U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

NSTX-U SOL reflectometer

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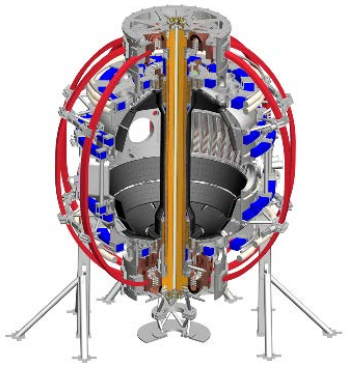
PPPL



Outline of this poster

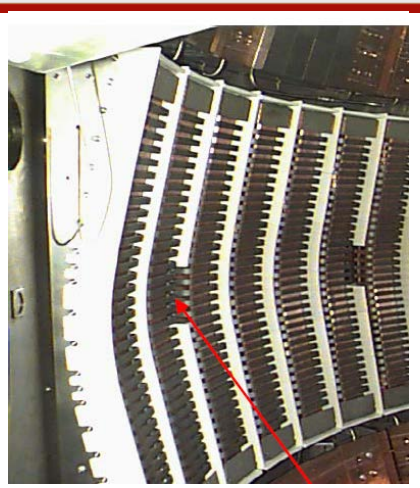
- Current status of this NSTX-U reflectometer
  - main physics goal is to better characterize SOL and support HHFW antenna operation
    - SOL losses and HHFW loading calculations
  - ORNL SOL reflectometer is functional and upgraded for NSTX-U

- 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

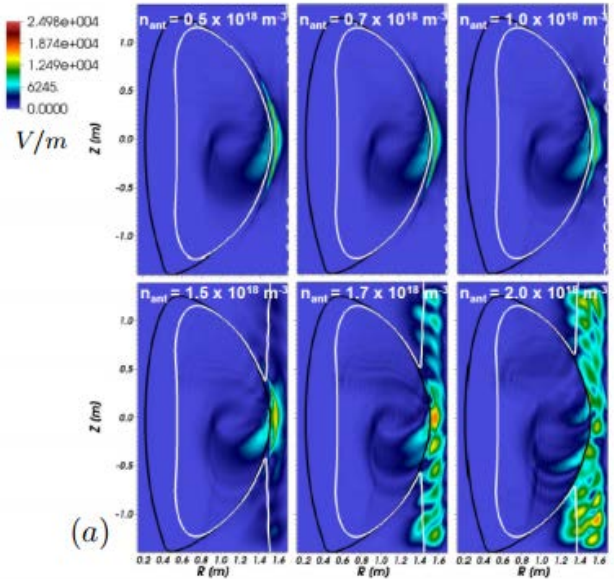
ORNL SOL reflectometer is an important diagnostic to understand HHFW physics

- ORNL SOL reflectometer 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
  - For fast wave operation in ramp-up, SOL density profiles are critical in determining HHFW operations

- 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



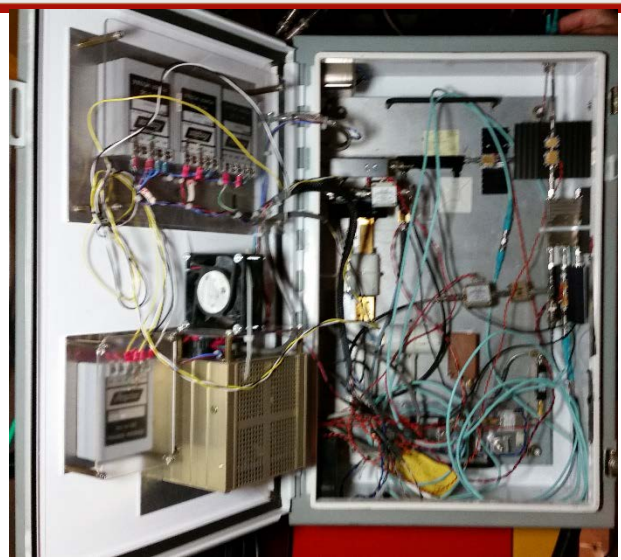
Location of reflectometer in 2001!

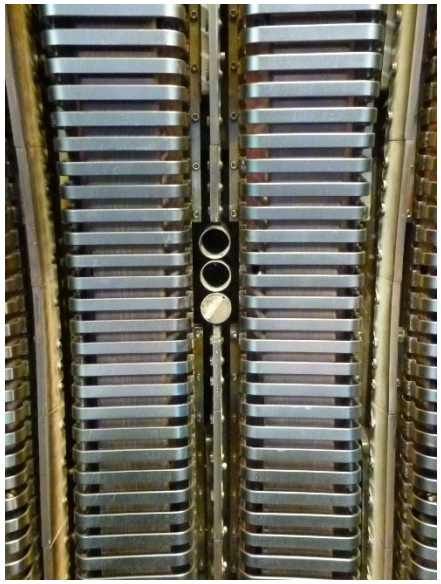


[1] Bertelli, NF 2014

Status of ORNL SOL reflectometer on NSTX-U (1/2)

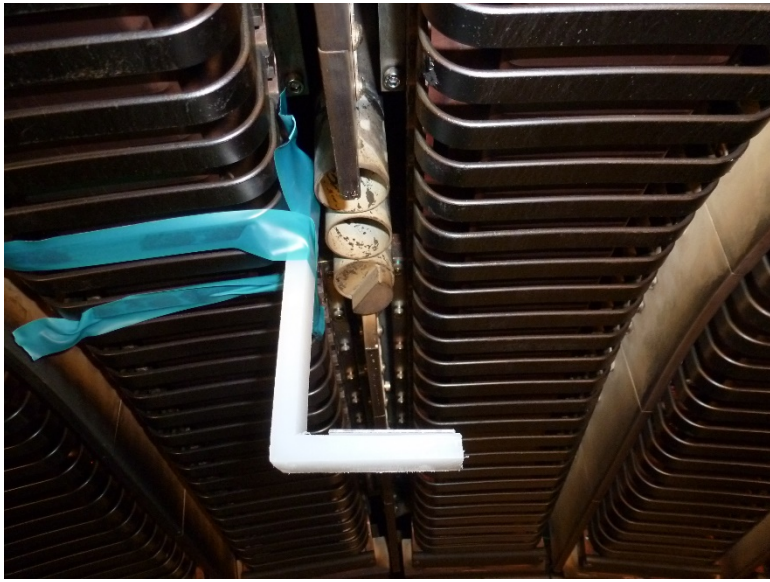
- ORNL SOL reflectometer electronics, waveguide is fully re-installed in NSTX-U test cell
  - computer, power switch still needs to be installed for between shot changes
- Digitizer is fully operational at up to 65 MSPS
- Two days of plasma shots before NSTX-U coil failure
  - However, plasma data is corrupted by electronics issues (next slide)
  - electronics is believed to be fixed after campaign





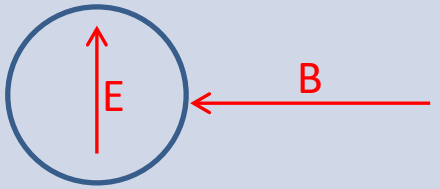
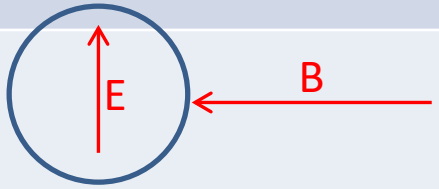
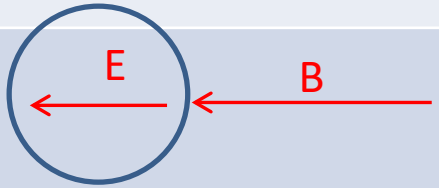
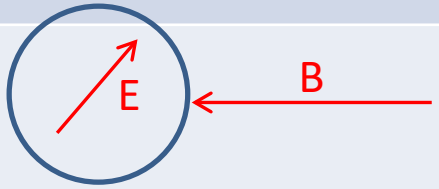
Status of ORNL SOL reflectometer on NSTX-U (2/2)

- In-vessel calibration confirmed last oscillator was ringing
  - This has been fixed approximately a month ago
  - Invessel calibration confirms plasma data noise is due to electronics, not plasma effects

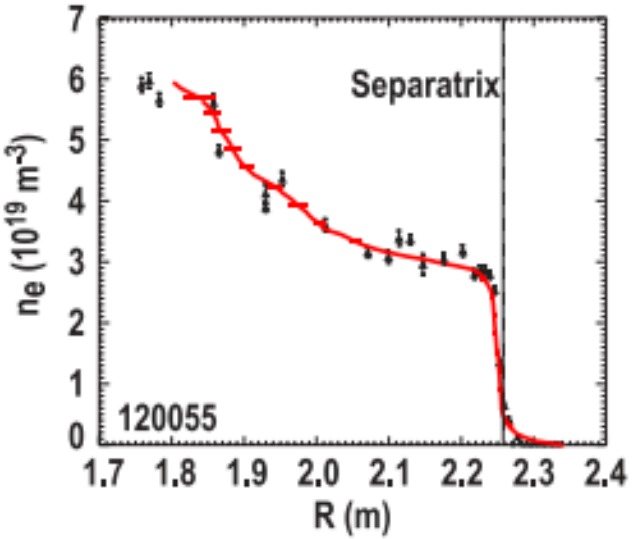


- Hardware should be “ready” for next campaign, unless other diagnostic debugging issues come up…

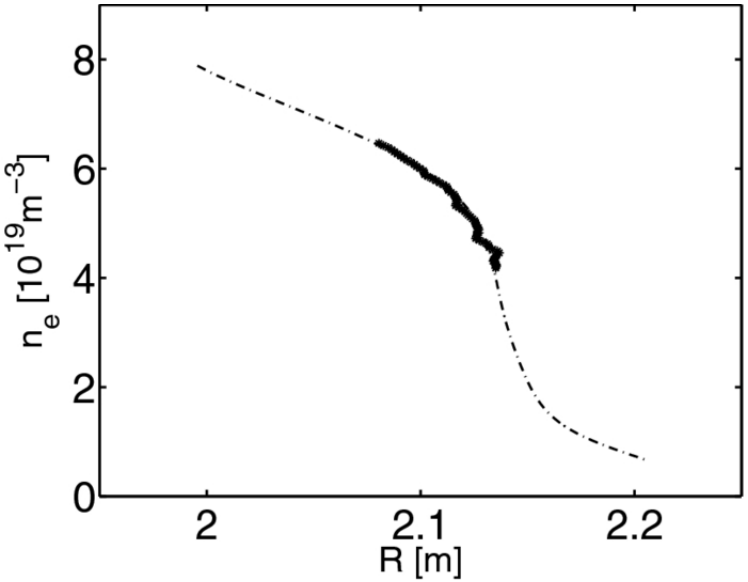
Review of cold electromagnetic waves that are applied to reflectometry

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

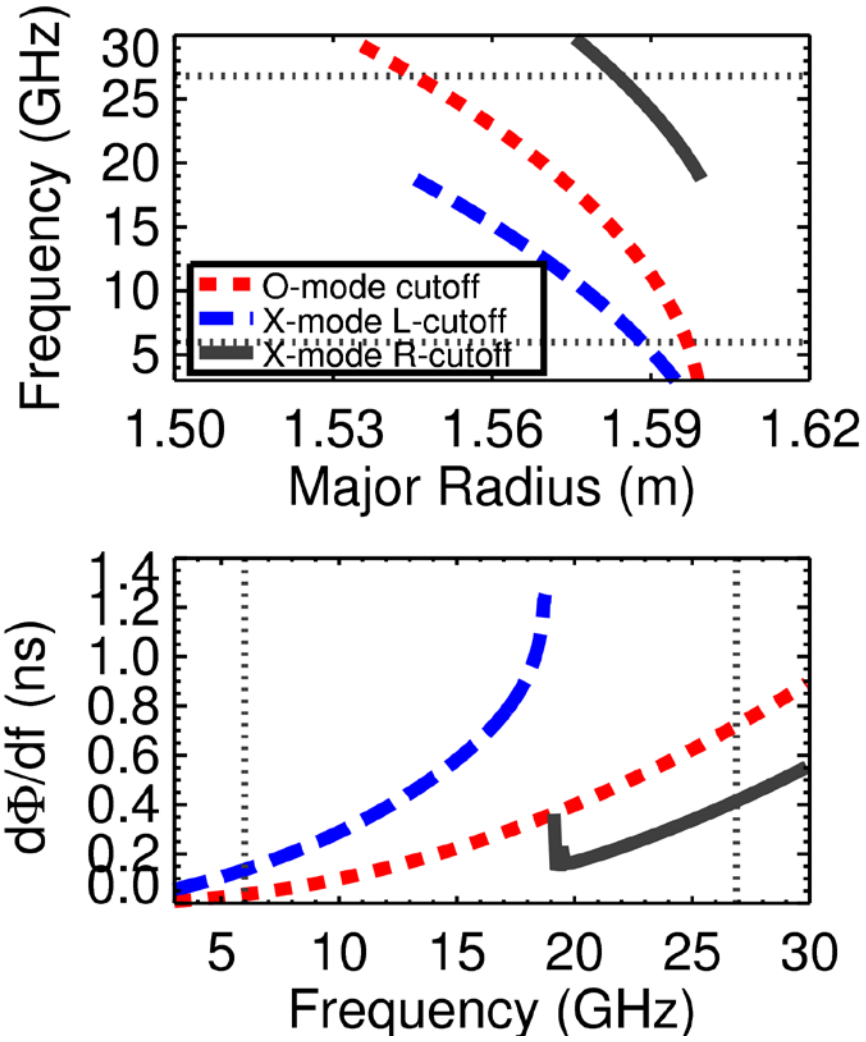


Comparison between the density profiles obtained with O-mode (dashed line) and with X-mode L cut-off (individual points) on ASDEX-U[2].

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

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

- X-mode 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
    - density gradient variations do not significantly affect results



Dual O-mode and X-mode reflectometer operation can provide two measurements

- O and X-mode cutoffs cover 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

$$\boldsymbol{r(\omega) = r_0 - \frac{c}{\pi}\int_0^{\omega} \frac{d\phi}{d\omega'} \frac{d\omega'}{(\omega^2 - \omega'^2)^{1/2}}}$$

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 measurements to obtain density profiles, 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 measure same radial region
- Requires low enough frequency, so that O-mode measurement is meaningful
- This is all achieveable for ORNL SOL reflectometer on NSTX-U

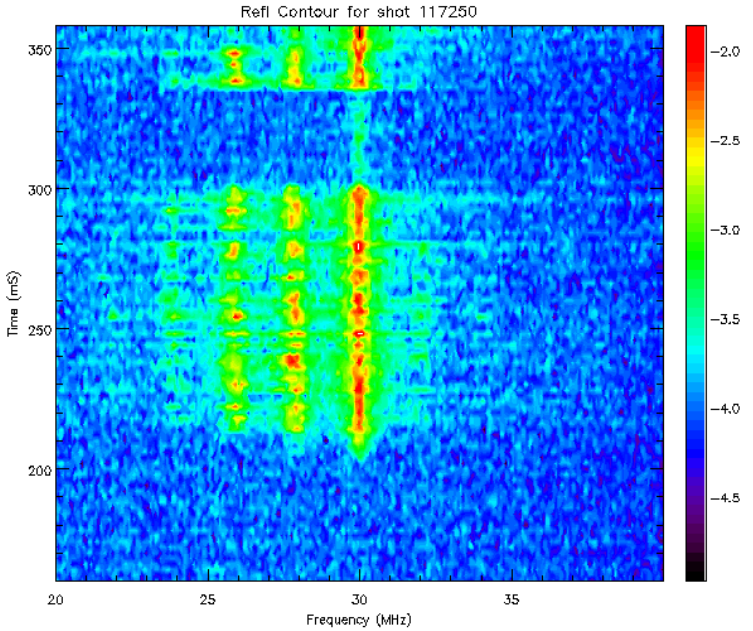
[1]Bottolier-Curtet, RSI 1987

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)

Conclusion

- Overview of ORNL SOL reflectometer on 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
  - using all modes will provide measurements at larger range of |B|
  - possibility of |B| profile measurement
- Future work discussed in this presentation
  - RF wave measurement