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Neoclassical Equilibrium in a Low-Aspect Ratio RFP Machine RELAX

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The reversed field pinch (RFP) has a great advantage in that it requires a relatively weak external toroidal magnetic field. Recent equilibrium analyses have shown that mode rational surfaces are less densely spaced by lowering the aspect ratio (A) of the RFP configuration. Moreover, in low-A equilibrium, self-induced bootstrap current tends to increase [1], and therefore, we have to analyze the neoclassical RFP equilibrium in low-A RFP configuration by taking into account the effect of bootstrap current self-consistently.

We have started the low-A RFP research in RELAX (REversed field pinch of Low-Aspect ratio eXperiment, R/a=0.5m/0.25m) with A of 2 [2, 3]. We have developed a neoclassical equilibrium reconstruction code RELAXFit by modifying the MSTFit code [4] to low-A regime and also by taking into account the effect of bootstrap current self-consistently.

In a neoclassical equilibrium state, the total toroidal plasma current I_ϕ^{eq} is expressed as

$$I_\phi^{eq} = I_\phi^{OH} + I_\phi^{PRP} + I_\phi^{BSb} + I_\phi^{BS\alpha}, \tag{1}$$

where I_ϕ^{OH} is the Ohmic current due to external electric current source, I_ϕ^{PRP} is the toroidal component of the Pfirsch-Schluter and diamagnetic currents, I_ϕ^{BSb} is the bootstrap current due to the bulk plasma, and $I_\phi^{BS\alpha}$ is the bootstrap current due to fusion-produced α particles. In this code, we neglect the contribution from α particles, because RELAX is operated with only hydrogen.

The bulk parallel bootstrap current density j^{BSb} is expressed as

$$\frac{\langle \vec{j}^{BSb} \cdot \vec{B} \rangle}{\langle \vec{B} \cdot \nabla\theta \rangle} = -\frac{p_e}{\langle 1/R^2 \rangle} \{ L_1 \left[(p_e'/p_e) + (T_i/T_e)(p_i'/p_i)/Z \right] + L_2(T_e'/T_e) + L_3(T_i'/T_e)/Z \} \tag{2}$$

where T and p are the temperature and pressure, respectively, Z is the effective ionic charge, L_k (k = 1,2,3) denote transport coefficients, θ is the poroidal coordinate, and the subscripts "e" and "i" denote electron and ion, respectively. In our calculation, we use the transport coefficient L_k, which is a function of Z and the ratio of trapped/non-trapped particles, given by the Hirshman model [5] that assumes a plasma composed of electrons and a single ion species in the collisionless limit. j^{BSb} depends on the plasma pressure and temperature profiles. The bootstrap current increases as A decreases because of the increasing anisotropy in the electron pressure tensor [1].

The ratio of trapped to non-trapped particles reflects the equilibrium magnetic field. The trapped particle fraction f_t is expressed as

$$f_t = 1 - 0.75\langle B^2\rangle \int_0^{\lambda_c} \frac{\lambda d\lambda}{\langle (1-\lambda B)^{1/2}\rangle} \tag{3}$$

where $\lambda = \mu/E$ is the pitch angle, and the critical value $\lambda_c = 1/B_{max}$ is defined by the boundary of the loss cone. The trapped particles are expected to have an intense effect in the RFP, because the ratio of the bounce frequency of banana orbit ν_b to the electron-ion collision frequency ν_{ei} become greater than its in the tokamak. In RELAX parameter region, $\nu_b \sim 2.0 \times 10^7$ and $\nu_{ei} \sim 2.3 \times 10^5$.

Now, we demonstrate a result of our equilibrium reconstruction of the standard discharge in RELAX. In RELAX, several edge diagnostics make uses of constraint conditions to obtain the equilibrium reconstruction. Figure 1 shows the results of an equilibrium reconstruction of a standard RELAX discharge based on several external diagnostics, plasma current I_p, average toroidal field $< B_\phi >$, edge toroidal and poloidal field $B_\phi(a)$, $B_\theta(a)$ and internal radial array of magnetic probes inserted from an upper port, it measures B_ϕ and B_θ at $r/a = 0.6 - 1.0$. A comparison between the reconstructed equilibrium and the diagnostic data used to constrain the fit is shown in Figure 1(a). The measured values of B_ϕ and B_θ are represented on the plot as cross symbols, while the fits are represented as solid and dashed lines. This reconstruction also matches edge measurements of the total plasma current, total toroidal magnetic flux, and the boundary toroidal and poloidal magnetic fields. In this reconstruction, the plasma pressure and temperature profiles are assumed as follows: $p(\psi) = p_0(1-\psi_{00}^3)$ and $T(\psi) = T_0(1-\psi_{00}^3)^{0.75}$, where ψ_{00} is normalized poloidal flux $\psi_{00} = (\psi - \psi_0/\psi_{lim} - \psi_0)$, where ψ_{lim} is the poloidal flux at the wall, and ψ_0 is the minimum poloidal flux, i.e., $\psi_{00} = 0$ at the magnetic axis. p_0 and T_0 are values of plasma pressure and temperatures at magnetic axis, respectively. The ratio of peak electron and ion pressures is set as a value typical for power balance calculations, $p_{e0}/p_{i0} = 1.07$ [6], and the ratio of temperatures is defined in a similar way.

Figure 1(b) shows the calculated j_ϕ^{BSb} (solid) and j_θ^{BSb} (dashed) bootstrap current densities. This result shows that I_ϕ^{BSb} has a hollow current profile, and that j_θ^{BSb} is greater than j_ϕ^{BSb}. The ratio of the bootstrap current fraction to the equilibrium plasma current is given by $I_\phi^{BSb}/I_\phi^{eq} =$ 2.7 [kA]/62 [kA] = 0.044. In such low temperature region, neoclassical effects may be relatively small.

Finally, a parameter survey is conducted by varying the plasma pressure and temperature profiles to find the most desirable equilibrium state having the higher β with the least power externally supplied to generate the steady-state configuration. The results of this parameter survey

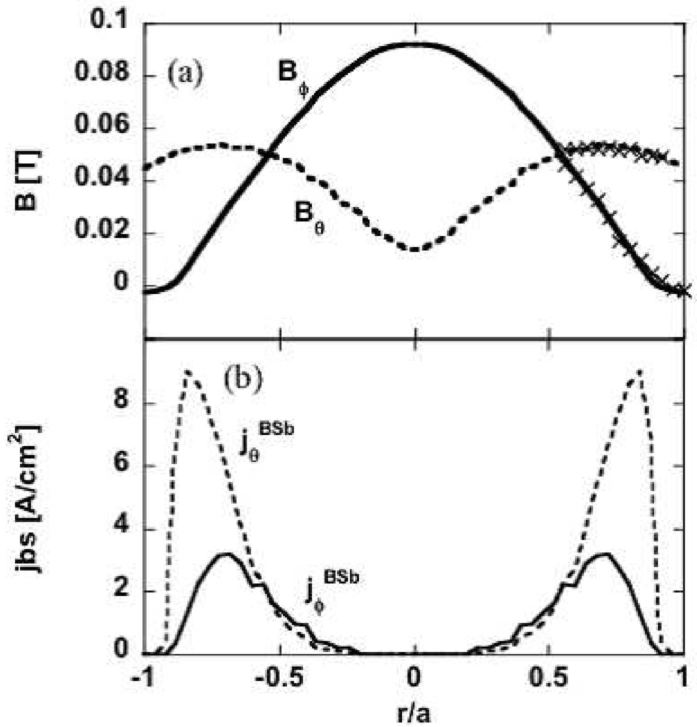

Figure 1: (a) Reconstructed magnetic field (b) Calculated bootstrap current density

are shown in Tables 1 and 2. In Table 1, we set $(ap, at) = 1.0, 0.75$, $bp = bt$ and $T_e(0) = 100$[eV]. From Table 1, it can be inferred that the ratio of the bootstrap current fraction to equilibrium plasma current increases with increasing number density $n_e(0)$, and that flattering of the profile results in an increase in β_p. In Table 2, we set some parameters higher to the extent possible in RELAX, i.e., $T_e(0) = 300$[eV], $n_e(0) = 4.0 \times 10^{19}$[/m^3]. In this parameter region, one of our findings is that if we could realize the supposed electron temperature and density, then the bootstrap fraction of ∼24% would be expected, depending on the pressure profile.

Table 1: Dependence of equilibrium on plasma parameters

bp, bt	$n_e(0)$ [$\times 10^{19}$/m^3]	β_p	I_ϕ^{eq} [kA]	I_ϕ^{BSb} [kA]	I_ϕ^{BSb}/I_ϕ^{eq}
2.0	1.0	0.09	49.0	1.97	0.040
2.0	4.0	0.25	58.1	7.45	0.128
1.0	1.0	0.05	47.4	2.13	0.045
1.0	4.0	0.16	52.0	7.53	0.145
0.5	1.0	0.03	45.7	1.43	0.031
0.5	4.0	0.09	46.3	6.85	0.148

These results indicate the importance of controlling the pressure and temperature profiles.

Table 2: Dependence of equilibrium on plasma parameters above upper limit on operation in RELAX

bp	bt	β_p	I_ϕ^{eq} [kA]	I_ϕ^{BSb} [kA]	I_ϕ^{BSb}/I_ϕ^{eq}
0.75	0.75	0.38	69.6	11.0	0.158
0.75	2.0	0.38	69.6	16.5	0.237
1.0	1.0	0.42	74.7	11.6	0.155
1.0	2.0	0.42	74.7	16.4	0.220
2.0	1.0	0.50	85.2	2.87	0.034
2.0	2.0	0.50	85.2	9.31	0.109

The code developed here may be versatile enough to study the neoclassical equilibrium for low-*A* RFP with various parameters. A study of stabilities of neoclassical equilibrium remains for future work.

References

[1] S. Shiina et al., Phys. Plasmas. **12** 080702 (2005)

[2] S. Masamune et al., *Proc. 33rd EPS Conference on Plasma Phys*, P4-136, (2006)

[3] S. Masamune et al., J. Phys. Soc. Jpn. **76** (No.12), 123501 (2007)

[4] J. Anderson et al., Nucl. Fusion. **44** 162 (2004).

[5] S. P. Hirshman., Phys. Fluids **31** (1988) 3150.

[6] D. A. Ehsta et al., Nucl. Fusion. **38** (1998) 13.