NSTX-U

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

Plan for Fast Wave, Electron Cyclotron and Electron Bernstein Wave Research

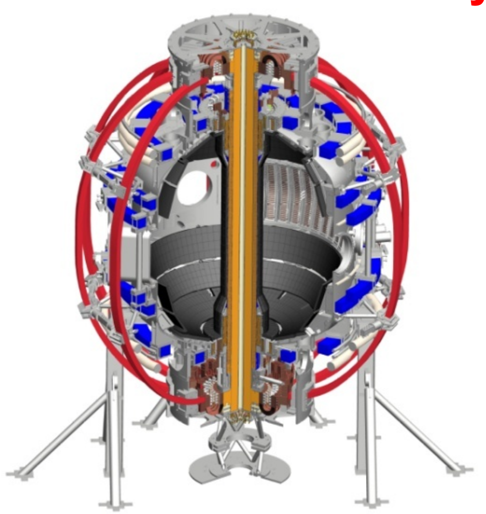
Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

Gary Taylor

Mario Podestà, Nikolai Gorelenkov

for the NSTX-U Research Team

NSTX-U 5 Year Plan Review
LSB B318, PPPL
May 21-23, 2013



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

RF research plan supports non-inductive (NI) operation and RF code validation

RF research thrusts support two high-level NSTX-U 5-year plan goals:

- **Demonstration of 100% NI operation at performance levels extrapolating to ≥ 1 MW/m^2 neutron wall loading in a FNSF**
- **Developing and understanding NI plasma current start-up and ramp-up in order to project to a FNSF-ST**

- Up to 6 MW of 30 MHz fast-wave (FW) heating will be available on NSTX-U to support RF research:
  - NSTX-U may be the only major US facility with a FW heating program in FY2014-18
  - Will study 4-5 ω_D heating → similar 3-4 ω_H heating regime that is potential candidate for ITER "low-activation" phase
- A 1 MW, 28 GHz heating system will be commissioned in FY 2016-17 to heat start-up plasmas

RF research plan supports non-inductive (NI) operation and RF code validation

RF research thrusts support two high-level NSTX-U 5-year plan goals:

- **Demonstration of 100% NI operation at performance levels extrapolating to ≥ 1 MW/m^2 neutron wall loading in a FNSF**
- **Developing and understanding NI plasma current start-up and ramp-up in order to project to a FNSF-ST**

- Up to 6 MW of 30 MHz fast-wave (FW) heating will be available on NSTX-U to support RF research:

  Back-up # 26-27

  - NSTX-U may be the only major US facility with a FW heating program in FY2014-18
  - Will study 4-5 ω_D heating → similar to the 3-4 ω_H heating regime that is potential candidate for ITER "low-activation" phase
- A 1 MW, 28 GHz heating system will be commissioned in FY 2016-17 to heat start-up plasmas

NSTX-U RF research thrusts support a FNSF-ST and ITER

Thrust RF-1 Develop FW/EC heating for fully NI plasma current start-up and ramp-up:

- FW-driven NI I_p ramp-up to a level that can confine fast-ions from the 2nd neutral beam
- Increase $T_e(0)$ in CHI and gun-initiated plasmas to allow NBI and FW heating
- Plasma start-up with only EBW heating at ~1 MW level

Thrust RF-2 Validate state-of-the-art RF codes for NSTX-U and predict RF performance in future burning plasma devices:

- Include high-fidelity SOL, antenna, fast-ion interaction, and edge turbulence models in RF codes
- Compare code predictions with NSTX-U RF heating results

NSTX-U RF research thrusts support a FNSF-ST and ITER

Thrust RF-1

Develop FW/EC heating for fully NI plasma current start-up and ramp-up:

- FW-driven NI I_p ramp-up to a level that can confine fast-ions from the 2nd neutral beam
- Increase $T_e(0)$ in CHI and gun-initiated plasmas to allow NBI and FW heating
- Plasma start-up with only EBW heating at ~1 MW level

Thrust RF-2

Validate state-of-the-art RF codes for NSTX-U and predict RF performance in future burning plasma devices:

- Include high-fidelity SOL, antenna, fast-ion interaction, and edge turbulence models in RF codes
- Compare code predictions with NSTX-U RF heating results

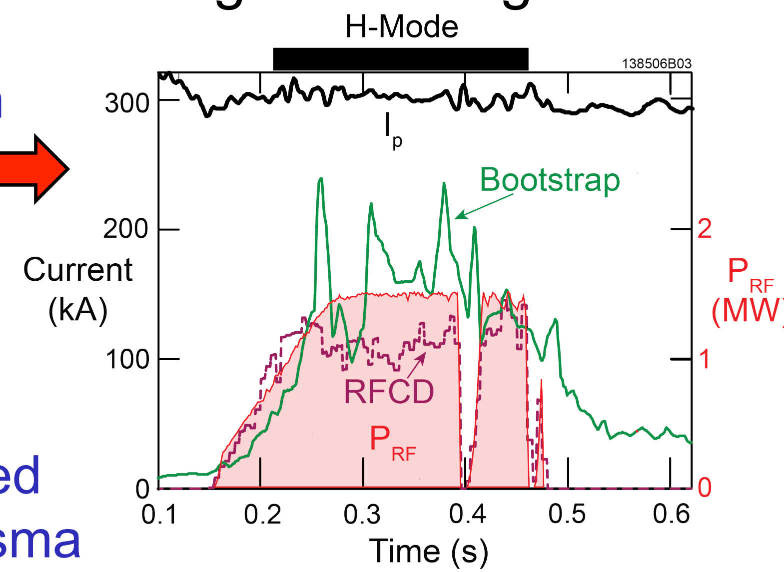
Ramp-up and sustain fully NI H-modes with fast wave power

- Generate sustained fully NI 300-500 kA H-modes with FW power using an inductively generated target discharge:

FY15

FY16

  - Achieved >70% NI fraction in an I_p = 300 kA H-mode plasma in FY2010 with P_{RF} = 1.4 MW*



  - Use boronization and minimal Li conditioning to optimize FW coupling to reach ~ 3 MW needed for fully NI I_p = 300 - 500 kA plasma
  - These FW H-mode experiments will benefit from new MSE-LIF q(r) diagnostic which uses non-perturbing neutral beam
- NI ramp-up of an FW-only H-mode from I_p = 300 to 500 kA:
  - Maintaining FW coupling during ramp-up may prove challenging

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

Assess 12-strap antenna performance and study RF power flows in SOL

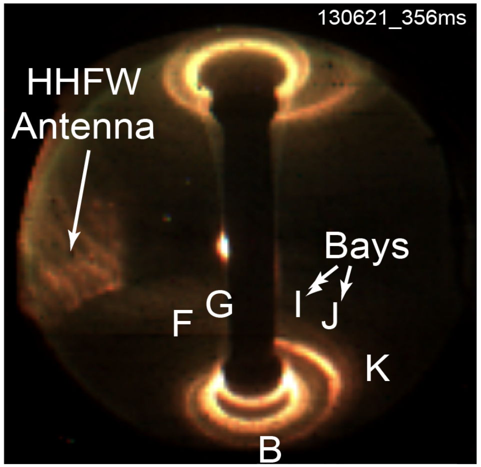
FY15 | FY16

- FY2009 double-feed FW antenna upgrade was never tested without extensive Li conditioning:
  - Assess antenna performance with NBI H-modes in discharges with boronization and minimal Li conditioning
- Study RF power flows along field lines observed in the SOL*:
  - Additional RF probes and IR cameras will study RF power flows during FW heated NBI H-modes

Back-up # 26

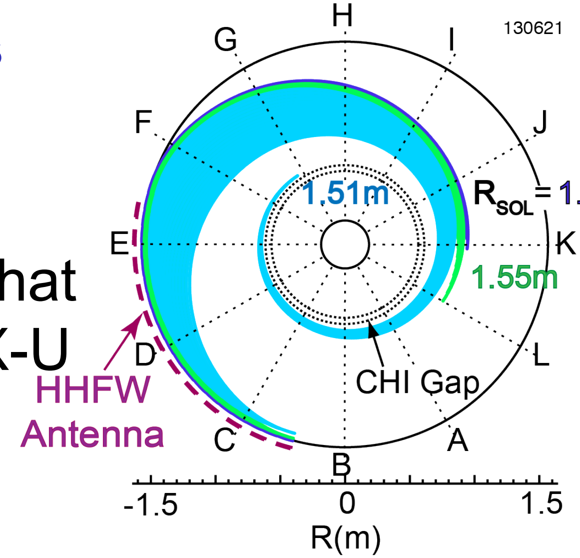
- Assess need for FW limiter upgrade that is compatible with higher P_{nbi} in NSTX-U

Visible image of RF power flow to Divertor



NSTX
H-Mode
P_{rf} = 1.4 MW
P_{NBI} = 2 MW

SPIRAL modeling of SOL field lines from FW antenna to divertor



Top View

*R. J. Perkins et al., Phys. Rev. Lett. **109** (2012) 045001

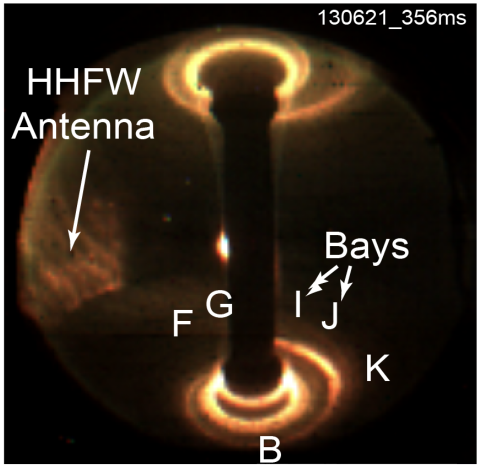
Assess 12-strap antenna performance and study RF power flows in SOL

- FY2009 double-feed FW antenna upgrade was never tested without extensive Li conditioning:
  - Assess antenna performance with NBI H-modes in discharges with boronization and minimal Li conditioning

FY16 — FY17

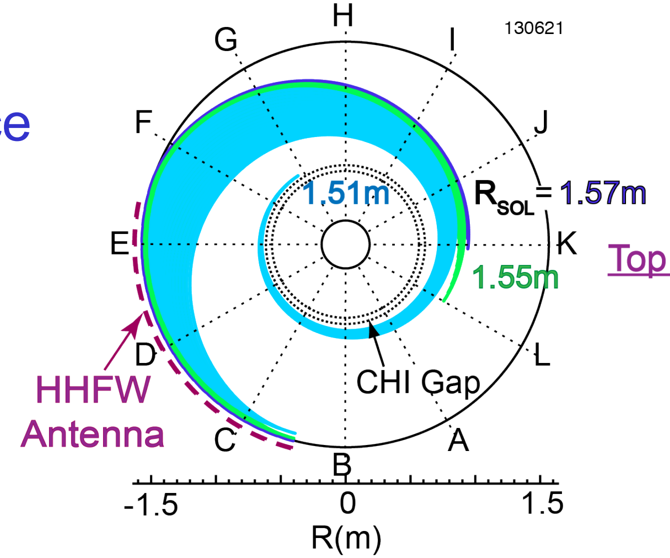
- Attempt to mitigate RF power flows along field lines with Li and gas puffs
  - Assess effect of cryo-pumping and 3-D fields on FW antenna performance

Visible image of RF power flow to Divertor



NSTX
H-Mode
P_{rf} = 1.4 MW
P_{NBI} = 2 MW

SPIRAL modeling of SOL field lines from FW antenna to divertor



Top View

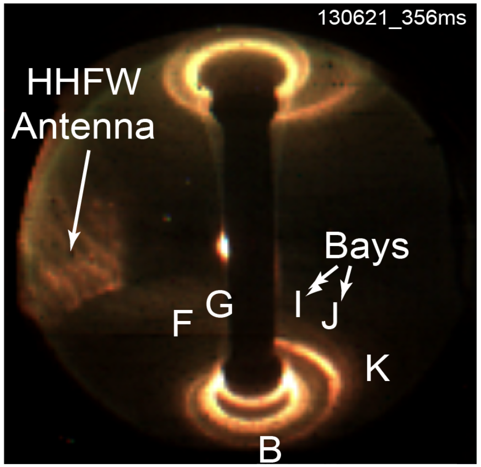
Assess 12-strap antenna performance and study RF power flows in SOL

- FY2009 double-feed FW antenna upgrade was never tested without extensive Li conditioning:
  - Assess antenna performance with NBI H-modes in discharges with boronization and minimal Li conditioning
- Attempt to mitigate RF power flows along field lines with Li and gas puffs
- Mockup reduced-strap HHFW antenna:
  - May reduce antenna straps to make room for antenna(s) to excite *AE modes and/or EHOs
  - *Test FW straps to excite EHO in FY2018 (incremental funding)*

Back-up # 34-36

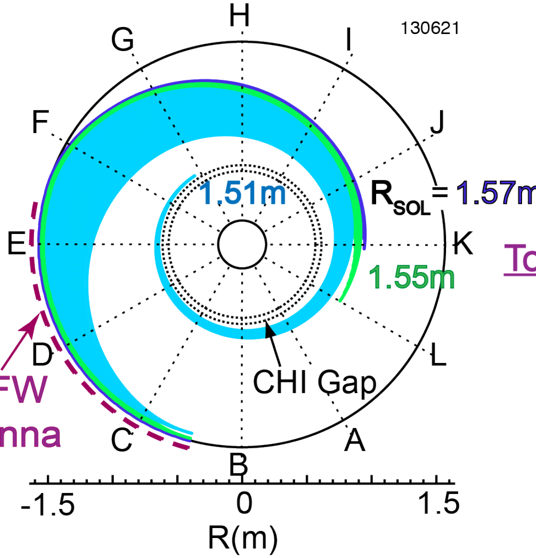
FY18

Visible image of RF power flow to Divertor



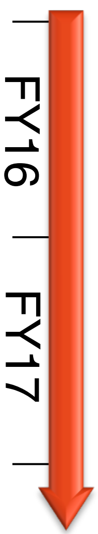
NSTX
H-Mode
P_{rf} = 1.4 MW
P_{NBI} = 2 MW

SPIRAL modeling of SOL field lines from FW antenna to divertor



Top View

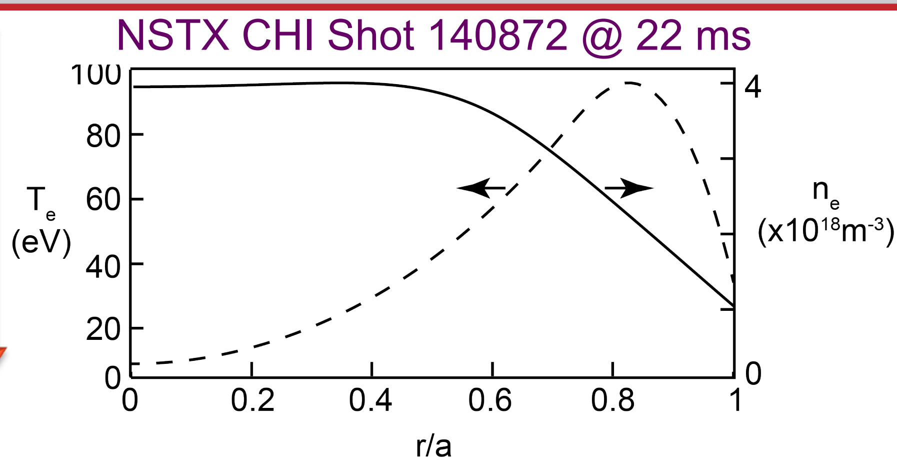
Assess impact of FW heating on NBI I_p ramp-up

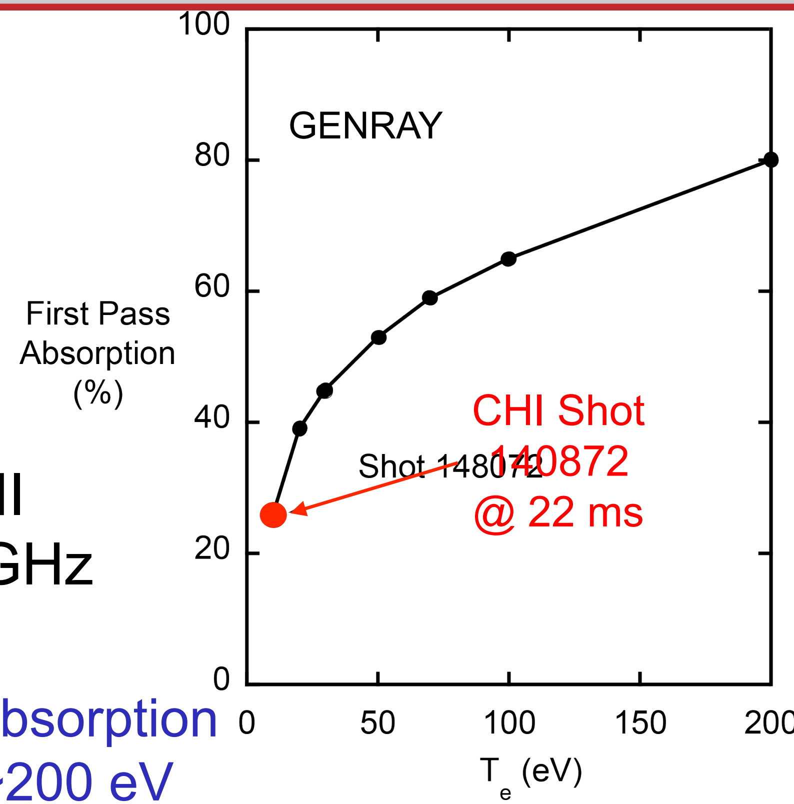


- Test impact of FW heating on NBI I_p ramp-up from 400 kA to ~ 1 MA:
  - TSC predicts bootstrap and NBICD will achieve this ramp-up in ~ 3 s
  - Start ramp-up with low inductance plasma with 4 MW of FW heating
  - Use this inductively-initiated plasma as a proxy for CHI target discharge where the loop voltage is turned off as NBI and FW heating is applied
  - Determine plasma parameters needed for fully NI ramp-up
- Extend FW heating to longer pulses and possibly into the flat-top:
  - Also assess impact of cryo-pump on FW coupling

Model 28 GHz EC/EBW heating system for NI plasma start-up

FY14





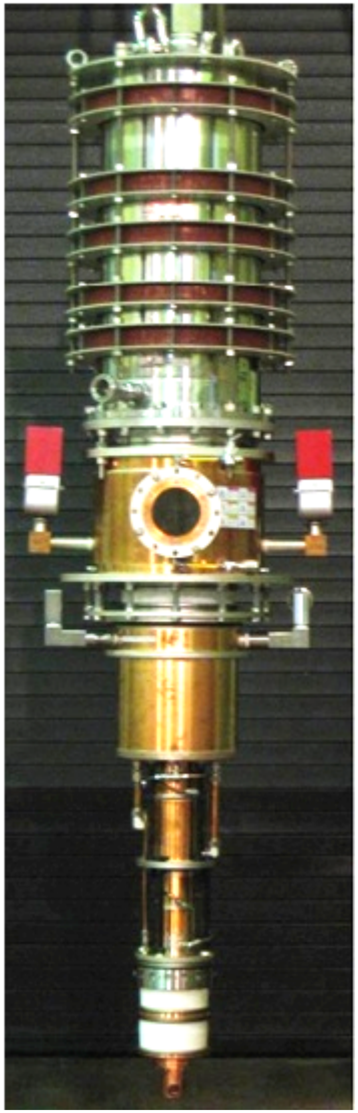
- Low density (3 - 4 x 10^{18} m^{-3}) CHI discharges are amenable to 28 GHz EC heating:
  - At $B_T(0)$ = 0.55 T first pass EC absorption ~ 25%, expect rapid heating to ~200 eV
- Design 28 GHz, 1 MW EBW start-up system using technique being tested on MAST
  - US (ORNL and PPPL) and Japan are collaborating with MAST on 100-150 kW EBW start-up experiments this year
  - Also extensive work on RF startup in Japan (TST-2, LATE, QUEST)

Back-up # 29

Design and implement 28 GHz EC/EBW heating system to support NI operation

- Use 1 MW Gyrotron design originally developed for GAMMA 10*
  - Fixed horn antenna & low-loss HE11 corrugated waveguide
  - Install grooved tile on center column in FY2016-17 to allow EBW plasma start-up in FY2018
  - Begin EC heating of CHI start-up plasmas in FY2017

FY15 | FY16 | FY17



1 MW, 28 GHz Gyrotron

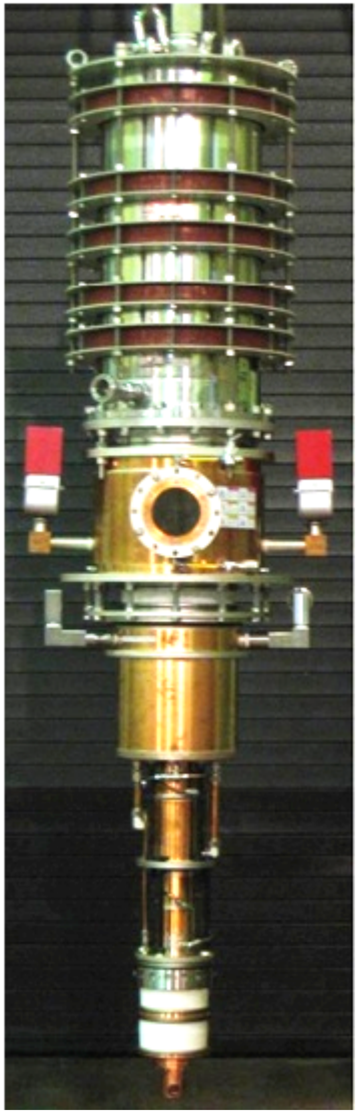
*T. Kariya et al., J. Infrared Millimetre and Terahertz Waves **32** (2011) 295

Design and implement 28 GHz EC/EBW heating system to support NI operation

- Use 1 MW Gyrotron design originally developed for GAMMA 10*
  - Fixed horn antenna & low-loss HE11 corrugated waveguide
  - Install grooved tile on center column in FY2016-17 to allow EBW plasma start-up in FY2018
  - Begin EC heating of CHI start-up plasmas in FY2017

FY18

- EBW plasma start-up experiments



1 MW, 28 GHz Gyrotron

28 GHz EC heating of CHI discharges and EBW start-up

- 28 GHz EC heating of CHI plasma:
  - Adjust target for maximum 28 GHz single pass absorption
  - If plasmas can be generated with $T_e(0) \geq 100$ eV they will then be heated with FW power to non-inductively ramp I_p
- Non-inductive start-up with EBW heating using the technique being developed on MAST:

Back-up # 29

  - MAST achieved I_p ~ 30 kA with ~ 50 kW of EBW power in 2009
  - MAST experiments this year aim to more than double EBW power
  - EBW start-up may allow more time to control plasma position and discharge evolution than CHI
  - It is possible that the EBW current drive will scale much weaker than linearly with EBW power
  - EBW start-up at power levels ≥ 500 kW will allow the viability of this technique to be tested at much higher power in NSTX-U

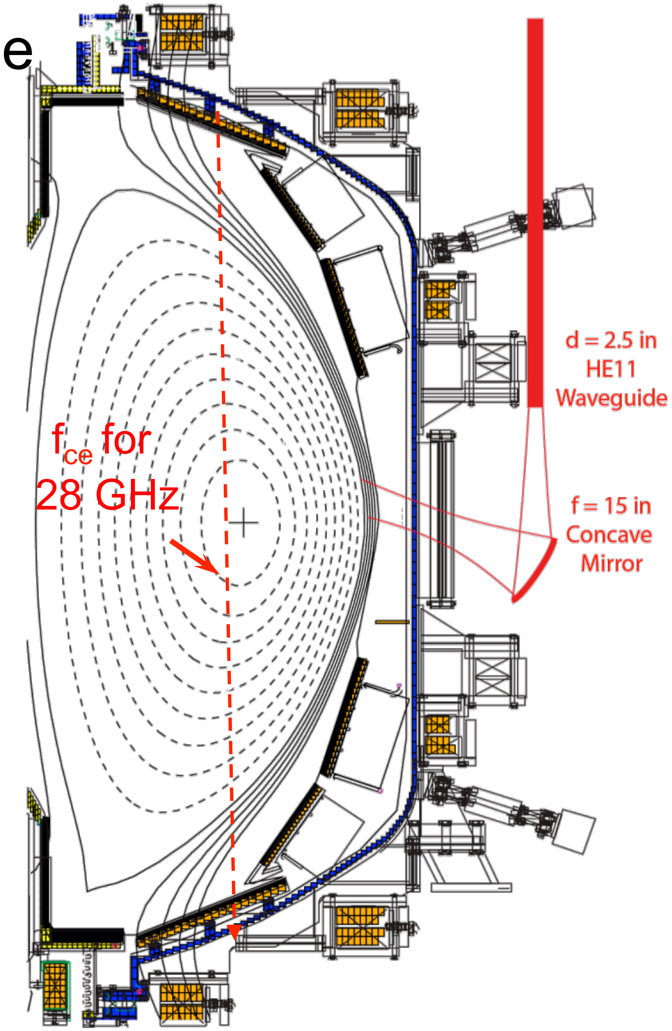
FY17

FY18

Develop and design 28 GHz EBW (O-X-B) heating and CD system for NSTX-U H-modes

FY14

- EBW simulations for an NSTX-U H-mode predict η_{eff} ~ 25 kA/MW on axis for $n_e(0) = 9 \times 10^{19} m^{-3}$ and $T_e(0)$ = 1.2 keV:
  - Can generate significant EBWCD at r/a > 0.8, where NBICD is negligible
  - Extend simulations to include realistic SOL and edge fluctuations **Back-up # 37**
- Measure O-X-B coupling with synthetic aperture microwave imaging (SAMI) (In collaboration with York U. and CCFE)
- Test 28 GHz O-X-B heating with fixed horn antenna:
  - Use B-X-O emission data acquired by SAMI to guide antenna aiming

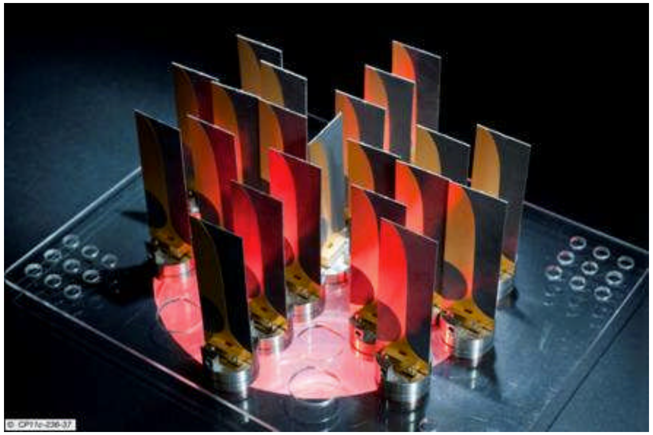


Conceptual implementation of 28 GHz EBW heating system using steerable mirror for O-X-B coupling

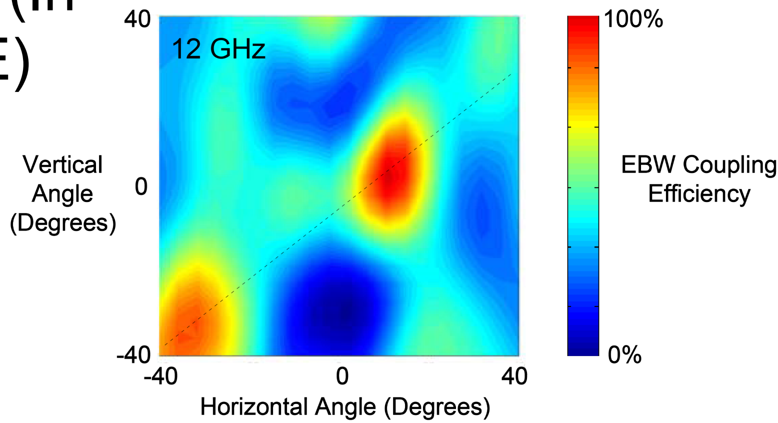
Develop and design 28 GHz EBW (O-X-B) heating and CD system for NSTX-U H-modes

FY15 — FY16

- EBW simulations for an NSTX-U H-mode predict η_{eff} ~ 25 kA/MW on axis for $n_e(0) = 9 \times 10^{19} m^{-3}$ and $T_e(0) = 1.2$ keV:
  - Can generate significant EBWCD at r/a > 0.8, where NBICD is negligible
  - Extend simulations to include realistic SOL and edge fluctuations
- Measure O-X-B coupling with synthetic aperture microwave imaging (SAMI) (In collaboration with York U. and CCFE)
- Test 28 GHz O-X-B heating with fixed horn antenna:
  - Use B-X-O emission data acquired by SAMI to guide antenna aiming



Synthetic aperture microwave imaging (SAMI) antenna array

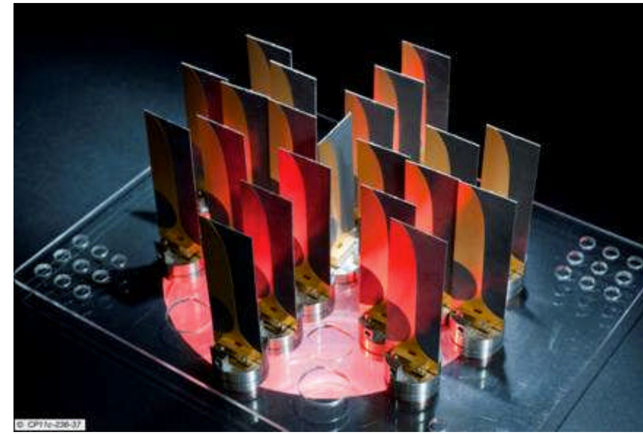


MAST SAMI EBW Emission Data

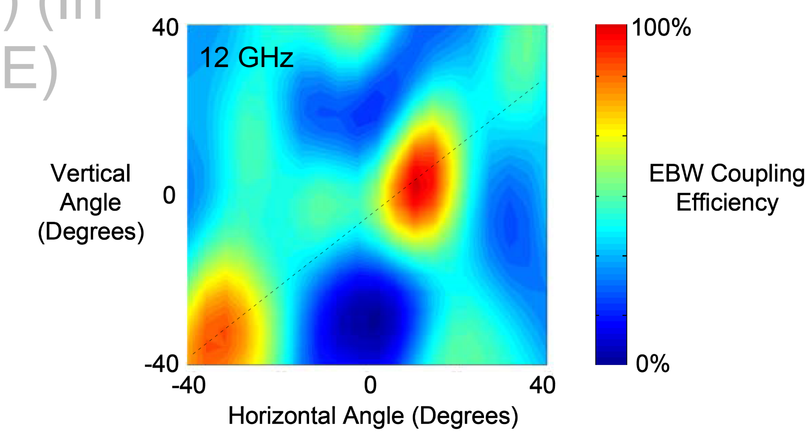
Develop and design 28 GHz EBW (O-X-B) heating and CD system for NSTX-U H-modes

- EBW simulations for an NSTX-U H-mode predict η_{eff} ~ 25 kA/MW on axis for $n_e(0) = 9 \times 10^{19} m^{-3}$ and $T_e(0) = 1.2$ keV:
  – Can generate significant EBWCD at r/a > 0.8, where NBICD is negligible
  – Extend simulations to include realistic SOL and edge fluctuations
- Measure O-X-B coupling with synthetic aperture microwave imaging (SAMI) (In collaboration with York U. and CCFE)
- Test 28 GHz O-X-B heating with fixed horn antenna:
  – Use B-X-O emission data acquired by SAMI to guide antenna aiming

FY18



Synthetic aperture microwave imaging (SAMI) antenna array



MAST SAMI EBW Emission Data

NSTX-U RF research thrusts support a FNSF-ST and ITER

Thrust RF-1 Develop FW/EC heating for fully NI plasma current start-up and ramp-up:

- FW-driven NI I_p ramp-up to a level that can confine fast-ions from the 2nd neutral beam
- Increase $T_e(0)$ in CHI and gun-initiated plasmas to allow NBI and FW heating
- Plasma start-up with only EBW heating at ~1 MW level

Thrust RF-2 Validate state-of-the-art RF codes for NSTX-U and predict RF performance in future burning plasma devices:

- Include high-fidelity SOL, antenna, fast-ion interaction, and edge turbulence models in RF codes
- Compare code predictions with NSTX-U RF heating results

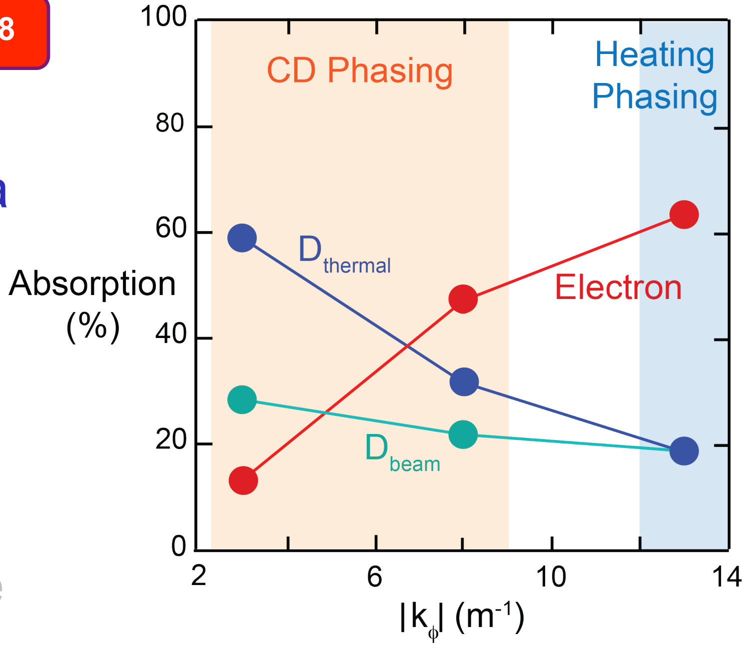
Simulate FW heating in NSTX-U with state-of-the-art RF codes

FY14

- Expect strong FW absorption on ions in NSTX-U NBI + FW H-modes for $|k_\phi| \leq 8\ m^{-1}$:
  - Higher $B_T(0)$ reduces electron absorption due to lower electron beta
  - T_i/T_e changes the power partitioning between ions and electrons, particularly for $|k_\phi| \leq 8\ m^{-1}$
- Include realistic SOL, VORPAL antenna model, and edge turbulence to simulate FW power flows in SOL:
  - Expect reduced edge losses and less fast-ion interaction with antenna at higher $B_T(0)$

Back-up # 38

NSTX-U NBI + FW H-Mode During I_p Flat-top



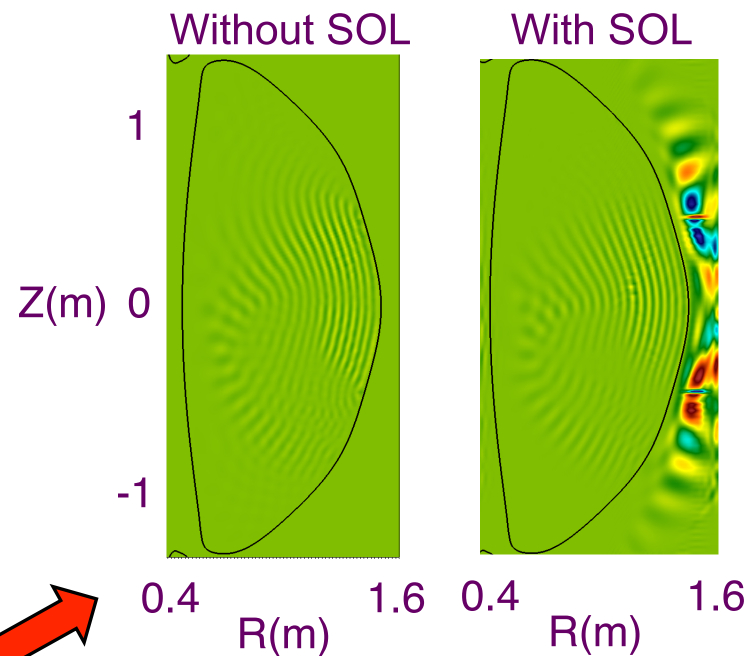
AORSA Modeling Results (from TRANSP simulation)

$B_T(0)$ = 1 T, I_p = 1.1 MA,
P_{nbi} = 6.3 MW, $n_e(0) = 1.1 \times 10^{20}\ m^{-3}$
$T_e(0)$ = 1.22 keV, $T_i(0)$ = 2.86 keV

Simulate FW heating in NSTX-U with state-of-the-art RF codes

FY14

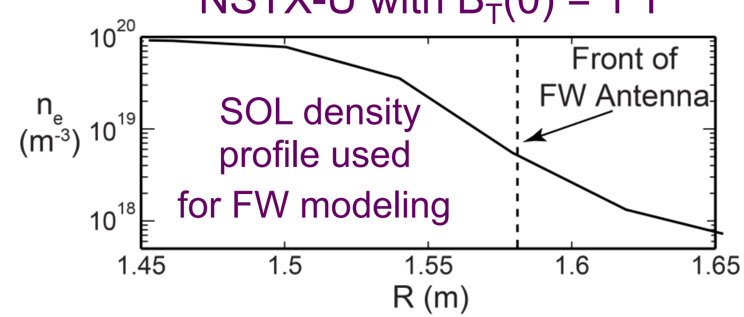
- Expect strong FW absorption on ions in NSTX-U NBI + FW H-modes for $|k_\phi| \leq 8\ m^{-1}$:
  - Higher $B_T(0)$ reduces electron absorption due to lower electron beta
  - T_i/T_e changes the power partitioning between ions and electrons, particularly for $|k_\phi| \leq 8\ m^{-1}$
- Include realistic SOL, VORPAL antenna model, and edge turbulence to simulate FW power flows in SOL:
  - Expect reduced edge losses and less fast-ion interaction with antenna at higher $B_T(0)$



AORSA Re($E_{//}$) Simulation

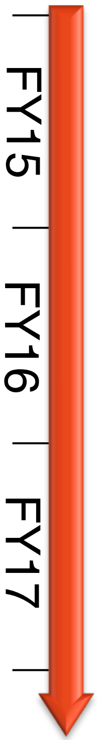
Without full 3D antenna model

30 MHz FW n_f = 12 heating in NSTX-U with $B_T(0)$ = 1 T

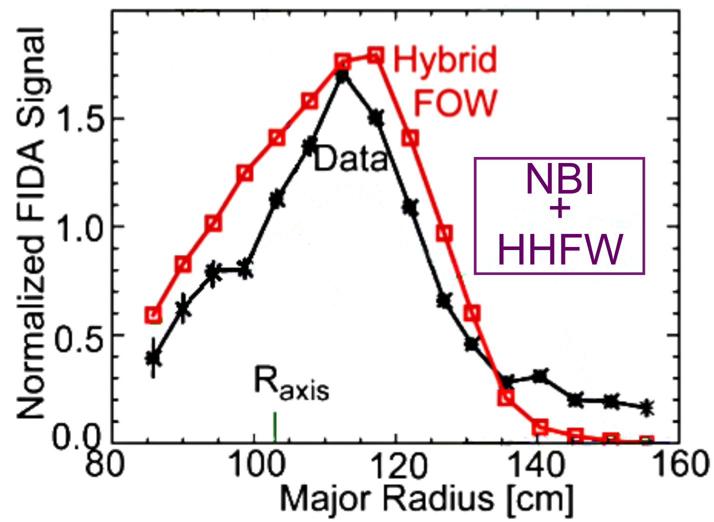


Back-up # 28

Upgraded RF codes and diagnostics will support studies of FW interaction with ions



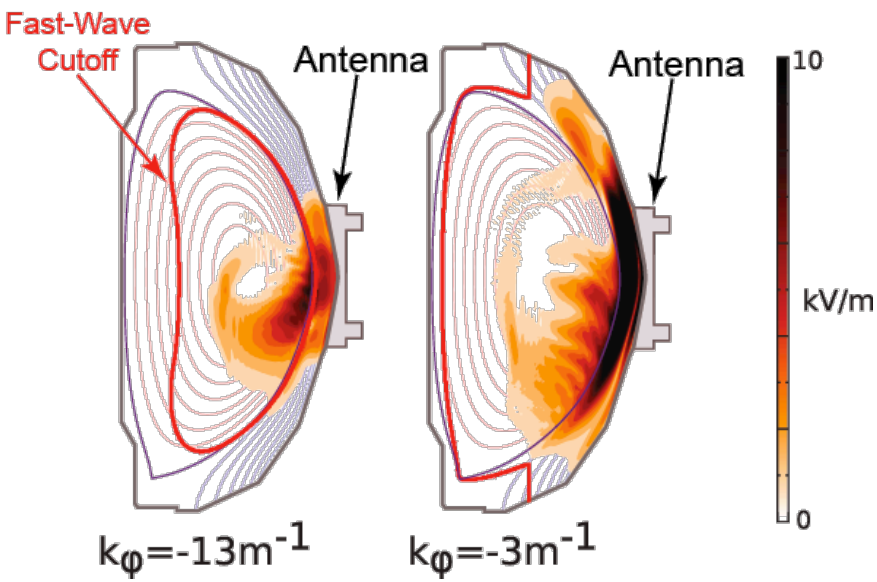
- Studies of the FW interaction with ions will benefit from improved simulation tools:
  - Full-orbit “Hybrid” finite orbit width version of the CQL3D Fokker-Planck code now shows good agreement with NSTX fast ion diagnostic (FIDA) data



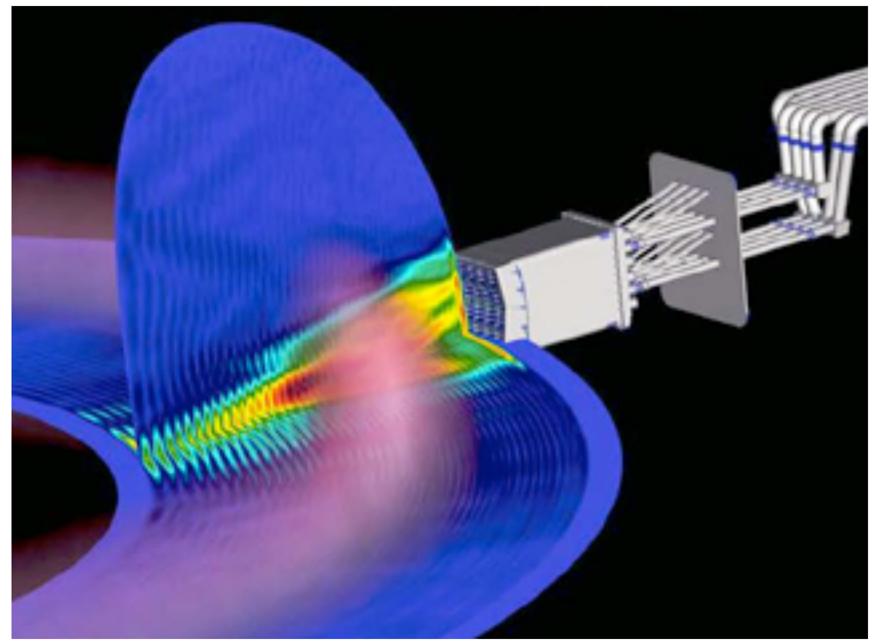
- Upgraded fast-ion diagnostic suite and upgraded RF codes will be employed to study FW interactions with ions in FW+NBI H-modes:
  - Vary antenna phasing, beam source mix, density and magnetic field
  - compare results to RF codes predictions

Use validated RF codes to predict FW performance in ITER and FNSF

- Having validated RF codes using data from the upgraded diagnostic suite on NSTX-U predict RF performance in ITER and FNSF



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



AORSA simulation of 3-D fast wave electric field propagating in the ITER plasma

FY17

FY18

Back-up # 30-32

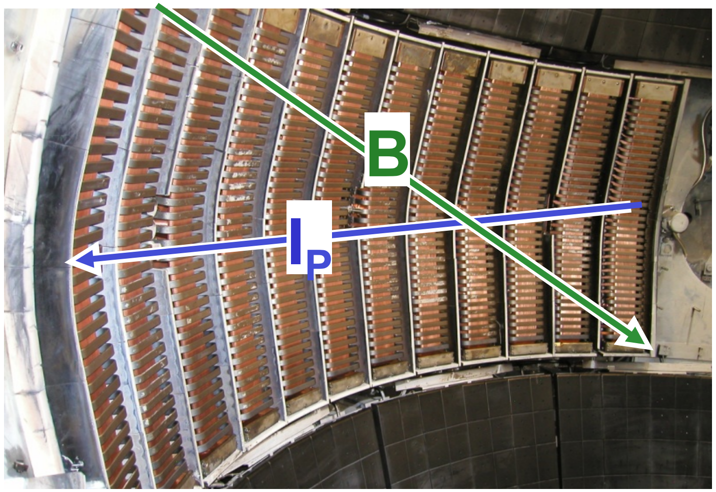
Summary

- NSTX-U RF research program supports fully NI plasma start-up and RF model validation for ITER ICRF
- New research tools on NSTX-U enable the development of RF research relevant to ITER and FNSF:
  - The higher magnetic field regime in NSTX-U is expected to have increased ion absorption and reduced edge losses
  - Cryo-pump may help control the SOL density and improve FW coupling
  - Better diagnostics, including MSE-LIF q-profile and FIDA fast-ion measurements, will help validation of RF codes
  - 28 GHz EC/EBW heating supports the NSTX-U NI strategy

Back-up # 33

Backup Slides

Several enhancements to the NSTX FW system will support NSTX-U operations



12-strap NSTX-U FW antenna extends toroidally 90°

- RF voltage stand-off tests using two antenna straps will be conducted on an RF test stand:
  - Identify location of RF-induced arcs and modify straps for higher stand-off
  - Determine if RF feedthroughs need to be modified for higher stand-off
- Disruption loads will be up to 4x higher in NSTX-U:
  - Install compliant connectors between feedthroughs and straps
  - New feedthroughs will be evaluated on the RF test stand

Additional RF, magnetic and Langmuir probes will support NSTX-U FW research

- Upgraded probe sets in divertor tiles to detect RF
- Langmuir probes in divertor to measure the FW fields
- Measure RF magnetic fields with RF loop probes
- Measure RF-induced currents in the vicinity of RF-produced spirals
- Probes in floor and ceiling will measure wave directionality and distinguish between propagating and standing waves:
  - Permits the study of any parametric decay instability (PDI) in the divertor regions
- Magnetic and Langmuir RF probes in tiles above and below antenna will measure relative strengths of RF fields propagating in each direction along magnetic field

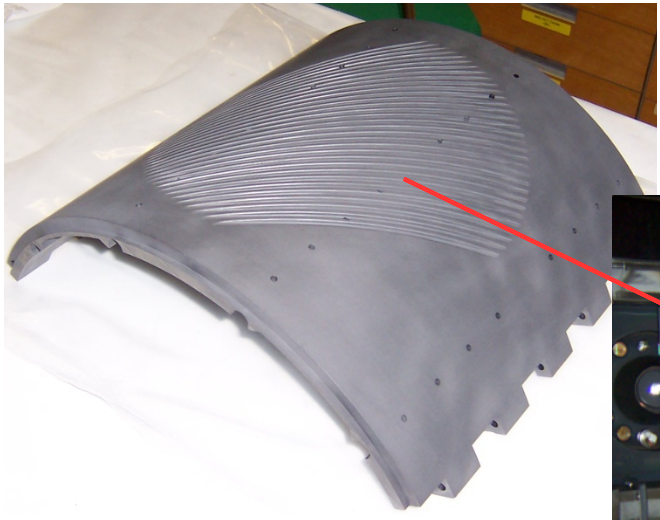
RF research will also benefit from upgraded fast-ion, current profile and edge density diagnostics

- Several diagnostics will provide information on fast-ion interactions with FW power in NSTX-U:
  - Vertical and tangential FIDA systems will provide time ($\Delta t \sim 10$ ms), space ($\Delta r \sim 5$ cm) resolved pitch and energy-weighted measurements of the fast-ion distribution
  - FIDA data will be complemented by an upgraded solid-state Neutral Particle Analyzer with 5 radial channels and ~ 1 MHz data rate
  - Also there will be a new charged fusion product profile diagnostic and a scintillator-based lost fast-ion probe
- New MSE diagnostic using laser-induced fluorescence will measure CD profile without needing high-power NBI blip:
  - Important for CD measurements in FW-only H-modes
- Upgraded 10-40 GHz refectometer and additional laser Thomson scattering channels will provide improved SOL density data

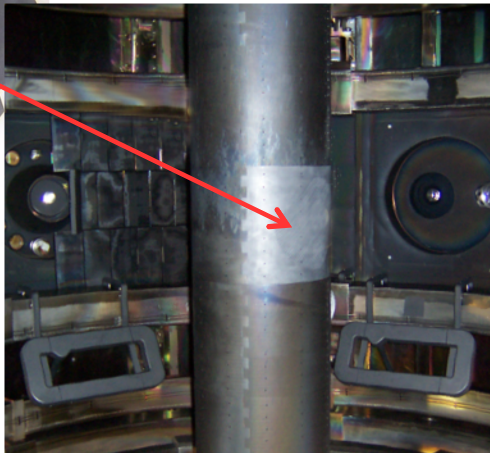
Reduced edge loss and less fast-ion interaction with antenna may improve FW heating in NSTX-U

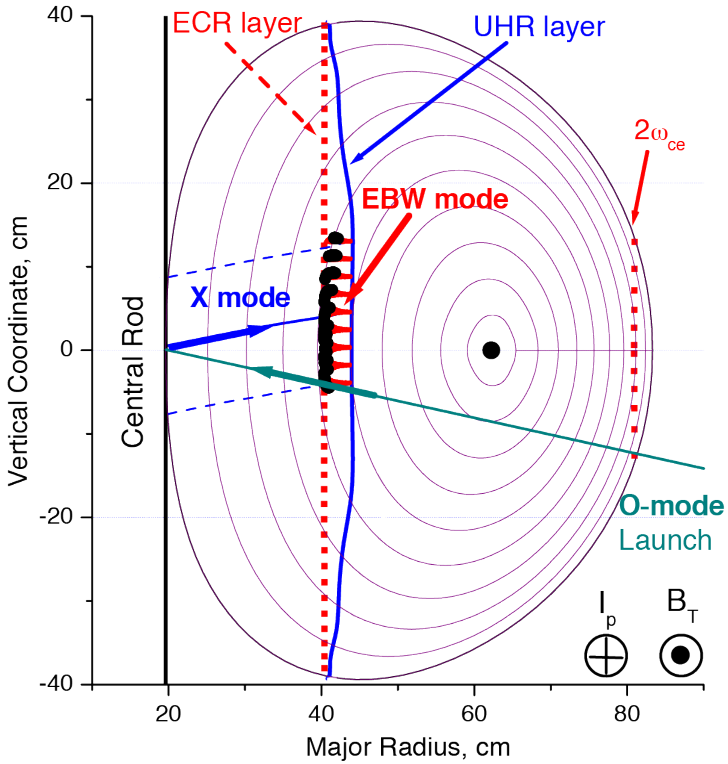
- B_T, I_p and P_{nbi} in NSTX-U will be up to twice as high as in NSTX
- This has implications for FW coupling & heating efficiency:
  - Higher B_T moves the FW cut off towards or inside the separatrix
    → reducing surface wave losses
  - Scrape off layer (SOL) width may shrink at higher I_p
    → also reducing surface wave losses
  - SOL density may be higher, moving FW cut off outside separatrix and closer to the 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

Will employ 28 GHz EBW heating for start-up using a technique used successfully in MAST*



Grooved reflecting polarizer machined into center column in MAST



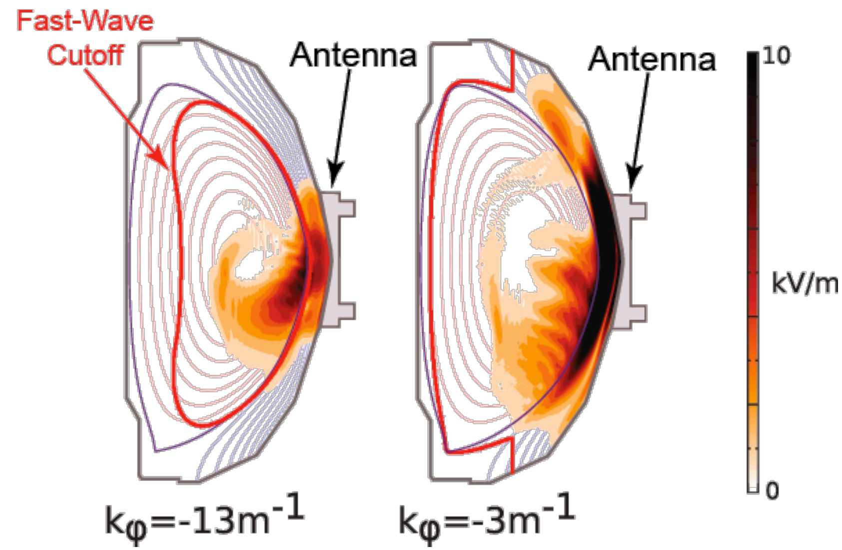


- O-mode EC waves launched from low field side are weakly absorbed (< 2%) below the cut off electron density of ~ 1 x 10^{19} m^{-3}
- Grooved reflecting polarizer on the center column converts O-mode to X-Mode that then ~ 100% converts to EBWs

* V. F. Shevchenko et al. Nucl. Fusion **50** (2010) 022004

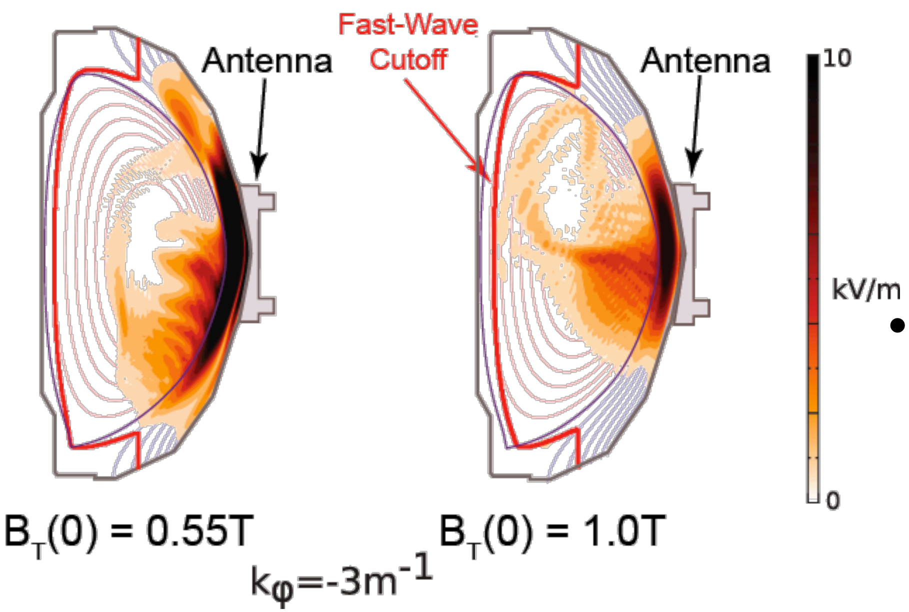
AORSA full-wave code predicts large amplitude coaxial standing modes in SOL in NSTX H-mode

- Edge coaxial mode seen in NSTX $B_T(0) = 0.55$ T simulations



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

- Edge mode is significantly reduced when $B_T(0)$ is increased from 0.55 T to 1 T



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

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

Improvements in TORIC and GENRAY are currently being implemented or planned

TORIC Full Wave Code:

- Present SOL model extends to the antenna Faraday shield, but assumes the antenna current strap is in vacuum:
  - In the near-term, use this simplified SOL model in simulations with no Faraday shield and with current strap at the edge of SOL
  - Surface wave excitation will then be studied (similar studies have already been started with AORSA)
  - In the long-term, the TORIC solver will be combined with an edge model with a realistic 3-D antenna and vacuum vessel

GENRAY Ray Tracing Code:

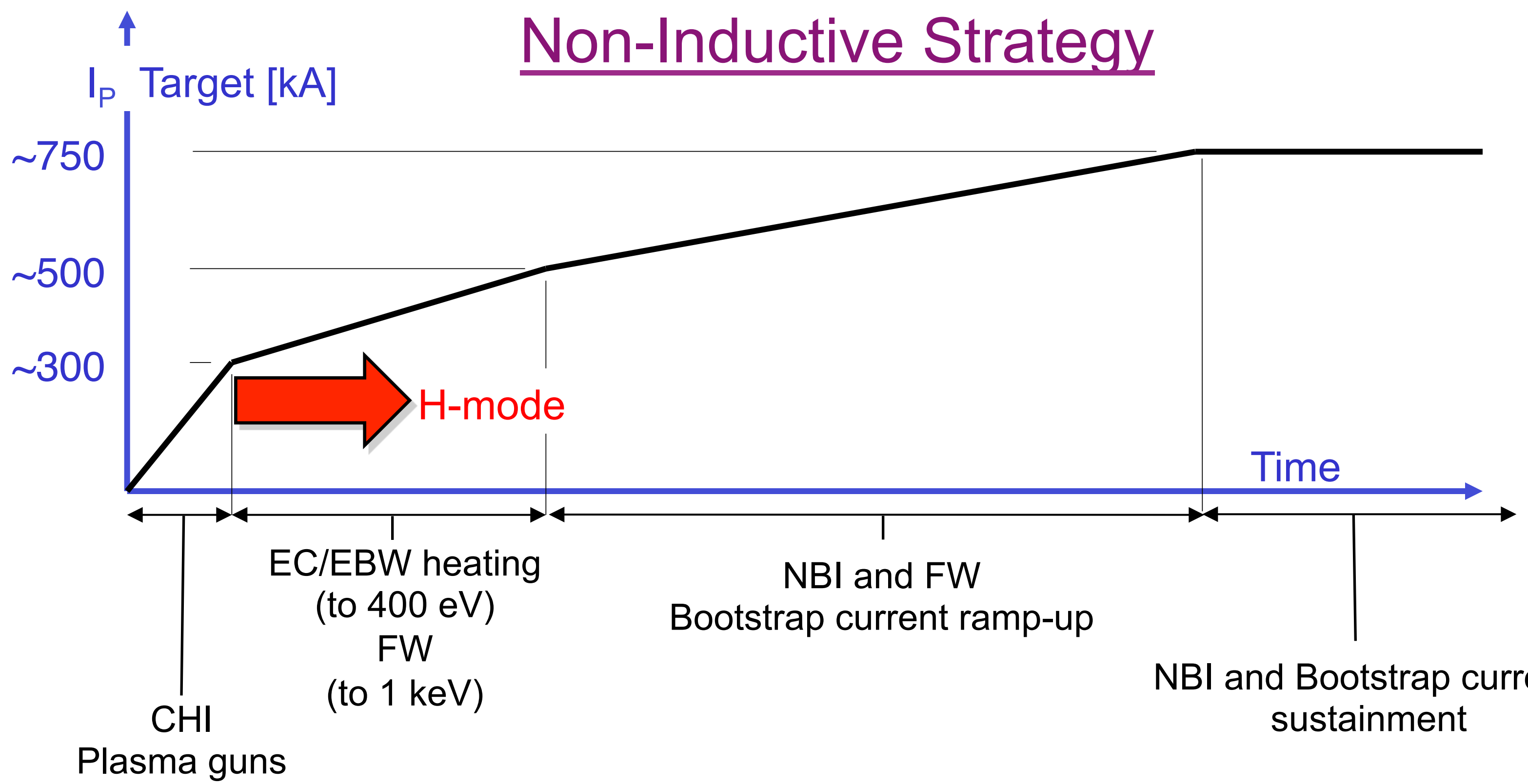
- Recently upgraded to include a 2-D model for the SOL:
  - An edge scattering model for the FW regime will be implemented to evaluate the impact of edge density fluctuations on coupling
  - The resulting output from GENRAY will be used in CQL3D to calculate the perturbed electron distribution and quasi-linear wave absorption

RF research supported by suite of numerical codes whose predictions will be validated

- RF code development for NSTX-U involves a collaboration between the NSTX-U, C-Mod and DIII-D RF programs
- Significant support from the USDoE RF-SciDAC Center for Simulation of Wave-Plasma Interactions
- Simulation codes being used to predict RF heating and CD performance in NSTX-U:
  - AORSA [E. F. Jaeger et al., Nucl. Fusion **46** (2006) S397]
  - TORIC [M. Brambilla, Plasma Phys. and Cont. Fus. **44** (2002) 2423]
  - GENRAY [http://www.compxco.com/genray.html]
  - TORBEAM [E. Poli et al., Comput. Phys. Commun. **136** (2001) 90]
  - CQL3D [http://www.compxco.com/cql3d.html]
  - ORBIT-RF [M. Choi et al., Phys. Plasmas **16** (2009) 052513]
  - SPIRAL [G.J. Kramer et al., Plasma Phys. Control. Fusion **55** (2013) 025013]

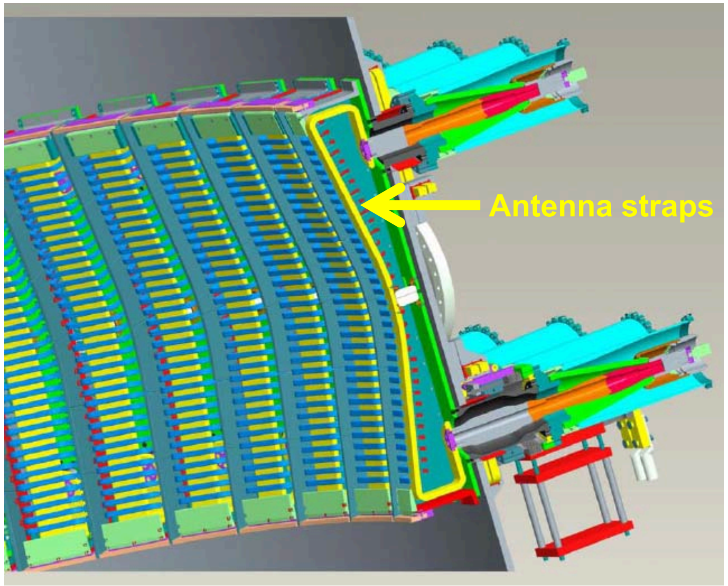
Thrust RF-1

Develop FW and EC heating for fully NI discharges

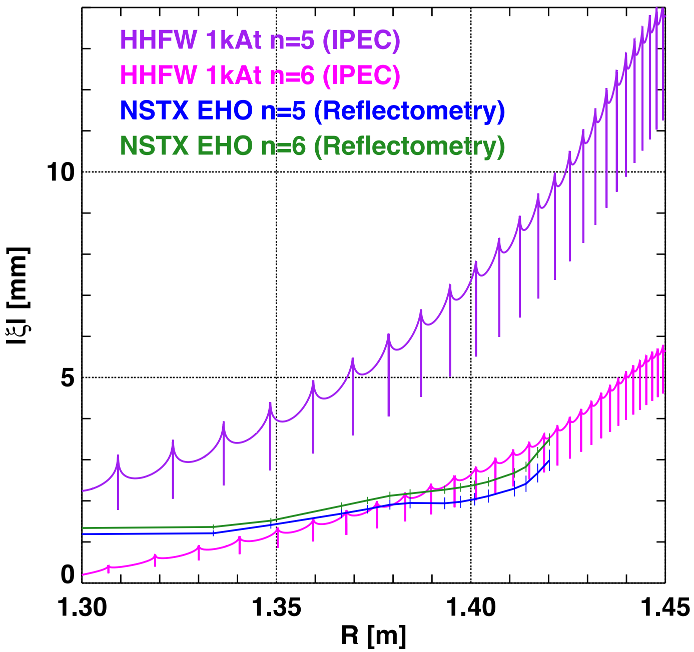


- Experiments in NSTX-U will initially develop NI start-up, ramp-up and plasma sustainment separately
- Reduced RF edge losses and fast-ion interactions with the FW antenna may yield improved RF coupling and heating efficiency

Is driving edge harmonic oscillations (EHOs) key to active edge control?

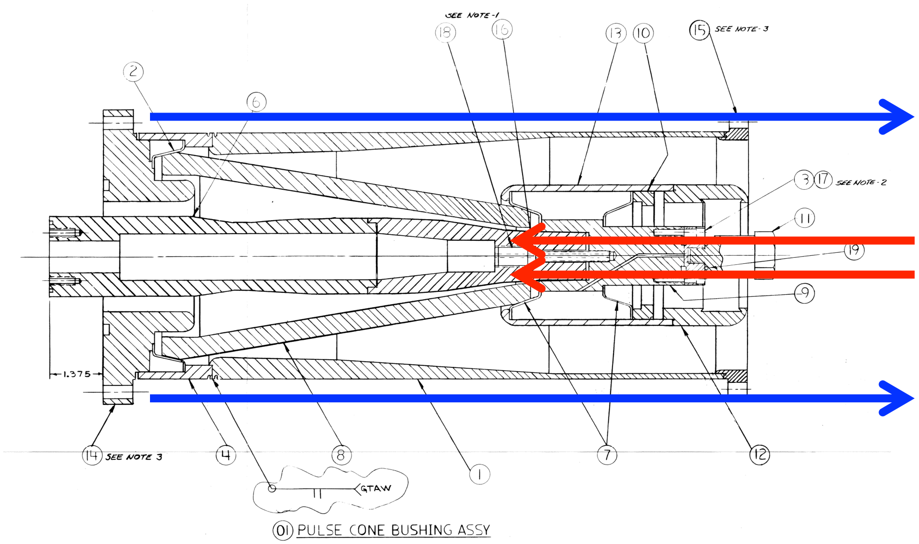


FW vs. NSTX EHO



- MHD calculations indicate we can amplify edge kinks by driving FW antenna straps at audio frequencies
- Can this give us external control over edge pressure gradient (and so ELMs) and/or the SOL width?

FW antenna has robust feed-throughs and low impedance at audio frequencies



Current path avoids thin copper cones

Antenna Impedance (single strap, 10 kHz)

R = 2.2 mW

L = 0.32 μH

⇒ @ 1 KA, 10 kHz

Resistive Voltage = 2.2V

Inductive Voltage = 20V

- Coupling circuit will need to minimize parasitic losses

Experimental plan for testing EHO drive

- *With incremental funding can test EHO drive using FW antenna straps in FY2017-18*

Proof-of-Principle

Induction Heater

- Fixed frequency, adjustable between shots
- Determine currents required to drive EHOs, see (or not) effects

Plasma Control

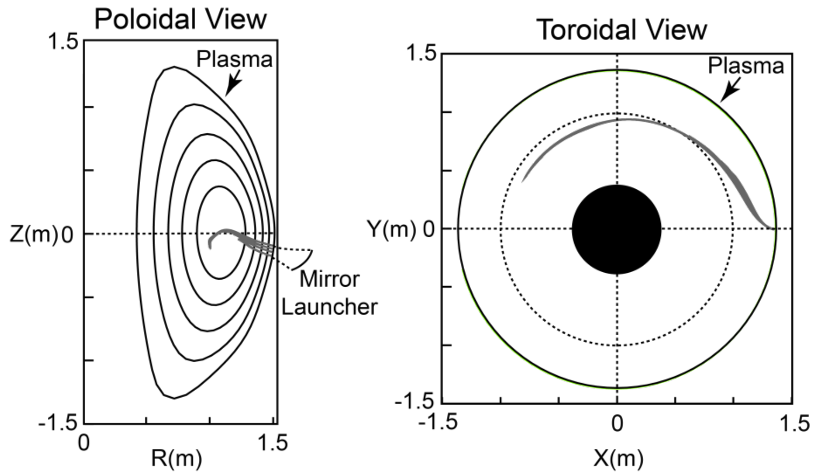
Audio Amplifiers

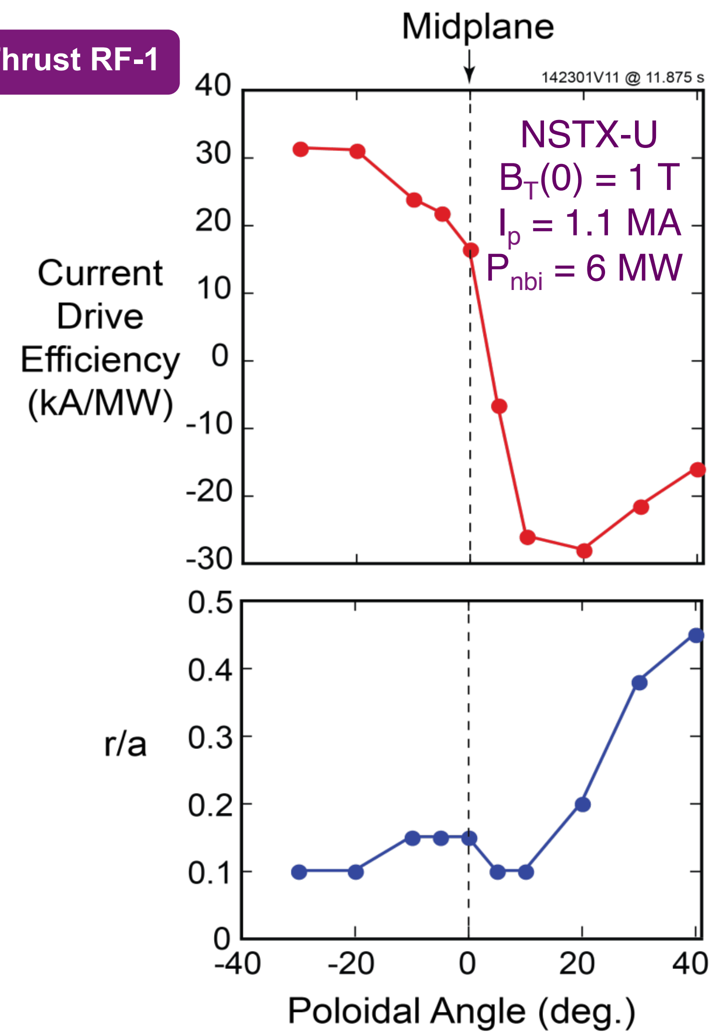
- Feedback control on frequency and amplitude to track EHOs and control pedestal ∇p

Simulate 28 GHz EBW heating and CD in NSTX-U H-modes

- EBW simulations for an NSTX-U H-mode predict η_{eff} ~ 25 kA/MW for $n_e(0) = 9 \times 10^{19} m^{-3}$ and $T_e(0)$ = 1.2 keV:
  - Can generate significant EBWCD at r/a > 0.8, where NBICD is negligible in NSTX-U

Thrust RF-1

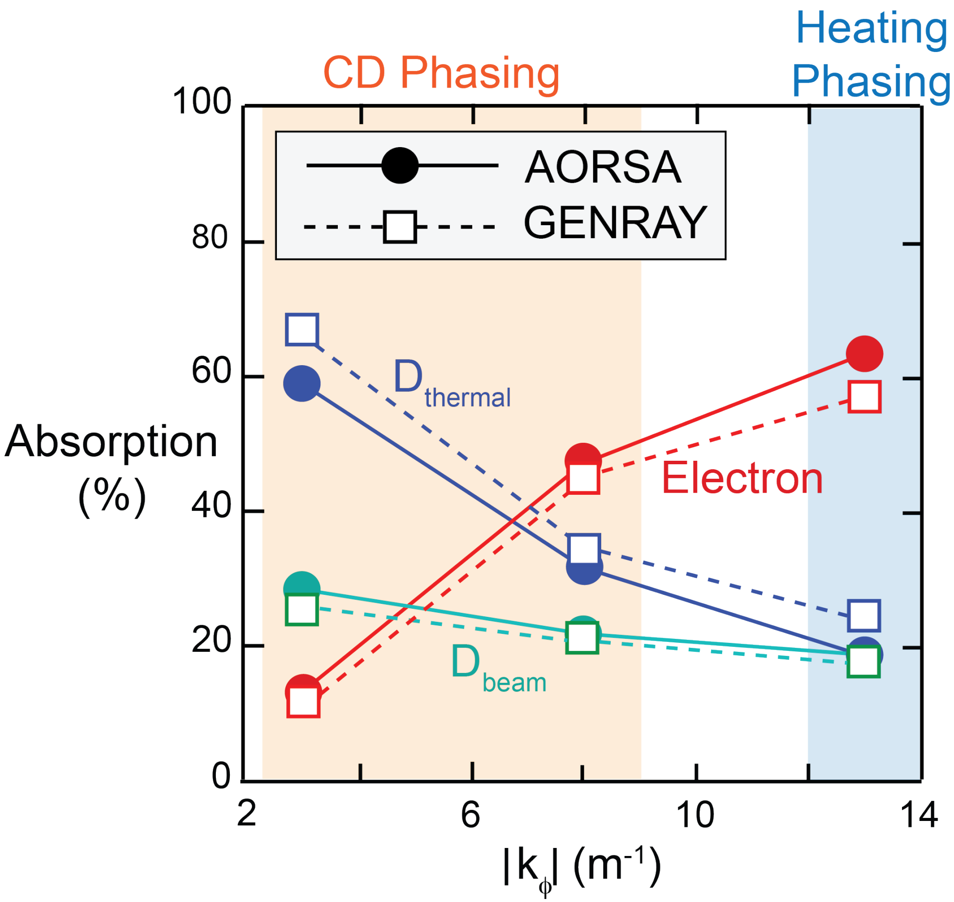




- Detailed modeling, including SOL and edge fluctuations will guide the conceptual design of the 28 GHz heating system

Good agreement between AORSA full wave code and GENRAY ray tracing code

NSTX-U NBI + FW H-Mode
During I_p Flat-top



AORSA and GENRAY Modeling Results (from TRANSP simulation)

$B_T(0)$ = 1 T, I_p = 1.1 MA,
P_{nbi} = 6.3 MW, $n_e(0) = 1.1 \times 10^{20}$ m^{-3}
$T_e(0)$ = 1.22 keV, $T_i(0)$ = 2.86 keV