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Field Line Mapping Results in the CNT Stellarator

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The Columbia Non-neutral Torus (CNT), located at Columbia University, is a toroidal, ultra-high vacuum stellarator designed to explore equilibrium, stability and confinement of pure electron and other nonneutral plasmas. CNT started operation in November 2004. A detailed mapping of the nested magnetic surfaces in the CNT stellarator has been developed using the fluorescent method. The experimental field mapping results are presented along with details of the field line mapping system and ways to visualize magnetic surfaces in three dimensions.

1. Introduction

CNT is a unique two period, ultralow aspect ratio stellarator. Its coil configuration is the simplest of any stellarator constructed, since it consists only of two pairs of circular planar copper coils: two 2.16 m diameter poloidal field (PF) coils placed outside the vacuum chamber, and two 0.81 m diameter interlocked (IL) coils inside the vacuum vessel. A 200 kW DC power supply drives the IL coils, while PF coils are powered by an independent 4.5 kW DC supply. CNT can achieve magnetic field strengths up to 0.33 Tesla on axis and its maximum pulse length (>15 s at full current and >60 s at half the design current) is determined by the allowable temperature rise of its four water cooled copper coils.

The angle between the two IL coils (the tilt angle) can be adjusted in three positions: 64, 78 and 88 degrees. These tilt angles were optimized and chosen such that each has a large volume of good magnetic surfaces and relative resilience against field errors, they scan the range of iotas from 0.12 to 0.64 and represent three generic shear configurations: positive (stellarator-like), near zero, and weak negative (tokamak-like) shear [2]

CNT's present configuration is at 64 degrees, which is characterized by an aspect ratio of A=1.8 and iota going from 0.12 at the magnetic axis to 0.22 at the last closed magnetic surface. At the 88 degrees configuration, the calculated aspect ratio is A=2.5 and iota is predicted to have a nearly flat profile, iota ~0.64.

2. Experimental setup

We used the fluorescent method [3] to determine the shape and quality of the magnetic surfaces. The magnetic surface mapping system consisted of a moveable electron gun and a moveable phosphor rod assembly.

An electron beam was emitted along a field line by a small moveable electron gun (0.375 inch diameter) inserted at the $\phi = 0$ symmetry plane, just below the bottom IL coil. The diameter of the beam was constrained to 0.060 inch at gun exit. Different beam energies (ranging from 50 to 200 eV) were used and typically the emission current was 2mA at 50 eV and 0.08 T. In order to obtain images of different magnetic surfaces, the electron gun could be moved in the radial direction by bellows allowing the operation in ultrahigh vacuum.

A moveable phosphor rod assembly was used for the mapping of the magnetic surfaces. The system was made of two aluminum rods (0.125 inch diameter) coated with fluorescent powder (ZnO:Zn) that emitted visible light when struck by the e-beam. A pivot mechanism operated manually by an external actuator arm allows the ZnO coated rods to scan a whole cross-section of the torus.

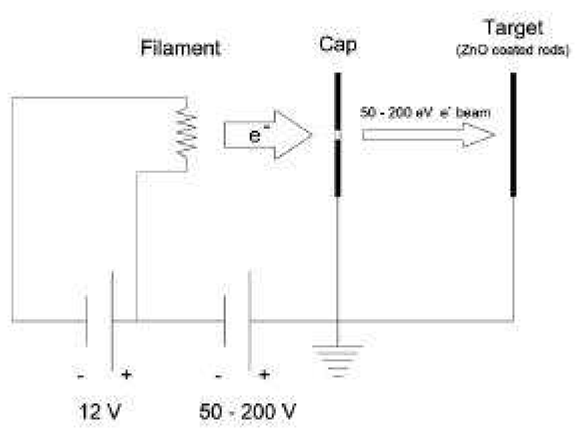

Figure 1. Egun electrical setup

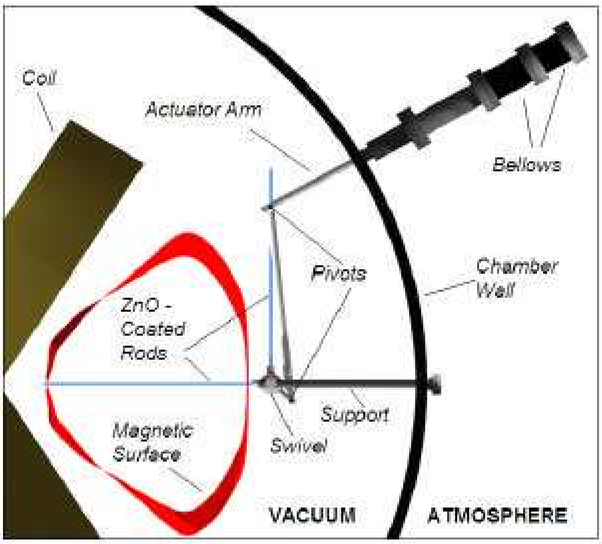

Figure 2. Moveable ZnO coated rod assembly

A standard digital camera took the images through a quartz viewport on the vacuum chamber. During a five second exposure and for each position of the electron gun, the phosphor rods were drawn across a whole cross-section of the torus obtaining a visual Poincaré map of a single magnetic surface.

Field line mapping was performed in several configurations at a variety of magnetic field strengths up to 0.1 Tesla and at pressures in the 10^{-8} Torr range. At these rather low fields

(CNT can be run up to 0.33 T) the magnets could be pulsed for minutes at a time, facilitating the field line mapping.

3. Results

The magnetic flux surface measurements in CNT were carried out for the 64 angle configuration and α = 3.64 (which is the ratio between the currents in the IL and the PF coils, $\alpha = I_{IL}/I_{PF}$). Photographs of multiple magnetic surfaces were taken and then manipulated and superposed using IDL software to obtain the composite image shown in Figure 3 – left.

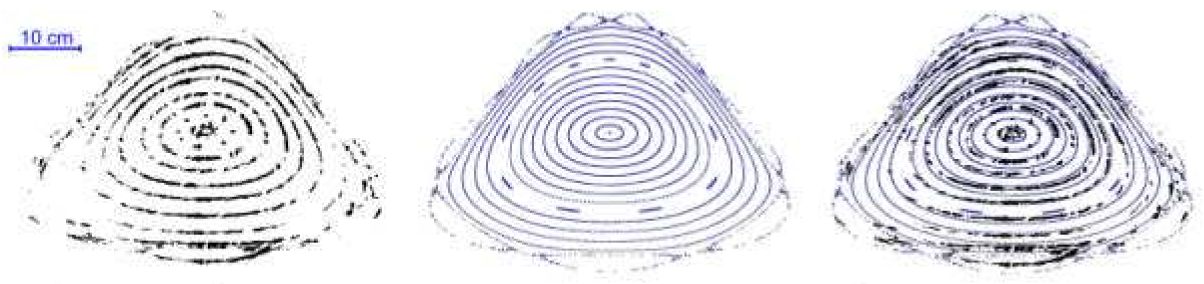

Figure 3 Left: Nested magnetic surfaces mapped out using a 100 eV e-beam and ZnO coated rods. Middle: Numerically calculated magnetic surfaces plot for 100 eV electrons at 64 angle configuration. Right: The composite image overlaid on the numerical surfaces.

The experimental results were compared with numerical calculations demonstrating that the obtained measurements are in good agreement with the theoretical predictions (as can be seen in Figure 3 – right). In particular, the current configuration has an ultralow aspect ratio ($A \leq 1.9$) with nested magnetic surfaces without any visible island chains in the interior of the plasma. The only detectable island chain can be seen at the plasma edge, in agreement with the numerical calculations. However, there are some discrepancies between the experimental measurements and the theoretical predictions at the edge and a 5 mm inward radial shift (upward on the shown pictures) has been applied to make the numerically calculated magnetic axis line up with the experimentally determined axis of the drift surfaces.

Experiments were also conducted to visualize the full three-dimensional shape of magnetic surfaces using an electron beam and a background neutral gas. The electron beam excites and ionizes the neutral gas which radiates visible light, allowing to clearly see field lines and even the whole magnetic surface on which the electron beam is injected. Different background neutral gases (such as air, argon and helium) were used and the gas pressure and electron beam energy were also varied in the experiment, however the best visualizations of glowing magnetic surfaces were obtained with a backfill of air at a pressure of $5\cdot 10^{-5}$ Torr using a 200 eV electron beam. Figure 4 shows an example of a glowing magnetic surface, as could be seen with the naked eye through a quartz window on the chamber.

Figure 4 Example of a glowing magnetic surface

4. Conclusions

A detailed mapping of the nested magnetic surfaces in CNT is one of the most relevant results achieved during the first months of operation of this experiment. The analysis of the experimental measurements confirms that the current configuration has excellent magnetic surface quality and an aspect ratio $A \leq 1.9$, which is the lowest aspect ratio of the present day stellarators.

References

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