NSTX-U

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Plans for Wave Heating and Current Drive Research in the NSTX-Upgrade

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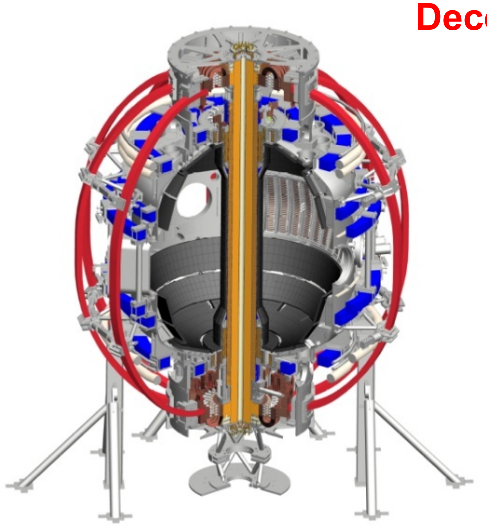

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Outline

- Introduction
- Long-Term Research Thrusts (5-10 years)
- Near-Term Research (2-3 years)
- Tools Supporting RF Research:
  - RF Simulation Capabilities
  - EC/EBW Heating System
  - Diagnostics & Other Facility Upgrades
- Summary

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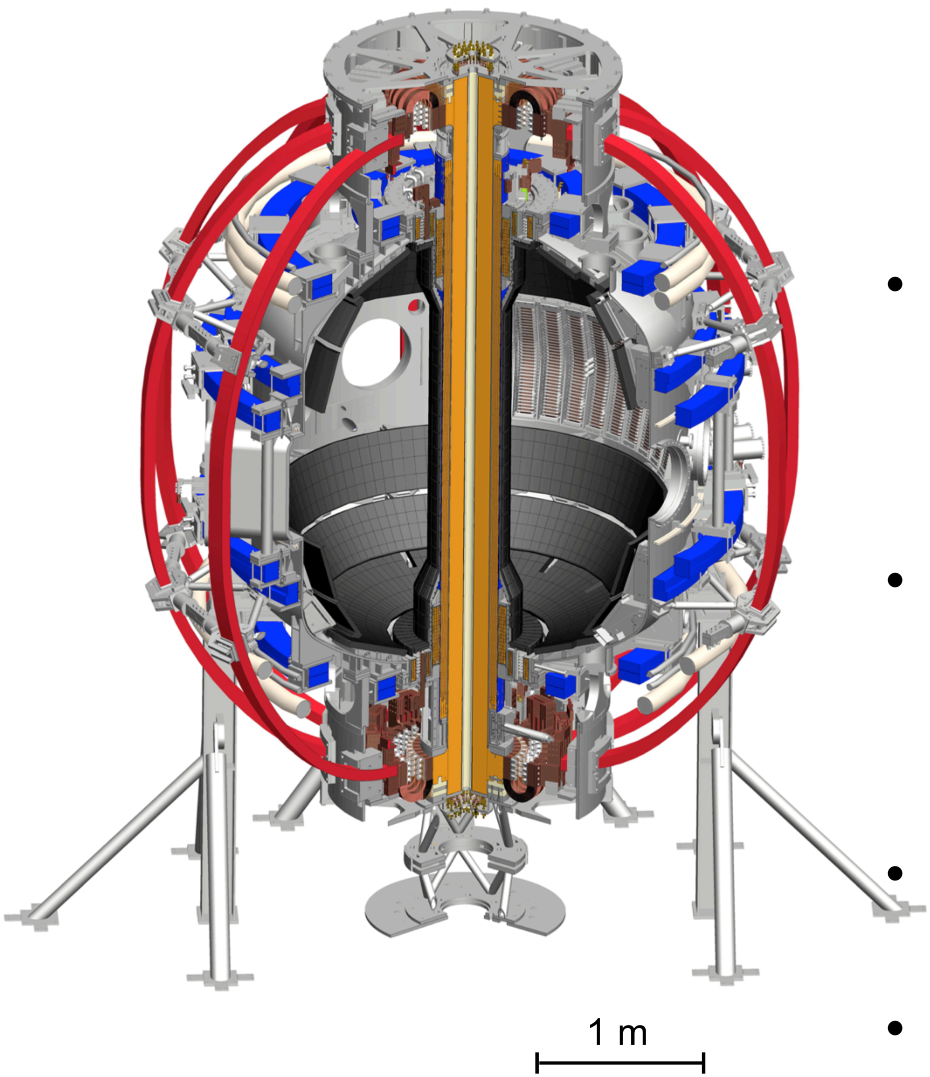
NSTX-Upgrade will address critical spherical torus (ST) plasma confinement and sustainment issues



- Center stack diameter increases from 20→40 cm; providing 2x I_p and $B_T(0)$, and 5x the pulse-length of NSTX (~5 s)
- Neutral beam injection (NBI) power will increase from 6→12 MW, with addition of three larger tangency radius beam lines
- Reduced collisionality will allow access to a regime relevant to a Fusion Nuclear Science Facility ST (FNSF-ST)
- 100% non-inductive current drive (CD) with controllable q(r)
- Plasma operations scheduled to begin in 2014

Long-term RF research goal is to support the development of fully non-inductive NSTX-U H-mode plasmas

- FNSF-ST will operate without a central solenoid → need to demonstrate fully non-inductive (NI) ST plasma operation
- High-harmonic fast-wave (HHFW) power can, in principle, ramp-up I_p in a FNSF-ST via heating and bootstrap current enhancement
- Up to 6 MW of 30 MHz HHFW heating will be available on NSTX-U to support NI operation
- FNSF-ST will be “overdense” → need electron Bernstein waves (EBWs) for local electron heating & CD, instead of “conventional” electron cyclotron (EC) waves
- 1 MW of 28 GHz power is planned for EC/EBW-assisted plasma start-up experiments in 2016-17

Reduced edge losses and less fast-ion interaction with the HHFW 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 HHFW 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

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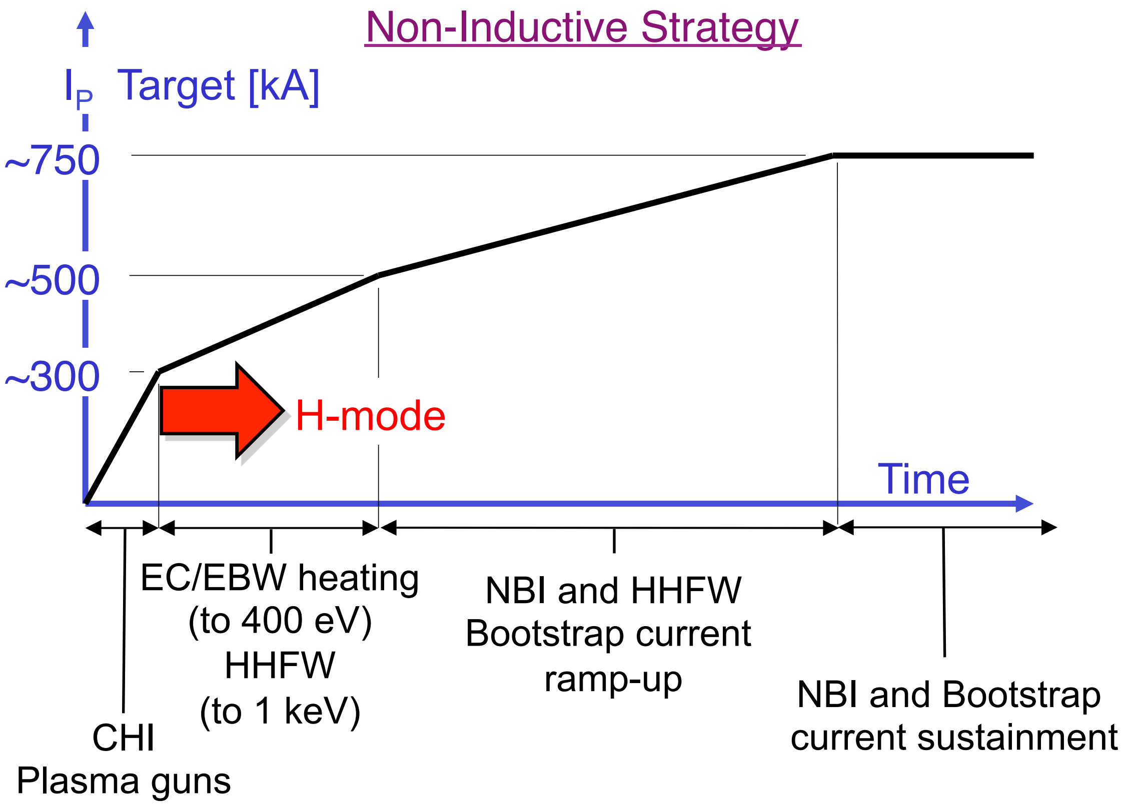
There are three long-term NSTX-U RF research thrusts supporting a FNFS-ST and ITER

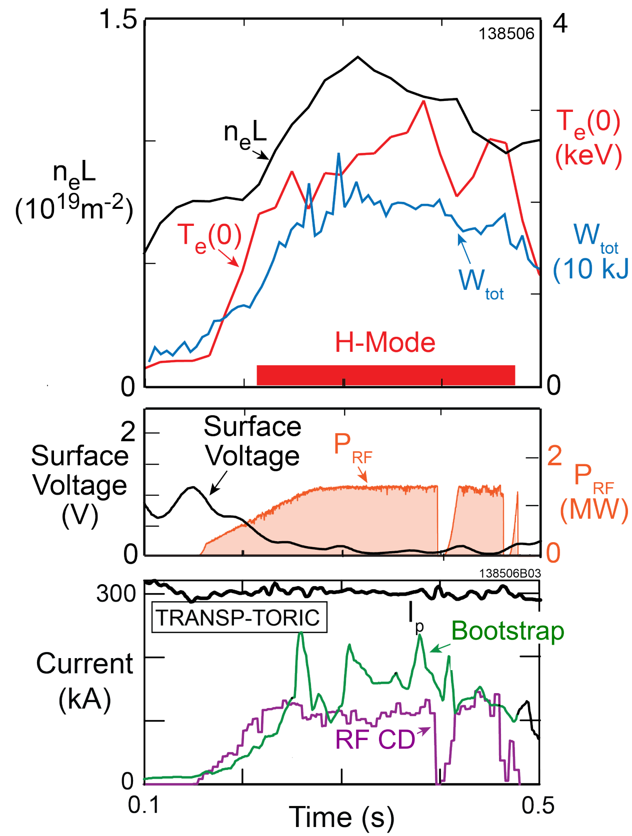
→ Develop RF heating and CD for fully NI plasma current start-up and ramp-up

→ Optimize HHFW CD in both HHFW+NBI and HHFW-only H-mode plasmas

→ Validate advanced RF codes for NSTX-U and predict RF performance in a FNSF-ST and ITER

Thrust #1: Development of RF for fully NI discharges



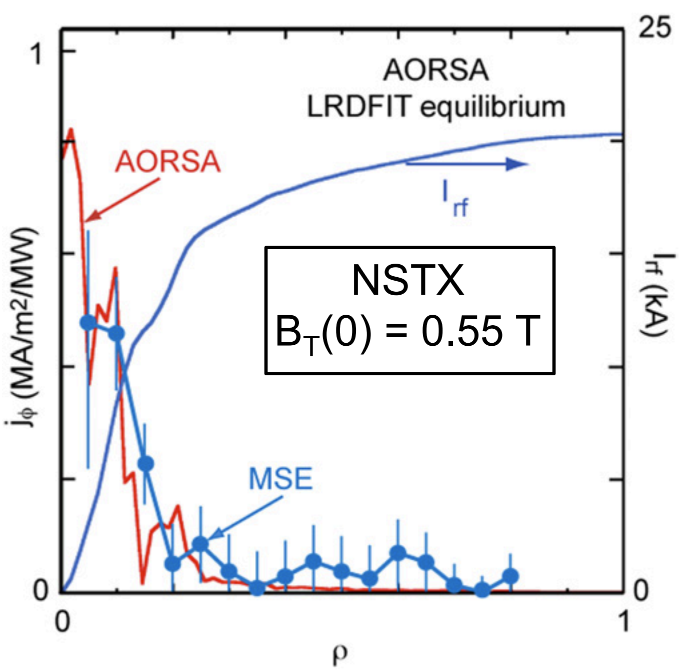


G. Taylor et al., Phys. Plasmas **19** (2012) 042501

- Experiments in NSTX-U will initially develop NI start-up, ramp-up and plasma sustainment separately:
  - In NSTX achieved >70% NI fraction* in an I_p = 300 kA H-mode plasma with 1.4 MW of HHFW → In NSTX-U use higher power and ramp I_p

Thrust #2: Optimization HHFW CD in H-mode plasmas

- There are several challenges for using HHFW for CD in NSTX-U:
  - At the higher $B_T(0)$ in NSTX-U FW heating of thermal ions is expected to be significant, especially for longer wavelength CD antenna phasing
  - Fast-ion heating in NBI + HHFW H-modes will also reduce CD efficiency
  - Lower RF coupling efficiency with CD antenna phasing
- Full wave simulations of HHFW CD in a $B_T(0)$ = 0.55 T NSTX L-mode plasma agreed with CD profile measured by a motional Stark effect (MSE) diagnostic*:
  - CD studies will be extended to H-mode discharges with $B_T(0) \leq 1$ T in NSTX-U

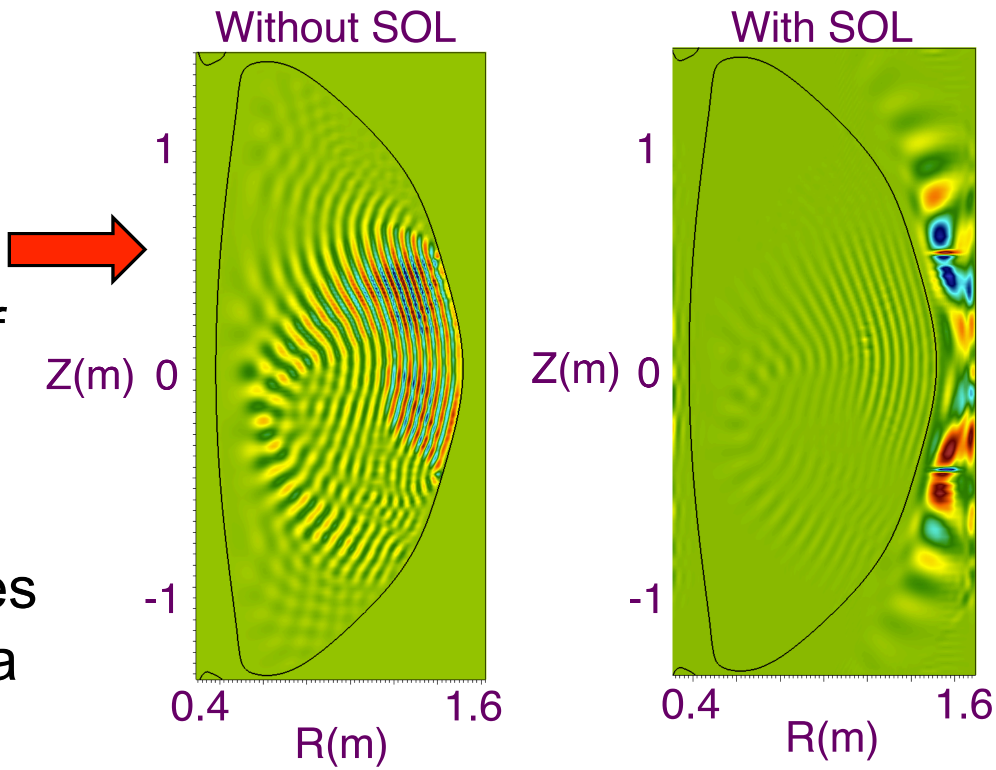


*C. K. Phillips et al., Nucl. Fusion **49** (2009) 075015

Thrust #3: Validation of advanced RF codes

- Advanced RF numerical codes, such as the AORSA full-wave solver, can be valuable tools for predicting the behavior of the wave fields in ITER and FNSF-ST

- Need to validate RF codes against experimental data on present devices, such as NSTX-U



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

- Accurate validation requires detailed measurements of SOL, edge fluctuations, RF power flows to divertor, power deposition and RF-driven current profiles

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Several near-term RF research areas will be pursued to support the long-term research thrusts

- Assess HHFW interaction with fast-ions, and develop the capability to heat high-power NBI H-mode plasmas
- Mitigate HHFW power losses in the SOL
- Model and design the megawatt-level EC/EBW heating system for NI plasma start-up
- Complete development of advanced codes that can accurately model RF waves in NSTX-U, including accurate SOL & antenna

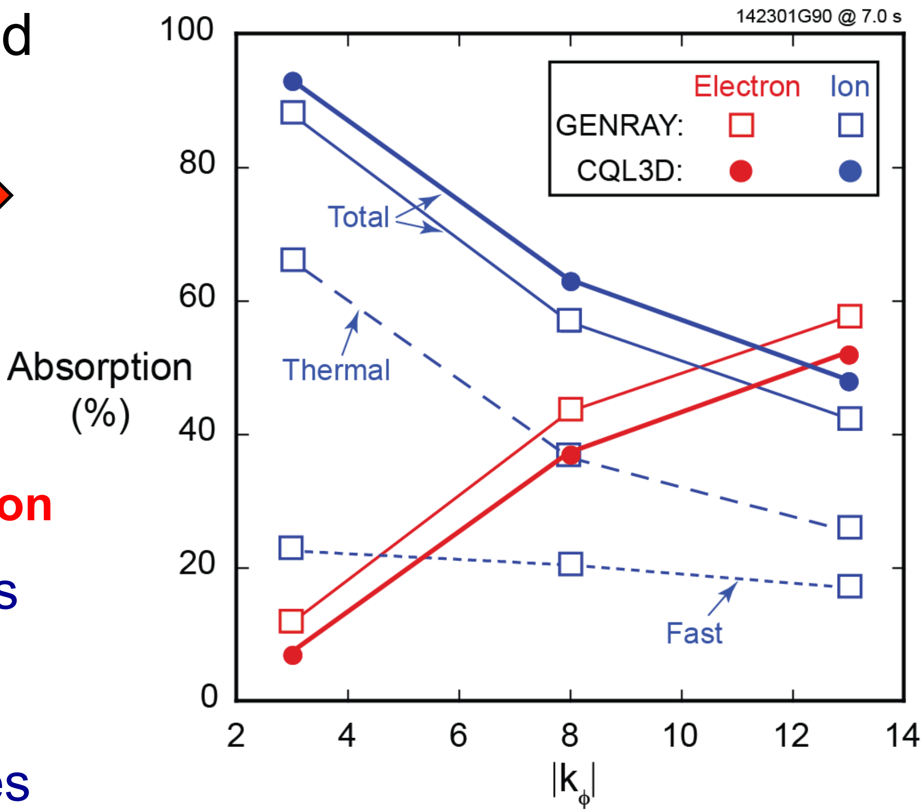
30 MHz HHFW heating simulations for $B_T(0)$ = 1 T NSTX-U discharges predict significant RF absorption on ions

- Interactions between HHFW power and ions (both thermal and fast beam ions) are expected to be important in NSTX-U:
  - GENRAY, CQL3D, AORSA and TORIC all predict strong HHFW absorption by ions in NSTX-U

→ **See N. Bertelli's talk P12 this afternoon**

  - HHFW+NBI heating experiments in NSTX-U will be used to validate and verify predictions of advanced RF simulation codes
  - These codes will in turn be used to predict FW interaction with fast-ions in ITER and other devices

NSTX-U NBI + HHFW H-Mode



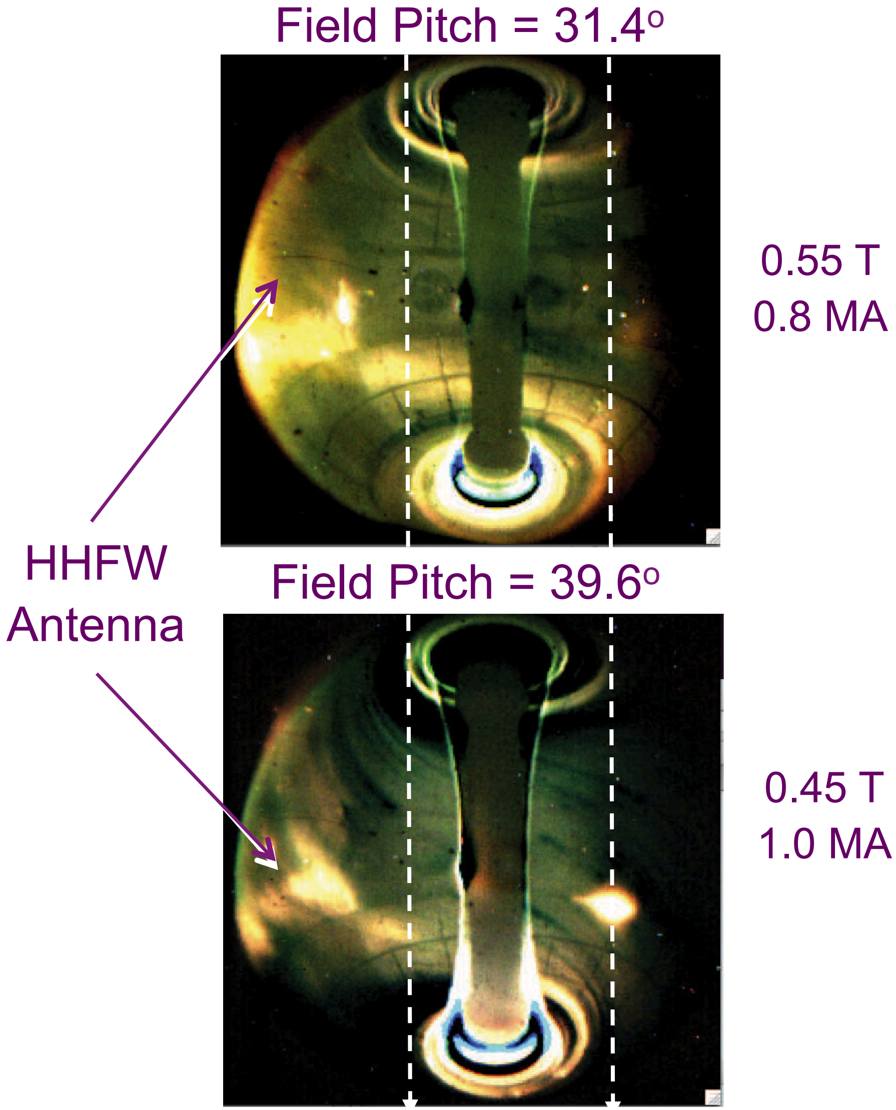
$B_T(0)$ = 1 T, I_p = 1.1 MA, P_{nbi} = 6.3 MW
$n_e(0) = 1.1\times10^{14}$ cm^{-3}, $T_e(0)$ = 1.22 keV,
$T_i(0)$ = 2.86 keV, and 6 cm outer gap

A new FW power loss mechanism has been identified in the SOL of NSTX during HHFW heating experiments

- In some cases this mechanism resulted in significant FW power flows towards the divertor regions along field lines in the SOL*

- Understanding the cause for this loss is critical for optimizing FW heating in other devices, especially for long-pulse FW heating in ITER

→ See R. Perkin's talk P13 and J. Hosea's talk P14 this afternoon



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

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

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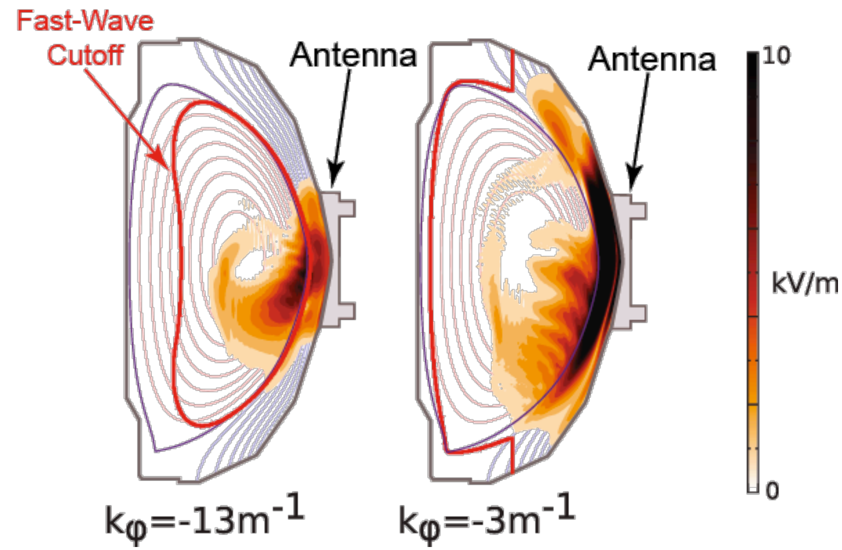
NSTX-U RF research supported by a suite of numerical codes whose predictions will be verified

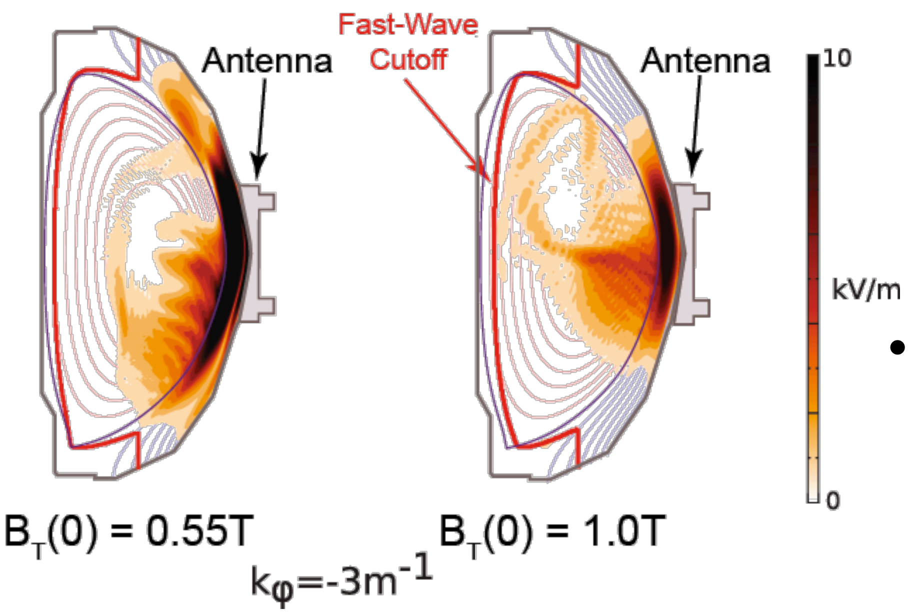
- RF code development for NSTX-U involves a collaboration between the NSTX-U, C-Mod and DIII-D RF programs
- Significant support from the USDoE RF-SciDAC Center for Simulation of Wave-Plasma Interactions
- Simulation codes being used to predict RF heating and CD performance in NSTX-U:
  - AORSA [E. F. 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]

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*



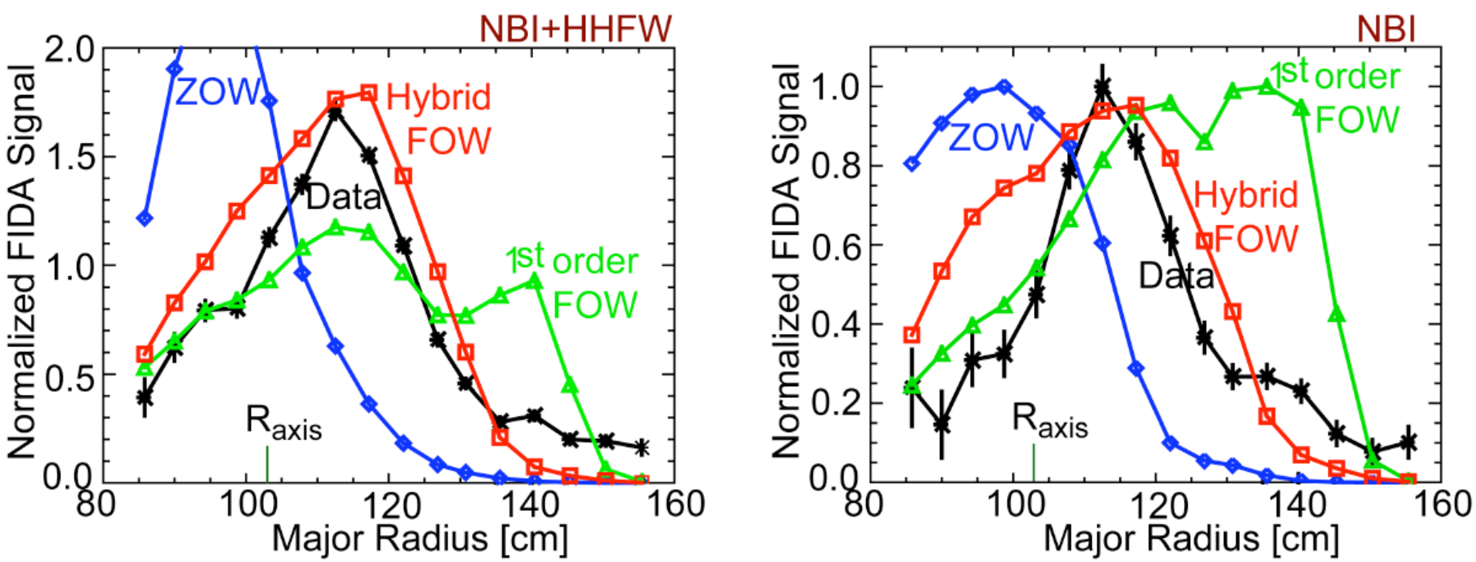
*D. L. Green et al., Phys. Rev. Lett. **107** (2011) 145001

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

OAK RIDGE National Laboratory

Finite-orbit-width (FOW) CQL3D Fokker-Planck code will predict neoclassical transport, ion loss & heat flowing to SOL

- Recent simulations using "hybrid" full-orbit FOW version of CQL3D show much better agreement with fast-ion diagnostic (FIDA) data:
  - "Hybrid" FOW CQL3D has full orbits but does not treat orbit topologies correctly at the trapped-passing boundary



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

CompX SM

Improvements to other RF codes 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 HHFW 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

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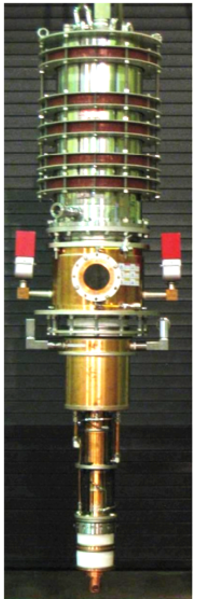
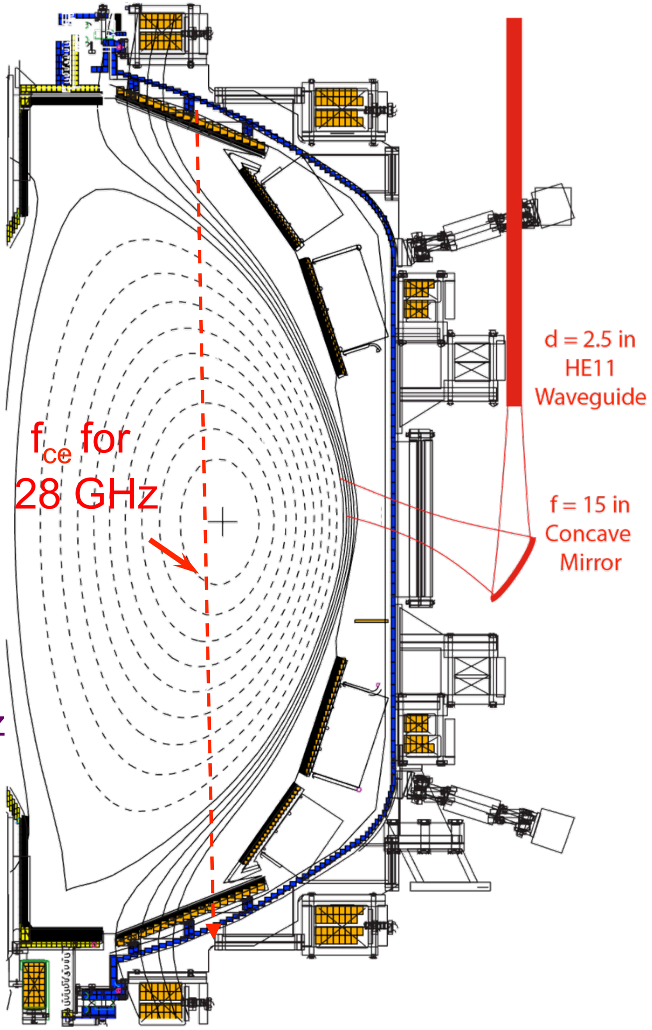
Solenoid-free start-up will be supported by implementing 28 GHz EC/EBW heating in 2016-17

- Initially install 1 MW 28 GHz gyrotron to support plasma start-up:
  - Use Gyrotron originally developed for GAMMA 10*
    → R. Miniami's talk T14 presented on Tuesday afternoon
  - Fixed horn antenna & low-loss HE11 corrugated circular waveguide
  - Power gyrotron with modified TFTR NBI power supply



1 MW, 28 GHz Gyrotron

- Possibly upgrade 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

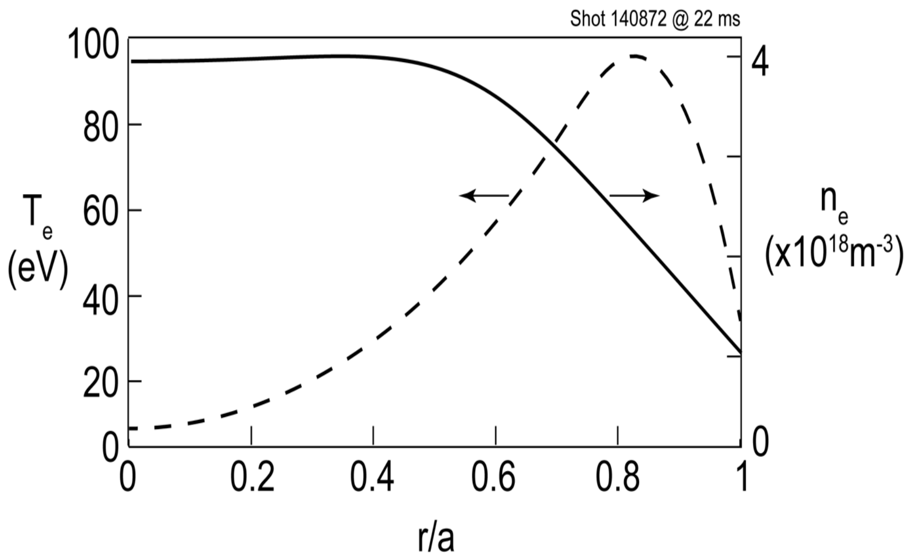


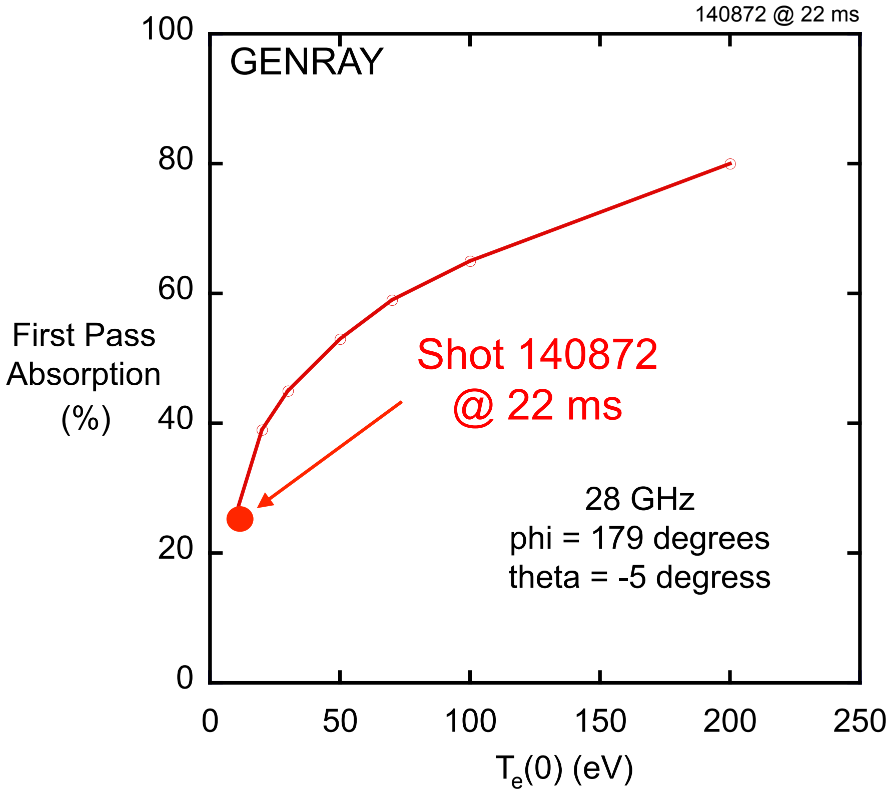
Conceptual implementation of 28 GHz EBW heating system using steerable mirror for O-X-B coupling

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

GENRAY modeling of 28 GHz EC heating of a CHI startup plasma predicts 25% first pass absorption

NSTX Shot 140872 @ 22 ms

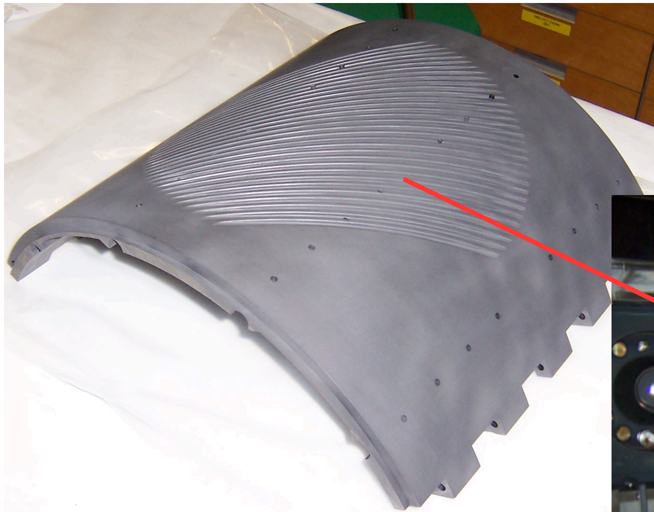




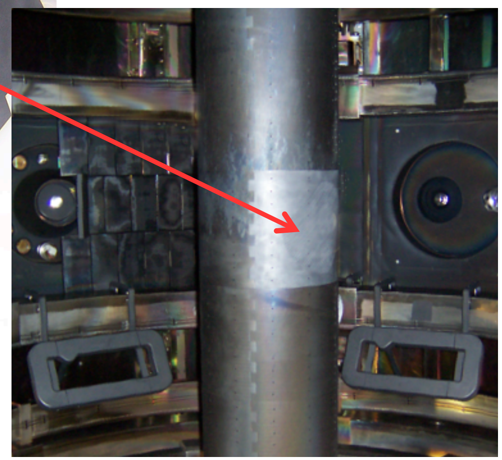
CHI plasma characterized by very hollow $T_e(R)$ profile with $T_e(0)$ ~ 5 eV

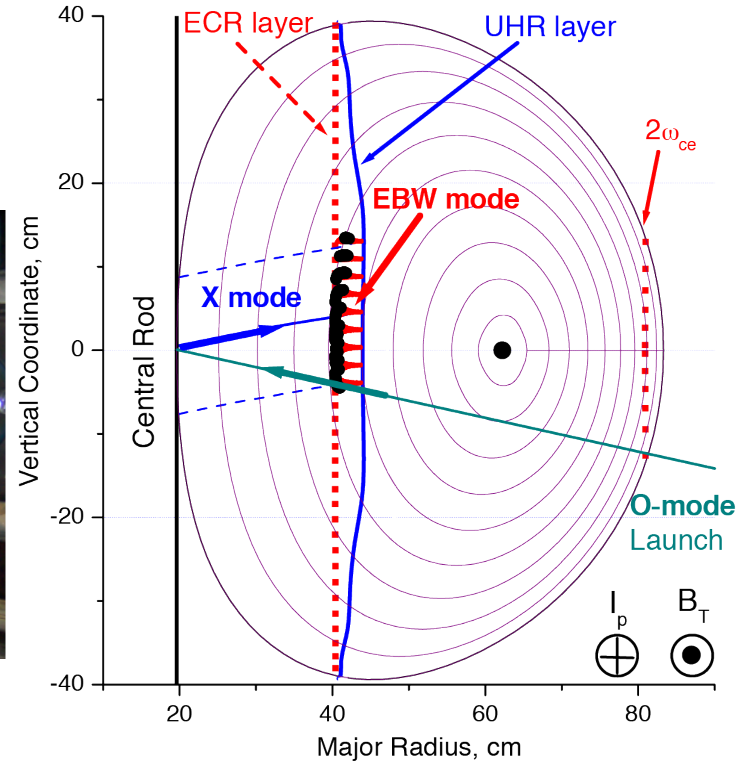
First pass absorption increases to 80% as $T_e(0)$ increases from ~ 5 to 200 eV

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

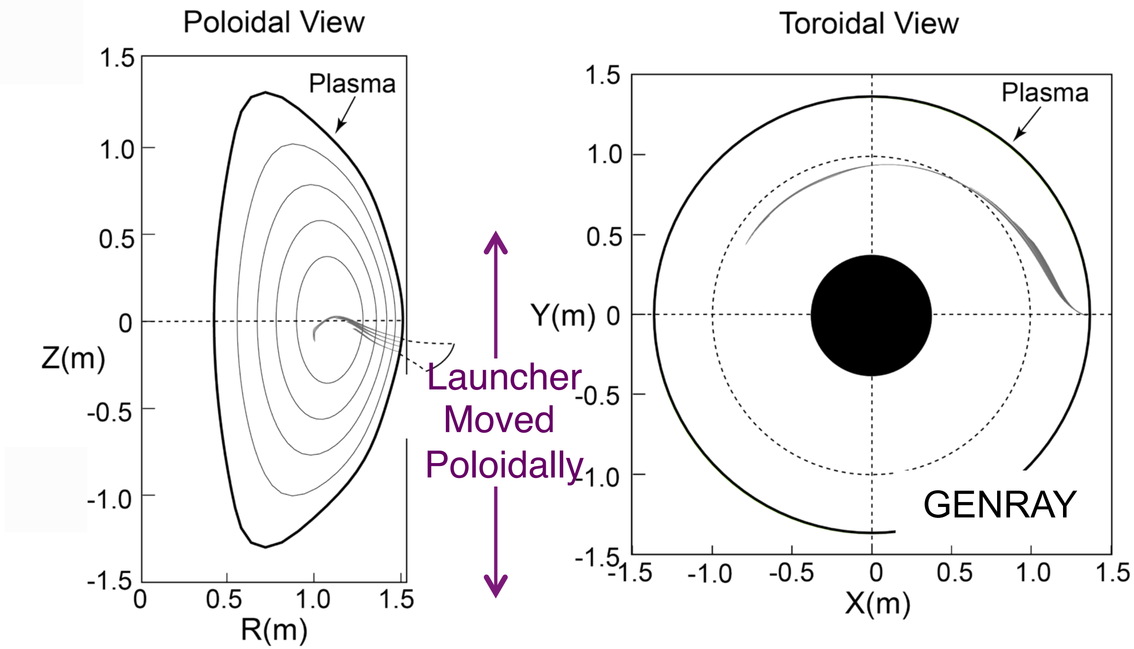


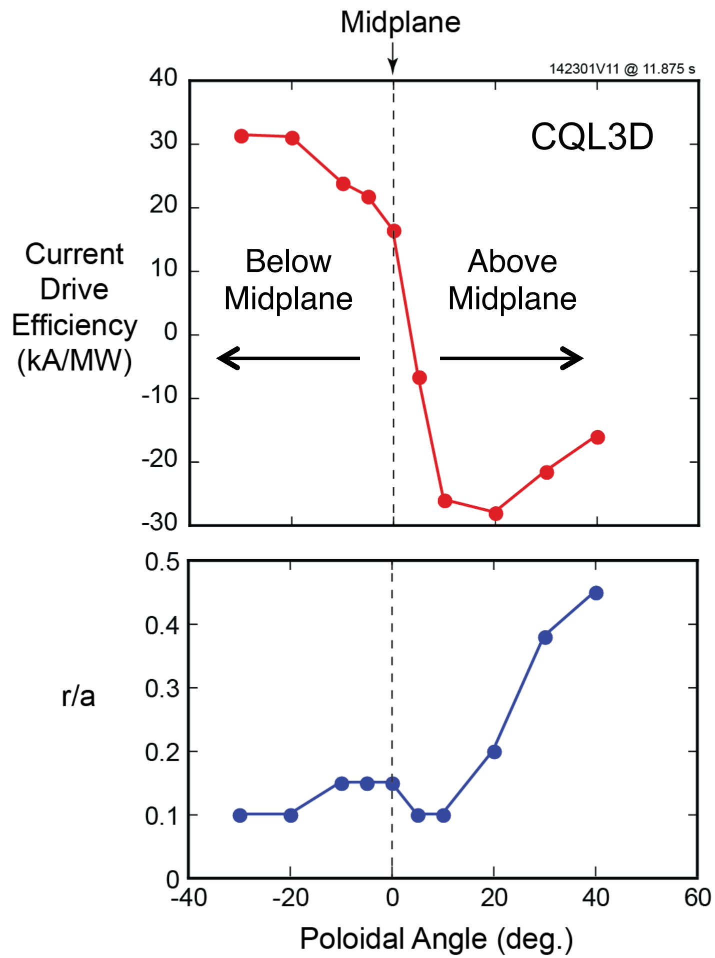


- O-mode EC waves launched from low field side are weakly absorbed (< 2%) below the cut off electron density of ~ 1 x 10^{19} m^{-3}
- Grooved reflecting polarizer on the center column converts O-mode to X-Mode that then ~ 100% converts to EBWs

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

GENRAY/CQL3D 28 GHz EBW simulations for NSTX-U NBI H-mode discharge predict well localized heating and CD





- Initial simulations used O-X-B launcher that was moved poloidally to change the heating location from r/a ~ 0.1 to 0.45:
  - CD efficiencies of 25-30 kA/MW predicted
- More detailed modeling, including SOL model, is planned for the near future

$B_T(0)$ = 1 T, I_p = 1.1 MA,
$n_e(0) = 9 \times 10^{13}$ cm^{-3},
$T_e(0)$ = 1.3 keV

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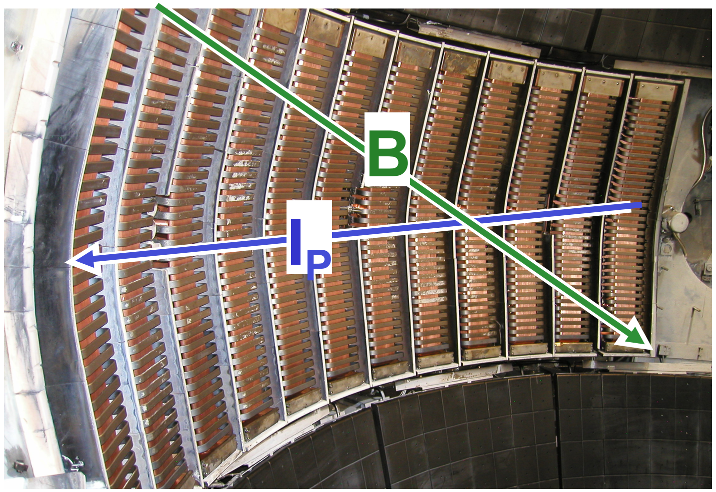
Several enhancements to the NSTX HHFW system are planned in 2013-14 to support NSTX-U operations



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

- RF voltage stand-off tests using two antenna straps will be conducted on an RF test stand in 2013-14:
  - 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
  - Evaluate new feedthroughs on the RF test stand

- In NSTX lithium compound dust entered HHFW antenna increasing antenna arcing → plan to install double Faraday shield

Additional RF, magnetic and Langmuir probes will be installed in NSTX-U to support HHFW research

- Upgrade existing probe sets in divertor tiles to detect RF
- Use 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 HHFW 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 HHFW-only H-modes
- Upgraded 10-40 GHz refectometer and additional laser Thomson scattering channels will provide improved SOL density data

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Wave heating and CD research in NSTX-U will test predictions of advanced RF codes in the ST regime

- NSTX-U will operate at twice the $B_T(0)$, I_p and P_{nbi} used on NSTX:
  - Operation planned to start in 2014 (full operating parameters by 2016)
  - Reduced RF edge losses and fast-ion interaction with HHFW antenna may yield improved RF coupling efficiency
- Three long-term RF research thrusts:
  - Fully non-inductive I_p start-up and ramp-up
  - Optimization of CD in H-mode plasmas
  - Validation of advanced RF codes and prediction of performance of RF in FNSF-ST and ITER
- Expect more FW interaction with ions in NSTX-U compared to NSTX:
  - Significant FW acceleration of thermal ions at full field in NSTX-U
- Megawatt-level 28 GHz EC/EBW-assisted I_p start-up planned for 2016-17