NSTX-U FY2014-18 5-Year Plan for Fast Wave and Electron Cyclotron Heating

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for the NSTX Research Team

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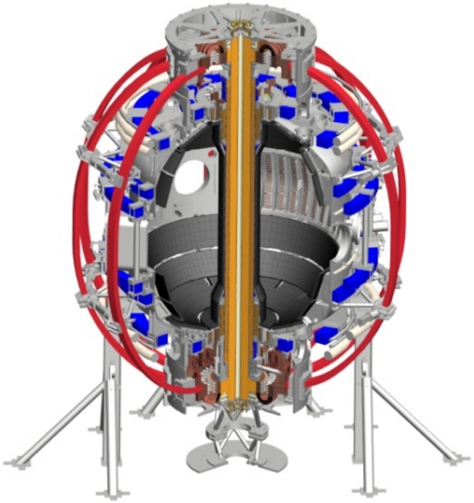

RF research goal is to support the development of fully non-inductive (NI) start-up and H-mode plasmas

- **High-level NSTX-U goal to generate fully NI discharges that extrapolate to neutron wall loading in FNSF (≥ $1 MW/m^2$)**
- **Fast-wave (FW) heating can, in principle, ramp plasma current (I_p) in a FNSF-ST via bootstrap current enhancement**

➢ Up to 6 MW of 30 MHz FW power and improved RF diagnostics available on NSTX-U to support RF research:

Back-up # 21-23

  ➢ At $B_T(0)$ ~ 1 T FW regime is the same as initial ITER “half-field” FW operation
  ➢ NSTX-U may be only major US facility with FW heating in FY2014-18

➢ 1-2 MW, 28 GHz electron cyclotron (EC) heating system will be implemented to heat low-density start-up plasmas

➢ FNSF-ST higher density H-mode plasmas will be “overdense” for EC heating → ultimately need electron Bernstein wave (EBW) heating:

  ➢ Test 1 MW, 28 GHz EBW heating on NSTX-U

Outline

- Research Thrusts
- FY2014 Plans: Model RF & Design ECH System
- FY2015-16 Plans: FW NI Ramp-up & Validate Codes
- FY2017-18 Plans: ECH & Use Codes for ITER/FNSF

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Two NSTX-U RF research thrusts support FNSF-ST, ITER and future burning plasma devices

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 level that can confine fast-ions from 2nd neutral beam
- Increase $T_e(0)$ in CHI and gun-initiated plasmas to allow NBI and FW heating
- Megawatt-level EBW heating for plasma start-up

Thrust RF-2

Validate advanced 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
- Predict RF performance in ITER and other burning plasma devices

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FY2014

Simulate FW heating for NI start-up, ramp-up and I_p flat top with advanced RF codes

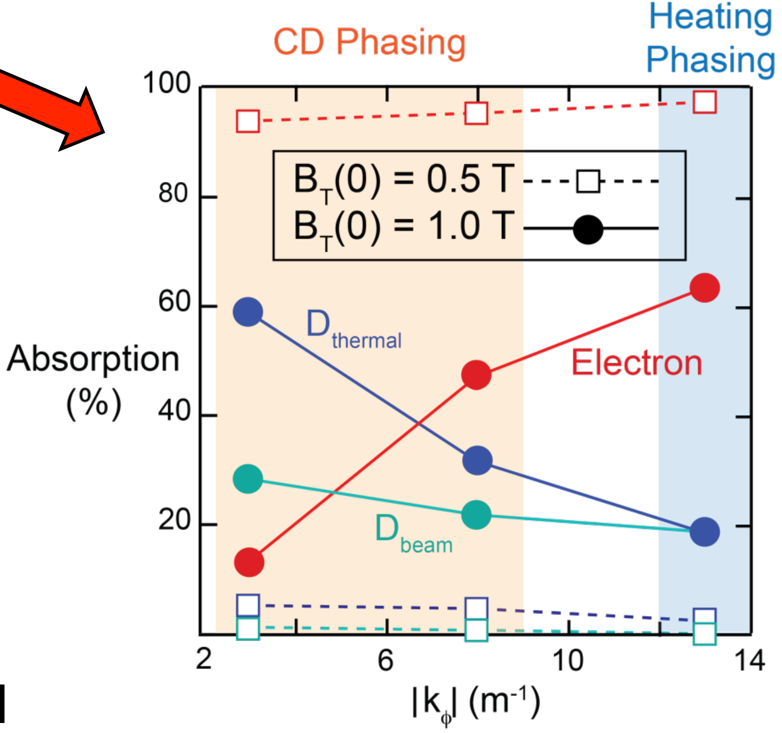
- Strong FW absorption on ions (thermal and beam) expected at $B_T(0) \sim 1$ T:
  - Primarily FW heating and bootstrap generation rather than direct FW current drive (CD)
- Reduced edge losses and less fast-ion interaction with the FW antenna may improve RF heating efficiency in NSTX-U

Back-up # 24

- Include realistic SOL and antenna geometry and assess the effect of edge turbulence on coupling efficiency & model FW power flows in SOL for NSTX-U discharges

Thrusts RF-1 & RF-2

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



AORSA Modeling Results

$P_{nbi} = 6.3$ MW, $n_e(0) = 1.1 \times 10^{14}$ cm^{-3}
$T_e(0) = 1.22$ keV, $T_i(0) = 2.86$ keV

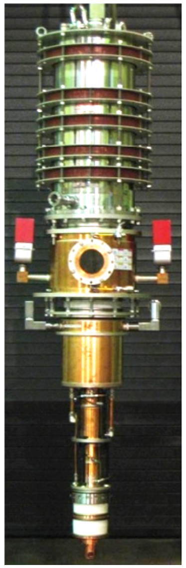
- Model FW interaction with NSTX-U's new more tangential NBI sources with CQL3D finite-orbit-width code

Thrusts RF-1 & RF-2

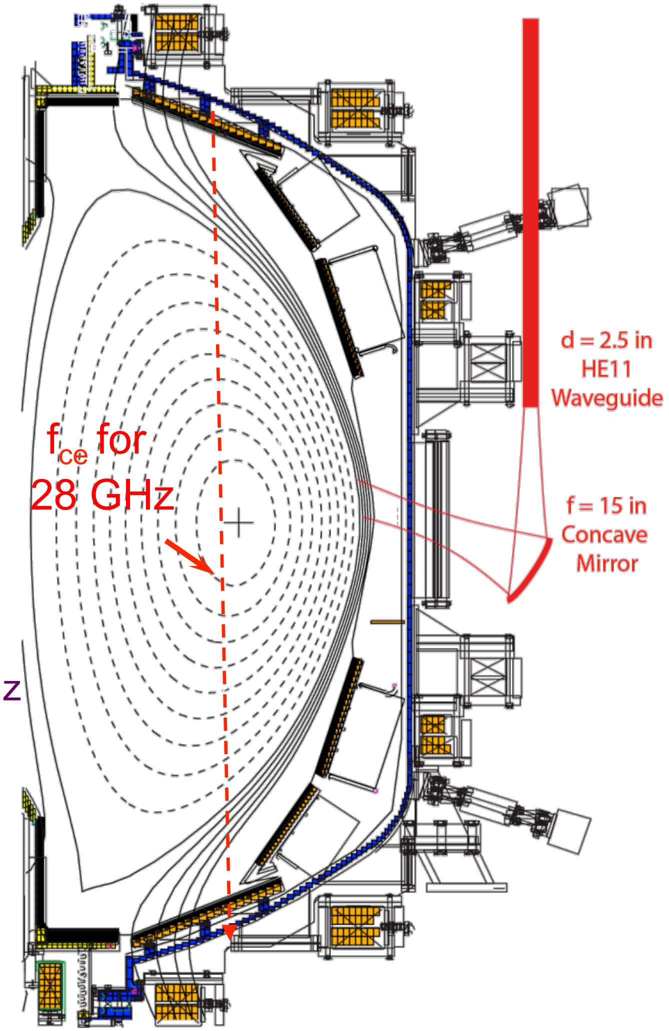
FY2014

Solenoid-free start-up supported by 28 GHz EC/EBW heating in FY2016-17

- Design 1-2 MW, 28 GHz EC heating system for plasma start-up: **Thrust RF-1**
  - Use Gyrotron originally developed for GAMMA 10*
  - Fixed horn antenna & low-loss HE11 corrugated circular waveguide
  - Power gyrotron with modified TFTR NBI power supply
- Possibly upgrade later to 2-4 MW oblique launch EBW off-axis heating and CD system:
  - Metal steerable mirror, designed for 5 s, 2 MW pulses, located near midplane, outside the vacuum vessel **Thrust RF-1**



1 MW, 28 GHz Gyrotron



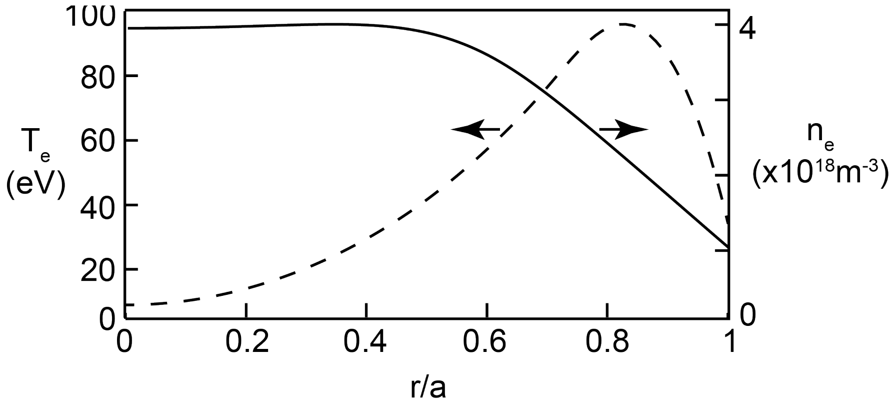
Conceptual implementation of 28 GHz EBW heating system using steerable mirror for O-X-B coupling

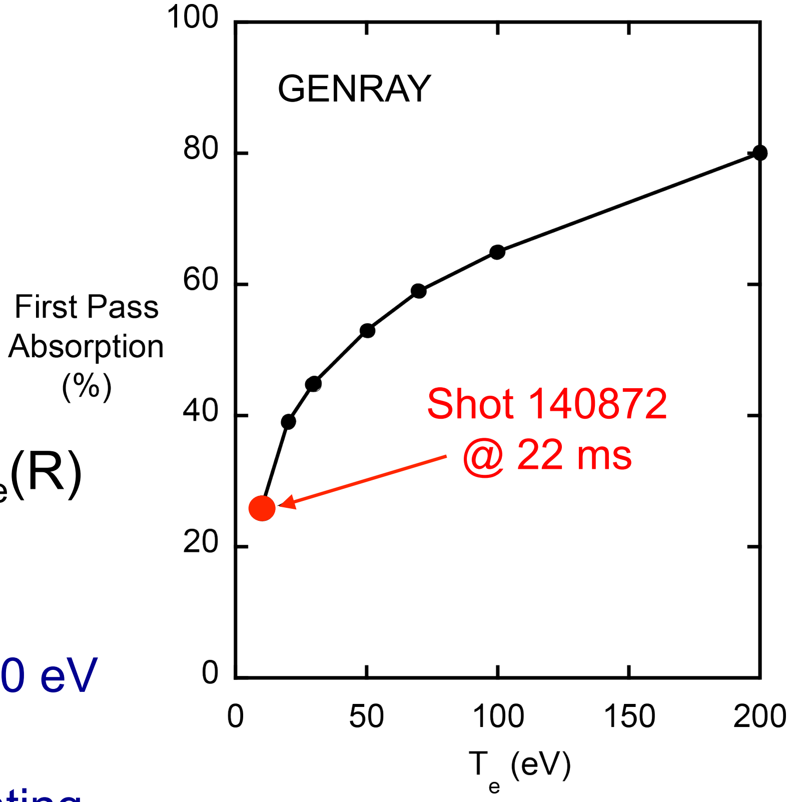
*T. Kariya et al., J. Infrared, Millimetre and Terahertz Waves **32** (2011) 295

FY2014

Model and design megawatt-level 28 GHz EC/EBW heating system for NI plasma start-up

NSTX Shot 140872 @ 22 ms





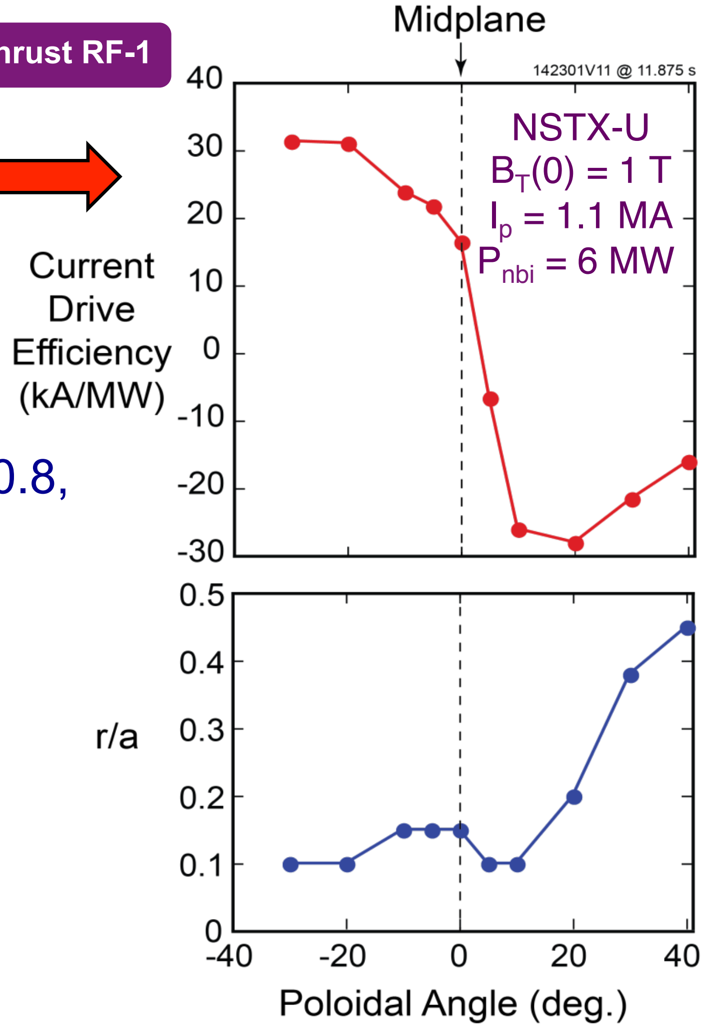
- CHI plasmas characterized by hollow $T_e(R)$ profile with $T_e(0)$ ~ 5 eV
  - First pass EC absorption ~ 25% at $T_e(0)$ ~ 5eV, expect rapid heating to ~200 eV
  - Low density (3 - 4 x 10^{18} m^{-3}) CHI target discharges amenable to 28 GHz EC heating
- Complete conceptual design of the 28 GHz EC heating system **Thrust RF-1**
- Explore implementation of 28 GHz, 1 MW EBW start-up on NSTX-U using the technique being tested this year on MAST **Thrust RF-1** **Back-up # 25**
  - ORNL & PPPL collaborating with MAST on ~ 100 kW EBW start-up

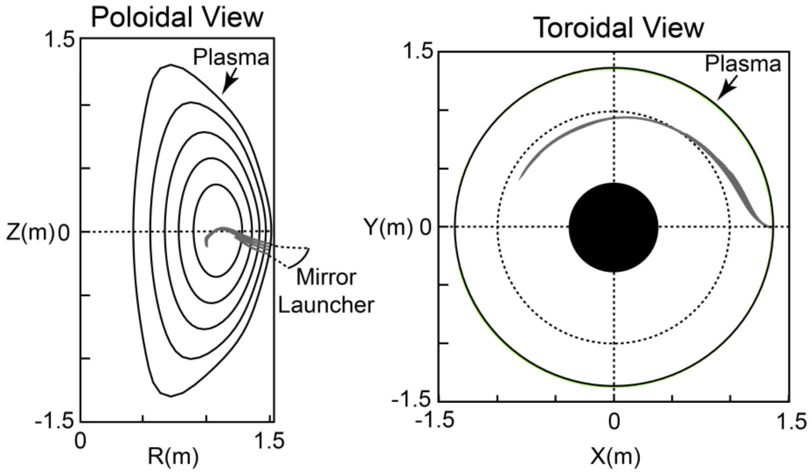
FY2014

Simulate 28 GHz EBW heating & CD in NSTX-U advanced scenario H-modes

Thrust RF-1

- EBW simulations for an NSTX-U H-mode with P_{nbi} = 6 MW predict η_{eff} ~ 25 kA/MW for $n_e(0) = 9 \times 10^{19} m^{-3}$ and $T_e(0)$ = 1.2 keV:
  - At r/a ~ 0.5 EBW-driven current density is ~ 7 A/cm^2/MW, where NBI-driven current density (with 6 MW of NBI) is ~ 15 A/cm^2
  - Possible to drive significant EBWCD at r/a > 0.8, where NBICD is negligible in NSTX-U





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

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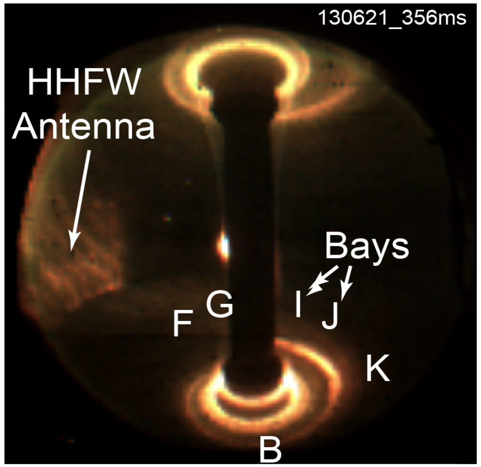
FY2015-16

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

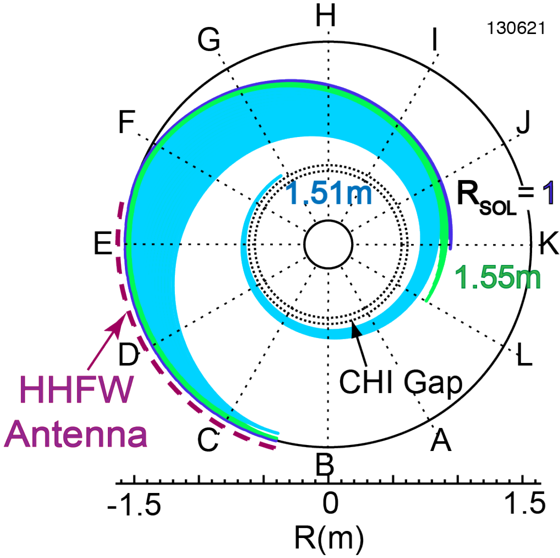
- FY2009 double-feed FW antenna upgrade was never tested without extensive Li conditioning: **Thrusts RF-1 & RF-2**
  - Assess antenna performance with NBI H-modes in $B_T(0) \leq 1$ T discharges with boronization and Li conditioning
- Study and mitigate RF power flows along field lines, previously observed in the SOL*: **Thrusts RF-1 & RF-2**
  - Additional RF probes and IR cameras will be used to study RF power flows during FW heated NBI H-modes with $B_T(0) \leq 1$ T **Back-up # 22**
  - Attempt to mitigate with Li, gas puffs, or cryo-pump in FY 2017-18

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

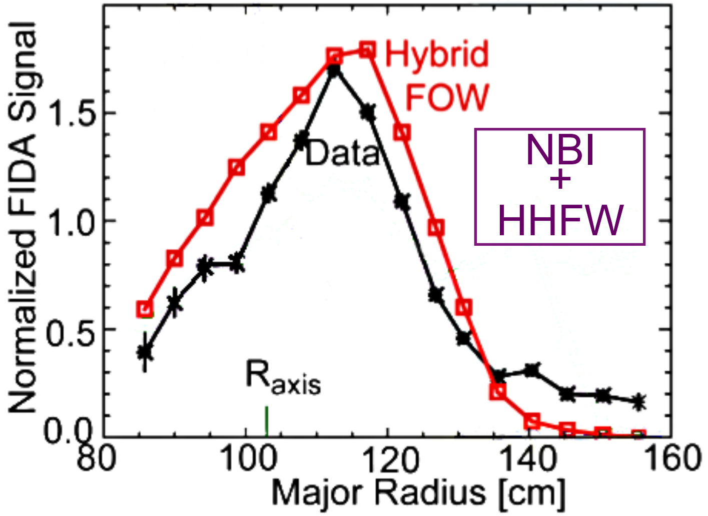
*R. J. Perkins et al., Phys. Rev. Lett. **109** (2012) 045001

FY2015-16

Higher $B_T(0)$ in NSTX-U extends FW heating to an ITER-relevant regime

- At full field NSTX-U will operate in a similar ion harmonic regime to the ITER half-field pre-activation phase:
  - In NSTX-U 40-50% of the FW power is predicted be absorbed by thermal and fast ions when the antenna is run with heating phasing ($k_\phi = 13\ m^{-1}$)
- Studies of the FW interaction with ions will benefit from improved simulation tools:
  - The full-orbit "Hybrid" finite orbit width version of the CQL3D Fokker-Planck code now shows good agreement with NSTX fast ion diagnostic (FIDA) data

Thrust RF-2



- The upgraded fast-ion diagnostic suite and advanced 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 and compare results to predictions from advanced RF codes

Thrusts RF-1 & RF-2

- Assess need for FW limiter upgrade to operate with higher NBI powers

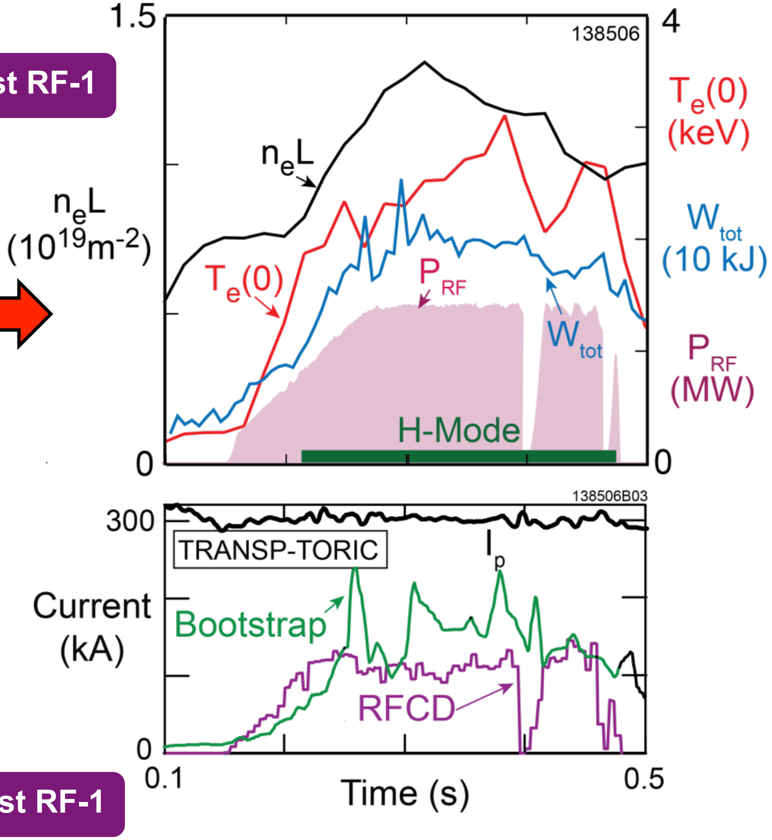
FY2015-16

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

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

Thrust RF-1

  - Achieved >70% NI fraction in an inductively started I_p = 300 kA H-mode plasma in FY2010 with 1.4 MW of HHFW power*
  - Will use boronization and minimal Li conditioning to optimize FW coupling to reach ~3 MW needed for fully NI I_p ~ 500 kA plasma



- NI ramp-up of I_p in an FW-only H-mode discharge from 300 to ~ 500 kA

Thrust RF-1

- FW H-mode experiments will benefit from new MSE-LIF q(r) measurements that use a non-perturbing diagnostic neutral beam

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

FY2015-16

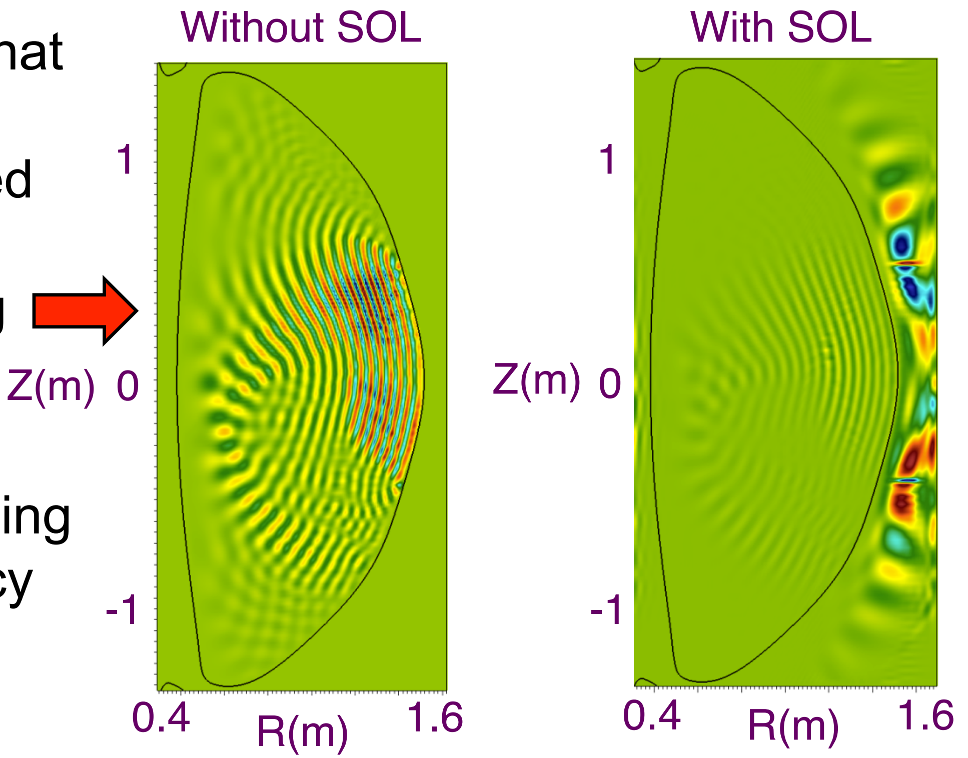
Verification of advanced RF codes and B-X-O emission measurements of coupling efficiency

- Validation of advanced RF codes that include accurate SOL and antenna model using data from the upgraded diagnostic suite for NSTX-U for H-mode scenarios with FW heating

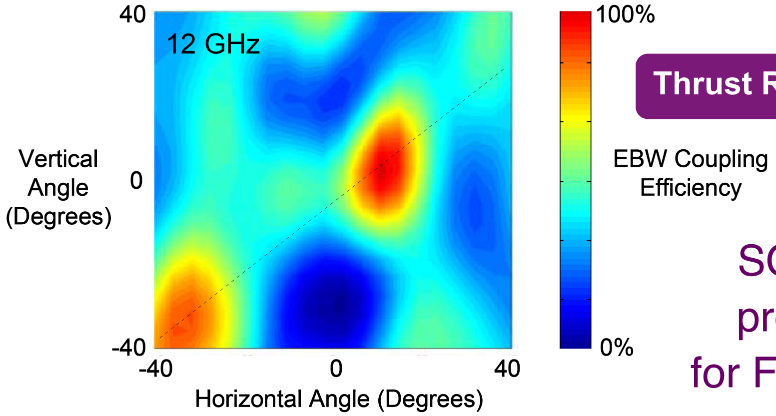
Back-up # 26-28

Thrust RF-2

- Acquire O-X-B emission data with synthetic aperture microwave imaging (SAMI) to assess coupling efficiency *(collaboration with York U. and CCFE)*



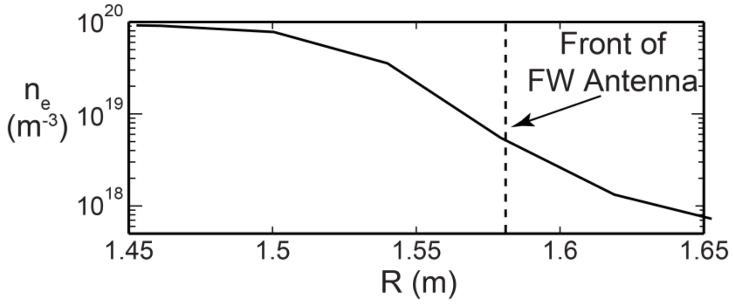
AORSA Re($E_{//}$) simulations for 30 MHz FW $n_\phi = 12$ heating in NSTX-U with $B_T(0) = 1$ T



SAMI EBW Emission Data
MAST Shot# 26815 @ 265-275 ms

Thrust RF-1

SOL density profile used for FW modeling



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FY2017-18

28 GHz EC heating of CHI discharges and application of advanced RF codes

- 28 GHz EC heating of CHI plasma with maximum EC absorption:
  - Adjust target for maximum 28 GHz single pass absorption
  - If plasmas can be generated with $T_e(0) \geq 100$ eV they will also be heated with FW power to non-inductively ramp I_p
  - *Attempt 28 GHz EC heating of a CHI plasma that extrapolates to FNSF-ST*

Thrust RF-1

- *Non-inductive start-up with EBW heating using technique being developed on MAST:*

Thrust RF-1

Back-up # 25

  - *Experiments on MAST achieved I_p ~ 30 kA with ~50 kW of EBW power*
  - *Megawatt level EBW start-up experiments in NSTX-U will allow current scaling to be tested at much higher EBW power than was used on MAST*
  - *EBW start-up may allow more time to control plasma position and discharge evolution than CHI*
- *Test 28 GHz EBW heating via O-X-B coupling with a fixed horn antenna*
- Use advanced RF codes to predict RF performance in ITER and other future burning plasma devices

Thrust RF-2

[Experiments in italics require incremental funding]

FY2017-18

Assess impact of FW heating on NBI I_p ramp-up and test reduced-strap antenna

- Assess impact of FW heating on NBI I_p ramp-up from 400 kA to ~ 1 MA:
  - TSC predicts bootstrap and NB current drive achieves ramp-up in 3 s
  - Ramp-up starts with low inductance plasma heated by 4 MW of FW power
  - First use inductively-initiated plasma as a proxy for CHI target discharge where the loop voltage is turned off as NBI and FW power is applied
  - Experiments will determine plasma parameters needed for fully NI ramp-up

Thrust RF-1

- Extend FW heating to longer pulse, or into flat-top, to assess effect of FW on NB NI I_p ramp-up:
  - Possible installation of upgraded FW limiter for long-pulse operation with NBI
  - Assess impact of cryo-pump on FW coupling

Thrust RF-1

- Reduced-strap HHFW antenna mockup experiments:
  - May eventually reduce number of straps from 12 to 8 for antenna(s) to excite *AE modes and/or EHOs → will first simulate and test reduced-strap antenna
  - *Test FW straps to excite EHO in FY2017-18 (incremental funding)*

Back-up # 30-32

Summary for the 5-Year Plan for Fast Wave and Electron Cyclotron Heating

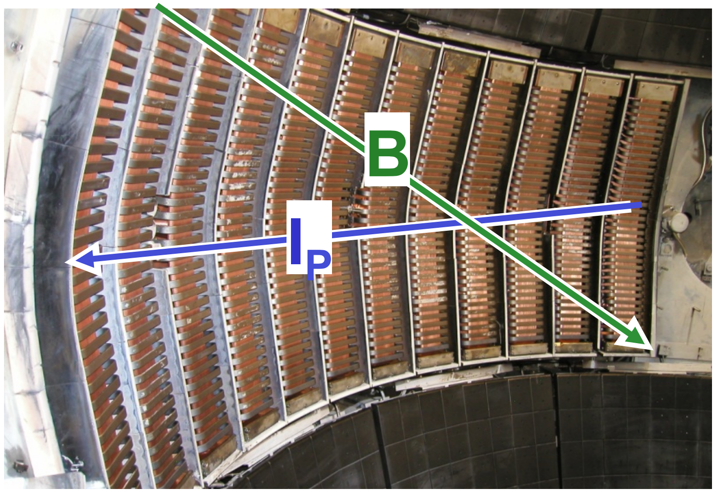
- NSTX-U RF research program supports fully NI plasma start-up and model validation for ITER ICRF

- New research tools on NSTX-U enable the development of RF research relevant to ITER and other burning plasma devices:
  - Higher magnetic field moves NSTX-U FW research into an ITER-relevant regime
  - This higher magnetic field regime may also 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 distribution measurements, will help validate advanced RF codes
  - 28 GHz EC/EBW heating supports the NSTX-U NI strategy

Back-up # 29

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 be installed in NSTX-U to support 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

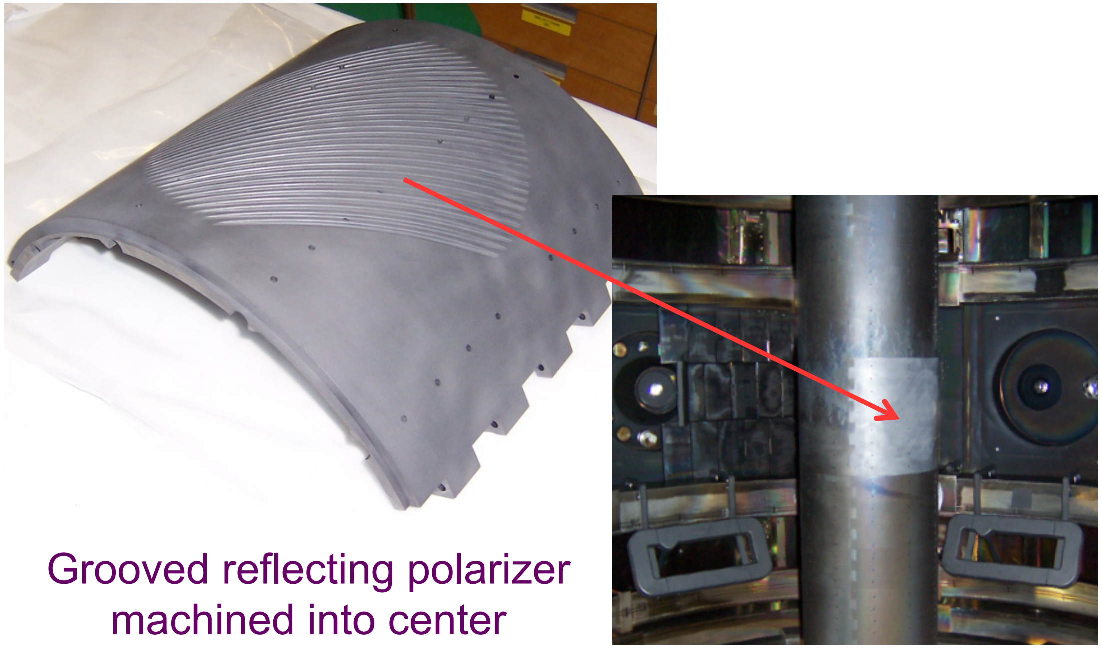
RF research in NSTX-U will also benefit from upgraded fast-ion, current profile and edge density diagnostics

- 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

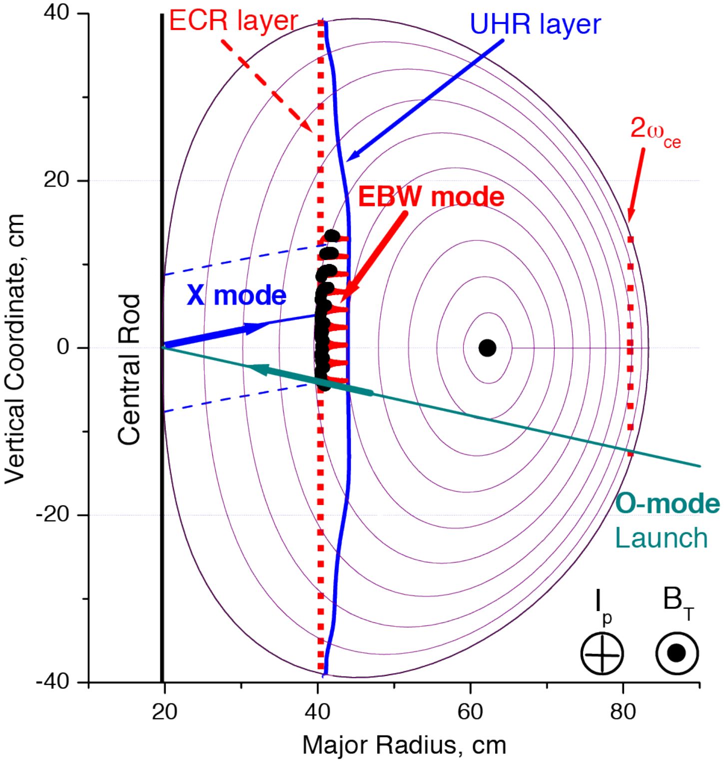
Reduced edge losses and less fast-ion interaction with the FW antenna may improve RF heating efficiency in NSTX-U

- 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

28 GHz EBW heating will also be used for plasma start-up in NSTX-U using a technique used successfully in MAST*



Grooved reflecting polarizer machined into center column in MAST

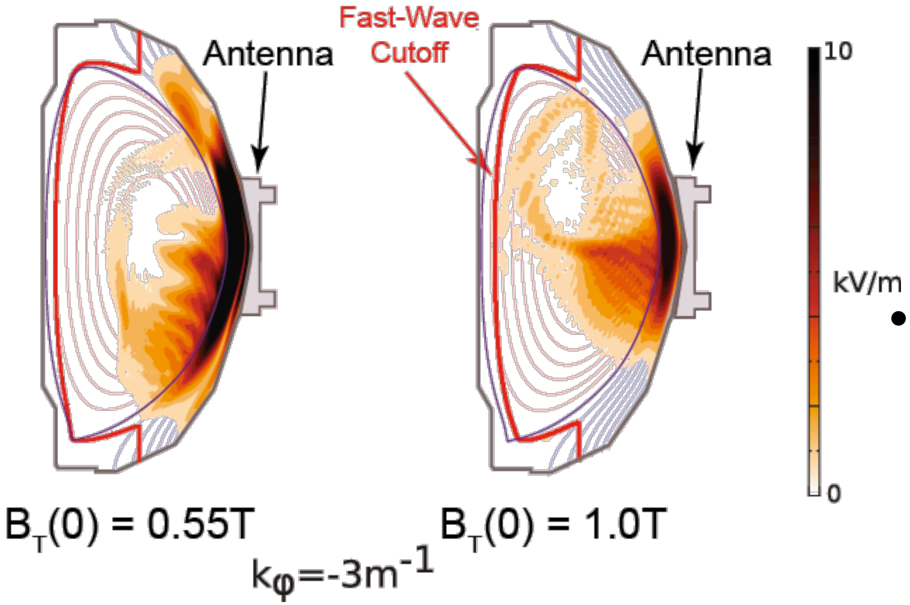


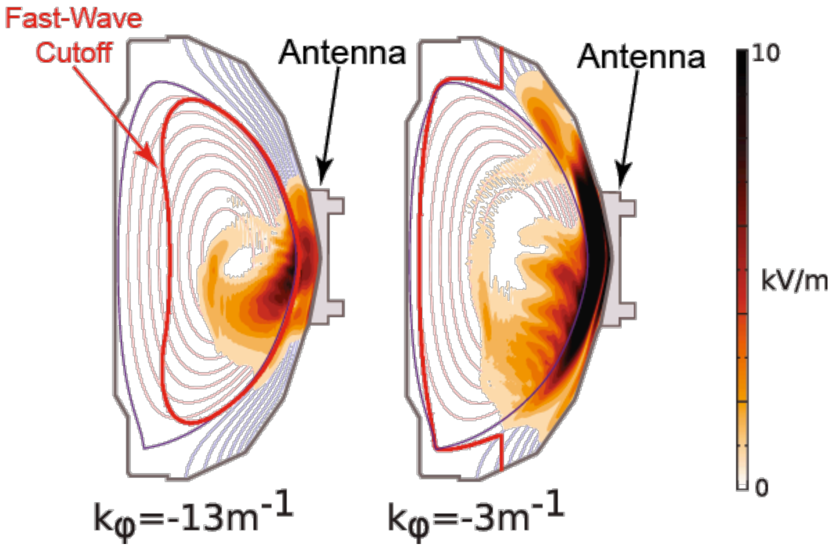
- O-mode EC waves launched from low field side are weakly absorbed (< 2%) below the cut off electron density of ~ 1 x 10^{19} m^{-3}
- Grooved reflecting polarizer on the center column converts O-mode to X-Mode that then ~ 100% converts to EBWs

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

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

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

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

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

OAK RIDGE
National Laboratory

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

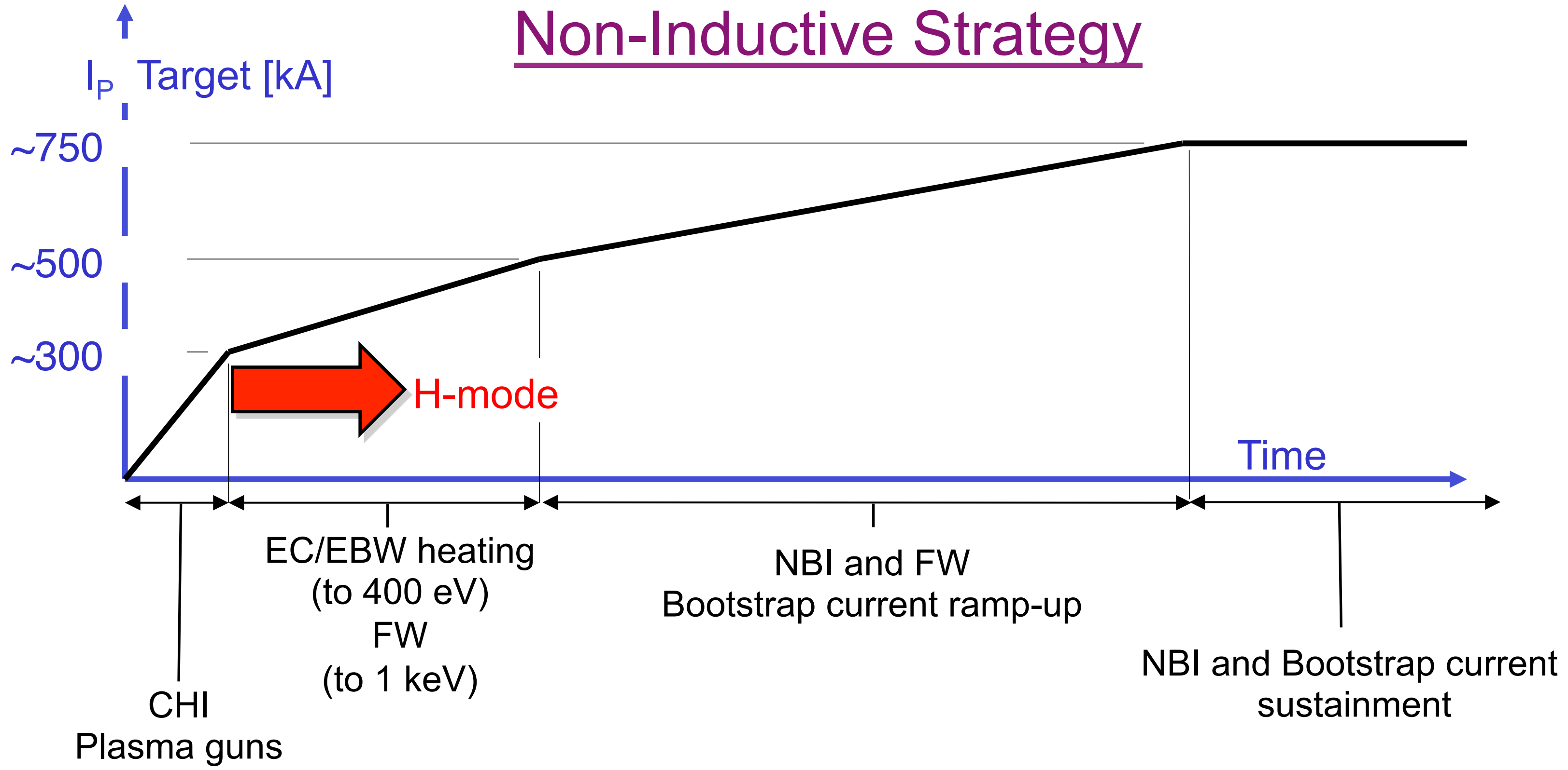
NSTX-U RF research supported by a suite of numerical codes whose predictions will be verified

- 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., 22nd IAEA Fusion Conf. (2008) CD-ROM file IT/P6-3]

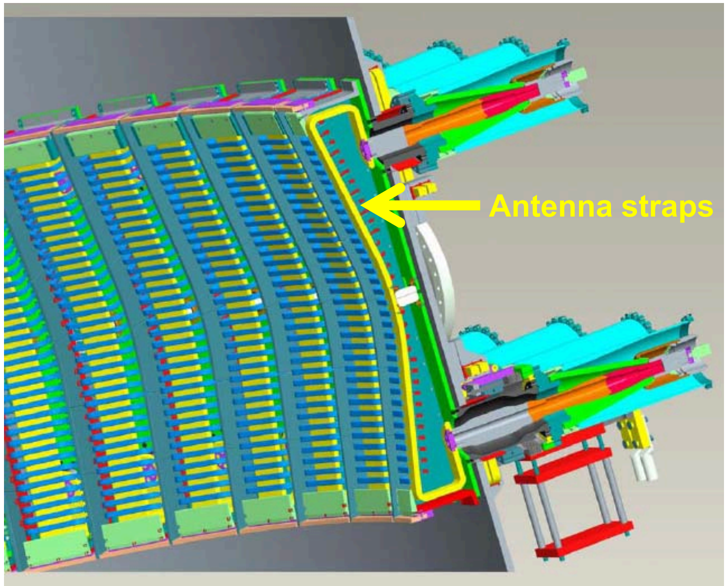
Thrust RF-1

Develop FW and EC heating for fully NI discharges

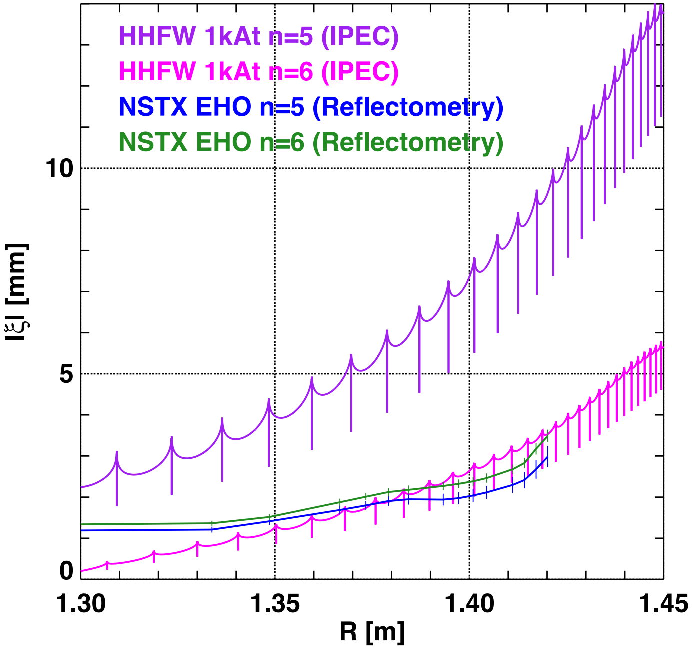


- Experiments in NSTX-U will initially develop NI start-up, ramp-up and plasma sustainment separately
- Reduced RF edge losses and fast-ion interactions with the FW antenna may yield improved RF coupling and heating efficiency

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



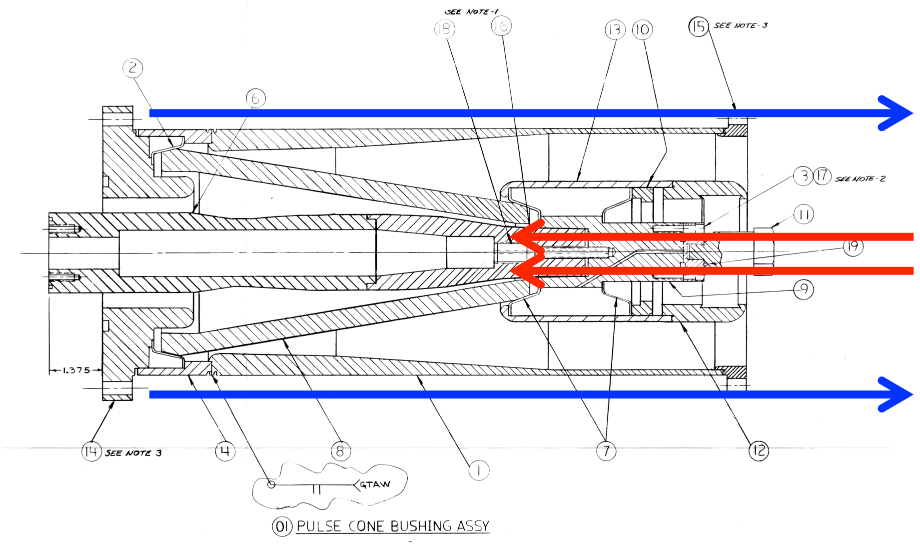
FW vs. NSTX EHO



- 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

Plasma Control

Induction Heater

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

Audio Amplifiers

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