High Frequency Probe Studies of Electrostatic Disturbances in E x B Plasmas

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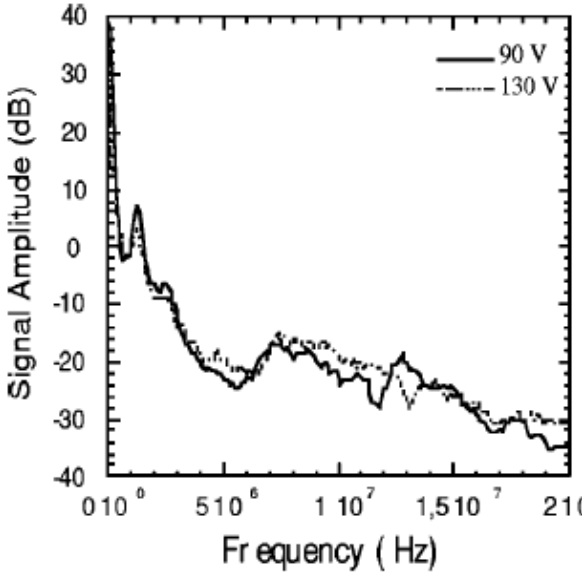
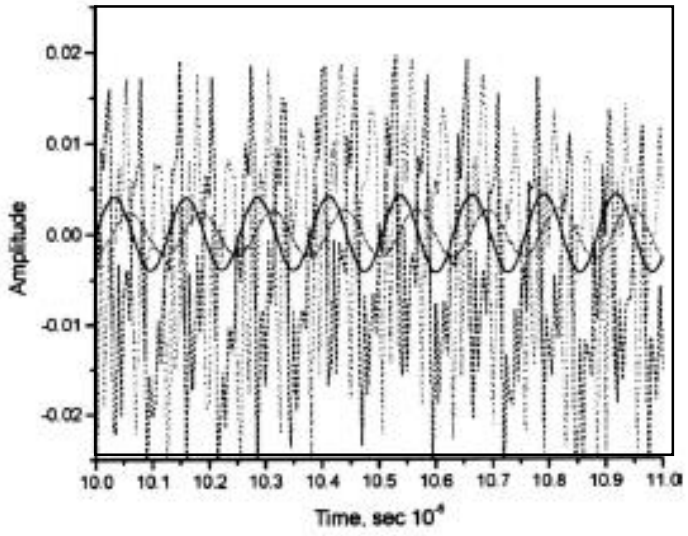
Princeton Workshop 2018

Motivation

- renewed interest in transport with new theories/simulations
- need for more validating data (inside and outside the channel)
- early HF probe data:
  - Guerrini and Michaut 1999 (single probe – 0.35 m beyond exit, high frequency)
  - Lazurenko et al, 2008 (probes beyond exit- correlation in activity with I-phase)
  - Litvak et al., 2004 (double probe – azimuthal wave in ionization zone)



Guerrini, 1999

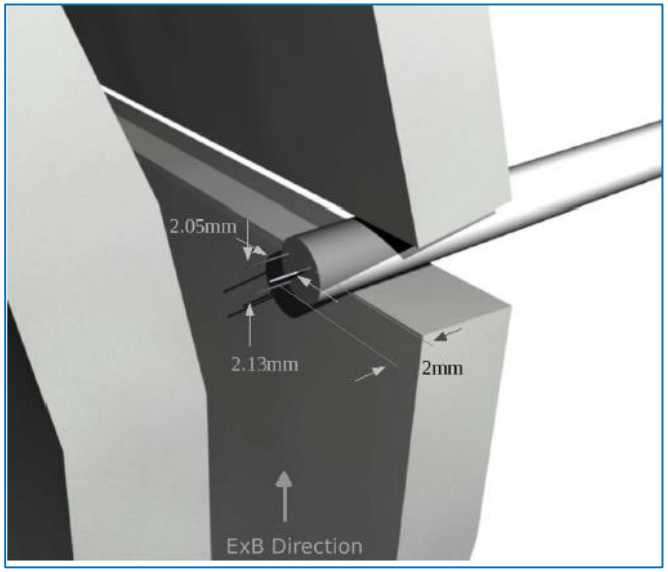


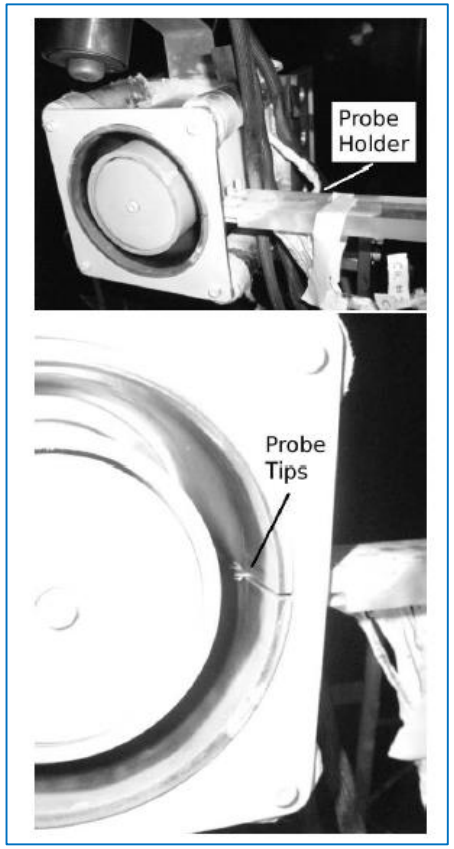
Litvak et al, 2004

Experiments at Stanford (~2010)

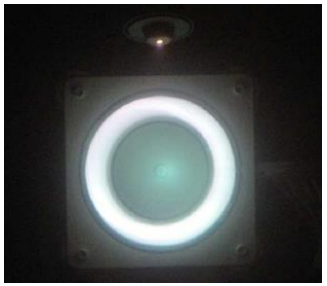
- A. Knoll thesis (now at Imperial College London)
- unpublished
- triple probes, good frequency response to ~20 MHz
- moderate Nyquist spatial frequency (resolve k = 3100 – 4200 rad/m)
- inside thruster channel

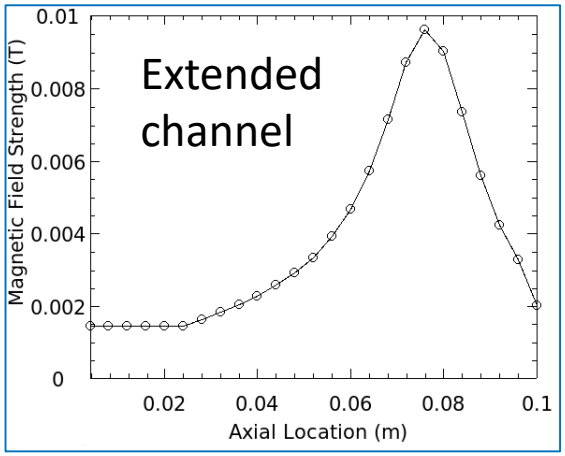
Triple probe fits in insulator slot





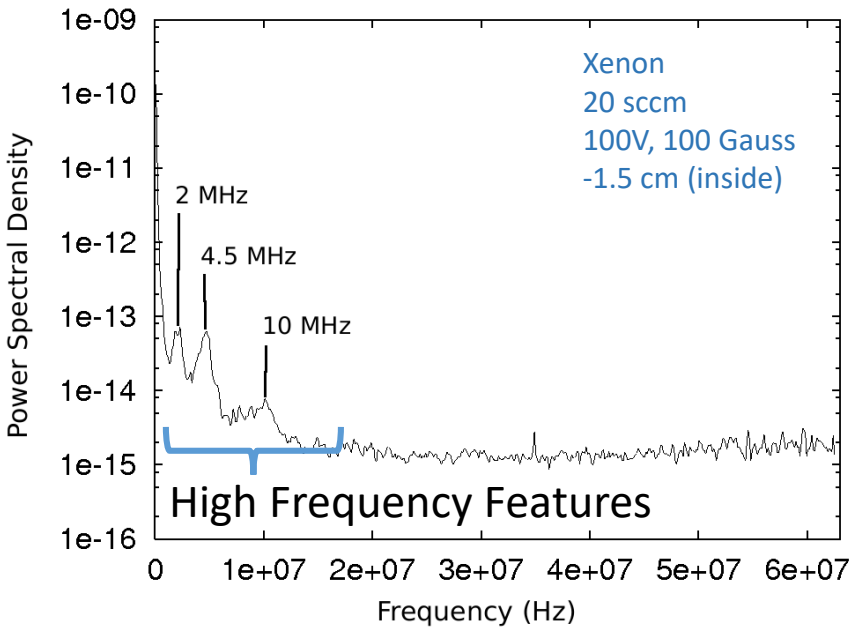
Stanford extended channel thruster



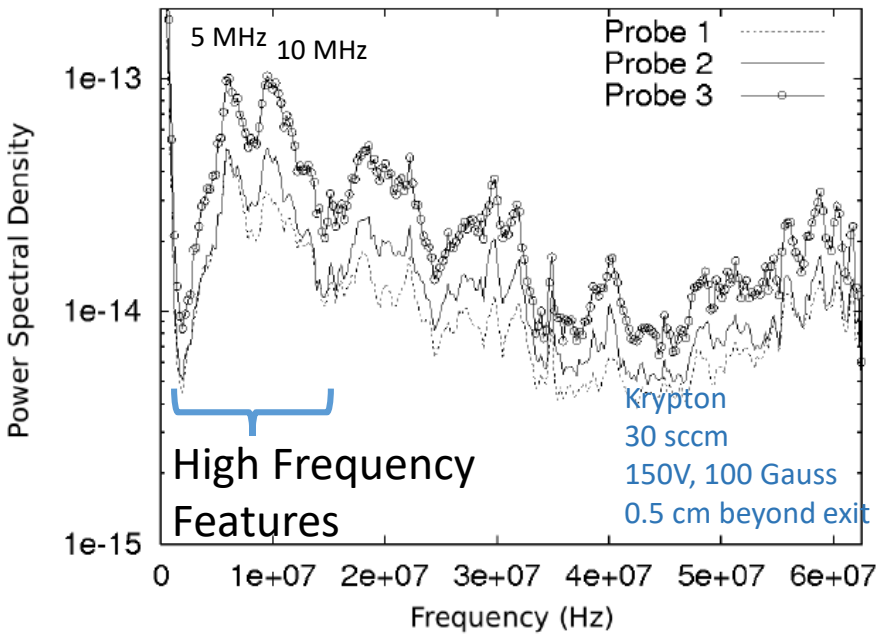


High Frequency Features

Xenon

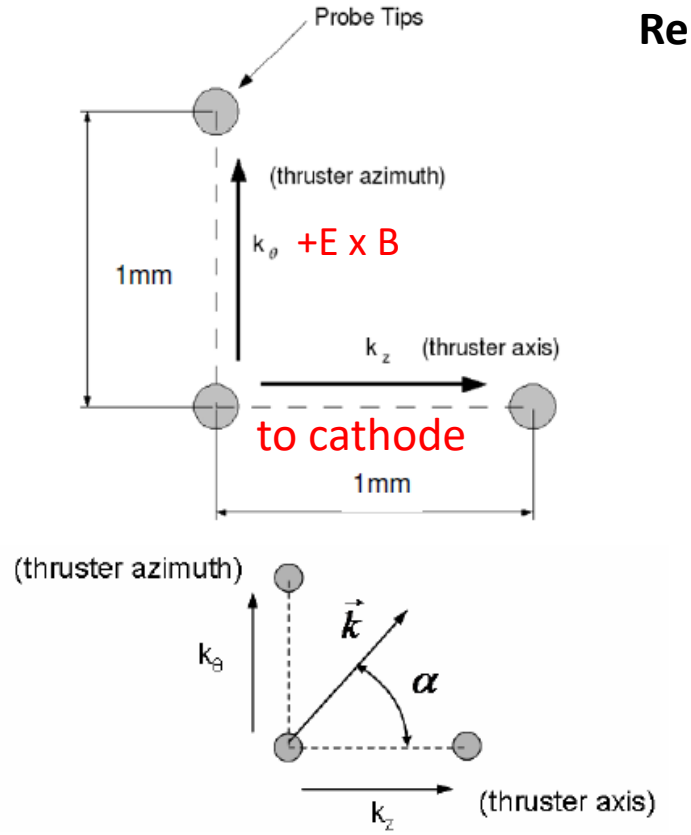


Krypton

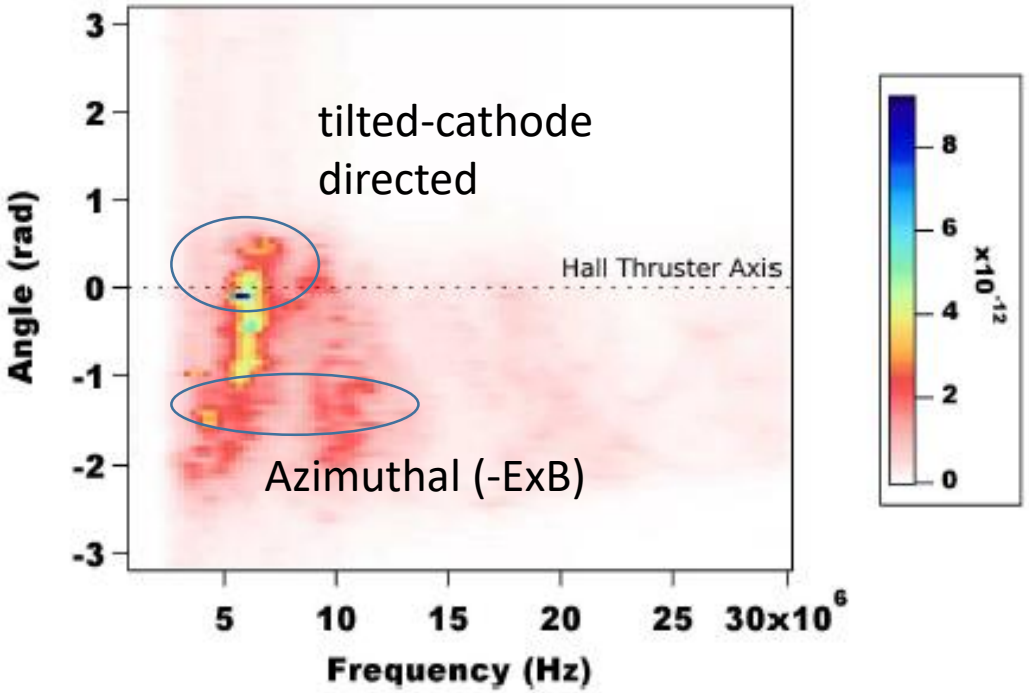


- distinct features seen in the 2-10 MHz range
- all three probes showed similar spectra
- independent of probe rotation (not shadow effects of probes)
- features less distinct with krypton vs xenon
- discharge operated at low voltage to minimize probe intrusion

Coherent Directionally-Favored Structures



Representative Directional Map from Wavelet Analysis

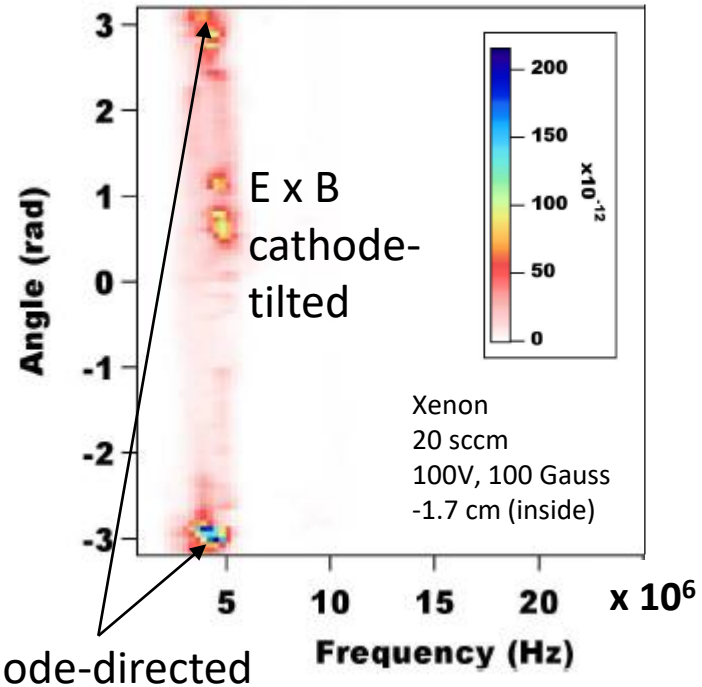


Positive angle: **E x B**
<$\pi/2$: cathode directed
>$\pi/2$: anode directed

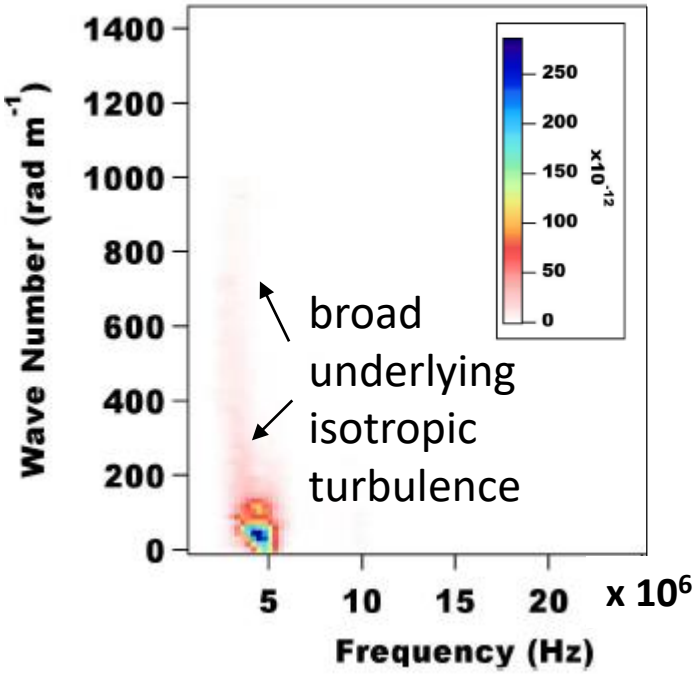
Negative angle: **-E x B**
<$-\pi/2$: cathode directed
>$-\pi/2$: anode directed

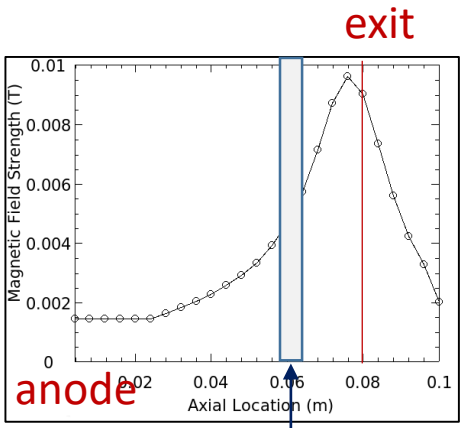
Xenon - Low Voltage – Upstream of Exit

100 V



strong anode-directed
(4 MHz, ~10 cm)

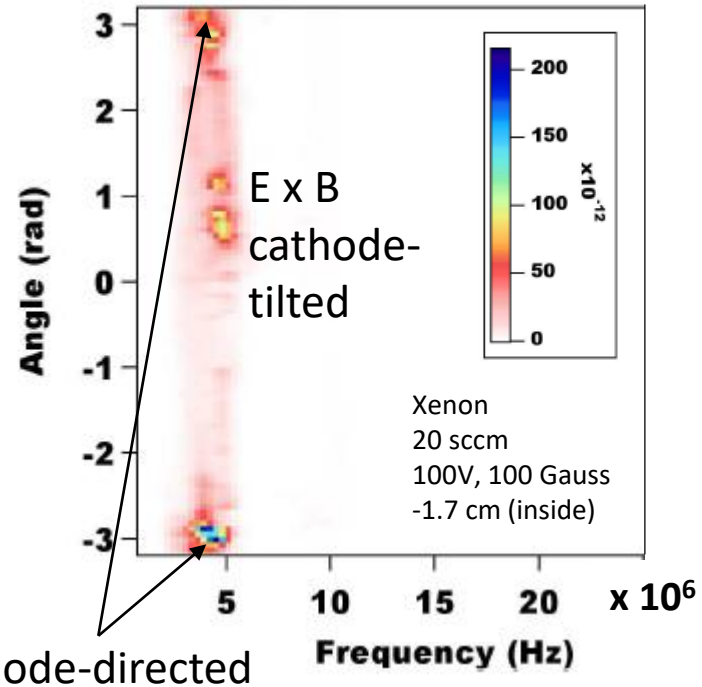




- two coherent features
  - anode directed axial waves
  - tilted azimuthal waves
- underlying isotropic “turbulence”
- artifact or cascades?

Xenon - Low Voltage – Upstream of Exit

100 V



strong anode-directed
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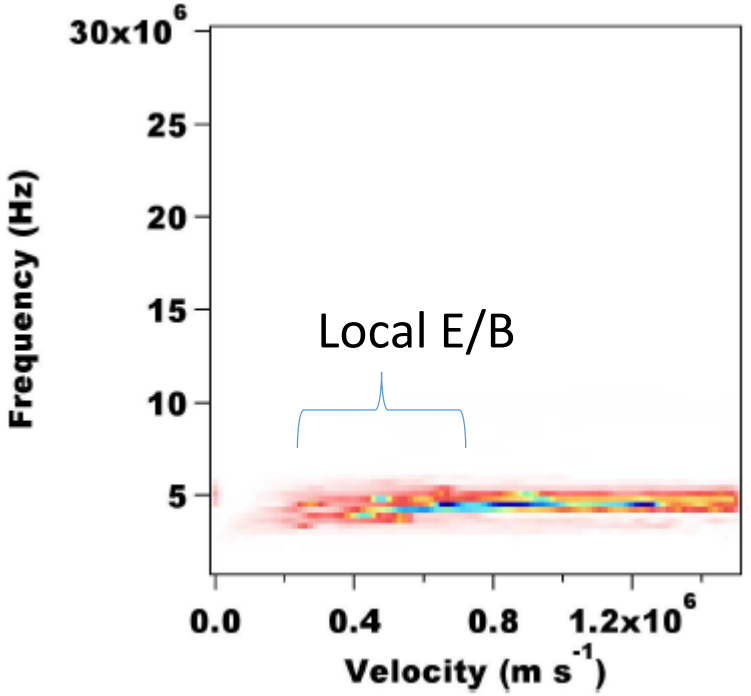
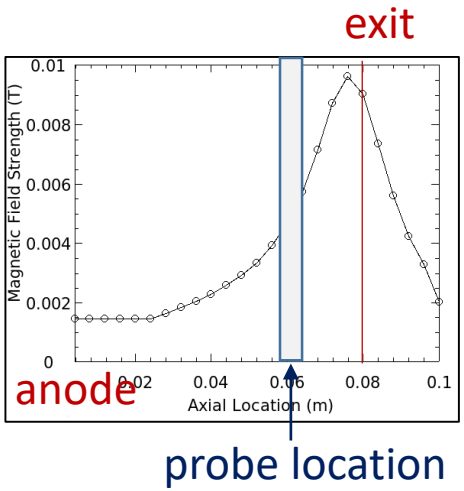
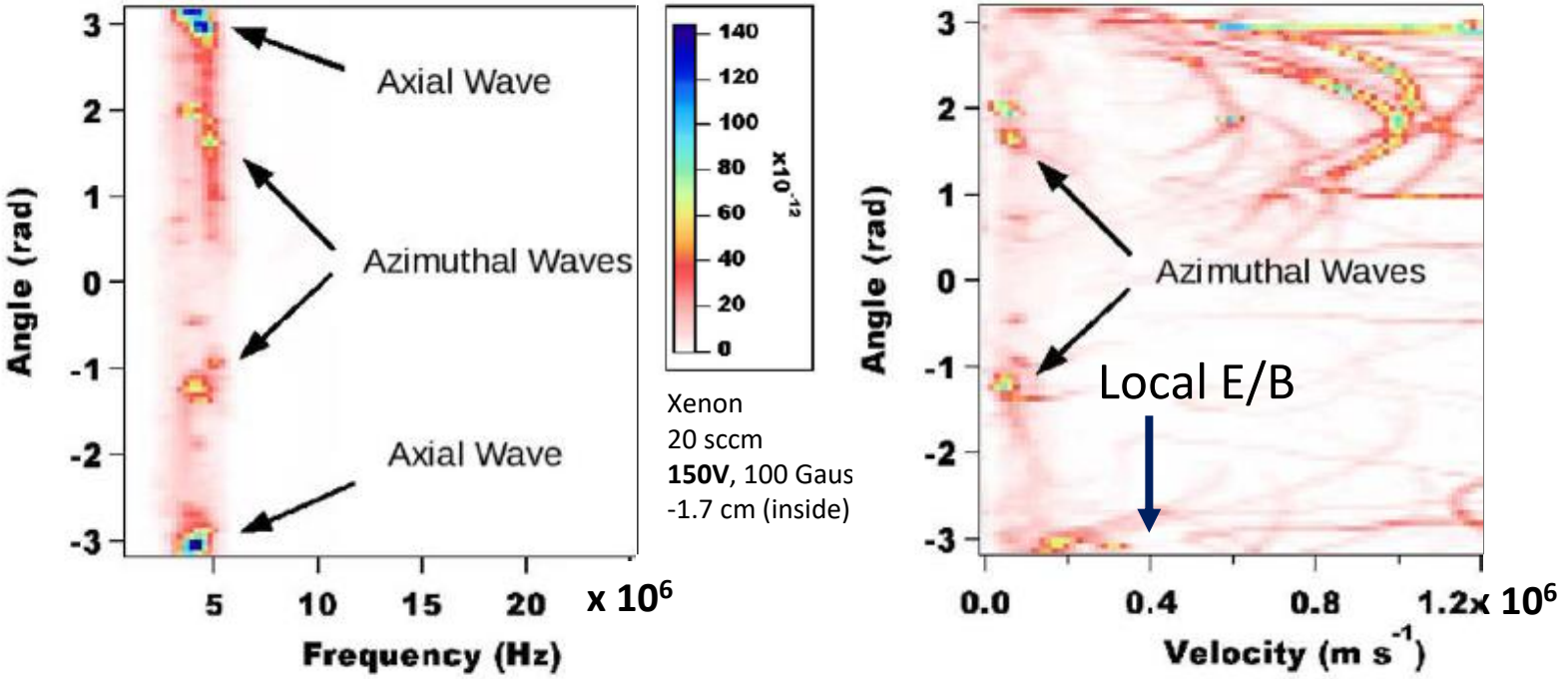




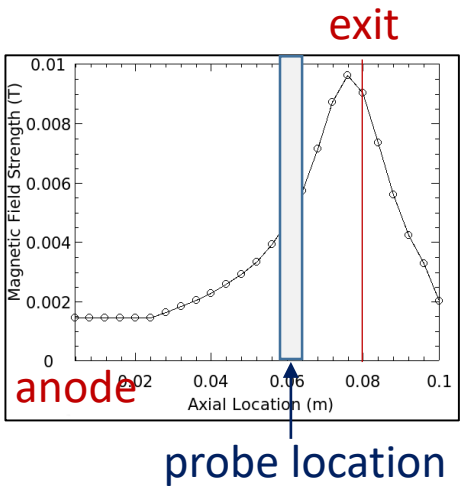
- Phase velocity of disturbances are spread over a broad range
  - 0.2 – (>) 1.5 x10^6 m/s
- of order the drift velocity

Xenon - Higher Voltage – Upstream of Exit

150 V



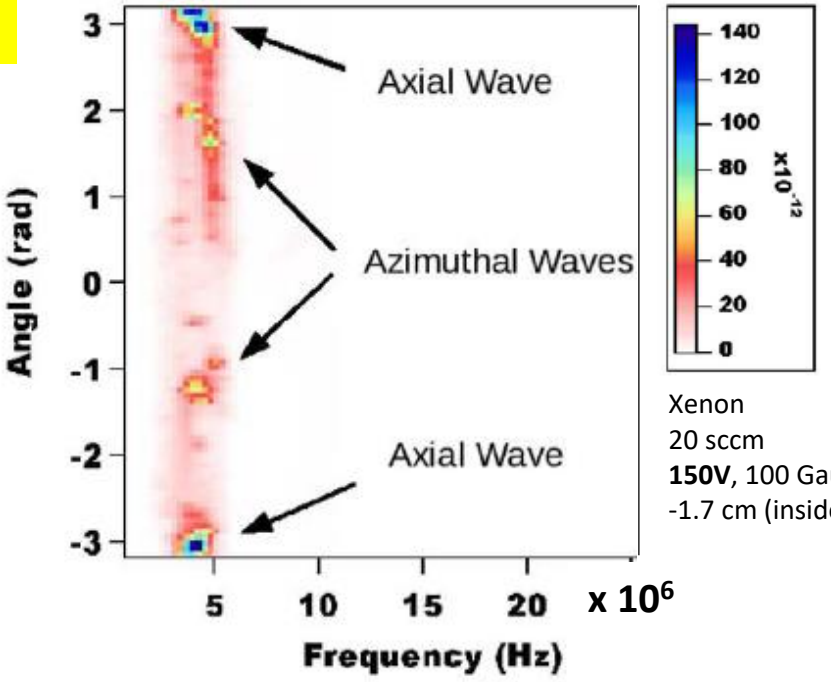
Xenon
20 sccm
150V, 100 Gaus
-1.7 cm (inside)



- counter-propagating azimuthal waves emerge
  - V_p~0.25 E/B, λ ~ 2.5 cm
- strong, broader disturbances in the +E x B directions at higher V_p
  - varying wavenumber (~10 cm)
  - **k-space** dispersive

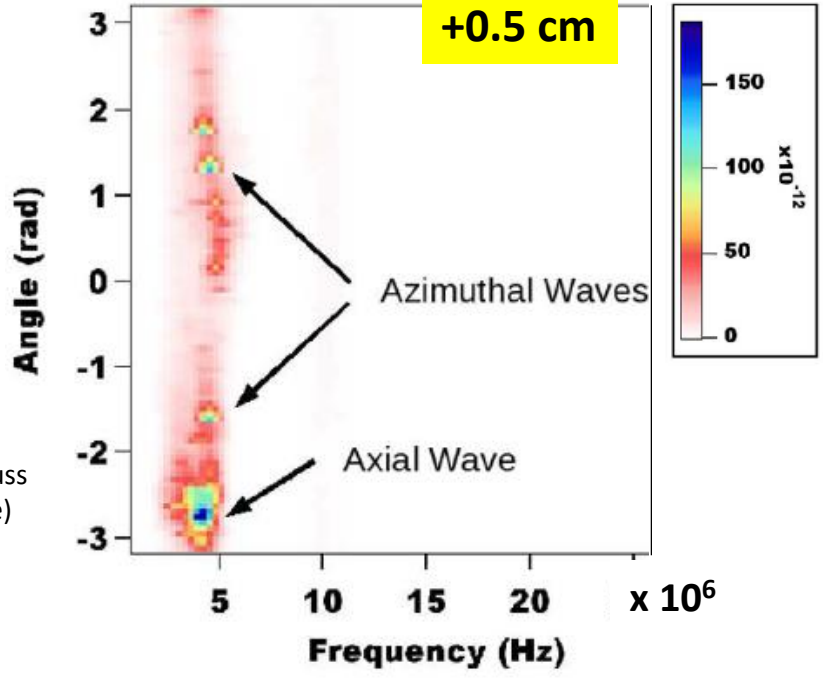
Xenon - Higher Voltage – Beyond Exit Similar

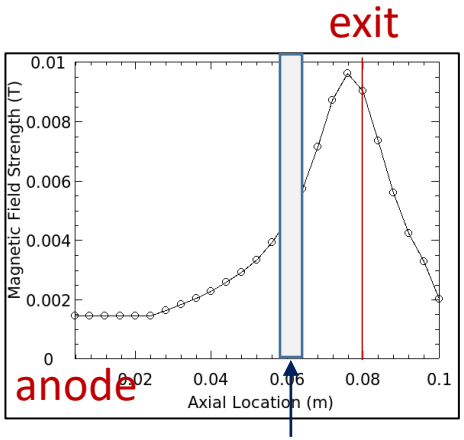
-1.7 cm

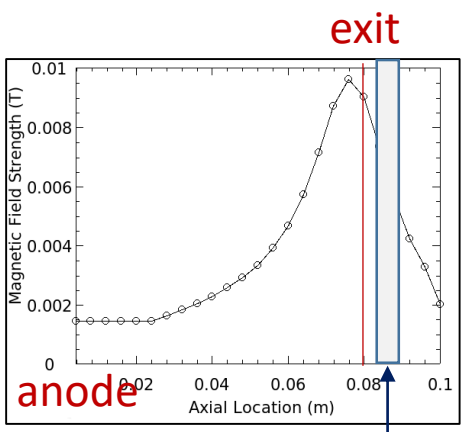


Xenon
20 sccm
150V, 100 Gauss
-1.7 cm (inside)

+0.5 cm

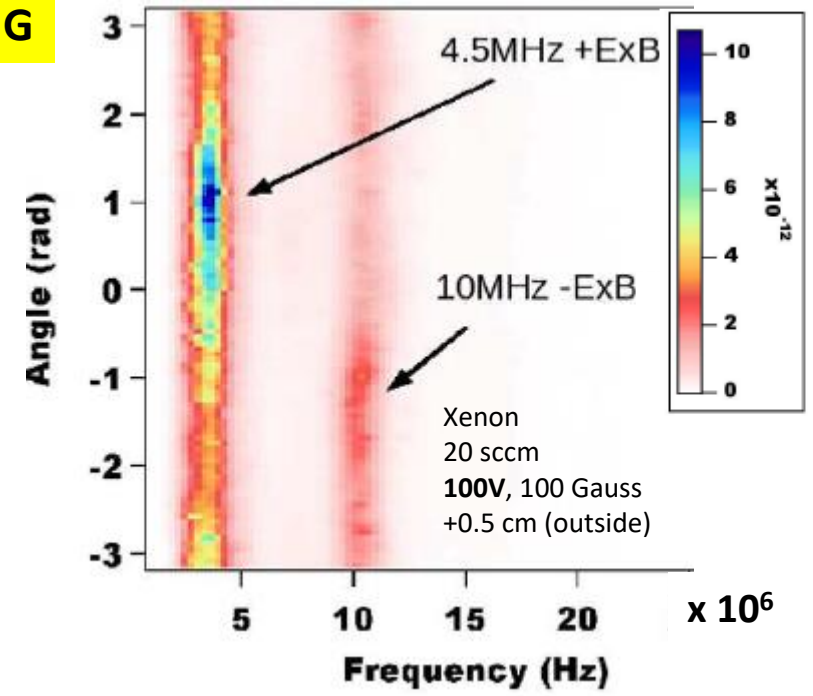




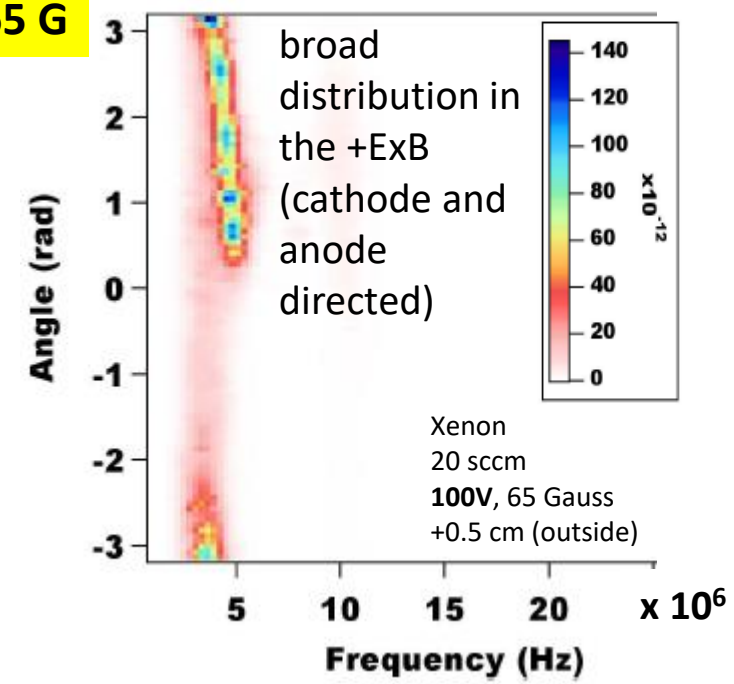


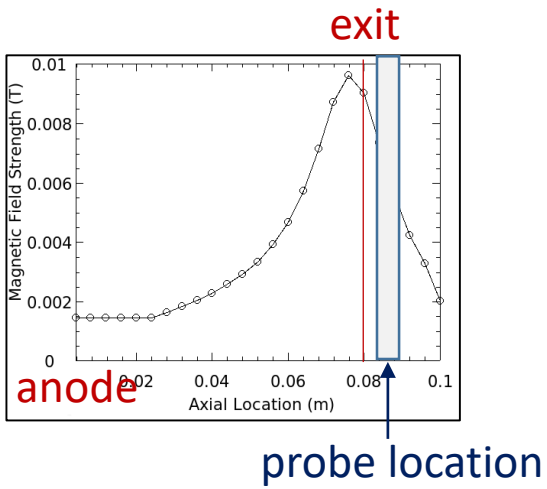
Magnetic Field Matters (Still Beyond Exit)

100 G



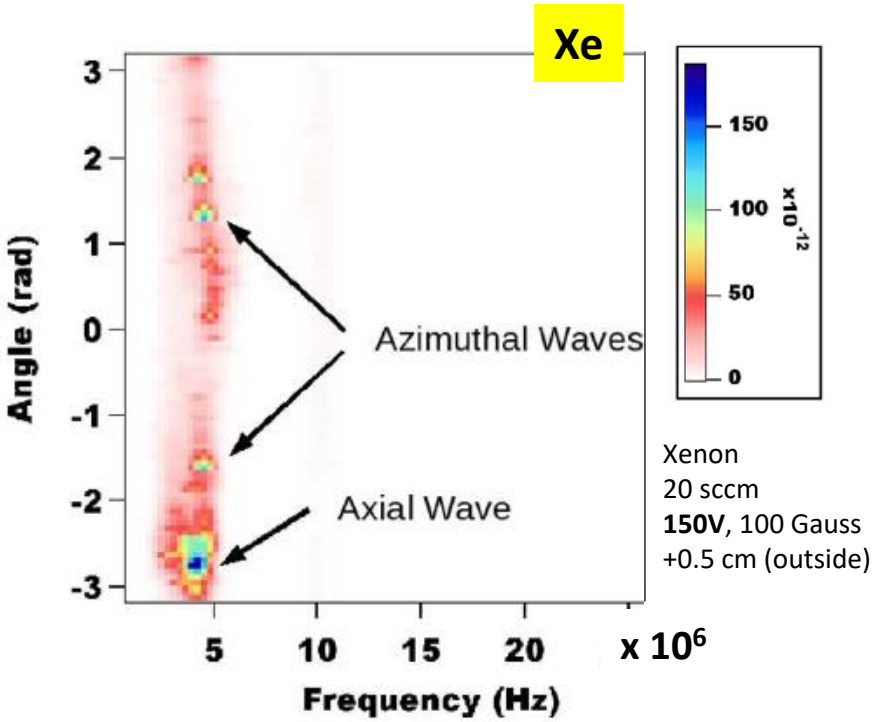
65 G



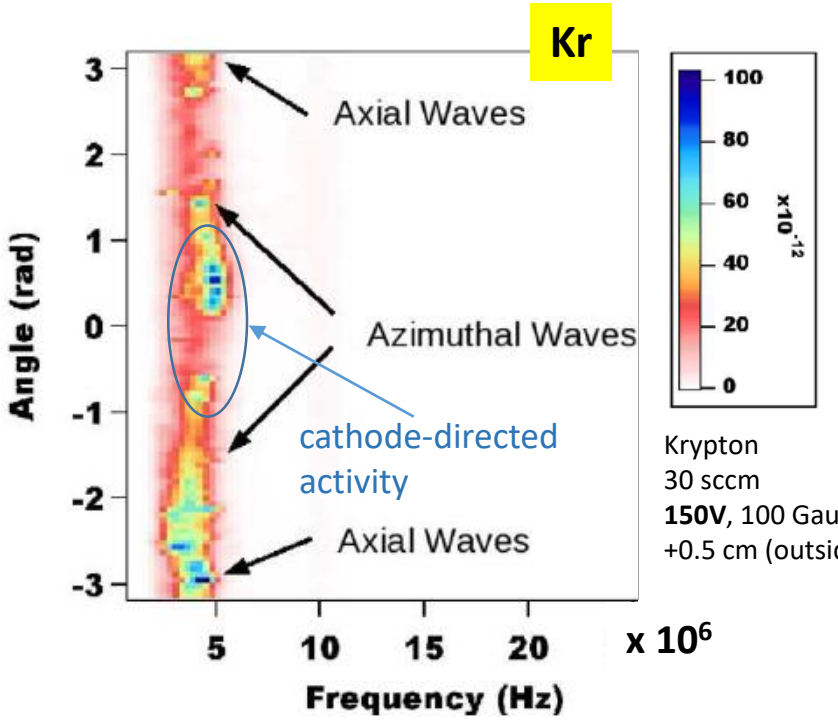


- dramatic changes
- emergence of higher frequency
  - favors – negative E x B
- lower frequency has strong azimuthal direction
- dispersion at lower B (frequency)

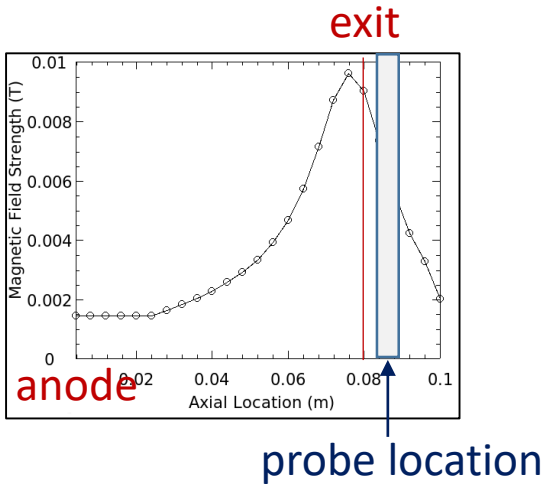
Xe vs Kr (Still Beyond Exit) – High Voltage



Xenon
20 sccm
150V, 100 Gauss
+0.5 cm (outside)



Krypton
30 sccm
150V, 100 Gauss
+0.5 cm (outside)



- Kr seems stronger in intensity
- …but somewhat similar dispersion
  - cathode and anode-directed waves
  - weak underlying isotropic features
  - - E x B disturbances stronger in Kr

Summary
(Generalizations)

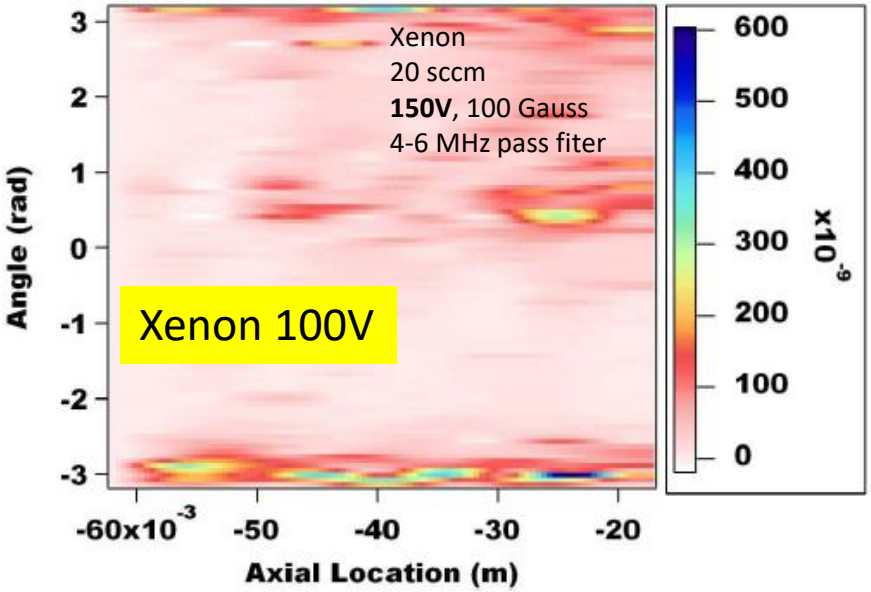
- spectra dominated by 2-10 MHz “coherent” features of relatively long wavelength [longer than the Nyquist limit of 2 mm]
  - some underlying “turbulence” (isotropic/k-space dispersion)
  - frequencies: ion transit (ion acoustic?)
  - velocities: closer to E/B (drift?)
- consistently see cathode and anode-directed waves
- sometimes see counter-propagating azimuthal structures
  - behavior depends on location, voltage, magnetic field (and less so on the gas)

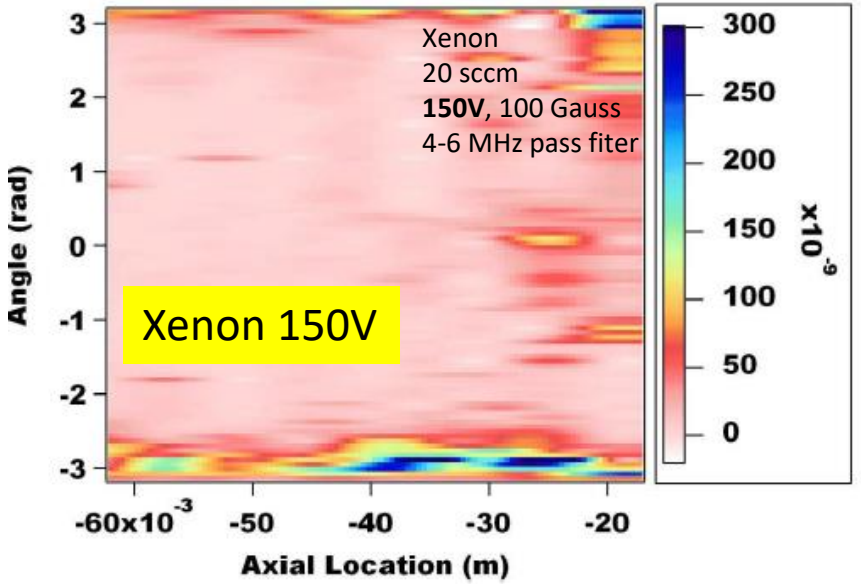
”Long” wavelength disturbances and transport?

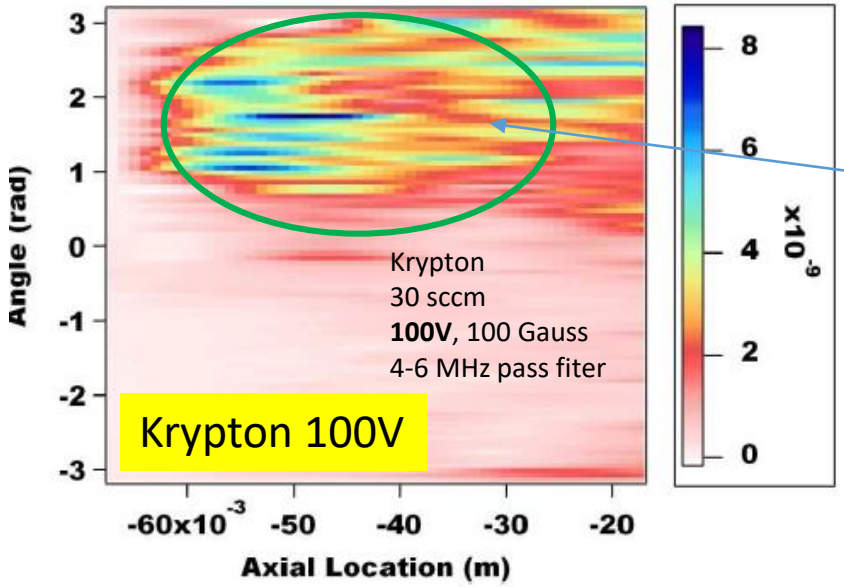
Supplemental Material

Supplemental

4 – 6 MHz Pass Filter



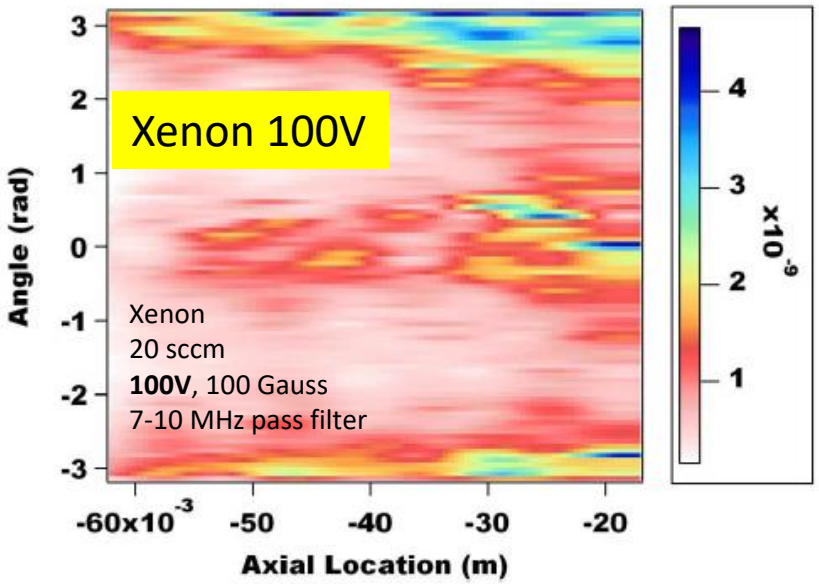


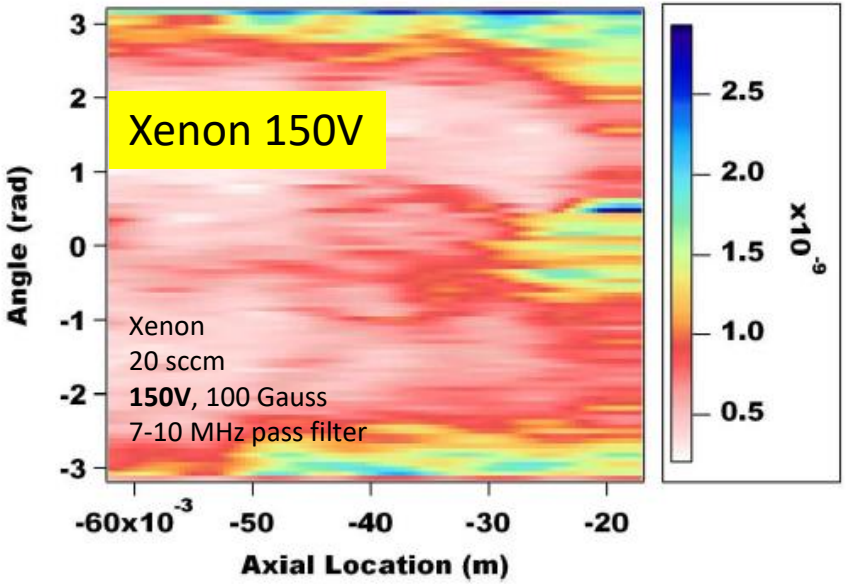


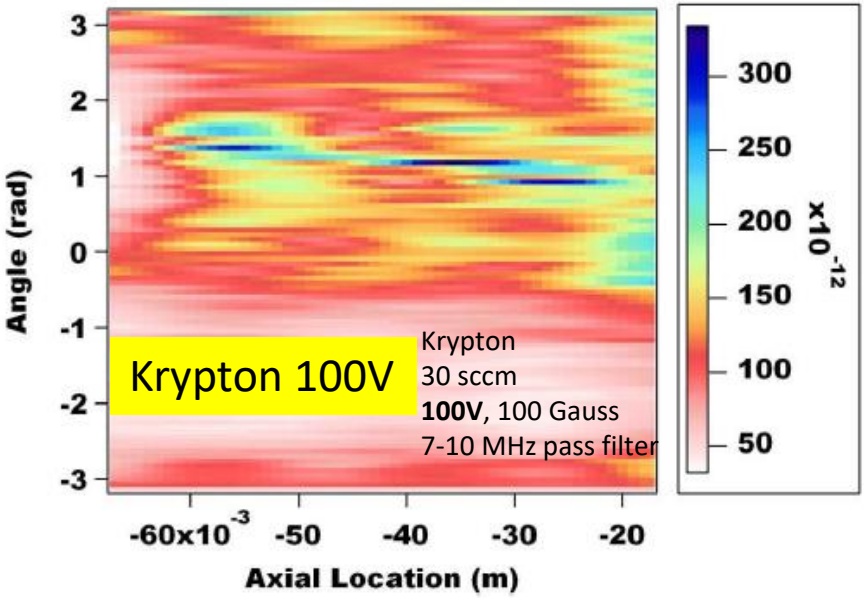
favored E x B directed activity within the channel

Supplemental

7 – 13 MHz Pass Filter

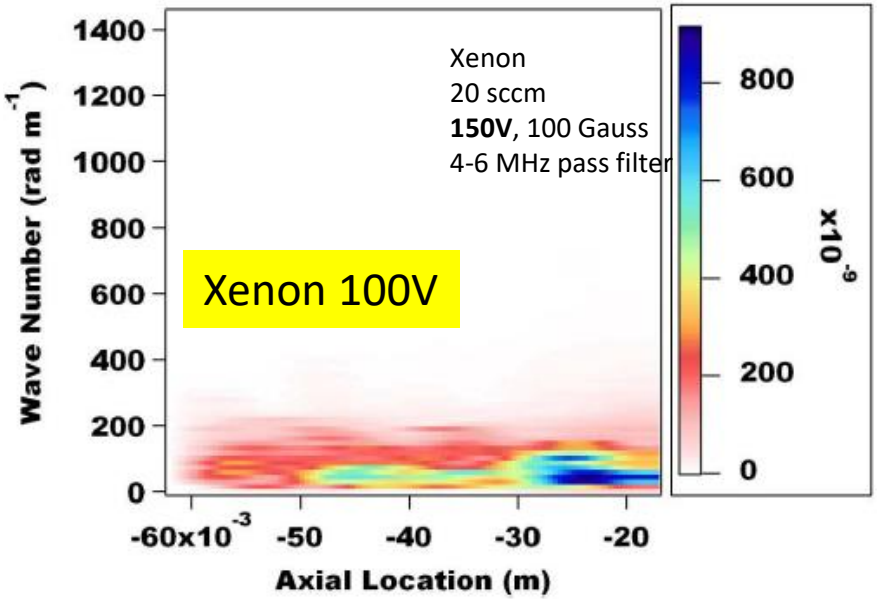


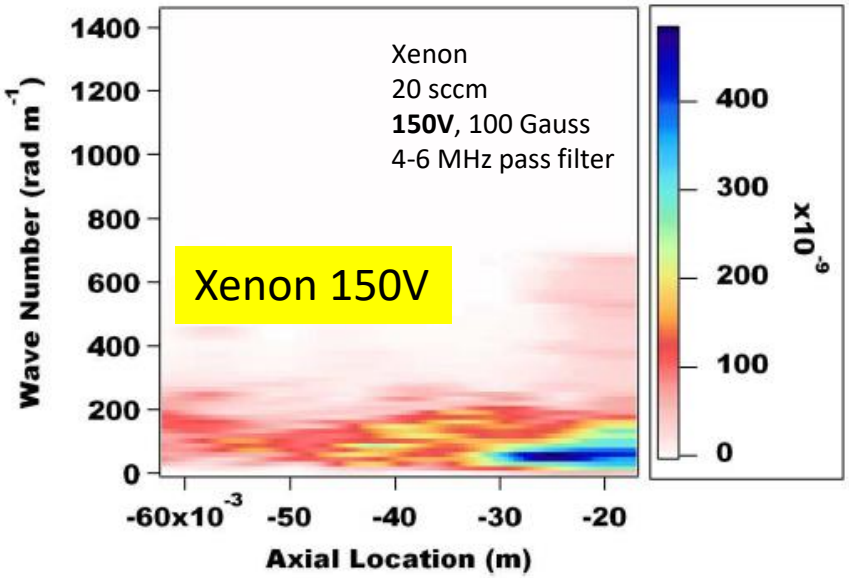


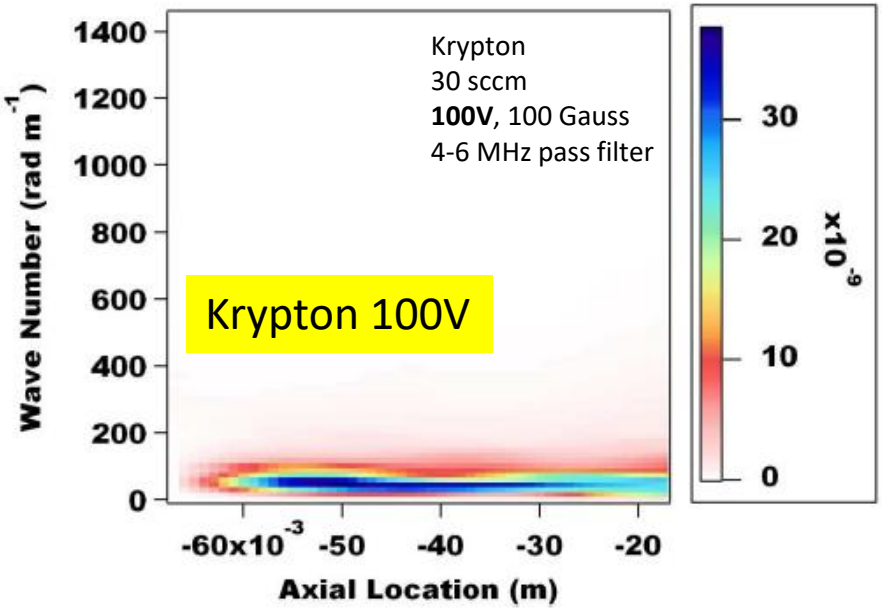


Supplemental

4 – 6 MHz Pass Filter

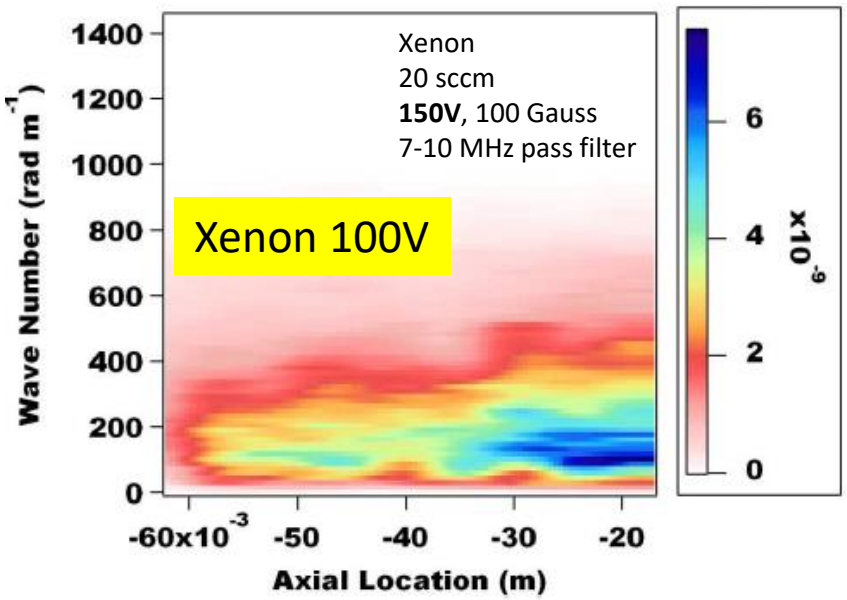


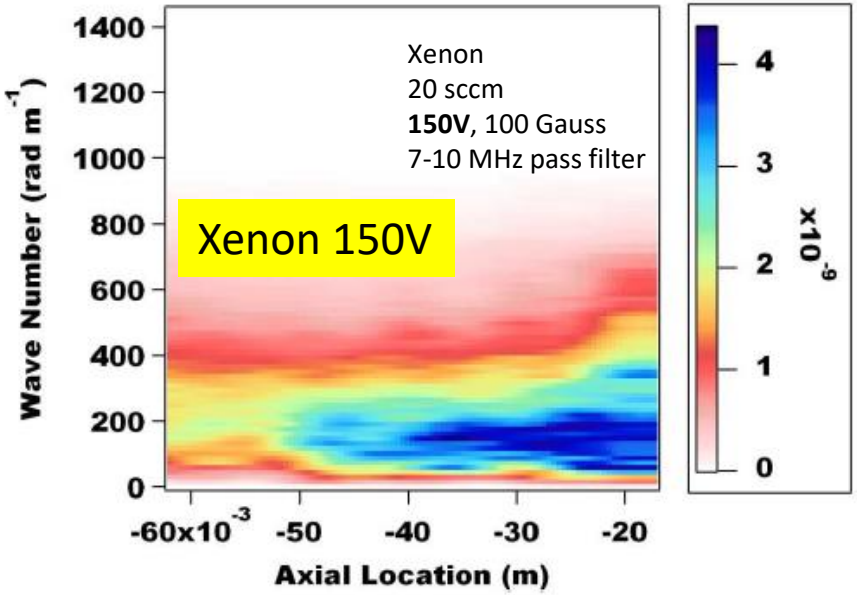


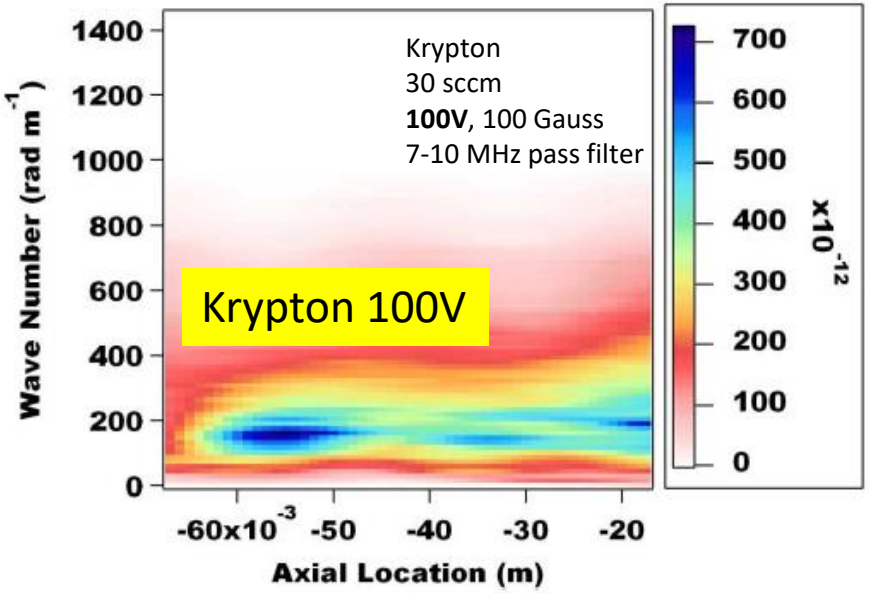


Supplemental

7 – 13 MHz Pass Filter

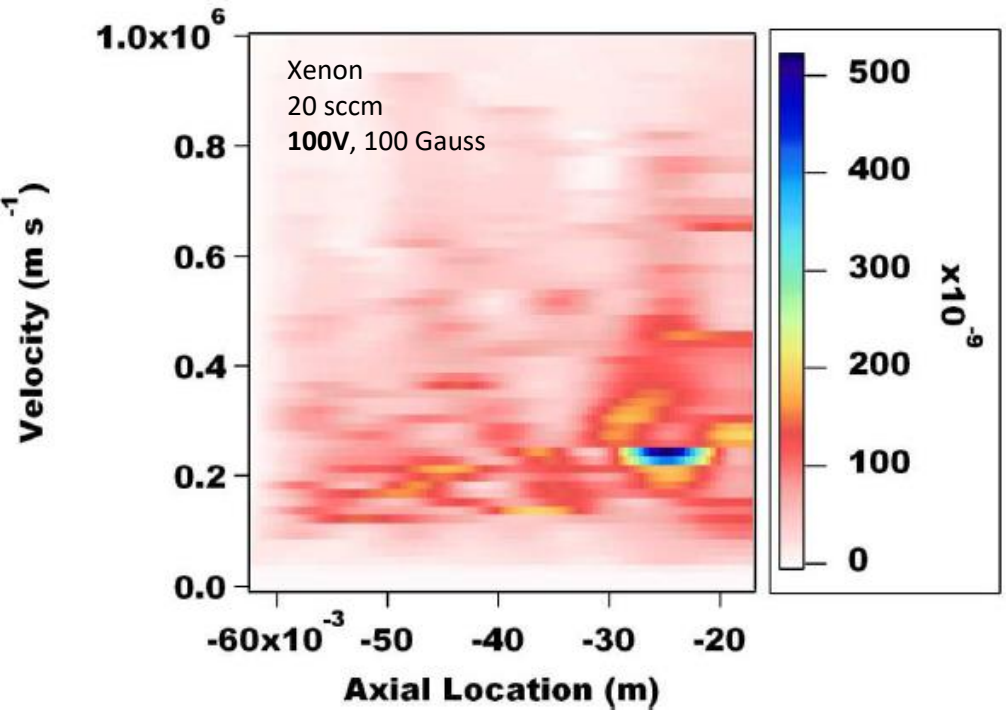




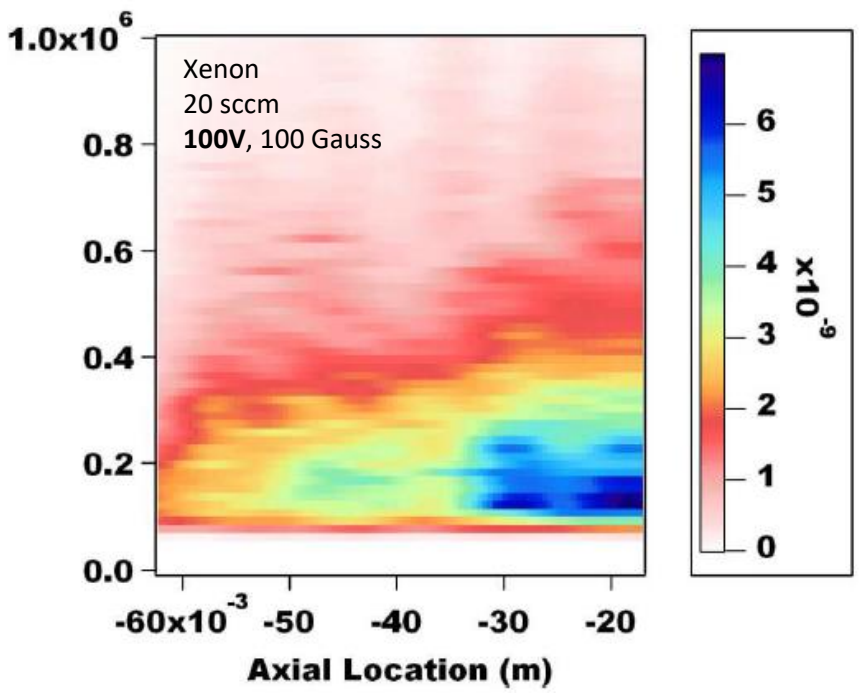


Supplemental

4 – 6 MHz Pass Filter



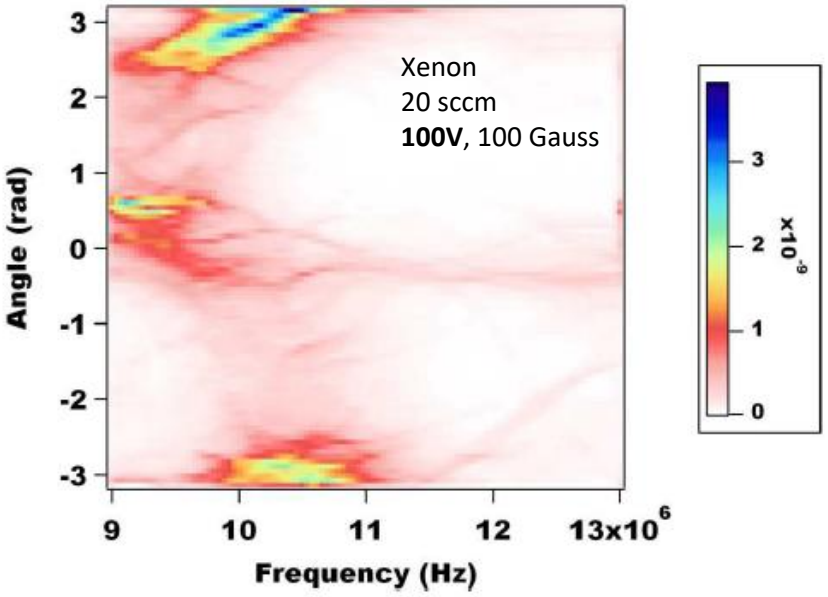
7 – 13 MHz Pass Filter



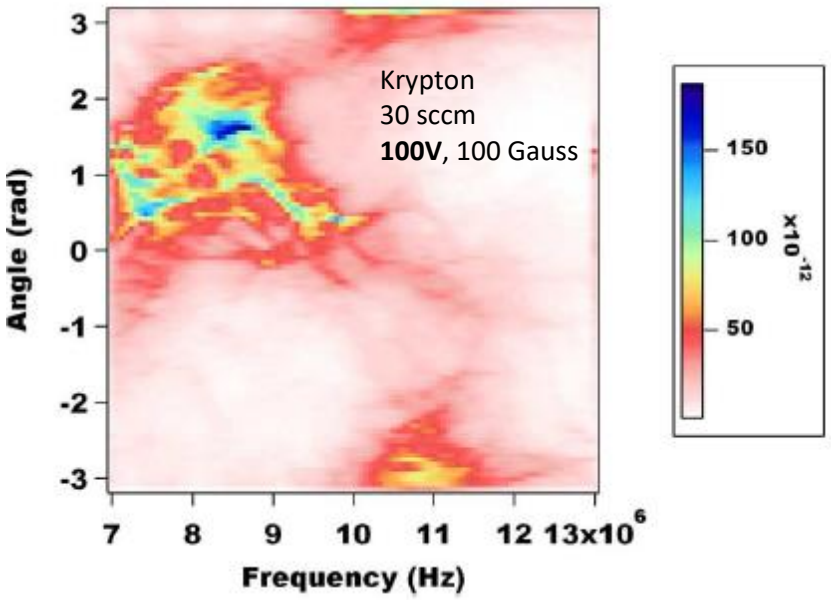
Supplemental

Higher Resolution Around 10 MHz

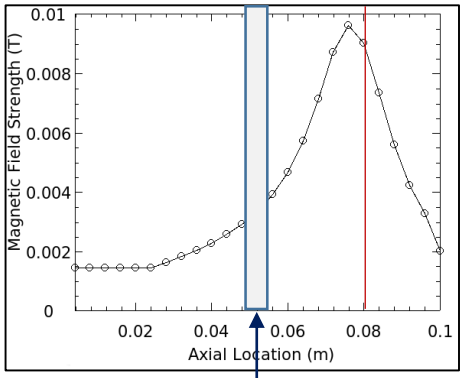
Xenon



Krypton

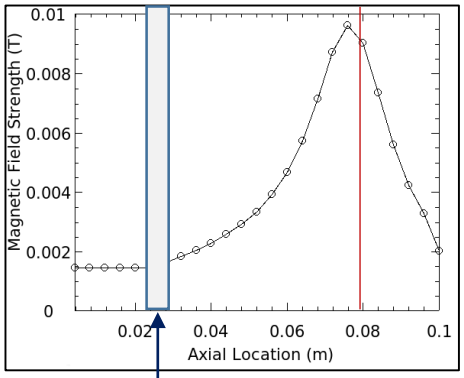


exit



probe location

exit



probe location