NSTX-U

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

Progress and Plans for Fast Wave and Electron Cyclotron Heating Research

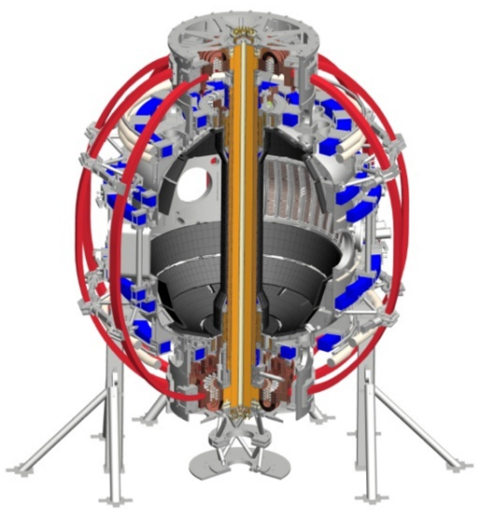
Rory Perkins

Gary Taylor, Nicola Bertelli, Mario Podestà, Nikolai Gorelenkov

for the NSTX-U Research Team

NSTX-U PAC-35 Meeting
PPPL – B318
June 11-13, 2014

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



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

Outline

- Motivation for Fast Wave (FW) & (future) Electron Cyclotron (EC) and Electron Bernstein Wave (EBW) research
- Progress during the past year
- Research goals and plans for FY 2015 & 2016
- Summary

Outline

- Motivation for Fast Wave (FW) & (future) Electron Cyclotron (EC) and Electron Bernstein Wave (EBW) research
- Progress during the past year
- Research goals and plans for FY 2015 & 2016
- Summary

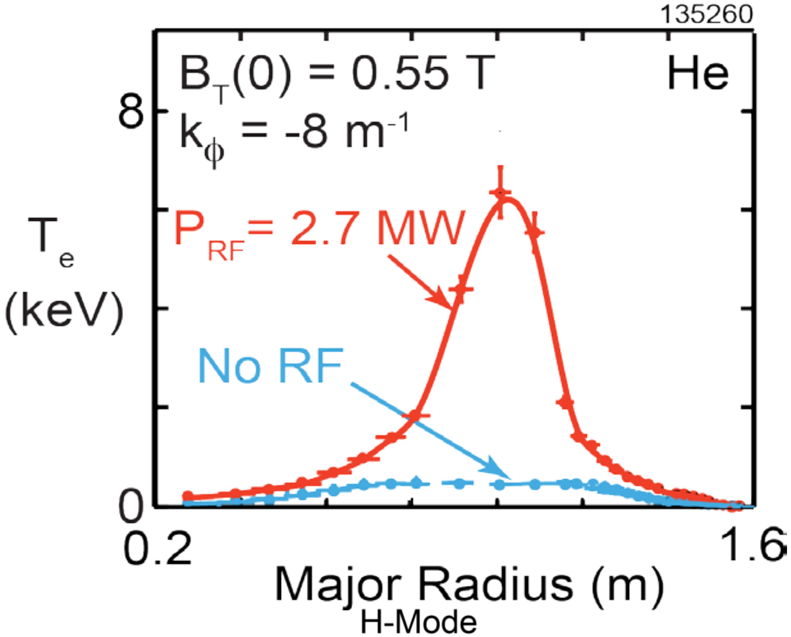
RF research in Five-Year Plan supports non-inductive (NI) operation

- 30 MHz FW and 28 GHz EC/EBW heating research support two high-level NSTX-U goals:
  - Developing and understanding NI plasma current start-up and ramp-up in order to project to a ST-FNSF
  - Demonstration of 100% NI operation at performance levels extrapolating to ≥ 1 MW/m^2 neutron wall loading in a FNSF

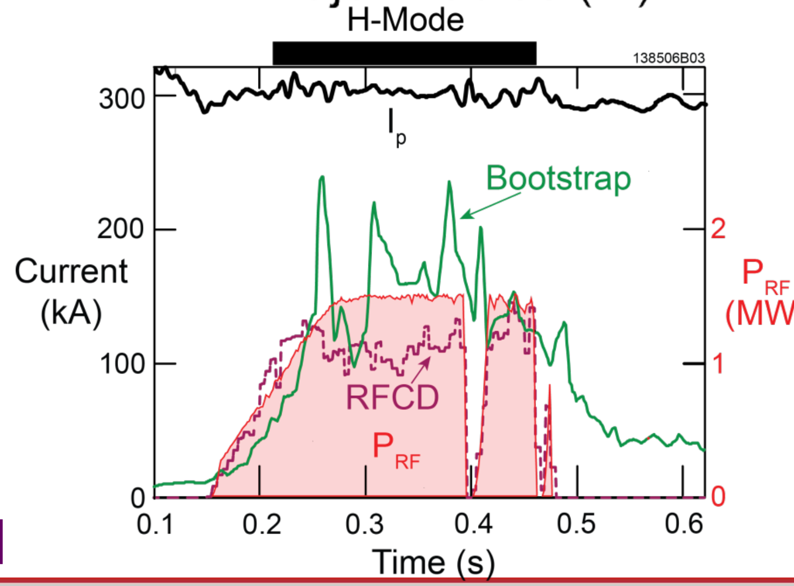
- FW, EC and electron Bernstein wave (EBW) heating can facilitate start-up, ramp-up, and sustainment:
  - EC heating can increase $T_e(0)$ in CHI and gun-initiated plasmas to allow NBI and FW heating
  - FW-driven NI I_p ramp-up to a level that can confine fast-ions from neutral beams
  - EBW heating can potentially provide CD in NBI H-mode plasmas

FW heating led to record high electron temperatures and support a largely NI 300 kA H-mode plasma on NSTX

- Record Te ~ 6.3 keV attained with 2.7 MW of FW power
  - L-mode Ohmic target plasmas
  - Can potentially be used for physics studies



- Sustained >70% NI I_p ~ 300 kA H-mode plasma
  - Mostly bootstrap current
  - P_{FW} ~ 1.4 MW; limited by antenna arcing (Li flakes or density drops)

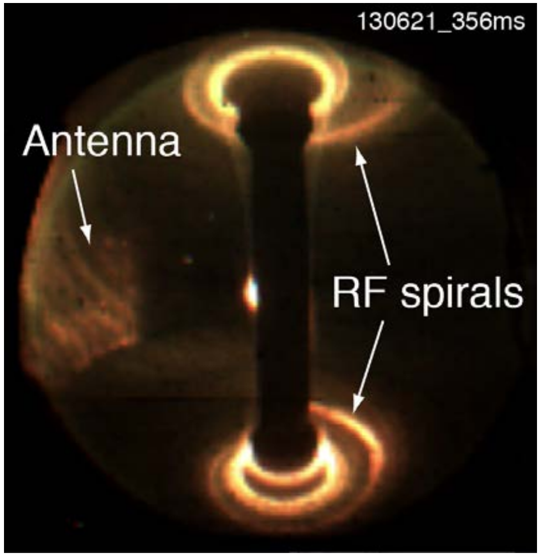


[G. Taylor et al., Phys. Plasmas **19** (2012) 042501]

Optimized FW heating requires understanding FW interactions with SOL and with ions

- FY16 milestone [R16-3]

- Field-aligned FW losses in SOL produced bright hot spiral on NSTX divertors
  - Up to 30% of applied FW power might be lost to the SOL in this fashion
  - Mechanisms responsible for this power loss have yet to be definitively identified



- Assess FW absorption on NB and thermal ions in NSTX-U:
  - Fast ions accelerated by FW power to loss orbits could significantly reduce heating efficiency
  - Can influence/suppress Alfvén eigenmodes [M. Podestà's talk]

Continue to develop and validate RF codes for ST parameters to predict future performance

- AORSA: full-wave code, all-orders in $k_{perp}\rho$
  - Compare computations of RF fields in SOL against measurements of RF fields in divertor over a range of SOL and antenna parameters
  - Validate partition of FW power absorption between fast ions, thermal ions, and electrons
- TORIC: full-wave code (reduced model) with TRANSP interface
  - Benchmark ion absorption of FW against AORSA and GENRAY
  - Study non-Maxwellian (fast ion) effects on FW propagation
- GENRAY (ray-tracing) & CQL3D (Fokker-Planck code)
  - Hybrid full-orbit, finite orbit width has potential to accurately describe beam-ion interaction with FW (collaboration with R. Harvey, CompX)

Outline

- Motivation for Fast Wave (FW) & (future) Electron Cyclotron (EC) and Electron Bernstein Wave (EBW) research
- Progress during the past year
- Research goals and plans for FY 2015 & 2016
- Summary

AORSA simulations show low FW losses in SOL depending on location of righthand cutoff

- Field-amplitude depends on location of righthand cutoff
  - Large amplitude when region in front of antenna is propagative
  - Low amplitude when region in front of antenna is cutoff
  - Transition is sharp

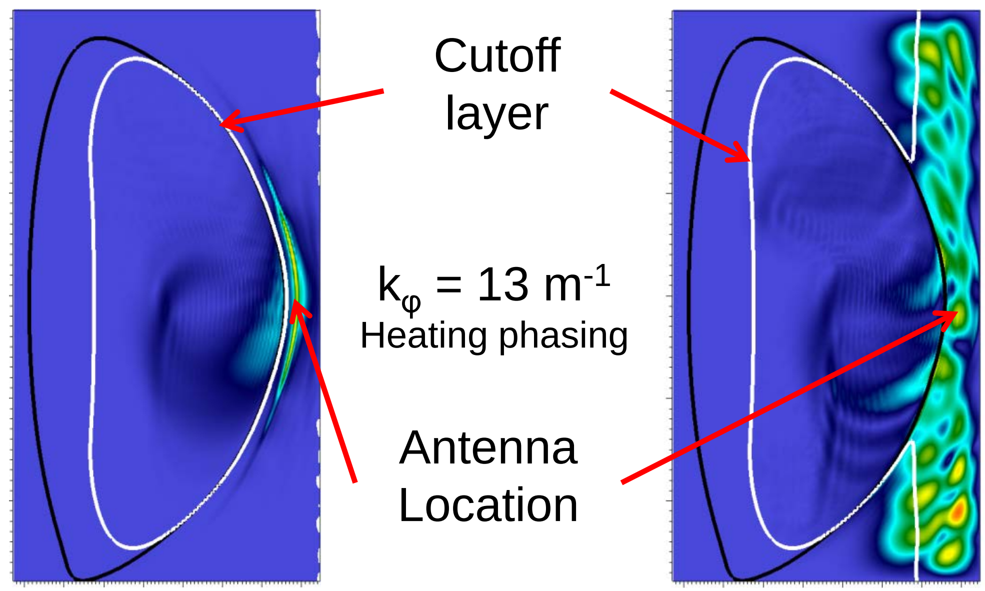
$$n_{\mathrm{e,FWcut-off}} \propto \frac{k_{\|}^2 B}{\omega}$$

- NSTX-U at $B_T(0)$ = 1.0 T will have wider evanescent region:
  - AORSA predicts reduced SOL losses
  - Previous experiments showed improved heating in going from 0.45 T to 0.55 T

[J. Hosea et al., Phys. Plasma 15 (2008) 056104]

Lower SOL density (n_{ant} = 1×10^{12} cm^{-3})

Higher SOL density (n_{ant} = 2×10^{12} cm^{-3})



[N. Bertelli et al., Nucl. Fusion 54 (2014) 083004]

Probe analysis suggests RF rectification is an important contributor to FW losses in SOL

- Heat flux to Langmuir probes is doubled underneath spiral relative to probe away from spiral (shot 141899)

q_{RF} = 0.209 MW/m^2 q_{noRF} = 0.103 MW/m^2

- RF fields produces negative shift in probe floating potential
  - $V_{fl\text{-}RF}$ and $V_{fl\text{-}noRF}$ floating potentials relative to tile with and without RF
  - RF voltage (V_{RF}) under spiral related to shift in floating potential:

$$\exp[(V_{fl\text{-}noRF} - V_{fl\text{-}RF})/T_e) = I_0(V_{RF}/T_e)$$

[A. Boschi and F. Magistrelli, Il Nuovo Cimento 29 (1963) 487]

- Sheath transmission factor with RF obtained by adding $V_{RF}\sin(\omega t)$ to potential drop and averaging γ over RF cycle

$$q_{surface} = \gamma \times j^{+}_{sat} \times T_e$$

$$\gamma_{noRF} = -\frac{V_f}{T_e} + \frac{V_{fl-noRF}}{T_e} + 2.5\frac{T_i}{T_e} + \frac{2}{1-\sigma_e}\exp\left[-\frac{V_{fl-noRF}}{T_e}\right]$$

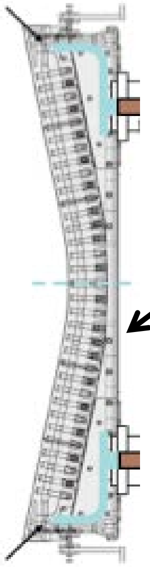
$$\gamma_{RF} = -\frac{V_f}{T_e} + \frac{V_{fl-noRF}}{T_e} + 2.5\frac{T_i}{T_e} + \frac{2}{1-\sigma_e}\exp\left[-\frac{V_{fl-RF}}{T_e}\right]$$

- Enhancement of heat flux probably larger at more intense portion of spiral
- Coaxial Langmuir probes on NSTX-U will permit direct measurement of V_{RF}

Using upgrade outage period to identify and implement improvements to FW antenna for NSTX-U

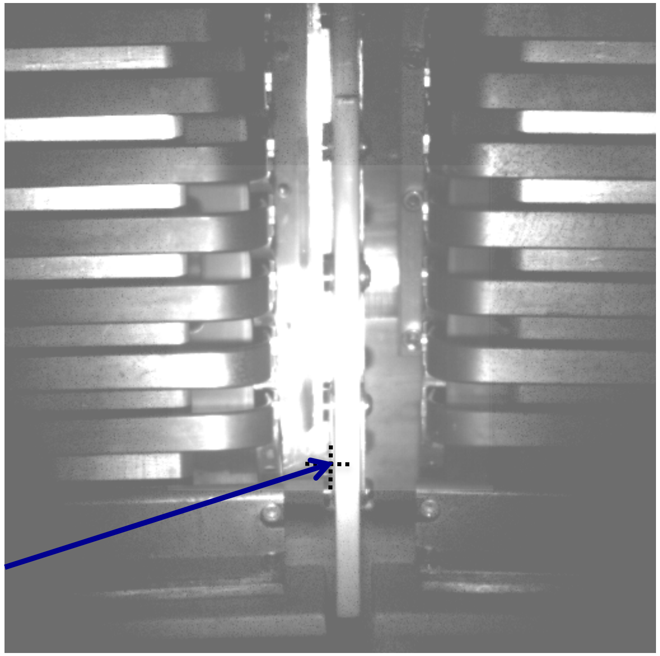
- Utilizing RF test-stand previously used for TFTR
- Arcing observed between straps near low-voltage point
  - Resolved with additional grounding to vessel wall
  - Being implemented on NSTX-U
- Good agreement between measured and predicted antenna heating (see backup)

Poloidal Cut of Antenna Strap



Additional grounding implemented

Face-on View of Two Antenna Straps



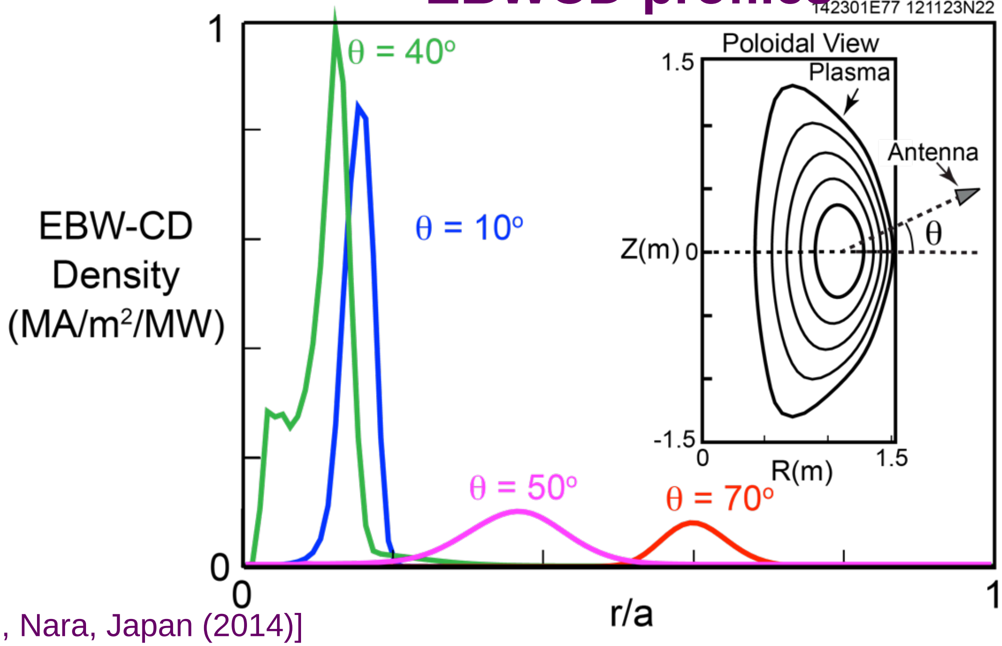
Location of arc

Modeling for EC/EBW heating and current drive performed for long-term NSTX-U goals

- ECH simulations suggest favorable performance in start-up
  - $B_T(0)$ = 1 T CHI start-up plasma (F. Poli's presentation)
  - First-pass EC absorption rising to ~ 50% from initial < 5 %
  - $T_e(0)$ increasing from 10 eV to ~ 1 keV in < 30 ms
  - 73 kA NI CD with 80 kW of EBW power during MAST EBW startup experiment last year (V. Shevchenko, G. Taylor in collaboration)

- EBW modeling for NBI H-modes predicts CD efficiencies ≤ 40 kA/MW:
  - 100% NI plasmas
  - Peak EBWCD density around 1 MA/m²/MW

EBWCD profiles



[G. Taylor, et al., Proc. 18th Joint Workshop on ECE and ECRH, Nara, Japan (2014)]

Outline

- Motivation for Fast Wave (FW) & (future) Electron Cyclotron (EC) and Electron Bernstein Wave (EBW) research
- Progress during the past year
- Research goals and plans for FY 2015 & 2016
- Summary

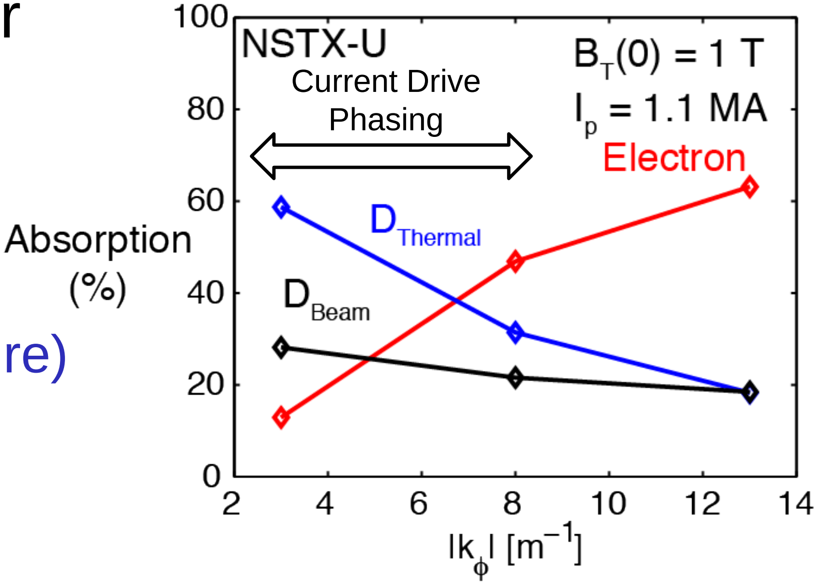
FY2015 Goal: Assess antenna performance and characterize field-aligned FW losses in SOL

- Assess performance of FW antenna in NBI H-mode $B_T(0) \leq 0.8$ T discharges:
  - Assess double-feed performance in both boronized and lithiated conditions
  - Assess interactions of beam-ions with antenna limiters
    - New dedicated IR camera will monitor antenna heat loads
- Optimize FW heating by varying the position of the righthand cutoff for $B_T(0) \leq 0.8$ T:
  – Vary the toroidal field strength (expect higher heating efficiency)
  – Modify edge density (gas puffing and Li conditioning)
  – Vary antenna phasing
  – Monitor SOL losses with wide-angle IR camera, dedicated Langmuir probe array, and poloidal bolometric array for SOL

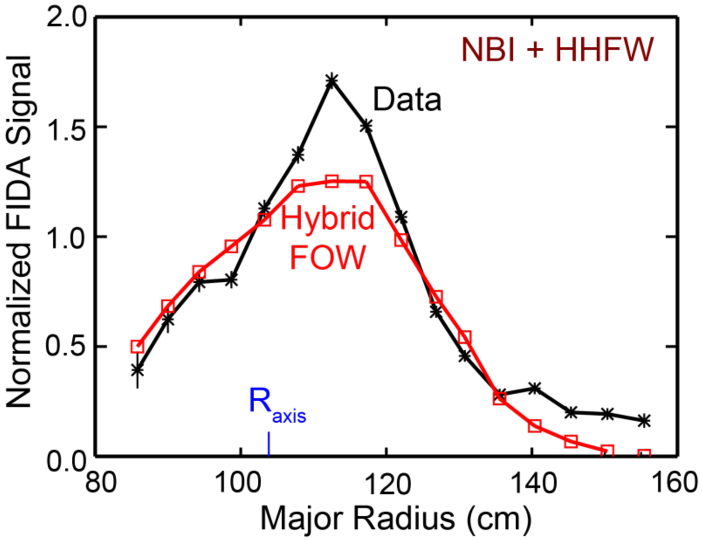
FY2015 Goal: Assess FW heating and current drive with NBI fast-ions in $B_T(0) \leq 0.8$ T discharges

- AORSA simulations predict greater deuterium heating when $T_i > T_e$
  - Ion heating increases and electron heating decreases as k_ϕ decreases
  - Results sensitive to T_i/T_e (= 2.5 in figure)
  - Current drive is mostly bootstrap

  [N. Bertelli, AIP Conf. Proc. 1580, 310 (2014)]



- Will vary the beam tangency radius, beam injection voltage, k_φ and T_i/T_e (varying density & heating source timing) in experiments
  - Continue validation of CQL3D with fast ion diagnostic (FIDA) data

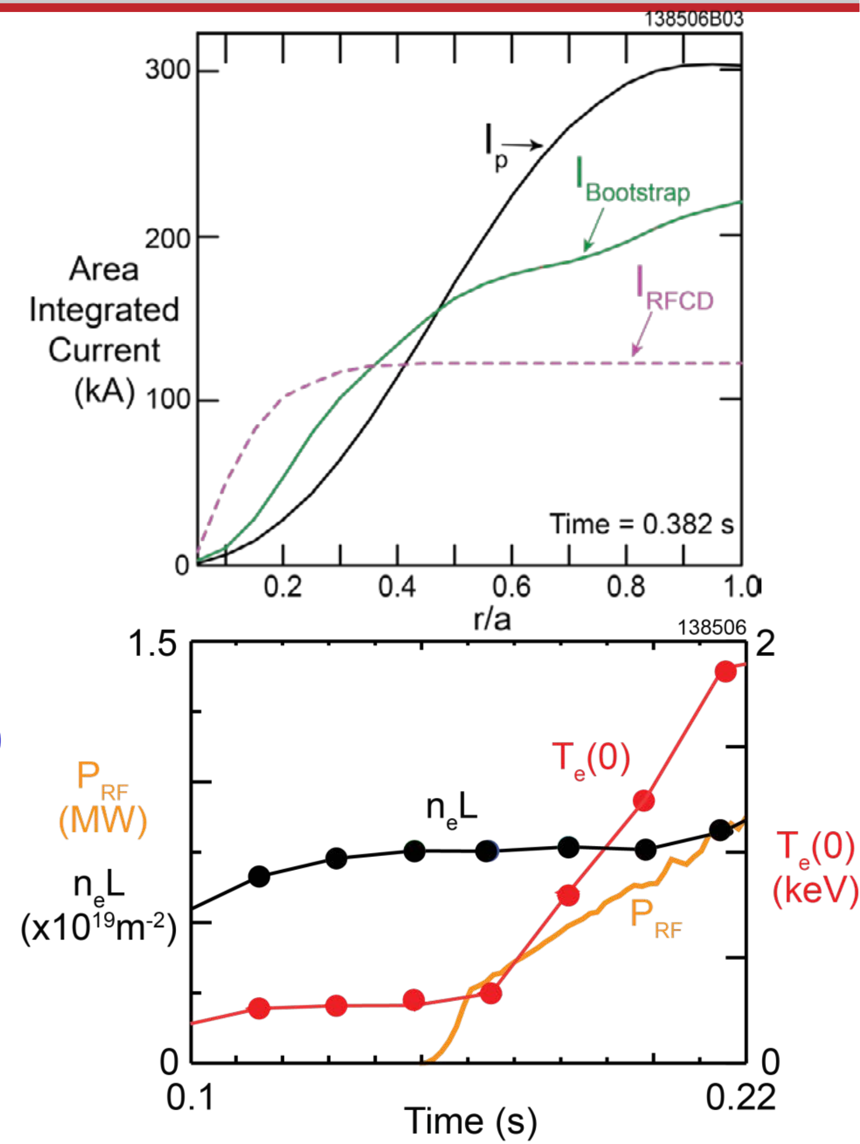


[Collaboration with R. Harvey & CompX]

FY2015 Goal: Sustain fully NI I_p ~ 300 kA H-mode plasmas with only FW power

- Previously generated >70% NI I_p = 300 kA H-mode
  - Rapidly heated plasma to T_e ~ 3 keV
  - P_{RF} ~ 1.4 MW; previously limited by antenna arcing

- This goal will be aided by:
  - Improved Li conditioning & high-voltage standoff of antenna
  - Improved FW coupling (increased B_T)
  - new MSE-LIF q(r) diagnostic
    - does not require heating beam
    - available end of FY2015

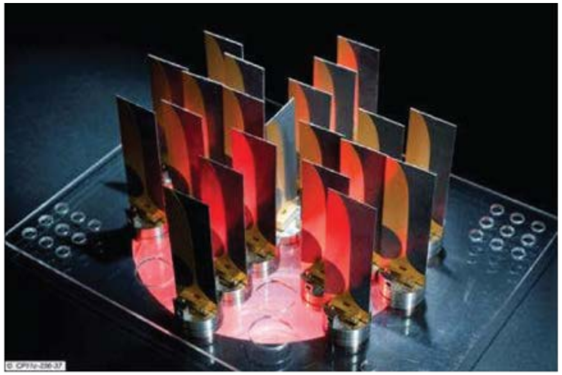


[G. Taylor et al., Phys. Plasmas **19** (2012) 042501]

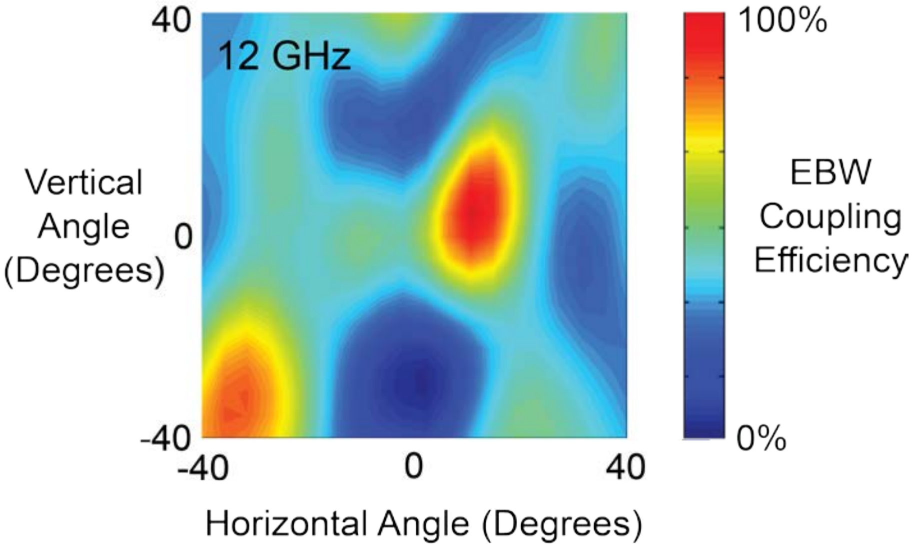
FY2015 Goal: Synthetic aperture microwave imaging (SAMI) diagnostic to image EBW emission

- Assess O-X-B coupling efficiency versus poloidal and toroidal angle
  - Important for EBW heating design (mirror aiming)
- Image Doppler reflectometry to measure edge plasma flows
- Can observe density fluctuation on millisecond timescale
- Will measure magnetic pitch near edge region

[Collaboration with University of York and CCFE



SAMI Antenna Array



MAST SAMI EBW Emission Data

Research goals and plans for FY2016

- Optimize FW heating at highest field values $B_T(0) \leq 1.0$ T
  - Field-aligned SOL losses expected to diminish with increased field
  - Study FW interaction with fast-ions at higher fields

- Assess need for FW limiter upgrade that is compatible with higher P_{nbi} available on NSTX-U:
  - If necessary, upgrade FW limiter during FY16-17 vacuum opening

- Test impact of FW on NBI I_p ramp-up from 400 kA to ~ 1 MA

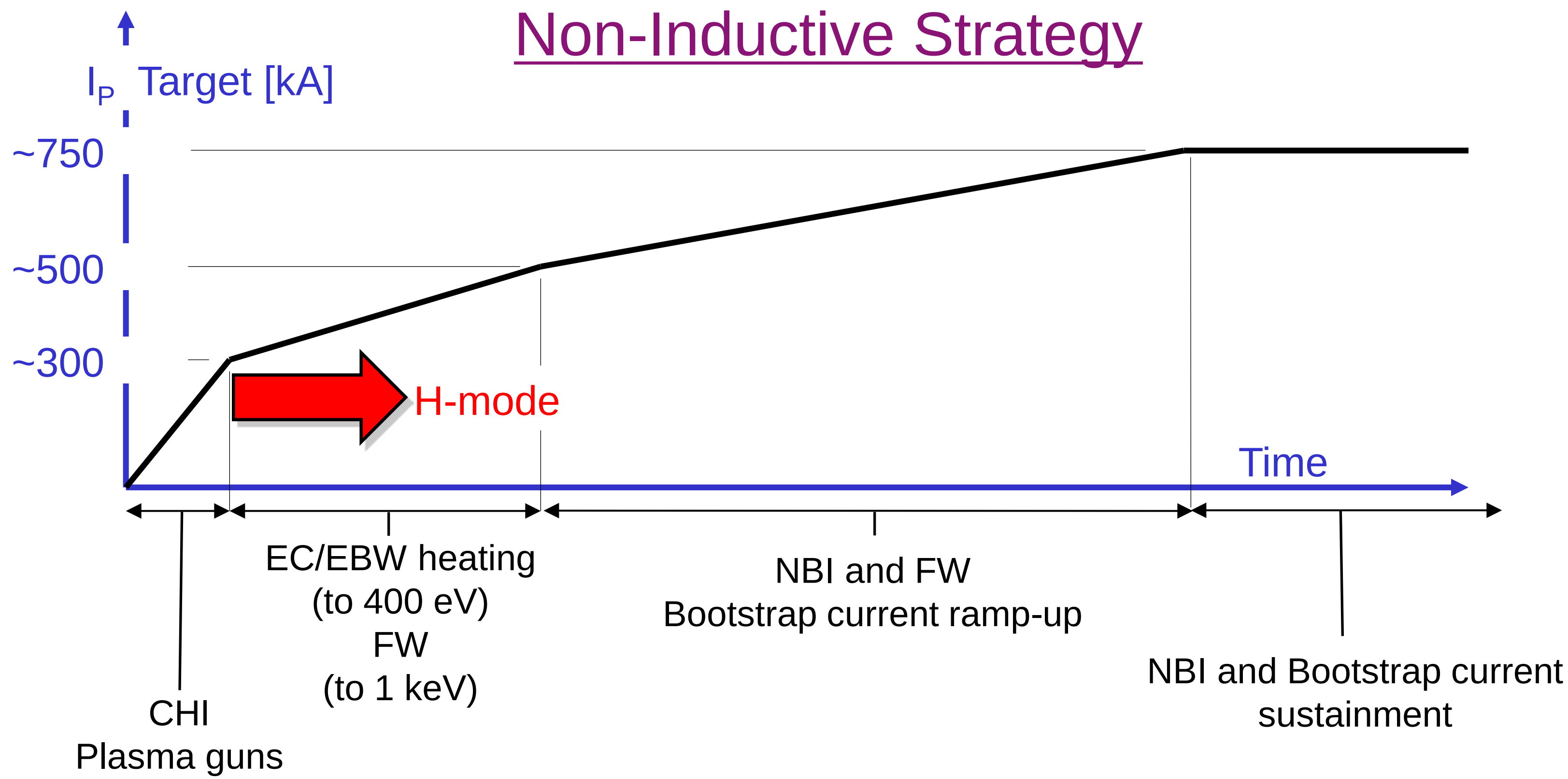
- Demonstrate NI ramp-up of an FW-only H-mode to higher currents (~ 400 - 500 kA)

Summary: NSTX-U FW and EC/EBW research supports non-inductive start-up / ramp-up necessary for ST-based FNSF

- Aim to deliver efficient and reliable coupling of 4 MW of FW power into low-current H-mode plasmas
  - Establish whether combining FW and NBI is operationally viable
  - Establish if upgraded FW limiter is needed to be compatible with NBI
- Demonstrate that FW heating and CD can (with future ECH assist) bridge the gap between CHI start-up and NBI ramp-up
- Establish physics design basis for 28 GHz heating system and complete engineering design:
  - Measure O-X-B coupling efficiency for a wide range of plasma scenarios to determine viability of EBW heating and CD

Backup Slides

Develop FW and EC heating for fully NI discharges

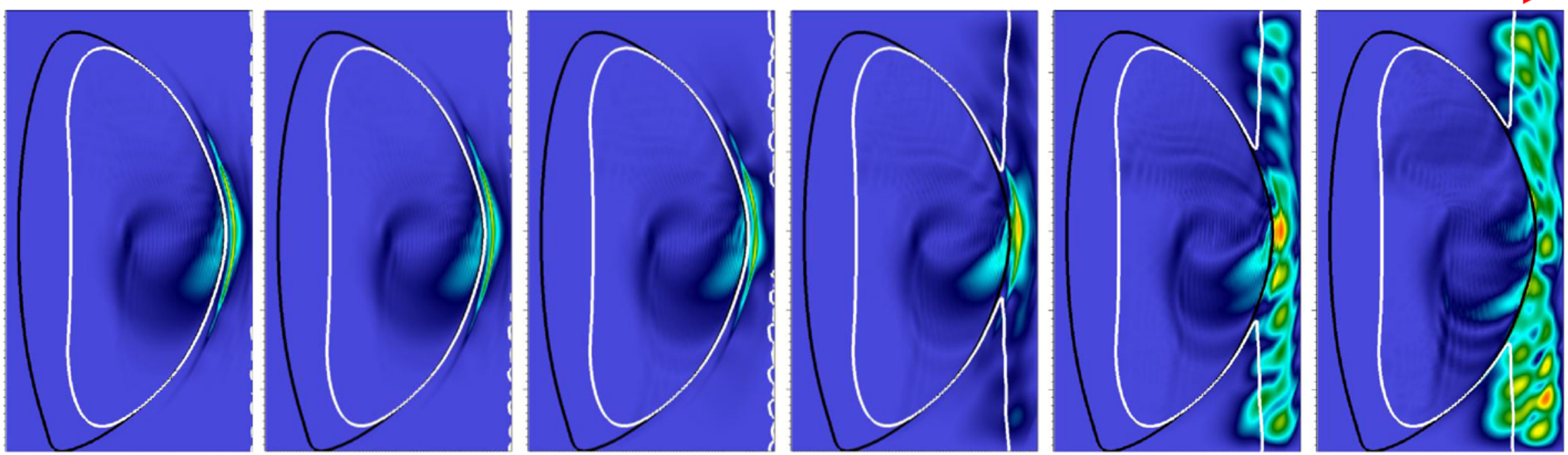


- Experiments in NSTX-U will initially develop NI start-up, ramp-up and plasma sustainment separately
- Reduced RF edge losses and fast-ion interactions with the FW antenna may yield improved RF coupling and heating efficiency

AORSA predicts RF field amplitude in SOL increases when FW cut-off is "open" in front of antenna

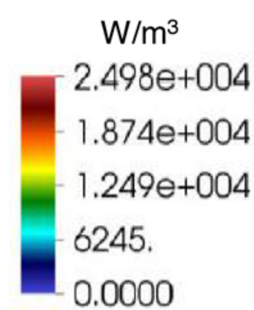
E_{tot} for n_ϕ = -21, $\Delta\phi$ = -150^o (for NSTX Shot# 130608)

$n_{min}[m^{-3}]$ = 0.5×10^{18} 0.7×10^{18} 1.0×10^{18} 1.5×10^{18} 1.7×10^{18} 2.0×10^{18}



- For very low density the RF field is strongly localized in front of the antenna

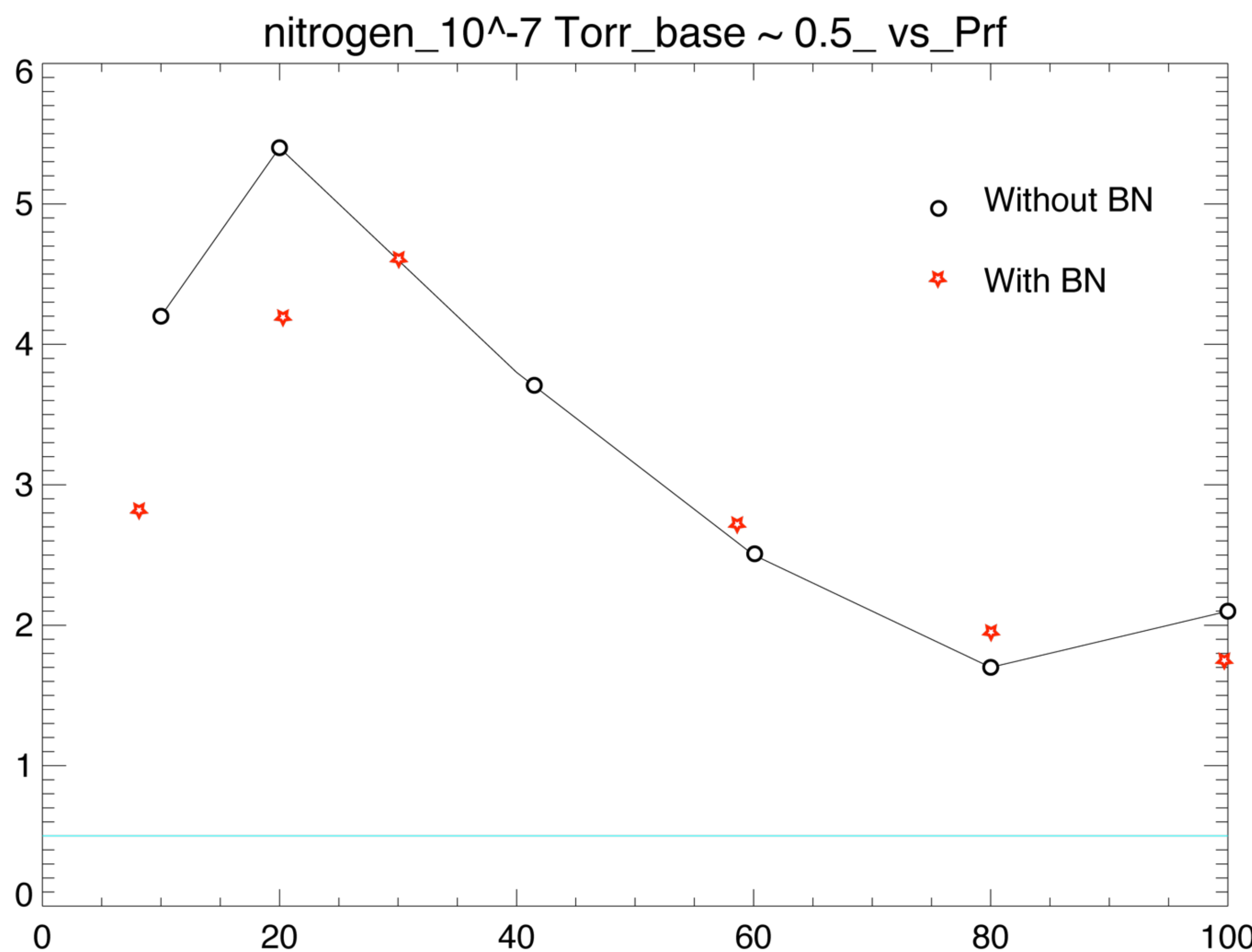
- Standing wave appears at higher density



[N. Bertelli, et al., accepted for publication in Nuclear Fusion (June 2014)]

Total pressure rise in test stand as a function of applied RF power

- Rise and fall in pressure with increased RF power suggests multipacting
- BN stands of the boron nitride septum pieces, which could be removed from test stand
  - Rise and fall is present both with and without boron nitride



Probe analysis suggests RF rectification is an important contributor to FW losses in SOL

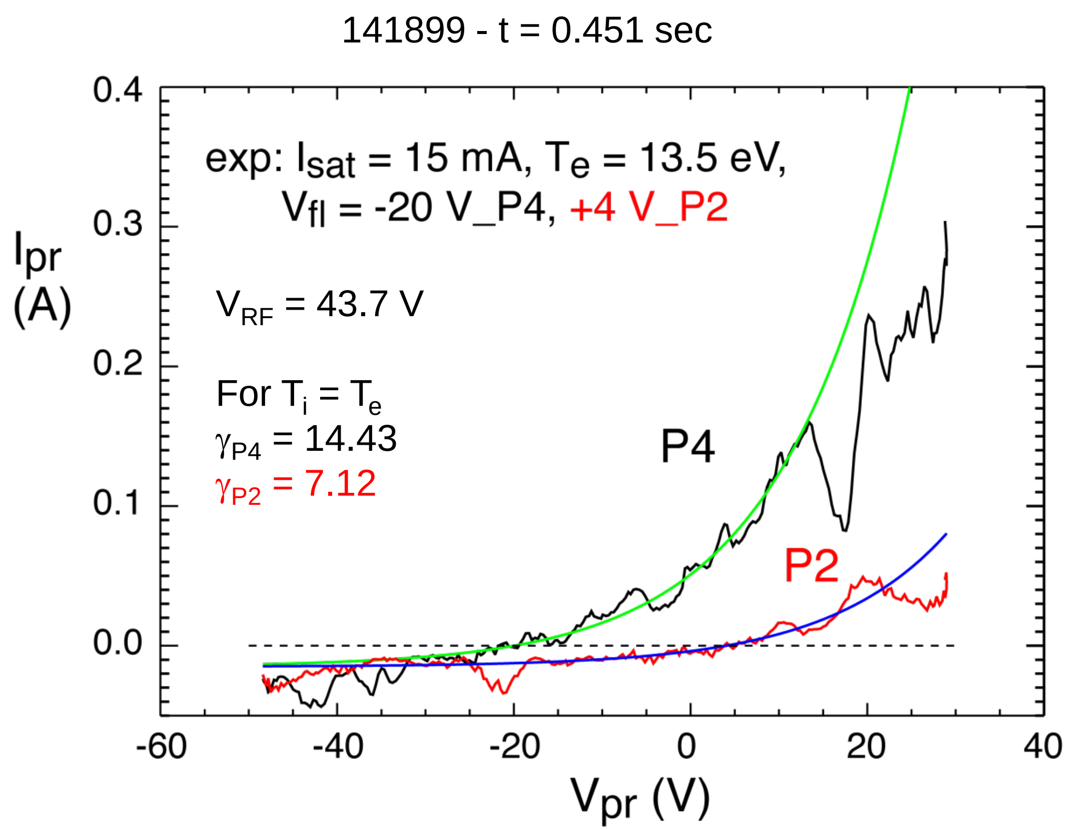
- Heat flux to Langmuir probes is double for Probe 4 (under spiral) relative to Probe 2 (away from spiral)
  - $q_{P4} = 0.209\ MW/m^2$
  - $q_{P2} = 0.103\ MW/m^2$
- Results obtained by:
  - Negative shift in floating potential V_f for P4 to P2
  - Gives RF voltage via the equation:

$$\exp(\Delta V_f/T_e) = I_0(V_{RF}/T_e)$$

[A. Boschi and F. Magistrelli, Il Nuovo Cimento 29 (1963) 487.]

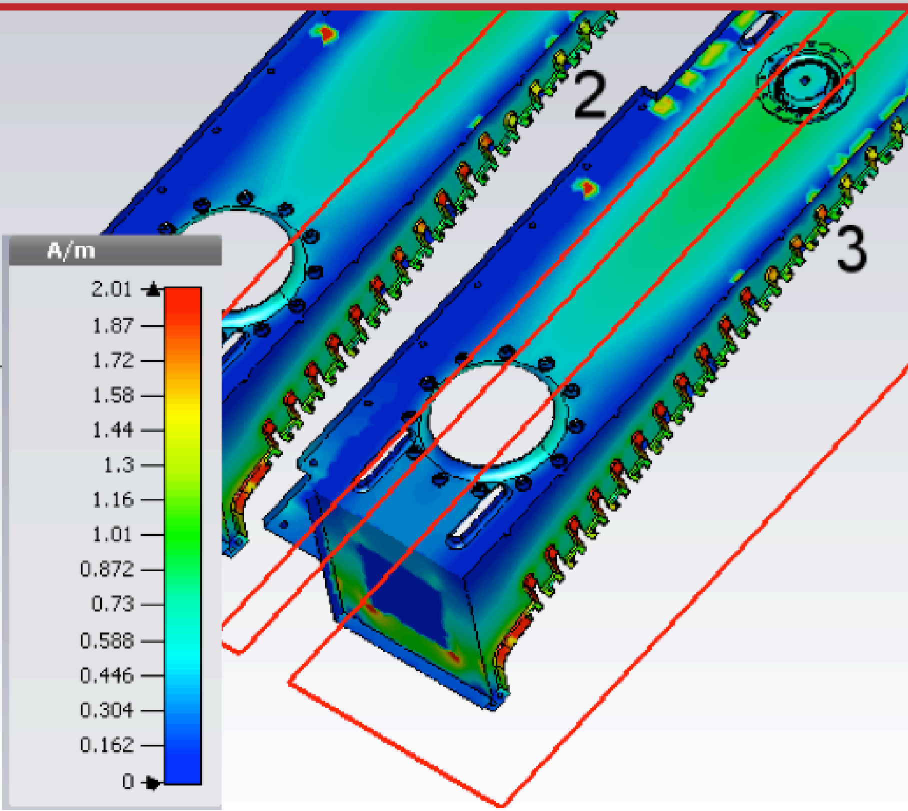
  - Average γ over an RF cycle of amplitude V_{RF}
  - Assumes same T_e and I_{sat} for both probes

$$\gamma = q_{surface}/(j^{+}_{sat} * T_e)$$



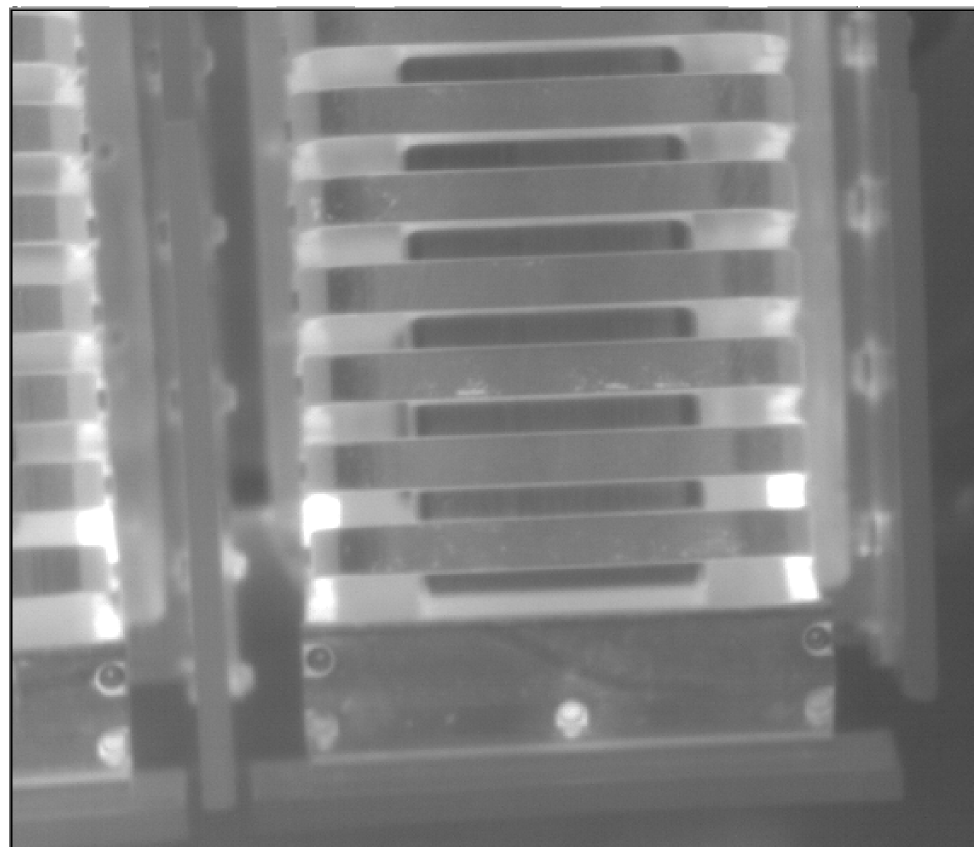
- Enhancement of heat flux probably larger at more intense portion of spiral
- Coaxial Langmuir probes on NSTX-U will permit direct measurement of V_{RF}

Return RF currents in antenna visualized with infrared camera and show agreement with simulations



Microwave Studio calculations of RF currents

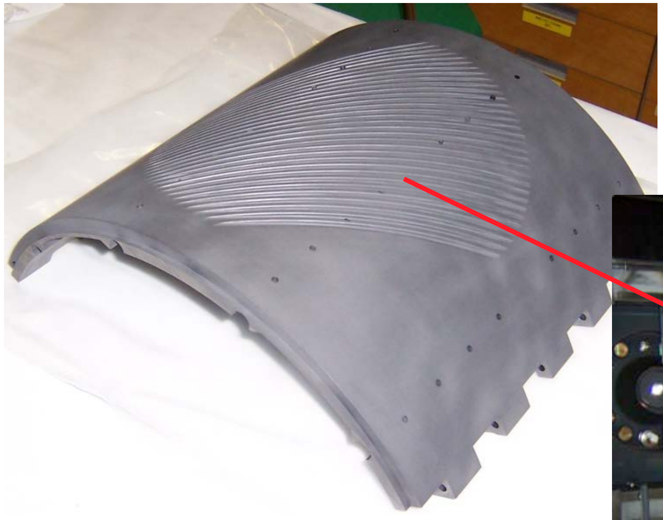
IR camera image after RF pulse



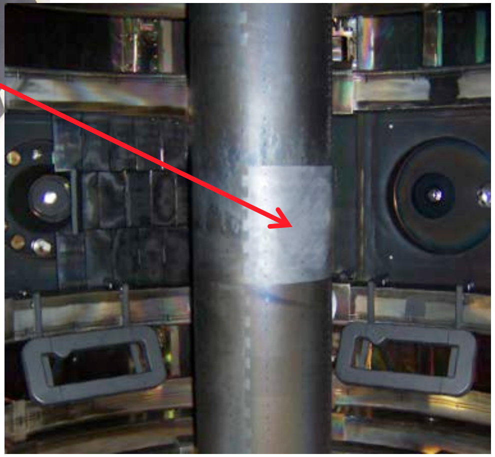
RF research will also benefit from upgraded fast-ion, current profile and edge density diagnostics

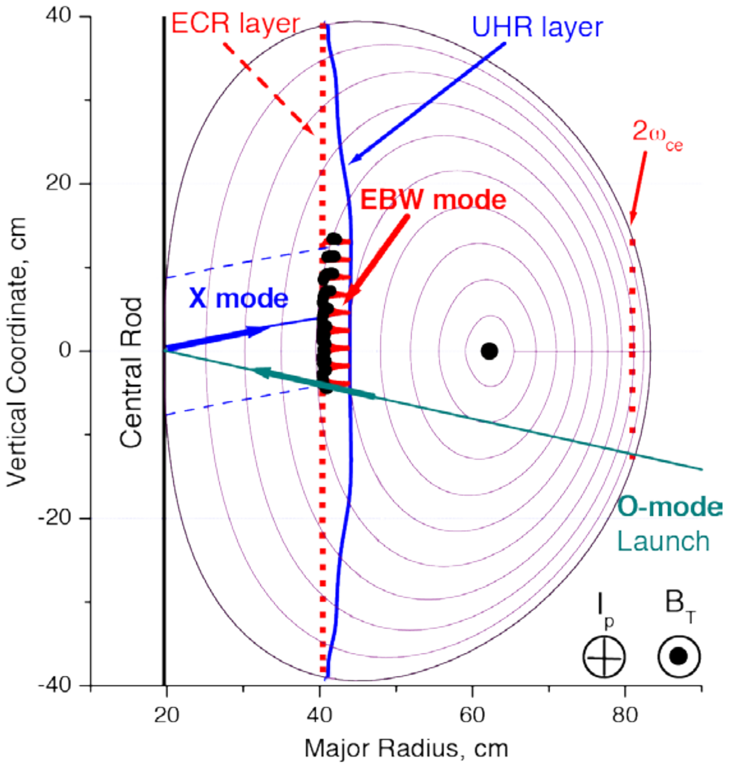
- Several diagnostics will provide information on fast-ion interactions with FW power in NSTX-U:
  - Vertical and tangential FIDA systems will provide time ($\Delta t \sim 10$ ms), space ($\Delta r \sim 5$ cm) and energy ($\Delta E \sim 10$ keV) measurements of the fast-ion distribution
  - FIDA data 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

28 GHz EBW heating will be used for plasma 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

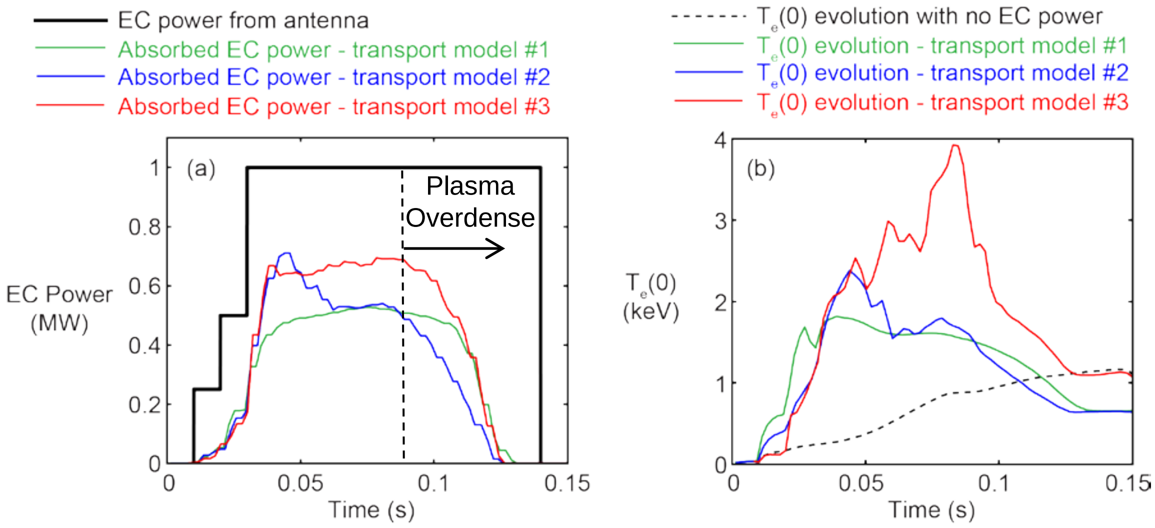
* V. F. Shevchenko et al. Nucl. Fusion **50** (2010) 022004

Simulations of EC heated NSTX-U start-up plasma predict rapid core electron heating

- TRANSP-TORAY simulations of 28 GHz O-mode were recently run for a $B_T(0) = 1$ T start-up plasma :
  - Various transport models were used resulting in variations in time evolution of the EC absorption and $T_e(0)$
  - All cases had first-pass EC absorption reaching ~ 50% and $T_e(0)$ increasing from 10 eV to > 1 keV within 30 ms

[G. Taylor, et al., Proc. 18th Joint Workshop on ECE and ECRH, Nara, Japan (2014)]

TRANSP-TORAY Simulation Results

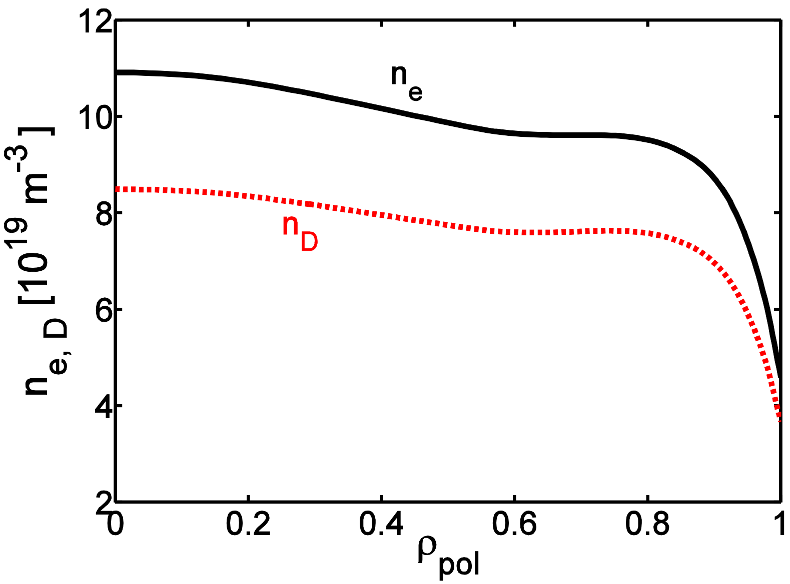


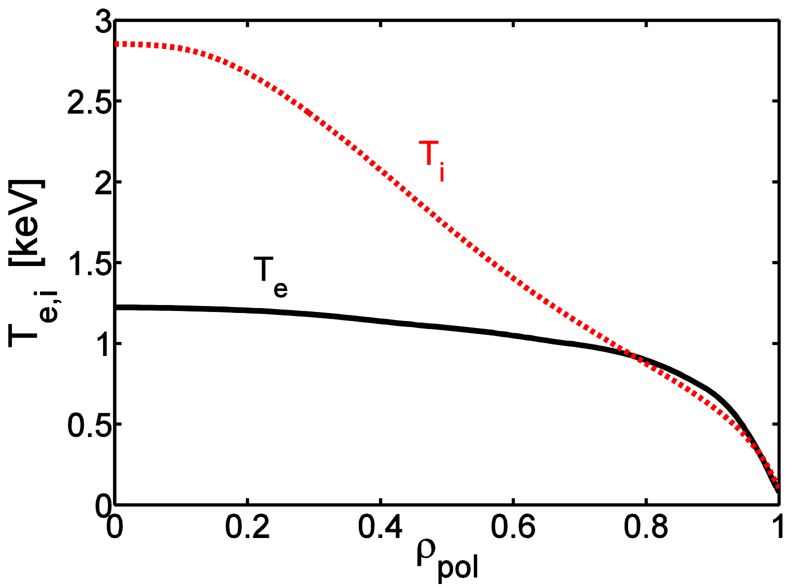
- Model #1: Analytic $n_e(r)$ that reproduce NSTX L-mode profiles.
- Model #2: $n_e(r)$ from NSTX CHI discharge (shot #142140)
- Model #1 and #2: Analytic I_p waveform starting at 100 kA and ramping to 300 kA in 50 ms.
- Model #3: $n_e(r)$ and I_p evolution from shot #142140

F. Poli

NSTX-U scenario used for computing FW power absorbed by ions and electrons

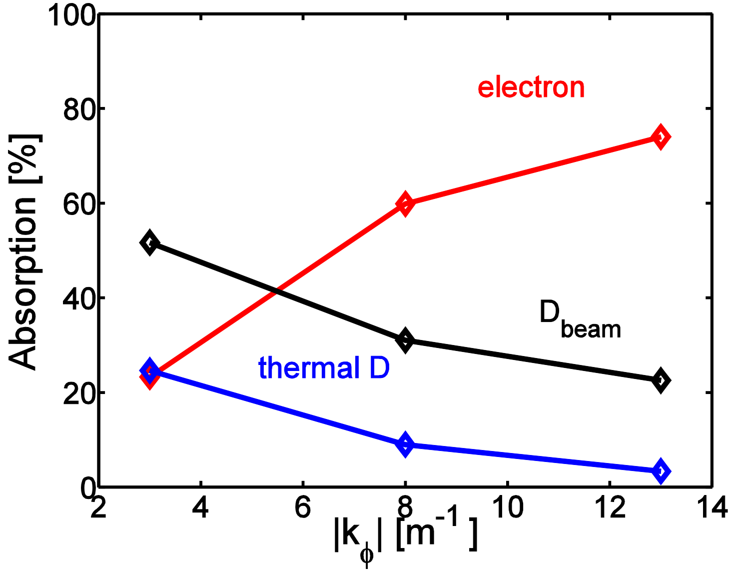
- H-mode scenario planned for NSTX-U, obtained by TRANSP simulations [S. P. Gerhardt, *Nucl. Fusion* **52**, 083020 (2012)]
- $B(R_0) = 1$ T, $I_p = 1.1$ MA, and $P_{NBI} = 6.3$ MW
- $n_e(0) = 1.1 \times 10^{20}$ m^{-3}, $T_e(0) = 1.22$ keV, and $T_D(0) = 2.86$ keV
- Density, temperature profiles used in the simulations:





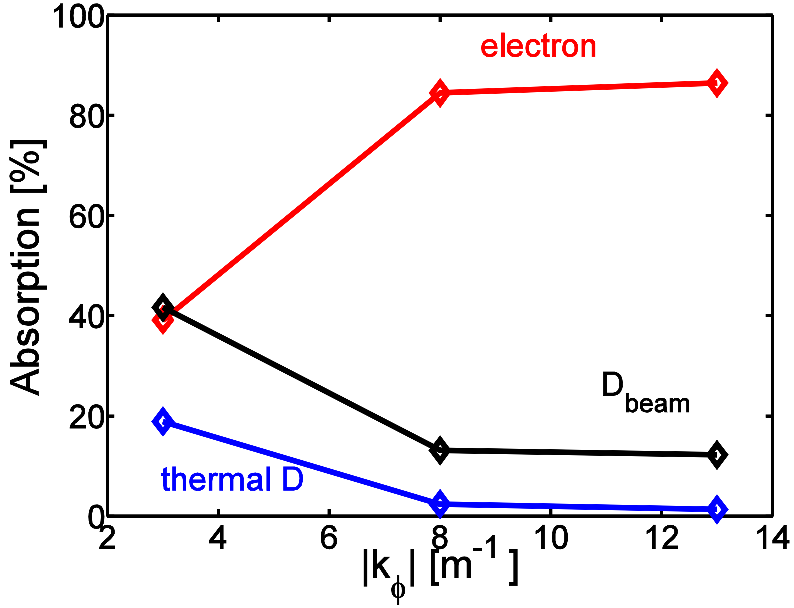
Large ion absorption of FW power decreases as when $T_e >= T_i$

$T_e(0)$ = 1.22 keV and $T_i(0)/2$ = 1.43 keV



- Electron and ion absorption is strongly sensitive to the ratio T_e/T_i
- Electron absorption increases when T_e/T_i increases
- Stronger effect for $|k_f| \geq 8$ m^{-1}

$2T_e(0)$ = 2.44 keV and $T_i(0)/2$ = 1.43 keV



- $|k_\phi| \geq 8$ m^{-1} favorable for heating electrons
- Thermal D and beam ions absorption decreases for T_e much larger than T_i
- $T_e > T_i$ in ramp-up phase

FY16 Milestone R16-3: Assess fast-wave SOL losses and core thermal and fast ion interactions at increased field and current

Use of high-harmonic fast wave (HHFW) injection for heating and current drive in NSTX-U is important to develop non-inductive start-up/ramp-up schemes, to achieve higher plasma performance, and to validate RF codes in support of the ITER FW program. The successful exploitation of HHFW depends on how much power can be coupled to the core plasma through the scrape-off layer (SOL) and how the coupled power is partitioned between different species in the core. For NSTX-U H-mode plasmas, the latter typically include thermal electrons/ions and fast ions from Neutral Beam (NB) injection. Mechanisms responsible for RF power losses in the SOL will first be addressed to optimize FW coupling to the core as a function of excited wave spectrum, toroidal field and plasma current (B_T and I_P). For instance, full-wave simulations with the AORSA code suggest a local enhancement of RF fields for propagating (rather than evanescent) fast waves in the SOL, which results in increased losses through damping. Losses are predicted to decrease at lower SOL density and/or at higher B_T. AORSA predictions will be tested against improved measurements of RF fields through dedicated probe arrays. The amount of lost power will be quantified through infrared cameras. The improved understanding of SOL loss mechanisms will provide more accurate estimations of the fraction of injected HHFW power reaching the core. The synergy between NB and FW injection in H-mode plasmas will be evaluated for the higher B_T and I_P of NSTX-U. In particular, the efficiency of thermal ions heating at higher B_T, predicted to increase by full-wave simulations, will be investigated. Similarly, modifications of the fast ion distribution, previously observed on NSTX, will be assessed with the enhanced fast ion diagnostics set of NSTX-U as a function of plasma parameters, FW spectrum and NB injection geometry, including the new (more tangential) NB lines. The characterization of scenarios with combined NB and FW injection will provide a valuable dataset to benchmark RF codes (e.g. AORSA, TORIC and CQL3D-FOW), which have been considerably improved in the past years. NSTX-U will provide the required data for extensive validation before their use for scenario predictions in future devices such as ITER and FNSF.

FY14-18 Wave heating and current drive research timeline *(assuming baseline funding)*

FY13 | 14 | 15 | 16 | 17 | 18

Upgrade Outage — **5 year plan period** — **5 year goal**

Physics

Supporting HHFW Research for Thrusts

- *Complete simulation of FW heating during I_p ramp-up and flat top*
- *Assess performance of 12-strap double-feed FW antenna and compatibility with NBI H-modes at higher B_T*
- *Measure and mitigate RF power flows in the SOL and to the divertors in the H-mode regime*
- *Assess effect of cryo-pumping and 3-D fields on FW antenna performance*
- *Simulate/mockup reduced- strap FW antenna performance*
- *Study FW interaction with NBI fast-ions*

Thrust 1

- *Complete simulation of 28GHz EC/EBW heating during I_p ramp-up and flat top*
- *Generate 100% NI I_p ~ 500 kA FW H-mode using inductively generated target*
- Assess FW electron heating during NBI NI current ramp-up
- *300 kA to 500 kA NI ramp-up with FW*
- *Measure B-X-O coupling*
- *28 GHz EBW start-up*
- *28 GHz EC heated CHI start-up*
- *Test O-X-B heating with "fixed" horn*

Thrust 2

- *Upgrade advanced RF codes to include SOL, realistic antenna, and accurate fast-ion modeling*
- *Validate advanced RF codes that include SOL, realistic antenna geometry, accurate modeling of fast-ion interaction and effect of edge fluctuations by comparing to NSTX-U data*
- *Use advanced RF codes to predict RF performance in FNSF and ITER*

5 year goal: *Develop plasma scenarios with fully non-inductive ramp-up and H-mode sustainment that utilize RF heating and current drive, and determine the validity of advanced RF codes.*

FY14-18 upgrades that support wave heating and current drive research *(assuming baseline funding)*

FY13 | 14 | 15 | 16 | 17 | 18

Upgrade Outage — **5 year plan period**

Tools

Diagnostics

- Diagnostics for measuring HHFW and EBW power deposition and current drive (eg. Upgraded MPTS, ME-SXR, MSE-LIF, MSE-CIF)
- Fast IR for RF power SOL power losses
- 10-40 GHz edge reflectometer for SOL measurements in front of antenna
- RF magnetic and Langmuir probes to measure RF power flow to divertor
- Tangential FIDA and upgraded ssNPA for measuring RF acceleration of NBI ions
- SAMI - microwave imaging diagnostic

Theory

- AORSA 3D high-resolution SOL
- Add high-fidelity realistic antenna geometry to AORSA-3D
- GENRAY with SOL edge fluctuations and wave scattering for RF coupling
- Full finite-orbit-width CQL3D and AORSA/ORBIT-RF for simulation of RF acceleration of NBI ions
- TORIC with SOL and SPIRAL modeling of RF power loss to divertor
- Include RF operator in NUBEAM
- Use RF operator in NUBEAM to accurately model fast-ion absorption

Facility

- Compliant HHFW feedthroughs
- 1 MW 28 GHz EC/EBW heating system with fixed horn antenna
- Test FW straps to excite EHO