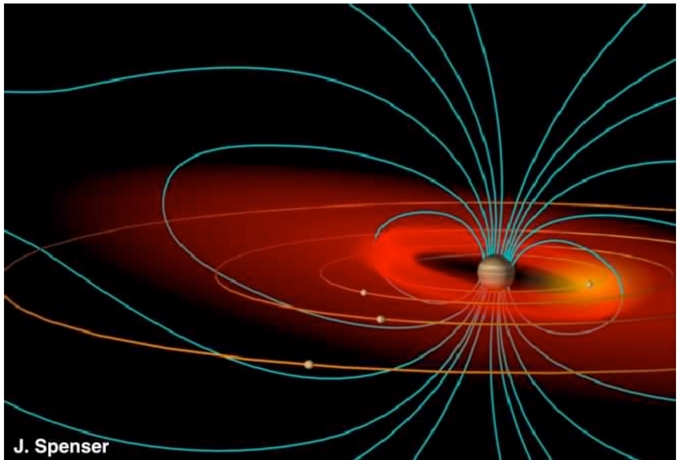
Imaging Equilibrium and Perturbed Flow of Dipole-Confined Plasmas

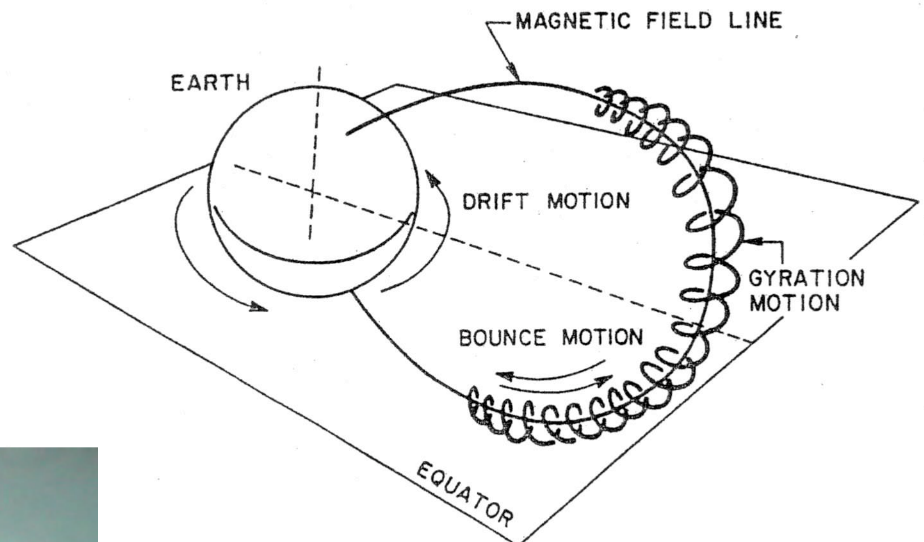
Brian A. Grierson, M. W. Worstell, M.E. Mauel
Collisionless Terella Experiment
Columbia University
Plasma Physics Laboratory

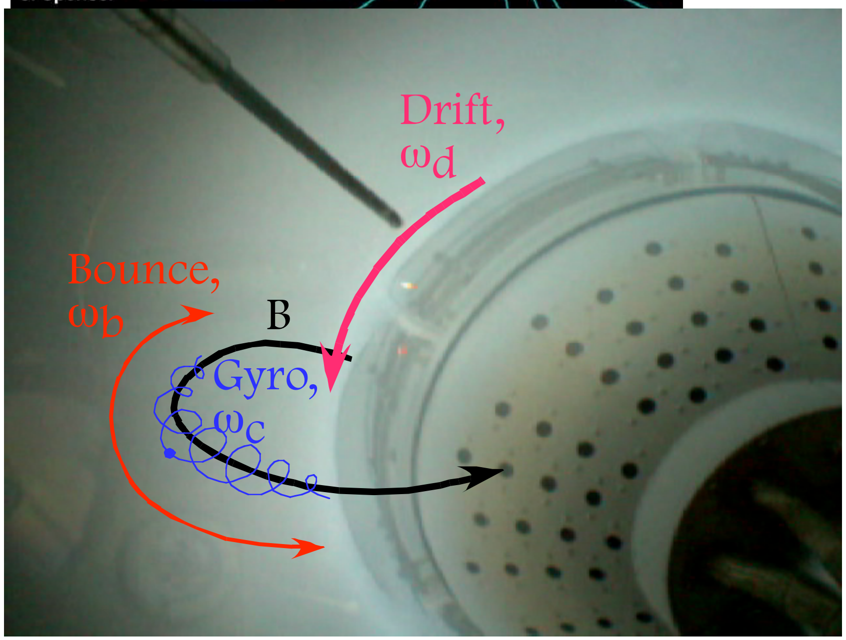
Abstract

Plasma confined in magnetospheres and laboratory terrella can be characterized by the loss current to the magnetic poles. In the Collisionless Terrella Experiment (CTX) the polar current is imaged at high speed with an array of 70 gridded particle detectors. The detectors measure electron and/or ion currents as a function of the particle's field-aligned energy and of the polar longitude and latitude. This poster will present new techniques to resolve the equilibrium and perturbed plasma structure from analysis of the detected polar currents. Electrostatic fields are used to modify plasma flow, and fast gas injection is used to perturb the plasma with a neutral gas. The interaction of the electric fields neutral population with the hot-electron interchange motion has been observed.

Magnetospheric Physics

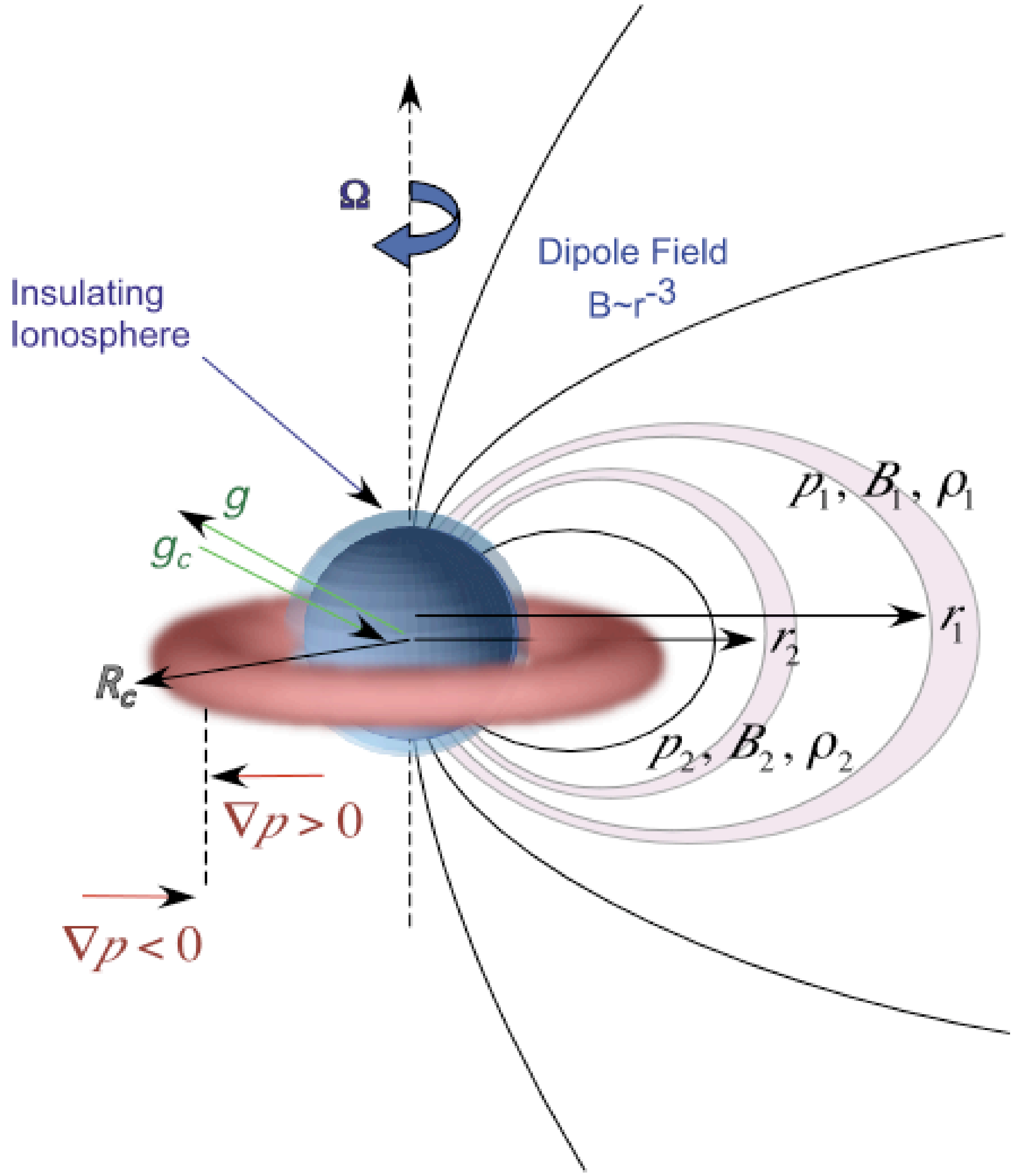






Charged particles in a Dipole Magnetic Field have three primary motions: Gyro, Bounce and Drift, each with their own frequency $(\omega_d << \omega_b << \omega_c)$. The Drift frequency arises from the magnetic gradient and curvature. The Gyro motion conserves μ and the bounce motion conserves J.

Interchange In a Dipole



Interchange of flux tubes in the Earth's magnetosphere is driven by gravity, pressure forces, magnetic gradients, curvature, and centrifugal forces.

Adiabaticity requires

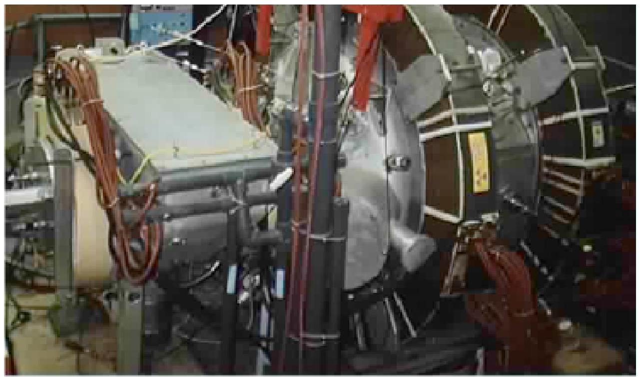
$$pV^{\gamma} = cnst, \ \gamma = 5/3$$

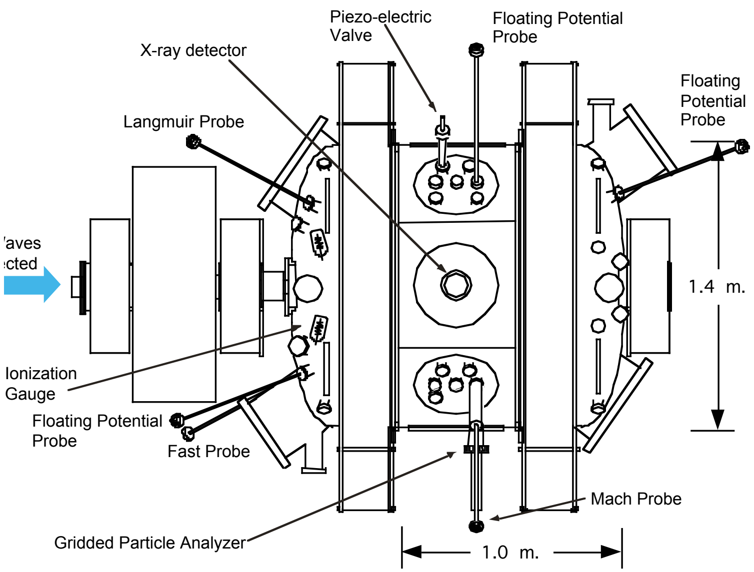
$$pr^{4\gamma} = cnst \rightarrow p \propto r^{-20/3}$$

Invariants

$$\mu = \frac{mv_{\perp}^2}{2B} \text{ and } J = \int v_{II} ds$$

The CTX Device





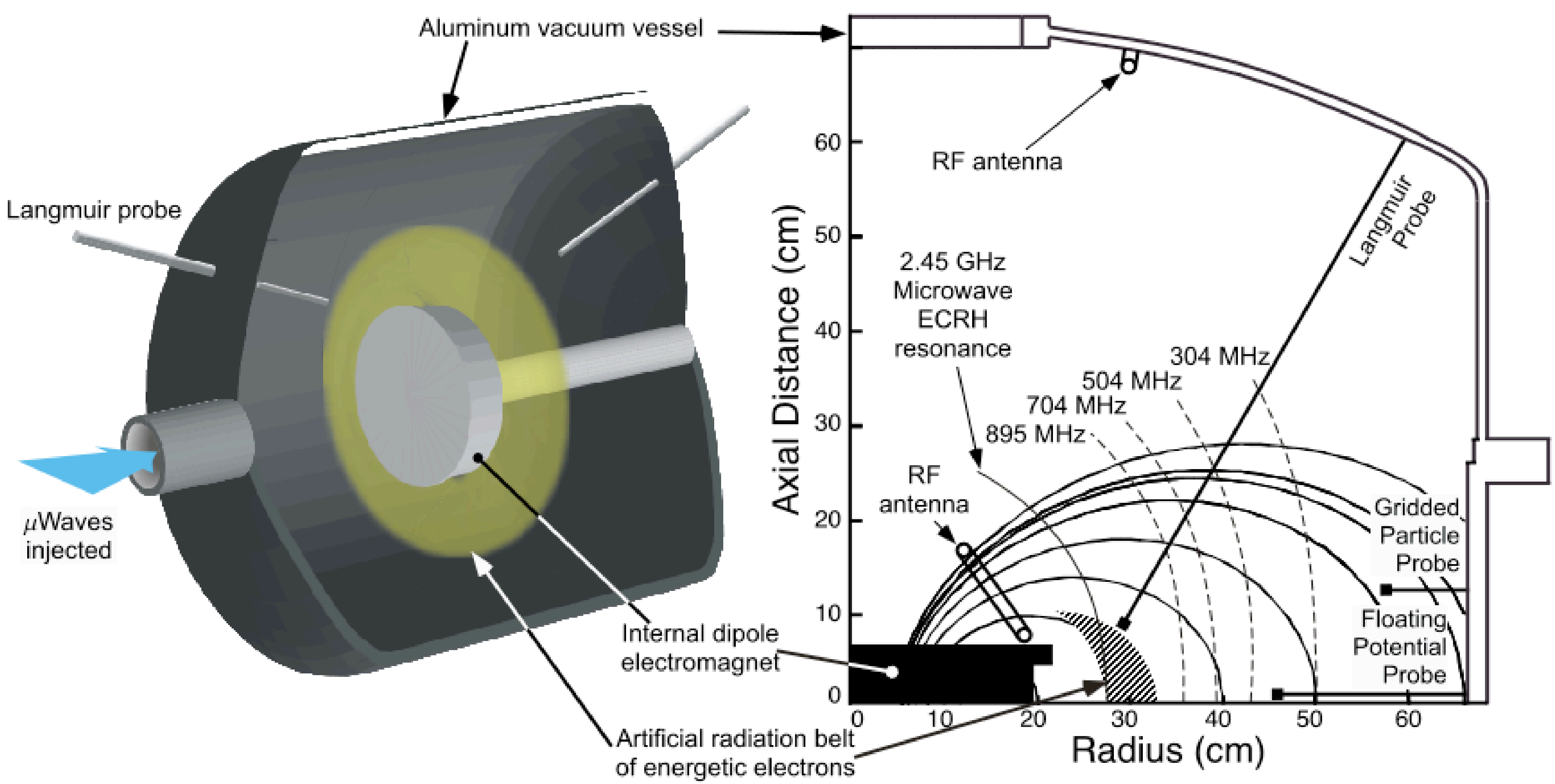
Basic parameters:

Magnetic field at equator, B_T	2 kG
Terrella radius, R_T	20 cm
Energetic electron energy, E_h	1-20 keV
Radius of peak intensity, L_h	1.5
Energetic electron density, n_h	$0.5 - 1 \times 10^{10}$ cm^{-3}
Total plasma density, n	$1 - 2 \times 10^{10}$ cm^{-3}

Dynamical parameters:

Cyclotron frequency, $\omega_c/2\pi$	2 GHz
Bounce frequency, $\omega_b/2\pi$	150 MHz
Drift frequency, $\omega_d/2\pi$	0.4 MHz

The Magnetic Field and ECRH

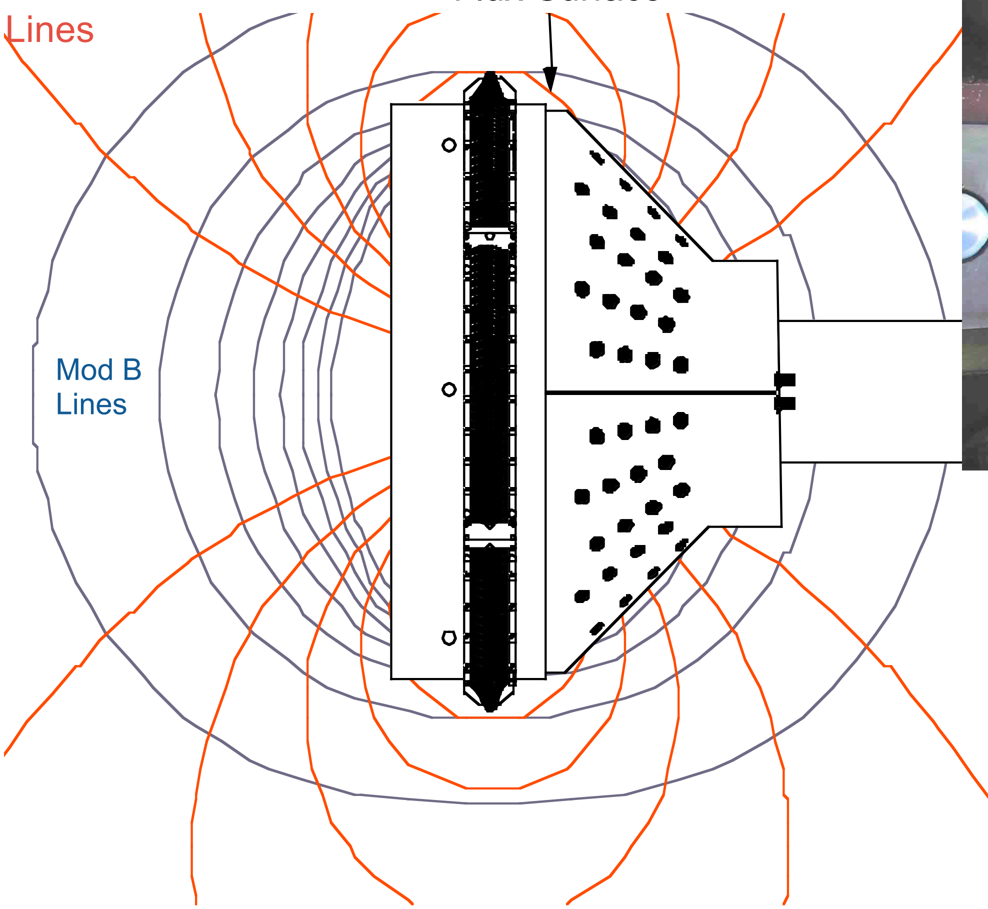


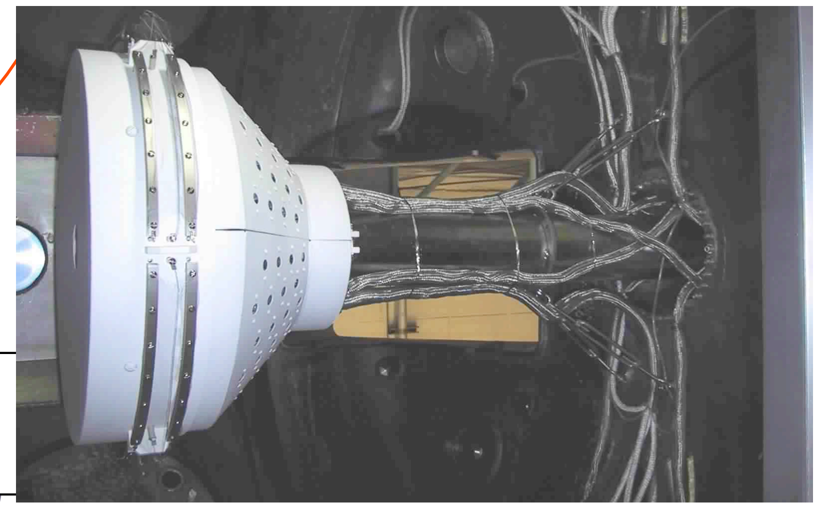
The Polar Imager Array

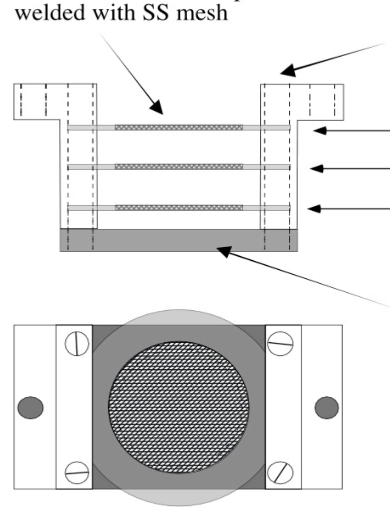
B_{max}=cnst ~2kG at Imager

96 Gridded Energy Analyzers

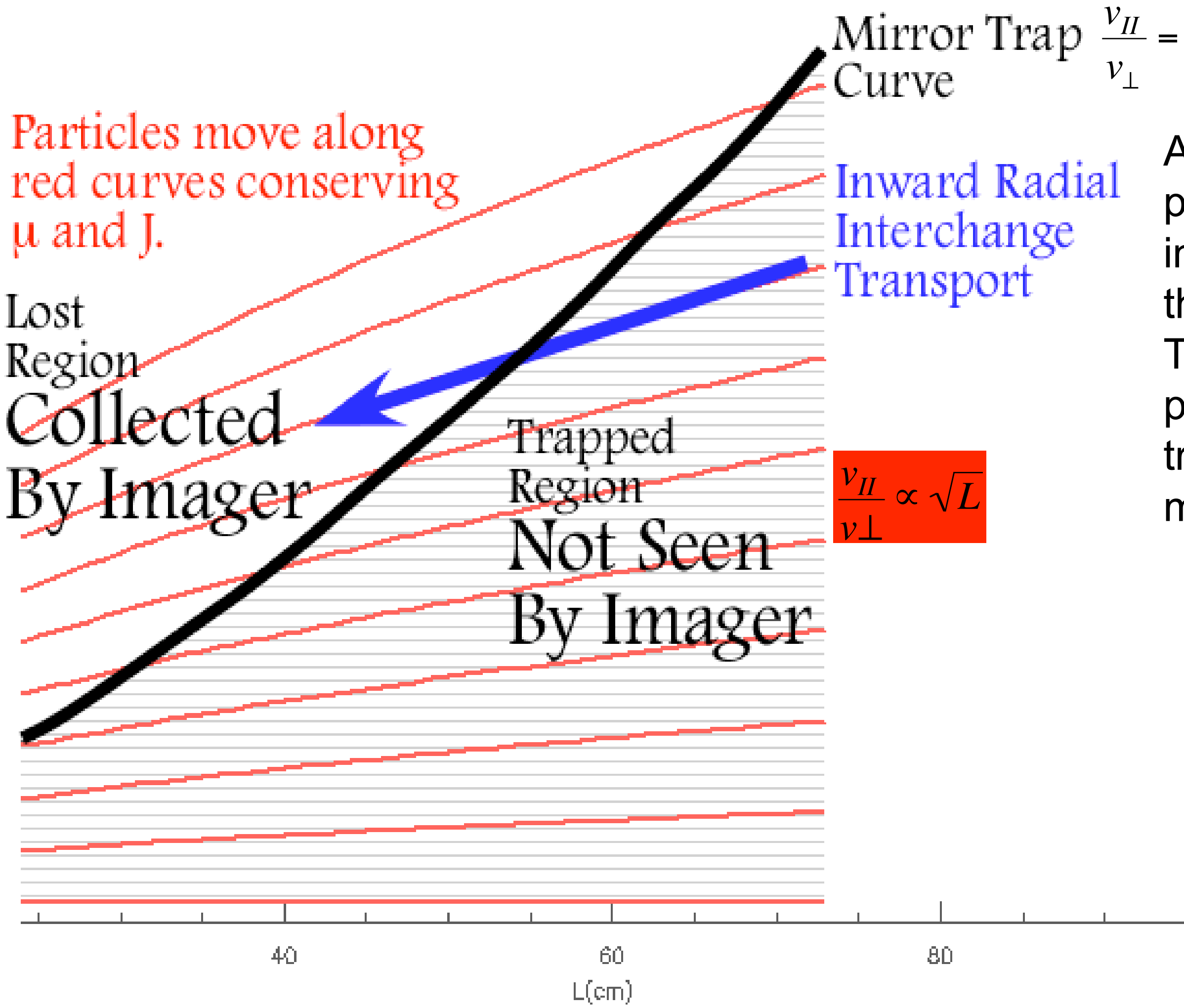
•Digitized at 1MHz provides fast imaging of current collected at the pole.







NEW INSIGHT: The Loss Cone



$$\frac{v_{II}}{v_\perp} = \sqrt{\frac{B_{max}}{B_{eq}} - 1} = \sqrt{\frac{B_{max}}{B_0} L^3 - 1}$$

As deeply trapped particles are transported inward they move into the loss cone.
Trapped particles are pushed deeper into the trapped region when moving outward.

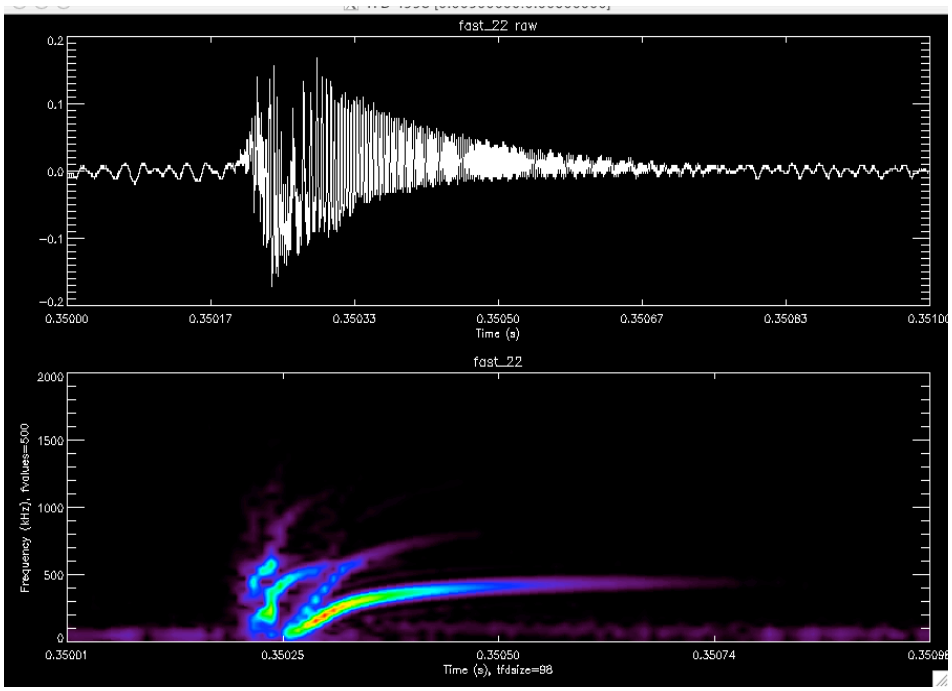
$$J \propto v_{II} L$$

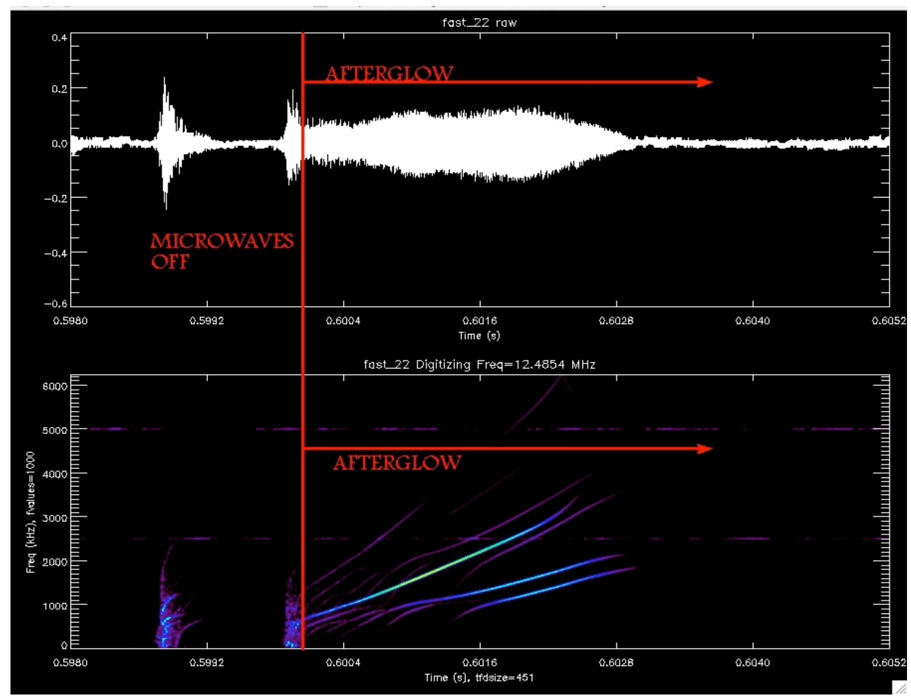
$$\mu = \frac{m_e v_\perp^2}{2B_{eq}} \qquad B_{eq} = B_0 / L^3$$

$$\frac{v_{II}}{v_\perp} = J\sqrt{\frac{m_e L}{2\mu B_0}} \propto \sqrt{L}$$

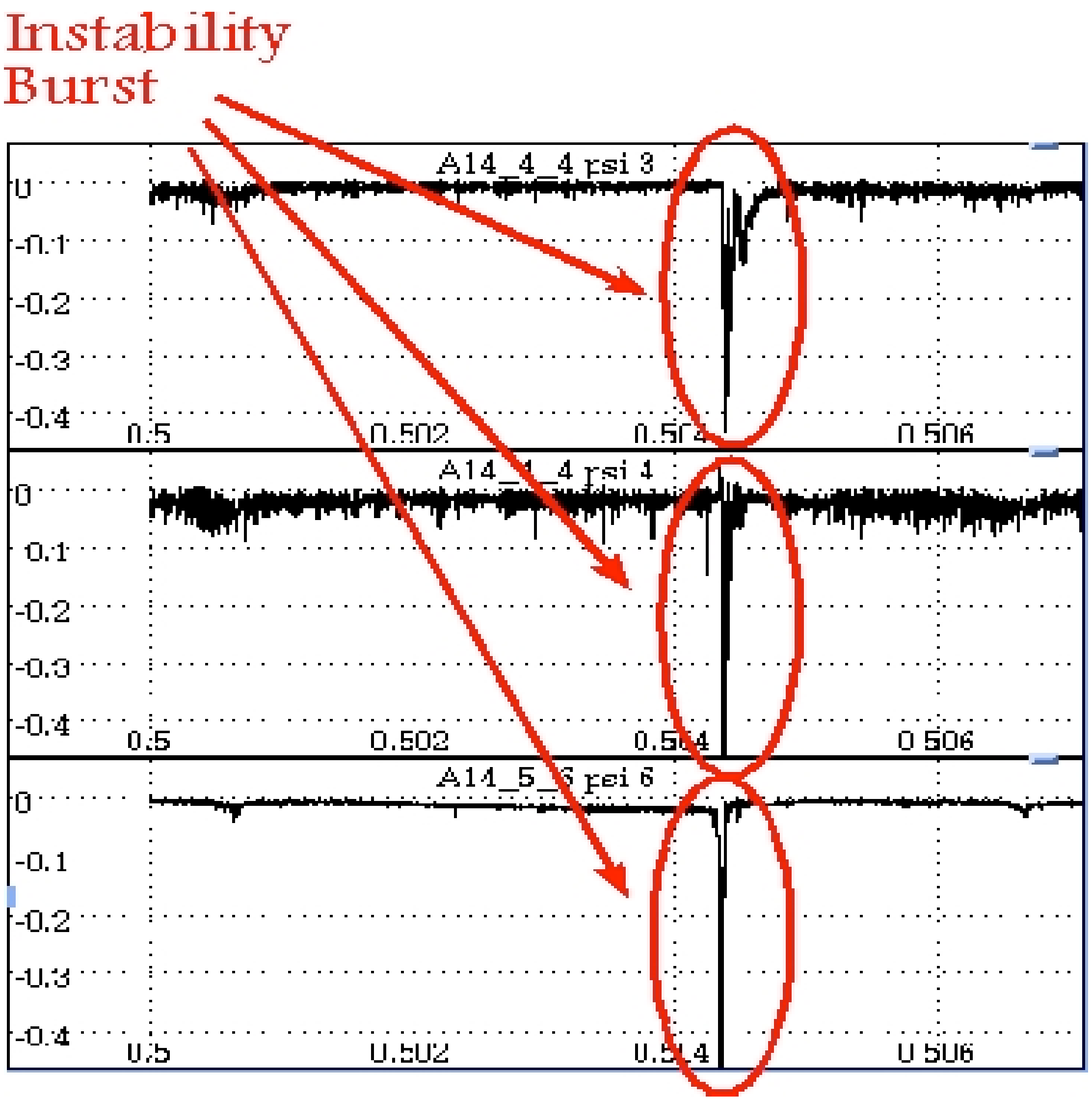
Hot Electron Interchange Instability (HEI)

- The HEI instability is driven by a population of energetic, deeply trapped particles with a steep outward pressure profile produced by ECRH.
- A wave-particle resonance occurs with a precessional grad(B) drift of hot electrons.
- Gives the instability a real frequency related to ω_d.





Sample Imager Data



Sample of current collected from 3 different magnetic surfaces.

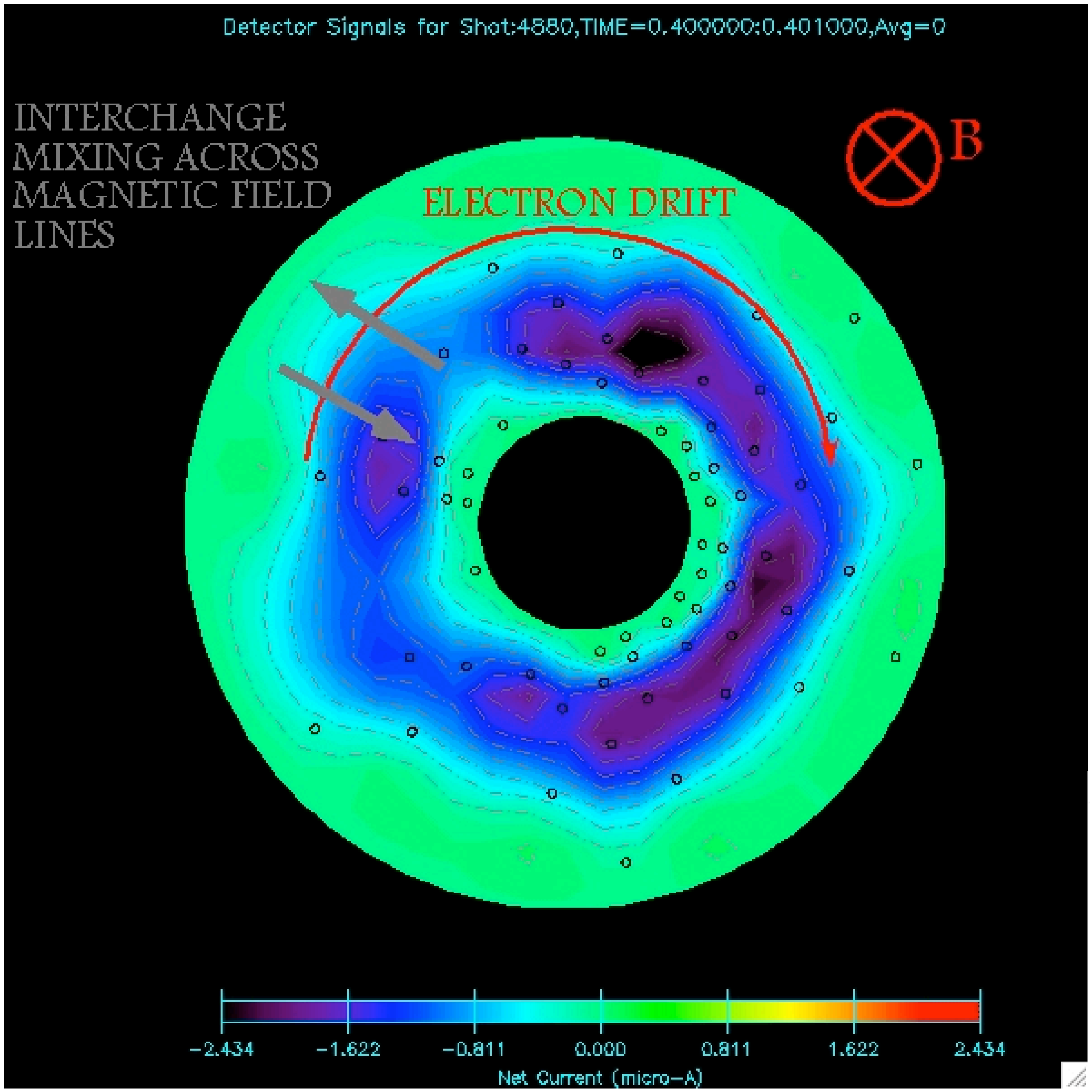
The trigger point for the detectors can be moved to observe different phenomena in the plasma. Different times include: secondary gas puff, afterglow, and heating regimes.

Many detector locations allow numerical interpolation over the entire equatorial cross section with irregularly gridded data points.

Digitized at 1MHz due to bandwidth limitation of amplifiers.

NEW HIGH FREQUENCY AMPLIFIERS IN PRODUCTION!!

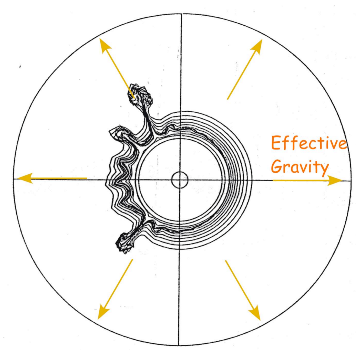
Observation of lost particles



The Polar Imager is used to reconstruct the electron density profile of the particles LOST to the magnetic pole.

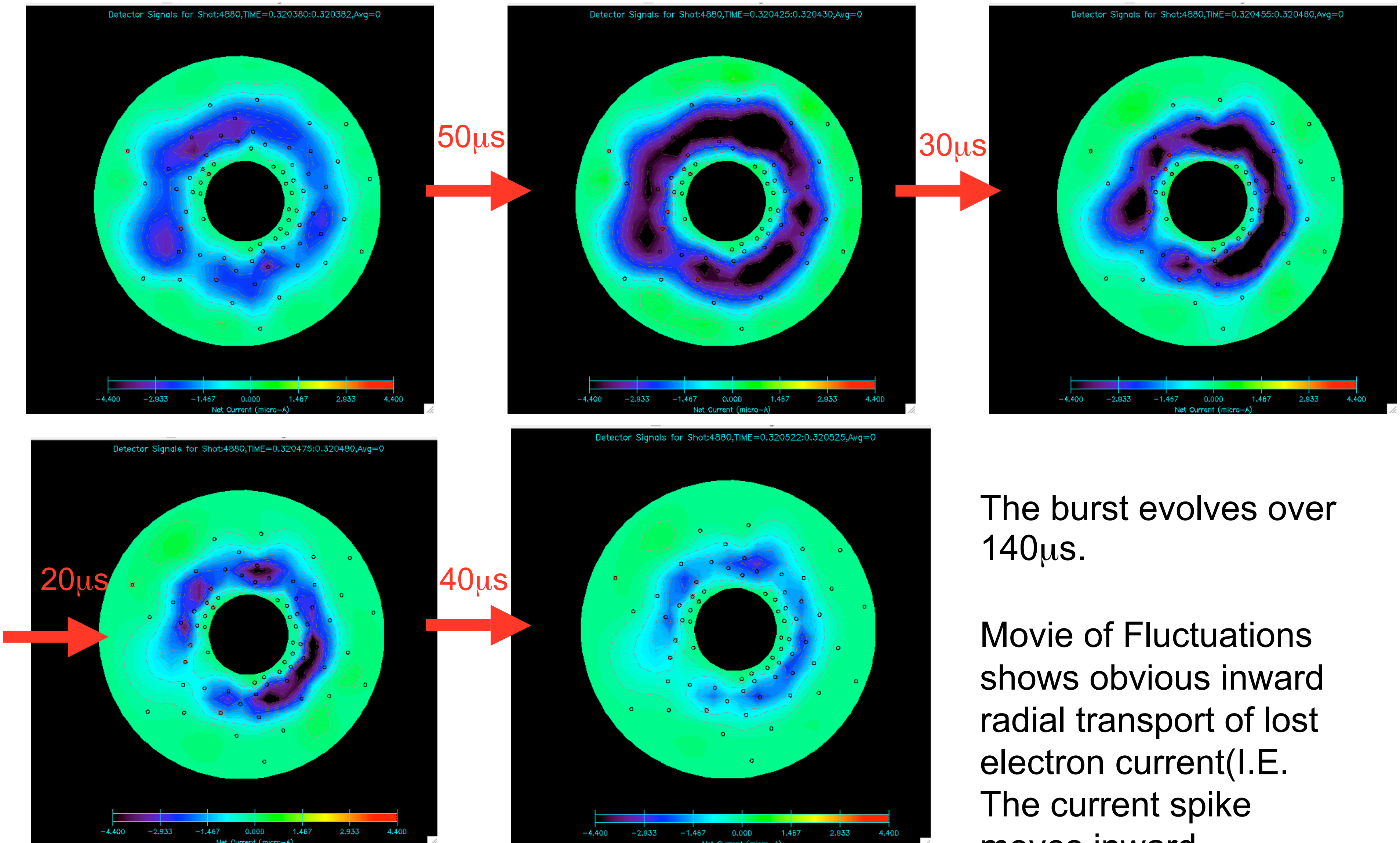
'Snapshot', time average, and fluctuation images can be made.

Movies and animations of the plasma dynamics allow observation of the Particles Lost due to radial interchange motion. Spontaneous Perpendicular Transport.



Both inward and outward transport occurs

Observation of HEI burst



The burst evolves over 140μs.

Movie of Fluctuations shows obvious inward radial transport of lost electron current(I.E. The current spike moves inward.

The Bi-Otrhogonal Decomposition

- The Bi-orthogonal Decomposition is a SVD method to decompose a spatio-temporal signal into orthogonal spatial and temporal functions.
- CTX's Polar Imager Array provides 96 spatial locations, and the temporal signal is digitized at 1 MHz.

$$Y_{ij} = y(x_j, t_i) = \sum_{k=1}^{K} A_k \varphi_k(x_j) \psi_k(t_i)$$

The scalar y(x,t) is the collected polar current.

$$\sum_{i=1}^{N} \psi_k(t_i) \psi_l(t_i) = \sum_{j=1}^{96} \varphi_k(x_j) \varphi_l(x_j) = \delta_{ij}$$

Orthogonality Condition.
N is the number of time steps sampled.

$$S_x \varphi_k = A_k^2 \varphi_k \text{ where } S_x = Y^T Y \quad (96 \text{ X } 96)$$

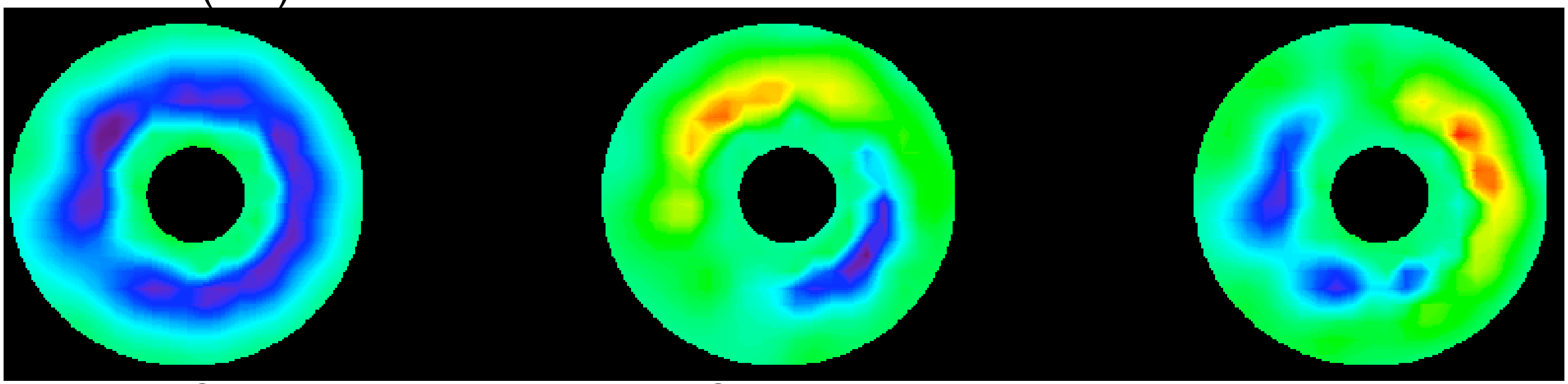
$$S_t \psi_k = A_k^2 \psi_k \text{ where } S_t = Y Y^T \quad (\text{N X N})$$

Eigensolution via SVD returns the
Spatial and
Temporal eigenfunctions.

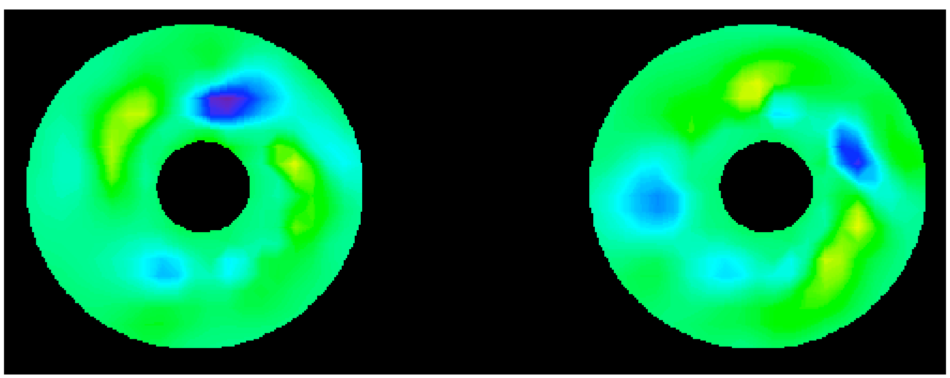
The Orthogonal Functions

- The Spatial Eigenfunctions are used to reconstruct the Equatorial and Fluctuation Mode Structure of the Plasma in the same manner as the ‘Snapshots’.
- The Temporal Eigenfunctions are subject to Fourier Analysis and Time-Frequency-Domain (TFD) Analysis.

m=0 (DC) m=1 m=1

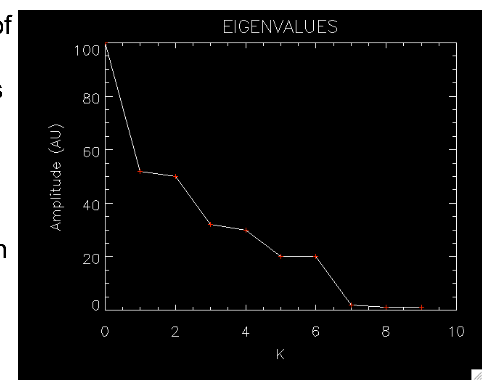


m=2 m=2

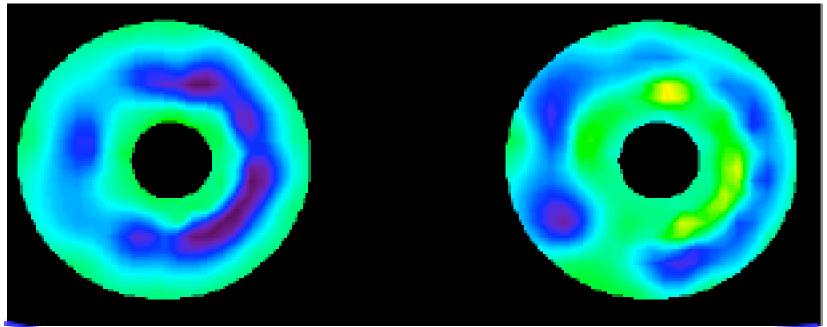


These plots are an example of a quiescent duration of a discharge while the heating is on displaying the grad(B) and Curvature drift with which the instability rotates with.

The sin and cos like plots with 90^0 phase shift are indicative of a rotating mode.

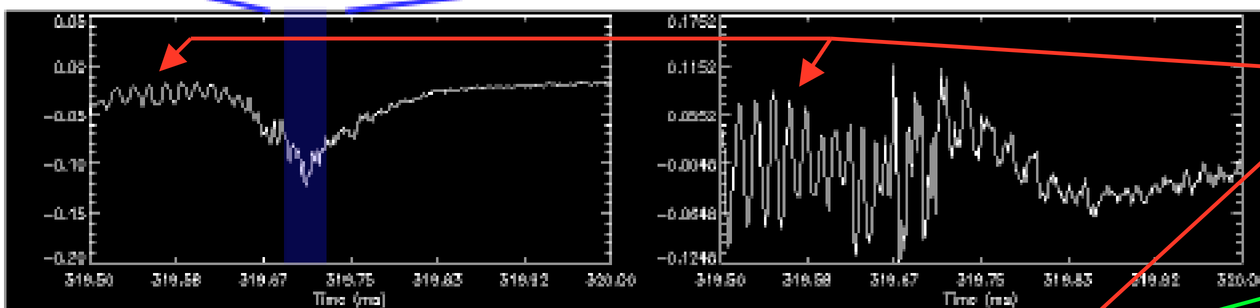


Bi-Orthogonal Decomposition for HEI Burst



Spatial Functions show the radial structure of the instability burst

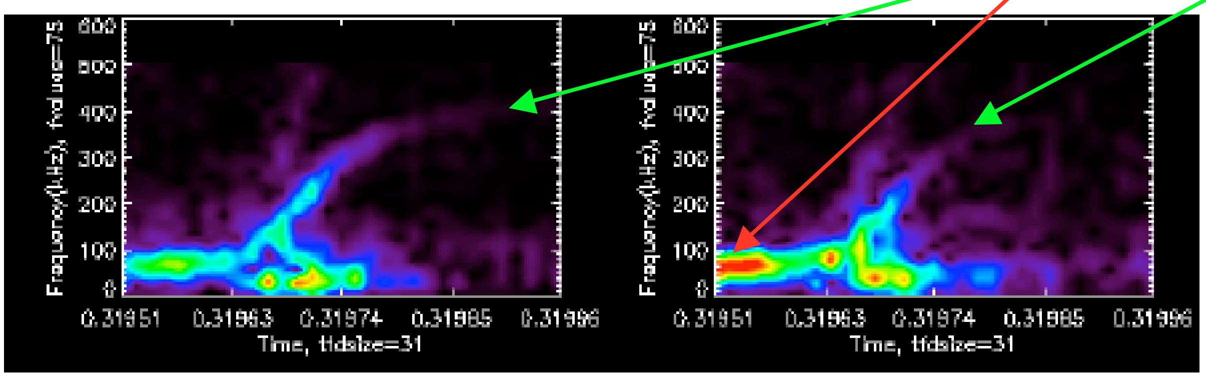
Temopral Functions show the current spike associated with the burst



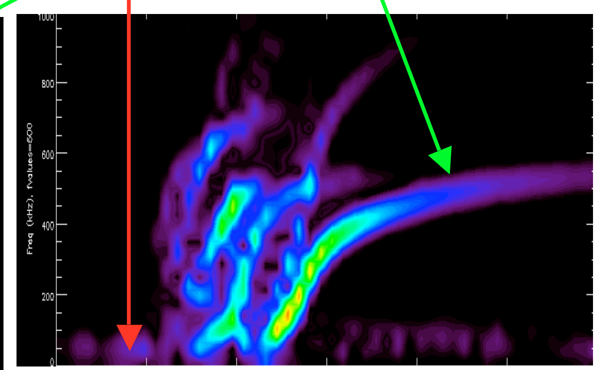
High Amplitude 50kHz

Evolves into 500kHz Mode

TFDs of Temporal eigenfunctions

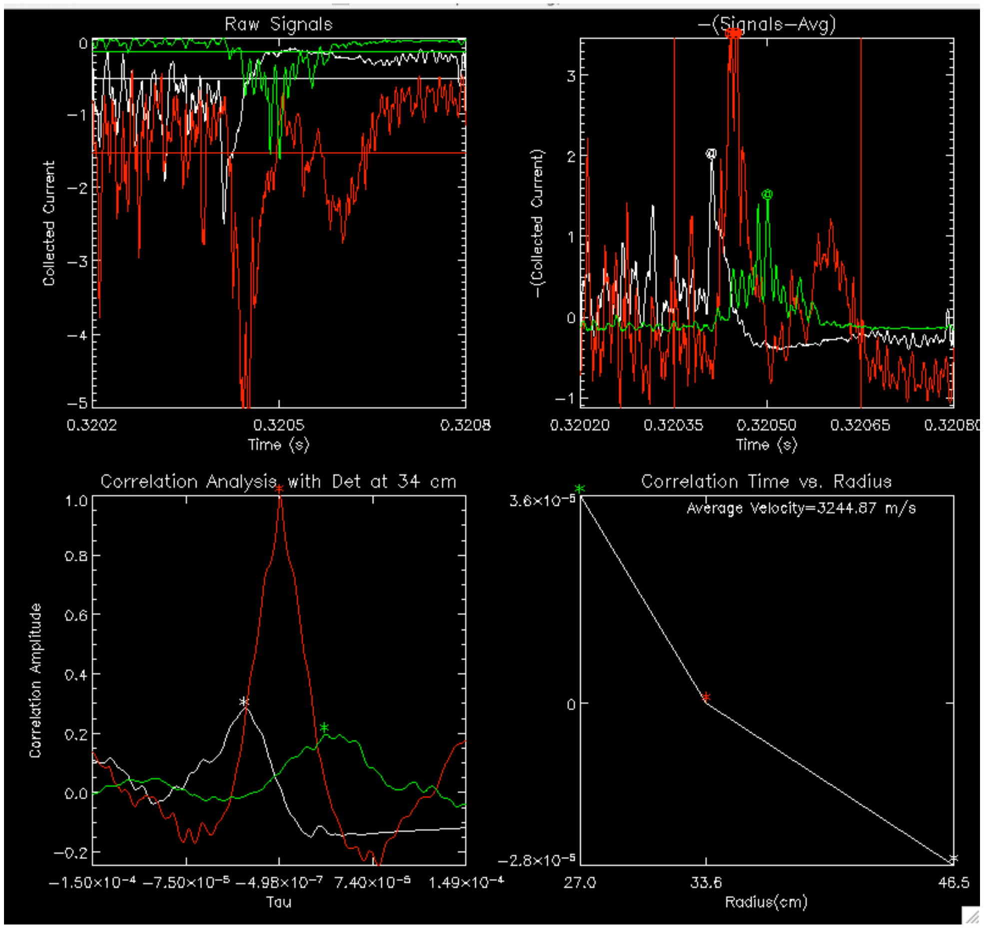


and Floating Potential



Correlation Analysis

- Correlation Analysis of floating potential and Imager signals is used to determine the rotation frequency of modes and velocity of Radial Interchange Transport

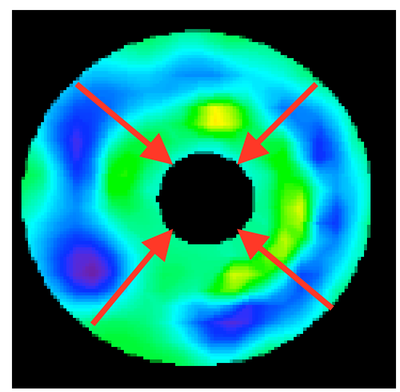


$$C_{01}(\tau) = \frac{\int_0^T S_0(t)S_1(t-\tau)dt}{\int_0^T S_0^2(t)dt}$$

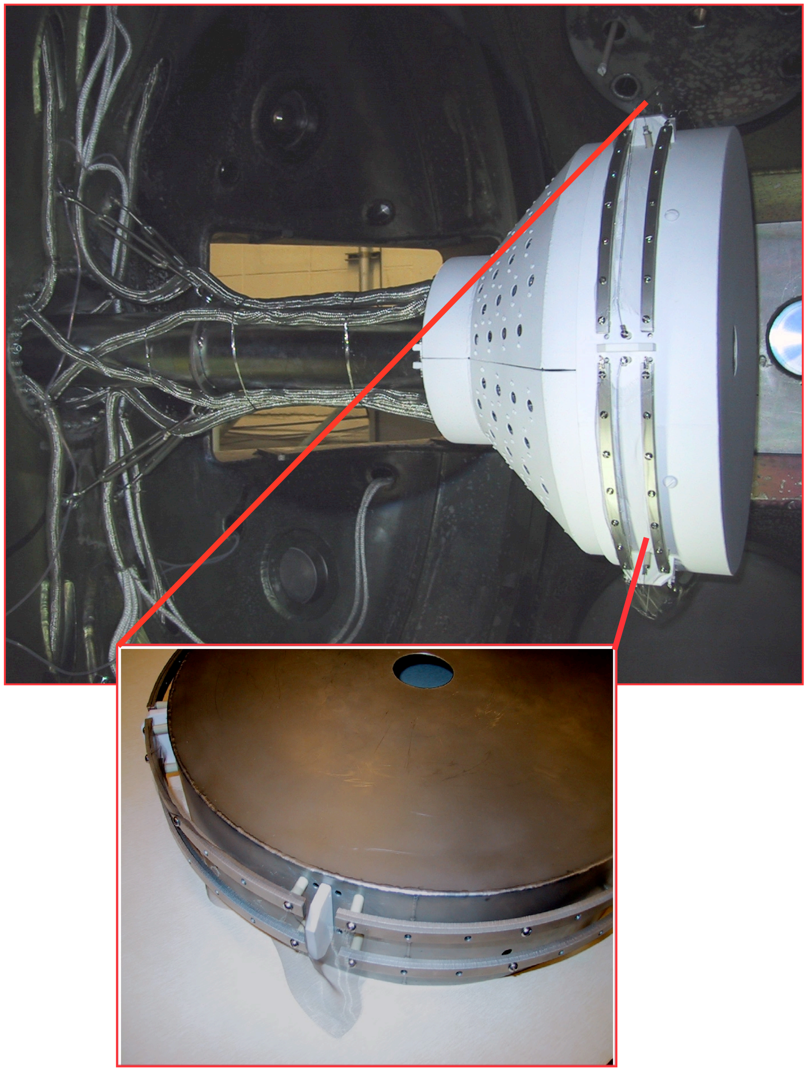
and $\tau|_{C\,\max}$ gives Correlation Time

Multiple(~20) azimuthal locations confirm the observed inward propagation of lost electrons at ~3-4 km/s

$\tau_{outside} < \tau_{middle} < \tau_{inside}$

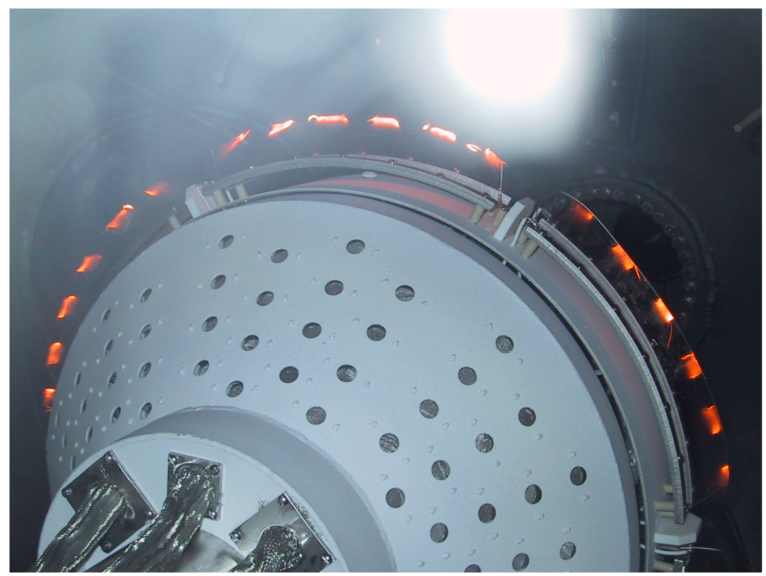


Tungsten Mesh Biasing Array



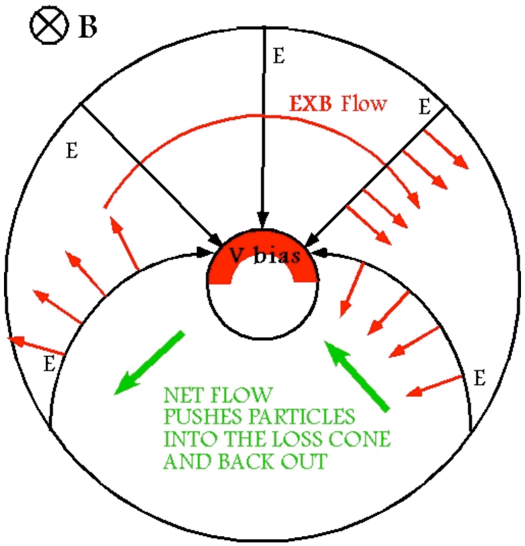
- 6 independently biased tungsten mesh filaments.
- Located at innermost flux surface.
- Cap insulated to ~4000V with 20 mils of alumina plasma spray coating.
- Resistively heated to emit electrons.

Only Biasing 3 Meshes!!

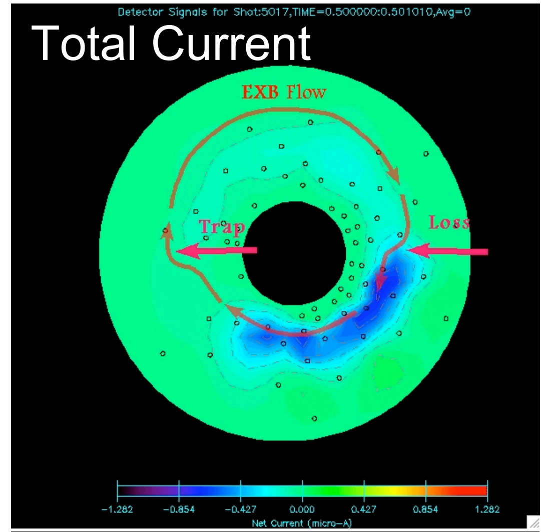


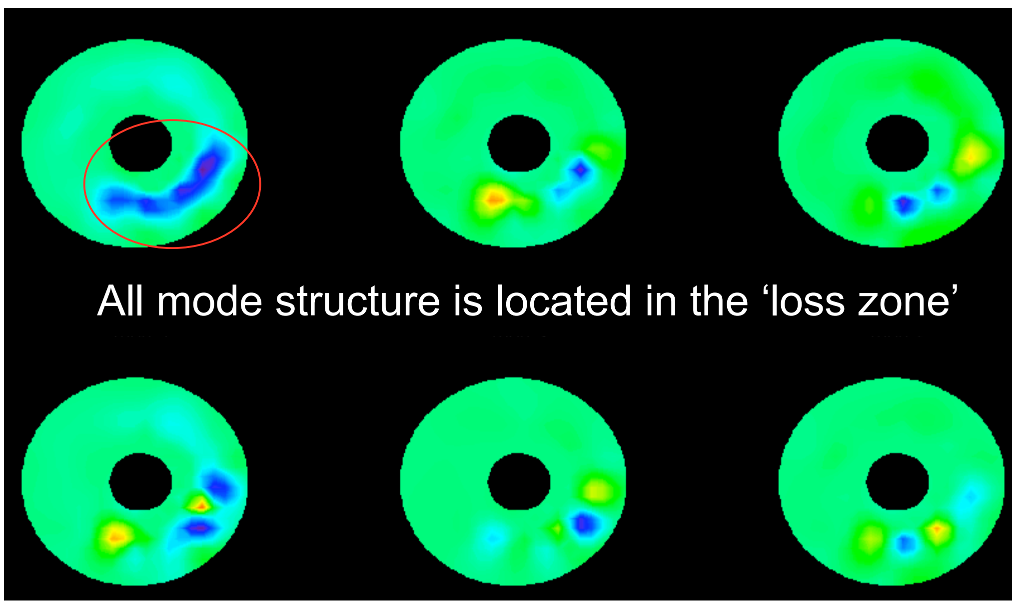
Driven Interchange by Non-Axisymmetric Bias

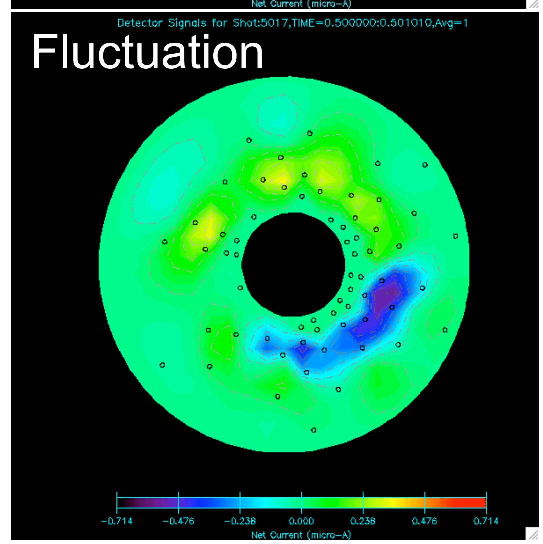
NEW RESULT!



High Voltage (-450V)
Drives Steady State
Interchange motion.
Local mode structure.
See movie.



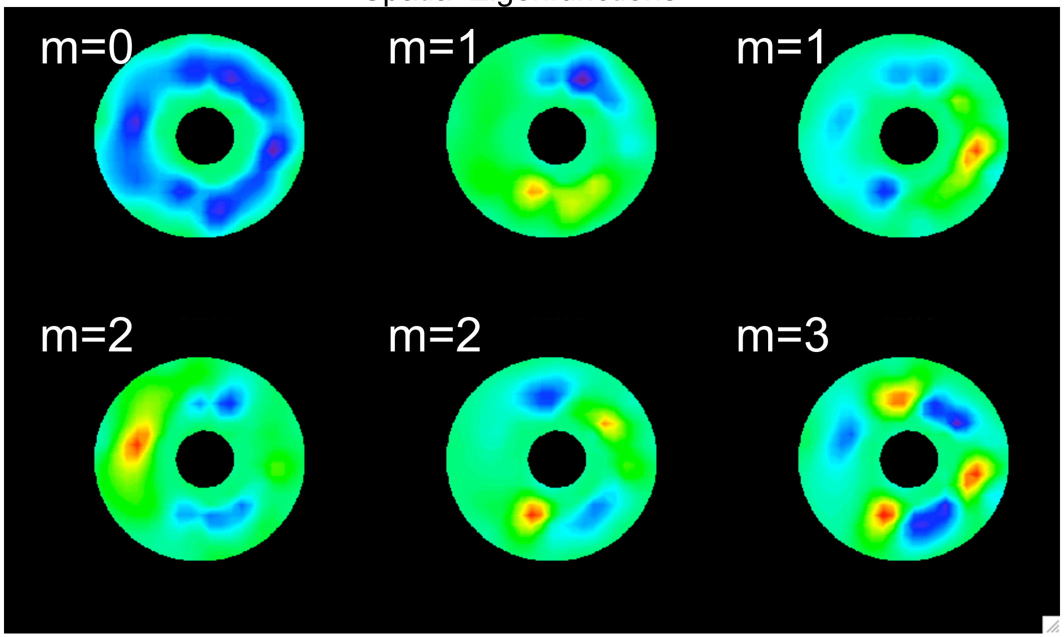




Lower Voltage (-70) Drift Frequency Modulation

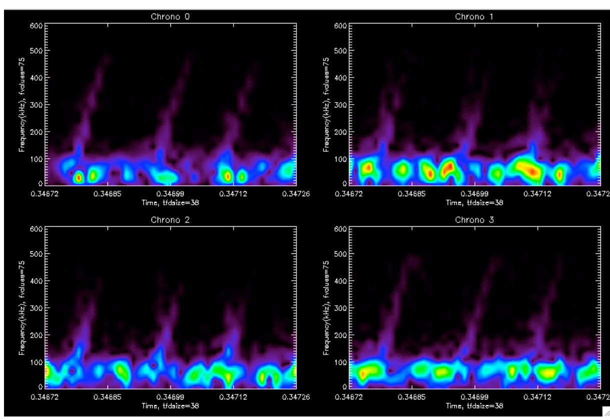
DC Non-axisymmetric Bias → Periodic Frequency Sweeping

Spatial Eigenfunctions.

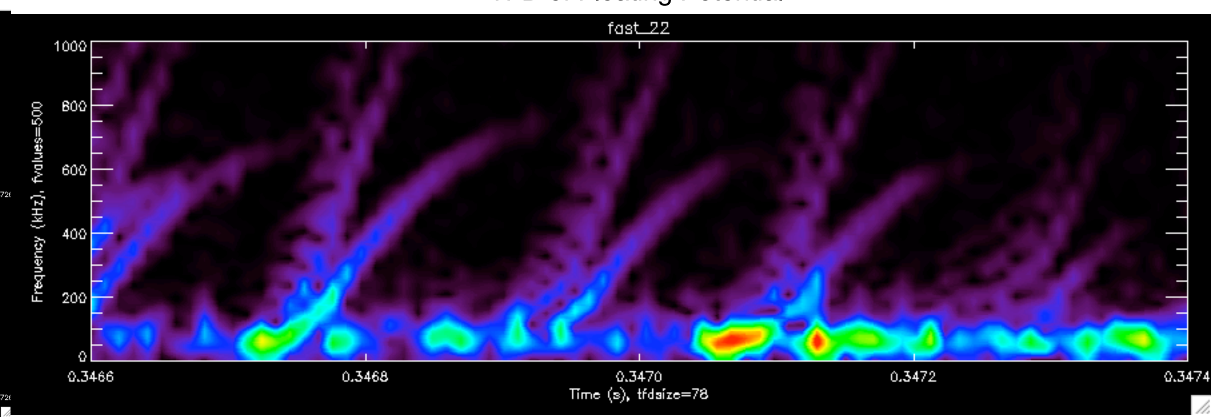


- Very strong mode structure.
- Quasi-periodic frequency sweeping.
- Easily seen in movies.
- Not Seen at Higher or lower Bias Voltages.
- This might be a marginal case, where the hot electron fraction is kept very near the critical value for a global interchange burst, but is not allowed to run away. This is only possible if our driven interchange is acting as a sink for hot electrons, or we're affecting the plasma in another way.

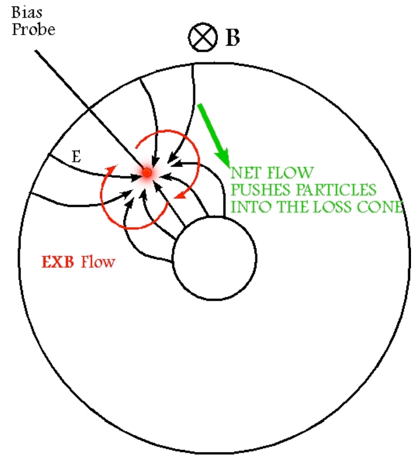
TFD of Temporal Eigenfunctions.



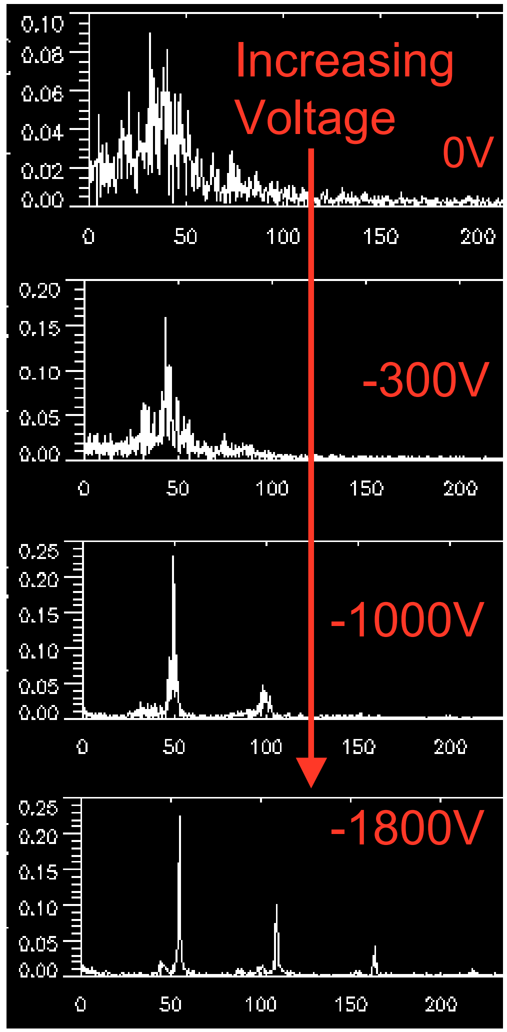
TFD of Floating Potential

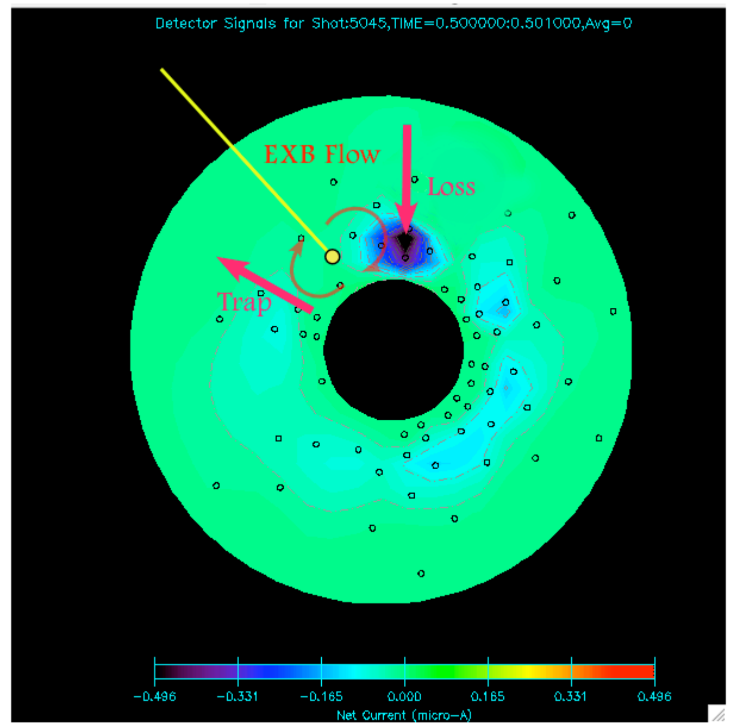


Driven Interchange By a Biased Probe: NEW RESULT!



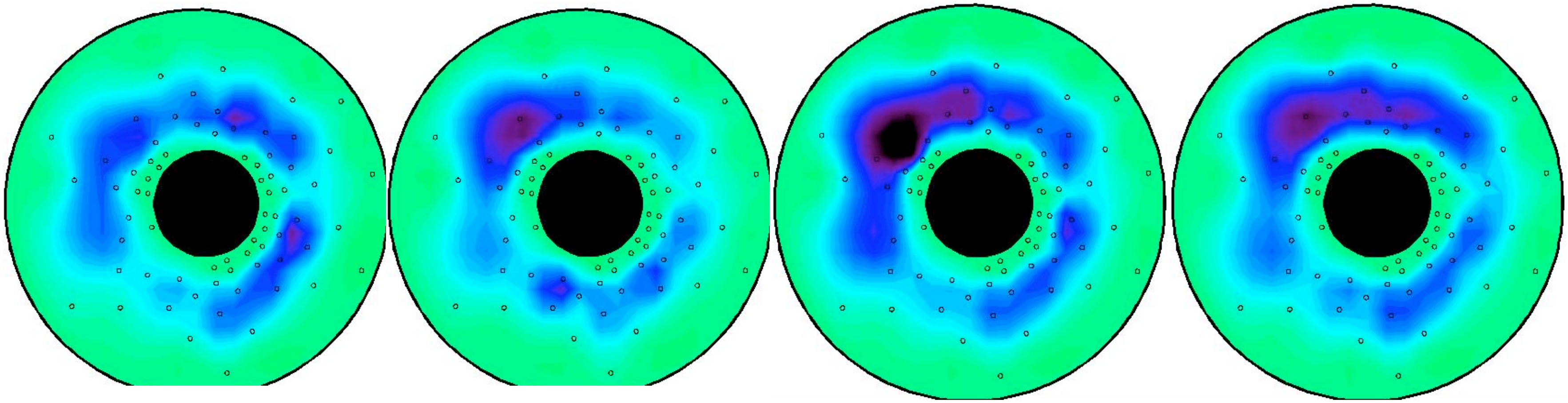
Locally driven interchange transport is Steady State. And causes trend towards sharply peaked floating potential spectrum.

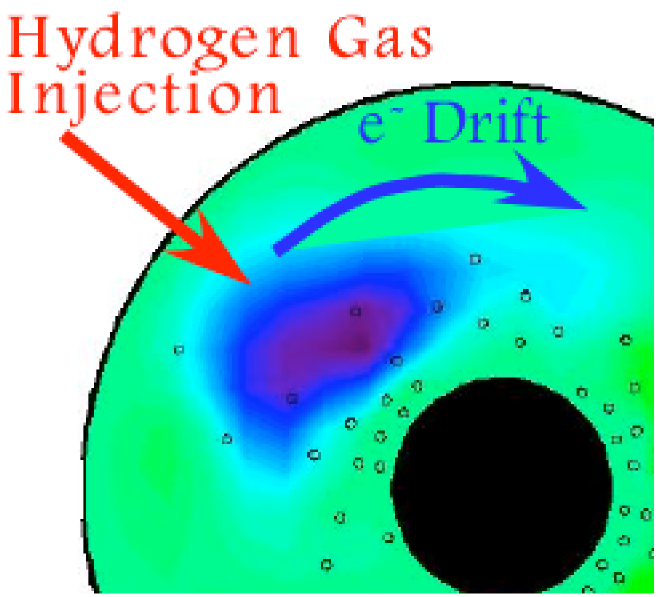




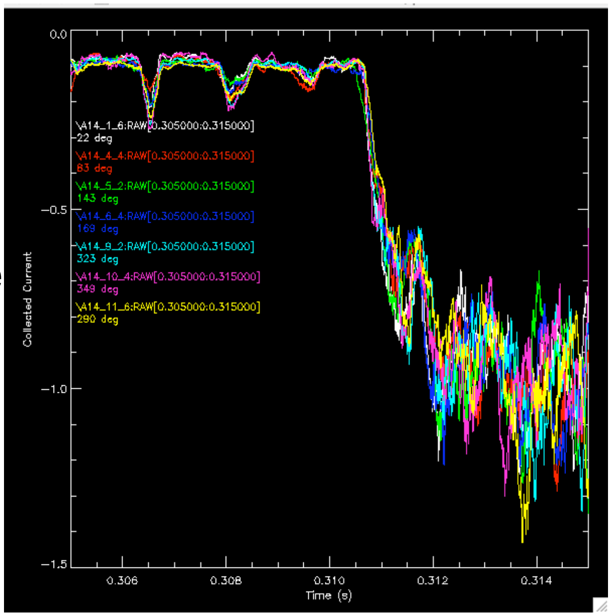
Convective Cell Circulates around the Bias Probe. Only inward moving plasma is lost to the Polar Imager via the loss cone mechanism.

Observation of Ionization and Mixing by an Injected Neutral Population.





•Neutral Hydrogen is injected at the chamber wall
•The neutral population enters the ECRH resonance zone and is ionized producing hot electrons.



Conclusions/Future Work

- The behavior of dipole-confined plasmas can be diagnosed by the polar loss current.
- The amount and location of lost particles are indicative of local, global, and cross-field transport events in the plasma.
- Plasma behavior can be identified using Correlation analysis, Time-Frequency Domain (TFD) Spectrum, and Bi-orthogonal Decomposition applied to multiple spatially and temporally varying detector signals.
- Imposing strong electric fields in dipole-confined plasmas causes time-varying and steady state flow patterns and convective cells.
- *To be installed next*: (1) Higher bandwidth detector amplifiers and (2) Adjustable Triple Probe Array (TPA) will improve spatial resolution and yield images of high-speed interchange and transport dynamics.