Experiments with a Supported Dipole

Reporting Measurements of the Interchange Instability Excited by Electron Pressure and Centrifugal Force

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Collisionless Terrella Experiment
Mike Mauel – ICC 2004

Outline

• Introduction
• Description of CTX Experiment
• Hot Electron Interchange Instability
  ➡ Centrifugal Interchange Instability
• Future Experiments and Campaigns
Introduction

- Interchange ($k \cdot B \approx 0$) mixing is a natural process in planetary magnetospheres that is either externally-driven (e.g. the solar wind) or internally-excited by instability (e.g. Jupiter’s Io torus).

- The Collisionless Terrella Experiment (CTX) was built to investigate interchange instability of “collisionless” plasma confined by a strong laboratory dipole magnet.

  ▶ CTX results have guided physics planning for LDX.

- Since a dipole field has no magnetic shear, exhibits strong compressibility/adiabaticity effects, and with $k \cdot B \approx 0$, interchange dynamics in a dipole is a fascinating 2D process.

  ▶ Beautiful nonlinear “wave-particle” interactions result!

  ▶ Good agreement between theory and experiment.

👋 Recently, Ben Levitt succeeded in exciting the centrifugal interchange instability in a rotating dipole plasma.
CHAPTER 3. COLLISIONLESS TERRELLA EXPERIMENT

The vacuum vessel, magnetic topology, microwave resonance location, diagnostics and new installations to the device to be discussed in Sec. 3.3.

High-field, 0.2 MA-turn Water-cooled Magnet

Biasing Array

μWave Power

Probe #1

Mach Probe #1

Probe #2

Mach Probe #3

Probe #4

Probe #5

Cyclotron Resonance

1 m

67 cm
CTX Plasma

(High Density Regime)
Creating an “Artificial Radiation Belt”

- Low-pressure microwave discharge in hydrogen (2.45 GHz, 1 kW)
- Energetic electrons (5 – 40 keV) produced at fundamental cyclotron resonance: an “artificial radiation belt”
- Electrons are strongly magnetized ($\rho/L \ll 1$) and “collisionless”. Equatorial drift time $\sim 1 \mu$s.
- Intense fluctuations appear when gas pressure is adjusted to maximize electron pressure
Close-up: Hot Electron Interchange Instability
Properties of Interchange Instability Driven by Energetic Electrons

- Instability acquires a real frequency, \( \omega \sim \omega_d \), from the rapid magnetic drift of the electrons.

- Stabilizing ion polarization currents allow pressure gradients to exceed the usual MHD limit, \( \delta(pV^Y) > 0 \), creating a threshold to instability and suppressing short azimuthal wavelength.

- Drift-resonance with electrons create “phase-space holes” (or “vacuum bubbles”) that propagate inward. These holes can be “plugged” by applying RF scattering with a secondary source [Maslovsky, PRL03].

- Strong modulations in electron density occur that are radially localized (but azimuthally extended) [Warren, PRL95] and have a shorter length-scale as the fluctuating potential [Levitt, POP03].
Self-Consistent, Nonlinear, Multi-Fluid, **Field-Line Integrated**, 2D Simulation Reproduces Dipole Interchange Dynamics and Mode Structure [Levitt, POP03]

**Dynamics: Frequency Rise**

**Structure: Broad, Multi-Mode**
Interchange Burst Causes Strong Localized Electron Modulations

[Warren, PRL95]

- Low energy electrons resonantly interact before (faster) high energy electrons.

- Field-line integrated phase-space spatial structures have complex energy dependence due to drift frequency differences.

- Oscillations persist due to at high energy drift resonance at hot electron pressure peak.
Observation of Centrifugal Interchange Instability
[Levitt, 2004]

- Axisymmetric bias voltage (≤ 500 V) applied to equatorial mesh placed at plasma’s inner boundary.
  - Axisymmetric radial current drives azimuthal E×B rotation.
  - Current increases with neutral pressure and fixed $\omega_e$.
  - “Near sonic” speeds ($\omega_e/2\pi \sim 18$ kHz) on outer flux tubes.
- Instability appears only with sufficient rotation drive.
- Low instability frequency, $\omega \approx \omega_e \ll \omega_{dh}$.
- Low amplitude, ~ 10% of HEI, Reduces central density peaking.
- Broad global mode structure, dominated by long azimuthal wavelengths ($m = 1, 2$) but with a weak radial “spiral”.
- Good agreement with theory/simulation when effects of fast electrons are included.
Driven Plasma Rotation Appears Rigid

- Floating potential scales with radius as $\Phi \sim R^{-2}$
- Corresponds to rigid rotation in a dipole, $\omega_e/2\pi = 18$ kHz
- Potential profile consistent with constant radial current proportional to the field-line integrated Pedersen conductivity:
  $$I \approx 8\pi M \omega_e(R) \Sigma_p(R)$$
- $\Sigma_p(R)$ is constant if density profile, $n \sim R^{-6}$, exceeds instability threshold.
Centrifugal Interchange

(kHz not MHz)

(Seconds not msec)
At Lower Density, Centrifugal Instability Mixes with Hot Electron Interchange Bursts

Outward Bursts of Energetic Electrons

Close-up: Hot Electron Interchange
Reduced B: Faster Rotation & Fewer Hot Electrons Excites $m = 2$ Dominated Mode Structure

$m = 1$  
$m = 2$
Nonlinear Simulation with Rigid Rotation
Computed in Rotating Frame
Unstable Growth and Saturation from Noise

5% Hot Electron Fraction

20% Hot Electron Fraction
Broad “Spiral” Mode Structure
Summary

- Supported dipole experiments have been used to study basic, low-frequency interchange mixing in a dipole plasma. Interchange instabilities are excited by
  - Steep energetic electron pressure gradients \((P(R) > R^{-7})\)
  - Steep density gradients \((n(R) > R^{-4})\) and rigid rotation
- Fast magnetic drift of energetic electrons imparts a real frequency to the interchange mode and creates stabilizing ion polarization effects. The hot electron interchange has a threshold above the MHD limit, and the growth of centrifugal interchange modes with short azimuthal wavelengths are suppressed.
- The radial structure of the fluctuating potential is broad.
- 2D nonlinear models for interchange \((k \cdot B \approx 0)\) dynamics reproduces both the dynamics and structure of observations.
This Summer

Cassini-Huygens Encounters Saturn
June 14: Phoebe
July 1: Orbit Insertion

LDX Creates First Plasma
See Poster Session #3 (Thurs)
Garnier, Hansen, Kesner

Launched 1997 $3B

Floating Coil Lifted for Final Assembly

Floating Coil within Charging Station