NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

HHFW & EBW Progress and Plans

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and the NSTX Research Team

NSTX-U PAC-31
PPPL B318
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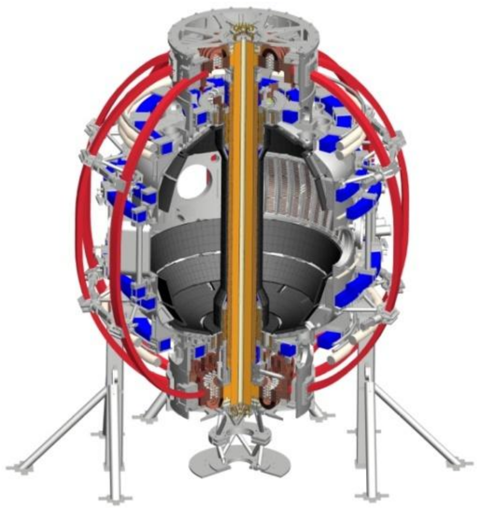

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Outline

- Research goals & milestones for the outage period
- FY2011-12 research highlights
- Activities during the outage that support NSTX-U
- HHFW coupling & compatibility with NBI in NSTX-U
- Research plans for first 5 years of NSTX-U

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

NSTX-U HHFW/EBW research goals:

- Develop HHFW heating and ECH/EBWH for fully non-inductive plasma start-up and H-mode sustainment
- Optimize HHFW current drive in HHFW and HHFW+NBI H-mode plasmas

Research needed to enable these goals:

- Mitigate HHFW power losses in scrape off layer (SOL) of H-mode plasmas
- Assess HHFW interaction with neutral beam fast-ions, and develop capability to heat NBI H-modes with HHFW
- Model ECH/EBWH for NSTX-U plasma scenarios

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

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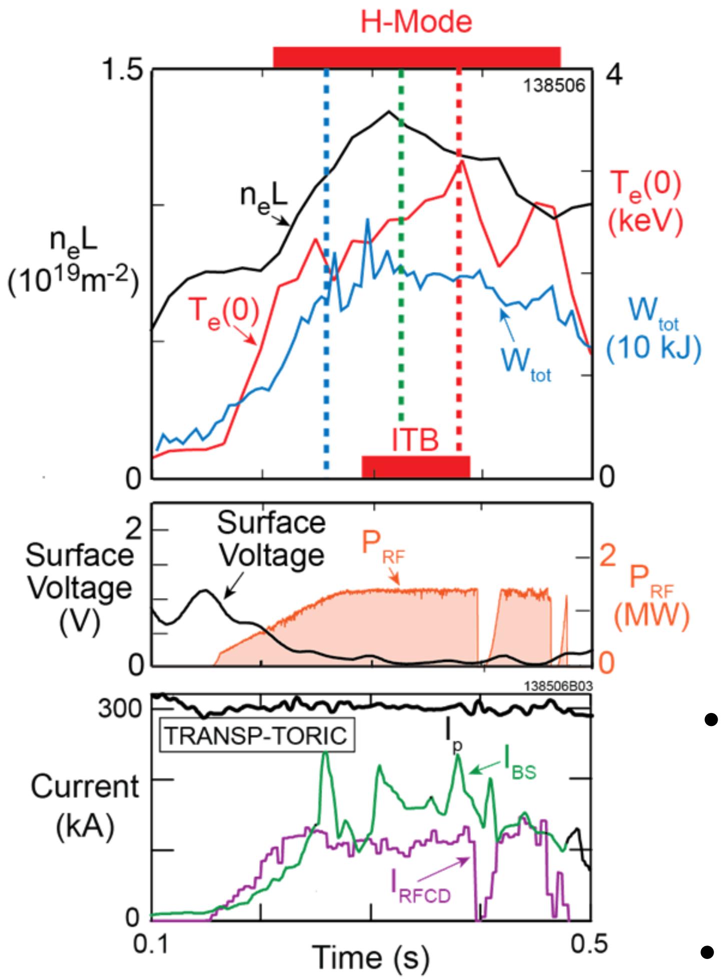
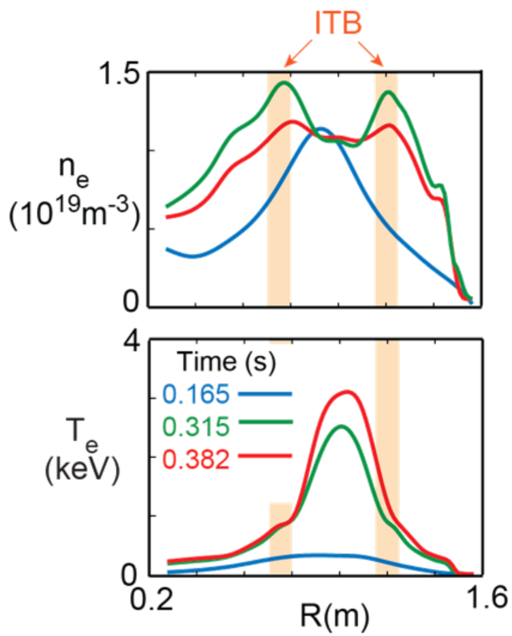
70-100% non-inductive I_p = 300 kA HHFW H-mode generated with only P_{RF} = 1.4 MW; proposed FW H-mode expts. in EAST





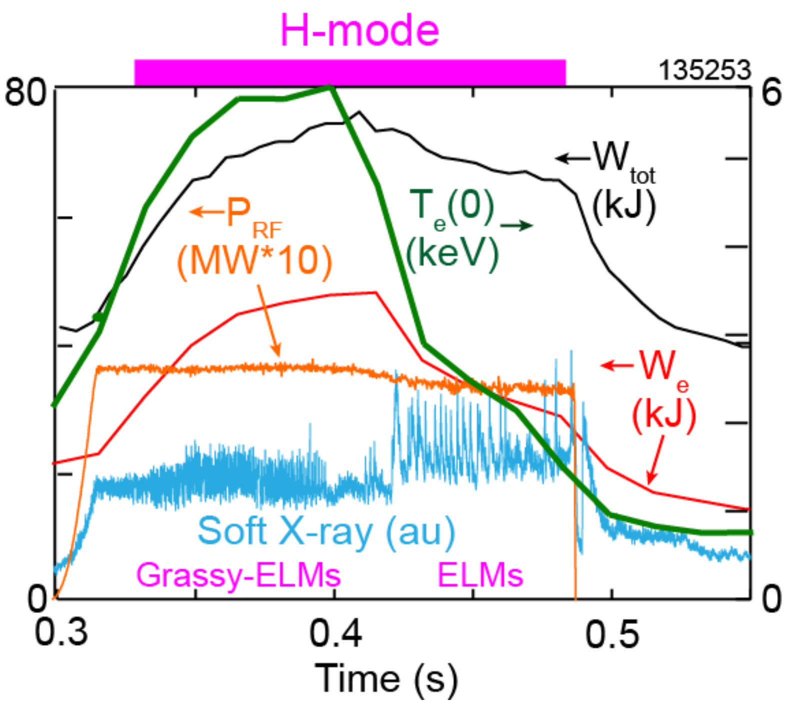
- ITB & higher $T_e(0)$ increased bootstrap current:
  - 25% of non-inductive current from direct RF current drive
- Do not know if density pump-out during ITB is carbon → no carbon profile data **PAC29-29**

- Continuing these experiments in NSTX-U at higher RF power, with optimized coupling, will have high priority **PAC29-35**

- PPPL has proposed I_p = 400-800 kA, fast-wave generated H-mode experiment using P_{RF} ≥ 3 MW during the 2012 EAST campaign

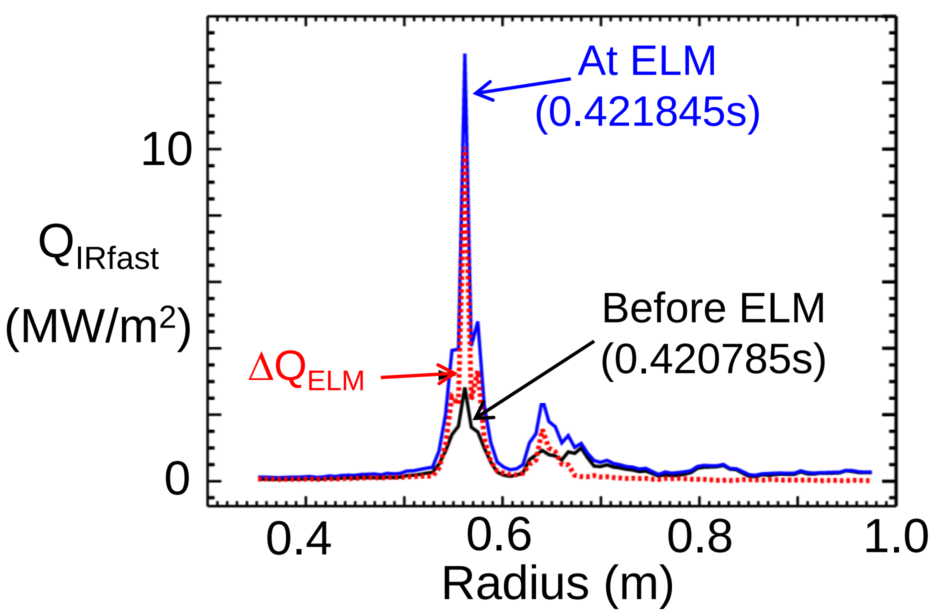
G. Taylor, *et al.*, Phys. Plasmas **19**, 042501 (2012)

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 larger ELMs

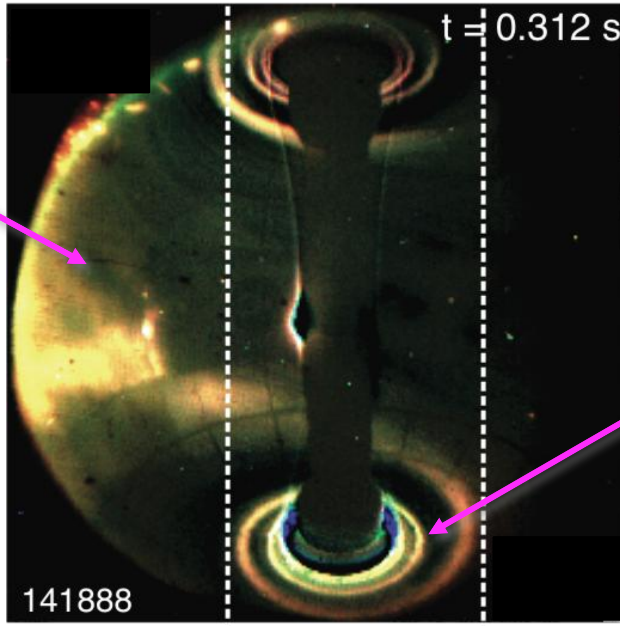
Fast IR Measurements of Lower Divertor Tiles



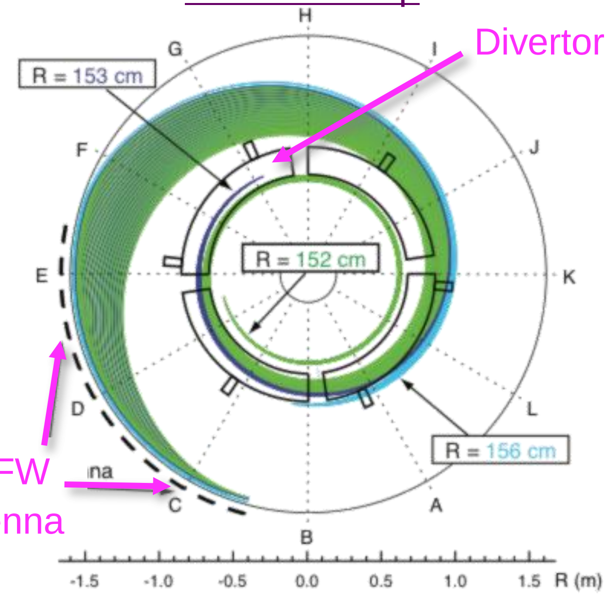
- Divertor heat flux, measured by fast IR camera, strongly peaked (~10 MW/m^2) at outer strike point during large ELM
- HHFW H-modes at higher I_p and B_T will be studied in NSTX-U

J. C. Hosea, *et al*., 38th EPS Conf. (2011) Paper P2.098

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



Visible camera image shows edge RF power flow follows magnetic field from antenna to divertor



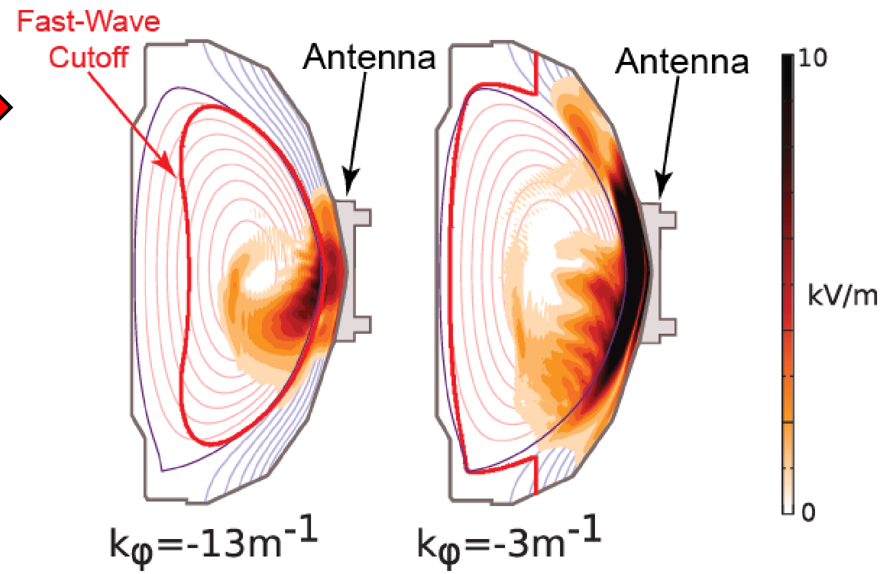
SPIRAL results show field lines (green) spiraling from SOL in front of HHFW antenna to divertor

- Field line mapping predicts RF power deposited in SOL, not at 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 to emphasize HHFW heating of high NBI power, long-pulse H-modes → assess effect of varying outer gap **PAC29-38**

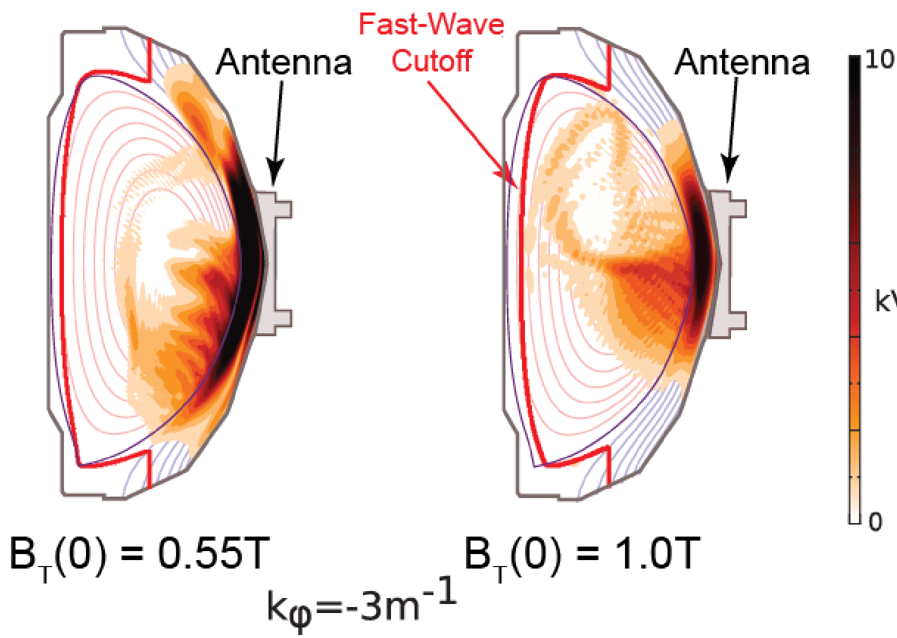
R. J. Perkins, *et al*., submitted to PRL (2012)

AORSA predicts large amplitude coaxial standing modes between plasma and wall in NSTX H-mode

- Edge coaxial mode seen in NSTX $B_T(0)$ = 0.55 T simulations
- Edge mode significantly reduced when $B_T(0)$ is increased from 0.55 T to 1 T



2-D AORSA simulation for HHFW in NSTX
$B_T(0)$ = 0.55T NBI H-mode shot 130608*

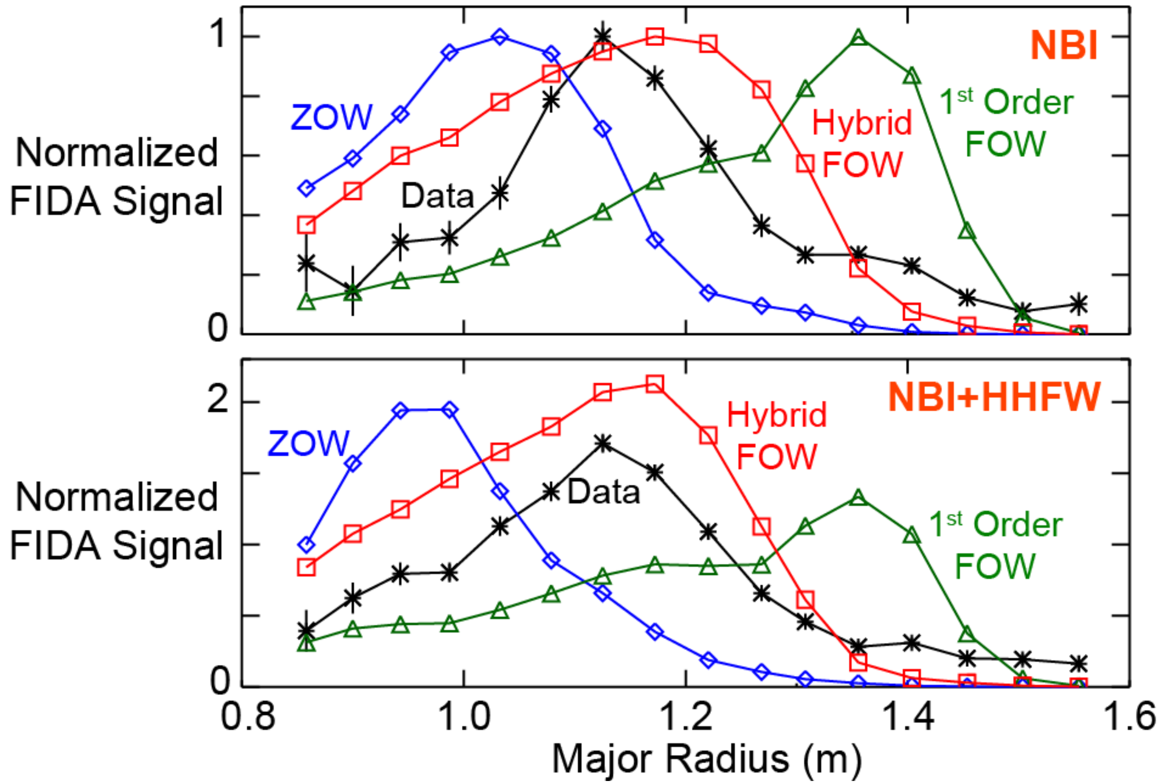


- Future plans call for a quantitative comparison of predicted SOL electric fields with measurements:
  - Requires better resolution in SOL and detailed antenna geometry

PAC29-30

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

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



- Recent FIDA simulations using "hybrid" full-orbit FOW CQL3D show much better agreement shift with FIDA data:
  - "Hybrid" FOW CQL3D has full orbits but does not treat orbit topologies correctly at trapped-passing boundaries
  - Expect proper treatment of orbit topologies will bring the simulations into even better agreement with FIDA data

- A full-orbit neoclassical transport model, and losses to SOL and wall still need to be implemented
- Initial tests of full-orbit FOW CQL3D show accurate modeling of fast-ion losses, power absorption and RF-driven current profiles

CompX SM

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EAST & DIII-D ICRH H-mode experiments in FY2012-14 help develop scenarios with better coupling & heating for NSTX-U

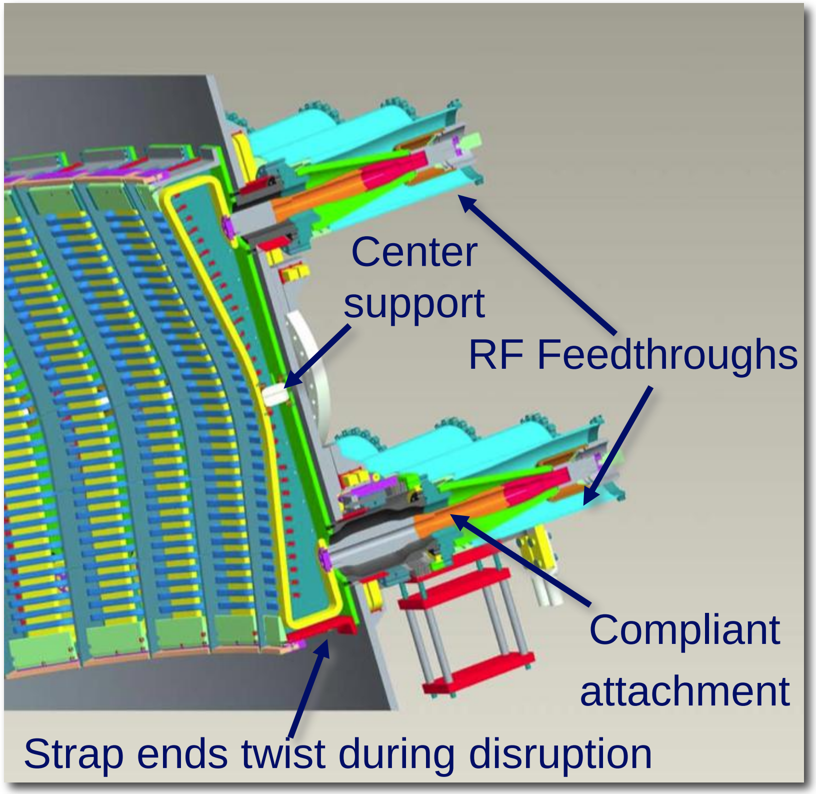
- ICRH H-mode experiments proposed in EAST:
  - EAST offers an opportunity to use both ICRH and lithium conditioning
  - EAST H-mode experiments have similar ELM-related tuning/matching issues
  - An experimental proposal submitted to EAST for 2012 run campaign extends NSTX high non-inductive fraction RF H-modes to higher power and I_p
  - ICRH+NBI & ICRH H-mode experiments in DIII-D:
  - Fast-wave heating in DIII-D has similar ion harmonic resonances to NSTX-U at $B_T(0)$ ~ 1 T
  - Fast-wave experiments proposed for 2012 would study fast-ion interactions and SOL RF power loss mechanisms similar to NSTX-U
  - PPPL has also proposed introducing lithium conditioning in DIII-D, which could help improve fast-wave coupling
  - Explore DIII-D and C-Mod PCI for HHFW measurements for NSTX-U
- Use advanced RF codes to model the fast-wave interaction with fast-ions in NSTX-U H-mode scenarios:
  - Include realistic SOL and detailed antenna model to assess, and mitigate edge RF power losses (eg. surface wave propagation)

PAC29-30

MAST EBW start-up experiments in FY2012 support NSTX-U EBW system design & research

- 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 ramp-up planning and design activities
- Model and design 28 GHz ECH/EBWH system for NSTX-U:
  - GENRAY and CQL3D will model plasma start-up using a 1 MW, ECH/EBWH system, and off-axis heating and current drive scenarios using a 1-2 MW, 500 ms EBWH/EBWCD system R(12-3) R(13-3)

Several key HHFW system and diagnostic improvements in FY2012-14 are needed to support NSTX-U research



- Require compliant attachments between antenna current straps and RF feedthroughs to withstand 4x increase in disruption loads:
  - Considering compliant bellows
- Need space for ECH/EBW and/or *AE or EHO antennas:
  - Considering using only 8 straps to free up space for other antenna(s)
  - Test two elements on test stand
  - Optimize voltage standoff in vacuum with aid of antenna modeling
- For compatibility with high NBI power, modify edge tiles of the NBI armor to extend into to R = 1.57 m to serve as the limiter for the HHFW antenna
- Add RF probes in protective tiles above and below antenna to document RF power flow to divertor for comparison to advanced RF codes

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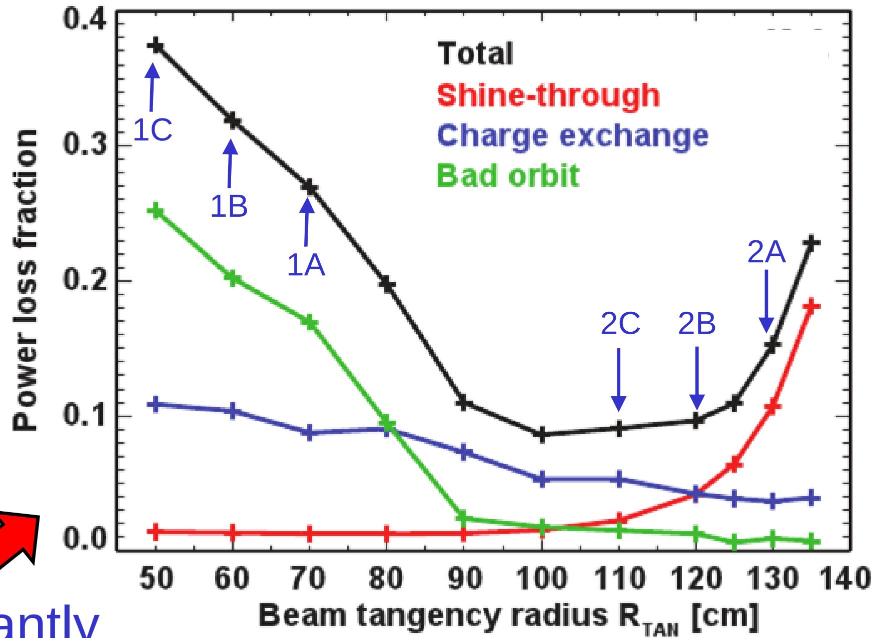
Reduced edge losses and less fast-ion interaction with the antenna may improve HHFW heating efficiency in NSTX-U

- B_T, I_p and P_{nbi} in NSTX-U will be 2x higher than in NSTX,
- What are the implications for HHFW coupling & heating efficiency in NSTX-U?:
  - Higher B_T in NSTX-U moves fast-wave cut off towards or inside the separatrix → reducing surface wave losses
  - Scrape off layer width may shrink at higher I_p → reducing surface wave losses
  - Higher n_e in NSTX-U may increase scrape off density, moving cut off outside separatrix and closer to wall → possibly increasing surface wave losses
  - Larmor radius (and banana width at high I_p) will be smaller → reducing fast-ion interactions with the antenna

More robust, graphite limiter, needed for HHFW compatibility with high-power, long-pulse NBI in NSTX-U

- 5-6 cm outer gap needed for efficiently HHFW coupling to NBI H-modes:
  - In NSTX using $P_{nbi} \geq 4$ MW with a 5-6 cm outer gap overheated the boron nitride antenna limiter
  - During outage modifiy graphite NBI armor edge tiles to serve as poloidal limiter at R = 1.57 m to protect the HHFW antenna
  - New NSTX-U beams have significantly less prompt loss than the old NSTX beams → less fast-ion interaction with the HHFW antenna



Power loss fraction calculated for an NSTX-U plasma with I_p = 0.6 MA, $B_T(0)$ = 0.9 T and a 7.4 cm outer gap

- Collaborations, advanced RF modeling and meeting the FY12-14 research milestones will help to address these compatibility issues

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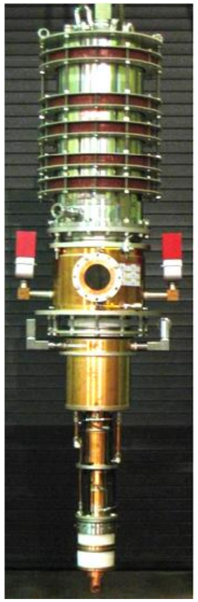
HHFW research for first two years of NSTX-U operation focused on assessing double-feed antenna performance

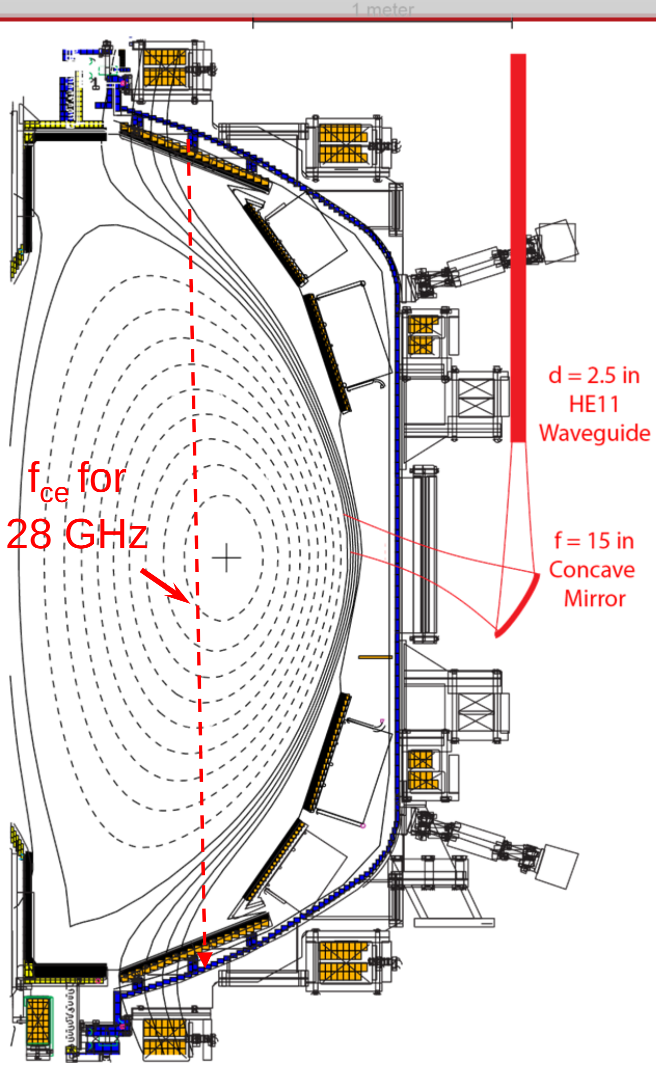
- Assess performance of 12-strap, double-feed antenna and compatibility with NBI H-modes: **PAC29-3** **PAC29-27**
  - Use boronization & minimum lithium conditioning needed to control edge density, and reduce surface wave excitation and other edge power losses **PAC29-28**
  - Will be conducted before significant lithium conditioning starts
  - Compare coupling and heating efficiency to single-feed operation in 2008
  - Assess HHFW 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 (NI) H-mode, and non-inductively ramp I_p with HHFW power:
  - 100% NI results important for supporting FNSF design → can be obtained one year earlier with incremental funding **PAC29-35** **PAC29-29**
  - Use NBI blips for MSE q profile measurements and C density pump out
  - Also use MSE-LIF to measure q profile without needing heating NBI blips
  - Similar 100% NI experiments are possible on EAST and DIII-D
- RF group support needed to design new antenna systems (*AE and/or EHO)

Solenoid-free start-up supported by implementing 28 GHz ECH system – to be later upgraded for EBWH

- Install 1 MW gyrotron, initially to support start-up:
  - Gyrotron originally developed in Japan for GAMMA 10; capable of 1-5 s pulses
  - Fixed horn antenna & low-loss HE11 corrugated circular waveguide
  - Locate gyrotron and associated equipment in former TFTR test cell
  - Analysis for NSTX CHI start-up plasma predicts 25-30% single-pass absorption for 28 GHz 2nd harmonic X-mode → reflections will enhance absorption (see backup slide #31)
- Upgrade ECH system later to O-X-B oblique launch EBWH system:
  - Metal steerable mirror, designed for 5 s, 2 MW pulses, located near midplane, outside the vacuum vessel



1 MW, 28 GHz Gyrotron



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

Research goals for years 3-5 of NSTX-U operation - I

- Test high-power ECH system for plasma start-up:
  - Assess impact on closed-flux current achieved, discharge pulse-length, and the non-inductive fraction
- Utilize HHFW to assist start-up plasma formation and compare to ECH
- Assess impact of HHFW electron heating on NBI current ramp-up
- Simulate/mock-up HHFW antenna performance using a reduced number of straps
- Implement EHO (see slide#32 in backup) and/or *AE antenna compatible

Research goals for years 3-5 of NSTX-U operation - II

- Modify HHFW antenna 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, 1-5s)
- Pending successful EBW heating results project EBW CD performance to a FNSF/CTF

Summary

- Near-term research milestones address simulation of heating and ramp-up of CHI start-up and the physics design of the ECH/EBWH system
- Advanced RF codes will aid development of strategies that mitigate RF SOL losses and minimize RF interaction with fast-ions in H-modes
- Collaborations with DIII-D, EAST and MAST in FY2012-14 will guide development of HHFW and EBW research plans for NSTX-U
- During the outage, modify NBI armor to provide a more robust limiter for the HHFW antenna to support high power, long pulse NBI H-mode operation
- HHFW research during first two years of NSTX-U operation will focus on assessing the performance of the double-feed antenna
- A high-power ECH start-up system is being proposed for NSTX-U, that can be upgrade to an EBWH system

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.

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

Responsible TSGs: Solenoid-Free Start-up, Waves and Energetic Particles, Advanced Scenarios and Control

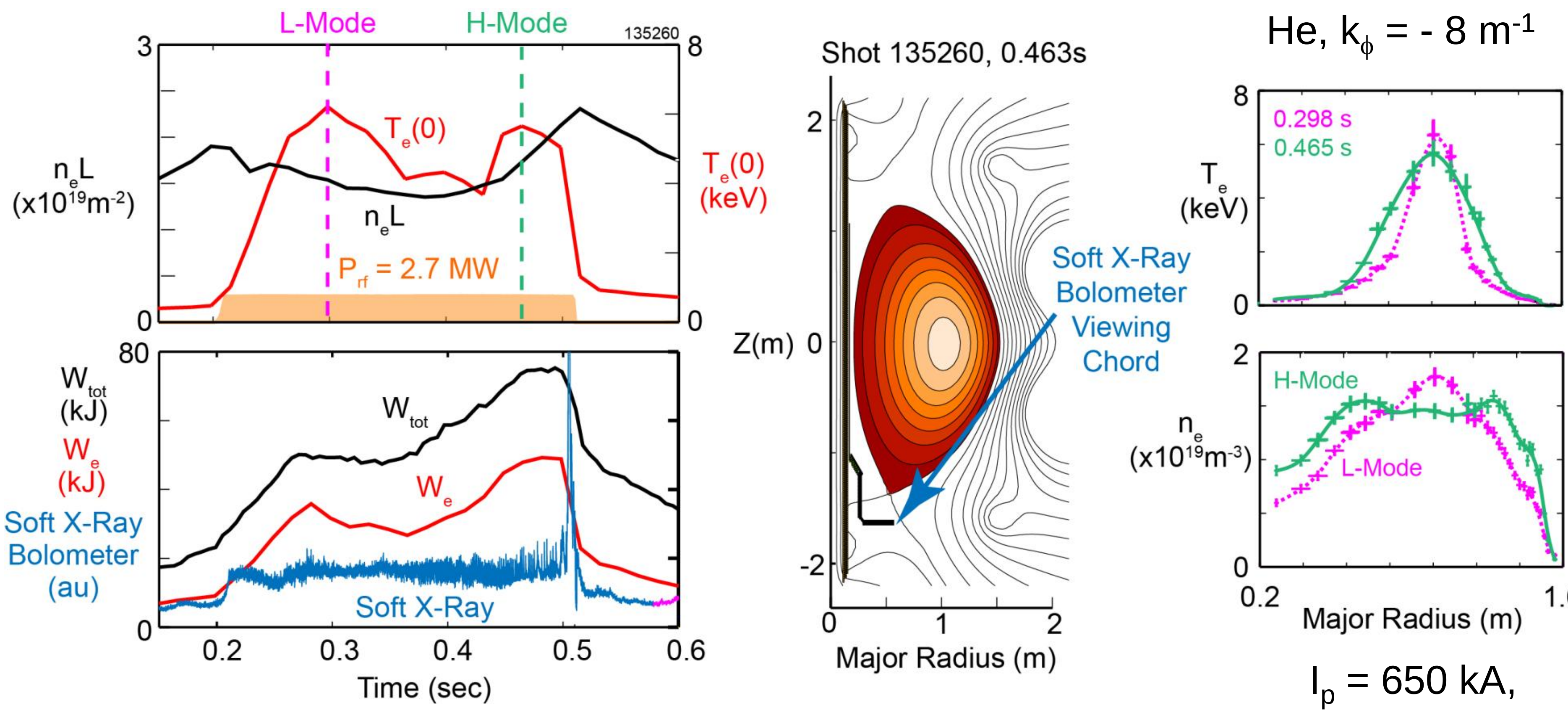
Elimination of the ohmic heating (OH) solenoid is essential for proposed ST-based nuclear fusion applications. Coaxial helicity injection (CHI) is a leading candidate method for plasma initiation without an OH solenoid. Understanding CHI plasma formation and sustainment is important for projecting non-inductive start-up and ramp-up efficiency to next-steps. CHI initiated plasmas have been successfully coupled to induction in H-mode plasmas with Neutral Beam Injection (NBI) heating. While these results are favorable, fully non-inductive plasma current ramp-up has not yet been achieved and is a major research goal of NSTX Upgrade. The Tokamak Simulation Code (TSC) has been successfully used to simulate CHI plasma formation, and these simulations will be extended with systematic variations of plasma transport parameters and other plasma parameters such as current, temperature, and density to study how NBI couples to these plasmas with low and zero loop voltage. These studies will inform the requirements for CHI plasma parameters for direct coupling to NBI. TRANSP calculations will also be performed using selected cases from TSC simulations to improve estimates for NBI heating and current drive profiles. Finally, optimized CHI target plasmas will be used as target plasmas for NBI ramp-up modeling using the present and 2nd NBI of NSTX Upgrade. High-Harmonic Fast Wave (HHFW) and (more recently) NBI heating of low-current ohmic targets have been demonstrated in NSTX and will be assessed in these modeling activities. This milestone will inform the early plasma and auxiliary heating and current drive requirements for non-inductive start-up and ramp-up for NSTX Upgrade and for next-step ST facilities.

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

Responsible TSGs: Waves and Energetic Particles, Solenoid-Free Start-up, Advanced Scenarios and Control

For a reactor-relevant ST operation it is critical to develop discharge initiation, plasma current ramp-up, and plasma sustainment techniques that do not require a central solenoid. Earlier ECH modeling of NSTX CHI startup plasmas with GENRAY and CQL3D predicted 25-30% first pass absorption. In addition, EBW startup experiments on MAST in 2009 showed good electron heating when the discharge became overdense. A few hundred kilowatts of coupled ECH/EBWH power in NSTX-U should heat a solenoid-free startup discharge sufficiently to allow coupling of 30 MHz high harmonic fast wave power, that will in turn generate non-inductive plasma current ramp-up. While pressure gradient-driven bootstrap current can provide a large fraction of the plasma current required to non-inductively sustain an ST plasma, an externally driven off-axis current may still be required to provide magnetohydrodynamic stability during the plasma current flat top. Electron Bernstein Wave current drive (EBWCD) can provide this non-inductive current and thus may play a critical role in enabling high beta, sustained operation of ST plasmas. A 28 GHz ECH and EBWH system is being proposed for NSTX-U. Initially the system will use short, 10-50 ms, 0.5-1 MW pulses to support development of non-inductive startup scenarios. Later the pulse length may be extended to 0.2-0.5 s and the power increased to provide EBWH and EBWCD during the plasma current flat top. EBW startup experiments are being planned on MAST for the summer of 2012 to extend the 2009 experiments to higher EBW power. Results from those experiments will support the design for the EBW startup system for NSTX-U. In 2012 and 2013 GENRAY and CQL3D ECH and EBWH modeling will be performed for NSTX-U plasma startup scenarios and for EBWH and EBWCD during the plasma current flat top for advanced NSTX-U plasma scenarios to support the physics design of the NSTX-U ECH/EBWH system.

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

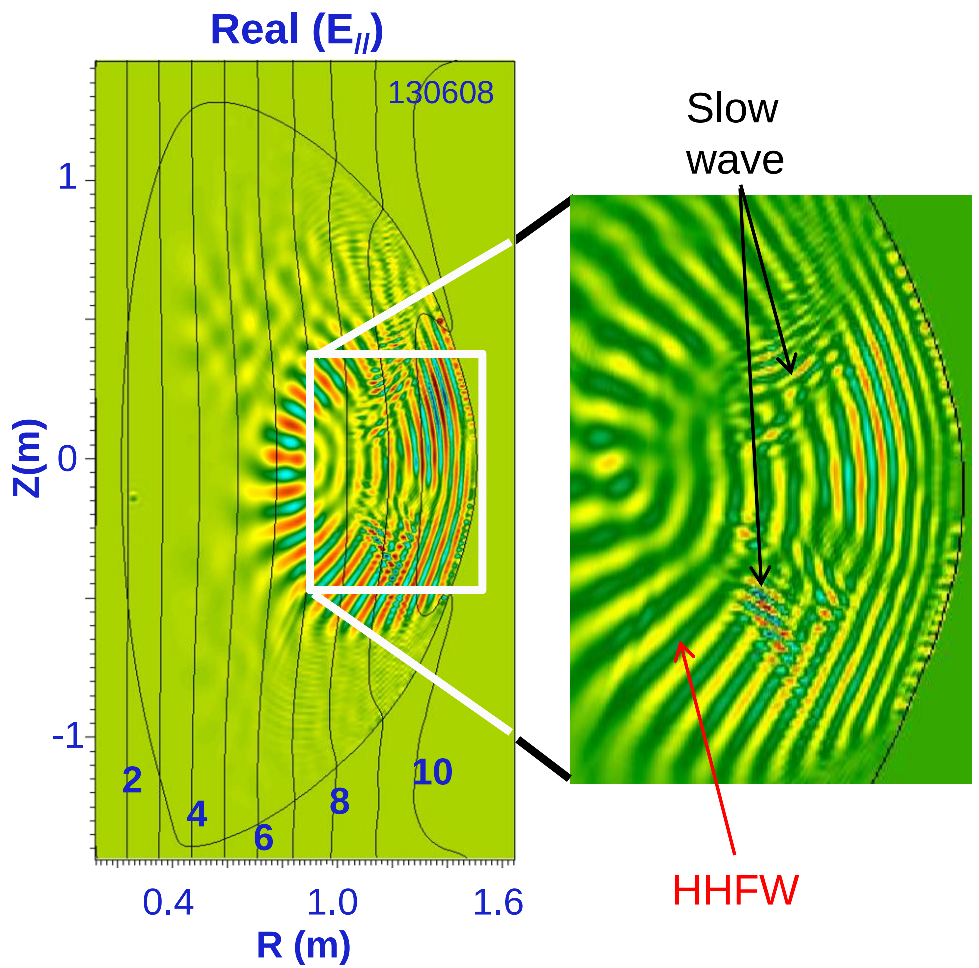


I_p = 650 kA,

$B_T(0)$ = 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

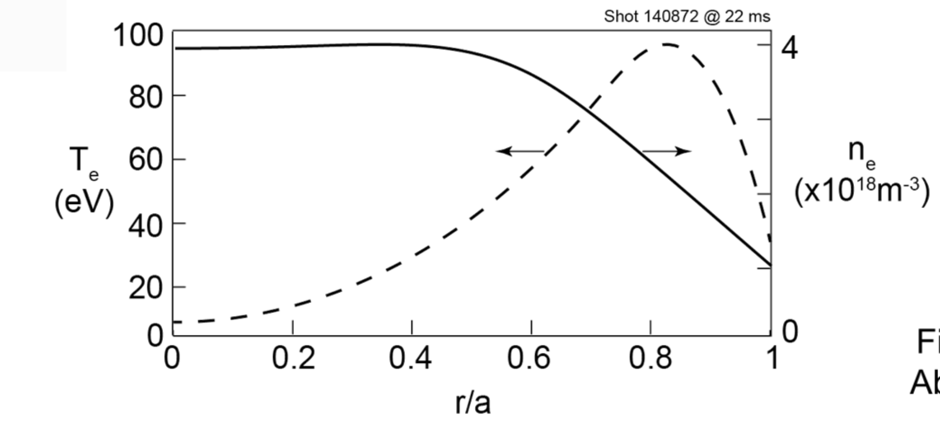


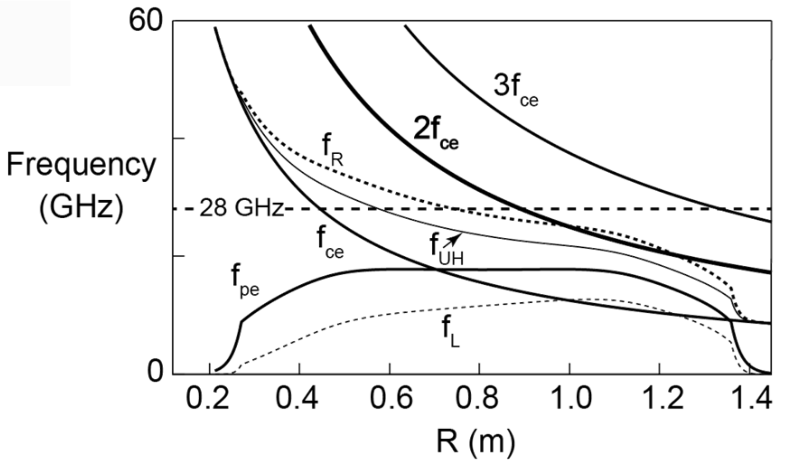
AORSA with 256 X 256 elements

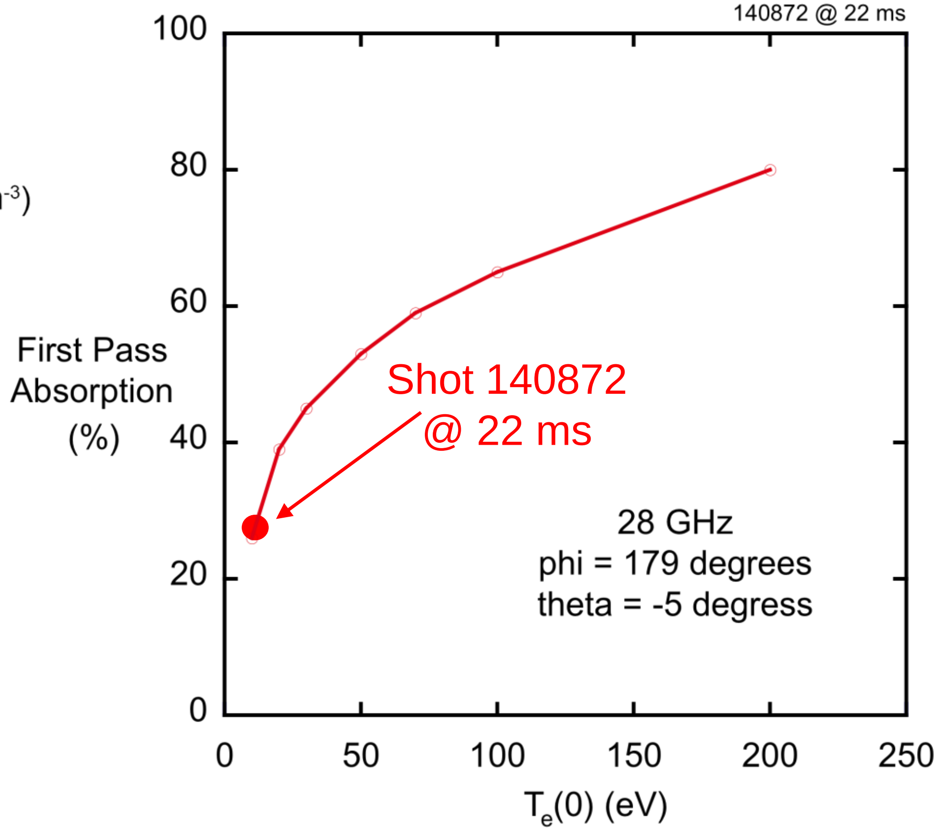
- Requires B_p upshift of $k_{//}$ and finite T_e
- Related to warm electrostatic ICW first observed by Motley and D'Angelo in a Q-machine (1961)
- Independent of T_i → not an IBW
- Electron damping, kinetic flux and finite $E_{//}$ associated with mode
- Fine grid spacing needed to resolve mode
- Also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

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

RF modeling of 28 GHz absorption in NSTX CHI startup plasma predicts 25% first pass absorption





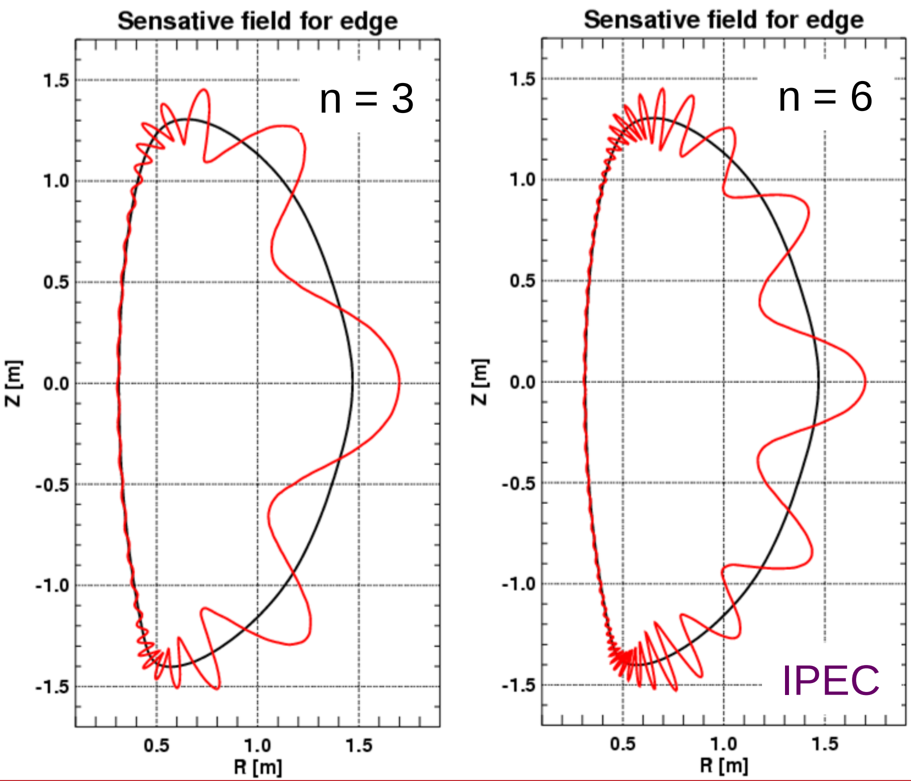


Density and temperature profiles of $B_T(0)$ = 0.5 T NSTX CHI startup plasma, shot 140872 at 22 ms show hollow T_e profile with $T_e(0)$ ~ 10 eV

- First pass absorption increases to 80% as $T_e(0)$ increases from 10 to 200 eV

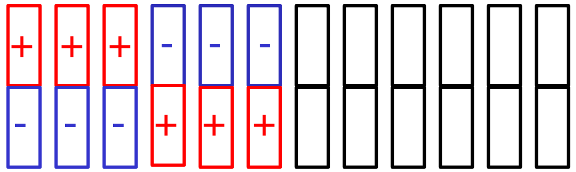
HHFW antenna may be able to drive EHOs

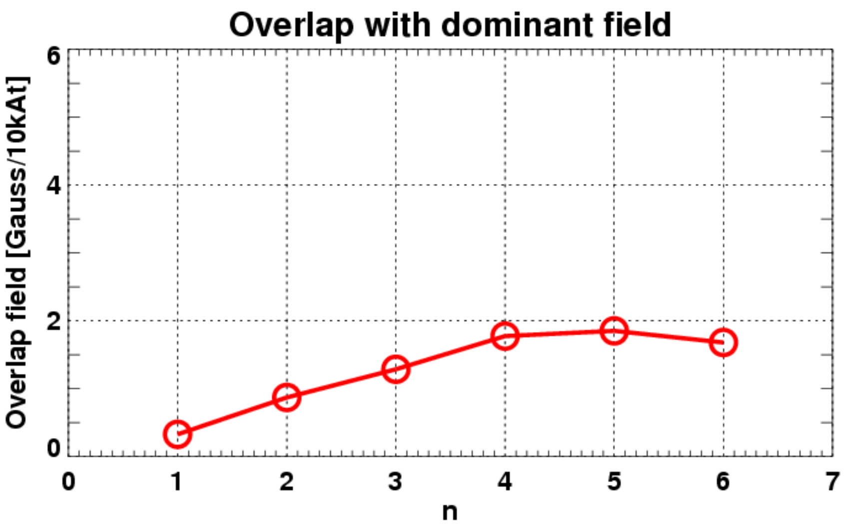
- For a given toroidal mode number n, there is a field distribution that the plasma is most sensitive to.
- Compute the "overlap" of the applied field with the most sensitive field as a measure of efficiency.



- Potential means of powering the antenna with best coupling to the higher toroidal mode numbers

HHFW Antenna





Could be important for NSTX-U, and future devices that cannot naturally access EHOs