Symmetry Breaking and the Inverse Energy Cascade in a Plasma

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The application of electrostatic bias to both low density plasma with coherent fluctuations and high density plasma with turbulent fluctuations confined by a magnetic dipole are investigated. Previously, electrostatic biasing of low density plasma was symmetric, drove rapid plasma rotation, and excited the centrifugal interchange instability. This research investigates the application of non-symmetric bias and the influence of broken symmetry on strongly turbulent plasmas. Non-symmetric bias is applied through either point biasing or an equatorial array spanning the device. In both cases, the spatial symmetry of applied bias dramatically effects the plasma fluctuations. With bias applied, the plasma achieves a new equilibrium characterized by amplified low order modes and diminished amplitude of higher order modes. Although the turbulent spectrum changes, the RMS fluctuation level is unchanged by the bias. Bias also causes the turbulent electrostatic fluctuations to coalesce into a quasi-coherent mode and the appearance of increased coherence. The effect of bias configuration is also seen to change the measured levels of nonlinear coupling. Non-symmetric biasing increases nonlinear coupling while symmetric biasing leaves the coupling unchanged. These results represent the first experimental demonstration of symmetry breaking driving the inverse energy cascade in a quasi-two dimensional plasma system. The application of dynamic and rotating electrostatic bias as well as plans for applying turbulent feedback are discussed.
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Chapter 1

Introduction

The results presented in this thesis explore the consequences of geometric electrostatic symmetry to the turbulence found in a dipole confined plasma. This Chapter briefly introduces the physics of plasmas confined by a magnetic dipole, including previous experimental results and observations of both laboratory dipole confined plasmas and plasmas trapped within planetary magnetospheres.

1.1 Plasmas in Nature

Historical mention of the aurora is nearly as old as the human written tradition [25]. The advent of the compass allowed study, and in 1741 Hiorter noted changes in the earth’s magnetic field are correlated to auroral activity [31]. In 1859 a British astronomer named Richard Carrington observed a particularly bright solar flare that was followed 18 hours later by a massive geomagnetic storm, now known as the Carrington Event [44]. While ordinarily confined to high latitudes, during this event the aurora were strong enough to be observed in Puerto Rico. Technological developments allowed great advances in the observational study of the aurora, in particular cameras and spectrometers.

The dawn of the space age allowed the study of aurora to move from observing at a distance to in situ measurements. In January 1958 the United States launched Explorer 1 carrying several scientific instruments, including radiation detectors onboard. Combined with Explorers 3 and 4, launched
throughout 1958, these probes discovered the existence of artificial radiation belts surrounding the earth \[60\]. It was soon realized that the radiation belts are only part of a larger region of space dominated by the earth’s magnetic field. This region was termed the “magnetosphere” in 1959 by Thomas Gold \[17\].

As satellites ventured further from the Earth we have gained a broader understanding of magnetosphere, solar wind, and eventually the magnetosphere of other planets. Studies of the magnetospheres of Jupiter and Saturn reveal extensive activity. The magnetosphere of Jupiter is fueled by the volcanic eruptions on Io, estimated to emit 1000kg/s of gas that becomes ionized and forms the Io plasma torus \[1\]. The plasma torus becomes entrained in the rapid rotation of Jupiter and the co-rotating high $\beta$ magnetosphere, creating an outward radial effective gravity that can drive an interchange instability, a plasma analog to the Rayleigh-Taylor fluid instability \[36\].

While the earth’s magnetosphere is stable to the interchange instability, interaction with the solar wind can drive large particle fluxes creating ionospheric currents \[13\]. The inner radiation belt is relatively stable, but geomagnetic storms have a larger effect on the outer radiation belt \[14\]. These storms have the potential to result in widespread terrestrial damage. During the Carrington Event the ionospheric currents were strong enough to allow telegraph operators to communicate disconnected from power sources \[9\]. It is estimated that CMEs of this magnitude occur roughly every 500 years \[44\]. A smaller event in 1989 resulted in loss of power to six million people in Quebec \[9\]. Future similar events could have impacts on communication, navigation, and satellites as well as the power grid. All of these motivate continued research in the field.

### 1.2 Laboratory Magnetospheres

In an effort to produce experimental verification of his theories of the aurora from 1901 to 1913 Birkeland constructed and experimented on a series of terellae, or “little earths” \[12\]. While study of the magnetosphere continued and later blossomed with the advent of satellite, the focus of most laboratory plasma experiments shifted to the search for controlled fusion via tokamaks and
stellarators. But the past twenty years has seen three laboratory magnetosphere experiments come into operation. Renewed interest in constructing laboratory magnetospheric experiments reemerged in the late 1980s, as a possible alternate route to achieve magnetic fusion energy [22].

The Collisionless Terella Experiment (CTX) was constructed in 1992 at Columbia University and has furthered the understanding of artificial radiation belts [43]. It also served as a test bed to characterize the Hot Electron Interchange (HEI) instability, and the use of RF waves to disrupt the instability [37, 42]. The discovery of the centrifugal interchange instability in a laboratory experiment verified observations of Saturn and Jupiter’s magnetospheres [38]. Recent work has focused on characterizing turbulent fluctuations and radial particle transport that results [21, 20].

The other two experiments investigating laboratory magnetospheric phenomena utilize a levitated magnetic coil. One is the Levitated Dipole Experiment (LDX) at the Massachusetts Institute of Technology run in conjunction with Columbia University. The levitated coil drastically reduces the dominant plasma loss mechanism in CTX, which occurs when plasma flows along field lines and strikes the magnet and support structure, closing the magnetic field lines [16]. Experiments at LDX have shown the ratio of plasma energy to magnetic field energy in excess of 20% [15]. LDX has also demonstrated an inward turbulent particle pinch whereby particles are transported radially into the heating resonance where the density peak occurs [6]. Stationary density profiles have also been observed, suggesting the energy confinement time may exceed the particle confinement time, opening the possibility of advanced fuels and aneutronic fusion [29].

The other experiment, Ring Trap 1 (RT-1), is located at the University of Tokyo. RT-1 can operate as either a quasi-neutral plasma with microwave heating, like CTX or LDX, or as a pure electron plasma. When operating as a pure electron plasma particle confinement times are very long, measured up to 300s [53]. Inward radial particle transport against the density gradient, reminiscent of LDX, is observed in both pure electron and quasi-neutral operation [67, 52]. Peak local $\beta$ reaches $\sim 70\%$ [51]. Of note, in a predecessor of RT-1, Proto-RT, applied electrostatic bias to the an electrode mounted to the magnet. Negative applied bias excited near sonic level flows while positive bias created a small vacuum bubble between the electrode and the plasma, and failing to produce an
interior electric field [50].

1.3 Principal Results

CTX provides a platform to investigate and modify plasma turbulence. The turbulence observed in CTX displays an interchange nature due to the lack of magnetic shear. The absence of field-aligned dynamics allows CTX to be investigated as a quasi-two dimensional system. A hallmark of two dimensional turbulence is the inverse energy cascade [33]. In this thesis electrostatic bias, previously a successful tool [39], is used in a search to experimentally modify the turbulent fluctuation spectrum. Table 1.1 details various biasing methods investigated in this thesis. It is found:

- The inverse energy cascade was observed by breaking the azimuthal symmetry by applying a non-symmetric equatorial bias. During the application of non-symmetric equatorial bias the high frequency fluctuations are seen to decrease while low frequency modes are enhanced. Best displayed in Subsections 7.3.1 & 7.3.3.

- During applied bias the coherence of these low frequency modes increase. This is observed by both floating potential probes and polar loss current detectors (Subsection 7.3.2).

- These effects are associated with an increase in nonlinear frequency coupling as measured with bicoherence in comparison to both a high density baseline and a symmetric bias case. Presented in Subsection 7.3.4.

- The non-symmetric response is independent of azimuthal mode structure, with \( m = 1, 3, 6 \) shown to produce a similar response to the fluctuation spectrum. Demonstrated in Subsections 7.3.1 & 7.3.4.

- The failure of a rotating non-symmetric equatorial bias to produce a plasma response demonstrates the observed inverse energy cascade is not a resonant process but results from static symmetry breaking caused by non-symmetric bias. Shown in Section 7.4.
### CHAPTER 1. INTRODUCTION

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Table 1.1: Table outlining the electrostatic bias configurations and chapter discussed in this thesis.

#### 1.4 Organization

This thesis is organized as follows: Chapter 2 provides a brief overview of turbulence and specific implications of two dimensional turbulence, and the application of these to laboratory plasmas; Chapter 3 discusses the device parameters, instrumentation of CTX, and signal analysis techniques; Chapter 4 details characteristic plasma discharges and the transition from low density plasmas dominated by coherent fluctuations, via additional fueling, to high density, turbulent plasmas; previous results from driving axisymmetric radial currents in low density are presented Chapter 5, and extended to the high density turbulent regime; the application of a point bias in the bulk plasma constitute Chapter 6; in Chapter 7 azimuthal symmetry breaking of applied equatorial bias is shown to drive the inverse energy cascade.
Chapter 2

Introduction to Turbulence

Turbulence is a ubiquitous, but poorly understood phenomenon, observed both in nature and the laboratory. Turbulent motion occurs across many size scales from blood flow, atmospheric weather, and accretion disks. This chapter will introduce some understanding of turbulence, discuss how the simplifying step of reducing the dimensionality from three to two dimensions complicates dynamics and point to the theoretical underpinnings that motivate experiments in subsequent chapters.

2.1 Turbulence in Fluids

The origins of turbulence can be found in the Navier-Stokes Equation in Equation 2.1,

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = \mathbf{f} - \nabla p + \mu \nabla^2 \mathbf{v} \tag{2.1}
\]

the representation of the momentum conservation for a fluid. Solutions to this equation show the evolution of the velocity field of a fluid. The system behavior is determined by the relative weighting between the second, nonlinear term on the left-hand side (\( \mathbf{v} \cdot \nabla \mathbf{v} \)), and the final term of the right-hand side (\( \nu \nabla^2 \mathbf{v} \)), representing viscous diffusion, with \( \nu = \mu/\rho \). The ratio of these terms can be found through nondimensionalizing the equation by characteristic scales,
CHAPTER 2. INTRODUCTION TO TURBULENCE

\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = \frac{\mathbf{f}}{\rho} - \frac{1}{\rho} \nabla p + \frac{1}{Re} \nabla^2 \mathbf{v}. \]  

(2.2)

The dimensionless constant preceding the diffusive term is known as the Reynolds number

\[ Re = \frac{VL}{\nu} \]  

(2.3)

giving a scale for the ratio of convective to diffusive terms present in a system. For low Reynolds number viscosity can damp away energy in the fluctuations and the behavior of fluid flow is laminar. As the Reynolds number increases, the diffusive term has smaller effect and the energy of the flow is increasingly transported via the nonlinear convective derivative. Turbulent behavior roughly emerges for Reynolds numbers of \( \sim 100 \) and is fully turbulent for Reynolds numbers of order 2000. Typical Reynolds numbers in laboratory fluid dynamics experiments are of the order of \( \sim 10^7 \), atmospheric Reynolds numbers are even higher, with values of \( \sim 10^{12} \).

The nonlinearity present in the convective derivative couples fluctuations at different spatial scales. In high Reynolds number turbulent flows, this coupling dominates the much smaller viscous diffusion term. Hence, larger scales couple to smaller scales, transferring energy down to smaller scales. Following this coupling down to smaller length scales we see the Reynolds number, \( \propto L \), decreases as well. At small enough scales the viscous term is no longer insignificant and energy is dissipated as heat. This process is known as the forward energy cascade and takes place in the inertial range, which spans the length scales from the energy injection scale to the viscous range where viscosity is no longer ignored. The range from injection to dissipation scale can be immense, an example is the Earth’s atmosphere where the fluctuations are driven at the scale of hundreds to thousands of kilometers while the diffusive scale length is on the order of millimeters, meaning the energy cascade spans nine orders of magnitude \([59]\). An intuitive example of the forward energy cascade is adding cream to coffee, initially the two liquids are separated but with stirring at a large scale, smaller scale vortices spin off, which spin off ever smaller scale vortices until neither black coffee nor white creamer is visible.
CHAPTER 2. INTRODUCTION TO TURBULENCE

2.2 Two Dimensional Turbulence

In an effort to simplify the study of turbulence researchers, notably Kraichnan, began to study two dimensional turbulence [32]. The assumption of incompressibility, $\nabla \cdot \mathbf{v} = 0$, and inviscid flow, $\nu = 0$ are made, the latter approximately saying the Reynolds number is large making the diffusion term insignificant until reaching very small scales.

A consequence of reduced dimensionality is the change in the behavior of the vorticity, $\omega = \nabla \times \mathbf{v}$, as vortex stretching is no longer possible. This results in the conservation of enstrophy, the mean square vorticity. A full derivation can be found in Tabeling’s monograph “Two-dimensional turbulence: a physicist approach” or the review by Boffetta and Ecke [58, 3]. The existence of two conserved quantities, energy and enstrophy, places a further constraint on the system and results in dual cascades in separate inertial ranges. A forward enstrophy cascade exists from the scale of the instability at moderate wavenumber values to high wavenumbers at fine scales. The second cascade is the inverse energy cascade, whereby the the energy of the instability nonlinearly couples
from the intermediate injection scale of the instability to smaller wavenumbers and larger spatial scales to form a condensate at roughly the system size. Figure 2.2 contrasts the behavior of the two-dimensional and three-dimensional turbulent cascades.

![Log-log plot of energy and enstrophy transfer](image)

Figure 2.2: Cartoon demonstrating the 3-D forward energy cascade from the injection scale, \( k_i \), to higher wavenumbers until dissipated at \( k_d \). 2-D turbulence exhibits very different behavior resulting from conservation of enstrophy. In 2-D a forward enstrophy cascade flows from \( k_i \) to \( k_d \) while an inverse energy cascade flows from moderate wavenumbers to smaller wavenumbers where damping dominates.

While no true two-dimensional systems exist a number of quasi-two-dimensional examples have been found in atmospheric flows, soap films, thin conducting fluids, and plasma physics [3]. In these examples flow is restricted to two dimensions by spatially limiting the third dimension or providing a strong magnetic field preferencing one dimension.

In 1986 Sommeria experimentally observed the inverse energy cascade by driving currents through a thin mercury film in a magnetic field [56]. This result was confirmed and expanded upon a decade by Paret and Tabeling driving electric currents through a thin electrolyte film in spatially varying magnetic field, demonstrating the inverse cascade is stationary [46, 47]. The presence of a strong planar vortex limits suppresses perpendicular motion enabling the inverse energy cascade in thick turbulent layers [64]. This mechanism is proposed as a method to enable upscale energy transfer in the atmosphere.
2.3 Plasma Turbulence

The Hasegawa-Mima equations conserve energy and enstrophy while studying nonlinear mode coupling [24]. The equivalence of the Hasegawa-Mima equations and the Charney equations governing the nonlinear interactions of Rossby waves in the atmosphere were soon realized [23]. In this way despite largely different governing equations, the equilibria of 2D MHD turbulence display the same features as 2D hydrodynamic turbulence [63]. This was validated with the identification of the inverse energy cascade in the H-1 toroidal heliac [65, 66, 55]. The presence of the upscale energy transfer is linked to the low-to-high confinement phase transition [55] and the generation of zonal flows. This interaction is nonlocal, meaning the high frequency modes couple directly to the zonal flow without intermediate coupling [40].

One method of measuring and altering the plasma turbulence is through the use of electrostatic bias probes [28, 26, 54, 7, 8]. In Iizuka et al. a short square wave pulse applied in the edge of a plasma column excited a convective cell [26]. Driving currents through a multipoint array at the plasma boundary of a plasma column can decrease broadband turbulence through amplification of a preselected mode [54]. In this configuration the transition to turbulence through driven excitation is seen to be local [8]. This is in contrast to toroidal geometry observations.

Outside of the laboratory turbulence is observed in the solar wind plasmas, with intermittency and the forward cascade observed [48]. At points in the observations the inverse energy cascade is observed [57]. The varying magnetic guide field is proposed as moderating this transition. Biferale et al. conducted simulations that provided evidence the inverse cascade can exist in 3D isotropic turbulence in limited cases [2].

Recent studies have shown the geometry of the system boundaries, in particular symmetry breaking, to impact turbulent dynamics. Nonaxisymmetric geometries were shown to cause rapid generation of angular momentum, and this phenomenon was demonstrated to be enhanced in MHD flows [4]. Symmetry breaking has been shown to lead to self-organization [5]. The role of symmetry breaking has also been shown to play a role in plasma intrinsic rotation through the turbulent modification of momentum transport [35].
2.4 Summary

Turbulence is both one of the most common and least understood physical processes. One hallmark result is the existence of a forward energy cascade in three-dimensional hydrodynamic turbulence. Another is the additional conserved quantity of two-dimensional turbulence. In 2D, it is found that in addition to conservation of energy, enstrophy is conserved as well. This conservation of enstrophy leads to a dual cascade. Energy is predicted to flow from the injection scale to large scales, typically of the system size. This is known as the inverse energy cascade. A forward enstrophy cascade exists with the enstrophy flowing from the injection scale to small scales then dissipates.

The inverse energy cascade has been experimentally observed in a variety of systems including plasmas and the CTX device [21]. The presence of symmetry breaking is shown to play a role in fluids through altering the momentum and angular momentum of the system and the characteristic size scales of the turbulence.
Chapter 3

Description of CTX Experiment

CTX is an ECRH generated plasma confined by a mechanically supported electromagnet capable of pulses a few seconds in length. Operating at densities approaching the 2.45GHz cutoff density, plasmas are diagnosed with moveable floating potential probes, a radial array of three triple probes, and a 16-point radial transport array. Non-perturbative diagnostics include hard and soft x-ray diodes as well as a photo diode array. A 96-point end loss current array allows visualization of plasma convection. Electrostatic bias can be applied either via a probe located in the bulk plasma, or a twelve segment array at the inner radial boundary on the magnet equator.

3.1 Vacuum System

The CTX device is a mechanically supported dipole electromagnet in a 1.4m diameter aluminum vacuum vessel. Experimental base pressure is reached from atmospheric pressure through the use of a series of pumps. A mechanical roughing pump brings the chamber from 760 Torr to $p < 100 \text{ mTorr}$ when pumping is switched to turbo molecular pump achieving $p \approx 1 \times 10^{-6} \text{ Torr}$. The final step employs a cryogenic pump that reaches and maintains a base operating pressure of $p \leq 1.5 \times 10^{-7} \text{ Torr}$ for all experimental conditions. Plasma production and heating is accomplished through electron cyclotron resonance heating (ECRH) with the application of 1kW of microwave power at 2.45 GHz. A piezo-electric valve connected to a hydrogen line allows fueling programming
in one or a series of puffs, with varying duration though typically $\approx 1 - 10 \mu s$, allowing variable plasma density.

Figure 3.1: Schematic top view of the CTX vacuum chamber including primary diagnostic probes. Also shown is the magnetic field structure and cyclotron heating resonance. On the magnet itself are both the equatorial biasing array and individual sensors of the polar imager.
Figure 3.2: Schematic of the equatorial cross-section of CTX illustrating primary $E \times B$ motion. Not labeled is reversed $E \times B$ flow inside the resonance layer.
3.2 Model CTX Magnetic Dipole

The CTX magnetic field is well described by the point dipole approximation [36]. The axisymmetric magnetic dipole field in Clebsch coordinates is

$$\mathbf{B} = \nabla \phi \times \nabla \psi = \nabla \chi$$  \hspace{1cm} (3.1)

where $\mathbf{B}$ is the vector magnetic field, $\phi$ is the azimuthal angle, $\psi$ is the magnetic flux, and $\chi$ is the magnetic scalar potential. For a point dipole and neglecting plasma diamagnetic currents the magnetic flux and magnetic scalar potential can be written in spherical coordinates

$$B(r, \theta) = \frac{M}{r^3} \sqrt{1 + 3 \cos^2 \theta}$$
$$\psi(r, \theta) = \frac{M}{r} \sin^2 \theta$$  \hspace{1cm} (3.2)
$$\chi = M \cdot \nabla \frac{1}{r} = \frac{M}{r^2} \cos \theta$$

A field line is labeled by two coordinates $(\psi, \phi)$. Alternately, the radial position of a field line can be written in terms of equatorial radius $L$, where $\theta = \pi/2$. In CTX, $M = B_0 L_0^3$, $B_0 \approx 0.0875$ T (875 Gauss). This is the field strength at the ECRH resonance resonance for 2.45 GHz occurring at the equatorial radius of $L \approx 0.27$ m, giving $M = 0.0017$ Tm$^3$.

There are three periodic particle motions in the vacuum magnetic field configuration: cyclotron, bounce, and drift; each with their own characteristic frequency $\omega_c \gg \omega_b \gg \omega_d$. Each periodic motion is also marked by an adiabatic invariant $\mu, J, \psi$, respectively [45]. The third invariant encloses the drift path of a particle around the dipole.

3.3 The Diagnostic Set

Plasma diagnostics are the means by which plasma parameters are measured either directly (e.g. probes, energy analyzers), or indirectly (e.g. photodiodes, fast cameras, x-ray emission). CTX is
outfitted with a wide spectrum of diagnostics to measure neutral pressure, microwave forward and reflected power, density, potential, x-ray emission (hard and soft), visible light (photodiodes, fast camera), particle flux, polar current and mach number for flow measurements.

3.3.1 Probes

This section presents a brief description of probes installed in CTX. A full explanation of Langmuir probe theory and design can be found in Demidov’s review “Electric probes for plasmas: The link between theory and experiment” [11].

Floating Potential Probes

CTX is outfitted with a number of high-impedance floating potential probes. These probes are stainless-steel wire tips with 100 kΩ resistors near the probe tip mounted on an insulating aluminum oxide rod. The probe is connected through a sliding seal allowing control of the radial position of the probe. Each probe tip is connected to a co-axial cable and run to amplifiers before being input into a high speed digitizer.

The Single-Electrode Langmuir Probe

The Langmuir probe in CTX, similarly constructed to allow radial positioning, is a flat square I$_{stat}$ probe (reference probe appendix) with area 2 cm$^2$. This Langmuir probe is biased at $V_b = -180V \gg T_e/e$ for the bulk electron temperature of $T_e < 10$ eV. The bias is applied through a battery pack coupled with a 0.1 $\mu$F capacitor in parallel to ensure high frequency response.

Bias Probe

An additional individual point probe was constructed to apply electrostatic bias in the bulk plasma. To this aim the impedance was kept low and the surface area increased to 20 cm$^2$ increasing the current drawn or emitted by the probe, Figure 3.3. This probe was placed off the equatorial axis of the plasma to decrease plasma perturbations. The probe additionally functions as a large area
CHAPTER 3. DESCRIPTION OF CTX EXPERIMENT

Figure 3.3: Photograph of the bias probe installed in CTX.

Langmuir probe when not biased better reflecting the DC floating potential due to the larger probe surface area. A voltage divider of the form

\[ V_{\text{out}} = V_{\text{in}} \frac{R_2}{R_1 + R_2} \]  

with \( R_1 > R_2 \), this allows a measured voltage to be scaled such that \( V_{\text{out}} < 5V \), the limit of the CTX digitizers.

Figure 3.4: Schematic of the bias probe installed in CTX during biasing with a voltage divider appropriate for high density.
Triple Probe

A triple probe array is also installed on CTX and is used to measure the edge plasma parameters of floating potential, temperature, and density (Figure 3.5). The array consists of three triple probes with radial separation of \( \sim 2.5 \) cm between the probe sets. There is a 0.45 cm separation between the individual probe tips, which is a few times the electron Debye length \( \lambda_{De} \approx 1 \text{ mm} \). The triple probe is wired with a large 10 M\( \Omega \) resistor for accurately measuring the floating potential, and a -180 V supply to collect ion saturation current as illustrated in Figure 3.6. The ion saturation current is calculated by measuring the voltage differential across the known \( R_+ \) resistor. All of the signals are transmitted through voltage dividers to reduce the amplitude to the digitizer input levels of \( \pm 5 \) V.

Figure 3.5: Photograph of the radial array of three triple probes.
Figure 3.6: Schematic of the circuitry for a single triple probe installed in CTX.

### 3.3.2 Rake Transport Array

A 16 point radial transport array constructed and installed on CTX is shown in Figure 3.7. The array spans 90° of the azimuthal section. The array is mounted coaxial to the magnet and can be moved along this axis, allowing measurements to be taken at different flux surfaces. The array is composed of 31 probe tips alternating between floating potential probes with 100 kΩ resistors at the tip and ion saturation probes. By differencing adjacent floating potential measurements the local azimuthal electric field is obtained, which is used to calculate the radial component of the $\mathbf{E} \times \mathbf{B}$ drift. The local radial particle flux is then

$$
\Gamma_r = \bar{n} \bar{v}_r = \bar{n} \frac{E_\phi}{B} = -\frac{\bar{n}}{BR} \frac{\partial \Phi}{\partial \phi}
$$

(3.4)

This multipoint flux measurement can be compared to the global particle flux field calculated through inverting the stream function using ion loss current measurements from the polar imager (see next section) as outlined by Grierson et al. [20]. For the experiments conducted in this thesis, the rake transport array was used as a multipoint array of floating potential measurements allowing fine resolution correlation analysis.
3.3.3 Polar Imager

The “polar imager” (shown in Figure 3.8) is an array of 96 gridded energy analyzers mounted on the south pole of the CTX dipole magnet. The detectors are situated at a place such that the the magnetic field at each detector aperture is $\approx 2$ kG. A result of maintaining a near constant magnetic field strength is the collected particles of a given species with equal perpendicular energy will share the same gyro-radius across detectors. This ensures detectors on different radii collect particles with the same range of energies. Additionally, with all detectors located at the same field strength each detector will be sampling an equal magnetic flux. This occurs despite the fact that flux tube volume grows strongly as equatorial radius increases, the flux tube volume is $\delta V = \int d\chi / B^2 \propto L^4$.

The array of particle detectors are mounted within a cap covering the CTX magnet which is spray coated with aluminum oxide to a thickness .3 mm, eliminating field-aligned currents as well as removing the possibility of individual flux tubes shorting to another flux tube.

Each gridded energy analyzer has a 1 cm$^2$ aperture and a series of four individually biased stainless steel meshes between the aperture and the stainless steel collector plate. The first set of
meshes is floating to electrostatically shield the bulk plasma from the applied voltages of the three following grids. These grids are used, respectively, to repel electrons, ions, and finally to suppress secondary electrons emitted from the collector plate. With no bias applied to either the electron or ion repeller grid the collected current is negative and an approximation of the flux-tube integrated electron distribution function. If the ion repeller voltage is set to a modestly low positive voltage ($\sim +10$ V) only electrons will be collected due to the lack of ion heating in CTX.

To eliminate electron collected current the electron repeller voltage must be set higher ($> -50$ V), at which point the collected polar current is the flux-tube integrated ion saturation current,

$$n \propto \frac{I_{\text{polar}}}{\delta V}.$$ (3.5)

Figure 3.8: Left, photograph of the CTX magnet with the polar imager installed during a discharge. Right, schematic of polar imager with the magnetic field and constant field contours displayed.

With the repeller grids set to exclude electrons or ions the polar imager collects a current proportional to the flux tube integrated density; be it electron or ion density. With the increased fueling required to enter the turbulent regime this current increases by over an order of magnitude. Separate amplifiers are used for low density and high density measurements. The amplifiers used in the low density regime are 2 M$\Omega$ transimpedance amplifiers ($|I_{\text{polar}}| < 0.25 \mu$A), while the high density amplifiers have a 51 k$\Omega$ transimpedance ($|I_{\text{polar}}| < 100 \mu$A). The field-aligned current increases by a factor of 400 from the low to high density regime, necessitating the production of low-gain
amplifiers.

### 3.3.4 Equatorial Biasing Array

The presence of the magnet inside the vacuum chamber and within the plasma produces four plasma/surface boundaries in CTX. The first two are field-aligned where the field lines reach the insulating magnetic cap, the remaining pair are radial boundaries; the outer boundary being the vacuum chamber while the inner one again intersects the magnetic polar cap.

A thermionic bias array was made from a series of six fine meshes about the equatorial section of the magnet. These meshes were configured to allow thermionic emission of electrons into the plasma by driving a current through the meshes. Connected into a single diagnostic the equatorial biasing array allowed excitation and exploration of the centrifugal interchange instability by driving an axisymmetric radial current [39].

![Photograph of the equatorial array as installed.](image)

For the experiments reported in this dissertation the equatorial array was modified in two key
aspects. First, the number of elements was increased from six to twelve to better investigate non-axisymmetric effects. This was accomplished by eliminating the thermionic emission configuration used in previous experiments. A portion of the upgraded array is shown in Figure 3.9.

Each of the dozen segments can be independently configured at the vacuum feedthrough to be biased, grounded or to function as a floating or current probe. Linking the segments together allows the imposition of a potential bias configured with a \( m = 0, 1, 2, 3 \) or 6 azimuthal mode structure as seen in Figure 3.10. Segments not biased are connected to a current sensor, effectively grounding them.

![Figure 3.10: Possible configurations of the upgraded equatorial biasing array.](image)

The second facet of the array upgrade was to adapt the array to drive higher currents, enabling operation in the turbulent high density regime. The six earlier array elements were tungsten meshes with 80% transparency. The effective area of an individual segment was increased by switching to 51 \( \mu m \) thick stainless steel shim stock. Each element was comprised of five pieces of shim stock 18mm × 90mm folded spot welded into a loop. Prior to the upgrade the equatorial array could
source 20 mA of current in an axisymmetric configuration, following the upgrade this number went up at least an order of magnitude (> 200 mA) and currents could exceed the capabilities of the system power supplies.

3.4 Signal Analysis

The data analysis contained in this thesis will look at time series measurements made of various parameters. Features of these measurements, such as signal means and RMS fluctuation levels, will be presented. Other analysis procedures will rely on converting the signal from the time domain to frequency space through the Fourier Transform. The analytical Fourier transform $\hat{\phi}(\omega)$ of a time series $\phi(t)$ is given by

$$\hat{S}_i(\omega) = \int S(t)e^{-i\omega t}dt$$

where $t, \omega$ denote time and frequency respectively. The result is a complex-valued array of frequencies with the varying amplitude allowing identification of the principal fluctuating components of the time series. This process is made more rapid and computationally less involved through the use of the Fast Fourier Transform (FFT).

Turbulent fluctuations are ‘non-stationary’, implying that the frequency value of a primary component may shift or decay in amplitude while another component may emerge. This necessitates averaging the spectra over many time windows, a process known as ‘ensemble statistics’. The ensemble spectrum of a time varying quantity $S(t)$ over sub-samples $S_{(i)}(t)$ is given as

$$\langle \hat{S} \rangle \equiv \frac{1}{M} \sum_{i=1}^{M} \hat{S}_{(i)}$$

where $\hat{S}_{(i)}$ being the Fourier transform of $S_{(i)}$. The time-series $S(t)$ is split into realizations, $S_{(i)}$, of length $\Delta t$. The width of the window sets the lowest frequency able to be resolved, $1/\Delta t$, and is also the increment of the frequency axis. The highest frequency able to be resolved is the Nyquist frequency given by $f_d/2$, half of the digitizing frequency.
CHAPTER 3. DESCRIPTION OF CTX EXPERIMENT

Turbulent quantities are frequently given as a function of wavenumber, an experimentally difficult measurement to make. However, if the dispersion relation between frequency and wavenumber is linear over a frequency range then frequency and wavenumber can be related by a constant phase velocity, \( k = \omega/v_\phi \). Grierson showed high density turbulent plasmas in CTX have a linear dispersion [19]. This results presented in this thesis are thus reported in frequency, not wavenumber.

3.4.1 Frequency Correlation

The ensemble spectrum can be calculated from the time series obtained from a single diagnostic by

\[
\langle |\tilde{S}(\omega)|^2 \rangle \equiv \langle \tilde{S}(\omega)\tilde{S}^*(\omega) \rangle, \tag{3.8}
\]

which is variably termed the auto-spectrum, or auto-power, or auto-correlation function. It will be referred to as the power spectrum in this thesis. The asterisk (*) denotes complex conjugate.

Using two diagnostics the cross-power and cross-phase can be obtained. They are defined as

\[
\langle \tilde{\mathcal{C}}_{1,2} \rangle \equiv \langle \tilde{S}_2\tilde{S}_1^* \rangle \\
\langle \alpha_{1,2} \rangle \equiv \tan^{-1}\left( \frac{\Im[\langle \tilde{\mathcal{C}}_{1,2} \rangle]}{\Re[\langle \tilde{\mathcal{C}}_{1,2} \rangle]} \right)
\]

and are calculated in an ensemble-sense. The cross-power is a complex quantity with both real and imaginary parts. There can be many peaks in the cross-power spectrum, and each peak has a phase value associated with it. With the known angular separation between diagnostics, \( \varphi \), the cross phase value at each peak can be used to find the azimuthal mode number, \( m = \alpha_{1,2}/\Delta\varphi \). The normalized cross-power is the squared cross-coherence

\[
\langle \kappa_{1,2} \rangle^2 \equiv \frac{|\langle \tilde{\mathcal{C}}_{1,2} \rangle|^2}{\langle \tilde{S}_1\tilde{S}_1^* \rangle \langle \tilde{S}_2\tilde{S}_2^* \rangle} \tag{3.9}
\]

which is bounded by \( \langle \kappa_{1,2} \rangle^2 \in [0, 1] \). The coherence provides a measure of how quickly the turbulent structures decorrelate in space and time.
3.4.2 Bispectrum

A useful tool to study turbulent nonlinear coupling is the bispectrum [30, 18, 49]. The bispectrum is a measure of the strength of quadratically nonlinear interactions in a signal for a group of three frequencies of the form \( f_3 = f_1 \pm f_2 \). When plotted over the range of frequencies of a signal the bicoherence allows identification of frequencies with high levels of coupling, indicating energy transfer amongst the frequencies. It is given by

\[
B(f_1, f_2) = \langle \tilde{S}(f_1) \tilde{S}(f_2) \tilde{S}^*(f_1 + f_2) \rangle
\]

and is a complex quantity. The bi-coherence is a power weighted bi-spectrum, and determines

\[
b^2(f_1, f_2) = \frac{|B(f_1, f_2)|^2}{\langle |\tilde{S}(f_1)\tilde{S}(f_2)|^2 \rangle \langle |\tilde{S}(f_1 + f_2)|^2 \rangle}
\]

which is essentially a quadratic correlation coefficient.

Figure 3.11: Bicoherence cartoon with domain components labeled.

Figure 3.11 is a cartoon bicoherence plot, highlighting salient features. To limit duplication the plot is restricted to positive values of \( f_1 \), plotted on the x-axis. The line \( y = x \) is equivalent to \( f_1 = f_2 \) is a line of symmetry so points above are omitted. The Fourier transform cannot resolve frequencies above half the sampling rate (called the Nyquist frequency), resulting in omission of
values beyond $f_1 + f_2 = f_{\text{Nyquist}}$. The line $y = -x$ corresponds to $f_2 = -f_1$ or $f_3 = 0$. A bicoherence plot with a regular grid pattern displayed shows high levels of harmonic coupling, corresponding to $f_1 \pm mf_2 = f_3$ with $m = 1, 2, 3, 4...$ More limited self coupling occurs along the $y=x$ axis. A broad line of elevated bicoherence represents a single frequency coupling across a broad range in the spectrum. A vertical line represents coupling with a fixed value of $f_1$, for $f_2$ the line will be horizontal. A diagonal line along $y - x = const$ represents coupling at a constant $f_3$.

Another feature of bicoherence analysis is the summed bicoherence, given by

$$B_c(f) = \frac{1}{N(f)} \sum_{f=f_1+f_2} b^2(f_1, f_2)$$

which is a function of frequency. Presented as a function of $\omega_3$ the summed bicoherence corresponds to integrating along the line $y - x = f_3$ in Figure 3.11. It represents the total amount of coupling across all available frequencies with the sum frequency $\omega_3$ and displays the individual frequencies that are coupling the most strongly.

### 3.5 Summary

This chapter discussed the setup for experiments including vacuum chamber and pumping system. The CTX dipole magnet can be approximated as a point dipole, and charged particle motion is characterized with three adiabatic invariants with separated frequencies [36].

The primary diagnostics employed in experimental studies analyzed in this dissertation are (i) Langmuir probes configured as floating potential probes and (ii) a polar array of gridded energy analyzers spanning the radial and azimuthal extent of the CTX plasma. The electrostatic bias perturbations applied were from two sources, either a large area bias probe inserted into the bulk plasma or a twelve point equatorial array located at the inner radial plasma boundary.

Ensemble spectral techniques are required due to the non-stationary turbulent measurements. Frequency correlation and coherence measurements were presented. Calculation of the bicoherence displays the quadratic nonlinear coupling present in the system.
Chapter 4

CTX plasmas

Plasmas in CTX and other laboratory magnetospheres heated with ECRH are categorized as either ‘low’ or ‘high’ density. Discharges with neutral pressure \( p_H < 10^{-5} \) Torr classified as low density, achieving plasmas around \( n \approx 10^{14} - 10^{15} m^{-3} \). As neutral pressures exceed \( p = 10^{-5} \) Torr a transition to the high density regime occurs where densities can exceed \( n \approx 10^{16} m^{-3} \). In the high density regime, plasma density approaches or exceeds the cutoff density \( n_c \approx 7.5 \times 10^{16} m^{-3} \). To create a high density plasma a second gas injection is triggered after a low density plasma has formed, leading to the transition to the high density turbulent state.

4.1 Low Density CTX Plasmas

The dynamics of the low density regime are dominated by quasi-periodic instabilities called the hot electron interchange (HEI) instability [37, 42, 62, 61]. Previous CTX dissertations studied the linear and nonlinear behaviors of the instability [36, 41]. In low density the the electron population in CTX is comprised of two components. A bulk, warm \(~70 eV\) population and a small, hot population with temperatures approaching 5keV. The HEI instability is governed by the ratio of these populations [34]. Previous work on CTX showed application of RF waves would drive phase space diffusion and suppress the HEI bursts [42].

Between HEI bursts in the low density regime the floating potential spectrum is dominated by a
coherent mode near 30kHz. Figure 4.1 displays a spectrograph of the floating potential spectrum over 3.4ms including a frequency sweeping event concluding an HEI burst where the primary 30kHz mode rises in frequency to above 200kHz in less than one millisecond with a second harmonic responding similarly. The 30kHz mode recovers, even while the frequency sweeping event is happening, and dominates the spectrograph.

Figure 4.1: Spectrograph of the floating potential power spectrum over 3.4ms in shot 5032, a low density discharge. At .5075s a frequency sweeping event follows an HEI burst, the mode rapidly rising in frequency from 30kHz to above 200kHz. Between bursts a coherent ∼30kHz mode exists.

HEI bursts and frequency sweeping dominate the floating potential spectrum in low density. Figure 4.2 compares the floating potential power spectrum from a quiescent period between HEI bursts and a time period inclusive of a burst. The black trace, representing the quiescent period, displays a clear 30kHz mode. The red curve of the burst-inclusive spectrum follows, at higher amplitudes, the quiescent spectrum for frequencies up to 60kHz. Above this frequency the spectral power remains nearly constant through 400kHz then sharply drops to the levels similar to the quiescent spectrum. The “flat region” in the spectrum is due to HEI bursts frequency sweeping above 10MHz [42].
4.2 Transition to Turbulent Regime

To initiate the turbulent, high density state a second gas injection is triggered. The transient period between the two density regimes has several interesting phenomena. Some control of the time duration of this transition is obtained through careful programming of the gas injection.

The transition to high density is marked by a high amplitude rotating $m = 1$ potential mode. At the beginning of the transition the frequency of this mode is near 18-20 kHz which then decreases just before the emergence of the turbulent high density regime. The DC value of the floating potential drops to $\Phi_f < -50V$, with large amplitude potential fluctuations of order $\sim 30V$. The hard X-ray emission drops and the soft X-ray emission rises, indicating a reduction of the high energy hot electron production. The plasma density only rises at the conclusion of the transition, independent of the length of the transition and often some time the additional gas fueling. At this point broadband fluctuations in potential and density are observed. We found changing the radial potential profile through equatorial bias inhibits the transition to high density.
4.3 Turbulence in High Density CTX Plasmas

The transition to high density coincides with an abrupt change in the plasma parameters. The measured ion saturation current jumps approximately a factor of 50, as seen in Figure 4.3. The electron temperature drops with the density increase. The increase of the plasma density is coupled with the drop in the hot electron population, as measured with hard x-rays. This changes the ratio of the hot and bulk populations and stabilizes the hot electron interchange mode \[15, 34\]. Measurements of density profiles are obtained through radially moving a Langmuir probe measuring ion saturation current (proportional to density). The density profile is measured to be slightly steeper than \( n \sim L^{-4} \) [19]. This is the marginally stable profile for rotationally driven interchange motion, suggesting that rotation may play a role in exciting fluctuations along with plasma pressure sustained with ECRH.

The DC floating potential, also presented in Figure 4.3, drops by at least half following the transition from low to high density. The potential profile inside the scrape off layer has been measured to follow an approximate \( 1/L \) trend in both low and high density operation [19, 39]. This indicates approximate rigid rotation of the plasma near the edge of the device in the electron diamagnetic drift, \(-\hat{\phi}\) direction. Floating potential correlation studies in high density have confirmed no field-aligned structure \((k_\parallel \approx 0)\) and the radial wavenumber to be low \((k_r \approx 1/L)\) [37].

The floating potential fluctuations roughly double between low density and high density. Figure 4.4 displays the RMS fluctuations of floating potential during low density, the transition, and high density. The initial 50ms until .15s capture the low level of fluctuations that occur with the large negative floating potential in low density. A brief spike in fluctuation intensity represents the transition before quickly settling in the high density at a level at least double the low density level. The jump in fluctuation levels results in strong density fluctuations \( \delta n/n_0 > 50\% \).

A significant change in the characteristics of the floating potential spectrum can be seen in Figure 4.5, which shows a spectrograph plotted with a log color scale. The low density beginning of the spectrograph displays a broad range of fluctuations above 30kHz resulting from the frequency sweeping of HEI bursts, which cannot be individually distinguished at this compressed time scale.
Figure 4.3: Overview of ion saturation current and DC floating potential signal during high density shot 7895. Ion saturation current reflects \( \sim 50 \times \) density increase following second gas puff. Floating potential sharply falls following the high density transition.

Figure 4.4: Figure of floating potential fluctuation intensity during shot 7895 with secondary gas puff at .15s triggering high density transition. High density fluctuation intensity is more than twice that of the low density regime, and the transition is higher by another factor of two.
Following the transition at .15s the peak frequency of fluctuations drops below 10kHz and the amplitude increases more than an order of magnitude. The broad power law nature of the high density fluctuation spectrum is evident from the horizontal color stripes representing the gradual drop of intensity with rising frequency.

Figure 4.5: Log spectrograph of the floating potential power spectrum of shot 7895, including both low and high density regimes. The second gas puff occurs at .15s, triggering the transition to high density where the peak fluctuation intensity jumps over an order of magnitude. The frequency value of the fluctuations drops from >30kHz to primarily <30kHz.

The floating potential coherence and cross phase show a clear m = 1 mode and a weak m = 2 mode. Figure 4.6 is the coherence and cross phase of two floating potential probes separated by 90°. In Figure 4.6(a) the peak coherence exceeds 75% at ~2.5kHz and a lower amplitude peak at 5kHz. In Figure 4.6(b) the cross phase is approximately 120° and -160°, respectively. These values best correspond to an m = 1 near 2.5kHz and an m = 2 mode at 5kHz.

The intermittent, turbulent nature of fluctuations after the transition to high density persists through the discharge. Figure 4.7 plots the end loss current signals from the eleven detectors of the polar imager located on a field line that passes through the magnetic equator at a radius of 33.6cm,
Figure 4.6: Plot of coherence versus frequency between two floating probes separated by 90° for 50ms starting at .5s during shot 7895. The coherence figure (left) displays coherence of a mode at 2.5kHz approaching 80% and the 5kHz mode reaching exceeding 70%. The cross phase (right) of these modes are ~90° and ~180°, implying $m = 1$ and $m = 2$ modes respectively.

here after referred to as L=33.6cm. Each plot is over 4ms separated by roughly 100ms during the discharge. That few stripes extend entirely from top to bottom indicates that modes coalesce and break apart with one azimuthal transit of the CTX device (or covering 360°). A relatively long duration mode is observed in Figure 4.7(c) beginning at .506s. While the intensity is not constant across the three plots, enough variation is present in each plot to convey the bursty nature. Additionally mode structure changes within each figure, often within a single transit of the device as multiple, narrow stripes can merge or a broad stripe will bifurcate.
Figure 4.7: Evolution of polar loss current at $L=33.6\,\text{cm}$ in shot 7895. Rotating modes are seen to coalesce and break apart with varying amplitude, coherence and mode number throughout the duration of the discharge.
4.4 Summary

Created through microwave heating, the plasmas of CTX can be characterized as either low or high density. The low density plasmas are two component plasmas with a hot electron tail displaying temperatures of up to 5 keV and X-ray production with a bulk population of warm electrons $\sim 70$ eV. Low density plasmas exhibit quasi-periodic bursts of HEI instability. Upon sufficient fueling with an additional gas puff, the plasma undergoes a transition to high density, the resultant plasmas are roughly two orders of magnitude more dense. We see very little evidence of a hot electron population. The HEI mode is stabilized and X-ray production is minimal with a bulk electron temperature of $\sim 10$ eV. The density and potential fluctuations assume power-law spectra characteristic of turbulence.
Chapter 5

Symmetric Bias

Plasma rotation in CTX is driven by axially symmetric biasing about the dipole magnet equator. Symmetric bias of the equatorial array drives a cross-field current radially across the plasma and induces plasma rotation. The increased plasma rotation excites the centrifugal interchange instability [39]. Following modifications of the equatorial biasing array, similar experiments are undertaken in the high density, turbulent state.

5.1 Symmetric Equatorial Bias Model

The cross-field plasma flows in CTX arise from the $\mathbf{E} \times \mathbf{B}$ particle drift and magnetic drifts due to finite electron temperature. With the magnetic field normal to the equatorial plane of the dipole magnet the electric field components that contribute to plasma flow are the azimuthal and radial components. To alter azimuthal plasma flows the radial electric field and potential profile are altered. Through biasing the inner radial boundary of the plasma, along the equator of the magnet, current can be driven across the plasma. The finite radial current creates a $\mathbf{R} \times (\mathbf{J} \times \mathbf{B})$ torque density on the plasma. The insulating magnet polar caps eliminate current from flowing along field lines and the divergence free nature of currents in plasma ensure current injected at the inner radial boundary flows radially across the plasma to reach the chamber wall. With plasma flow governed by $\mathbf{E} \times \mathbf{B}$ flow, with $\mathbf{E} = -\nabla \Phi$, the contours of equal electrostatic potential, $\Phi$, become the streamlines
5.2 Low Density Equatorial Bias

When a strong negative bias was applied to the equatorial array in the CTX low density regime, the radial potential profile changed and the driven radial current caused rapid plasma rotation [38, 39]. The applied bias in low density plasma increased to -500V, drawing a current of \( \sim 2\)mA as seen in Figure 5.1. (Positive is defined to be ions flowing to the probe or current flowing from the probe to the power supply.) Increasing the plasma rotation resulted in the first experimental observation of the centrifugal interchange instability [38]. This is illustrated by the spectrogram in Figure 5.2 with the upward sloping arcs from before .2s through after .5s, representing the increasing frequency of modes in the plasma. The lowest frequency mode corresponds to an \( m = 1 \) azimuthal structure that increases in intensity as well as frequency due to application of the radial bias. The spectrogram shows an \( m = 2 \) mode of higher/comparable amplitude at the beginning and end of the
Figure 5.2: Excitation of the centrifugal interchange mode resulting from symmetric equatorial bias. Time evolution of floating potential power spectrum with application of in shot 4727.

A full discussion of the centrifugal interchange instability can be found in Levitt et al. [39]. At these parameters the centrifugal interchange instability competes with the still present HEI, as can be seen by the jumps in frequency of the dominant mode. These are a small HEI bursts altering the frequency evolution of the centrifugal interchange instability mode, it is observed that as the centrifugal mode drive increases the quasiperiod between hot electron bursts increases. The balance between the two instabilities can be adjusted by varying the gas fueling level, for example lengthening the gas puff. This works through two mechanisms. Firstly increased fueling diminishes the amplitude of the HEI bursts by lowering the hot/warm ratio through increasing the warm electron population. Secondly, increased neutral and plasma densities leads to higher cross-field conductivity allowing more current to be driven radially and a higher torque be applied to the plasma. Previous theses have shown that the observed mode structure favors the lowest order mode as seen by the higher order modes beginning to fade out as the voltage and instability drive increase [36].

The fluctuation spectrum during symmetric bias is displayed in Figure 5.3. This is a direct
Figure 5.3: Plasma mode frequency is doubled in response to bias increasing the plasma rotation. Comparison of floating potential spectra in shot 4727 at the beginning of the bias ramp (black, .2 to .25s) and during peak applied bias voltage (red, .5 to .55s).

Comparison of the ensemble averaged frequency spectrum from a 50ms time period just after the radial bias is switched on and a later time period near the peak applied bias. The black curve, representing the early spectrum, displays a peak near 16kHz and an even larger peak around 30kHz. (Significant spectral power is present at higher frequencies up to 90kHz.) After the applied bias saturates and the centrifugal mode evolves the broadband fluctuations are decreased, leaving more coherent rotating modes. The primary mode is the lower frequency of the two, centered around 32kHz with a much lower amplitude mode observed near the first harmonic frequency of 70kHz. The increase in plasma rotation was measured to correspond to driving sonic flow in the plasma [39].

Calculating the cross phase of two floating potential probes allows the mode structure of the oscillations to be determined. The two floating potential probes used for this analysis are separated by a quarter period. Figure 5.4(a) displays two modes with coherence peaks approaching 80%, the modes at 16 & 30kHz previously mentioned. In Figure 5.4(c) plotting the corresponding cross phase the 16kHz mode has a converged cross phase of nearly 90°, corresponding to an azimuthal mode...
Figure 5.4: \( m = 1 \) mode coherence increases as a result of symmetric equatorial bias, \( m = 2 \) basically unchanged. Plot of coherence and cross phase versus frequency between two floating probes separated by 90° at two times during shot 4727. Figures on the left are the coherence and cross phase over 50ms at the beginning of the bias portion of the discharge, the right figures are at the end of the bias portion.
number of 1. The higher frequency 30kHz mode is seen to have a cross phase of 180°, making it a $m = 2$ harmonic of the 16kHz mode. Looking later in the discharge in Figure 5.4(b) we can see the peak mode around 32kHz displays excellent coherence broadly above 80% and with a peak above 90%. The cross phase of the 32kHz mode maintains a steady value near 90°, indicating an $m = 1$ mode. The 70kHz mode is seen to be a $m = 2$ mode with a high level of coherence exhibiting a cross phase just below 180°, Figures 5.4(b) and 5.4(d), respectively.

5.3 High Density Equatorial Bias

Symmetric equatorial bias produces a much smaller effect during high density than during low density. Proportionally increasing the applied current in line with the increase in density produces a small response. Doubling the radial current increases the coherence of the dominant mode but the frequency shift is much smaller than seen during low density. Experiments undertaken varied the applied electrostatic bias, both positive and negative with respect to the plasma floating potential.

5.3.1 Limited Response to Positive Bias

As observed in previous work as well as in other laboratory magnetosphere experiments biasing the electrodes positively with respect to the floating potential to draw higher levels of current in the electron saturation regime were unsuccessful [39, 50]. Figure 5.5 displays the applied voltage and current collected by the equatorial array versus time. For these discharges the mean collected current level during positive bias is -10mA, in contrast, the mean was 94mA during the negative bias shot. This discrepancy is likely related to the cross-field nature of the currents being driven. Cross-field ion mobility is much higher than that of electrons due to the larger ion gyroradius and higher collision frequencies. Experiments in this thesis primarily use negative bias due to the larger achievable current levels.
Figure 5.5: Current levels are one order of magnitude higher during negative bias (black) in comparison to positive bias (red). Top figure plots voltage applied to equatorial biasing array in time, lower figure the current collected by the array.

5.3.2 Symmetric High Current Equatorial Bias

The maximum applied symmetric bias was -100V resulting in ~200mA of radial current. An overview of a characteristic shot is presented in Figure 5.6. The ion saturation current collected by the Langmuir probe is approximately constant and unchanged by application of an equatorial bias, as detailed in the middle panel displaying the bias triggering on at .35s for a duration of 200ms and turning off for the final 50ms of the discharge. The magnitude of the average collected current is approximately 200mA in all similar shots, two orders of magnitude higher than low density current levels.

This high current level modifies the plasma fluctuations. The floating potential signal characteristics, as measured off the magnetic axis in the bulk of the plasma during the final 50ms of applied bias, are detailed in Figure 5.7(a). The response is representative of a similar response observed in ion saturation current and polar loss current measurements. Looking at the spectrum the driven spectrum is observed to have a higher amplitude at essentially every frequency value throughout the
Figure 5.6: Overview of high current, high density symmetric bias discharge parameters through the course of shot 7890. Top plot is ion saturation current, middle plot applied bias voltage, and the bottom plot shows collected ion current.

At the low, dominant frequencies amplification of the primary mode is observed, with a slight upshift in frequency. The change in frequency is of the order 10%. This is smaller than the frequency doubling previously reported resulting from low density equatorial biasing. The higher frequency harmonics are also excited as shown in Figure 5.7(a). The wide band of frequencies above 8kHz shows a power law dependence but at higher intensity. The floating potential in the time domain the RMS fluctuations in Figure 5.7(b) are significantly enhanced with respect to an unbiased high density discharge.

Identifying the modes present in a high current, strongly driven symmetric discharge is performed through frequency domain correlation analysis. The three modes under 10kHz observed in the single point floating potential spectra all display a coherence equal or greater than the lone dominant unbiased mode as calculated across two floating potential probes in the bulk of the plasma separated by a quarter period. The two lowest frequency modes had peak coherences reaching 90% and the third mode at 80% in Figure 5.8(a). The mode slightly below 3kHz is the most powerful
Figure 5.7: Amplification of three modes <10kHz and a broadband increase for frequencies >10kHz are seen in high current symmetric bias (red). The increase in power across frequencies is also seen in the elevated RMS fluctuation level. Comparison of the floating potential measurements in a high current symmetric discharge (shot 7890) to an unbiased discharge (shot 7895) from .5 to .55s. (a) Ensemble spectra (b) RMS fluctuations.

mode and has a cross-phase near 90° in Figure 5.8(b), identifying it as a $m = 1$ mode. The next prominent mode at 5.5kHz displays slightly less coherence, despite having a similar peak coherence the majority of the mode coherence is less than the $m = 1$ mode. The calculated cross-phase is slightly above 180° indicating an $m = 2$ mode. The last clear mode exists between 8 & 9kHz and a cross-phase near zero, suggesting it is an $m = 4$ mode and not a simple harmonic of the other two modes. At higher frequencies the measured cross-coherence does not exceed 50% and the cross-phase values no longer neatly converge.
CHAPTER 5. SYMMETRIC BIAS

Figure 5.8: High current symmetric bias displays highly coherent \( m = 1, 2 \) modes and lower coherence \( m = 4 \) mode. Plot of coherence versus frequency between two floating probes separated by 90° during shot 7888. Figure on the left is the coherence over 50ms at the end of the biased portion of the discharge, right figure is at the cross phase from the same time.

5.3.3 Low Current Equatorial Bias

When the applied bias is reduced to drive \( \sim 100\text{mA} \) of current the plasma response is similar, but diminished, to the high current response. This is the current level consistent with proportional scaling from low density biasing. It is also the bias level utilized for the non-symmetric biasing cases presented in Chapter 7. Bias voltage was switched on for 200ms in the middle of the discharge at .35s as shown in the middle panel of Figure 5.9. The top panel shows the ion saturation current is unaffected by the application of bias.

The floating potential signal response to moderate current symmetric bias does not change markedly when compared to a standard discharge as a baseline. The floating potential power spectrum shown in Figure 5.10(a) displays a small amplification of the peak low frequency mode is observed just above 3kHz, slightly shifted higher in frequency than the unbiased case. A small secondary mode is observed between 5 and 6kHz. The existence of a third higher frequency mode is difficult to ascertain from this spectrum and then following the frequencies higher we see agreement between the moderate current bias case and the standard turbulent high density discharge. This is reflected in Figure 5.10(b) with the RMS fluctuation levels very similar between the two cases.

The frequency correlation analysis between the same pair of floating potential probes is consistent in displaying a decreased response with the lowered radial current drive. Looking at the
Figure 5.9: Overview of low current, high density symmetric bias discharge parameters through the course of shot 7893. Top plot is ion saturation current, middle plot applied bias voltage, and the bottom plot shows collected ion current.

Figure 5.10: At this lower current level the power spectra closely match, only slight enhancement of the $m = 1, 2$ modes. Comparison of the floating potential measurements in a low current symmetric discharge (shot 7893, red) to an unbiased discharge (shot 7895, black) from .5 to .55s. (a) Ensemble spectra (b) RMS fluctuations.
coherence over 50ms from .5s in Figure 5.11(a) the lowest frequency mode at 3kHz is still the most coherent with a peak coherence of 90%. The secondary mode at 6kHz is still present, but at lowered values of coherence than in the high current case present in Figure 5.8(a). The coherence does not show a third mode present and only exceeds 60% for brief isolated points above 6kHz. The cross phase over the same time window reveals the two modes present are the same \( m = 1 \) and \( m = 2 \) modes characterized in the high radial current case.

Figure 5.11: Coherence levels decline at lower current levels with no clear mode past \( m = 2 \). Plot of coherence versus frequency between two floating probes separated by 90° during shot 7893. Figure on the left is the coherence over 50ms at the end of the biased portion of the discharge, the right figure is at the cross phase from the same time.

### 5.3.4 Spectra Evolution in Time

During the application of symmetric radial bias, the turbulent spectra evolves in time. Both spectrograms and snapshot ensemble Fourier spectra illuminate temporal dynamics. The high applied current case dramatically alters the floating potential power spectrum.

As seen in Figure 5.12, bias is applied from .35s to .55s. Immediately after the equatorial biasing, the fluctuation spectra broadens, and higher intensity appears at higher frequencies. This is another representation of the alteration of the spectrum and increased RMS fluctuations as seen in Figure 5.7(a). Although twice as much current as was required to excite near sonic flows in low density plasmas, in higher density plasmas there is effectively no change in the observed frequencies under the application of a bias. However, high current symmetric equatorial bias
increases the amplitude and coherence of fluctuations during the bias interval. The previously identified \( m = 1, 2, 3 \) modes are readily seen in the spectrogram and persist for the duration of applied bias.

![Spectrogram](image)

**Figure 5.12:** Symmetric bias shows increase in intensity and coherence of modes. Time evolution of floating potential power spectrum during shot 7890 with application of a high current symmetric radial bias.

At lower current bias, we observe only a moderate effect on the spectrogram. Here injected current levels are \( \sim 50 \) times the current level injected into previous low density plasmas. Again the duration of the applied equatorial bias is from .35s through .55s. The floating potential power spectrogram in Figure 5.13 displays the familiar broad fluctuation spectrum with possible, indistinct and intermittent modes in the range from 6 to 9kHz. With the application of bias the modes in the plasma become more distinct at approximately 3 and 6kHz, with perhaps a final harmonic at 9kHz representing the \( m = 1, 2 \) and 3 modes pointed out previously in Figure 5.11(b). The lowest frequency mode is dominant and easiest to identify. Consistent with the results from previous sections the amplitude and coherence of these modes are less than in the high current case. Once the equatorial bias is removed the primary fluctuation energy returns to higher frequencies as observed prior to the application of bias.
Figure 5.13: Effects of symmetric bias are less pronounced at current levels comparable to non-symmetric bias studies. Time evolution of floating potential power spectrum with application of a symmetric radial bias during shot 7893.

Another representation of this same spectral data is shown in Figure 5.14 where the spectra appear as snapshots in a flipbook as opposed to the continuously evolving movie of the spectrogram. Each spectrum is an ensemble average over 10 component spectra. These are drawn from time periods before, during, and following the application of bias in a discharge.

Figure 5.14(a) displays the floating potential power spectrum snapshots typical for a high density plasma. When a large symmetric bias is applied driving a large current the resultant spectra are presented in Figure 5.14(b). Here the top and bottom spectra are before and following the applied bias, respectively. With little frequency response immediately following .35s we begin to start seeing the emergence of the $m = 1$ and $m = 2$ modes concurrently from .41s to .44s. 60ms later both of these modes are more prominent, with some $m = 3$ activity present. In the final frame during bias the low order modes are very well defined. After the removal of bias the spectrum begins relaxing.

The evolution of the plasma fluctuations can also be observed by looking at signals from the polar imager. In Figure 5.15 all the detectors located at a radius of 33.6cm are plotted versus time with low current symmetric equatorial bias applied for the latter two plots. In Figure 5.15(a) displays
Figure 5.14: Amplitude of the $m = 1, 2$ modes increase together during high current symmetric bias. Ensemble floating potential power spectra advancing in time. Bias triggered on from at .35s through .55s.

A 4ms time window before the equatorial bias is triggered. The turbulent nature of the fluctuations is visualized in the random structure of the rotating plasma fluctuations. Intermittently a longer lived mode coalesces and slanted stripes appear, each individual stripe represents a full transit of the device. Occasionally strong fluctuations will appear and disappear in under a single transit. Also observed is a broadening or splitting of fluctuations displaying multimode or harmonic behavior. The application of equatorial bias also affects the collected end loss currents during low current bias, but Figures 5.15(b) & 5.15(c) show the intermittency of the mode decreases and therefore more clear stripes are visible throughout sampled periods.
Figure 5.15: Application of symmetric bias increases coherence and longevity of plasma modes. Contour plot displaying the evolution of the spatial mode structure before and during application of low current symmetric bias. Note: Color scales are not fixed across plots.
5.3.5 Symmetric Bias and Nonlinear Coupling

The effect of applied bias on the nonlinear coupling can be observed through the changes in the bicoherence measured during biased portions of the discharge. Discharges in the turbulent high density regime exhibit a moderate amount of bicoherence, the largest components being broad harmonic coupling between the \( m = 1 \) and \( m = 2 \) modes. The rest of the bicoherence is diffusively spread throughout the frequency domain as seen in Figure 5.16.

![Bicoherence](image)

Figure 5.16: The bicoherence from a high density discharge with no applied bias, displaying harmonic coupling but no broadband coupling. Bicoherence plotted for 100ms at .45s, corresponding to end of bias window during biased shots.

With the application of symmetric bias this pattern is changed. In the low current example shown in Figure 5.18 the coupling is at lower amplitude and displays limited harmonic content. The elongated “chevrons” at \( f_2 = \pm 3\text{kHz} \) show the \( m = 1 \) mode has low level coupling across a broad range of frequencies.

Doubling the bias drive current as in Figure 5.17 produces higher levels of localized coupling without much increasing the overall coupling, with the localized peaks occurring at frequency triplets corresponding to harmonic coupling. The broadband coupling characterized by chevrons is still present, but does not appear enhanced through driving additional current. At these high current levels the beginnings of a second, nested chevron begins to emerge associated with the dominate
Figure 5.17: Limited broadband coupling is seen with the coupling levels highest for harmonic coupling during high current symmetric bias. Bicoherence plotted for final 100ms of high current symmetric bias.

$m = 2$ mode in saturated symmetric biasing.

A direct comparison of the summed bicoherence, representing the total coupling of a single frequency with all other frequencies in the spectrum, reveals moderate bicoherence increases only at mode locations. In Figure 5.19 we can see the high current symmetric bias (the red curve) producing an increase in the coupling of the two high amplitude, low order modes by approximately 50% and 100% for the $m = 1$ and $m = 2$ modes, respectively. At other frequencies we can see only minor enhancement. The low current symmetric bias (green curve in same figure) displays a modest increase of bicoherence with respect to the unbiased example (black curve) for the majority of the spectrum. The small frequency upshift observed with symmetric bias at both current levels is preserved in the peaks of the summed bicoherence.
Figure 5.18: Limited broadband coupling is seen during low current symmetric bias. Bicoherence plotted for final 100ms of low current symmetric bias.

Figure 5.19: A figure comparing the magnitudes of the summed bicoherence of the three cases, symmetric bias increases coupling only at $m = 1, 2$ modes.
5.4 Summary

In this chapter the application of symmetric equatorial bias to drive a radial current is reported. This method is seen to increase the mode frequency in low density discharges by driving strong azimuthal flows. For high density discharges, symmetric bias did not alter the plasma mode frequency even when driven at a proportionally stronger level than the low density plasmas. However, increasing the bias current resulted in a substantial increase mode coherence. Also, at the highest current levels nonlinear coupling increased as evidenced by increased mode harmonics and increased bicoherence.
Chapter 6

Non-Symmetric Bias with a Probe

This chapter presents results of the investigation of the effects of a non-symmetric applied electrostatic bias point probe. The probe localizes perturbations to a specific radius of flux tubes carried past the probe by the drift motion of the plasma. Breaking the symmetry drives currents both radially and azimuthally, altering the plasma fluctuations. Acting as a localized current this perturbation is able to couple to fluctuations of any wavelength. The bias probe is applied to both low density plasmas and high density plasmas.

6.1 Low Density Point Bias

For these experiments, the bias probe voltage was constant for the duration of a plasma shot. Having a constant electrostatic bias dramatically alters the measured characteristics of the discharge, which is especially apparent when the applied bias voltage magnitude increases to -1.8 kV. These large potentials could be maintained even with a very low collected current to the bias probe at levels of approximately 0.5mA. When a larger negative potential was applied, the ion saturation current levels fell and eventually were negative, providing evidence that applied static point modified the plasma floating potential, eventually driving it below the bias point of the $I_{sat}$ probe (-180V), which resulted in a negative collected current. Similar behavior was observed during low density symmetric biasing as the applied equatorial bias climbed towards its maximum amplitude the collected $I_{sat}$ current
dropped and eventually changed sign, only recovering when the equatorial bias was turned off [36].

Additionally, the end loss currents collected by the polar imaging diagnostic were modified with enhanced electron current collection in a region downstream from the bias probe via $\mathbf{E} \times \mathbf{B}$ drift. High levels of applied bias stabilize the HEI bursts that dominate the dynamics of the low density regime, shown in Figure 6.1.

In addition to the above effects observed in the plasma equilibrium, application of a static bias in the bulk plasma had profound effects on the observed fluctuation spectrum. These modifications were seen in both the $I_{sat}$ and $V_f$ measurements. Figure 6.1(b) is a spectrogram displaying the frequency evolution of the floating potential fluctuation power late in the discharge. The observed spectrograph with bias is significantly changed from the unbiased low density floating potential power spectrum seen in Figure 4.2. Under the influence of applied bias all the fluctuation intensity becomes a coherent mode. Harmonics are clearly visible up to $m = 3$. The HEI instability is nearly stabilized with quasi-periodic bursts resulting in small rises in the frequency of the observed mode and a small change in amplitude. With no bias, the extremely high amplitude of HEI bursts that are roughly two orders of magnitude higher intensity.

![Spectrographs](image)

(a) Shot 5032, Low Density  
(b) Shot 5045, Static Bias

Figure 6.1: Spectrographs of floating potential spectrum, comparing (a) HEI-dominated low density shot and (b) shot with the HEI stabilized through the application of electrostatic bias using point probe in the bulk plasma. The saturated spectrum is dominated by a primary mode and its harmonics.

To allow direct comparison of a low density discharge with and without an applied point bias the time sample analyzed will be reduced to 2ms. This shorter duration allows comparison of the spectra
during time intervals without HEI instability bursts changing the unbiased low density signals. The left plot in Figure 6.2 contrasts the signal of a low density floating potential power spectrum during the quiescent period between HEI instability bursts in black with the floating potential power spectrum resultant from -1.8kV point bias throughout the discharge, displayed in red. While several points are worth remarking on the immediate, most striking, observation is the dramatic increase in the magnitude of the peak modes during bias, by nearly two orders of magnitude in comparison with the unbiased case. Also clearly evident is the series of harmonics through at least $m = 7$ resulting from the point bias. Excepting the mode and its harmonics, the broadband power levels during bias are diminished below 100kHz and comparable thereafter compared to a standard low density discharge. This plot also clearly demonstrates the increase in mode frequency under the application of point bias, with the dominant unbiased modes at 17 and 32 kHz, values that more than double when bias is applied to 45 and 90 kHz. In the adjacent plot of the biased shot displays an increase of roughly a factor of five in fluctuation intensity over the same time period.

![Figure 6.2](image)

**Figure 6.2:** One the left, a comparison of floating potential power spectrum with (Shot 5045, -1.8kV, in red) and without (Shot 5032, in black) the application of electrostatic bias using point probe in bulk plasma. The mode and harmonics in the biased spectrum are strongly amplified while background power levels are at or below unbiased levels. Right, a comparison of RMS fluctuation levels showing biased fluctuation levels roughly tripled.

Further investigation of the same time period from discharges 5032 and 5045 offers more insight into the mode characteristics in Figure 6.3. Here the coherence and cross phase are calculated between two floating probes with 90° separation. Figure 6.3(a) presents the coherence of fluctuations in a quiescent period between instability bursts, with a number of modes present, but with the
exception of the 30kHz mode that reaches 80%, all display coherence levels below 70%. Coherence levels in Figure 6.2 show the three lowest frequency modes exhibit coherence levels exceeding 95%.

The cross phase in Figure 6.3(c) can be used to identify the mode numbers of the harmonics but the cross phase at the peak coherence value of 30kHz is multi-valued. The fluctuations spread from 45-60kHz show a cross phase value of 90°, matching the probe separation and indicating an \( m = 1 \) mode. This indicates the fluctuations are separate modes and not simply harmonics of a base mode.

Figure 6.3(d) displays a similar collection of modes during the application of point bias. The 45kHz mode displays a phase difference just above 0°, a lack of phase difference between the two probe reveals an \( m = 0 \) global mode. The cross phase of the next mode at 90kHz is an \( m = 1 \) mode with a cross phase of slightly higher than 90° and the 140kHz mode having a cross phase of nearly -180° illustrative of an \( m = 2 \) mode.

Figure 6.3: Low density point bias increases mode coherence to nearly unity. Figures on the left are calculated during a standard discharge, the right figures are at the end of the bias portion. Plot of coherence and cross phase versus frequency between two floating probes separated by 90°.
The power spectrum from low density discharges can be observed changing through a scan of applied electrostatic biases. The floating potential power spectra excerpted from such a scan are shown in Figure 6.4 utilizing time windows with no instability bursts. Presented on the same scale the steady increase in amplitude of the peak mode is abundantly clear with higher harmonics beginning to emerge in the third spectra from the top and very clear with a second and third harmonic present at the highest applied bias. The increase in frequency of the dominant mode also closely tracks the amplitude of applied bias.

![Power Spectrum](image_url)

Figure 6.4: Scan of the floating potential power spectrum with varying applied bias. The magnitude and frequency value of the primary mode increase as the bias voltage rises.

The quadratic coupling present in the floating potential fluctuations during high amplitude point bias is seen in the bottom panel of Figure 6.4. The bicoherence seen in Figure 6.5 from a shot with
a constant applied bias of -1800 V displays the highest levels of nonlinear coupling observed in CTX, approaching unity.

Another very striking aspect of Figure 6.5 is the regular, gridded pattern of the bicoherence peaks with limited bicoherence between peaks. This grid pattern indicates the presence of a full range of harmonics of the primary mode at \( f \approx 45\text{kHz} \). The upper righthand feature in Figure 6.5 is at \( f_1 = 180\text{kHz}, f_2 = 135\text{kHz} \). This implies nonlinear coupling is transferring energy between harmonics as high as the \( m = 3, m = 4 \) and \( m = 7 \) modes.

![Figure 6.5: Nonsinusoidal floating potential waveform creates high levels of harmonic coupling in the bicoherence during the application of electrostatic bias using a point probe in bulk plasma, 50 ms duration, shot 5045.](image)

In an attempt to perturb the plasma less, a series of experiments were conducted where the probe bias was triggered on and off during course of a plasma discharge. The bias voltage increases and falls throughout the duration of the shot, triggering on at .2s and off at .6s as seen in Figure 6.6. The bias rose over that time period to -1600V and began to fall after the power supply was triggered off. Triggered application of point bias resulted in \( \sim 4\times \) increase in current emitted from the bias probe. The emitted current levels with triggered point bias are very similar to the low density equatorial
symmetric bias [36]. The ion saturation current collected was more stable showing only a small
decrease as the bias was increased and unlike the static bias case presented earlier remaining positive
at all times. The combination of these factors suggest that the plasma density was higher during
triggered biasing and the floating potential was not as severely effected.

![Ion Saturation Current and Bias Voltage](image)

**Figure 6.6:** Overview of measured ion saturation current and applied bias for a triggered
electrostatic bias discharge using the point probe during shot 5509.

The HEI instability bursts were no longer stabilized when the bias probe was triggered during the
discharge. The application of triggered point bias did decrease the amplitude of the instability bursts
relative to an unbiased low density discharge. Additionally the presence of point bias elongates
the HEI quasiperiod [37], which at this density is roughly 6ms without triggered point bias to the
approximately 20ms seen in Figure 6.7. With the repeated instability bursts the spectral harmonic
content is greatly diminished with occasional $m = 2$ fluctuations present. The HEI bursts also
break up the fluctuations of the $\sim 35 - 40$kHz dominant mode, only for it to reemerge later in
the quiescent period between instability bursts. The peak frequency of this mode rises as the bias
voltage amplitude is slowly increased during a shot, likely through steepening the radial floating
potential profile thereby increasing the azimuthal $\mathbf{E} \times \mathbf{B}$ drift velocity.

When intervals with HEI bursts are avoided, comparing the floating potential power spectrum
between a low density shot with and without applied point bias can be insightful. This is shown
Figure 6.7: Spectrograph of floating potential fluctuation (not power) spectrum at the peak applied voltage during triggered electrostatic bias using the point probe in shot 5509. The cycle of the biased mode intensifying then being disrupted by an HEI is seen.

in Figure 6.8 with triggered point bias highlighted in red during 50ms between major HEI bursts. The flat signal response in the unbiased shot from 100kHz to 300kHz is likely from a very small frequency sweeping event following an instability burst. Looking at the power spectrum on the left of Figure 6.8 the intensity of the dominant mode is several times larger than without applied bias. The frequency of the biased floating potential power spectrum also increases from roughly 30kHz to 40kHz. While significant, this shift in frequency is less than the frequency shift seen in Figure 5.3 that results from low density symmetric equatorial biasing. The $m = 2$ and $m = 3$ harmonics are evident, if small, in the power spectrum at 80kHz and 120kHz, respectively. The RMS fluctuations over the same time period displayed in the right panel of Figure 6.8 more quantitatively display the increase of fluctuation intensity as time increases following a HEI burst qualitatively seen in the spectrogram.

Figure 6.9 shows the coherence and cross phase between two floating potential probes separated by 90° in the time period between HEI bursts from .53 to .544s. In the left plot the coherence
Figure 6.8: On the left, a comparison of floating potential power spectrum with (shot 5483, red) and without (shot 5480, black) the application of electrostatic bias using point probe in bulk plasma. A frequency upshifted peak and two harmonics are present with the broad spectrum at high power unlike the unbiased case. Right, a comparison of RMS fluctuation levels for the same time shows the biased RMS rising between HEI bursts.

exceeds 80% in three frequency bands. The first, and highest is frequencies between 30-35kHz with coherence above 95% and a cross phase of nearly 90° indicating a $m = 1$ mode. This is the strongest mode that is identified in the spectrogram in Figure 6.7. The coherence of the next mode between 45 and 60kHz is right at 80% and the third mode exhibits coherence between 80% and 90% for frequencies from 70 to 75kHz. Both of these higher frequency modes have cross phases of approximately 180°, indicating $m = 2$ modes. The higher frequency $m = 2$ mode is the harmonic of the dominant mode, but the intermediate frequency mode is not easily identified in either the spectrogram or ensemble spectrum.

Figure 6.9: Plot of coherence and cross phase versus frequency between two floating probes separated by 90° in shot 5509.

The bicoherence present between HEI bursts in a triggered point bias shot are diminished when
compared to the static point bias. The peak bicoherence amplitude of any frequency triplet was reduced from 1.0 to 0.7 in the transition from static to triggered point bias. While lower than during the static point bias discharges, these levels are significantly higher than the bicoherence of an unbiased low density discharge. While the axes have changed between the triggered bicoherence in Figure 6.10 and the static bicoherence previously discussed in Figure 6.5, the most striking change is the restriction of nodes with quadratic coupling present. In the triggered point bias in Figure 6.10 we see limited coupling between the $m = 1$ and the lowest frequency or DC modes at $f_1 = 35kHz$, $f_2 = \sim 0kHz$ and $f_1 = 35kHz$, $f_2 = -35kHz$ with the majority of coupling occurring between the $m = 1$ and $m = 2$ modes at $f_1 = 35kHz$, $f_2 = 35kHz$ (implying $f_3$ is the $m = 2$ harmonic at 70kHz) and the “mirror” at $f_1 = 70kHz$, $f_2 = -35kHz$.

![Bicoherence](image)

Figure 6.10: Bicoherence of floating potential signal for 50ms during the application of electrostatic bias using point probe in bulk plasma. The plot demonstrates coupling is present between two pairs of modes: the $\approx 0kHz m = 0$ and 35kHz $m = 1$ and stronger coupling with the 35kHz $m = 1$ and 70kHz $m = 2$ modes.
6.2 High Density Probe Bias

Triggered bias of the bias probe was also applied to the high density turbulent plasma discharges. Increasing the plasma density increases the plasma cross field conductivity allowing much larger currents to flow. The equipment utilized for these experiments was limited by total power available, so once current levels exceeded 12mA a different amplifier was required but had a voltage limit of ±600V. Because the plasma density is orders of magnitude larger than the low density regime, we were able to achieve a lower rotation rate than seen in the previous low density centrifugal mode experiments.

For the representative high density point bias shot analyzed here the current increases a single order of magnitude from ∼2mA to ∼20mA. This resulted in a limited plasma response to strong negative point bias. Still, a strong negative point bias does effect the high density plasma response. The results were similar in some ways to the application of symmetric equatorial bias in high density.

Figure 6.11 displays a representative high density point bias shot where a strong negative bias is applied from .35 to .55s. The presence of the point bias does not affect the ion saturation current levels displayed in the top frame. The current collected by the biased probe is plotted in the bottom frame and varies dramatically throughout the shot. Starting very close to zero the current initially climbs at .15s when the second gas puff initiates the high density regime. At this point the strong negative current of -20 to -40mA maintains the potential at the probe at 0V and then at approximately .23s the voltage at the probe drops allowing the required current to fall close to zero again. The collected current jumps to almost 30mA once the bias is triggered on to -500V and then slowly ramps down to 15mA by the end of applied bias, whereupon the current is again roughly -40mA to maintain the programmed zero voltage condition at the probe.

The spectrograph in Figure 6.12 displays the evolution of the floating potential power spectrum in time before, during and after a -500V point bias is applied. The spectrum very closely resembles that of an unbiased high density discharge. When the bias is switched on at .35s the primary mode at ∼3.5kHz no longer drifts lower in frequency as typically seen in high density shots, until the
Figure 6.11: Overview of measured ion saturation current, applied bias, and collected current for a high density triggered electrostatic bias discharge using the point probe during shot 7408.

bias is removed when it falls lower at .55s. Additionally the fluctuations below the dominant mode decrease in intensity during bias just as fluctuations at higher frequencies increase. This is seen in the spectrograph as it grows “taller” as bias is switched on and then drops as it is removed.

The evolution of the floating potential power spectrum during bias, in comparison to an unbiased discharge, is further illustrated in Figure 6.13. Comparing the ensemble power spectra of the biased and unbiased shots over the 100ms before the bias is triggered in Figure 6.13(a) illustrates the reproducibility of CTX plasmas with both spectra peaking close to 4kHz. Looking at the last 100ms of the bias period in Figure 6.13(b) the biased spectrum peak has remained very close to the same frequency while the peak of the unbiased high density spectrum has shifted lower to below 3kHz. Also shown are the change in power levels for the biased shot. Power levels drop for frequencies below the 4kHz mode and grow for those frequencies above the mode while the primary mode amplitude is nearly unchanged. The net effect of amplifying and suppressing points in the spectra does not affect the total fluctuation intensity, as shown in the comparison of the RMS fluctuation levels in Figure 6.14. As would be expected from the similar power spectra the RMS levels are very
similar throughout. The biased discharge does show a small increase in RMS fluctuations of less than 10% commencing with the last quarter of the applied bias.

The turbulent nature of the high density floating potential measurements in comparison to low density is immediately clear looking at the coherence levels in Figure 6.15 for two floating potential probes with a 90° separation. A single mode is at 80%, even during biasing, with all other frequencies below 50%. The graphs presented are for 50ms starting at .5s. For the dominant mode in Figure 6.15(a) at 2-3kHz the cross phase is \( \approx -150° \) or closest to a \( m = 2 \) mode. The 3.5kHz mode in Figure 6.15(b) displays a similar cross phase of \( \approx -160° \) during bias, it is the same \( m = 2 \) that has not shifted lower in frequency due to the applied bias. The low coherence fluctuations between 1 and 2kHz display a rather stable cross phase of 90° suggesting a transient \( m = 1 \) at a subharmonic of the dominant mode.

Further underscoring the turbulence present in high density plasmas the nonlinear coupling present in high density floating potential measurements is markedly changed from the low density regime. Figure 6.16(a) displays the bicoherence in 49 realizations over the time period from .45 to .55s. Low level, broadband coupling is present across a broad range of frequencies up to 15kHz.
Figure 6.13: The floating potential power spectra are similar before bias is applied (left), later in the shot the unbiased mode frequency drops by $\sim 33\%$ while the bias mode is within $10\%$ of the earlier frequency (right). Comparison of the floating potential power spectrum in high density between a shot with -500V point bias (red, shot 7408) and one without (black, shot 7409).

Figure 6.14: Fluctuation levels are very similar in high density between a shot with -500V point bias (7408, red) and one without (7409, black).
Figure 6.15: Coherence of the dominant mode marginally increases under the influence of bias (top plots). Plot of coherence and cross phase versus frequency between two floating probes separated by 90°. Figures on the left are calculated near the end of an unbiased high density discharge, the right figures at the same time during a -500V point bias discharge.
The highest amplitude coupling is with the lowest resolvable frequency along the $f_2 = 0$kHz line and the $f_3 = 0$kHz (or the $y = -x$ line). Some additional coupling is present at $f_1, f_3 = 3$kHz where the dominant mode exists in Figure 6.13(b). The nonlinear coupling surprisingly decreases under the effect of bias, plotted on the same scale in Figure 6.16(b) from the same time period representing the last 100ms of negative applied bias. The coupling peak at $f_2, f_3 = 0$kHz does not occur. In addition to lower amplitude at each frequency triplet the frequencies that do register coupling are shifting lower in value, funneling in towards the $f_1 = 0$kHz, $f_2 = 0$kHz point. This is despite the peak mode frequency at 4kHz during biasing versus >3kHz without applied bias and indicates that while frequencies above the principle mode were amplified it was not through a nonlinear process.

![Bicoherence](a) No Applied Bias  
(b) -500V Point Bias

Figure 6.16: Bicoherence drops during point bias, particularly at the lowest frequencies in plots contrasting the nonlinear coupling levels present in the floating potential measurements in high density.

### 6.3 Summary

In low density discharges a strong point bias stabilizes the hot electron interchange mode. The resulting floating potential spectrum contains an upshifted fundamental mode and harmonics up to $m = 7$ with very high levels of quadratic frequency coupling between each. When the point bias is triggered during the discharge the characteristic mode frequency increases a smaller amount and the number of harmonics is reduced to one. The driven mode does not wholly outcompete the HEI
instability though the quasi-period of HEI bursts increases. The bias current levels during bias probe operation are comparable those seen in low density symmetric equatorial bias, but triggered bias probe experiments affect the plasma equilibrium less.

When point bias experiments were extended to the high density turbulent regime the effects were much more subtle. The application of a strong negative bias did not appreciably change the floating potential RMS fluctuation level, or alter the coherence or cross phase between two floating probes. The peak frequency of the principal mode was maintained with applied bias, in contrast to the unbiased drop in frequency. This response is very similar to that seen in high density symmetric equatorial bias shots but at lower emitted currents. In contrast to high density symmetric equatorial bias the nonlinear frequency coupling was not increased, in fact, it decreased during applied point bias.
Chapter 7

Non-Symmetric Equatorial Bias

This chapter investigates the effects of the application of a non-symmetric equatorial applied bias. Breaking the azimuthal symmetry drives currents both radially and azimuthally, altering the plasma $\text{E}\times\text{B}$ flows. The equatorial biasing array was configured with multiple azimuthal mode numbers and the change to the turbulence spectra were observed as the bias voltage and current increased. (Figure 3.10) In low density CTX plasmas the effects of a non-symmetric equatorial bias were nearly indistinguishable from the case of low density symmetric equatorial bias. However, when a static negative voltage was applied to a non-symmetric equatorial configuration of the bias array in high density, then a clear plasma response was observed, and characterized by amplification of the lowest order modes and decreased power to frequencies above $\approx 8\text{kHz}$. The quadratic coupling to the large amplitude, low order modes increased by over a factor of two during non-symmetric bias. A rotating equatorial bias, both in the direction of plasma rotation and counter-propagating, do not produce a similar response indicating that it is not a resonant perturbation but a change in the underlying nonlinear process brought about by broken azimuthal symmetry.

7.1 Non-Symmetric Bias Model

The aim of applying a non-symmetric bias is to deform the plasma streamlines from their unperturbed surfaces. This section estimates the extent by which the equilibrium streamlines are perturbed due
to a steady non-symmetric equatorial bias.

Figure 7.1: Illustration of the additional current paths during non-symmetric equatorial bias.

In previous work focusing on driving symmetric radial currents, the radial electric field was calculated showing very good agreement with experimental measurements, predicting a $1/r$ potential profile leading to the plasma rigidly rotating [39]. The model is based on a constant current, which when injected into the plasma via the equatorial biasing array must flow radially and exit at the chamber walls. This constraint implies no current flows along the field lines, which is a good assumption given the insulating magnetic cap. Additional assumptions are needed to estimate the Pedersen conductivity remaining constant across the plasma. We assume low collisionality dominated by ion-neutral collisions with an isotropic neutral density across the plasma. With the strong magnetic field of CTX the Hall term does not significantly contribute to the observed dynamics. In this way the current density is given entirely by the Pedersen conductivity

$$J = \sigma \cdot E_\perp = \sigma_p E_\perp - \sigma_H (E_\perp \times \hat{b}) + \sigma_o E_\parallel \approx \sigma_p E_\perp. \quad (7.1)$$

When this model is modified to allow non-symmetric equatorial bias the current injected at the inner boundary flows both radially and azimuthally. The change reconfigures the current channels in each subdomain as depicted in Figure 7.1. One result of breaking the symmetry is that the exponent of the radial potential dependence increases with rising azimuthal mode number. The dependence is shown in Table 7.1. While the increase is slightly less than linear the change when the mode
number is increased from $m = 3$ to $m = 6$ implies the radial potential changes from $\sim r^{-3}$ to a far steeper $\sim r^{-5}$, it should be expected that higher modes penetrate more shallowly into the plasma resulting in a smaller perturbation.

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Radial Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>$\alpha = -(1 + \sqrt{1 + 2m^2})/2$</td>
</tr>
<tr>
<td>1</td>
<td>-1.37</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>3</td>
<td>-2.68</td>
</tr>
<tr>
<td>4</td>
<td>-3.37</td>
</tr>
<tr>
<td>5</td>
<td>-4.07</td>
</tr>
<tr>
<td>6</td>
<td>-4.77</td>
</tr>
</tbody>
</table>

Table 7.1: Power law dependence of the radial component of potential for non-symmetric biasing.

With this model equipotential contours can be calculated given the mode number, injected current, and the non-symmetric fraction of that current. Figure 7.2 plots the results for an $m = 3$ structure and reasonable current values for CTX in solid curves and dashed curves showing the symmetric, zero current case. The equipotential contours are the $v_{E\times B}$ streamlines showing plasma flow. The streamlines arising from a non-symmetric current show flow deviations from pure azimuthal motion across most of the plasma, with the radial departures of 2cm at $L=50cm$. At inner radii streamlines actually impinge upon the magnet. Non-symmetric bias applied to the boundary of a cylindrical plasma was calculated to have a similar effect [10].
Figure 7.2: Contour plot of plasma equipotential contours during non-symmetric $m = 3$ equatorial bias (solid, grey lines). Overplotted are the equipotential contours without applied bias (dashed, blue lines). Calculations assume similar current levels and non-symmetric fractions as measured experimentally. Deviation from unbiased contours increases approaching the bias source with some inner streamlines impinging on the magnet.

### 7.2 Low Density Non-Symmetric Equatorial Bias

The plasma response to low density non-symmetric equatorial bias was very similar to low density symmetric response discussed in Chapter 5.2. Creating plasma discharges in the low density plasma regime using the upgraded equatorial biasing array proved challenging. In contrast to the centrifugal interchange mode studies conducted by Levitt, the upgraded equatorial array allowed driving larger, more perturbative currents, while the plasma densities studied here were lower than the symmetric equatorial bias studies in Chapter 5 due to decreased neutral gas fueling [39].

The non-symmetric discharges presented here are higher density than the point bias discharges analyzed previously in Chapter 6. This fueling difference may explain the shift in frequencies for the modes and fluctuations discussed. For these low density studies the equatorial biasing array was in the $m = 6$ azimuthal configuration. Results from both negative (Figure 7.3(a)) and positive (Figure 7.3(b)) discharges are presented.
The difference in the plasma response to the polarity of applied bias is shown in Figure 7.4. With -250V bias applied from .35 to .55 seconds in Figure 7.4(a) the amplitude of floating potential spectral peak increases by roughly an order of magnitude for the duration of the applied bias (see Figure 7.5(b)). The dominant mode frequency during bias is very similar to the low amplitude fluctuations preceding the application of bias, but the correlation analysis will show during bias the peak is a higher amplitude and lower mode number similar to the symmetric bias plasma response. The low frequency fluctuations below 10kHz are also seen to diminish in amplitude during biasing.

In contrast, applied positive bias only marginally changes the modes seen in Figure 7.4(b). The effect observed is also only lightly dependent on the magnitude of the applied bias, set to +500V in Figure 7.4(b). Unchanged in amplitude, the mode frequencies shift lower by a small amount and the higher mode number, 23kHz mode, becomes the dominant mode.

A direct comparison of the floating potential spectra and RMS fluctuations before and during the application of $m = 6$ bias further shows the difference in the plasma response to differing polarity. This is illustrated in Figure 7.5. The ensemble spectra for shots with positive and negative bias match closely for the 50ms before the application of bias, as seen in Figure 7.5(a). In Figure 7.5(b) the high amplitude mode excited during negative bias (black curve) is an order of magnitude higher than the other modes present, regardless of polarity. Higher harmonics are also present in the negative bias spectrum.
Figure 7.4: Spectrograph of the floating potential power spectrum for a $m = 6$ non-symmetric equatorial bias in low density with applied voltage of (a) -250V, and (b) +500V. Negative bias excites a strong coherent mode, not seen in the positive bias case. The frequency axis is zero suppressed to eliminate the obscuring signature of the HEI bursts.
With positive bias (red curve) we see a single dominant mode in Figure 7.5(b). This is different from the spectrogram in Figure 7.4(b) that indicated the presence of a lower amplitude and frequency mode. The intensity across all frequencies is similar before and during positive bias. This is in contrast to the negative bias case, where the fluctuation intensity for frequencies outside the excited modes are lower across the entire frequency band sampled.

![Power Spectra](image)

(a) Before Bias  
(b) During Bias

Figure 7.5: Floating potential power spectrum mode amplitude increases over an order of magnitude and generates harmonics in response to negative non-symmetric bias (black). Positive bias (red) displays small mode increase. Comparison of the floating potential power spectrum resulting from \( m = 6 \) non-symmetric bias of positive (red) and negative (black) polarity in low density. The FFT frequency axis is zero suppressed to eliminate the obscuring signature of the HEI bursts.

Analyzing frequency correlations from these two times periods under different biasing conditions will further the understanding of the mode response and facilitate mode identification. Figure 7.6 presents the coherence and cross phase over 50ms between two floating potential probes at three points: at .25s prior to application of positive bias, from .45s once the applied positive bias has reached the full level, at .45s again during a shot with negative bias applied. To better illustrate mode dynamics above the low frequency HEI burst quasiperiod, the frequency (horizontal) axis does not extend to zero but starts at 10kHz. Looking at the coherence before the application of bias in Figure 7.6(a) the dominant mode is \( \sim 17-19kHz \) with coherence of 80%, a higher frequency mode with coherence above 60% exists at \( \sim 26-28kHz \). Comparing the cross phase in Figure 7.6(b) the dominant mode at 180° is an \( m = 2 \) mode and the higher frequency mode is an \( m = 3 \) mode.
with a cross phase of -140° a bit below the expected phase of -90° likely a result of the lower mode coherence value. During positive bias in Figure 7.6(c) the coherence levels of the $m = 3$ mode increase and that of the $m = 2$ mode falls. This was suggested in the spectrograph in Figure 7.4(b) with the mode frequencies also shifting lower, the $m = 2$ shifts from 17-19kHz to 14-16kHz as its coherence drops below 60% and the $m = 3$ mode shifts from 26-28kHz to 22-23kHz while its coherence increases above 80%.

Negative applied bias elicits a different plasma response, consistent with the differences previously presented in the spectrograph and power spectrum. Figure 7.6(e) displays the coherence levels increasing as a result of applied bias, with the dominant mode near 16kHz exhibiting near 100% coherence and the higher frequency mode at 32-36kHz exceeding 80%. This makes even the sub-dominant mode as coherent as the dominant mode in either the time period before applied bias or during positive applied bias. In Figure 7.6(f) the dominant low frequency mode has a cross phase of very close to 90° making it an $m = 1$ mode while the higher mode is an $m = 2$ mode with a cross phase of nearly 180°. This result parallels the previous centrifugal mode results on CTX where under the presence of a strong negative bias the rotation frequency of the dominant $m = 1$ mode increases to roughly the frequency of the unbiased $m = 2$ mode while also becoming more coherent and larger in amplitude.

When nonlinear interactions are analyzed with bicoherence, the dominance of the HEI bursts is apparent for low density non-symmetric bias. The bicoherence is calculated over 100ms during biasing beginning at .45s using 49 realizations. The primary feature for both positive and negative applied bias is very low frequency coupling at roughly the inverse of the instability quasi-period as seen in Figure 7.7. In the case of positive applied bias shown in Figure 7.7(a) the peak coupling is 80% at the lowest resolvable frequencies with limited coupling between the low frequency mode and the primary 22kHz, $m = 3$ mode.

The nonlinear coupling in a negative bias discharge presented in Figure 7.7(b) has a lower peak amplitude of 60%. More significantly, the coupling peak shifts from low frequency dominated to coupling between the 16kHz $m = 1$ mode and the lowest frequency, that of the instability
Figure 7.6: Negative bias in the low density non-symmetric case drives a very coherent $m = 1$ mode and $m = 2$ harmonic. A coherent, higher frequency $m = 3$ mode results from positive bias. Figures are calculated between two floating probes separated by $90^\circ$, figures on the left are coherence and the right are cross phase.
quasi-period. This is best represented by the coupling on either side of $f_2 = 0$kHz line. The dominant frequency triplets are $f_1 = 16$kHz, $f_2 \sim 0$kHz, $f_3 \sim 0$kHz and $f_1 = 16$kHz, $f_2 = -16$kHz, $f_3 \sim 0$kHz).

![Bicoherence plots showing (a) low frequency coupling for +500V non-symmetric bias, and (b) high levels of coupling between the dominant mode and low frequencies for -250V non-symmetric bias.](image)

Figure 7.7: Bicoherence plots showing (a) low frequency coupling for +500V non-symmetric bias, and (b) high levels of coupling between the dominant mode and low frequencies for -250V non-symmetric bias.

### 7.3 High Density Non-Symmetric Bias

The plasma response to applied static non-symmetric bias changes significantly in the high density turbulent regime. As will be shown in this section, this response is independent of the azimuthal structure of applied non-symmetric bias and arises from the breaking of azimuthal symmetry. An inverse cascade is observed with applied bias of $m = 1, 3, 6$ at current levels of $\sim 100$mA.

Figure 7.8 provides an overview of shot parameters during a shot with $m = 3$ bias. The measured ion saturation current is also displayed and not affected by gating the bias on or off. The second panel displays the voltage applied to biased elements of the equatorial array, a duration of 200ms starting at .35s. Equipment limitations prevent the voltage from immediately reaching the full programmed level of -400V, reaching the full level approximately 60ms following the trigger. The collected current displays a similar notch and recovery but maintains a level close to 100mA, the maximum current rating for the power supply. When the bias was set to higher voltages the power
supply became current-limited with decreased performance and equipment variations were polluting the results.

![Ion Saturation Current](image1.png)

![Bias Voltage](image2.png)

![Bias Current](image3.png)

Figure 7.8: Overview of shot 7874, detailing the measured ion saturation current and applied $m = 3$ non-symmetric bias.

The level of current emitted in the two bias schemes is another measure that the plasma response to equatorial bias was changed by the breaking of the azimuthal symmetry. Figure 7.9 displays the average equatorial emitted current across a series of shots as the applied bias voltage is scanned between -250 and +600V for both symmetric and $m = 1$ non-symmetric bias. Notice the difference in current levels as the polarity changes, consistent with prior positive bias experiments. Once the bias voltage becomes negative the current levels increase significantly. Comparing the two traces we see the emitted current levels only match at the expected value of 0V (grounded) applied bias. Moving away from that point we see the emitted current grow much faster for symmetric bias than for non-symmetric bias. Part of the increased current may result from symmetric bias employing twice the surface area as all twelve segments are biased rather than six segments for all non-symmetric setups. However, the difference in emitted current cannot be accounted for solely through doubling the number of biased elements. The measured currents of the symmetric cases are four times higher than the non-symmetric cases at the same applied bias, implying twice the current
driven per biased segment of the equatorial array.

Figure 7.9: Average emitted current across voltages is larger for symmetric (black) than non-symmetric ($m = 1$, red) equatorial bias array configurations.

The azimuthal mode structure and applied voltage were varied in a series of experiments. During this scan the current driven by the power supply to maintain the prescribed bias voltage was measured. For non-symmetric discharges the current through non-biased segments was also measured. The measured values presented in Table 7.2 with multi-shot averages over the final 50ms of applied bias ensuring sampling during a driven steady-state period. The final column presents the ratio between the two measured currents, representing the fraction of current that traveled azimuthally instead of radially. Table 7.2 underscores the difference in measured current between symmetric and non-symmetric equatorial bias. The non-symmetric current fraction varies across a range from 16% to nearly 30% and is observed to increase with both higher applied voltage and increased azimuthal mode number. Given the non-symmetric fraction is always well under 50% the large symmetric current component results in a superposition of symmetric and non-symmetric currents. The $m = 3$ bias current is actually a sum of both equatorial currents, $m = 3 + 0$.

The following presented results show that the plasma response to non-symmetric bias is better correlated than with non-symmetric current than relative current fraction. The plasma response
Table 7.2: Non-symmetric current levels rise with increasing equatorial bias mode number. Current values are listed in mA and applied voltage in V.

to higher non-symmetric current levels is unknown, but the continued increase in the symmetric response suggests a bigger response from a larger driven current.

The similarity of the plasma response to a varying applied azimuthal mode number is shown in a series of floating potential power spectrographs in Figures 7.10(a)-7.10(c). All three examples display broad fluctuations with a peak intensity from 6-8kHz in the period before bias is applied at .35s. Other fluctuations at lower frequencies appear to be present but subdominant, except in Figure 7.10(a) where the 2kHz mode appears to be nearly the same magnitude as the higher frequency fluctuations. In the period between .35 and .4s, where the bias has been triggered on and is ramping up the applied current and voltage, the fluctuations appear to transiently weaken before strengthening around .4s. At this point in time a higher amplitude and more coherent mode develops and decreases in frequency from roughly 5 to 4kHz. At some later point during bias another mode is excited at frequencies below 2kHz. When the bias is switched off at .55s the spectrum adjusts quickly to roughly a 3kHz mode at roughly the same intensity as during applied bias. This is very different from the late discharge floating potential spectrum displayed in a shot with no applied bias (Figure 7.10(d)). Additionally, higher frequency fluctuations are weaker as a result of bias, best seen in Figure 7.10(c) with the larger black portion representing fluctuations below the colorbar scale.
Figure 7.10: Various non-symmetric bias configurations display a similar response to non-symmetric bias. Figure 7.10(d) shows a high density discharge without bias for contrast.
7.3.1 Non-Symmetric Bias Power Spectra

Another comparison of the fluctuations can be achieved through analyzing the floating potential power spectra before and during applied bias. Figure 7.11 presents floating potential ensemble power spectra over the 100ms before the application of bias from .25 to .35s. In Figure 7.11(a) the ensemble power spectra are plotted for all three azimuthal bias formations. The spectra above 9kHz are identical for all the non-symmetric cases. The \( m = 1 \) case, plotted in purple, differs from the other cases for frequencies below 9kHz with a slightly higher frequency low mode closer to 3kHz and lower amplitude near 6kHz. Figure 7.11(b) plots a comparison of ensemble power spectra for an unbiased high density case, a low current symmetric bias case, and a repeat of the \( m = 3 \) non-symmetric bias case for comparison.

Figure 7.11: Floating potential ensemble power spectra over 100ms starting at .25s. The spectrum of shot 7874 (red) is reproduced to simplify comparison. Spectra are similar for all non-symmetric bias cases (left) and comparison of unbiased with both symmetric and non-symmetric cases (right).

The effect of non-symmetric bias is clear in Figure 7.12 comparing discharges having no applied bias, an \( m = 3 \) non-symmetric bias, and a symmetric bias with comparable total current levels. In this plot the non-symmetric bias has two dominant modes present at \( \sim 1.5kHz \) and 3kHz at roughly an order of magnitude higher intensity than the standard high density discharge. The symmetric bias does produce an enhanced mode peak, but it is at the same magnitude as other fluctuations in the spectrum and still well below the values of the non-symmetric fluctuations. Not only does
the non-symmetric bias display enhanced power in the low frequency modes, but the intensity displays a pronounced decrease for frequencies above 8kHz with respect to either the high density or symmetric bias case. As presented before, for low symmetric current no enhancement in the intensity of high frequency fluctuations is observed. In addition to the changes in the relative intensity, the frequency values of the dominant mode shifts because of applied bias in Figure 7.12. While the symmetric mode peaks shift slightly higher as a response to bias, the non-symmetric peaks are shifted lower by nearly 50%. Non-symmetric power spectra shown in Figure 7.13 are strongly similar, regardless of the applied equatorial bias azimuthal structure.

Figure 7.12: The floating potential power spectrum from the non-symmetric bias case differs markedly from both the symmetric and unbiased cases. Two high amplitude low frequency modes are seen and intensity at high frequencies is decreased for all frequencies above 8kHz. Power spectra are calculated over 100ms starting at .45s.

Despite the large changes in the ensemble power spectra, the RMS fluctuation levels are largely unchanged as a result of applying an equatorial bias. In Figure 7.14(a) the RMS fluctuation levels are very similar for \( m = 1, 3, 6 \) azimuthal configurations with varying in time by roughly 20%. The RMS levels begin peaking before the bias is triggered and continue rising through the bias ramp, reaching a steady state from roughly .4 to .5s, then declining through the end of the discharge. As seen in Figure 7.14(b) the RMS fluctuations levels are very similar across non-symmetric, high
CHAPTER 7. NON-SYMMETRIC EQUATORIAL BIAS

Figure 7.13: Comparison of the floating potential power spectra for non-symmetric bias cases. The three cases, $m = 1, 3, 6$, display the same spectral response. Power spectra are calculated over 100ms beginning at .45s.

density or low current symmetric discharges. Although the spectral changes (and large amounts of power being applied to the plasma) the fluctuation levels are unchanged.

Figure 7.14: Floating potential RMS fluctuations are similar over 400ms independent of biasing configuration.
7.3.2 Non-Symmetric Bias Mode Coherence

The coherence of the floating potential fluctuations is enhanced during non-symmetric bias. This change occurs independent of the imposed azimuthal structure. Figure 7.15 only draws from an \( m = 3 \) discharge for simplicity. Focusing on the coherence plot in Figure 7.15(a) three strongly coherent modes are seen. The coherence of the first mode at \( \sim 1.5 \text{kHz} \) exceeds 90\%. This value is slightly higher than seen with a similar current level during symmetric bias, itself more coherent than an unbiased shot. The most striking change in the coherence is the very pronounced modes at \( \sim 3.5 \text{kHz} \) and 5kHz with coherence values exceeding 90\% and 80\%, respectively. A second higher frequency mode was observed in low current symmetric bias shots, but a third mode was not evident. High density shots with no applied equatorial bias did not consistently have a second coherent mode above 60\%. Using the cross phase in Figure 7.15(b) to identify mode numbers is difficult. The low frequency mode has a cross phase of \( \sim 135^\circ \), but will shortly be shown to be an \( m = 1 \) mode. The second mode cross phase is right at -90\°, consistent with an \( m = 3 \) mode, though this is the first integer multiple of the lowest frequency mode. Indeed, the following analysis will confirm this as an \( m = 2 \) mode. The 5kHz mode cross phase is very nearly 0\°, consistent with an \( m = 4 \) mode but also not far from being the second integer multiple of the primary mode.

![Figure 7.15](image)

**Figure 7.15:** Coherence and cross phase plots between two floating probes separated by 90° over 50ms starting at .5s for shot 7874.

The cross phase is calculated for the polar imager in Figure 7.16, allowing more direct visual-
ization of the spatial mode structure. Each polar plot displays the ensemble averaged cross phase between each polar imager detector and a reference detector. The averaged cross phase is then averaged across a .2kHz frequency bin around each coherence peak. Given the radial decorrelation and extremely low signal levels on the outermost radii the central core is most useful in identifying the mode numbers. For the lowest frequency mode, pictured in Figure 7.16(a), a clear \( m = 1 \) structure exists with negative phase differences at the top of the plot and positive phase differences near the bottom. Figure 7.16(b) shows the intermediate mode to have an \( m = 2 \) structure. With the decreasing coherence of the 5kHz mode the mode number identification is more challenging, but an \( m = 3 \) structure can be deduced at inner radii in Figure 7.16(c).

![Polar plots showing mode structures](image)

**Figure 7.16:** Calculated polar imager cross phase of 50ms during \( m = 3 \) bias in shot 7874 across a .2kHz frequency band corresponding to the coherence peaks in Figure 7.15(a).

Application of non-symmetric bias increases the fluctuation coherence across a broad portion of the plasma. As seen in Figure 7.17 plotting the coherence between each polar imager detector and a fixed reference detector, plotting the average coherence level of a 200Hz frequency band centered on the most coherent mode over 50ms at the end of applied bias. For shot 7896 shown in Figure 7.17(a) a higher frequency 7kHz mode is shown. The region of peak coherence is limited to a small radial zone that does not span an entire azimuth. In contrast, Figure 7.17(b) from shot 7873 shows that during \( m = 3 \) non-symmetric bias the region of elevated coherence covers the full period
and exhibits radial broadening as well. This result is consistent with an inverse cascade creating a large scale condensate and the observed changes in the floating potential spectrum. As the lower frequency, larger modes intensify, the plasma coherence should increase given the larger portion of the plasma the mode occupies. This behavior is in line with 2D MHD theory and long radial correlation lengths have been observed in toroidal plasma turbulence [63, 27].

![Contour plots comparing coherence with and without bias](image)

Figure 7.17: Contour plot displaying the polar imager coherence of the peak mode over 50ms for two shots, with no applied bias (a) and $m = 3$ non-symmetric bias (b). The coherence increases during non-symmetric bias to cover the entire azimuth with as well as becoming more radially broad.

### 7.3.3 Spectral Evolution in Time

Figure 7.18 presents ensemble power spectra with fewer windows from shorter periods of time to capture the floating potential spectrum evolution. The spectra are also presented in linear plots to identify changes in amplitude of each individual mode as time evolves from before, during and following bias application. The top panel shows two modes $\sim 6$-8kHz at relatively low amplitude preceding bias. The second panel shows amplification and the frequency of the modes shifting lower. In the two middle panels the frequency values of the modes does not shift but the relative
intensities do. From .44 to .47 the spectrum is dominated by what appears to be a 4kHz $m = 2$ mode with $m = 1, 3$ modes at lower amplitude alongside. By the following 20ms time window the $m = 1$ mode is dominant with decreasing amplitude for the $m = 2, m = 3$, and possibly even higher order modes. The final spectrum during bias, from .52 to .55, shows a very high level $m = 1$ mode with low amplitude $m = 2, 3$ modes. Following the bias the mode structure begins to relax with a lower amplitude and higher frequency mode present.

The evolving mode structure can also be visualized using the polar imager. Looking at 4ms of data from all detectors at $L=33.6cm$ in Figure 7.19 the plasma response to $m = 3$ bias clear. Figure 7.19(a) is drawn from the data series before non-symmetric bias is triggered. The mode structure is not well established, occasionally a plasma structure extends completely across the figure, indicating a mode that persists through an entire revolution around the experiment. More often, the plasma structures break up, split, or merge. After the bias has been switched on and is at peak value in Figure 7.19(b) the mode is more coherent lasting through multiple transits of the machine. Looking vertically at a particular time, like .404s, two peaks and two troughs are evident indicating an $m = 2$ mode. Figure 7.19(c) is drawn from only a few dozen milliseconds before the bias is triggered off. At this point in time the mode structure has evolved to a strong $m = 1$ that displays some bifurcations and breadth indicating that higher order $m = 2, 3$ structures are present. The overall rotational frequency is related to the pitch of each “stripe”, the lower the frequency, the longer it takes to transit the device and the modes appear horizontally stretched. This can be seen in the difference between the pitch of the strong fluctuation at .316 s in Figure 7.19(a) and all in Figure 7.19(c).
Figure 7.18: Series of floating potential power spectra showing the evolution in time as a response to $m = 3$ non-symmetric bias in shot 7873.
Figure 7.19: Contour plot displaying the evolution of the spatial mode structure from low coherence before bias to increased coherence in an $m = 2$ mode to high coherence in an $m = 1$ mode during application of $m = 3$ non-symmetric bias. Note: These figures are intended to illustrate spatial structure and not amplitude as the intensity scales are not fixed.
7.3.4 Non-Symmetric Bias and Nonlinear Coupling

The use of non-symmetric equatorial bias increases both the intensity and the spatial extent of nonlinear frequency coupling. This is clearly evident in Figure 7.20 plotting the floating potential bicoherence over the final 100ms of applied $m = 1, 3, 6$ bias. Breaking the bias symmetry clearly enhances the peak coupling levels, as the range is 25% higher than the symmetric plots (Figures 5.18 & 5.17) or unbiased plot (Figure 5.16). In the latter plots the peak levels of coupling where very localized between the $m = 1$ and $m = 2$ harmonics. The non-symmetric bicoherence plots display this, with additional strong levels of coupling spread across frequencies. Having a mode couple broadly across frequencies produces the extended lines most easily seen in Figure 7.20(a). Horizontal lines indicate broadband coupling with $f_2$, while the diagonal lines represent broadband coupling with $f_3 (\equiv f_1 \pm f_2)$.

Broadband coupling was not observed in unbiased shots. Symmetric equatorial bias displayed low levels of broadband coupling, even at double the non-symmetric current levels. The lines of broadband coupling seen represent the $m_1=1.5kHz$ and $m_2=3.5kHz$ modes that dominate the late time spectra in Figure 7.13.

The relative intensity of the nonlinear coupling does exhibit shot-to-shot variation, but the lower levels seen in Figure 7.20(b) persist across shots, indicating the $m = 6$ biasing is less effective in altering the coupling and changing the power spectrum. Also not evident in the bicoherence is any coupling with the lowest frequency fluctuations that was evident in low density biasing.

The summed bicoherence levels for the different non-symmetric bias configurations are similar and represent the enhanced nonlinear coupling seen in Figure 7.20. A comparison of a non-symmetric bias discharge, a symmetric discharge with comparable current level and a discharge with no applied bias is presented in Figure 7.21 over the final 100ms of the bias window. The two dominant modes seen in the power spectra that correspond with the chevrons in the bicoherence plots dominate the plot with peaks exceeding twice that of either unbiased or symmetric bias shots. Additionally, the non-symmetric case displays elevated coupling across the high frequency range from 8-20kHz. This is particularly notable given the lower power levels present in the
Figure 7.20: Bicoherence plots over 100ms starting at .45s for three spatial configurations of non-symmetric equatorial bias. All three configurations demonstrate enhanced coupling, both in coupling levels and amount of coupling across a broad band of frequencies.
non-symmetric power spectrum above 8kHz. The total bicoherence, \( B_t = \frac{1}{N_{tot}} \sum_{f_1,f_2} b^2(f_1,f_2) \) with \( N_{tot} \) the number of terms in the sum, representing all coupling in bicoherence plane more than doubles during non-symmetric bias versus a high density discharge. In comparison, the symmetric bias increase is about 10% at either current level.

Figure 7.21: Non-symmetric bias displays sharply higher summed bicoherence than either high density or symmetric bias across nearly all frequencies. Current levels are comparable for the non-symmetric bias (red, shot 7874) and symmetric bias (blue, shot 7894) at \( \sim 100\text{mA} \).

### 7.4 Rotating/Zero Net Current Equatorial Bias

Experiments were undertaken investigating the effect of a rotating non-symmetric equatorial bias and the possibility of a resonance between the rotating plasma and the rotating bias.

The rotating equatorial bias setup allowed the possibility to apply a zero net current perturbation, with the current into the plasma from the emissive equatorial segments being equally matched by the current drawn by the oppositely biased collecting equatorial segments. In such a configuration the applied bias would be purely \( m = 3 \), in contrast to static applied bias where the applied bias is
represented by $m = 3 + 0$ incorporating the wholly radial component or symmetric current fraction. To achieve zero net current the equatorial segments were separated into two groups such that segments alternated, with each group of six segments connected to one of two high speed amplifiers. Having two amplifiers and two groups of segments allowed the bias to be driven in quadrature, rotating either in the direction of plasma rotation or opposing the plasma rotation through changing the phasing of the second amplifier and corresponding equatorial segments to either lead or lag the initial signal. A function generator created a pure tone at a prescribed frequency that was phase shifted and fed into the pair of amplifiers to drive the equatorial array.

![Ion Saturation Current and Floating Potential](image)

**Figure 7.22:** Overview of plasma fundamentals in response to a zero net current $m = 3$ rotating bias applied from .4 to .6s in the direction of plasma rotation in shot 6834.

The plasma response to applied rotating bias was not present in the equilibrium levels of either the collected ion saturation current or the measured floating potential. Shown in Figure 7.22 are plots taken from shot 6834 with a co-rotating $\pm 100V$, $4kHz$ bias triggered from .4 through .6s. These traces are representative of all the rotating bias parameters scanned, varying the location of the ion saturation current probe, the floating potential probe as well as the direction and frequency of the applied rotating bias, with no discernible change in the measured signal levels when the bias
switches on or off.

A single millisecond zoom of the applied bias and emitted current is shown in Figure 7.23. The emitted current is measured from the positive lead of the one of the amplifiers configured in quadrature. The applied voltage to each leg is shown in the lower plot. In the plot the black and green traces comprise the positive and negative outputs of one amplifier. The blue and red traces show the properly phased positive and negative leads of the other amplifier. The emitted current in the top plot is very close to symmetric about zero current, but lower than in the static non-symmetric case. This inability to drive large amounts of current is likely related to the observed inability to effectively apply positive bias to CTX plasmas. All four rotating voltage signals are limited to low positive applied bias levels.

![Figure 7.23: Top figure showing the measured voltages of each component of $m = 3$ rotating equatorial bias, with $90^\circ$ phasing. Lower plot displays the emitted current (black) associated with the applied voltage for one component of the rotating bias, also displayed in black.](image)

Spectrographs of the floating potential power spectrum are similar for both directions of rotating bias and an unbiased high density discharge 6847. Figure 7.24(c) displays a shot with no applied rotating bias. After the high density transition in this shot a strong mode is observed near 2kHz
through .3s before fading out before .4s. A higher frequency mode between 6-7kHz persists longer, though at diminishing amplitude. This is in contrast to both rotating bias cases, as shown in Figures 7.24(a) and 7.24(b), where the low frequency mode was subdominant to a high frequency mode throughout the discharge.

Figure 7.24: The spectral similarity between co- and counter-rotating equatorial bias in seen in spectrographs with rotating $m = 3$ equatorial bias applied at 4kHz from .4 to .6s.

The ensemble averaged spectra more quantitatively display the enhancement of low frequency floating potential fluctuations during the application of rotating bias. Figure 7.25 displays the ensemble spectra for the 100ms before and the 100ms after the rotating bias is triggered. These time windows were selected to minimize the effect of the strong low frequency mode early in shot 6847 and to include the plasma response that diminishes in magnitude after .5s. The distribution of fluctuation intensity across the full frequency range is remarkably similar for the co-rotating and counter-rotating equatorial bias discharges both before and during the application of rotating
equatorial bias. Figure 7.25(a) shows the frequency response before applied bias is the same for all three cases above 7kHz, while both rotating bias discharges the power in the signal in the range 5-7kHz is elevated and less than the baseline across the low frequencies from 1-4kHz.

The application of rotating equatorial bias doubles the amplitude of low frequency modes. While the fluctuation power in frequencies below 10kHz falls at later time in the unbiased shot, the high frequency mode present in the rotating bias shot remains at the same amplitude but shifts left to lower frequencies, as observed in the Figures 7.24(a) & 7.24(b). Meanwhile the low frequency power from 1-2kHz is increased by roughly a factor of 2. The direction of rotation of the applied bias does not impact the power levels. The mode frequency is not shifted either up or down by the direction of rotating bias.

Figure 7.25: Comparison of floating potential power spectra shows small difference between rotating bias and no bias, but no difference in direction of rotation before and during $m = 3$ rotating bias.

The floating potential RMS fluctuations are presented in Figure 7.26 for the 200ms before and during application of rotating bias, triggered at .4s. In the first half of the figure the fluctuations levels are independent of the presence or direction of rotating bias. For the second half, which during the application of rotating bias, both discharges with rotating bias applied display RMS levels $\approx$10% higher than the high density discharge. This is consistent with the peaking of the power spectra during rotating bias observed in Figure 7.25. Figure 7.26 shows the relative increase in RMS results from rotating bias maintaining the RMS fluctuations while the unbiased RMS continues to
Figure 7.26: Floating potential RMS fluctuations showing slightly elevated fluctuation levels during rotating bias.

The coherence and cross phase of the frequency fluctuations are consistent with the power spectra. Figure 7.27 presents the coherence and cross power between a pair of floating probes for a shot with no applied bias, as well as co-rotating and counter-rotating equatorial bias shots for the 100ms following the bias trigger at .4s. The coherence levels displayed in Figure 7.27(a) with no applied bias show very low amplitude peaks, ∼40%, between 1-2kHz and 4kHz with the primary structure visible in the spectrograph at 7kHz with marginal coherence levels just above 60%. The cross phase for the lower amplitude modes seen in Figure 7.27(b) correspond to a weak or intermittent $m = 1$ mode. The principal mode at 7kHz has a cross phase of about -150° characteristic of an $m = 2$ mode. The coherence calculated for the co-rotating (Figure 7.27(c)) and counter-rotating (Figure 7.27(e)) display the same two large mode peaks at the frequencies above 1kHz and very nearly 4kHz. The coherence of the co-rotating fluctuations are slightly, but noticeably, higher than the counter-rotating case. With the higher coherence levels observed in both rotating bias cases the cross phase values enable less ambiguous mode number identification. In both Figure 7.27(d) & 7.27(e) the ∼1kHz cross phase is the expected 90° of an $m = 1$ mode and the 4kHz cross phase is 180° indicative of an $m = 2$ mode. The respective cross phase plots of the co-rotating and counter-rotating cases clearly show the direction of rotation for the equatorial
bias does not affect the plasma. If the counter-rotating perturbation forced the plasma to rotate in the opposite direction the cross phase for the $m = 1$ would flip from $+90^\circ$ to $-90^\circ$, and the general slope of the phase versus frequency curve would reverse. This is not the case for the studied counter-rotating equatorial bias shots.

Investigating the level of quadratic frequency coupling during rotating bias also shows very little differentiating activity when directly compared to a standard high density plasma discharge. All three plots in Figure 7.28 display low-level disperse coupling with no appreciable features. The peak level of coupling does occur during the counter-rotating bias shot, but this peak is very localized and does not display any broadband coupling across other frequencies.

The total levels of nonlinear frequency coupling across the three shots investigated here show little differentiation. Figure 7.29 plots the total level of bicoherence at a specific frequency, showing no clear difference in the level of coupling between co-rotating and counter-rotating bias. At low frequencies close to the modes previously discussed the summed bicoherence levels are slightly elevated when compared to a high density discharge, but the marginal change is far less distinct than that of static equatorial bias.
Figure 7.27: Coherence and cross phase plots between two floating probes separated by 90° over 100ms starting at .4s. Presented are plots for both directions of rotating $m = 3$ equatorial bias and an unbiased baseline.
Figure 7.28: No significant change in bicoherence resulting from applying a rotating $m = 3$ equatorial bias over 100ms starting at .4s.
7.5 Summary

Static high density non-symmetric bias did have a strong plasma response, and one that was nearly independent of the azimuthal mode structure of the applied bias. The symmetry breaking resulted in enhanced nonlinear coupling with the total bicoherence doubling. This increased energy flow exhibited an inverse cascade to the largest scale in the device, enhanced $m = 1, 2$ modes and diminished high order modes, while overall fluctuation levels were unchanged. Application of a bias rotating either against or in the direction of plasma rotation did not alter the power spectrum or levels of nonlinear coupling. This demonstrates the inverse cascade is not a resonant process but arises from symmetry breaking by non-symmetric bias. Plasma response to a static low density non-symmetric bias is similar to the low density symmetric response.
Chapter 8

Conclusions and future work

Turbulence is ubiquitous in fluid and plasma flows and are relevant to a broad range of fields such as combustion, fluid dynamics, atmospheric research, plasma physics and astrophysics. For low frequency fluctuations of a plasma in a strong dipole magnetic field, turbulence is two-dimensional. We have shown for the first time the driven inverse energy cascade through breaking the symmetry of applied electrostatic bias. With bias applied the plasma exhibits a new equilibrium with amplified low order modes and decreased higher order modes for unchanged fluctuation levels. This response is shown to be independent of the non-symmetric azimuthal structure of the applied bias. Bias configuration increases the levels of nonlinear coupling.

<table>
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<tr>
<th>Bias Scheme</th>
<th>Low Density</th>
<th>High Density</th>
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</thead>
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<tr>
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<td>Dominated by HEI</td>
<td>Interchange Turbulence</td>
</tr>
<tr>
<td>Equatorial Bias (Symmetric)</td>
<td>Excites Rotational Interchange Instability</td>
<td>Limited Spectral Response</td>
</tr>
<tr>
<td>Point Bias</td>
<td>Frequency Shift, Linearly Saturated Modes</td>
<td>Limited Spectral Response</td>
</tr>
<tr>
<td>Nonsymmetric Equatorial Bias</td>
<td>Excites Rotational Interchange Instability</td>
<td>Drives Inverse Energy Cascade</td>
</tr>
<tr>
<td>Rotating Equatorial Bias</td>
<td></td>
<td>No Response, Independent of Rotation</td>
</tr>
</tbody>
</table>

Table 8.1: Table of the electrostatic bias configurations and results discussed in this thesis.
8.1 Conclusions

The results of experiments presented in this thesis demonstrate the existence of the inverse energy cascade in the low frequency interchange turbulence in the strongly magnetized plasmas of CTX.

- The inverse energy cascade was observed by breaking the azimuthal symmetry by applying a non-symmetric equatorial bias. During the application of non-symmetric equatorial bias the high frequency fluctuations are seen to decrease while low frequency modes are enhanced. Best displayed in Subsections 7.3.1 & 7.3.3. This configuration was found through experiments employing a variety of perturbations presented in Table 8.1.

- During applied bias the coherence of these low frequency modes increase, consistent with two-dimensional fluid turbulence simulations[27, 63]. This is observed by both floating potential probes and polar loss current detectors (Subsection 7.3.2).

- These effects are associated with an increase in nonlinear frequency coupling as measured with bicoherence in comparison to both a high density baseline and a symmetric bias case. Presented in Subsection 7.3.4.

- The non-symmetric response is independent of azimuthal mode structure, with $m = 1, 3, 6$ shown to produce a similar response to the fluctuation spectrum. Demonstrated in Subsections 7.3.1 & 7.3.4.

- The failure of a rotating non-symmetric equatorial bias to produce a plasma response demonstrates the observed inverse energy cascade is not a resonant process but results from static symmetry breaking caused by non-symmetric bias. Shown in Section 7.4.

8.2 Future Research Opportunities

The research presented in this thesis demonstrates how breaking the symmetry of applied bias alters the nonlinear coupling in the floating potential spectrum, allowing visualization of the two-
dimensional inverse energy cascade through changing the nonlinear coupling and increasing the global plasma coherence. These results suggest several areas of future research:

- First, increased bias current could uncover more dramatic results given the increased plasma response to higher currents during symmetric equatorial bias. An equipment upgrade would allow testing more of the non-symmetric bias parameter space.

- Second, use of the multi-tip radial transport array (see Figure 3.7) would illuminate how radial transport changes under the different equatorial biasing regimes. Symmetric biasing drives a radial current, an associated change in radial transport levels is expected.

- Third, investigate turbulent plasma feedback. This intriguing prospect could assume any number of forms through varying the placement and configuration of sensors and actuators in the vacuum chamber or applying an analog or digital filter to signal before application to the plasma.

- Fourth, numerical computation of the effects of non-symmetric equatorial bias or a point bias in the bulk plasma could be undertaken. A code previously shown to well reproduce experimental results from CTX exists and with modifications could shed further light onto results presented in this thesis.
Bibliography


