NSTX-U

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Upgrades to the NSTX SOL reflectometer to study plasma-antenna coupling and RF-edge interactions

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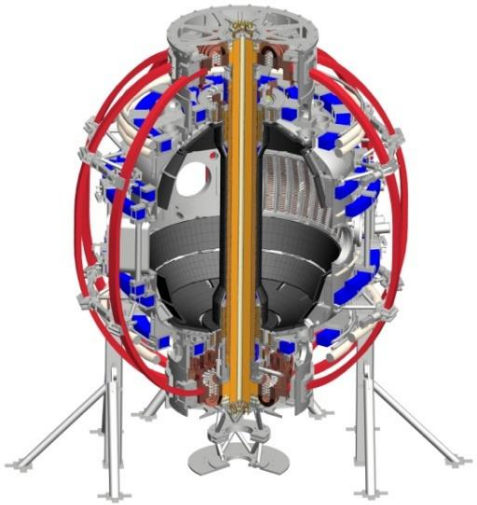

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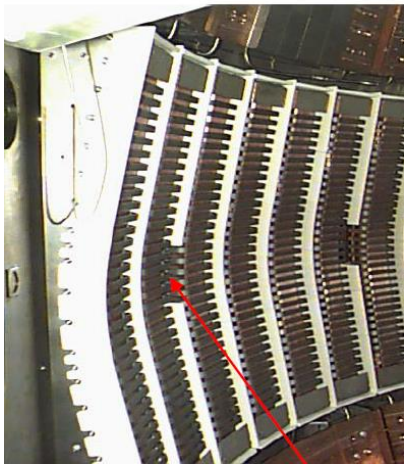
Outline of this poster

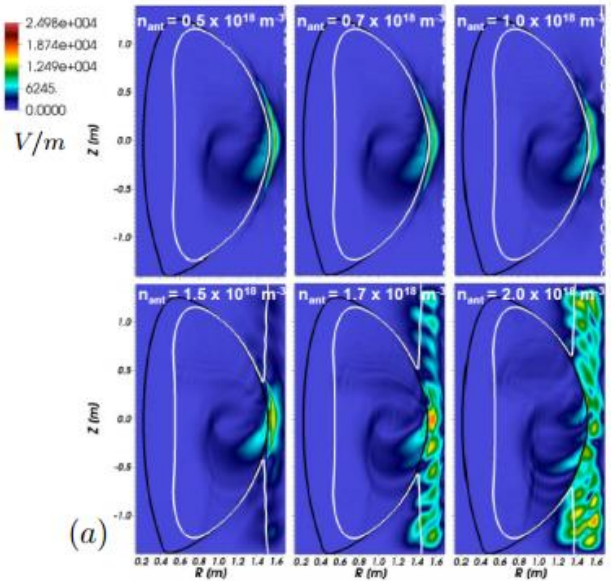
- Overview of ORNL SOL reflectometer on NSTX and NSTX-U
  - main physics goal is to better characterize SOL and support HHFW antenna operation
  - ORNL SOL reflectometer is being upgraded for NSTX-U
- Use of X-mode L, R, and O-mode cutoffs to measure SOL density profiles for NSTX-U
  - |B| is now doubled of NSTX parameters
  - using all modes will save time/money as well as provide measurements at larger range of |B|
  - possibility of |B| profile measurement
- Future work discussed in this presentation
  - RF wave measurement
  - COMSOL simulation

ORNL SOL reflectometer is an important diagnostic to understand HHFW physics

- ORNL SOL reflectometer on NSTX was designed to originally measure SOL density profiles at HHFW antenna to study antenna-plasma coupling
  - antenna-plasma loading is exponentially sensitive to distance from antenna to fast wave cutoff
- Recent results[1] using 3D AORSA simulation (with collisional damping as proxy), demonstrates importance of fast wave cutoff location
  - if SOL density is too low, antenna-plasma loading dominates loss
  - if SOL density is too high, some SOL absorption mechanism dominates loss



Location of reflectometer in 2001!



[1] Bertelli, NF 2014

ORNL SOL reflectometer on NSTX

- ORNL SOL reflectometer used to measure SOL density profiles (and density fluctuations) since 2000[1]
  - 6-27 GHz X-mode R-cutoff used
    - Density coverage from ~ 5×10^{16} m^{-3} to 8×10^{18} m^{-3}
  - pair of double-ridge antennas with coaxial inputs are used to launch and receive waves
    - can be manually rotated to adjust wave polarization
    - located ~ 2 cm behind Faraday shield (~ 1.58m)
  - I/Q detector used and digitized at 5 Ms/s
    - Digitization rate limited sweep speeds to 100μs

- Upgraded to measure sub-30 MHz RF waves and PDI in 2005-2006[2]
  - separate receiver electronics and 100 MHz digitizer used to detect signals

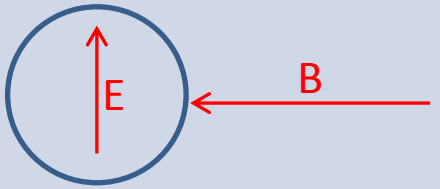
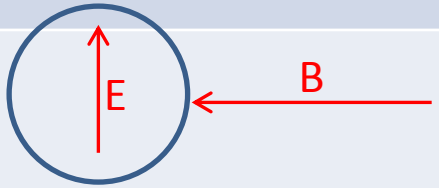
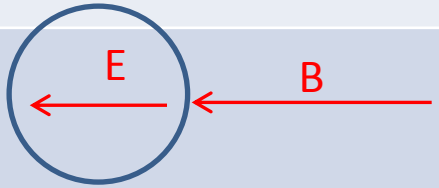
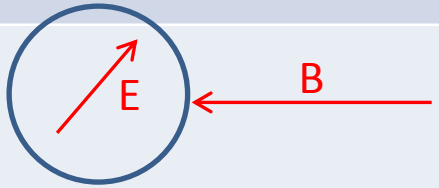
[1] **Wilgen (unpublished)**
[2] **Wilgen RSI 2006**

ORNL SOL reflectometer upgrades on NSTX-U

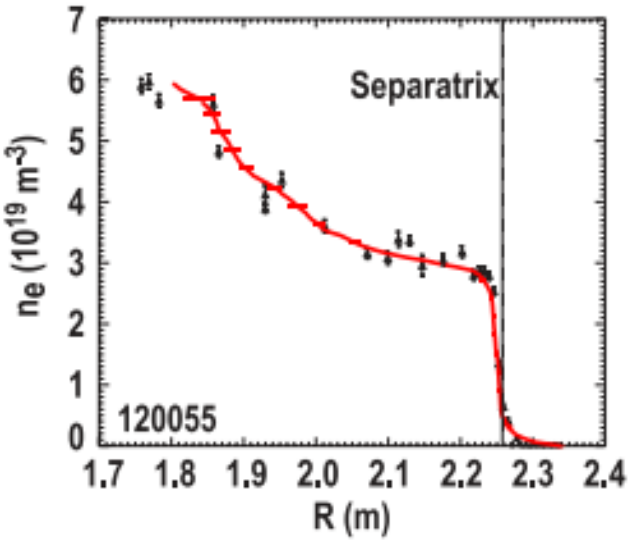
- Initial goal is to maintain and improve capability of ORNL SOL reflectometer to measure density profiles on NSTX-U
  - doubling of |B| on NSTX-U is expected to provide a challenge
    - The use of only X-mode R-cutoff will require using 10-40 GHz, which will require substantial modifications to electronics and transmission lines!
  - use of 6 to 27 GHz X-mode L, R, and O-mode cutoffs will give same density coverage on NSTX-U as 10-40 GHz X-mode R-cutoff operation
    - using all modes will save time/money as well as provide measurements at larger range of |B|
    - possibility of measuring |B| profiles?
  - digitization rate upgraded from 5 Ms/s to 65 Ms/s
    - Video amps, sweep driver circuit, cable lengths modified to upgrade sweep rate from 100μs to 20μs.

- Density fluctuations and RF wave measurements are in future plans
  - upgraded 4 channel 65 MHz digitizer can also be used to measure 30 MHz RF waves
    - No other modification necessary

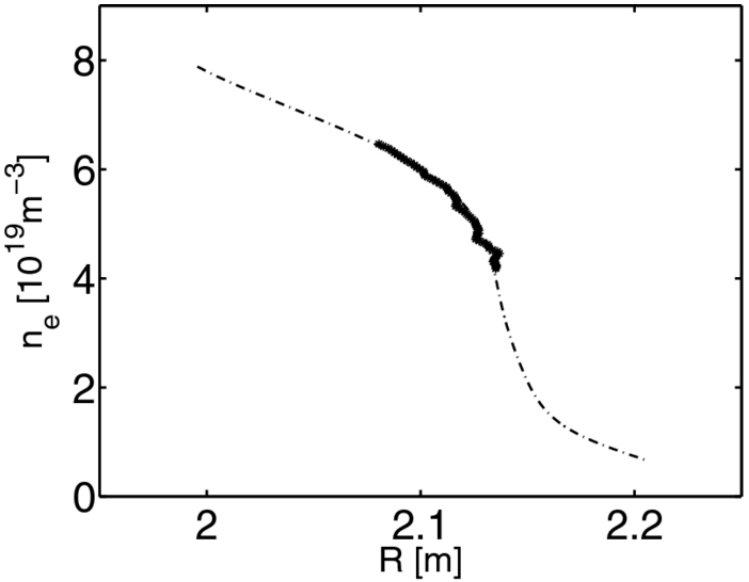
Review of cold electromagnetic waves that are applied to reflectometry in fusion plasmas

Name	Cutoff Frequency	Characteristics	Antenna Polarization
X-mode R-cutoff	$\omega_R = \frac{\sqrt{\omega_{ce} + 4\omega_{pe}{}^2} + \omega_{ce}}{2}$	k ⊥ B, E ⊥ B	
X-mode L-cutoff	$\omega_L = \frac{\sqrt{\omega_{ce} + 4\omega_{pe}{}^2} - \omega_{ce}}{2}$	k ⊥ B, E ⊥ B	
O mode cutoff	$\omega_O = \omega_{pe}$	k ⊥ B, E ∥ B	
O and X mode cutoffs	discussed above	k ⊥ B E ~30-60° to B	

Using multiple reflectometry cutoffs has been successful on DIIID and ASDEX-U



Comparison of 32-72 GHz reflectometry (red) to Thomson scattering (black) on DIIID[1]. O-mode cutoff and X-mode R-cutoff is necessary to obtain expanded density range of reflectometer



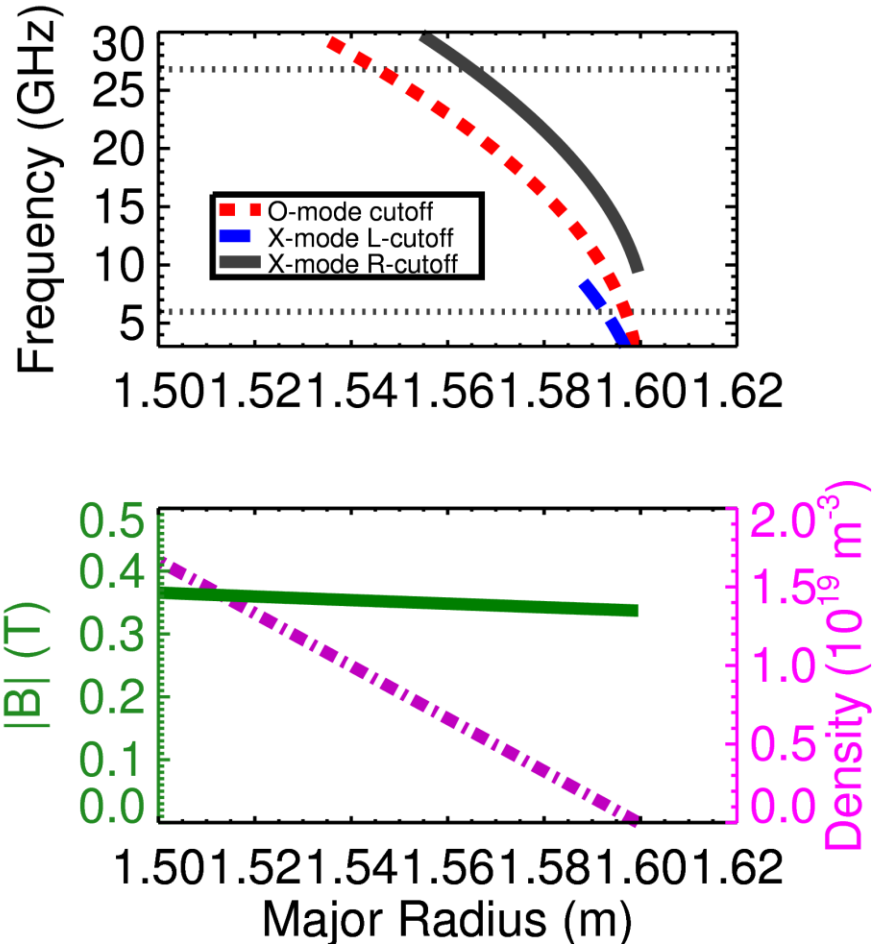
Comparison between the density profiles obtained with O-mode (dashed line) and with X-mode L cut-off (individual points) on ASDEX-U[2].

- Three reflectometer launchers (1 to send O/X, 2 to receive O or X) are used to distinguish O-mode and X-mode on DIIID[1]
- Time averaged spectrogram is used to distinguish beat frequency of O-mode and X-mode on ASDEX-U[2]

[1] G. Wang (NF 2006)
[2] P. Varela (RSI 2012)

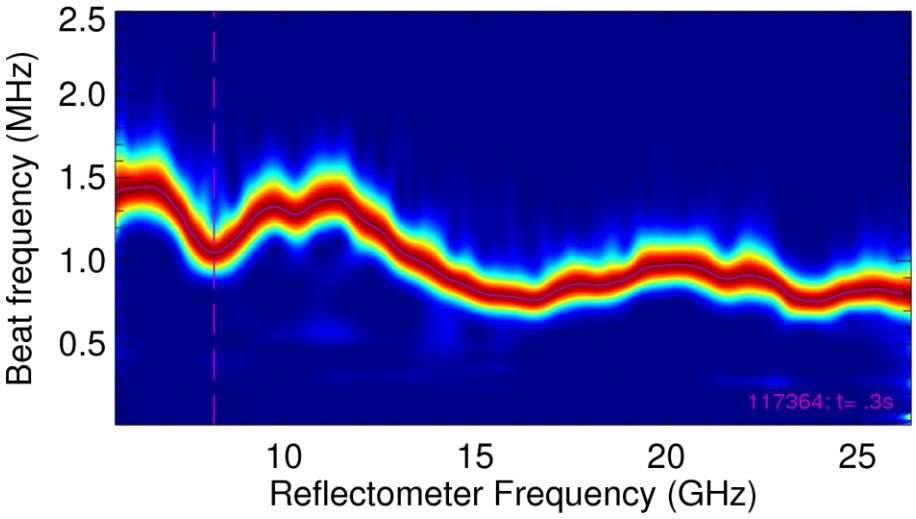
6-27 GHz X-mode R-cutoff frequencies can measure up to ~8x10^{18} m^{-3} on NSTX

- Simple study done to evaluate reflectometer response on NSTX and NSTX-U
  - linear density profile assumed, B ~ .45 T from EFIT on typical discharge
  - X-mode L, R and O-mode cutoffs shown
    - X-mode L-cutoff surprisingly appears in LFS SOL, although for a limited density range
  - X-mode L-cutoff frequency is only shown up to its accessibility limit for LFS reflectometry
  - UH, LH, cyclotron resonance are not drawn since they are not a concern for accessibility



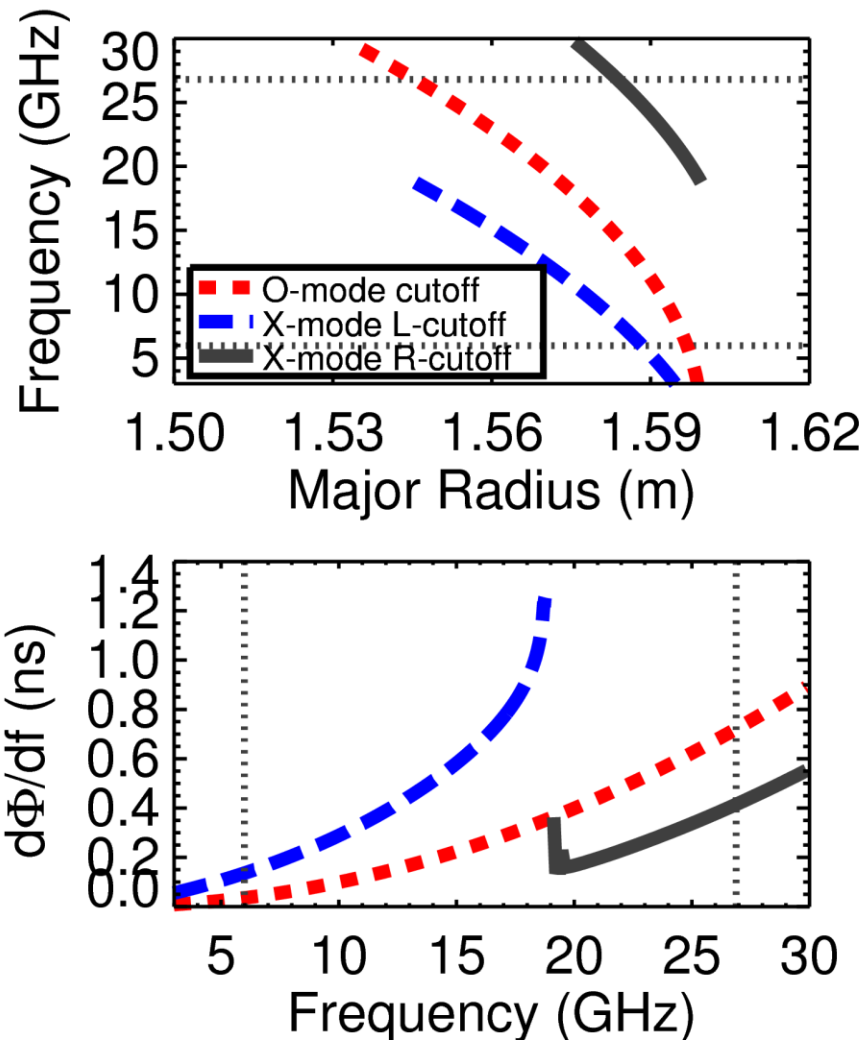
X-mode L-cutoff is likely observed on NSTX

- Data from time averaged scalogram shows coherent mode below minimum cyclotron frequency
  - X-mode R-cutoff should not be detected below minimum cyclotron frequency
  - X-mode L-cutoff is suspected
    - waveguide launchers are preferentially polarized to launch and receive X-mode
    - Not previously used in analysis for NSTX due to its limited density coverage
  - complete waveguide calibration needs to be done for density inversion and confirmation of X-mode L-cutoff
    - DIII-D and ASDEX-U results give more confidence



6-27 GHz X-mode L and R-cutoff frequencies can measure up to ~1x10^{19} m^{-3} on NSTX-U

- X-mode L-cutoff will be important for 6-27 GHz operation on NSTX-U
  - same density as NSTX case, but |B| is now doubled
  - X-mode R-cutoff density coverage is substantially reduced
    - Minimum cyclotron frequency is still expected to be within 6-27 GHz operation
  - X-mode L-cutoff has expanded density coverage
  - use of both X-mode L-cutoff and R-cutoffs will allow for operation for range of NSTX-U's density and |B| field
    - NSTX-U is expected to start at low |B| field before raising |B| field in later campaigns
    - density gradient variations do not significantly affect results



Dual O-mode and X-mode reflectometer operation can provide two measurements at overlapping densities in SOL

- For both NSTX and NSTX-U conditions, O-mode and X-mode cutoffs covers overlapping radial range
  - 6-27 GHz O-mode covers 4.5×10^{17} m^{-3} to 9×10^{18} m^{-3}
    - O-mode depends only on density
  - 6-27 GHz X-mode R-cutoff and L-cutoff covers ~ 5×10^{16} m^{-3} to 1×10^{19} m^{-3}
    - X-mode depends on density and magnetic fields
  - Simultaneous measurement of both X-mode and O-mode at overlapping density range may give both density and magnetic field[1]
  - time averaged scalogram or spectrogram should be able to measure group delay and distinguish O-mode and X-mode
    - If waveguide launchers are polarized to launch and receive both O and X-modes, signal processing is likely to resolve dual modes over reflectometer frequency range[1]
    - if not possible, 3 waveguide launchers (1 to send O/X, 2 to receive either O or X) will also work[2]

[1]Varela, RSI 2012
[2]Wang, RSI 2004

Using O and X-mode to determine density and |B| profile

$$\phi(\omega) = 2\frac{\omega}{c}\int_{r_0}^{r(\omega)} N dr - \pi/2$$

Reflectometer equation

$$\boldsymbol{r}(\omega) = \boldsymbol{r}_0 - \frac{\boldsymbol{c}}{\pi}\int_0^{\omega} \frac{\boldsymbol{d}\phi}{\boldsymbol{d}\omega'}\frac{\boldsymbol{d}\omega'}{(\omega^2 - \omega'^2)^{1/2}}$$

O-Mode

$$r(\omega_{i+1}) = r_0 - f(\phi_i, \phi_{i-1}..., \omega_i, \omega_{i-1}..., r(\omega_i), r(\omega_{i-1})..., B(r(\omega_i), r(\omega_{i-1})))$$

X-mode[1]

- use O-mode phase measurement to obtain density profile, r(ω)
- use r(ω) from O-mode phase measurement and X-mode phase measurement to obtain B(r)
- requires X-mode and O-mode to both measure the same radial region
  - achievable with ORNL SOL reflectometer on NSTX-U

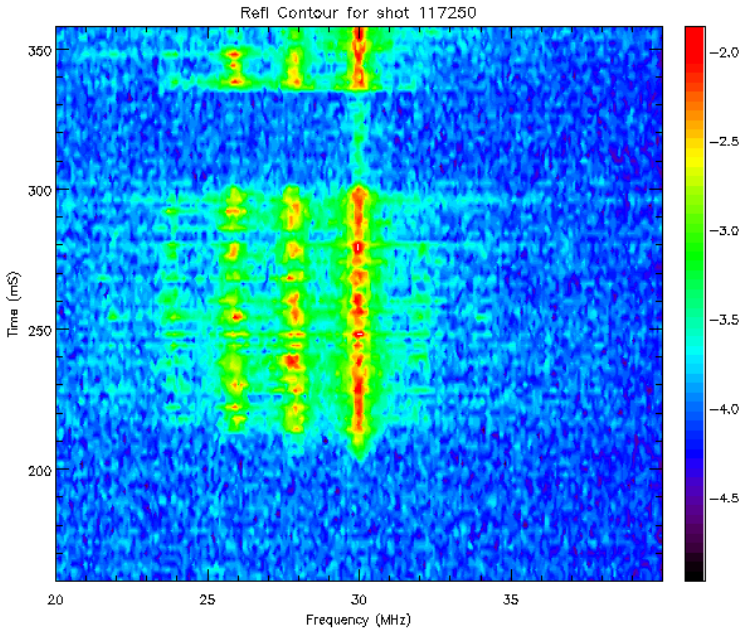
[1]Bottolier-Curtet, RSI 1987

Possible issues for |B| measurement

- Significant issues still need to be determined:
  - determining location of minimum cyclotron frequency for X-mode R-cutoff
    - typical signal amplitude approach will not work due to presence of X-mode L-cutoff
    - discontinuity of beat frequency is not always clear in the NSTX data
  - assumption for shape of density profile below 4.5×10^{17} m^{-3} (6 GHz O-mode cutoff density)
    - sensitivity of magnetic field profiles to this assumption will need to be studied
    - extending reflectometer to lower frequencies will help
  - effect of density fluctuations on density profile
    - needs to be studied in steady state conditions
  - if B_p is desired, accuracy of B_t calibration needs to considered

HHFW waves measurement

- Sub-30 MHz RF wave and PDI measurement is next priority
  - low-frequency circuit already used in 2006
  - simultaneous density profile and RF wave measurement may be possible during frequency sweep?
    - Use of new 65 MHz digitizer may make this easier, as density profiles and RF wave measurement will be on same digitizer
  - data mining from NSTX-U, and improved data analysis will be desirable



PDI measurement (Wilgen APS 2006)

3-D finite element method of NSTX HHFW antenna has been recently initiated

- goal is to eventually have a 3-D FEM model using COMSOL multiphysics with a cold plasma model and realistic antenna and magnetic geometry on NSTX-U HHFW antenna
  - similar to previous COMSOL models by Garrett[1], Jacquot[2], Shiraiwa[3], Hillairet[4] for minority heating ICRF and LHCD regimes on Alcator C-Mod and Tore Supra
  - physics of HHFW is different, however, and may be a numerical challenge?

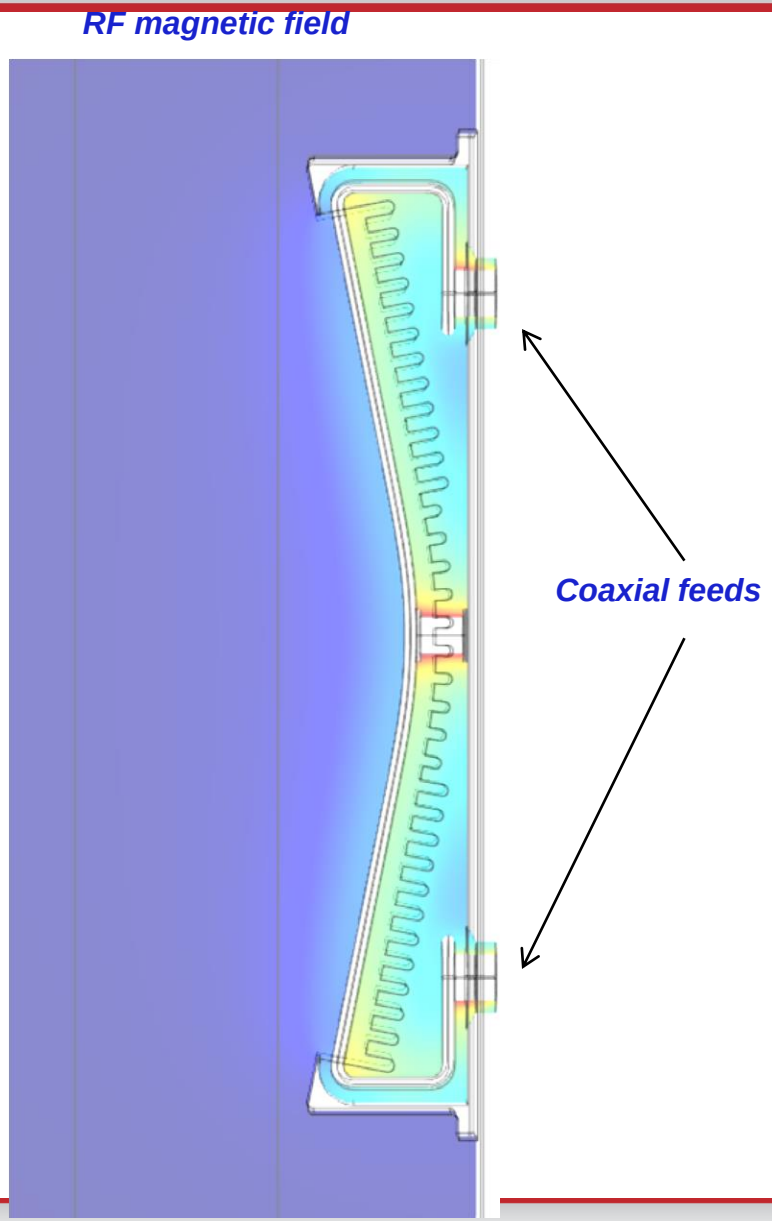
- envisioned to help understand NSTX RF physics results related to RF-SOL interactions, such as antenna loading[2,3,5], RF electric fields[4], rectified sheaths[1], and RF-driven convective cells[5]

- envisioned to interpret diagnostic results related to RF physics
  - reflectometer density profile measurement is critical input to COMSOL model
  - COMSOL model may help understand RF-driven effects to reflectometer density profile and wave measurements

[1] Garrett, FED 2012 [2] Jacquot, PPCF 2013 [3] Shiraiwa, NF 2011
[4] Hillariet, private comm. [5] Lau, PPCF 2013

Current status of NSTX COMSOL simulations

- 1 strap antenna geometry has been re-drawn using COMSOL multiphysics (August,2014)
  - Faraday screen has temporarily removed due to meshing issues
- Simulation in vacuum has been achieved
  - Continue to work on meshing optimization
- Plasma scenario is still work in progress
  - currently having numerical convergence issues
- full 12 strap geometry is in progress



Conclusion

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  - main physics goal is to better characterize SOL and support HHFW antenna operation
  - ORNL SOL reflectometer is being upgraded for NSTX-U
- Use of X-mode L, R, and O-mode cutoffs to measure SOL density profiles for NSTX-U
  - |B| is now doubled of NSTX parameters
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  - possibility of |B| profile measurement
- Future work discussed in this presentation
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  - COMSOL simulation