NSTX

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High-Harmonic Fast Wave (HHFW) Heating Results on NSTX

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In collaboration with

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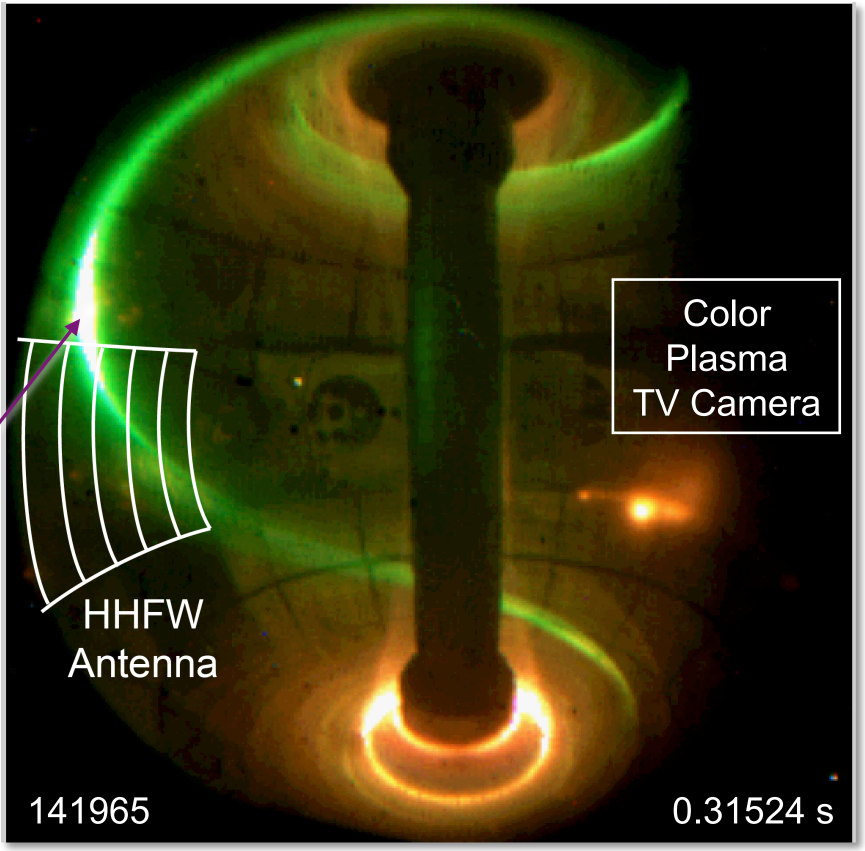
Introduction

- Seek to maximize HHFW heating inside last closed flux surface (LCFS) to support fully non-inductive I_p ramp-up & sustainment
- 12-strap antenna has well-defined spectrum, providing good control of deposition & RF current drive direction
- Double-feed antenna upgrade installed in 2009:
  - Stand off voltage did not improve as much as predicted
  - Voltage appears limited by RF currents induced in antenna surface
  - Voltage limit increases with sufficient antenna conditioning
- Last year reported improved RF coupling to NBI H-modes & low I_p discharges by using lithium conditioning:
  - This year extensive lithium conditioning seriously compromised RF performance

Extensive lithium conditioning this year significantly degraded antenna performance compared to 2009

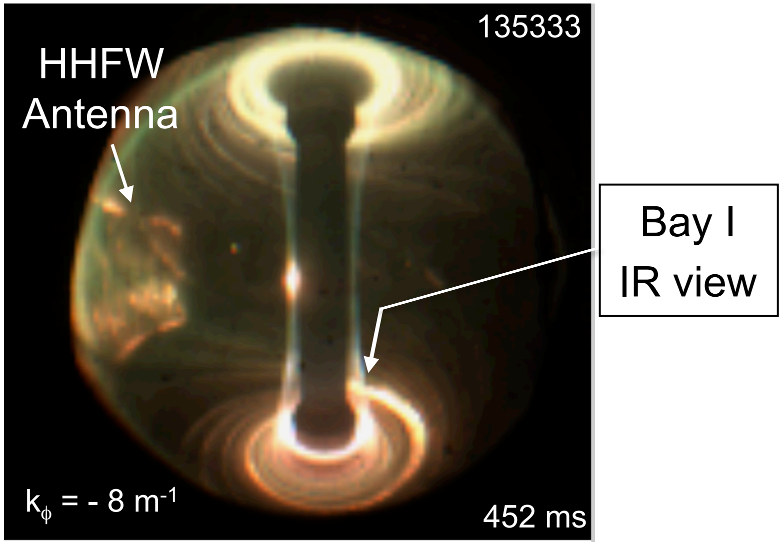
- In 2009 quickly reached arc-free P_{RF} = 2-3 MW & arc-free P_{RF} ~ 4 MW by end of campaign
- Following extensive lithium conditioning this year only reached P_{RF} ~ 1.5 MW arc-free operation & observed copious lithium ejection associated with arcing ➡
  - Before lithium conditioning quickly reached a stand-off voltage of 25 kV during RF vacuum conditioning
  - Later in campaign difficult to reach even ~ 15 kV

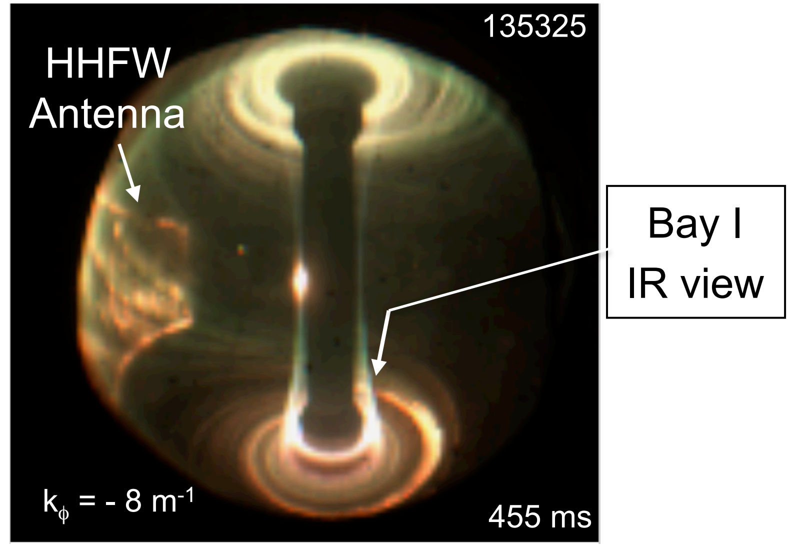
Lithium ejection (green light) from top of antenna at time of RF arc



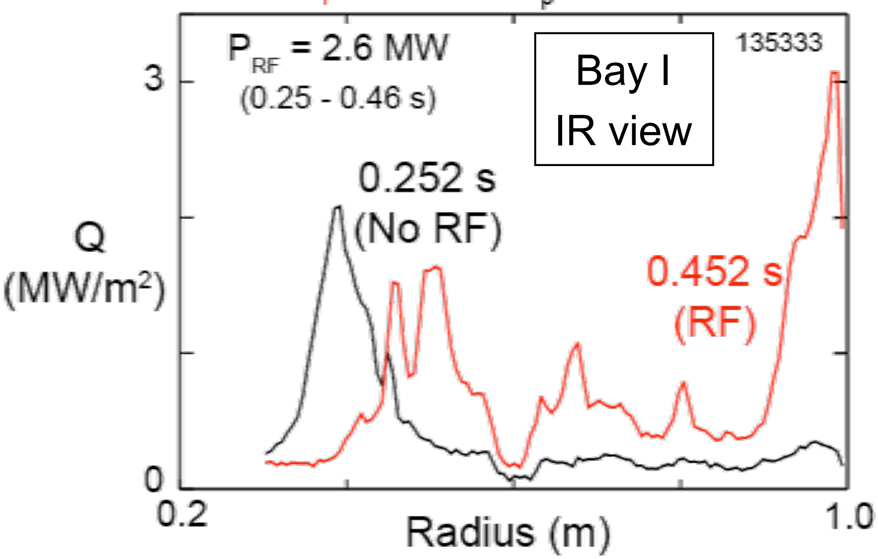
P. M. Ryan, et al., Poster BP9.00073, Mon AM

Significant RF power flow to lower divertor: RF heating pattern on the divertor plate follows the magnetic pitch

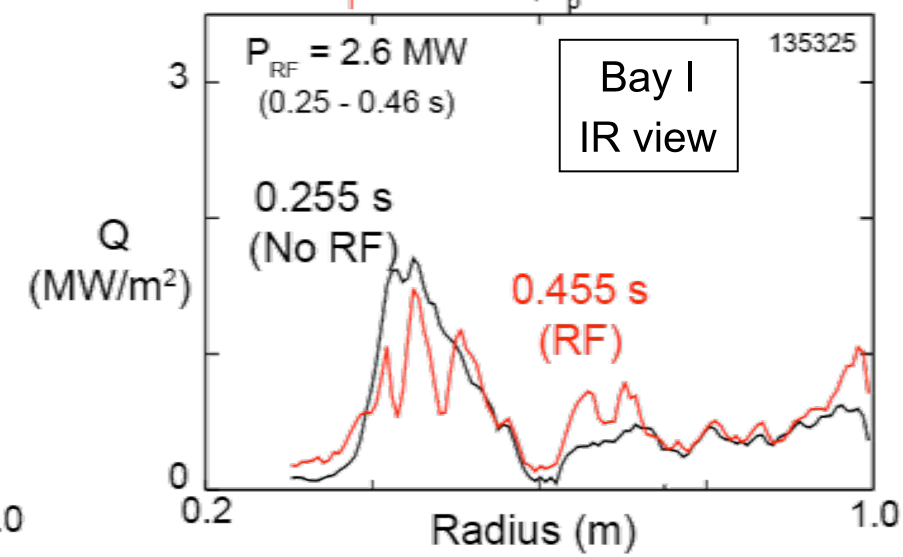




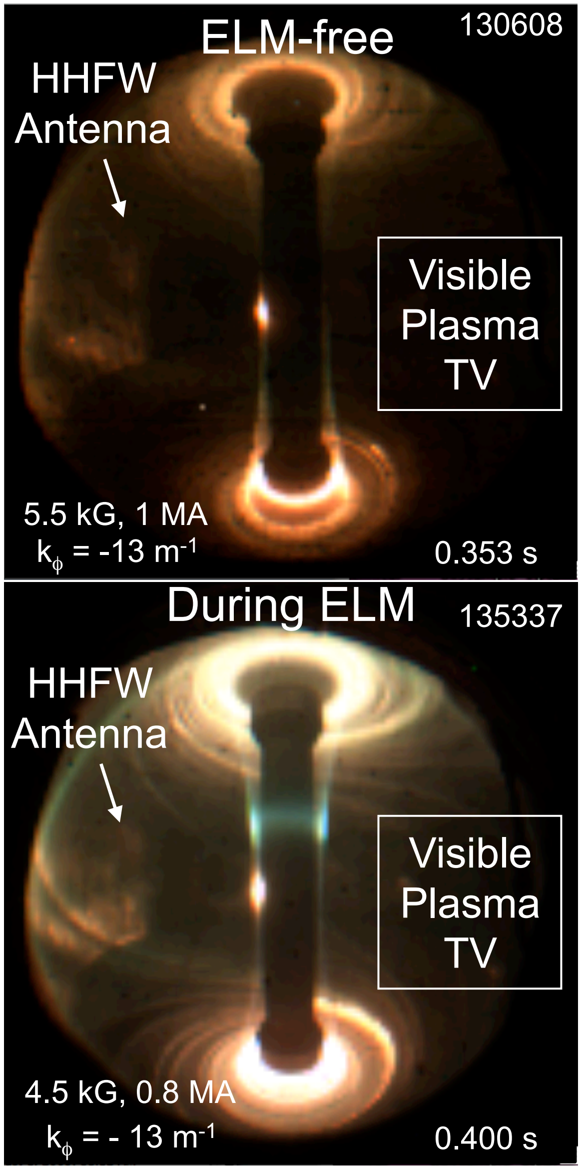
B_T = 4.5 kG, I_p = 0.8 MA

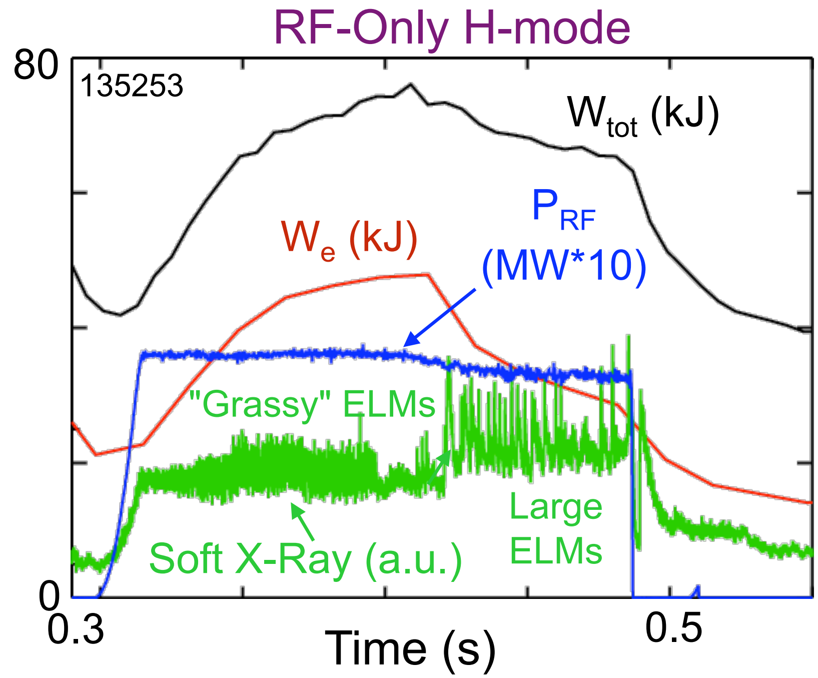


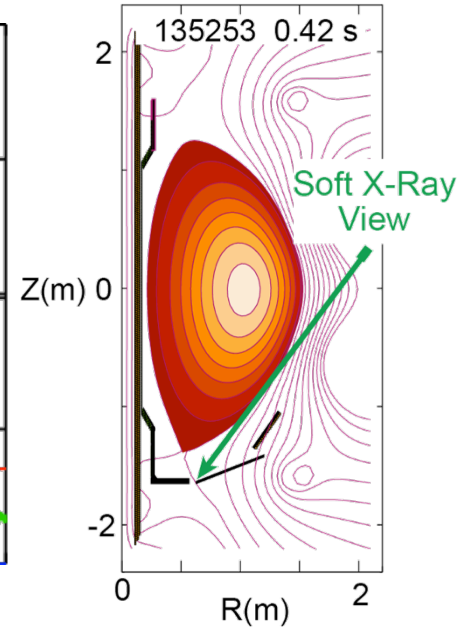
B_T = 5.5 kG, I_p = 0.8 MA



Large ELMs create higher RF power flow to lower divertor & reduce RF heating efficiency in RF+NBI & RF-only H-modes







- Significant RF power loss to divertor during large ELMs due to direct core heat loss and higher edge density:
  - ➢ IR camera images show ELMs heat plasma strike point in divertor, not the primary RF-heated zone
  - ➢ Much less RF power loss to divertor in ELM-free H-mode or during "Grassy" ELMs

J. Hosea, et al., Poster BP9.00074, Mon AM

TRANSP-TORIC analysis of matched NBI+HHFW & NBI-only ELM-free H-modes predicts ~ 50% of P_{RF} is absorbed inside LCFS

- Fraction of P_{RF} absorbed within LCFS (f_A) obtained from TRANSP-calculated electron stored energy:

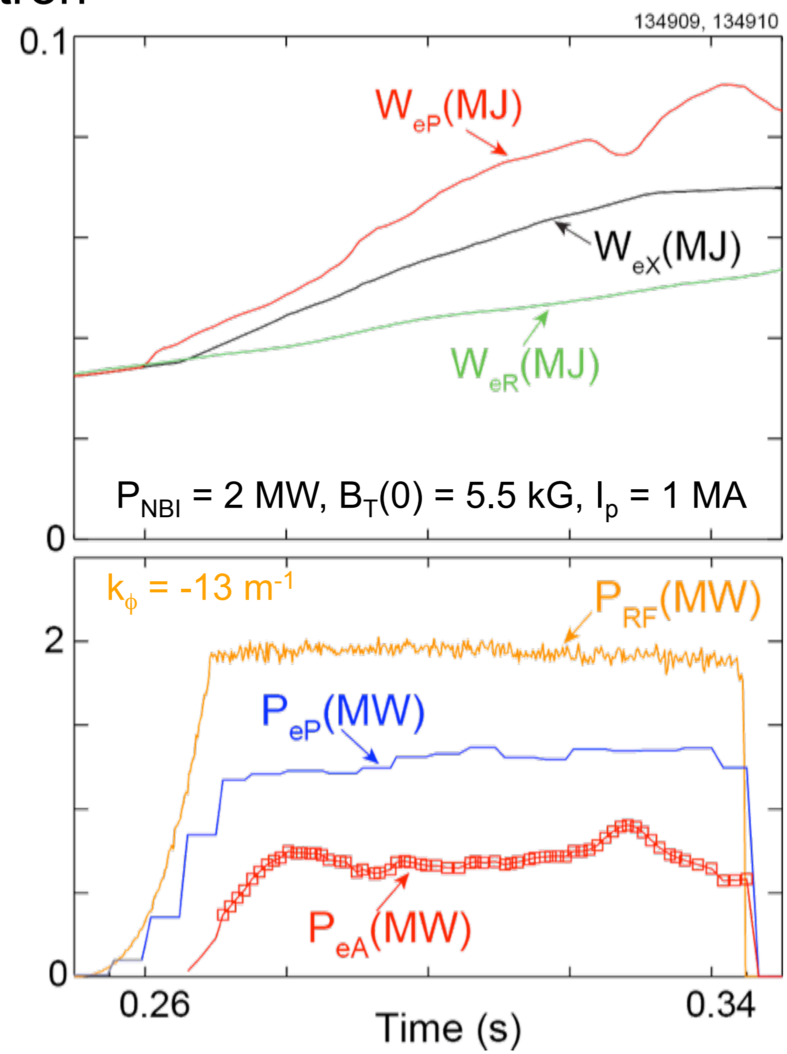
  W_{eX} – from HHFW+NBI H-mode

  W_{eR} – from matched NBI-only H-mode

  W_{eP} – using χ_e from NBI-only H-mode to predict T_e in HHFW+NBI H-mode

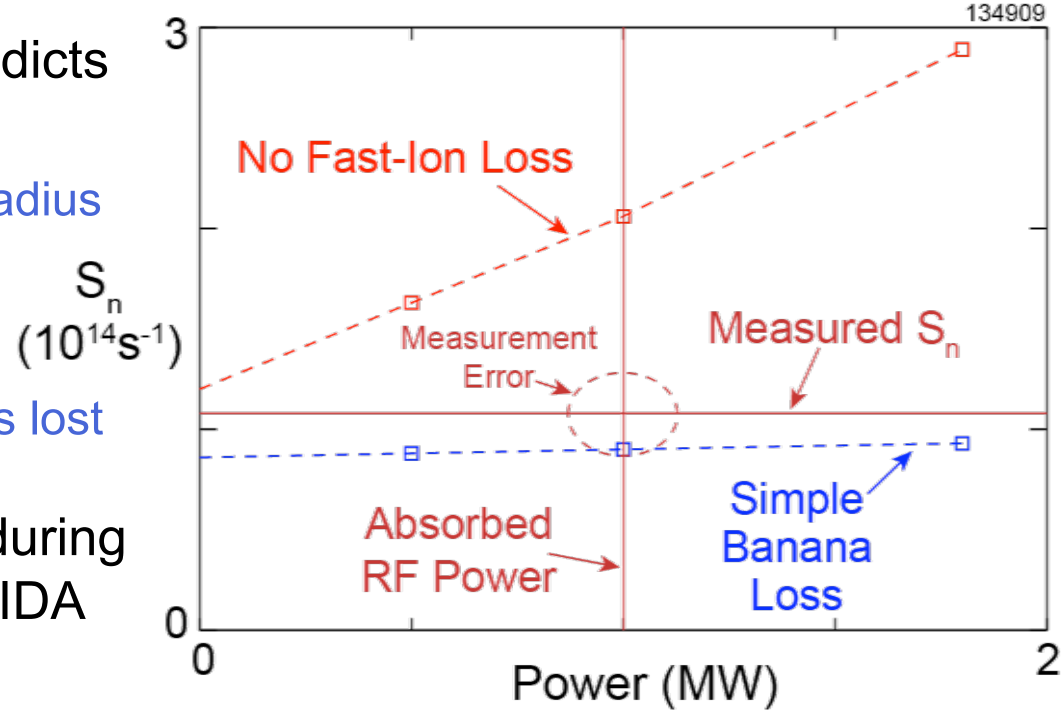
- $f_A = (W_{eX}-W_{eR})/(W_{eP}-W_{eR}) = 0.53 \pm 0.07$
- TORIC used to calculate the power absorbed by electrons (P_{eP}) assuming 100% RF plasma absorption
- Electron absorption, $P_{eA} = f_A \times P_{eP}$

  For P_{RF} = 1.9 MW:
  - 0.7 MW ➡ electrons
  - 0.3 MW ➡ ions



CQL3D Fokker-Planck code predicts significant fast-ion losses in HHFW-heated ELM-free NBI H-modes

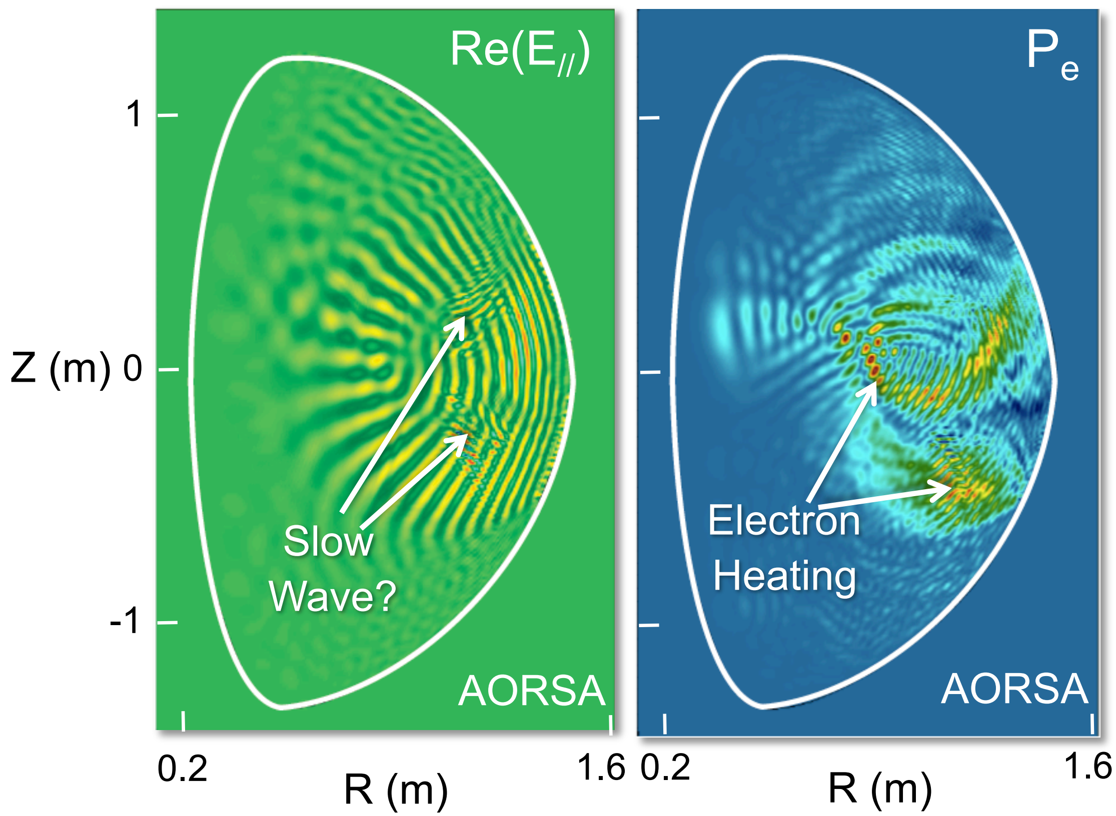
- Without fast-ion loss CQL3D predicts much higher neutron production rate (S_n) than is measured
- Simple-banana-loss model predicts S_n just below measured S_n :
  - ➢ Assumes fast-ions with gyro radius + banana width > distance to LCFS are promptly lost
  - ➢ ~ 60% RF power to fast-ions is lost
- No change in fast-ion density during HHFW heating measured by FIDA



- First-order finite-orbit width loss model being implemented in CQL3D

B. P. LeBlanc, et al., Poster BP9.00076, Mon AM

Strong electron absorption associated with "Slow Wave" in "high-resolution" full-wave simulations of HHFW in NSTX

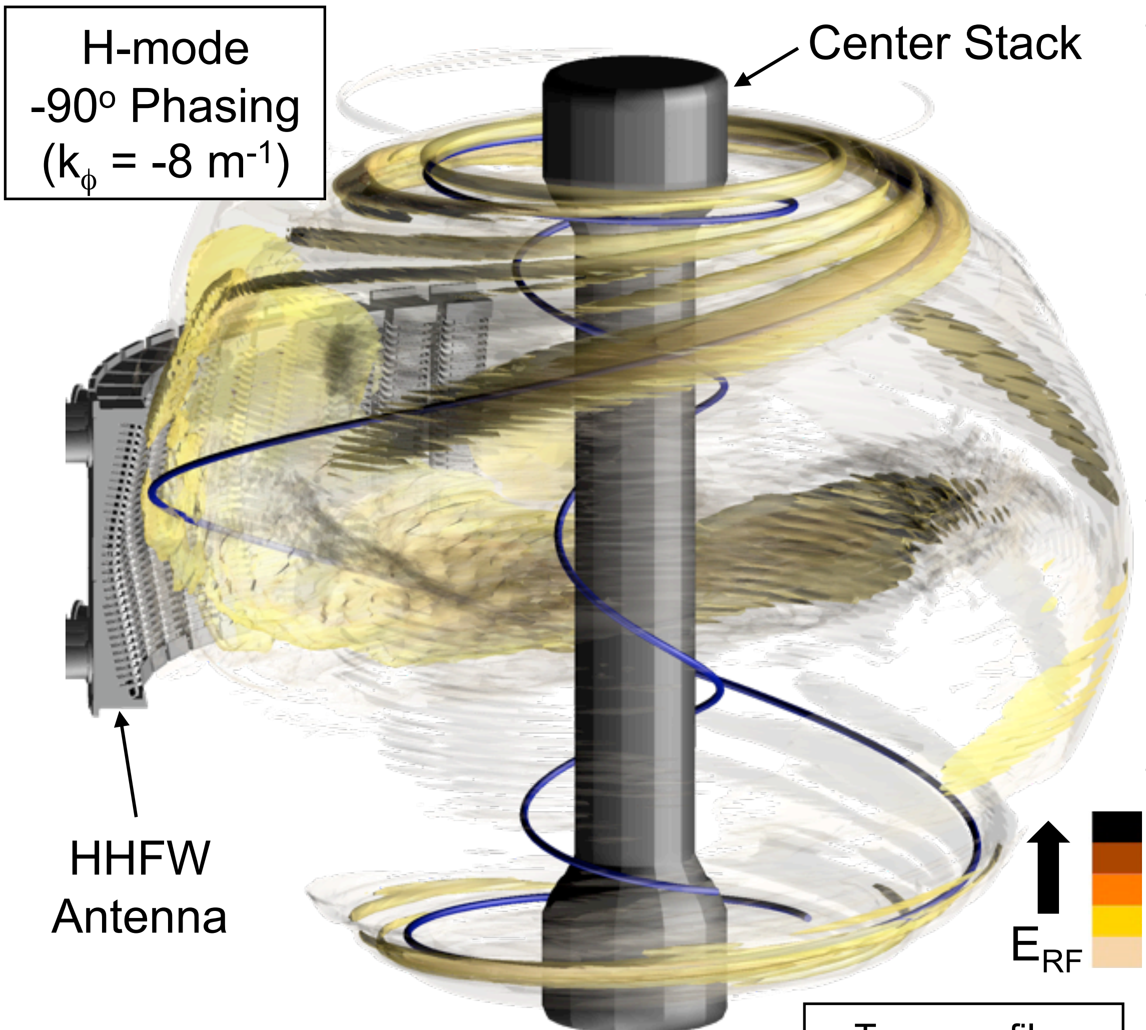


HHFW+ NBI H-mode Shot 130608 with $k_{//}$ ~ -7.5 m^{-1}

C. K. Phillips, et al., Poster BP9.00075, Mon AM

- "Slow Wave" mode seen mainly in $E_{//}$, not E_+ or E_-
- Mode is localized mainly off mid-plane
- Model predicts strong electron absorption near the "Slow Wave" propagation regions
- "Slow Wave" mode seen in both AORSA and TORIC full-wave simulations

AORSA full-wave model with limiter boundary predicts large E_{RF} fields following magnetic field near top & bottom of plasma



- Some fast-wave power propagates as an edge localized eigenmode just inside LCFS
- Magnitude of edge E_{RF} eigenmode is larger for negative antenna phasing
- Similar to plasma TV images – but E_{RF} stronger towards upper divertor in simulation
- For -30° antenna phasing (k_ϕ = -3 m^{-1}) fast-wave propagates outside LCFS to wall

T_e, n_e profiles consistent with 120470, 72 & 45

OAK RIDGE National Laboratory

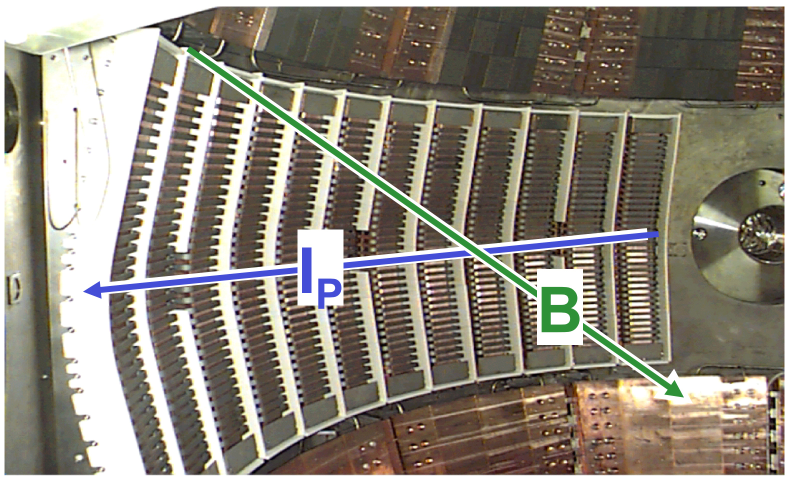
D. L. Green, ORNL

Summary

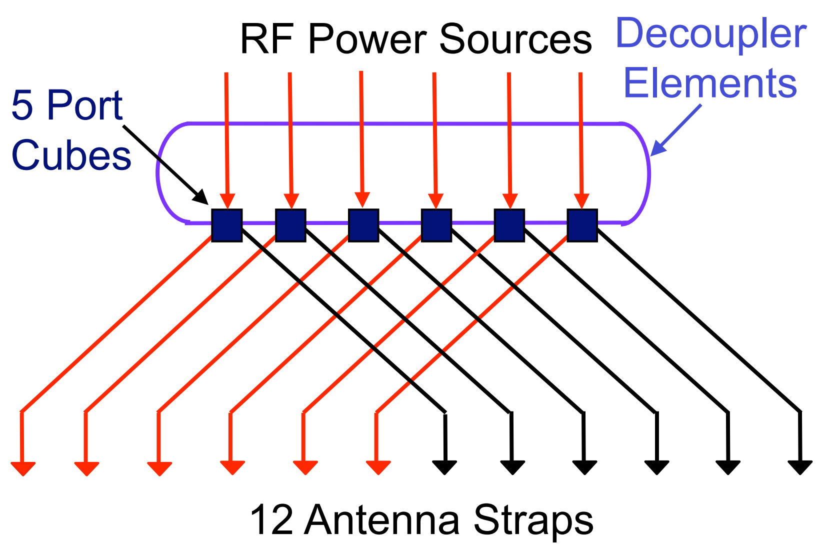
- Extensive lithium conditioning significantly degraded RF performance; arc-free P_{RF} ~ 1.5 MW, compared to P_{RF} ~ 4 MW in 2009
- Pattern of RF heating on divertor during H-mode follows magnetic field
- RF power flow to divertor is higher during large ELMs
- ~ 50% P_{RF} absorbed inside the LCFS during ELM-free RF+NBI H-modes
- Strong electron absorption associated with "Slow Wave" seen in "high-resolution" full-wave simulations
- 3-D AORSA full-wave simulations with boundary at limiter predict E_{RF} follows magnetic field near top and bottom of plasma

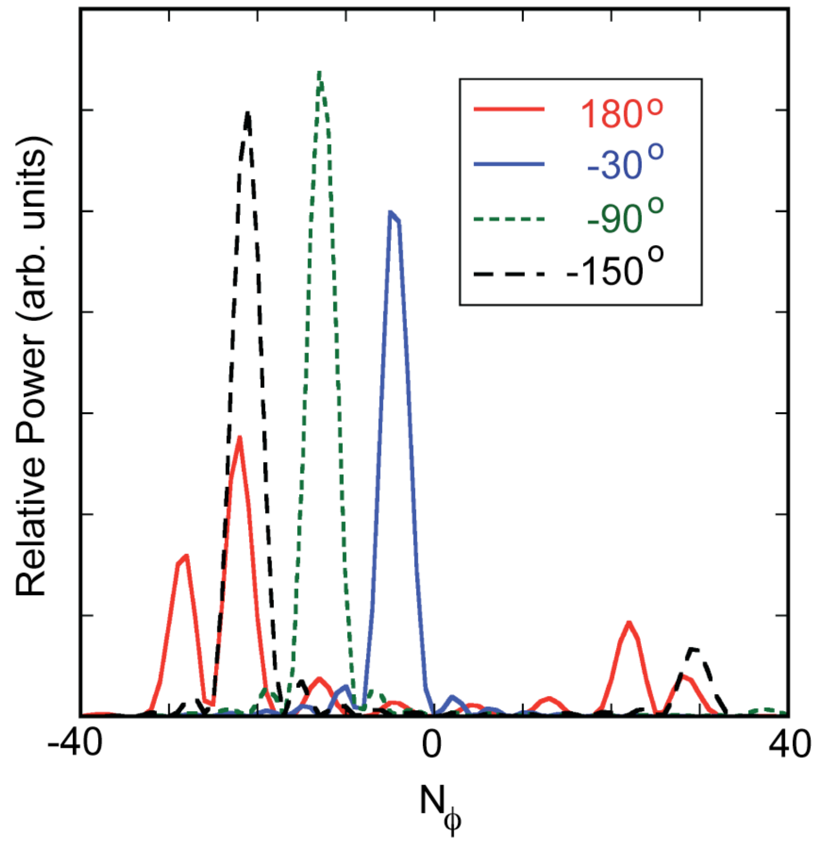
Backup Slides

NSTX HHFW Antenna Has Well Defined Spectrum, Ideal for Studying Phase Dependence of Heating



HHFW antenna extends toroidally 90°





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

Some progress in heating low I_p (~300 kA) RF-only H-mode plasma, but only achieved f_{NI} ~ 0.6 due to low P_{RF} (~1.5 MW)

- Spherical torus needs fully non-inductive I_p ramp-up & sustainment
- Low I_p HHFW experiments in 2005 could not maintain P_{RF} during H-mode
- This year generated sustained RF H-mode with internal transport barrier (ITB)
  - Better plasma-antenna gap control than in 2005 (Reduced PCS latency)
  - V_{loop}~ 0 and dI_{OH}/dt ~ 0, but need $P_{rf} \geq 3$ MW for fully non-inductive H-mode