Dynamics of Fluctuations in the Presence of Sheared Flows in a Magnetized Laboratory Plasma

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Abstract

Laboratory experiments are described which utilize a set of concentric bias rings to affect the velocity (flow) shear in the linear HELCAT (HELicon-CAThode) device at the University of New Mexico. HELCAT is 4 m long, 0.5 in diameter, with $B_0 \leq 2.2$ kG, and utilizes two plasma sources: an RF helicon at one end of the device, and a thermionic cathode at the other. With increasing ring bias, relative to the vacuum chamber wall, it is found that both axial and azimuthal flow shear change by only a small amount in magnitude, but move inward to the plasma core from the wall. As bias is increased, drift waves decrease in magnitude and are eventually fully suppressed, then the Kelvin-Helmholtz (K-H) mode is destabilized. It appears that the azimuthal flow shear is mainly responsible for suppression of drift modes, while the azimuthal shear is the primary driver of the K-H instability. While bias applied to rings at any radii suppresses drift fluctuations with nearly equal effectiveness, the K-H mode is more easily excited by biasing at the plasma edge. Fluctuations show increasingly chaotic and intermittent behavior as bias increases, up to V ~ 10kTe/e, when the chaos disappears, as indicated by a rapid drop in correlation dimension, and very bursty behavior. Additionally, detached edge “blobs” are observed in cathode plasmas, but appear to be absent from helicon discharges, even when other operating parameters (magnetic field, background pressure) are identical. Experimental results and comparisons with theory are described.

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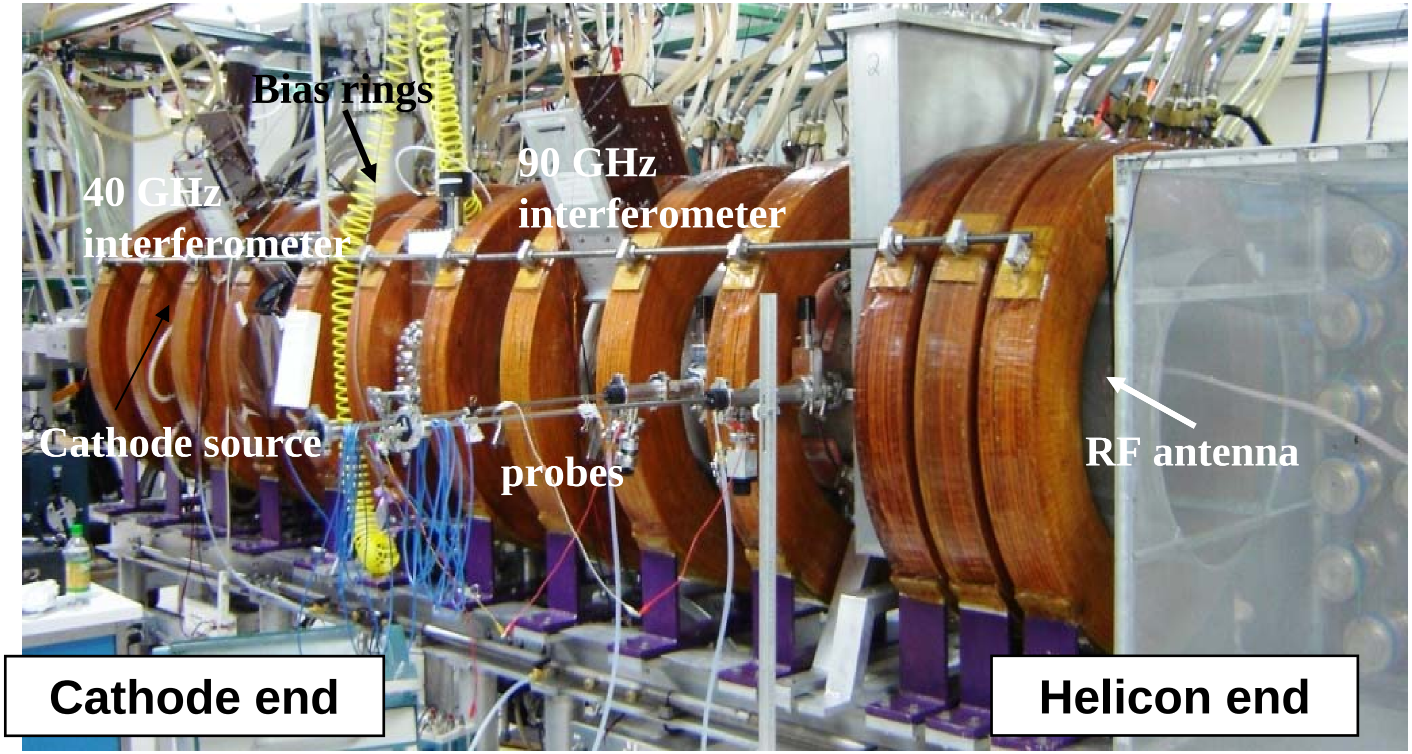
Overview

- A detailed investigation of the nonlinear dynamics of gradient-driven fluctuations in the presence of controlled sheared flows is underway in the linear HELCAT device.
- Concentric bias rings are utilized to achieve some control over flow profiles. Both perpendicular and parallel flows are modified.
- Two different plasma sources (RF helicon and thermionic cathode) are utilized. Fluctuation dynamics of the two plasmas are significantly different.
- Weakly nonlinear drift fluctuations are present in helicon plasmas. Under biasing, drift fluctuations can be fully suppressed. Increased bias produces chaotic or intermittent drift fluctuations, and (intermittent) Kelvin-Helmhotz instability. *No convective blobs have been observed in helicon discharges.*
- Cathode plasmas exhibit broadband edge fluctuations, and *signatures of convective blobs are observed* in the far edge.

Experimental Setup: the HELCAT Device

HELCAT: (HELicon-CAThode)

- **Length: 4 m**
- **Diameter: 50 cm**
- **B_z: ≤ 2 kG**
- **Plasma Sources: Cathode & RF Helicon**



RF helicon plasma

- **n ~ 1-5 × 10^{19} m^{-3}**
- **Te ~ 5 – 10 eV**
- **Ti ~ 0.1 eV**
- **D = 10 – 15 cm (FWHM)**

Cathode plasma

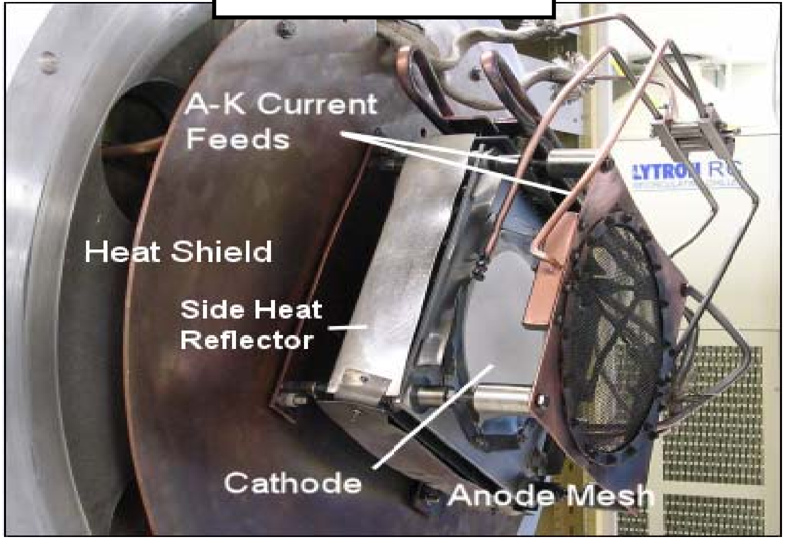
- **n ~ 1-5 × 10^{18} m^{-3}**
- **Te ~ 5 – 10 eV**
- **Ti ~ 1 eV**
- **D (Plasma Diameter) = 10 – 20 cm (FWHM)**

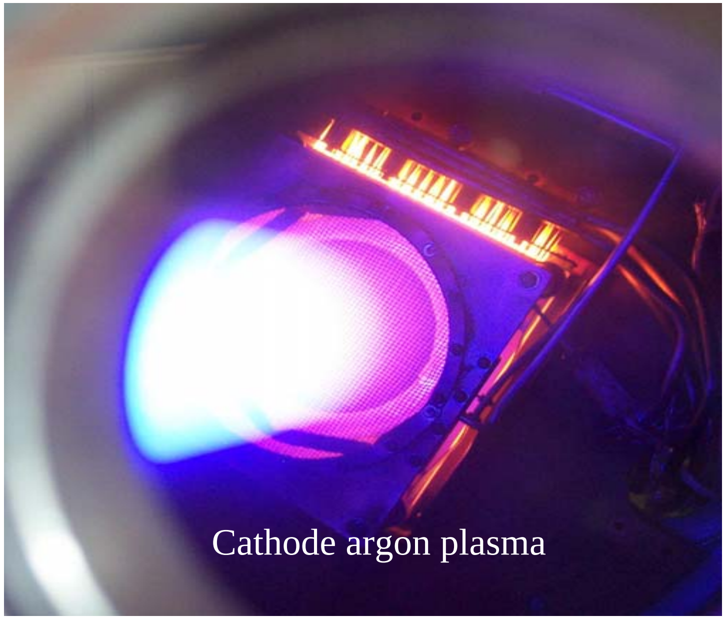
Diagnostics

- **Electrostatic and magnetic probes**
- **40 and 94 GHz interferometers**
- **Visible spectroscopy**
- **LIF**
- **Fast framing camera**

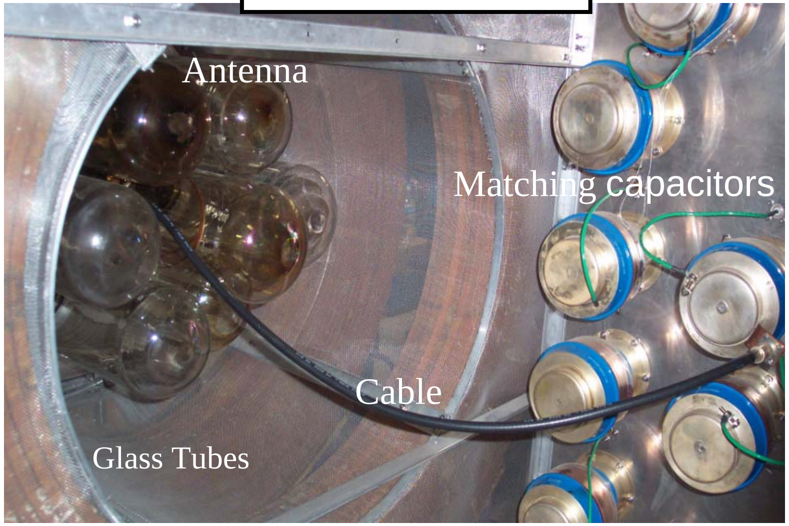
Dual Plasma Sources

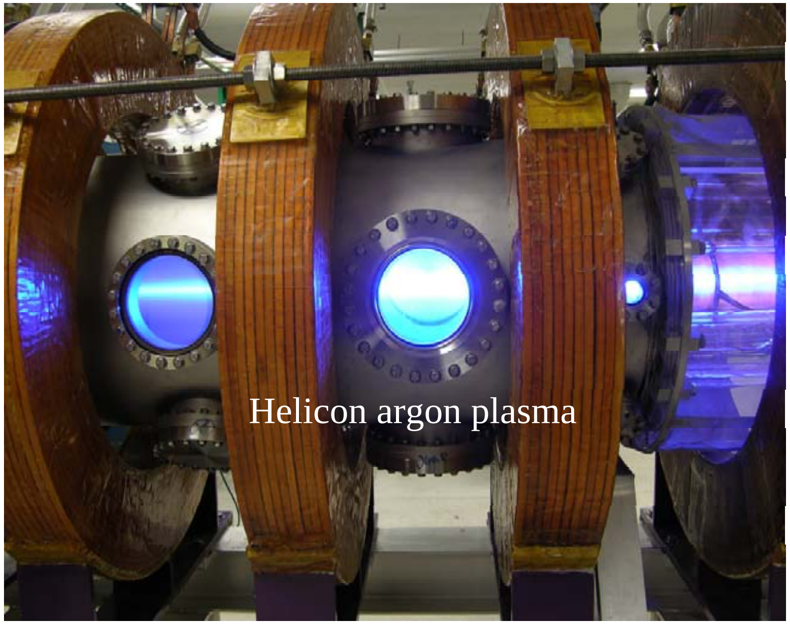
Cathode




Cathode argon plasma

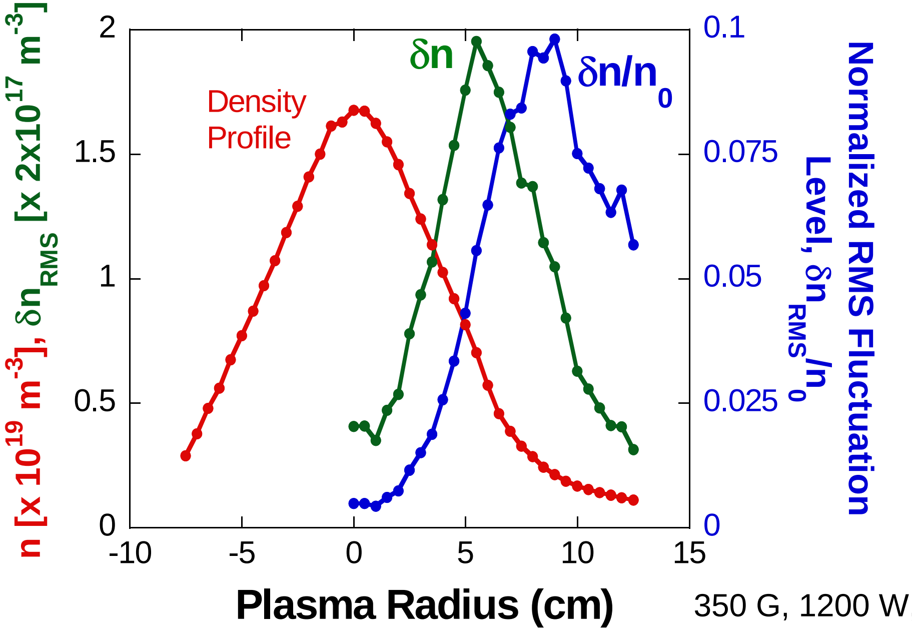
RF Helicon




Helicon argon plasma

Helicon Plasma Profiles

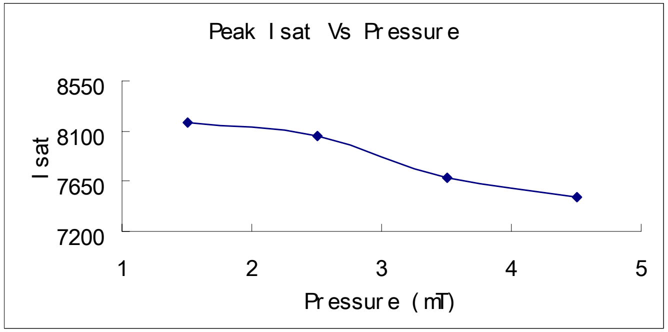
Typical Profiles of Density and Density Fluctuations in Ar



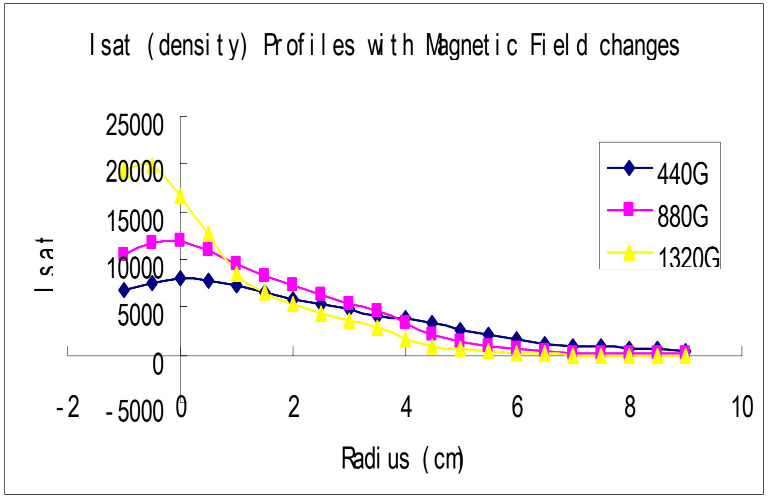
350 G, 1200 W,
2.5 mTorr

- Low RF power, < 800 W, produces unstable plasmas
- Increasing RF power, > 1000 W, increases density with little effect on gradients

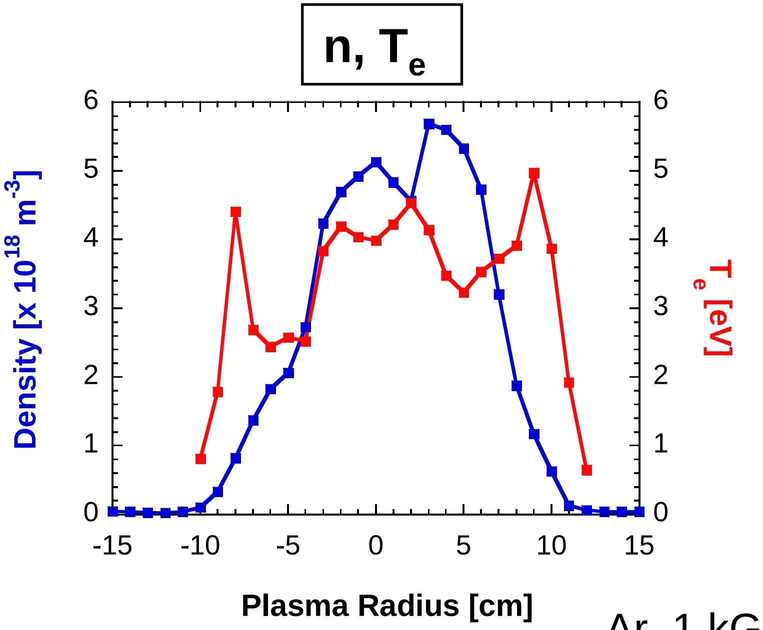
- Increasing gas fill pressure raises peak density, but has little effect on the density gradient

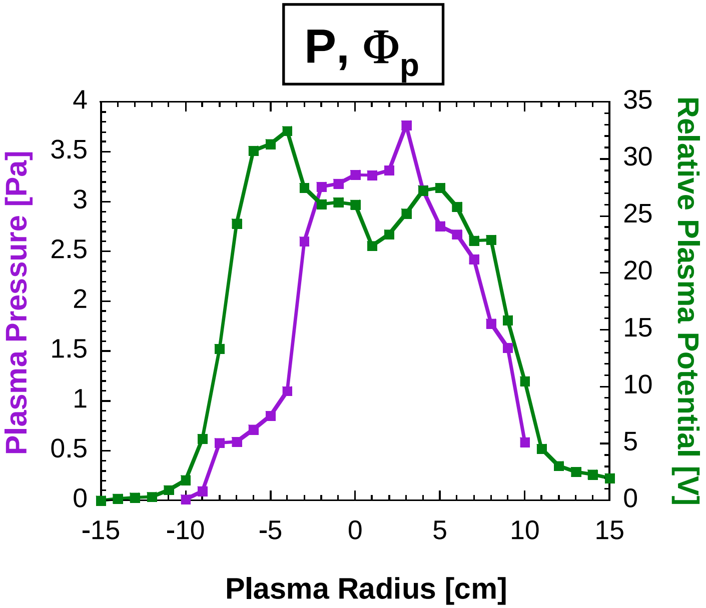


- Density Profile steepens with B-field



Cathode Plasma Profiles



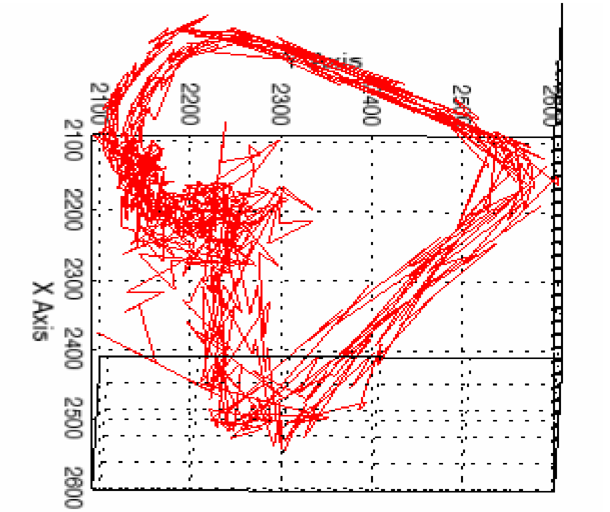


Ar, 1 kG, I_{dis} = 500 A,
P_{fill} = 5×10^{-4} Torr

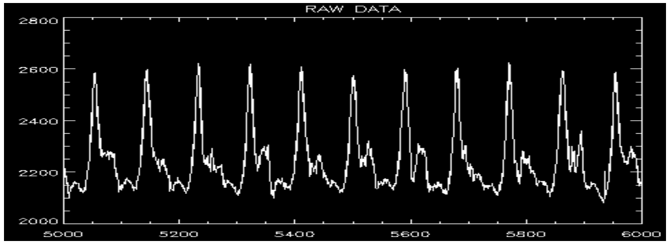
- n, T_e profiles strongly dependant on cathode discharge current, but nearly independent of B-field

Chaotic Drift Fluctuations in Helicon Plasmas

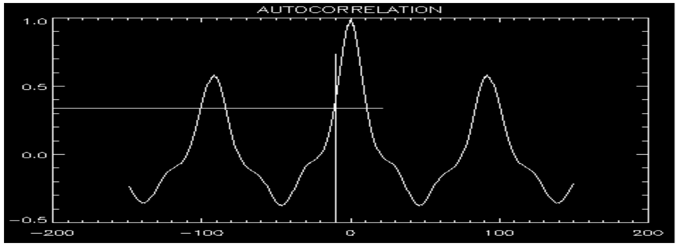
- Chaos is observed in HELCAT helicon argon plasmas under a variety of conditions



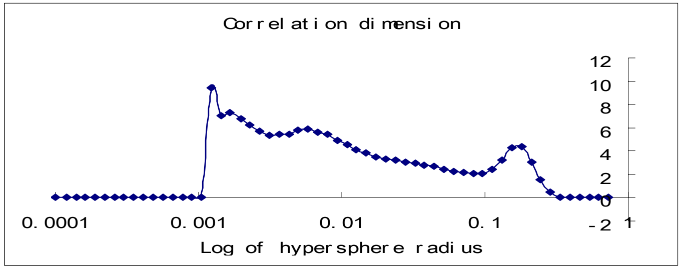
3-D phase plot, Dcorr=3.894



Raw Isat data



Autocorrelation

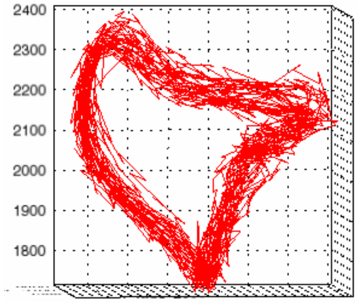


Correlation dimension

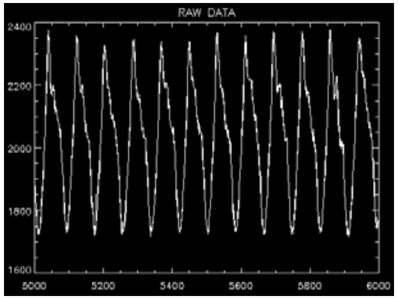
- I_{isat} measured by double probe
- Probe at R = 5.5cm
- RF input power = 1400W
- Pressure = 2.5mT
- Magnetic field = 440G

Chaotic Fluctuations Show Increased Correlation Dimension with Increasing Magnetic Field (Helicon)

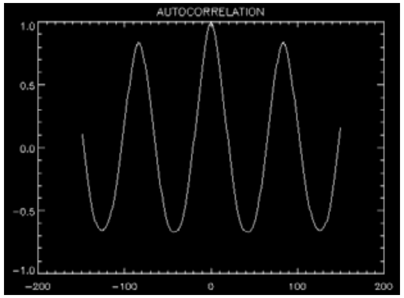
Top: RF input power = 1400W, P_{fill} =1.5mT, B_0 = 440G, Correlation dimension: 2.85



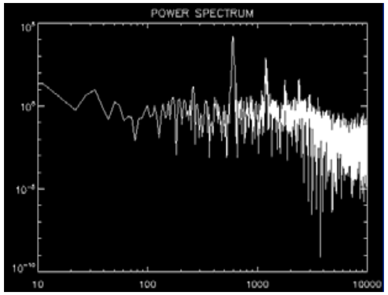
Phase Lag



Raw I_{isat}

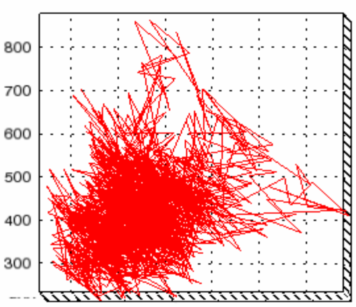


Autocorrelation

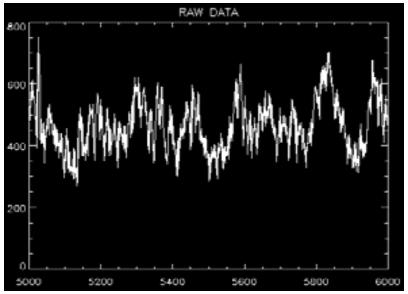


Power Spectrum

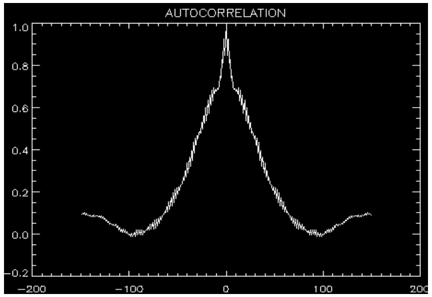
Bottom: RF input power = 1400W, P_{fill} = 1.5mT, B = 1320G, Correlation dimension: 7.8 (turbulence)



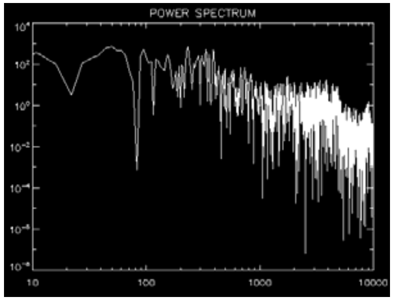
Phase Lag



Raw I_{isat}



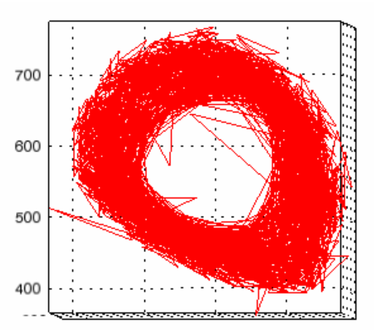
Autocorrelation



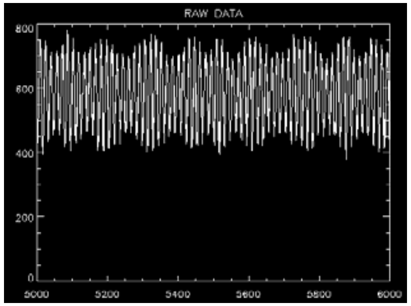
Power Spectrum

Chaotic Fluctuations Show Increased Correlation Dimension with Increasing RF Input Power (Helicon)

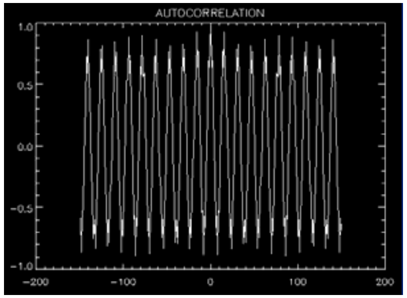
Top: RF input power = 800W, P_{fill} =1.5mT, B_0 = 880G, Correlation dimension: 2.37



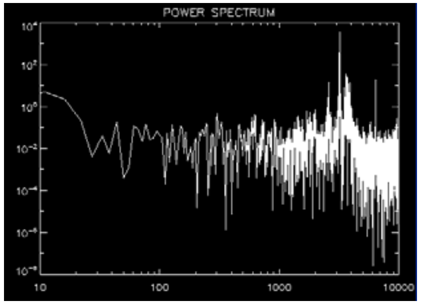
Phase Lag



Raw I_{isat}

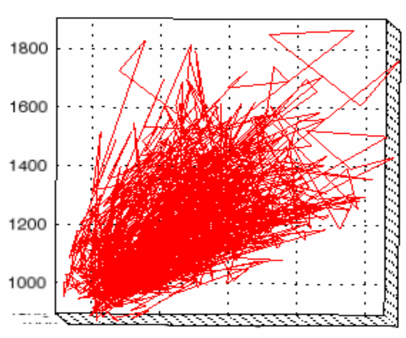


Autocorrelation

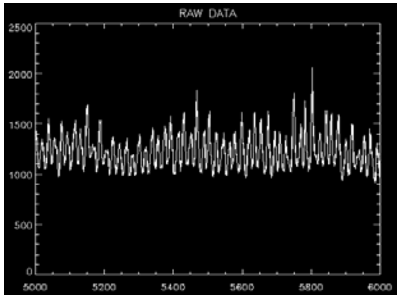


Power Spectrum

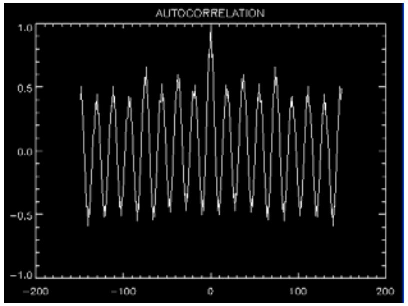
Bottom: RF input power = 2000W, P_{fill} = 1.5mT, B = 880G, Correlation dimension: 6.72



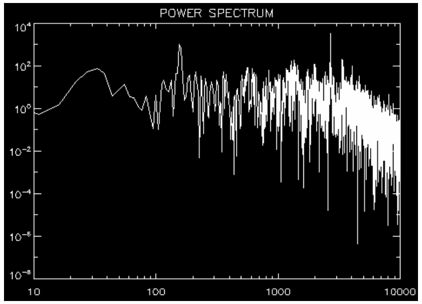
Phase Lag



Raw I_{isat}



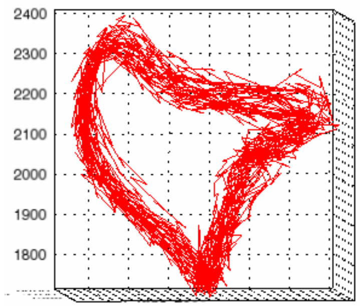
Autocorrelation



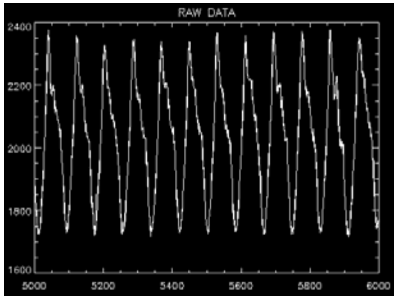
Power Spectrum

Correlation Dimension of Chaotic Fluctuations Changes with Increasing Fill Pressure (Helicon)

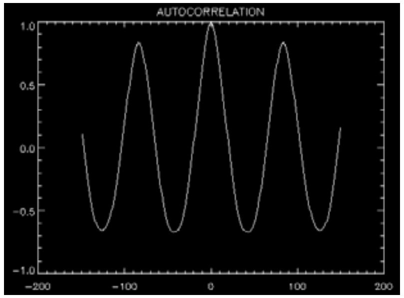
Top: RF input power = 1400W, P_{fill} =1.5mT, B_0 = 440G, Correlation dimension: 2.85



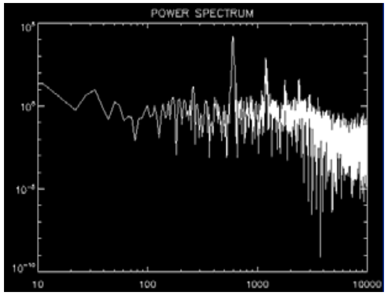
Phase Lag



Raw I_{isat}

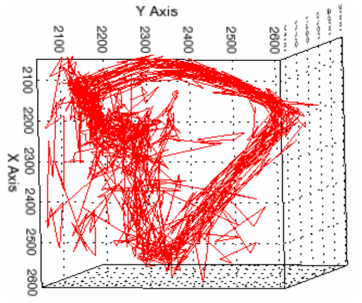


Autocorrelation

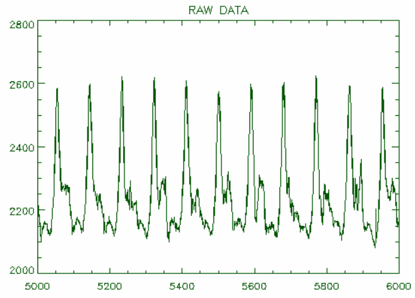


Power Spectrum

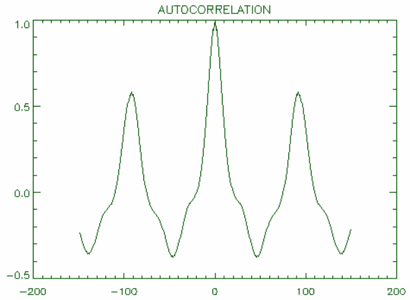
Bottom: RF input power = 1400W, P_{fill} = 2.5mT, B = 440G, Correlation dimension:3.89



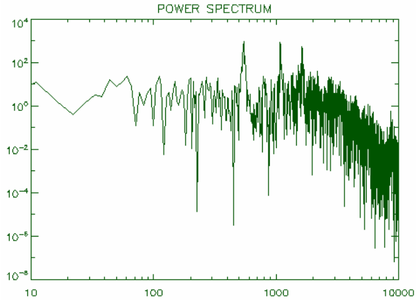
Phase Lag



Raw I_{isat}

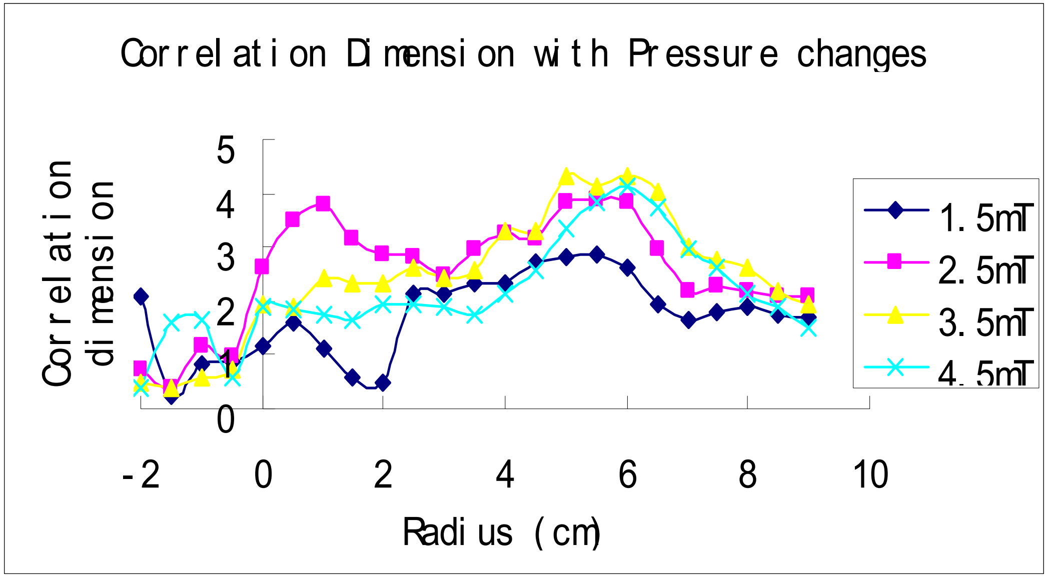


Autocorrelation



Power Spectrum

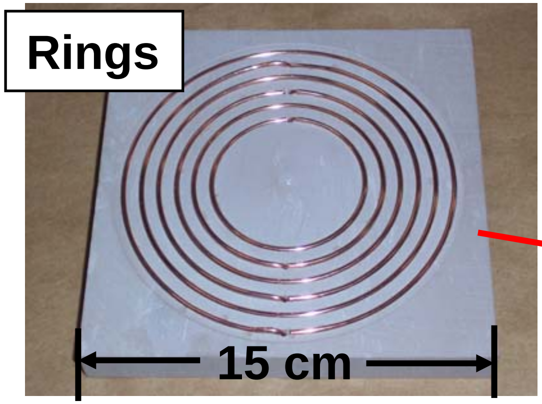
Correlation Dimension Changes with Neutral Fill Pressure (Helicon)



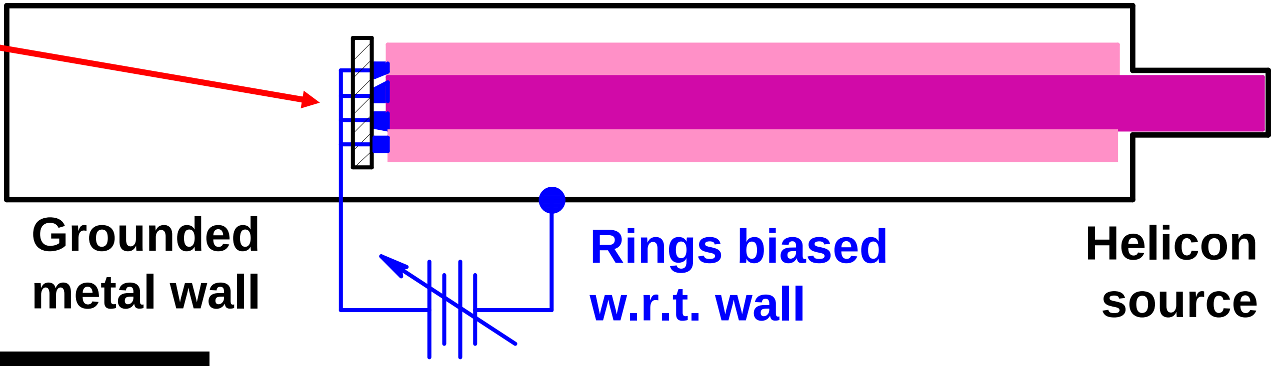
Chaos' dimension plot (input power: 1400W, magnetic field: 440 Gauss)

- Correlation dimension increases when gas fill pressure increases from 1.5mT to 2.5mT, then saturates at 3.5mT, and finally decreases at higher pressure.

Simple Biasing Can Suppress Drift Fluctuations at Low Magnetic Field (Helicon)



- **Positive bias toward plasma center**
- **Inner rings connected together, outer rings connected to wall**
- **Biasing between any pairs of rings almost equally as effective**

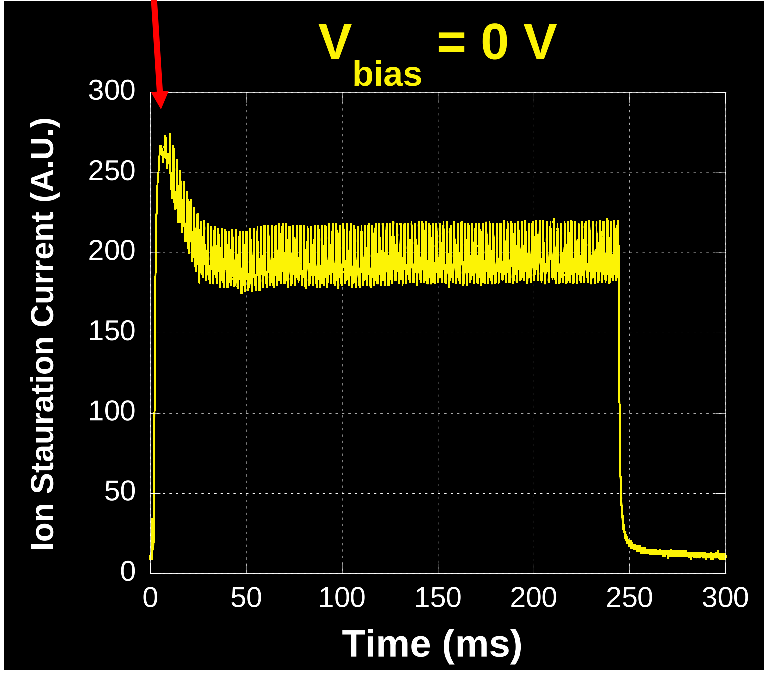


Grounded metal wall

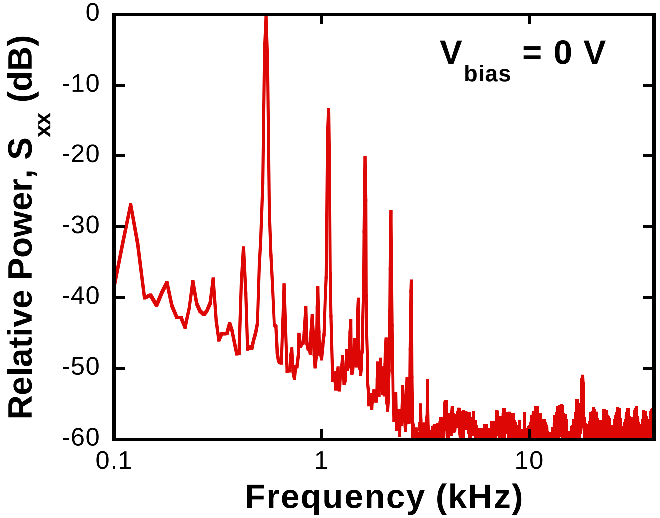
Rings biased w.r.t. wall

Helicon source

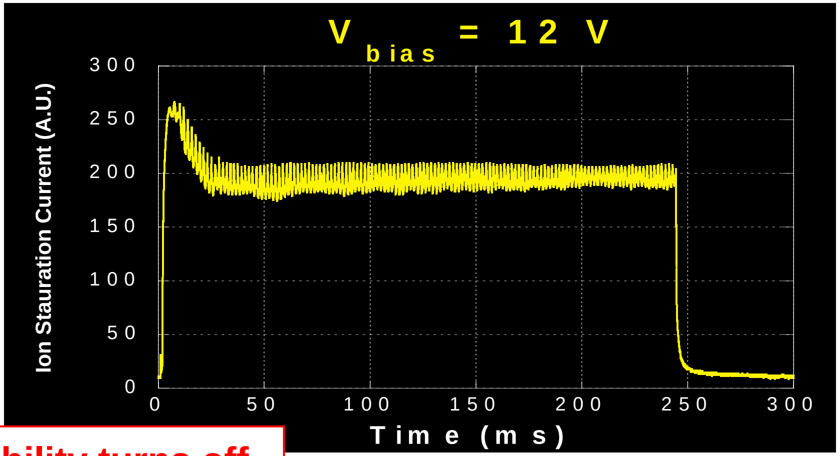
Instability turns on

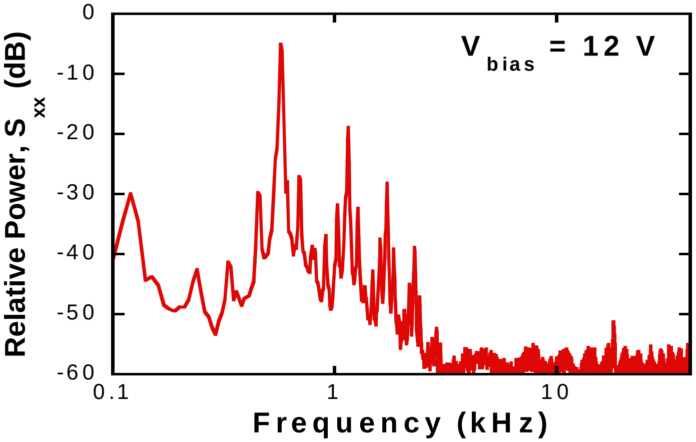


Ion saturation current, probe @
R = 5.5 cm, Ar, B_0 = 350 G, ρ_s ~ 4cm

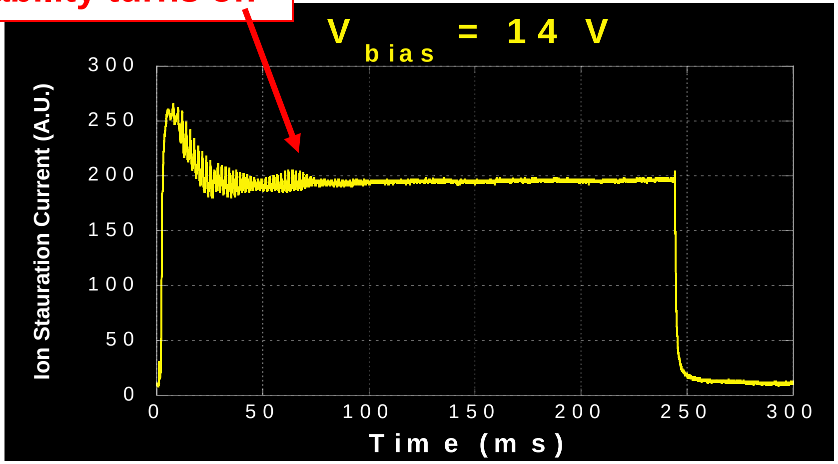


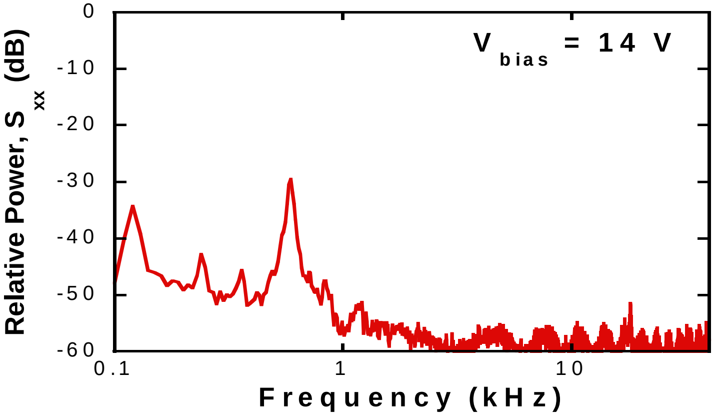
Increasing bias

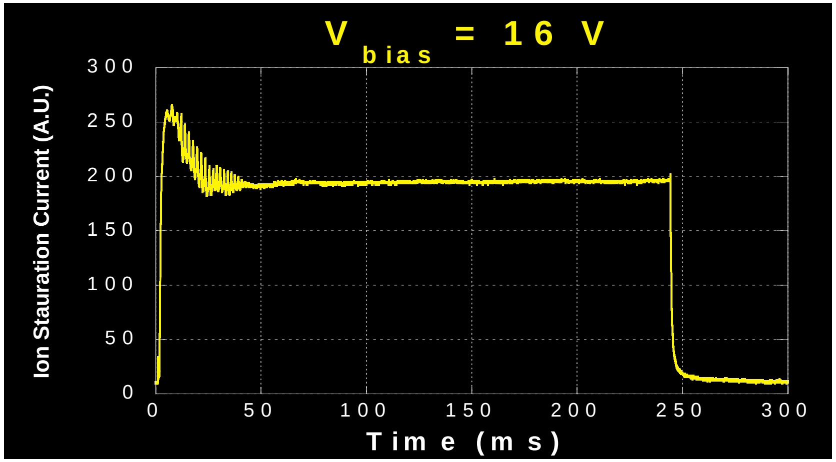


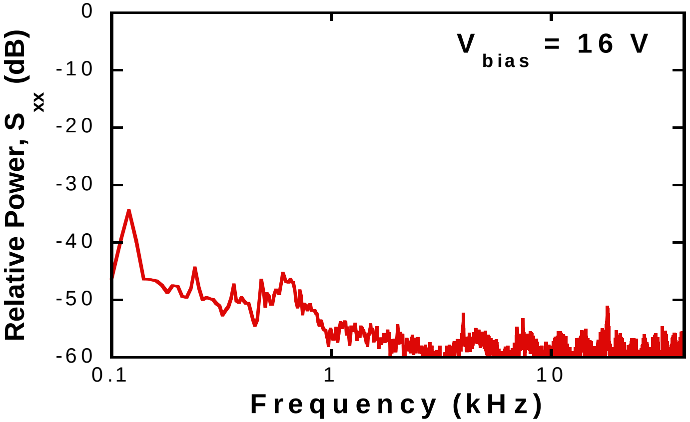


Instability turns off



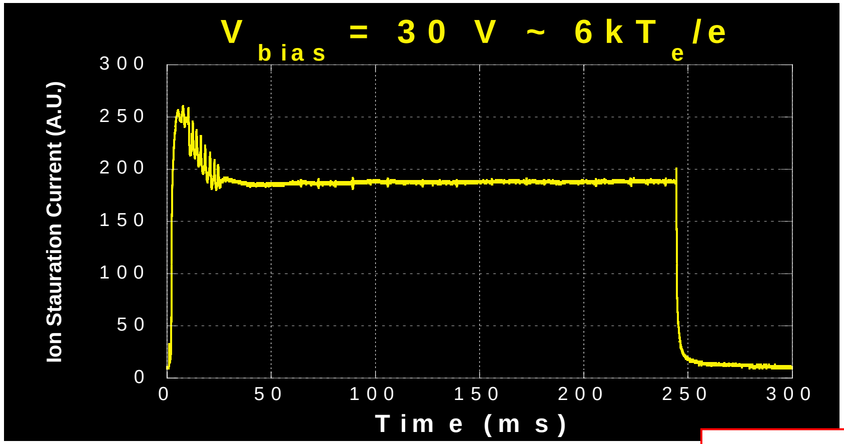


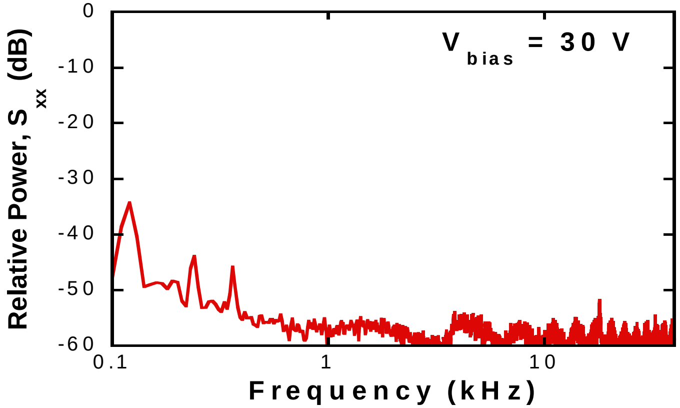




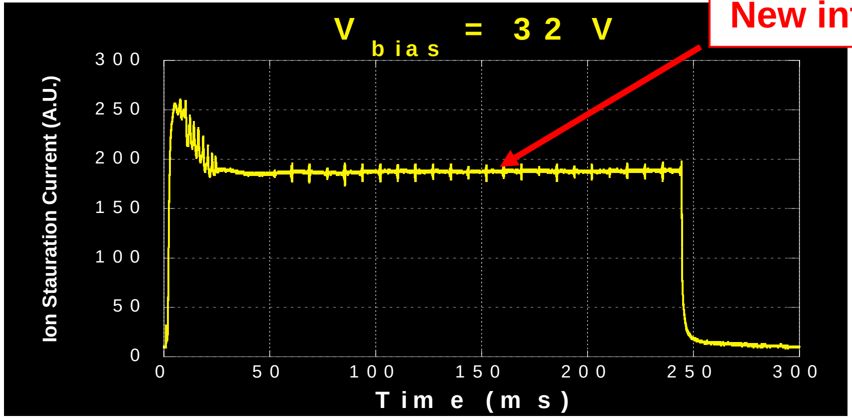
Second, Intermittent Instability Driven at Higher Bias

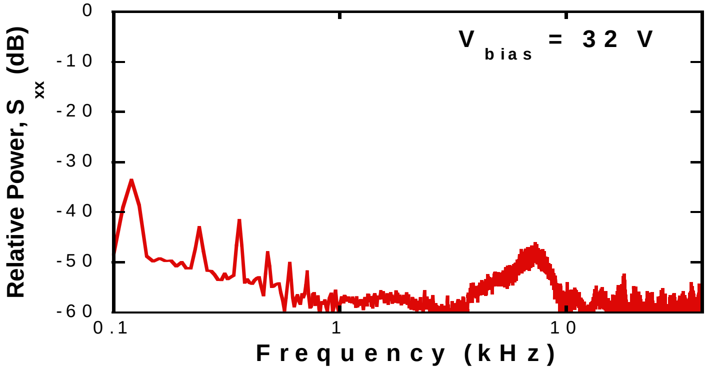
Increasing bias

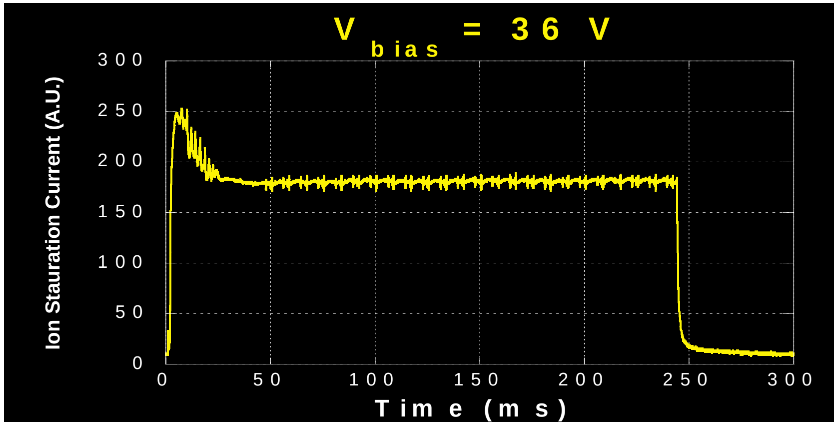


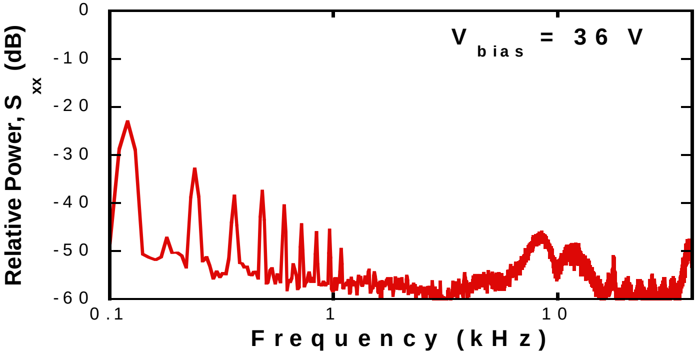


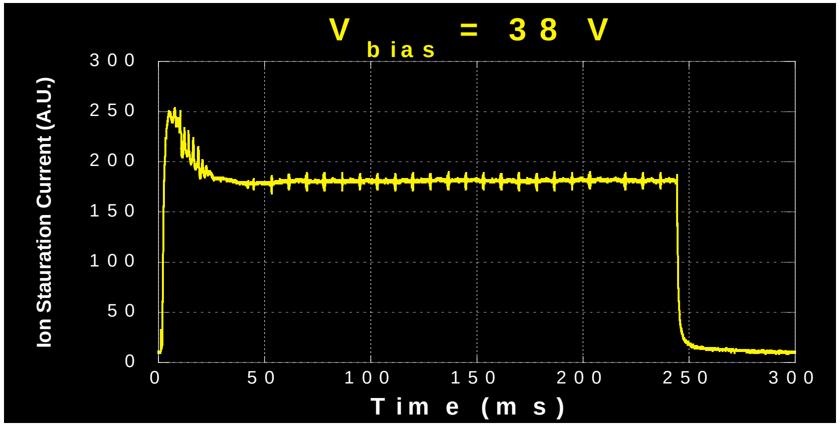
New intermittent instability appears

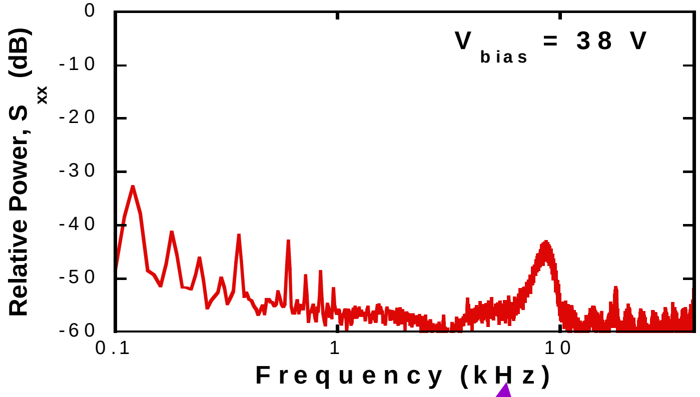








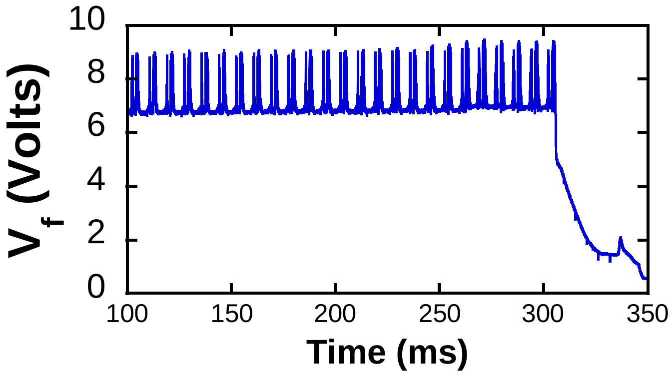




New mode.

Has large potential fluctuations

[$\delta\phi/(e/kT_e) \sim 5(\delta n/n)$]

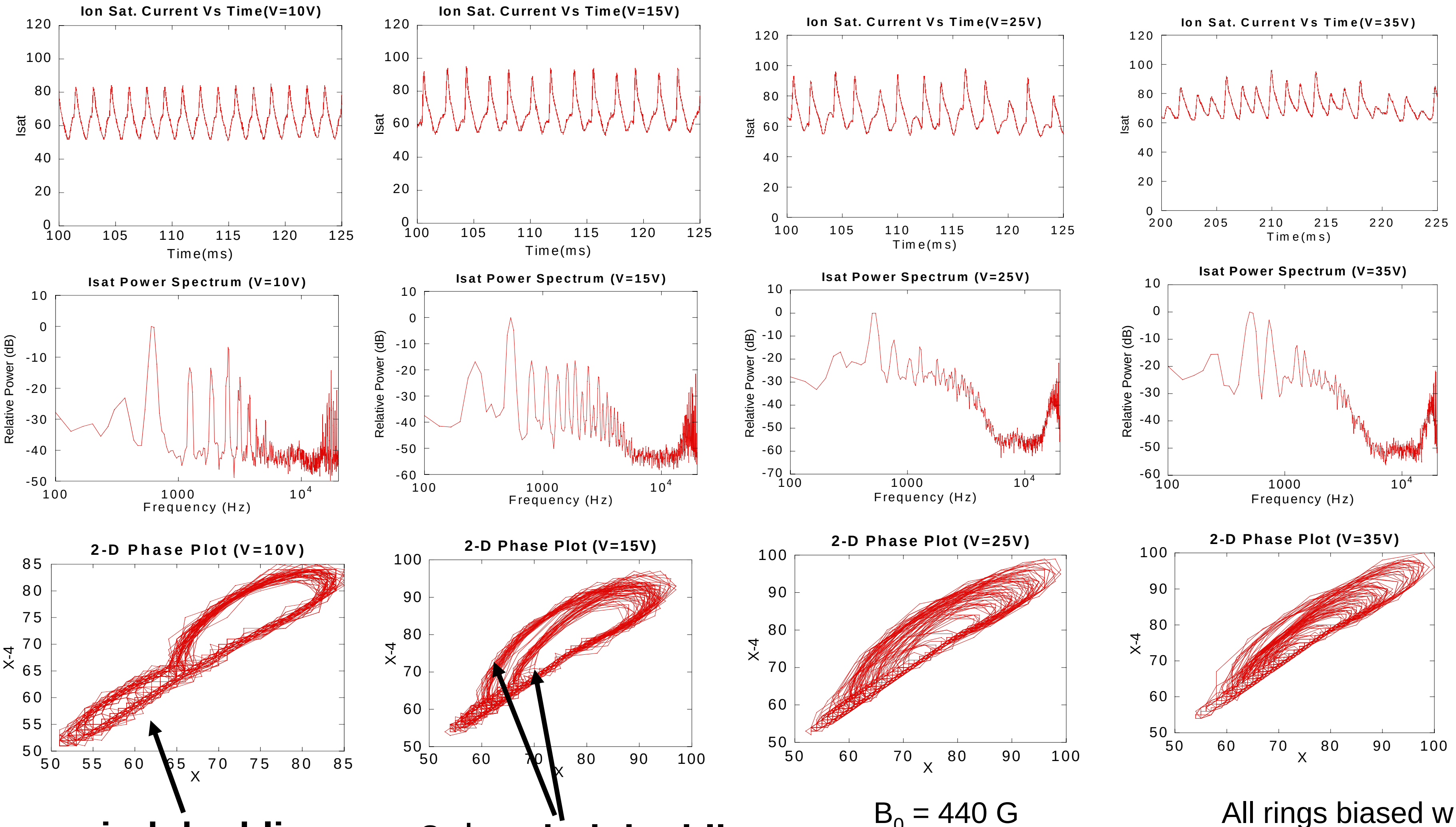


- **Second mode appears to be a Kelvin-Helmholtz (K-H) Instability, driven by both axial and azimuthal flow shear at the bias ring ceramic substrate edge (see flow plots below).**
- **This instability is driven more easily when bias is applied between outer ring and wall ⇒ flow in “scrape off layer” most important**
- **KH instability turns on at $\Delta v_z \sim V_{ti}/5$, rather than $\Delta v_z \sim V_{ti}$ as predicted by D’Angelo in the collisionless case with no azimuthal flow [D’Angelo (1965), Phys Fluids 8, 1748]. Azimuthal shear appears to play a role.**

Chaos Observed in Fluctuations During Simple Biasing

- ***As bias is increased, drift fluctuations are reduced, then become chaotic as K-H instability develops (Helicon)***

10 V **15 V** **20 V** **35 V**



period doubling

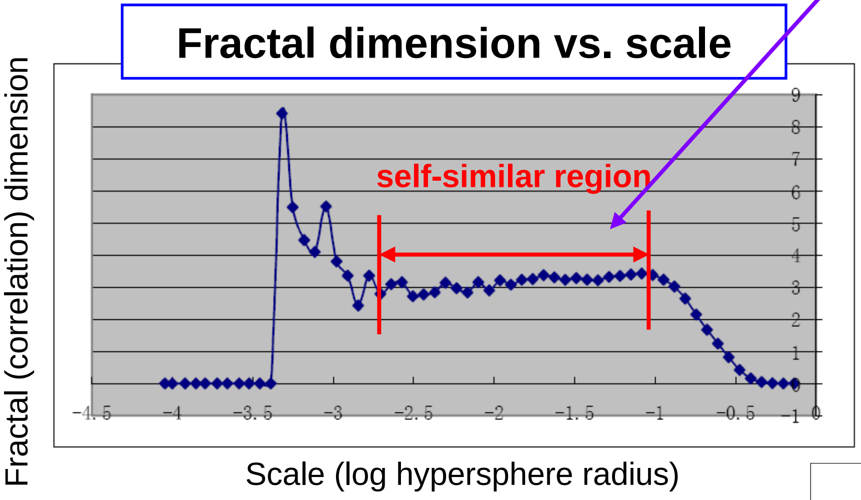
2nd period doubling

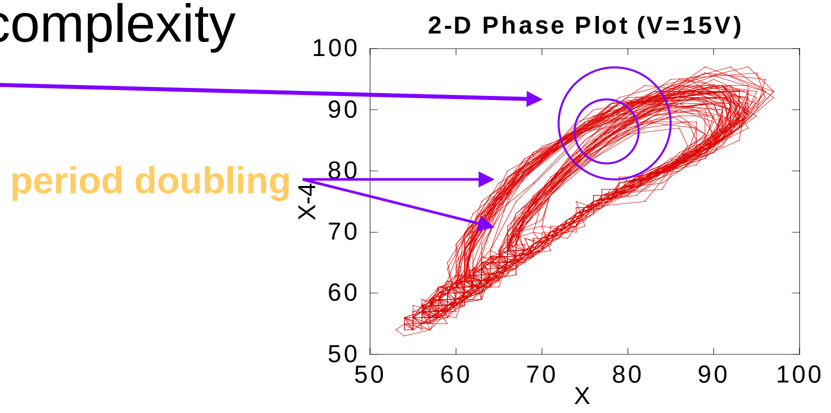
B_0 = 440 G
probe @ R = 6.5 cm

All rings biased w.r.t. wall

Chaos Observed During Simple Biasing cont. (Helicon)

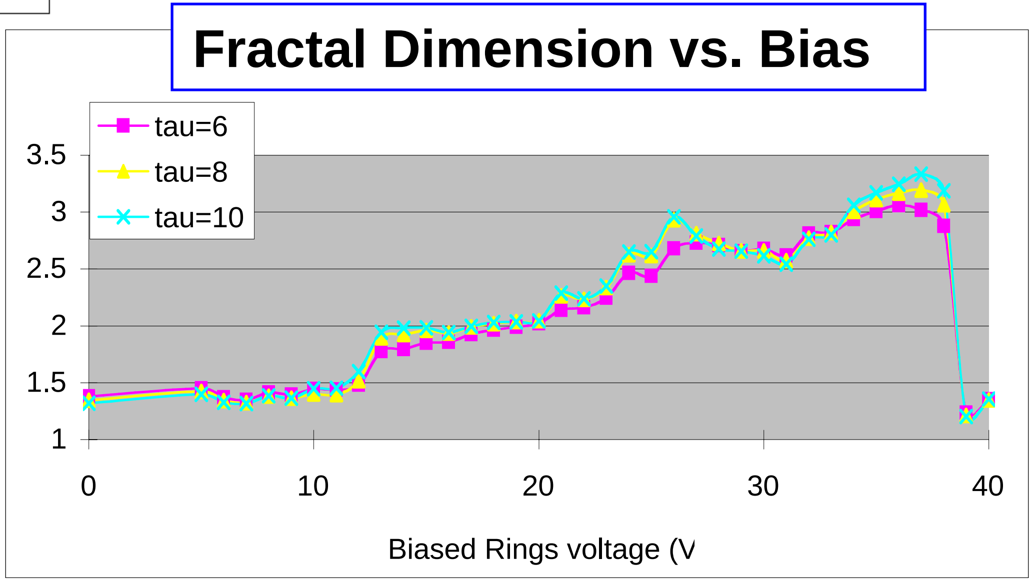
- Fractal dimension measures dynamical complexity
  - -Self-similar structure at small scales
  - - **D > 2 is chaotic**





Delay embedding used to reconstruct fractals

- **Dynamical complexity of fluctuations increases with bias**
- **becomes chaotic at ~ 20 V (~ 4×kT$_e$/e)**



- Here, all rings biased biased w.r.t. wall

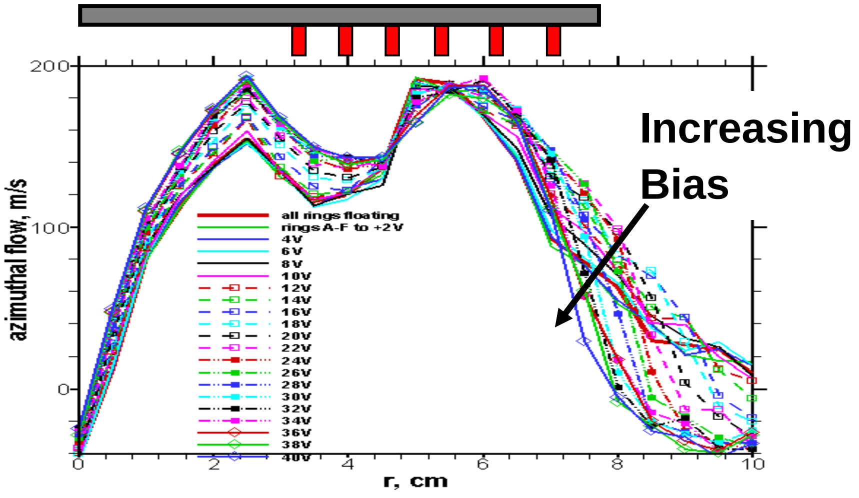
Flow and Fluctuation Profiles During Biasing

- Flow measured by 4 tip Mach probe
- All rings biased w.r.t. wall in this case

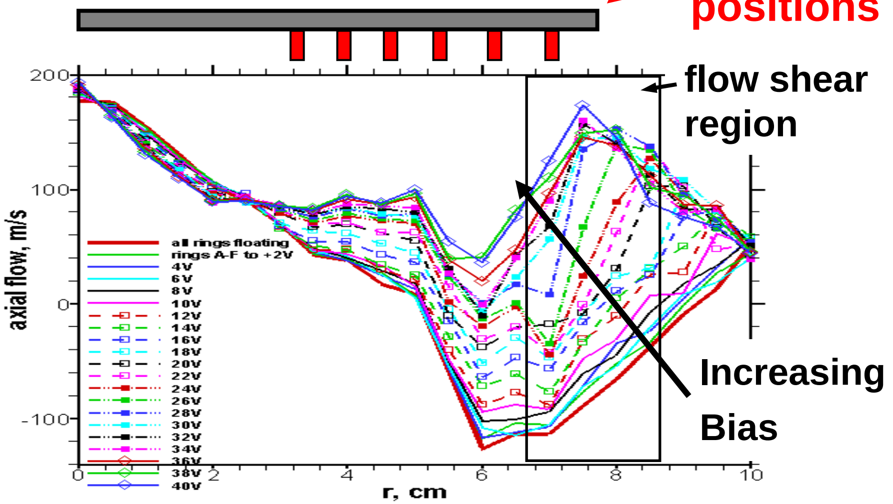
Azimuthal Flow

Axial Flow

Ring and ceramic positions



Increasing Bias

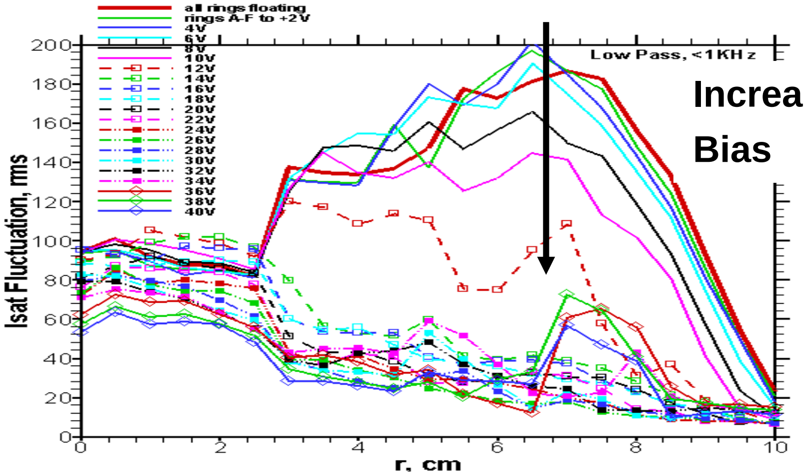


flow shear region

Increasing Bias

Fluctuations: Drift Waves, f < 1 kHz

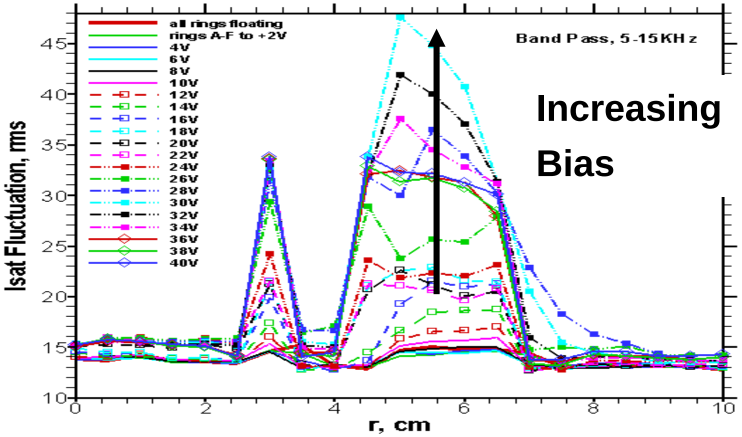
Suppress as bias increased 0→16 V



Increasing Bias

Fluctuations: KH, 5 kHz ≤ f ≤ 10 kHz

Grow as bias increased 12→ 40 V

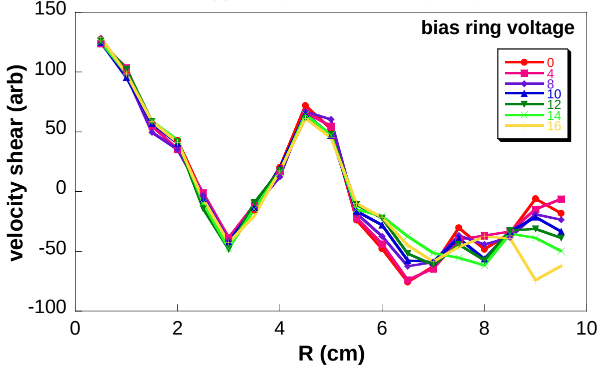


Increasing Bias

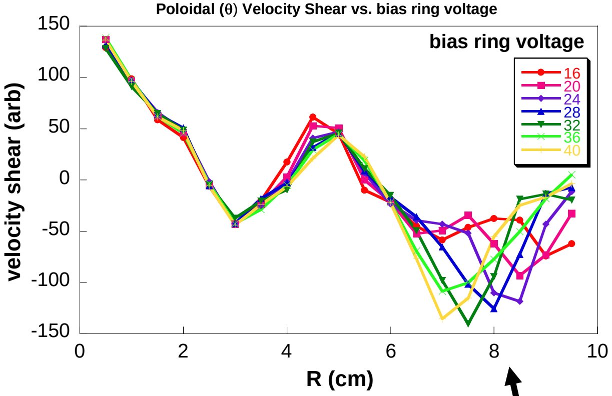
Changes in Velocity Shear with Bias

Azimuthal Shear

Poloidal (θ) Velocity Shear vs. bias ring voltage

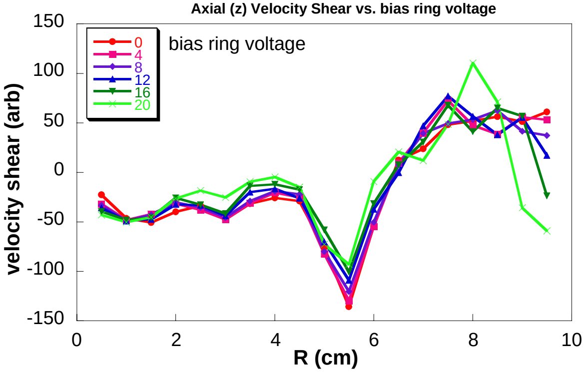


Poloidal (θ) Velocity Shear vs. bias ring voltage

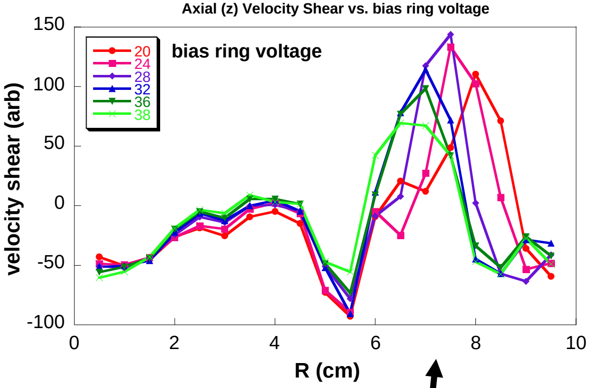


Axial Shear

Axial (z) Velocity Shear vs. bias ring voltage

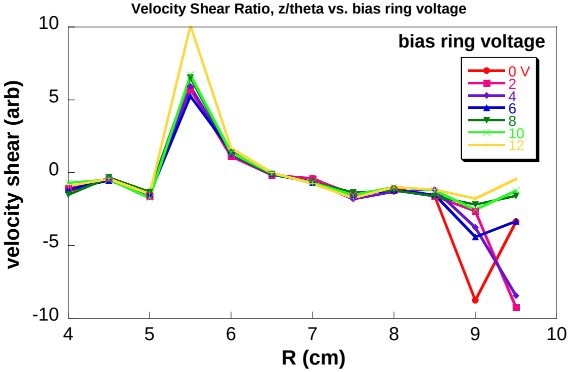


Axial (z) Velocity Shear vs. bias ring voltage

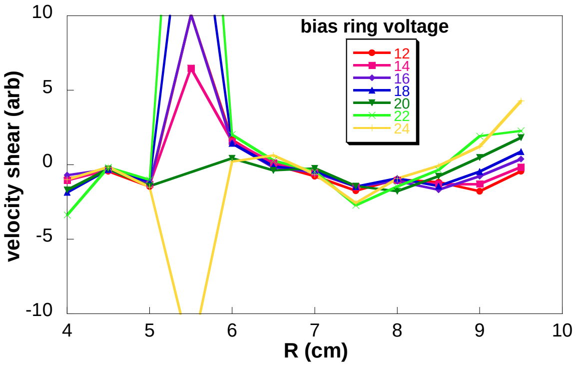


Axial/Azimuthal Ratio

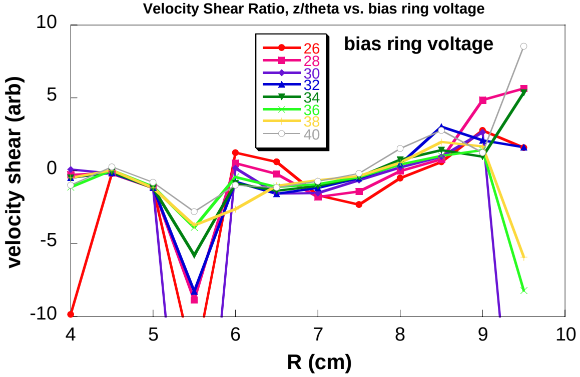
Velocity Shear Ratio, z/theta vs. bias ring voltage



Velocity Shear Ratio, z/theta vs. bias ring voltage

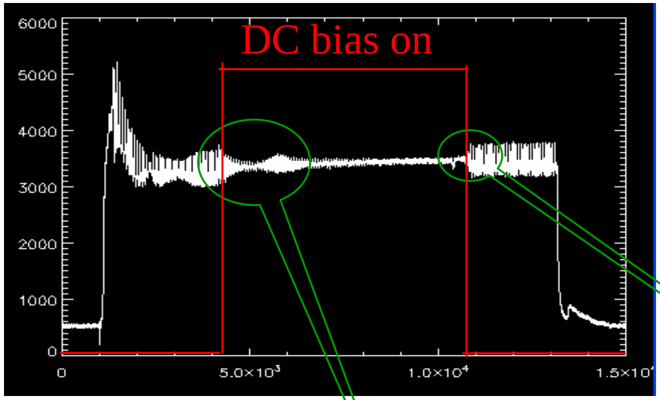


Velocity Shear Ratio, z/theta vs. bias ring voltage



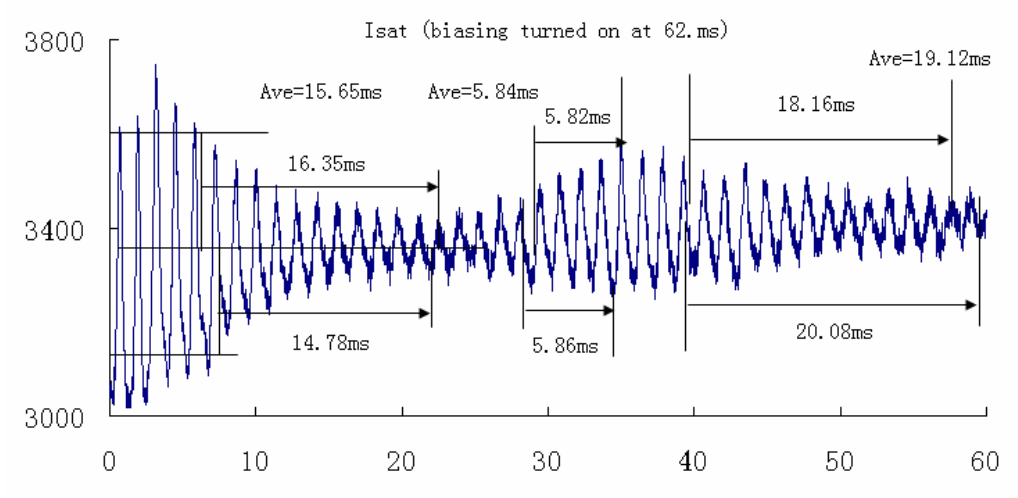
- At bias > 12V, where drift fluctuations suppress, velocity shear region – both azimuthal and axial - moves inward from the outside edge

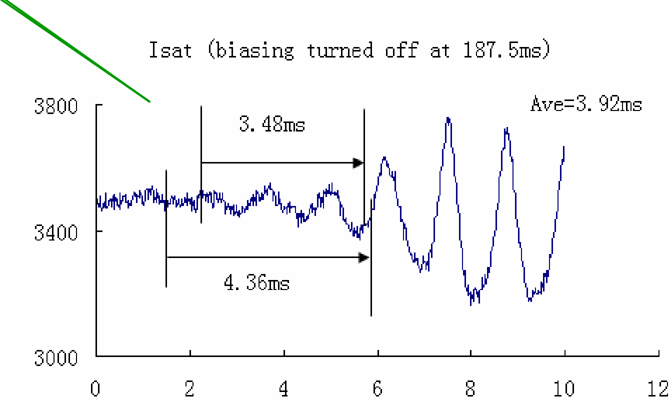
Decay and Growth Time of Fluctuations When Bias Turned On & Off



Calculation of decay time:

- Curve fit upper and lower envelopes
- Average upper time and lower 1/e growth or decay times
- Need to measure corresponding growth and decay times of flows

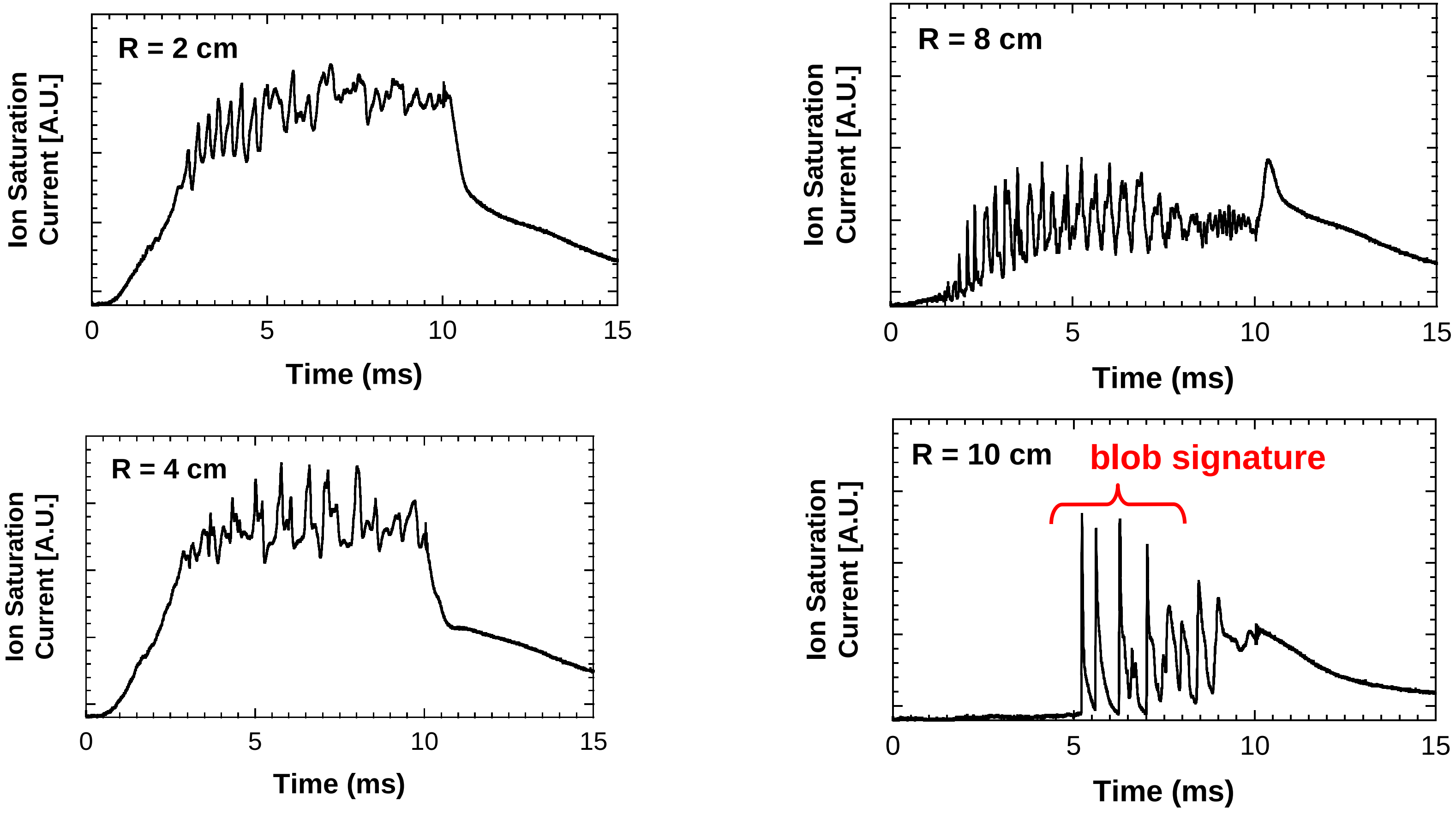




Convective Blobs in HELCAT

- Convective blobs are seen in the edge of HELCAT cathode plasmas, but NOT in helicon plasmas, even at the same neutral fill pressure and magnetic field. **Why?**

Cathode Plasma Ion Saturation Current



Convective Blobs in HELCAT cont.

- Convective blobs are seen in the edge of HELCAT cathode plasmas, but NOT in helicon plasmas, even at the same neutral fill pressure and magnetic field. **Why?**

  - High neutral fill pressure for helicon plasmas

    ⇒ have produced very low gas fill pressure helicon plasmas ($P_{\text{fill}} = 2\times10^{-4}$ Torr), same as cathode plasma

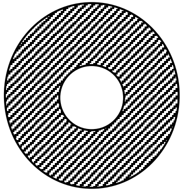
  - Steeper gradients (P, n, T_e, Φ_p, $v_{E\times B}$, $v_{\text{diagmagnetic}}$) in cathode plasmas (e.g. cathode: $L_n \sim 2$ cm, helicon: $L_n \sim 5$ cm)

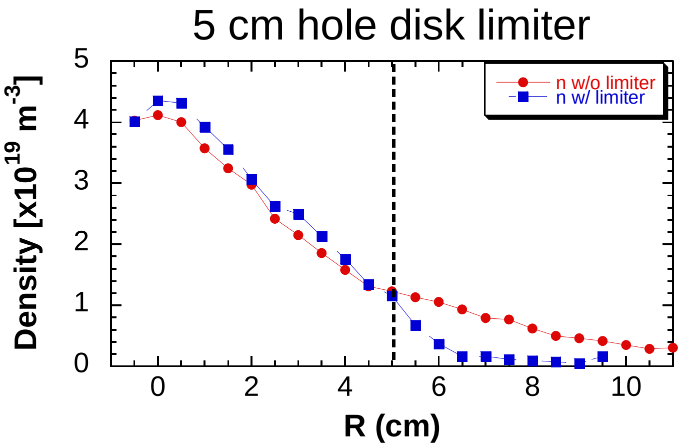
    ⇒ create steeper gradients in helicon plasmas via limiters

    1. vertical edge limiter ⇒ *no blobs*

    2. disk limiter: R = 5 cm

       ⇒ little effect on profile, smaller hole needed





Convective Blobs in HELCAT cont.

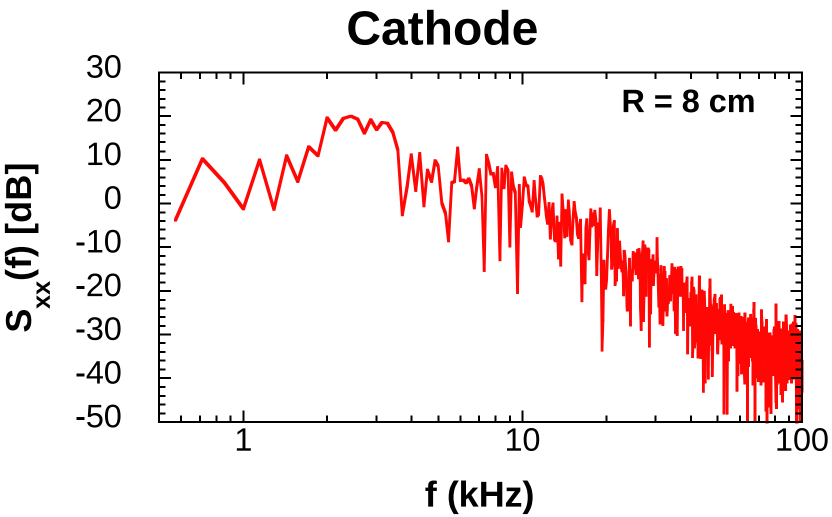
- Convective blobs are seen in the edge of HELCAT cathode plasmas, but NOT in helicon plasmas, even at the same neutral fill pressure and magnetic field. **Why?**

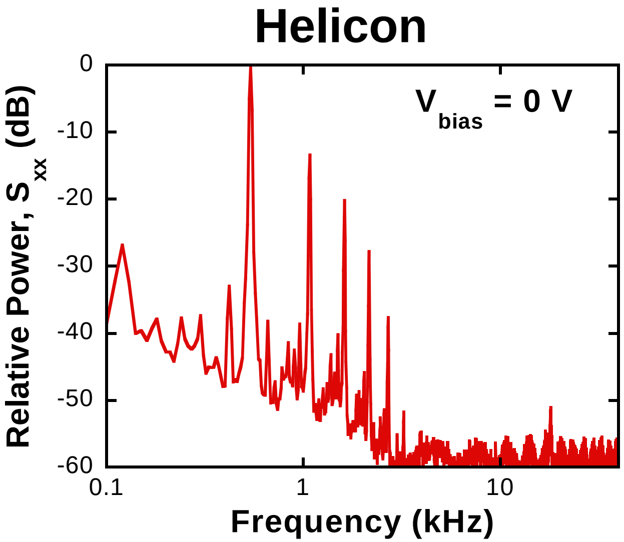
  - Edge drift fluctuations in cathode are broadband, i.e. turbulence is more fully developed

    ⇒ nonlinear solitary structures may be more easily generated in cathode plasma

  - A steeper natural velocity shear layer may exist at the edge of cathode plasmas (due to steep ∇P + radial force balance)

Power Spectra of I_{isat} Fluctuations





Summary

- **Drift fluctuations in helicon and cathode plasmas in HELCAT have significantly different dynamical characteristics.**

- **In helicon plasmas, <u>simple biasing</u> of concentric rings <u>can suppress drift fluctuations</u> easily at low B_0. Biasing between <u>any pairs of rings</u> (with outer rings connected to the vacuum wall, and inner rings connected together) is nearly as effective.**

- **Higher bias voltage is required at higher B_0. At higher B_0, there is a range of bias voltages where suppression is intermittent, before full suppression is observed.**

- **At large bias values (> 5-6 × kT_e/e at 350 G) a second, intermittent instability - likely Kelvin-Helmholtz - appears. Biasing at outer radii drives this mode more easily.**

- **Increasing RF input power, gas fill pressure and magnetic field, causes an increase in the correlation dimension of drift fluctuations.**

- **Convective blobs are observed in the outside edge in cathode plasmas, but not helicon plasmas, even at the same neutral fill pressure and magnetic field.**

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