# EFFECT OF BOOTSTRAP CURRENT ON MHD EQUILIBRIUM BETA LIMIT IN LHD PLASMA

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## 1. Introduction

The neoclassical theory of stellarators predicts the existence of the bootstrap current particularly for rare collisional plasmas[1]. We already showed the possibility that MHD equilibrium beta limit with consistent bootstrap current significantly decrease in the low collisional regime comparing with currentless case depending on the vertical field control methods in finite beta and magnetic configurations[2].

We have studied the effect of bootstrap current on MHD equilibrium beta limit in LHD plasma for various magnetic configurations systematically by using SPBSC code[3]. In SPBSC code, the consistent bootstrap current and MHD equilibrium are calculated iteratively. We show the dependence of MHD equilibrium beta limit on the magnetic configurations and pressure profiles.

## 2. Calculation Results

We have studied the MHD equilibrium beta limit with self-consistent bootstrap current for a device with LHD like configuration. LHD has the following device parameters: L=2/M=10, $R_C$=3.9m, $B_0$=3T. In this paper, we apply the following assumptions: simple plasma consisting of primary ions and electrons, and both are in 1/ν collisional regime, $Z_{eff}$=1. In our present models, $Z_{eff}$ is reflected just in the collision frequency[3] and the difference of obtained bootstrap current is within several % due to change from $Z_{eff}$=1 to $Z_{eff}$=3.

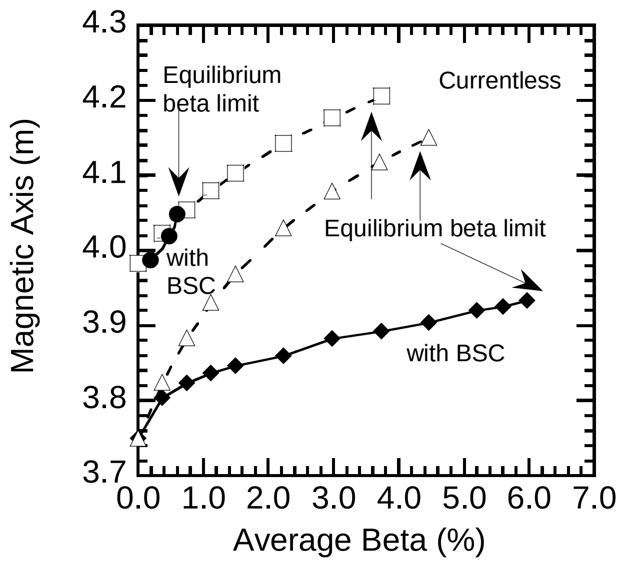


**Fig. 1.** Dependence of MHD equilibrium beta limit on the magnetic axis position in vacuum field

Figure 1 shows the dependence of magnetic axis shift in finite beta under the fixed boundary condition with different magnetic configurations. Here pressure profile is proportional to $(1-\psi)^2$, $\psi$ is normalized toroidal flux. Shafranov shift with self-consistent bootstrap current is much smaller than currentless case in $R_{ax}^V$=3.75m configuration (magnetic axis not located in torus outward shift) because bootstrap current flows in the direction that the rotational transform increases in the configuration[3]. Shafranov shift with bootstrap current for $R_{ax}^V$=3.975m (magnetic axis located in torus outward shift) case is smaller than currentless case for $\beta_0 \leq 1\%$. On the contrary, for $\beta_0 \geq 1\%$ it is larger than currentless case, where bootstrap current flows in the direction that the rotational transform reduces near plasma center, which we call negative current. We cannot get the convergence results of VMEC[4] calculation as beta increases more and negative current becomes larger. The negative current leads to the larger shafranov shift because rotational transform is reduced. The larger shafranov shift causes larger negative current. Such positive feedback leads to no convergence calculation result, which leads to no existence of MHD equilibrium.

This feature is closely related to the dependence of geometric factor in 1/ν collisional regime, which is proportional to bootstrap current, on the magnetic axis in heliotron type device[2]. According to the dependence of the geometric factor in LHD, it decreases as the magnetic axis shifts torus outward and finally the bootstrap current flows in the direction so as to reduction of rotational transform. This is common feature in heliotron type devices. From the dependence of the geometric factor, we can consider that $R_{ax} \approx 4.00$m is the criterion that the consistent MHD equilibrium with bootstrap current exists for a configuration like LHD. According to the calculation results the MHD equilibria with consistent bootstrap for $R_{ax}^V \leq 3.90$m have the magnetic axis $R_{ax}$<4.00m even in the high beta regime. Here $R_{ax}^V$ is the magnetic axis position in vacuum.

Figure 2 shows the dependence of MHD equilibrium beta limit on the magnetic axis position in vacuum under the fixed boundary condition. Here pressure profile is proportional to $(1-\psi)^2$. The MHD equilibrium beta limit is decided by large Shafranov shift ($(R_{ax}-R_{00}(1))/a_p$ larger than 2/3) or non-convergence in the VMEC calculation. Here $R_{00}(1)$ is the major radius of the outermost magnetic surface and $a_p$ is the plasma minor radius.

In this criterion, the MHD equilib-rium beta limit in LHD is ~4% in currentless cases. Here the equilib-

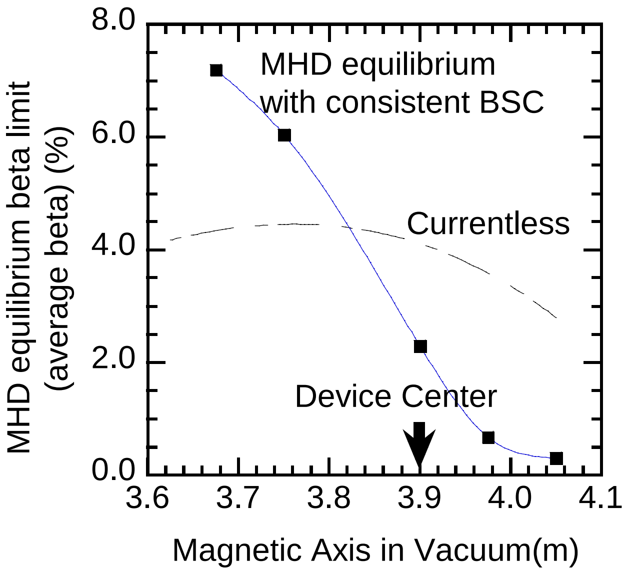


**Fig. 2.** Dependence of magnetic axis shifts for different magnetic configuration.

rium beta limits are decided by large shafranov shift. The configurations with large inward magnetic axis in vacuum, $R_{ax}^{V}$<3.7m, and consistent bootstrap current have larger MHD equilibrium beta limit than currentless cases by about twice. On the contrary, the MHD equilibrium beta limit with large outward magnetic axis in vacuum, $R_{ax}^{V}$>4.0m, and consistent bootstrap current is much smaller than currentless cases. It should be noticed that the negative current in the cases with self-consistent bootstrap current decides the equilibrium beta limits. As already mentioned, this picture depends on the feature of 1/ν collisional regime geometric factor on the magnetic axis position in heliotron devices.

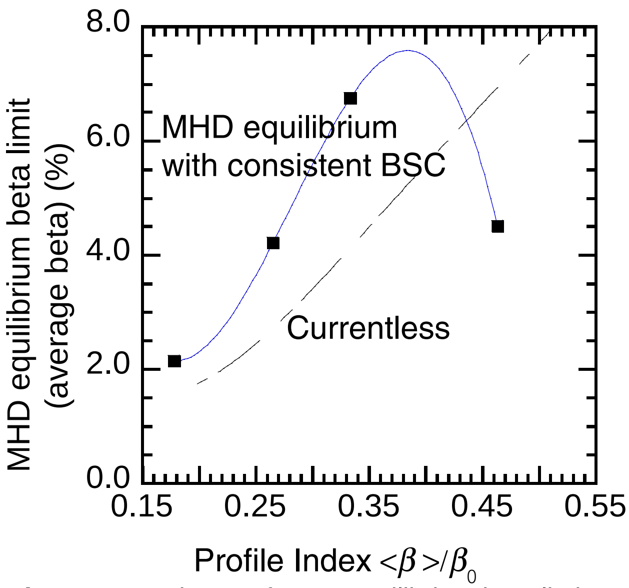

**Fig. 3.** Dependence of MHD equilibrium beta limit on the pressure profile

Figure 3 shows dependence of MHD equilibrium beta limit on the pressure profile. Here $<\beta>/\beta_0 \approx 0.18$ corresponds to $\beta \propto (1-\psi)^5$ and $<\beta>/\beta_0 \approx 0.46$ $\beta \propto (1-\psi)(1-\psi^3)$, respectively. For currentless case, as flatter is pressure profile, as larger is MHD equilibrium beta limit. Because shafranov shift is almost proportional to central beta and shafranov shift with peak pressure profile is larger than flat one. On the contrary, the MHD equilibrium beta limit with bootstrap current is decided by competition of the effects of central pressure and net toroidal current on the shafranov shift. For same volume average pressure cases, peak pressure profile leads to the large shafranov shift and to the large bootstrap current, which reduces the shafranov shift. When $<\beta>/\beta_0 \approx 0.4$, MHD equilibrium beta limit becomes maximum in the configuration with $R_{ax}^{V}$=3.75m. According to the dependence of pressure profile on shafranov shift, more peak pressure plasma has larger shafranov shift in currentless cases. On the contrary, shafranov shift with same volume average beta is almost same with bootstrap cases.

## 3. Discussion

The physical picture obtained from previous section's results is valid to other magnetic strength. The reason is the following. Beta profile and magnetic configuration decide MHD equilibria without net toroidal current. MHD configuration with net toroidal current are decided by increment of rotational transport due to net toroidal current in addition to above. The bootstrap current in 1/ν collisional regime, $I_{BSC}^{1/\nu} \propto G_{bs} R_0 B_0 \beta / L_p$, where $R_0$ is the major radius of device, $B_0$ is the toroidal magnetic field strength at device center, $L_p$ is the non-dimensional pressure gradient length and $G_{bs}$ is non-dimensional geometric factor. On the contrary, $\Delta\iota_{BSC}\approx(B_0/R_0)/(I_{BSC}^{1/\nu}/a_p^2)$, then $\Delta\iota_{BSC}\approx(L_p/\beta)(a_p^{\,2}/R_0^2)/G_{bs}$. It is noted that plasmas with the same magnetic configuration, beta and its profile and consistent bootstrap current in $1/\nu$ collisional regime have the same shafranov shift, $\Delta R_{ax}/a$, and MHD equilibrium beta limit.

We already studied the effect of MHD equilibrium beta limit on vertical field control in finite beta[2]. The equilibrium beta limit for the free-boundary condition without vertical field control is smaller than for the fixed boundary condition because the magnetic axis for the free-boundary is located more outward than for the fixed boundary condition. Here, the fixed boundary corresponds to the vertical field controlled as to keep the outermost magnetic surface at the almost same position. Here the free boundary corresponds to no vertical field control and the outermost magnetic surface is located at the same point, which the plasma volume decreases as beta increases. If we don't control the vertical field control, the MHD equilibrium beta limit for the configuration with $R_{ax}^V$>4.0m become lower than $\langle\beta\rangle<0.3\%$. We will easily confirm that our prediction of the negative current effect is true or not in no vertical field control and low collisional plasmas with large $R_{ax}^V$.

## 4. Concluding Remarks

We have studied the MHD equilibrium beta limit with self-consistent bootstrap current for a device with LHD like configuration for low collisional regime. There is the possibility of increasing and decreasing the MHD equilibrium beta limit, which depends on the magnetic axis location in finite beta. This picture doesn't changes for device parameters like as magnetic field strength and device size. If we choose the appropriate pressure profile and magnetic configuration, we can produces MHD equilibrium with more than $\langle\beta\rangle=7\%$. The control of bootstrap current or net toroidal current might be very important to produce the low collisional plasma with high beta.

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