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Experimental Studies of Formation and Relaxation of Merging Spherical Torus Plasma with Varied External Toroidal Magnetic Field

外部トロイダル磁場を変化させた
合体球状トーラスプラズマの生成と緩和に関する実験的研究

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１. Introduction

The next phase of tokamak research is the ITER project, which is expected to create plasma of 100 MW for 1000 seconds. Despite the promising performance, the huge cost of building such a large device motivates us to search for lower-cost routes to fusion reactors. Features such as compact size and high beta are desired.

1.1 Spherical Tokamak (ST)

Spherical tokamak (ST) is a compact version of tokamak, and is characterized by its small aspect ratio (A = major radius/minor radius < 2), as opposed to a typical tokamak which usually has A ~ 3-5. The advantage of small aspect ratio is that it naturally has large edge q, improving the stability of macroscopic MHD modes at higher pressure gradient, leading to higher plasma beta, while maintaining compact size.

1.2 Spheromak

Spheromak is characterized by its zero toroidal magnetic field at the edge and finite toroidal magnetic field inside the plasma. Spheromak tends to relaxe toward a minimum energy state, but it is also inherently tilt/shift unstable, and it undergo dynamo when helicity injection causes its toroidal flux and poloidal flux balance to be altered from equilibrium, affecting its energy confinement.

1.3 Low-q ST

A spheromak can be converted to a low-q ST by applying small external toroidal field current (Itfc) through the symmetric axis. In other words, it is possible to transition from a spheromak to a low-q ST, then to a high-q ST continuously by varying the magnitude of Itfc. Therefore, it is interesting to study the macroscopic equilibrium and stability during this transition, since ST and spheromak have drastically different MHD behavior.

２. Research Purpose

Past research in TS-3 showed that plasma became stabilized in the low-q region when increasing Itfc[1][2], but TS-4 experiments showed that plasma became violently unstable at Itfc in the low-q region[3]. The phenomenon in TS-4 was attributed to n=1,m=1 instability, while the stabilization in TS-3 was attributed to n=1 mode suppression, so the truth is not clear. Therefore, it is worth re-investigating plasma equilibrium and stability by scanning Itfc on the new TS-6 device. Thus, the goal of this research is:

A) Modify TS-6 device to enable experiment at low-q.
B) Build a new magnetic probe array system that measures Bz and Bt components in the 2d r-z plane.
C) Conduct Itfc scan experiment using TS-6 experiment and clarify its effect on plasma stability.

３. TS-6 Plasma Merging device.

TS-6 is a ST/CT device with aspect ratio ~ 1.5, capable of formation and merging of two torus plasma through PF current swing. Low-q discharge is enabled by inserting 4 pairs of electrodes sandwiching PF coils on both sides, with a total of 16 electrodes inserted. The electrodes provide toroidal flux injection independent of external toroidal field.

4. 2d Magnetic Probe Array

The basic principle for the magnetic probe array is based on Faraday’s law of induction. Assuming that magnetic field is uniform in the cross section of the coil, then the time derivative of B_avg is proportional to loop voltage via coefficient NS. The coils are 5mm in size, and their spacing is ~ 10mm, which is comparable to ion larmour radius (H), and smaller than ion skin depth ~20-50mm and ion mean free path ~ 10-30 mm. L/R~5us for Bz and ~2us for Bt coils. The coils are mounted on a 3d printed probe holder for better spatial precision.

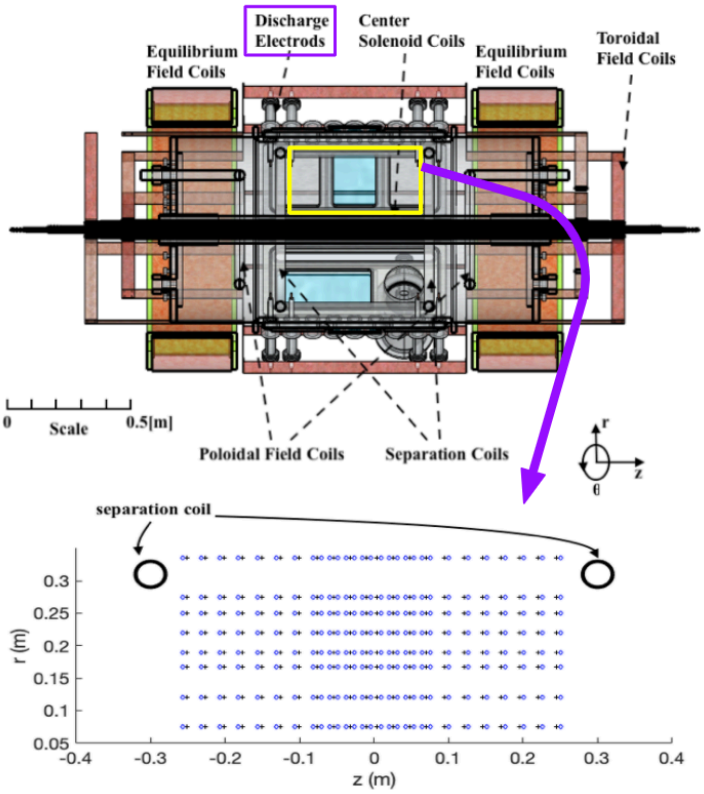

Figure 1: TS-6 with electrodes and magnetic field diagnostics

5. Results

5.1 Itfc scan

By scanning Itfc from 0 to 12 kA, the relation between Itfc and common flux magnitude after merging is shown in Figure 2, and its relation with plasma decay time at 480 us is shown in Figure3. From magnetic field profile, it is evident that low Itfc ST generally has low safety factor. As shown in Figure 4, it was observed that for small Itfc q_a near magnetic axis can be lower than 1, this is related to low-n mode and low-m mode.

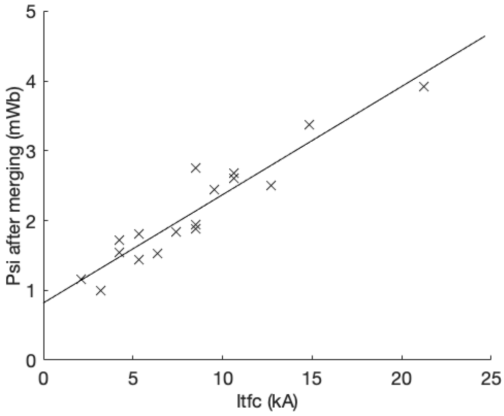

Figure 2: Common flux psi magnitude at 480 us vs Itfc

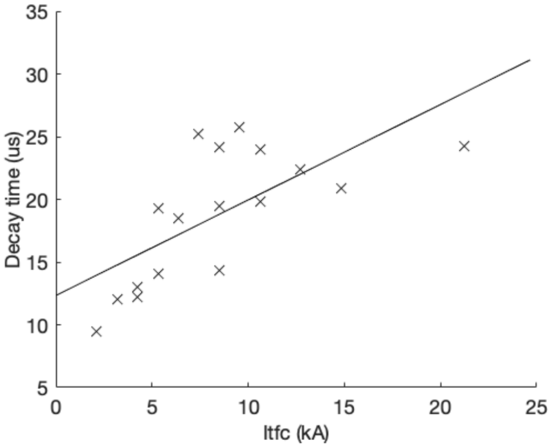

Figure 3: Common flux psi decay time at 480 us vs Itfc

Therefore, plasma decays faster at small Itfc and results in smaller magnitude of common flux after merging, and the result agrees with that of TS-3.

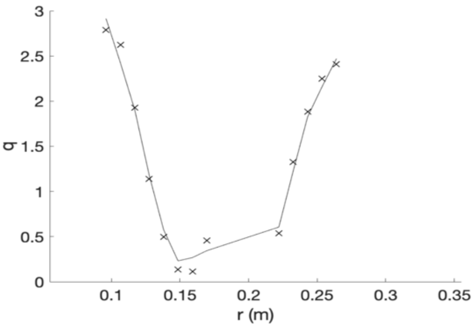

Figure 4: Safety factor of low-q ST

5.2 Spheromak experiment

Spheromak formation and merging experiment was attempted, but Bz of the plasma is weak (max~100 G), and Bt of the plasma is too weak to be observed in a meaningful way. This may be due to broken crowbar switch, un-optimized location of electrodes, or insufficient Bt coil alignment.

6. Summary

In order to understand macro-stability of plasma in low-q region, Itfc scan was performed using TS-6 device, with 2d magnetic diagnostics. The result shows that larger Itfc is associated with large q _a, which results in stability, agreeing with results from TS-3. Spheromak experiments were not successful, and further optimization of formation method on TS-6 is necessary.

Reference

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