Finite beta effects on the island bundle diverter of CFQS

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Finite beta effects on the island bundle diverter of CFQS

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CFQS is a new stellarator program with the magnetic configuration of the quasi-axisymmetry. This program NSJP is an international joint project conducted by NIFS (National Institute for Fusion Science), Japan and SWJTU (Southwest Jiaotong University), Chengdu China. The number of toroidal period is 2 and the major radius of the device is 1 m. The magnetic strength is 1 T targeting an ECH plasma with high electron temperature. Magnetic configuration of CFQS is designed based on the CHS-qa design [1], which was completed in NIFS for the succeeding program to the CHS experiment. The quasi-axisymmetry was successfully designed for CHS-qa giving strongly improved neo-classical transport. The design of modular coils for the device was also completed with the engineering supporting structure design. However, the work for the magnetic divertor configuration was not sufficiently done except a preliminary study of magnetic field line structures outside the last closed magnetic surface.

For CFQS, a special type of the island divertor configuration, the island bundle divertor (IDB), is studied more intensively. This island divertor has very large islands surrounding the core confinement region with a clear interface of magnetic separatrix [2]. However, the formation of islands strongly depends on the rotational transform, which changes very much with the bootstrap current. Because the quasi-axisymmetric stellarator has a large bootstrap current similar to standard tokamaks, it is important to study the effect of plasma beta on the island divertor.

Figure 1 shows the rotational transform profiles of CFQS standard configuration and the IDB configuration with zero plasma pressure. The IDB configuration is produced by adding negative auxiliary toroidal field in a simple analytic formula (B_{ext} = -0.05 T*1/R: R is the major radius of the point), which moves up the rotational transform (in vacuum). Values of the rotational transform are plotted as a function of the averaged minor radii. For the IDB configuraion (in red), dots with the rotational transform value of 0.4 and shrunk values of averaged minor radii (around 0.25 m) corespond to the magnetic surfaces formed in the islands. Figure 2 shows the magnetic surface plots for these two configurations [2].

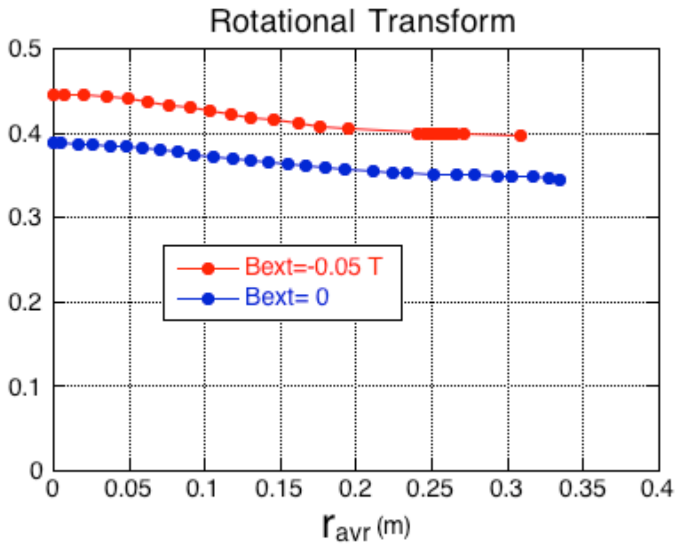

Figure 1 Rotational transforms of standard configuriaon of CFQS and island bundle divertor configuration.

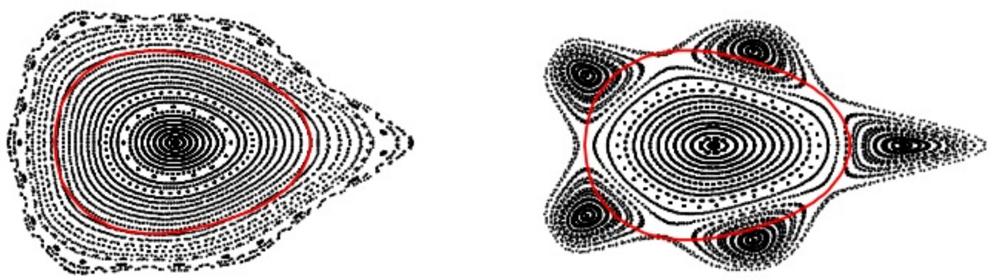

Figure 2 Punctual plots of magnetic surfaces for CFQS configuration (left) and IBD configuraion (right).

The bootstrap current was calculated with the BOOTSJ code for arbitrary pressure profiles corresponding to the plasma conditions with ECH heating [3]. In order to obtain rough estimate of toroidal current value and profile, we calculated the bootstrap current for the density and temperature profiles both in parabolic, namely, $n_e = n_{e0}*(1-(r/a)^2)$ and $T_e = T_{e0}*(1-(r/a)^2)$. For the plasma parameters of the central density of $n_{e0} = 1 \times 10^{19} cm^{-3}$ and the central temperature of $T_{e0} = 0.6$ keV ($T_e = T_i$ is assumed), the calculated bootstrap current is about 15 kA for the plasma beta value of 0.6 %. This value is in the range of target plasma parameters with the available heating power of CFQS experiment. Figure 3 shows the dependence of bootstrap current on averaged plasma beta calculated with BOOTSJ code. However, we need to use other calculation tools for higher plasma beta case because usual operation in stellarators for getting higher beta is increasing the density which violates the calculation condition of low collisionality in BOOTSJ code.

Because bootstrap current flowing in the quasi-axisymmetric stellarator, in general, increase the rotational transform, the island bundle divertor (IDB) in CFQS device is generated by the finite beta effect of the plasma without adding auxiliary toroidal field. We can call this effect as a self formation of the IDB configuration with increased beta. Figure 4 shows changes of the rotational transform due to the beta increase. This data was obtained from the VMEC equilibrium calculation and it is not possible to obtain the island structure from the calculation with this code. An advanced code, e.g., HINT code, for the equilibrium calculation without assuming the closed magnetic surface structure can bring the IDB structure with finite plasma beta and current. In Fig.4, the rotational transform with the bootstrap current I = 13 kA is supposed to give island structure because it has the rational value of 0.4 near the plasma boundary. It is not certain that such an area would form big island structures shown in Fig. 2. The experimental study is only the way to give us real solution for this type of question.

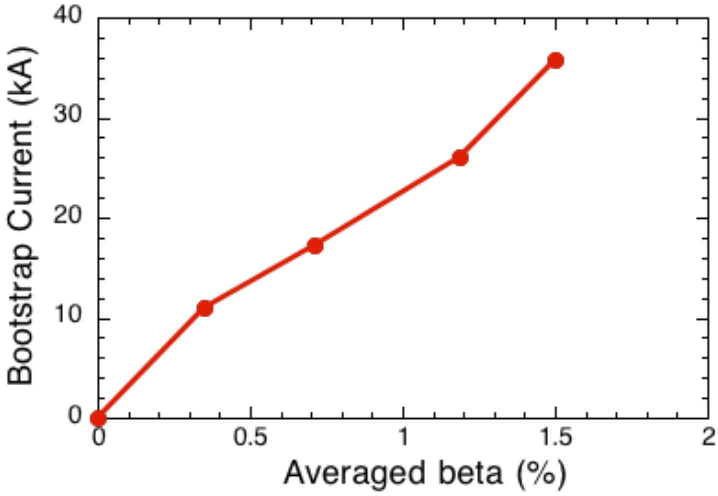

Fig. 3 Dependence of bootstrap current on averaged plasma beta

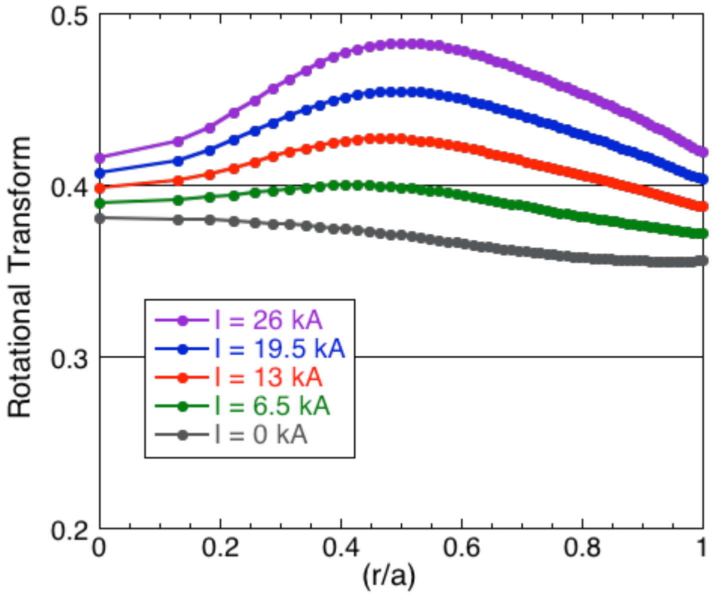

Fig.4 Change of rotational transform profile caused by increase of plasma beta. Rotational transform with I = 13 kA forms island bundle divertor (IDB).

The IDB structure pattern in Fig. 2 is calculated using the magnetic field line tracing with the vacuum magnetic field of CFQS and analytical formula of the auxiliary uniform toroidal field. Such type toroidal field is obtained with a strong current in the central core of the torus with the return current paths flowing very far from the torus, which is the standard toroidal field design in spherical torus experiments. However, in CFQS device design, we could not make such a current path design for the auxiliary toroidal field because of the interference to the mechanical support structure and the device cost problem. Since the current in the toroidal coil is relatively small because this field is just for modification of the main stellartor field, we made very simple auxiliary toroidal coil design.

In CFQS, the toroidal coils are wound on the surface of the vacuum chamber and the number of coils is 12. Because the position of these coils is closer to the plasma boundary than the main modular coils, these toroidal coils introduce toroidal field ripples which is larger than that produced by the modular coil themselves. However, the effect of these additional ripple is not significant because the averaged magnitude of auxiliary toroidal field is relatively small compared to the main toroidal field produced by the modular coils. When the plasma beta is increased and the rotational transform value exceeds the rational value of 0.4 everywhere in the plasma, we need to decrease it by introducing the auxiliary toroidal field. Figure 5 shows the rotational transform profile obtained by the vmec free boudary calculation with larger bootstrap current (I = 15 kA) and the auxiliary toroidal field pushing it down. The crossing point of 0.4 is recovered for creating the island bundle divertor. Such an effect has to be verified in the experiment as well.

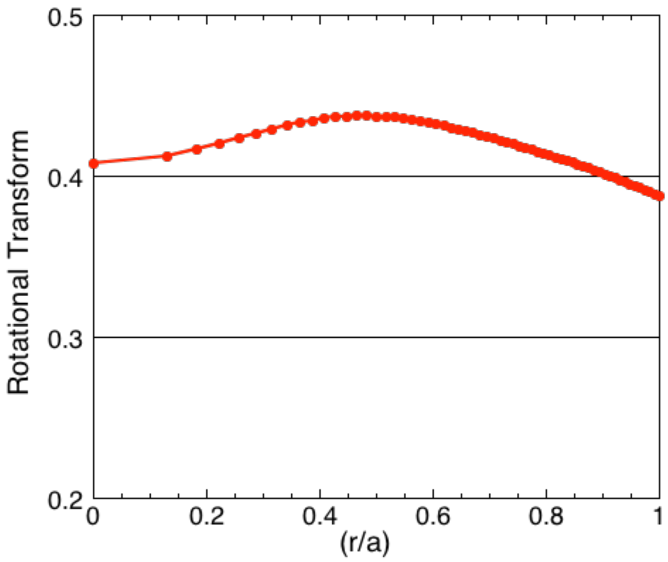

Fig. 5 Rotational transform with larger bootstrap current with auxiliary toroidal field pushing down for island divertor formation.

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