Effect of aspect-ratio on confinement properties of planar-axis and non-planar-axis stellarators

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For the toroidal magnetic confinement fusion, the most basic geometric parameter is the aspect ratio of the torus. It is fundamental both in the physics of the plasma confinement and the technological aspect of the reactor design. In the present stellarator world, we have many different types of the experimental devices which have different values of aspect ratio as well. In tokamak fusion reactor designs, we have made lots of hard discussions in selecting the aspect ratio of the configuration. On the other hand, the reactor designs based on the stellarator configuration have not yet given systematic discussions in selecting the aspect ratio.

Presently we have two large-scale stellarator programs: LHD is running more than 15 years and another Wendelstein 7-X is just starting experiment this year. They have very different magnetic field configurations. As the consequence of these programs, we have two major streams of stellarator reactor design, which adopt almost direct extrapolations of the existing device configurations. Aspect ratio of these devices are relatively large compared to the one of tokamaks. It is because we had been believing that the toroidiciy term in stellarator configuration generally degrade the confinement of neoclassical transport untill we found the idea of the quasi-axisymmetric stellarator. The aspect ratio of LHD is about 6 and the one for W 7-X is 10. These numbers are both more than twice larger than tokamaks but there is a factor of 2 difference between these numbers. In this paper, we will discuss the effect of the modifying the aspect ratio of LHD configurations on the confinement properties considering the origin of the difference between two devices.

Comparison of the confinement properties is made with the effective helical ripples [1] at two minor radii [(r/a) = 1/3 and 2/3] as the measure of the neoclassical confinement and the specific volume of the magnetic flux at the plasma boundary as the measure of the MHD stability. The equilibrium calculation was made for the vacuum field in this paper but the value of the edge specific volume gives a good index of the MHD stability of finite beta equilibria [2]. Because we discuss the general characteristics of stellarator geometry with different aspect ratio, we will select the most basic magnetic configuration of stellarator in the comparison work. In the equilibrium calculation of VMEC [3], we will take only 5 pairs of Fourier elements of r(m,n) and z(m,n) for the boundary shape, which are essential components to construct the stellarator equilibrium field. It was confirmed that these limited components are sufficient for constructing the LHD magnetic field with the magnetic axis position of R_{ax} = 3.6 m, which is the standard configuration of LHD experiments [4].

The confinement properties of LHD magnetic configuration varies very much depending on the magnetic axis position R_{ax}. Because the best value of R_{ax} might be different for different aspect ratio values, we compare configurations with different aspect ratios by calculating the dependence of confinement properties on R_{ax} for the configuration of given aspect ratio. Since we calculate the equilibria with the VMEC Fourier components of the boundary shape, we need a good combination of the Fourier elements to controlling the magnetic axis position. It was discussed in the paper [2] that r (0,1) and z (0,1) are the elements that represent the essential change of the magnetic configuration with the shift of the magnetic axis position. Moreover, the complex Fourier element of Δ_{11} is a good variable as the controlling parameter of the magnetic axis shift effect. The formula to express the boundary shape with such complex Fourier elements is shown below, where θ

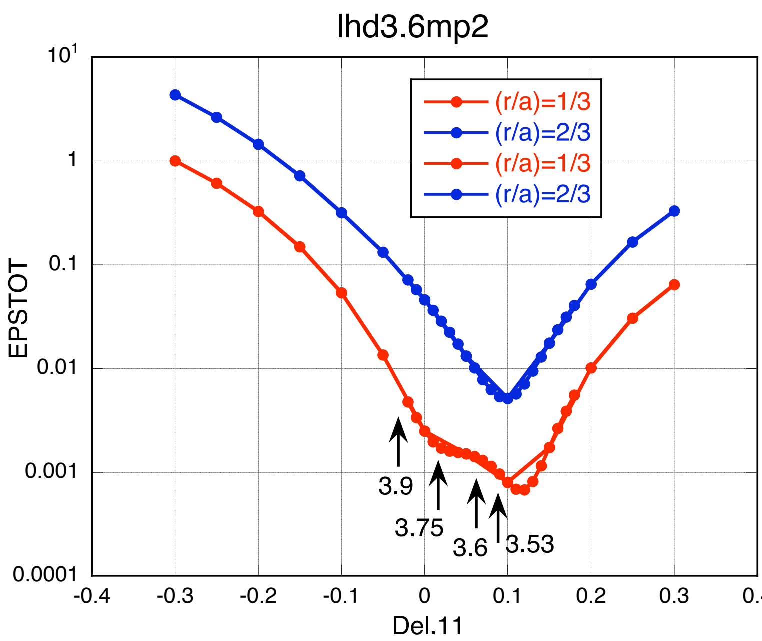

Fig. 1 Effective helical ripples at (r/a) = 1/3 and 2/3 as functions of Δ_{11}. Arrows with numbers show the corresponding values for the LHD configurations with different positions of magnetic axis.

where θ and ϕ are two (poloidal and toroidal) angle parameters mapped on the magnetic surface. R and Z define a point on the magnetic surface in a cylindrical coordinate system.

$$R(\theta,\phi) + iZ(\theta,\phi) = \exp(i\theta)\sum \Delta_{mn} \exp(-im\theta + in\phi)$$

Figure 1 shows the dependence of effective helical ripples on Δ_{11} for the LHD standard configuration. Arrows point the positions in the figure for the equivalent configurations of LHD experiment (numbers are the magnetic axis positions in meter). In the real operation of LHD experiment, Δ_{11} is scanned for a small range from -0.05 to 0.1. The purpose of scanning Δ_{11} in a much wider range in this figure is to compare LHD with W 7-X, which has Δ_{11} value of 0.3. Such equilibrium calculations were made for different aspect ratio configurations and different number of toroidal period NFP. For example, the equilibrium was calculated for higher NFP value of 12 (LHD has NFP = 10), with the same major radius and minor radius. For this configuration, the geometrical helical torsion of the boundary shape is stronger than LHD. Another equilibrium of NFP = 12 was calculated with a larger major radius keeping the same minor radius. Such configuration has the same geometrical torsion of the boundary but the aspect ratio becomes larger. Finally the equilibrium with a larger aspect ratio but with NFP = 10 was calculated. This configuration has a weaker geometrical torsion than LHD. These calculations were made for NFP = 8, 12, 16, that is, smaller and larger aspect ratio than LHD and for the similar value of the aspect ratio to W 7-X. For the neighboring values of the aspect ratio, configurations with the same geometrical torsion have similar dependence of the effective helical ripples to LHD case. The edge specific volumes are also similar to LHD. The configurations with stronger geometric torsion have the higher effective ripples even for the optimized value of Δ_{11}.

Figure 2 shows the dependence of the effective helical ripples on Δ_{11} for the very high aspect ratio configuration. The aspect ratio is 9.65 which is similar value to the W 7-X aspect ratio of 10. When we keep the geometric torsion at the same level as LHD for this aspect ratio, NFP should be 16. Such equilibrium has a very sharp peak of small value of the effective helical ripple at Δ_{11} = 0.05. On the other hand, when we

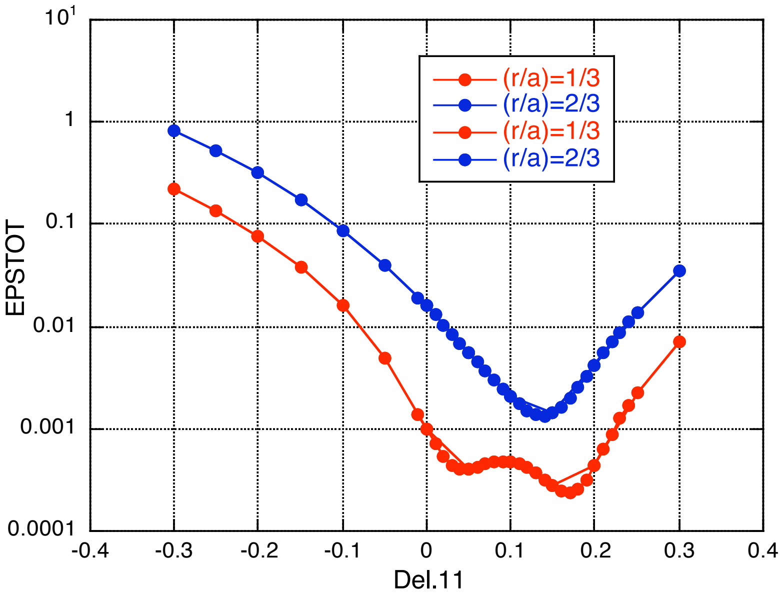

Fig. 2 Effective helical ripples at (r/a) = 1/3 and 2/3 as functions of Δ_{11} for high aspect ratio LHD-type planar-axis stellarator.

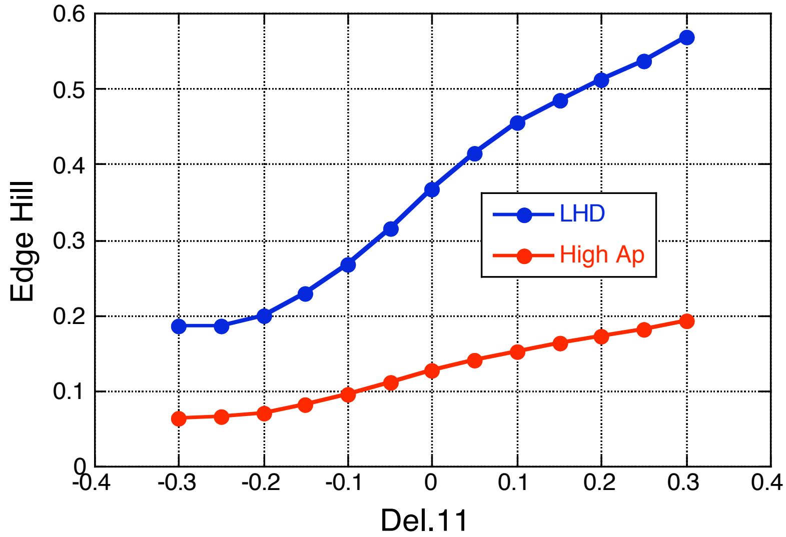

Fig. 3 Specific volume at plasma edge as functions of Δ_{11} for LHD and high aspect ratio LHD-type planar-axis stellarator.

take NFP = 10 same as LHD with a week torsion, a wide range of Δ_{11} value appears for small effective helical ripples shown in Fig. 2. This means that the confinement does not change much (does not deteriorate) for the modification of the equilibrium due to the plasma pressure increase. This configuration might be good candidate for the high aspect ratio planar-axis stellarator reactor design.

The comparison of dependence of the edge specific volume on Δ_{11} for the LHD standard configuration and the high aspect ratio configuration is shown in Fig. 3. The magnetic well for the vacuum field exists in the Δ_{11} range smaller than -0.05 for LHD configuration, but it does not exist for the high aspect ratio one. However plasmas with high plasma pressure have the magnetic well produced by the Shafranov shift. The small value of edge specific volume for the high aspect ratio configuration would help the magnetic well creation with the plasma pressure.

References

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