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# Studies of a Parallel Force Balance Breaking Instability in a Stellarator

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**Abstract.** An instability has been observed in non-neutral plasmas confined on magnetic surfaces in the presence of a finite ion fraction [Phys. Rev. Letters **100**, 065002 (2008)]. The dependence of the frequency and amplitude of the instability on neutral pressure, magnetic field strength, and ion species show that the mode consists of interacting perturbations of ions and electrons. In the Columbia Non-neutral Torus (CNT) the instability has a poloidal mode number of m=1. This does not correspond to a rational surface, implying that the parallel force balance of the electron fluid is broken. Here the diagnostic methods used to study this instability are described in detail, and some key results are shown.

**Keywords:** Non-neutral plasmas, pure-electron plasmas, instability, magnetic surfaces, stellarator, trapped particles.
**PACS:** 52.27.Jt, 52.35-g, 52.55.Hc.

## INTRODUCTION

CNT is a simple stellarator configuration, consisting of nested magnetic surfaces generated entirely from four circular, planar magnetic coils [1, 2]. The nested magnetic surfaces of a stellarator have a finite magnetic winding number $\iota$, defined as the number of poloidal transits of the magnetic field per toroidal transit. In CNT $\iota$ ranges from $\iota$ =0.12 at the magnetic axis to $\iota$=0.23 at the boundary of the plasma. The underlying physics governing the stability of non-neutral plasmas confined on a magnetic surface configuration like CNT is different from the physics of non-neutral plasmas confined in Penning and Pure-toroidal traps [3, 4]. This is because electron plasmas on magnetic surfaces are in a minimum energy state [5, 6], where low frequency oscillations can in principle damp out by electrons streaming along the magnetic field from a high density part of the perturbation to a low density part. This was thought to happen unless the mode structure of the instability corresponded to a surface where $\iota$ is a rational number, and hence electrons could not stream along the magnetic field to damp out the instability.

Despite this, an ion-driven instability has been observed in CNT which has a poloidal mode number of m=1 [7], which does not correspond to a rational

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surface of CNT. The measured frequency and amplitude dependence of the mode show that the mode consists of interacting perturbations of ions and electrons [7]. The fact that there is an unstable electron component that does not resonate with a rational surface implies that the parallel force balance of the electron fluid is being broken.

The ion driven instability in CNT was diagnosed using internal floating emissive probes and external capacitive probes. This paper describes the diagnostic methods in detail and elaborates on some of the results presented in ref. [7].

## PARAMETER DEPENDENCE OF INSTABILITY

Floating emissive probes where used to study how the frequency and amplitude of the instability varied with magnetic field, electric field, neutral pressure, and the ion species introduced. These experiments showed that the unstable mode appears when the ion density exceeds approximately 10% of the ion density. Below this threshold, the plasma is stable. It was also found that the frequency decreased with increasing magnetic field, but did not scale as 1/B, and depended on the species of ion in the plasma. These, and other important results, are shown in ref. [7].

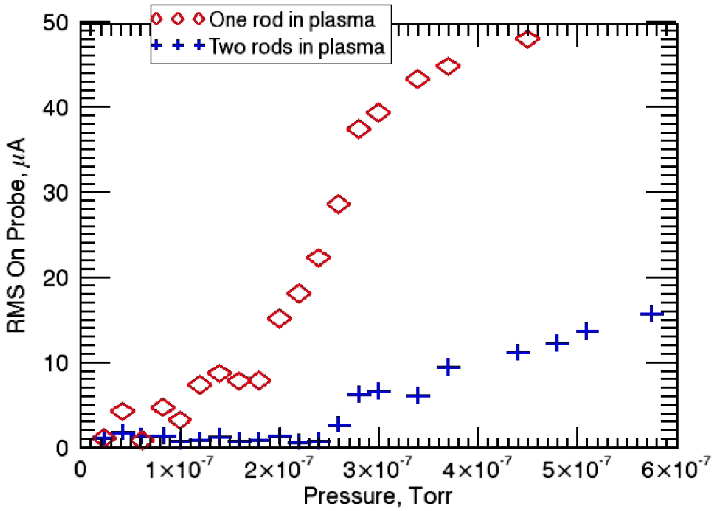


**FIGURE 1.** Measurements of the RMS of the signal on an emissive probe as a function of neutral pressure of air, with one or two ceramic rods inside the plasma, at B=0.02 T, $\varphi_{plasma}$=-200 volts.

Ions are introduced into the plasma by raising the neutral pressure. Electron impact ionization then creates ions in the plasma. The rods which are used to hold the tungsten filaments in the plasma act as a sink for ions, causing the amount of ions to reach a steady state [11].

It was important to determine if it was ions or neutrals that were destabilizing the plasma. This was accomplished by measuring the threshold neutral pressure for instability with one and two ceramic rods inside the plasma. The ceramic rods used for this experiment are at symmetric locations in the plasma (shown in fig. 1 of ref. 9), so that the steady state ion fraction when there are two rods in the plasma will be half of what it is when there is just one rod in the plasma, at a given neutral pressure.

Fig. 1 shows the RMS of the amplitude of the oscillation measured on a floating emissive probe, vs. neutral pressure, with one and two rods in the plasma. The floating emissive probe is 7.6 cm away from the magnetic axis, in the thin cross section of the plasma where the electron density is high. In fig. 1, a large jump in the amplitude of the oscillation is seen at $1.2\times10^{-7}$ Torr when there is one rod in the plasma, and a jump is seen at $2.8\times10^{-7}$ Torr when there are two rods in the plasma. This shows that the threshold for instability is at a given ion fraction, and not at a given neutral pressure. Thus it is ions and not neutrals that are destabilizing the plasma.

CNT has a complicated geometry, where the strengths of the electric and magnetic fields vary by a large amount inside the confining region [9, 1]. The strength of the magnetic field can be adjusted while keeping the magnetic geometry the same by proportionally changing the current in all four magnetic coils [1]. The scalar strength of the magnetic field in CNT is defined as the strength of the magnetic field on the magnetic axis in the thin cross section of the plasma. The electric fields in CNT can be adjusted (approximately proportionally) by varying $\varphi_{plasma}$, the potential on the electron emitter. For the experiments shown here, the electric emitter was on axis in the thin cross section of the plasma.

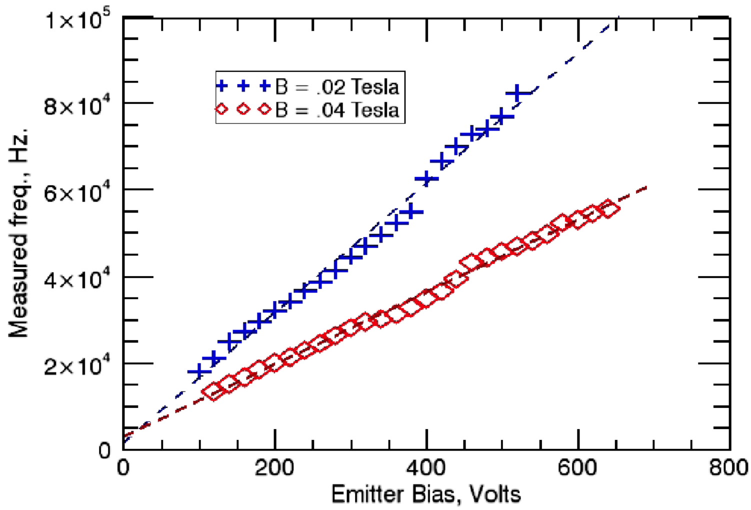


**FIGURE 2.** The frequency of the instability vs. $\varphi_{plasma}$ at two different magnetic field strengths. The background neutral pressure is $2.5\times10^{-7}$ Torr of $N_2$.

Fig. 2 shows the frequency of the mode vs. $\varphi_{plasma}$, at two different magnetic field strengths. The mode is increasing approximately linearly with $\varphi_{plasma}$, as expected for a mode that scales with the **E**×**B** drift of the electron plasma. The frequency of the mode is decreasing with magnetic field strength. However, the frequency of the mode does not scale exactly as 1/B, and depends on the species of ion introduced [7]. The frequency scaling indicates that the mode involves interacting perturbations of ions and electrons.

## Description of Floating Emissive Probe Diagnostic

The measurements described above were made with the same tungsten filaments that were used to measure the electron temperature, density, and the plasma potential [8] in CNT. When being used to measure oscillations, a 10 nF capacitor is placed in between the diagnostic circuit and the probe, to prevent DC current from flowing into the circuit and to allow the heated filament to charge up to close to the plasma potential. It takes approximately 0.5 seconds for the electron current collected by the filament to saturate the voltage of the 10 nF capacitor. Because of this, the plasma is allowed to run for at least 5.5 seconds before data is taken. An op-amp current to voltage converter is used to measure current fluctuations at the probe.

The floating emissive probe has both resistive and capacitive coupling to plasma oscillations. The resistive coupling exists because the hot filament collects and emits electrons as the relation between the local plasma potential and the probe potential changes. The capacitive coupling comes about from image charges in the conducting filament coupling to local potential oscillations. The measured signal from the capacitive coupling is 90° out of phase with the measured signal from resistive coupling. The capacitive coupling of these probes is small (~ 1 pF) but can compete with the resistive coupling in regions of low density. This phase ambiguity makes it difficult to measure the modal structure of the instability with floating emissive probes, and is one of the reasons why external, capacitive probes were used to measure the modal structure of the instability.

## SPATIAL STRUCTURE OF THE INSTABILITY

A set of 4 external image charge probes where built in order to make non-perturbing, purely capacitive measurements of the spatial structure of the instability. These capacitive probes are made of 5 cm copper discs that are each held in place with an aluminum rod. The aluminum rods are thin enough so that they can be bent and manipulated, but are strong enough so that they will hold the probes in a set location when they are installed. The copper disks are attached with metal screws to a tapped bore in the aluminum rods, and are electronically insulated from the aluminum and from the screws with a pair of ceramic washers. The capacitive probes are soldered to shielded cable which is attached to a UHV electrical feedthrough. When the CNT chamber is not under vacuum, the aluminum rods can be adjusted to set the location of the capacitive probes. A picture of this probe array before installation is shown in fig. 4.1 of ref. [12].

In order to measure the poloidal mode number of the instability, the capacitive probes were placed poloidally around the thick ($\varphi = 90°$) cross section of the plasma, where the plasma is approximately cylindrical. Fig. 3 shows a schematic of the location of the 4 probes, along with the last closed flux surface and the magnetic axis. The angle θ is defined using the magnetic axis as the vertex.

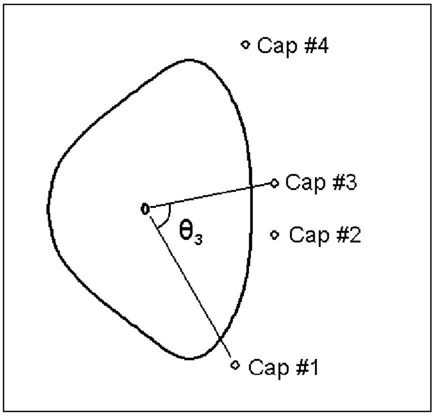


**FIGURE 3.** The location of the external capacitive probes, along with the last closed flux surface of the $\varphi = 90°$ cross section, and the magnetic axis.

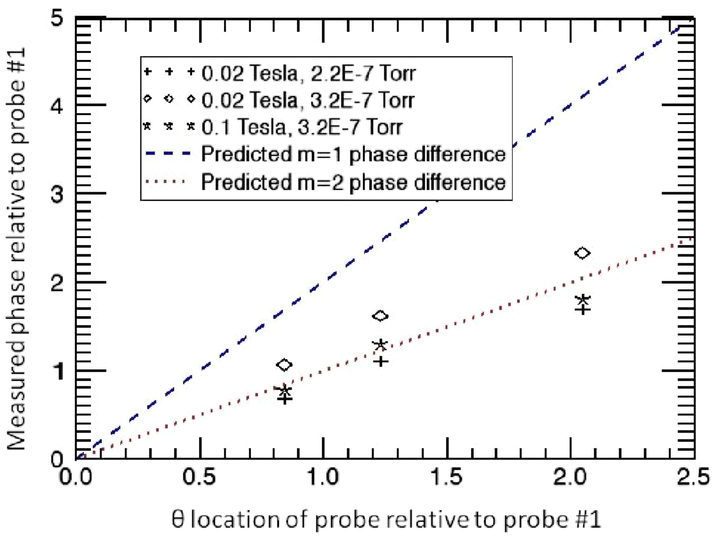


**FIGURE 4.** The measured phase of the instability on probes 2-4 relative to the phase on probe 1, plotted as a function of the θ difference between these probes and probe 1.

Fig. 4 shows the measured phase between the image charge probes vs. the angle θ between the probes, with probe #1 as a reference, for three different plasma parameters. Also shown are the predicted phase relations if the instability has a poloidal mode number of m=1 or m=2. Although the measured phase difference changes as experimental parameters are varied, the mode is always clearly m=1.

Because there are only a finite number of capacitive probes, it was possible (although unlikely) that there was actually a much higher poloidal mode number, and the apparent m=1 mode was a result of spatial aliasing. In order to verify that this was not the case, the third capacitor was moved by 1 cm, and the experiments were repeated. If spatial aliasing was happening, than the measured phase difference of the third probe would change by a large amount when the probe was moved. This was not observed, confirming that the mode is m=1.

## CONCLUSION

In CNT, an instability has been identified that consists of interacting perturbations of ions and electrons. The instability has a poloidal mode number of m=1, which does not correspond to a rational surface. A global instability that does not resonate with a rational surface has never before been observed in a stellarator. Numerical simulations indicate that a large fraction of electrons in CNT are mirror trapped due to parallel variations in the magnetic and electric fields. These trapped electrons cannot stream along the magnetic field to damp out the instability. It is likely that the unstable electron component consists of these trapped particles.

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