NSTX-U

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HHFW & EBW Progress and Plans

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NSTX-U PAC-31
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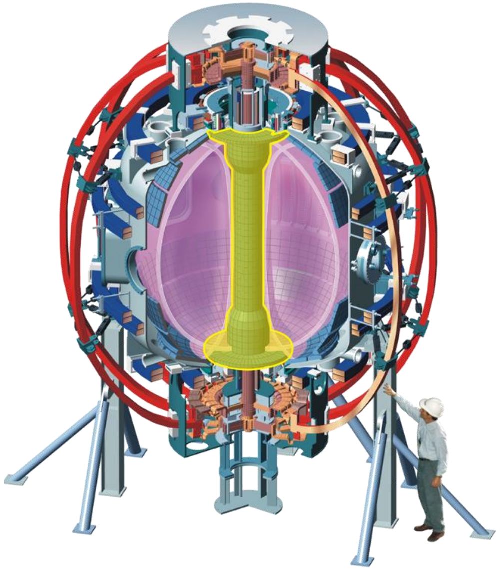

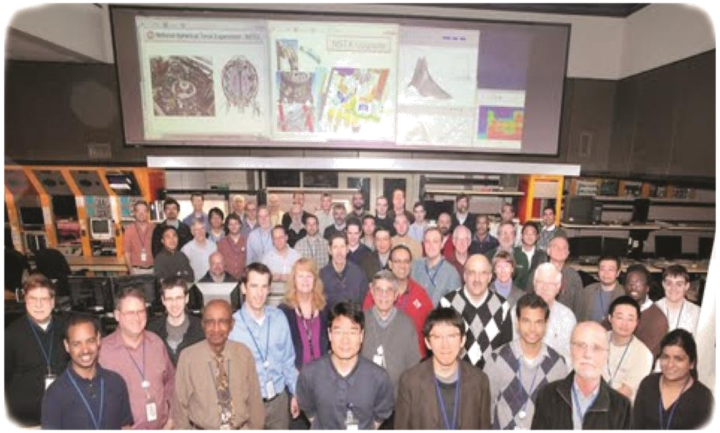

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Long-term, FY2014-18, research goal is to use RF heating to enable fully non-inductive RF+NBI H-mode plasmas

NSTX-U HHFW/EBW research goals:

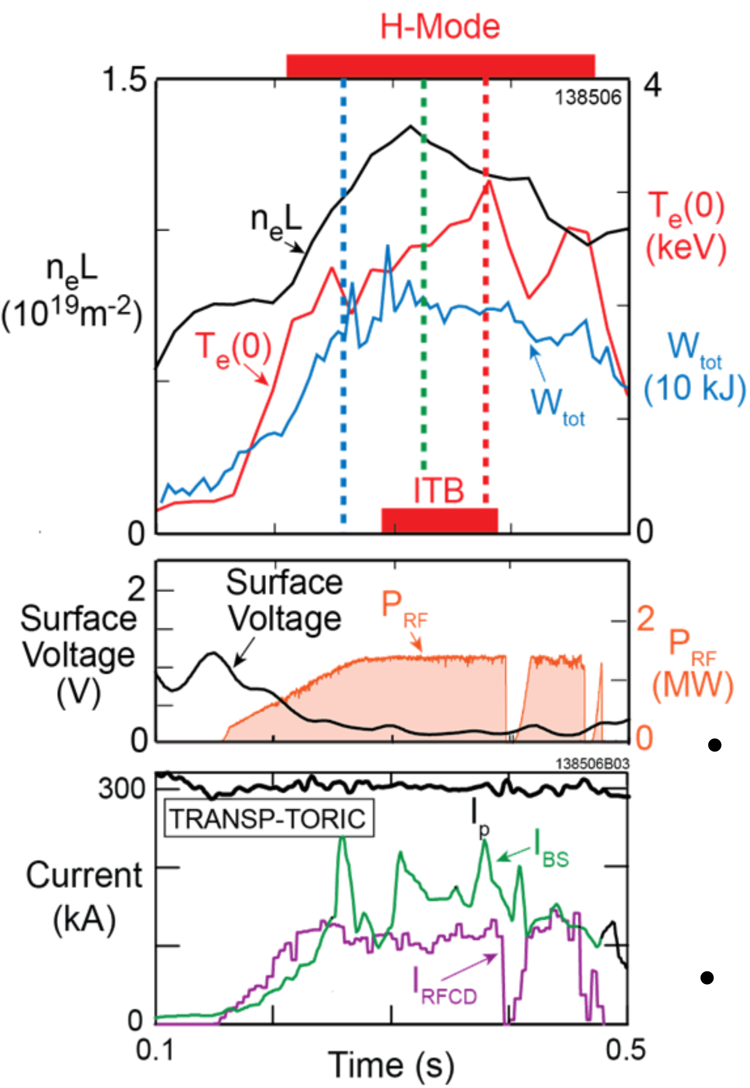
- Mitigate HHFW power losses in scrape off layer (SOL) of H-mode plasmas
- Optimize HHFW current drive in HHFW and HHFW+NBI H-mode plasmas
- Assess HHFW interaction with neutral beam fast-ions, and develop capability to heat NBI H-modes, that have up to 12 MW of NBI, with HHFW
- Develop HHFW and ECH/EBWH for fully non-inductive plasma start-up and H-mode sustainment

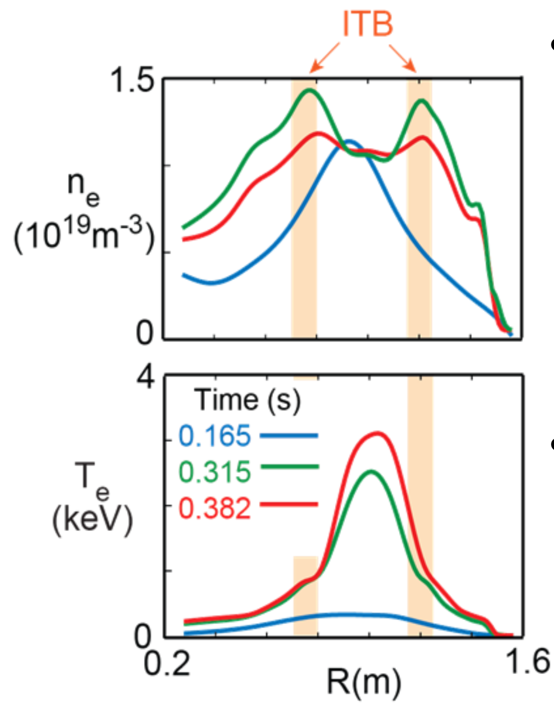
Near-term research milestones: (with SFSU & ASC TSGs)

R(12-3): Simulate confinement, heating, and ramp-up of CHI start-up plasmas

R(13-3): Perform physics design of ECH/EBWH system for plasma start-up and current drive in advanced scenarios

> 70% non-inductive I_p = 300 kA HHFW H-mode generated with only P_{RF} = 1.4 MW; proposed FW H-mode expts. in EAST



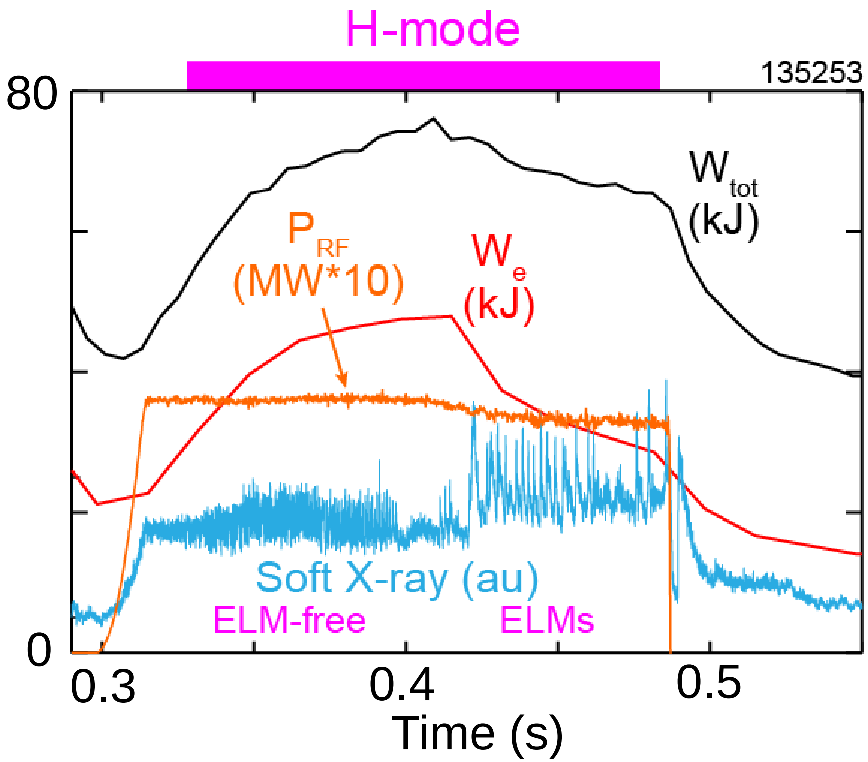


- Combination of internal transport barrier and higher $T_e(0)$ significantly increased bootstrap current and HHFW current drive
- Do not know if density pump-out during ITB is carbon - no carbon profile data **_PAC29-29_**

- Continuing these experiments at higher HHFW power, and with optimized coupling, in NSTX-U will have a high priority **_PAC29-35_**

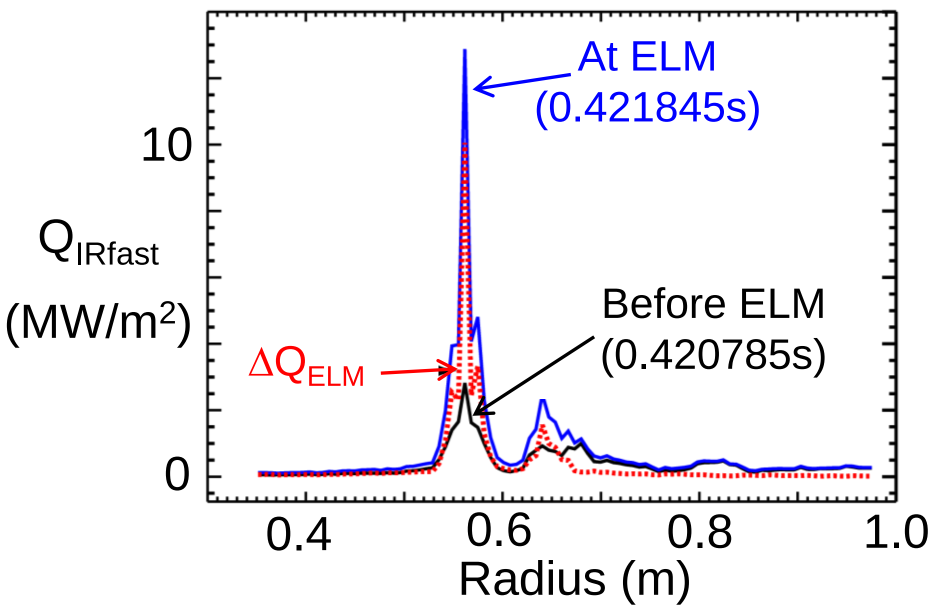
- PPPL has proposed I_p = 400-800 kA, fast-wave H-mode experiments using $P_{RF} \geq 3$ MW during the 2012 EAST campaign

Large ELMs reduce stored energy in HHFW-heated H-modes; divertor heat flux strongly peaked near outer strike point



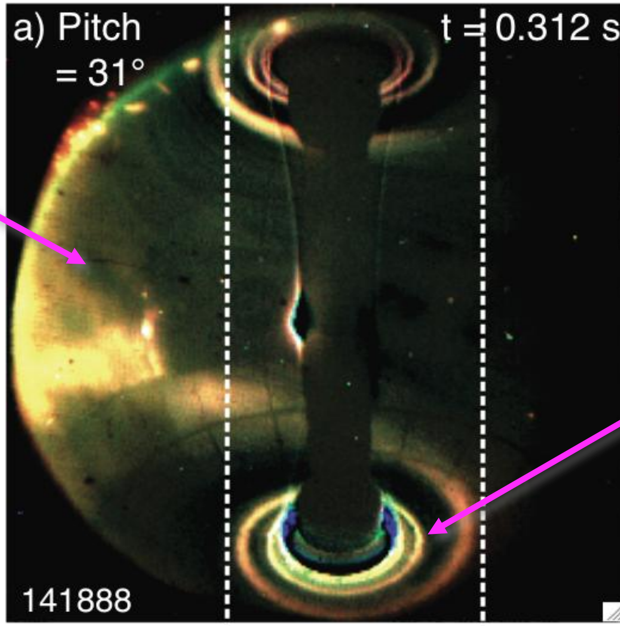
- I_p = 650 kA, $B_T(0)$ = 0.55 T H-mode generated by P_{RF} ~ 3.7 MW exhibits "ELM-free-like" phase with increasing W_e and W_{tot}:
  - Sustained $T_e(0)$ = 5 - 6 keV
- Substantial decrease in W_e and W_{tot} at onset of large ELMs

Fast IR Measurements of Lower Divertor Tiles

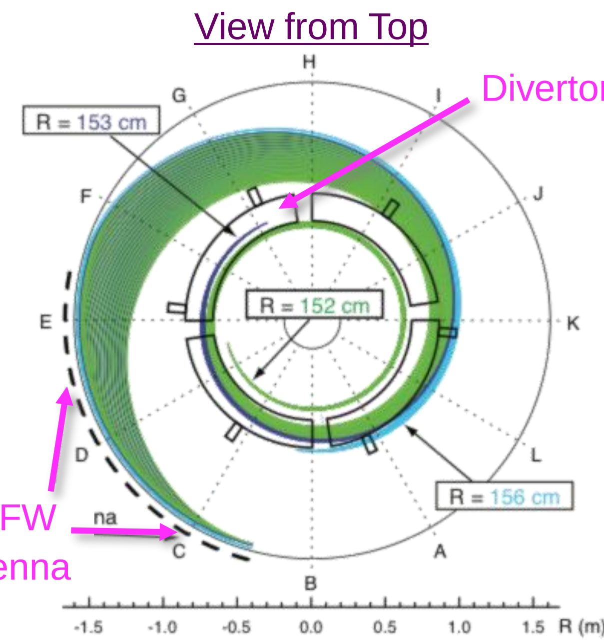


- Divertor heat flux, measured by fast IR camera, strongly peaked (~10 MW/m^2) at outer strike point during large ELM
- HHFW H-modes at higher I_p and B_T will be studied in NSTX-U

Significant fraction of the HHFW power may be lost in the SOL in front of antenna and flow to the divertor region



Plasma TV image shows edge RF power deposition spiral flowing from HHFW antenna to the divertor region for edge field pitch = 31°

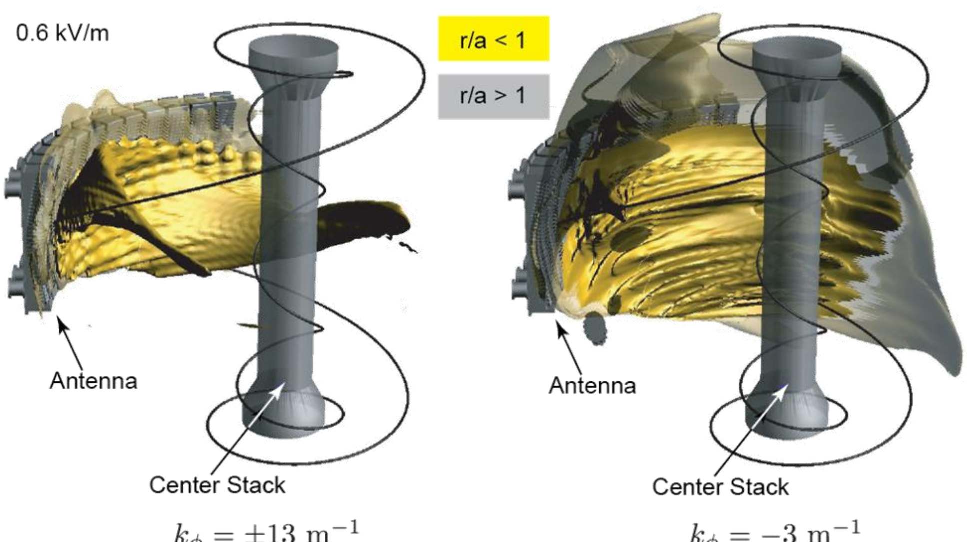


SPIRAL code results for edge field pitch = 31° show field lines (green) spiraling from the SOL in front of HHFW antenna to the lower divertor

- Field line mapping predicts RF power deposited in SOL, not antenna face
  - 3D AORSA will assess surface wave excitation in NSTX-U (next slide) **PAC29-30**
- Proposed DIII-D experiment to look for RF edge losses during 2012 run
- NSTX-U experiments and modeling will emphasize HHFW heating of high NBI power, long-pulse H-modes – assess effect of varying outer gap **PAC29-38**

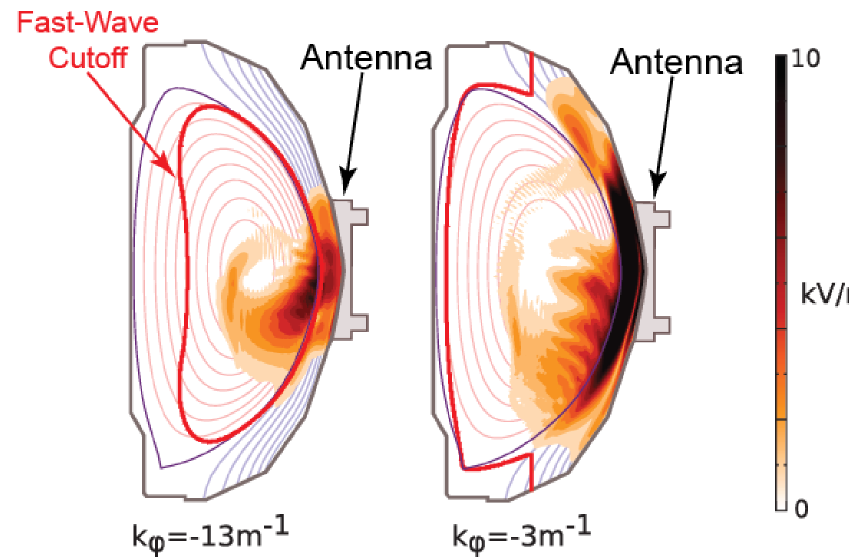
AORSA full-wave modeling predicts excitation of large amplitude coaxial standing modes between plasma and wall

- Coaxial modes not seen in linear plasma wave dispersion or ray tracing approaches
- Has implications for ITER ICRH, where the distance between the antenna/wall and the separatrix is large (0.1-0.2 m)



3-D AORSA simulation for HHFW on NSTX shot 130608*

*D. L. Green, *et al.*, Phys. Rev. Lett. 107, 145001 (2011)

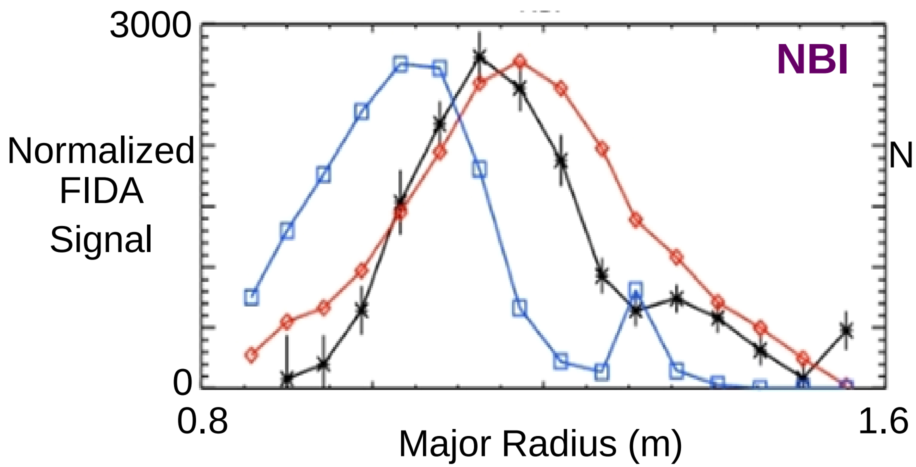


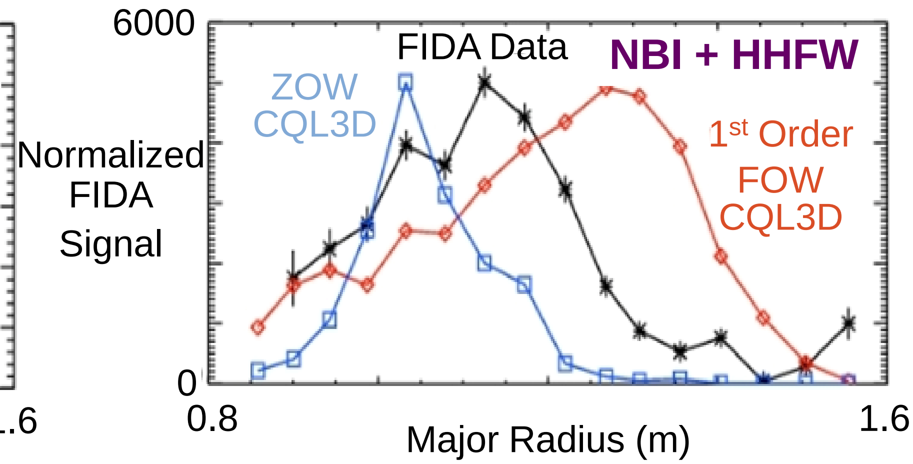
2-D AORSA simulation for HHFW on NSTX H-mode shot 130608*

- Future plans call for a quantitative comparison of predicted SOL electric fields with measurements:
  - Requires better resolution in the SOL & including geometry of the antenna & Faraday shield

PAC29-30

Full-orbit, finite-orbit-width (FOW) CQL3D will accurately model neoclassical transport, ion loss & heat flowing to SOL

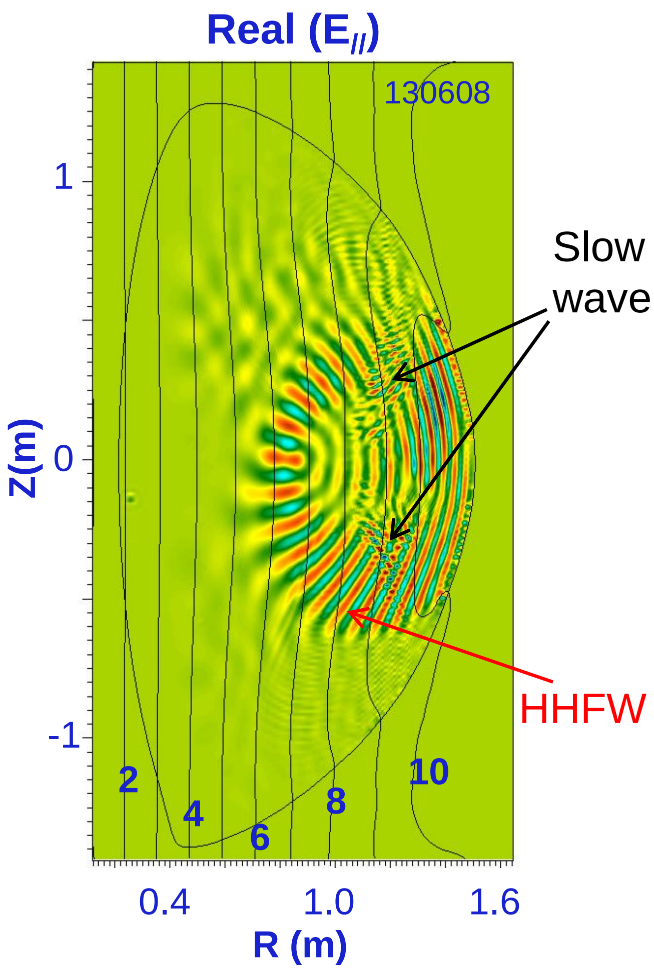




- First-order FOW CQL3D Fokker-Planck code implemented last year:
  - Good agreement with FIDA for NBI; over estimates radial shift for NBI + HHFW
- Recent results from full-orbit FOW CQL3D show reduced orbit shift:
  - Big differences between predicted HHFW power absorbed by ions and electrons for ZOW (no losses), ZOW (1st order banana loss), and full-orbit FOW CQL3D
- Full-orbit neoclassical transport, an interface to the FIDA fast-ion diagnostic, and modeling of losses to SOL and wall are now being implemented
- Initial tests of full-orbit FOW CQL3D show accurate modeling of fast-ion losses and broader profiles of power absorption and RF-driven current

CompX SM

A new short wavelength mode is seen in AORSA and TORIC high resolution simulations of NSTX HHFW experiments



AORSA with 256 X 256 elements

- Requires B_p upshift of $k_{//}$ and finite T_e
- Related to warm electrostatic ICW first observed by Motley and D'Angelo in a Q-machine (1961)
- Independent of T_i → not an IBW
- Electron damping, kinetic flux and finite $E_{//}$ associated with mode
- Fine grid spacing needed to resolve mode
- Also found in high resolution modeling results for C-Mod ICRF discharges

→ May provide another path for power absorption in ST's and tokamaks

ICRH collaboration activities on EAST & DIII-D in FY2012-13 support NSTX-U HHFW research in FY2014-15

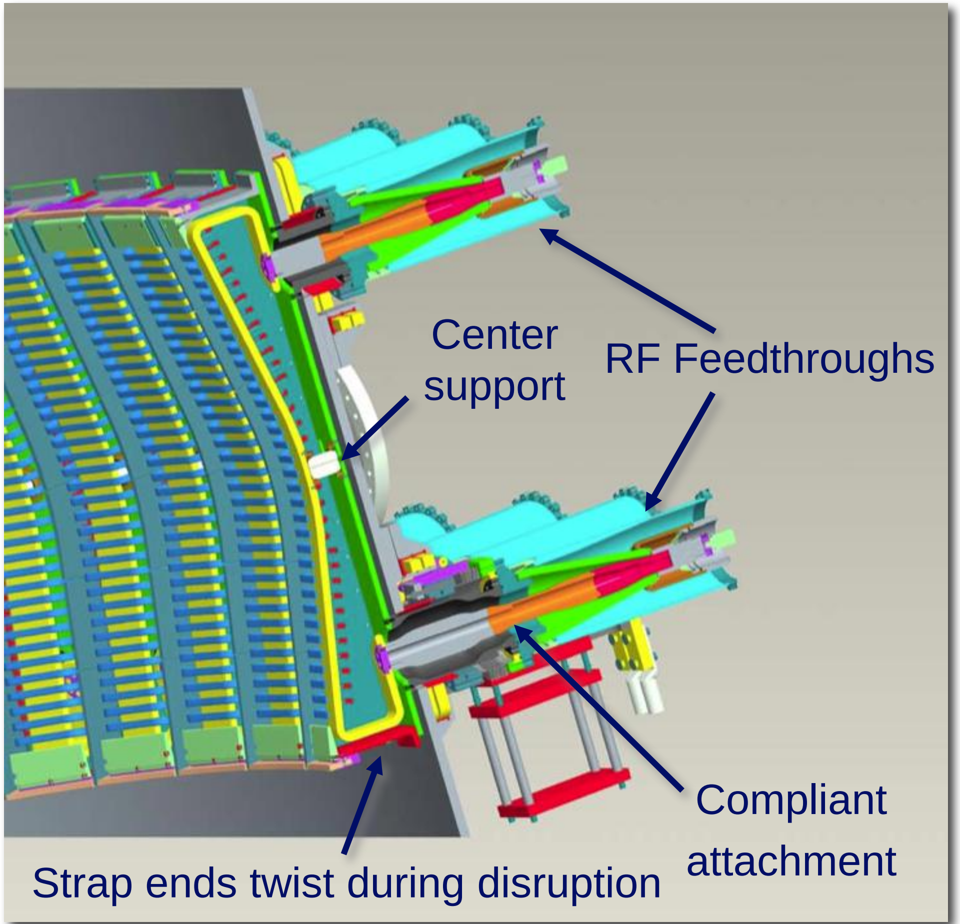
- Conduct ICRH-generated H-mode experiments in EAST:
  - EAST and NSTX-U are the only machines that currently offer an opportunity to use both ICRH and lithium conditioning
  - ICRH-generated H-mode proposal has been submitted to EAST for this years run campaign
  - PPPL physicists are visiting EAST this year to support ICRH experiments
- ICRH+NBI H-mode experiments proposed in DIII-D:
  - Experiments proposed for 2012 run campaign
  - PPPL has also proposed introducing lithium conditioning in DIII-D, which may help improve ICRH coupling
  - Study SOL RF power loss mechanisms during ICRH+NBI H-modes
  - Assess and optimize ICRH coupling efficiency in H-modes
  - ICRH+ECH & ICRH H-mode experiments have also been proposed for DIII-D

MAST EBW start-up collaboration & HHFW/EBW modeling in FY2012-13 support NSTX-U in FY2014-15 & beyond

PAC29-30

- HHFW modeling for NSTX-U:
  - Using advanced RF codes (ORBIT-RF/AORSA, sMC/AORSA, new full-orbit FOW CQL3D) to model the fast-wave interaction with fast-ions in NSTX-U H-mode scenarios
  - Include NSTX-U realistic SOL model to assess, and enable mitigation of, edge RF power losses (eg. surface wave propagation)
- Collaborate with MAST on EBW plasma start-up experiments:
  - 28 GHz EBW start-up experiments in 2009 exhibited good electron heating
  - Experiments at higher RF power are planned for this summer; PPPL physicist will visit MAST to collaborate during these experiments
  - MAST experiments provide important input to the NSTX-U EBW plasma start-up and plasma current ramp-up design & planning activities
- Model & design 28 GHz ECH/EBWH system for NSTX-U:
  - GENRAY and CQL3D will model plasma start-up using a 0.5-1 MW, 10-50 ms ECH/EBWH system, and off-axis heating and current drive scenarios using a 1-2 MW, 500 ms EBWH/EBWCD system

HHFW system and diagnostic improvements in FY2012-13 needed to support NSTX-U research in FY2014-15 & beyond



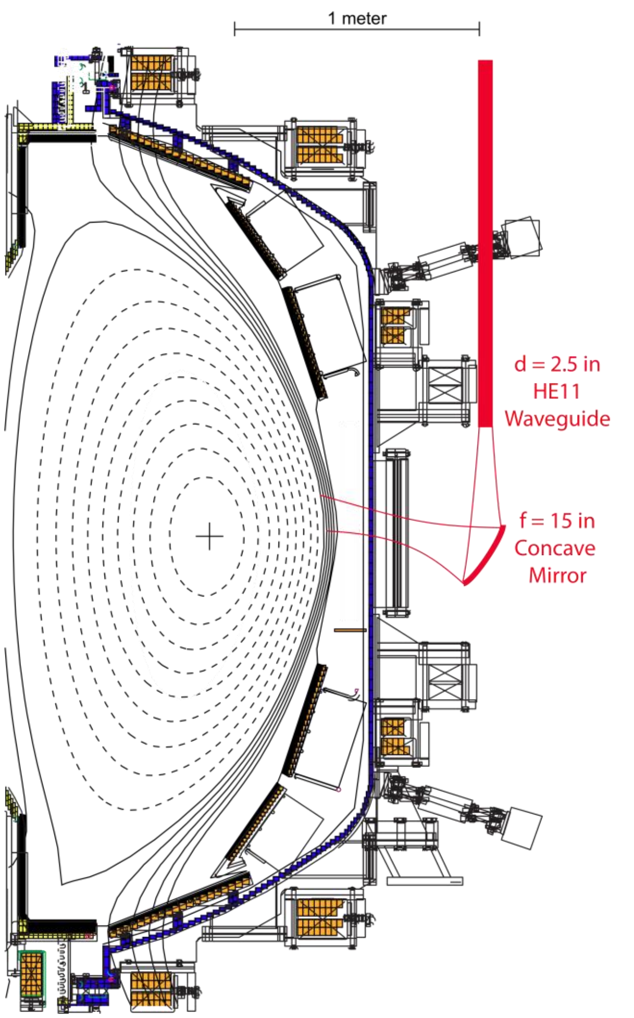
- Require compliant attachments between antenna current straps and RF feedthroughs:
  - In NSTX-U: 2 x B_T, 2 x I_P ⇒ 4 x disruption load on straps
  - Considering compliant bellows as first concept
- Need to improve voltage standoff to support 5 MW operation with 8 straps in FY 2016-18:
  - Test two elements on test stand
  - Optimize voltage standoff in vacuum with aid of antenna modeling
- Antenna boron nitride limiter needs to be made more robust for P_{NBI} =12 MW
- Additional RF probes in protective tiles above and below antenna needed to document RF power flow to divertor for comparison to advanced RF codes

Plans for FY2014-15 HHFW research in NSTX-U

- Assess performance of 12-strap, two-feed antenna for full power HHFW heating & demonstrate compatibility with NBI: **PAC29-3** **PAC29-27**
  - Use boronization & minimum lithium conditioning needed to control edge density, and reduce surface wave excitation and other edge power losses **PAC29-28**
  - Will be conducted before significant lithium conditioning starts
  - Compare coupling and heating efficiency to single-feed operation in 2008
  - Assess HHFW performance coupling to high-NBI power H-modes at higher magnetic field and higher plasma density **PAC29-38**
- Heat I_p ~ 300 kA plasma with HHFW power to achieve sustained 100% non-inductive H-mode, and non-inductively ramp I_p with HHFW power:
  - NBI blips for MSE q profile measurements and C density pump out **PAC29-35**
  - Also use MSE-LIF to measure q profile without heating NBI blips **PAC29-29**
- Heat CHI start-up plasma coupled to induction
- Design edge harmonic oscillation (EHO) antenna using HHFW straps, or some other location

Solenoid-free start-up in FY2016 supported by implementing a short-pulse 28 GHz ECH system – later upgrade to EBWH

- Initially provide 10-50 ms, 0.5-1 MW ECH pulses for start-up:
  - Earlier analysis, for NSTX, T_e~25 eV, CHI start-up plasma, predicted 25-30% absorption for 28 GHz second harmonic X-mode
- Possibly upgrade ECH system in FY2017-18 to O-X-B oblique launch EBWH system with 500 ms,1-2 MW pulses
- Will use low-loss HE11, 2.5 inch diameter circular, corrugated waveguide
- Employ metal steerable mirror, designed for 1 s, 2 MW 28 GHz pulses, located near midplane, outside the vacuum vessel
- Gyrotrons and associated equipment located in former TFTR test cell, next to NSTX-U



Conceptual implementation of 28 GHz ECH/EBWH system waveguide and mirror

Research goals for FY2016

- Test short-pulse, high-power ECH system for plasma start-up support and assess impact on the closed-flux current achieved, pulse-length extension, and the non-inductive fraction

- Utilize HHFW to assist start-up plasma formation and compare to short-pulse ECH

- Assess impact of HHFW electron heating on NBI current ramp-up

- Simulate/mock-up HHFW antenna performance using reduced number of straps

- Implement EHO antenna compatible with HHFW antenna requirements (eg. the number of antenna straps)

Research goals for FY2017-18

- Modify HHFW antenna system to have reduced number of straps
- Test reduced-strap HHFW system and optimize plasma start-up, ramp-up, and sustainment during NBI H-mode
- Test EHO antenna for impact on density/particle control
- Test upgraded 28GHz system for EBW heating and current drive studies (1-2 MW, 500 ms)
- Pending successful EBW heating results in FY2018, begin further upgrade of 28GHz system power and pulse-length for further EBW heating and current drive studies (2-4MW, 1-5s),
- Project EBW CD performance to a FNSF/CTF

Summary

- FY2012 & FY2013 research milestones call for simulating heating and ramp-up of CHI start-up & performing ECH/EBWH system physics design
- Advanced RF codes will help to develop strategies that mitigate RF SOL losses and minimize fast-ion acceleration in HHFW+NBI H-modes
- Collaboration activities on DIII-D, EAST & MAST in FY2012-13 will guide development of NSTX-U HHFW & EBW research plans for FY2014-18
- In FY2014-15, focus on assessing double-fed HHFW antenna performance during non-inductive ramp-up and heating of long-pulse NBI-generated H-modes
- High power, short-pulse ECH start-up system is being planned for FY2016, may upgrade to higher power, longer-pulse EBWH system in FY2017-18

Backup Slides

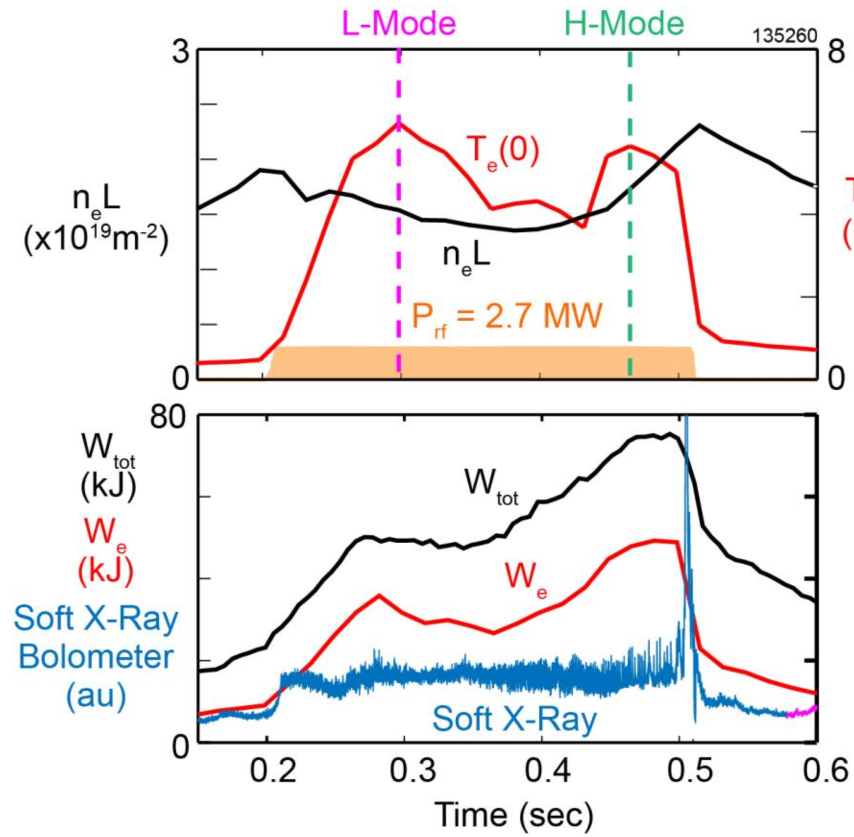
Responses to PAC Recommendations - I

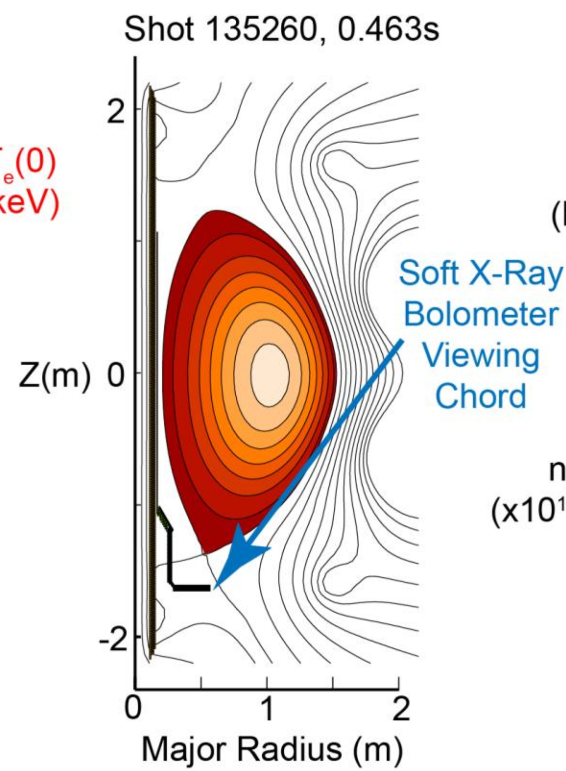
	Recommendation	Response
PAC29-3	Demonstrate two-feed antenna, full- power HHFW heating and compatibility of HHFW with NBI before lithium conditioning.	Some lithium will probably be needed to reduce edge density and edge losses, however we plan to perform the first HHFW experiments after boronization and before significant lithium is introduced.
PAC29-27	Perform baseline antenna operation with boronization and before the start of the lithium campaign to allow a more direct comparison to single-feed antenna performance.	See response to PAC29-3. We will compare to single-feed antenna performance in 2008.
PAC29-28	Perform HHFW+NBI H-modes at higher plasma current to establish their feasibility and assess the level of parasitic losses.	In 2012 and 2013 we will be performing HHFW modeling for various NSTX-U scenarios with AORSA-3D, AORSA/ORBIT-RF and CQL3D to assess edge losses and fast-ion interaction.
PAC29-29	Observed density pump-out in H-mode plasmas should be pursued to determine if this is a carbon pump-out effect.	Believe the PAC is referring to the pump-out observed during the HHFW H-mode shot 138506. No NBI was used during this shot so no carbon profiles were measured. We will be using NBI blips in future HHFW H-mode experiments that will allow carbon profile measurements.

Responses to PAC Recommendations - II

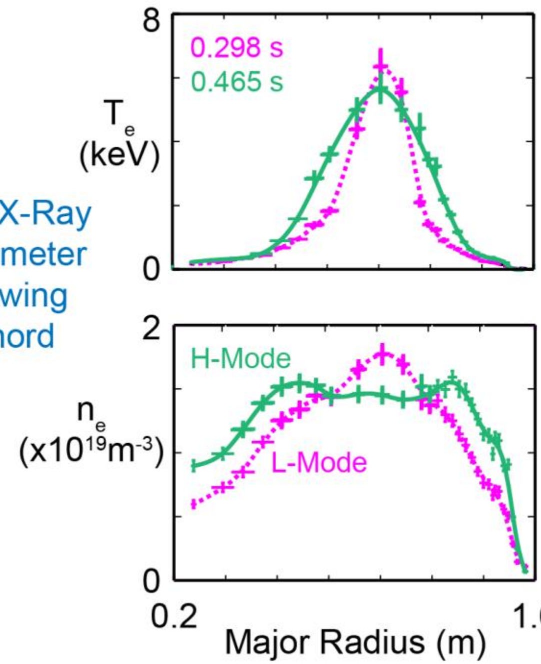
	Recommendation	Response
PAC29-30	Model HHFW fast-ion interactions for NSTX-U HHFW+NBI plasmas using AORSA/ORBIT-RF simulations capability to assess HHFW-NBI interaction at lower harmonic and 3-D AORSA simulations to assess surface wave excitation.	See response to PAC29-28.
PAC29-35	Maintain focus on non-inductive sustainment in steady current conditions to optimize HHFW, emphasizing the importance of HHFW experiments early in the campaign, before large amounts of lithium.	Modeling indicates that we already achieved > 70% non-inductive HHFW H-modes at I_p = 300 kA with only 1.4 MW of RF power. We plan to continue these experiments at higher RF power early in the first NSTX-U run campaign.
PAC29-38	Increased emphasis should be placed on determining the compatibility of HHFW (in particular plasma-antenna gap) and long-pulse, high power NBI.	We plan to model the effect of changing the outer gap and edge density profile and the interaction of HHFW with fast-ions for long-pulse high NBI HHFW-heated NBI H-modes in 2012 and 2013. Heating high-NBI power, long-pulse H-modes will be given a high priority when NSTX-U operation begins.

Improved antenna conditioning produced "ELM-free-like" HHFW H-modes at I_p = 650 kA with $P_{RF} \geq 2.5$ MW





He, k_ϕ = - 8 m^{-1}

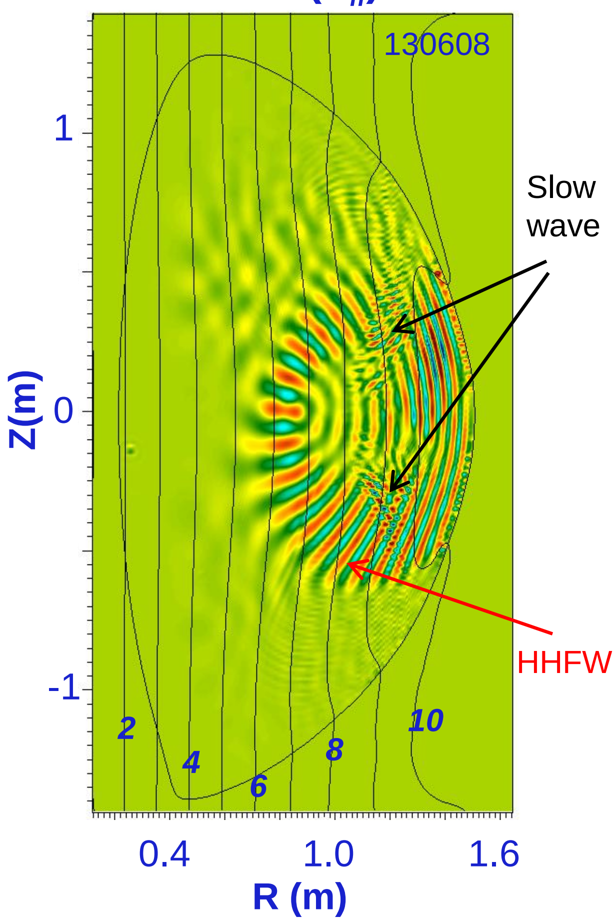


I_p = 650 kA,

$B_T(0)$ = 0.55 T

- Substantial increase in stored energy during H-mode
- Sustained $T_e(0)$ = 5 - 6 keV
- HHFW H-modes at higher I_p and B_T will be studied in NSTX-U

A new short wavelength mode is seen in AORSA and TORIC high resolution simulations of NSTX HHFW experiments



AORSA with 256 X 256 elements

Simple dispersion relation predicts that a slow wave can propagate when $\omega^2 < k_{//}^2 v_{te}^2$

$$n_\perp^2 = -\frac{K_{zz,e}}{S}(n_{//}^2 - S) \rightarrow -\frac{2\omega_{pe}^2}{k_{//}^2 v_{te}^2 |S|}(n_{//}^2 - S),\ (S<0)$$

- requires B_p upshift of $k_{//}$ and finite T_e
- related to warm electrostatic ICW first observed by Motley and D'Angelo in a Q-machine (1961)

•is independent of T_i (not an IBW)

•electron damping, kinetic flux and finite $E_{//}$ associated with mode

•fine grid spacing required to resolve mode

•also found in C-Mod ICRF discharges

•code convergence problems at even higher resolutions are under investigation

→ May provide another path for power absorption in ST's and tokamaks