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Global Stability of Oblate FRCs in TS-3 Experiment

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1 Introduction

A Field-reversed Configuration (FRC) is a confined plasma in the form of an elongaed compact toroid with primarily poloidal magnetic field. The prolate FRC plasmas have been formed by many theta-pinch devices since 1970. As Dr. Tuszewski reported,they exhibited reasonably good global stability if their s/e values were smaller than 0.2-0.3[1]. On the other hand, we have been producing oblate FRC plasmas in TS-3 merging device using two merging spheromaks with opposing toroidal field. Typical elongation of our FRC 1.0, is much smaller than those of the conventional FRCs 5-20[2]. The ideal magnetohydrodynamic(MHD) theory predicts that FRCs and spheromaks become unstable against the internal tilt mode if their shape is prolate. This operation regime which elongation is smaller than 1.0 has not been studied experimentally whether those FRCs are stable or unstable. So, we studies at first which of the tilt and shift mode are unstable the n=1 instability, second, suppression of tilt instability, and the last, study of stability boundary.

In our laboratory, the oblate FRCs have been produced by merging spheromaks. First, two spheromaks with opposing toroidal field are collided together along with the center line. Their magnetic reconnection converts the toroidal magnetic energy of the initial spoheromaks to ion thermal energy of the produced FRCs.

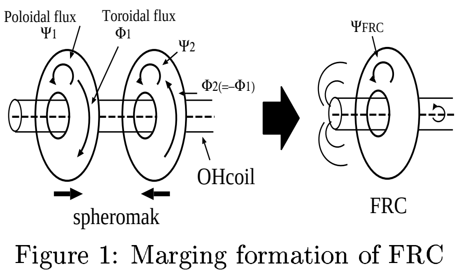

Figure 1: Marging formation of FRC

Unlike the fast formation by the theta-pinch, this slow formation by merging has the formation efficiency as high as 10-20%, because it eliminates the fast speed capacitor bank.

The produced FRCs can be sustained about 200-300 μsec by the center OH coil. Since the formation speed is slow, the OH coil can be located along the symmetric axis without affecting the FRC formation. Its duration time is expected about 200 μsec.

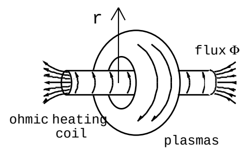

Figure 2: Ohmic heating coil

2 About instabilities of FRCs

The duration time of OH coil is expected about 200 μsec, but experimentally, plasma life time is shorter than 200 μsec. Our previous experiments indicates the growth of n=1 instability is the most probable reason for this plasma termination. A question is which of the n=1 tilt mode or the n=1 shift really terminated the FRC sustained by the OH coil current. I performed for the first time a new type of toroidal mode mode measurement to distiquwish the tilt mode from the shif mode by use of 2-D magnetic probe array on the r-theta plane.

The tilt instability has Br component at midplane. On the other hand, shift instability has Bz component at midplane. Therefore I made r-theta magnetic probes that have two components, Br and Bz and judge which instability is occur.

3 The TS-3 device and the measurement system

In the TS-3 device, external toroidal field coil, poloidal field ciol, discharge electrodes and OH coil are established. Besides to sustain plasma rings and to rainforce them, equilibrium field coil and equilibrium correct field coil are established. With them, spheromak plasmas are formed.

Two dimentional profile of axial, toroidal and radial magnetic fields are measured using a 2-D magnetic probe array on the r-z plane. The poloidal flux

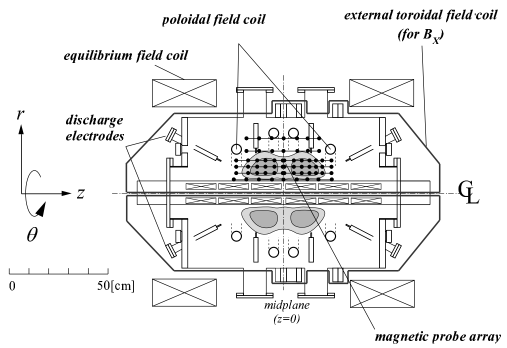

Figure 3: The TS-3 device

contours of the produced FRC are calculated form the measured 2-D B field data. Another 2-D array of magnetic probe is located on the midplane to measure the toroidal mode amplitude and phase.

The OMA system is located in the midplane to measure radial profile of ion temperature. Ion temperature is calculated by Doppler sift, and we used $H_\beta 486.1nm$ line.

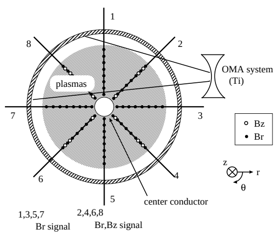

Figure 4: The measurement system

4 Index control

An advantage of the FRC merging formation is that it can produce oblate FRCs. We have attempted to suppress the instability by changing the n-index of the equilibrium field. The n-index is calculated as Eq.1.

$$n = (-\frac{dB_z}{dr})(\frac{r_o}{B_z})\Big|_{r=r_o} \quad (1)$$

So, we tried the reversal current of side(PF) coil large. As a result, we could produce the oblate FRCs and prolong the time of positive n-index. When n-index is positive, the shape of FRC is expected to become oblate, while it is negative, it will become prolate. The time evolutions of n-index with n-index control and without n-index control is shown in Fig.5

In this study, the index control means positive n-index. You can see that under the n-index control

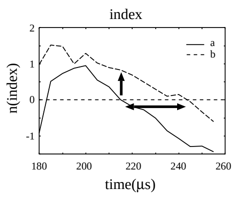

Figure 5: The time evolutions of n-index

the n-index remains positive for about 30μsec longer than that without n-index control. So, we have experimented under two conditions that with and without the n-index control.

5 Instability of FRC with OH current drive

Fig.6 and Fig.7 show the poloidal flux contours on the r-z plane and the Br contour on the midplane during FRC formation and sustainment without n-index control. Fig.6 contours and Fig.7 contours are measured by the 2-D magnetic probe arrays on the r-z and the midplanes, respectively.

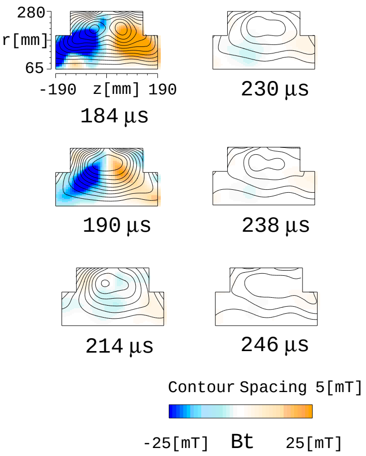

Figure 6: The poloidal flux contours (without n-index control)

At 184μsec, two spheromaks with opposing toroidal field are formed, and start merging at 180μsec. The merging formation of FRC is completed by 200μsec. At 190μsec, we can not observe any n=1 mode of Br component but an n=1 mode is observed to grow from t=230 to 246 μsec. Finally, the whole FRC contour on the r-z contour also shifts to the right and collapsed due to the induced magnetic reconnection.

From the n=1 mode amplitude of Bz component on the midplane as a function of time, we calculated

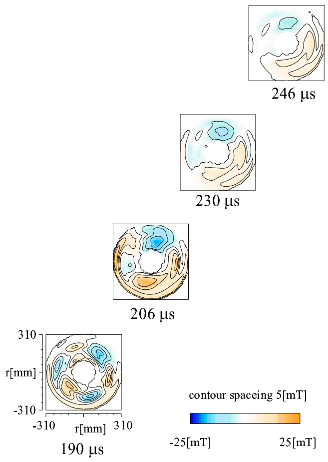

Figure 7: The Br contours (without n-index control)

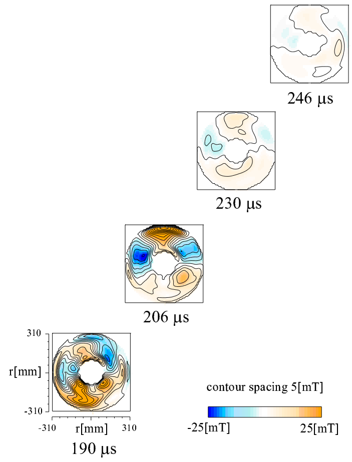

Figure 9: The Br contours (with n-index control)

the length of shift. As a result, the length is estimated about 0.5-1.0cm, which is equivalent to about 3% of plasma. So, the shift instability is negligibly small. The clear n=1 mode in the Br contour indicates that the major n=1 mode for the FRC termination is the tilt instability.

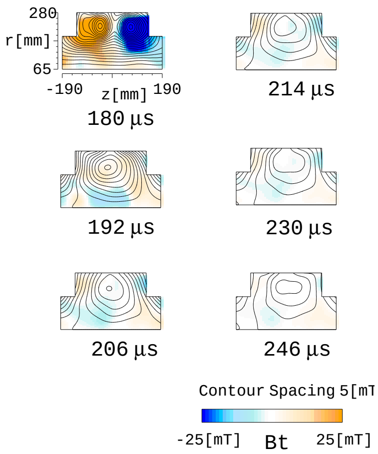

Figure 8: The poloidal flux contours (with n-index control)

Next, Fig.8 and Fig.9 show the poloidal flux contours on the r-z plain and the Br contour on the mid-plane under the n-index control.

The n=1 mode was observed to be quite small in the Br contour during the FRC sustrainment. The n-index control was found effective to supress the tilt instability.

To investigate the tilt instability, Fig.10 compare the time evolutions of n=1 mode amplitudes with and witout the n-index control.

The n=1 mode is increase after 230μsec with n-index control, on the other hand, the growth of the

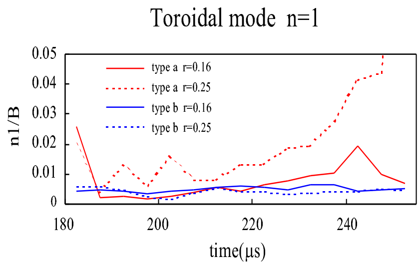

Figure 10: The comparison of toroidal mode n=1

n=1 mode is fully suppressed by the n-index control. So, the n-index control is concluded effective for suppression of the Br n=1 mode.

The n=1 mode is measured by our magnetic fluctuation signals in agreement with the toroidal mode measurement.

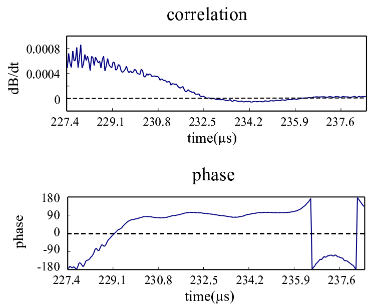

Figure 11: The results of magnetic fluctuation

Fig.11 shows the cross correlation of two Br signals. Their measurement points has 90 degree difference in the theta direction but their positions on the r-z plane are exactly the same. That is to say the phase difference of the two signals is another 90 degree. This fact indicates that the n=1 mode with wave length of 180 degree is the dominant mode inagreement with the toroidal mode measurement.

6 Stabilizing effect

The stablity boundary of the n=1 tilt mode has been studied by Dr. Ji et al.in the parameter space of s and plasma elongation E. Since the plasma elongation E is controlled by the n-index control, E is also a key parameter to explain the tilt stability. The s value is another important key parameter bacause small s value is expected to stabilize the tilt mode of the conventional FRC through the non-MHD effects such as ion gyro effect and ion viscosity[3][4][5][6][7]. Fig.12 shows the s value of the FRC without n-index control as a function of time. The s value is calculate by Eq.2.

$$s = \frac{R_s}{< \rho_i >} = 10^4 \frac{R_s B_{z,s}}{\sqrt{T_i}} \qquad (2)$$

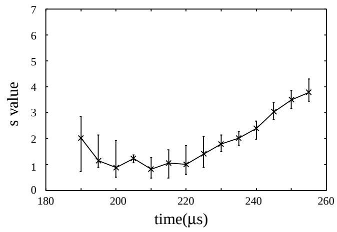

Figure 12: The time evolution of s

From Fig.12, s value increases from 1 to 4 after 220μsec. The decrease in kinetic stabilizing effect is expected to promote the tilt instability.

Next, we consider the stabilization effects of elongation and s value in our FRC experiments, and the result is shown in Fig.13

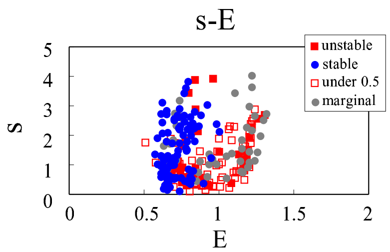

Figure 13: s-E diagram

It is also observed that the tilt stability of FRC depend mostly on whether E is smaller or larger than the critical value 0.7-0.9. The effect of E on the tilt stability is much larger than that of s-value in the present small-E operation regime. We can conclude that the stability boundary of tilt mode is located around E=0.7-0.9.

We have considered the results of experiments, from here, disucuss the theoretically stability boundary using the cylindrical rigid body model by Dr. Ji[8]. In this calculation, we considered $\boldsymbol{j} \times \boldsymbol{B}$torque, ion gyro-viscosity and plasma rotation. Fig.14 show the result of calculation, each plots represent an FRC eqilibrium located on the stability boundary.

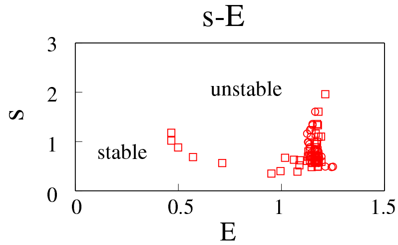

Figure 14: The theoretically stability boundary

It is observed that theoretically stability boundary is located at E=0.5. This value is smaller than that of experimental results. The most probably reason for this difference is that eddy current flowing in the shell of the OH coil provides additional stabiling effect for the tilt mode.

The ion tying effect is another candidates to explain the difference between experiment and theory. As Dr Horiuchi studied, plasma ions around the separatrix tend to tie the field lines inside and outside of separatrix[9]. This effect is not included in the theoretical caluculation. Fig.15 shows the time evolution of the separatrix β for the FRC with and without n-index control. The separatrix β is calculated by Eq.3. P is the pressure and Ψ denotes the poloidal flux function. Ψ_{ax} is the value of Ψ at the null.

$$\beta_{sp} = P(\Psi = 0)/P(\Psi = \Psi_{ax}) \qquad (3)$$

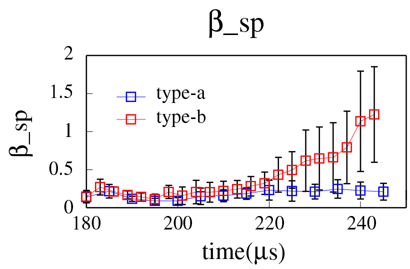

Figure 15: The time evolution of separatrix β

Large separatrix β means large number of ions tie the field lines inside and outside of separatrix and cycling ions contribute the suppression of the tilting motion. Fig.15 indicates that the separatrix β without n-index control is almost constant in time. However, that with n-index control increases by factor 2 after 220μsec. Since large n-index equilibrium field compress the FRC axially, the separatrix β of FRC tends to increase due to the compression effect. The tilt stabilization effect of n-index control is explained not only the small elongation but partly by the relatively large separatrix β.

7 Conclusion

- FRCs of various elongations were produced by merging spheromaks under n-index control.
- Amplitude of the n=1 shift mode was much smaller than that of tilt mode.
- The n=1 mode was consistently observed in our FRCs both in the toroidal mode and magnetic fluctuation measurements
- Amplitude of the n=1 tilt mode was observed to grow only when E value of FRC was larger than 0.7-0.9.
- The stability boundary for the tilt mode was donfirmed in s-E diagram experiments has good correspondence with that of theoretical calculation with cylindrical rigid body model. The boundary E value of experiment is about 0.7-0.9, while that of theoretical results is 0.5. This difference is possibly explained by eddy current induction in the shell of OH coil.

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