Design of auxiliary coils for divertor operation of quasi-axisymmetric stellarator CFQS

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An international joint project NSJP has been conducted for the collaborations of National Institute for Fusion Science, Japan and Southwest Jioatong University, China. The target of this project is to construct a new advanced stellarator device CFQS (Chinese First Quasi-axisymmetric Stellarator) [1] in China and to make plasma confinement experiments based on the new concept of stellarator magnetic configuration with the quasi-axisymmetry [2]. The construction of the device started in 2018 and the manufacturing of modular coils is in progress [3]. In addition to the new concept of stellarator magnetic field configuration, this device will have a new divertor configuration with a clear separatrix structure between core and peripheral confinement regions [4]. The magnetic structure of diverter legs between null points of the separatrix and the divertor target plates is also very unique compared to the existing stellarator designs.

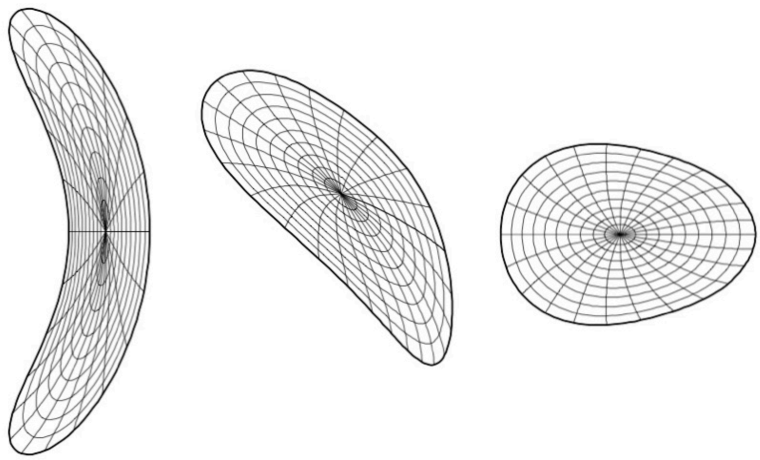

Fig. 1 Last closed magnetic surfaces for CFQS configuration design. Cross sections for three toroidal positions are shown. Torus center is at the left side of the cross section.

Figure 1 shows the three toroidal cross section shapes of the VMEC boundaries of the CFQS plasma. The device parameters are: the major radius of the device is R=1 m and the nominal magnetic field strength is 1 T. The plasma spect ratio is 4.0. The rotational transform profile of vacuum magnetic configuration of CFQS is between 0.38 (at magnetic axis) and 0.35 with decreasing magnetic shear toward the edge. Because the profile does not cross the low order rational values, no big magnetic island is created in the configuration. When the auxiliary toroidal magnetic field (negative amplitude) is applied to the stellarator field, the rotational transform is increased and big magnetic islands appears at the rotational transform value of 0.4 (m=5/n=2 islands). The radial location of islands can be controlled by adjusting the auxiliary toroidal field amplitude. When the rotational transform value of the stellarator field at the boundary (0.35) is increased to 0.4, a clear island diverter configuration is formed as shown in Fig. 2.

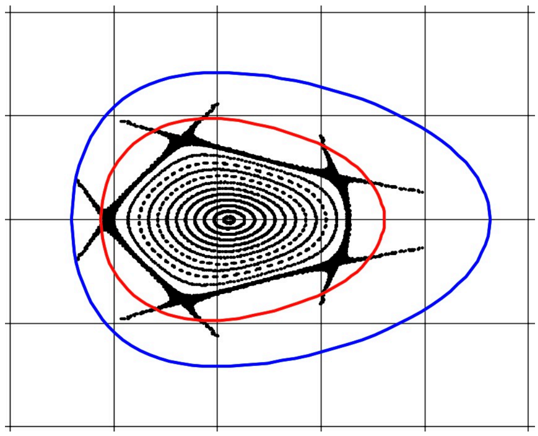

Fig. 2 Island bundle divertor configuration at the right-most cross secion in Fig. 1. Grid size is 10 cm. Red curve corresponds to the shape of VMEC boundary in Fig. 1. Blue curve reflects the shape of vacuum chamber wall of the device.

Diverter leg shape was drawn by following the magnetic field lines with the trace start points aligned along the separatrix of the configuration. This separatrix is the last closed magnetic surface of this configuration. The field lines are traced until they hit the vacuum chamber wall. In this configuration, the hitting points are at inboard side of the chamber wall. Because the island is at m=5/n=2 resonance, the diverter field lines are wandering around the torus, namely, they visit all five diverter legs before hitting the chamber wall (five legs among ten are for the divertor field lines with the same toroidal directions). The connection length of these diverter field lines is in the range of 500 to 1000 m.

For the diverter field line calculation shown in Fig. 2, a model field for the auxiliary toroidal field can be used ($B_t = 1/R\ B_{aux}$). This model field structure corresponds to the toroidal field for the spherical torus. Toroidal field coil of spherical torus is a current conductor at the torus center and many return current conductors around the torus. In the engineering design of CFQS, we could not find the space for the central current conductor because the device shape is very compact (low aspect ratio). Instead, we designed auxiliary toroidal field coils (TFC) as they run along the outer surface of the vacuum chamber wall. Figure 3 shows the engineering design of the CFQS coil system for 16 modular coils (MC) and 12 TFCs.

Because we designed the arrangement of the diagnostic ports so that we will have as

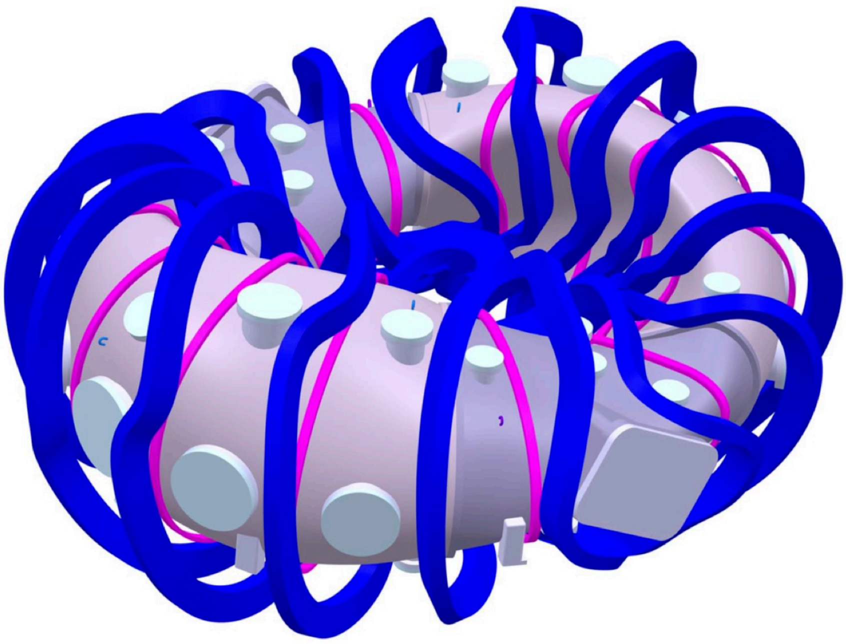

Fig. 3 Magnetic coil system for CFQS device. Modular coils are in blue color and auxiliary toroidal coils are in magenta color. Shapes of vacuum chamber and major ports are also shown.

many ports as possible for the convenience of the plasma physics study on this device, it was hard to find the place for the TFC winding. The final solution was shown in Fig. 3. Since the device has the n=2 stellarator symmetry, it has four identical units with the same magnetic field

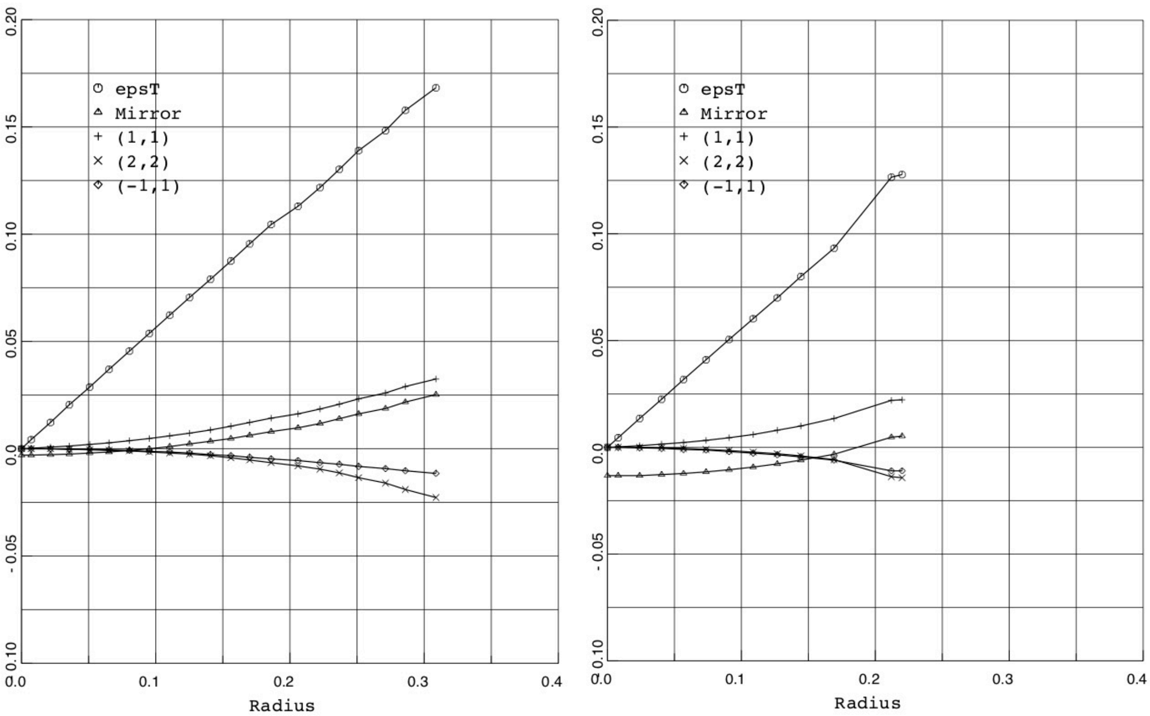

Fig. 4 Boozer specta for (left) standard quasi-axisymmetric configuration with modular coils and (right) island bundle divertor configuration with modular coils and TFC coils.

configuration and mechanical shape. Therefore, one unit has three TFCs and four MCs. From the point of view of keeping the quasi-axisymmetry in the island bundle diverter (IDB) configuration, the auxiliary toroidal field need to have toroidal symmetry, namely, the form of B_t = 1/R B_{aux}. However, we have unfortunately smaller size TFCs than MCs, which causes big ripples in the toroidal field strength along the toroidal direction. Fig. 4 shows the Boozer spectra of the magnetic field ripples for the standard quasi-axisymmetric configuration and the IDB configuration.

The right-hand plots of Fig. 4 shows that a good axisymmetry is kept for the IDB configuration except the simple mirror components produced by TFC field. In order to evaluate the effect of these ripples created by the TFC on the neoclassical transport, the effective helical ripple was calculated using the NEO code [5] comparing two cases of the standard operation of CFQS and IDB operation. The quantity of the effective helical ripple is a part of the neoclassical transport coefficient useful for comparing two different magnetic configurations.

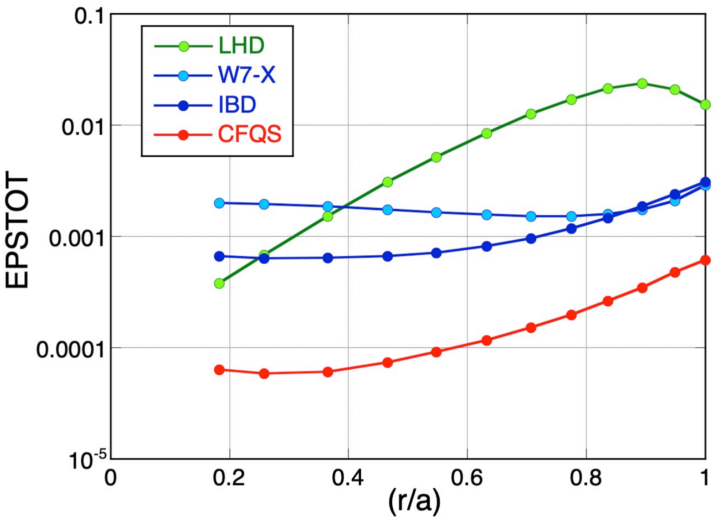

Fig. 5 Profiles of effective helical ripples as the function of the minor radius.

Figure 5 shows the radial profiles of the effective helical ripple for four different magnetic configurations. The red curve is for the standard CFQS configuration and the blue curve is for the IBD configuration. The neoclassical transport is increased about one order of magnitude due the the mirror field shown in Fig. 4. We plot two profiles for two large stellarators from the world, namely, from Wendelstein 7-X and LHD for the reference. The neoclassical transport for IDB is lower than these two cases.

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