Local Regulation of Interchange Turbulence in a Dipole-Confined Plasma Torus using Current-Collection Feedback

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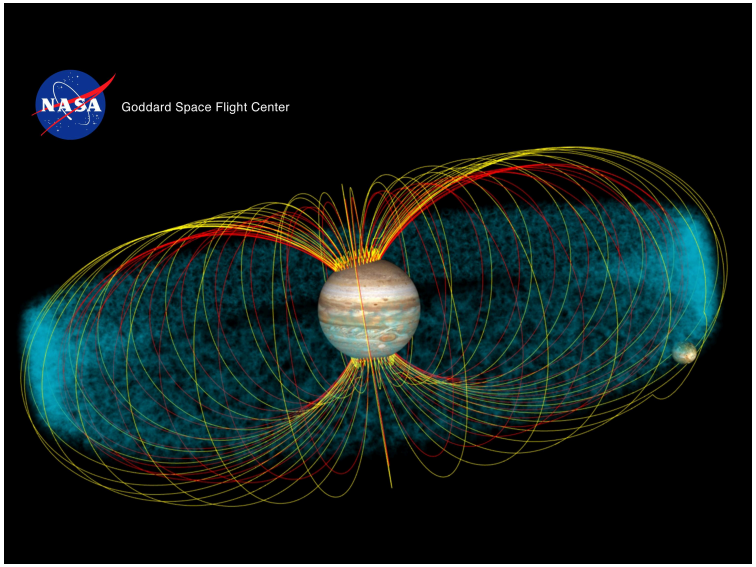
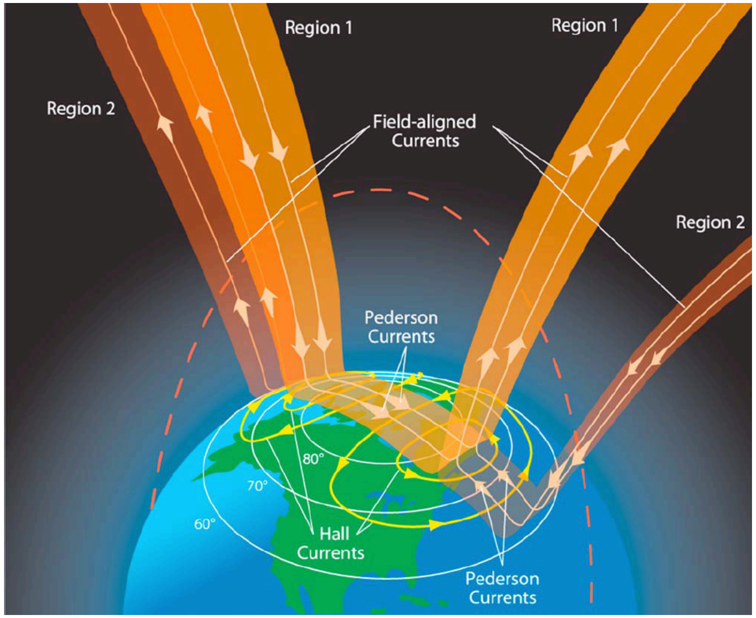
Outline

- Introduction
  - Magnetospheric Configurations in Space and the Lab
  - CTX Device and Interchange Turbulence
- Current-Collection Feedback in CTX
- Four Types of Experiments
  - Coherent Current-Collection (feed-forward)
  - Triggered Feedback
  - Gain and Phase Scans
  - Varying Sensor and Electrode Positions
- Linear Flux-Tube Averaged Gyro-Fluid Model
- Ongoing Work and Conclusion

Planetary Magnetospheres have Field-Aligned Currents

- Planetary magnetospheres have dipolar magnetic geometries.
- Solar wind drives steady magnetospheric convection.
- Cross-field conductivity is much higher in the ionosphere.
- Field aligned currents couple these systems.
- Magnetospheric generator is **regulated** by ionospheric load.



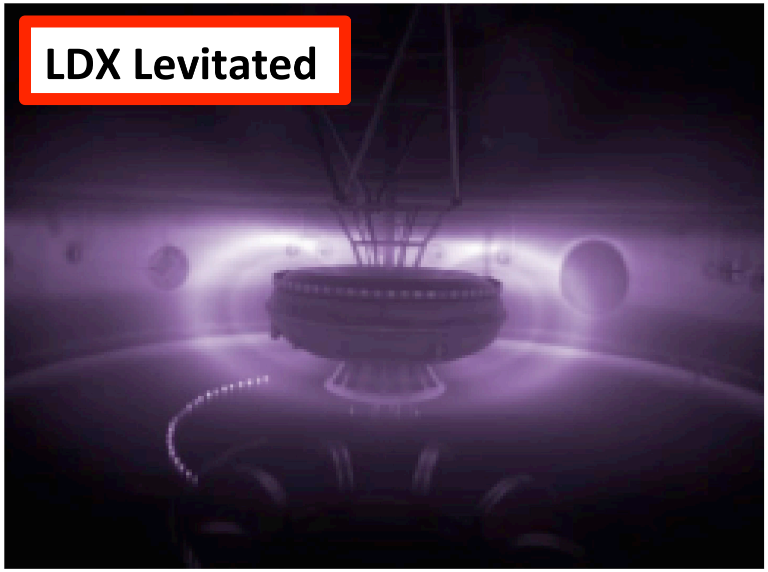


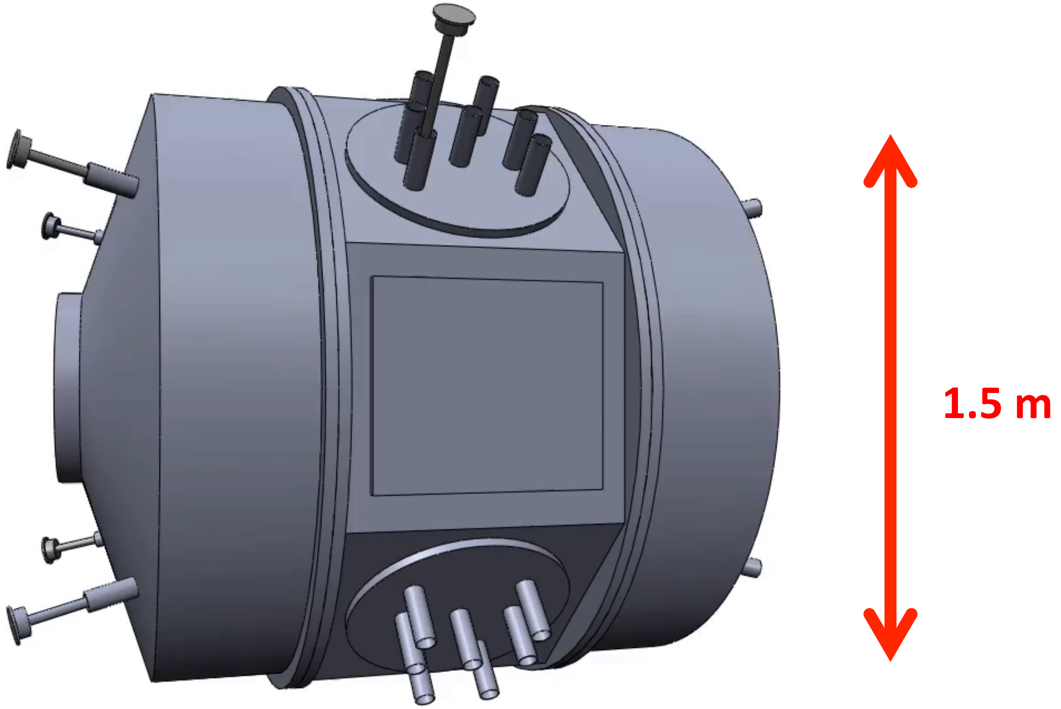
Le, G.; J. A. Slavin; R. J. Strangeway (2010) J. Geophys. Res. 115 (A07202).

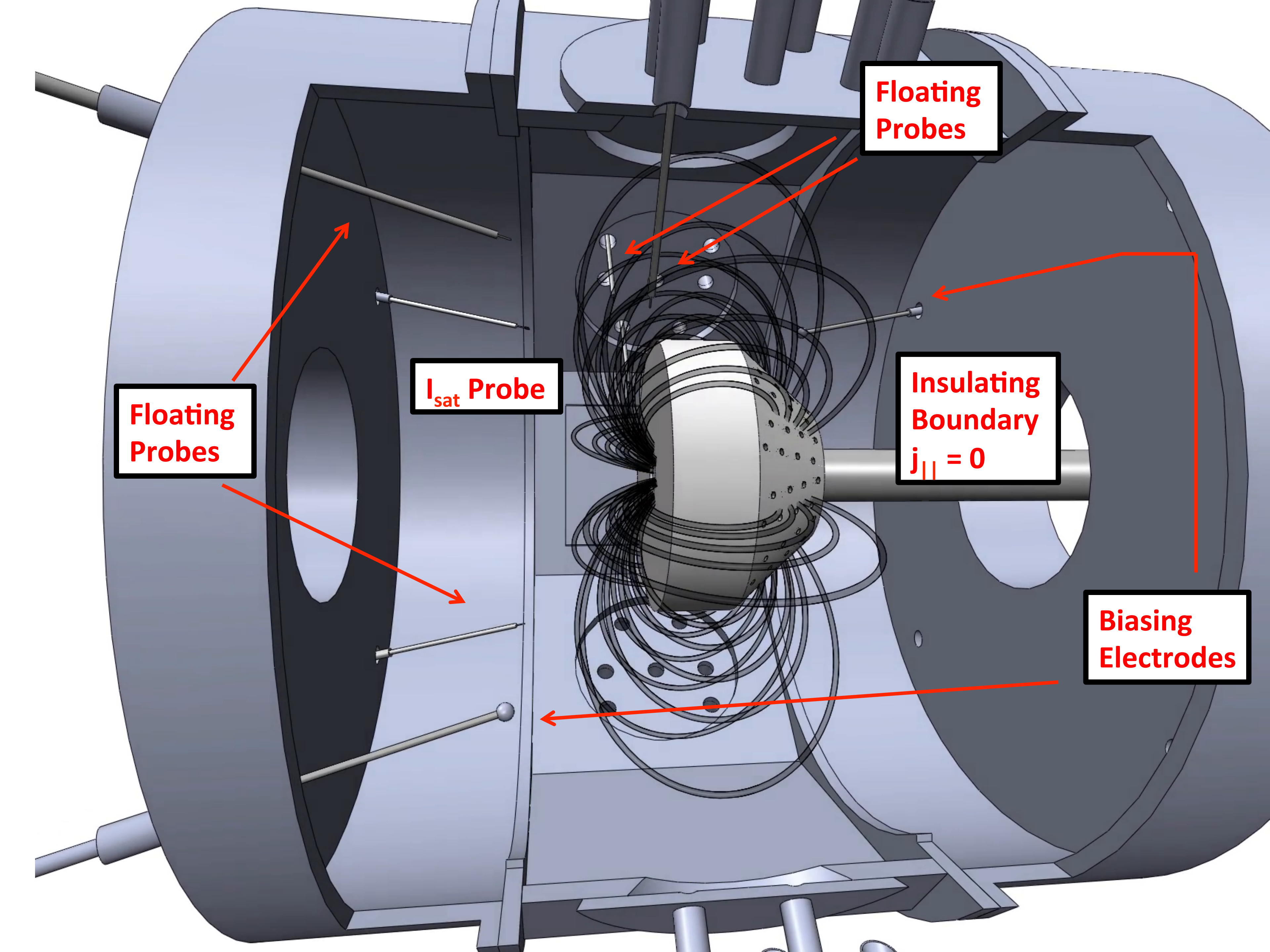
Laboratory Magnetospheres with No Field-Aligned Currents

- LDX has a levitated superconducting coil with closed field lines, no parallel currents
- CTX has insulating polar caps which prevent field aligned currents.
- New Result: Controlled addition of current to individual flux-tubes allows us to explore the response of global interchange motion.

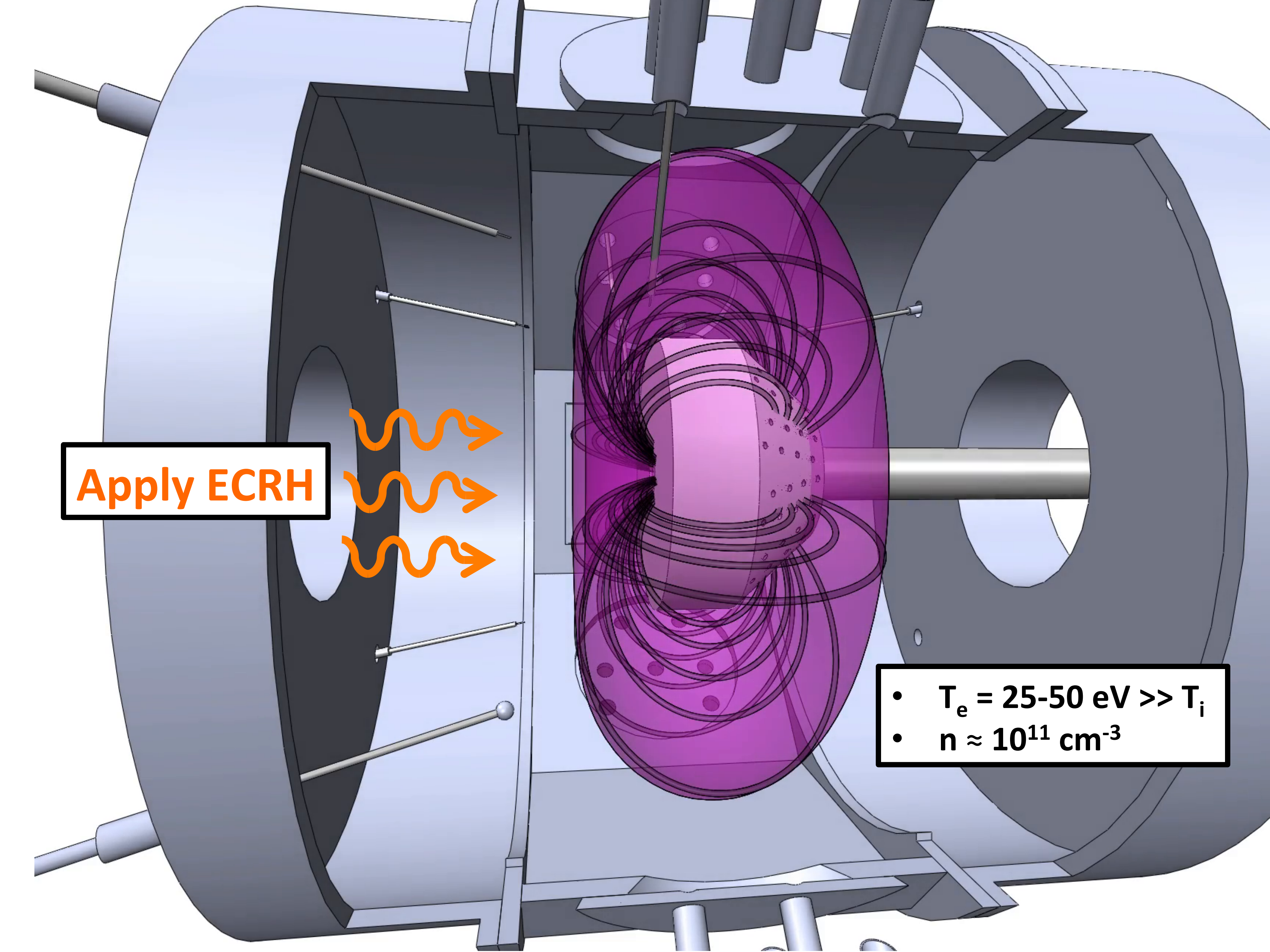
Like a “controlled ionosphere”



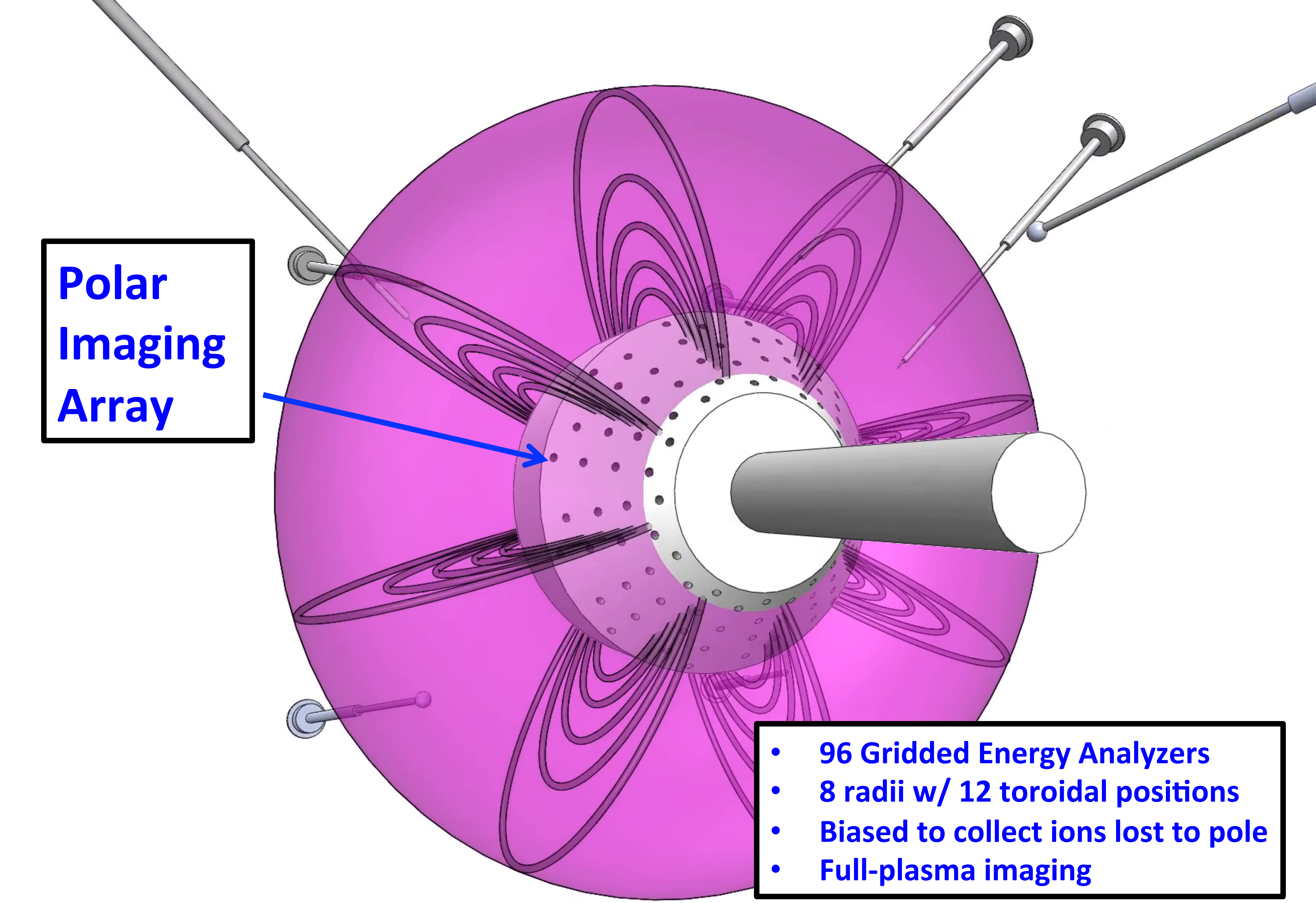

1.5 m



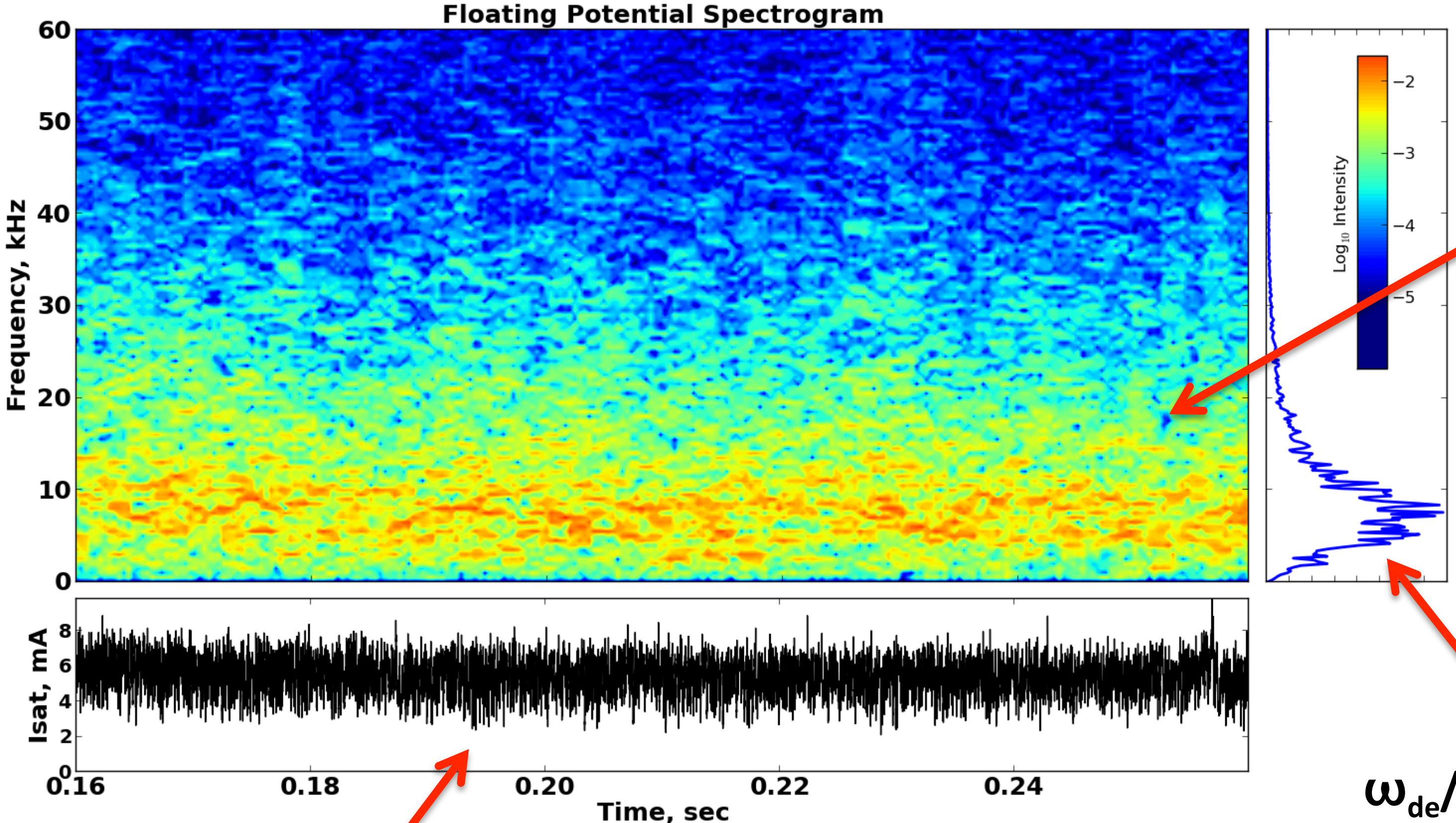
Floating Probes
Floating Probes
I_{sat} Probe
Insulating Boundary $j_{||} = 0$
Biasing Electrodes



Apply ECRH
• T_e = 25-50 eV >> T_i
• n ≈ 10^{11} cm^{-3}


Polar
Imaging
Array
96 Gridded Energy Analyzers
8 radii w/ 12 toroidal positions
Biased to collect ions lost to pole
Full-plasma imaging

Characteristics of Quasi-Steady Interchange Turbulence



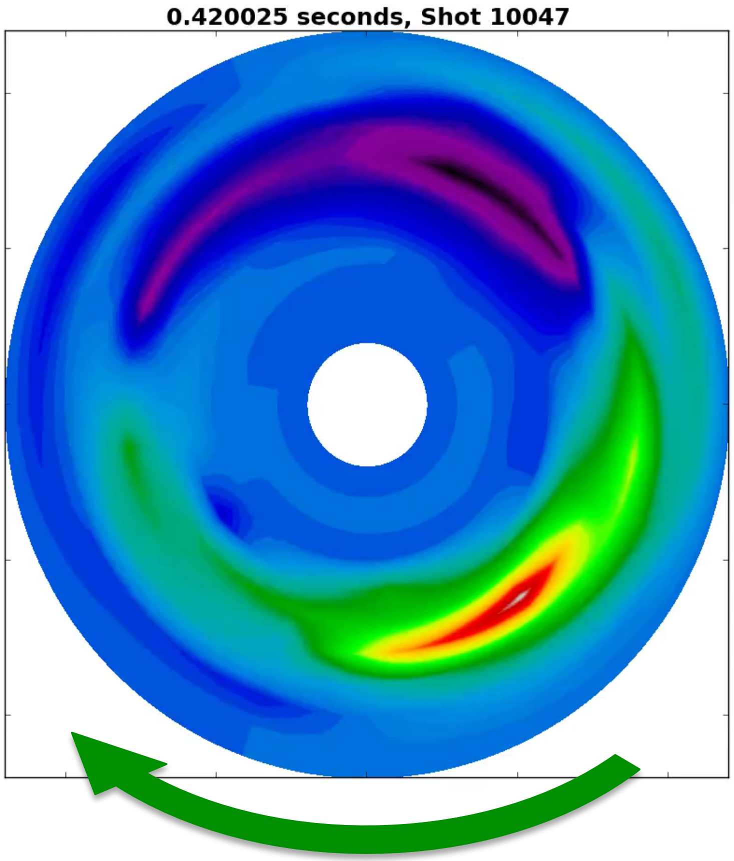
Audio range dynamics

$\omega_{de}/2\pi \approx$ **2-4 kHz**

Electron Magnetic Drift Frequency

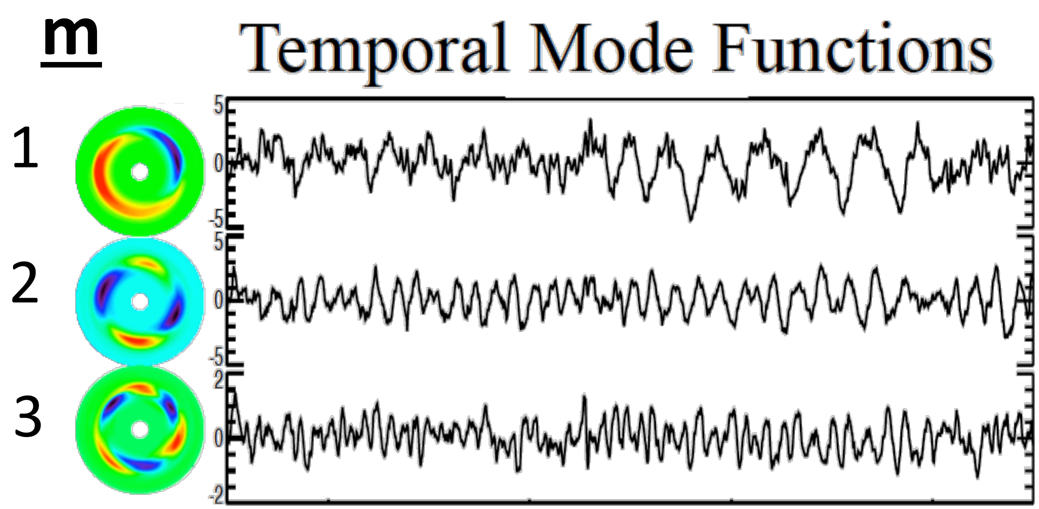
$$\frac{\delta n}{\langle n \rangle} \sim \frac{\delta I_{sat}}{\langle I_{sat} \rangle} \sim \pm 30\% \qquad \tilde{V}_{float} \sim \pm 5V$$

Structure of the Turbulence



Electron magnetic drift direction

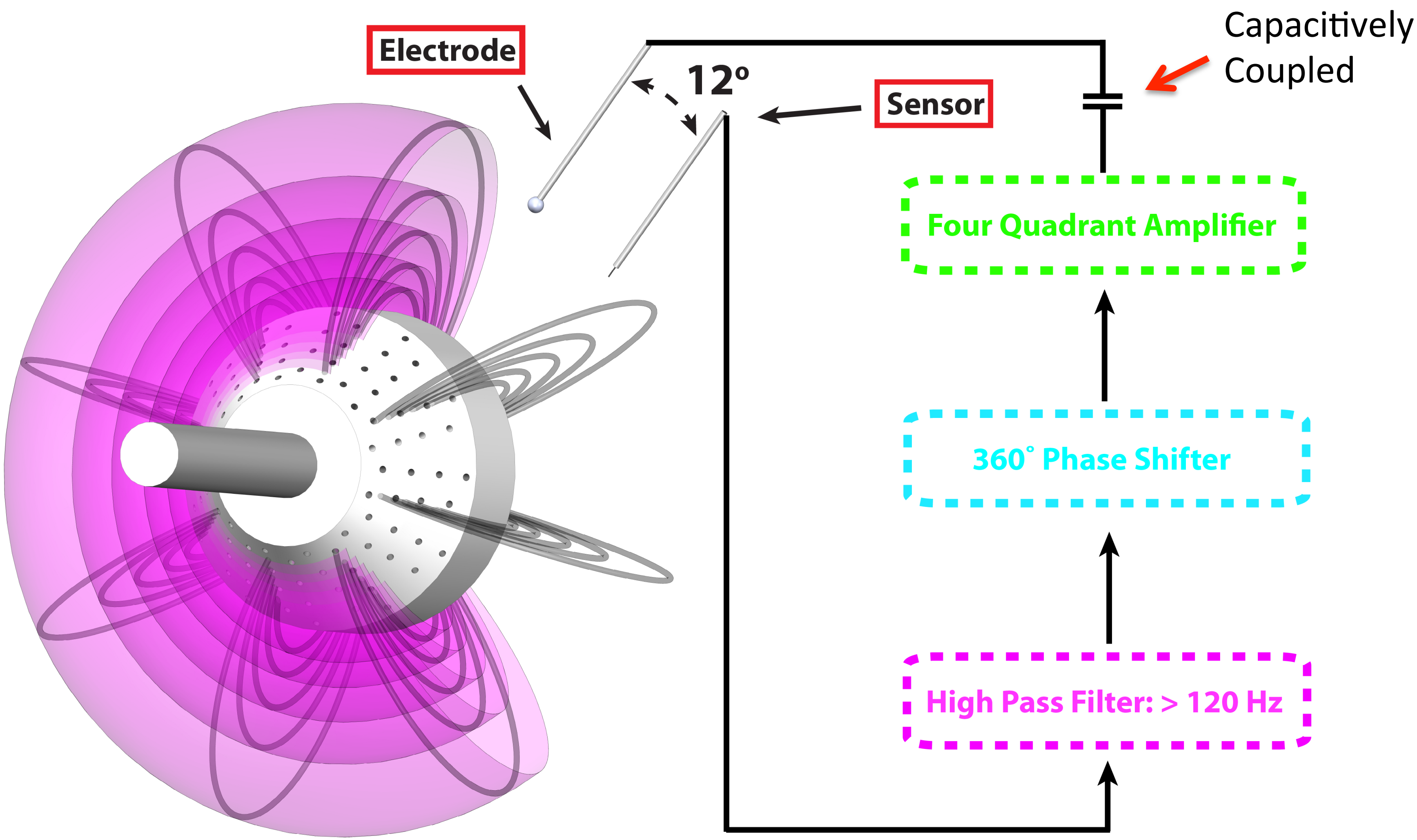
- Radially broad flute-like modes ($k_{||} \approx 0$)
- Low azimuthal mode number, m = 1, 2, 3
- Mode rotate with the electron magnetic drift



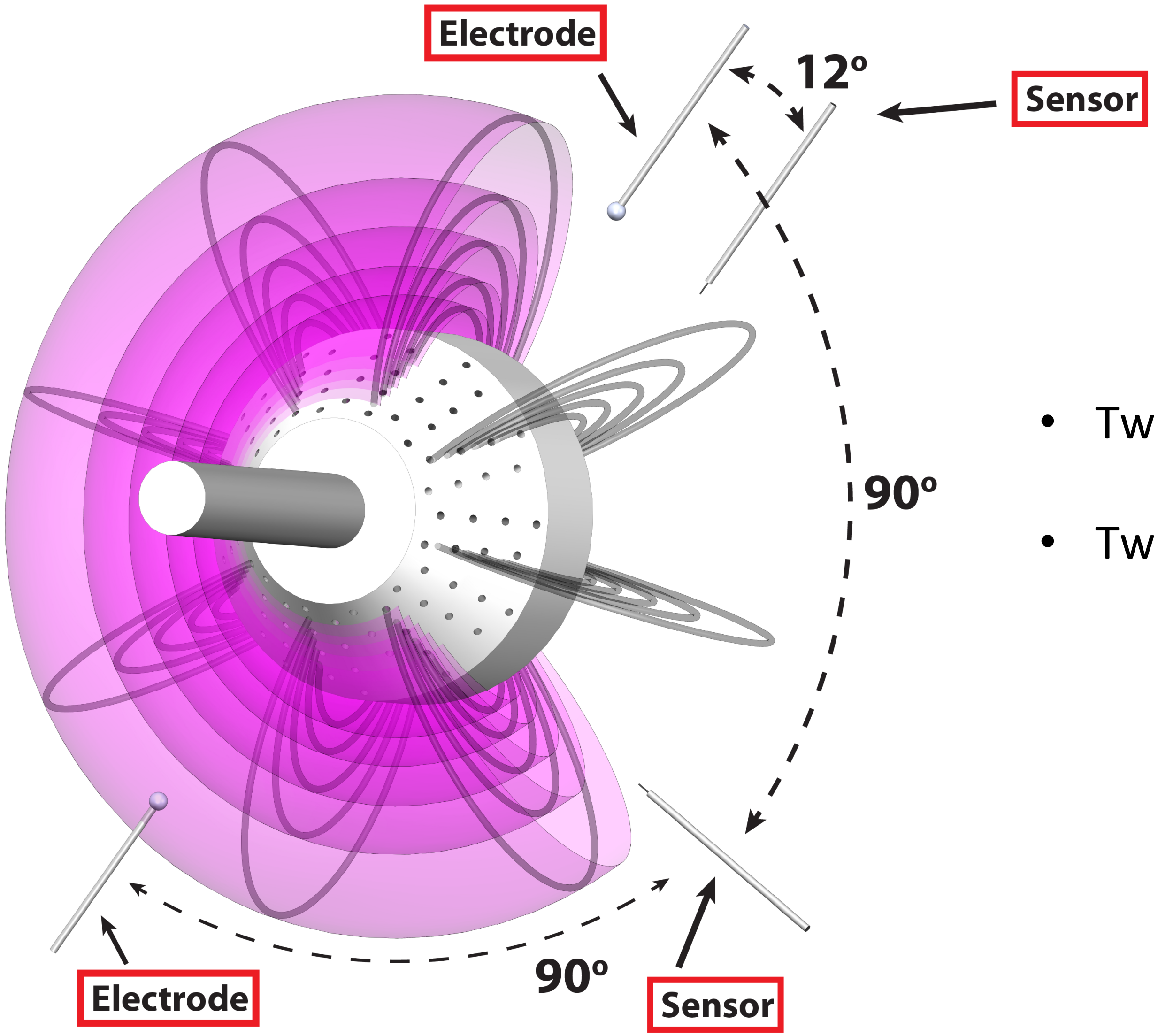
- Chaotically varying amplitude and phase
- Combined correlation length of 50-75˚

B. Grierson, M. Worstell, and M. Mauel, *Phys Plasmas*, **16**, 055902 (2009).

Current-Collection Feedback



Current-Collection Feedback



- Two sensor locations
- Two electrode locations

Related Experiments with Feedback

- Feedback on Interchange Modes
  - Prater applied narrow-band feedback with a biasing electrode to suppress large growth rate flute modes.

  (R. Prater, *Phys. Rev. Lett.* **27**, 132 – July 1971)

- Feedback in Turbulent Plasmas
  - TEXT group used biasing electrodes to suppress broadband drift wave turbulence in tokamak edge.

  (B. Richards, *Phys. Plasmas* **1**, 1606 (1994))

  (T. Uckan, *Nucl. Fusion* 35 487 (1995))

- The feedback in CTX is different from both of the above cases:
  - **Broadband** feedback is applied to global **interchange** turbulence in the magnetospheric configuration.

Current-Collection Experiments

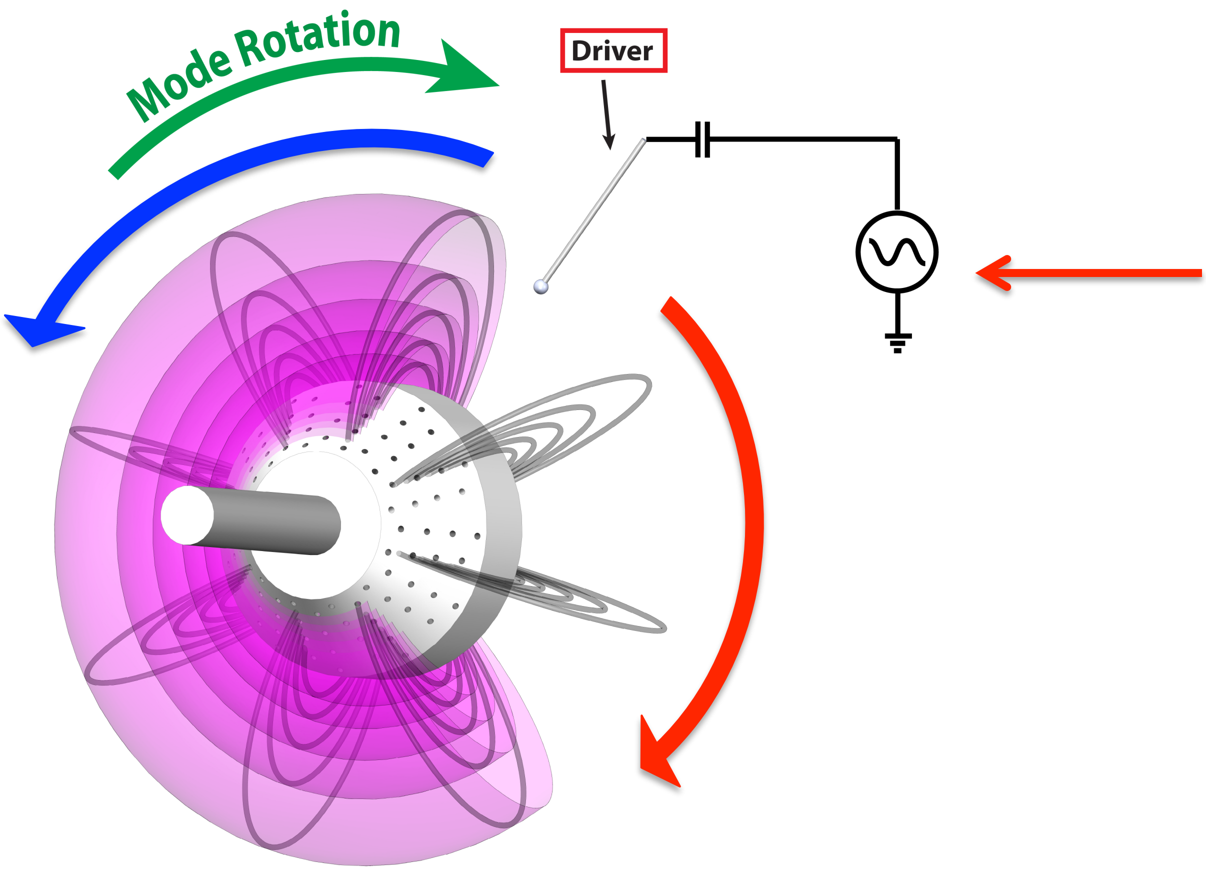
1. **Plasma responds to coherent current-collection (feedforward)**

2. Triggering feedback on and off shows amplification and suppression of fluctuations and a localized effect.

3. Varying the gain and phase of the current relative to the floating potential significantly changes the spectrum.

4. Varying the separation between the sensor and electrode shows the effect of decorrelation on feedback influence.

Driving a Coherent Current Oscillation

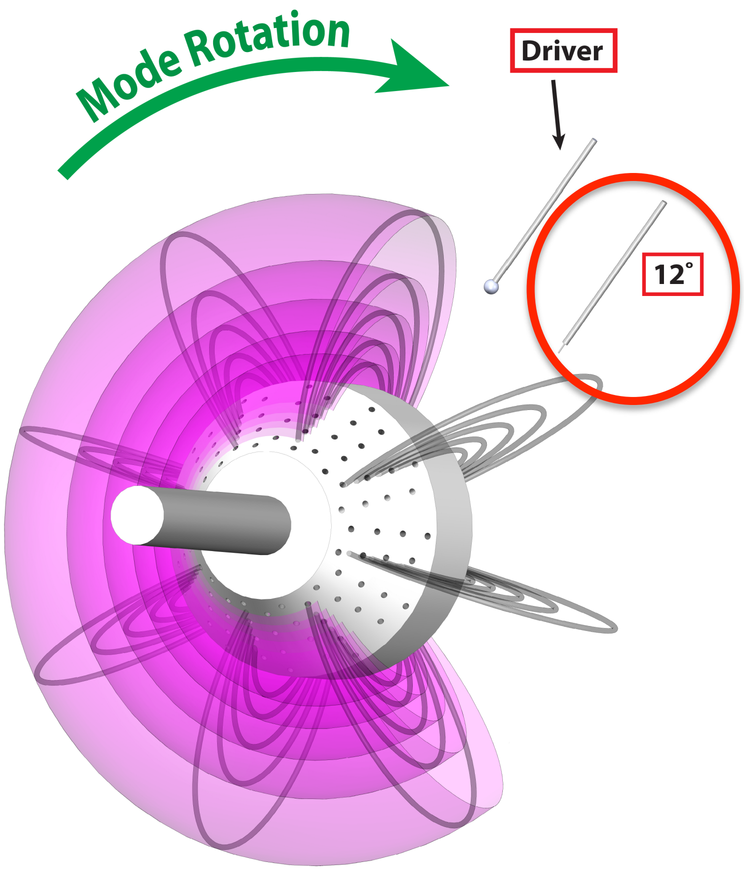


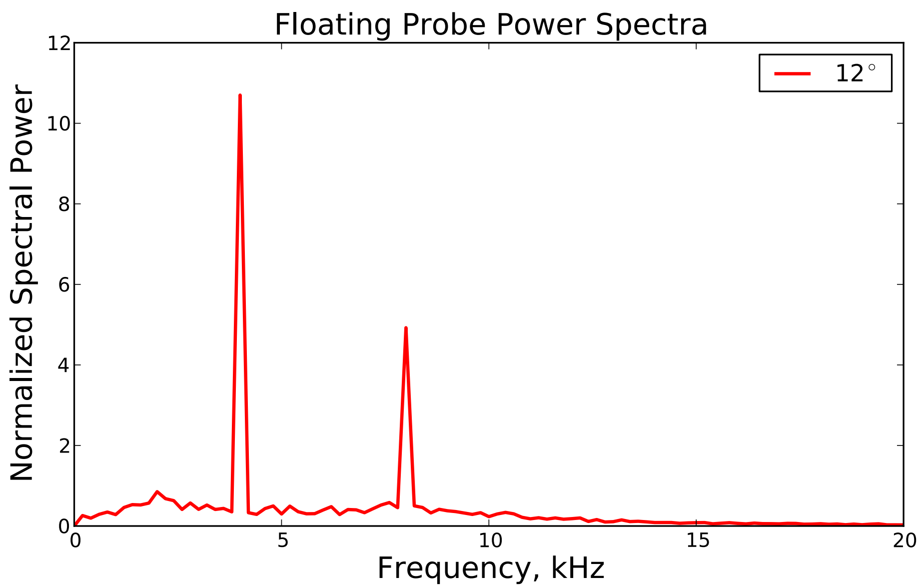
Electrode biased with 4 kHz sine wave, ±40 V

Downstream: Plasma has moved past electrode

Upstream: Plasma has yet to move past electrode

Driving a Coherent Current Oscillation





- Electrode biased with 4 kHz sine wave, ±40 V

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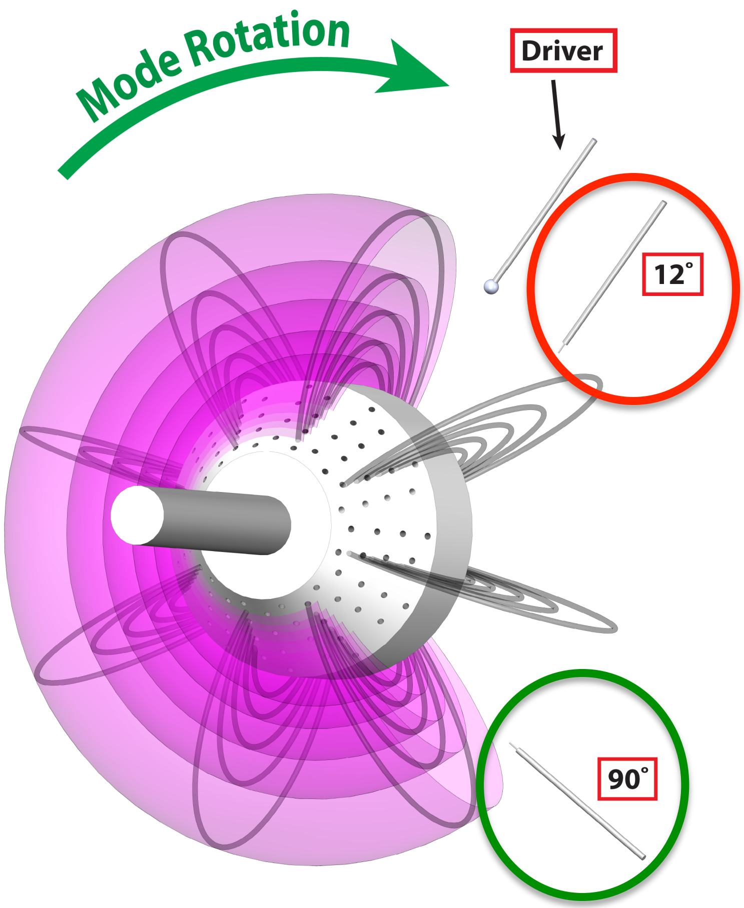
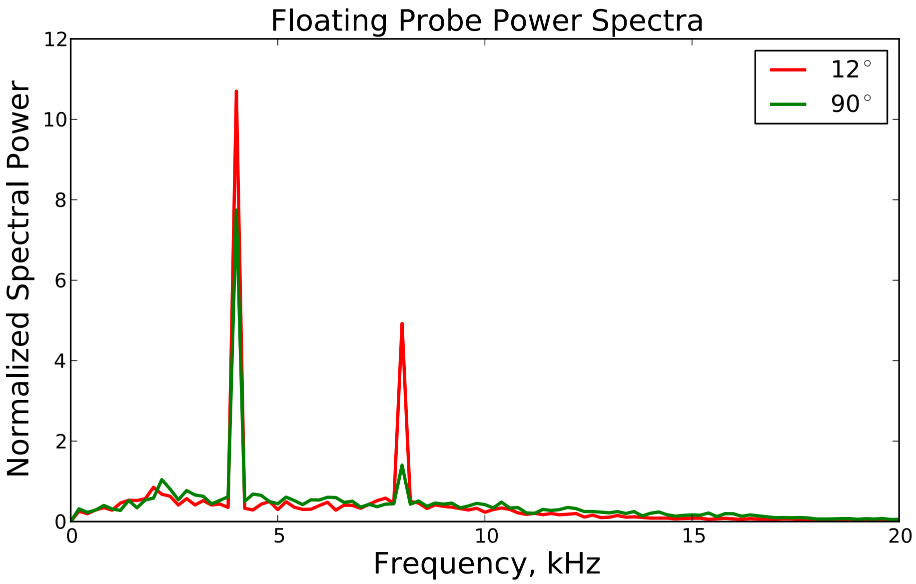
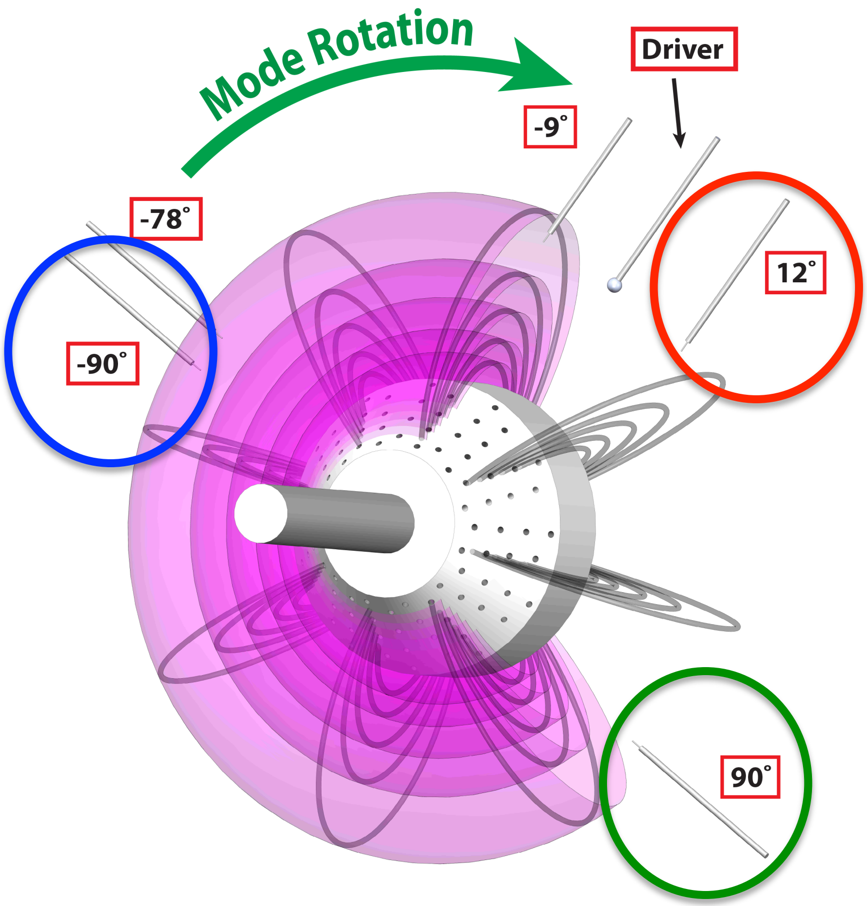
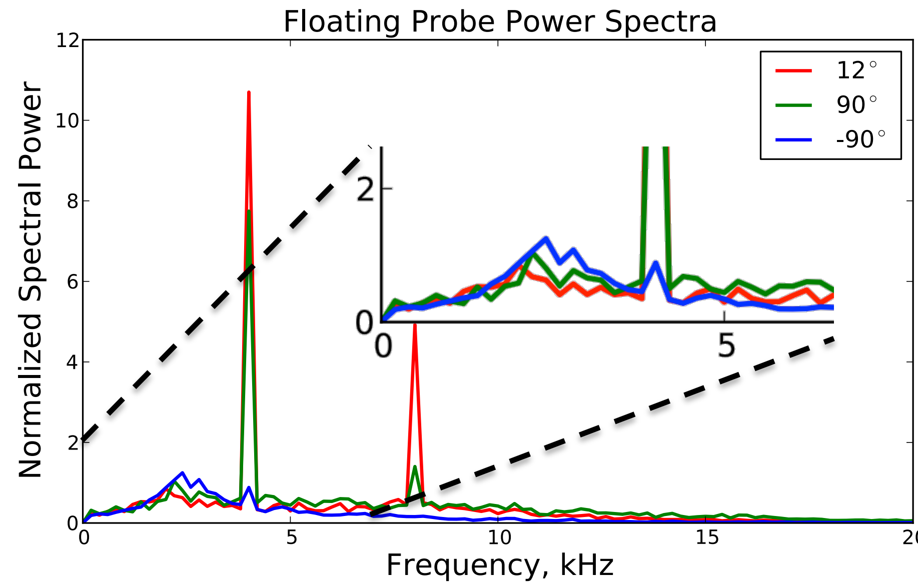


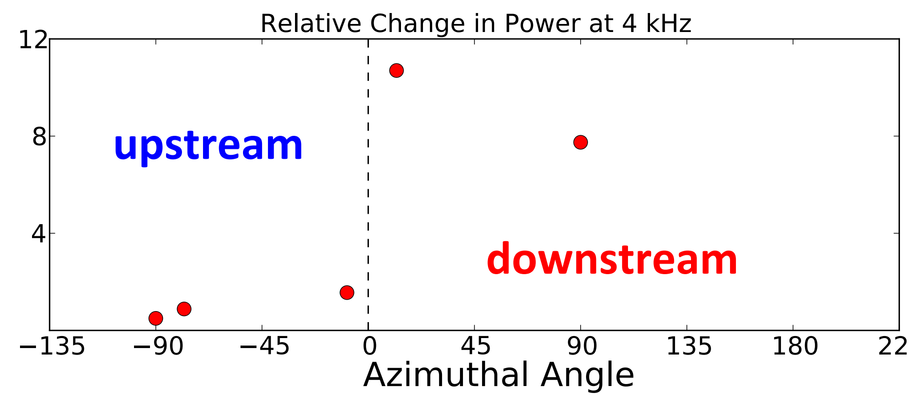


- Electrode biased with 4 kHz sine wave, ±40 V

Driving a Coherent Current Oscillation







- Electrode biased with 4 kHz sine wave, ±40 V
- Launches coherent wave in direction of mode rotatic
- Downstream influence significantly greater

Current-Collection Experiments

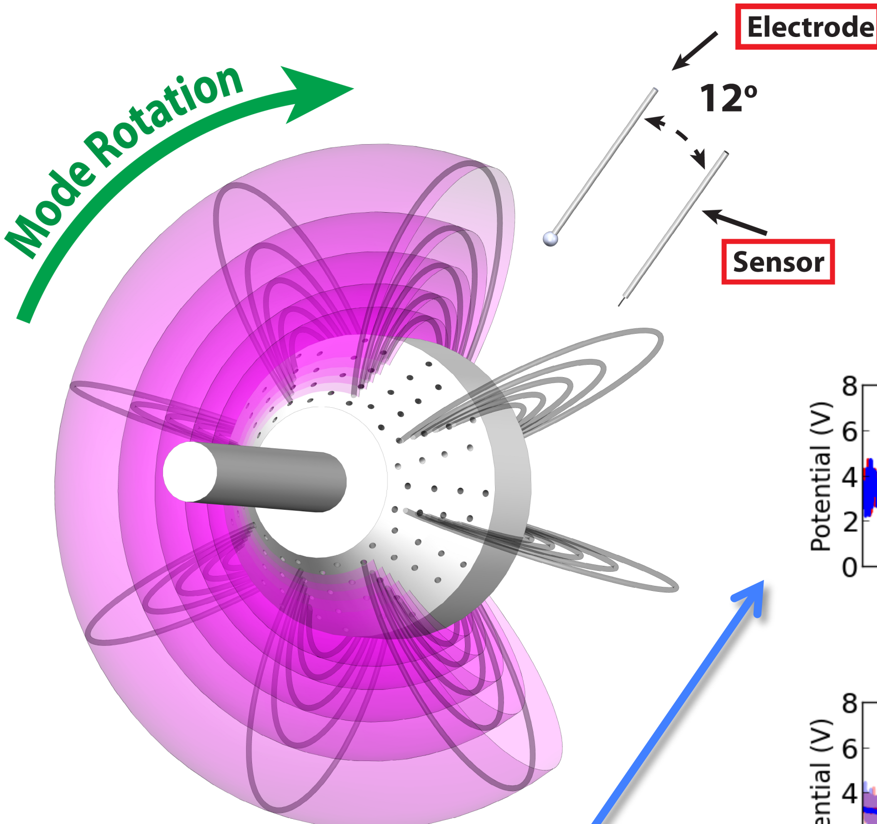
1. Plasma responds to coherent current-collection (feedforward)

2. **Triggering feedback on and off shows amplification and suppression of fluctuations and a localized effect.**

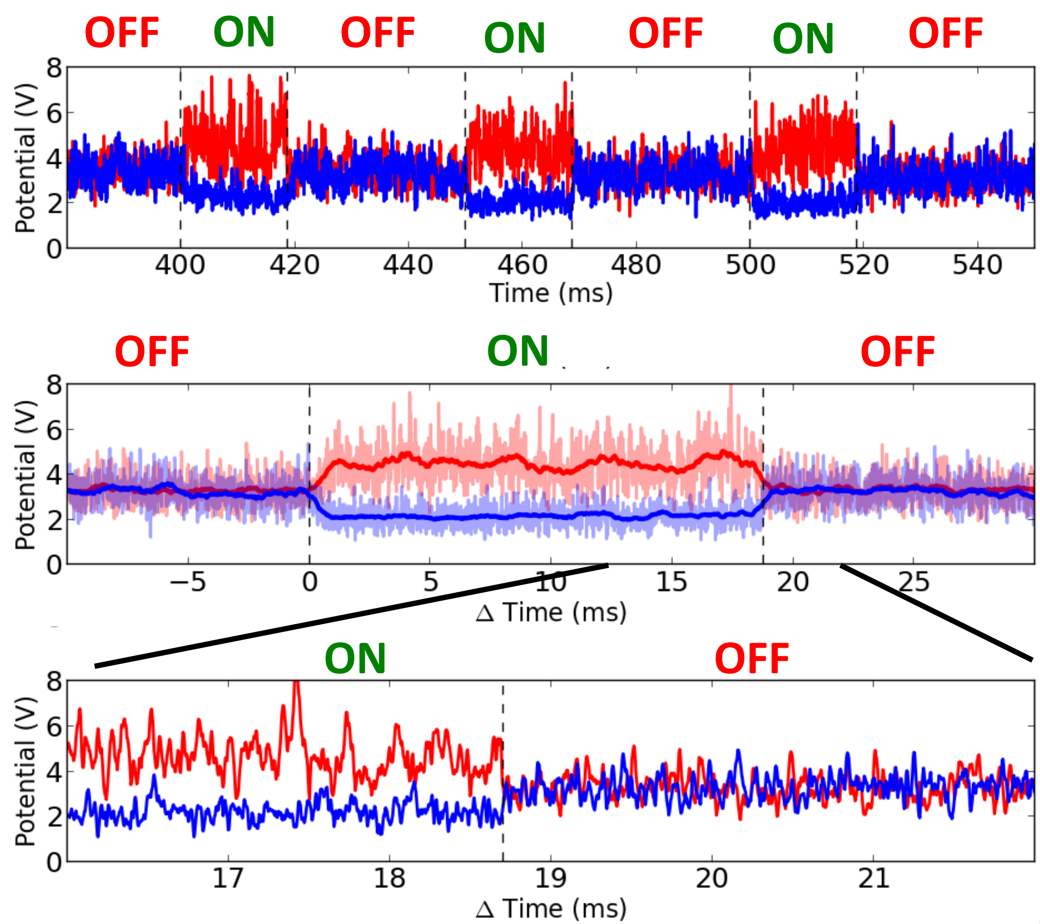
3. Varying the gain and phase of the current relative to the floating potential significantly changes the spectrum.

4. Varying the separation between the sensor and electrode shows the effect of decorrelation on feedback influence.

Triggered Feedback Show Amplification and Suppression



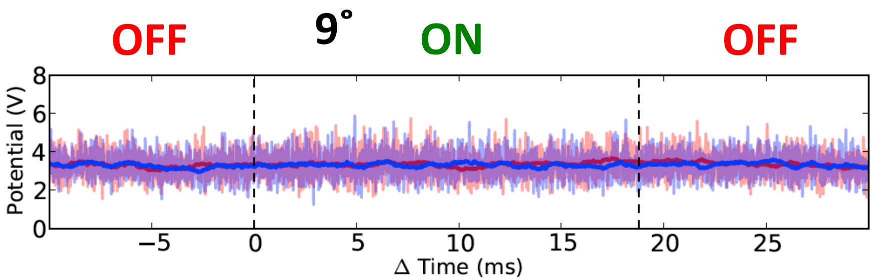
- G = ± 4
- **Amplification** -> + 30%
- **Suppression** -> -30%
- Relaxation time < 20 us



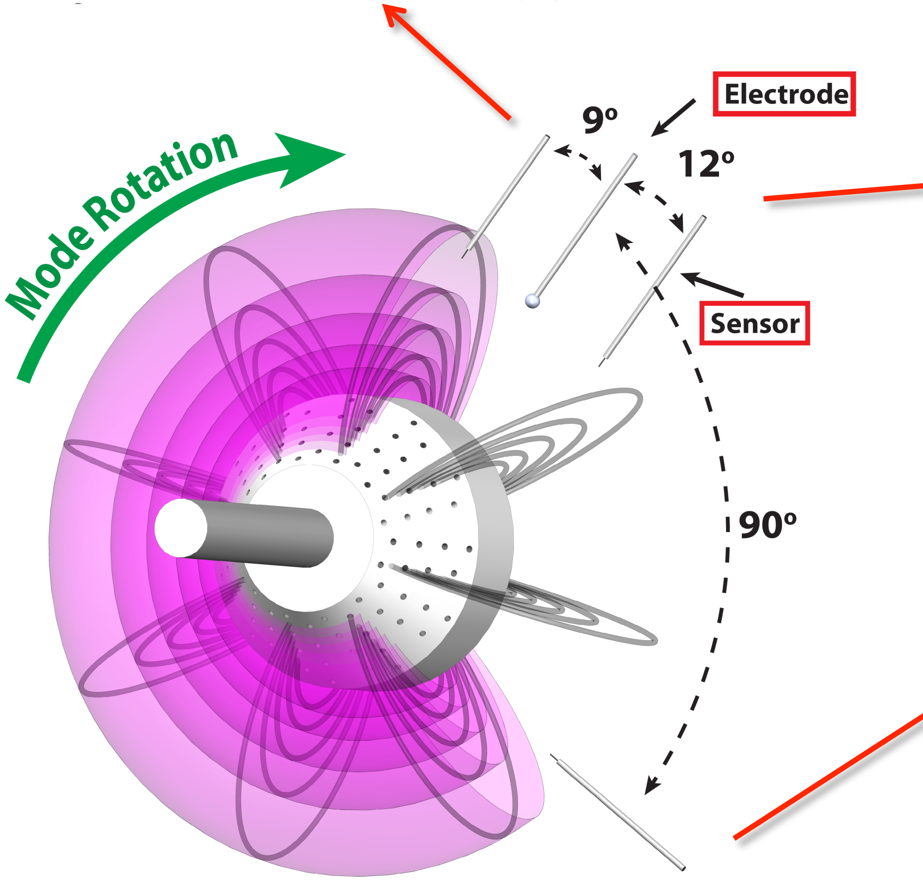
Moving RMS Fluctuations of Floating Potential

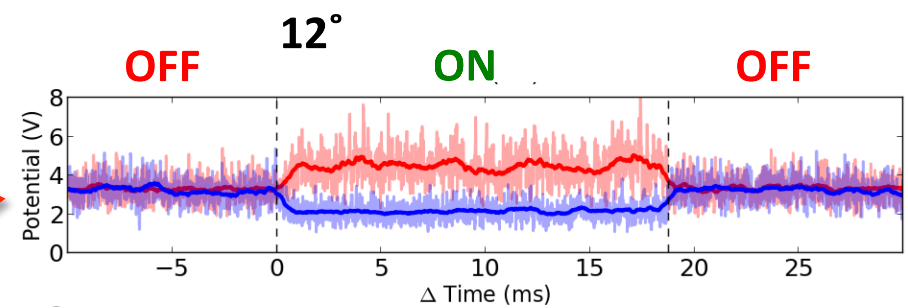
Averaging of triggering events

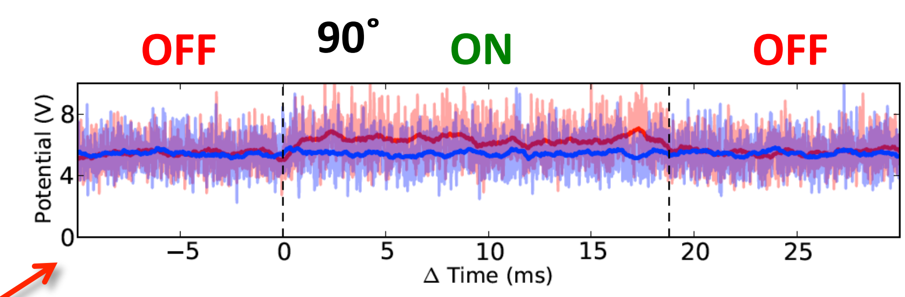
Influence Diminishes with Azimuthal Separation



Nearby “upstream” probe sees no response

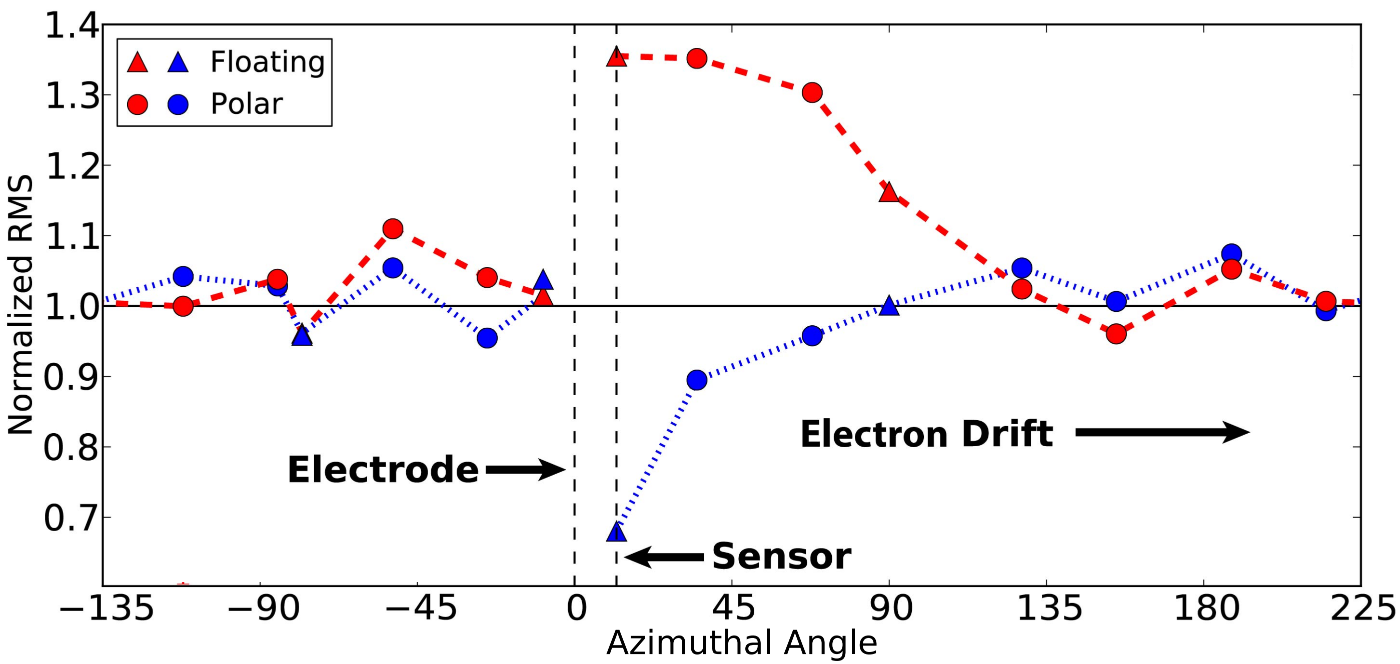




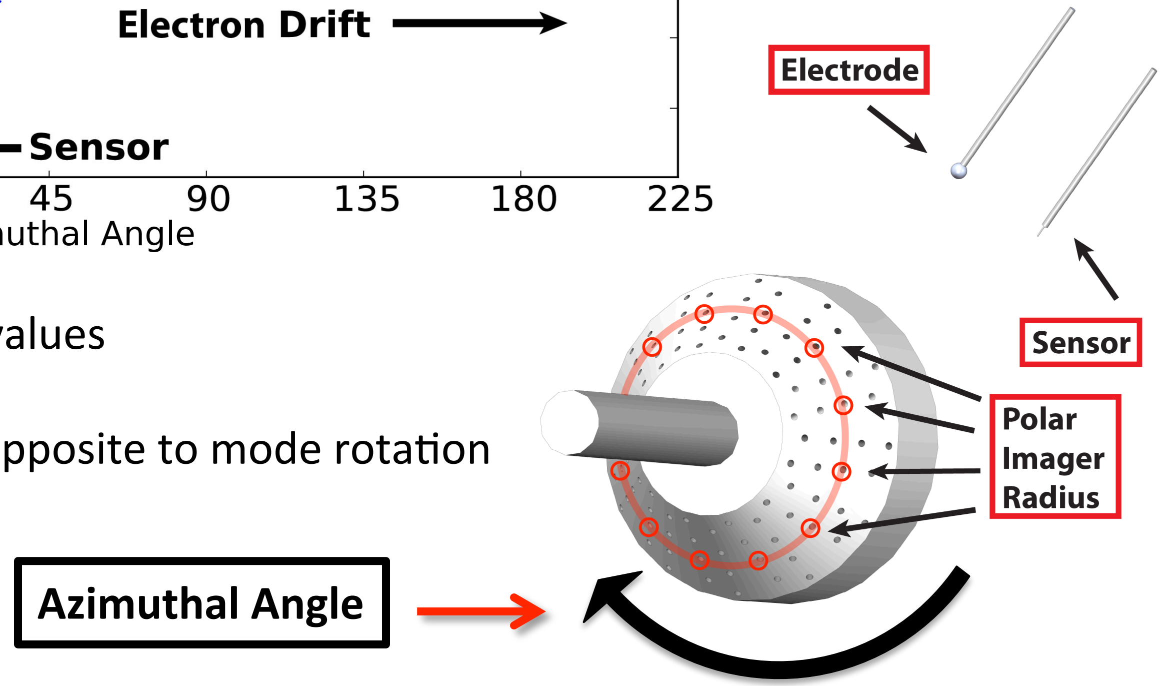


“Downstream” probe sees reduced response

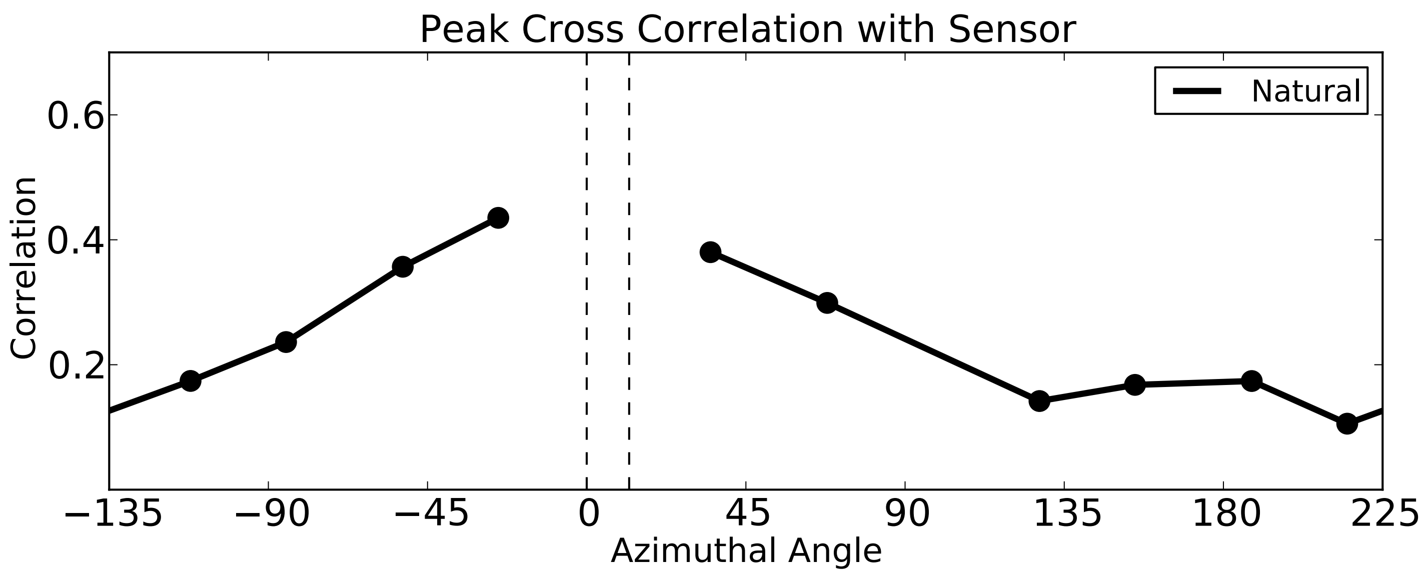
Influence of Feedback is Spatially Localized

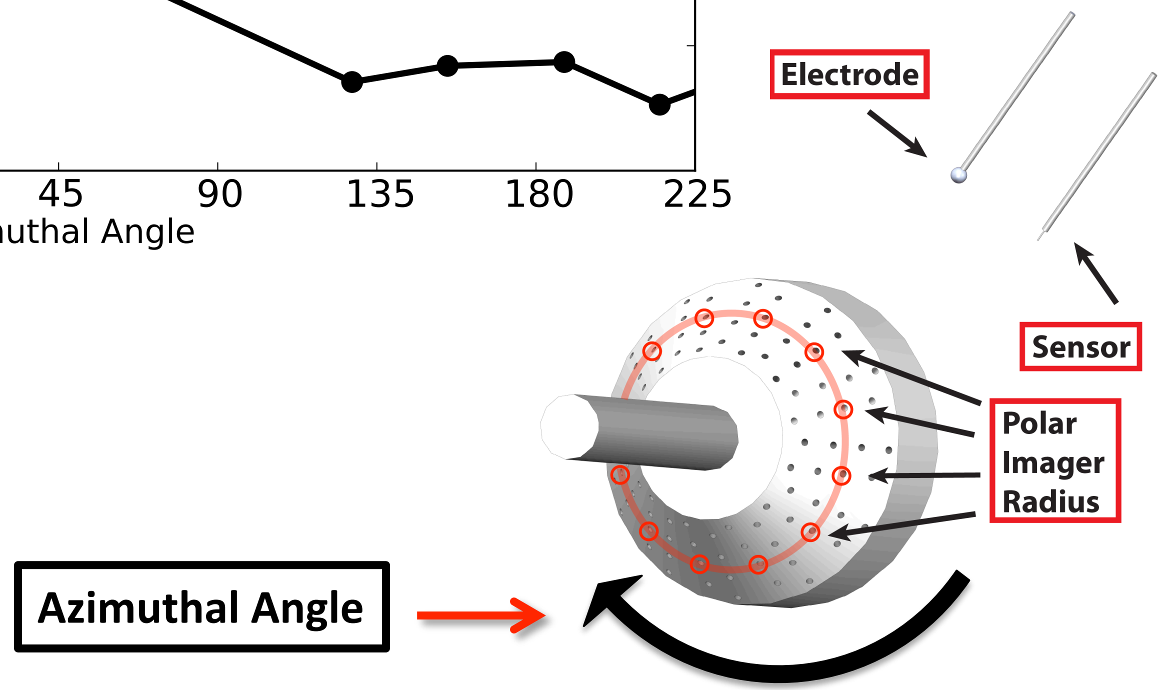


- RMS normalized to "natural" values
- No influence in the direction opposite to mode rotation



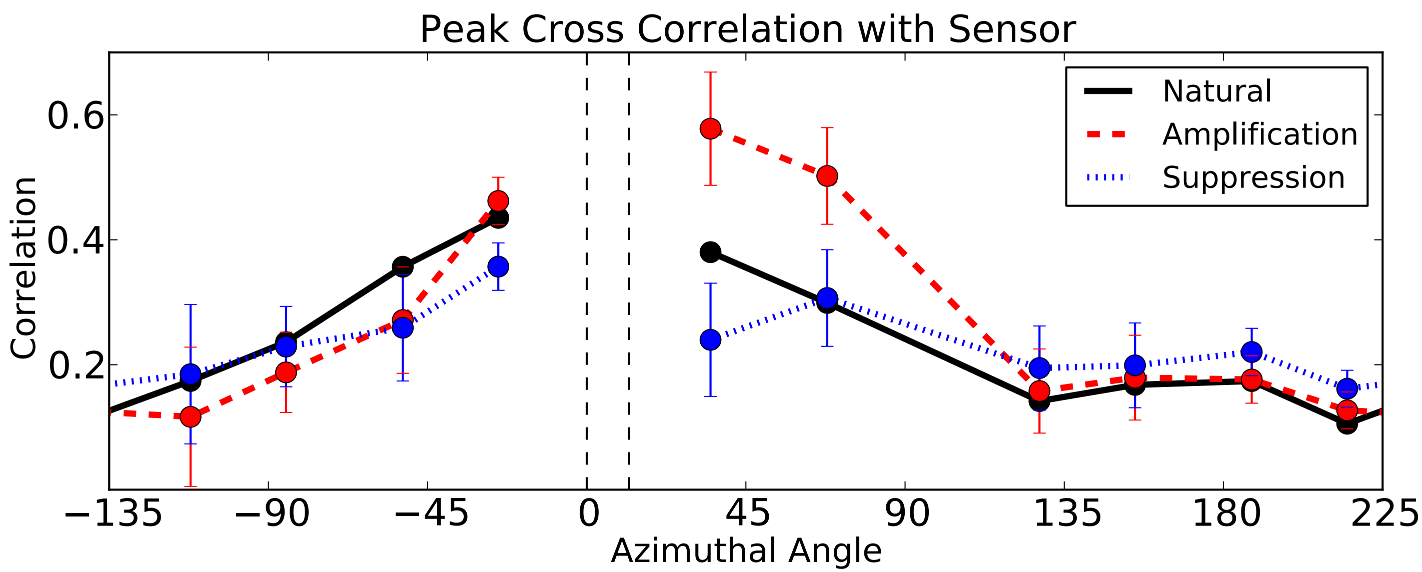
Feedback Increases or Decreases Correlation

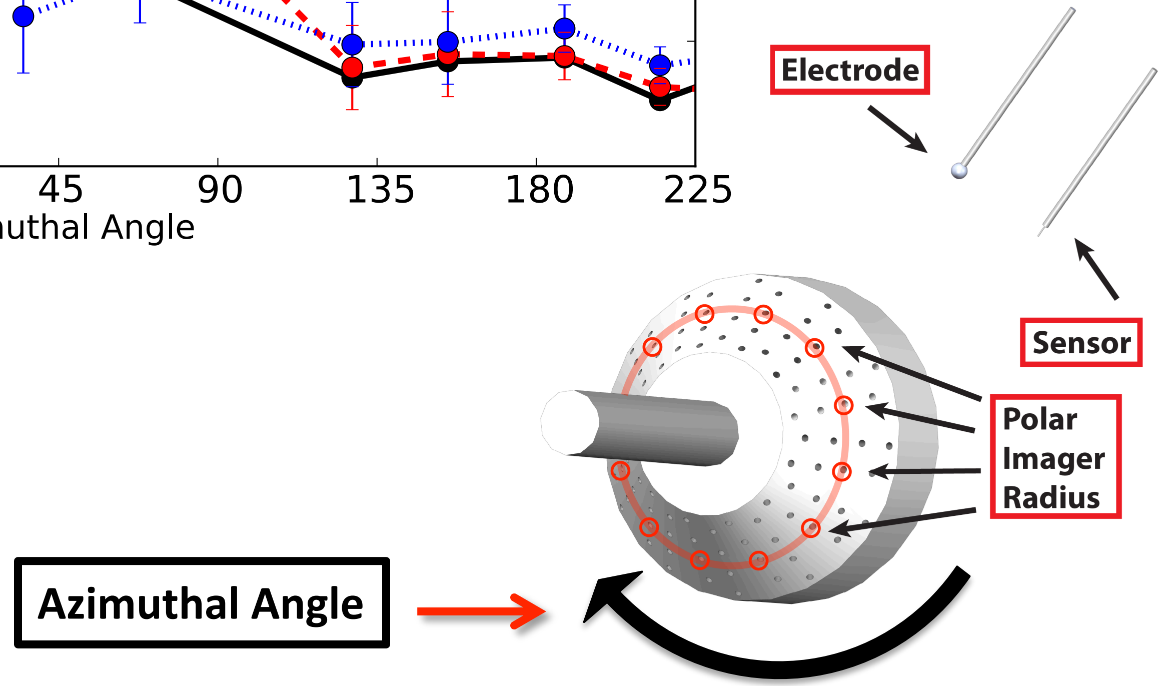




Feedback Increases or Decreases Correlation

Correlation stronger with positive feedback, reduced with negative feedback





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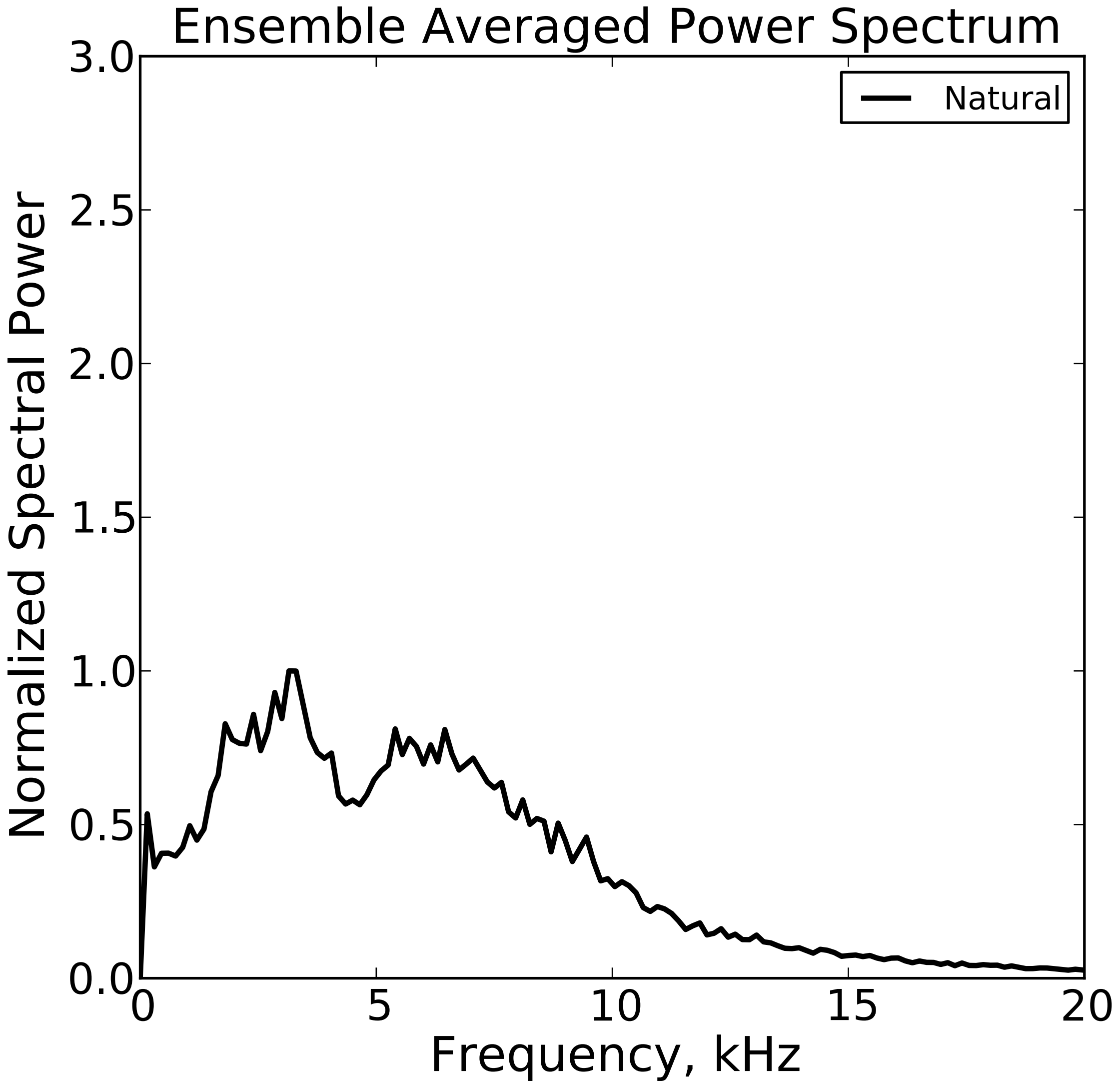
Turbulent Spectrum Shows Influence of Feedback



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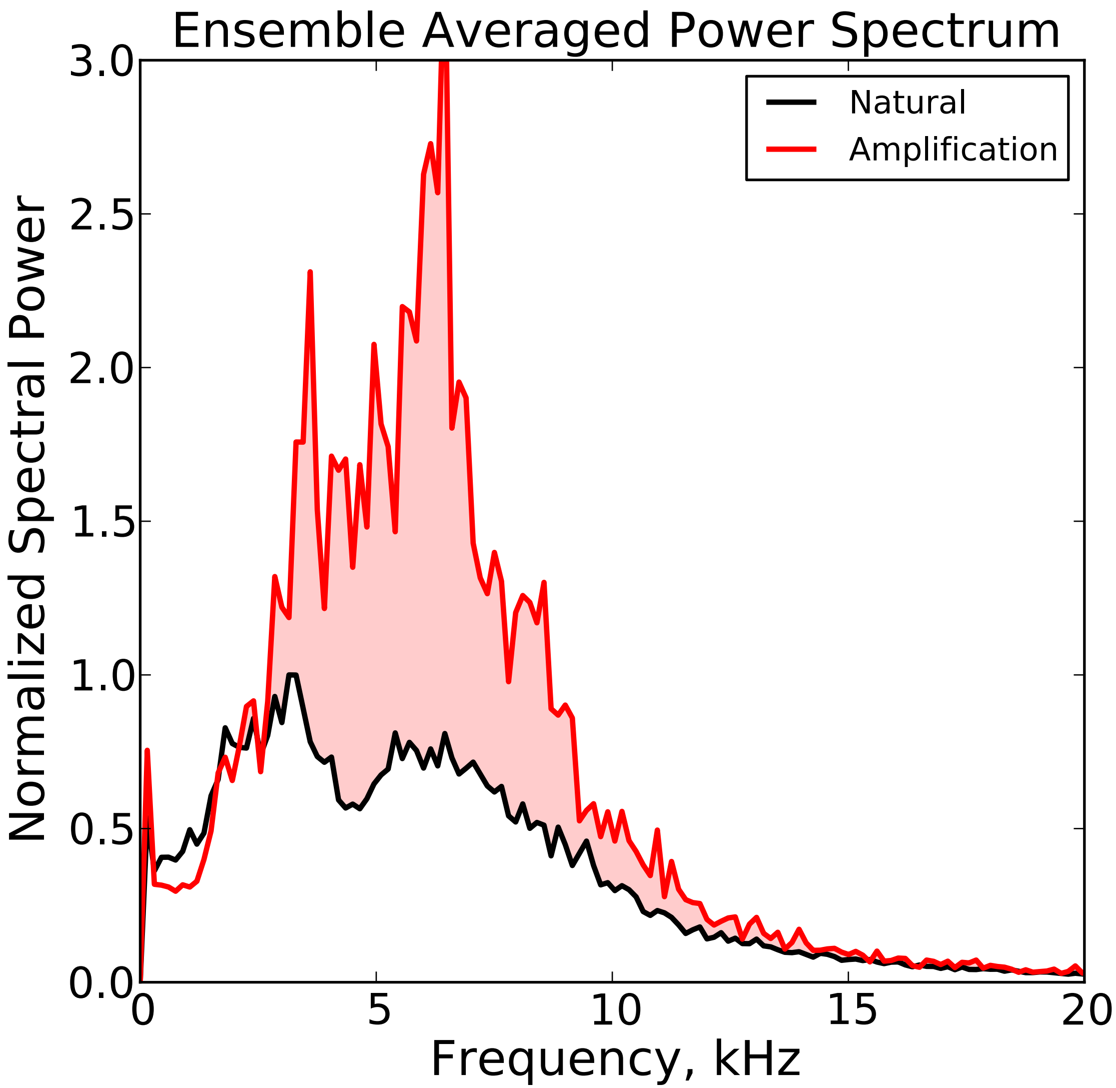
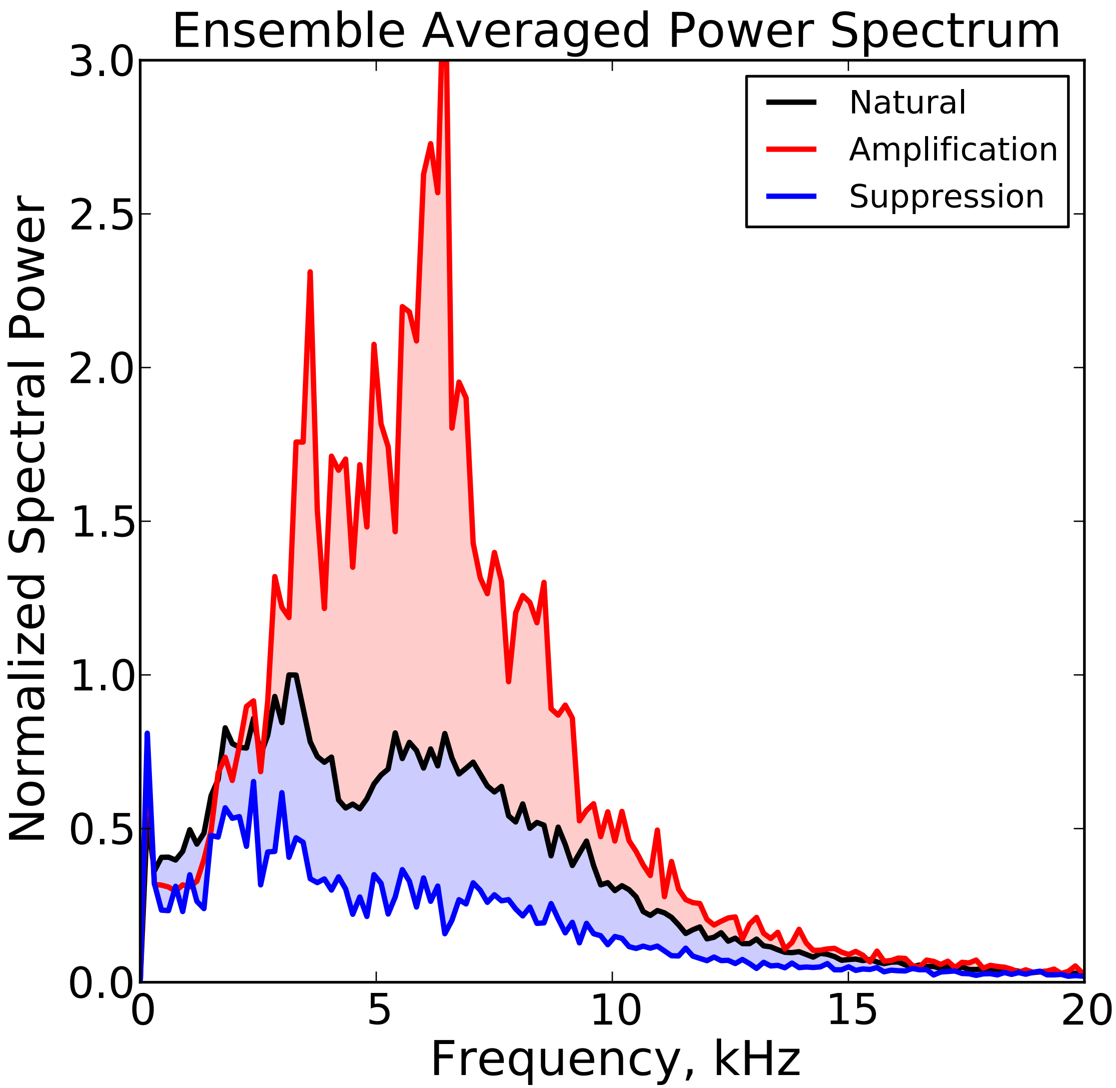
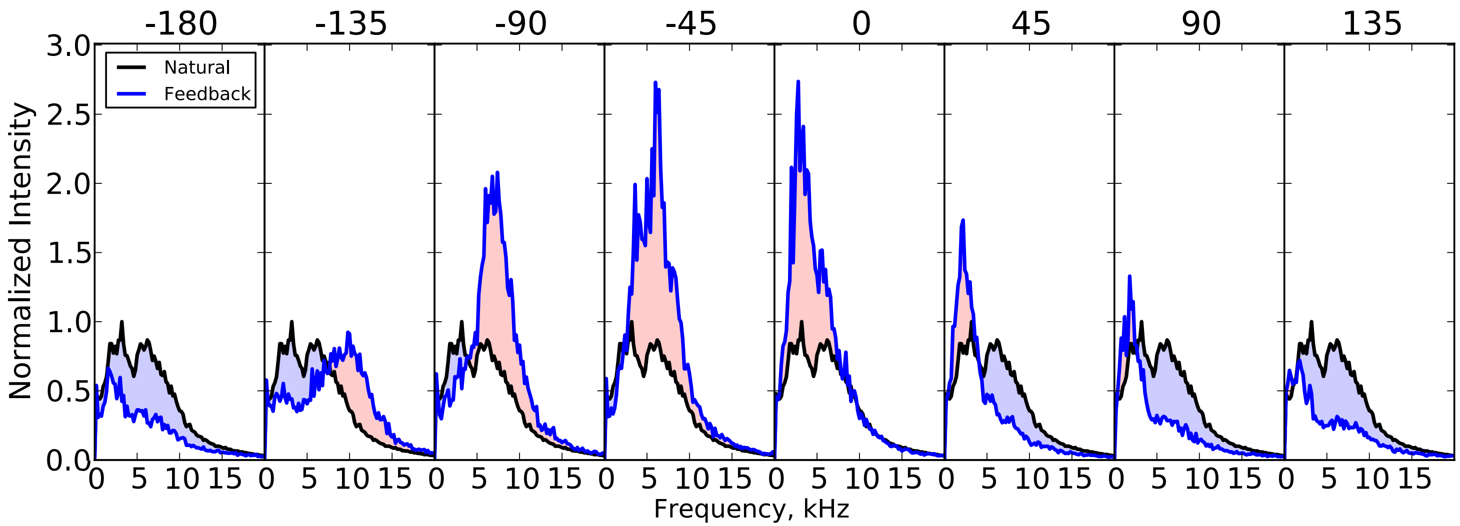


Turbulent Spectrum Shows Influence of Feedback

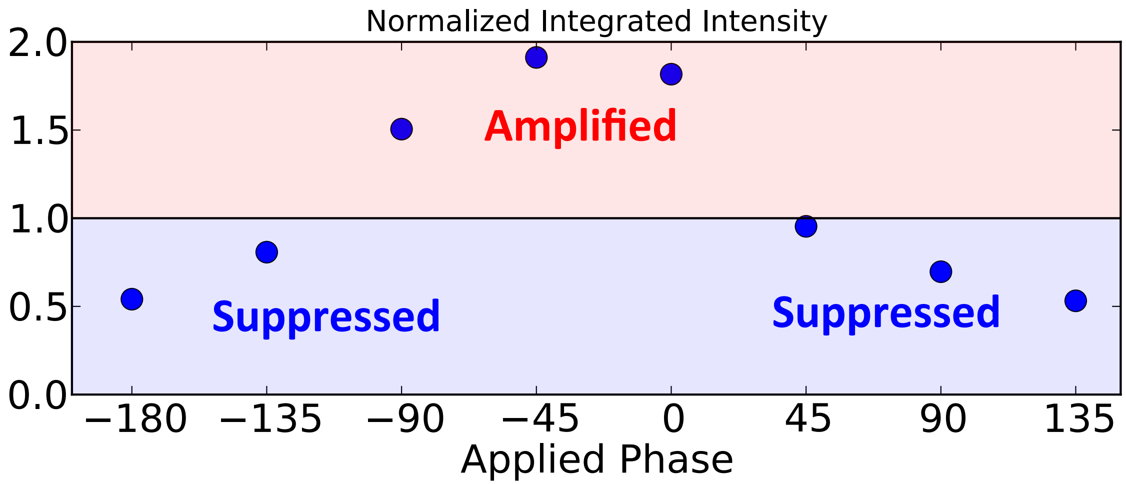


Changing Turbulent Spectrum with Phase

Fixed gain of 4



Band Integrated (1-10 kHz) Spectral Intensity



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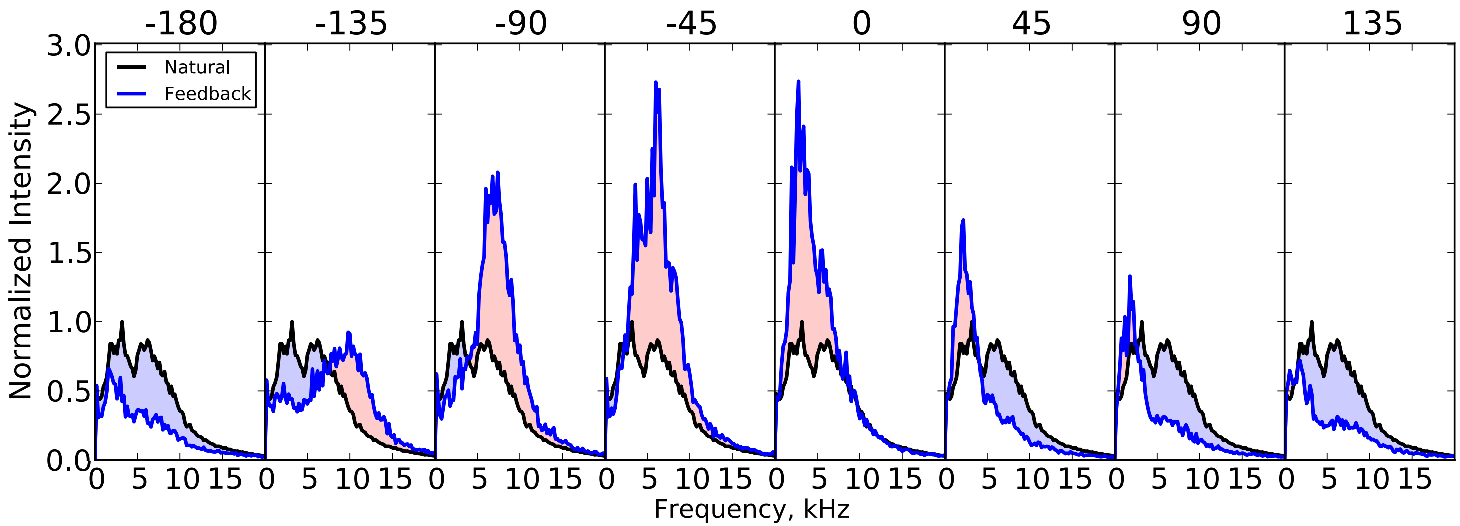
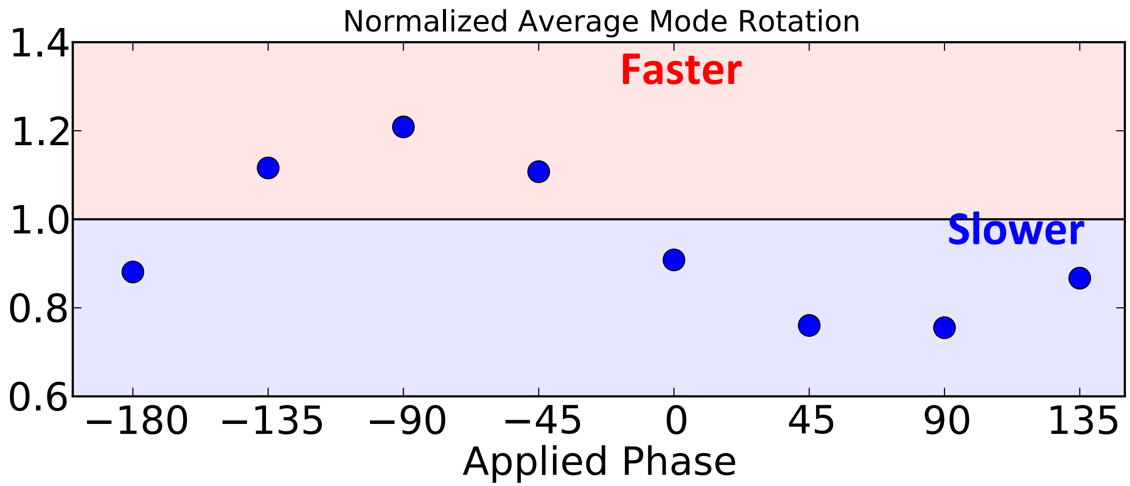
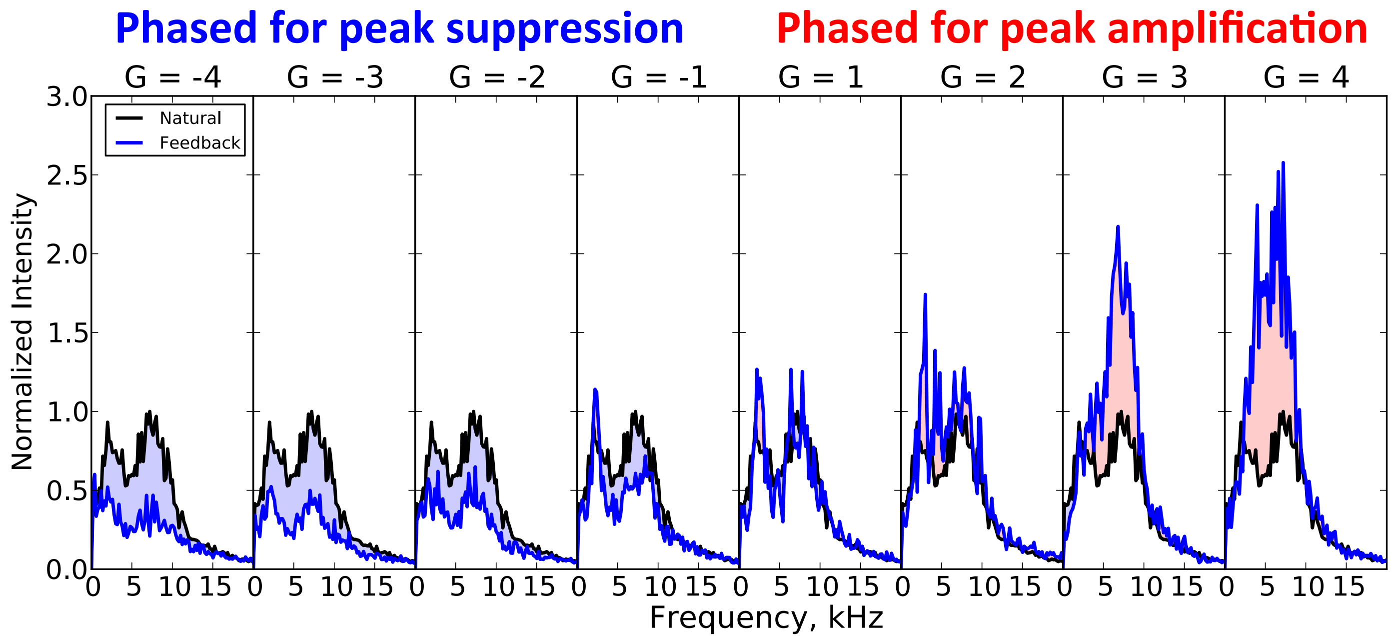


Frequency of amplified modes changes with phase

Intensity Weighted Frequency (1-10 kHz)



Gain Scan: +G -> Amplification, -G -> Suppression



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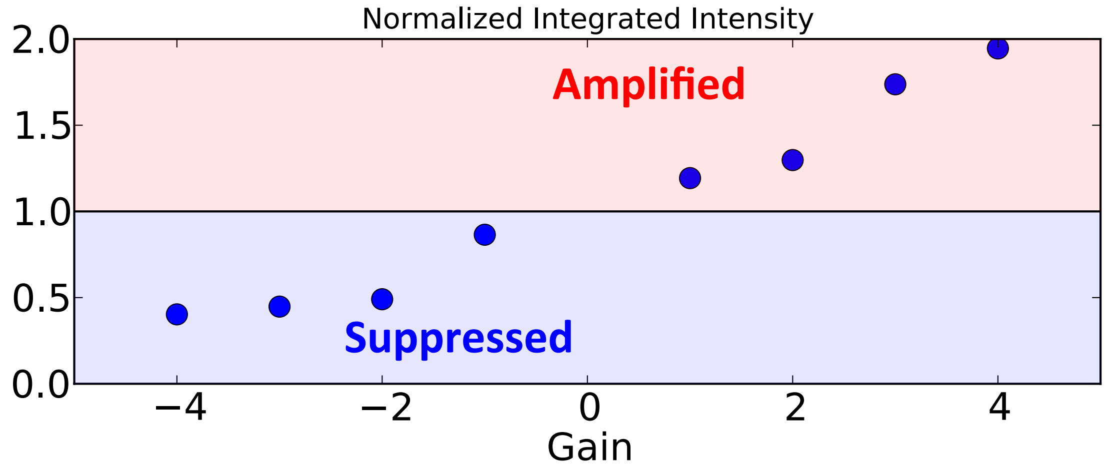


Defining Power and Conductance

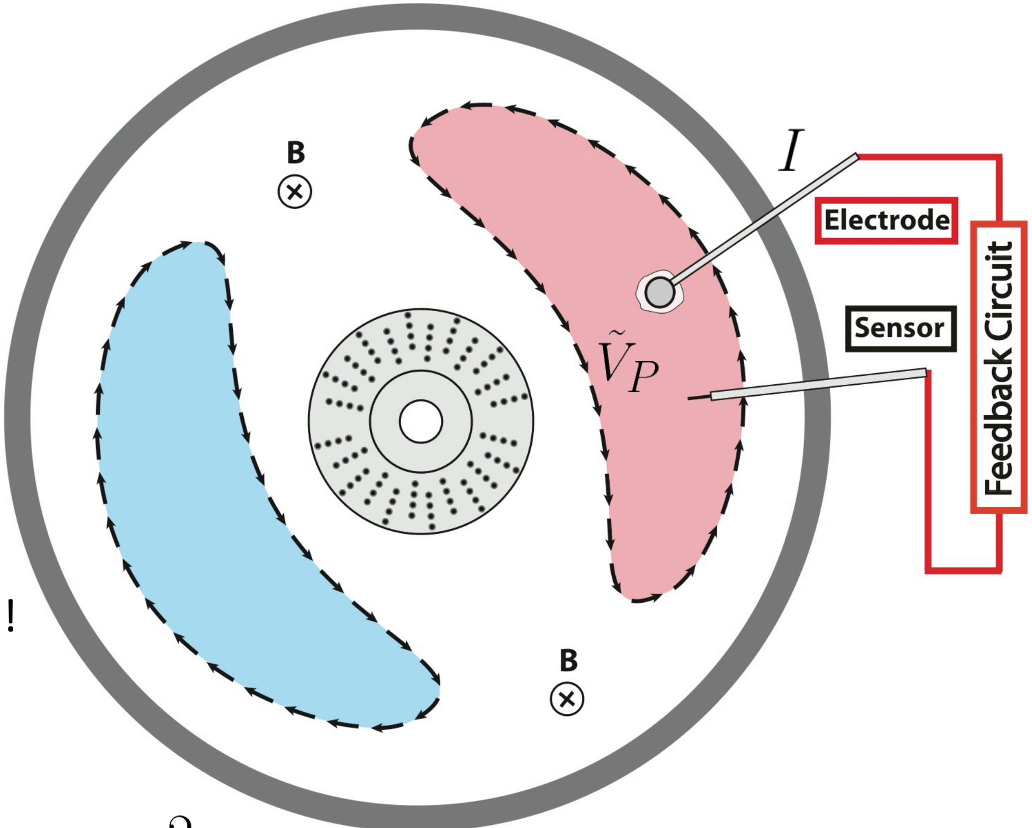
Time Average Power

$$\langle P \rangle \equiv \frac{1}{T}\int_0^T I(t)\tilde{V}_P(t)dt$$

$\langle P \rangle > 0$ **Power into plasma**

$\langle P \rangle < 0$ **Power out of plasma**

Like the magnetosphere!



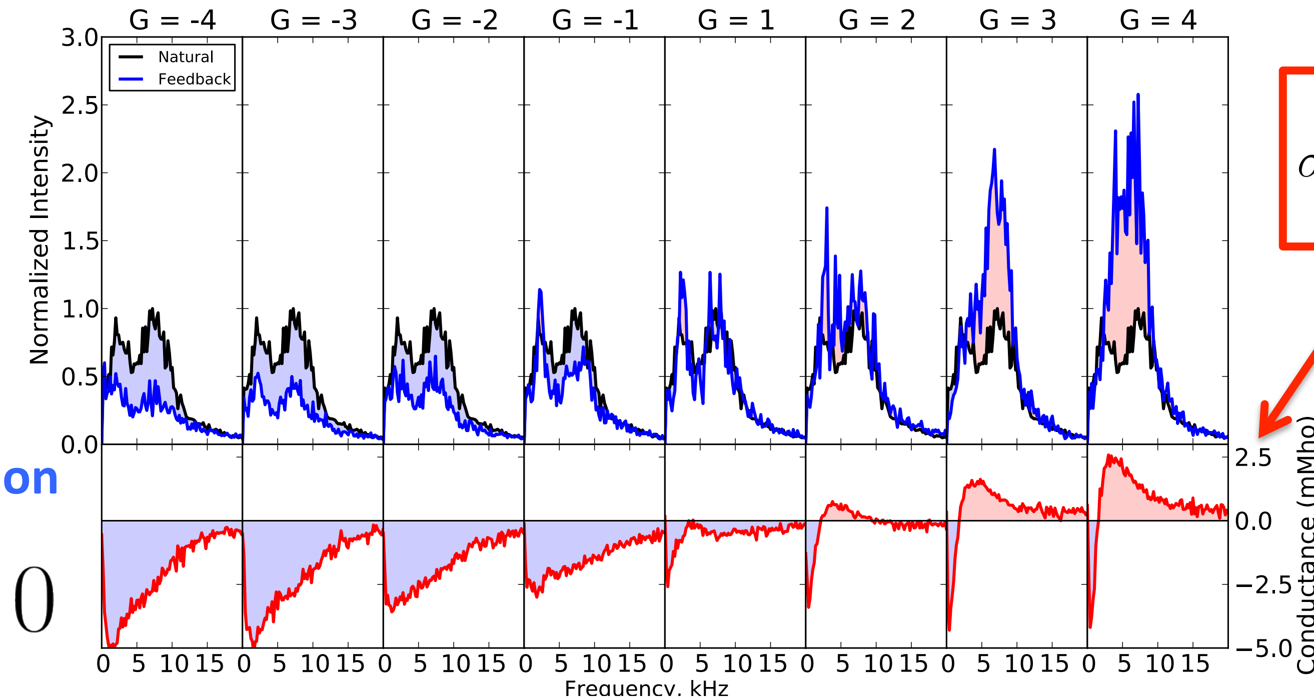
Spectral Power Flow: Conductance

$$\tilde{V}_P(\omega)^* I(\omega) = \tilde{V}_P^*(Y\tilde{V}_P) = Y|V_P|^2$$

Admittance $$Y = \frac{\tilde{V}_P^* I}{|V_P|^2}$$

$$\sigma = Re\left(\frac{\tilde{V_s}^* I}{|\tilde{V}_s|^2}\right)$$ **Conductance**

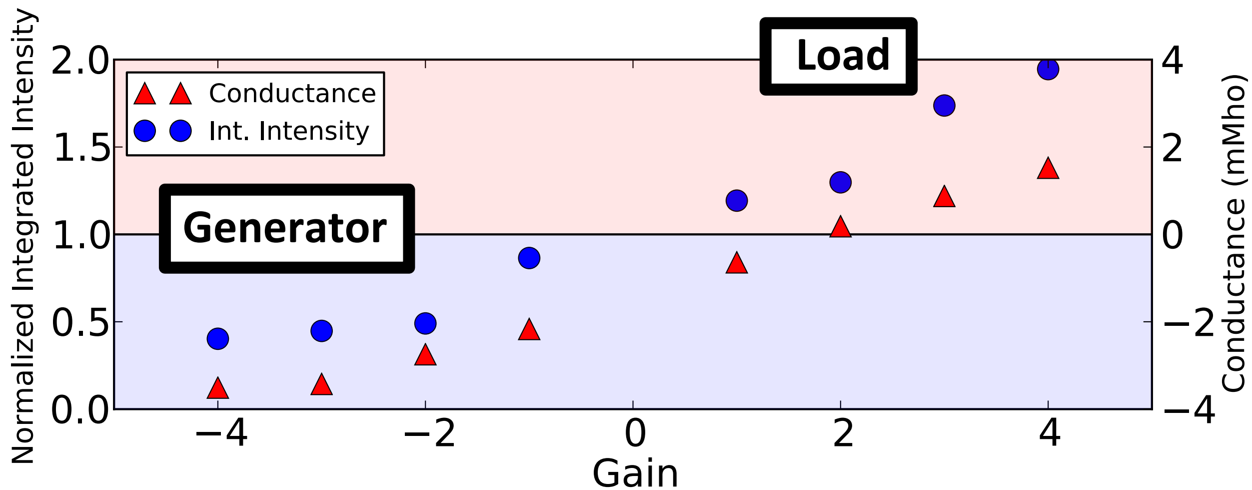
Sign of Conductance Determines Power Flow



$$\sigma = Re\left(\frac{\tilde{V_s}^* I}{|\tilde{V_s}|^2}\right)$$

Suppression where $\sigma < 0$

Amplification where $\sigma > 0$



Band Integrated (1-10 kHz) Spectral Intensity

Band Averaged (1-10 kHz) Conductance

Current-Collection Experiments

1. Plasma responds to coherent current-collection (feedforward)

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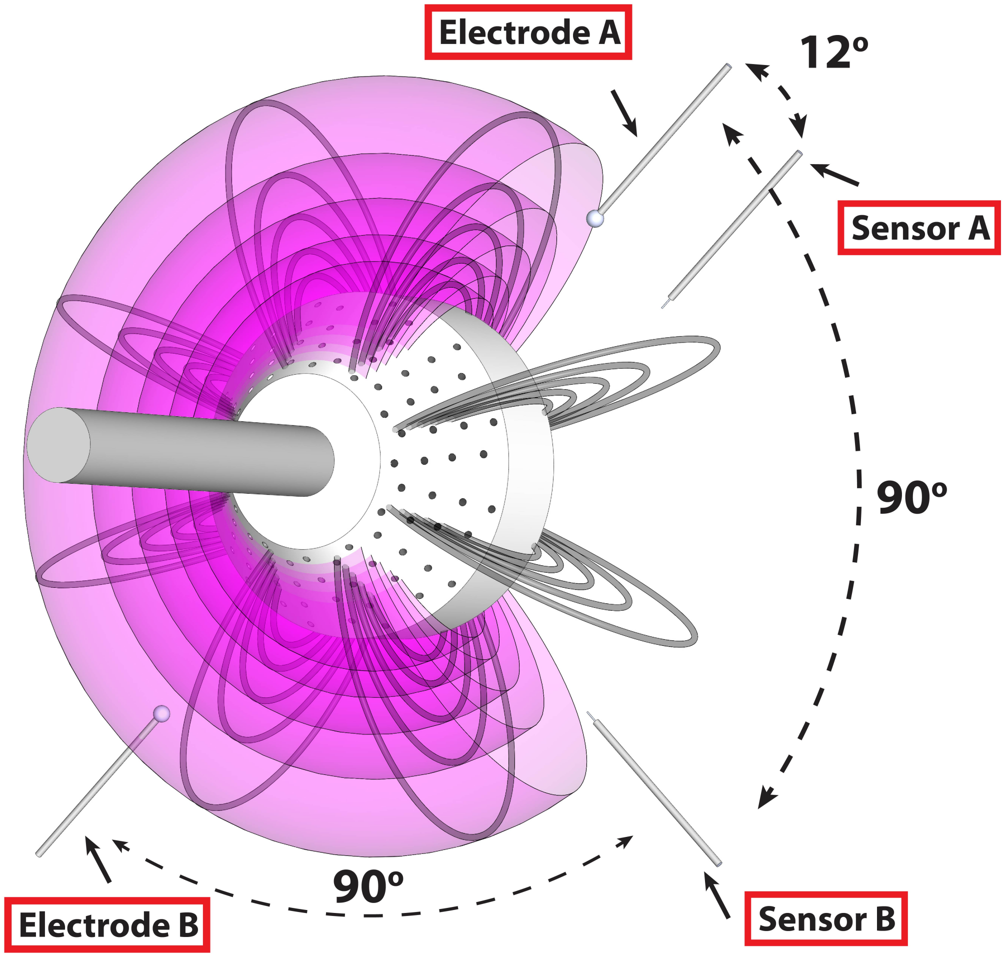
3. Varying the gain and phase of the current relative to the floating potential significantly changes the spectrum.

4. **Varying the separation between the sensor and electrode shows the effect of decorrelation on feedback influence.**

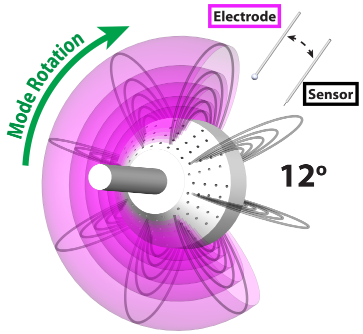
Varying the Separation between the Sensor and Electrode

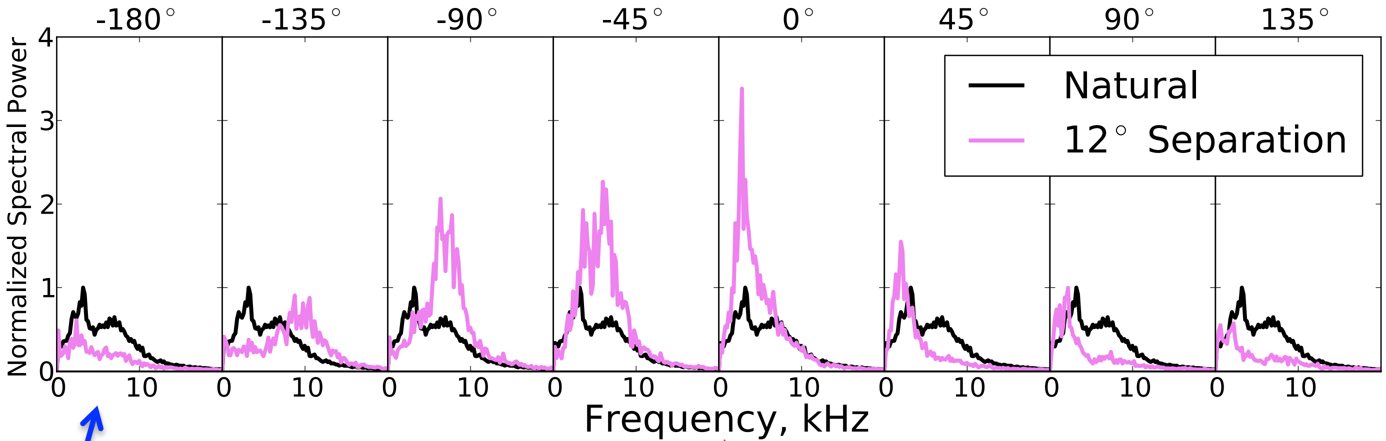


Adjust the toroidal separation

- Reposition sensor/electrodes
- Reverse mode direction

Varying the Separation between the Sensor and Electrode



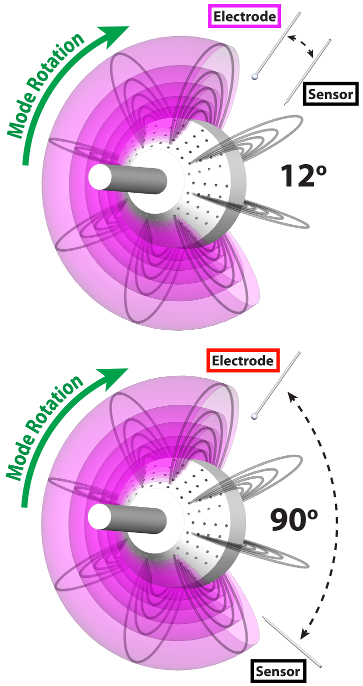


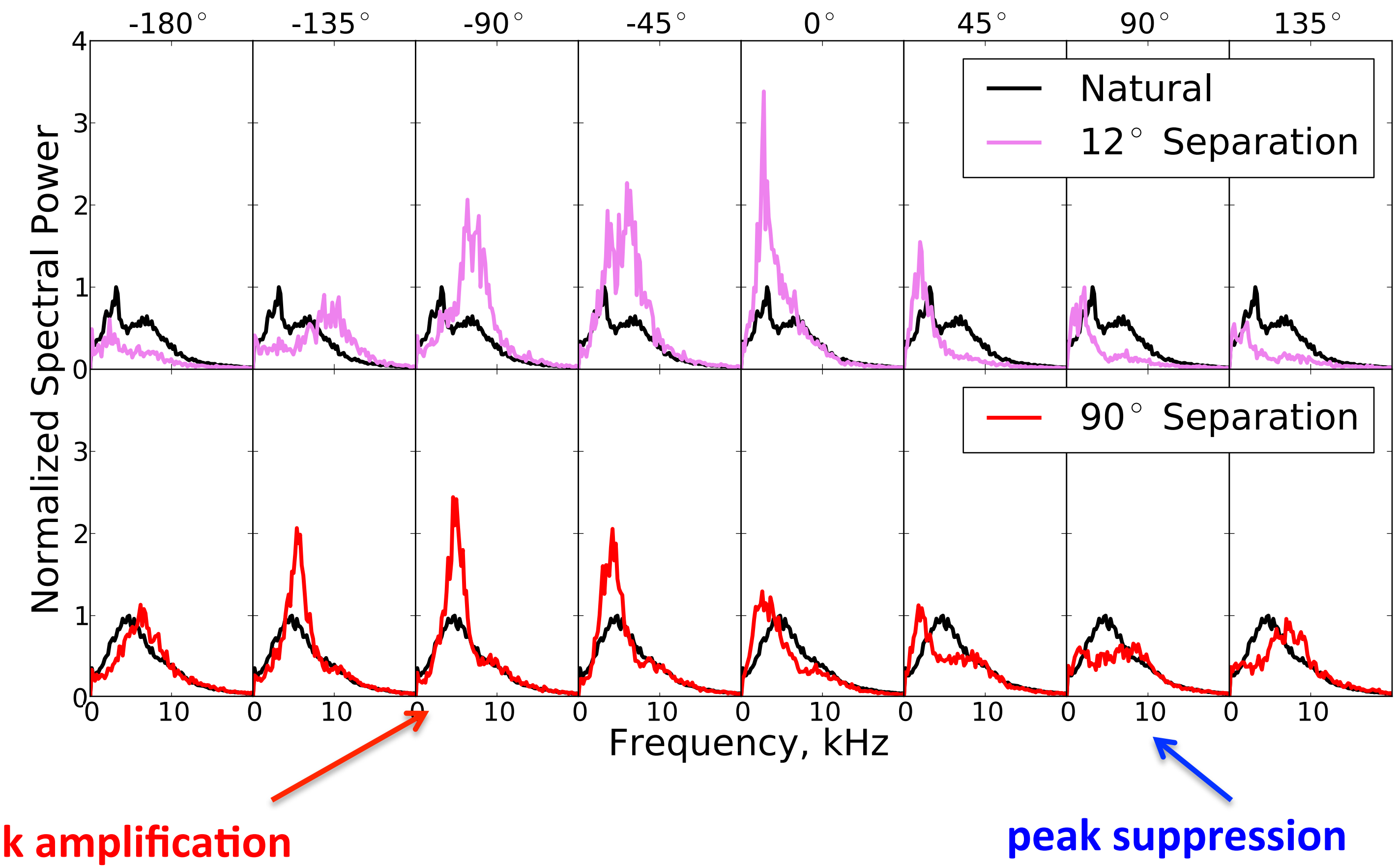
peak suppression

peak amplification

- Fixed gain of 4
- Electrode **leading** the sensor

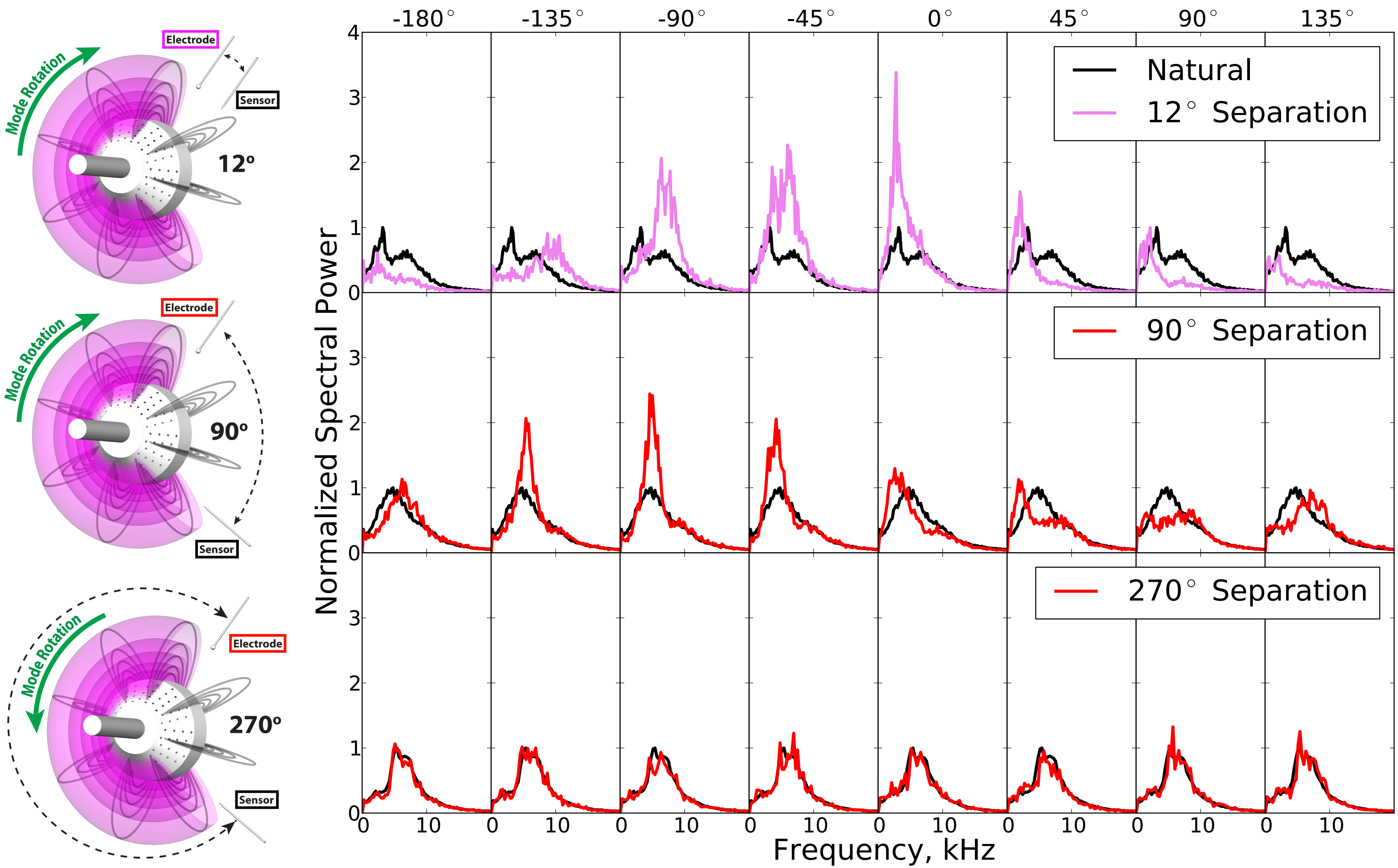
Varying the Separation between the Sensor and Electrode





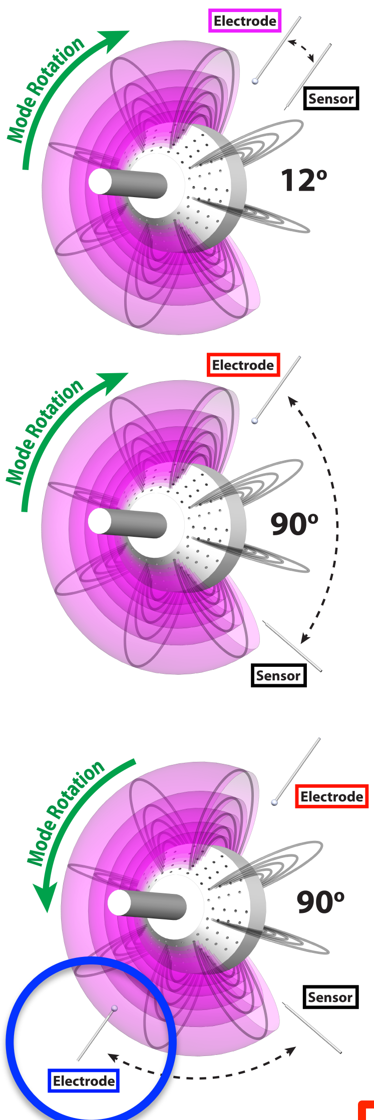
- Shift in phase of peak amplification and suppression
- Reduced response, particularly in suppression

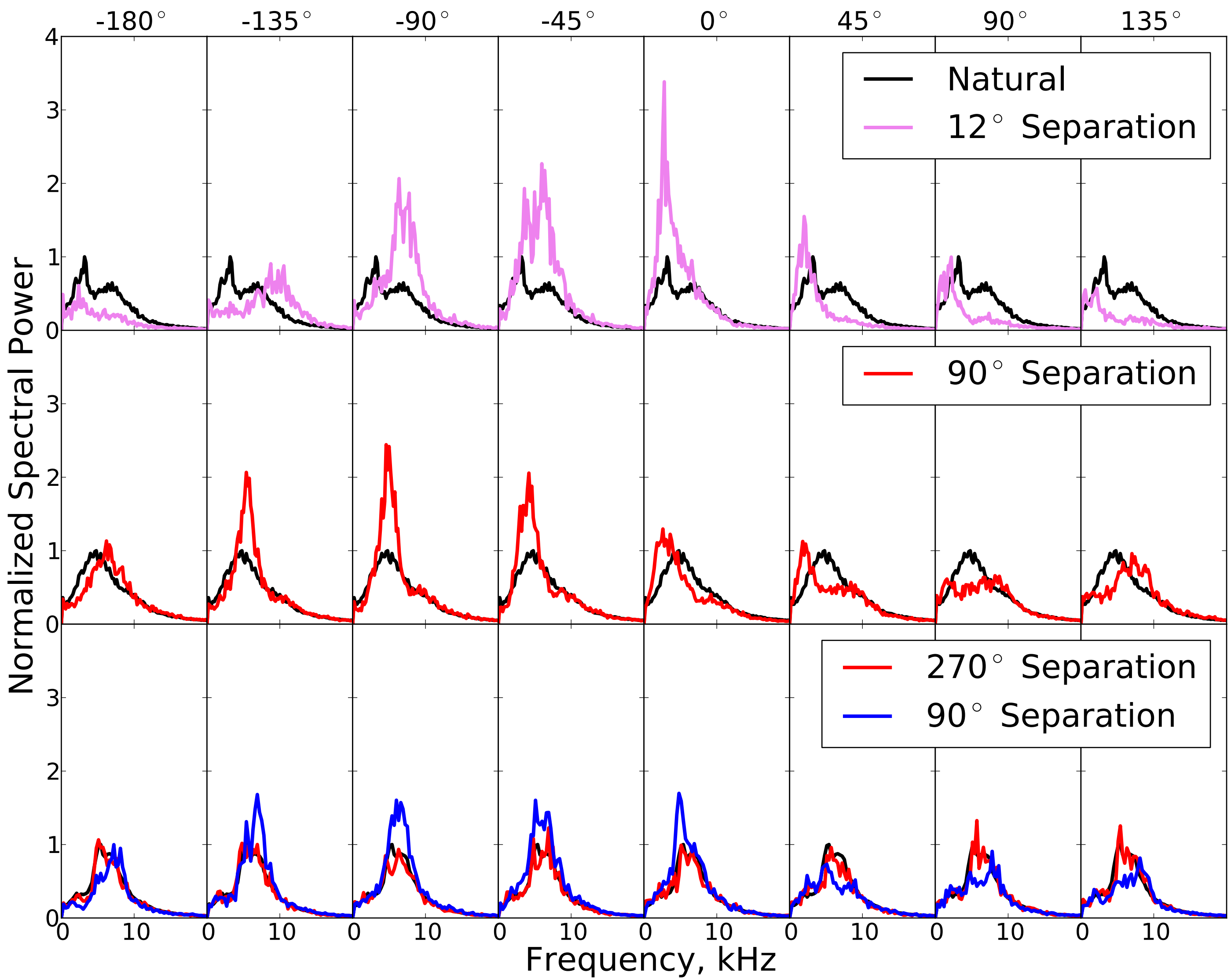
Varying the Separation between the Sensor and Electrode



No response with effective 270˚ separation

Varying the Separation between the Sensor and Electrode





"Upstream" electrode produces similar response

Flux-Tube Averaged Gyro-Fluid Model

$$J_\perp = J_{dia} + J_{inertial}$$

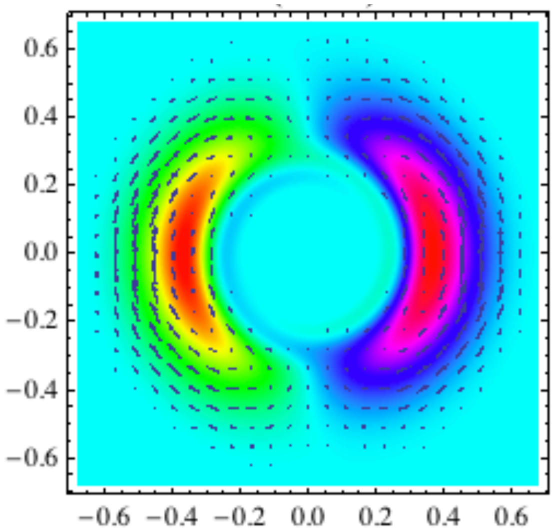
Electron diamagnetic and ion inertial currents

Flux-Tube Average →

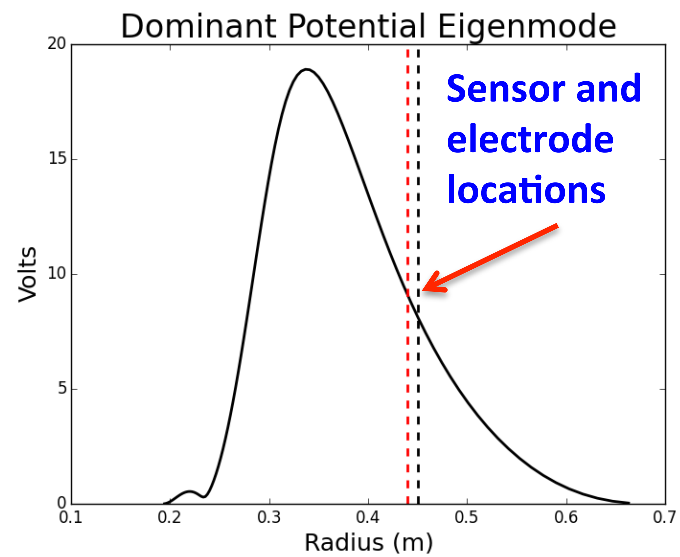
$$\int \frac{ds}{B}(\nabla_\perp \cdot J_\perp) = \begin{cases} -\frac{\hat{b}\cdot J_{||}}{B} & \text{Ionosphere} \\ 0 & \text{No FACs; CTX LDX} \\ I\delta(\vec{x}-\vec{x}_e) & \text{Feedback} \end{cases}$$

- Linearized and flux-tube averaged gyro-fluid model (Drake and Antonsen, 1984) (Ricci, 2006)
- Linear eigenmode, radially broad, low order azimuthal structure
- Profiles consistent with measurements yield mode rotation of 4.5 kHz

$\tilde{V}_p \quad (m=1)$



$$I = (|G|e^{i\varphi} - 1)\frac{\tilde{V}_P}{R_s}$$

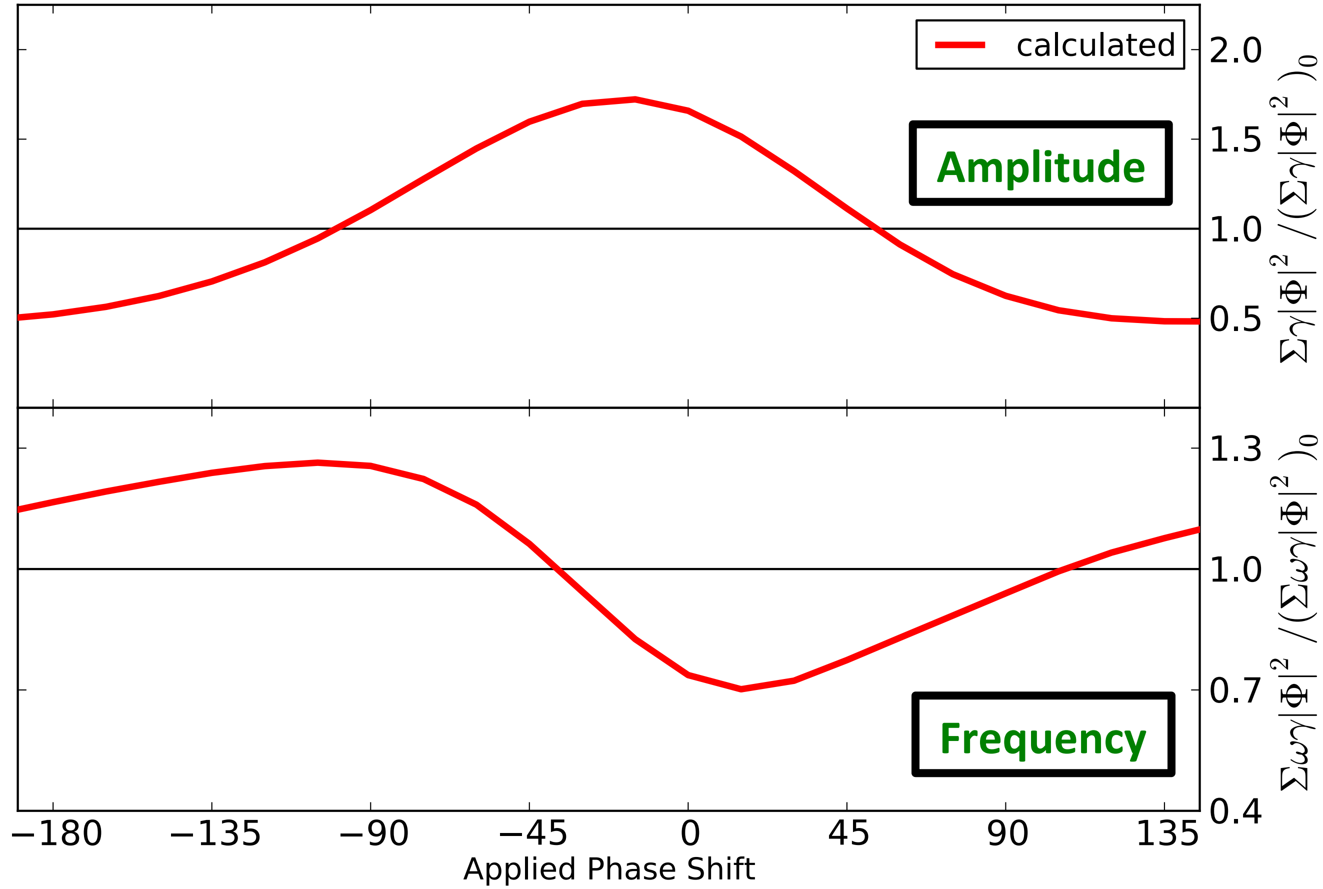


Flux-Tube Averaged Linear Model Shows Some Agreement

Fixed gain of 4
360 Phase Scan

Band Integrated (1-10 kHz) Spectral Intensity

Intensity Weighted Frequency (1-10 kHz)

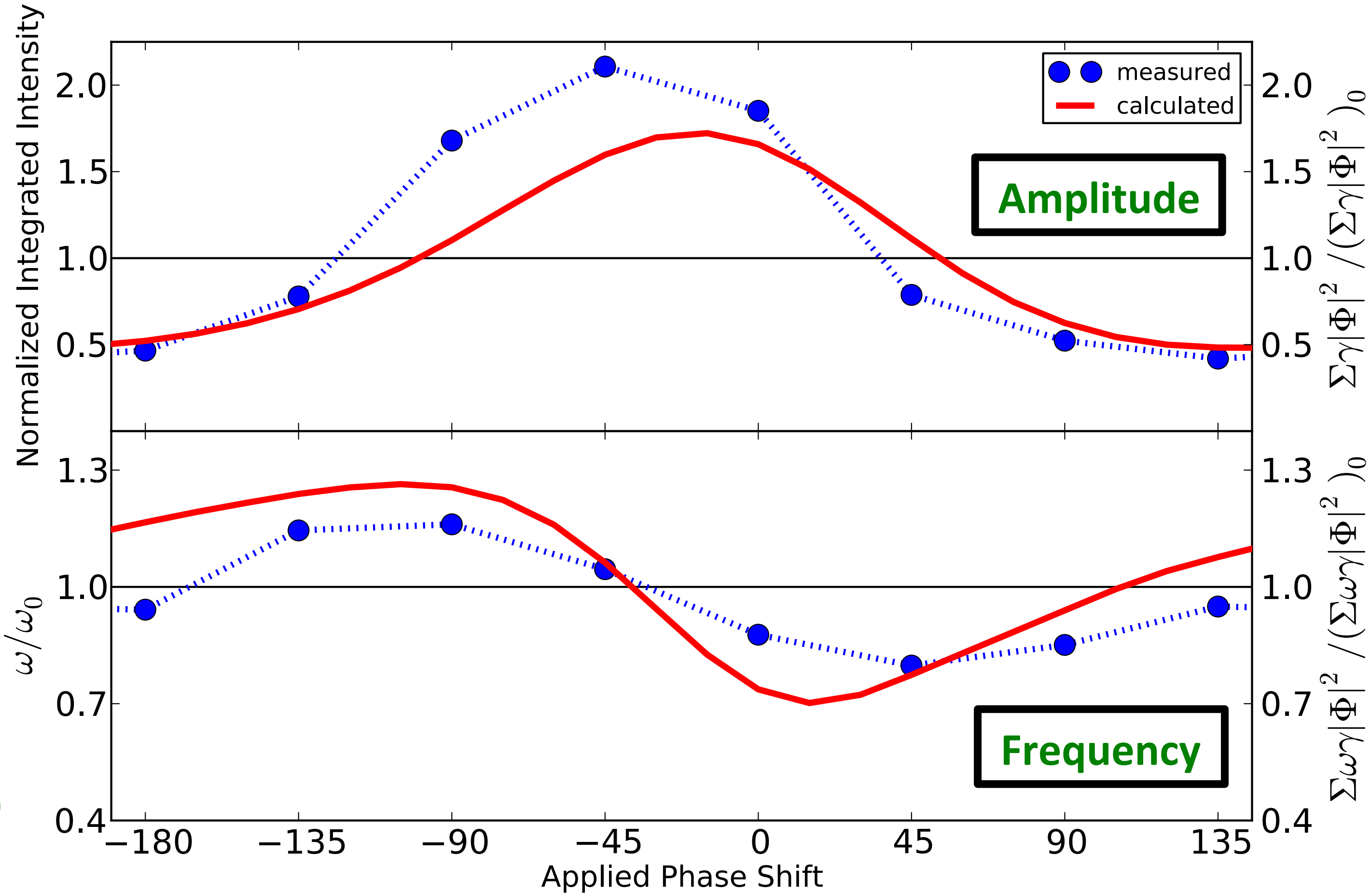


Flux-Tube Averaged Linear Model Shows Some Agreement

Fixed gain of 4
360 Phase Scan

Band Integrated (1-10 kHz) Spectral Intensity

Intensity Weighted Frequency (1-10 kHz)



Ongoing Work

- Current-collection feedback in a nonlinear gyro-fluid simulation.
- Multiple independent feedback systems, and multipoint FPGA controlled feedback.
- Turbulence control on LDX with levitated superconducting dipole.

Results and Conclusions

- Broadband current-collection feedback amplifies or suppresses the interchange-turbulence.
- Current-collection feedback is localized and in the direction of mode rotation.
- Depending on phase, feedback is a generator or a load, either injecting or extracting power from the fluctuations.
- A linear flux-tube averaged gyro-fluid model including a point current source shows some agreement with experiment.

Thanks

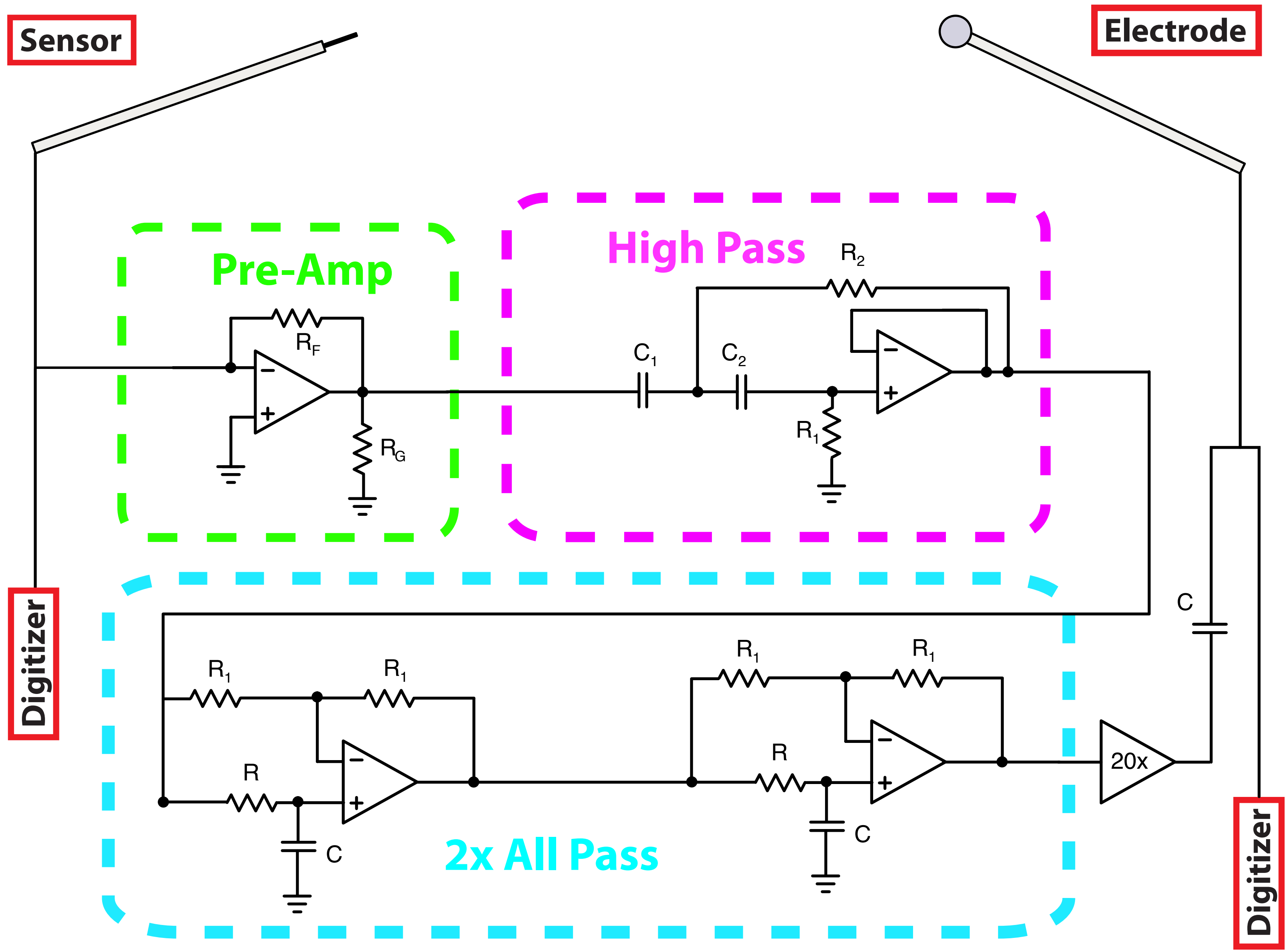
Thanks to the help of many contributors:

Michael Mauel, Jay Kesner, Darren Garnier, Matthew Worstell, Matthew Stiles Davis, Kristina Lynch, Abed Balbaky

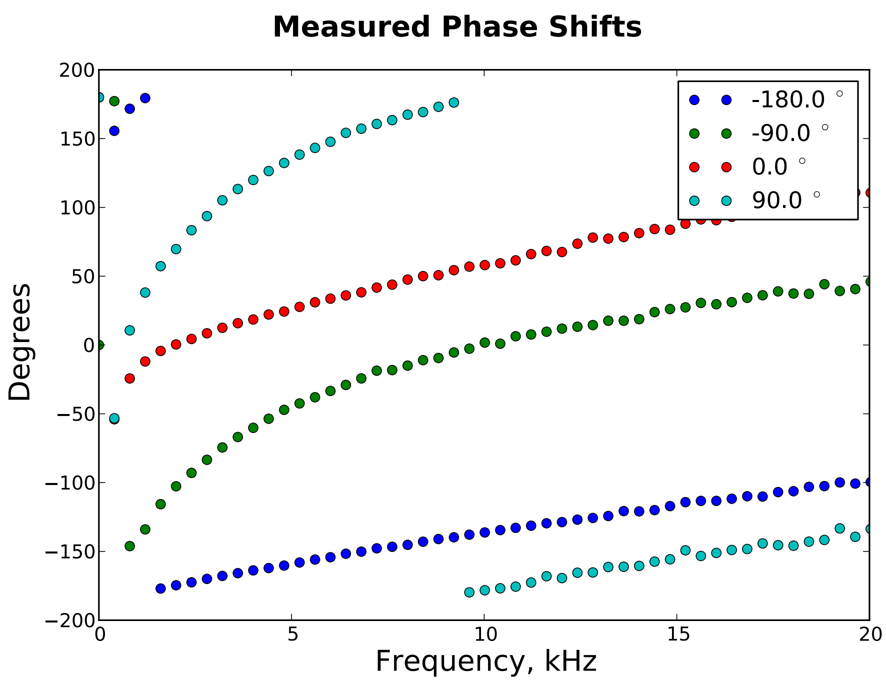
Extra Slides

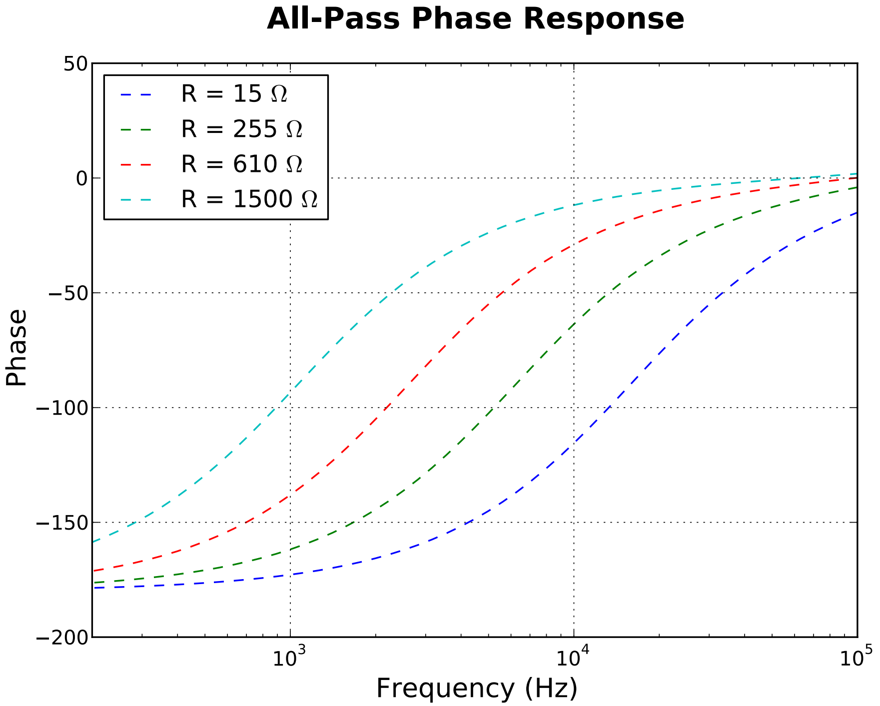
- Phase response and circuit
- Showing “current model”
- Showing full gyro-fluid model
- Experiments with parallel currents

Phase Shifting Circuit



Phase Shifting Circuit



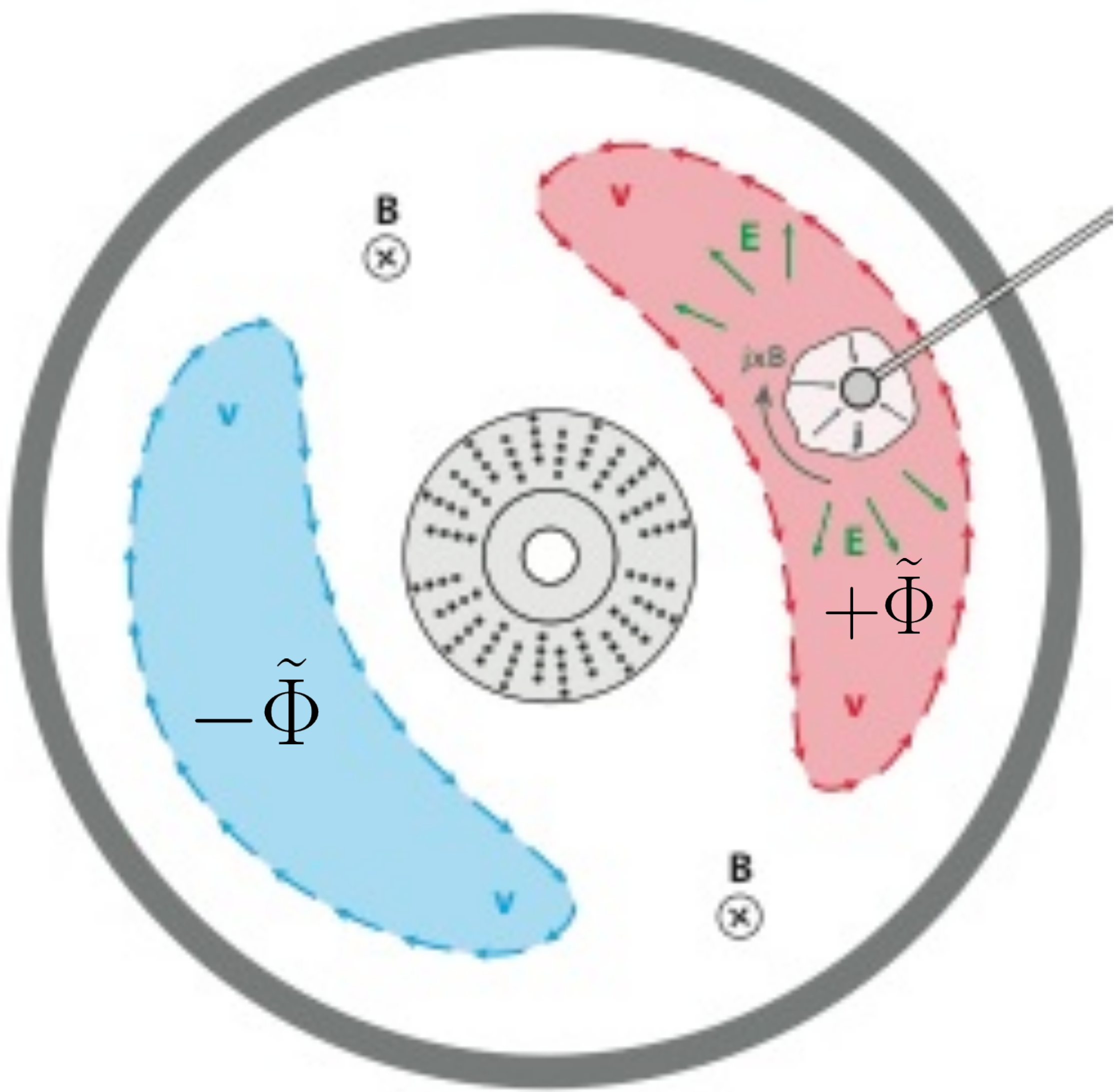


Defining Current-Collection Feedback

$$\rho\frac{\partial\vec{v}}{\partial t} = \vec{j}\times\vec{B} - \nabla$$

$$\vec{v} \approx \frac{\vec{E}\times\vec{B}}{B^2}$$

$$\frac{\rho}{B^2}\frac{\partial E}{\partial t} = j$$



Defining Current and Power

$$\tilde{V}_S \approx \tilde{V}_P$$

$$\tilde{V}_A = G\tilde{V}_S \approx |G|e^{i\varphi}\tilde{V}_P$$

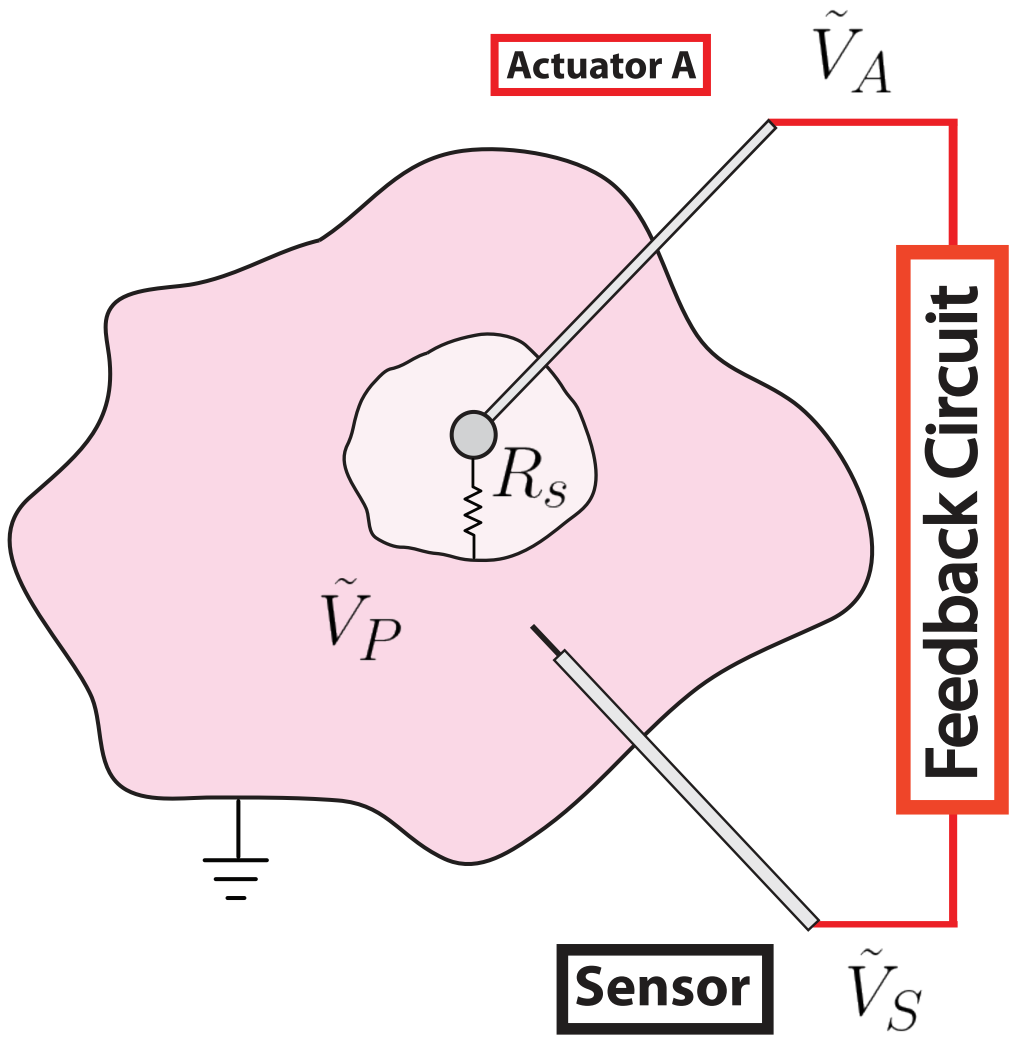
$$I = \frac{\tilde{V}_A - \tilde{V}_P}{R_s}$$

$$\approx \left(|G|e^{i\varphi} - 1\right)\frac{\tilde{V}_P}{R_s}$$

$$\tilde{P}_A = I\tilde{V}_A$$

$$\tilde{P}_s = I(\tilde{V}_A - \tilde{V}_P)$$

$$\tilde{P}_P = I\tilde{V}_P$$



Time Averaged Power in Frequency

$$P(t) = I(t)V(t)$$ Instantaneous Power

$$\langle P(t) \rangle = \langle I(t)V(t) \rangle = \frac{1}{T}\int_0^T I(t)V(t)dt$$ Time Averaged Power (0 Hz)

$$FFT\big(P(t)\big) = I(\omega) * V(\omega) = \int_{-\infty}^{+\infty} I(\omega^{'})V(\omega - \omega^{'})d\omega^{'}$$

Time averaged power is the convolution with omega = 0

$$FFT\big(P(t)\big)[\omega = 0] = \int_{-\infty}^{+\infty} I(\omega^{'})V(-\omega^{'})d\omega^{'}))) = \langle P(t) \rangle$$ (0 Hz)

$$I(\omega)V(-\omega) = \big(Y(\omega)V(\omega)\big)V^*(\omega)$$

$$Y(\omega) = \frac{IV^*}{|V|^2}$$ → $$\langle P(t) \rangle = \int_{-\infty}^{+\infty} Y(\omega)|V(\omega)|^2 d\omega$$

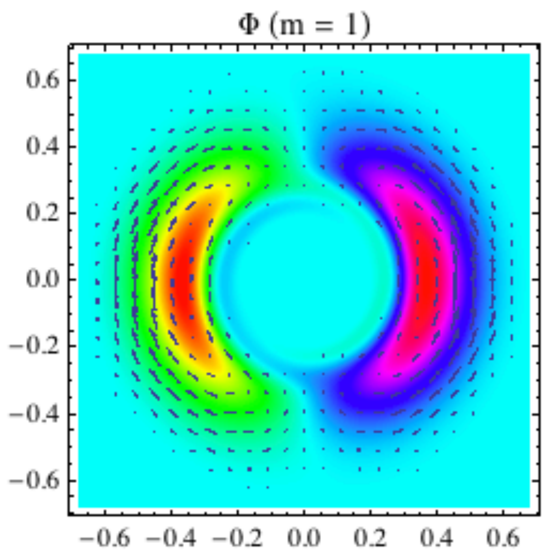
Flux-Tube Averaged Gyro-Fluid Model

diamagnetic, inertial, warm electrons

$$J_\perp = \frac{1}{B^2} B \times \nabla p_e + \frac{nM_i}{B^2} B \times \frac{dV_E}{dt} \qquad v_e = \frac{E \times B}{B^2} - \frac{B \times \nabla p_e}{enB^2}$$

Flux-Tube Average

$$\left\{ \begin{array}{c} \nabla \cdot J_\perp = 0 \qquad \dfrac{\partial n}{\partial t} + \nabla \cdot n v_e = 0 \\ \dfrac{\partial p_e}{\partial t} + \nabla \cdot (p_e V_E) + (\gamma - 1) p_e \nabla \cdot V_E = \gamma \dfrac{2}{\omega_{ci}} \kappa \dfrac{\partial}{\partial \varphi} (p_e C_s^2) \end{array} \right\}$$

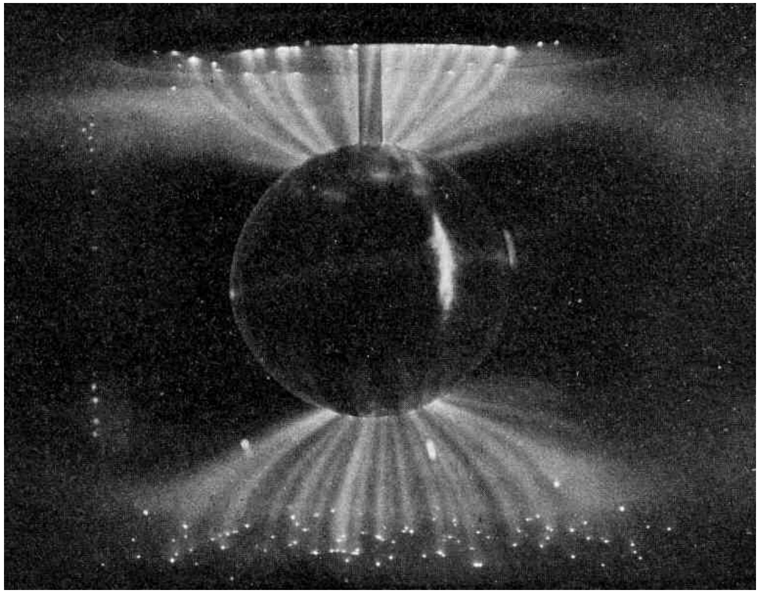


- Linear eigenmode, radially broad, low order toroidal structure
- Eigenvalue is mode growth rate and rotation

$$\nabla \cdot J_{FB} = I \delta(\psi, \varphi) \qquad I = (|G| e^{i\varphi} - 1) \frac{\tilde{V}_P}{R_s}$$

J.F. Drake and T.M. Antonsen Jr, Physics of Fluids 27, 898 (1984).

Experiments with parallel currents



Kristian Birkeland, **1913**

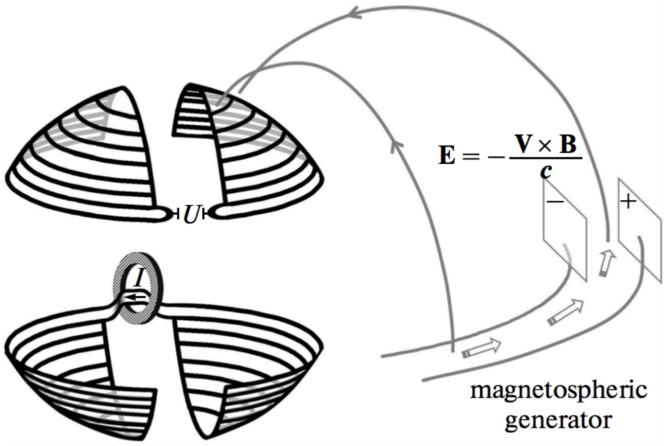


Fig. 3. Schematic location of plates on the dipole frame for measuring the potential and current between the dawn and dusk sides. The scheme of the magnetospheric generator is also shown on the dusk side.

I.F. Shaikhislamov, **2014**, Vol. 52, No. 4, pp. 296–306, Cosmic Research