NSTX

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Performance of High Non-Inductive Current Fraction H-Modes Generated by HHFW Heating in NSTX*

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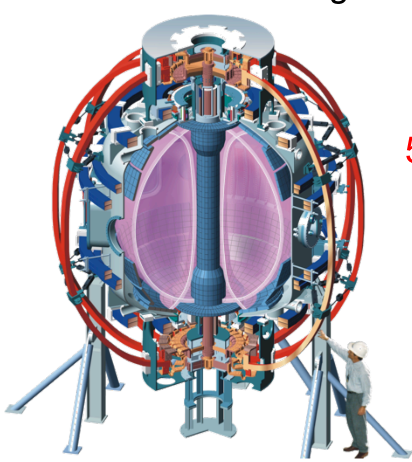

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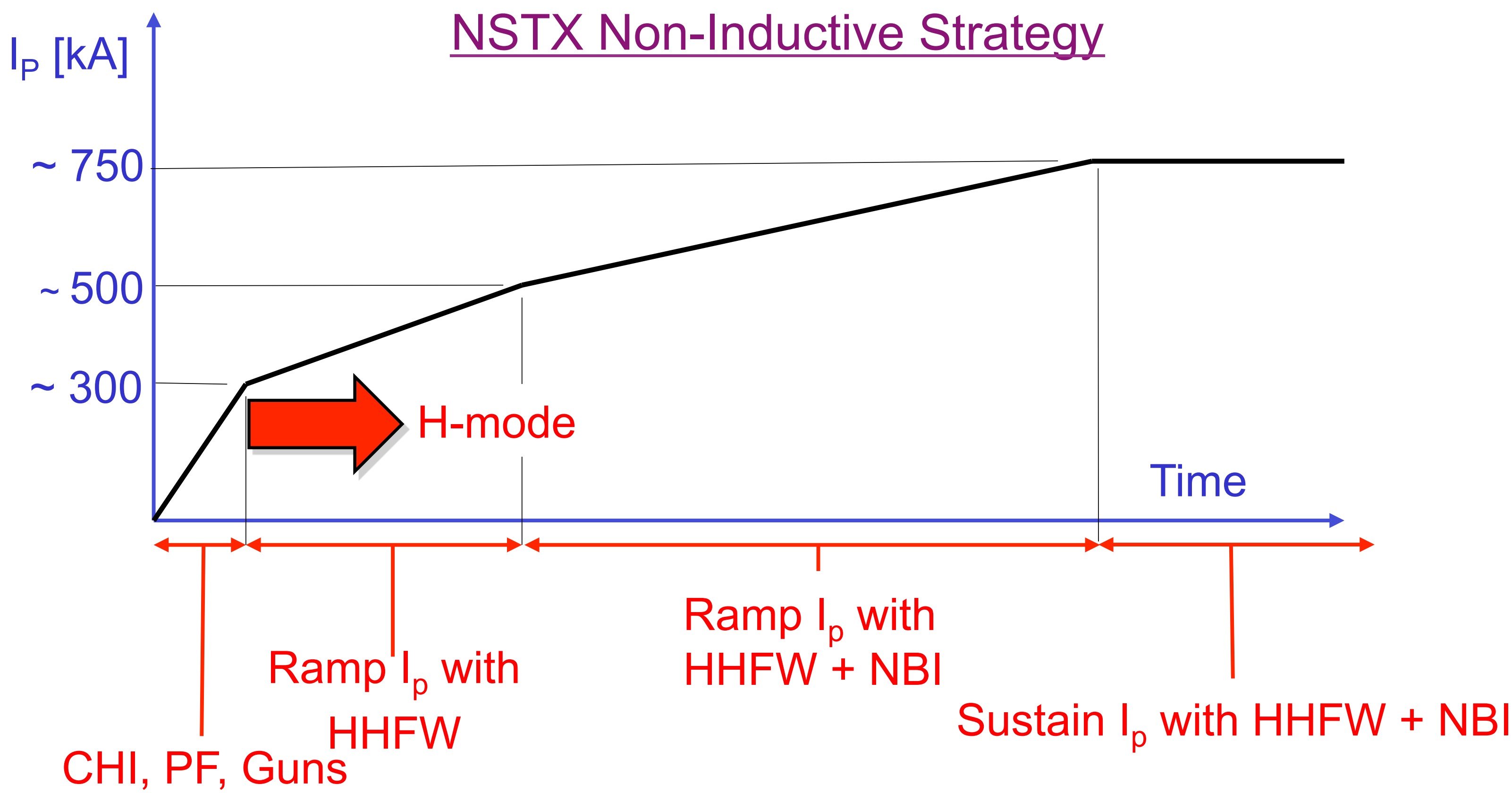
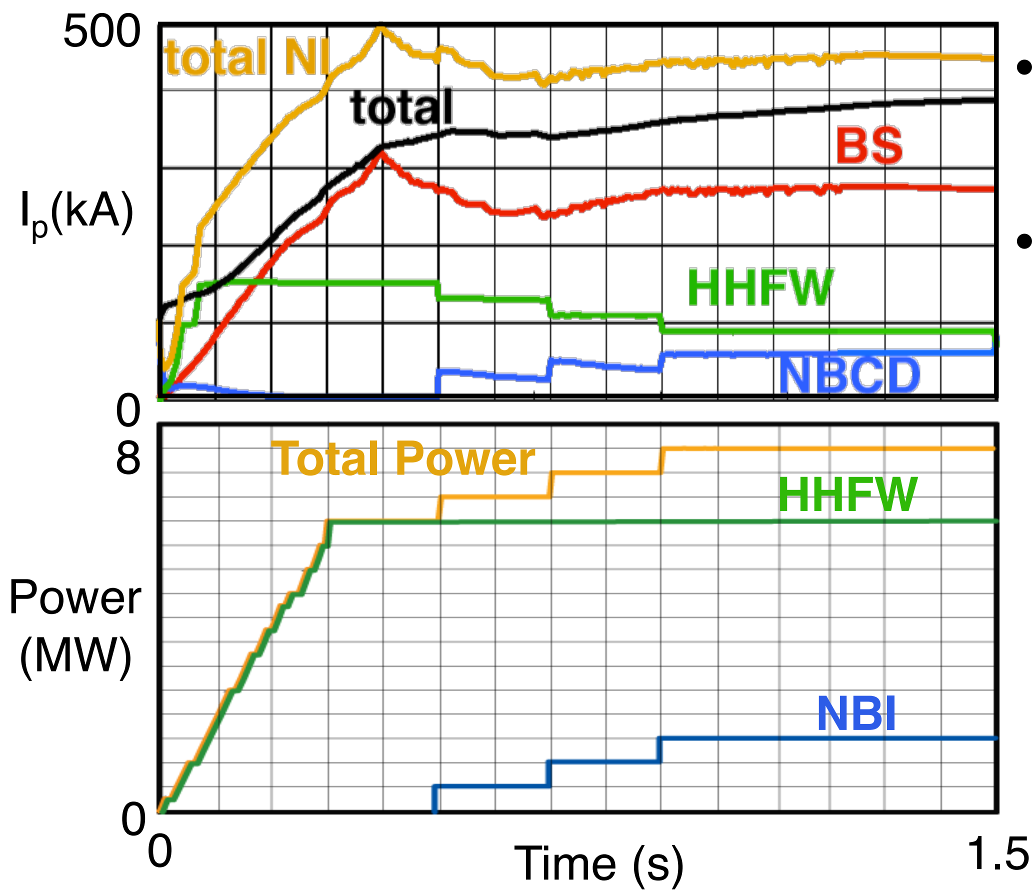
INTRODUCTION

High-Harmonic Fast-Wave (HHFW) heating on NSTX supports non-inductive I_p ramp-up and bulk electron heating



- Future spherical torus devices need to operate without a central solenoid:
  - HHFW enables fully non-inductive I_p ramp-up through bootstrap current drive (BSCD) and direct fast-wave CD (RFCD) during early HHFW H-mode
  - Also provides bulk electron heating of NBI H-Mode during I_p flat top

TSC modeling* predicts 5-6 MW of HHFW heating can achieve fully non-inductive I_p ramp-up in NSTX



- HHFW provides heating & CD at low I_p and T_e
- HHFW-assisted I_p ramp-up started at 100 kA
  - 6 MW HHFW ($k_{||}$ = 8 m^{-1}) Co-CD phasing
  - 6 MW NBI added when $I_p \geq$ 400 kA (only 2-3 MW absorbed due to slow I_p ramp rate in 1.8 s plasmas)

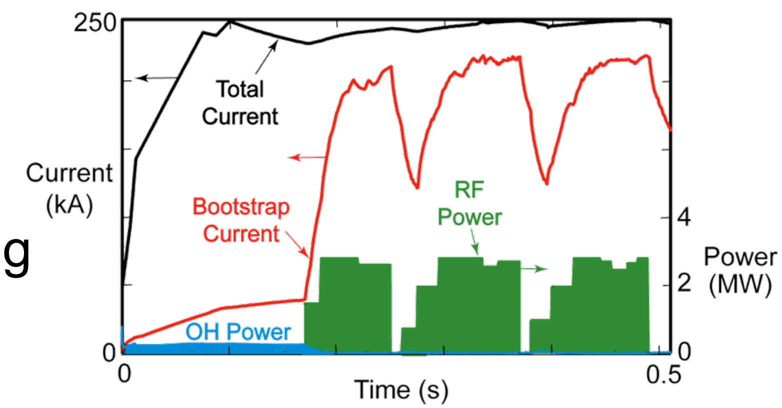
[*C. E. Kessel, *et al.*, Nuclear Fusion **45**, 814 (2005)]

Improvements in HHFW heating since 2005 support development of HHFW-assisted I_p ramp-up

- Since 2005 approach to developing HHFW-assisted I_p ramp-up has been to heat low I_p plasmas (I_p ~ 250-300 kA)

2005:

- Transiently generated 85% BSCD in HHFW-heated B_T = 0.45 T, I_p = 250 kA H-mode with P_{RF} ~ 2.8 MW, using heating antenna phasing ($k_{||}$ = 14 m^{-1})
- Plasma position control system (PCS) could not maintain antenna-plasma gap at L-H transition, causing HHFW power to trip off



2006:

- Higher B_T (0.45 T ⇒ 0.55 T) resulted in improved HHFW heating efficiency in I_p ≥ 600 kA L-modes

2007-9:

- Reduced PCS latency & Li conditioning improved HHFW heating efficiency in H-modes at I_p ≥ 600 kA

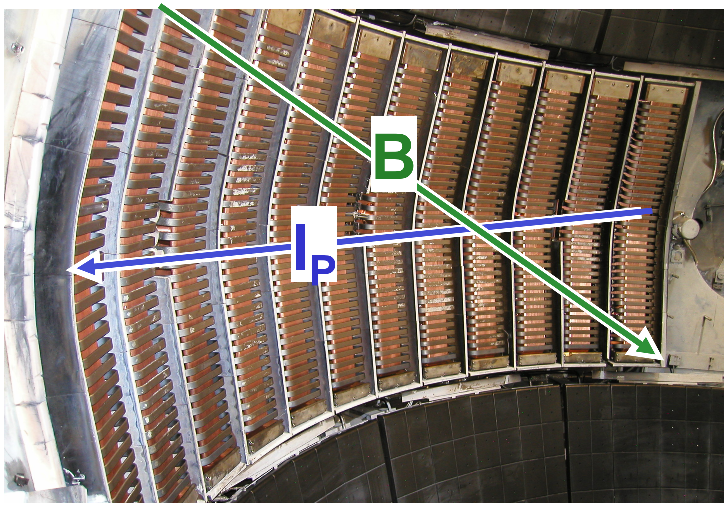
Experiments in 2010 studied HHFW H-Modes and NBI+HHFW H-modes at I_p = 300 kA, $B_T(0)$ = 0.55 T

- Achieved non-inductive fraction (f_{NI}) ~ 0.65 with only 1.4 MW of HHFW power, using co-current drive antenna phasing ($k_{||}$ = -8 m^{-1}), in HHFW-generated H-mode

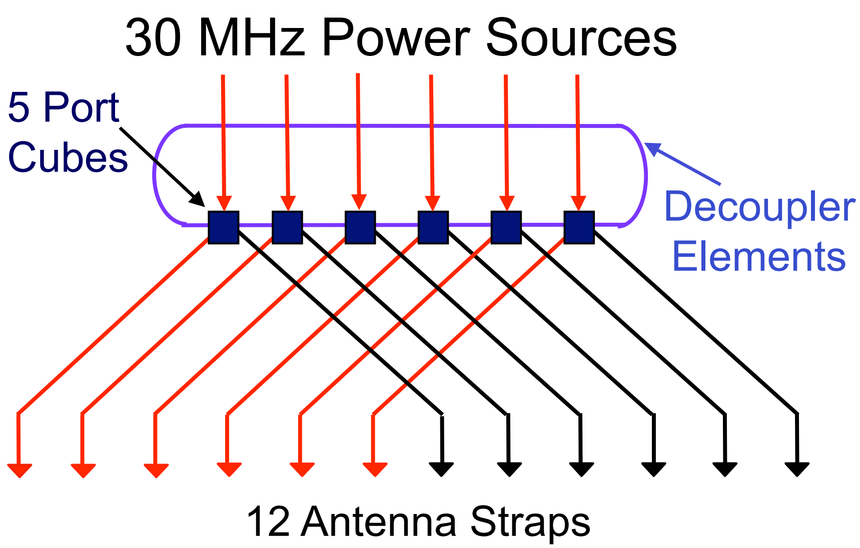
- Attempts to heat NBI-generated H-mode with 1.4 MW of HHFW power produced only f_{NI} ~ 0.45, due to significant RF-enhanced fast-ion interaction with antenna

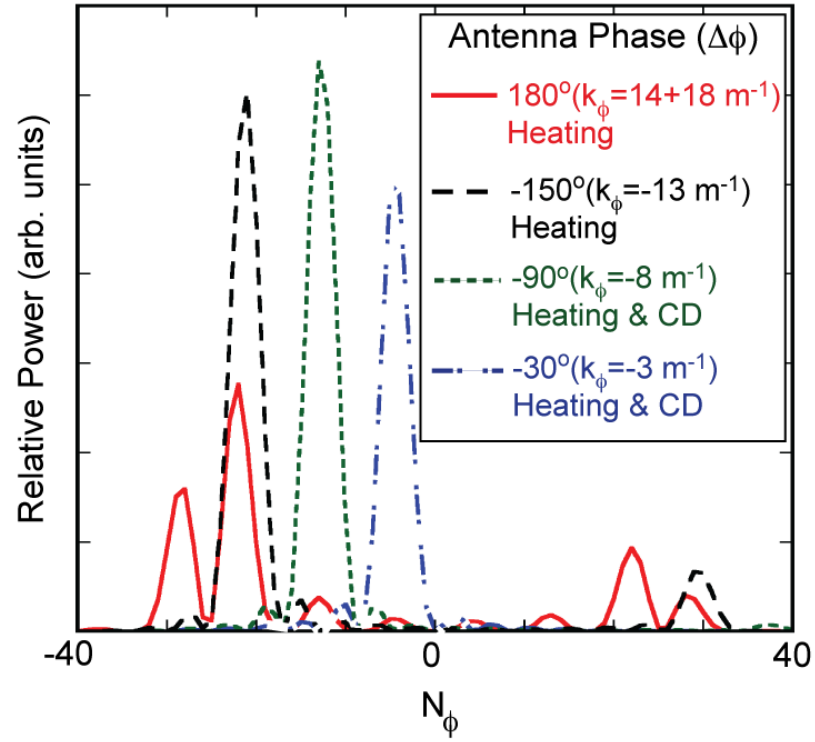
NSTX HHFW SYSTEM

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



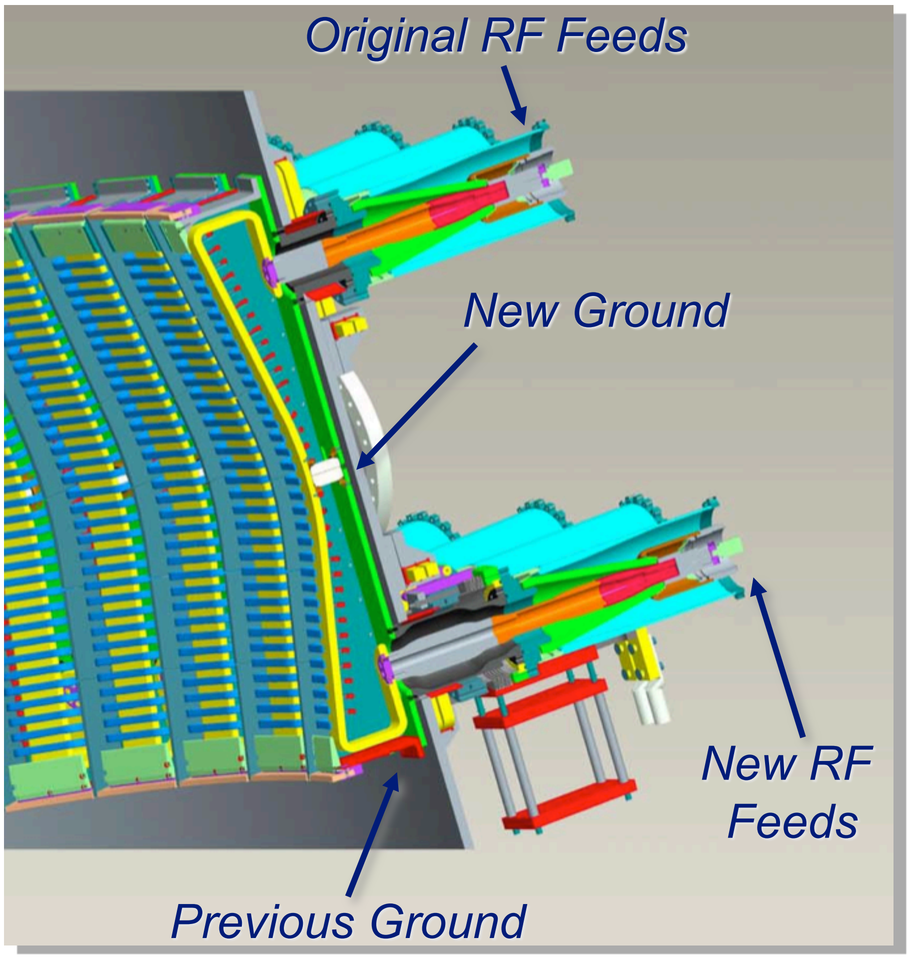
12-strap antenna extends toroidally 90°





- Many fast wave ion resonances: 7-11 Ω_D
- Strong single pass direct absorption on electrons

Arc-free HHFW power limited to ≤ 1.4 MW in 2010



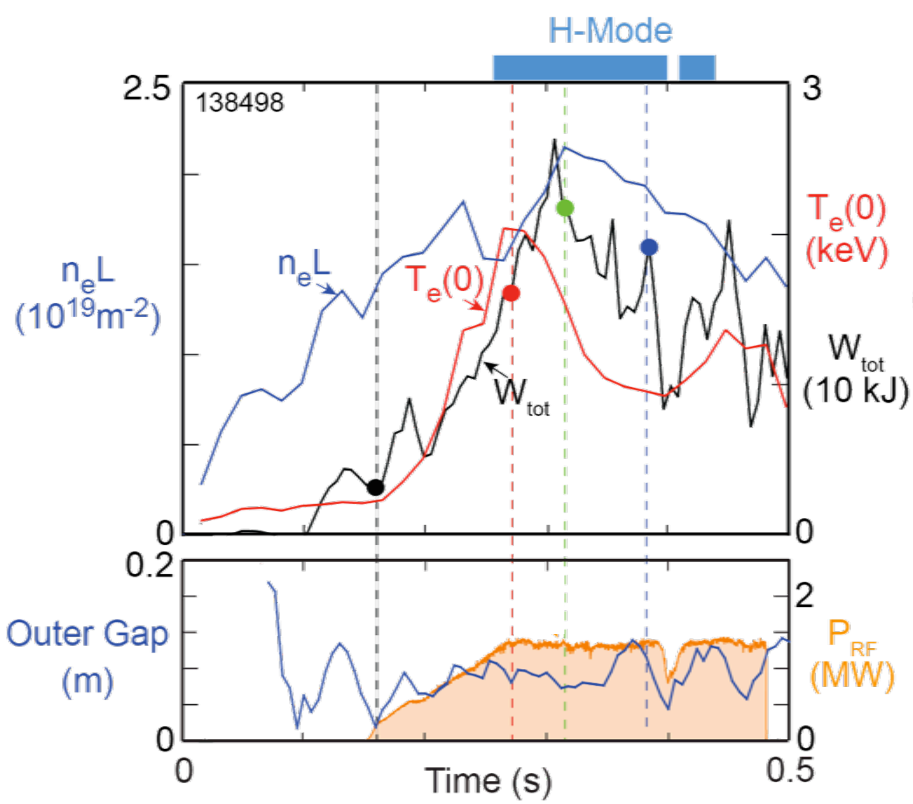
- Double feed antenna upgrade in 2009 designed to bring system voltage limit with plasma (~15 kV) to limit in vacuum (~25 kV):
  - Increasing P_{RF} ~ 2.8 times
- Upgrade was beneficial; reached arc-free P_{RF} ~ 4 MW after a few weeks of operation at the end of 2009 run
- In 2008-9, Li conditioning enhanced HHFW coupling, but in 2010 a combination of massive Li injection, no boronization, and no between shots glow limited arc-free $P_{RF} \leq 1.4$ MW *

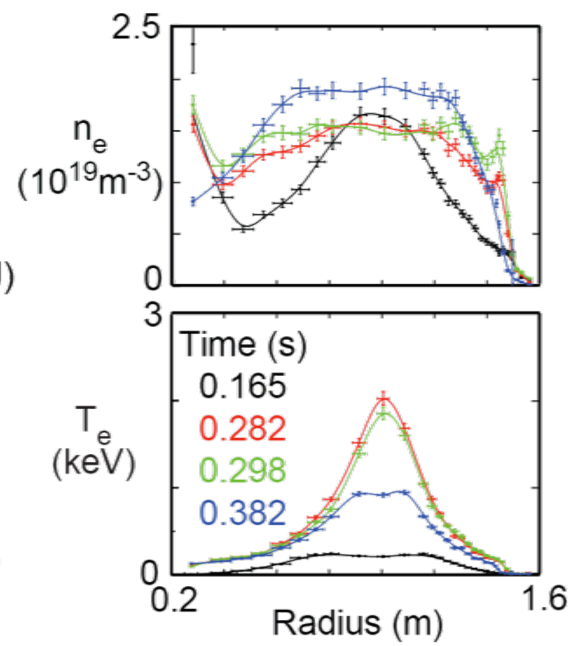
[*P. M. Ryan *et al.*, Poster PP9.00063]

HHFW-Generated I_p = 300 kA H-Mode

Most I_p = 300 kA HHFW H-modes run in 2010 did not show sustained core RF heating, even with good outer gap control

- Large increase in $T_e(0)$ and W_{tot} as RF power ramped up
- But $T_e(0)$ and W_{tot} collapsed near start of flat top in RF power
- PCS controlled antenna-plasma outer gap through the L-H transition and during most of the H-mode, except at a large MHD event ~ 0.39 s





I_p = 300 kA

$B_T(0)$ = 0.55 T

Deuterium

k_ϕ = - 8 m^{-1}

GENRAY predicts that if RF coupling efficiency, η_{eff} ~ 100%, there should be good on axis heating even late in H-mode

Shot 138498

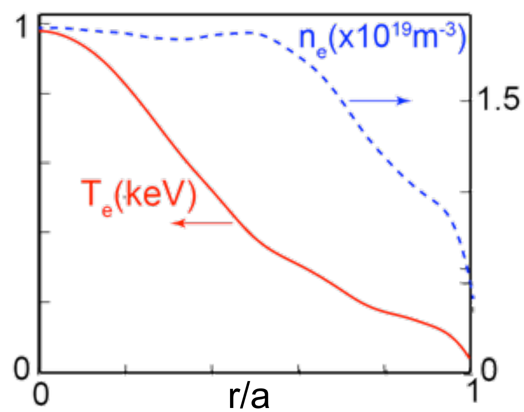
Time = 0.382 s

I_P = 300 kA

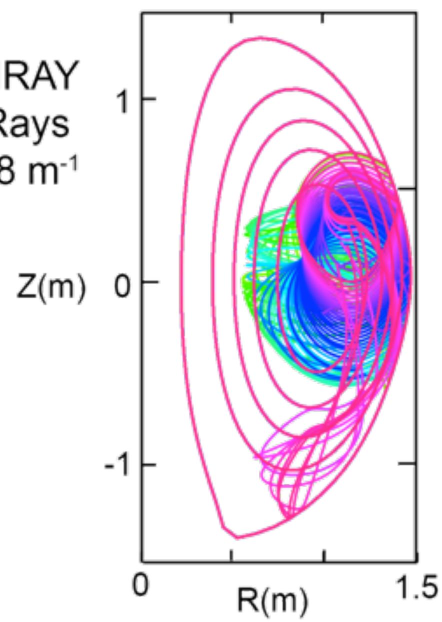
B_T = 5.5 kG

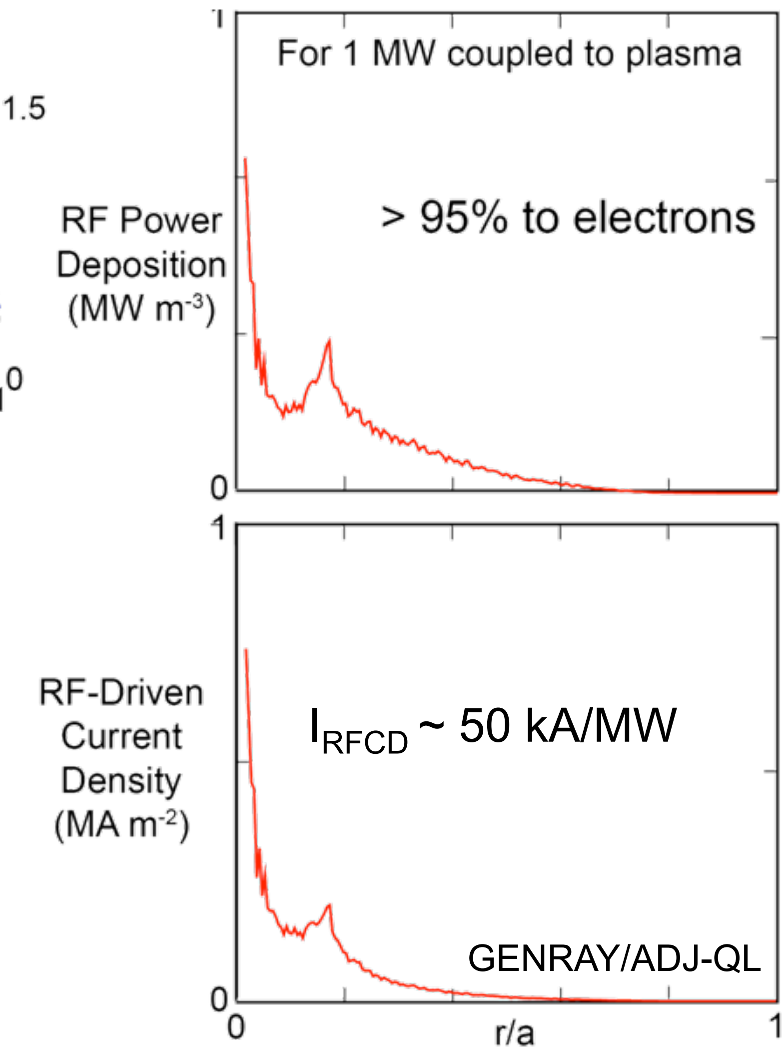
Deuterium

RF H-mode

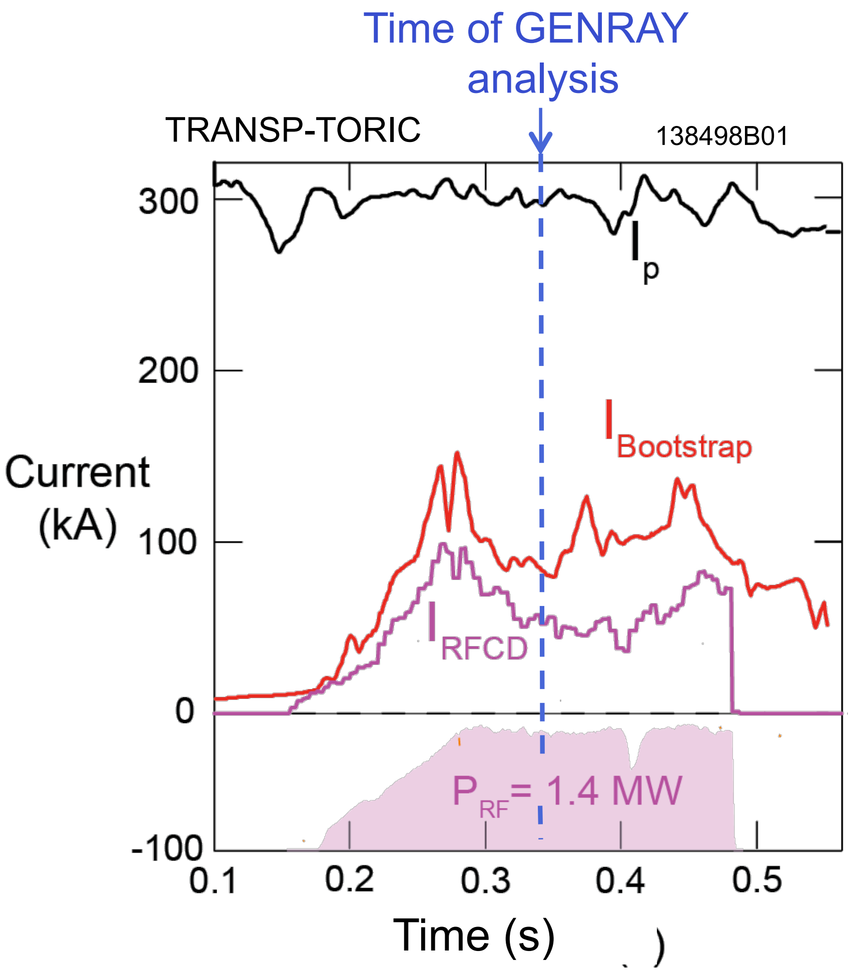


GENRAY
41 Rays
k_ϕ=-8 m^{-1}





Time dependent TRANSP-TORIC modeling, assuming η_{eff} = 100%, also predicts sustained heating and current drive



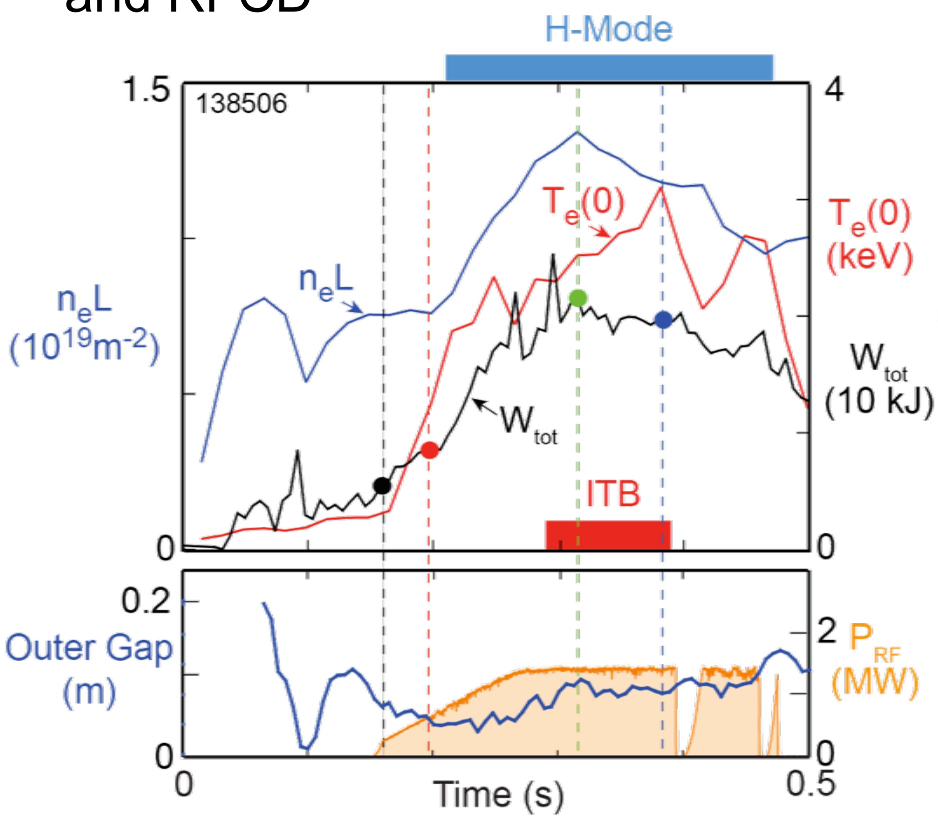
- The observed decreases in core electron heating appears to be due to a large drop in η_{eff} during RF pulse
- $\eta_{eff} \sim \Delta W_T/(\tau^* P_{RF})$
- At 0.382 s:

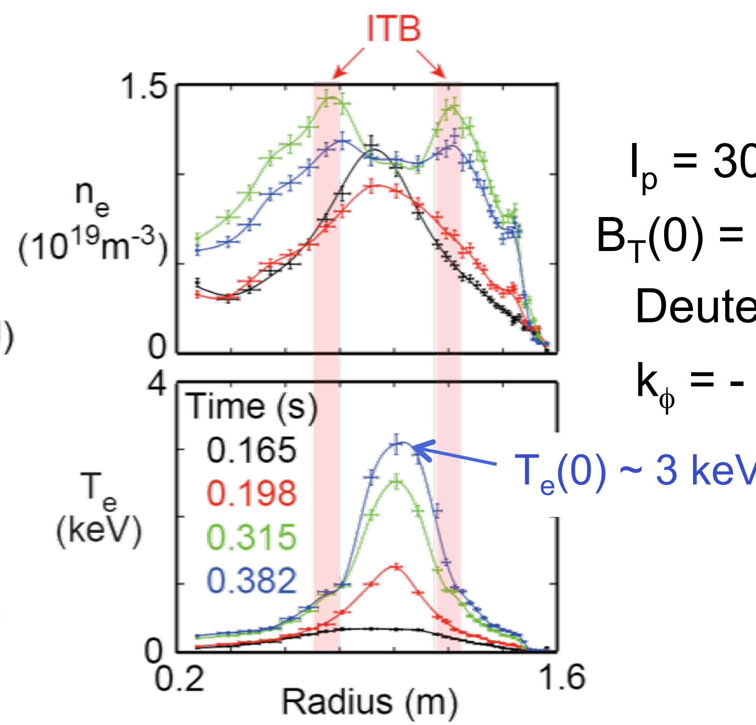
  $\Delta W_T \sim$ 15 kJ
  $\tau \sim$ 20 ms
  $P_{RF} \sim$ 1.4 MW) → $\eta_{eff} \sim$ 50%

	For η_{eff}=50%
I_{BS}	50 kA
I_{RF}	25 kA
f_{NI}	0.25

Eventually achieved sustained I_p = 300 kA H-mode with internal transport barrier (ITB) by lowering plasma density

- Reduced plasma density resulted in sustained HHFW-generated H-mode that reached $T_e(0)$ ~ 3 keV with only 1.4 MW of RF power
- Combination of ITB and higher $T_e(0)$ significantly increased BSCD and RFCD





I_p = 300 kA

$B_T(0)$ = 0.55 T

Deuterium

k_ϕ = - 8 m^{-1}

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

Shot 138506

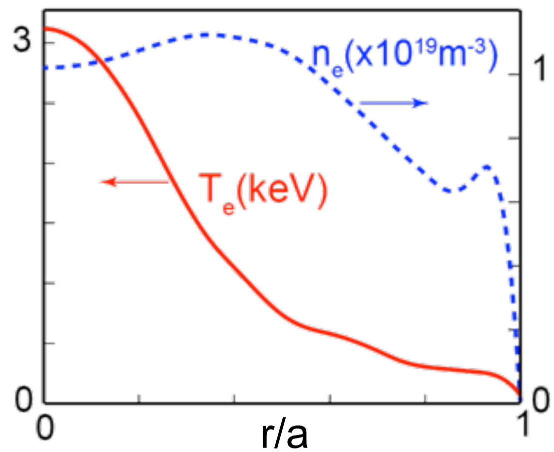
Time = 0.382 s

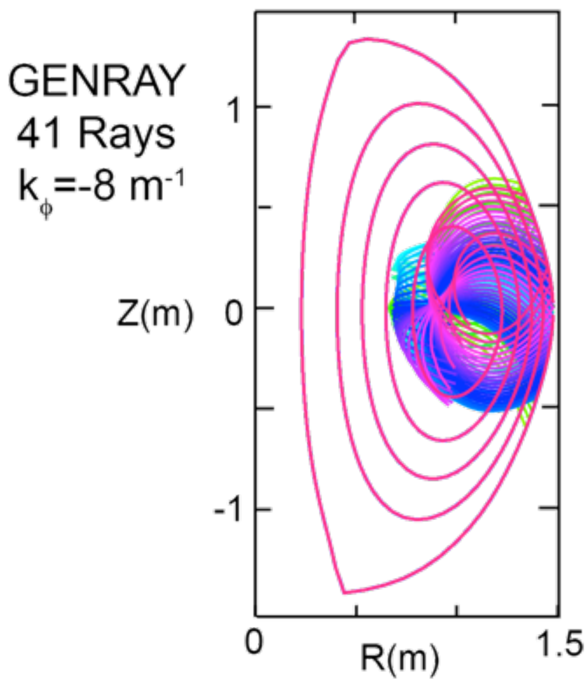
I_P = 300 kA

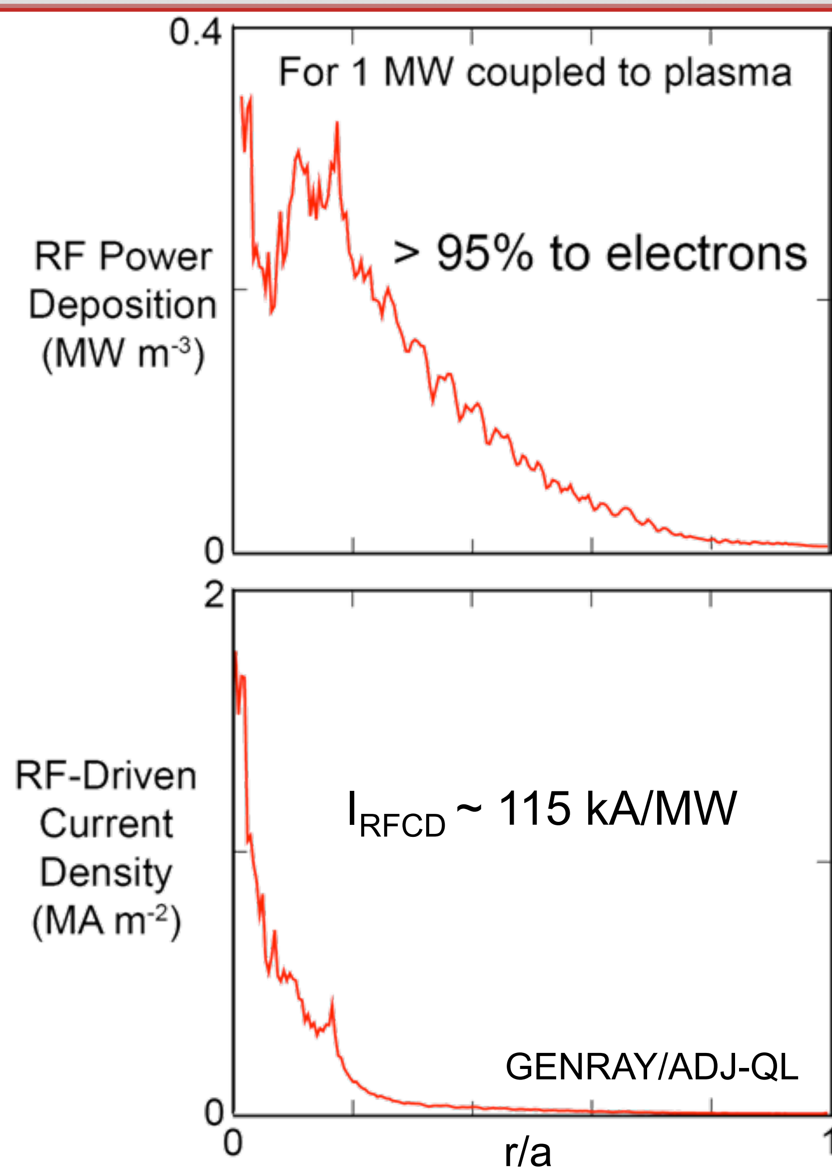
B_T = 5.5 kG

Deuterium

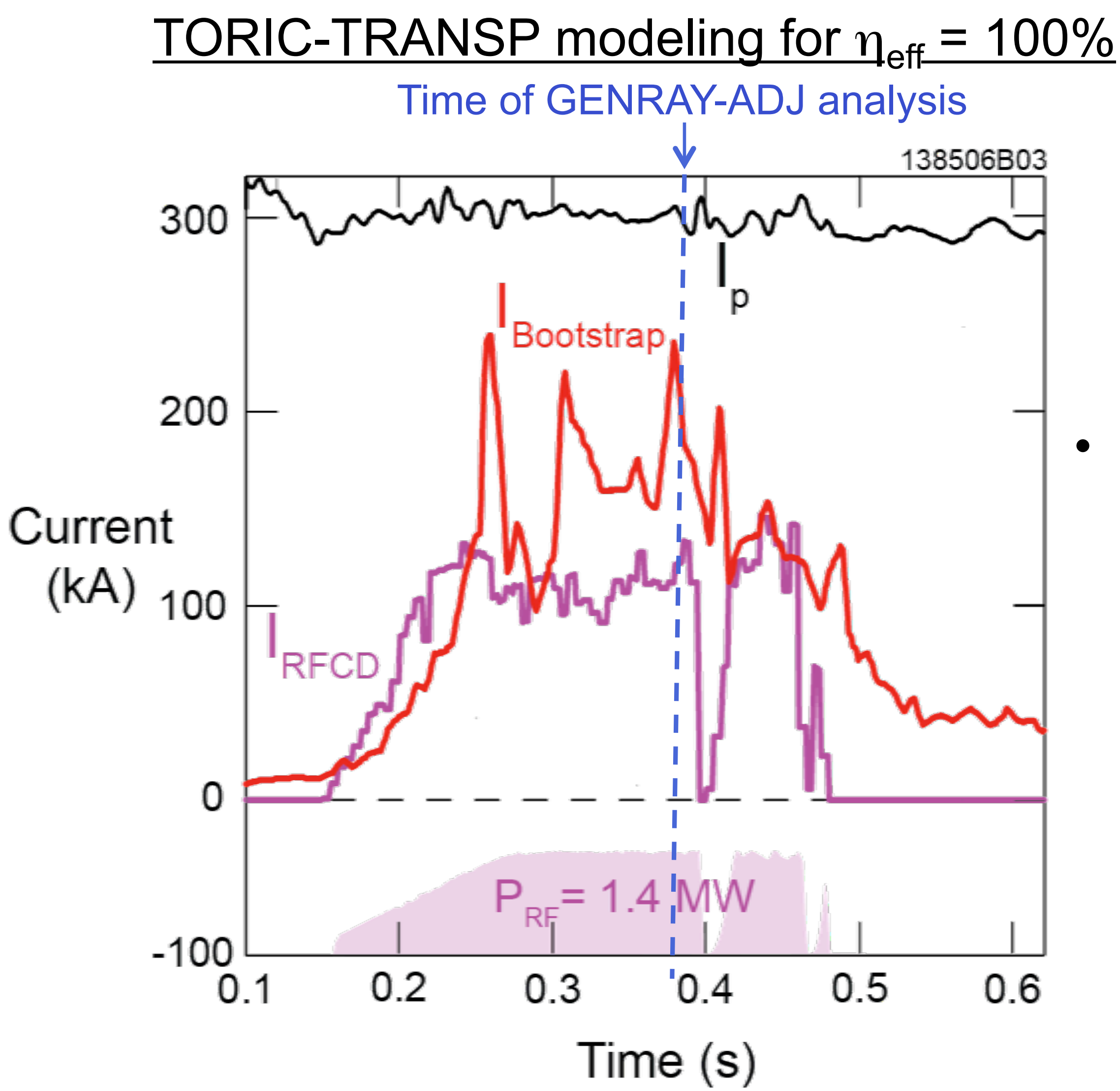
RF H-mode







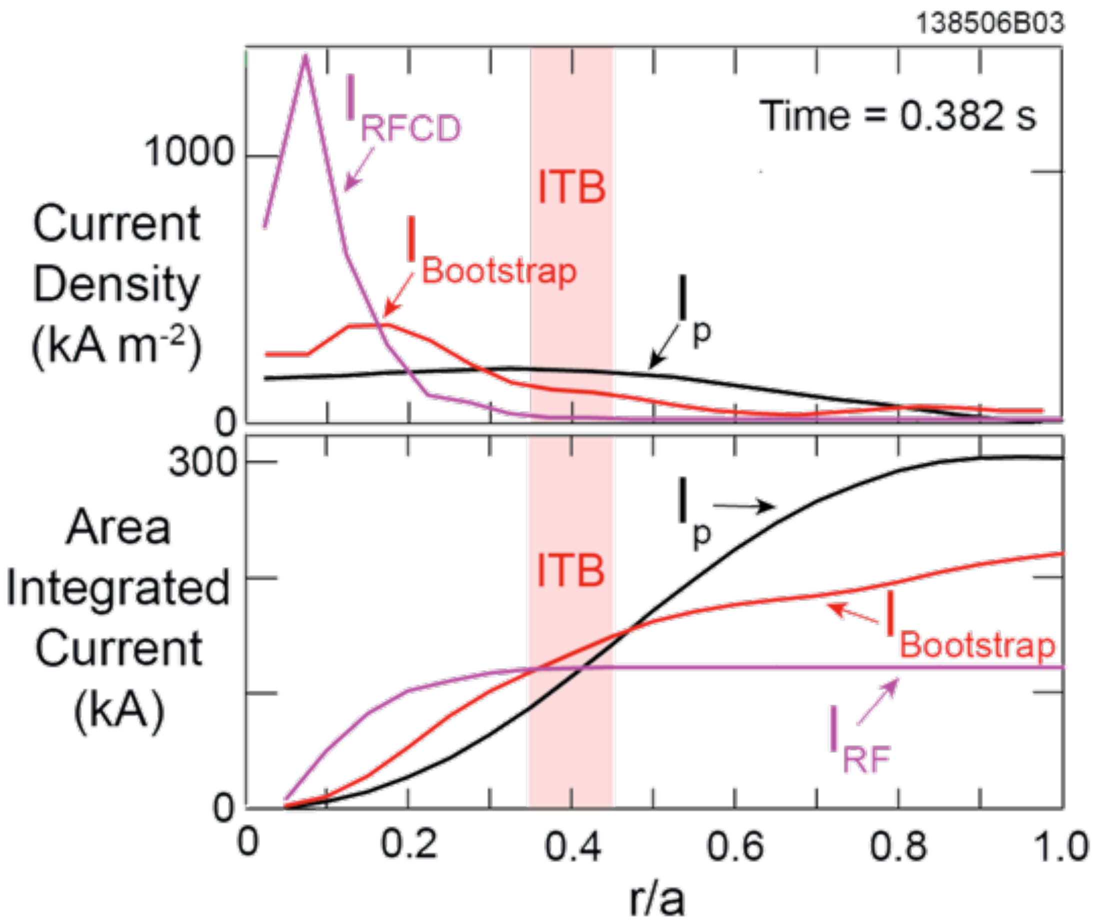
TRANSP-TORIC simulation, assuming η_{eff} = 100%, predicts $I_{Bootstrap}$ = 220 kA and I_{RFCD} = 120 kA



- TRANSP-TORIC predicts ξ_{CD}~ 85 kA/MW at GENRAY analysis time:
  - GENRAY ξ_{CD}~ 115 kA/MW

80% of the non-inductive current generated inside ITB; Actual η_{eff} ~ 60% → f_{NI} ~ 0.65

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



- $\eta_{eff} = \Delta W_T/(\tau^* P_{RF})$

  ΔW_T ~ 15 kJ

  τ ~ 15 ms

  P_{RF}~ 1.4 MW

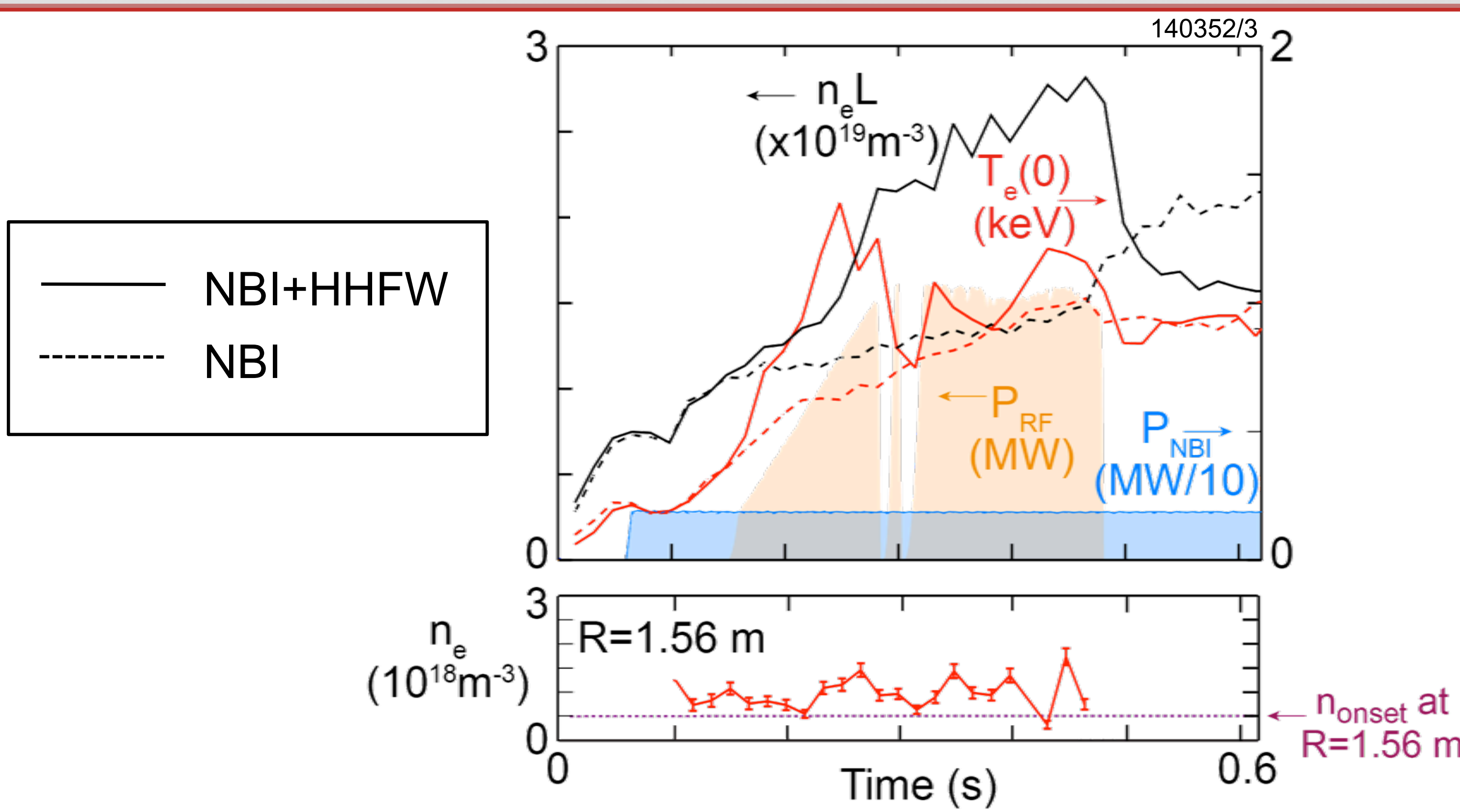
  → η_{eff} ~ 60%

For η_{eff} = 60%

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

HHFW-Heated I_p = 300 kA NBI H-Mode

Coupling P_{RF} = 1.4 MW into I_p = 300kA, P_{NBI} = 2 MW H-mode resulted in significant fast-ion interaction with antenna



- 50% of injected NBI fast-ions promptly lost at this low I_p
- Core density increased during HHFW heating due to NBI fast-ion interaction with the antenna
- n_e @R = 1.56 m > onset density for fast-wave propagation (n_{onset}) → η_{eff} only ~ 40%

40% of coupled RF power accelerates NBI fast-ions that are mostly promptly lost at this low I_p

Shot 140352

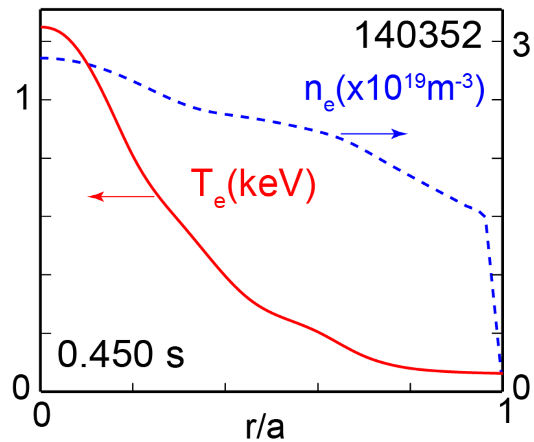
Time = 0.450 s

I_P = 300 kA

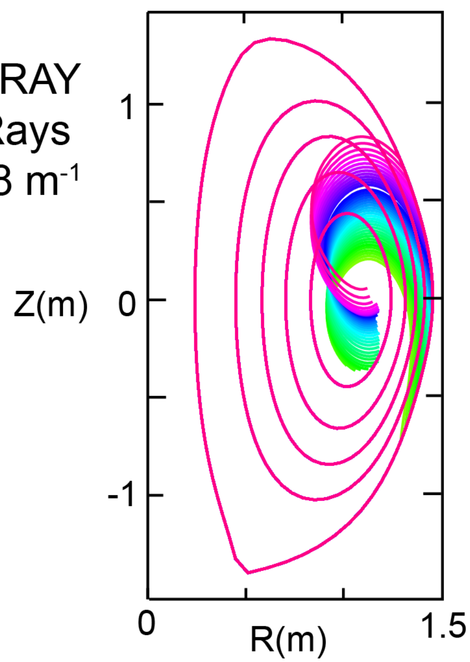
B_T = 0.55 T

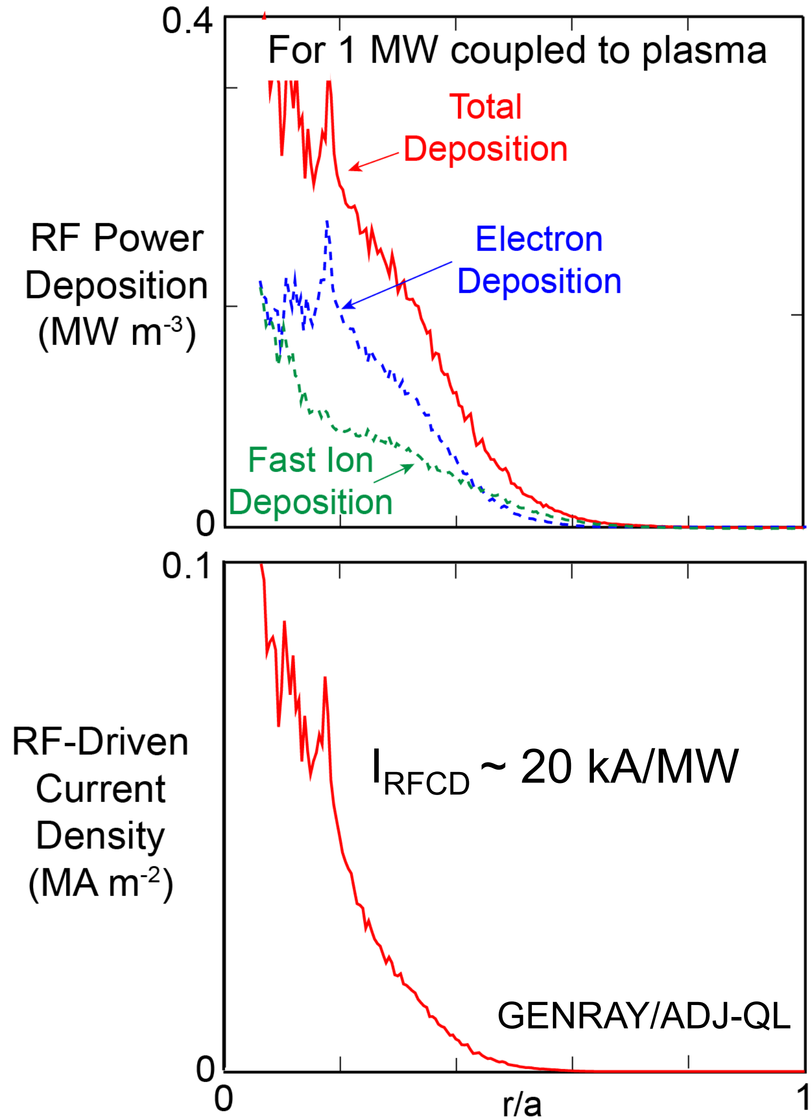
Deuterium

NBI+HHFW H-mode



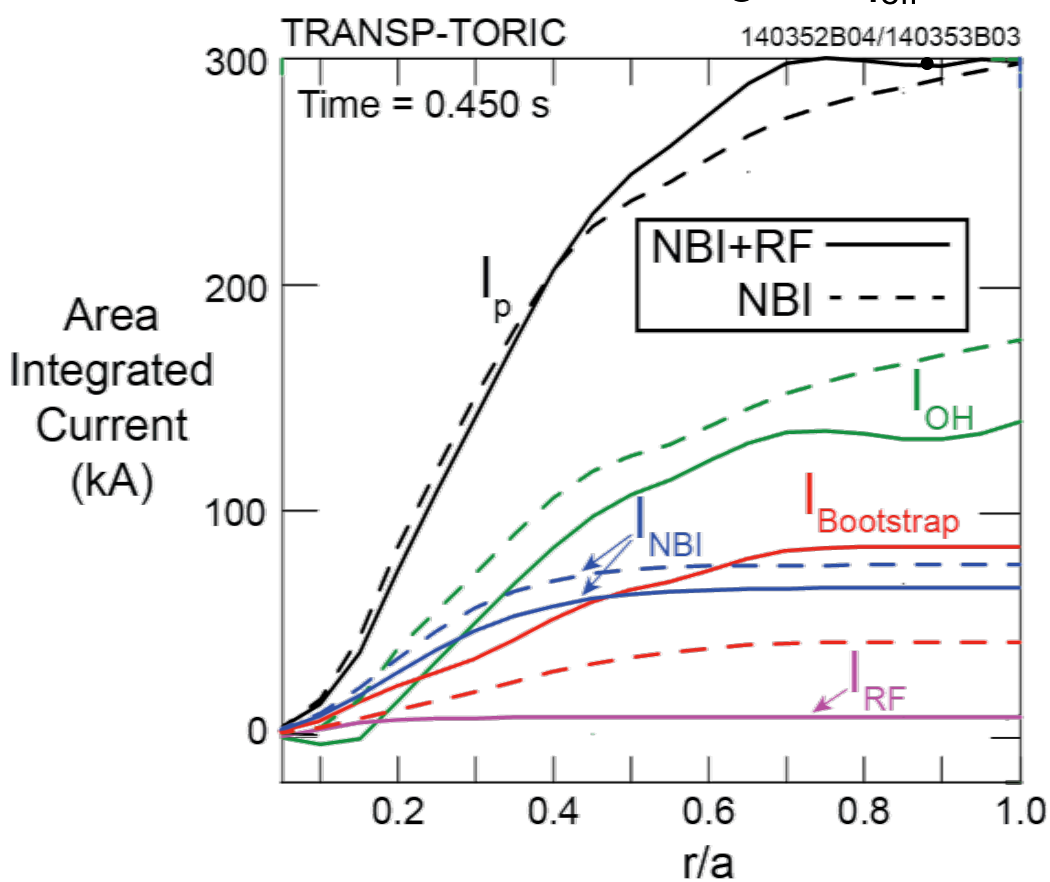
GENRAY
41 Rays
k_ϕ=-8 m^{-1}





NBI+HHFW H-mode had f_{NI} ~ 0.45, significantly lower than the HHFW H-mode, due to lower $T_e(0)$, η_{eff} and higher n_e

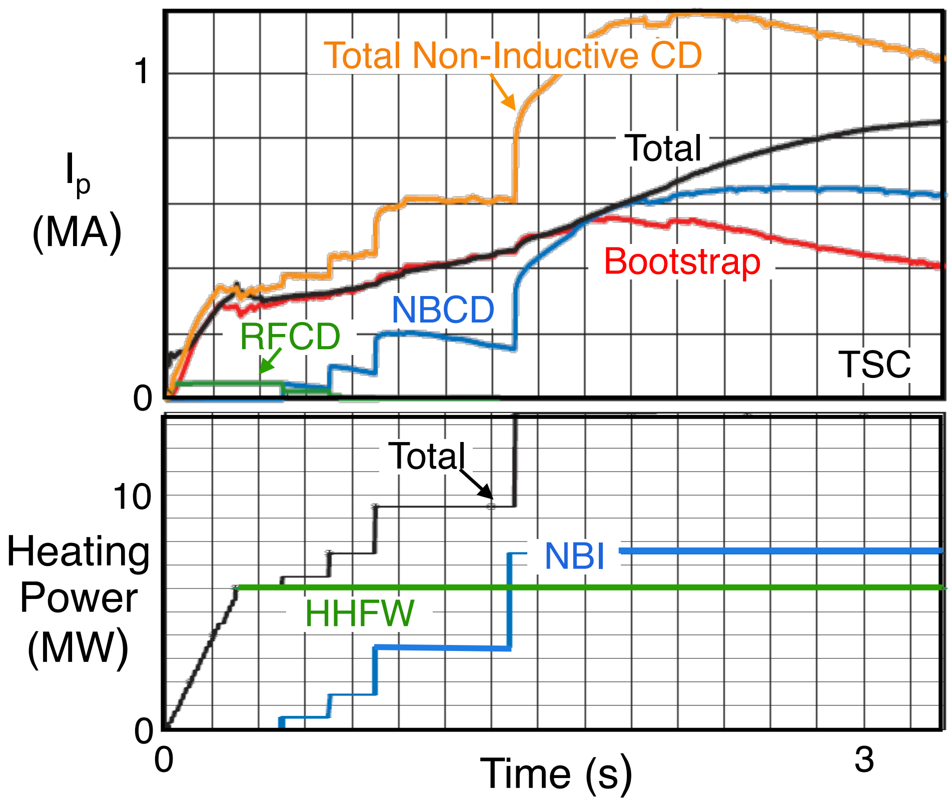
TORIC-TRANSP modeling for η_{eff} = 100%:



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

On NSTX-U I_p ramp-up experiments will benefit from center stack upgrade to $B_T(0)$ = 1T & 2nd NBI system



- Simulation of non-inductive I_p ramp-up at $B_T(0)$ = 1 T predicts I_p ~ 1 MA is possible
- 6 MW HHFW Co-CD phasing ($k_{||}$ = 8 m^{-1}) used at beginning of I_p ramp-up:
  - 7 MW NBI added when $I_p \geq$ 600kA
  - 3 s pulse needed for ramp-up to higher I_p

- Higher HHFW & NBI power absorption at increased B_T eases ramp-up requirements
- HHFW antenna design changes will be implemented to reduce fast-ion interaction

Summary

- Experiments run in 2010 generated a sustained deuterium HHFW I_p = 300 kA H-mode with $T_e(0)$ ~ 3 keV, an ITB and f_{NI} ~ 0.65
  - ➢ A combination of massive Li injection, no boronization, and no between shots glow in 2010 limited arc-free P_{RF} to ≤ 1.4 MW
- Attempts to heat I_p = 300 kA NBI H-mode with P_{RF} = 1.4 MW produced only f_{NI} ~ 0.45 due to significant RF-enhanced fast-ion interaction with antenna
- Experiments originally planned for this year to extend the the low I_p HHFW H-mode experiments to f_{NI} ≥ 1 using P_{RF} ~ 3-4 MW were cancelled due to NSTX TF failure
- High f_{NI} low I_p and I_p ramp-up HHFW experiments will benefit from the improved operational parameters of NSTX-U beginning in 2014