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HHFW Coupling into High Bootstrap Fraction RF H-Modes in NSTX*

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G. Taylor

S.P. Gerhardt, J.C. Hosea, C. Kessel, B.P. LeBlanc, D. Mueller, J.R. Wilson, S. Zweben and the NSTX Team

Princeton Plasma Physics Laboratory

R. Maingi, P.M. Ryan, J.R. Wilgen

Oak Ridge National Laboratory

R. Raman

University of Washington

*Work supported by US DoE contracts DE-AC02-09CH11466 and DE-AC05-00OR2272

US-EU-Japan RF Technology Workshop
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Outline

- Role of HHFW in NSTX fully non-inductive startup
- Earlier low I_p HHFW heating results in NSTX
- Recent results from low I_p RF H-mode experiments
- Summary, plans & proposed collaboration

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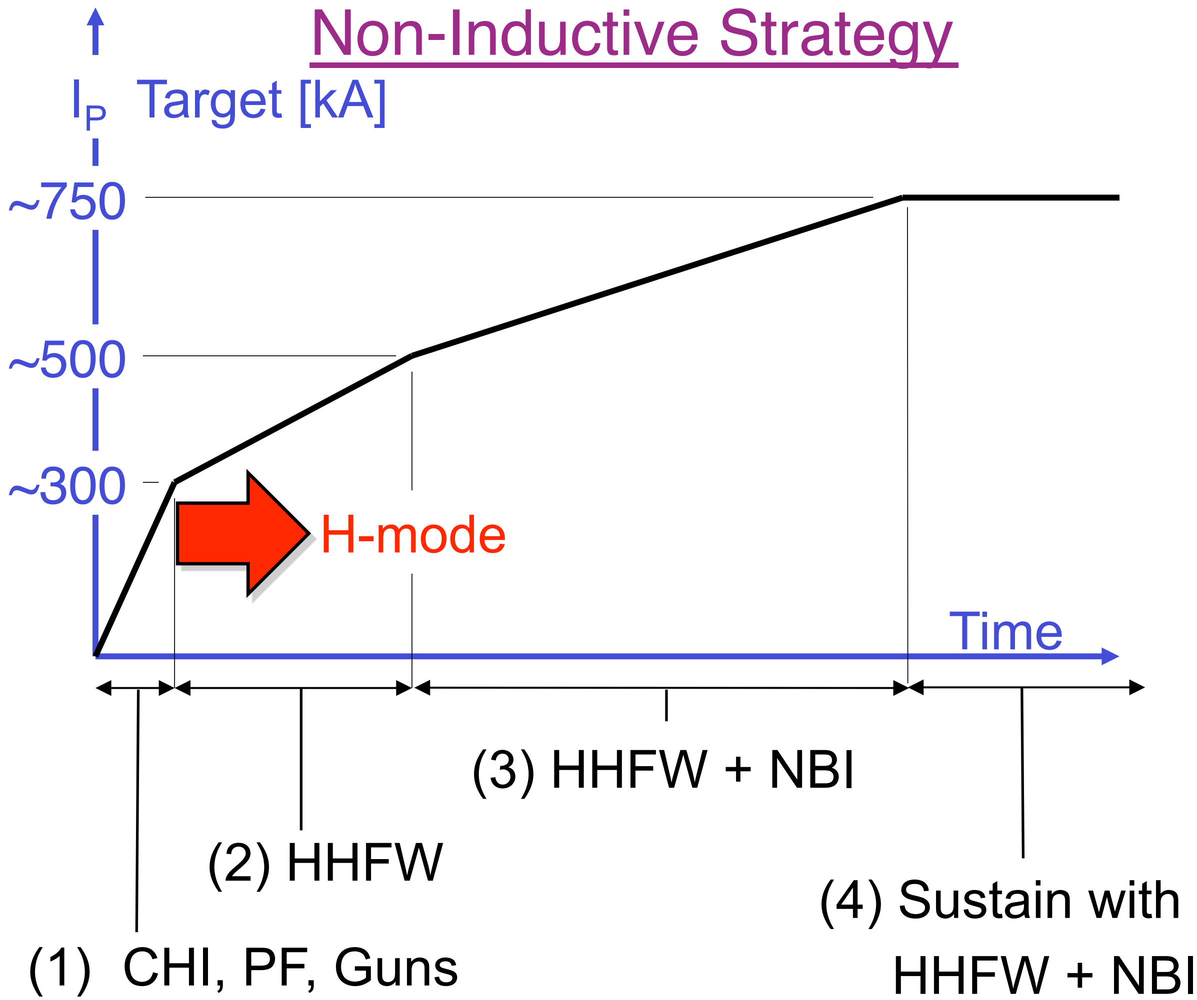
Early HHFW heating drives plasma into H-mode providing I_p overdrive from bootstrap current

- Ultimately Spherical Torus needs to run non-inductively

Non-Inductive Strategy



Role of HHFW

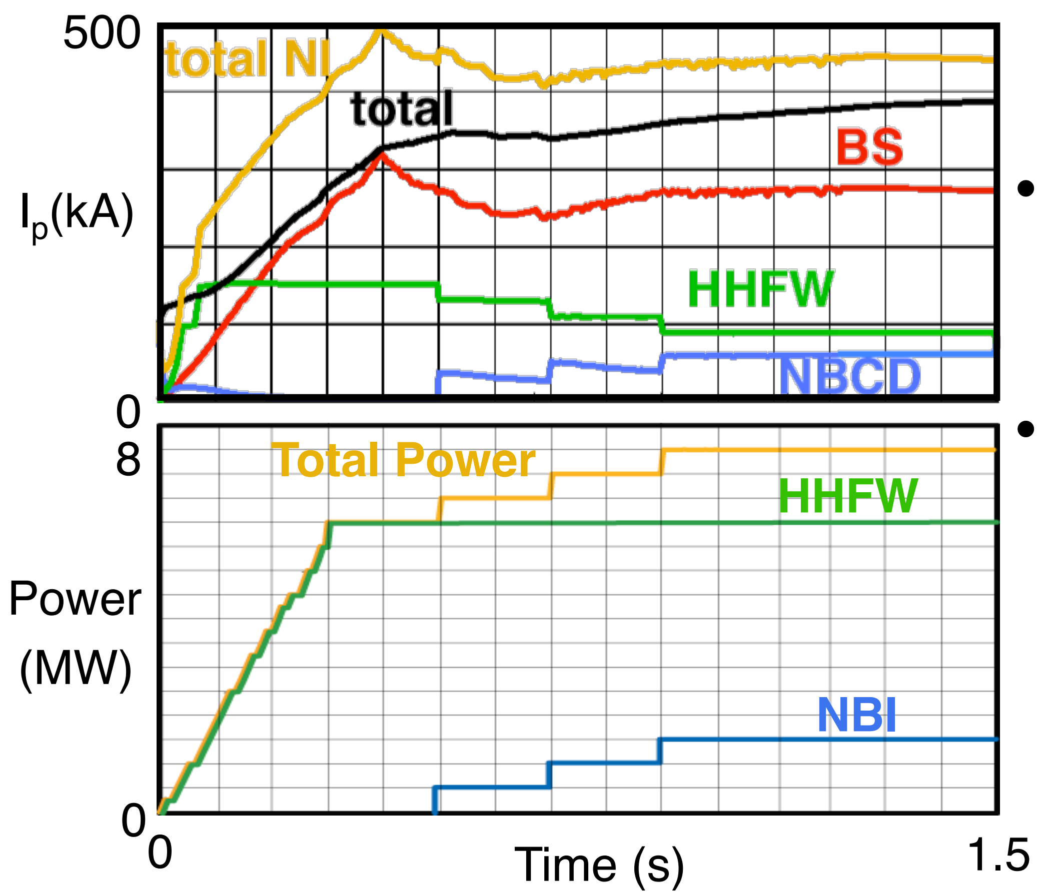
(1) HHFW couples to start-up plasma

(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

Modeling predicts 5-6 MW of HHFW power can achieve fully non-inductive I_p ramp-up in NSTX



- Tokamak Simulation Code used to model I_p ramp-up
- 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

- 5-6 MW of HHFW projected to result in bootstrap current overdrive

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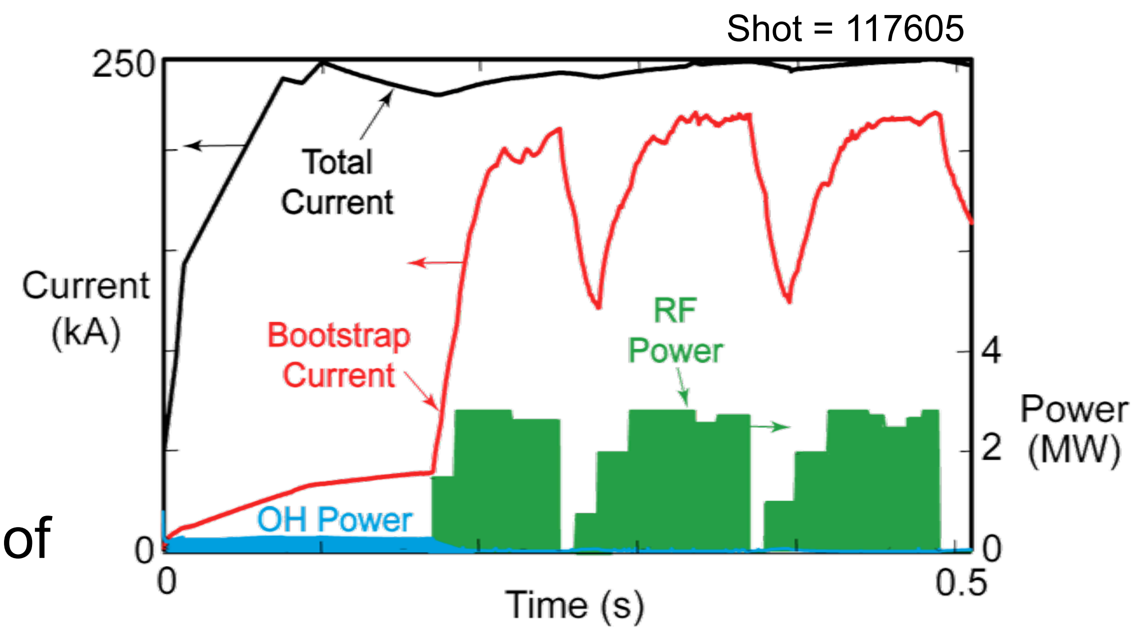
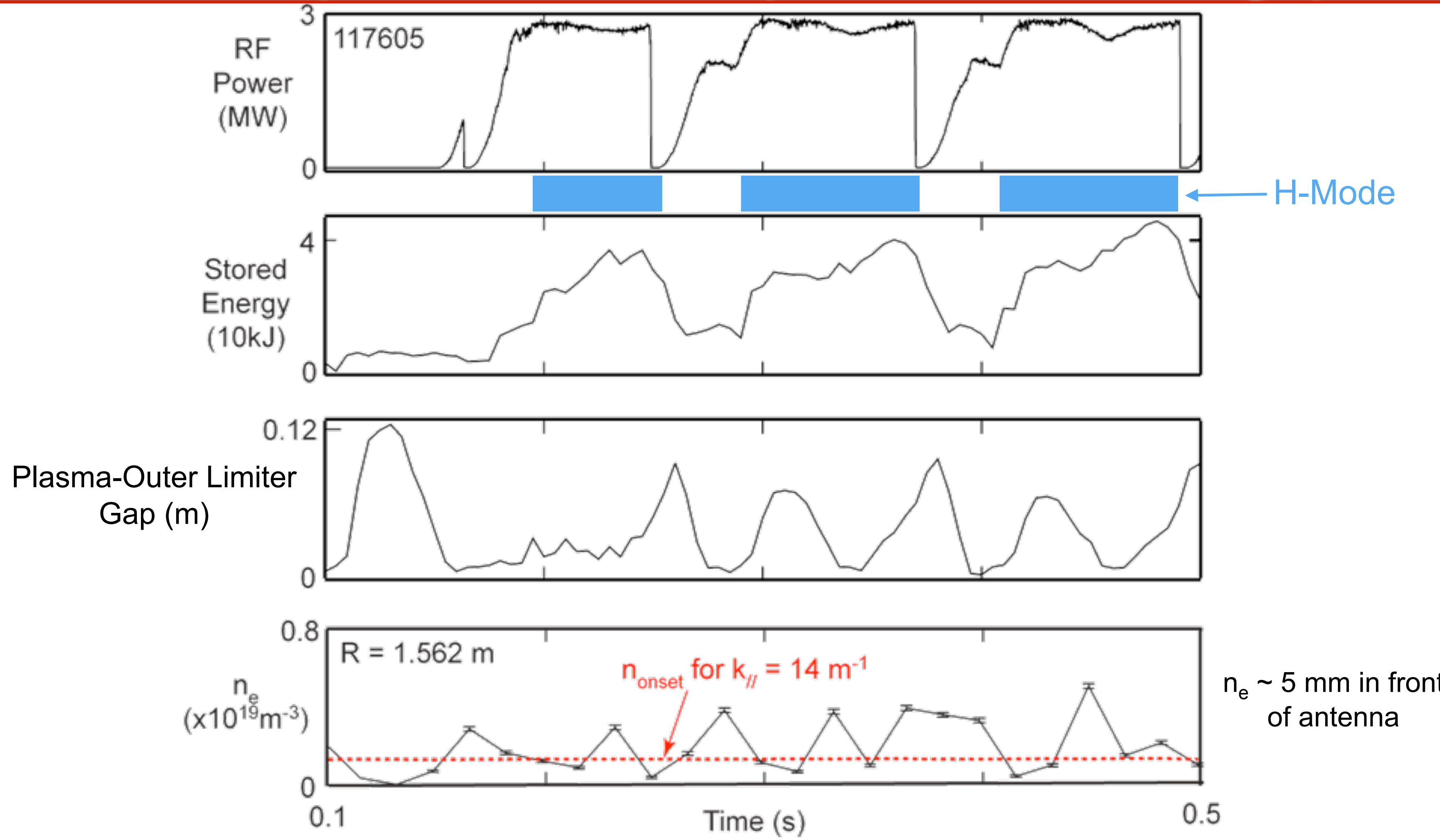
Low I_p experiments in 2005 generated ~ 80% bootstrap current, but did not maintain RF coupling

- 65-80% bootstrap current generated in HHFW heated D_2 H-mode plasmas at I_p = 250 kA
- Transiently produced H-mode, $V_{loop} \leq 0$ and $dI_{OH}/dt \approx 0$
- H-mode needed for effective replacement of inductive current



- Could not maintain RF coupling during H-mode

Large changes in stored energy during RF H-mode result in poor control of plasma-antenna gap



- Also difficult to control density near antenna to be at or below fast wave propagation onset density ($n_e \leq n_{onset}$)

Plasma control system (PCS) could not maintain plasma shape & position during low I_p H-mode

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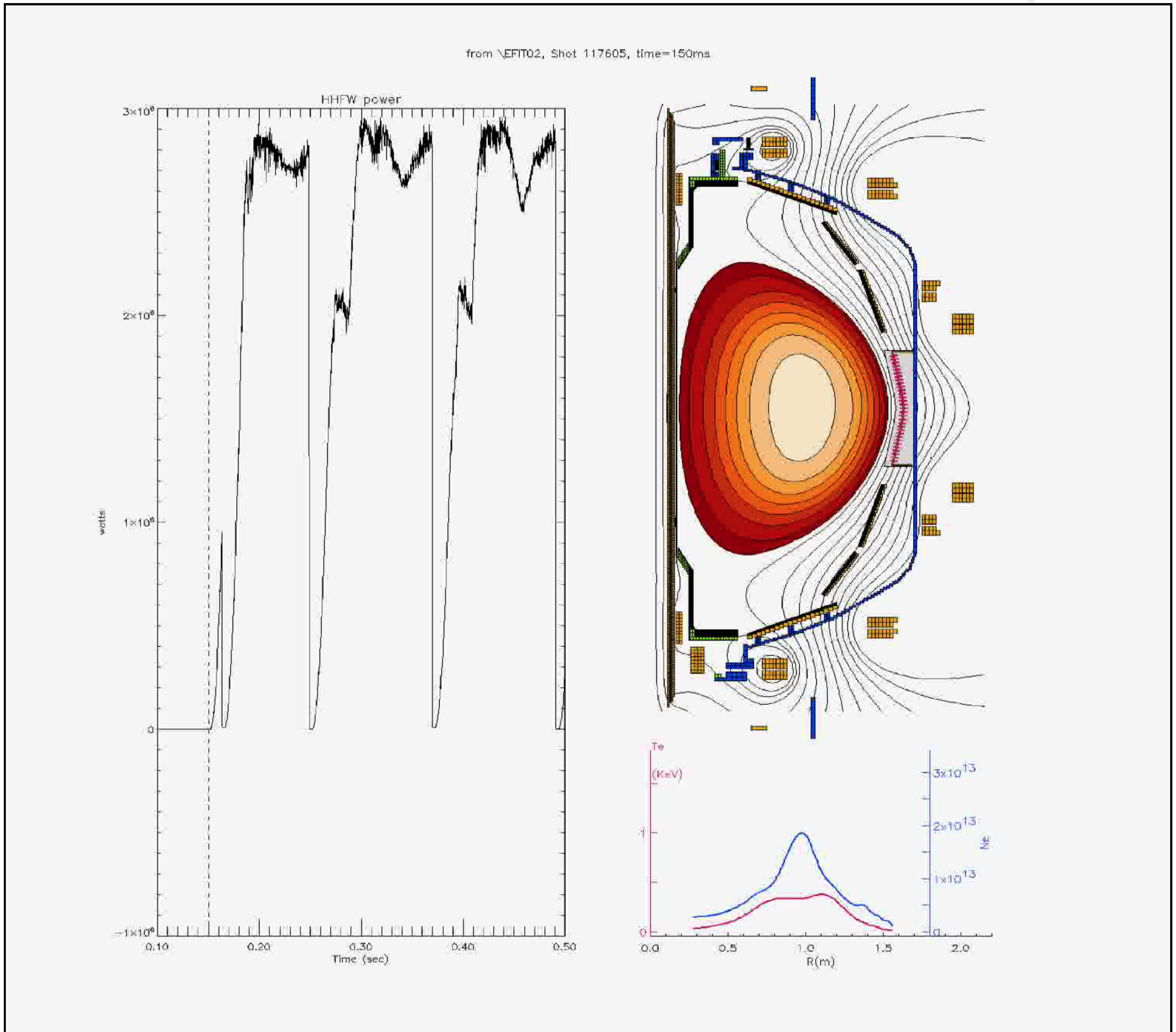
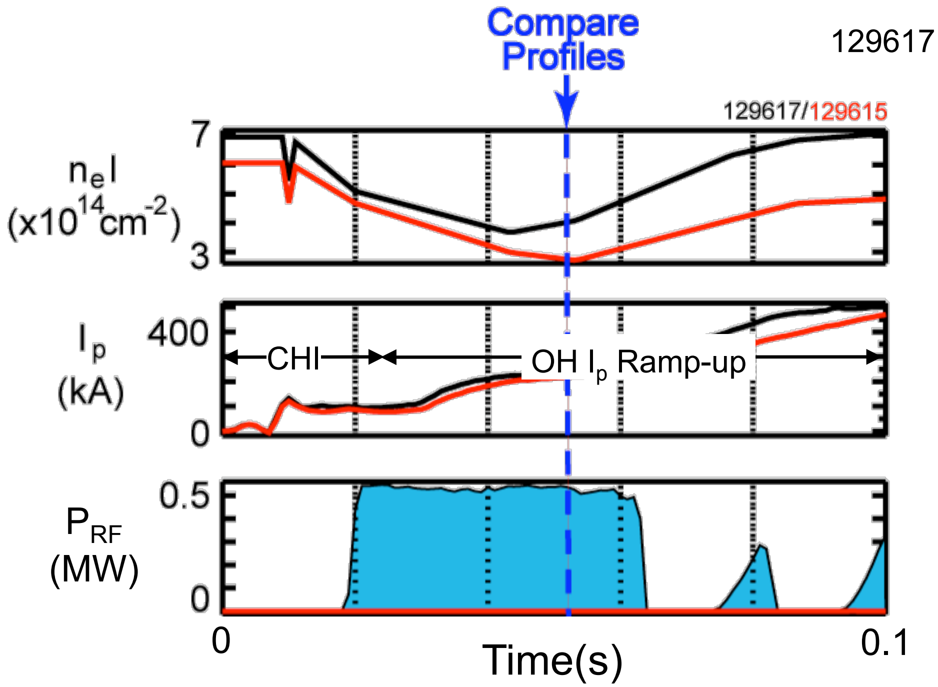
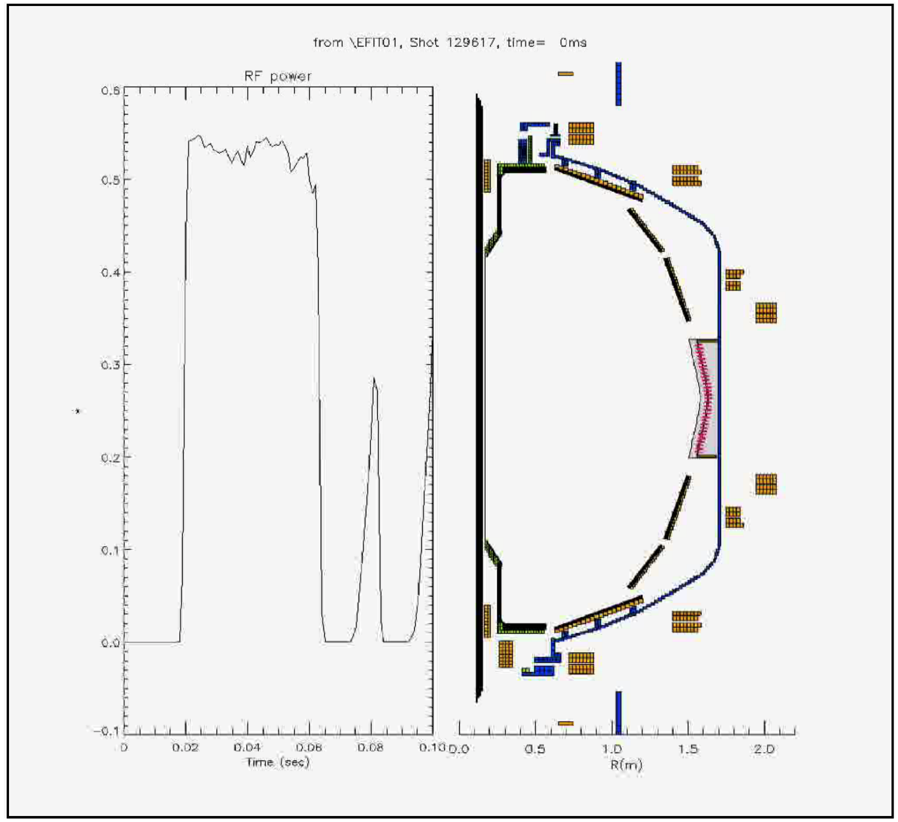


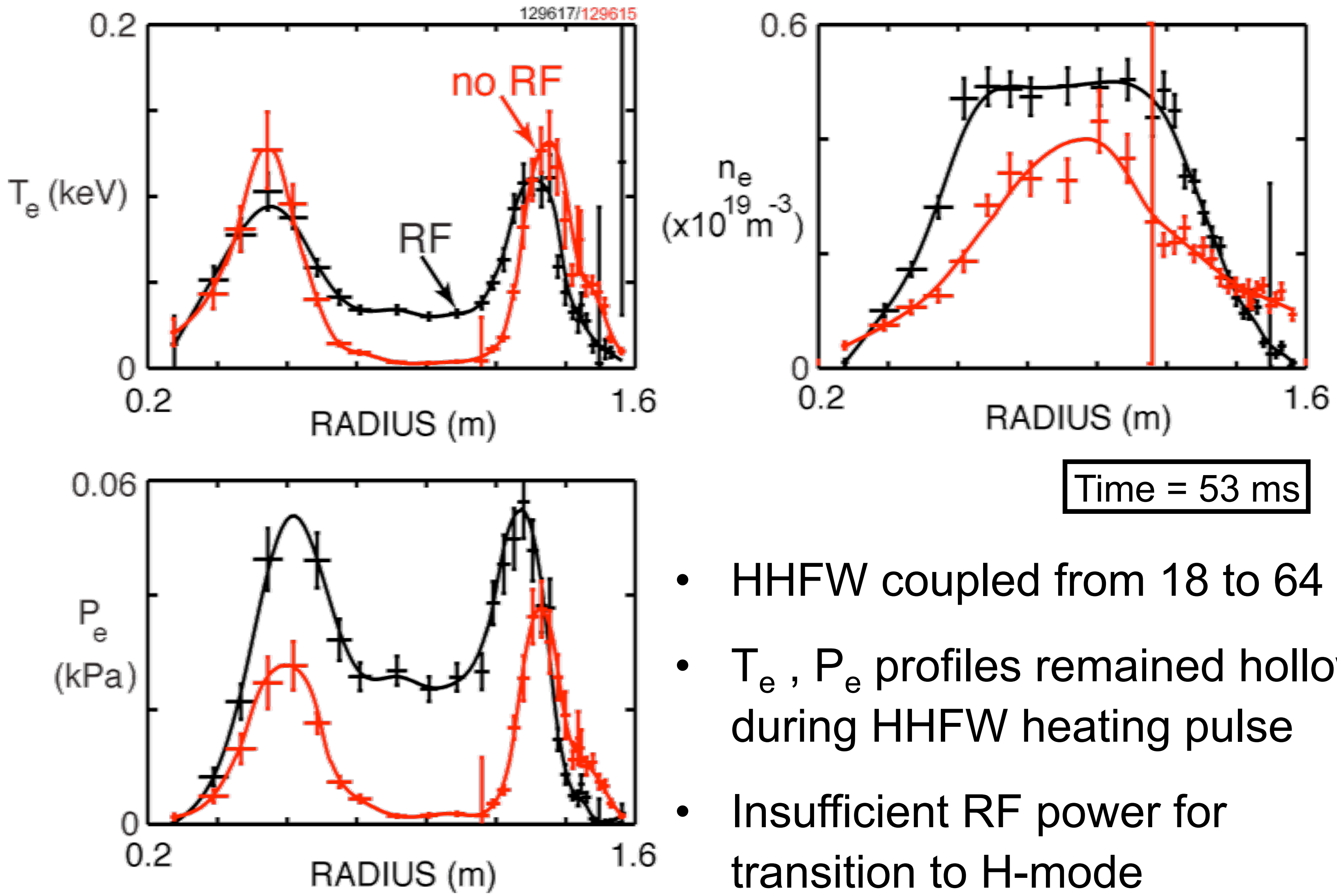
HHFW power coupled during transition from Coaxial Helicity Injection (CHI) start-up to I_p ramp-up





- 550 kW of RF power coupled when I_p was ramping from 100 to 300 kA
- Poor plasma position control resulted in RF power trip

Despite plasma control problems HHFW did heat during I_p ramp-up from 100 to 300 kA



Time = 53 ms

- HHFW coupled from 18 to 64 ms
- T_e , P_e profiles remained hollow during HHFW heating pulse
- Insufficient RF power for transition to H-mode

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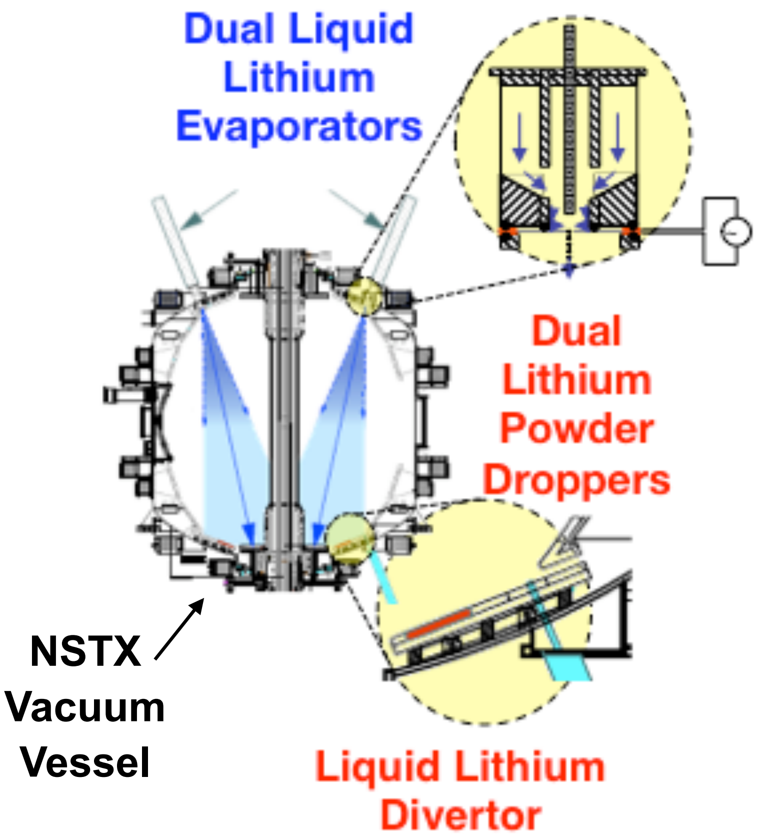
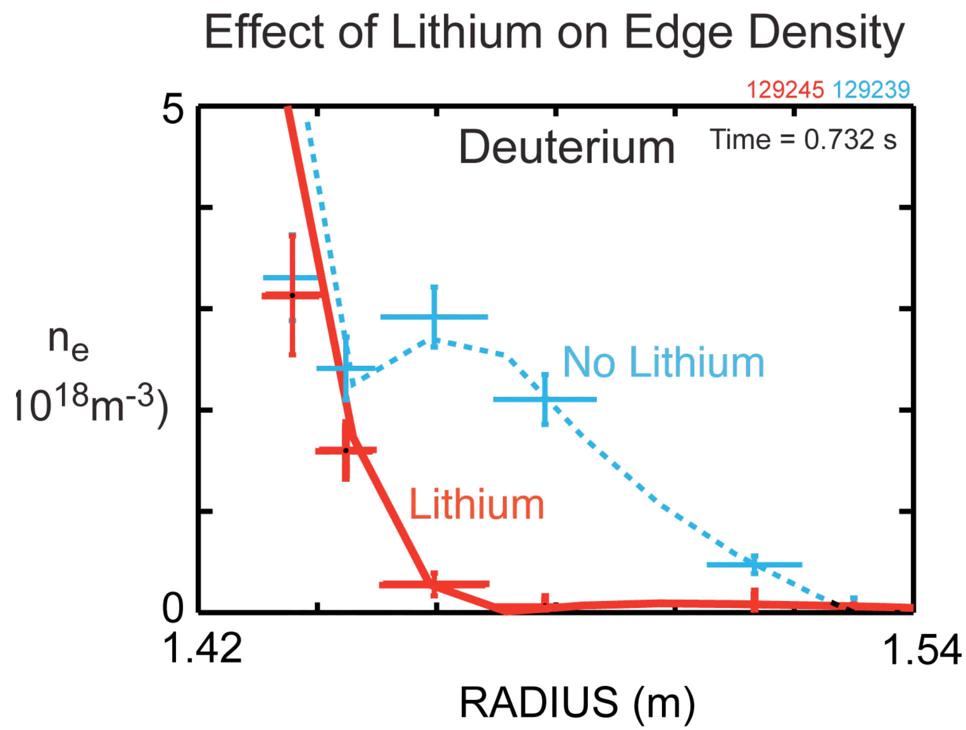
Recent upgrades to NSTX and HHFW system support low I_p RF H-mode operation

- Double feed antenna upgrade may improve rf coupling resilience during low I_p plasma operation:
  - Maintain rf coupling during large variations in antenna-plasma gap during L-H transition
- Major upgrade to the NSTX PCS produced 700% increase in processor speed:
  - Latency between between stimulus signal and control response now only 0.6 ms, 5 times shorter than earlier PCS

Li conditioning reduces edge n_e ➡ moves n_{onset} off antenna, reducing RF power to vessel wall

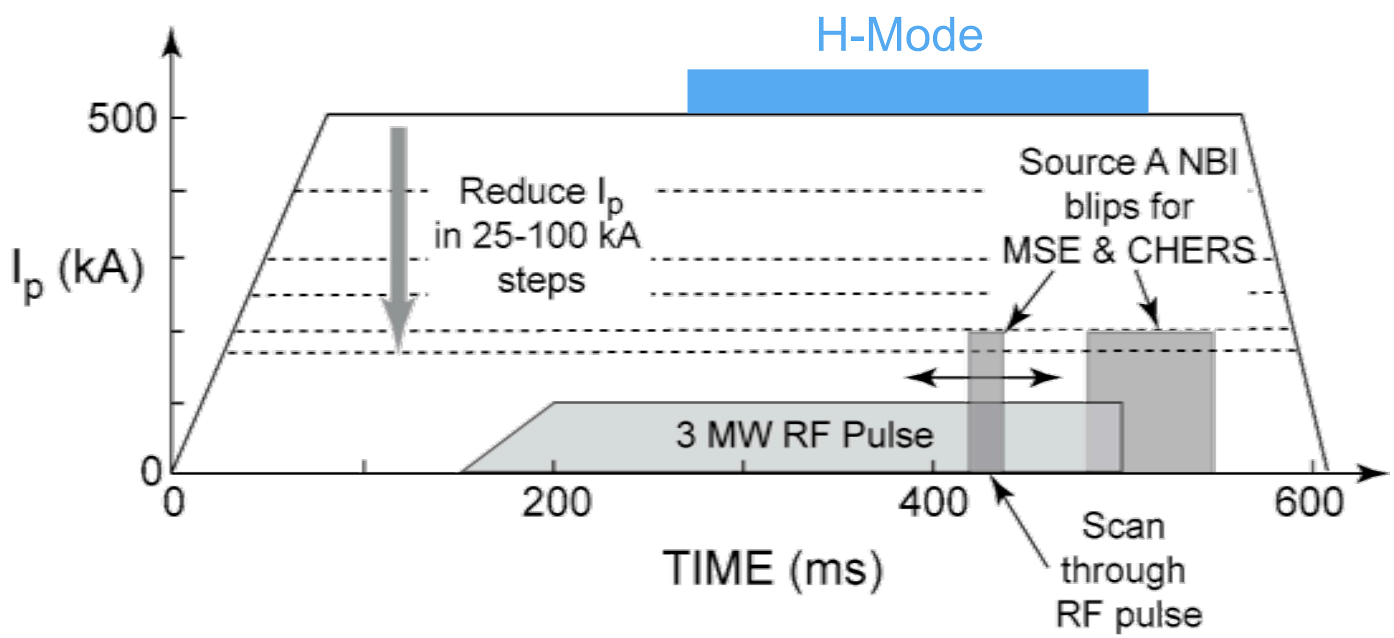




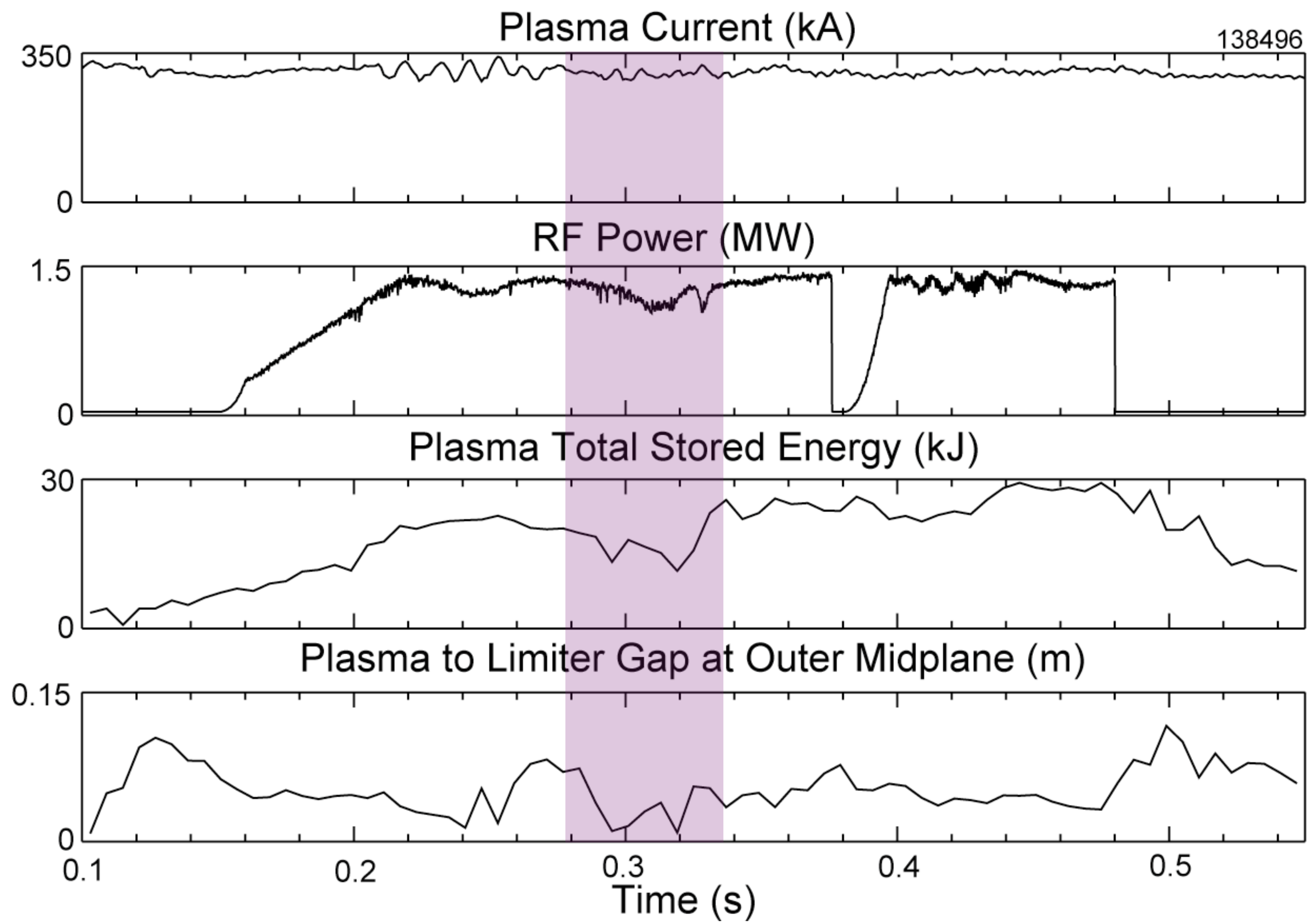
- However, Li deposited on the antenna and Faraday shield contributed to arcing, requiring extensive vacuum and plasma conditioning

Low I_p RF H-mode experiments in 2010 focused on achieving 100% RF-driven non-inductive current

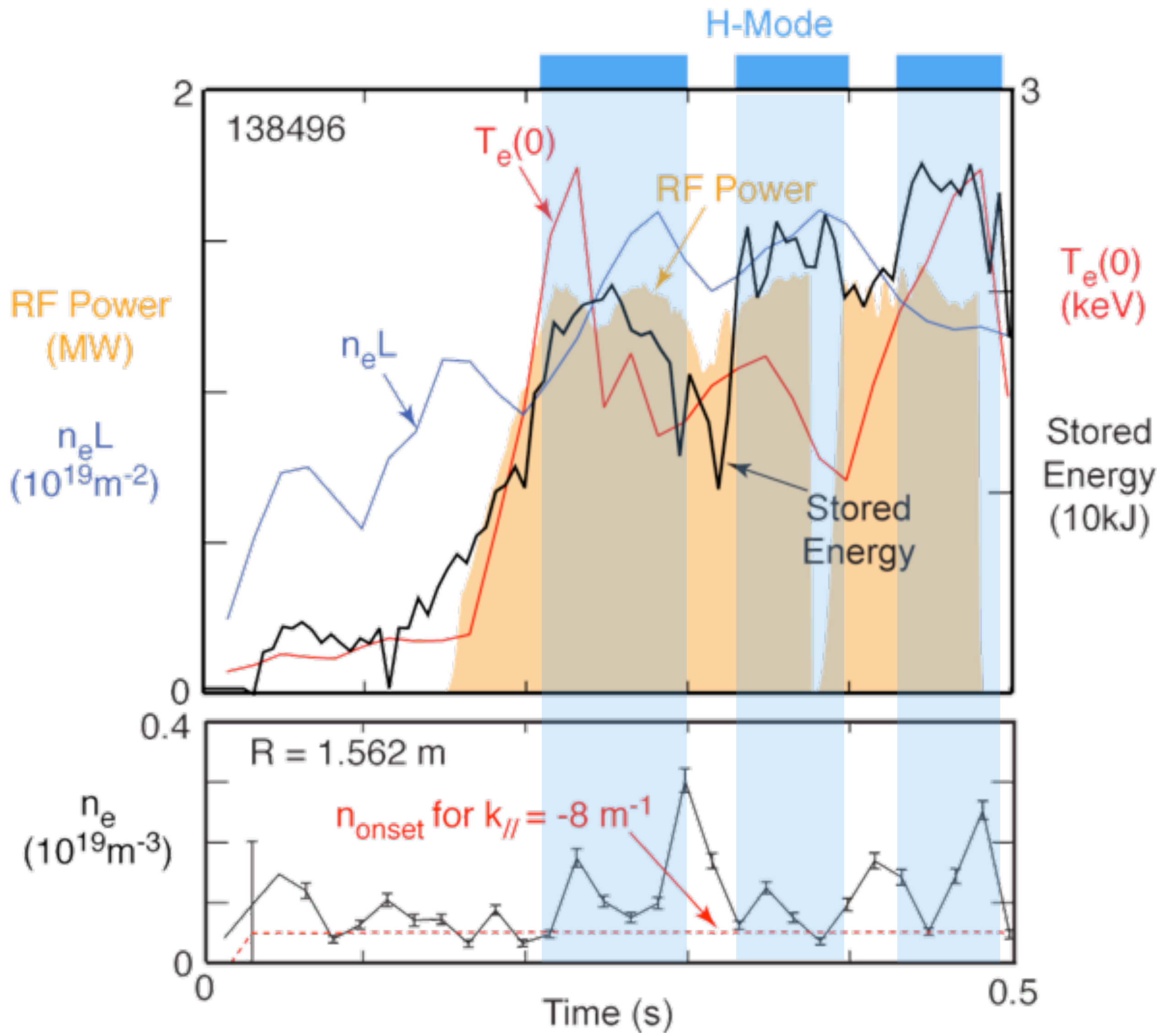
- RF coupling at $I_p \leq 300$ kA & RF powers up to 5 MW:
  - Neutral beam blips enable measurement of q profile with motional Stark effect (MSE) & T_i with charge exchange recombination spectroscopy (CHERS) diagnostics



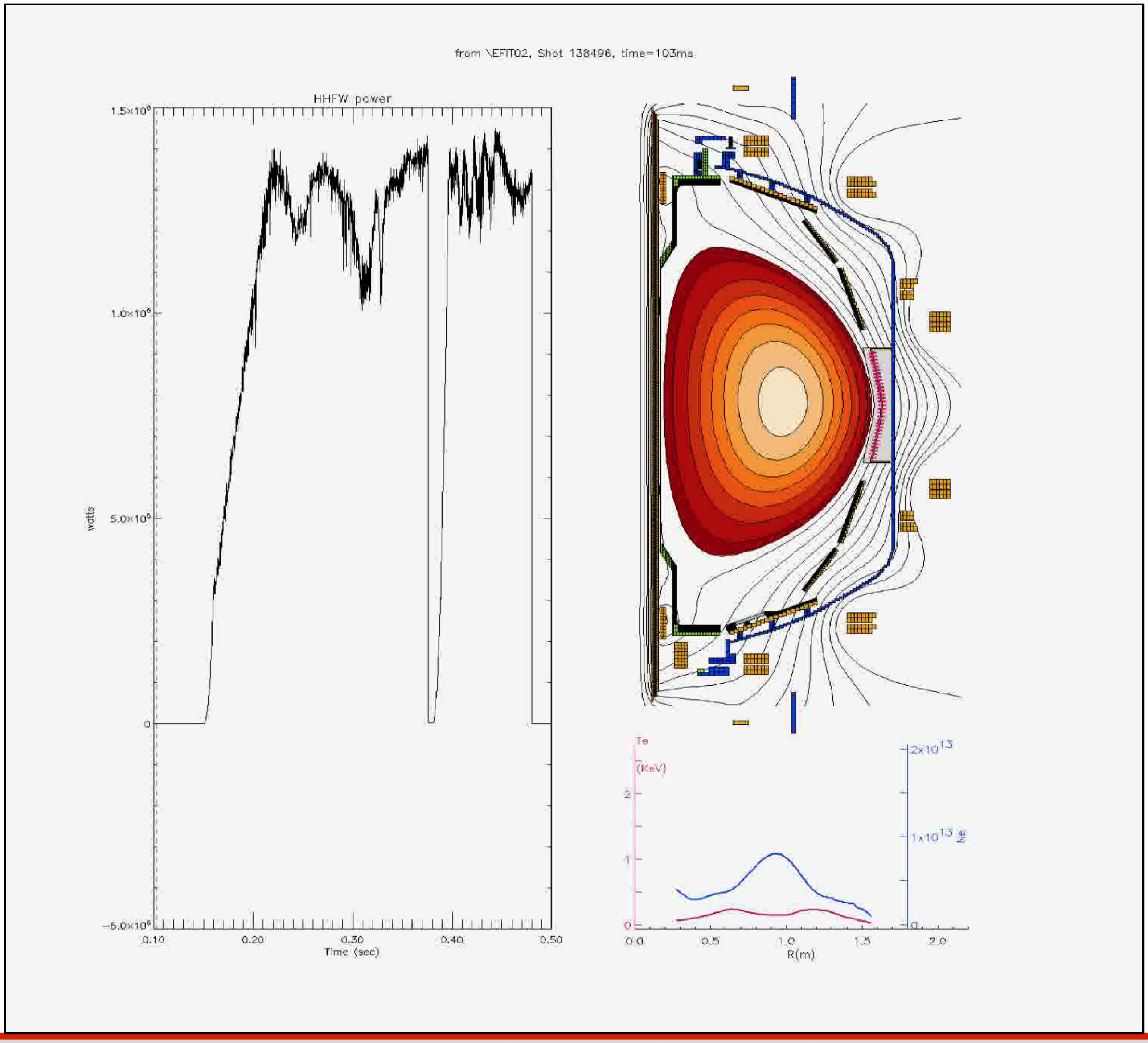
Low I_p RF H-mode experiments started with I_p = 300 kA Ohmically heated target & P_{rf} = 1-2 MW



Large increase in stored energy during H-mode phases



Large changes in plasma shape and RF power resulted in RF H-mode not being sustained



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- Relatively large changes in coupled RF power during pulse
- Plasma hits HHFW antenna

Lithium influx appears to cause some of the drop in RF power during pulse

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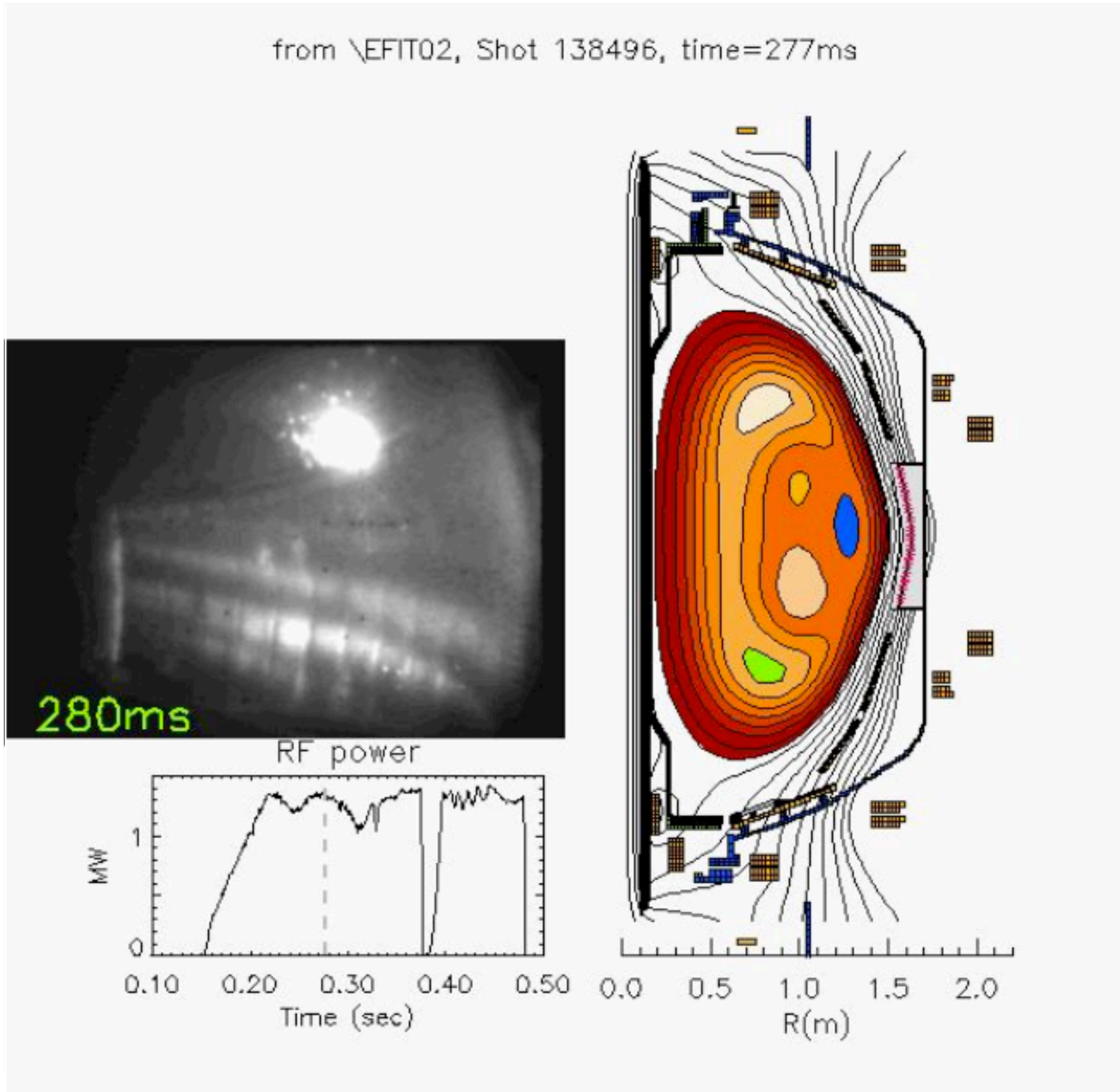
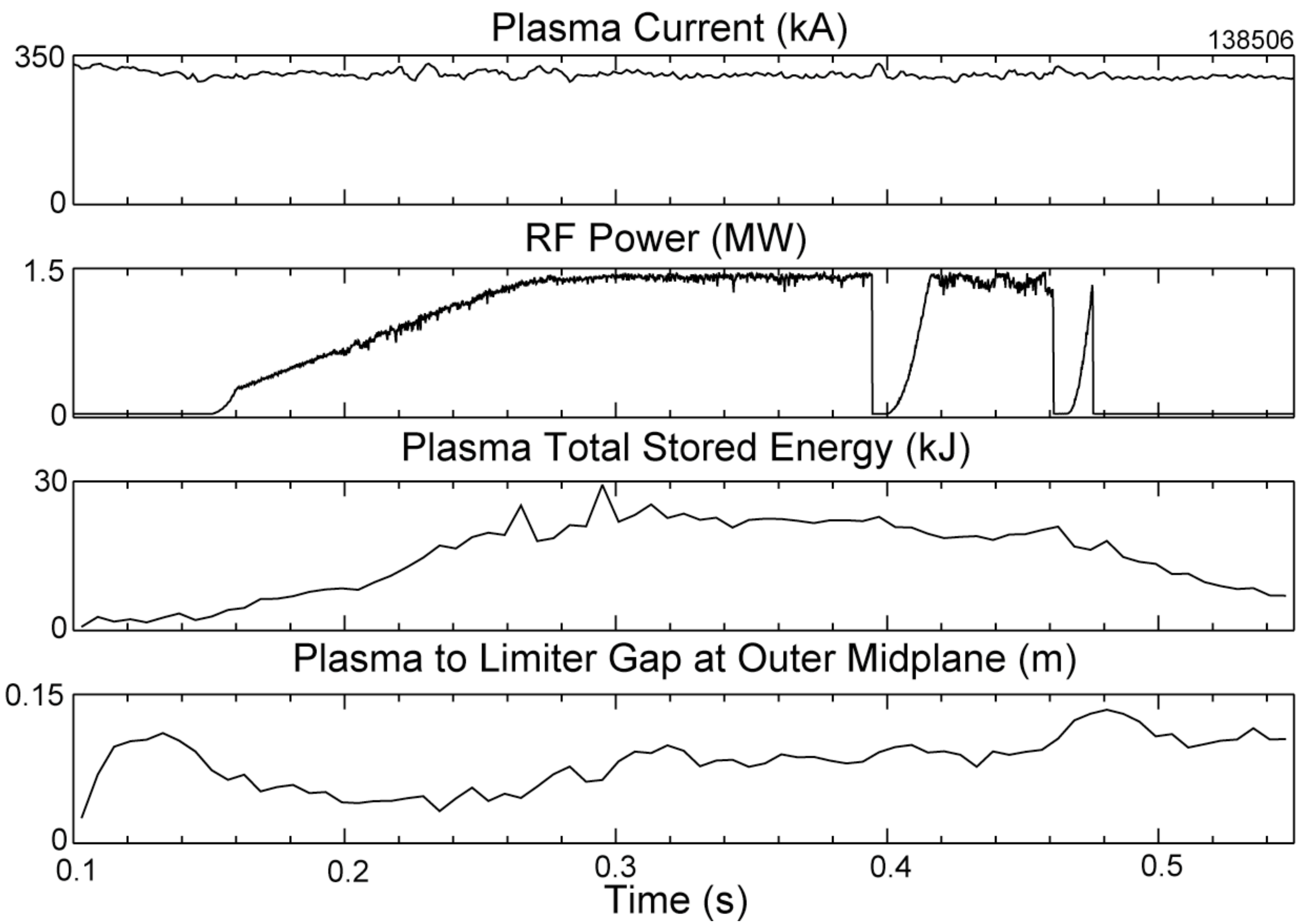
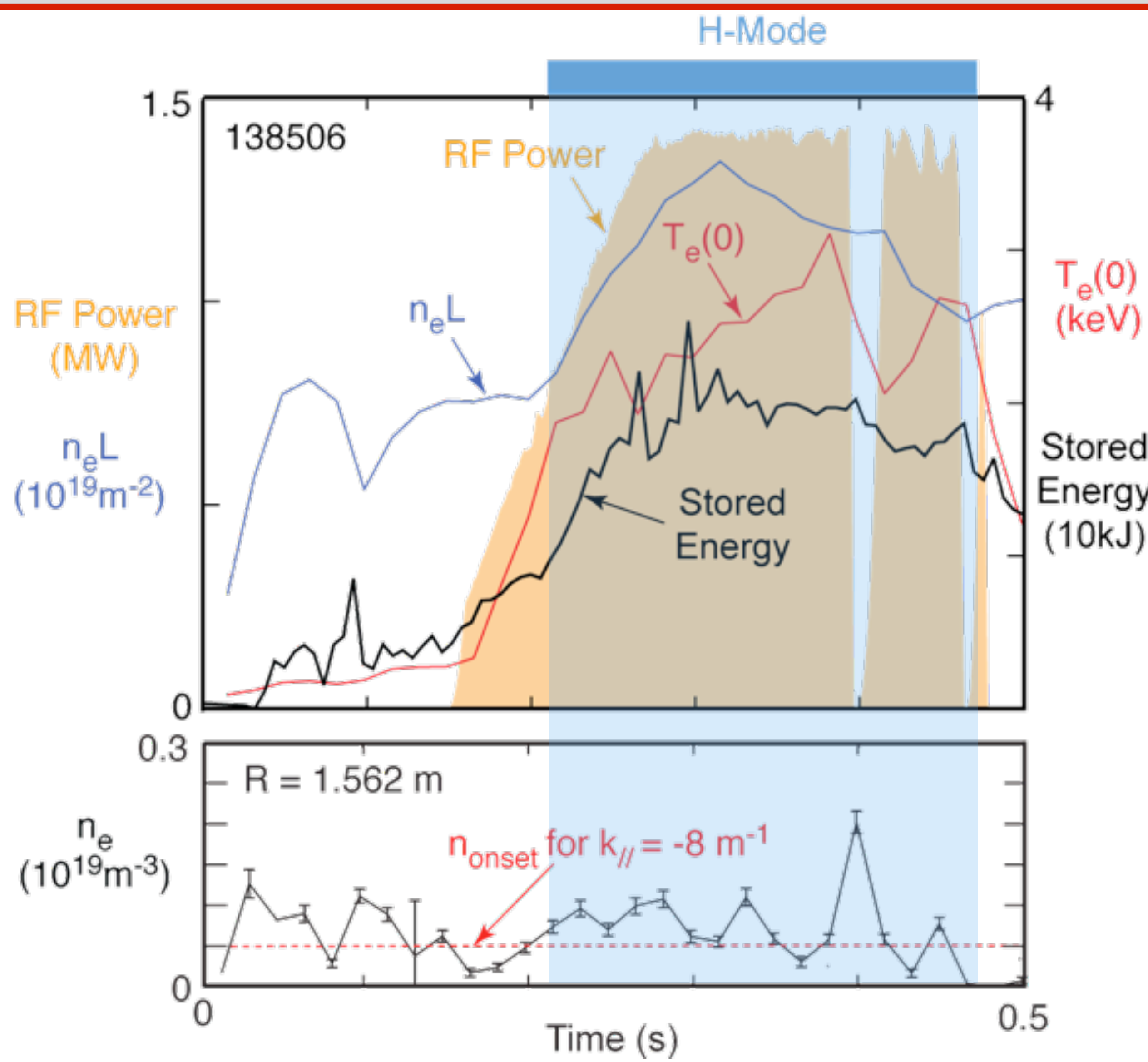


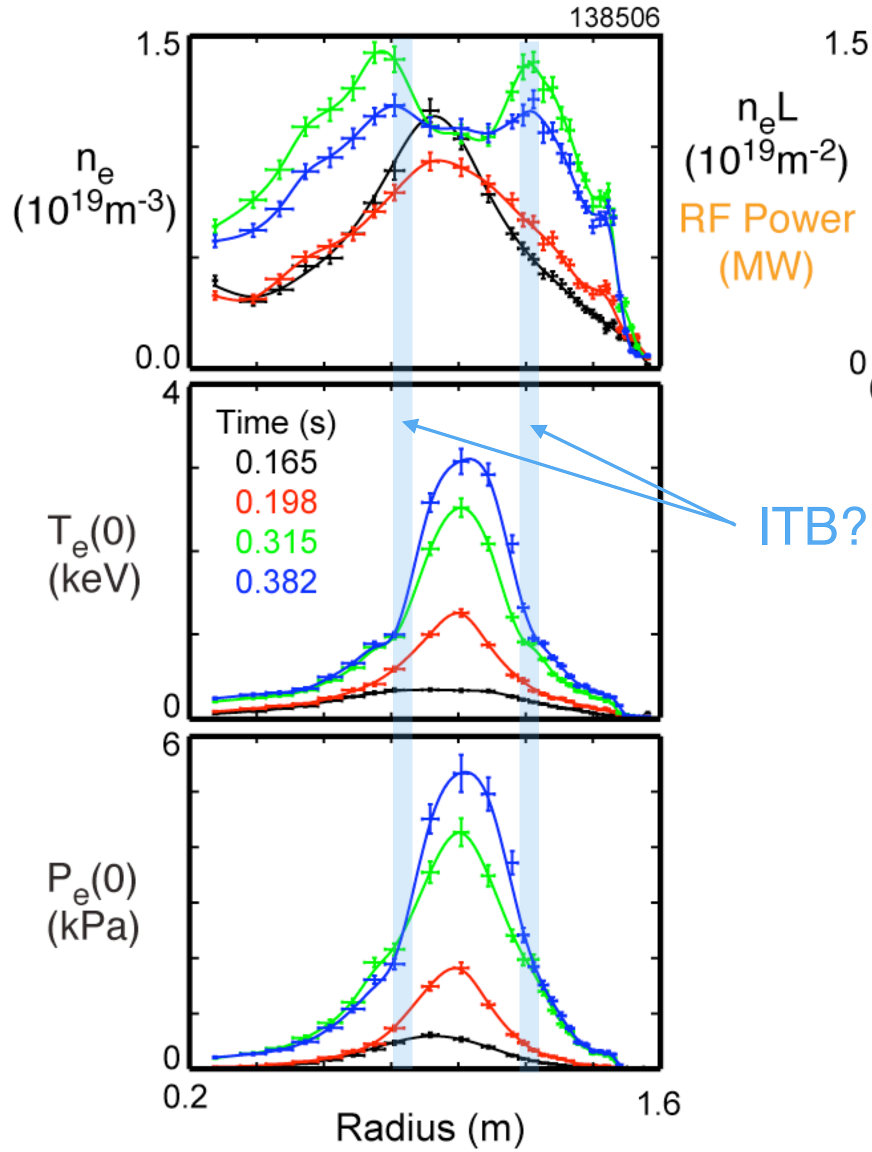
Better control of plasma-antenna gap achieved recently, resulting in sustained RF coupling

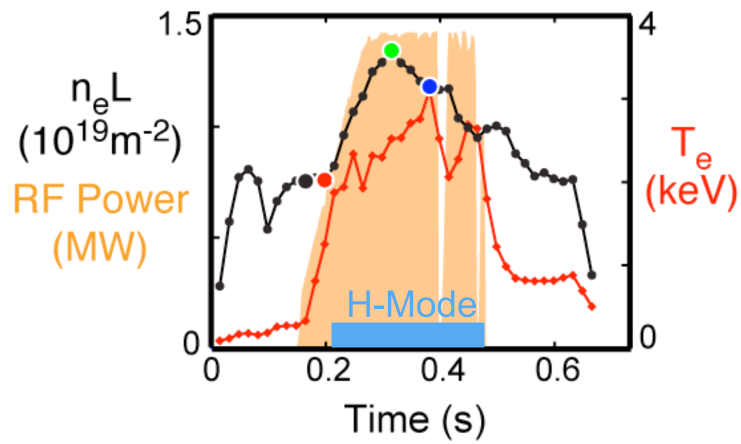


Starting to gain better control of plasma position, but still difficult to control edge density



Indications of an internal transport barrier (ITB)





- Electron density profile becomes hollow as central electron pressure peaks

- ITB may be formed when RF current drive generates region of reversed shear near core

Time evolution of sustained low I_p RF H-mode

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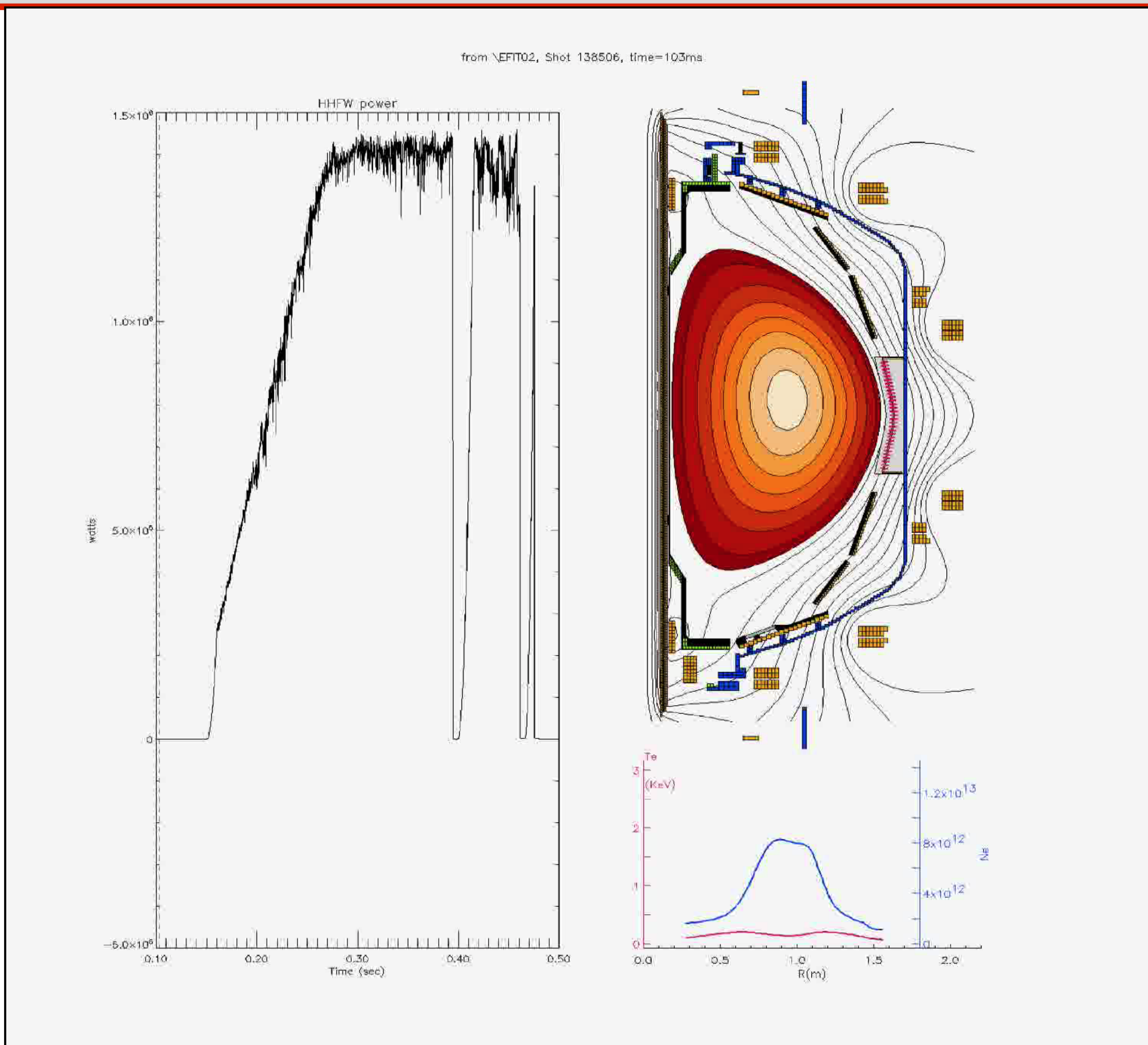

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- 65-80% bootstrap current achieved with HHFW in 2005 :
  - Demonstrated need for RF H-mode to replace inductive current
  - Plasma control at low I_p proved difficult during L-H transition
  - Could not sustain RF coupling during H-mode
- Reduced latency in the NSTX PCS, the double-feed HHFW antenna upgrade, and Li conditioning are starting to generate more stable low I_p RF H-modes:
  - However, Li deposition near antenna can lead to antenna arcs, requiring extensive RF conditioning
- Propose collaboration with TST-2 group at the University of Tokyo on HHFW-assisted I_p ramp-up