NSTX

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# High Harmonic Fast Wave Progress and Plans


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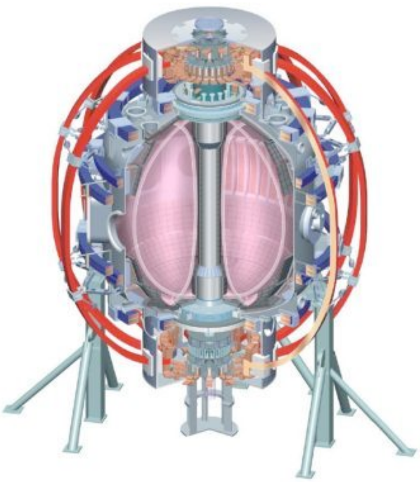
**Gary Taylor, PPPL**

*for the NSTX Team*


**25th NSTX Program Advisory Committee Meeting (PAC-25)**
**LSB-318, PPPL**
**February 19, 2009**

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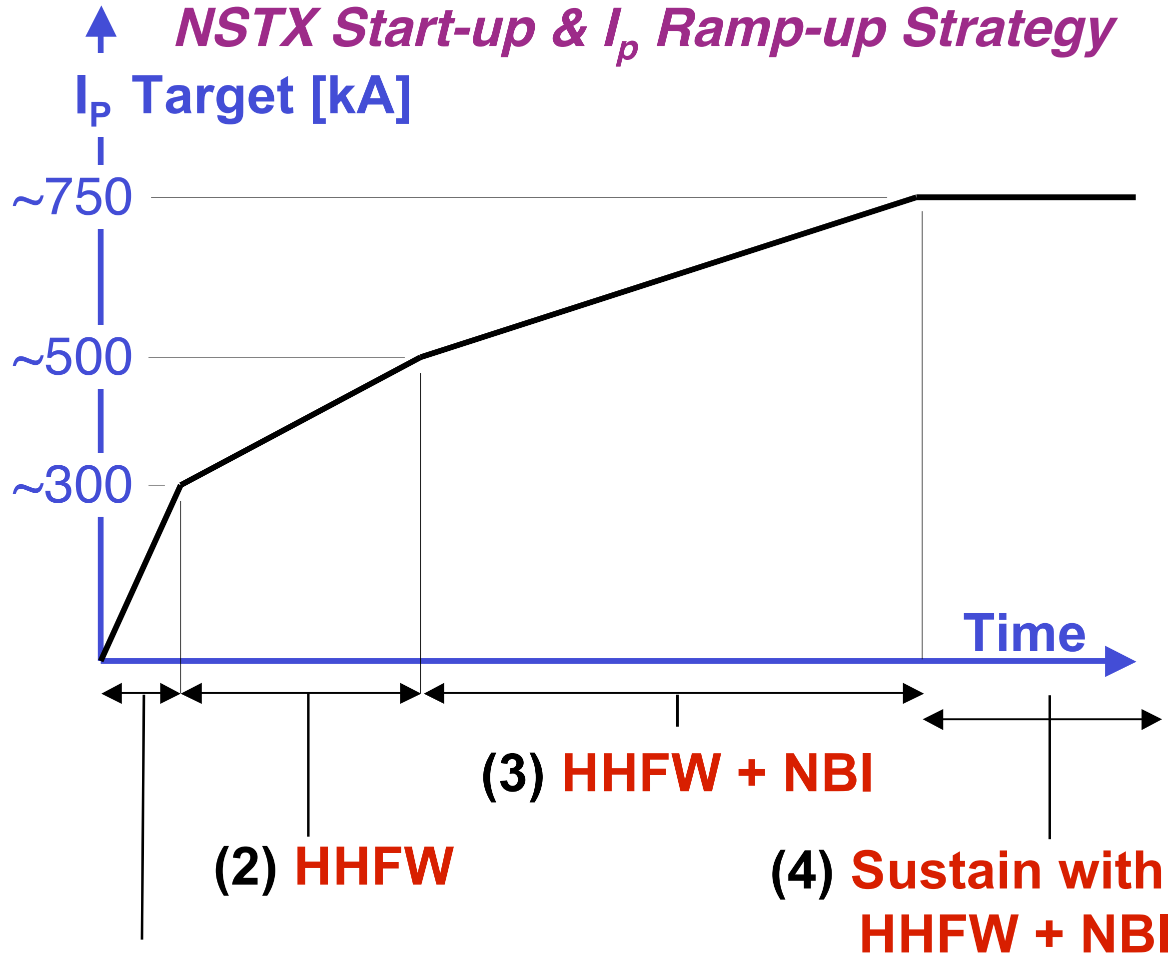
# Outline

- Role of HHFW in NSTX Program
- Recent Advances in HHFW Research & Modeling
- Research Strategy for 2009-11 & Beyond

# 30 MHz HHFW Heating & CD Aims to Support Non-Inductive Ramp-up, Bulk Heating & q(0) Control

***NSTX Start-up & $I_p$ Ramp-up Strategy***




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

**⇒ Non-Inductive ramp-up FESAC-TAP priority #1**

**⇒ Ramp-up will be discussed in next talk**

***Start-up/Ramp-up Requirements***

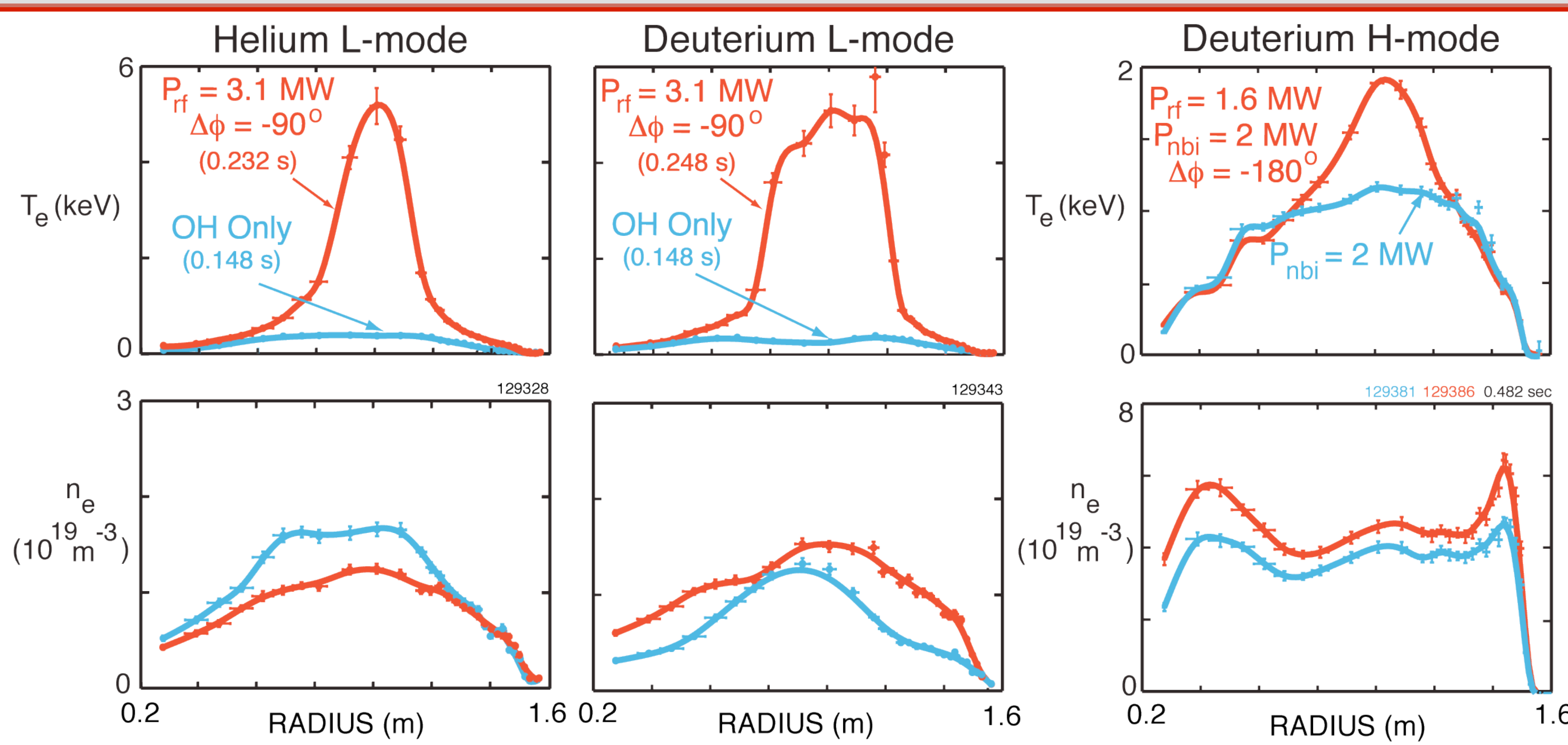
**(1→2)** Target plasma generated with CHI, guns or PF-only. ECH likely needed to heat plasma to allow HHFW coupling

**(2)** $I_P$ overdrive using bootstrap & HHFW CD

**(2→3)** HHFW generates sufficiently high $I_P$ to absorb NBI

**(4)** HHFW provides q(0) control & bulk heating

# Improved HHFW Heating in 2008 Provided Important Tool for Transport Studies

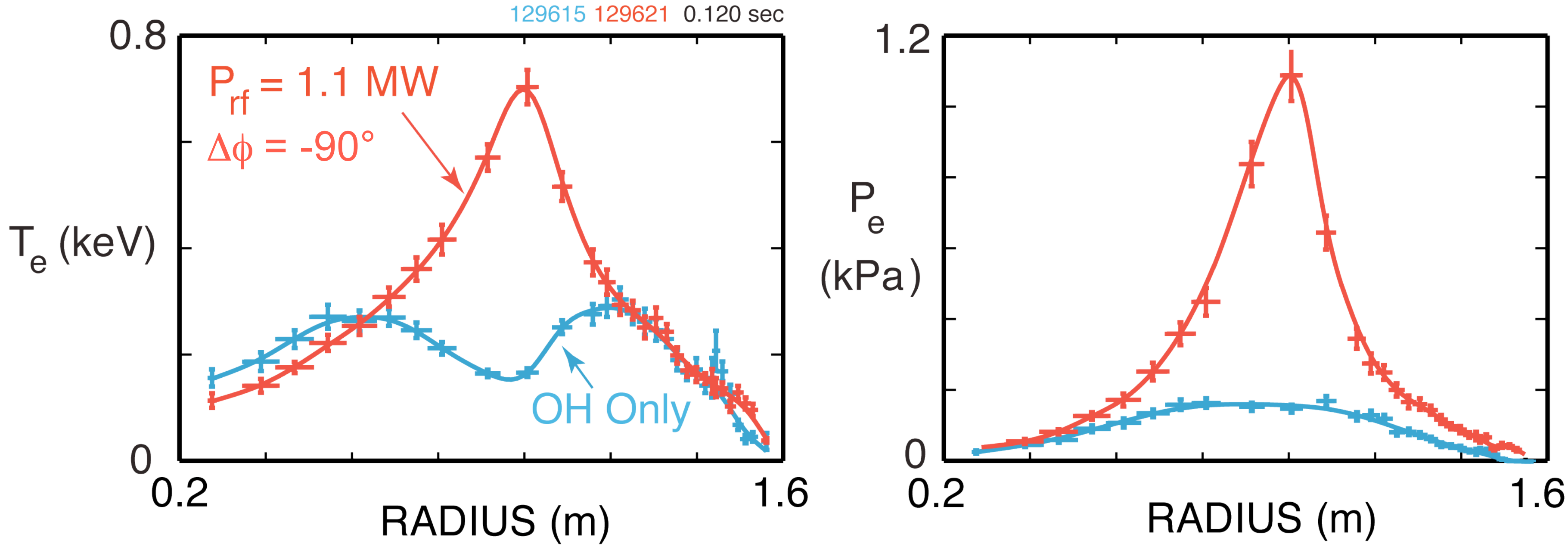



- NSTX record $T_e(0)$ ~ 5 keV & strong $T_e$ gradient
  - Supports high-k scattering study of small scale turbulence in He & $D_2$
- First HHFW core heating in $D_2$ NBI H-mode achieved with Li

- Experiments in 2009-10 will use Li injection & LLD to improve HHFW heating & CD in H-mode

PAC23-03
PAC23-10

# HHFW Experiments During Early $I_p$ Ramp-up Show Good Electron Heating in $D_2$ with CD Phasing




- HHFW coupled into $I_p$ ~ 300 kA, $n_e(0)$ ~ $6x10^{18}$ $m^{-3}$
- CD phasing in $D_2$ at low $I_p$ required for ramp-up studies

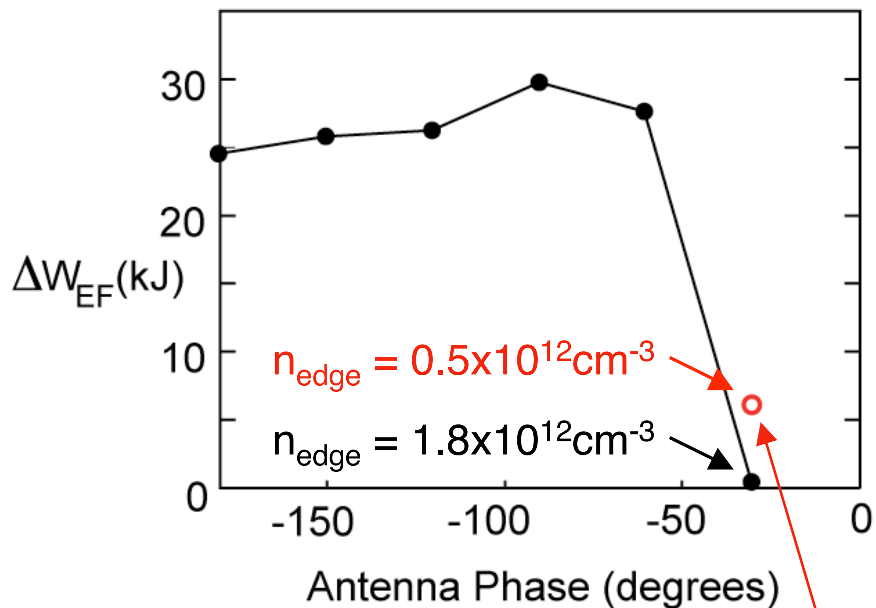
- HHFW-assisted ramp-up experiments, including phase scans & Li conditioning, are planned for 2009

PAC23-10
PAC23-11

# Improved Heating due to Better Understanding of Important Role of Edge-Wave Interactions

- Edge power loss increases when perpendicular propagation onset density is near antenna
- Heating efficiency improved ($\Delta W_{EF}$) by reducing edge density ($n_{edge}$) with Li conditioning
- Strong first pass absorption in NSTX ideal for studying competition between core rf heating & edge-wave power loss

$P_{rf}$ ~ 1.1 MW in D plasmas
(~230 ms RF pulse duration)

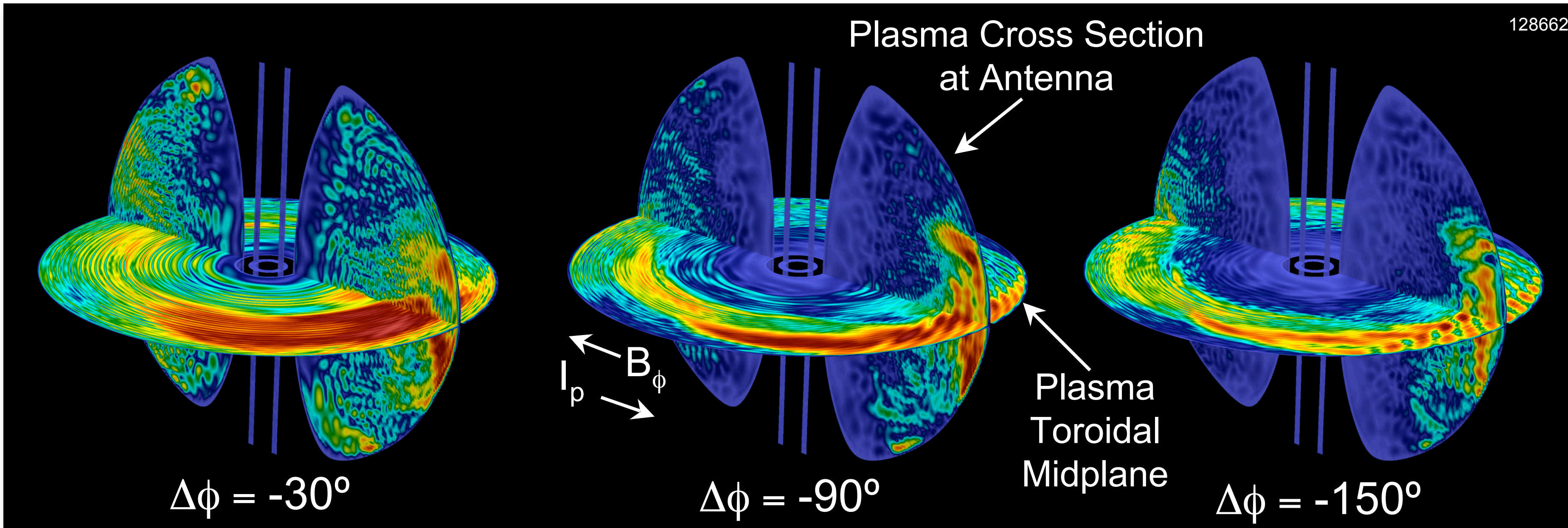



Improved $\Delta W_{EF}$ at $\Delta\phi$ = -30° in D plasmas with Li conditioning, even with shorter 67 ms RF pulse

⇒ Edge-wave interactions could be important for ITER ICRF heating

# 3D Codes Using Full Toroidal Spectrum to Include Surface Damping and CD Effects

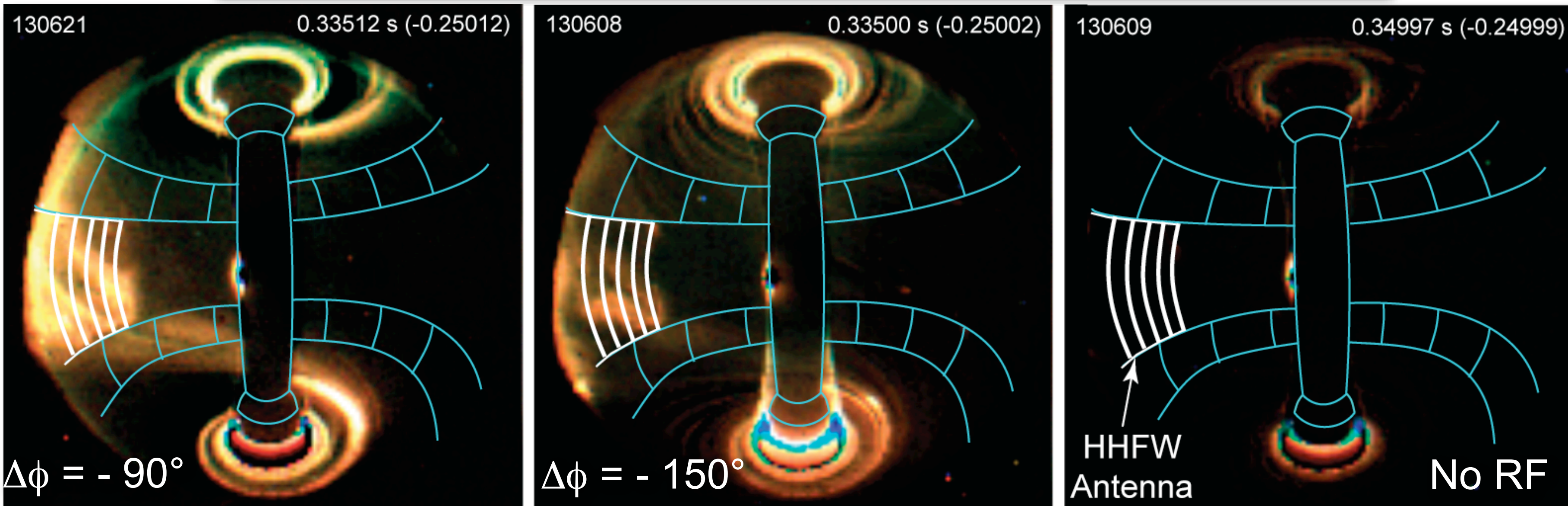
*AORSA $|E_{RF}|$ field amplitude with 101 $n_\phi$ modes*




- Waves propagate around plasma axis in + $B_\phi$ direction
- Wave fields very low near inner wall
- Edge loss mechanisms will be identified experimentally and included by RF SciDAC in advanced codes

# Stronger Interaction Between Antenna & Divertor Along Field Line at Lower Phase/Longer Wavelength

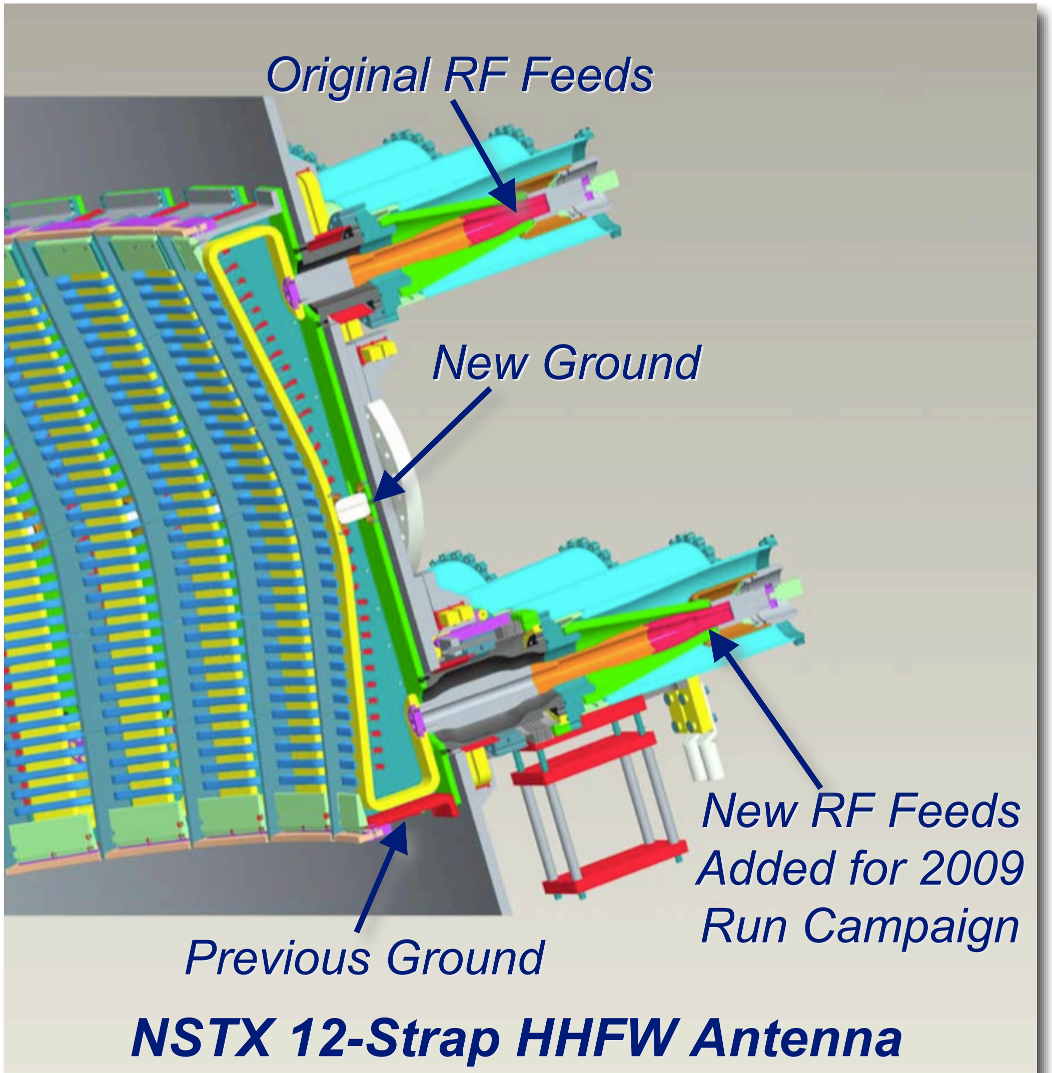
$P_{rf}$ = 1.8 MW, $P_{nbi}$ = 2 MW, $I_p$ = 1 MA, $B_T$ = 5.5 kG, H-Mode




- Do not know how much power is lost through interaction:
  - Implications for CD & HHFW-ELM interaction
  - Incorporate divertor interaction into 3-D ray tracing & full wave modeling

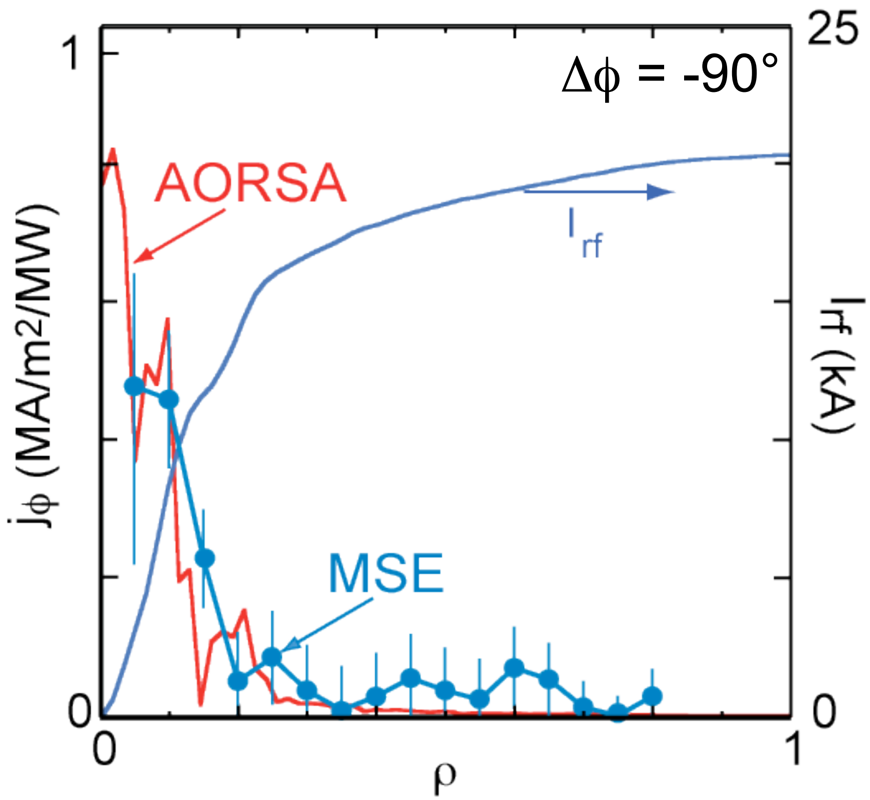
- 2009 HHFW experiment to study edge effects in L- and H-mode

# Building on Positive 2007-8 Results, Antenna Upgrades Increase Coupled Power & ELM Resilience




- Double feed upgrade implemented for 2009 run:
  - $P_{rf}$ increased from ~ 3 MW to ~ 6 MW
  - 4-6 MW likely required for BS overdrive ramp-up
  - Permits larger plasma-antenna gap, reducing NBI fast ion interaction with antenna
- ELM resilience system will be added in 2010-2012:
  - Electronic detection & $P_{rf}$ notch at ELM in 2010
  - Hybrid ELM dump in 2011-2012

# Motional Stark Effect (MSE) Measurement of Core HHFW CD Profile Consistent with Modeling

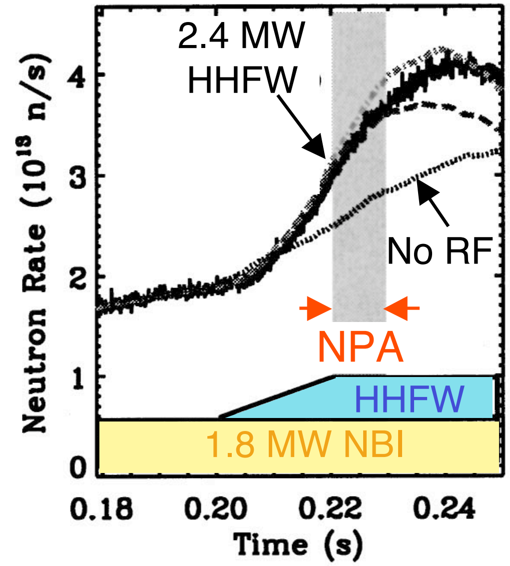



- Measured CD profile consistent with AORSA prediction using MSE-constrained LRDFIT equilibrium, full toroidal spectrum, Ehst-Karney approximation & trapping
  - MSE & AORSA $I_{rf}$ ~ 20 kA
  - MSE reconstructions essential for good match with measured CD

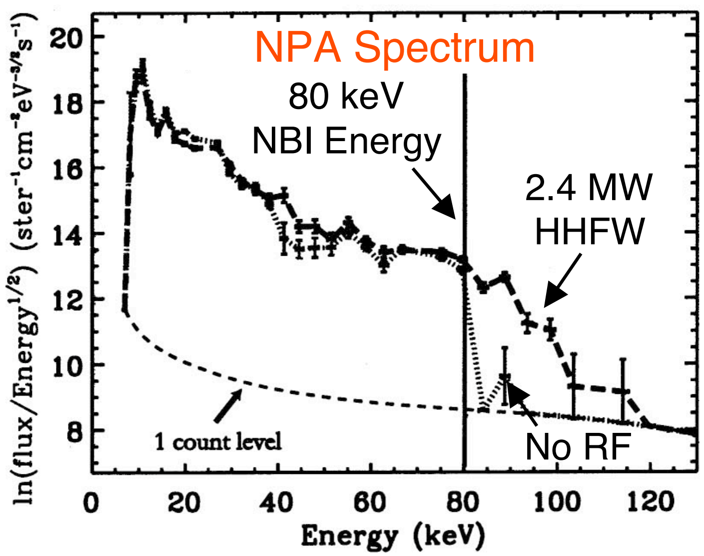
- Measured q(0) drops from 1.0 to 0.6 with $P_{rf}$ ~ 1.2 MW
  - Counter-CD should provide tool to raise q(0) in advanced scenarios, avoiding sawteeth & locked modes
- MSE-LiF will provide q(r) without heating NBI, dramatically enhancing HHFW CD research in 2011

# Edge Loss Mechanisms will be Identified & Included in RF Codes; RF-Fast Ion Interaction will be Modeled

- Search for edge RF power loss due to collisions, sheaths, PDI, antenna reactive field & propagating FW:
  - Using edge reflectometry, edge CHERS, PDI probes, visible & IR cameras, core reflectometry with 30 MHz δn(r) [& δE(r)] capability, and enhanced MPTS [incremental]




- Measure & Model RF-fast ion interaction seen previously on NSTX:
  - Perpendicular & tangential FIDA, NPA
  - HHFW-NBI interaction will be modeled with CQL3D (Bob Harvey - CompX)
  - Simulate counter-CD for advanced scenarios



# HHFW Research Plan for 2009-10

**2009:**

- Understand physics of the edge-wave interactions using upgraded double fed antenna:
  - Employ extended edge measurements & guidance from rf modeling
- Heating & CD studies in $D_2$ H-mode with Li injection
- Coupling/heating into low $I_p$,$T_e$ during $I_p$ ramp-up
- HHFW heating of H if L-H threshold is studied in H & He PAC23-12

**2010:**

- HHFW Heating, CD and $I_p$ ramp-up in $D_2$ H-mode using ELM resilience system [R(10-2) milestone]:
  - Use larger plasma-antenna gap to reduce NBI fast ion interaction with antenna
  - Fast feedback control for greater stability & higher power coupling
  - LLD to likely further reduce antenna neutral pressure

# HHFW Research Plan for 2011-13

**2011:**

- Heating & CD operation with NBI H-mode with fully upgraded HHFW antenna, Li injection & LLD:
  - Benchmark core CD against advanced RF codes upgraded to include interaction with fast ions & use FIDA to diagnose interaction
- HHFW coupling during $I_p$ ramp-up with 28 GHz* ECH-assisted start-up
  - MSE-LiF to provide q(r) without heating NBI

**Research Utilizing New CS and/or $2^{nd}$ NBI (2012-2013):**

- High power long pulse HHFW heating & CD with improved heating at $B_t(0) \sim 1$ T, made possible with new center stack
- HHFW to support very long pulse scenario
- HHFW heating of 28 GHz* ECH-assisted CHI & PF-only startup

* 28 GHz 350 kW ECH only possible with incremental funding

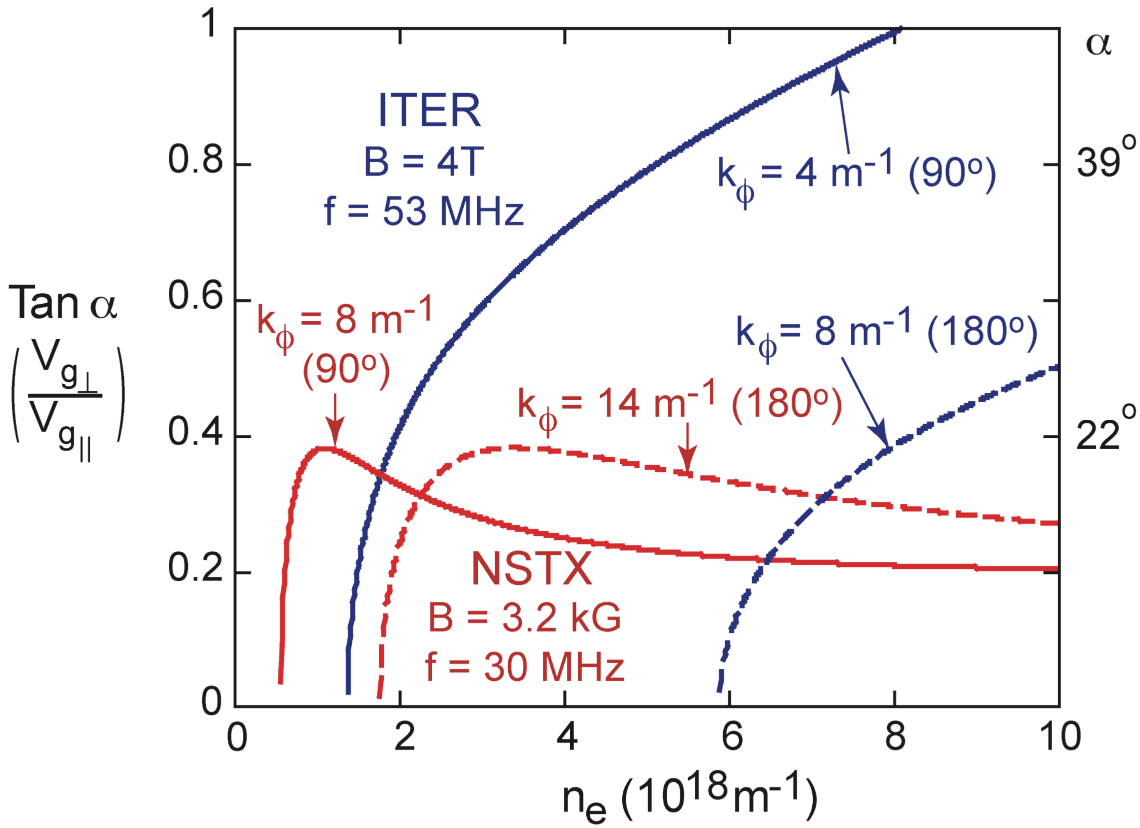
# Understanding Importance of Edge-Wave Interaction has Enabled HHFW to be Powerful Tool

- Heating & CD performance significantly improved by increasing $B_t(0)$ & through edge density pumping via Li conditioning
- 2009 HHFW experiments seek better understanding of edge-wave interaction physics
- Antenna upgrades in 2009-10 provide higher power, reduced fast ion-antenna interaction & better resilience to ELMs
  - HHFW experiments also benefit from combining LLD & Li injection
- HHFW experiments in 2009-11 will study heating & CD in $D_2$ H-mode & heating during $I_p$ ramp-up
- Initial HHFW CD measurements are now consistent with AORSA & TORIC simulations:
  - RF SciDAC initiative important for studying edge loss & providing accurate CD estimates

# Backup Slides

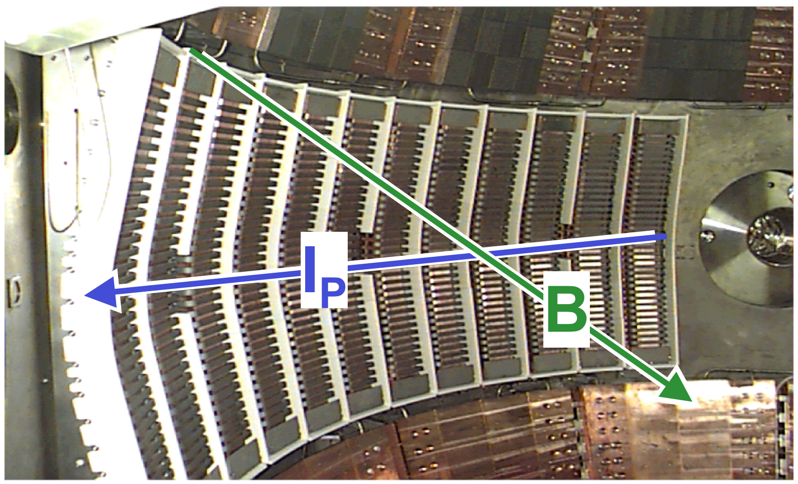
# NSTX Results Indicate Surface Wave Damping Could be Important for ITER ICRF Heating

Angle of wave propagation relative to magnetic field

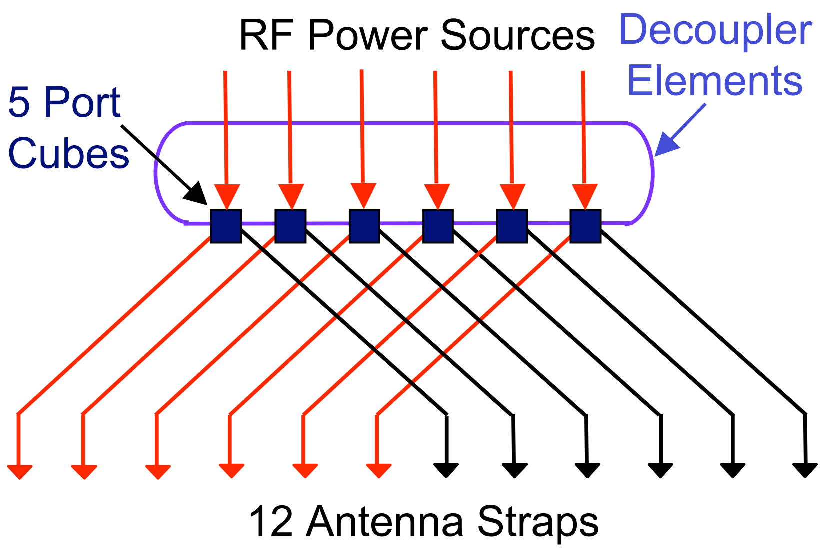


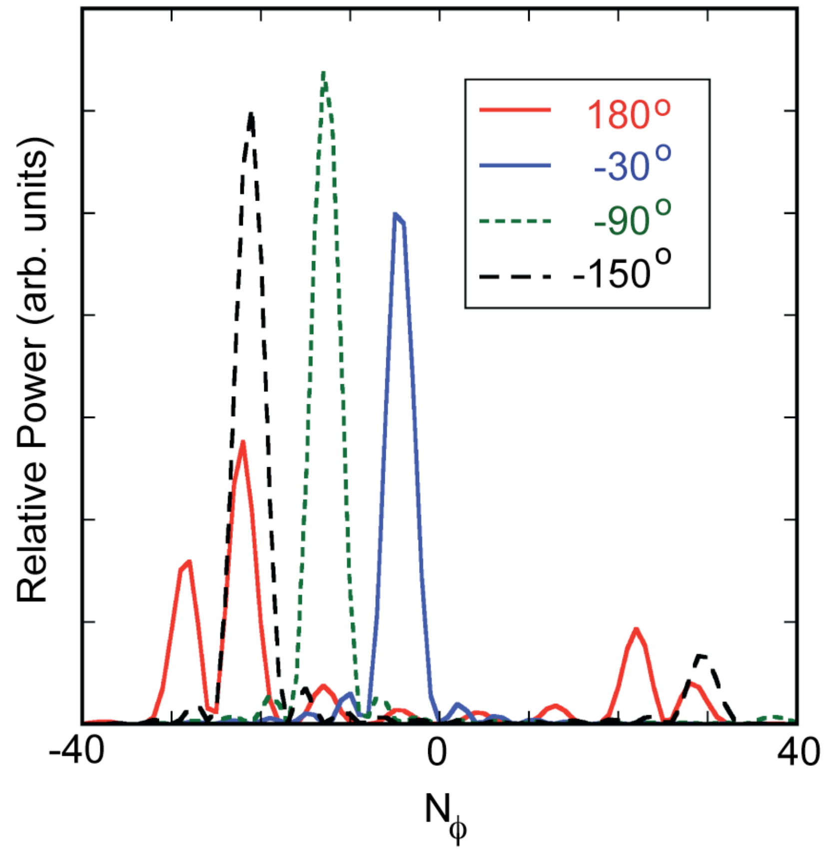

- $k_\phi \sim 4\ m^{-1}$ at 53 MHz for CD phasing in ITER
- Propagation onset density is relatively low: ~ $1.4 \times 10^{18}\ m^{-3}$
- For scrape off density above onset density, surface wave damping should be significant

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




*HHFW antenna extends toroidally 90°*

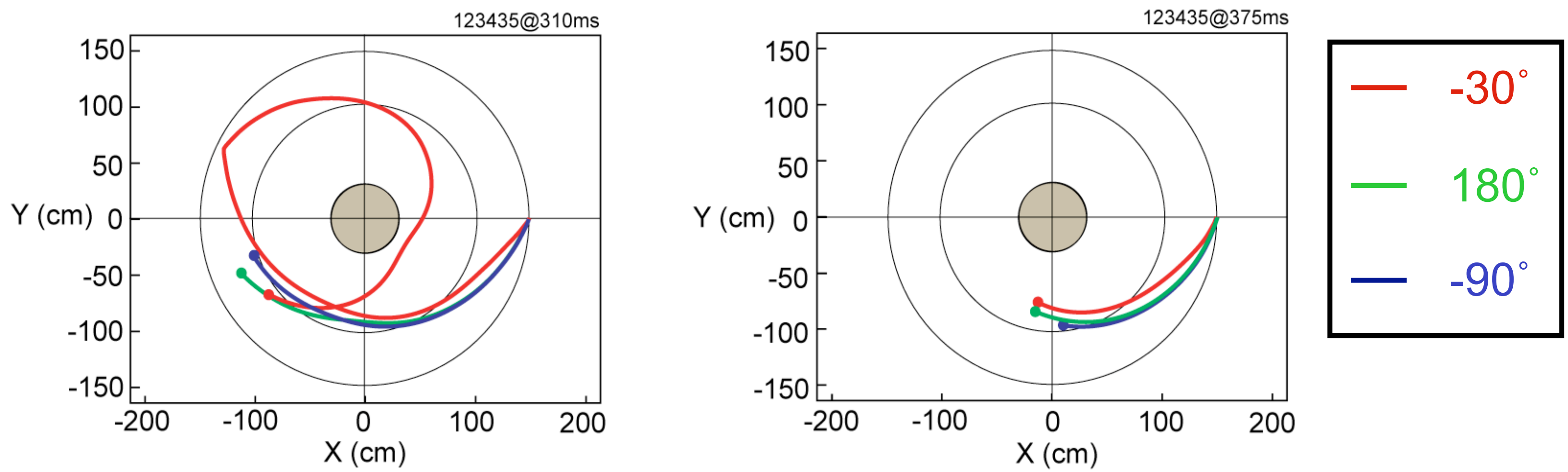


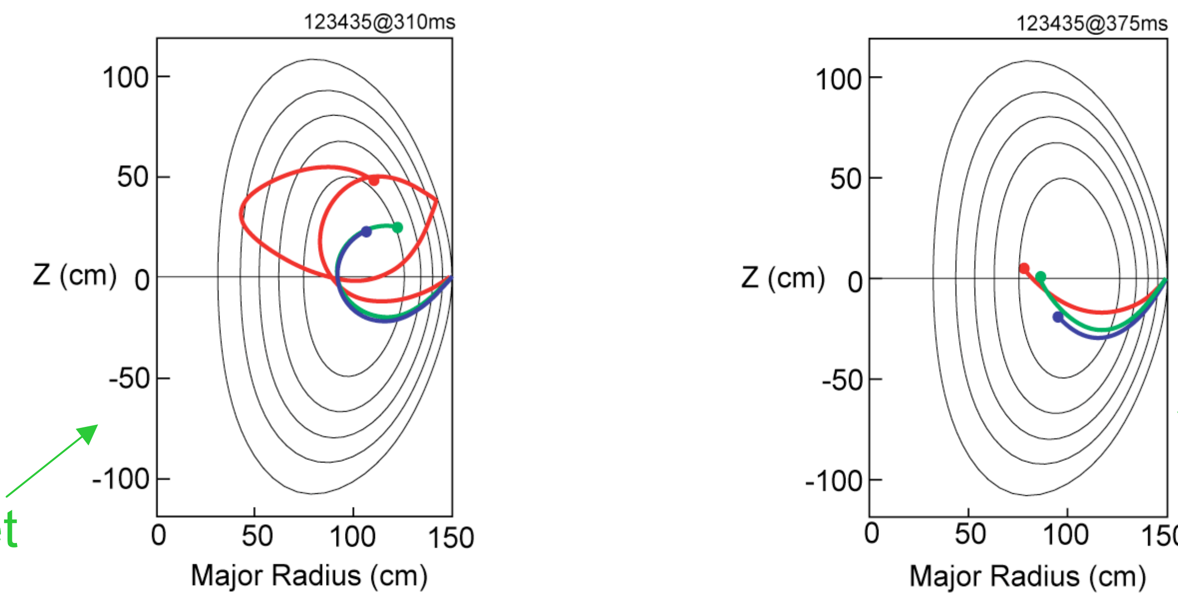

- Phase between adjacent straps easily adjusted between $\Delta\phi = 0°$ to $\Delta\phi = 180°$

# Strong "Single Pass" Absorption Ideal for Studying Competition Between Core & Edge Power Loss

Toroidal views →




Poloidal views →



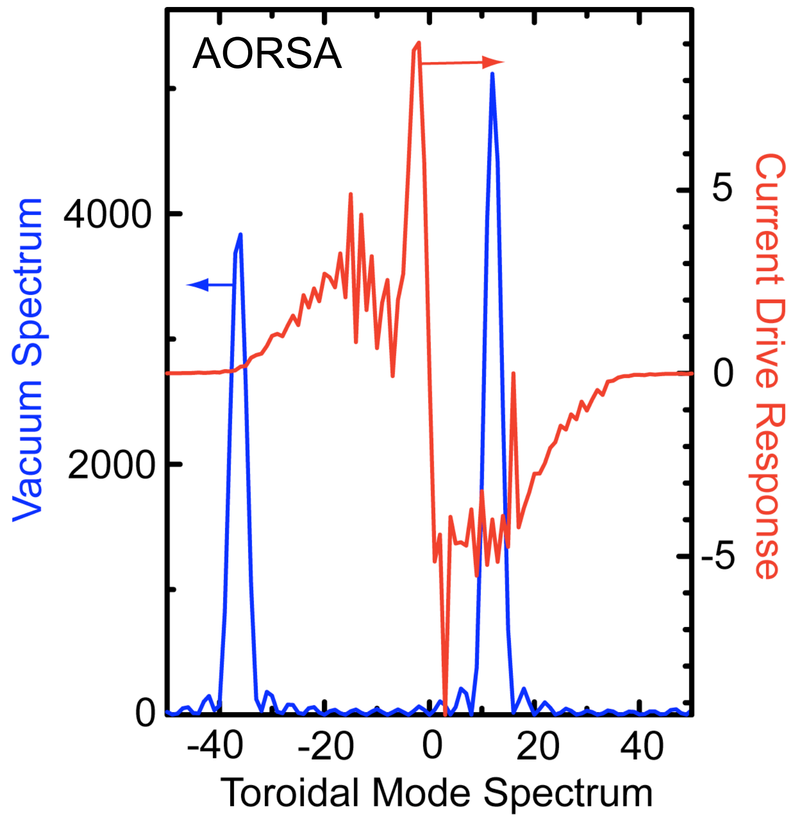

rays stopped when 80% of initial power is damped

OH target

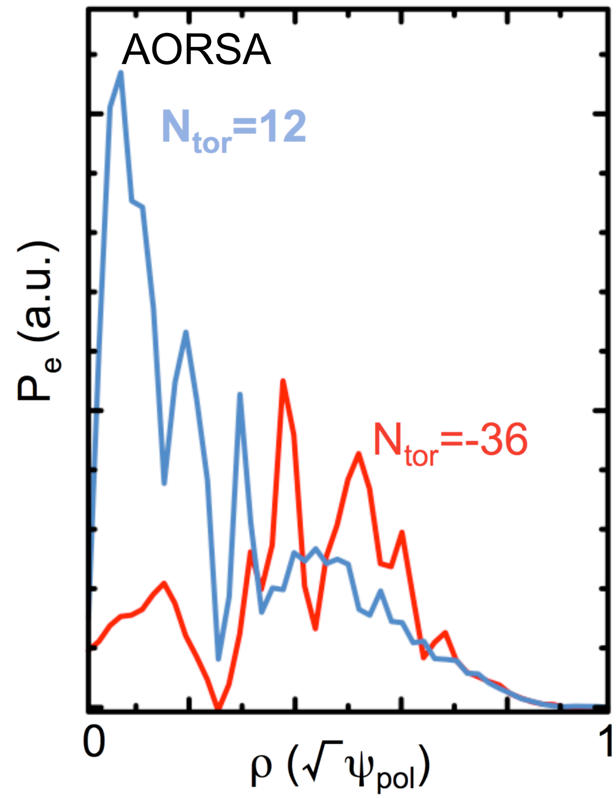
RF heated plasma

# Modeling Must Include Power Spectrum of Launched Waves for Quantitative Agreement with MSE

Driven Current Spectrum




Power Deposition Profile




Ehst-Karney:

$$J_{rf} \propto P_e$$

- Large edge field pitch affects wave spectrum in plasma core
- Current driven by the back propagating lobe is localized well off-axis and lost due to trapping effects

# ECW/EBW Research Plan for 2009-11

**2009-10:**

- Collaborate with MAST 28 GHz ECH/EBWH startup experiments
  - ORNL providing 350 kW gyrotron this year
  - MAST 28 GHz system uses grooved center stack tile to change polarization from O- to X-mode which then 100% coverts EBW near axis

**2011:**

- 350 kW 28 GHz ECH-assisted* CHI, PF ramp and plasma gun start-up with fixed horn antenna
  - Transition from ECH-assisted startup to HHFW current ramp-up
  - Study whether Li evaporation & LLD can improve EBW coupling with fixed horn antenna during current ramp-up

* 28 GHz 350 kW ECH only possible with incremental funding