

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

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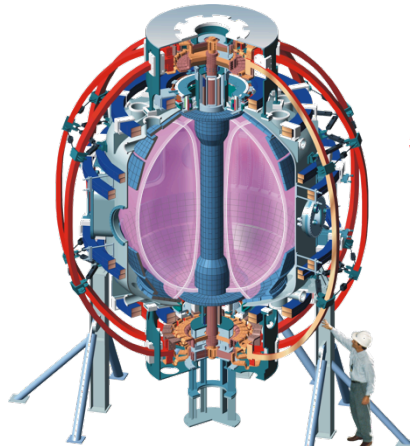
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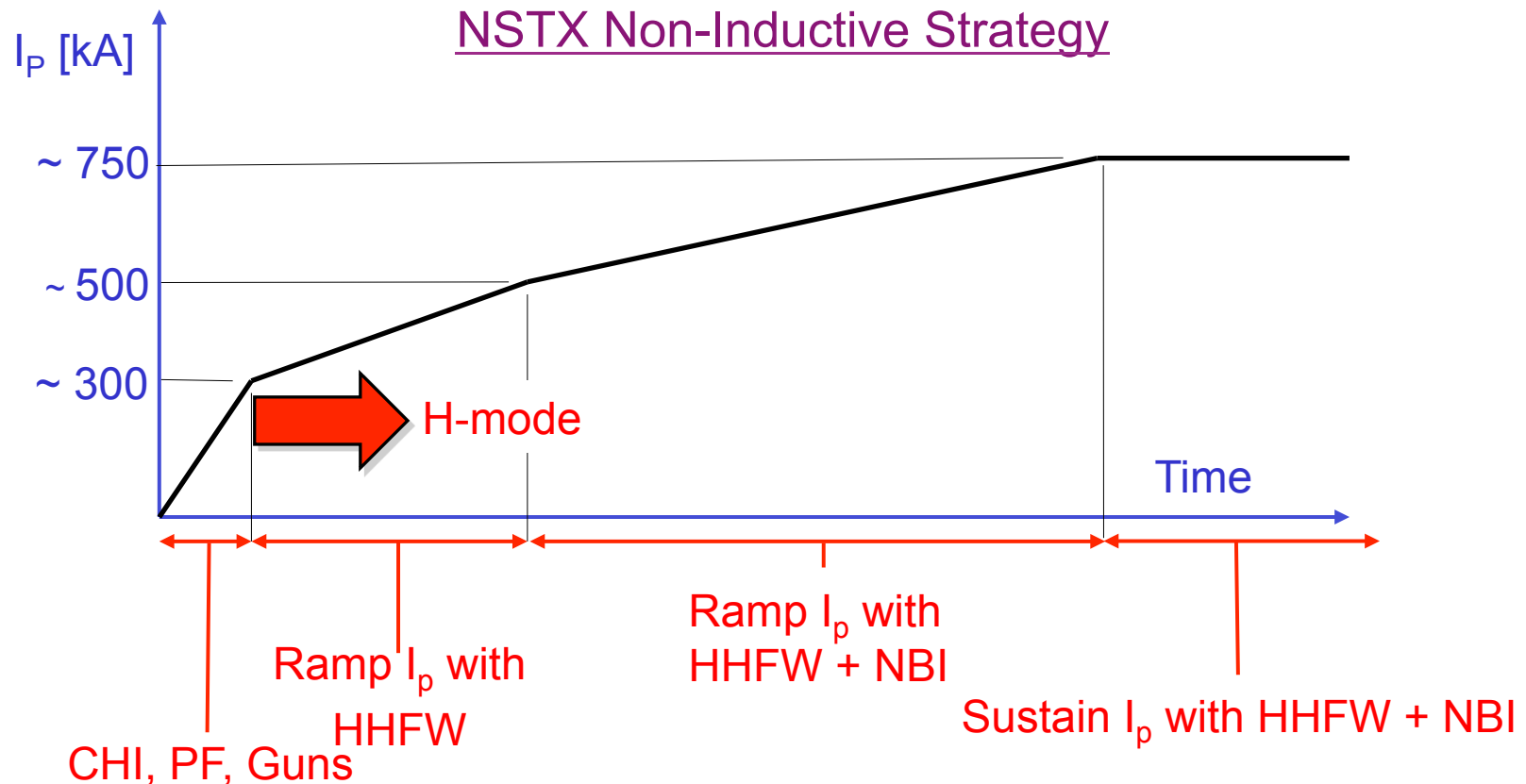
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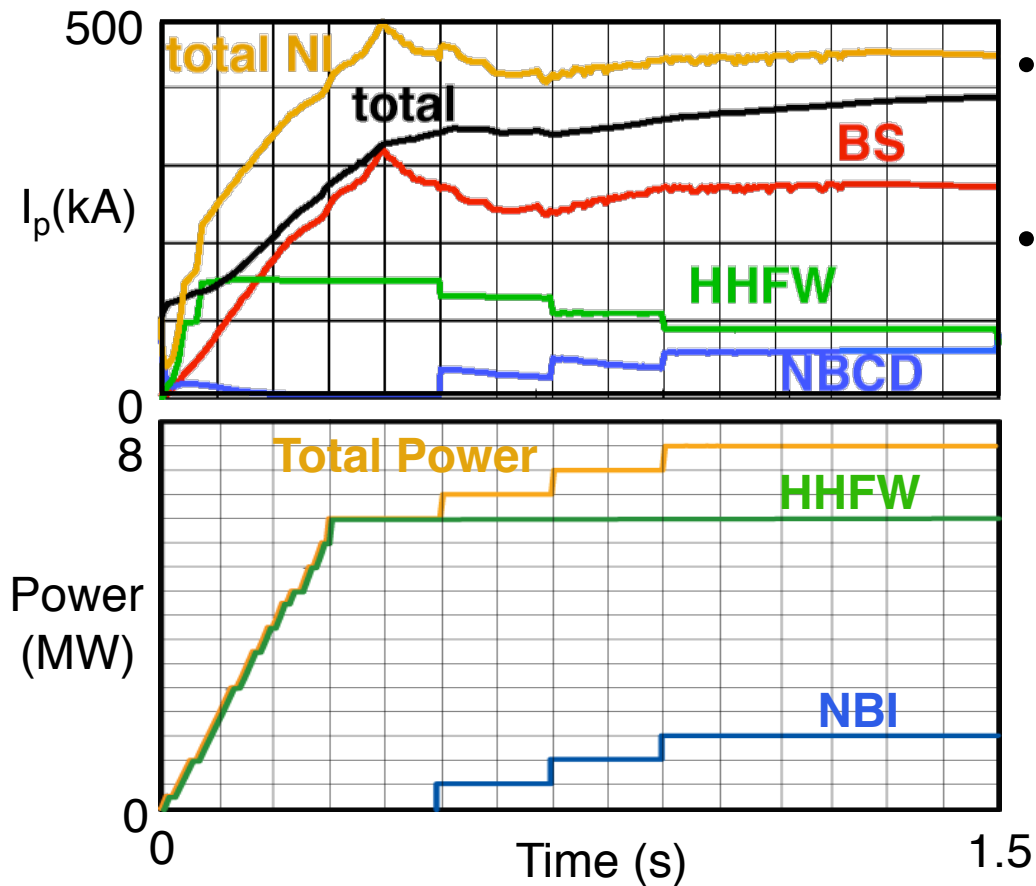
# INTRODUCTION

# 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 ( $k_{||} = 8 \text{ m}^{-1}$ ) Co-CD phasing
  - 6 MW NBI added when  $I_p \geq 400 \text{ kA}$  (only 2-3 MW absorbed due to slow  $I_p$  ramp rate in 1.8 s plasmas)

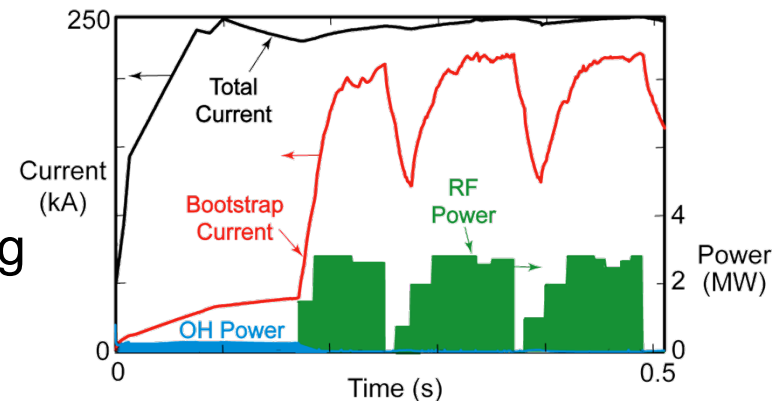
[\*C. E. Kessel, *et al.*, Nuclear Fusion **45**, 814 (2005)]

# 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 ( $I_p \sim 250$ -300 kA)

## 2005:

- Transiently generated 85% BSCD in HHFW-heated  $B_T = 0.45$  T,  $I_p = 250$  kA H-mode with  $P_{RF} \sim 2.8$  MW, using heating antenna phasing ( $k_{||} = 14$  m<sup>-1</sup>)
- 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  $\Rightarrow$   $0.55$  T) resulted in improved HHFW heating efficiency in  $I_p \geq 600$  kA L-modes

## 2007-9:

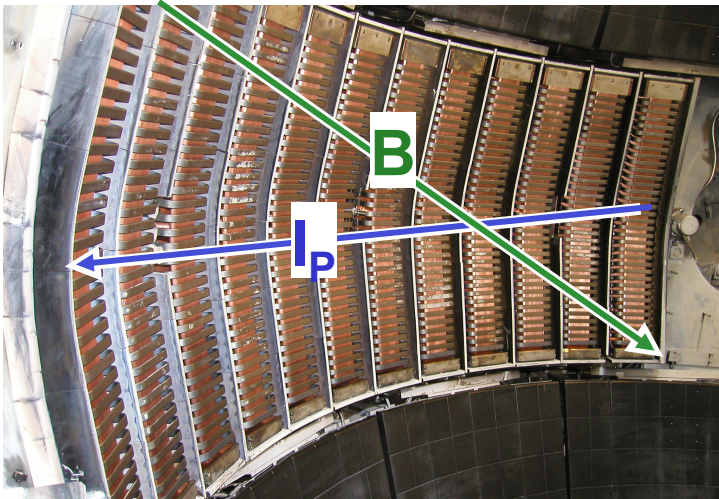
- Reduced PCS latency & Li conditioning improved HHFW heating efficiency in H-modes at  $I_p \geq 600$  kA

## 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 ( $f_{NI}$ )  $\sim 0.65$  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  $f_{NI} \sim 0.45$ , due to significant RF absorption on fast-ion population

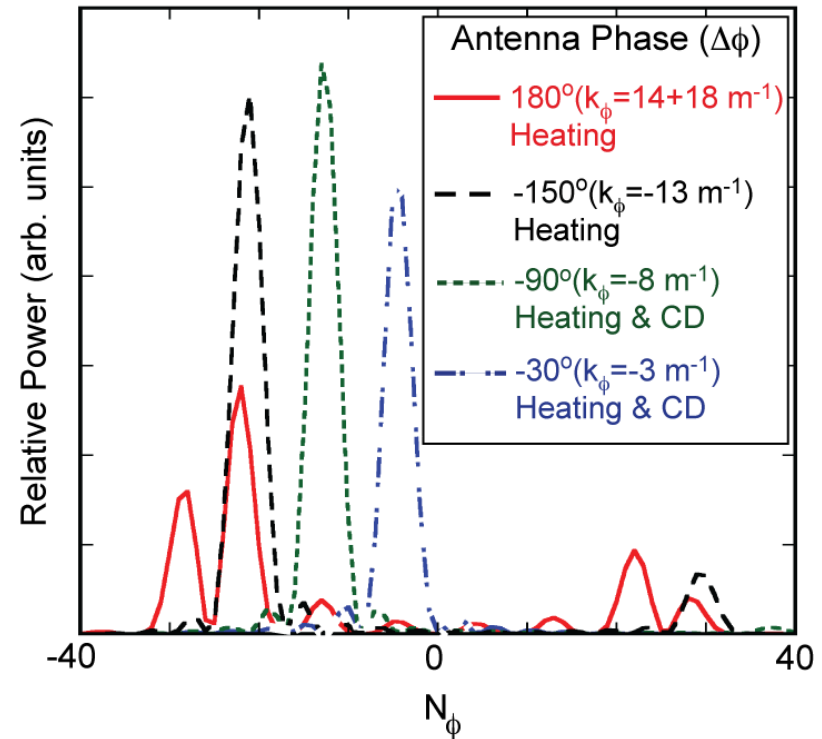
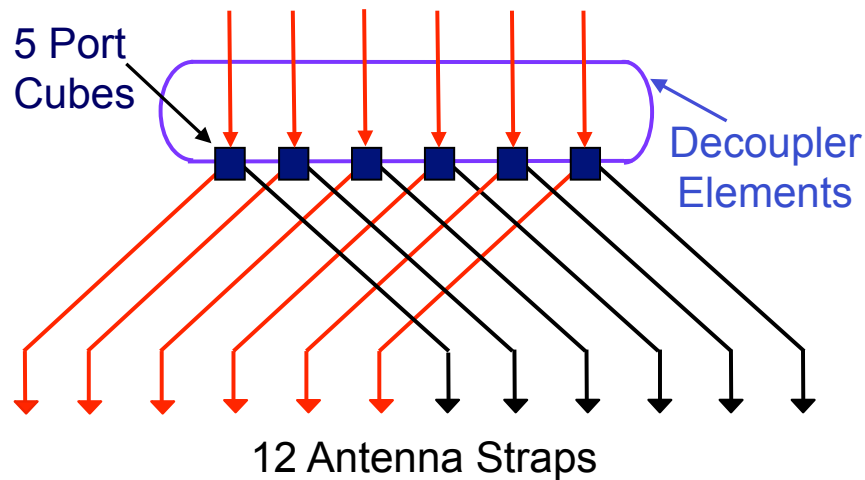
# NSTX HHFW SYSTEM

# Well defined HHFW antenna spectrum, ideal for studying phase dependence of heating and CD



12-strap antenna extends toroidally  $90^\circ$

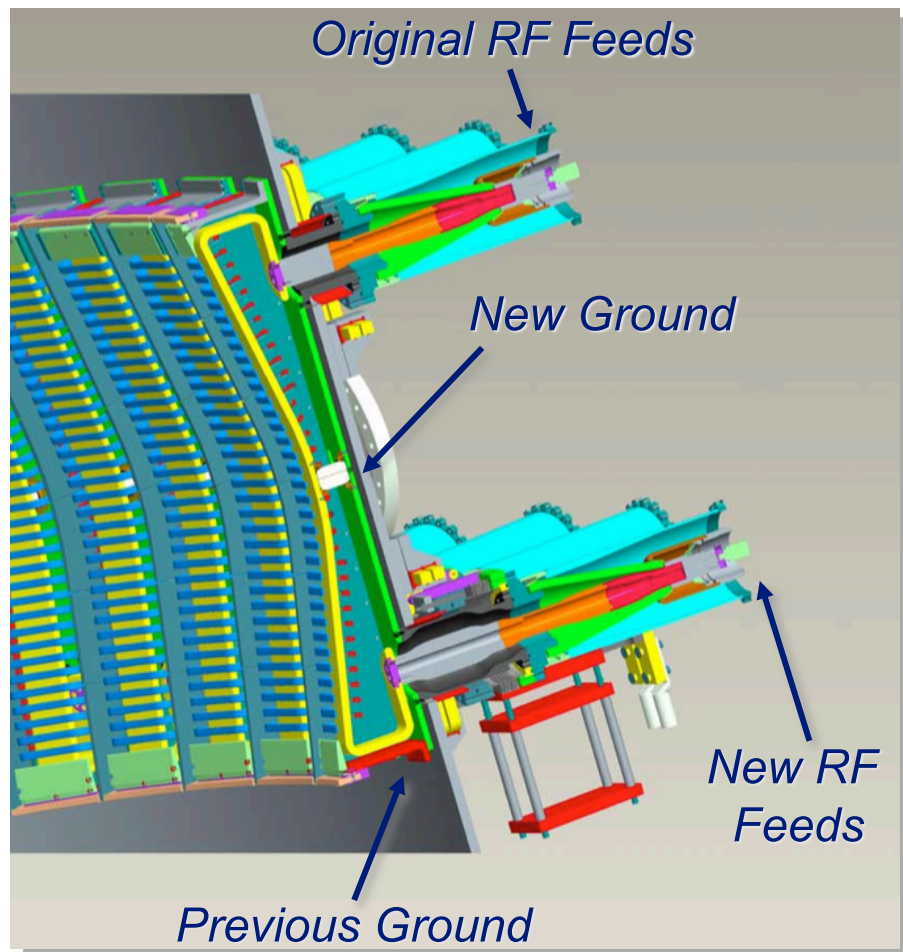
30 MHz Power Sources



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



## Arc-free HHFW power limited to $\leq 1.4$ MW in 2010



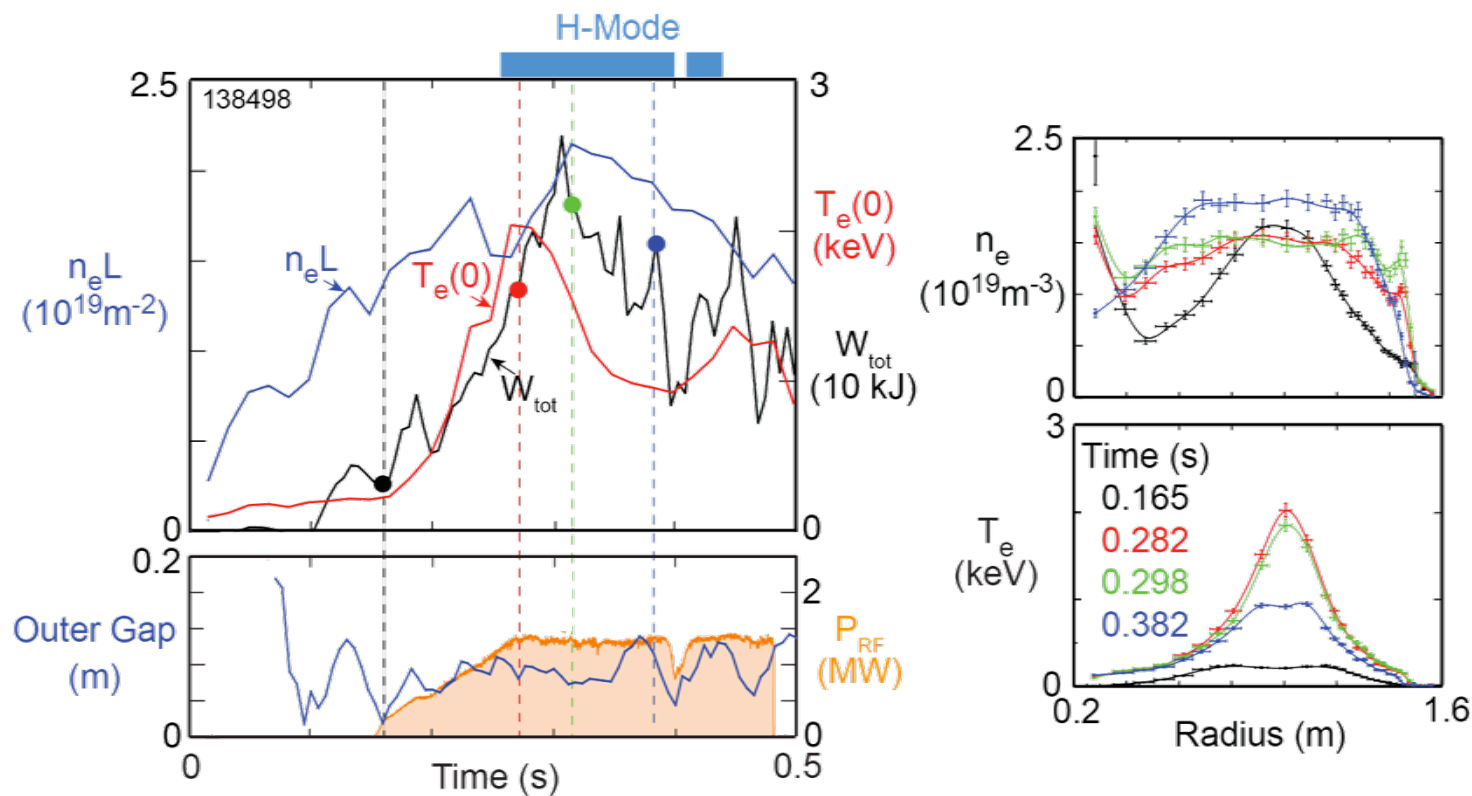
- Double feed antenna upgrade in 2009 designed to bring system voltage limit with plasma ( $\sim 15$  kV) to limit in vacuum ( $\sim 25$  kV):
  - Increasing  $P_{RF} \sim 2.8$  times
- Upgrade was beneficial; reached arc-free  $P_{RF} \sim 4$  MW after a few weeks of operation at the end of 2009 run
- 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  
 $I_p = 300 \text{ kA H-Mode}$

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

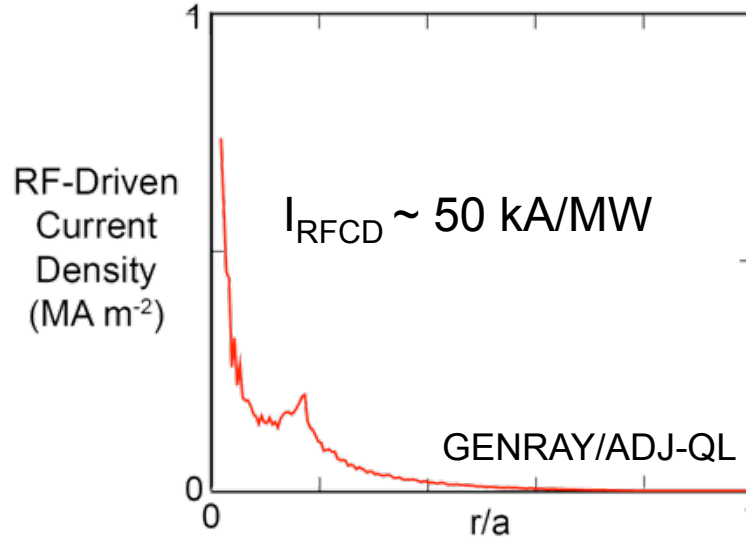
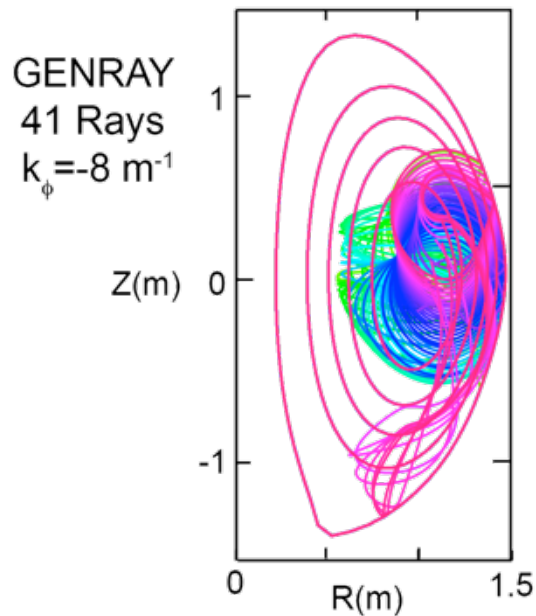
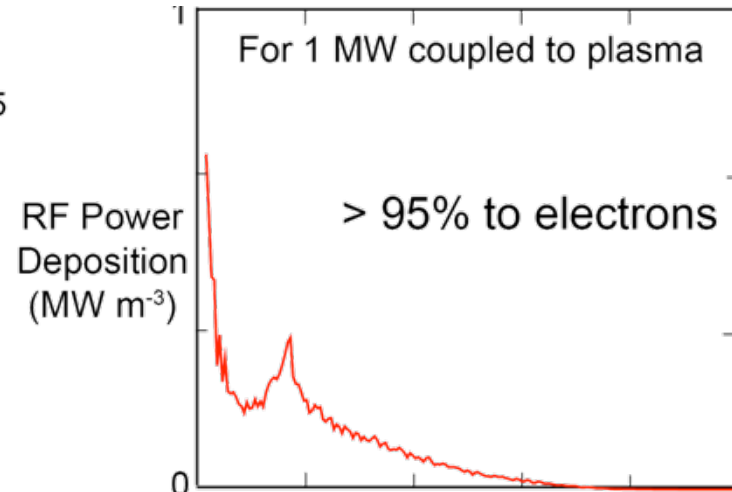
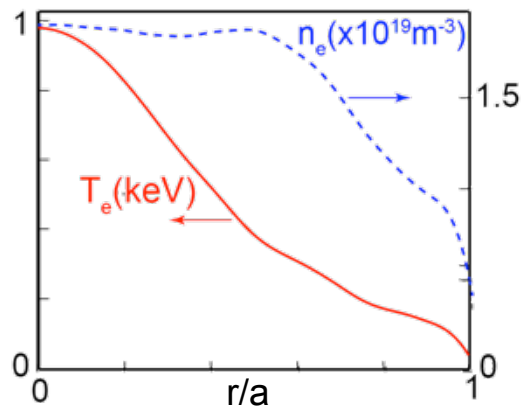
- Large initial increase in  $T_e(0)$  and  $W_{tot}$  as RF power ramped up
- However  $T_e(0)$  and  $W_{tot}$  collapsed near start of RF power flat top
- PCS controlled antenna-plasma outer gap through the L-H transition and during most of the H-mode, except at a large MHD event  $\sim 0.39$  s



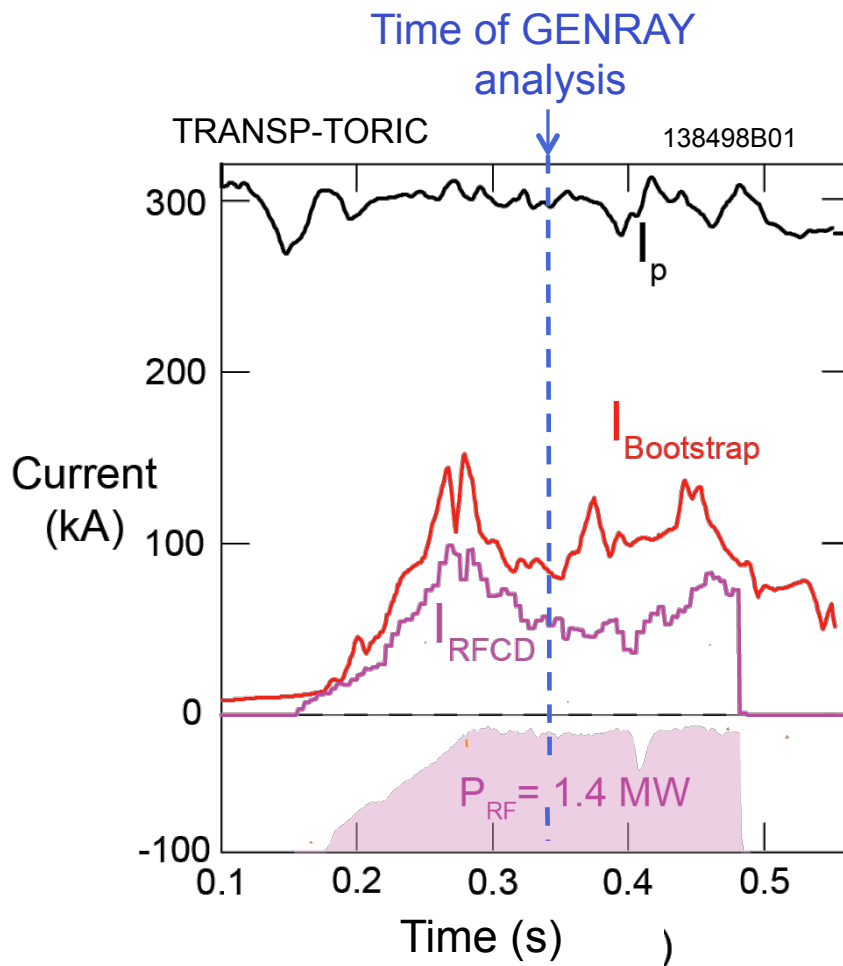
$I_p = 300$  kA  
 $B_T(0) = 0.55$  T  
 Deuterium  
 $k_\phi = -8 \text{ m}^{-1}$

# GENRAY predicts that if RF coupling efficiency, $\eta_{\text{eff}} \sim 100\%$ , 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



# Time dependent TRANSP-TORIC modeling, assuming $\eta_{\text{eff}} = 100\%$ , also predicts sustained heating and current drive



- The observed decrease in core electron heating appears to be due to a large drop in  $\eta_{\text{eff}}$  during the RF pulse

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

- At 0.382 s:

$$\Delta W_T \sim 15 \text{ kJ}$$

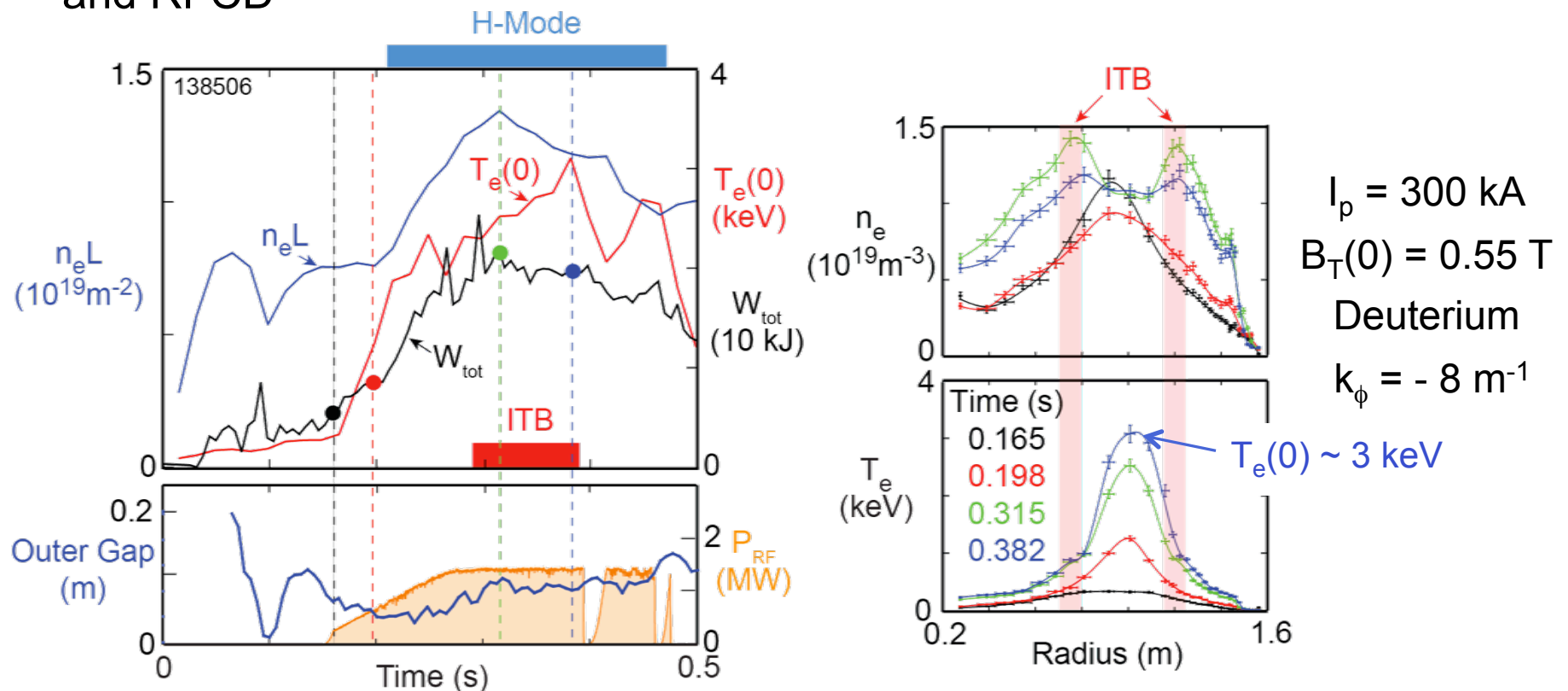
$$\tau \sim 20 \text{ ms}$$

$$P_{\text{RF}} \sim 1.4 \text{ MW}) \rightarrow \eta_{\text{eff}} \sim 50\%$$

For $\eta_{\text{eff}} = 50\%$	
$I_{\text{BS}}$	50 kA
$I_{\text{RF}}$	25 kA
$f_{\text{NI}}$	0.25

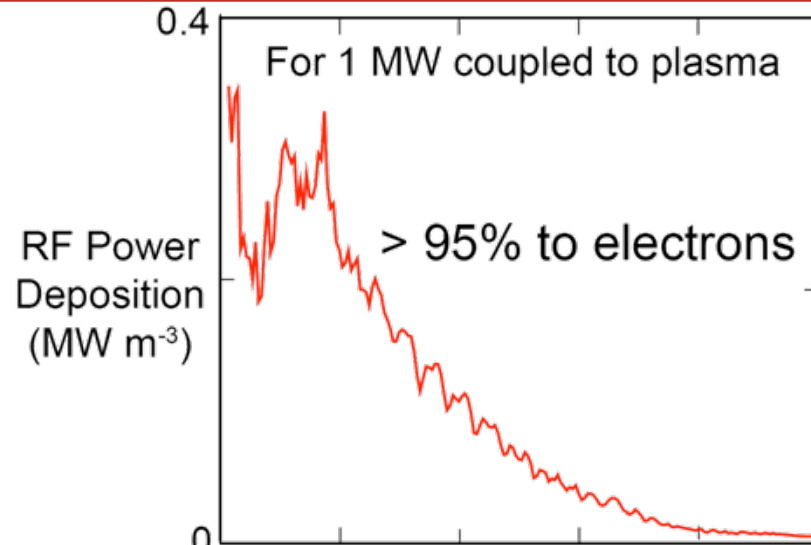
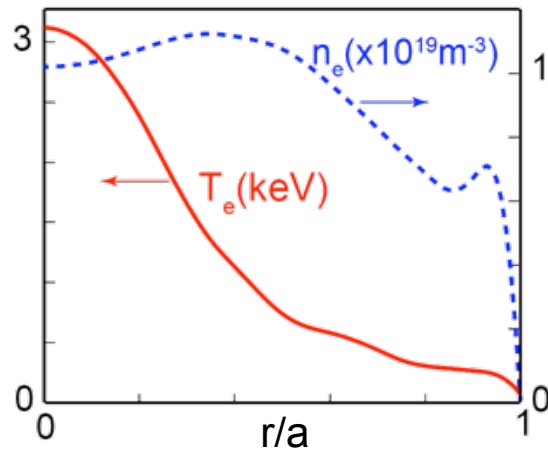
# Eventually achieved sustained $I_p = 300$ kA H-mode with internal transport barrier (ITB) by lowering plasma density

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

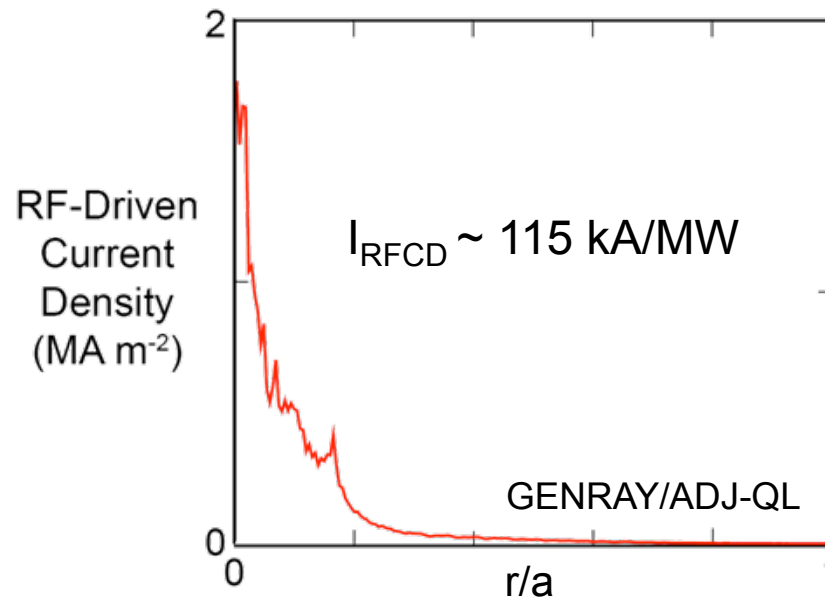
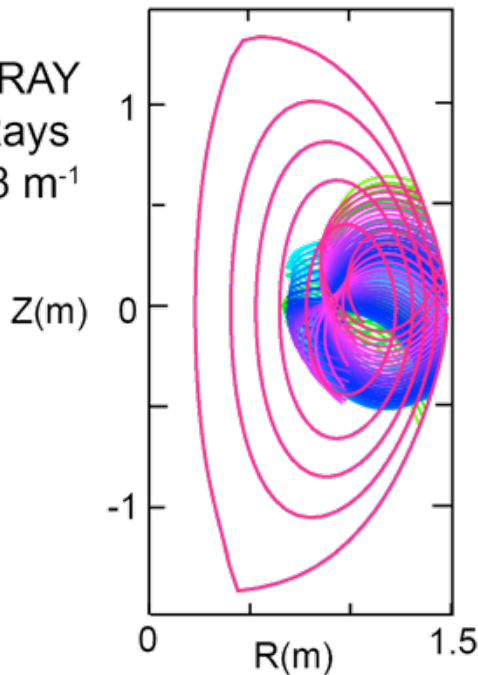


# GENRAY predicts peaked RF deposition on electrons and RF CD efficiency of 115 kA/MW

Shot 138506  
 Time = 0.382 s  
 $I_p = 300$  kA  
 $B_T = 5.5$  kG  
 Deuterium  
 RF H-mode



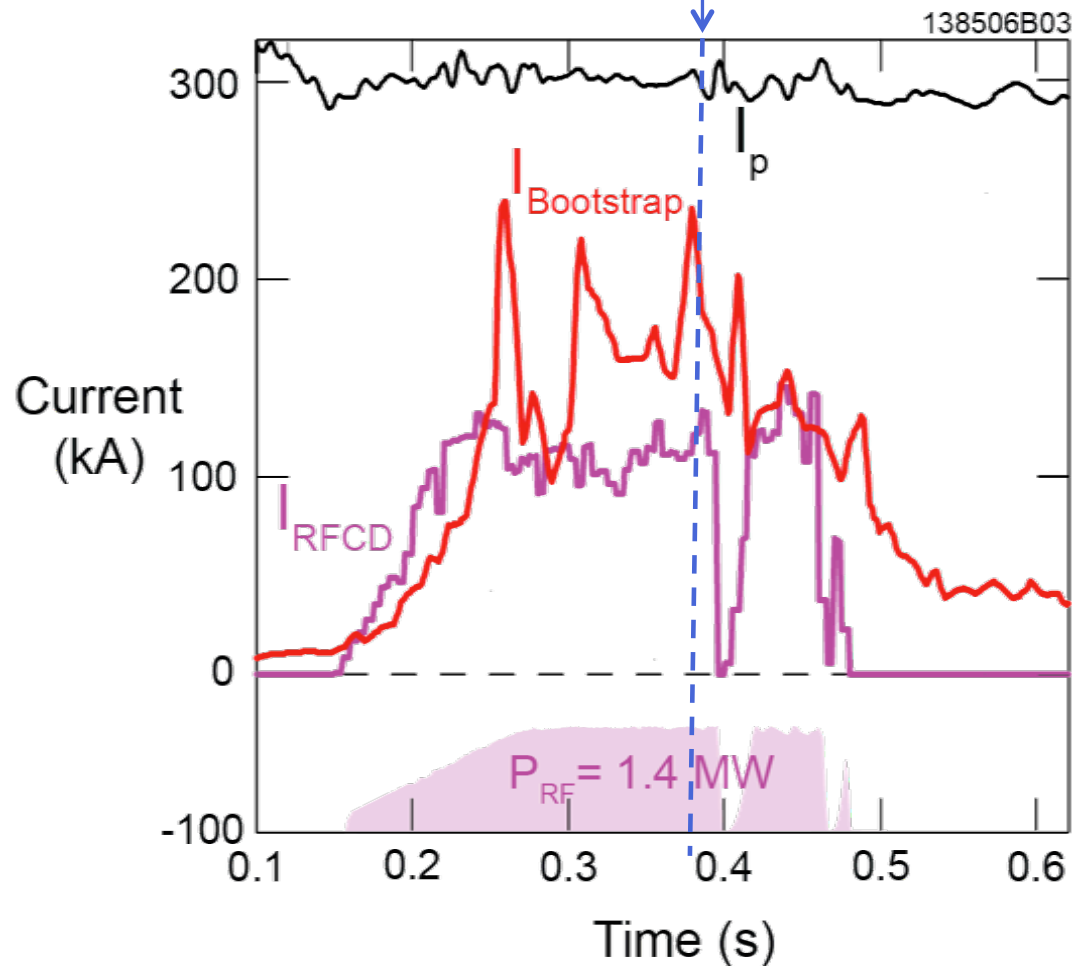
GENRAY  
 41 Rays  
 $k_\phi = -8 \text{ m}^{-1}$



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

TORIC-TRANSP modeling for  $\eta_{\text{eff}} = 100\%$

Time of GENRAY-ADJ analysis

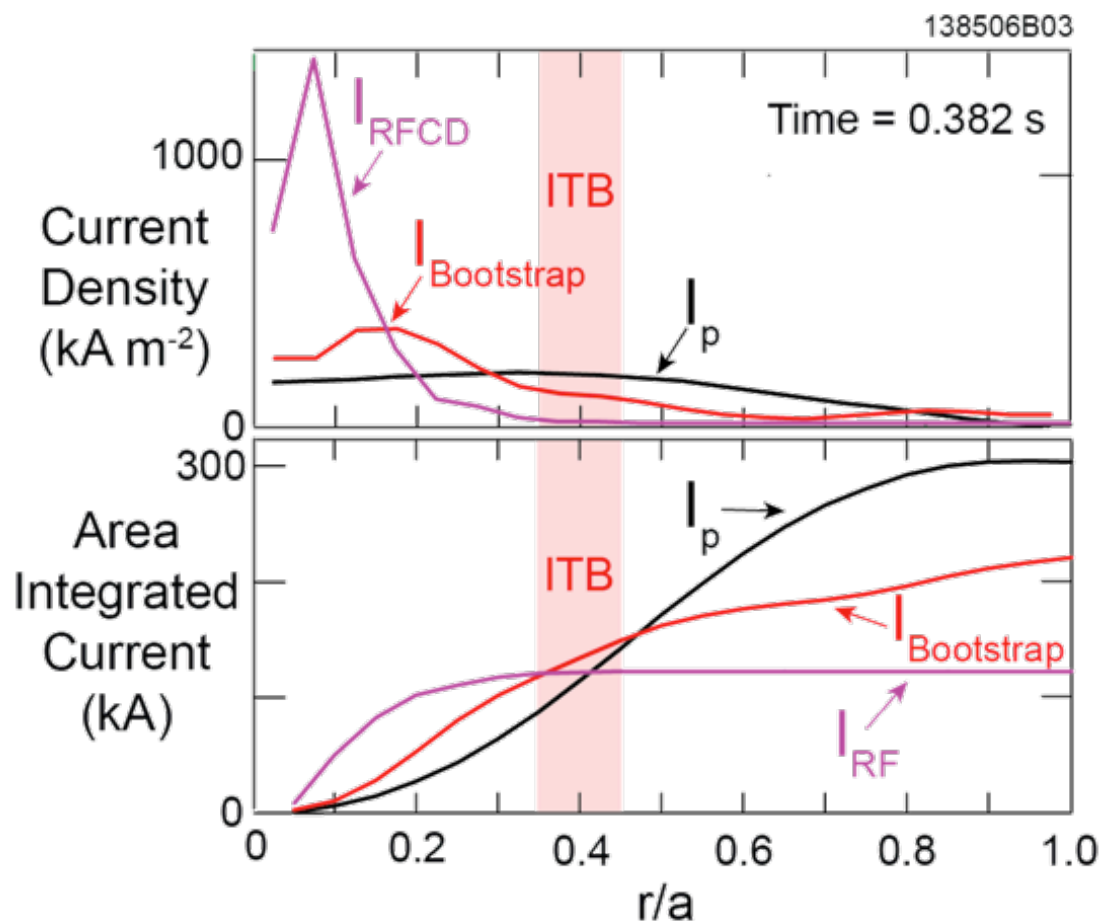


- TRANSP-TORIC predicts 85 kA/MW at GENRAY analysis time:
  - GENRAY  $\sim 115 \text{ kA/MW}$



80% of the non-inductive current was generated inside ITB;  
 Actual  $\eta_{\text{eff}} \sim 60\% \rightarrow f_{\text{NI}} \sim 0.65$

TORIC-TRANSP modeling for  $\eta_{\text{eff}} = 100\%$



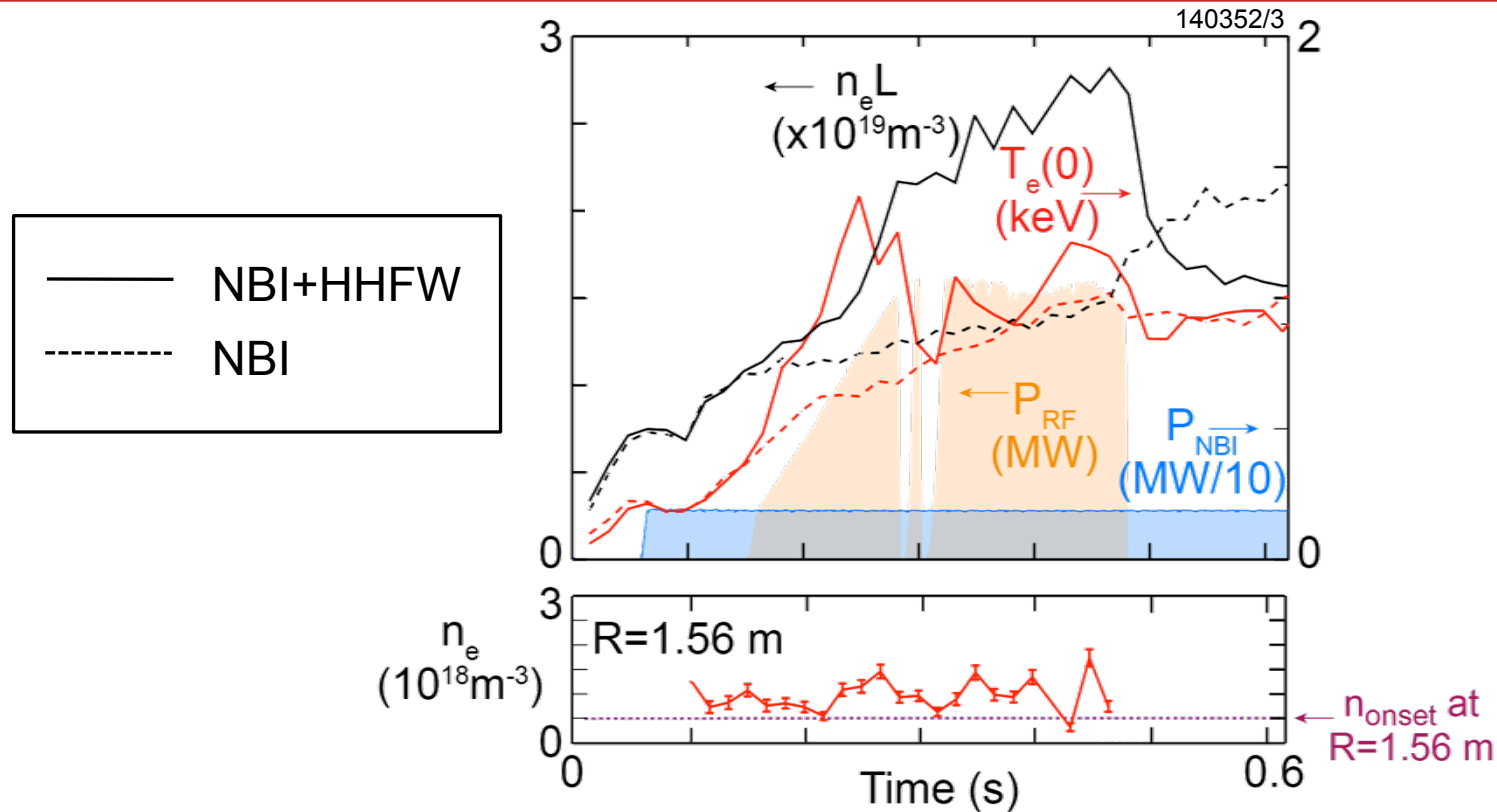
- $\eta_{\text{eff}} = \Delta W_T / (\tau * P_{\text{RF}})$   
 $\Delta W_T \sim 15 \text{ kJ}$   
 $\tau \sim 15 \text{ ms}$   
 $P_{\text{RF}} \sim 1.4 \text{ MW}$   
 $\rightarrow \eta_{\text{eff}} \sim 60\%$

For  $\eta_{\text{eff}} = 60\%$

$I_{\text{BS}}$	130 kA
$I_{\text{RF}}$	70 kA
$f_{\text{NI}}$	0.65

HHFW-Heated  $I_p = 300$  kA  
NBI H-Mode

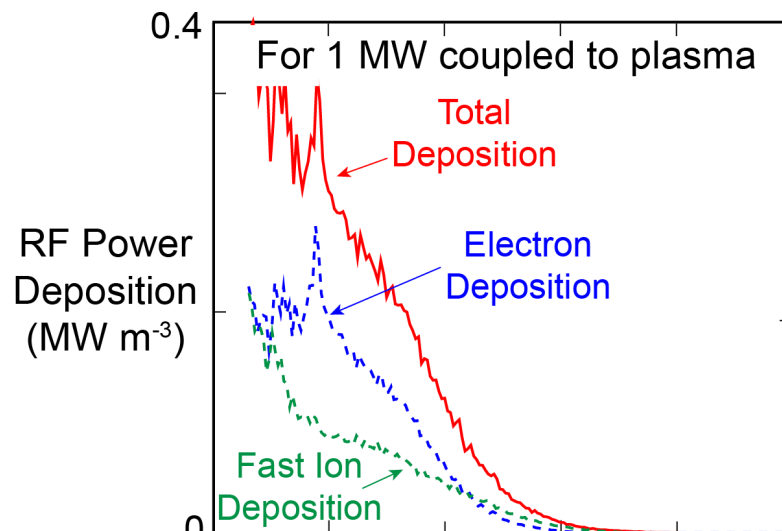
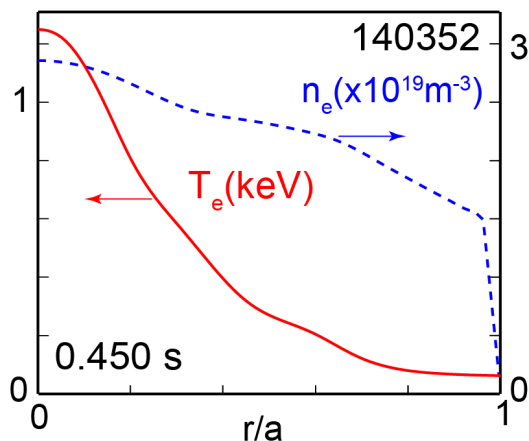
# Coupling $P_{RF} = 1.4$ MW into $I_p = 300$ kA, $P_{NBI} = 2$ MW H-mode resulted in significant RF acceleration of fast ions



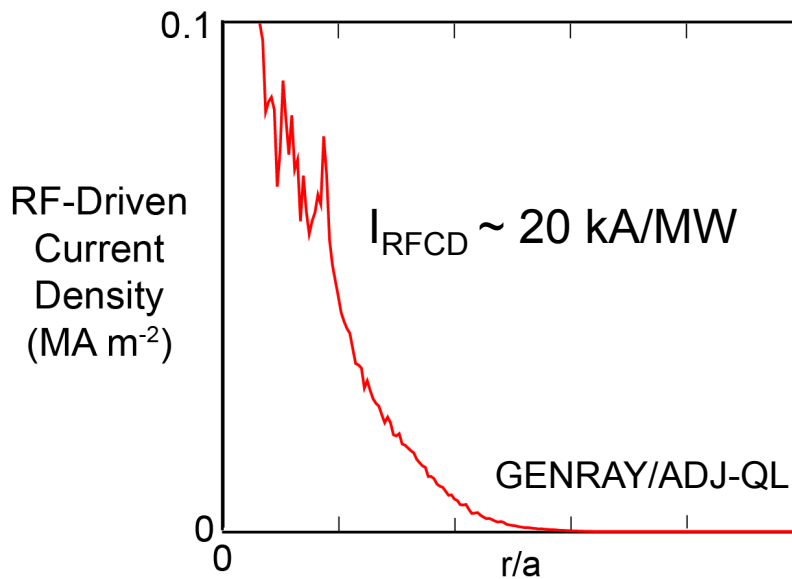
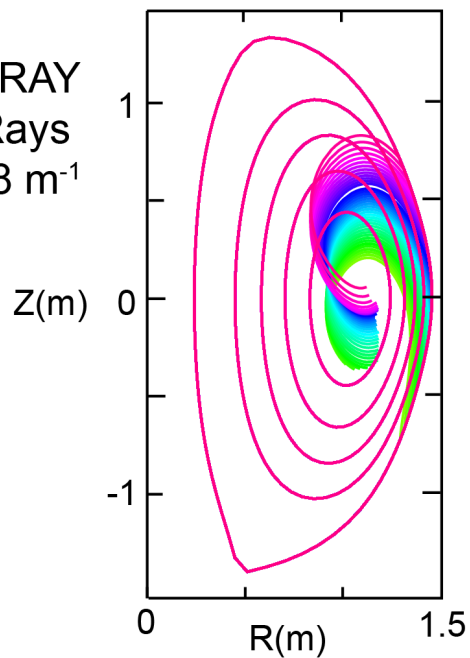
- 50% of injected NBI fast-ions promptly lost at this low  $I_p$
- Core density increased during HHFW heating due to fast-ion interaction with the antenna
- $n_e @R = 1.56$  m  $>$  onset density for fast-wave propagation ( $n_{onset}$ )  
 $\rightarrow \eta_{eff}$  only  $\sim 40\%$

# 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

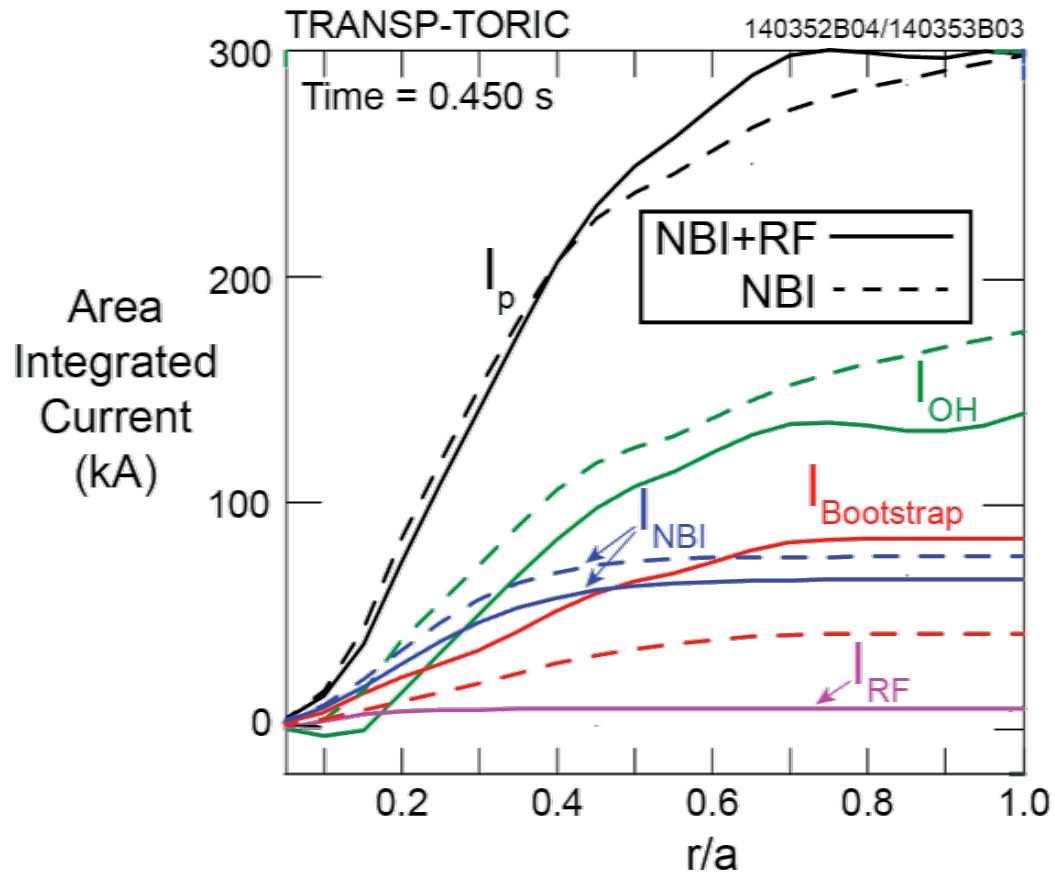


GENRAY  
 41 Rays  
 $k_\phi = -8 \text{ m}^{-1}$



NBI+HHFW H-mode only produced  $f_{NI} \sim 0.45$ , due to RF-interaction with fast ions, lower  $T_e(0)$  and  $\eta_{eff}$ , and higher  $n_e$

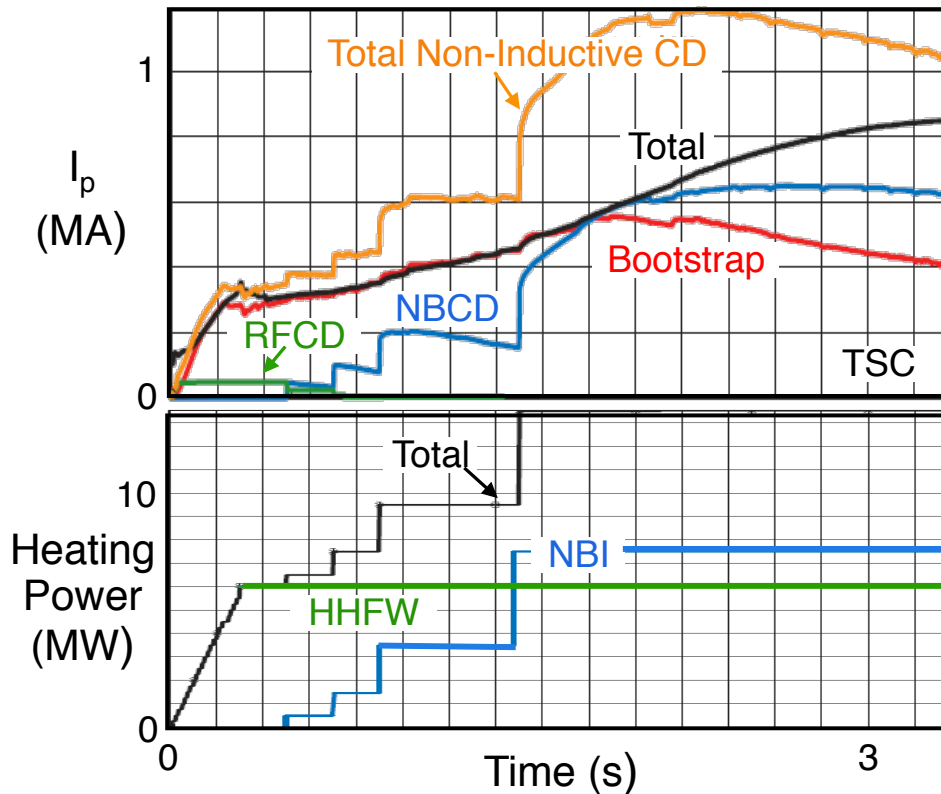
TORIC-TRANSP modeling for  $\eta_{eff} = 100\%$ :



For  $\eta_{eff} \sim 40\%$ :

	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 $B_T(0) = 1\text{T}$ & 2<sup>nd</sup> NBI system



- Simulation of non-inductive  $I_p$  ramp-up at  $B_T(0) = 1\text{ T}$  predicts  $I_p \sim 1\text{ MA}$  is possible
- 6 MW HHFW Co-CD phasing ( $k_{\parallel} = 8\text{ m}^{-1}$ ) used at beginning of  $I_p$  ramp-up:
  - 7 MW NBI added when  $I_p \geq 600\text{kA}$
  - 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  $T_e(0) \sim 3$  keV, an ITB and  $f_{NI} \sim 0.65$ 
  - A combination of massive Li injection, no boronization, and no between shots glow in 2010 limited arc-free  $P_{RF}$  to  $\leq 1.4$  MW
- Attempts to heat  $I_p = 300$  kA NBI H-mode with  $P_{RF} = 1.4$  MW produced only  $f_{NI} \sim 0.45$  due to significant RF power deposition on fast-ions
- Experiments originally planned for this year to extend the low  $I_p$  HHFW H-mode experiments to  $f_{NI} \geq 1$  using  $P_{RF} \sim 3-4$  MW were cancelled due to the 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