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/ν 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 : $T=T(0)\cdot(1-s)$, $T_e(0)$=2.0keV, $T_i(0)$=1.5keV, $n=n(0)\cdot(1-0.8\cdot s+1.3\cdot s^2-1.5\cdot s^3)$, $n_e(0)=n_i(0)$ =2.0x10^{19} 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 $<\beta>$ of 1.2 % (β_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).

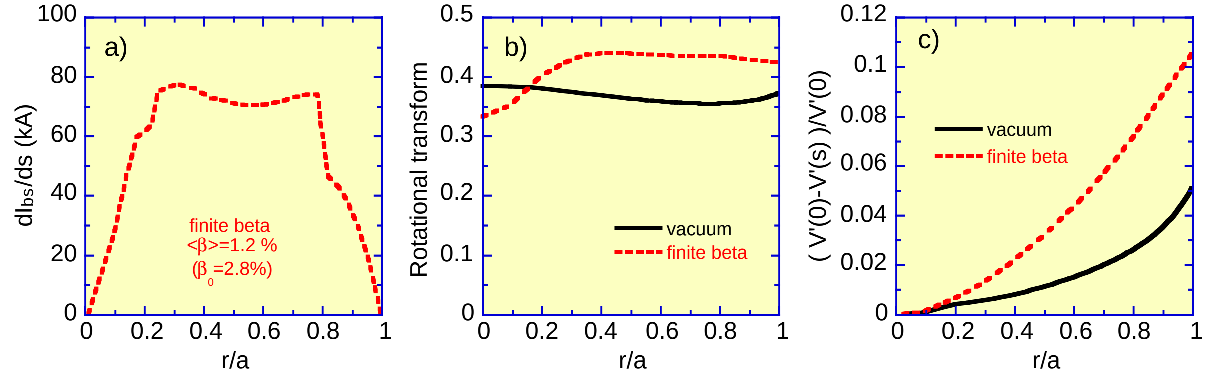

Fig. 1. Bootstrap current in the finite b plasma of CHS-qa at B_t=1 T, a) BS current density dI_{bs}/ds, b) Rotational transform $\iota/2\pi$ in vacuum and finite beta equilibrium, c) Magnetic well.

The finite β equlibria including BS current with different density profiles are also calculated to see their influence on dI_{bs}/ds and resulting $\iota/2\pi$. The parameters are the same as used in Fig.1 and then only the density profile is changed. The parabolic profile (n=n(0)·(1-s)) produces dI_{bs}/ds which has a peak at r/a = 0.3 and it results in the reversed shear-like $\iota/2\pi$ 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)·(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 $\iota/2\pi$ 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 <β>. The calculation was made for high n_e ($n_e(0)=1.0\text{x}10^{20}$ m^{-3}) and low n_e ($n_e(0)=2.0\text{x}10^{19}$ 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 <β> increases and reaches 100 kA when <β> exceeds 2 %. On the other hand, in

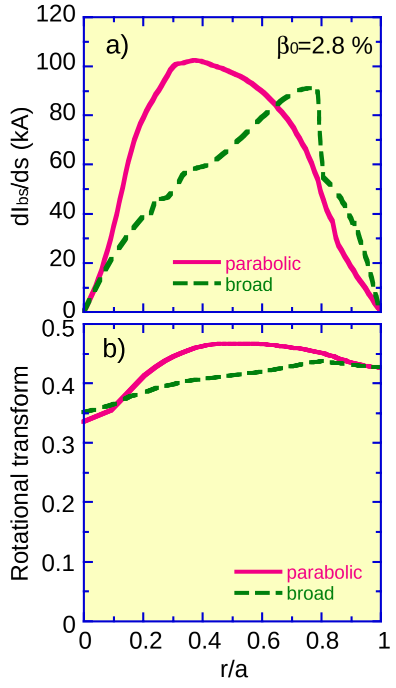

Fig. 2. a) BS current densites, b) $\iota/2\pi$ in parabolic and broad n_e profile.

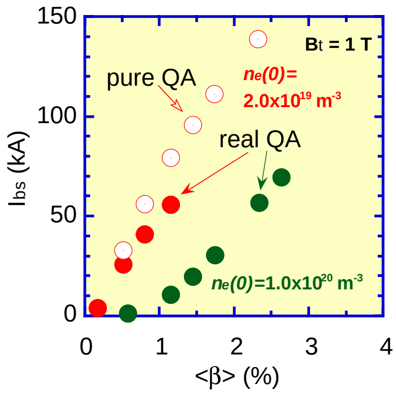

Fig. 3. Bootstrap current as a function of <β> for different n_e case. Closed circles represent I_{bs} in real QA. Open circles stand for I_{bs} in pure QA.

the high n_e plasmas, the BS current at the same <β> 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 <β> 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 ι/2π, i.e. I_{bs} by the use of the global MHD stability code for 3-D toroidal plasma, CAS-3D [4]. In this analysis, ι/2π was shifted as seen in Fig. 4 with keeping ι/2π 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 ι/2π 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 <β> value for the external kink stability is roughly 2.5-3 %, by judging from <β> 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

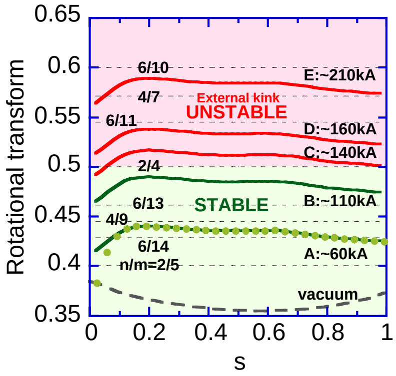

Fig. 4. External kink analysis for different rotational transforms. The currents are for B_t of 1 T.

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 Jz and check whether the tearing mode is stable or not at the rational surface of interest with increasing Jz. 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.

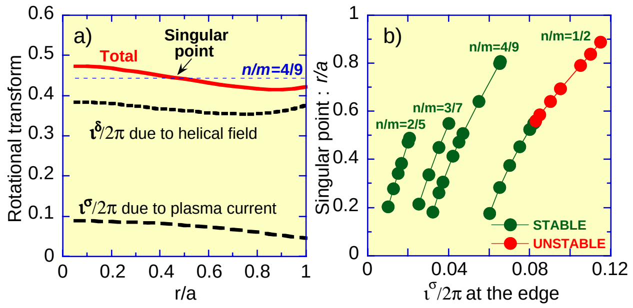

Fig. 5. a) An example of helical and current ι used for tearing mode analysis for n/m=4/9, b) Δ' analysis result.

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 ι/2π 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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