NSTX

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High Harmonic Fast Wave Progress and Plans

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for the NSTX Team

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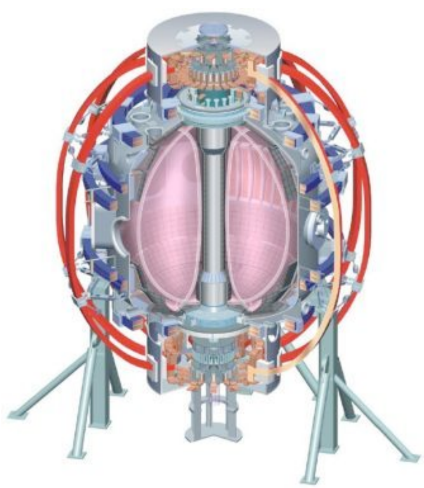

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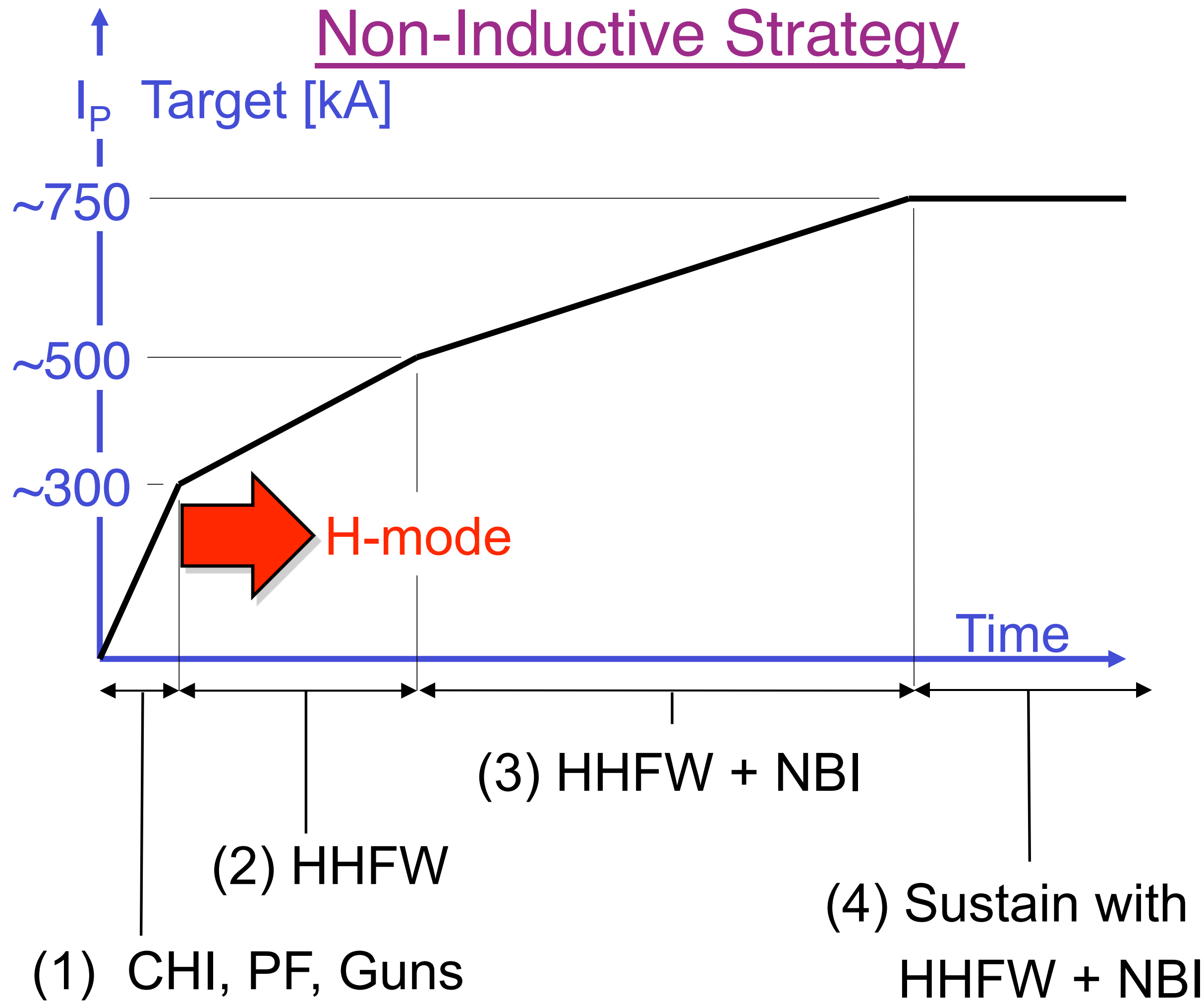
Outline

- Role of HHFW in NSTX Program
- Recent Advances in HHFW Research & Modeling
- Research Plan for 2010-12

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

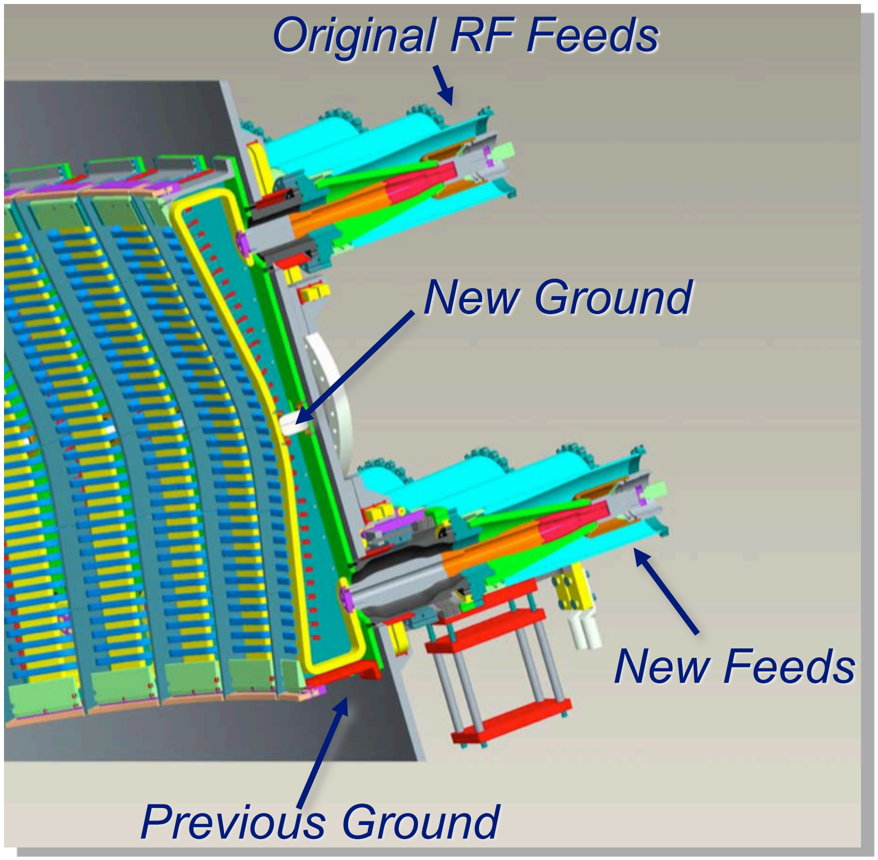
(1) HHFW couples to start-up plasma

(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

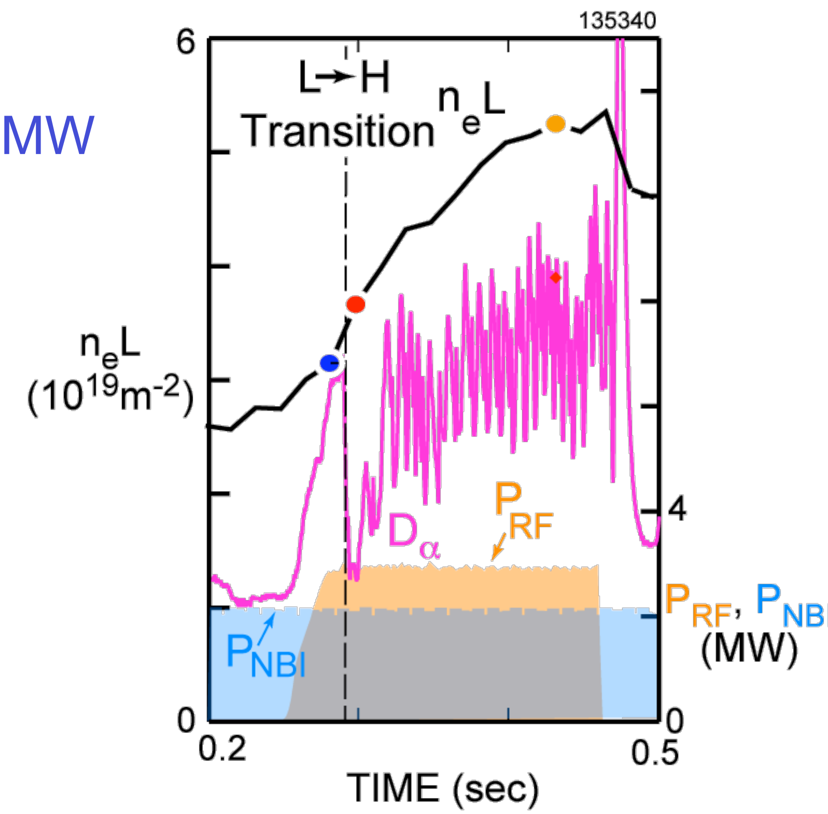
HHFW Double End-Fed Upgrade Installed in 2009 Shifts Ground from End to Strap Center



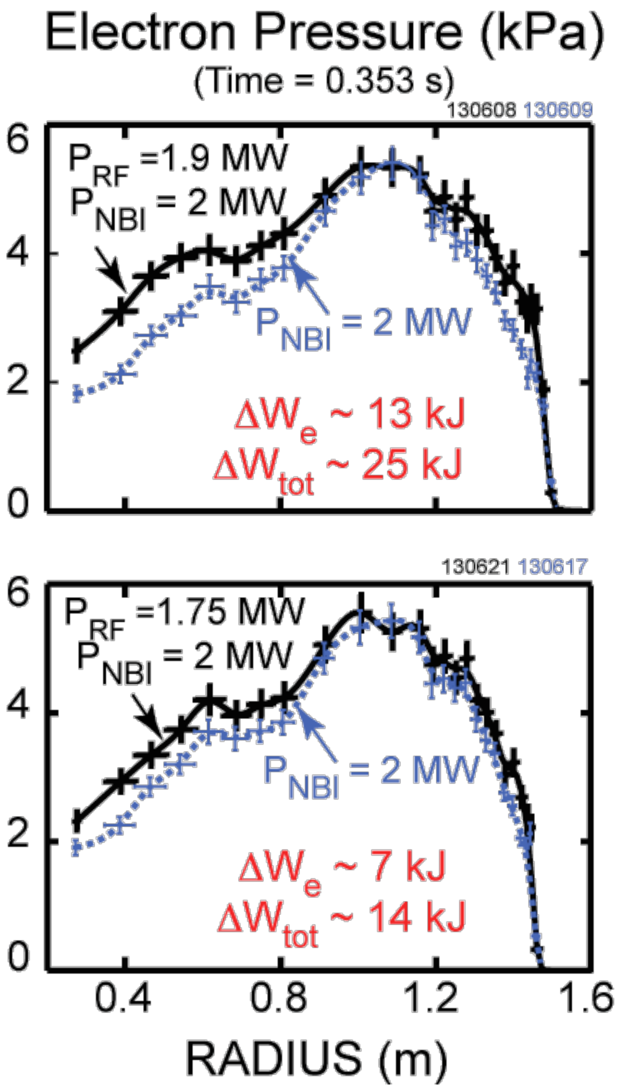
- Designed to bring system voltage limit with plasma (~15 kV) to limit in vacuum (~25 kV):
  - Increases P_{RF} ~ 2.8 times
- While Li pumping improves rf coupling, arcs occur when rf currents in straps ablate Li on antenna, driving Li into the high voltage regions inside antenna
  - Use rf plasma conditioning in 2010 to remove Li coating on antenna, increasing arc-free rf power limit
- Electronic ELM/arc discrimination system to be tested in 2010:
  - Arc produces faster change in reflected power signal than ELMs

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

- Modifications to external transmission line completed in June
  - Operated RF into plasma during July & August
- New antenna reached 2-3 MW more quickly than previous antenna
- Improvements likely due to a combination of antenna upgrade and Li conditioning:
  - 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
  - Maintained HHFW coupling through L-H transition and during relatively large repetitive ELMs during D NBI-fuelled H-modes
  - Continue to evaluate new antenna performance in 2010



HHFW Heating of H-Mode Plasmas Less Efficient at Lower k_ϕ, Due to Increased Edge Losses



k_ϕ = -13 m^{-1}
η_{eff} ~ 66%

k_ϕ = -8 m^{-1}
η_{eff} ~ 40%

- During k_ϕ = -13 m^{-1} HHFW heating of NBI H-mode plasmas ~ 1/3 of the rf power is lost outside plasma separatrix
- The fraction of rf power lost in the edge increases to ~ 2/3 for k_ϕ = -8 m^{-1} HHFW heating
- A major goal of the NSTX HHFW research is to identify and, if possible, mitigate edge rf power loss mechanisms

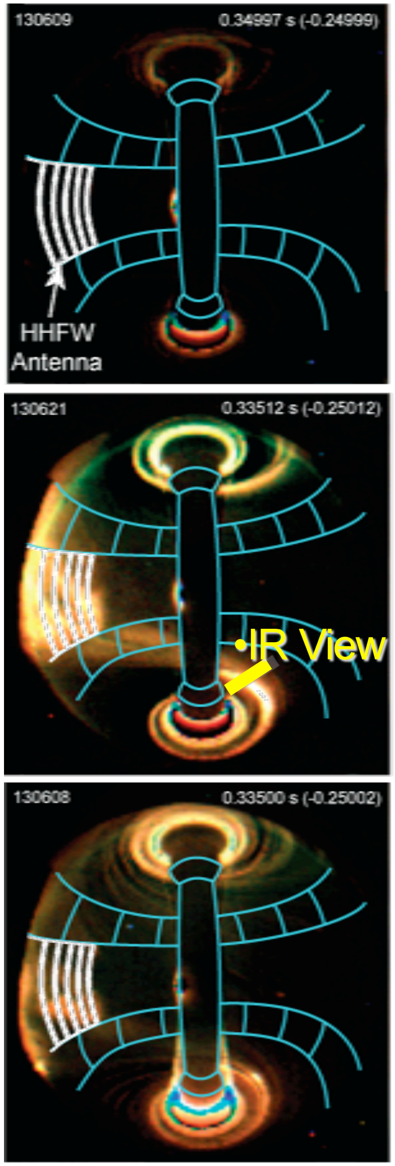
New IR Camera Measurements Show Higher RF Power Heat Flux to Divertor for Lower k_ϕ

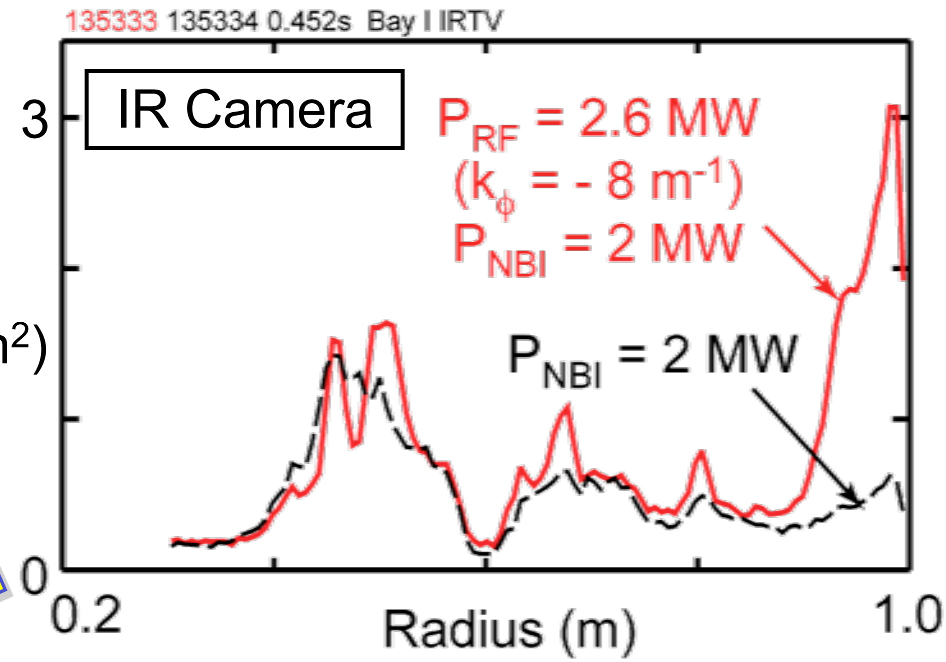
Visible Camera

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}
- 3 MW/m^2 measured by IR camera during 2.6 MW of k_ϕ = - 8 m^{-1} RF heating
- Increased visible & IR camera coverage for 2010 campaign

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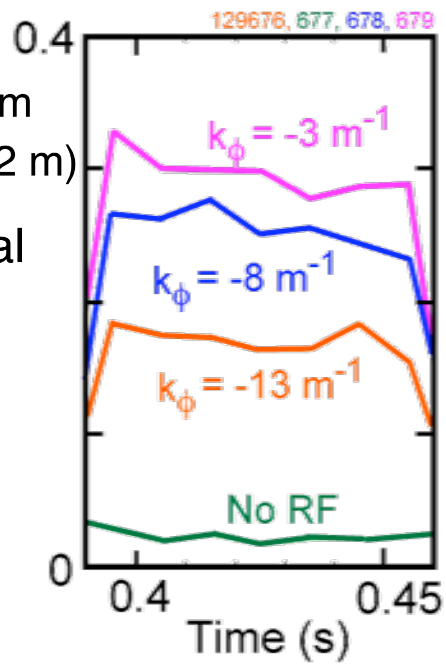
Full Wave Model Predicts P_{RF} ~ 100-200 kW Can Drive PDI; P_{RF} Needed to Drive PDI Falls with k_ϕ

C III Passive Spectroscopic T_i Shows PDI Heating of Edge Ions

R=1.50 m
(R_{edge}=1.52 m)

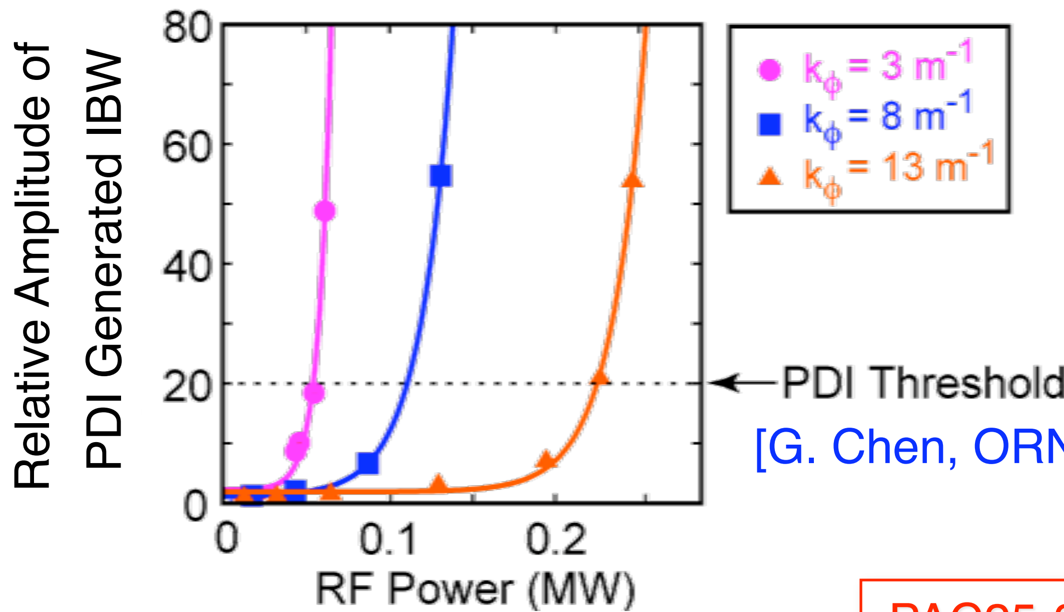
Poloidal

T_i(eV)



P_{RF} = 1.2-1.3 MW

1-D Extended Boundary, Nonlinear, AORSA Full Wave Model Shows Dependence of PDI Threshold on k_ϕ



[G. Chen, ORNL]

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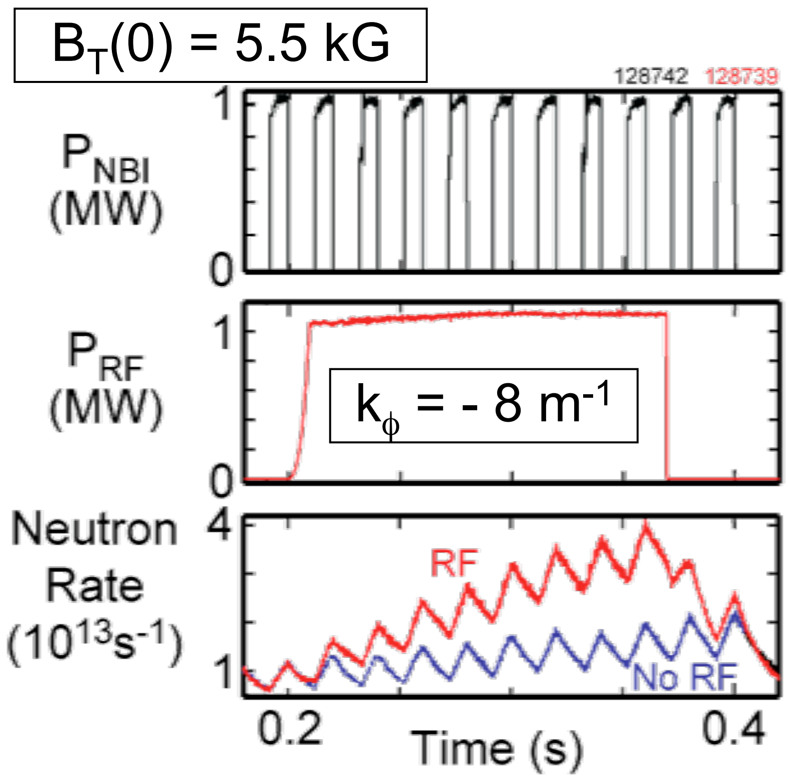
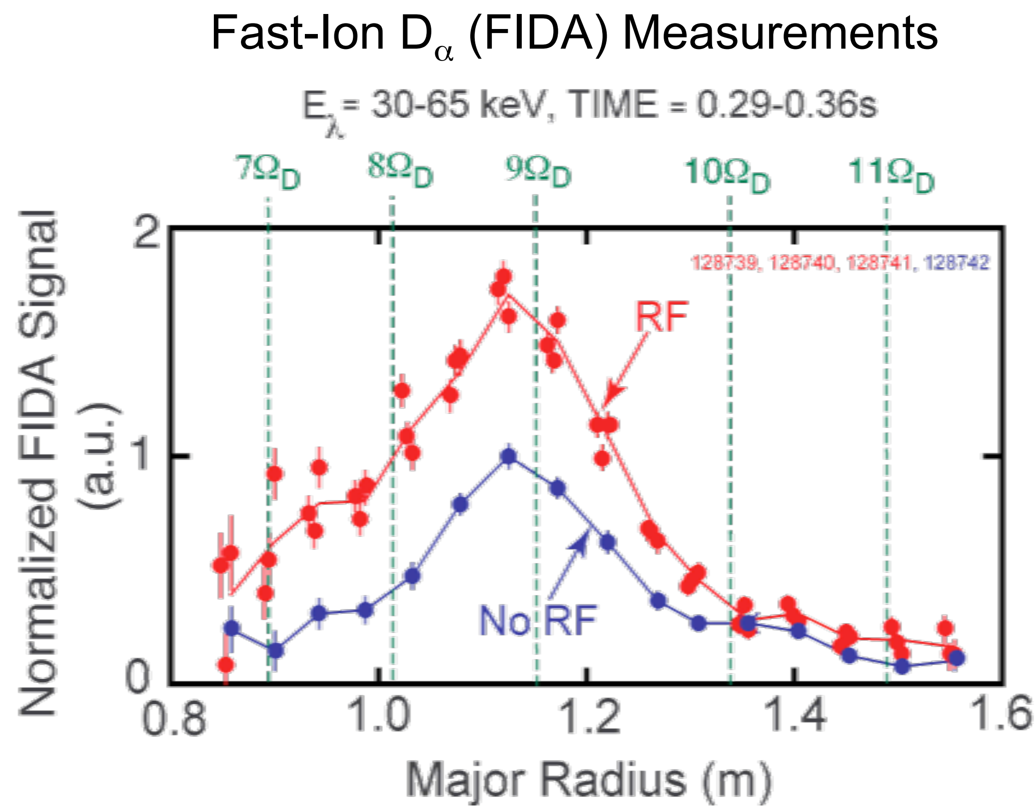
- Previously estimated up to 20% of RF power may be lost to PDI
- Develop modeling & measurements in 2010-12 to better quantify importance of RF power loss due to PDI

Significant Interaction Between HHFW & NBI Fast-Ions Over Multiple Cyclotron Harmonics





- Measured acceleration of NBI fast-ions and large increase in neutron rate during HHFW + NBI plasmas
  - ➢ As predicted originally by CQL3D/GENRAY

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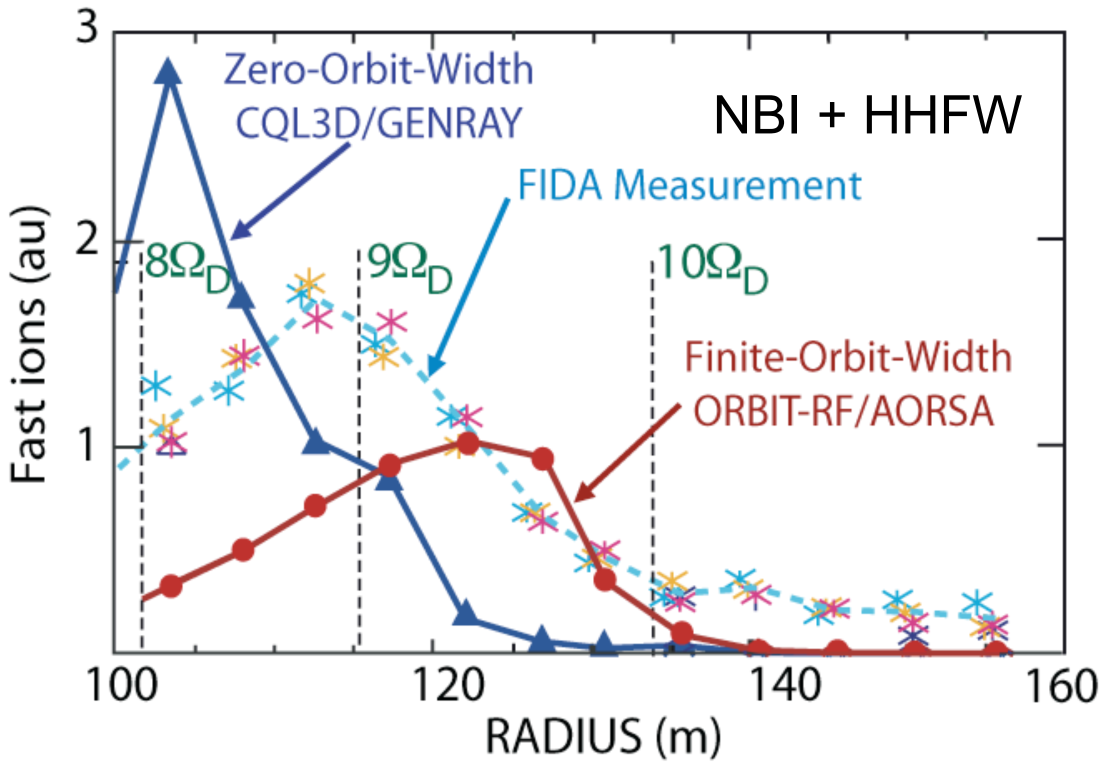
- Measured significant enhancement & broadening of fast-ion profile when HHFW power is applied

Finite Lamor Radius & Banana-Width Effects Broaden Fast-Ion Profile in NSTX



- Zero-orbit-width Fokker-Planck CQL3D/GENRAY ray tracing model predicts fast-ion profile peaked on axis
- Finite-orbit-width Monte-Carlo ORBIT-RF/AORSA 2D full wave model predicts broader outwardly shifted fast-ion profile

- Differences between the ORBIT-RF/AORSA simulation and the FIDA data are being investigated
- CQL3D modeling with first order orbit-width correction in progress this year
- A full-finite orbit width version of CQL3D is planned for 2011, but funding for this upgrade is uncertain at this time

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HHFW Research Plan for 2010 – (1)

- 2010 research milestone to characterize HHFW Heating & CD in D H-mode, and at low I_p

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- Heating & ramp-up of low I_p plasmas: [1.5*(0.5)*+1(SFSU)] IOS-5.2
  - RF heating of low I_p (~ 200 kA) plasmas
  - Sustain 100% non-inductive D_2 HHFW H-mode
- HHFW interactions with ELMs & SOL: [1.5+0.5(ITER)] IOS-5.2
  - HHFW power coupling & ELM activity
  - RF heating in divertor SOL during NBI + RF H-modes
- Fast-ion interactions, rotation effects & RFCD: [1*(0.5)*] IOS-5.2, TC-9
  - HHFW heating efficiency of NBI plasmas & fast-ion study
  - RF clamping of edge rotation
  - MSE measurement of HHFW CD

[ ] = priority 1 run days *( ) = priority 2 run days* ITPA task

HHFW Research Plan for 2010 – (2)

- Beginning to integrate HHFW into advanced scenarios (ASC TSG):
  - HHFW pre-heating, lower collisionality targets for improved NBCD & RF generated reversed-shear L-modes [2*(0.5)*]
    [ ] = priority 1 run days *( ) = priority 2 run days*
- 4 days for HHFW plasma conditioning:
  - 2-day conditioning campaign early in run
  - 3-4 HHFW experimental campaigns, lasting 3-4 days each, preceded by ~ 1/2 day of conditioning
  - Plasma conditioning includes machine proposal to assess performance of the double-fed antenna
- Improved visible & IR camera imaging of antenna and divertor:
  - RF/Langmuir probe will be located at or near divertor “hot” streak
- Evaluate electronic ELM/arc discrimination to minimize RF trips
- Develop extended boundary AORSA & implement first order finite-orbit correction in CQL3D & AORSA
- Interviewing candidates for new RF post-doc position

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HHFW Research Plan for 2011-12

2011:

- Heating & CD operation with NBI H-mode with double fed antenna, arc/ELM discrimination, Li injection & LLD:
  - Benchmark core CD against advanced RF codes upgraded to include interaction with fast ions & use new tangential FIDA
- HHFW coupling during I_p ramp-up
  - MSE-LiF to provide q(r) without NBI heating
  - Prepare for 2010 milestone coupling HHFW into CHI-initiated plasma
  - RF edge losses significant at low I_p; AORSA needs to include these edge losses, funding probably insufficient to complete this upgrade by 2011

2012:

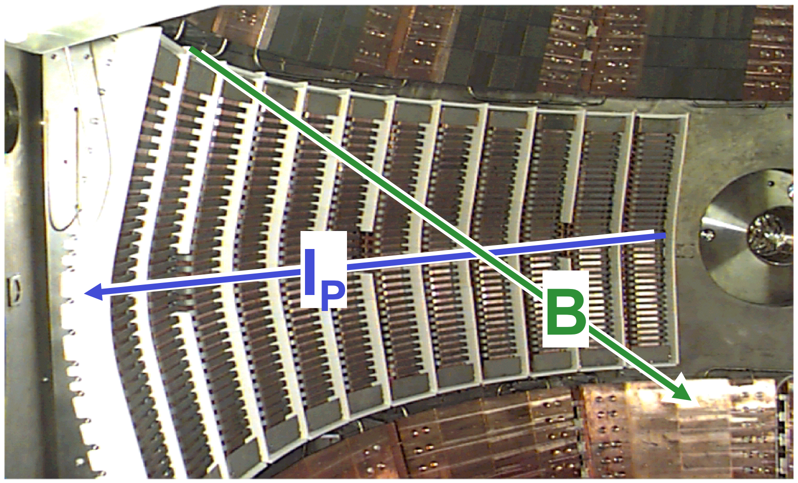
- **Milestone:** Assess confinement, heating, and ramp-up of CHI start-up plasma (with SFSU TSG)
- Complete full-finite orbit width version of CQL3

Summary

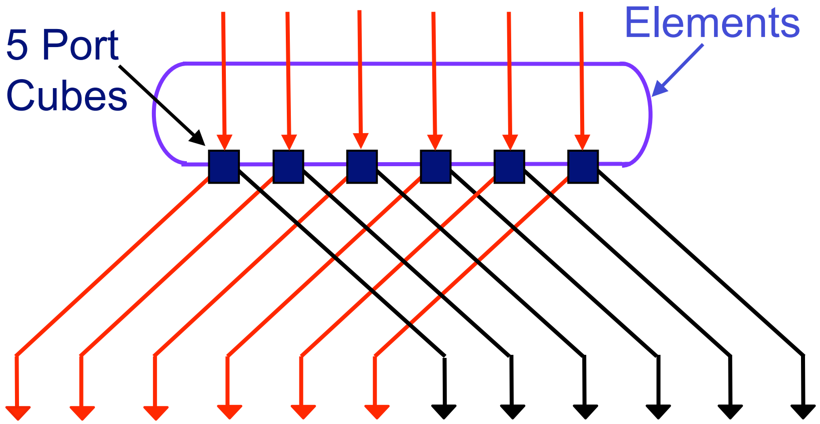
- Initial operation of the double end-fed antenna was encouraging:
  - Increased arc-free power capability & produced RF H-modes in He & D
  - Coupling maintained during NBI through L-H transition & ELMs
- Use upgraded antenna & LLD in 2010 to improve coupling in H-modes & low I_p regime – generate 100 % NI fraction in H-mode
- Fast-wave interaction with the edge & divertor appear to be an important RF power loss mechanism, particularly at low k_ϕ
  - 2010 expts with improved visible/IR camera coverage & RF probes
- HHFW experiments in 2011-12 will study heating & CD in D H-mode & CHI-initiated, HHFW-driven I_p ramp-up
- Extended boundary AORSA & finite-orbit upgrade to CQL3D & AORSA being developed in 2010-11

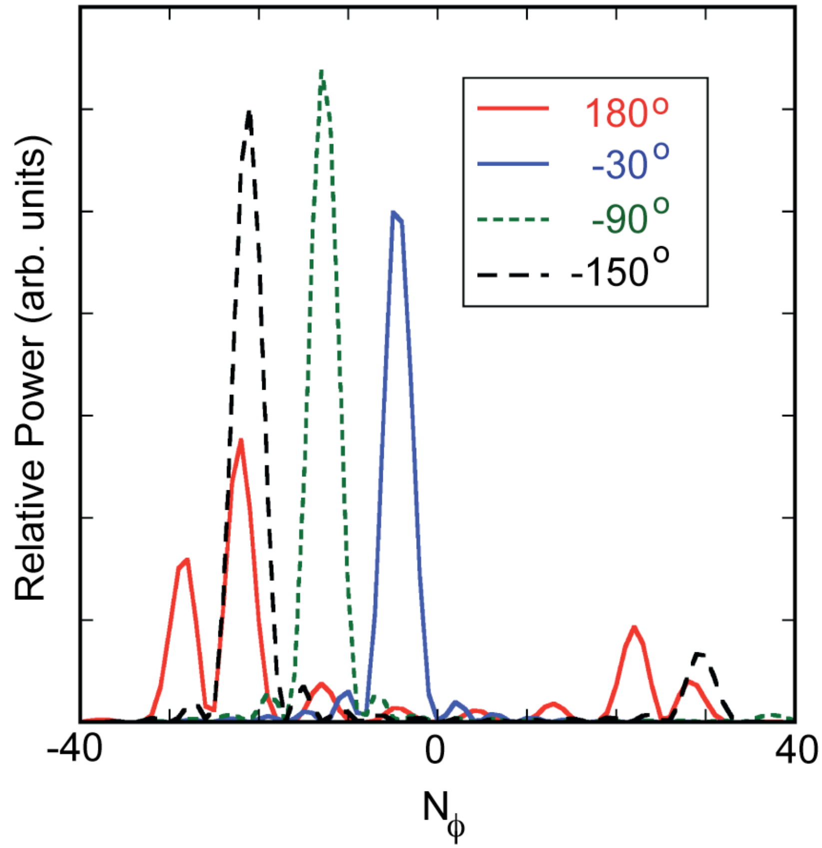
Backup Slides

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



HHFW antenna extends toroidally 90°

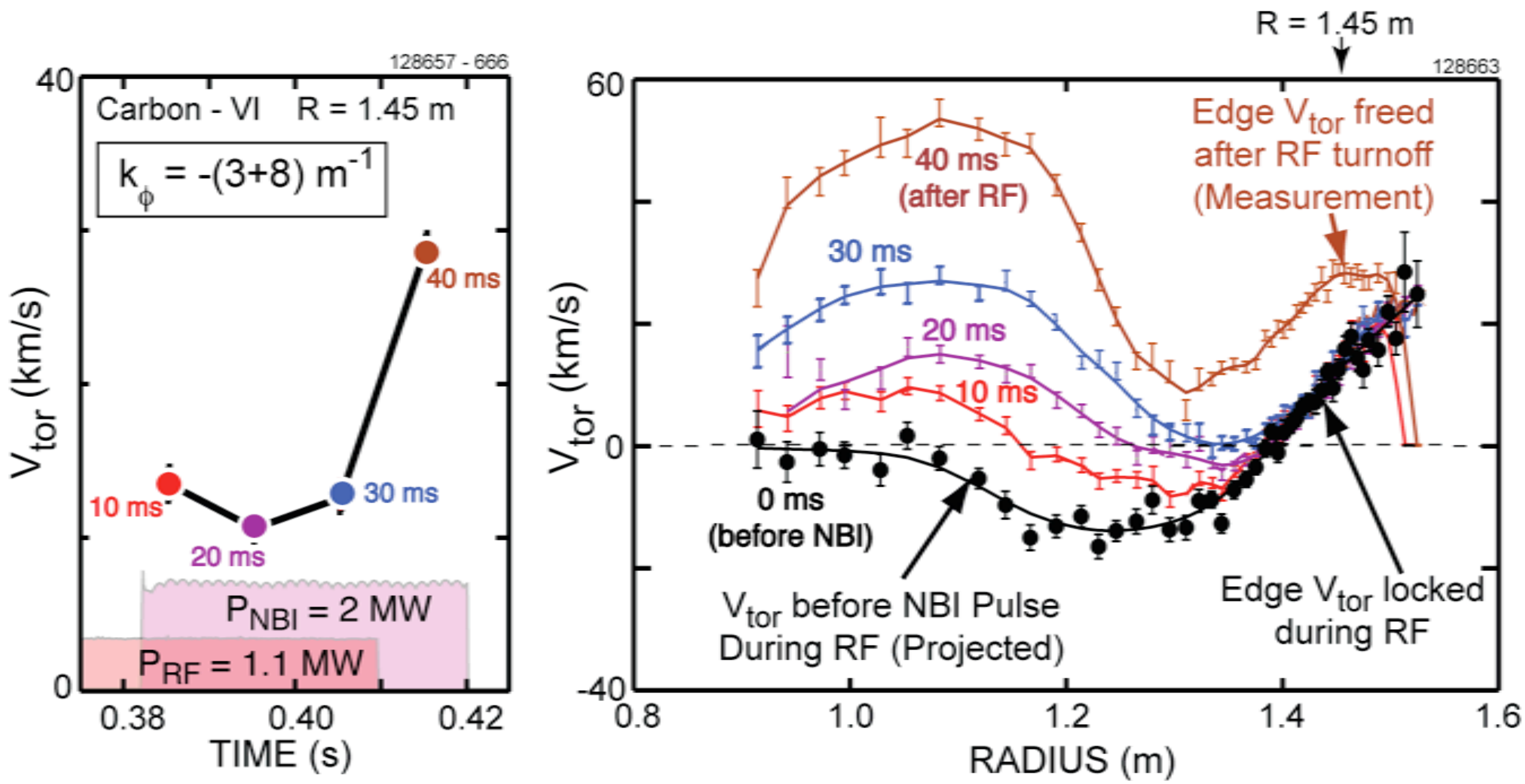




- Phase between adjacent straps easily adjusted between $\Delta\phi = 0°$ to $\Delta\phi = 180°$

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

V_{tor} Measured by Charge Exchange Recombination Spectroscopy

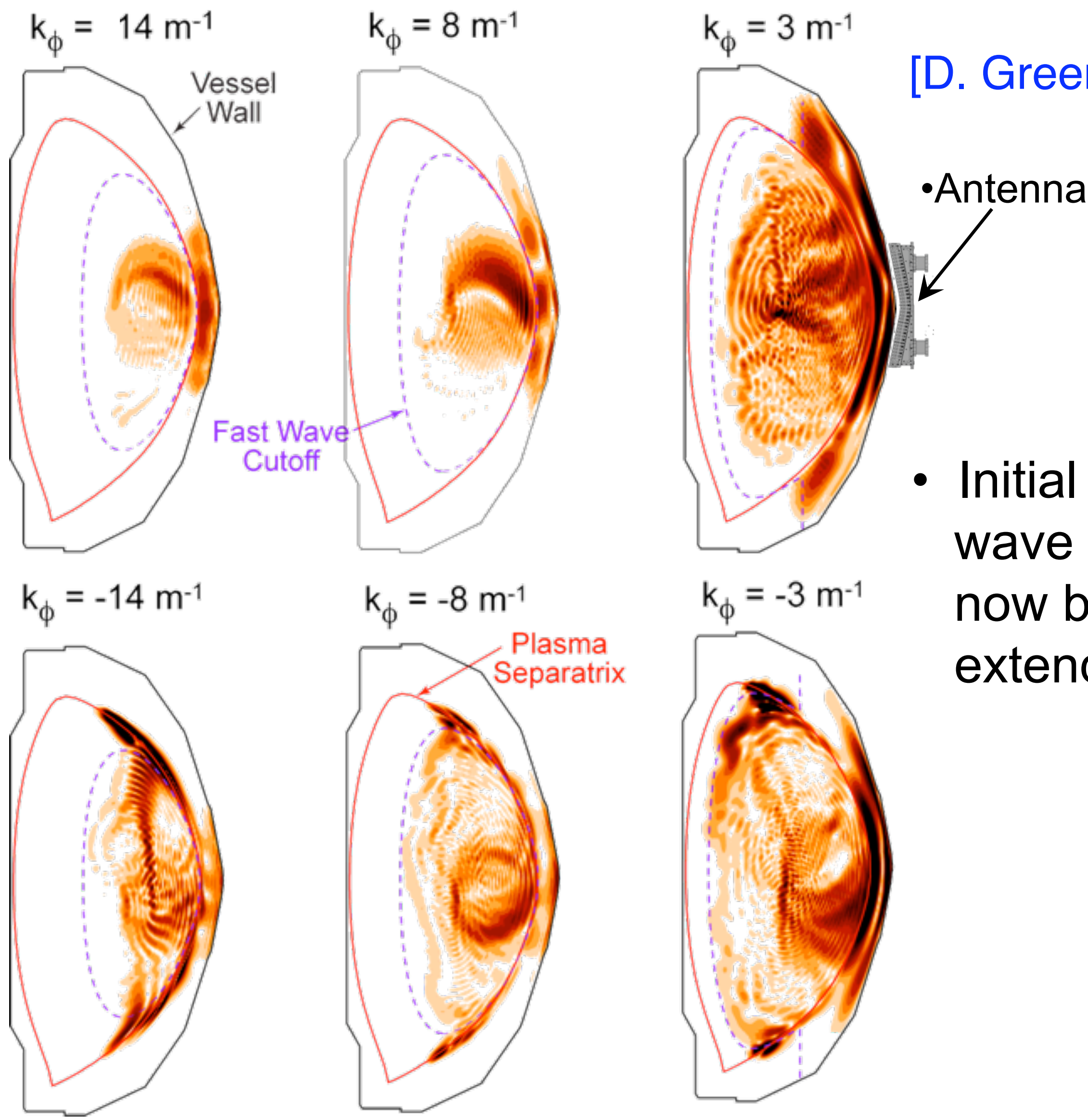


- Mechanism not understood, but may point to edge ion loss
- RF apparently provides a drag on core plasma rotation as well

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

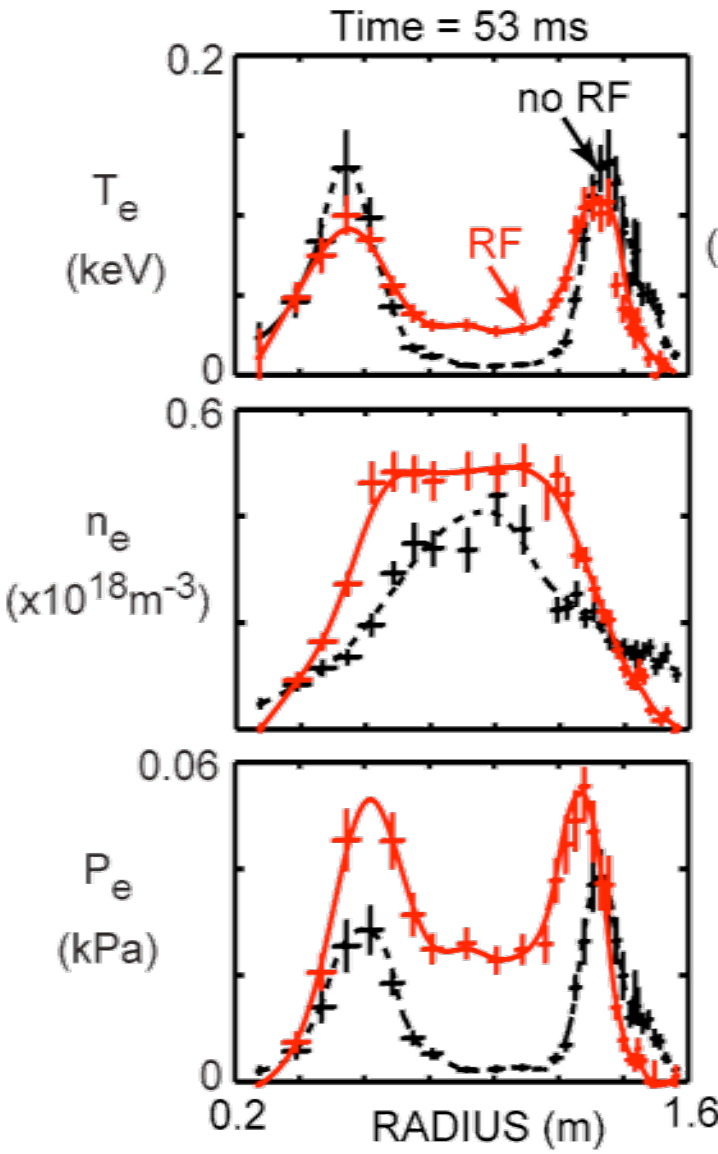


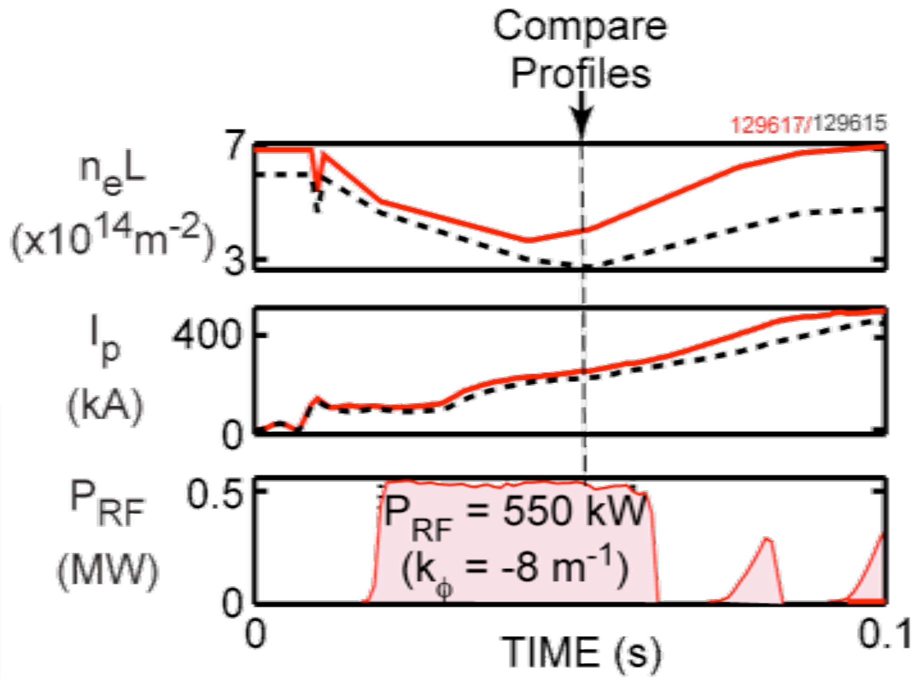
[D. Green, ORNL]

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

Preliminary Results

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

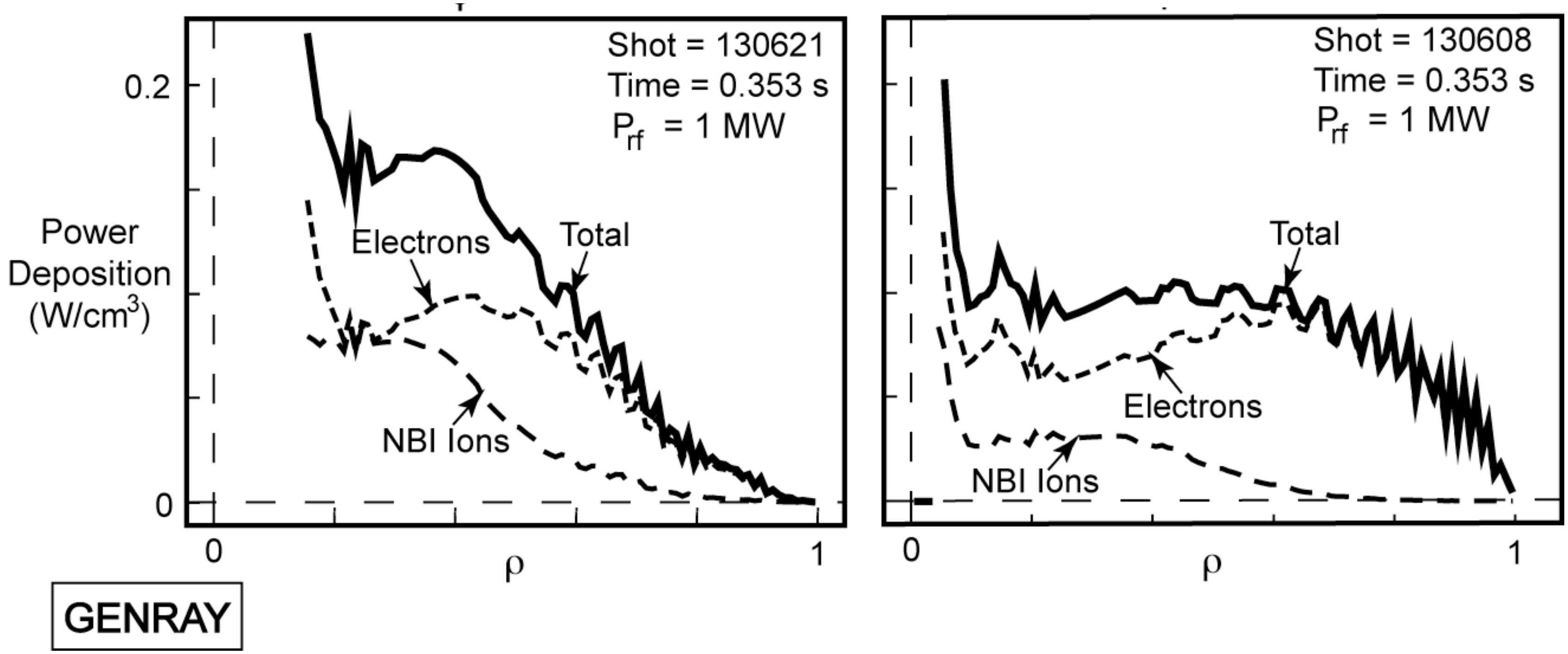




- Core HHFW electron heating also measured during CHI start-up
- HHFW-assisted ramp-up and HHFW heated low I_p experiments planned for 2010

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

$k_\phi = -8\ m^{-1}$	$k_\phi = -13\ m^{-1}$
P_e = 73%	P_e = 84%
P_{fi} = 27%	P_{fi} = 16%



- Modeling does not include RF acceleration of fast ions