

# CONFINEMENT AND STABILITY OF DRIFT-ORBIT-OPTIMIZED CONFIGURATION IN CHS

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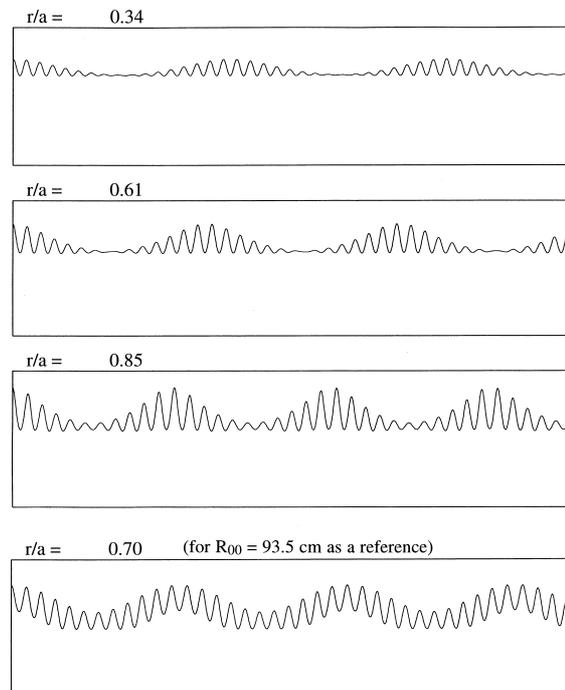
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Various efforts have been made recently to find new stellarator configurations which give better confinement than the conventional ones. Large part of such study is devoted to improve the trapped particle orbits because the drift motions of such particles are the origin of the degradation of transport in stellarators within the framework of neoclassical transport. The magnetic field configuration of heliotron/torsatron has a strong helical ripples in the boundary region. Deeply trapped particles in these ripples do not escape directly from the confinement region. They circulate around following the helical structure of weak magnetic field region, i.e., between two helical coils. It is one of solutions for the configuration improvement to make such drift orbits and the magnetic surfaces coincide with each other. Because the virtual center of drift motions is shifted to the inboard side of torus, such configuration is produced by shifting the magnetic surfaces inward with vertical field control. Such configuration gives the magnetic field ripple structure shown in Fig. 1. Three traces for different minor radii are shown with a bottom trace for the non optimized configuration as a reference. The minimum value of field strength at all bottoms of ripples is almost constant. In this configuration, the drift orbits of deeply trapped particles stay in the vicinity of a single magnetic surface.

In the discussions of the plasma experiment operation of heliotron/ torsatron devices, such configuration is usually excluded because it is (supposed to be) not MHD stable. The ideal interchange stability is given by the combination of magnetic well and magnetic shear stabilizing effects. It is general tendency for all heliotron/torsatron devices that the stability is lost when the magnetic surfaces are shifted inward because the magnetic well disappears and the magnetic shear is decreased. It has been discussed that there is no exact compatibility of the drift-orbit-optimization and the MHD stability for heliotron/torsatron systems.

Figure 2 shows the ideal interchange stabilities of CHS plasmas calculated with the Mercier criterion. The plasma position is defined as an averaged major radius of the last closed magnetic surface. Two thick lines in the



**Fig. 1.** Magnetic field ripple structures for drift-orbit-optimized configuration

figure indicate the stability boundaries. A thick solid line shows the ideal interchange mode stability boundary given by the Mercier criterion. The left side of the line is unstable region. Since the low mode instabilities are most dangerous ones, there is a region of low growth rate which is practically stable for the laboratory plasmas even with the Mercier unstable condition. A thick dotted line gives such a low mode stability boundary. The drift-orbit-optimization shown in Fig. 1 is realized at the plasma position of 90 cm. Fig. 1 shows the field line ripple structures for three different radii. In order to obtain the optimized structure for full radius, the control of quadrupole field (plasma shaping control) is necessary in addition to the position control.

The experiments have been done to examine the confinement improvement effects of the drift-orbit-optimization and the MHD stability of those configurations. Both ECH and NBI heated plasmas were studied. 53 GHz ECH ( $P_{\text{ECH}} \sim 200$  kW,  $B_t = 0.95$  T at the magnetic axis) was used for the confinement study of low collisionality plasmas and NBI plasmas ( $P_{\text{NBI}} \sim 800$  kW) were used for the MHD stability study with higher beta values. The beta values and the plasma positions of selected discharges are plotted in Fig. 2. Temperature and density profiles were measured for all discharges in order to put into the MHD stability analysis since the pressure profile is very important for the evaluation of the stability.

Figure 3 shows the electron temperature and density profiles for an NBI discharge with  $R_{00} = 92$  cm. The temperature profile is roughly parabolic ( $\propto (1-\Psi)$ :  $\Psi$  is the toroidal flux) and the density shows a little more peaky profile. The ion temperature measurement shows the similar parabolic profile. Because the shear stabilization effect for the ideal interchange mode remains in the outer boundary region even for the magnetic hill configuration of heliotron/torsatrons, the special pressure profile which has the pressure gradient only in the boundary region can be Mercier stable. But the measured profile tells the results of present experiments is not in such a condition. As noted above, the profile measurements were made throughout all discharges in the experiments. No peculiar profiles were found which changes the conclusion of stability analysis. There is a first stability region for very low beta values given by the magnetic shear. But it is below the beta values of ECH discharges shown in the figure. The measured pressure profiles of ECH plasmas give similar shapes to NBI plasmas since the density profiles are flatter but the temperature profiles are more peaky. The existence of stable discharges of ECH plasmas excludes the possibility of the stabilization effect given by the relatively large beam pressure in the discussion of MHD stability for the magnetic hill configuration.

Figure 4 shows the magnetic fluctuations measured in different configurations for NBI discharges shown in Fig. 2 as a function of the plasma beta. The magnetic fluctuations of CHS plasmas are generally larger for the inward shifted discharges than for the outward shifted ones for  $R_{00} > 92$  cm. However they did not increase for those discharges ( $R_{00} < 92$  cm) even though the Mercier stability condition becomes worth as the plasma position is moved inward. This observation is consistent to the fact that the simple Mercier criterion does not apply to the conditions which determines the plasma MHD behaviors in CHS. On the other hand, the magnetic fluctuations are good diagnostics of the MHD activities appearing in CHS, and small sawtooth crash phenomena in the density measurement and the soft X-ray measurement have been observed for various discharge conditions with magnetic fluctuations. But these MHD activities have never limit the plasma beta so far. It is generally

easy to increase the plasma beta by increasing the density with the fuelling up to the limit given by the radiation.

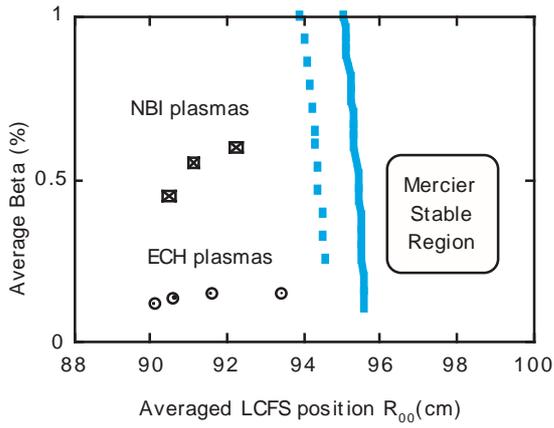
When the plasma position of CHS is controlled, largest volume is obtained for  $R_{00} = 95$  cm. The inward shift makes a plasma volume smaller. The volume of drift-orbit-optimized configuration ( $R_{00} = 90$  cm) is about 45 % of the largest volume. The most standard selection of plasma position is  $R_{00} = 93.5 - 94$  cm which gives minimum magnetic field ripple on the magnetic axis. The highest beta value of CHS was obtained with these configurations. When the plasma position was shifted inward for NBI discharges from the standard configuration, the total plasma energy did not decrease even though the plasma volume decreased for the position range  $R_{00} > 91$  cm. However the total energy decreased for  $R_{00} = 90$  cm which is the final optimized configuration in the experiments. Small global confinement improvement was observed for the fully collisional NBI plasmas with inward shifted operation for  $R_{00} > 91$  cm. The result for  $R_{00} = 90$  cm is ambiguous. Two conditions should be taken into account. Because the plasma boundary is in contact with the inboard side of vacuum chamber wall, careful wall conditioning is necessary for such new operational parameters. The power deposition of NBI also changes for the small volume of plasmas.

The confinement of low density ECH plasmas is more important for the subject of drift-orbit-optimization. The electron temperature profiles are compared for different plasma positions keeping the densities for all configurations roughly constant ( $n_e \sim 6 \times 10^{12} \text{cm}^{-3}$ ). The measurements of four configurations are plotted in Fig. 5. The measurement points (major radius) of each configuration are converted to the minor radius using the equilibrium calculation results. The profile did not change much for the plasma position range  $R_{00} > 91$  cm. The total energy did not change either which is the similar results to NBI discharges. However it is now clear that the temperature profile decreased for  $R_{00} = 90$  cm which is unexpected result from the present optimization scenario. The largest change is for the central temperature. It dropped a lot for the small change of configuration from  $R_{00} = 91$  cm to 90 cm. Since the collisionality is sufficiently low for these ECH plasmas, the experimental result shows the configuration optimization based on the alignment of bottom values of ripples does not work. The quantitative analysis is necessary to understand the observed results.

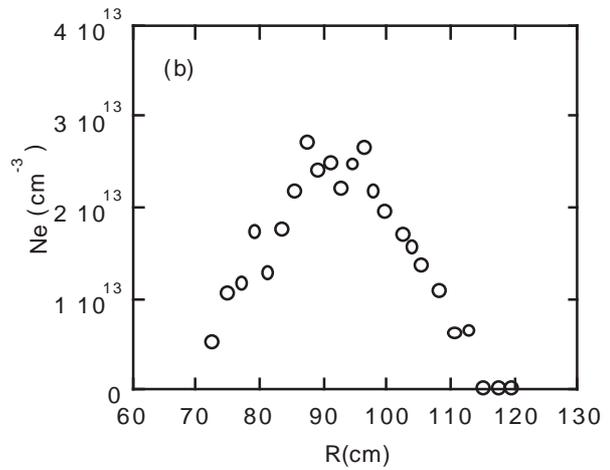
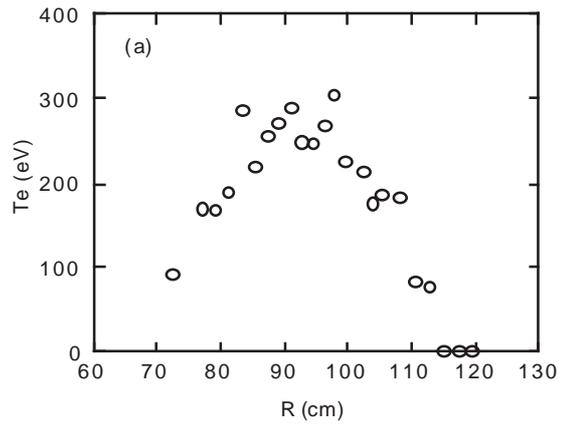
It might be important to note that the field ripple on the magnetic axis increases for the inward shifted configuration. In the experiments, the plasma initiation with ECH became more difficult for the inward shifted case, and more delicate selection of the field strength was necessary. The process of ECH power deposition should be also examined. The increased field ripple should have large effect on it.

It is known that a simple optimization scenario with the field bottom value is not sufficient. The alignment of top values of ripples is simultaneously needed for the full optimization. Such optimization is not possible within the flexibility of heliotron/torsatron systems.

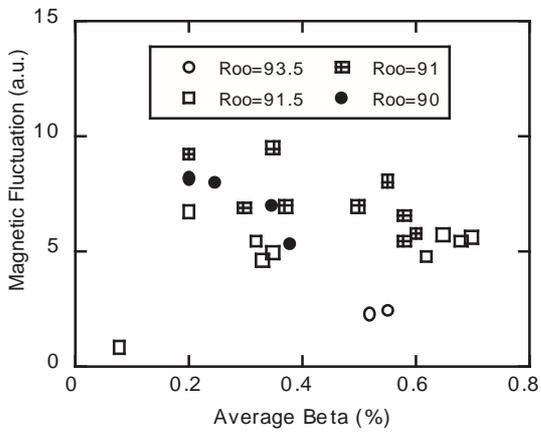
The effect of the plasma position control was fully investigated including the drift-optimized-configuration of heliotron/torsatron. Such study became possible because the MHD instability predicted by the ideal interchange model did not appear in CHS both for ECH and NBI plasmas. The confinement improvement was observed for the position range  $R_{00} > 91$  cm, but the final optimized configuration did not give the best confinement so far.



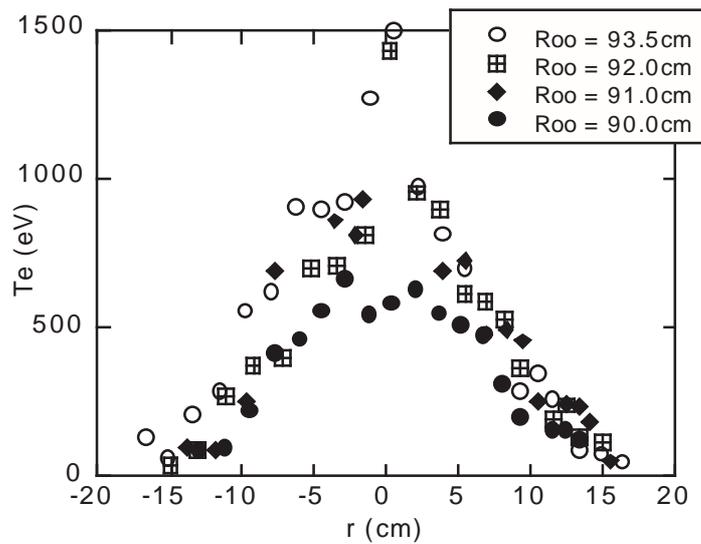
**Fig. 2.** Mercier stability diagram of CHS plasmas



**Fig. 3.** Electron and density profiles of NBI plasmas



**Fig. 4.** Magnetic fluctuations in inward shifted plasmas



**Fig. 5.** Electron temperature profiles for inward shifted configurations