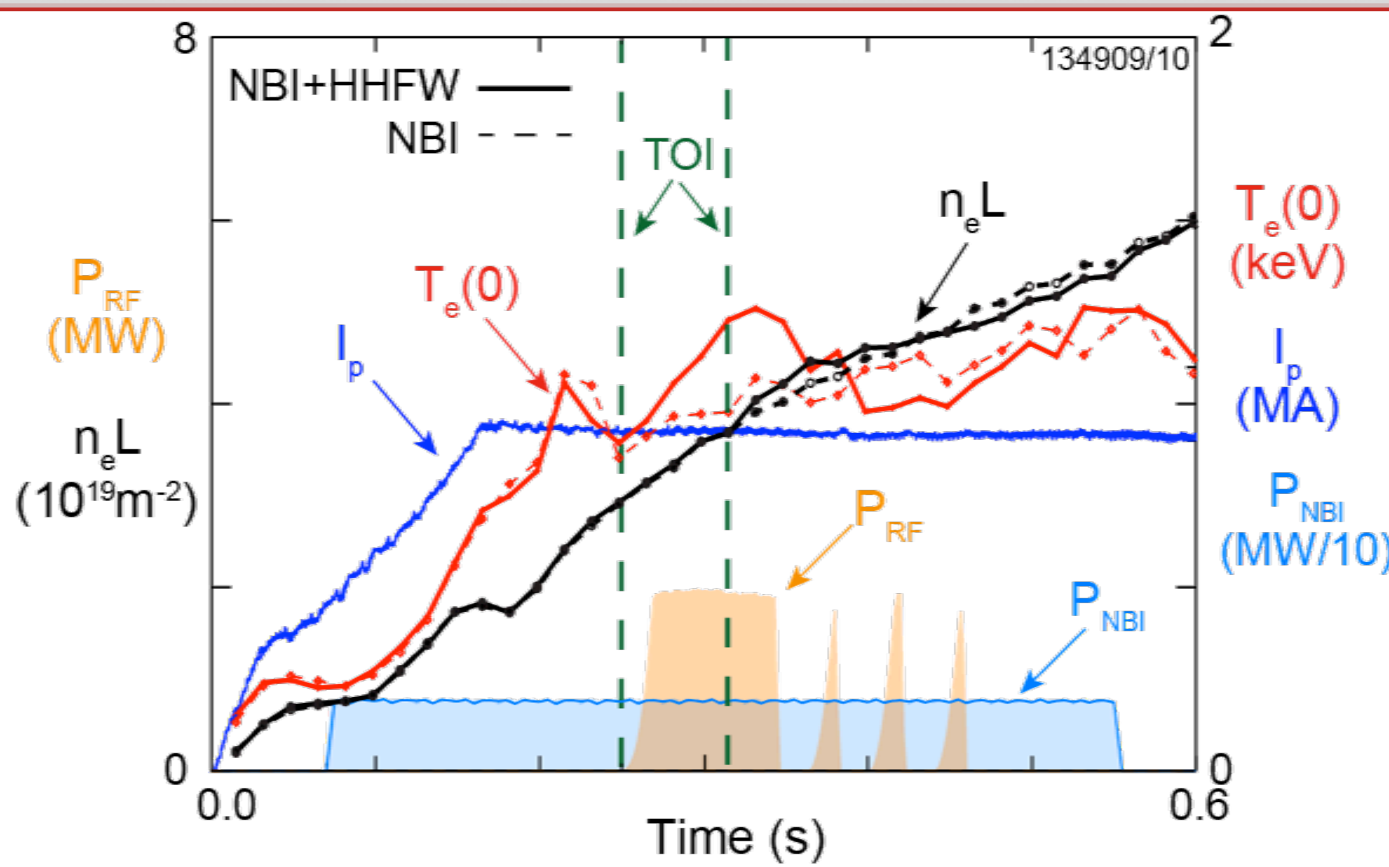
- Designed to bring system voltage limit with plasma (~15 kV) to limit in vacuum (~25 kV):
  - Increasing P_{RF} ~ 2.8 times
- Antenna upgrade was beneficial:
  - Reached arc-free P_{RF} ~ 4 MW after a few weeks of operation at the end of 2009 campaign
- In 2008-9, Li wall conditioning was observed to enhance HHFW coupling by decreasing edge density

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





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