NSTX

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Recent Advances in High Harmonic Fast Wave Research on NSTX*

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

Gary Taylor[1]

In collaboration with

J-W. Ahn[2], R.E. Bell[1], P.T. Bonoli[3], E. Feibush[1], G. Chen[2], M. Choi[4], D.L. Green[2], R.W. Harvey[5], W.W. Heidbrink[6], J.C. Hosea[1], E.F. Jaeger[2], B.P. LeBlanc[1], D. Liu[7], R. Maingi[2], C.K. Phillips[1], M. Podesta[1], L. Roquemore[1], P.M. Ryan[2], E.J. Valeo[1], J.B. Wilgen[2], J.R. Wilson[1], and the NSTX Team

[1]Princeton Plasma Physics Laboratory
[2]Oak Ridge National Laboratory
[3]Massachusetts Institute of Technology
[4]General Atomics
[5]CompX
[6]University of California Irvine
[7]University of Wisconsin - Madison

* Work supported by US DoE contract DE-AC02-09CH11466

Presented at the Institute of Plasma Physics
Hefei, China, April 7, 2010

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

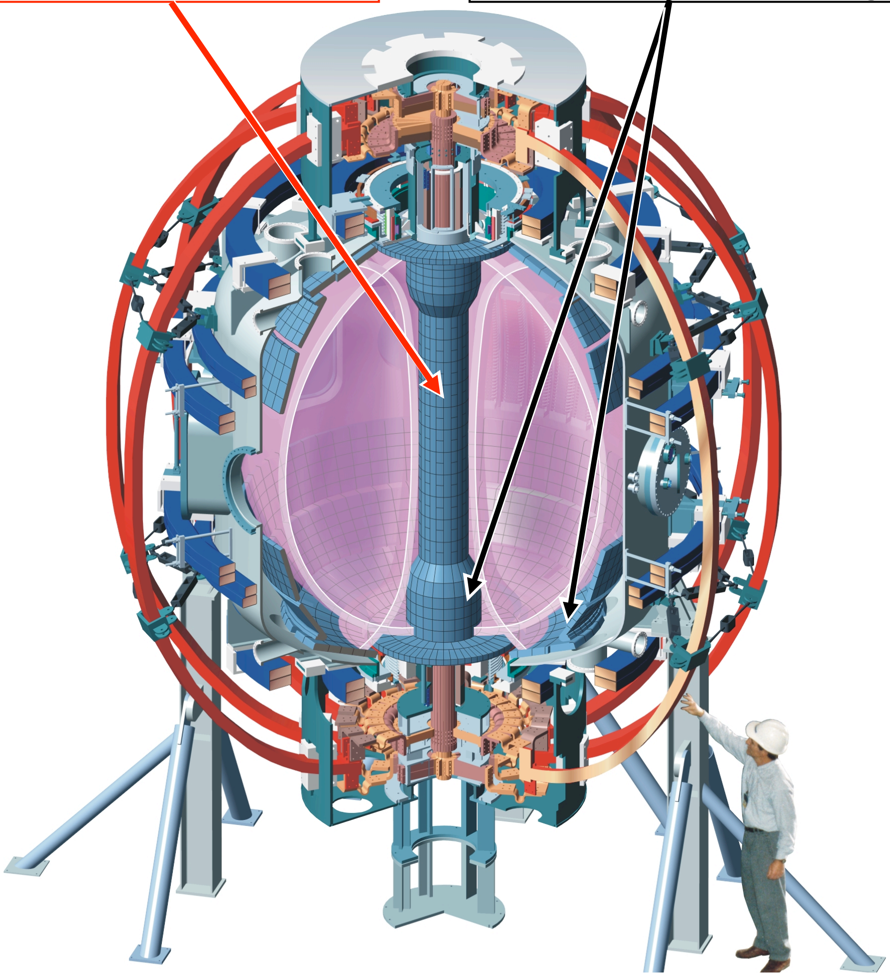
Outline

- Introduction to NSTX & the HHFW Research Program
- Improved HHFW heating with lithium conditioning
  - First Core HHFW electron heating observed in NBI H-mode
  - Significant RF interaction with NBI fast-ions
- RF interaction with plasma edge, ELMs & divertor
  - Direct RF power flow to divertor, RF edge heating & clamping
- Recent results with new double end-fed antenna
  - Increased arc-free power capability, RF H-modes in He & D_2
- Summary

Outline

- Introduction to NSTX & the HHFW Research Program
- Improved HHFW heating with lithium conditioning
  - First Core HHFW electron heating observed in NBI H-mode
  - Significant RF interaction with NBI fast-ions
- RF interaction with plasma edge, ELMs & divertor
  - Direct RF power flow to divertor, RF edge heating & clamping
- Recent results with new double end-fed antenna
  - Increased arc-free power capability, RF H-modes in He & D_2
- Summary

NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio

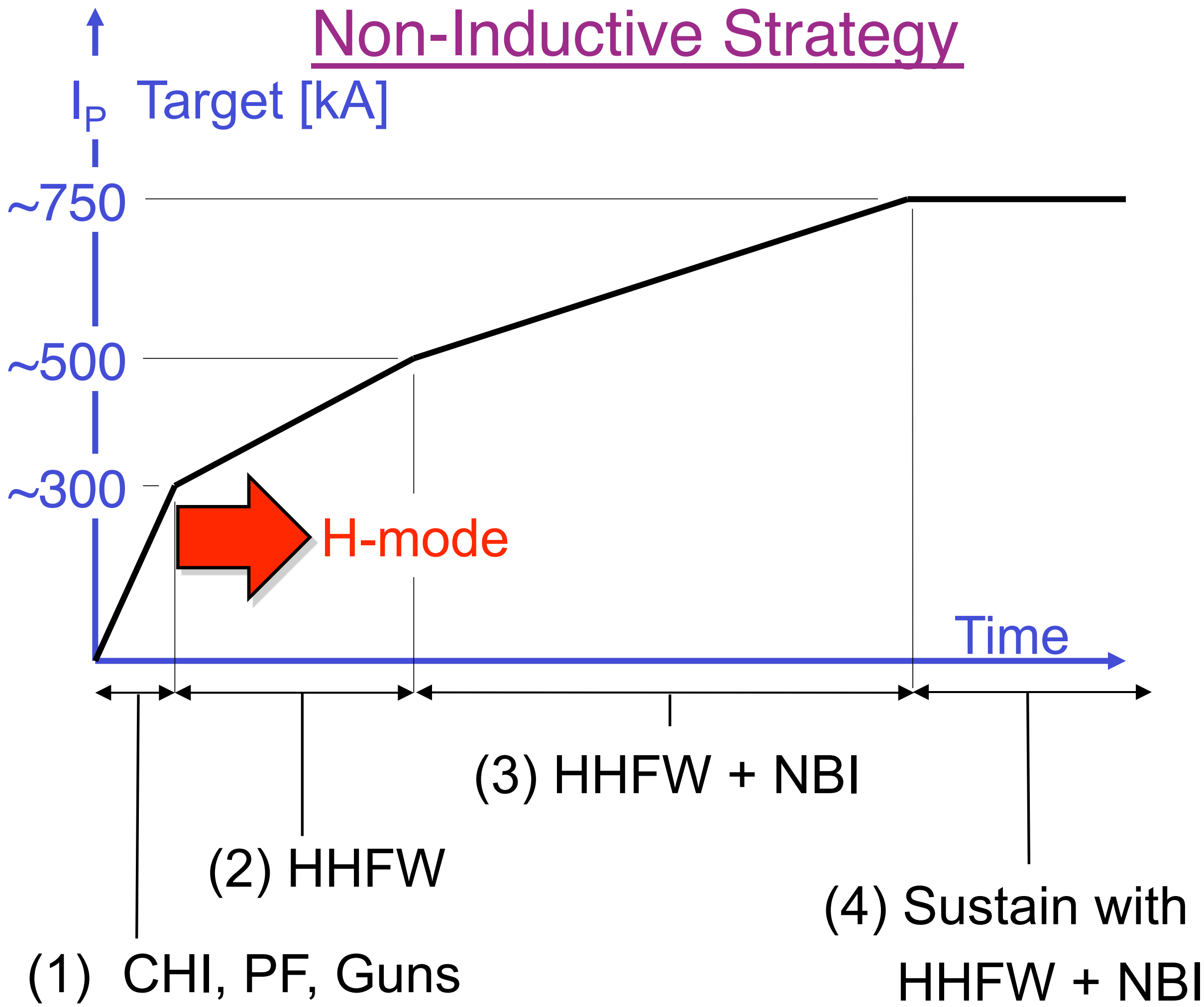


Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius	0.85 m
Toroidal Field B_{T0}	0.4 – 0.55 T
Plasma Current I_p	0.7 – 1.5 MA
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 6 keV
Central density	$\leq 1.2 \times 10^{20}$ m^{-3}
Toroidal beta β_T	10 – 40 %

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

- Ultimately Spherical Torus needs to run non-inductively

Non-Inductive Strategy



HHFW Goals

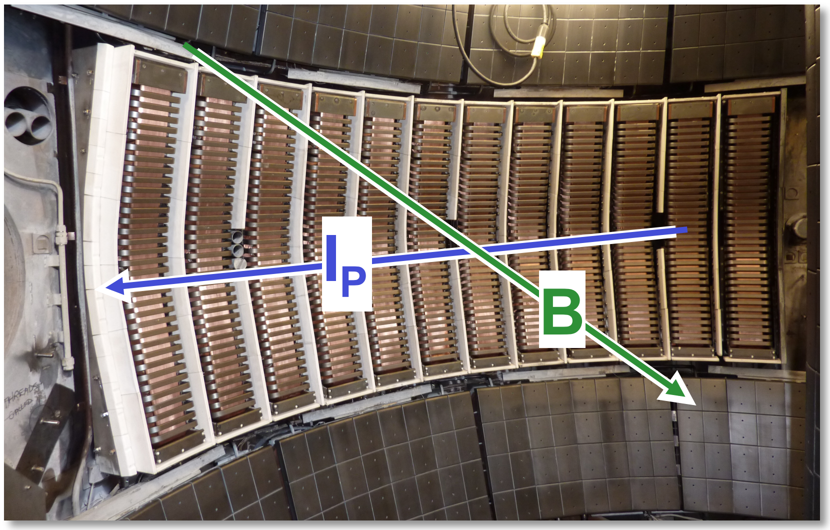
(1) HHFW couples to start-up plasma

(2) HHFW for I_P overdrive through bootstrap & HHFW CD

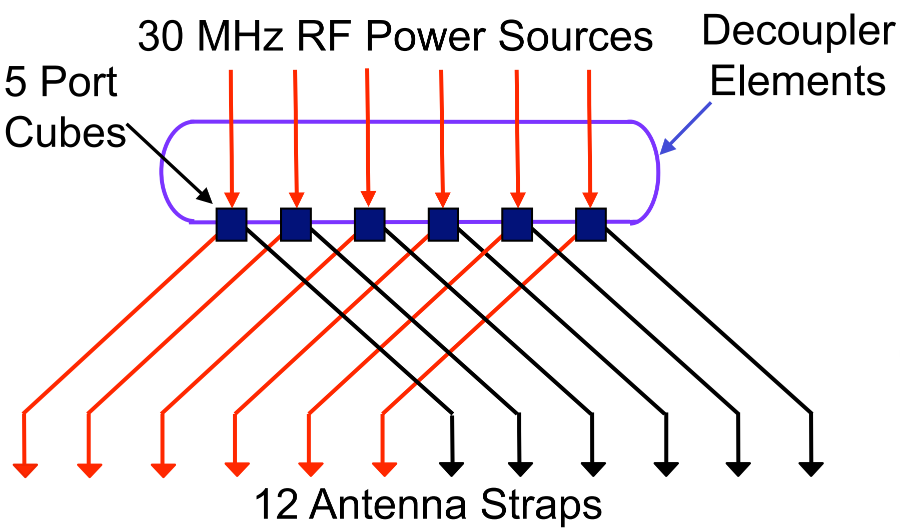
(3) HHFW generates sufficient I_P to confine NBI ions

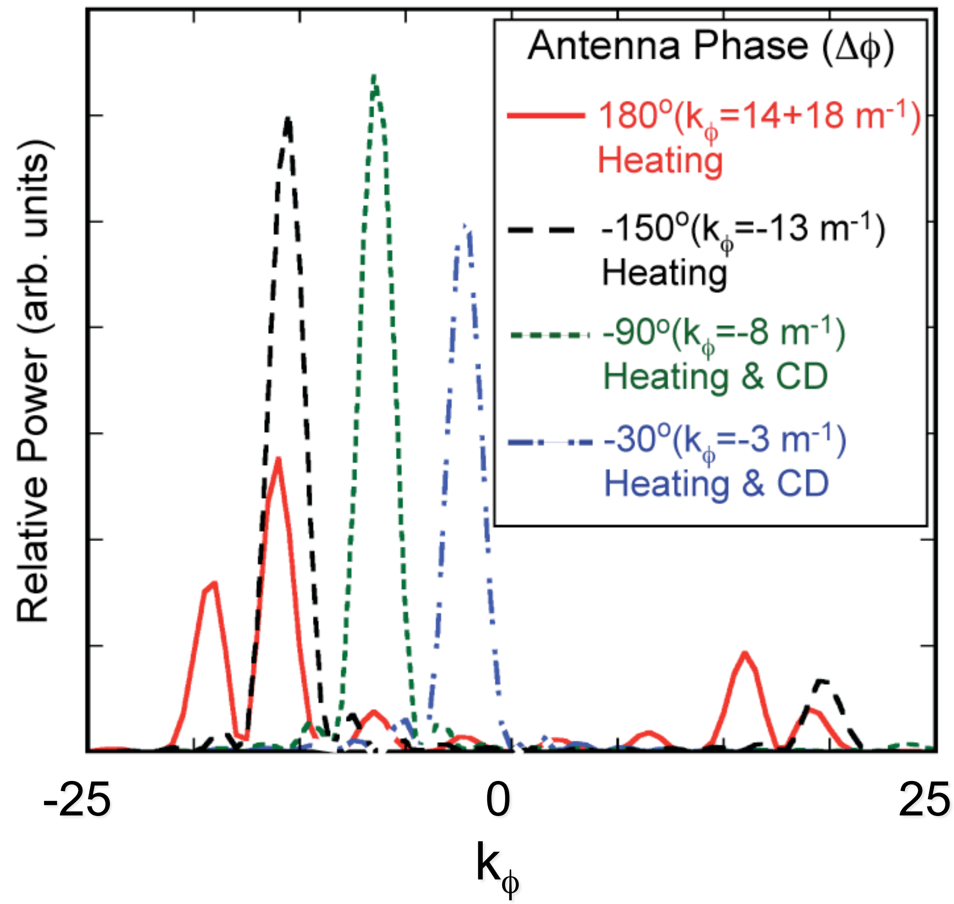
(4) HHFW provides bulk heating & q(0) control in H-mode

HHFW Antenna Has Well Defined Spectrum Ideal for Controlling Deposition, CD Location & Direction



HHFW antenna extends toroidally 90°

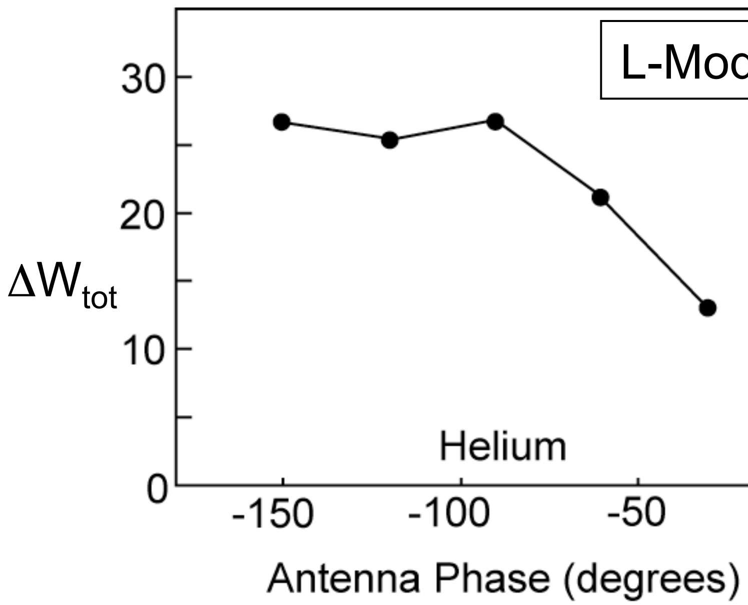




- Phase between adjacent straps (Δφ) easily adjusted from 0° to 180°

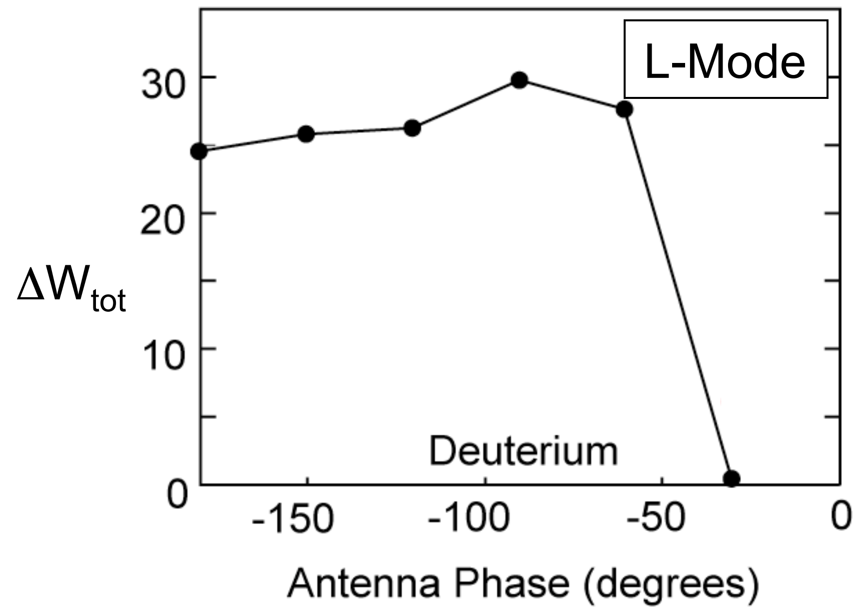
Core Heating Efficiency Degrades with Decreasing k_ϕ in He & D_2 L-Mode & D_2 H-Mode Plasmas

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



Decreasing k_ϕ →

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



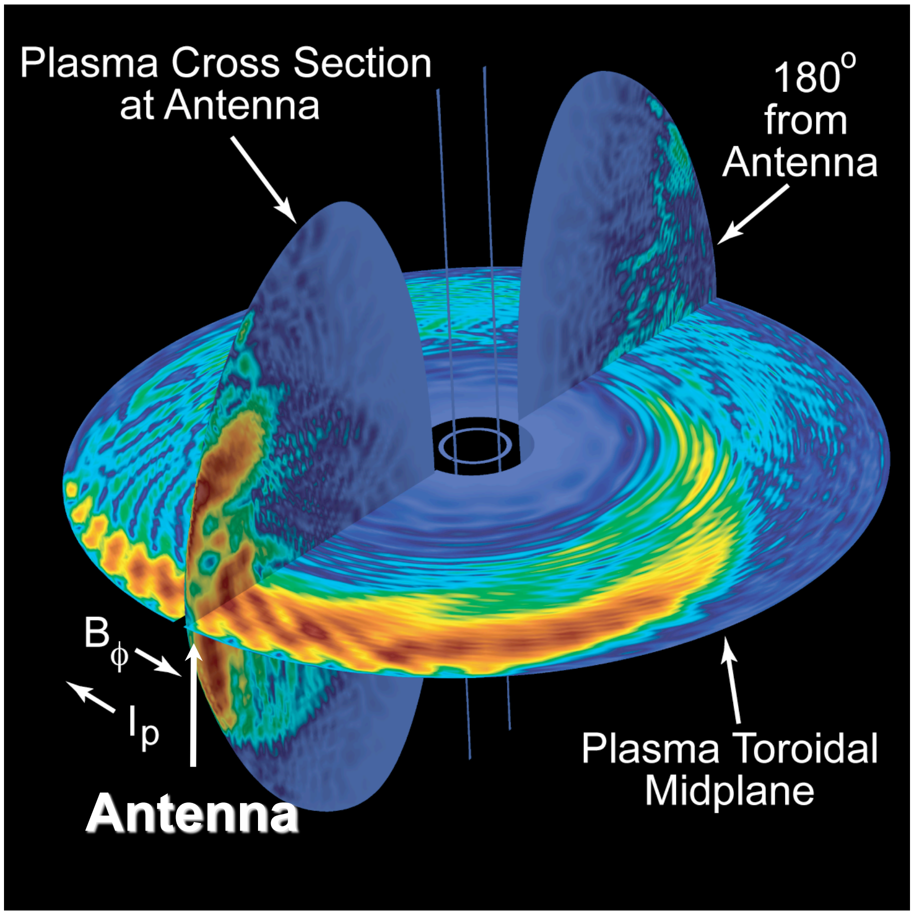
Decreasing k_ϕ →

- Also measure a degradation in core heating efficiency with decreasing k_ϕ In D_2 H-mode

J. Hosea, *et al.*, Phys. Plasmas **15**, 056104 (2008)
C.K. Phillips, *et al.*, Nucl. Fusion **49**, 075015 (2009)

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

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



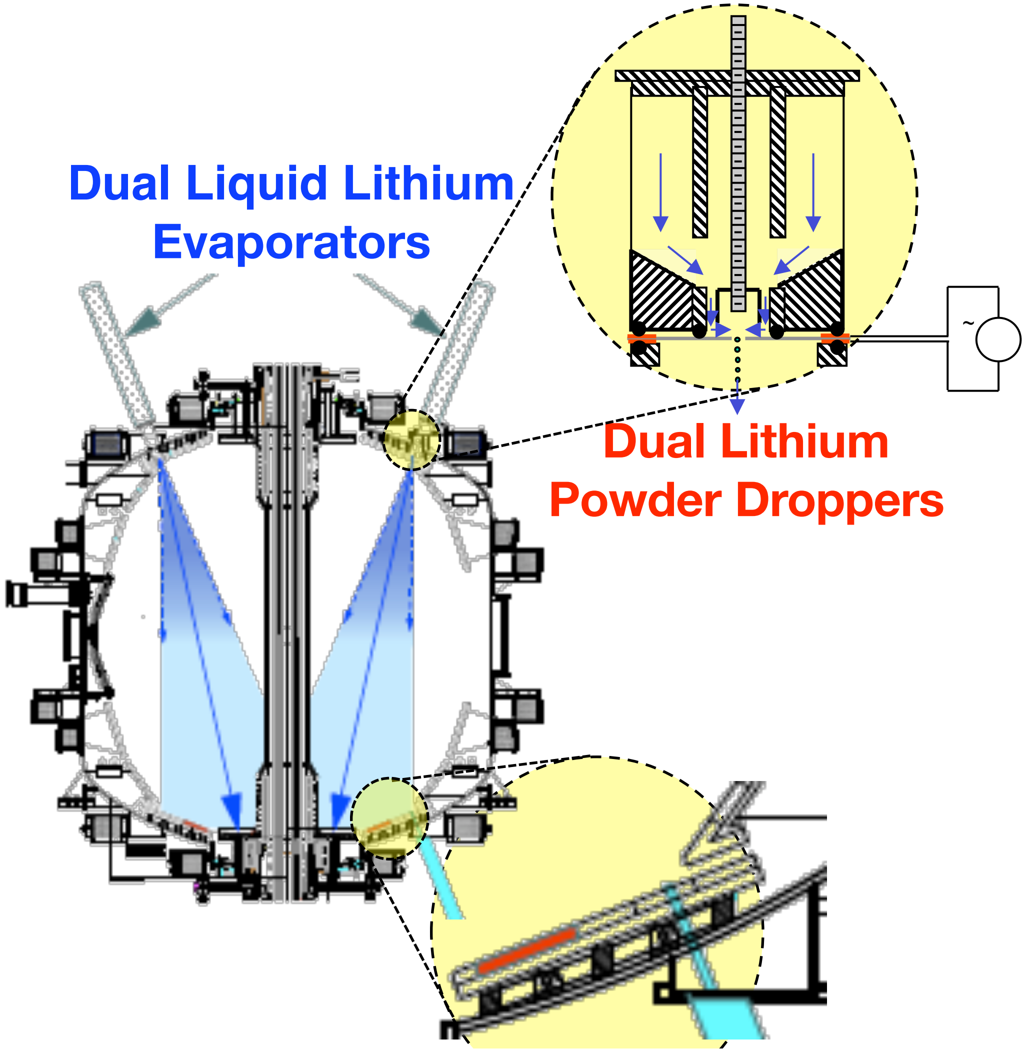
- Maximize RF heating efficiency (η_{eff}) in NBI + HHFW plasmas by understanding & mitigating edge RF losses
  - ➢ Important for ICRF on ITER
- η_{eff} degrades when n_e near antenna exceeds critical density (n_{crit}) for perpendicular fast wave propagation
- Li conditioning reduces edge n_e; moves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

Outline

- Introduction to NSTX & the HHFW Research Program
- Improved HHFW heating with lithium conditioning
  - First Core HHFW electron heating observed in NBI H-mode
  - Significant RF interaction with NBI fast-ions
- RF interaction with plasma edge, ELMs & divertor
  - Direct RF power flow to divertor, RF edge heating & clamping
- Recent results with new double end-fed antenna
  - Increased arc-free power capability, RF H-modes in He & D_2
- Summary

Li Evaporators, Li Droppers & Fast IR Cameras Provide New Capability for Controlling & Studying RF Edge Interaction

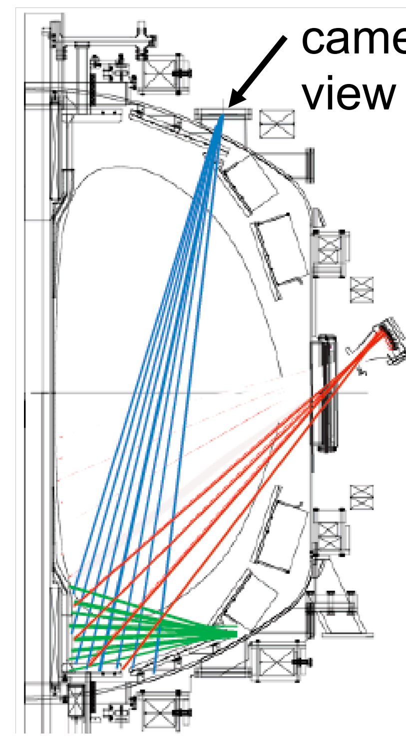
Dual Liquid Lithium Evaporators



Dual Lithium Powder Droppers

Liquid Lithium Divertor (2010)

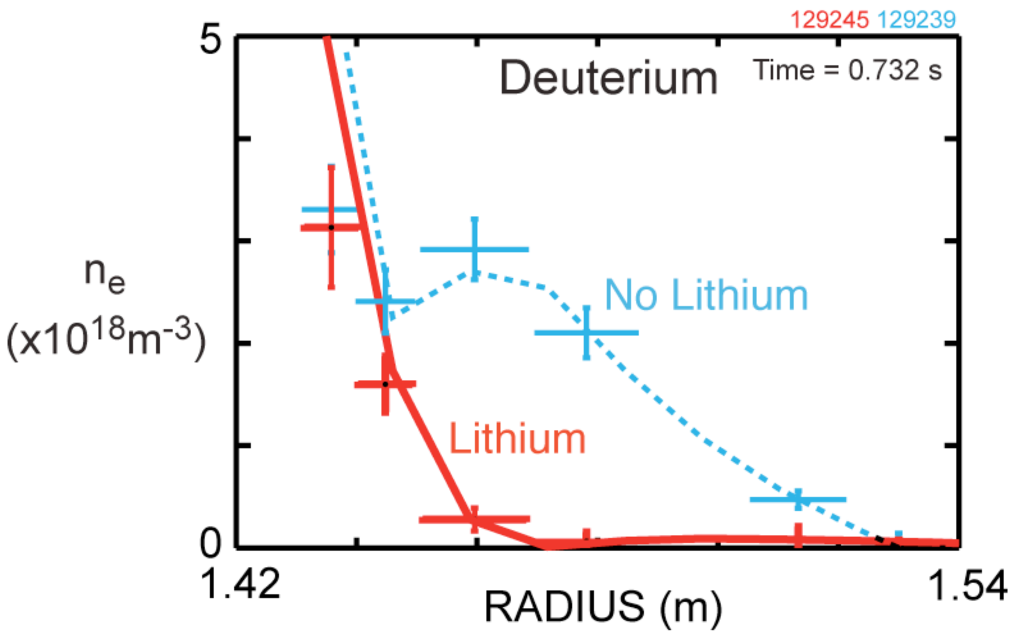
Fast IR camera for studying ELM-resolved heat flux



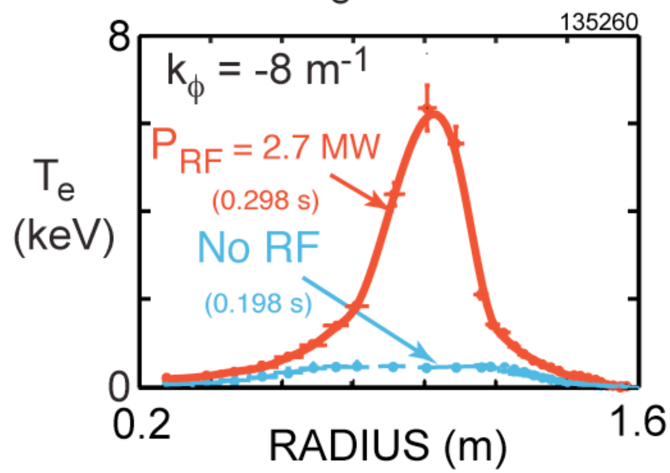
Three bolometer views for studying divertor radiation

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

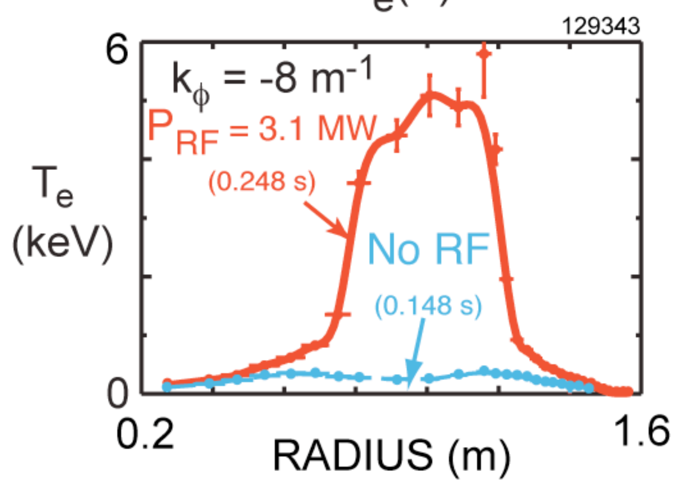
$B_T(0) = 0.55$ T



Helium: $T_e(0)$ = 6.2 keV



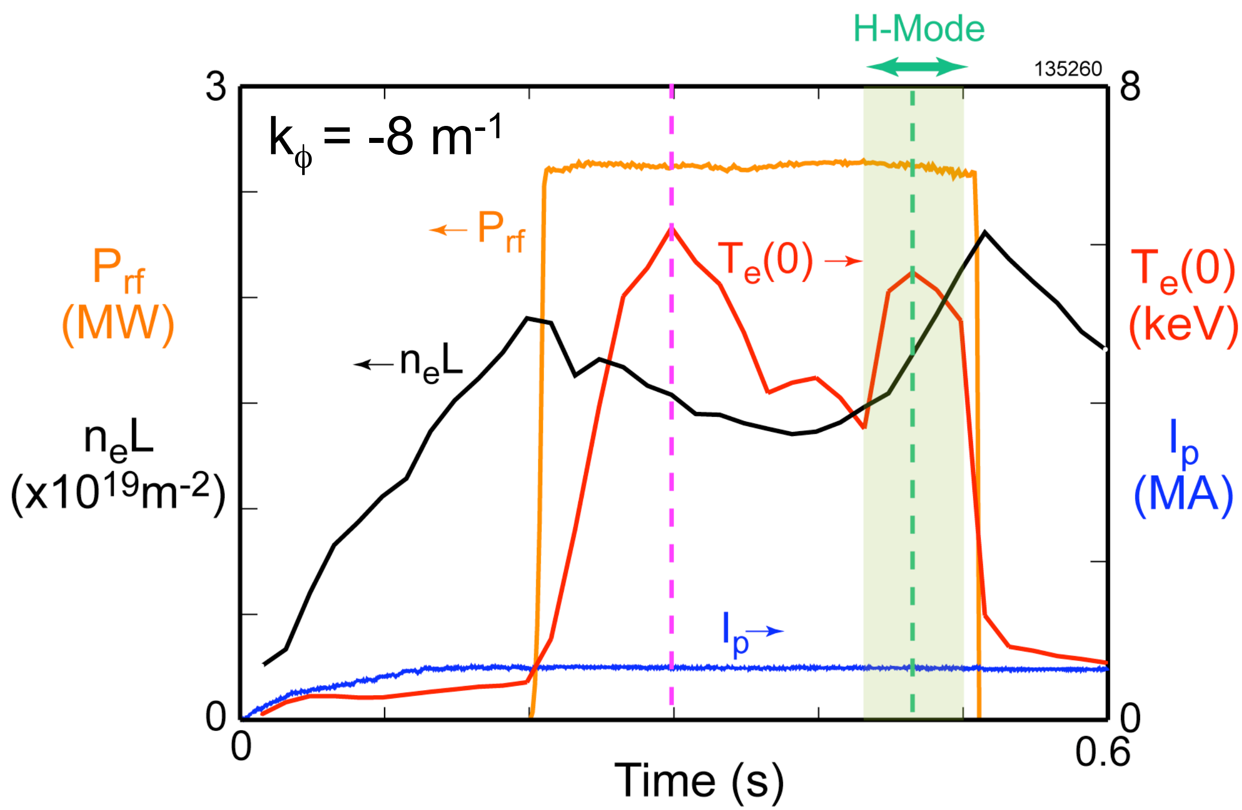
Deuterium: $T_e(0)$ = 5.2 keV

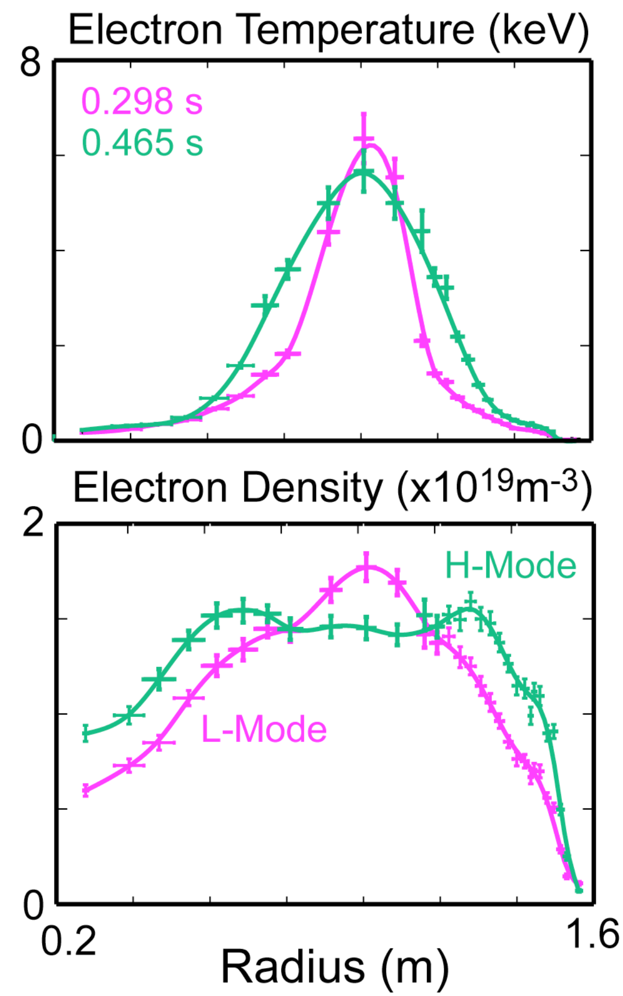


- Lithium reduces edge density – improves core heating efficiency

Ohmically-Heated Helium Target Plasma Transitions to H-Mode During 2.6 MW HHFW Pulse

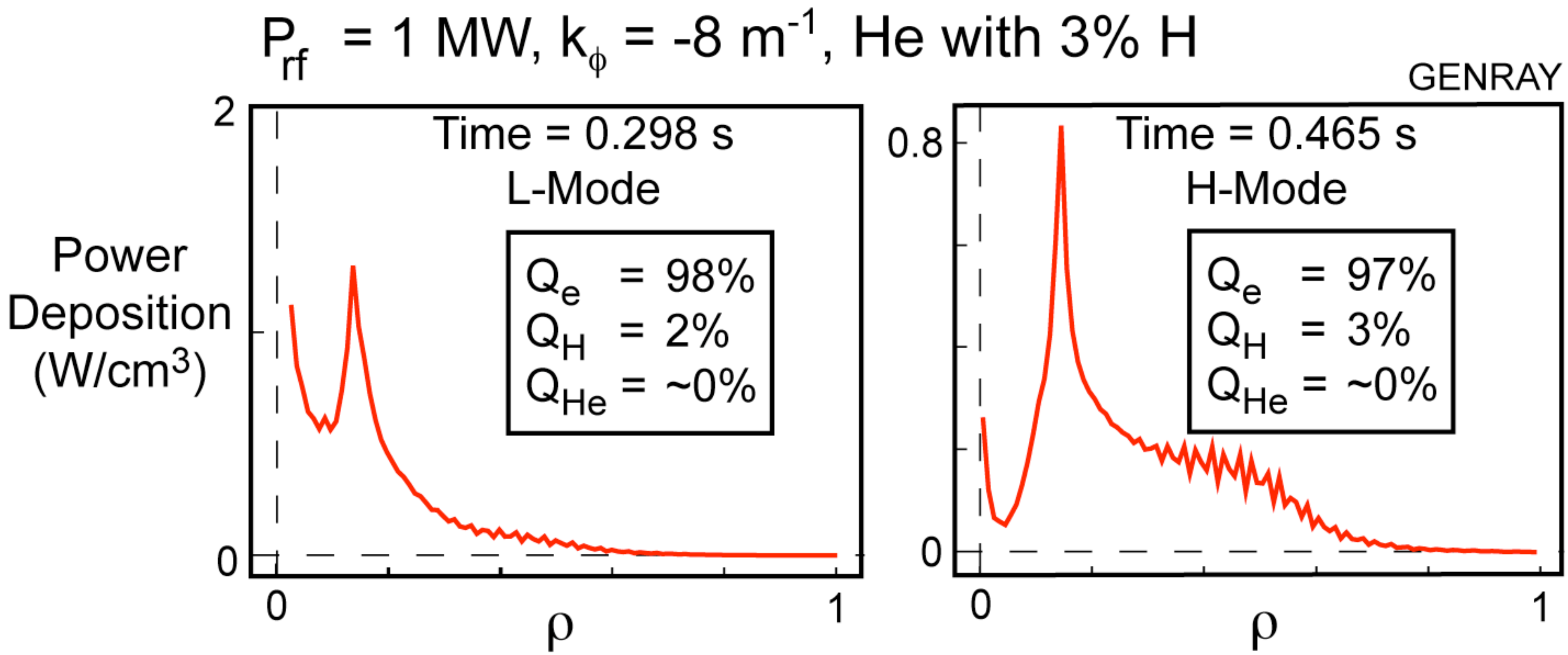
Shot 135260





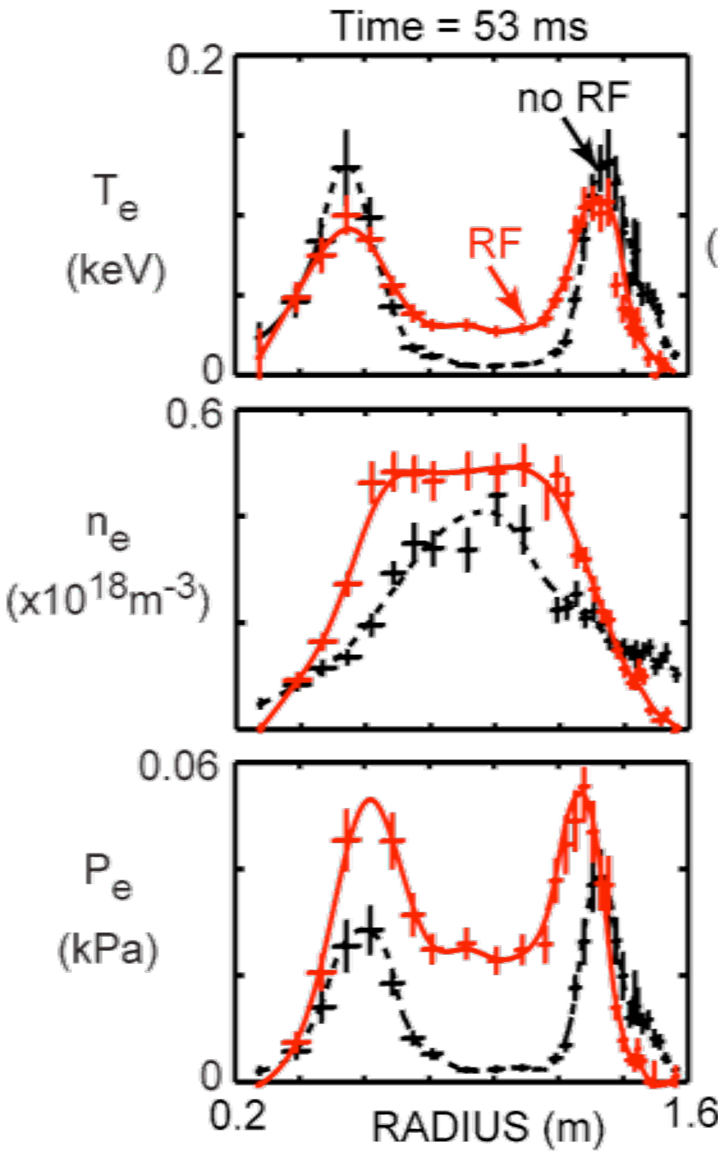
Ray Tracing Simulation Predicts > 90% of RF Power Deposited on Electrons Inside ρ ~ 0.6

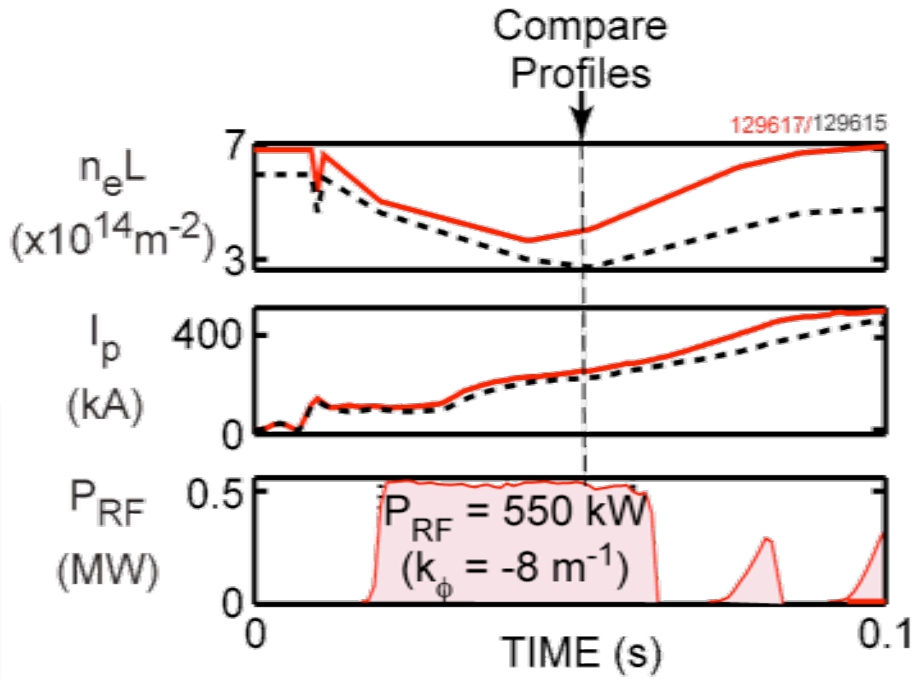
Shot 135260



- Broader HHFW power deposition during H-Mode

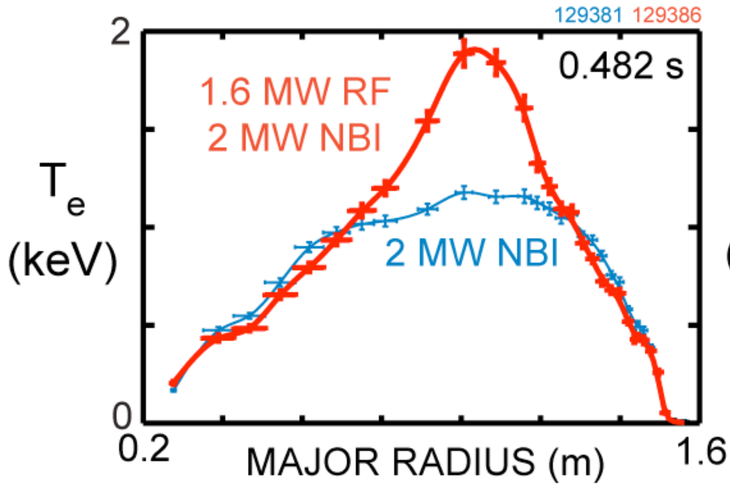
Lithium Wall Conditioning Enabled HHFW Heating of Core Electrons During Early I_p Ramp

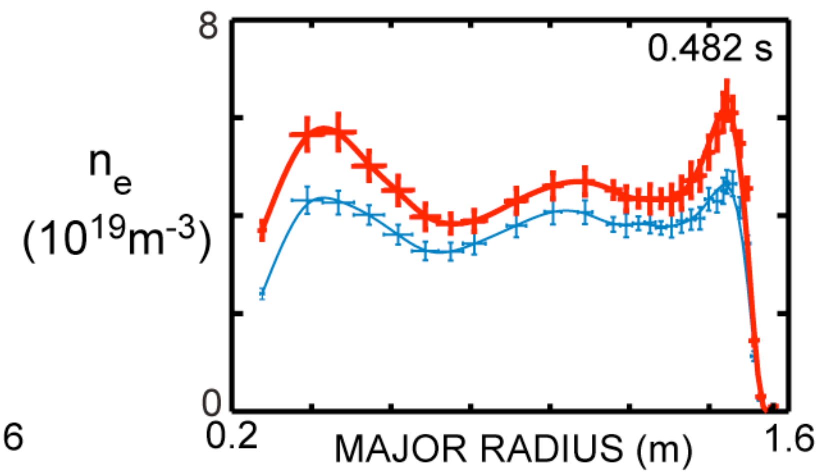


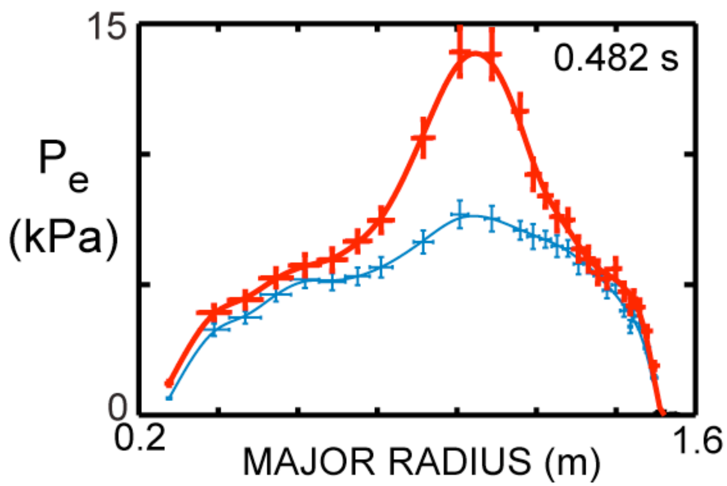


- Core HHFW electron heating also measured during CHI start-up
- High-bootstrap fraction HHFW heating experiments planned for 2010

Lithium Enabled Significant HHFW Heating of Core Electrons During Some D_2 NBI-Driven 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*

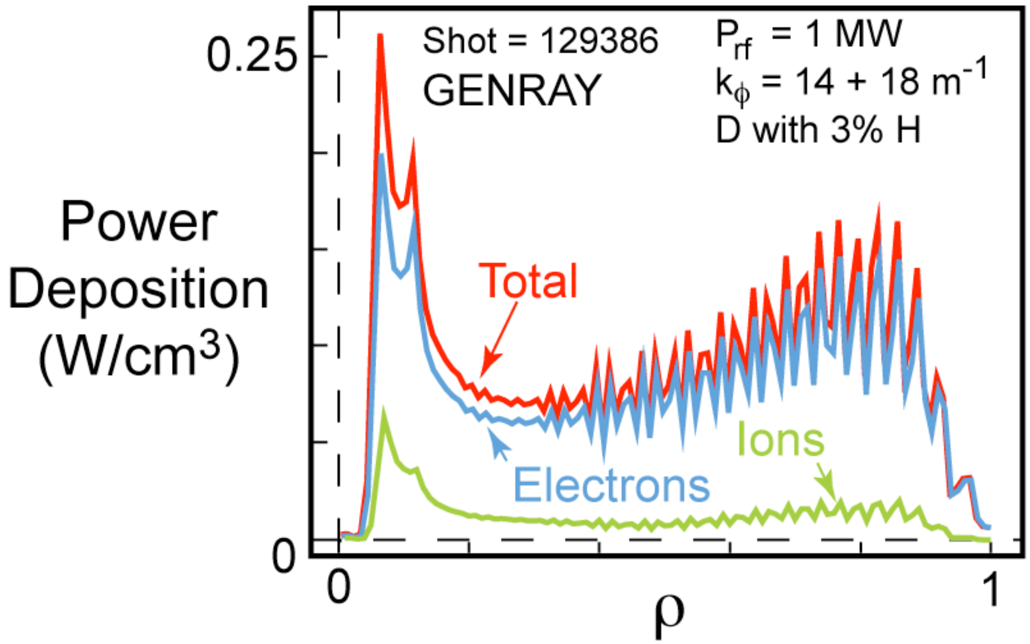
*B. LeBlanc, *et al.*, AIP Conf. Proc. **787**, 86 (2005)

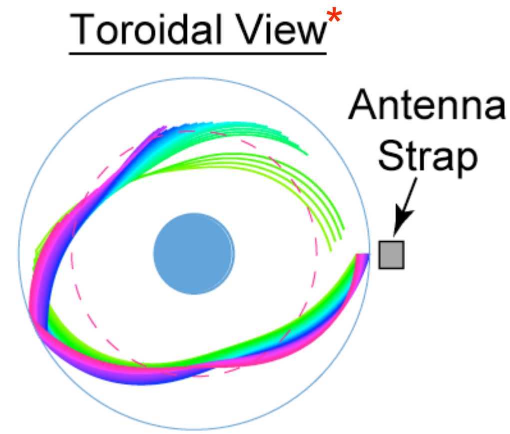
Ray Tracing Predicts ~ 90% RF Absorption by Electrons During RF + NBI H-Mode

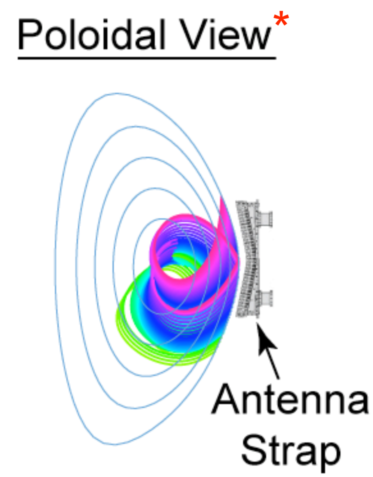
RF+NBI Shot 129386

Q_e = 88%
Q_{fast} = 5%
Q_H = 7%

Time = 0.48 s
(End of H-Mode)



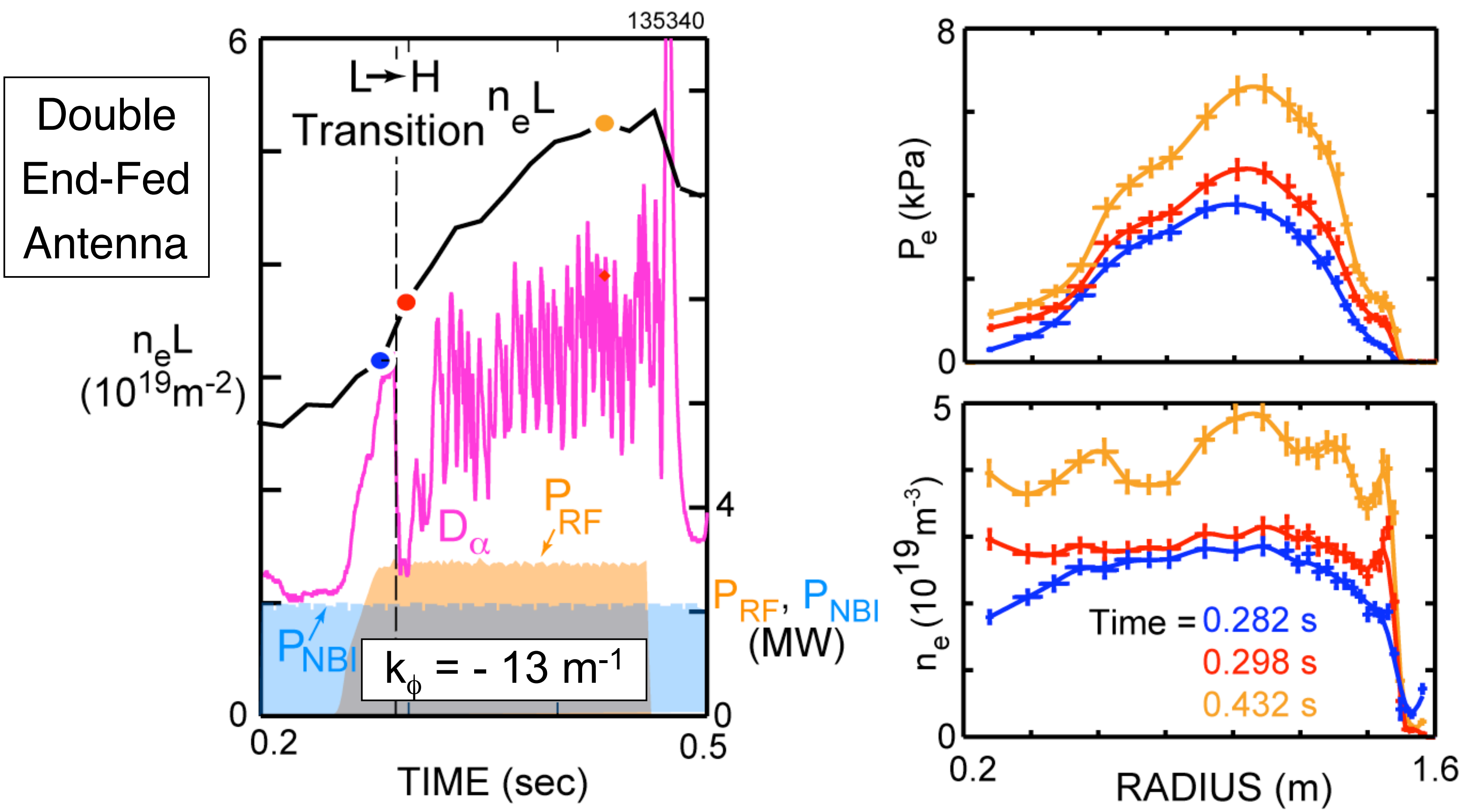




* Rays end when 99.9% of RF power is absorbed

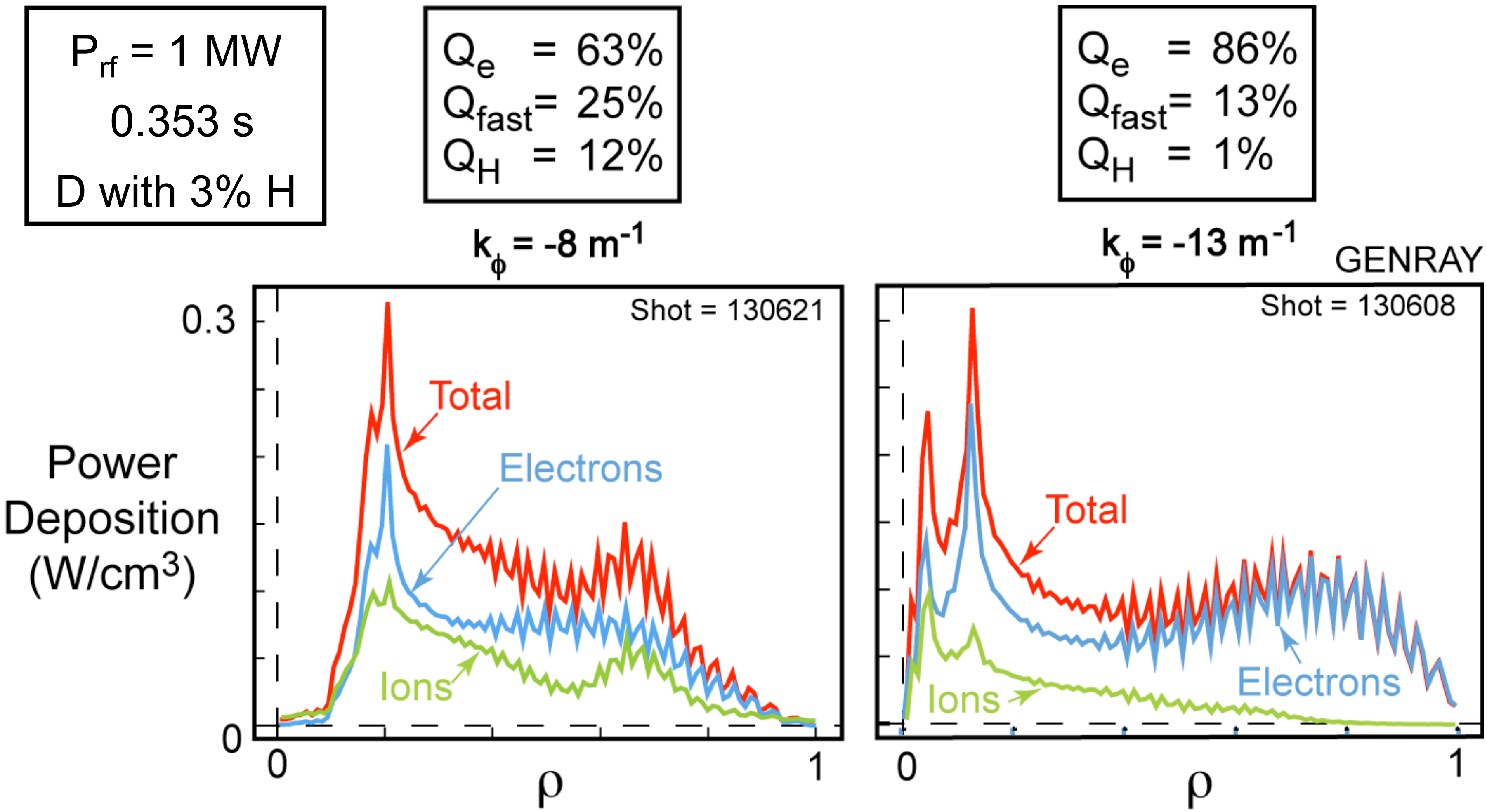
- NBI fast-ion density and effective temperature provided by TRANSP transport analysis of similar NBI-only H-mode

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



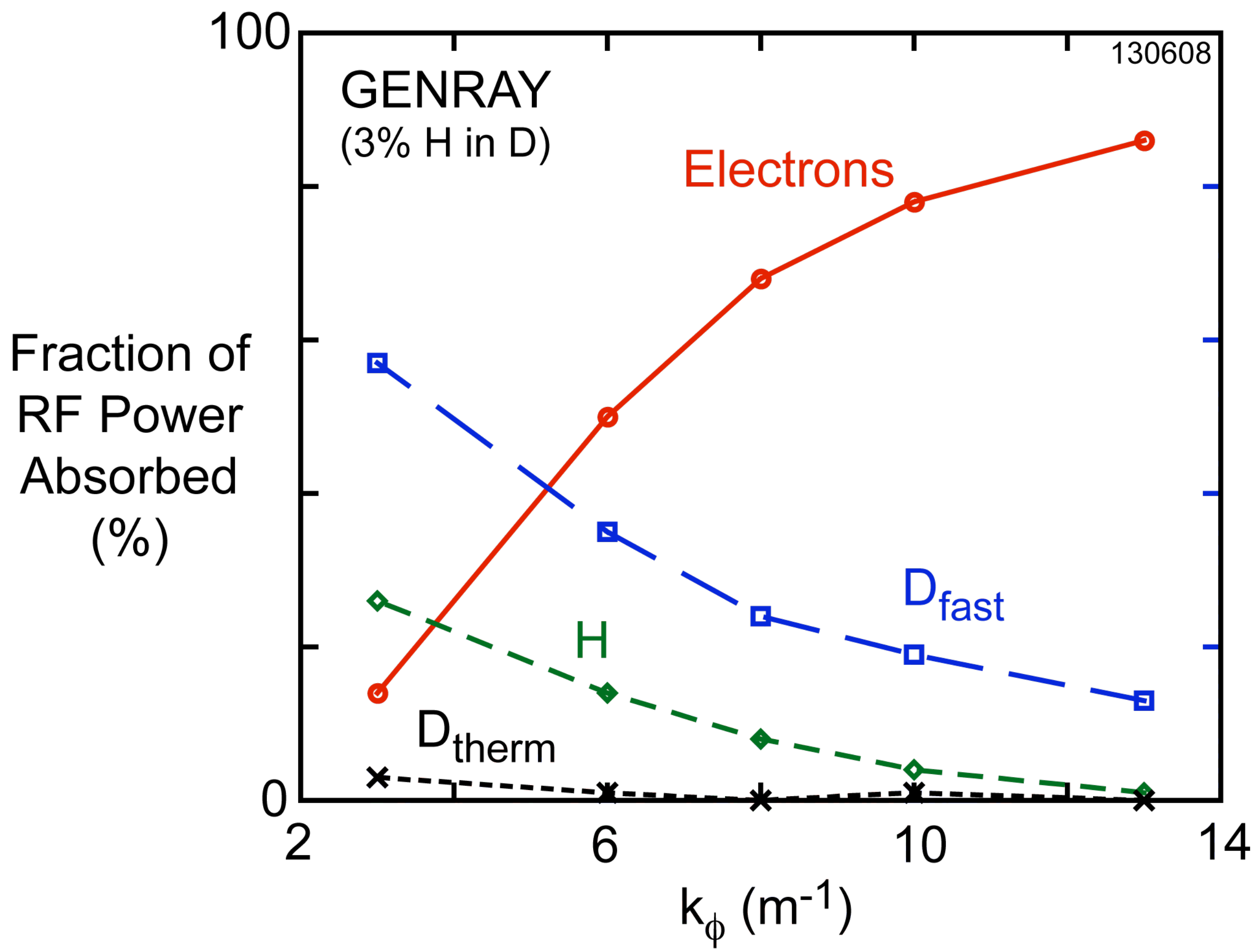
- Transition to H-mode occurs after RF turn on and without RF arc

Broader RF Power Deposition at Higher k_ϕ During RF-Heated NBI H-Mode



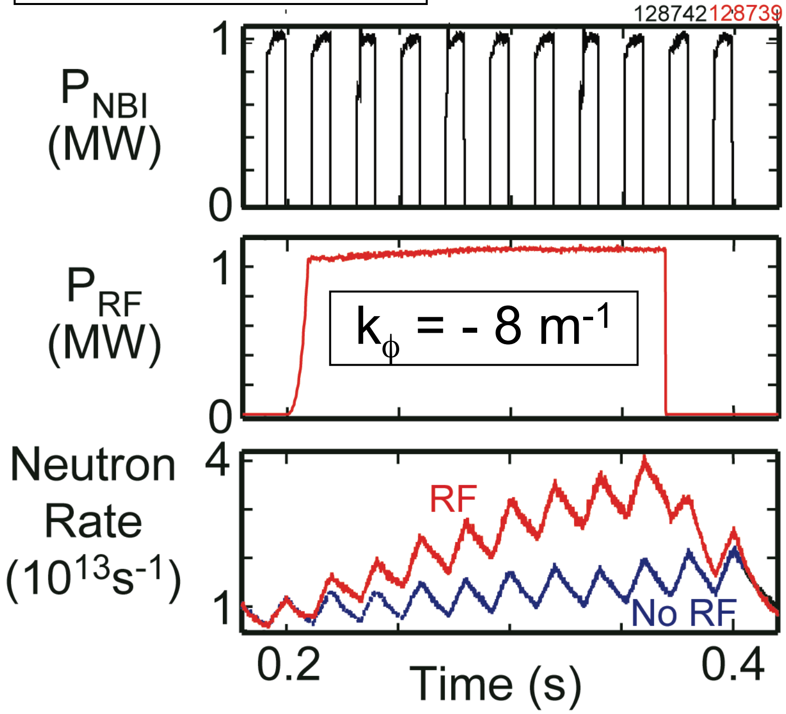
- Strong competition between RF heating of NBI fast-ions and electrons, particularly near magnetic axis

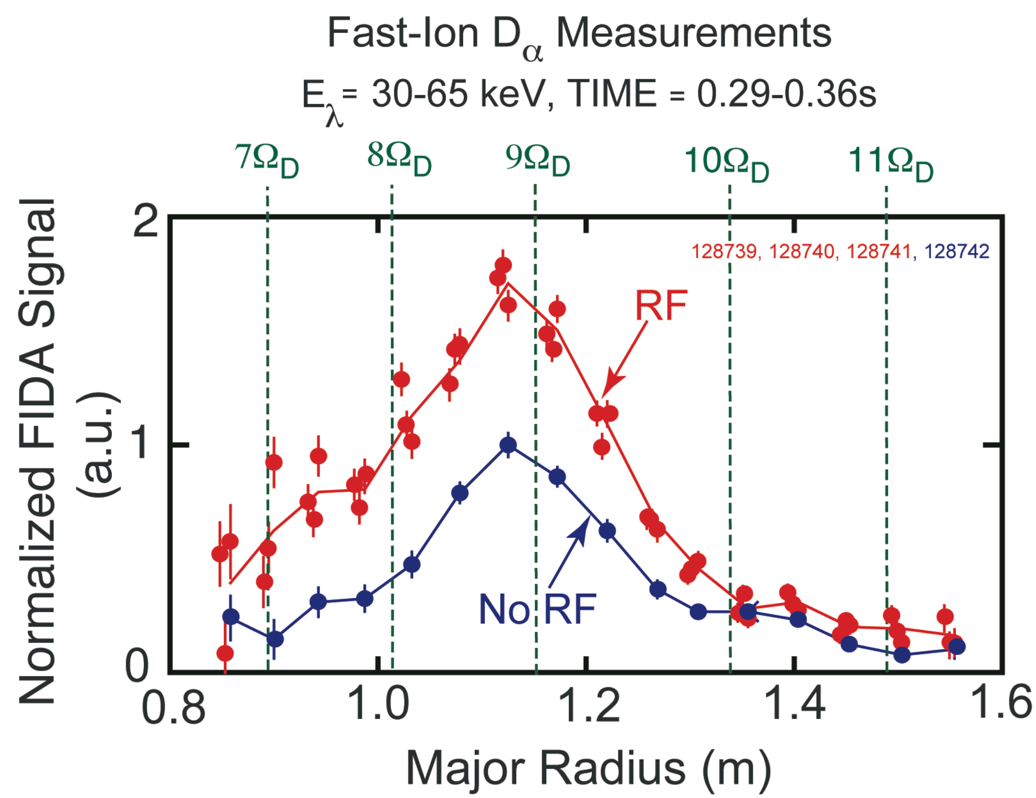
RF Deposition to Ions Increases Significantly at Lower k_ϕ During RF-Heated NBI H-Mode



Fast-Ion D_α (FIDA) Measurement Shows Significant Interaction Between HHFW and NBI Ions

$B_T(0)$ = 5.5 kG





- Large increase in neutron rate during HHFW + NBI plasmas
- FIDA measures significant enhancement & broadening of fast-ion profile when HHFW power is applied to NBI plasma*

*D. Liu *et al.*, Plasma Phys. Control. Fusion **52**, 025006 (2010)

Integration of TORIC Full-Wave Solver into TRANSP Provides New Capability to Model HHFW in NSTX

- TORIC* full-wave solver, that can compute HHFW propagation and absorption in NSTX, now included in TRANSP

- TORIC calculates power deposition into all species, including fast-ions

  - No RF Monte-Carlo Fokker-Planck operator presently in TRANSP

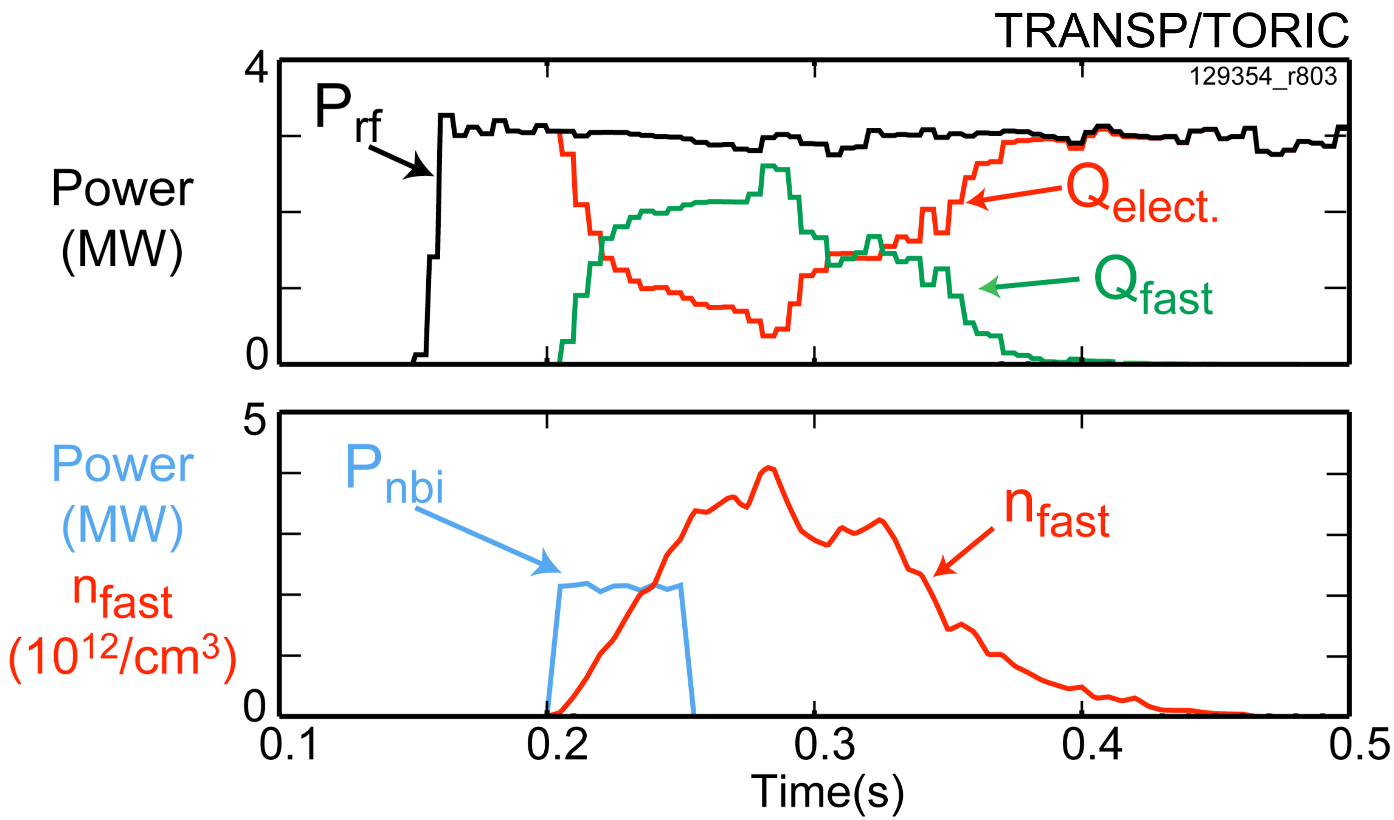
  - Self-consistent calculation of fast-ions not available for RF-heated NBI plasmas

  - Use CQL3D Fokker-Plank code to estimate neutron rate generated by fast-ions

*M. Brambilla, Plasma Phys. Control. Fusion **44**, 2423 (2002)

TRANSPP/TORIC Modeling Predicts RF Absorption by NBI Fast-Ions Lasts Well After NBI Turn Off

$k_\phi = -8\ m^{-1}$

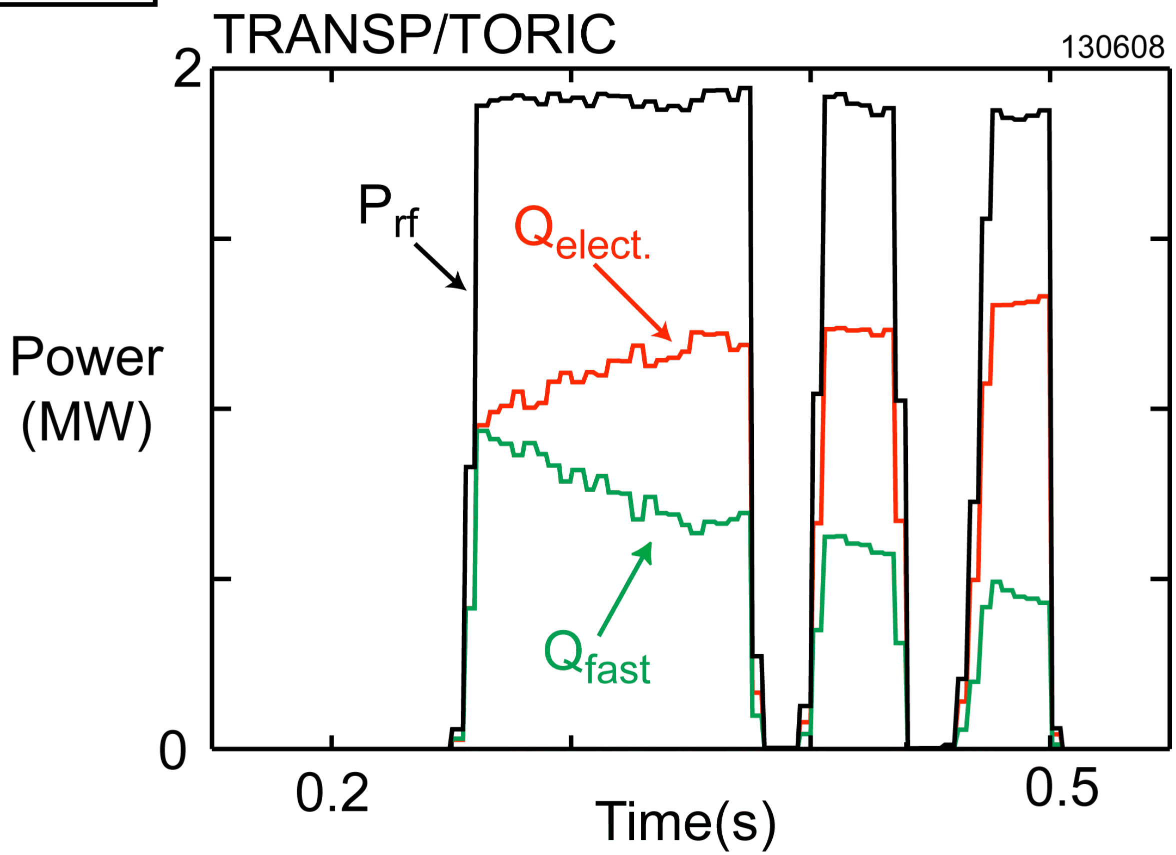


- All rf power absorbed by electrons prior to NBI pulse
- After NBI turn-on, the fast-ion population absorbs HHFW power at the expense of the electrons
  - ➢ Trend confirmed by single time point calculations with AORSA, GENRAY and TORIC

RF Power Absorption by Fast-Ions Decreases as Fast-Ions Thermalize During RF-Heated NBI H-Mode

Shot 130608

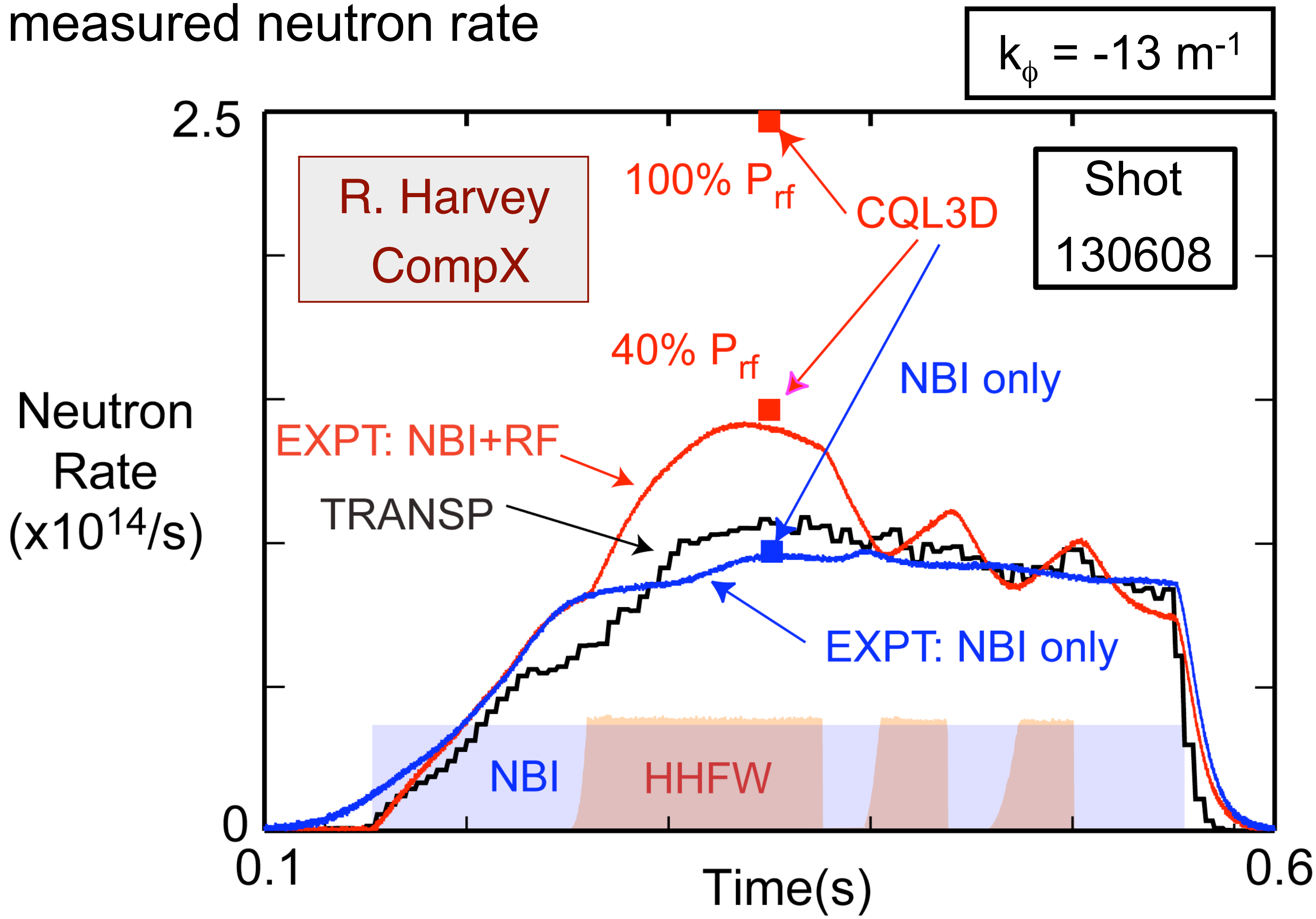
$k_\phi = -13\ m^{-1}$



- Electron β increases with time as density rises, increasing RF heating on electrons

CQL3D Simulation Predicts ~ 40% of RF Antenna Power Coupled to Plasma for k_ϕ = -13 m^{-1} Heating

- P_{rf} used in CQL3D modeling reduced to match simulated and measured neutron rate

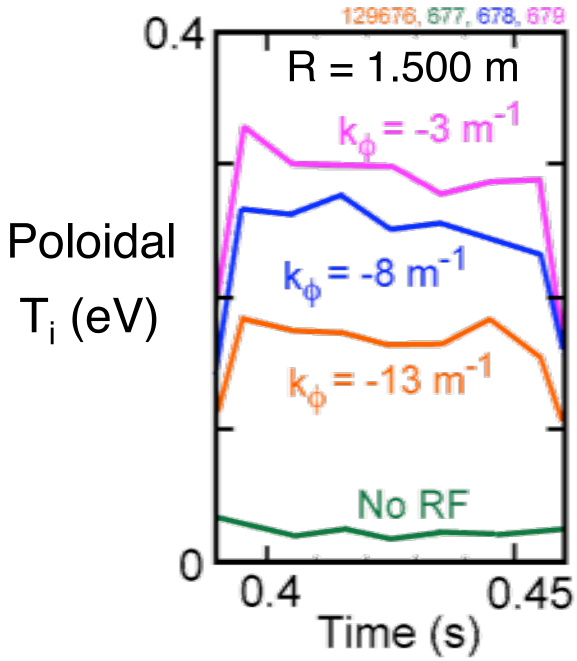


Outline

- Introduction to NSTX & the HHFW Research Program
- Improved HHFW heating with lithium conditioning
  - First Core HHFW electron heating observed in NBI H-mode
  - Significant RF interaction with NBI fast-ions
- RF interaction with plasma edge, ELMs & divertor
  - Direct RF power flow to divertor, RF edge heating & clamping
- Recent results with new double end-fed antenna
  - Increased arc-free power capability, RF H-modes in He & D_2
- Summary

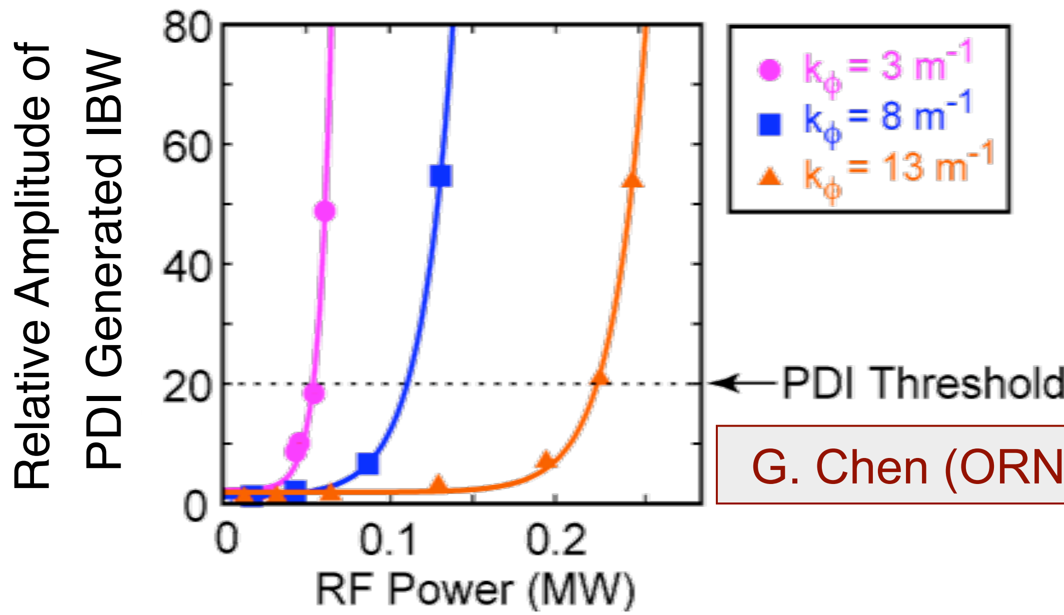
1-D Full Wave Model Predicts P_{RF} ~ 100-200 kW Can Drive PDI; P_{RF} Needed to Drive PDI Falls with k_ϕ

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



P_{RF} = 1.2-1.3 MW

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



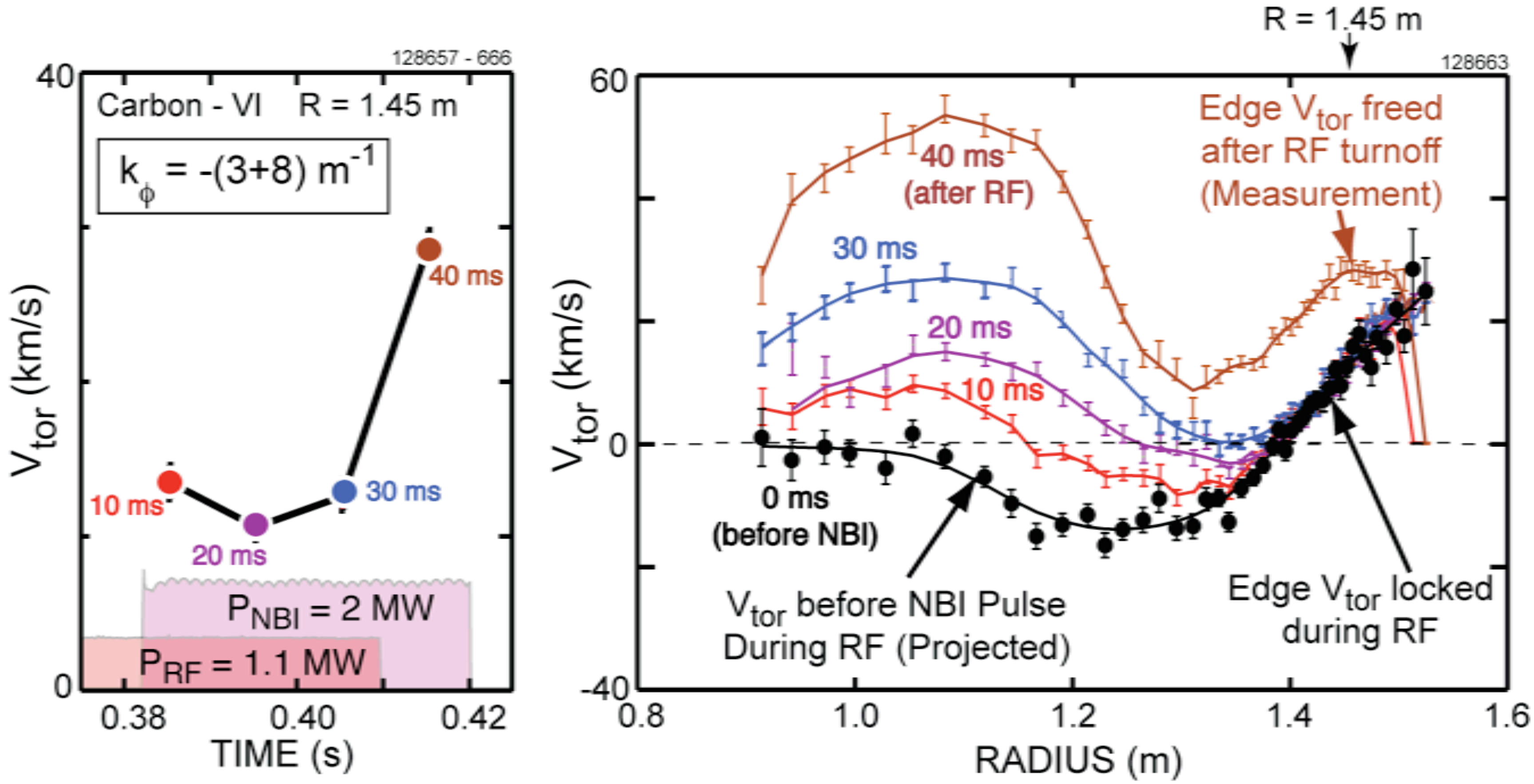
G. Chen (ORNL)

- 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

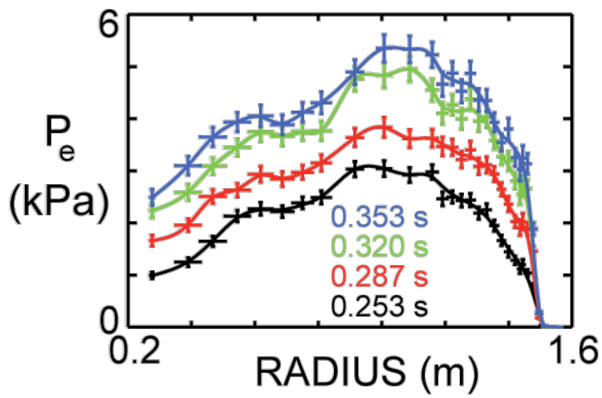
V_{tor} Measured by Charge Exchange Recombination Spectroscopy



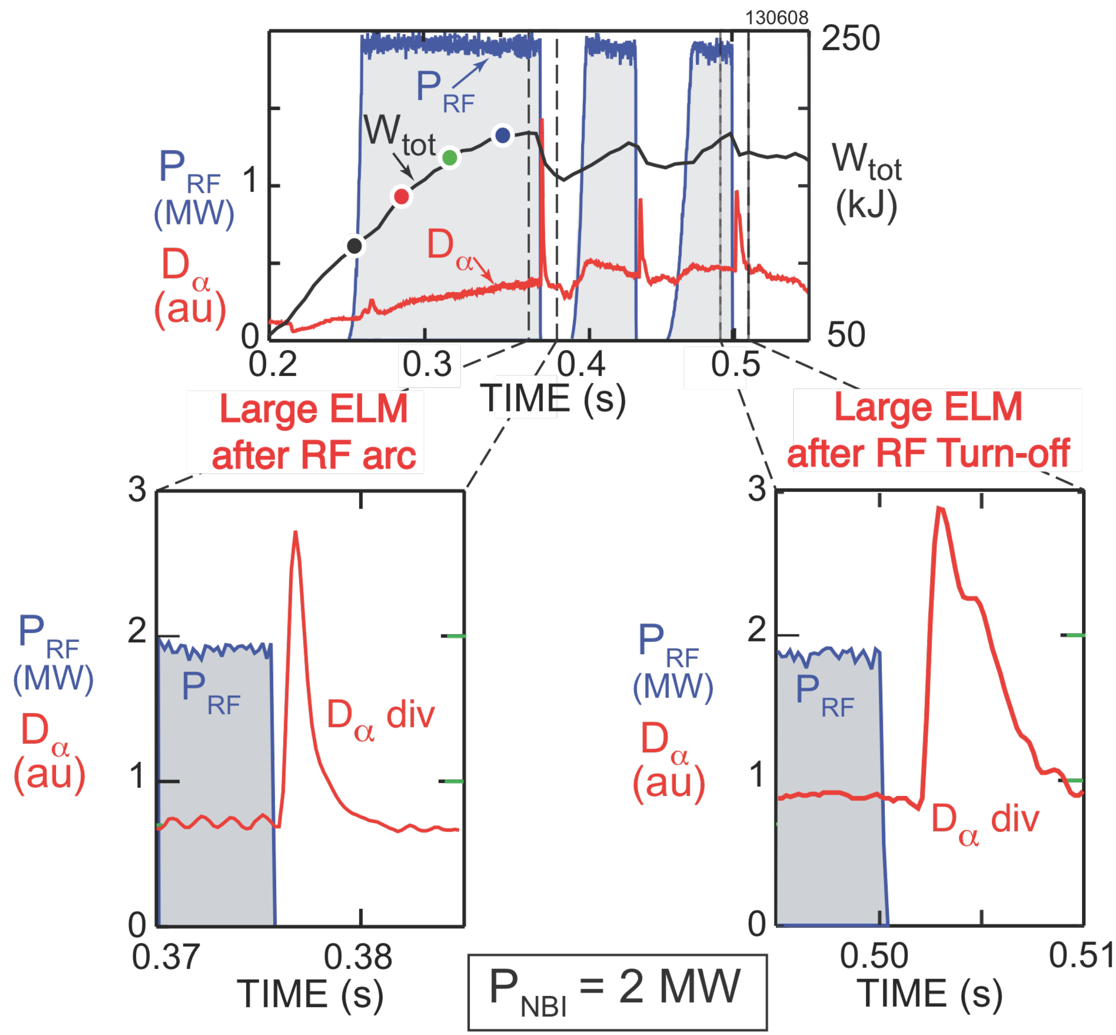
- Mechanism not understood, but may point to edge ion loss
- RF apparently provides a drag on core plasma rotation as well

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

$k_\phi = -13\ m^{-1}$

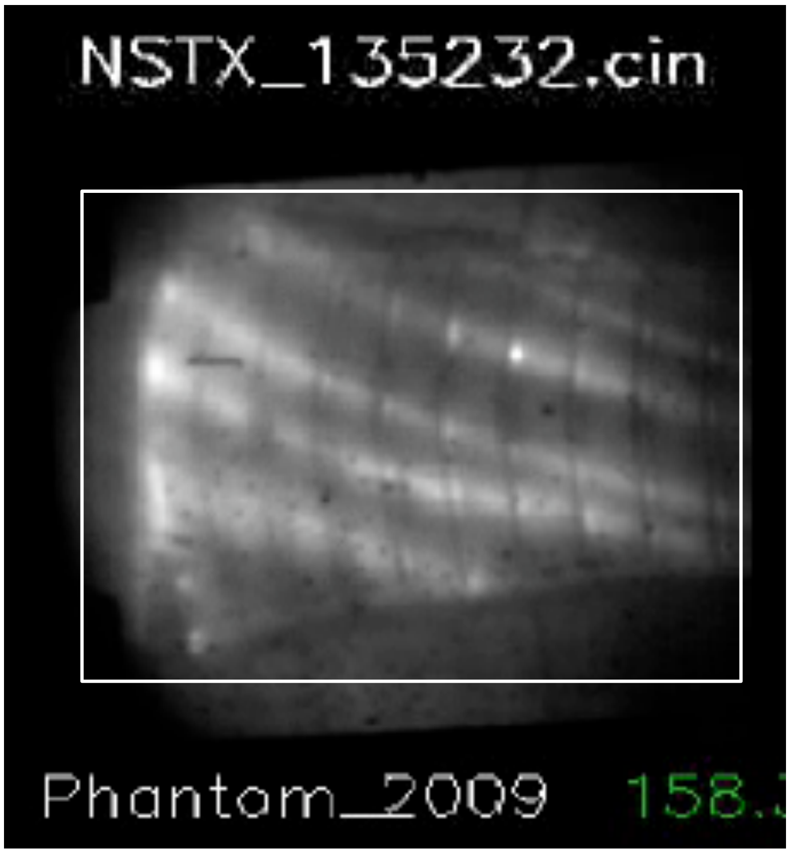


- Strong edge pressure gradient appears to lead to ELM
- Arcs occur prior to excursion of D_α light
- Similar behavior observed for $k_\phi = -8\ m^{-1}$ heating



Particle Eruptions from Antenna, Observed with Visible Cameras, Sometimes Result in Antenna Arcs

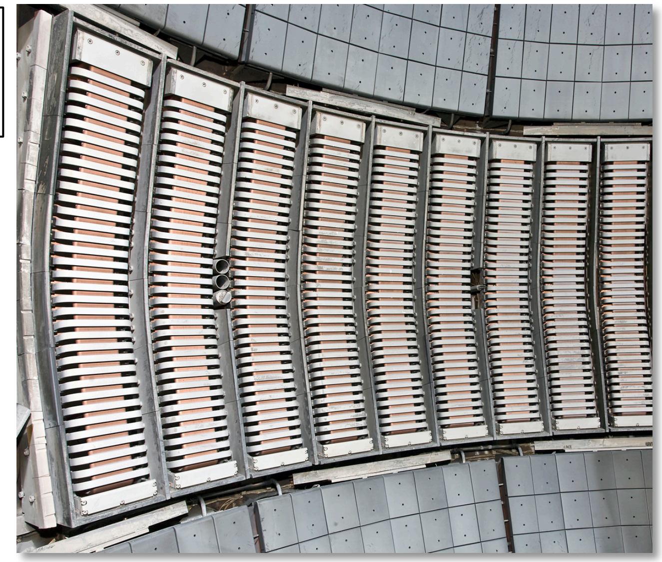
Visible TV Camera



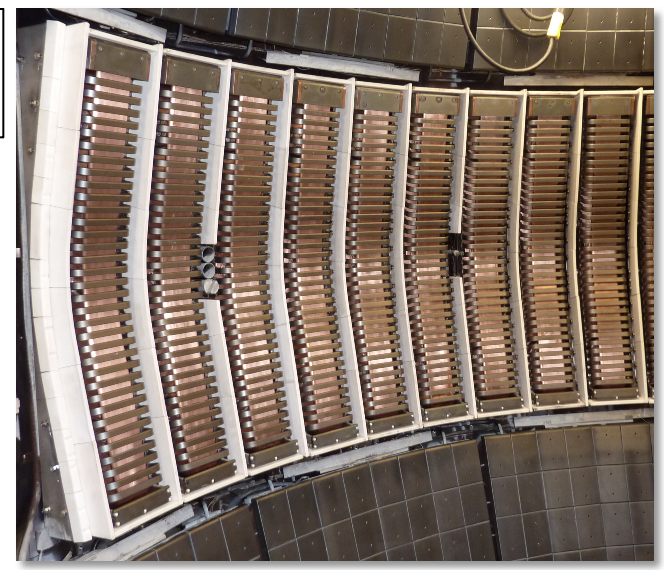
←Time (ms)

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

Li Coated Antenna



Clean Antenna



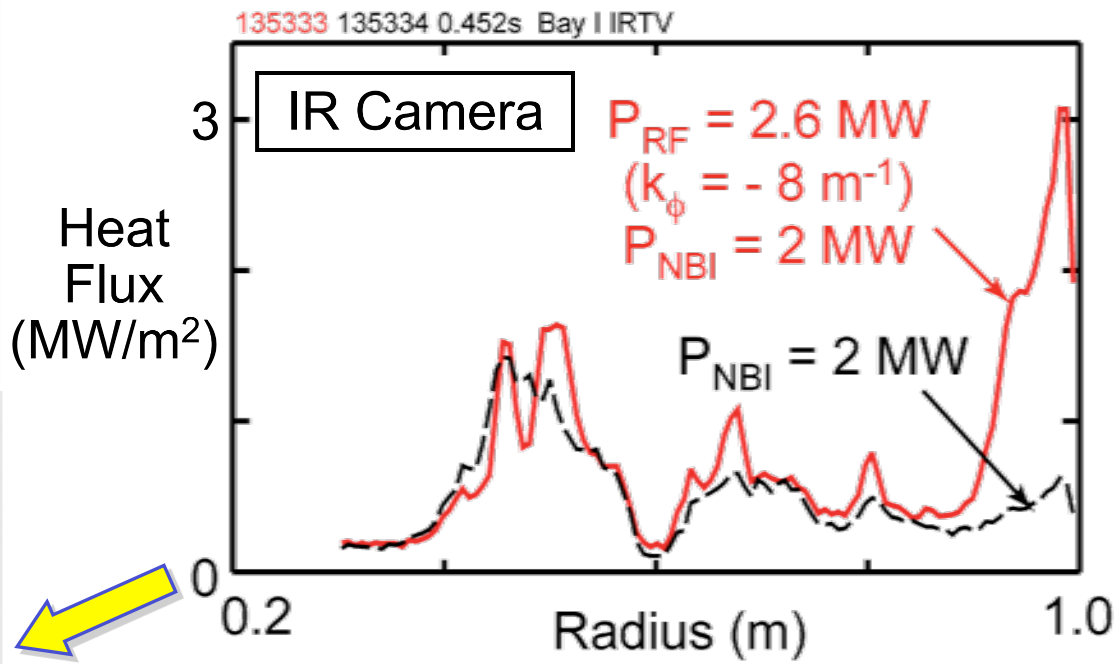
Visible & IR Images Show Significant RF Power Flows to Divertor, Particularly for Lower k_ϕ Heating

Visible Camera (with NBI-only light subtracted)

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



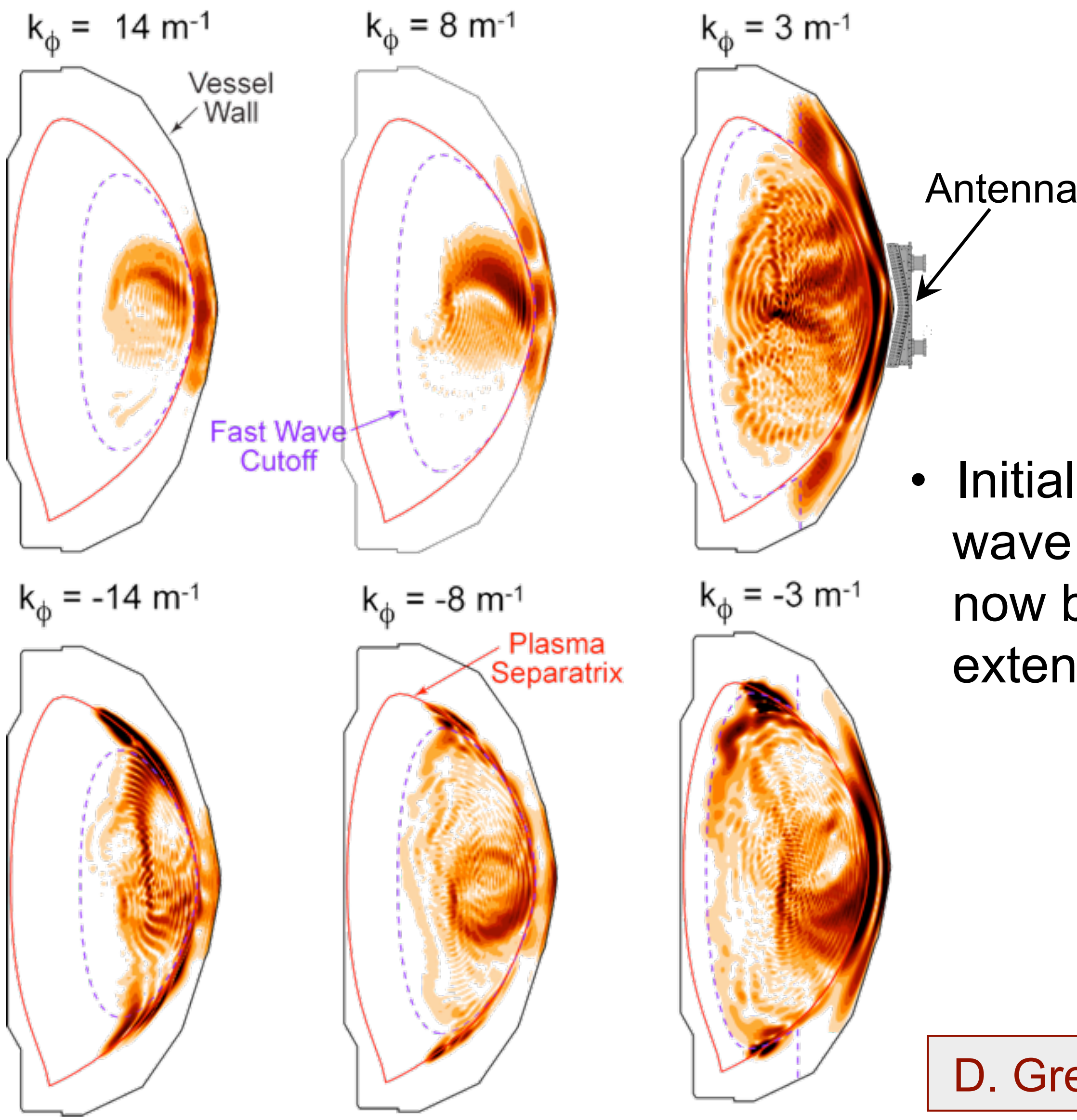
- "Hot" region in outboard divertor more pronounced at k_ϕ = - 8 m^{-1} than - 13 m^{-1}
- Linked along field lines to scrape-off plasma in front of antenna
- 3 MW/m^2 measured by IR camera during 2.6 MW of k_ϕ = - 8 m^{-1} RF heating

Summary Results & Plans for HHFW Coupling & Heating in H-mode Plasmas During ELMs

- Plasma conditioning of antenna to high power is required to avoid antenna arcs
  - Sputtering appears to be the cause of the arcs observed previously in ELM-free case
- Arc produces faster change in reflected power signal than ELMs
  - Electronic ELM/arc discrimination system to be tested in 2010
- Edge losses are larger when ELMs are present
- Divertor RF heat pattern depends strongly on magnetic field pitch
- Effect of ELMs on HHFW edge heating will be quantified in experiments later this year

AORSA Full-Wave Model with Boundary at Wall Predicts Extensive RF Fields in Scrape-off at Low k_ϕ

2-D AORSA Full Wave Model :
$|E_{RF}|$ Field Amplitude



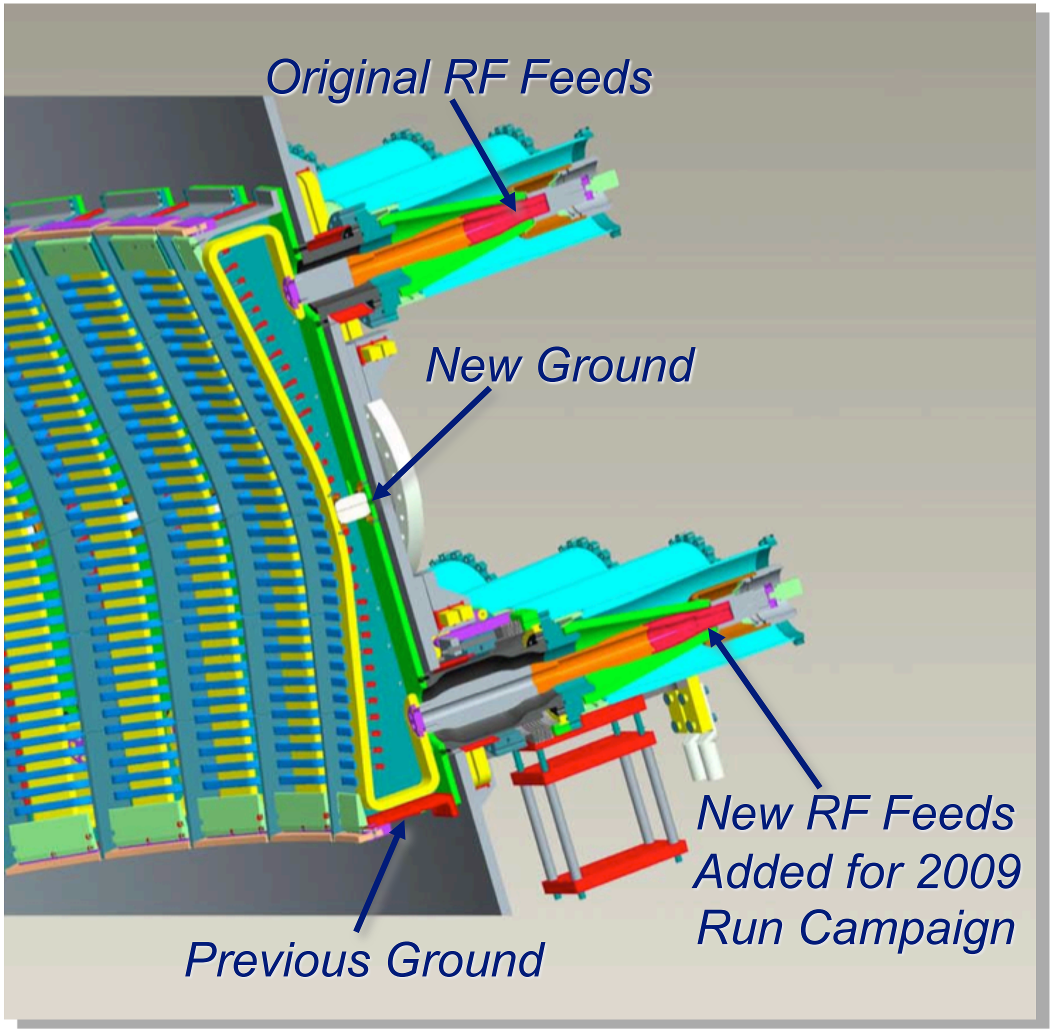
- Initial 2-D full wave results now being extended to 3-D

D. Green (ORNL)

Outline

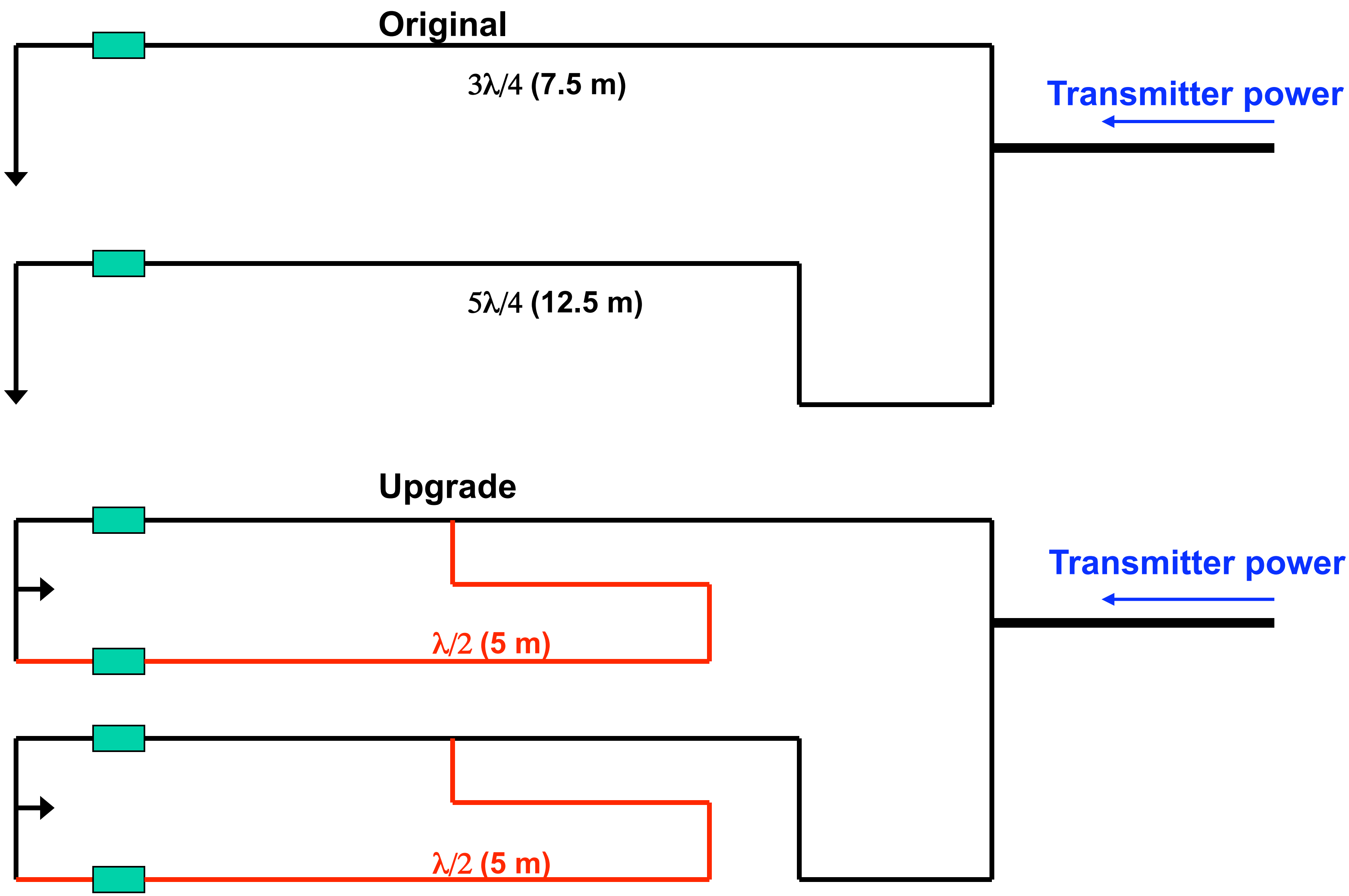
- Introduction to NSTX & the HHFW Research Program
- Improved HHFW heating with lithium conditioning
  - First Core HHFW electron heating observed in NBI H-mode
  - Significant RF interaction with NBI fast-ions
- RF interaction with plasma edge, ELMs & divertor
  - Direct RF power flow to divertor, RF edge heating & clamping
- Recent results with new double end-fed antenna
  - Increased arc-free power capability, RF H-modes in He & D_2
- Summary

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

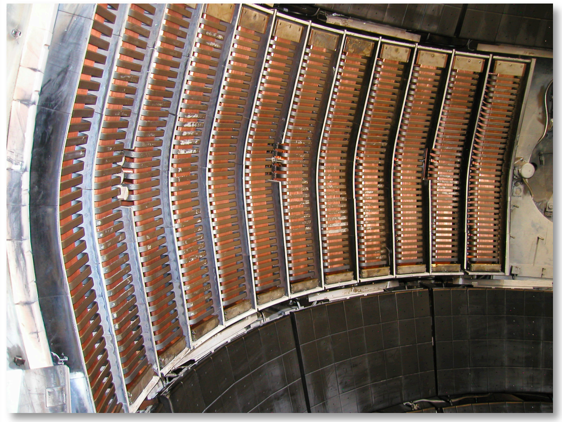


- Goal was to bring system voltage limit with plasma (~15 kV) up to its vacuum limit (~25 kV):
  - Would increase power limit by ~ 2.8 times
- Tests whether electric field in strap/Faraday shield sets limit for plasma operation

Transmission Line Modifications



HHFW System Upgrades Completed by June 2009



12 new double-fed antenna straps were installed inside NSTX

- In-vessel strap upgrades completed in December 2008
- External transmission line upgrades completed in June 2009
- Operated RF into plasma July & August 2008

Approximately 60 m of additional $\lambda/2$ loops were installed outside NSTX

Double End-Fed Antenna Performance Significantly Improved in 2009 Compared to 2008 Operation

- New antenna reached 2-3 MW more quickly than in past
  - No substantial increase in system voltage limit during initial operation
  - Vacuum & plasma conditioning increased power levels throughout initial run, removed Li coatings from antenna
  - Currents flowing on antenna frame/Faraday shield may determine arcing threshold
- Coupled > 4 MW into He L-mode
- Record $T_e(0)$ ~ 6.2 keV with P_{rf} ~ 2.7 MW
- Allowed study of L-H & H-L transition in He & D with RF
- Extensive RF vacuum & plasma conditioning campaign in 2010 to evaluate new antenna performance

Outline

- Introduction to NSTX & the HHFW Research Program
- Improved HHFW heating with lithium conditioning
  - First Core HHFW electron heating observed in NBI H-mode
  - Significant RF interaction with NBI fast-ions
- RF interaction with plasma edge, ELMs & divertor
  - Direct RF power flow to divertor, RF edge heating & clamping
- Recent results with new double end-fed antenna
  - Increased arc-free power capability, RF H-modes in He & D_2
- Summary

Summary

- Significant progress in heating NBI H-mode & during early I_p ramp
  - Li reduced edge n_e enabling first core HHFW electron heating during NBI H-mode
  - Coupling maintained through L-H transition and during ELMs
  - Competition between RF acceleration of NBI fast-ions & direct electron heating, particularly at lower k_ϕ
- Fast-wave interaction with the edge & power flow to divertor 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