Resonant Wave Heating of Argon Ions in the Hot hELicon eXperiment (HELIX)

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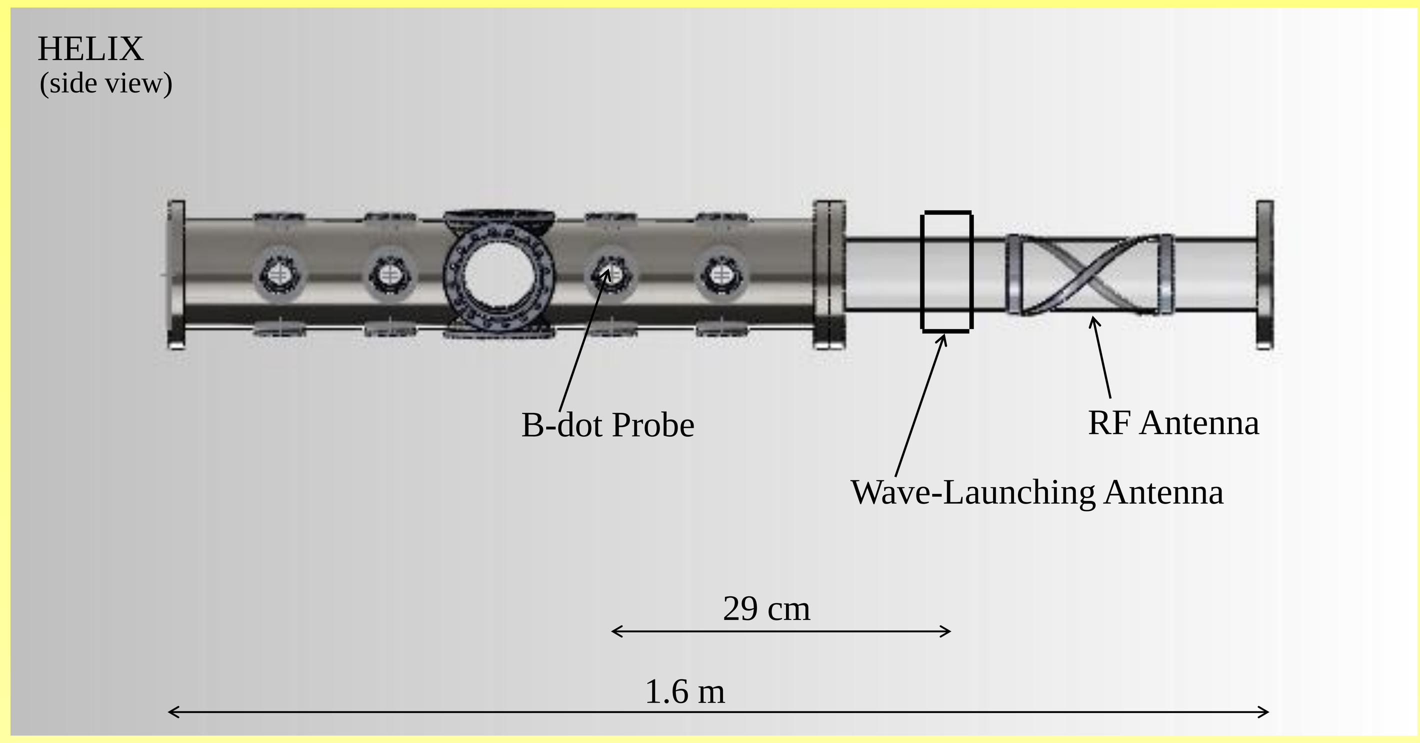
Motivation and Background

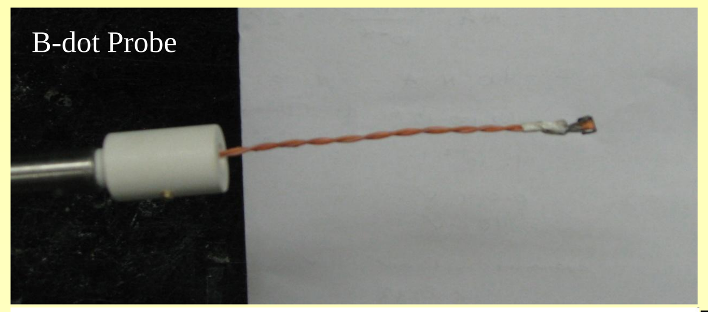
Alfvén wave damping is the dominant physical process invoked in leading theoretical models of ion heating in the solar corona. It has been suggested that low-frequency ($\omega_A < \omega_{ci}$) Alfvén waves are responsible for the observed ion heating. With a newly-constructed external wave-launching antenna, the West Virginia University helicon source group is investigating ion heating of Argon plasma in the presence of low-frequency Alfvén waves (in this case ω_A=157x10³ rad/s while ω_{ci} =205x10³ rad/s , B_1~1% of B_0). . A new, small-scale magnetic sense coil provides sub ion gyroradius spatial resolution of plasma perturbations and new differential amplifiers block the ambient rf noise at high frequencies. Here we present the first measurements of plasma perturbations and spatially-localized field measurements in HELIX, as well as comparisons of these experimental results with simple Alfvén wave dispersion predictions. Both shear and compressional Alfvén waves are detected downstream of the launching antenna and the observed wave behavior is highly-dependent on the plasma density and density gradient. The predictions for wave propagation presented here are made with the cold plasma dispersion relation for kinetic (β>1) Alfvén waves.

Experimental Apparatus

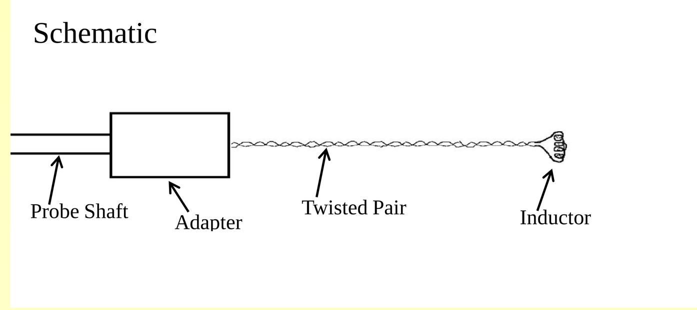


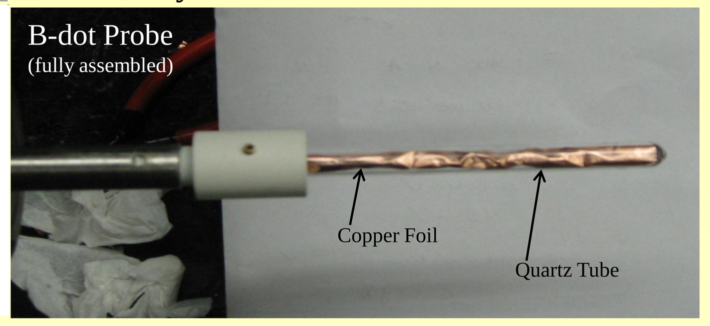
HELIX Specifications
- Length = 1.6 m
- Diameter= 14 cm
- Driving Frequency = 9.5 MHZ
- Magnetic Field Strength= 850 G
- Density= 10^{12} -10^{13} cm^{-3}

Wave-Launching Antenna Specifications
- Height= 15 cm
- Width= 7 cm
- Separation Between Coils= 15 cm
- Stanford Research Systems Function Generator
  - Sine wave at 25 KHz, 1.5 Vpp
- Carvin DCM 3800 L amplifies signal to ~ 10 Vpp
- Maximum B field produced ~ 10 G

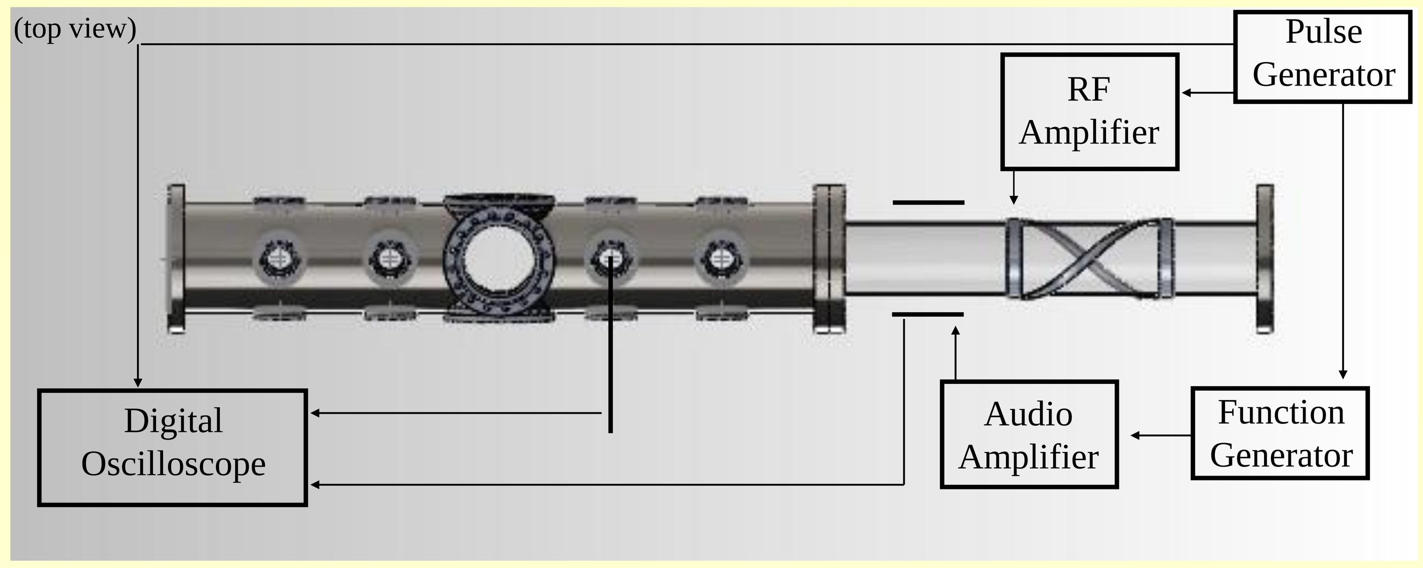


B-dot Probe Specifications
- Coil Craft Inductor (model 1812LS-105XJLB)
  - Size= 4.95 mm x 3.81 mm x 3.43 mm
  - Approximately 30 turns
- Assembled Probe Size= 8 mm (diameter)
  - 9 cm (length)
- Sensitivity ~ 0.01 G

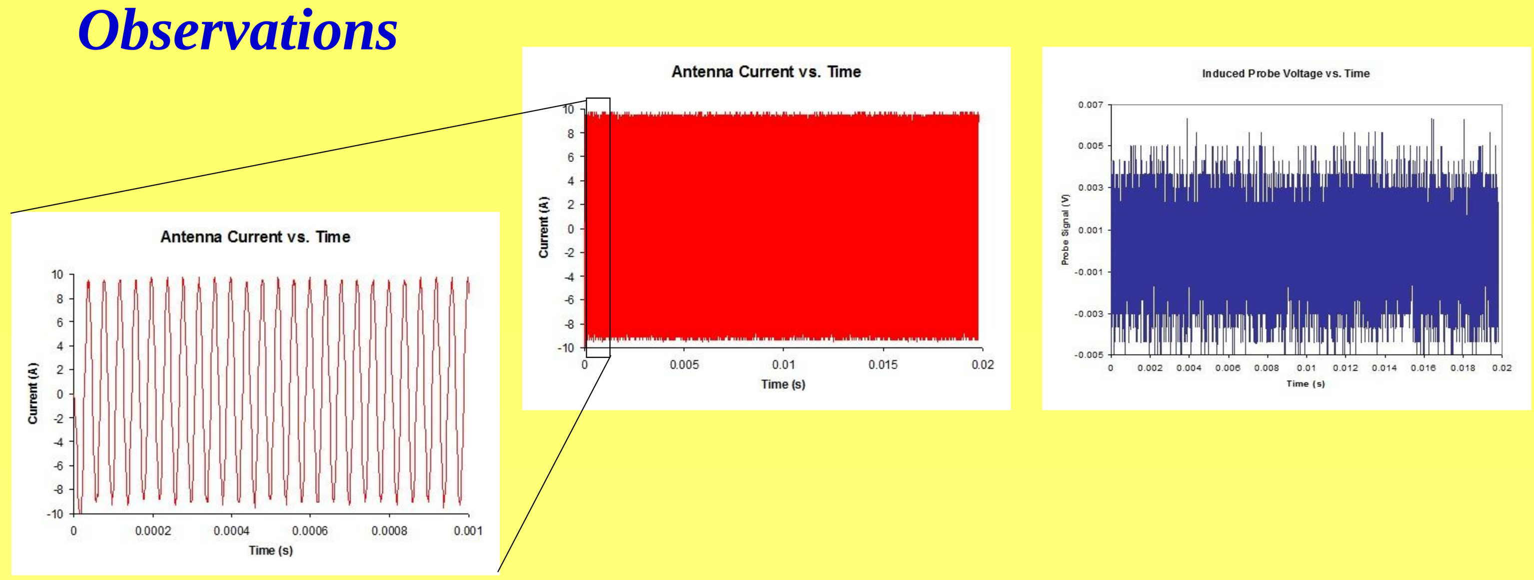


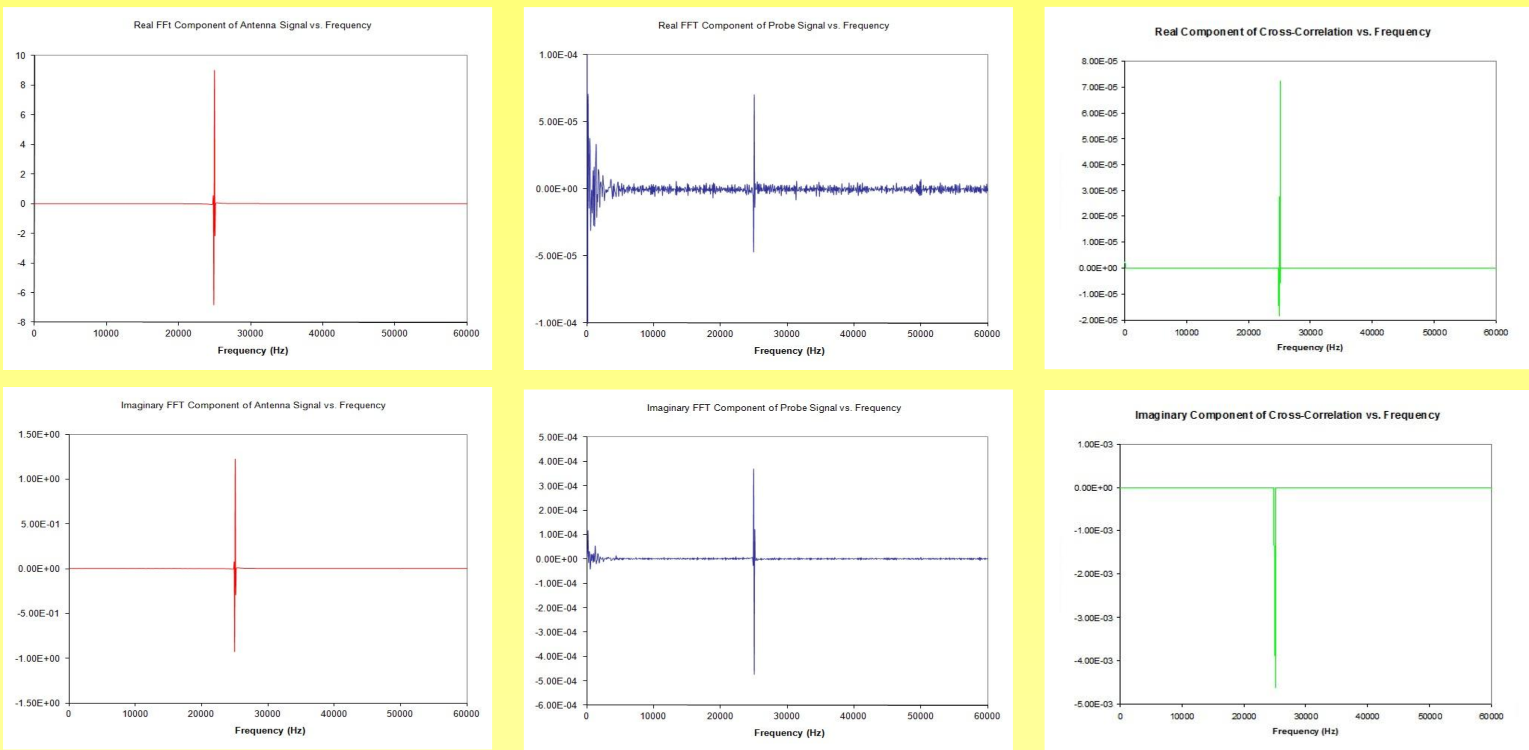


Trigger and Pulse Configuration



Observations





Signal Processing Algorithm

Let S_1 and S_2 be two time-dependent signals
(in this case, S_1 is the current through the antenna and S_2 is the induced voltage of the b-dot probe).

Define F_1=FFT(S_1)=Re[FFT(S_1)]+iIm[FFT(S_1)]
F_2=FFT(S_2)=Re[FFT(S_2)]+iIm[FFT(S_2)] as the Fast-Fourier Transforms of S_1 and S_2

These can be re-written as $F_1=a+ib$
$F_2=c+id$

Then the cross-correlation of signals S_1 and S_2 is $C=F_1{}^*F_2=\int_{-\infty}^{+\infty} F_1(\tau)F_2(t+\tau)d\tau$

$$C=(ac+bd)+i(ad-bc)=C_r+iC_i$$

The phase (time delay between the signals) of the cross-correlation signal is $\theta=\tan^{-1}(C_i/C_r)$

The magnitude of the cross-correlation signal is $M=(C_r^2+C_i^2)^{1/2}$

$$v_{Alfvén}=\frac{B}{(\mu_0 n_i m_i)^{1/2}}=2.95\ \text{x}\ 10^{14}/n_i^{1/2}$$

$$\lambda_{Alfvén}=v_{Alfvén}/f=(2.95\ \text{x}\ 10^{14}/n_i^{1/2})/(25\ \text{kHz})=1.18\ \text{x}\ 10^{10}/n_i^{1/2}$$

$$k=2\pi/\lambda_{Alfvén}$$

$$\theta=d/\lambda_{Alfvén}\cdot(360°)=29\ \text{cm}/(1.18\ \text{x}\ 10^{10}/n_i^{1/2})\cdot(360°)=(360°)\cdot 2.46\ \text{x}\ 10^{-11}\cdot n_i^{1/2}$$

$$\omega^2=k_{\parallel}^2 v_{Alfvén}^2\left(\frac{1-\omega^2/\Omega_i^2}{1+k_{\perp}^2\delta_e^2}\right)\quad \Omega_i=qB/m_i\quad \delta_e=c/\omega_{pe}\quad \omega_{pe}=\sqrt{n_e e^2/m_e\varepsilon_0}$$

Conclusions

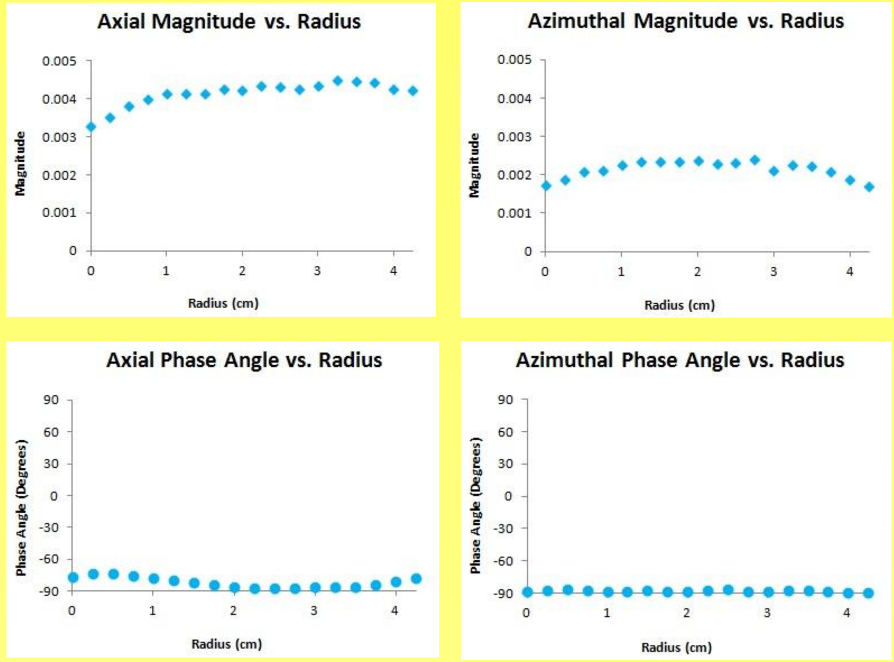
Low-frequency ($\omega_A < \omega_{ci}$) Alfvén waves have been launched from the edge of HELIX.
These waves are larger in magnitude (B_1~1% of B_0) than waves previously launched in HELIX.
The propagation characteristics of the waves are highly-dependent on the local density.
Reflection of waves at the density gradient at the edge of the plasma core is observed in some cases.
Although the launching perturbation is predominantly shear, both shear and compressional waves are detected downstream.
The axial (compressional) wave behavior is fundamentally different than the azimuthal (shear) wave behavior.
Simple dispersion calculations agree with wave behavior observed in the core, but not in the less-dense edge plasma.

Future Work

Use LIF to observe plasma heating in the presence of waves.
Better density profile measurements of the plasma column in all cases.
Compare experimental observations to PIC simulation of Alfvén wave propagation in inhomogeneous plasma

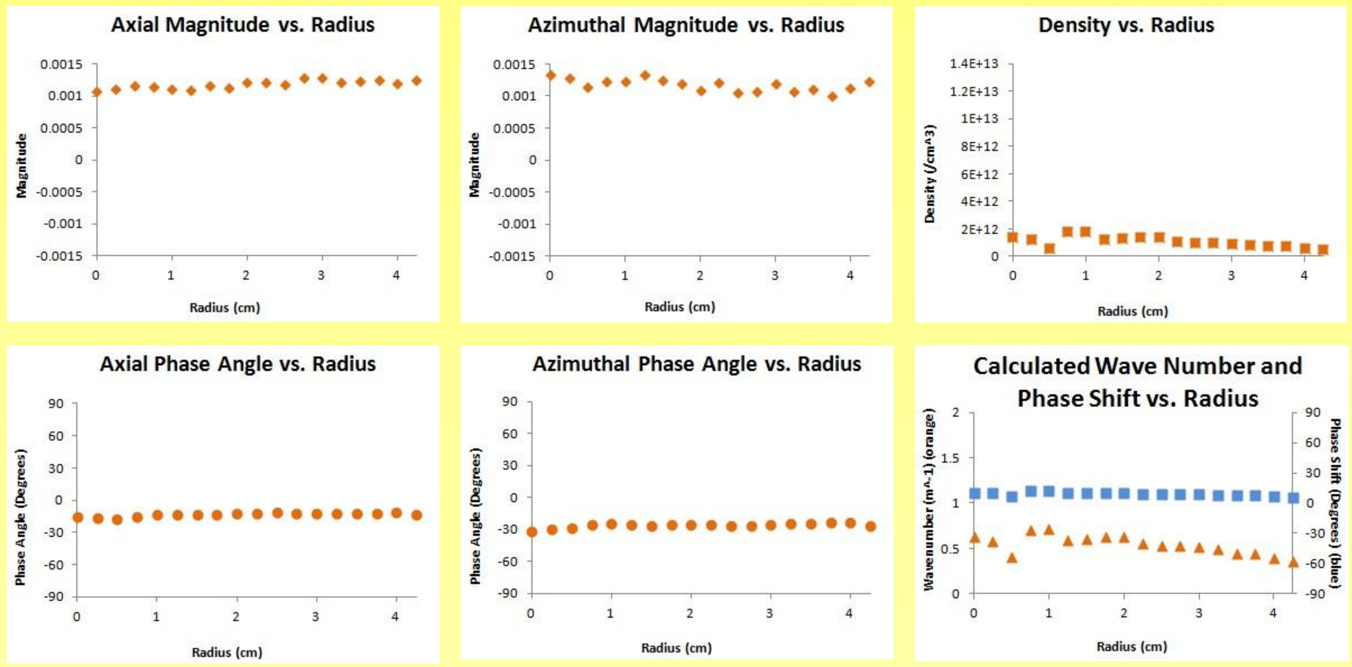
Observations

No Plasma (Background) Case



Low Density Case

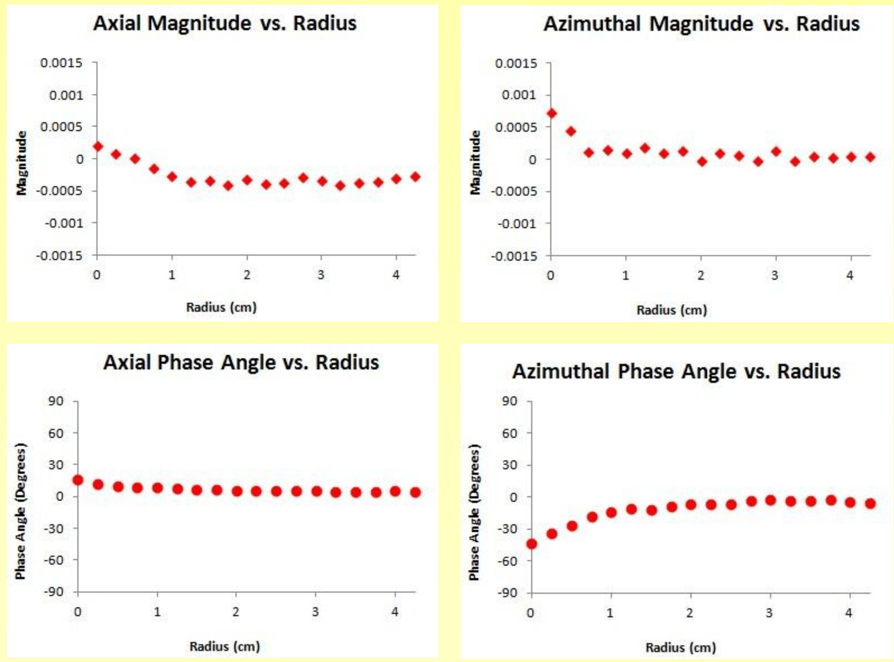
(Background measurements have been subtracted)



Higher Density Case

(Background measurements have been subtracted)

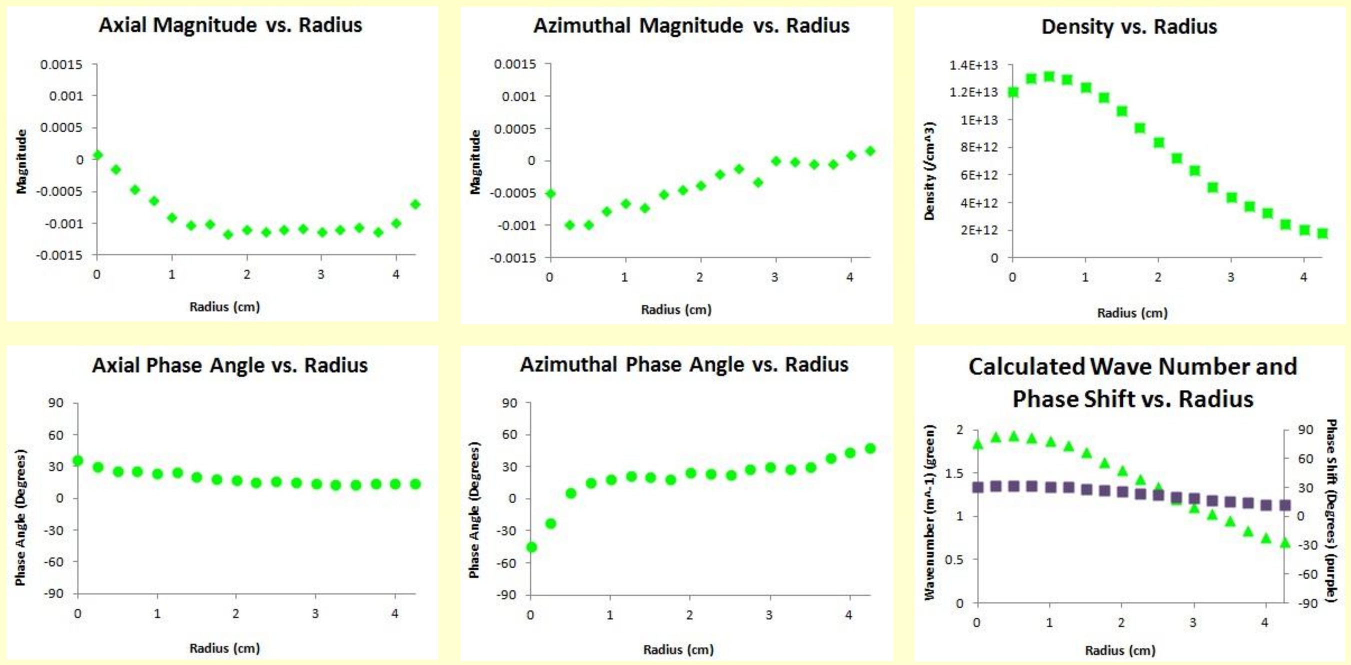
NOTE: Negative magnitude indicates measured signal magnitude is smaller than background (no plasma) signal magnitude.



Highest Density Case

(Background measurements have been subtracted)

NOTE: Negative magnitude indicates measured signal magnitude is smaller than background (no plasma) signal magnitude.



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