NSTX

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High Harmonic Fast Wave Progress and Plans

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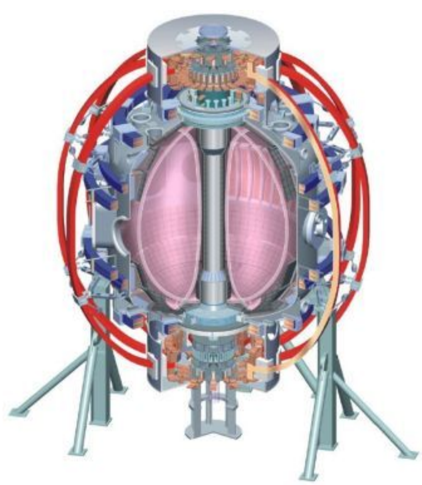

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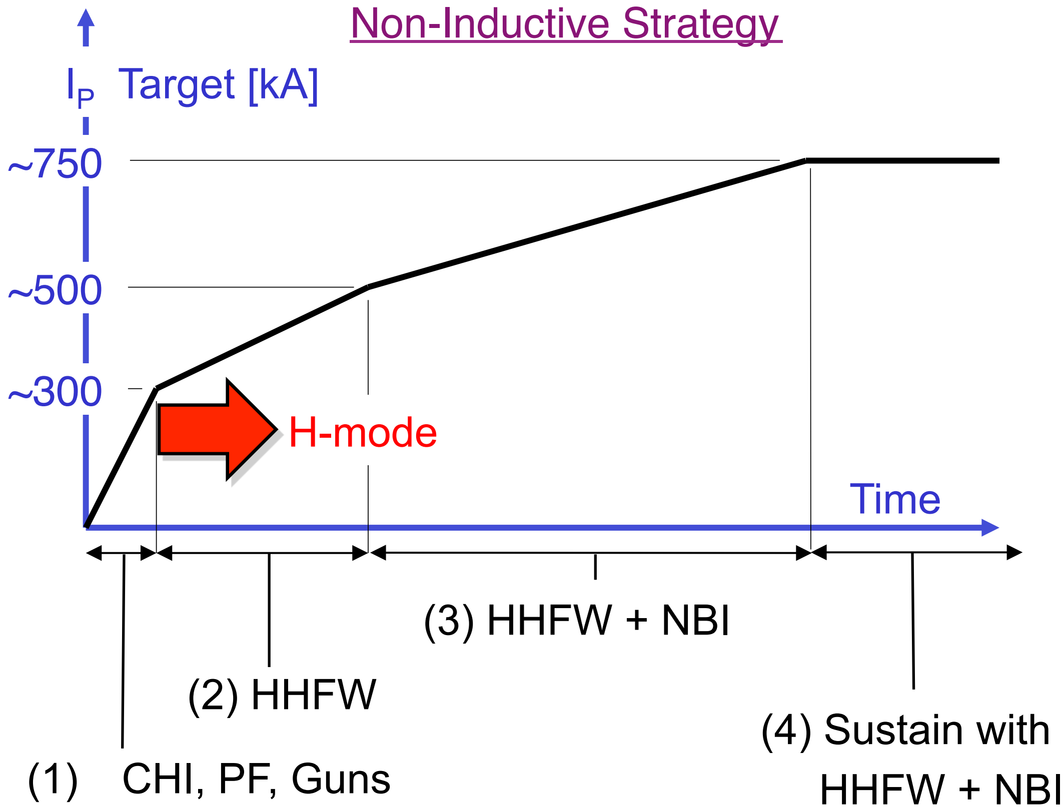
Outline

- Role of HHFW in NSTX Program
- Status of HHFW Research & Response to PAC-27
- HHFW Research Plan for FY11-12
- Plans for FY13-14 Outage

HHFW heating & current drive (CD) being developed for non-inductive ramp-up, bulk heating & q(0) control

<u>Non-Inductive Strategy</u>



<u>HHFW Goals</u>

(1) HHFW couples to start-up plasma

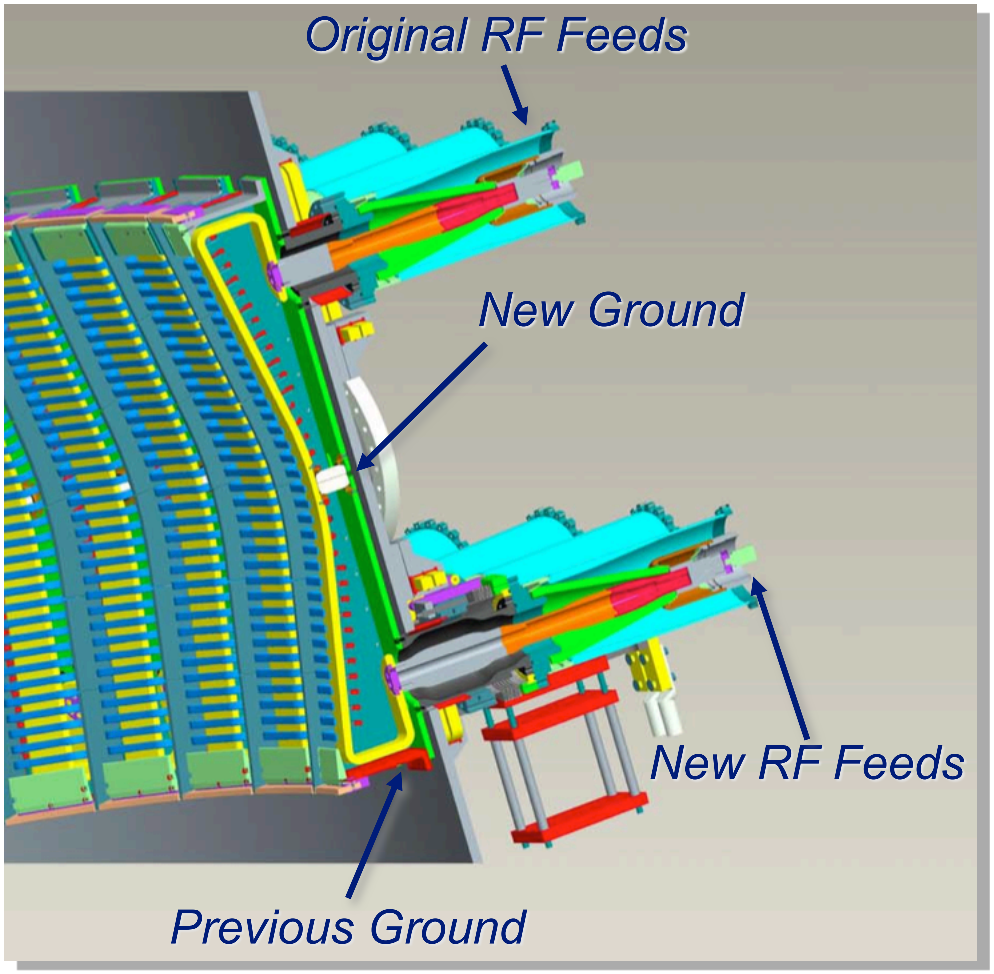
(2) HHFW for I_P overdrive through bootstrap & HHFW CD

(3) HHFW generates sufficient I_P to confine NBI ions

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

- Near-term approach is to heat low-I_p ohmic plasmas and access 100% non-inductive current drive

HHFW double end-fed upgrade was installed in 2009, shifted ground from end to strap center to increase maximum P_{RF}

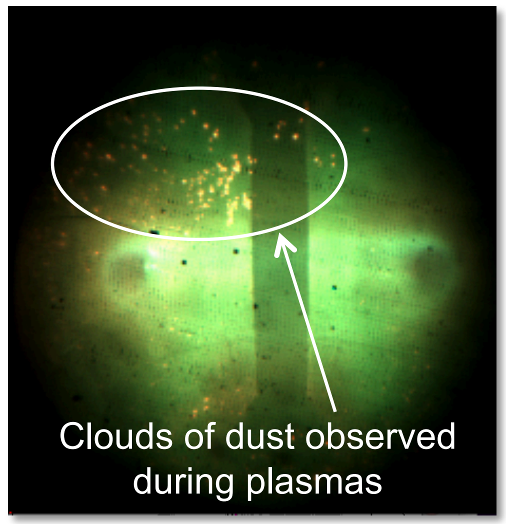


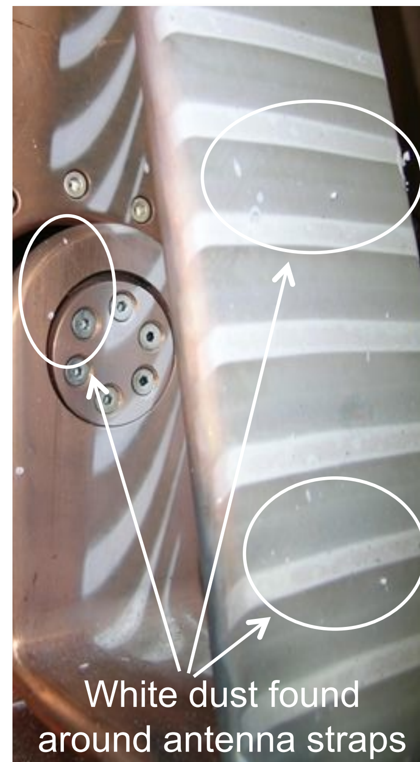
- Designed to bring system voltage limit with plasma (~15 kV) to limit in vacuum (~25 kV):
  - Increasing P_{RF} ~ 2.8 times
- Antenna upgrade was beneficial:
  - Reached arc-free P_{RF} ~ 4 MW after a few weeks of operation at the end of 2009 campaign
- In 2008-9, Li wall conditioning was observed to enhance HHFW coupling by decreasing edge density

PAC27-27

Increased lithium usage in 2010 significantly degraded performance of the upgraded antenna compared to 2009

- In 2010 RF plasma operations started after extensive Li injection, only reached arc-free P_{RF} ~ 1.4 MW; observed copious Li ejections during arcs
  - ➢ Before run quickly reached stand-off voltage ~ 25 kV during vacuum conditioning
  - ➢ After extensive Li injection difficult to reach ~ 15 kV in vacuum
  - ➢ Dust seen during plasmas & inside antenna



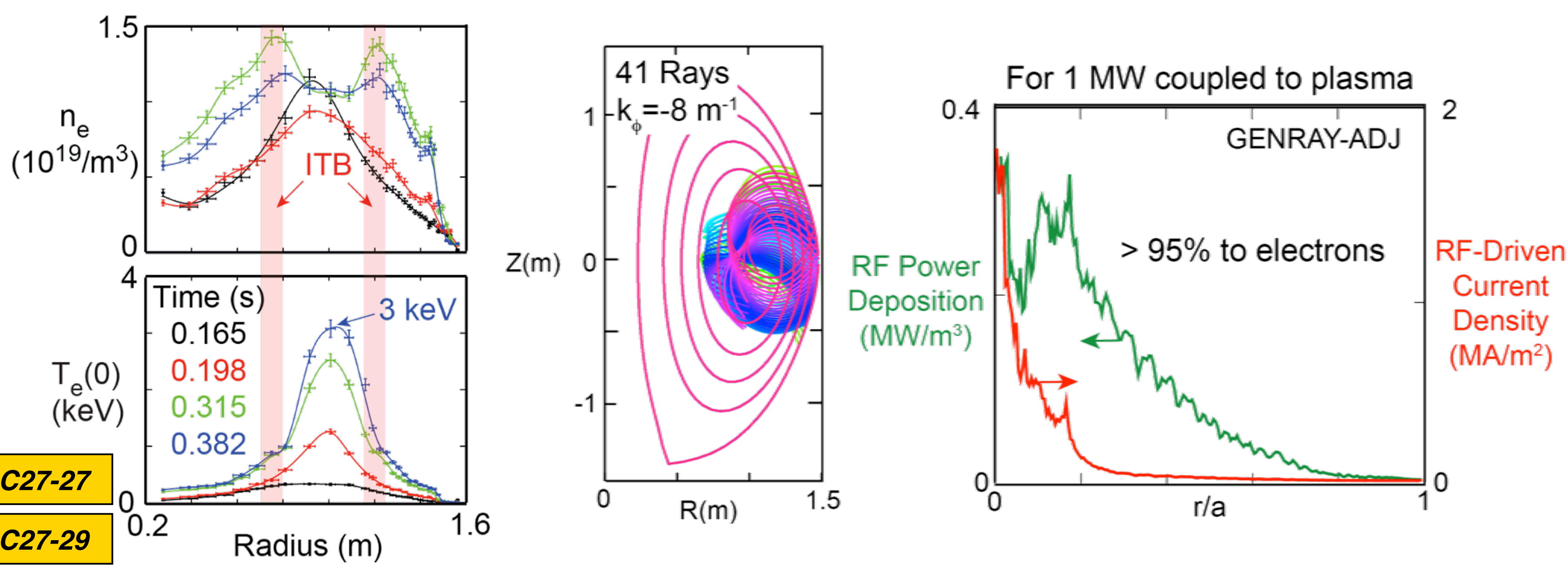


- For FY11-12 will return to FY09 Li levels:
  - ➢ should be okay for HHFW operations
- Tested prototype ELM/arc discrimination system in 2010:
  - ➢ Worked well on bench using recorded data, but tripped undesirably 20-30 times during real shot

PAC27-27 **PAC27-28**

Progress made in sustaining HHFW heating during I_p=300 kA RF-only H-mode plasma; $T_e(0)$ = 3keV with only 1.4 MW

- Low I_p HHFW experiments in 2005 could not maintain P_{RF} during H-mode
- Produced sustained RF-only H-mode in 2010:
  - ➢ Better plasma-antenna gap control than in 2005, due to reduced PCS latency
  - ➢ Modeling predicts I_{RFCD} ~ 85 kA, $I_{Bootstrap}$~ 100 kA → f_{NI} ~ 60%
  - ➢ High f_{NI} enabled by positive feedback between ITB, high $T_e(0)$ and RF CD
  - ➢ f_{NI} ~ 100% requires P_{RF} ~ 3 MW, well below arc-free P_{RF} available in 2009
  - ➢ No q-profiles for these RF-only plasmas – MSE-LIF will enable this in FY11-12



PAC27-27

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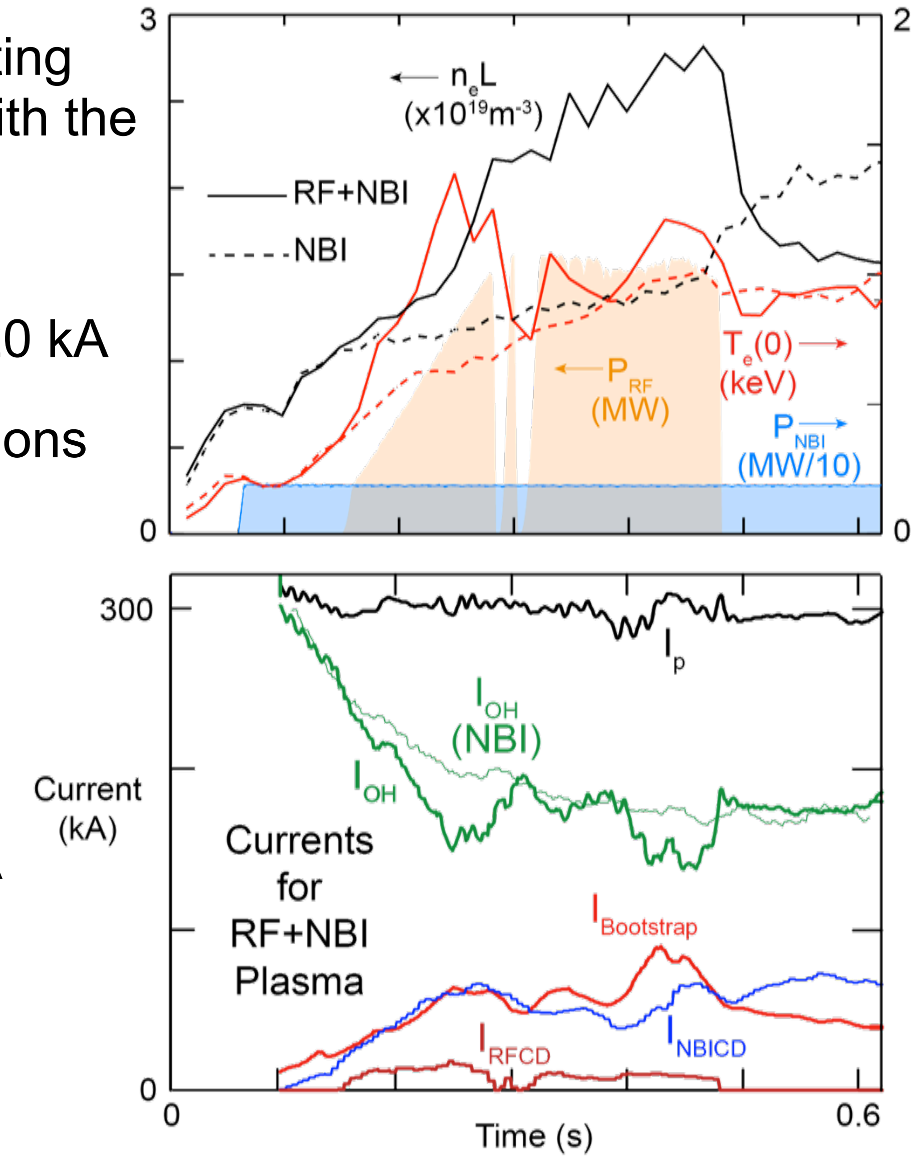
Adding NBI to P_{RF} = 1.4 MW, I_p = 300kA plasma resulted in lower f_{NI} due to RF absorption on fast-ions & higher n_e

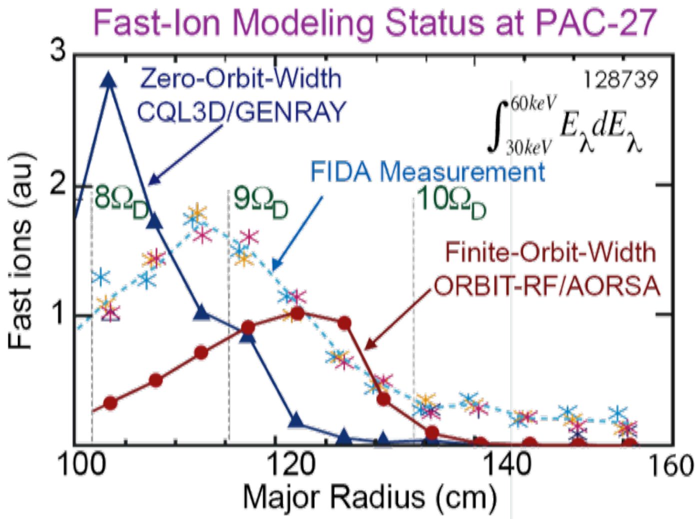
- Density increased during HHFW heating probably due to fast-ion interaction with the antenna
- Much lower $T_e(0)$ & higher $n_e(0)$ than RF-only H-mode, resulted in I_{RFCD} ~ 20 kA
- 60% of P_{RF} to electrons, 40% to fast-ions
- ~ 50% of injected NBI fast-ions are promptly lost at this low current:
  - Predict ~ 80% will be confined using more tangential 2nd NBI in NSTX-U
- $I_{Bootstrap}$ = 60-90 kA, I_{NBICD} = 50-70 kA
- f_{NI} ~ 50%

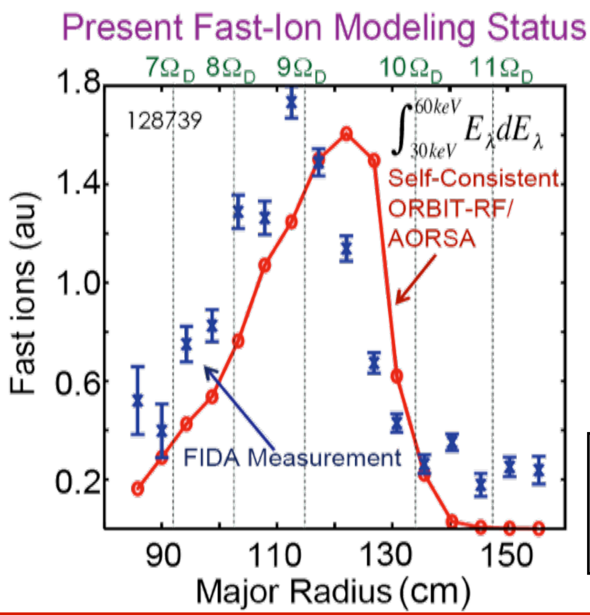
PAC27-27

PAC27-29



Self-consistent finite-orbit-width (FOW) ORBIT-RF/AORSA in good agreement with FIDA data for NBI+HHFW plasmas





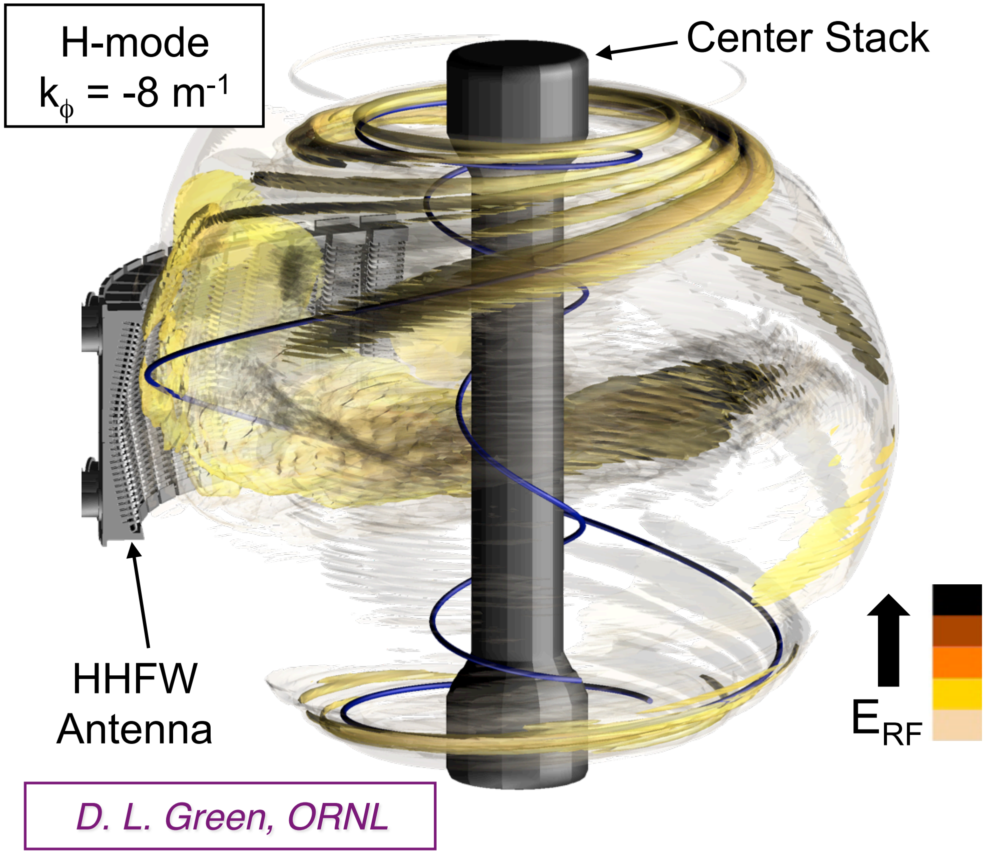
- HHFW interaction with NBI fast-ion can be significant
- At PAC-27 there was significant disagreement between modeling & FIDA fast-ion profiles
- Good agreement between modeling & FIDA has now been achieved by including additional iterations between AORSA & FOW ORBIT-RF
- Work has also begun on a full FOW correction to CQL3D which is expected to be completed in late 2011

P_{NBI} = 1 MW
P_{RF} = 1 MW

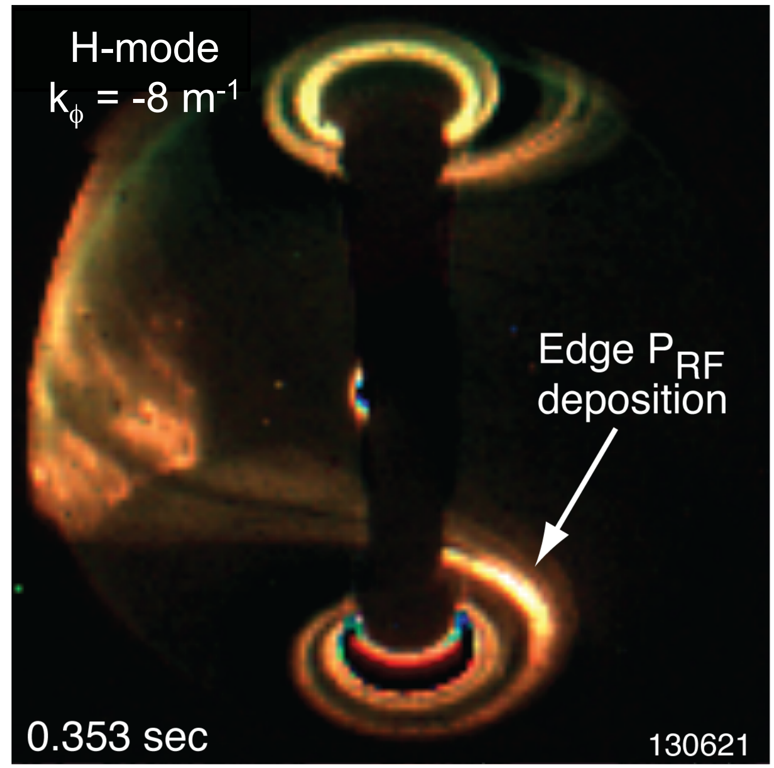
M. Choi, GA

PAC27-28

3-D AORSA full-wave model with 2-D wall boundary predicts large E_{RF} following magnetic field near top & bottom of NSTX



Edge RF eigenmode looks similar to striated structures imaged by visible plasma TV



- In addition to RF power coupling to core, AORSA predicts some RF power propagates just inside LCFS as an edge localized RF eigenmode
- Beginning to make divertor tile current measurements to compare to theory

PAC27-28

HHFW coupling & heating efficiency on NSTX-U

- B_T, I_p and P_{nbi} in NSTX-U will be 2x higher than NSTX, what are the implications for HHFW coupling & heating efficiency on NSTX-U?:
  - Higher B_T in NSTX-U moves fast-wave cut off towards or inside the separatrix, reducing surface wave losses
  - Higher n_e in NSTX-U may increase scrape off density, moving cut off outside separatrix and closer to wall, increasing surface wave losses – although SOL width may shrink at higher I_p
  - Higher P_{nbi} in NSTX-U may cause more fast-ion interactions with antenna, requiring larger antenna-plasma gap
  - Larmor radius (and banana width at high I_p) will be smaller, helping to reduce antenna interaction
- Will revisit higher I_p RF+NBI H-mode plasmas in FY11-12, including discharges with P_{nbi} up to 6 MW
- AORSA modeling of NSTX-U scenarios is also planned for FY11-12

PAC27-28

HHFW research plan for FY11-12 – (1)

- Assess "clean" antenna performance in plasma early in FY11-12 campaign
- Operate antenna strap on test stand to increase standoff voltage in vacuum

1st Priority:

- HHFW coupling at low I_p & during I_p ramp-up (with SFSU TSG): IOS-5.2 R(12-2)
  - HHFW heating of low I_p plasma
  - Couple HHFW into CHI-initiated plasma
  - Assess I_p ramp-up of an inductively generated discharge to 250-400kA with HHFW + bootstrap current overdrive

2nd Priority:

- Prepare for NSTX-U by running RF+NBI high I_p H-modes at P_{nbi} up to 6 MW: IOS-5.2, TC-9, TC-14
  - Study interaction of fast-ions with antenna and antenna heating
  - Study surface waves at maximum available P_{rf} & P_{nbi}
  - Study dependence of heating and CD efficiency on $k_{||}$, outer gap, n_{edge}

ITPA task NSTX milestone

HHFW research plan for FY11-12 – (2)

3rd Priority:

- Many HHFW experiments not started in FY10 due to RF power limitations, if time permits complete these experiments: IOS-5.2, TC-9, TC-14
  - HHFW interactions with ELMs & SOL
  - Fast-ion interactions, rotation effects & RFCD

High Priority Modeling Activities:

- Complete full FOW CQL3D
- Benchmark core HHFW CD in RF+NBI H-mode against advanced RF codes upgraded to include interactions with fast-ions
- Use non-linear gyrokinetics modeling to identify source of transport during HHFW heating and compare to that during NBI heating:
  - Especially effect of varying collisionality (microtearing vs ETG)

New & Upgraded Diagnostics will Aid HHFW Research in FY11-12:

- MSE-LiF will provide q(r) without NBI heating
- Additional MPTS channels will improve RF modeling
- Tangential FIDA will improve the study of RF fast-ion interaction

ITPA task NSTX milestone

HHFW plan FY13-14 outage period

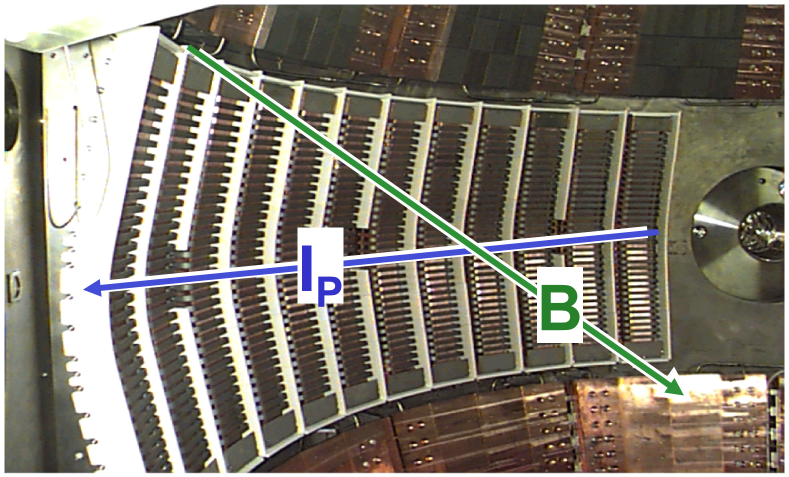
- Analysis and publication of low-I_p results, fast-ion interactions, and divertor heating by RF
- RF modeling NSTX-U plasma scenarios with the extended boundary AORSA-3D and full FOW CQL3D codes
- Implement design changes to antenna to minimize Li deposition inside the antenna box:
  - May install double "closed" shield configuration
- Assess possible change to six-strap antenna configuration:
  - Full control of spectral peak location (~3 -14 m^{-1}) through arbitrary phasing
  - Simplified, less crowded power distribution system
  - Frees up mid plane port space for possible CAE and/or EHO antenna
  - Would need to increase strap current and maximum system voltage by 40% to obtain same power
  - Run AORSA with six straps to see if there are any unexpected changes

Summary

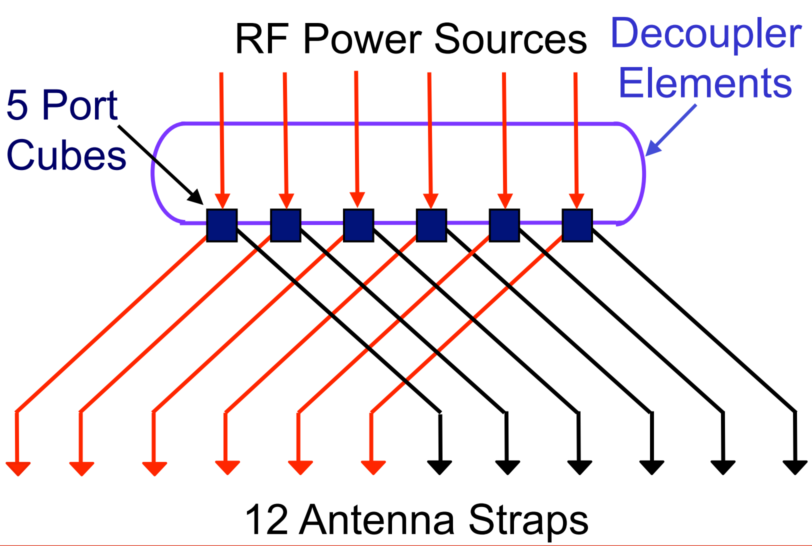
- Sustained I_p = 300 kA RF-only H-mode with P_{rf} = 1.4 MW achieved f_{NI} ~ 60%; project f_{NI} ~ 100% achievable with P_{RF} ~ 3 MW
- In FY10 Li compounds inside antenna limited arc-free $P_{RF} \leq$ 1.4 MW
- Improved agreement between modeling & FIDA for NBI+HHFW plasmas
- Modeling predicts edge RF eigenmodes may drive significant power flows
- FY11-12 experiments will focus on CHI-initiated, HHFW-heated plasmas and NBI+HHFW H-modes with P_{nbi} up to 6 MW

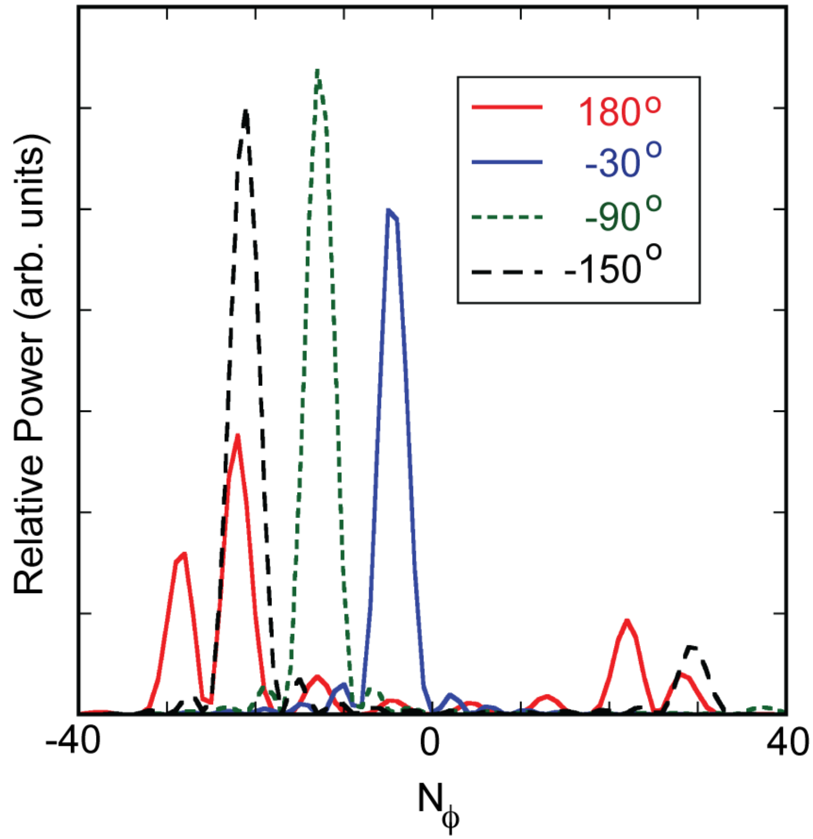
Backup Slides

NSTX HHFW antenna has well defined spectrum, ideal for studying phase dependence of heating



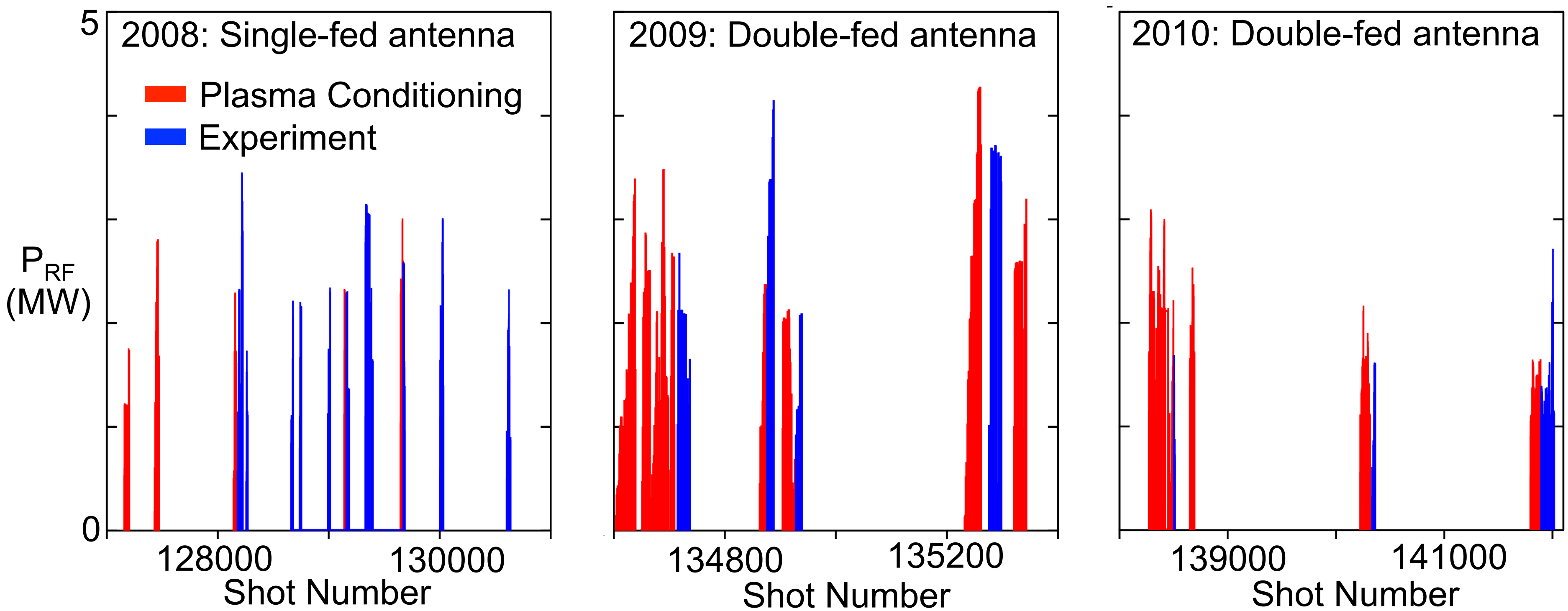
HHFW antenna extends toroidally 90°





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

Double-fed HHFW antenna operation improved with time in 2009, but degraded over time in 2010

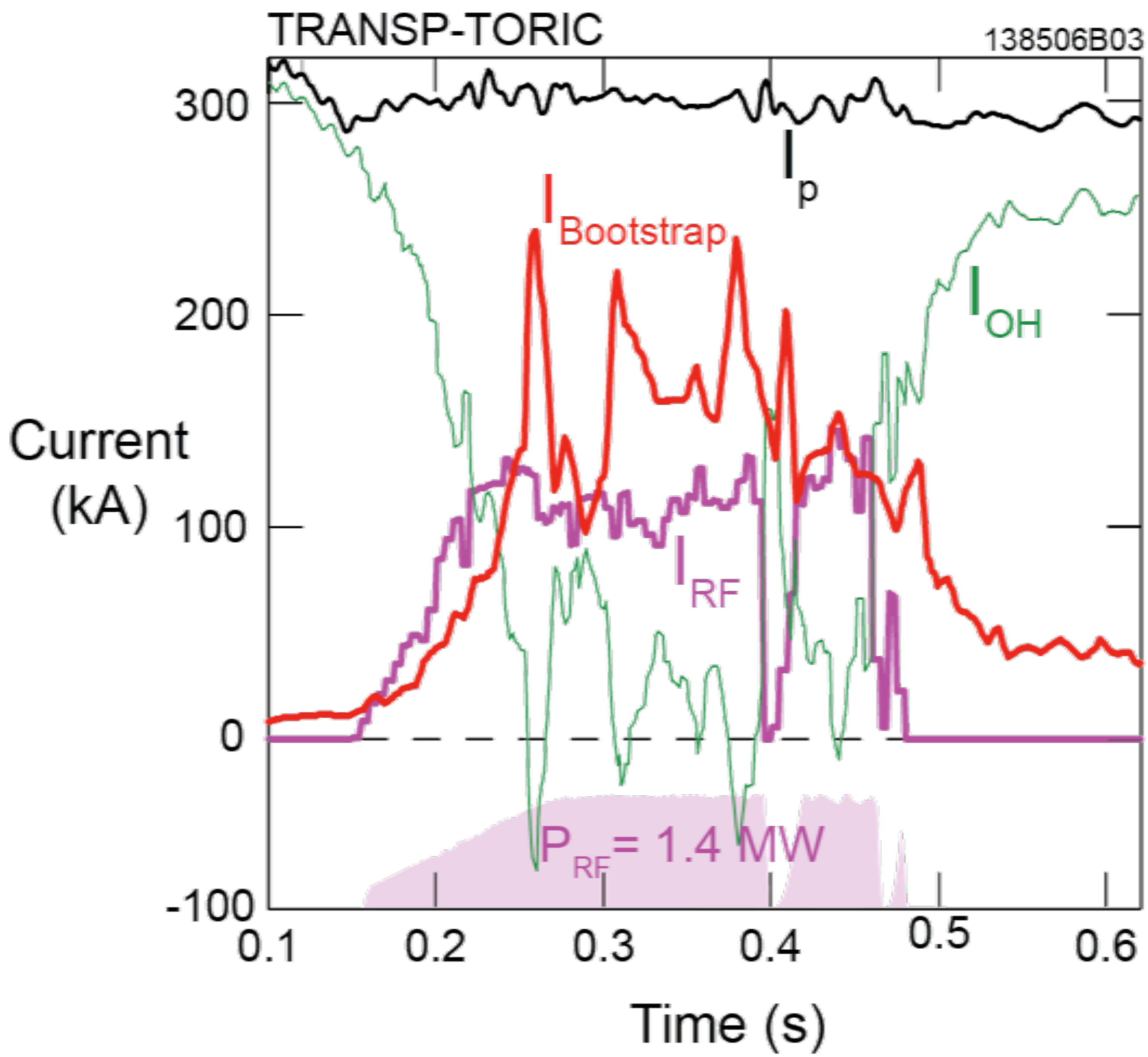


- Operation spread out evenly over ~ 5 months
- Initial plasma conditioning, then majority of time on experiments
- Most operation in 2-3 MW range throughout campaign

- 2009 operation concentrated in last 4 weeks
- Majority of time spent on plasma conditioning
- Operation in 2.5-4 MW range, improved with time

- 2010 operation widely separated over ~4 months
- Almost all time spent on plasma conditioning
- Operation < 3 MW, deteriorated with time

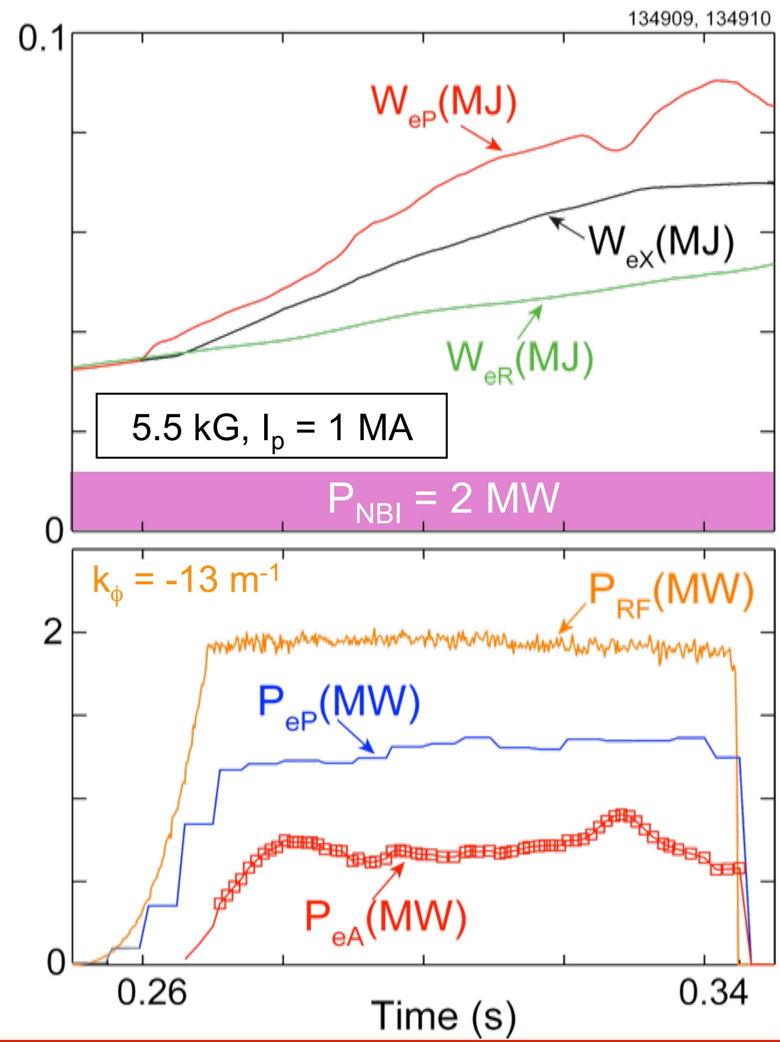
TRANSP-TORIC simulation with no RF coupling losses predicts ~180 kA Bootstrap CD + ~120 kA RFCD



- RF coupling efficiency is typically ~ 60% for H-mode, giving f_{NI} ~ 60%
- TRANSP-TORIC RF CD efficiency of ~ 85 kA/MW
- GENRAY-ADJ RF CD efficiency ~ 115 kA/MW

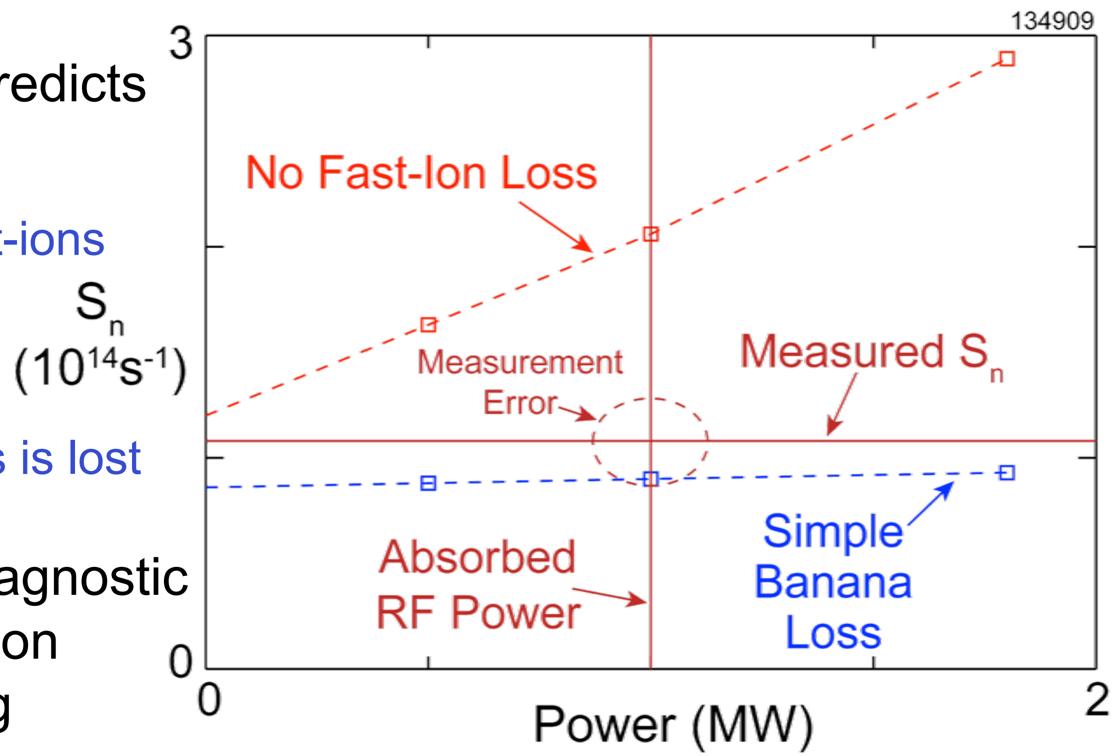
TRANSP-TORIC analysis of matched NBI+HHFW & NBI-only ELM-free H-modes predicts ~ 50% of P_{RF} is absorbed inside LCFS

- 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



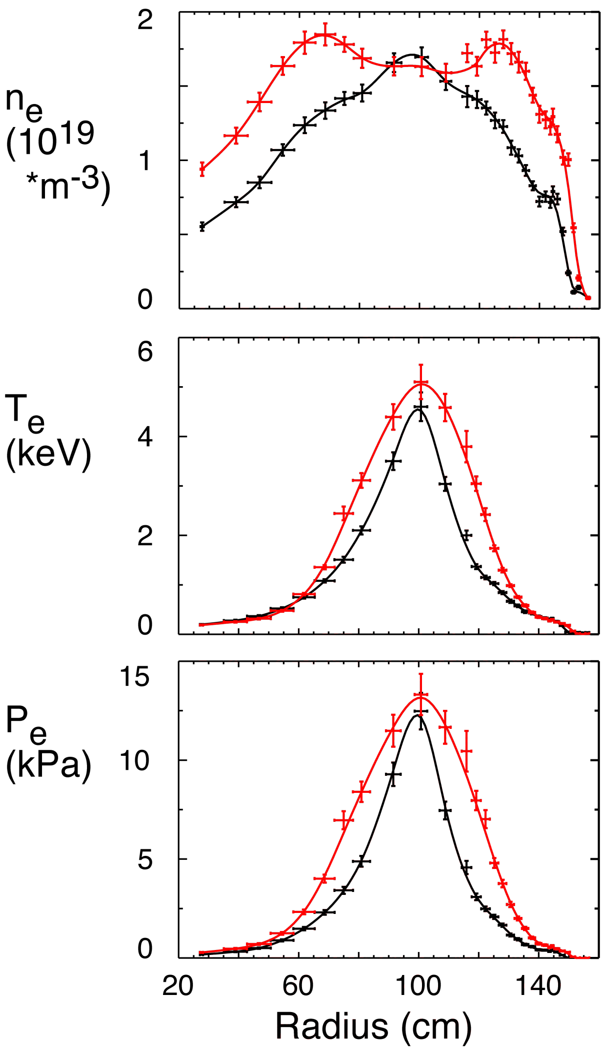
CQL3D Fokker-Planck code predicts significant fast-ion losses in HHFW-heated ELM-free NBI H-modes

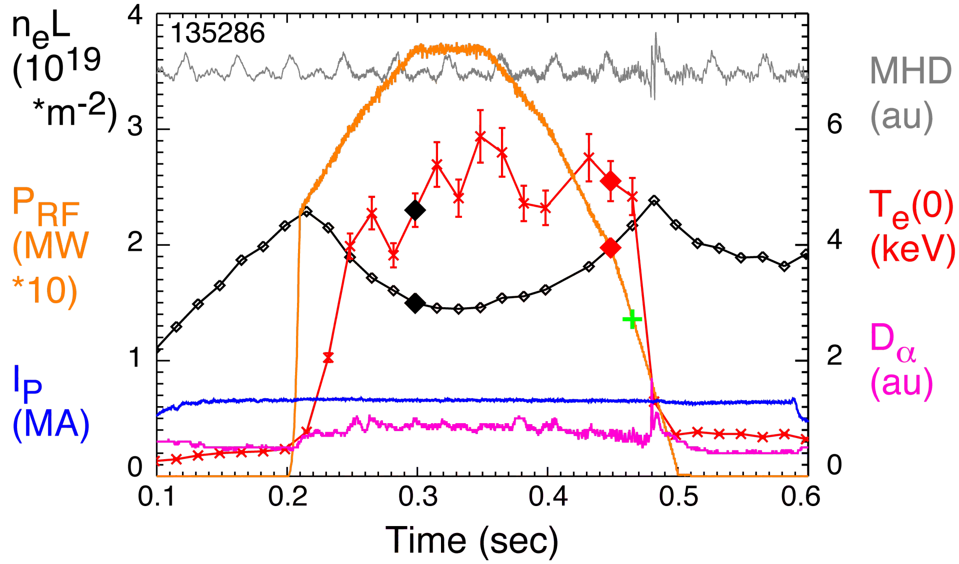
- Without fast-ion loss CQL3D predicts much higher neutron production rate (S_n) than is measured
- Simple-banana-loss model predicts S_n just below measured S_n :
  - Assumes prompt loss of fast-ions with a gyro radius + banana width > distance to LCFS
  - ~ 60% RF power to fast-ions is lost
- For this shot FIDA fast-ion diagnostic measures no change in fast-ion density during HHFW heating



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

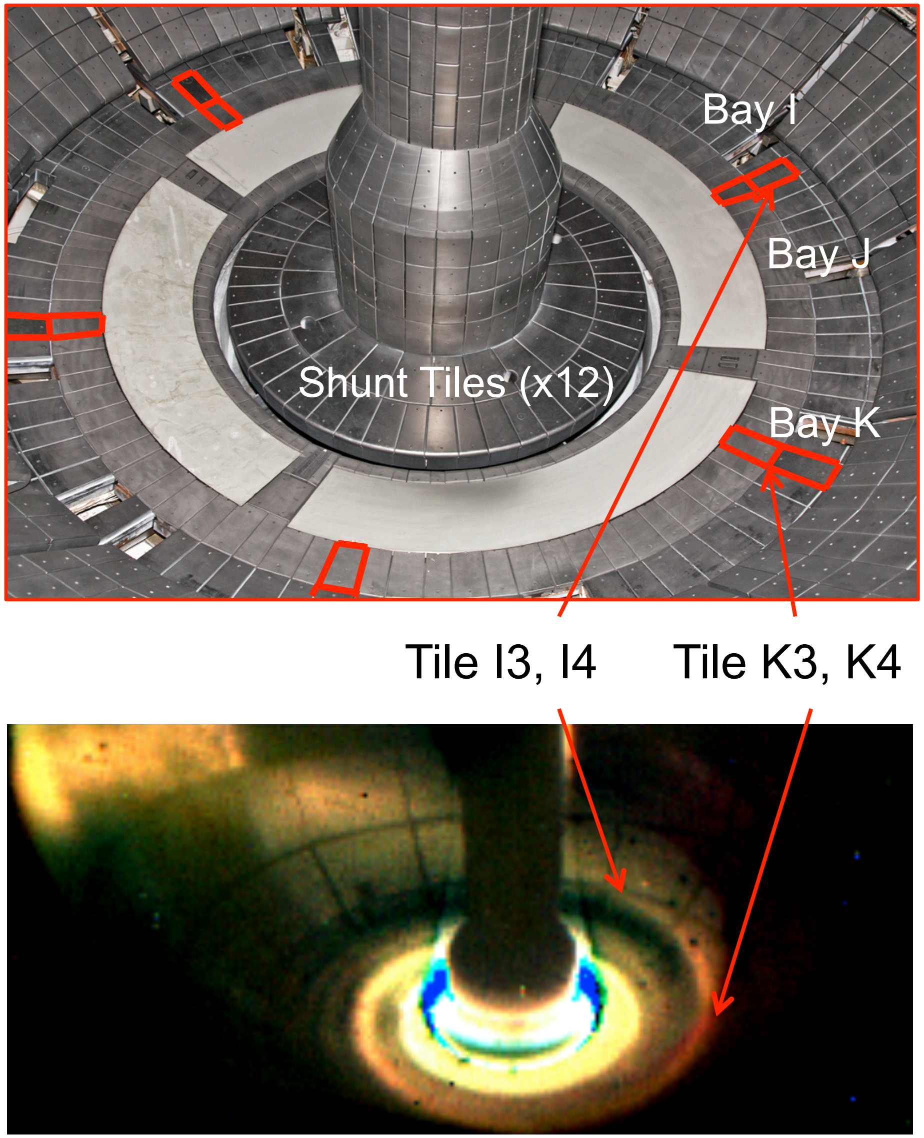
Slow fall of P_{RF} results in sustainment of high $T_e(0)$ and core electron heating even down to P_{RF} < 1.4 MW





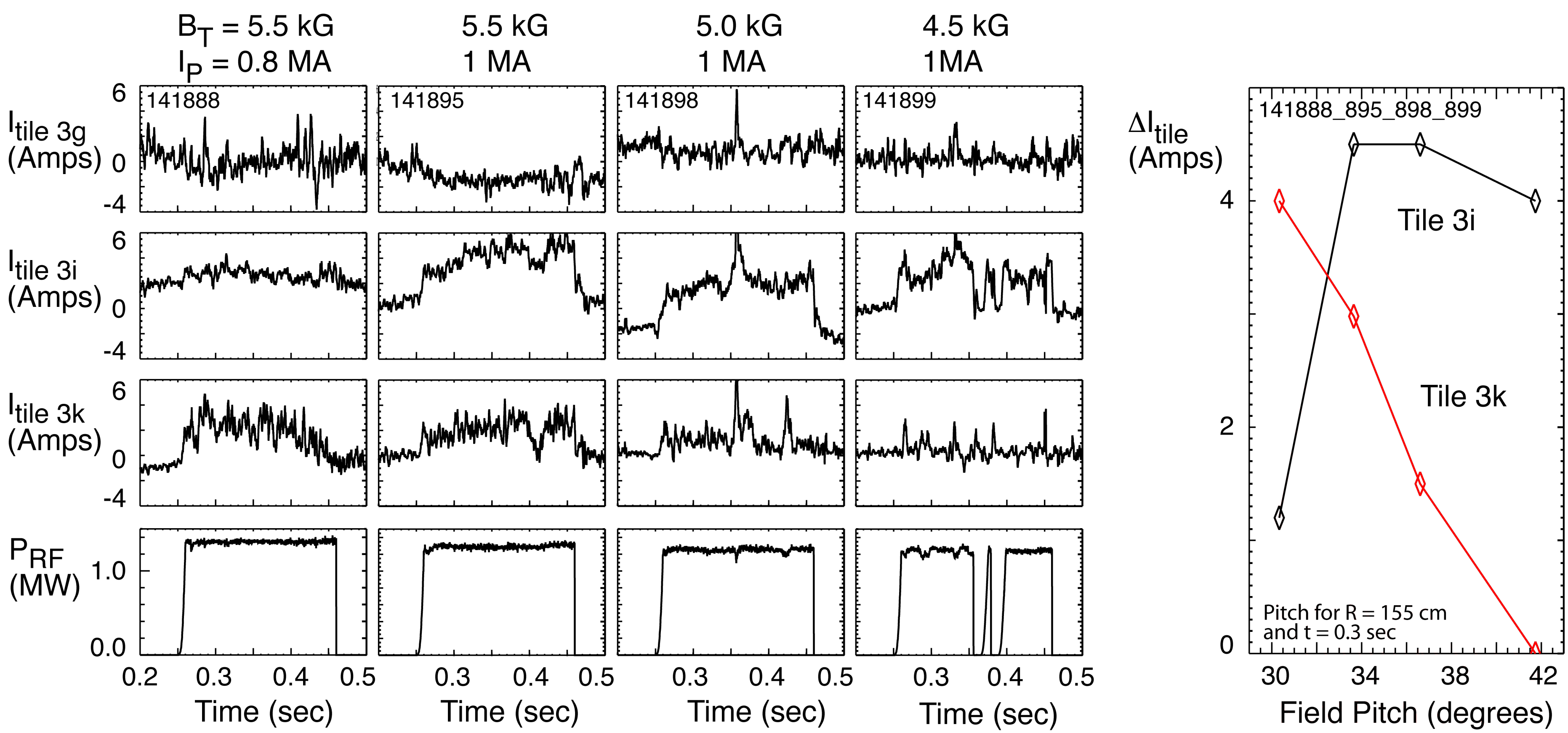
- Slow transition to H-mode from L-mode as power is ramped to 3.7MW
- During slow ramp down of P_{RF}, the core temperature is maintained and broadened in radius even down to 1.36 MW
- Large ELM at even lower power strongly reduces the stored electron energy and marks the transition back to the L-mode

Divertor tile currents are used to track presence of RF fields (sheath) and driven currents



- Tiles in row 3 and 4 of divertor plate are instrumented with Rogowski sensors
- Bay I and K tiles are in line with “hot” zone for RF edge deposition

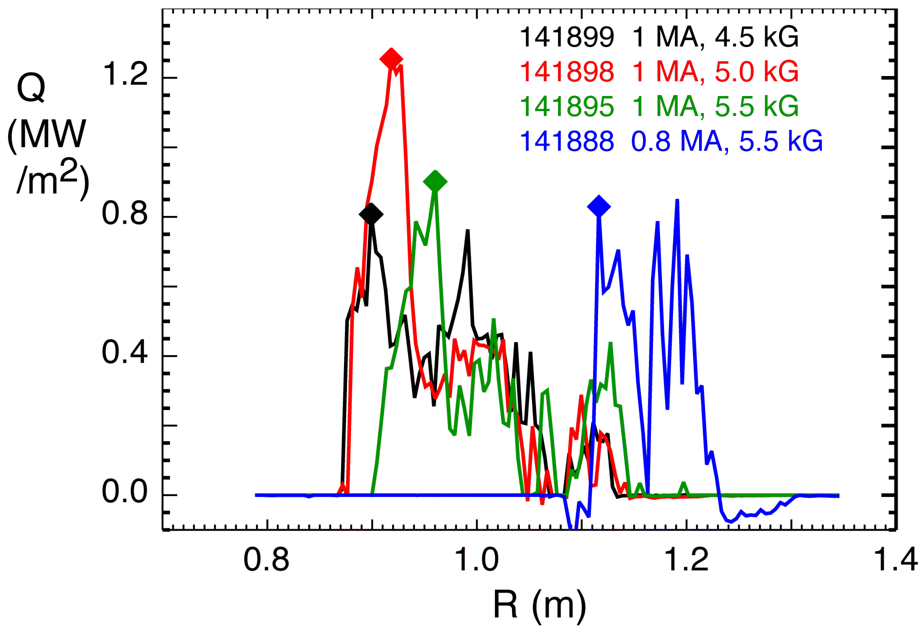
Divertor tile currents in row 3 show movement of RF hot zone across tiles as magnetic field pitch is increased



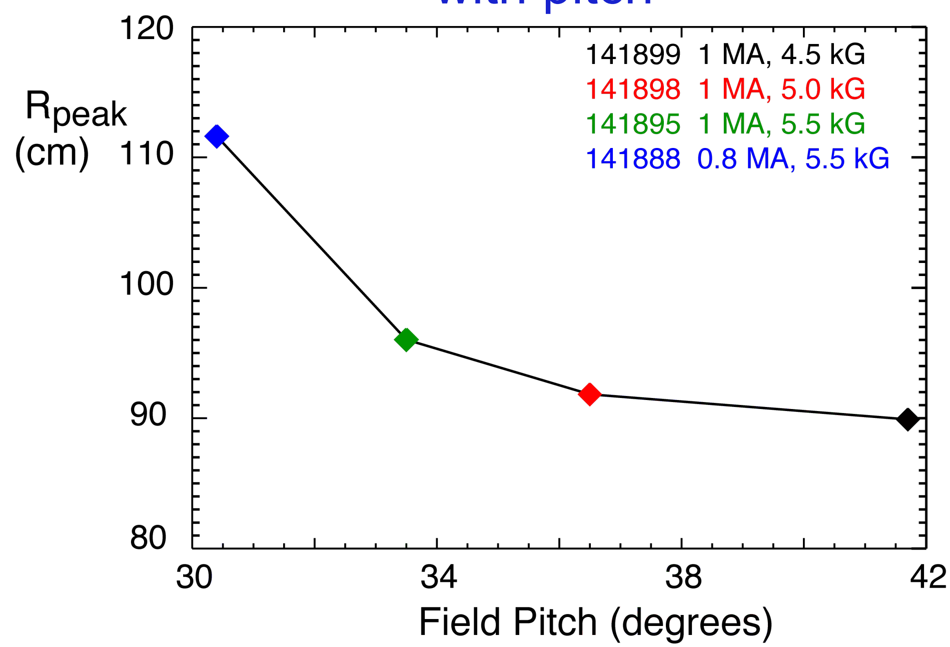
- $\Delta I_{tile\ 3k}$ decreases and $\Delta I_{tile\ 3i}$ increases as magnetic field pitch increases and RF spiral hot zone moves toward the center stack

Tile currents in row 3 are consistent with RF hot zone movement measured with the fast IR camera at Bay H

Fast IR at Bay H vs field pitch for t = 0.450 sec



Shift of RF hot zone with pitch



- Movement of RF hot zone with magnetic field pitch is relatively fast in the lower pitch range but slows considerably in the higher pitch range