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IN THE FM-1 SPHERATOR

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Observation of Magnetic Islands in the FM-1 Spherator

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ABSTRACT

Time independent spatially periodic variations in the density and floating potential have been observed in the FM-1 spherator. On the exterior of the plasma $\Delta n/n$ and $\Delta \phi/\phi$ are found to be as much as 0.3. Experimental evidence indicates these variations are due to magnetic islands created by small field errors produced by the levitated ring. Calculations of the expected island size agree well with observations.

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I. INTRODUCTION

A number of experiments on multipole devices have been aimed at determining the effects of small field errors on plasma structure and containment. Earlier experiments were concerned with systems which had no toroidal field.^{1,2} Considerable particle loss was observed even when mechanical tolerances were kept to a minimum. With the addition of a toroidal field,^{3,4} field lines were hindered from spiraling outward, and particle loss to the walls was reduced considerably. The toroidal field acts somewhat like a restoring force, preventing the field lines from staying in phase with the field errors. In the presence of a toroidal field, small field errors tend to produce island structures instead.⁵⁻⁷ However, even very small field errors can produce islands of substantial size.

Recently there has been considerable interest in the presence of magnetic islands in tokamaks. It is thought that the existence of these structures is responsible for disruptive instabilities,^{8,9} anomalous current penetration,¹⁰ and possibly the observed energy confinement time scaling ($\tau_e \sim n_e$). For example, the appearance of voltage spikes during the disruption process can be explained by assuming that the presence of growing magnetic islands causes an interchange of current channels near the plasma center.^{11,12} This phenomena can account for the observed flattening of the density and temperature profiles after a disruption, and the sinusoidal x-ray oscillations observed

immediately preceding a disruption. Since a tokamak is very susceptible to the production of islands, any small perturbation in the plasma current would easily cause islands of considerable size (for example, $\Delta B/B$ of 0.001 in a PLT discharge would produce islands of several centimeters).

In this paper, the observation of magnetic islands in the FM-1 Spherator will be reported. Spatial mapping of both the ion saturation current and the floating potential indicate that a large number of island chains exist with widely varying toroidal periodicity. Their effect on the plasma structure is quite dramatic, causing stationary density variations of up to 30% on the exterior of the plasma. Their perturbation on the plasma is large enough to cause diffusion comparable to that observed in previous experiments.¹³ This may be particularly true in higher temperature regimes where the mean free paths are longer. Computer calculations of island structure using known field errors in the FM-1 superconducting ring show good agreement with the observed structures.

II. EXPERIMENTAL APPARATUS

The present experiments were performed on the FM-1 spherator at Princeton University. The FM-1 spherator is an axisymmetric toroidal machine with a levitated superconducting ring. Typical magnetic surfaces for the machine are shown in Fig. 1. Ring currents ranged between 100 and 250 kA. Typical discharges of $n_e = 5.0 \times 10^{10}$ to 5.0×10^{11} were formed by applying 100-200 watts of microwave power at the electron cyclotron resonance frequency

(10.4 GHz). Temperatures of the order $T_i = 0.2-2.0$ and $T_e = 1.0-5.0$ eV were normal.

Most of the measurements discussed in this paper were made using simple single tip Langmuir probes. A carousel drive was used to rotate several of these probes in an azimuthal direction around the machine. The drive was capable of a 270-degree rotation around the machine and of poloidal motion through the plasma. Two probes in particular were used on this drive. Their position with respect to the spherator flux surfaces is shown in Fig. 1. Analog data was digitized with a Biomation Model 1015 Waveform Recorder which was interfaced to an IBM 1800 computer. When further time-consuming analysis was needed, the data was transferred to a PDP-10 computer.

III. EXPERIMENTAL RESULTS

Initial observations using the carousel probes indicated that stationary variations in the floating potential and the ion saturation current were quite small in the main body of the plasma. However, toward the edge of the plasma substantially larger structures were observed. These structures were found to vary in RMS value from less than 3% in the center of the plasma to 10-30% on the plasma exterior. In addition these structures were found to have widely differing toroidal m numbers depending on their distance to the ring and on the magnetic configuration. Typical examples of these structures are seen in Fig. 2. The data in this figure were taken by rotating the carousel probe in the azimuthal direction while holding its poloidal position fixed. Afterglow experiments, which will be

discussed later, indicate that the structures are not caused by non-uniform heating effects.

In an effort to demonstrate that these effects were due to magnetic islands formed from field errors, a study of the structures as a function of toroidal field was performed. The result of these experiments is summarized in Fig. 3. In order to obtain this result, it was necessary to Fourier analyze the raw data. A toroidal variation of the form shown below was assumed.

$$f(\theta) = \sum_m f_m e^{im\theta} \quad (1)$$

Plotted as the ordinate are the squares of the absolute values of the Fourier components of the $m = 4$ and $m = 6$ structures. Although other m numbers were observed, the $m = 4$ and $m = 6$ structures were substantially larger and are, therefore, the only amplitudes plotted. As the toroidal field current was increased, structures of different m number appeared to move poloidally. Calculations which will be discussed in Sect. IV confirm that as the toroidal field current is changed from 3 KA to 4 KA per turn (there are 72 turns in the TF winding), the m number of the probe surface changes from approximately 6 to 4. This effect is consistent with the structures being caused by magnetic islands. Further, in experiments at other ring currents similar effects have been observed. Various structures have been seen ranging from $m = 2$ to $m = 12$. Each of these structures has been found to have an m number which is equal to (or in a few cases a multiple of) the corresponding m number of the field line.

From the width of these islands as a function of current in the TF coils, their spatial width can be inferred. The spatial width has been estimated according to

$$\Delta r = \frac{\partial r}{\partial I} \Delta I \quad (2)$$

where $\partial r / \partial I$ is the first derivative of the position of the $m = 4$ surface with respect to the TF current. The quantity ΔI is taken from Fig. 3 to be approximately 1.2 KA. Using the computed values for $\partial r / \partial I$, this gives an island width of about 4 cm. Since the flux surfaces of FM-1 are not uniformly separated poloidally, the island width varies substantially. The above estimate was made for the flux surfaces nearest the TF column where the measurement was made (see Fig. 1). At large major radius, the island width becomes about 1 cm.

Because the $m = 6$ structure was somewhat obscured by the presence of the larger $m = 4$ structure, a similar estimate of its width is difficult. However, an estimate of its width can be made from amplitude considerations. The amplitude, f_m , of a particular structure should be roughly related to the density gradient, ∇n , and the island width, Δx , by $f_m \sim \nabla n \times \Delta x$. Given similar density gradients, and an amplitude for the $m = 6$ structure of approximately 1/2 that of the $m = 4$ structure, one can infer an $m = 6$ width of about 1.5 cm.

The summary of experimental data up to this point indicates that the observed structures are caused by magnetic islands. A series of experiments was also performed to determine the origin of these islands. The most plausible sources of field errors were:

1. Field errors introduced from the stabilization (stab) system. FM-1 has a set of coils to keep the ring properly positioned. Although estimates of the field from this system indicate only a small effect, the geometry is quite complicated and difficult to estimate accurately.
2. Field errors introduced from the toroidal field system. This system was made up of a discrete number of coils. Any slight misalignment in this system could produce a non-axisymmetric configuration.
3. Field errors from the floating ring. Measurements made on this ring before its installation indicate that its current center was only accurate to tolerances of about 25 mils. As will be discussed later, this effect can account for the observed islands.

In order to examine which of these effects might be important, the floating ring was put into a rotating motion in the toroidal direction. In this mode the carousel probe was held stationary, while the ring rotated. It was observed that the islands moved with the ring. As the ring rotated the islands passed by the probe at the same rate as the ring. This effect rules out the possibility that the field errors were due to the toroidal field columns, which are stationary. Any stationary structure with constant currents could not cause the islands to appear to move. This did not eliminate the possibility that the effect could have been due to the stab system. As the ring rotated, these currents were constantly changing.

To eliminate the possibility that the stab system was the cause of these islands, the system was run in two different

modes. In the first mode the stab system was tuned to minimize the currents, while in the second mode the system was detuned maximize the stab currents. The ring was again held stationary and the amplitude of the islands was observed. Essentially no differences were observed between the two cases. It was concluded therefore that the islands were caused by field errors from the levitated ring.

Experiments were also performed in the afterglow plasma. It was observed that the stationary variations in the floating potential ($\Delta\phi/\phi$) decreased rapidly after the X-band heating was terminated. The quantity $\Delta\phi/\phi$ decayed from about 0.15 to 0.05 in a period of less than a millisecond. During the same experiment, the RMS value of the density variations remained essentially the same for several hundred milliseconds before also decaying.

It is important to notice that the floating potential, ϕ , is not completely determined by the electrostatic potential, V , of the plasma. The floating potential includes strong electron temperature effects as well. The relation between the two potentials is sometimes approximated by $\phi \approx 4KT_e + V$.¹⁴

The fact that both the floating potential and the density structures decay does not indicate that the islands have disappeared. Rather, it indicates that the temperature and density gradients have disappeared. It is well established that in FM-1 the temperature and density gradients flatten out in times comparable with what has been observed here. (Note that although the temperature profile flattens out in less than a millisecond, the overall temperature decay time is of the order of several

milliseconds.) In the case of the floating potential, it is concluded that the major source of the periodic structures must be temperature gradient effects rather than electrostatic effects. This indicates that the presence of magnetic islands modifies the temperature profile and therefore contributes substantially to the heat diffusion process.

IV. COMPUTER CALCULATIONS

Calculation of magnetic island formation in FM-1 is complicated by the difficult geometry of the machine. In an effort to determine the expected size and periodicity of these islands, it was found necessary to simulate the field errors with the use of a computer. A field line following program was modified to include the measured field errors of the ring.¹⁵ Figure 4 indicates the source of errors used in the calculations. These measurements were made before the floating ring was installed in the machine by integrating the current from a loop as the ring was rotated toroidally. Shown in this figure is the measured deviation of the current center of the ring as a function of the toroidal angle. In some spots the center is observed to vary by as much as 30 Mils.

The result of calculations using these field errors is shown in Fig. 5. This figure was generated using the computer program to follow field lines around the machine while adding the appropriate errors to the trajectories. Each time a field line crossed the midplane of the machine its position was recorded. After the calculation was completed the locus of these points was plotted. Points belonging to a single field line

were joined together to make clear the actual structure of islands and surfaces.

It is apparent in Fig. 5 that a wide variety of islands is expected to be formed. This is consistent with experimental findings. In the exterior plasma region in particular, Fig. 5 shows rather large islands. These islands possess many different m numbers, including $m = 4$ and $m = 6$ which have been experimentally observed to be dominant. The calculated width of the islands appears to agree well with the observed widths. Figure 5 agrees with the observed width of 4 cm for the $m = 4$ island. Both the computer calculation and the experimental results give a consistently smaller width for the $m = 6$ island.

Figure 5 shows that in the interior of the plasma only small magnetic islands should exist. The field lines in this region wander radially, but this effect is small. This effect coupled with the smaller density gradients in the center of the plasma indicates that negligible density variations should be observed in the interior plasma region. This is consistent with the experimental observation that the interior of the plasma does not contain large amplitude variations. Large disturbances were found only in the exterior plasma.

Estimates of field line braiding effects have also been made. Braiding^{11,12} is an effect which occurs when island structure becomes large compared to interisland distances. Field lines tend to become ergodic and fill up spatial regions between islands. Although field line braiding may be important in tokamaks, calculations of this effect for FM-1 show that it is not particularly strong. When field line starting points were

chosen near separatrix of an island chain, some braiding was observed. However, most random starting points between islands produced field lines which reproduced themselves quite accurately after each toroidal revolution. Thus, the braiding is not thought to be strong enough to cause major diffusion effects. A larger contribution to the diffusion mechanism from the magnetic islands is thought to come from the island structures themselves. The simple filling of island structures by particle and heat diffusion along field lines is probably the major effect present.

V. SUMMARY AND CONCLUSIONS

Spatially stationary variations in the density and floating potential of FM-1 were observed to have amplitudes approaching 30% of the background levels. The structures were identified as magnetic islands and shown to be caused by small mechanical errors in the superconducting ring. The fact that the FM-1 islands are caused by current perturbations in the levitated ring is similar to the concept that islands in a tokamak are caused by perturbations of the current channel. Rough calculations of possible sources of errors indicate that the only viable candidate in a well-engineered tokamak is a disturbance in the main current channel. For example, allowing a 1° tilt in a toroidal field coil would produce only very slight island structure. More likely, the tilt would be on the order of a tenth of a degree, producing negligible structure. However, since the plasma current is obviously not restricted by mechanical

tolerances, the structure of nearby field lines should be dependent on its profile.

The effect of island structure on diffusion is not easily calculable, but it is evident that islands contribute to the diffusion process. The fact that the islands are observed indicates that they modify the density and temperature profiles. Although the major contribution of magnetic islands to diffusion effects in FM-1 is from the filling out of the island structures, in a tokamak discharge braiding may play the more important role, particularly during a disruption.

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Fig. 1. Flux surfaces and probe positions for the FM-1 spherator.

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Fig. 2. Typical ion saturation and floating potential data plotted as a function of toroidal angle.

Fig. 3. Fourier analysis of the toroidal variation in the ion saturation current.

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Fig. 4. Measured deviation of the current center of the ring plotted as a function of toroidal angle.

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Fig. 5. Computer calculation of island structure expected in the FM-1 spherator using known field errors in the superconducting ring.