

Neoclassical bootstrap current in CHS-qa quasi-axisymmetric stellarator

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1. Introduction

A quasi-axisymmetric stellarator[1] is being designed in National Institute for Fusion Science from both aspects of physics and engineering as a post-CHS device, CHS-qa($R=1.5$ m / $B_t=1.5$ T)[2]. A substantial bootstrap(BS) current is expected in CHS-qa because of the quasi-axisymmetry, enhancing the rotational transform $\iota/2\pi$. In this work, a code which calculates the three dimensional MHD equilibrium including neoclassical BS current self-consistently in the whole collisionality range from $1/\nu$ to Pfirsch-Schlüter regime [3] has been employed to study the effect of BS current on the finite β equilibrium of CHS-qa and the β dependence of total BS current I_{bs} in different collisionality regimes. The stability of external kink and tearing mode for CHS-qa is also examined.

2. BS current and its effect on equilibrium of CHS-qa

BS current density dI_{bs}/ds , $\iota/2\pi$ and magnetic well depth in the vacuum and finite β equilibria are shown in Fig.1 for the "2b32" configuration, which has A_p of 3.2 and N of 2 [2]. The plasma parameters are : $T=T(0)\cdot(1-s)$, $T_e(0)=2.0\text{keV}$, $T_i(0)=1.5\text{keV}$, $n=n(0)\cdot(1-0.8\cdot s+1.3\cdot s^2-1.5\cdot s^3)$, $n_e(0)=n_i(0)=2.0\times 10^{19}\text{ m}^{-3}$ and $B_t = 1$ T. Here, s is the label representing the normalized toroidal flux. I_{bs} is evaluated to be 56 kA at the averaged beta value $\langle\beta\rangle$ of 1.2 % ($\beta_0 = 2.8$ %) and it pushes up $\iota/2\pi$. The magnetic well becomes deeper than that in vacuum equilibrium as is seen in Fig. 1(c).

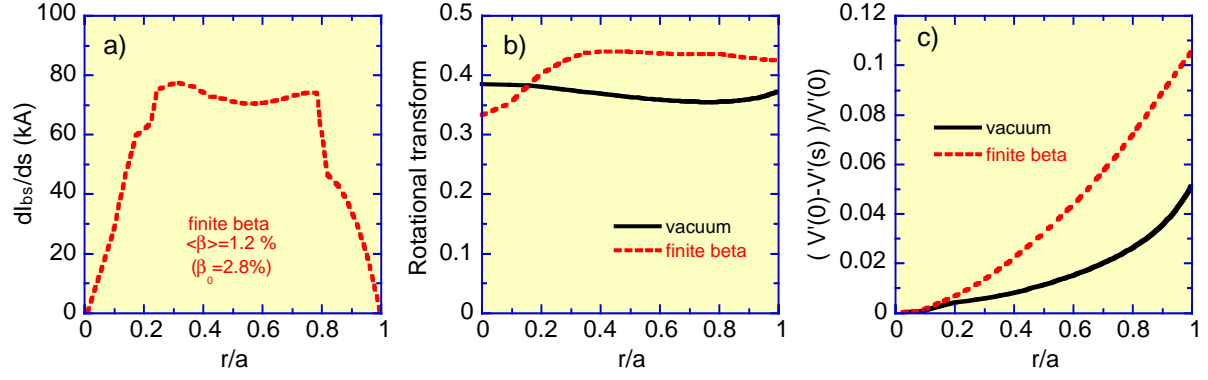


Fig. 1. Bootstrap current in the finite β plasma of CHS-qa at $B_t=1$ T, a) BS current density dI_{bs}/ds , b) Rotational transform $1/2\pi$ in vacuum and finite beta equilibrium, c) Magnetic well.

The finite β equilibria including BS current with different density profiles are also calculated to see their influence on dI_{bs}/ds and resulting $1/2\pi$. The parameters are the same as used in Fig.1 and then only the density profile is changed. The parabolic profile ($n=n(0)\cdot(1-s)$)

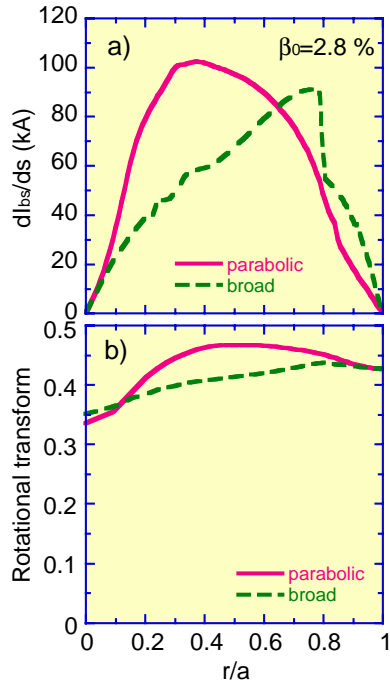


Fig. 2. a) BS current densities, b) $1/2\pi$ in parabolic and broad n_e profile.

produces dI_{bs}/ds which has a peak at $r/a = 0.3$ and it results in the reversed shear-like $1/2\pi$ profile in tokamaks (see Fig.2). On the other hand, dI_{bs}/ds gradually rises toward the outer region in the broad density profile ($n=n(0)\cdot(1-s^3)$) and reaches the peak at $r/a=0.8$, which results in the so-called stellarator shear. This gives us the flexibility of CHS-qa experiment under a variety of $1/2\pi$ profiles if the density profile can be controlled by means of electron cyclotron heating, pellet injection and so on. Fig. 3 shows

I_{bs} as a function of $\langle\beta\rangle$. The calculation was made for high

n_e ($n_e(0)=1.0\times 10^{20} \text{ m}^{-3}$) and low n_e ($n_e(0)=2.0\times 10^{19} \text{ m}^{-3}$), i.e.

for different collisionality regimes at B_t of 1 T. By keeping the density and temperature profile same as in Fig. 1, $T(0)$ is changed in this calculation. In the low n_e plasmas, I_{bs} steeply increases as $\langle\beta\rangle$ increases and reaches 100 kA when $\langle\beta\rangle$ exceeds 2 %. On the other hand, in

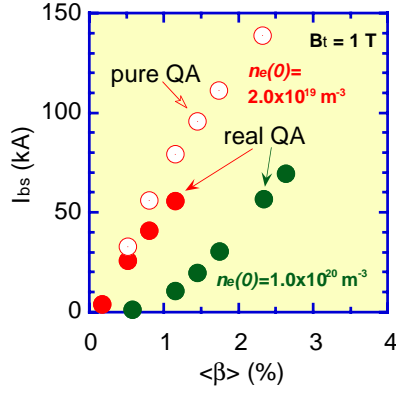


Fig. 3. Bootstrap current as a function of $\langle\beta\rangle$ for different n_e case. Closed circles represent I_{bs} in real QA. Open circles stand for I_{bs} in pure QA.

the high n_e plasmas, the BS current at the same $\langle\beta\rangle$ is much lower than that in low n_e plasmas as expected. In order to see the effect of non-axisymmetric magnetic field component on I_{bs} , the calculation on "pure QA" is made by eliminating non-axisymmetric magnetic field components. Open circles in Fig. 3 stand for I_{bs} in the pure QA condition. I_{bs} in the pure QA is always larger, e.g. by about 40 % at $\langle\beta\rangle$ of 1.2 %, than

that in real QA. A benchmark study between our code and DKES for the role of non-axisymmetric components in the BS current is now in process.

3. Current-driven MHD stability analysis

3.1 External kink study

The current-driven MHD instabilities are important issues in CHS-qa. Especially, the stability of external kink mode, which is known to be the most dangerous instability in tokamaks, is of our interest because fairly large BS current exists in a high β plasma of CHS-qa. External kink instabilities have been analyzed for various values of $\iota/2\pi$, i.e. I_{bs} by the use of the global MHD stability code for 3-D toroidal plasma, CAS-3D [4]. In this analysis, $\iota/2\pi$ was shifted as seen in Fig. 4 with keeping $\iota/2\pi$ profile which is the same as in Fig. 1. The CAS-3D code indicated that the external kink mode is stable in relatively low β plasmas but it becomes unstable when $\iota/2\pi$ increases over 0.5 at the plasma edge. It corresponds to I_{bs} of ~ 140 kA (case C). If a CHS-qa plasma is in low collisionality regime, a crucial $\langle\beta\rangle$ value for the external kink stability is roughly 2.5-3 %, by judging from $\langle\beta\rangle$ vs. I_{bs} plot shown in Fig. 3. However, the external kink instability might be actually not a serious problem in NB-heated discharges of CHS-qa because the NB-heated plasma is supposed to be in high collisionality

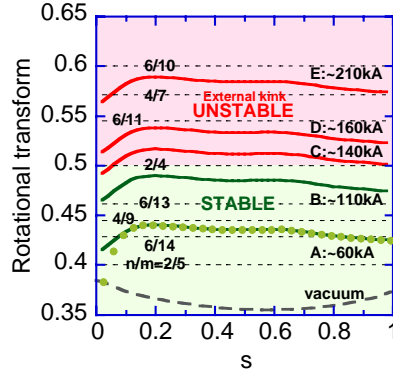


Fig. 4. External kink analysis for different rotational transforms. The currents are for B_t of 1 T.

regime.

3.2 Tearing mode analysis

The tearing mode stability, which is determined by Δ' , is also analyzed for existing singular point in the plasma region with the same code described in Ref. 5. Here, we consider a pressureless plasma in the cylindrical system with parabolic

net toroidal current density J_z and check whether the tearing mode is stable or not at the

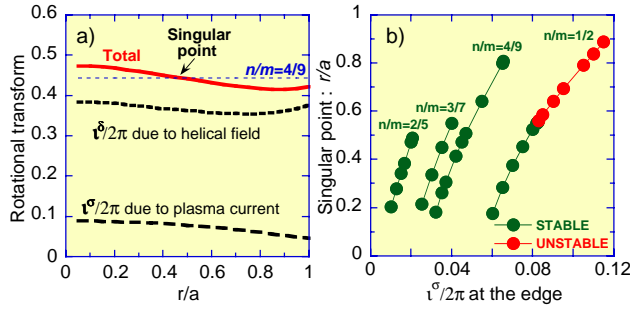


Fig. 5. a) An example of helical and current ι used for tearing mode analysis for $n/m=4/9$, b) Δ' analysis result.

rational surface of interest with increasing J_z . The tearing mode is stable for rational surfaces $n/m=2/5$, $3/7$, $4/9$ and $1/2$ in the core domain(see Fig. 5(b))

but the analyses indicate that it becomes

unstable when singular point is in outer region ($r/a > 0.6$) for $n/m=1/2$.

4. Summary

The BS current property for CHS-qa has been investigated. There is significant effect of the BS current on the MHD equilibrium, especially in low collisionality high β plasma. The stability analysis for the external kink mode suggests it becomes unstable when $\iota/2\pi$ at the edge exceeds $1/2$. The rational surface of $n/m=1/2$ is also crucial for the tearing mode.

References

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