Advances in High-Harmonic Fast Wave Physics in NSTX*

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In collaboration with

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IPP, Jülich
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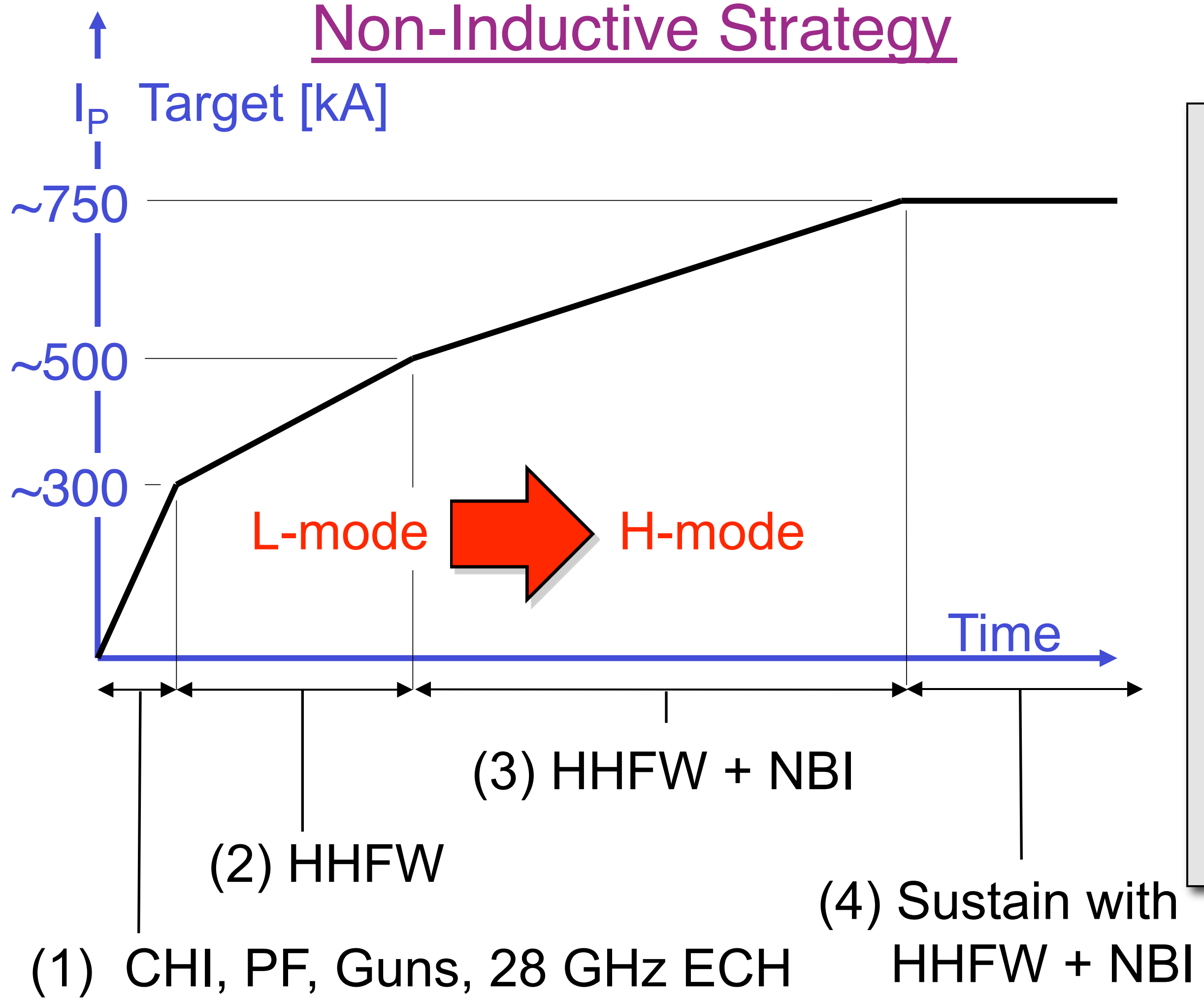
ASCR, Czech Rep
U Quebec

HHFW Heating & Current Drive being Developed for Non-Inductive Ramp-up, Bulk Heating & q(0) Control

- Ultimately Spherical Torus needs to run non-inductively

Non-Inductive Strategy



(1) CHI, PF, Guns, 28 GHz ECH

(2) HHFW

(3) HHFW + NBI

(4) Sustain with HHFW + NBI

HHFW Requirements

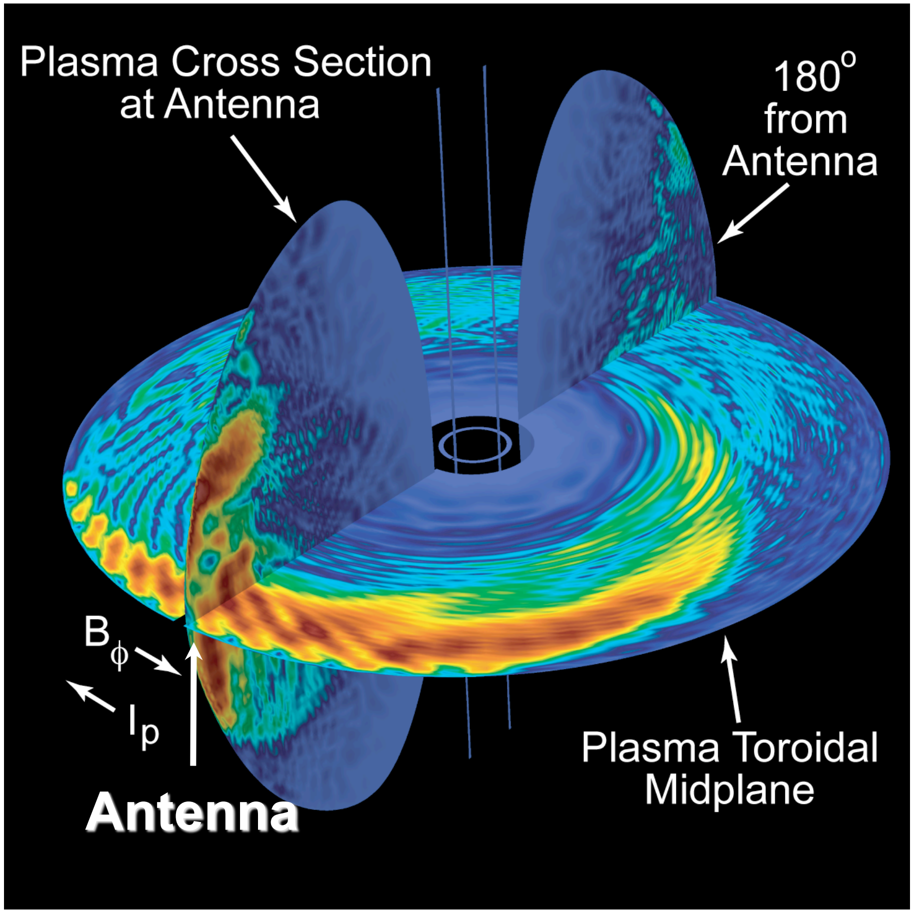
(2) HHFW needed for I_P overdrive through bootstrap & HHFW current drive (CD)

(3) HHFW needs to generate sufficient I_P to confine NBI ions

(4) HHFW needs to provide q(0) control & bulk heating in H-mode

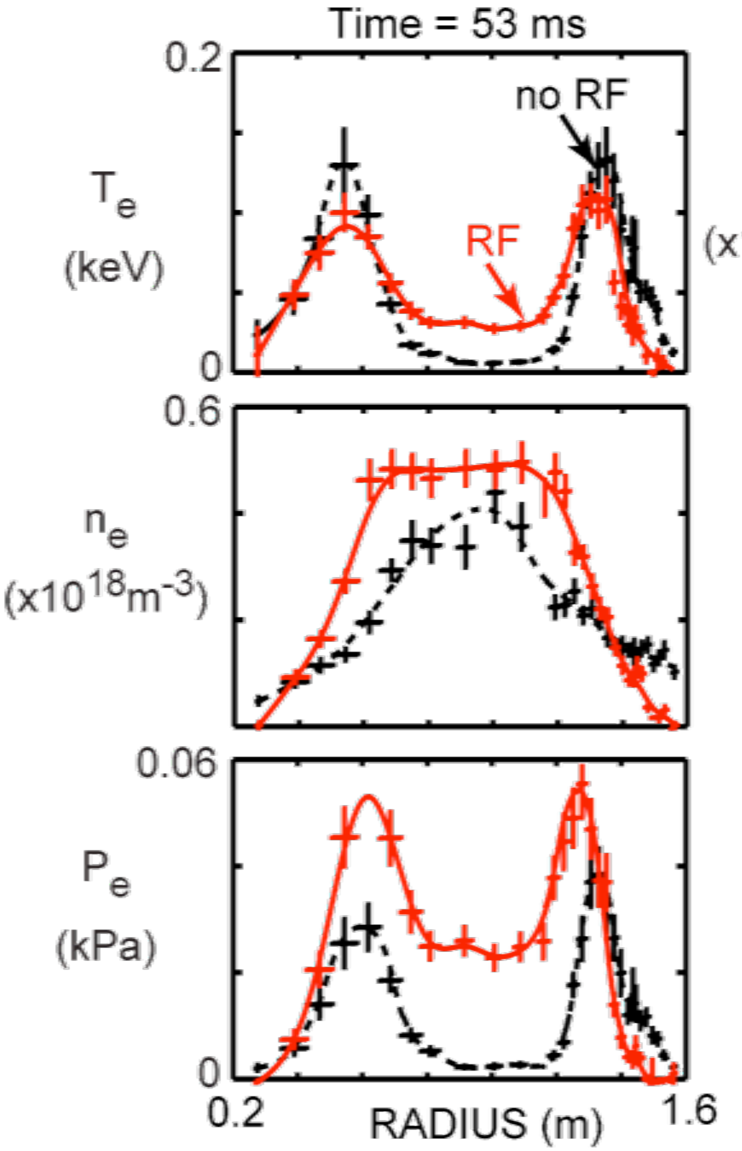
Strong Single-Pass RF Damping; Edge RF Power Losses Near Antenna Dominate

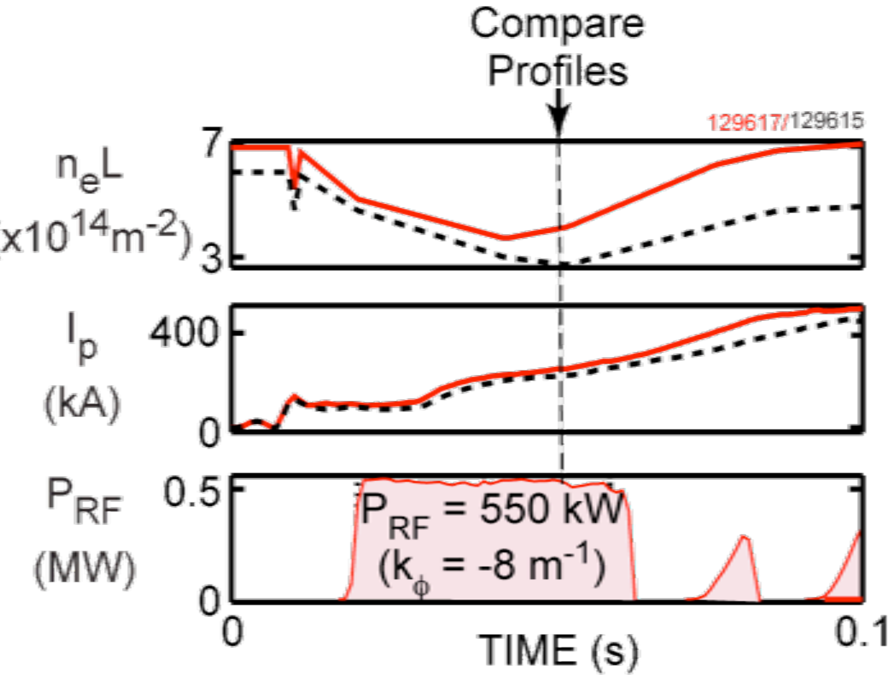
AORSA: $|E_{RF}|$ field amplitude for $k_\phi = -8\ m^{-1}$ & 101 n_ϕ modes



- Maximize η_{eff} in NBI + HHFW plasmas by understanding & mitigating edge RF losses
  - Important for ICRF on ITER
- η_{eff} degrades when n_e near antenna exceeds critical density (n_{crit}) for perpendicular fast wave propagation
- Li conditioning reduces edge n_e; moves n_{crit} away from antenna & improves η_{eff}
- Studying RF edge loss in NSTX & RF interaction with fast-ions

Lithium Wall Conditioning Enabled HHFW to Provide Core Electron Heating Early in I_p Ramp





- Core HHFW electron heating also measured during CHI start-up
- Dedicated HHFW-assisted ramp-up experiments planned for 2010

Outline

- Brief introduction to the NSTX HHFW system
- Improved HHFW heating with lithium conditioning
  - ➢ First Core HHFW electron heating observed in NBI H-mode
- RF interaction with plasma edge, divertor & fast-ions
  - ➢ Direct RF power flow to divertor, RF edge heating & clamping
  - ➢ Measured significant RF interaction with fast-ions
- Recent results with new double end-fed antenna
  - ➢ Increased arc-free power capability, RF H-modes in He & D_2
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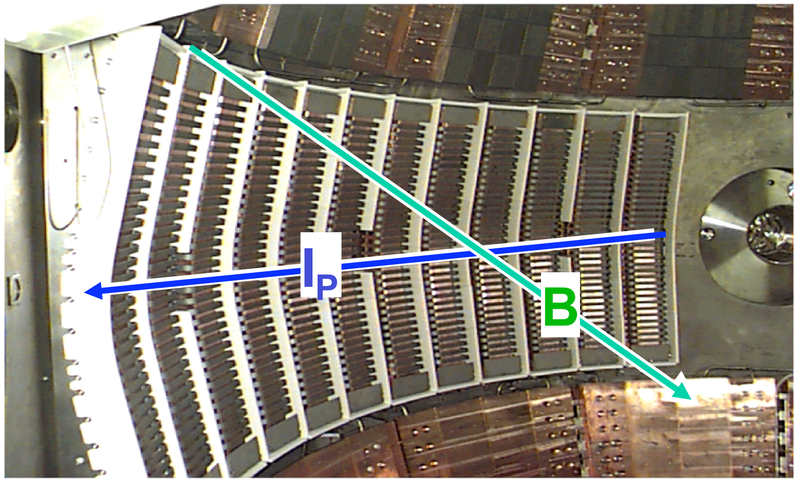
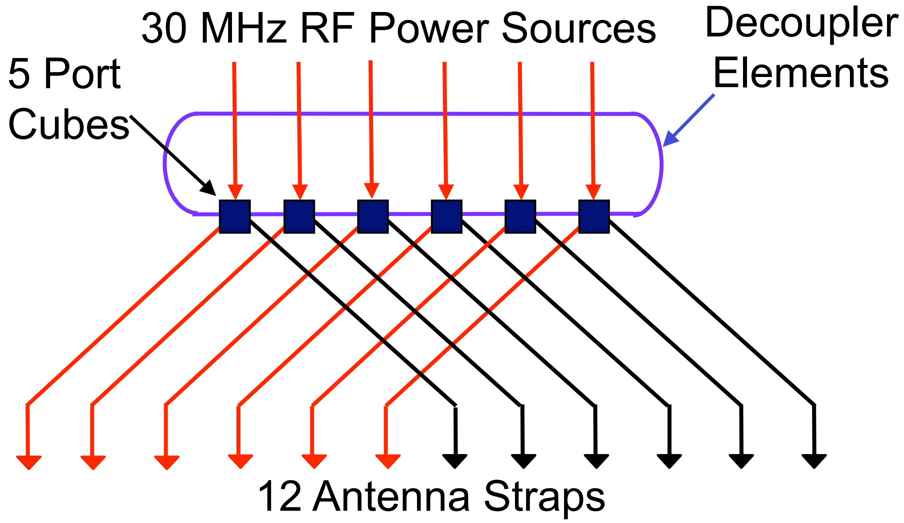
NSTX Antenna Produces Well Defined Fast Wave Spectrum for Studying Heating & Current Drive (CD)



HHFW antenna extends toroidally 90º

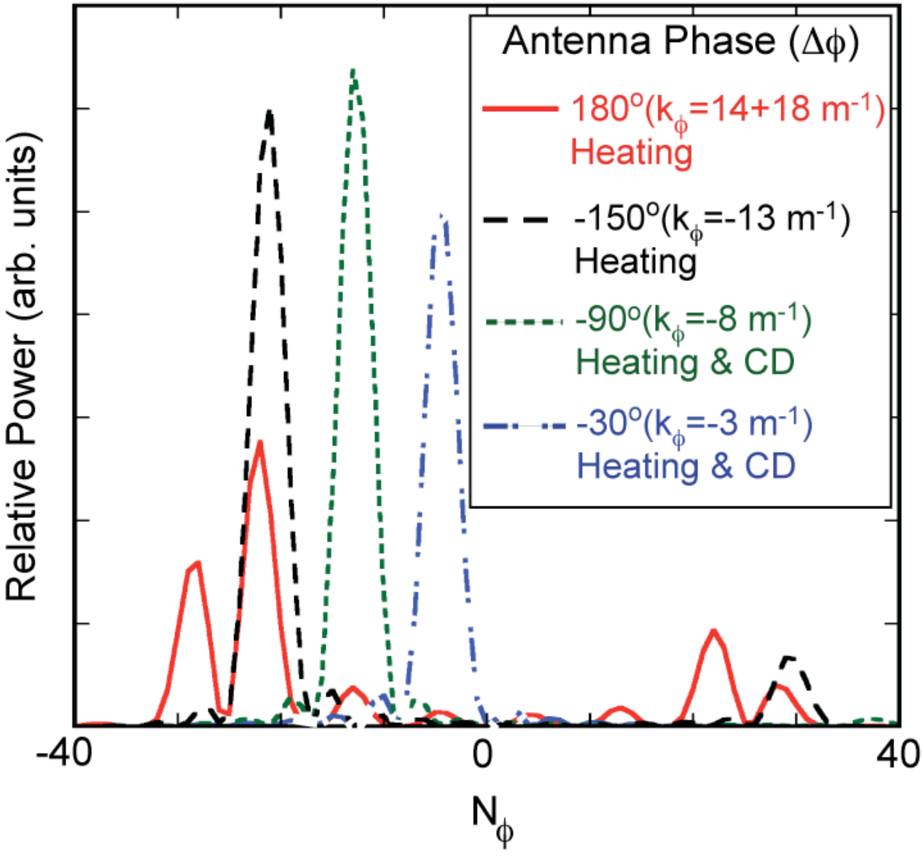


30 MHz RF Power Sources

Decoupler Elements

5 Port Cubes

12 Antenna Straps



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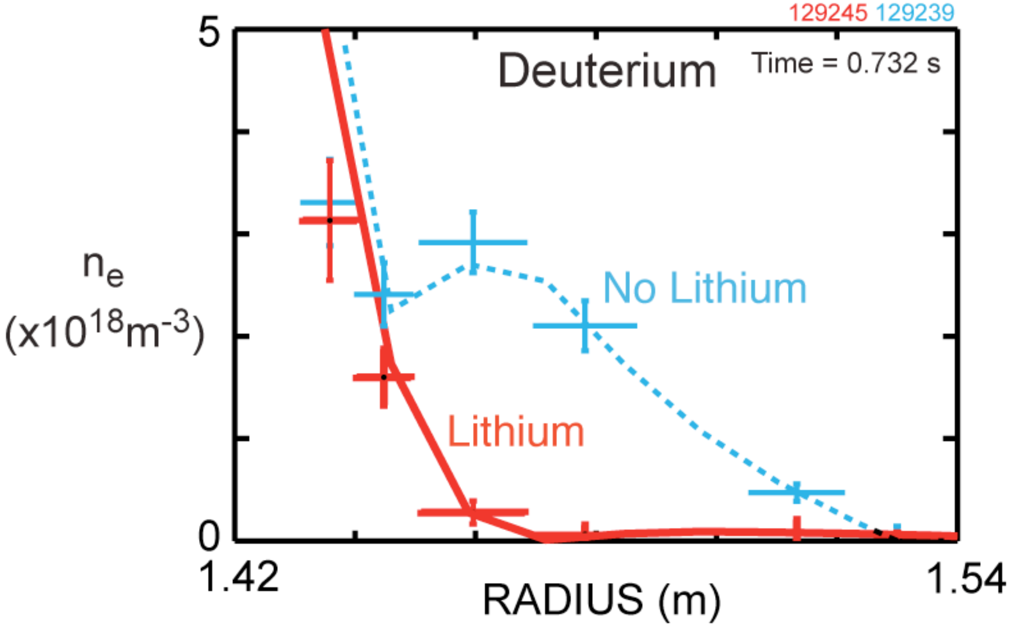
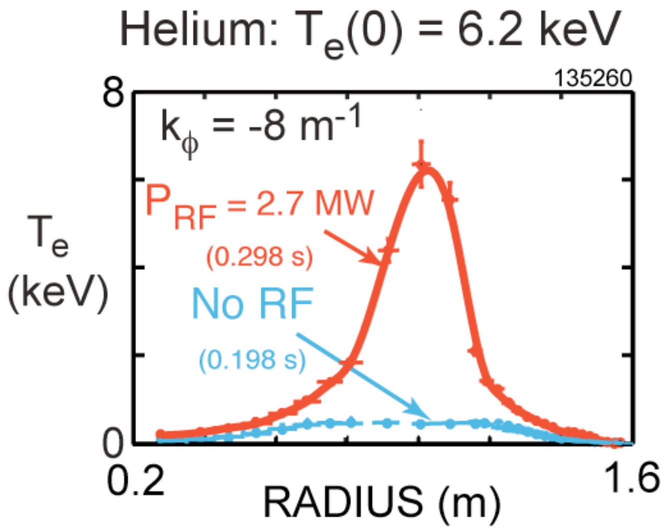
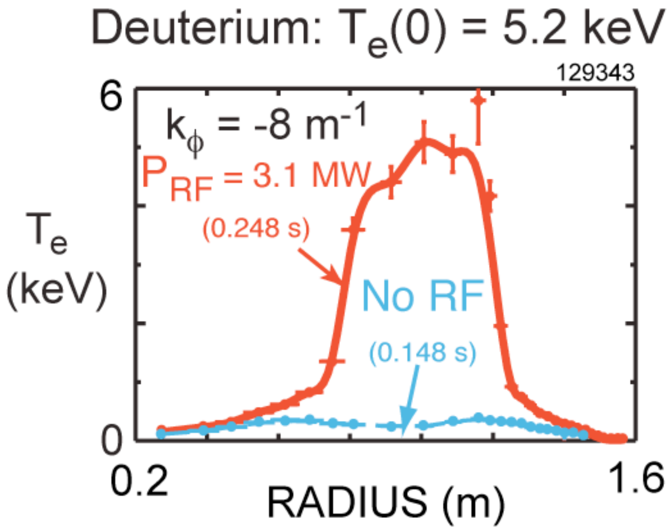
Lithium Wall Conditioning Enabled NSTX Record $T_e(0)$ in He & D_2 in L-Mode with P_{RF}~ 3 MW

$B_T(0)$ = 0.55 T

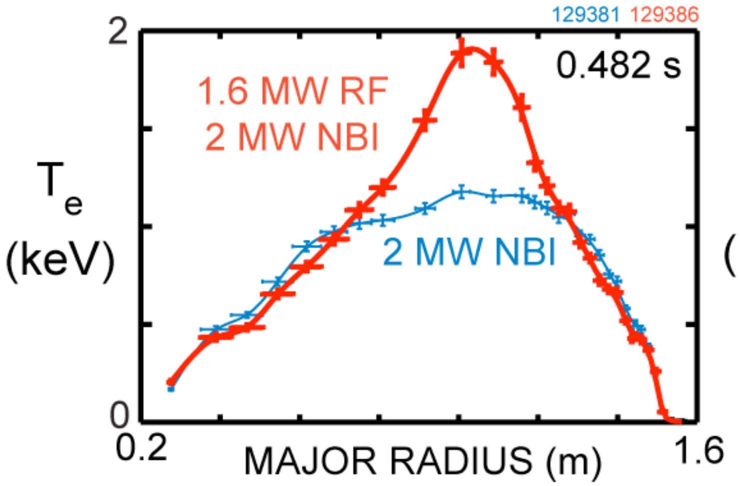


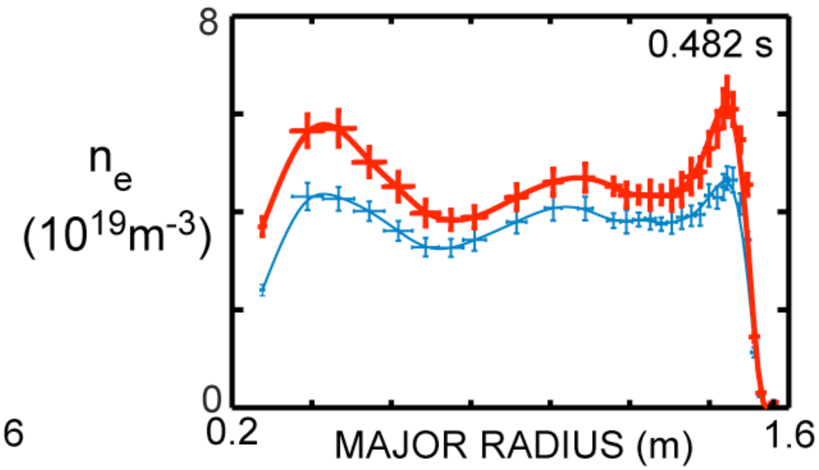
- Lithium reduces edge density – improves core heating efficiency


Helium: $T_e(0)$ = 6.2 keV

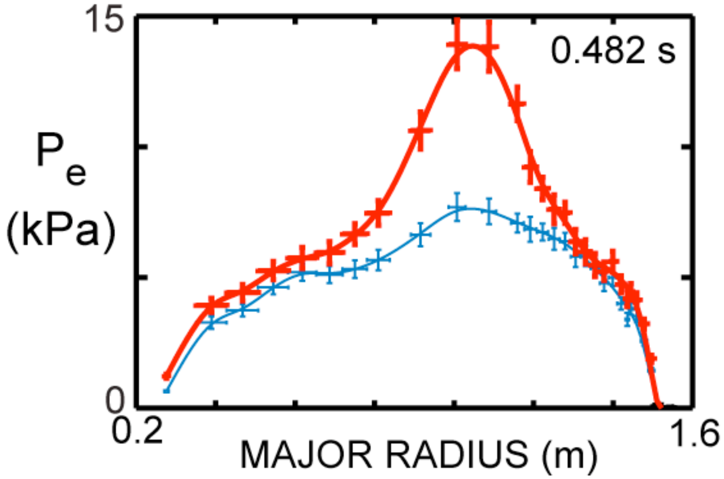

Deuterium: $T_e(0)$ = 5.2 keV

Lithium Enabled Significant HHFW Heating of Core Electrons During NBI D_2 H-modes





k_ϕ = 14 & 18 m^{-1}
$B_T(0)$ = 5.5 kG
Li Conditioning

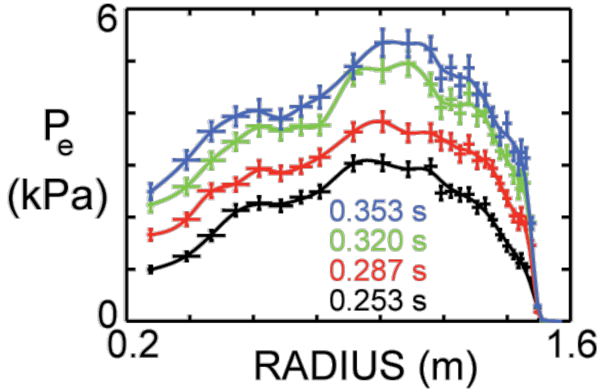


- At $B_T(0)$ = 4.5 kG & without Li, HHFW did not heat core of D_2 NBI H-mode

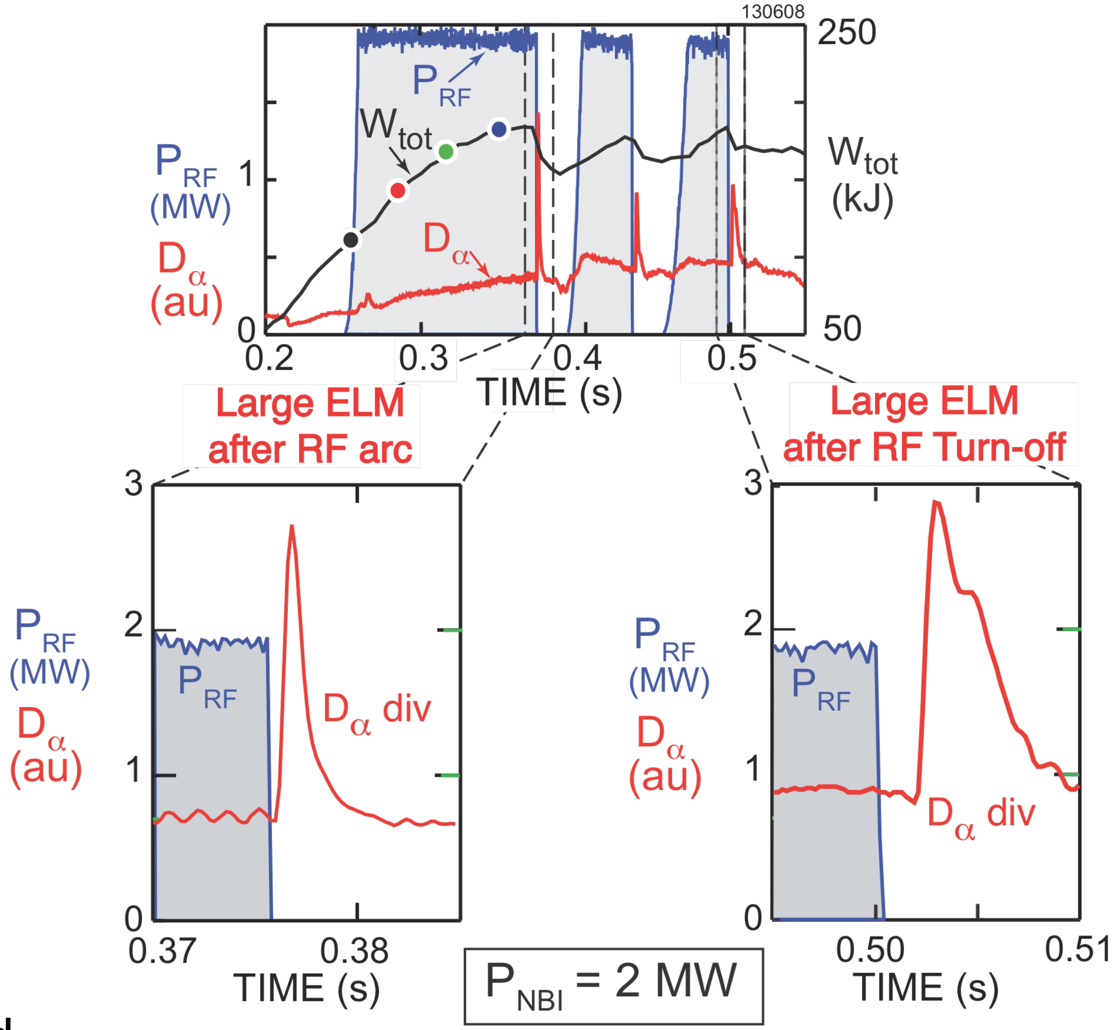
[B. LeBlanc, *et al*, AIP Conf. Proc. **787**, 86 (2005)]

Large Type 1 ELM Often Follows HHFW Power Turn-off or Arc During D_2 H-Modes

k_ϕ = -13 m^{-1}

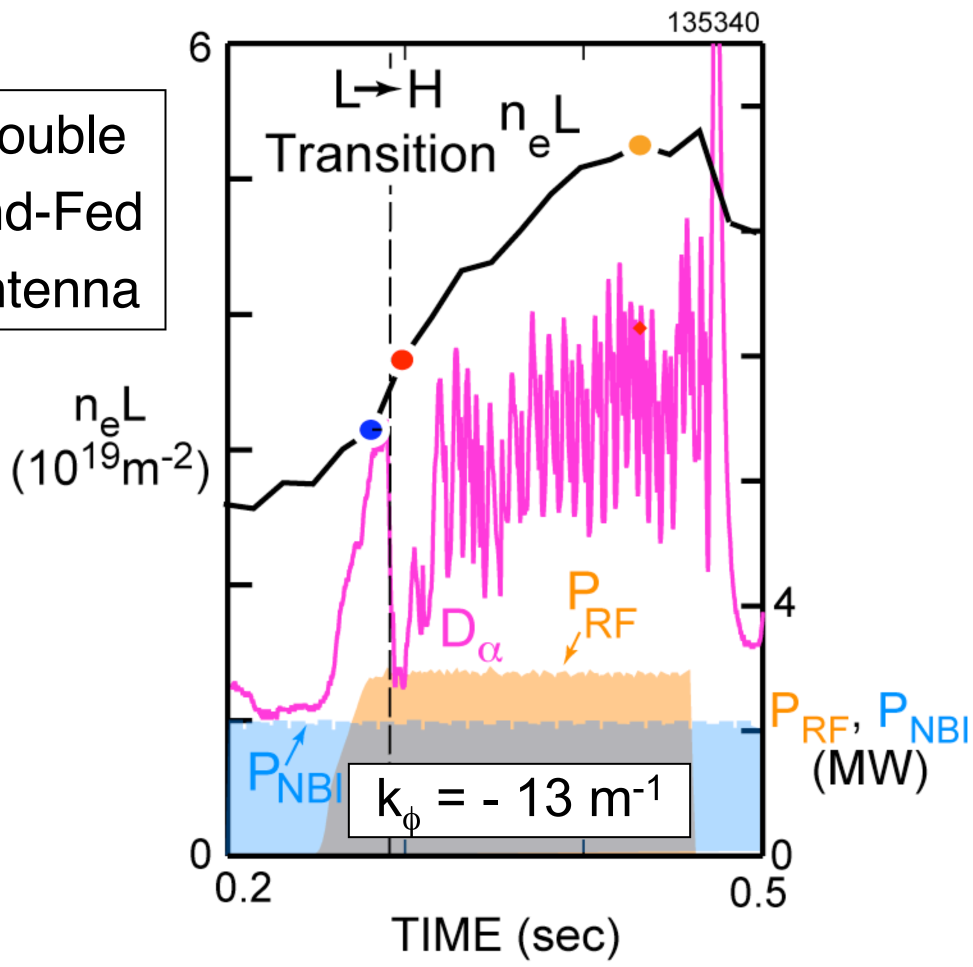


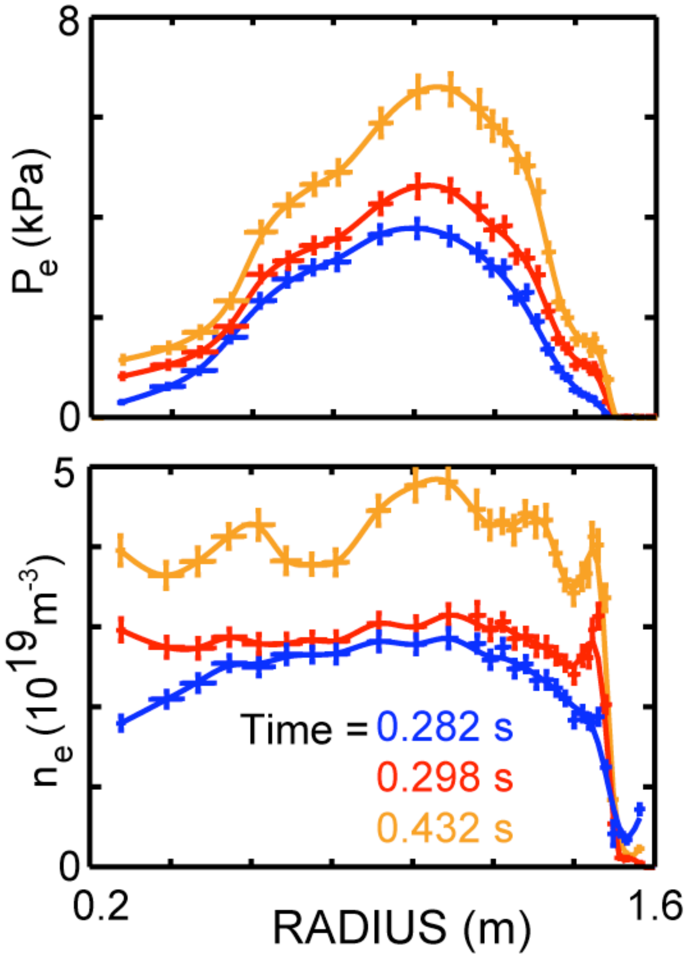
- Strong edge pressure gradient appears to lead to ELM
- Arcs occur prior to excursion of D_α light
- Arcs due to sputtering in antenna
- Similar behavior observed for k_ϕ = -8 m^{-1} heating



H-mode Initiated & Maintained Through ELMs with P_{RF} ~ 2.7 MW During ~ 2 MW D_2 NBI

Double
End-Fed
Antenna





- Transition to H-mode occurs after RF turn on and without RF arc

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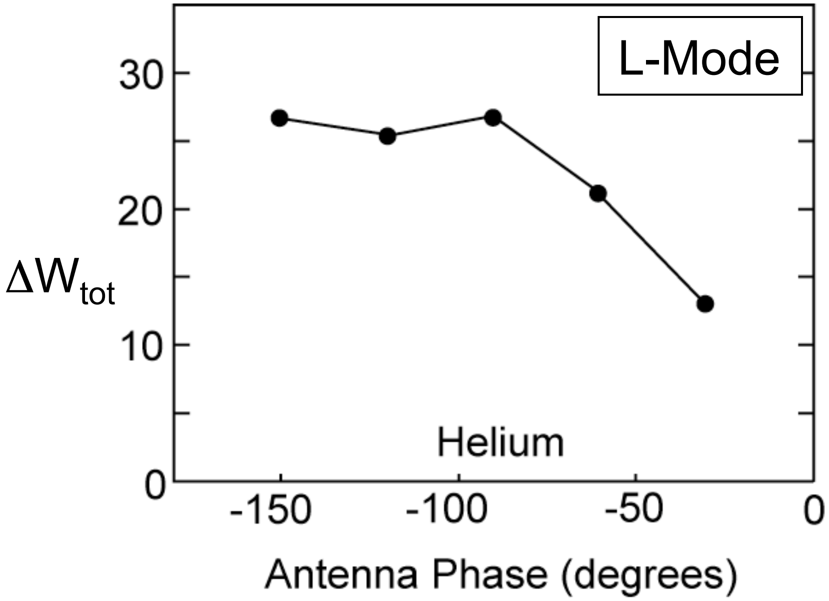
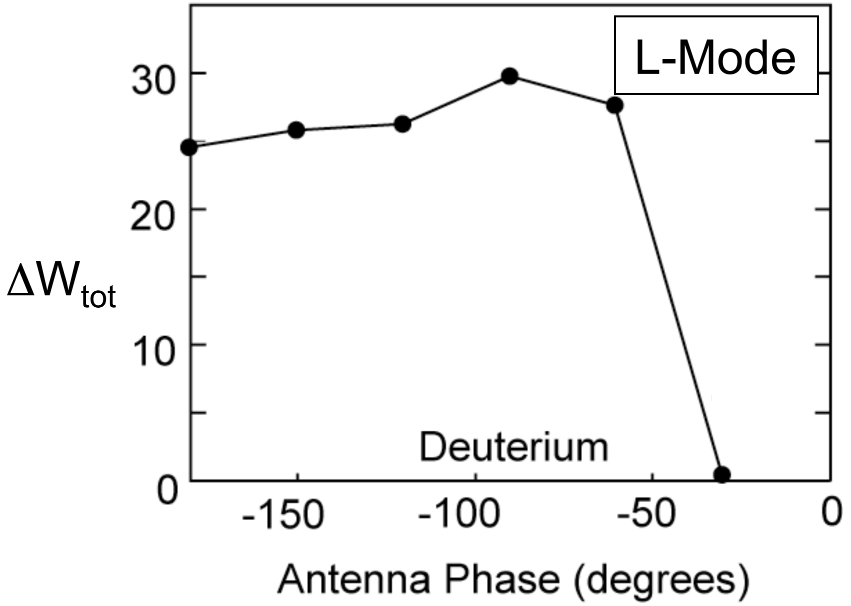
Core Heating Efficiency Degrades with Decreasing k_ϕ in L-Mode & H-Mode Plasmas

P_{RF} ~ 1.8 MW
(~ 80 ms duration)



Decreasing k_ϕ →

P_{RF} ~ 1.1 MW
(~ 230 ms duration)



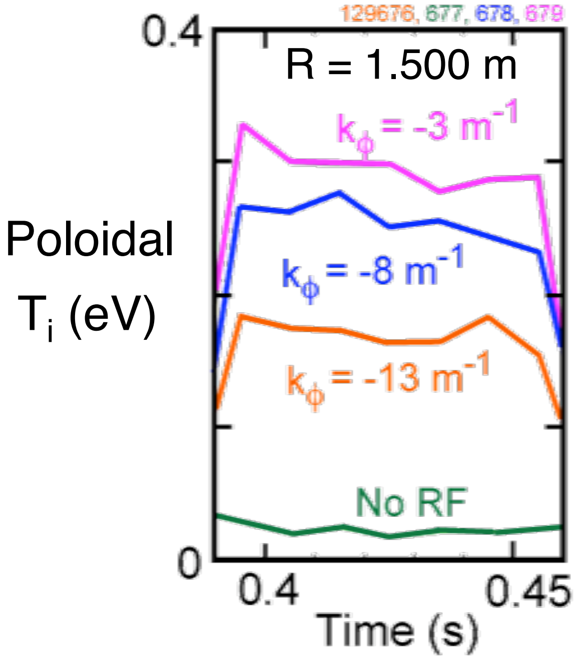
Decreasing k_ϕ →

- Also measure a degradation in core heating efficiency with decreasing k_ϕ In D_2 H-mode:
  - ~ 66% efficiency at k_ϕ = -13 m^{-1}, decreasing to ~40% at k_ϕ = -8 m^{-1}

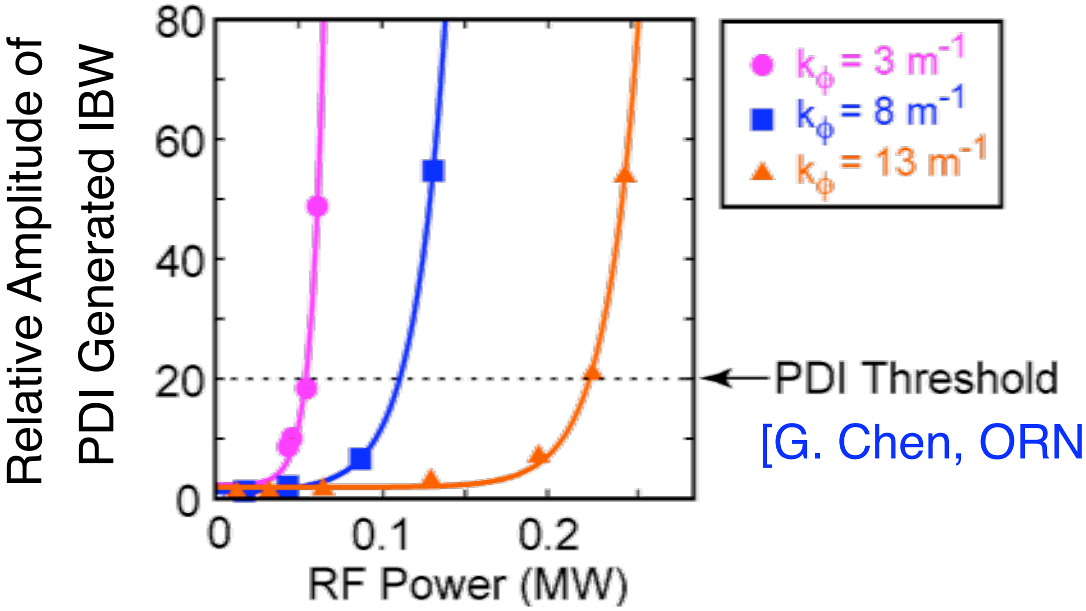
1-D Full Wave Model Predicts P_{RF} ~ 100-200 kW Can Drive PDI; P_{RF} Needed to Drive PDI Falls with k_ϕ

C-III Passive Spectroscopic T_i Shows PDI Heating of Edge Ions

1-D Full Wave Model Shows Dependence of PDI Threshold on k_ϕ



P_{RF} = 1.2-1.3 MW



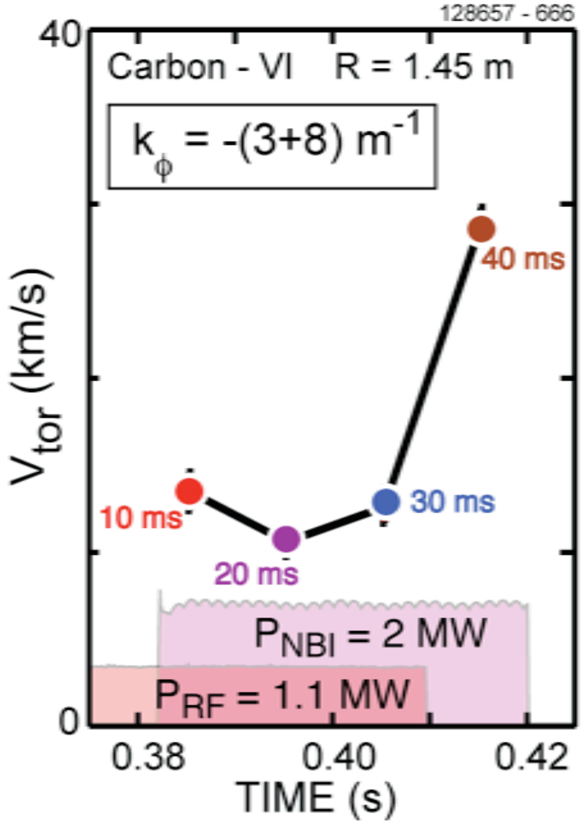
[G. Chen, ORNL]

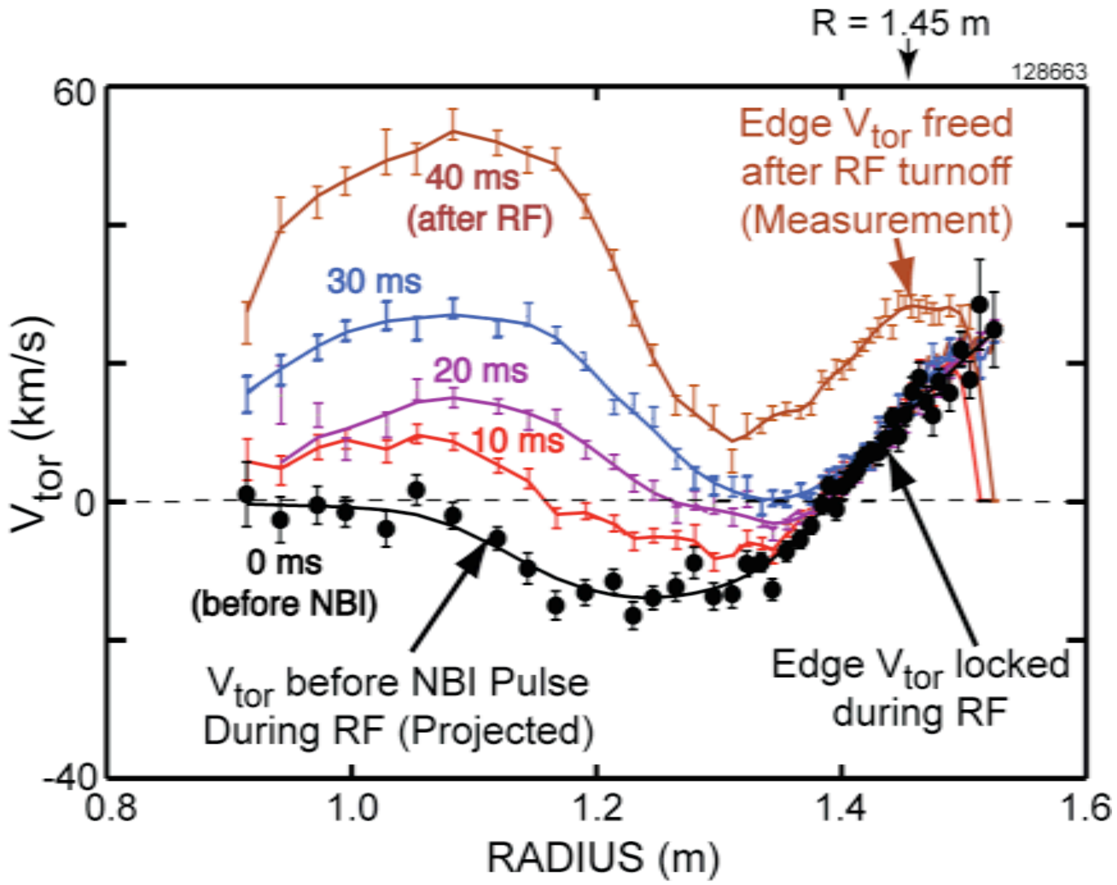
- Previously estimated 16 - 23 % RF power lost to PDI, through collisional coupling of energetic ions to edge electrons

  [T. Biewer *et al*, Phys. Plasmas **12**, 056108 (2005)]

Toroidal Edge Rotation Appears to Lock During RF, Especially at Lower k_ϕ

V_{tor} Measured by Charge Exchange Recombination Spectroscopy





- Mechanism not understood, but may point to edge ion loss
- RF apparently provides a drag on core plasma rotation as well

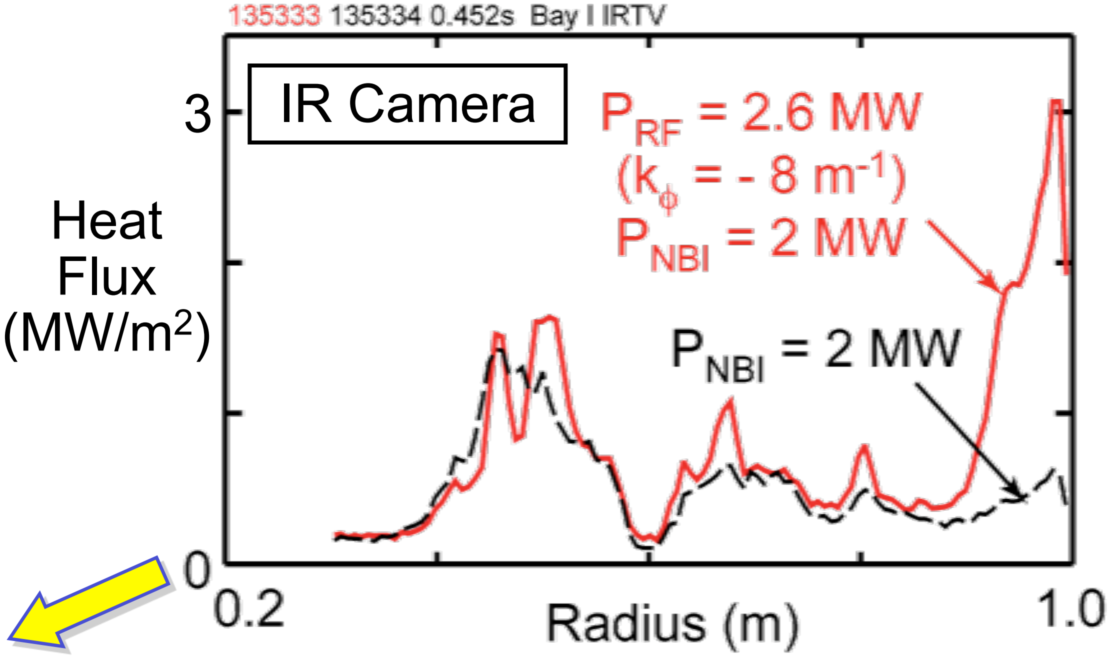
Visible & IR Measurements Show Higher RF Power to Divertor for Lower k_ϕ

Visible Camera

P_{nbi} = 2 MW

P_{rf} = 1.8 MW
k_ϕ = - 8 m^{-1}
P_{nbi} = 2 MW

P_{rf} = 1.8 MW
k_ϕ = -13 m^{-1}
P_{nbi} = 2 MW

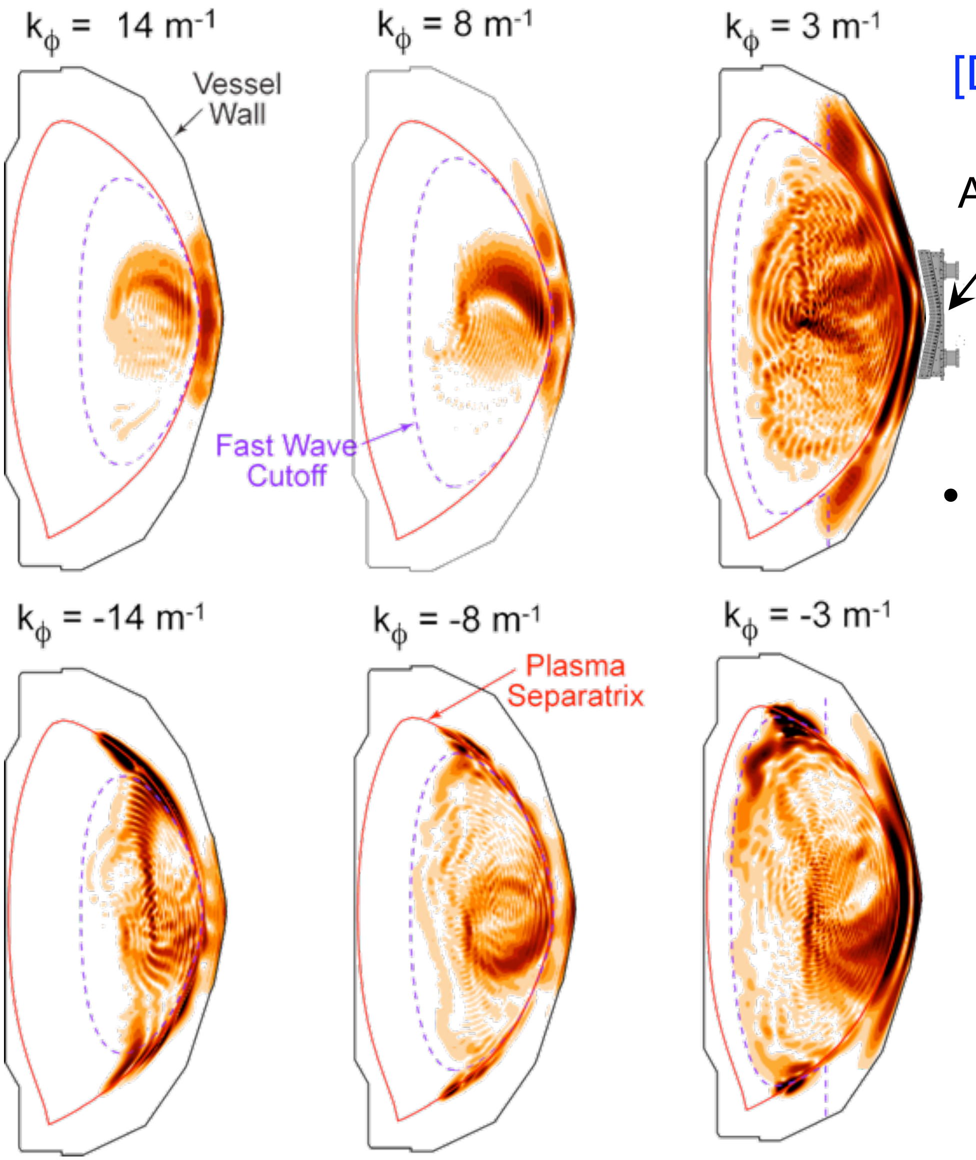


- "Hot" region in outboard divertor more pronounced at k_ϕ = - 8 m^{-1} than - 13 m^{-1}
- Linked along field lines to scrape-off plasma in front of antenna
- 3 MW/m^2 measured by IR camera during 2.6 MW of k_ϕ = - 8 m^{-1} RF heating

AORSA with Boundary Extended Outside Separatrix Predicts More Extensive $|E_{RF}|$ in Scrape-off at Low k_ϕ

2-D AORSA Full Wave Model :

$|E_{RF}|$ Field Amplitude

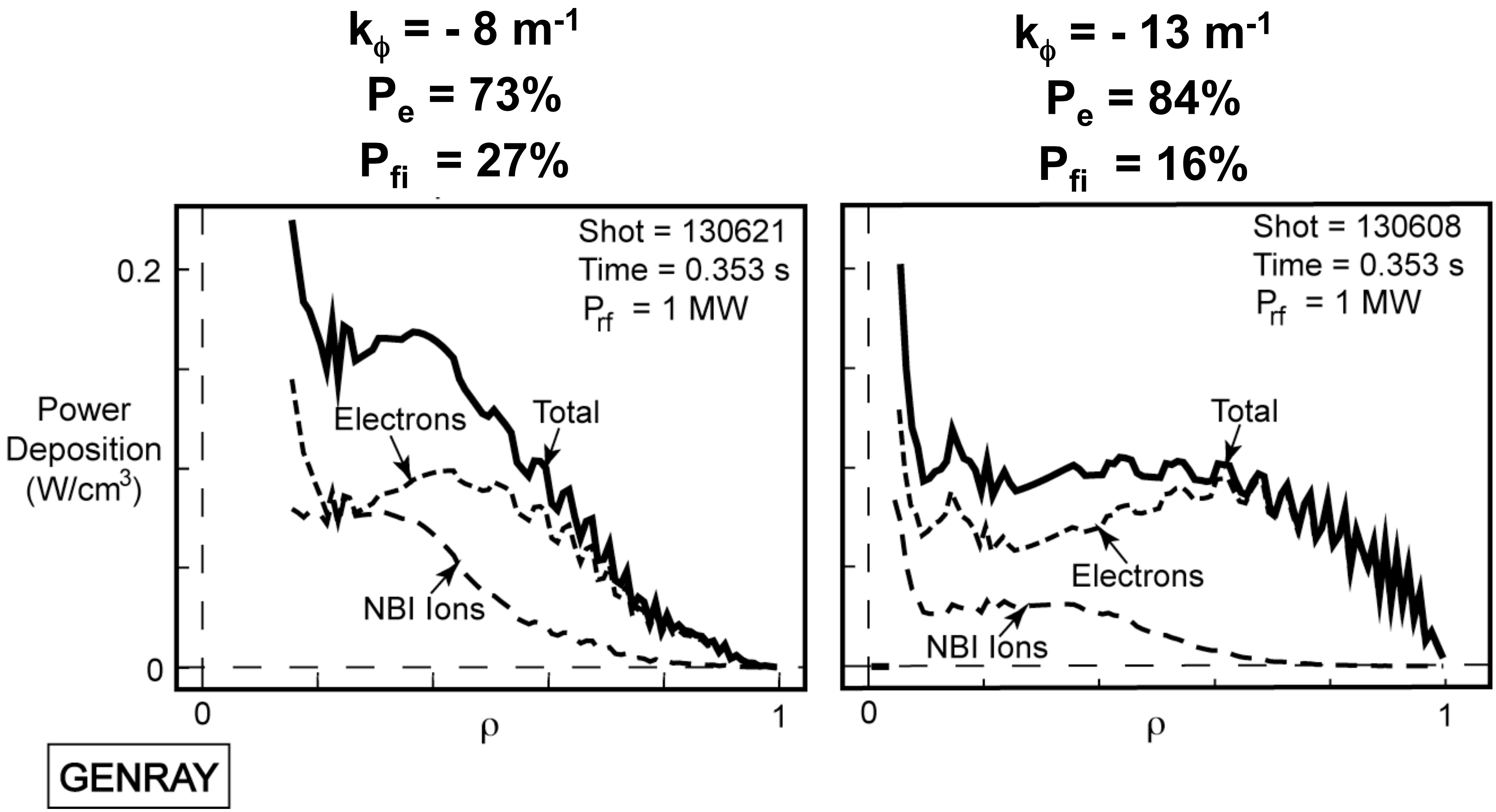


[D. Green, ORNL]

- Initial 2-D full wave results now being extended to 3-D

Preliminary Results

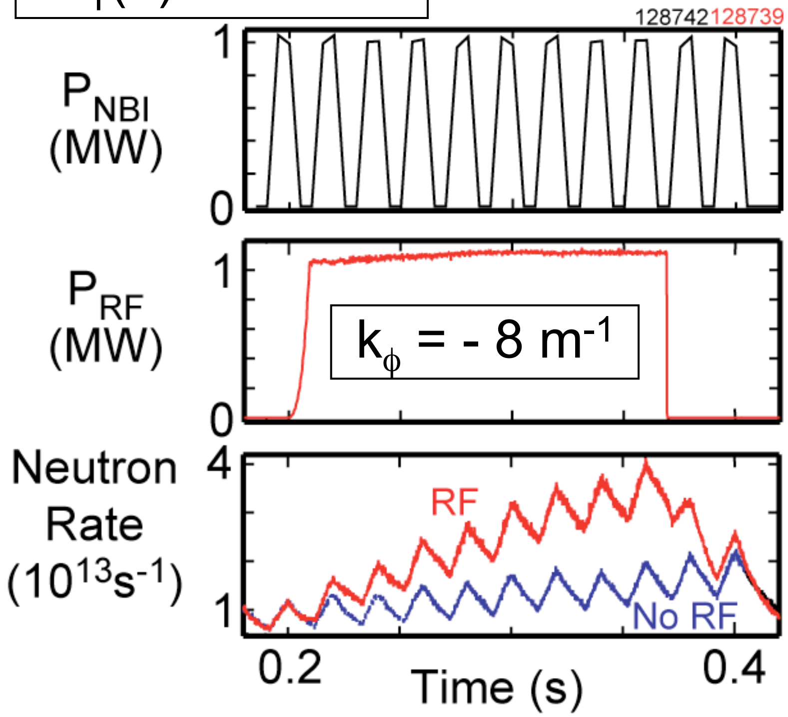
Significant RF Power Deposition on Slowing NBI Ions in Core During H-Mode, Particularly at Lower k_ϕ

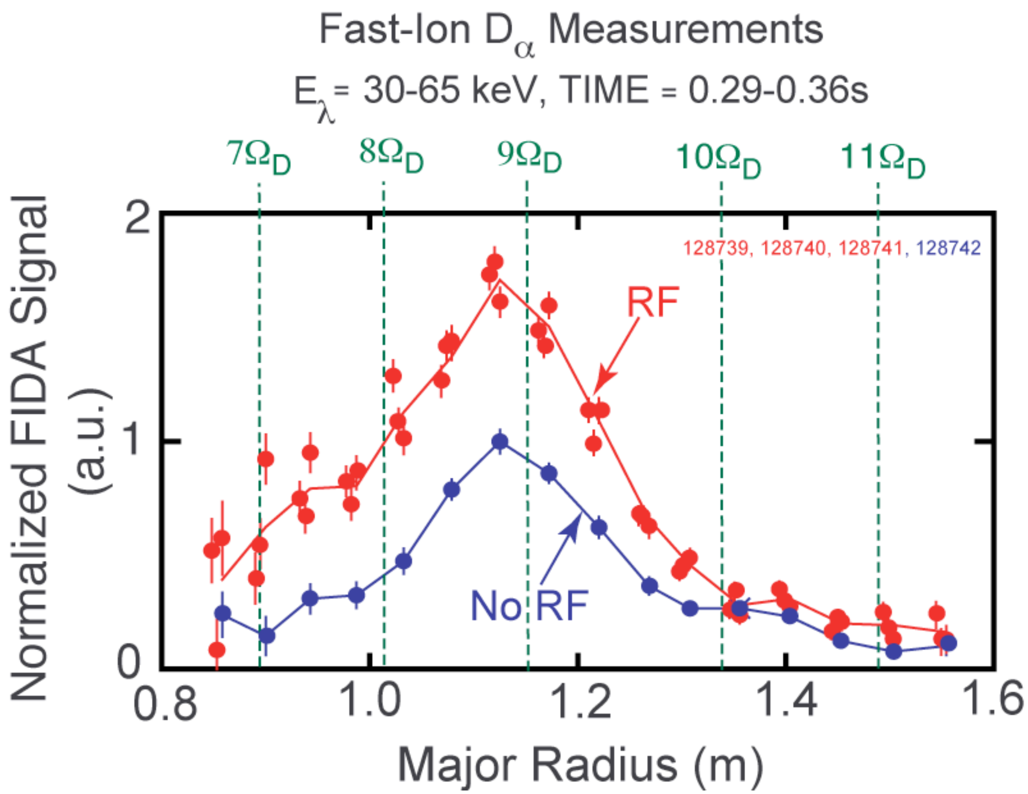


- Modeling does not include RF acceleration of fast ions

Interaction Between NBI Ions & HHFW Can Be Significant

$B_T(0) = 5.5$ kG





- Measured acceleration of NBI fast-ions and large increase in neutron rate during HHFW + NBI plasmas
  - ➢ As predicted originally by CQL3D/GENRAY
- Measured significant enhancement & broadening of fast-ion profile when HHFW power is applied

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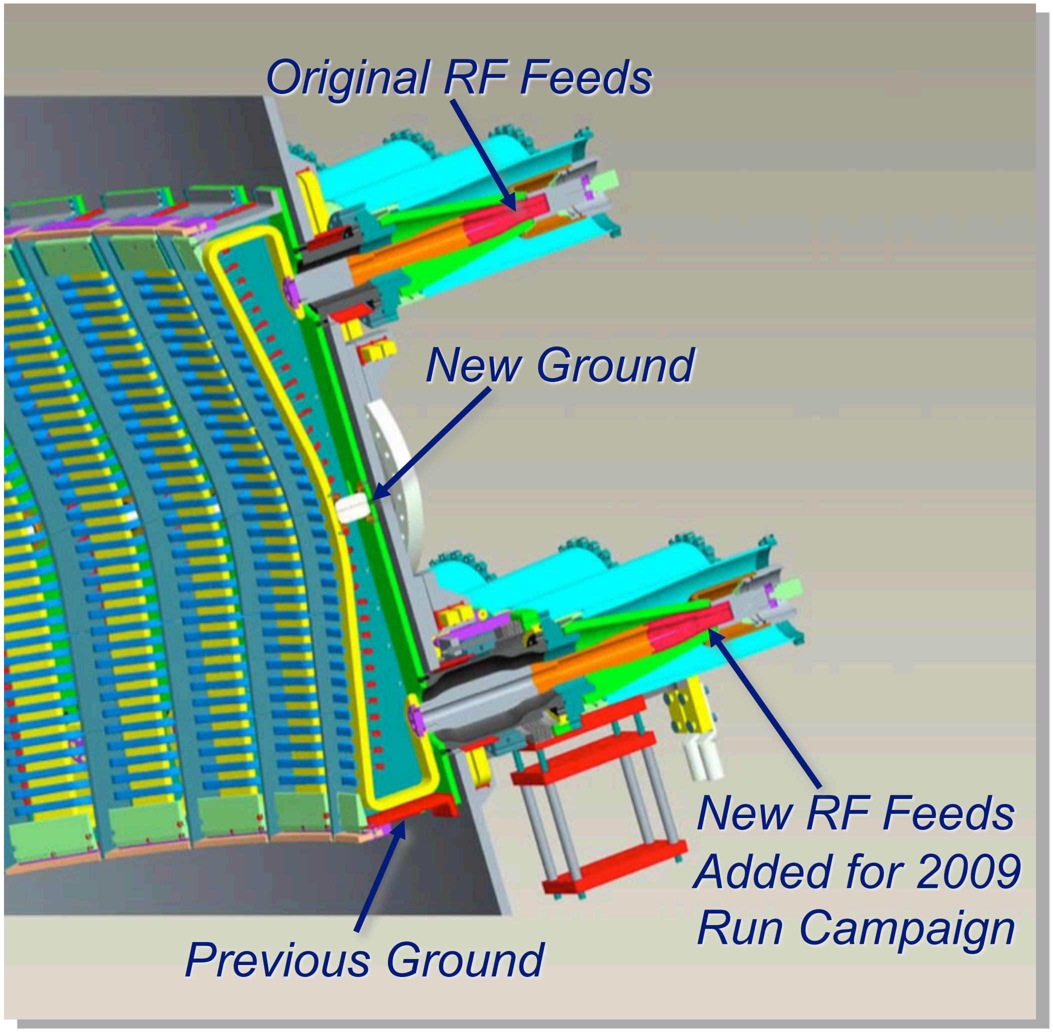
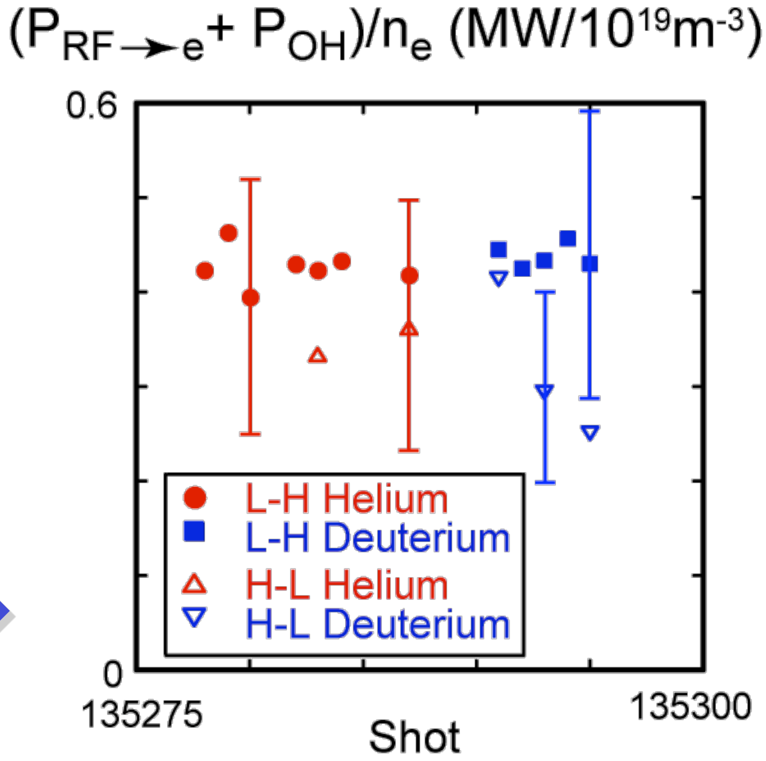
Double End-Fed Upgrade Installed for 2009 Campaign Shifts Ground from End to Strap Center



- Goal was to bring system voltage limit with plasma (~15 kV) up to its vacuum limit (~25 kV):
    - Would increase power limit by ~ 2.8 times
- Tests whether electric field in strap/Faraday shield sets limit for plasma operation

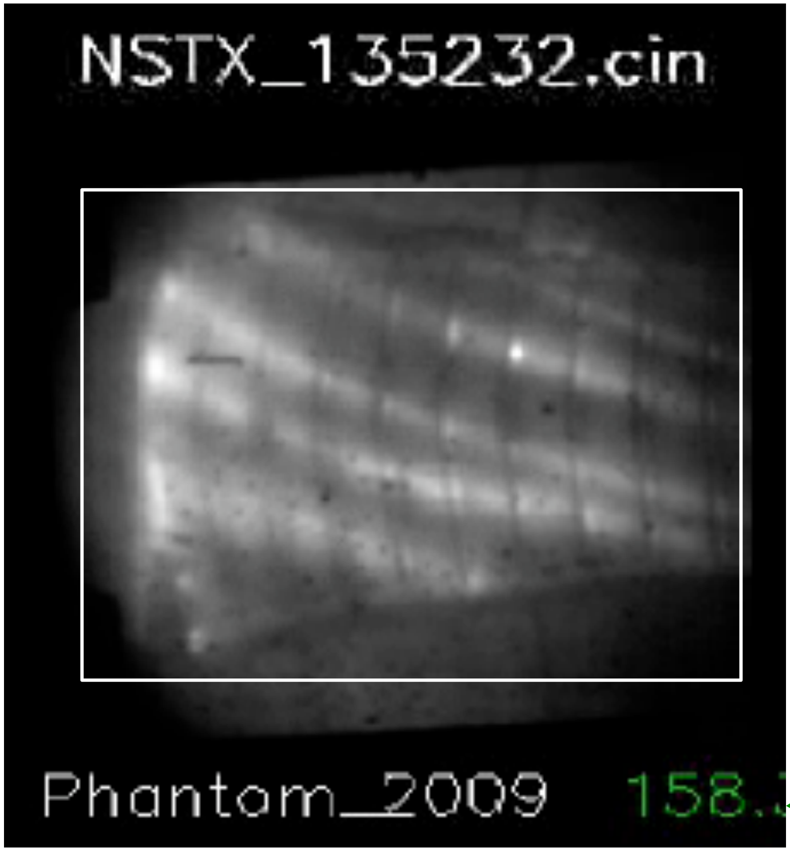
Double End-Fed Antenna Performance Significantly Improved Compared to 2008 Operation

- Modifications to external transmission line completed in June
  - Operated RF in July & August
- New antenna reached 2-3 MW more quickly than previous antenna
- HHFW performance significantly improved over last year:
  - Coupled > 4 MW into He L-mode
  - $T_e(0) \sim 6.2$ keV with $P_{rf} \sim 2.7$ MW
  - Maintained HHFW coupling through L-H transition and during relatively large repetitive ELMs during D_2 NBI-fuelled H-modes
  - Studied L-H and H-L transition in He & D_2 with RF



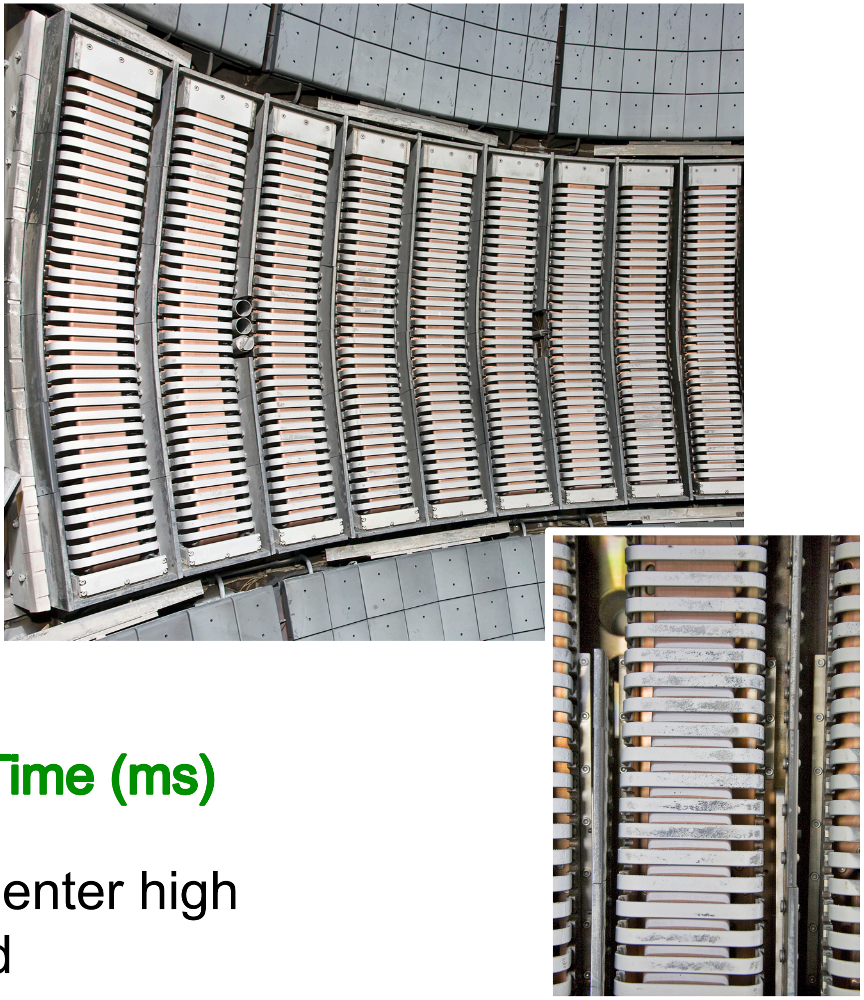
Large Particle Eruptions Observed with TV Cameras, Sometimes Resulting in Antenna Arcs

Visible TV Camera



Time (ms)

Antenna Coated with Li after Campaign



- Arcs probably occur when particles enter high voltage region inside Faraday shield

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Significantly Improved HHFW Operation with Li Conditioning & Double End-Fed Antenna

- Significant progress in heating early I_p ramp & during NBI H-mode
  - Li reduced edge n_e enabling first core HHFW electron heating during NBI H-mode
  - Coupling maintained through L-H transition and during ELMs
  - Significant RF acceleration of NBI fast-ions
- Fast-wave interaction with the edge may be an important RF power loss mechanism, particularly at low k_ϕ
- First operation of the double end-fed antenna has been encouraging
  - Increased arc-free power capability & produced RF H-modes in He & D_2
  - In 2010 use upgraded antenna with new liquid lithium divertor to improve coupling in H-modes and during I_p ramp