48th EPS Conference on Plasma Physics, June 27 – July 1, 2022, Online

Suppression of three-dimensional magnetic islands by toroidal currents in the CFQS quasi-axisymmetric stellarator

X. Su[1*], X. Q. Wang[1], Y. Xu[1], S. Okamura[2], A. Shimizu[2,3], M. Isobe[2,3], H. F. Liu[1], J. Huang[1], J. Cheng[1], X. Zhang[1], H. Liu[1], Y. Luo[1], C. J. Tang[4]

[1] Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China
[2] National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Gifu 509-5292, Japan
[3] The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan
[4] School of Physical Science and Technology, Sichuan University, Chengdu 610041, China

I. Abstract

Magnetic islands and related tearing mode physics are major issues in the Chinese First Quasi-axisymmetric Stellarator (CFQS). The non-inductively current drive, i.e. electron cyclotron current drive (ECCD) can be used as one of the approaches to adjust the rotational transform, and hence, affecting the generation of magnetic islands in the CFQS. In this study, we have applied additional toroidal magnetic field produced by the auxiliary toroidal field coil (TFC) with a current of 30 kA to generate *m*/*n*=5/2 magnetic islands in the low beta operation on CFQS so that the influence of the bootstrap current is negligible. Then, we have investigated the impact of ECCD on the three-dimensional magnetic islands using the HINT code. It is found that the islands can be significantly suppressed by using the flat or Gaussian profile of the ECCD current, depending on the direction and the amplitude of the current. In case of the positive direction where the current direction is the same as the direction of ϕ in the cylindrical coordinate (R, ϕ, Z), with a small ECCD current (~1 kA) the rotational transform profile becomes flat at the *m*/*n*=5/2 rational surface and the magnetic island width increases. However, when the ECCD current increases to 5 kA, the rotational transform profile changes and is away from *m*/*n*=5/2 rational surface so that the island is healed. More interestingly, when the direction of ECCD current is reversed, with increasing ECCD current the magnetic island width decreases as a result of the enhanced magnetic shear. It is concluded that the ECCD current-induced changes of the rotational transform and magnetic shear both play important roles in the dynamic evolution of the 3D magnetic islands in CFQS device.

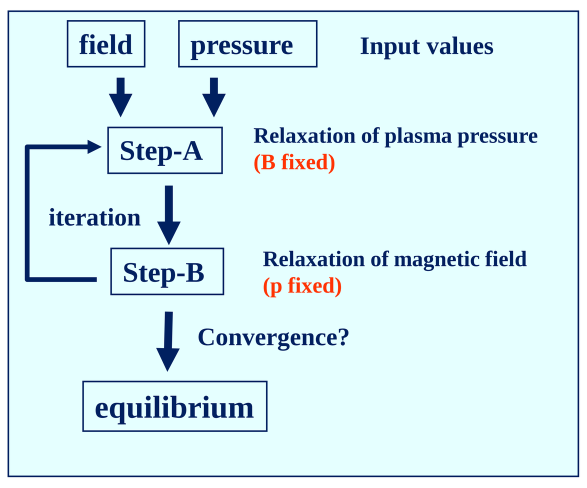
II. 3D equilibrium calculation code

HINT is a 3D MHD equilibrium calculation code without assumption of nested flux surfaces. ⇔ VMEC (assuming nested flux surfaces)

- •relaxation method (initial value problem)
- •Eulerian coordinate(cylindrical coordinate (R, ϕ, Z))

Pressures tend to be constant along the same magnetic field line

$$\mathbf{B}\cdot\nabla p = 0$$



$$\frac{\partial \mathbf{v}}{\partial t} = -f_C\left[\nabla p - (\mathbf{j}-\mathbf{j}_0)\times\mathbf{B}\right]$$

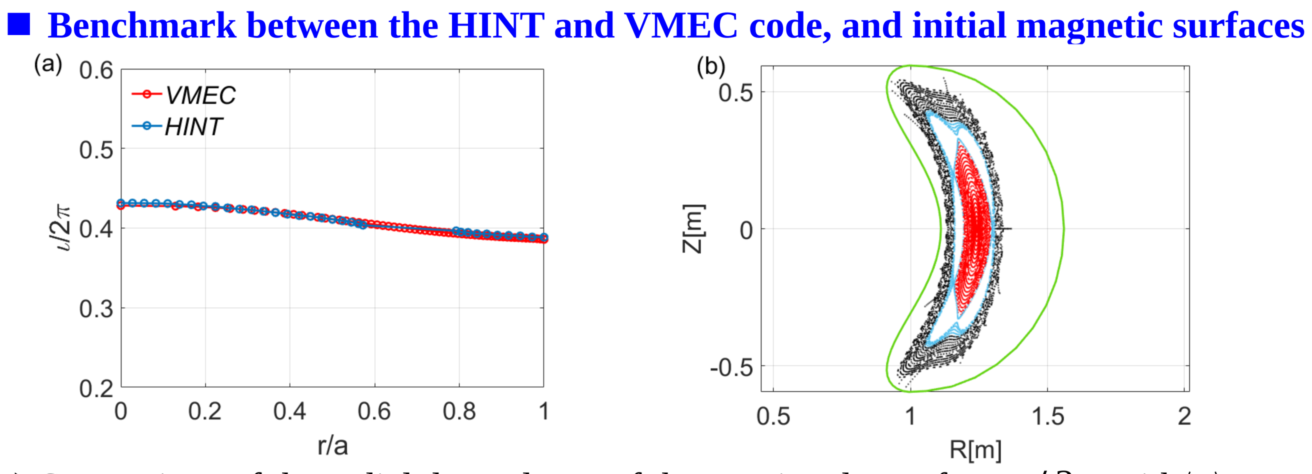
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times\left[\mathbf{v}\times\mathbf{B} - \eta(\mathbf{j}-\mathbf{j}_0-\mathbf{j}_{\mathrm{net}})\right]$$

$$\mathbf{j} = \nabla\times\mathbf{B}$$

If *dv/dt* and *dB/dt* => 0, calculation is convergence!

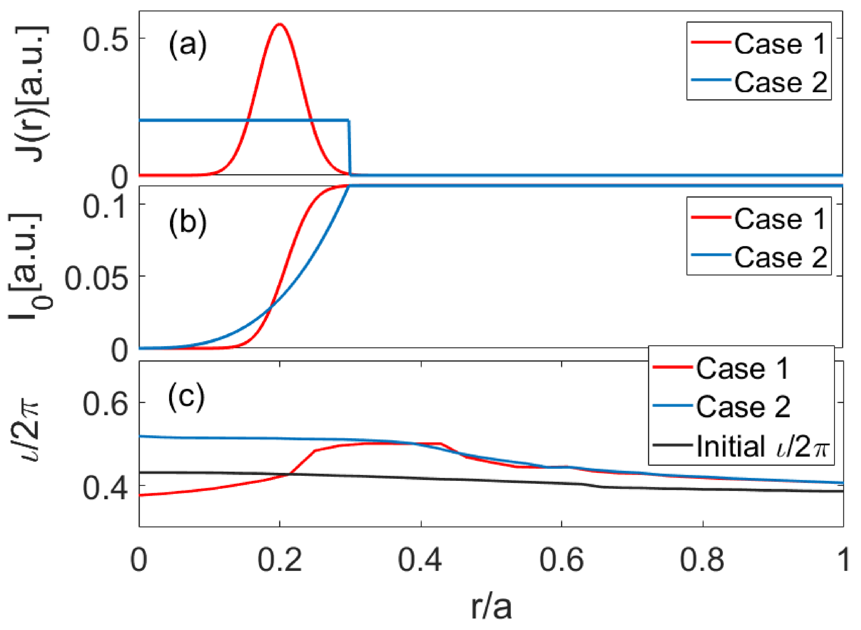
III. Simulation Results

■ Benchmark between the HINT and VMEC code, and initial magnetic surfaces



- ➢ (a).Comparison of the radial dependence of the rotational transform $\iota/2\pi$ with $\langle\beta\rangle=0.5\%$
- ➢ (b).The poincaré plots of initial magnetic surfaces, where the black, blue and red colors mark the regions of $p/p_0<1\%$, $1\%\le p/p_0\le 10\%$ and $p/p_0>10\%$, respectively The green line denotes the boundary of the vacuum vessel.

■ Sketch of rotational transform modification due to a toroidal current



Case 1:

- ➢ The Gaussian current density profile

Case 2:

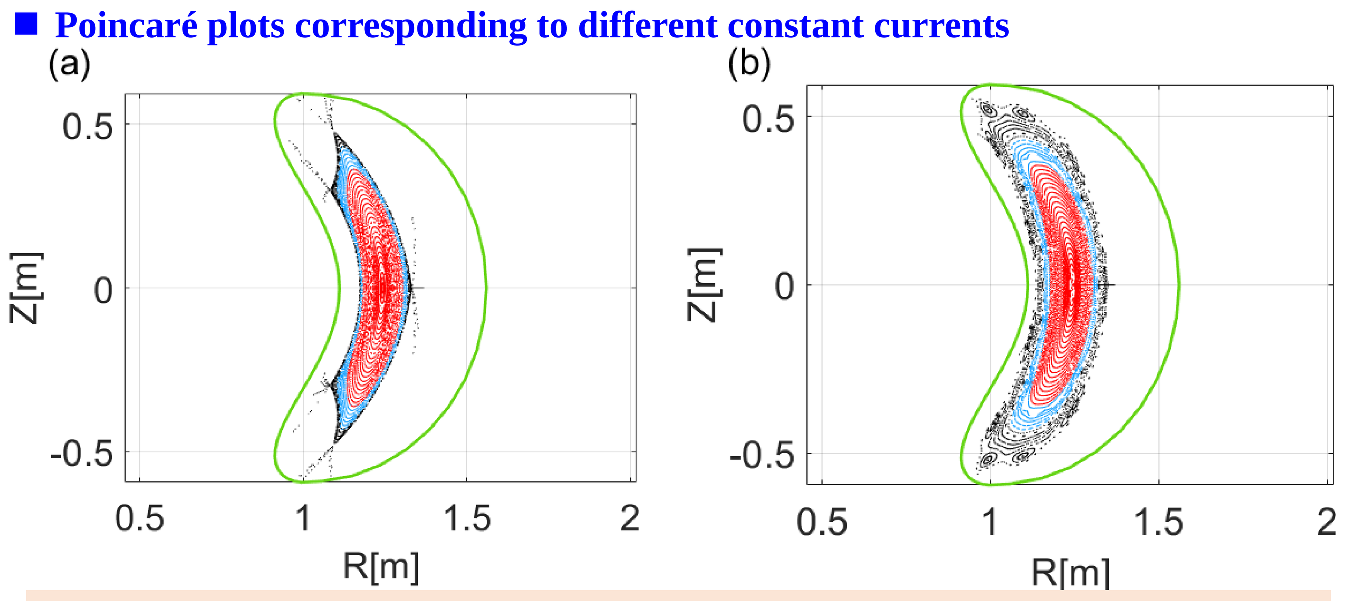
- ➢ The flat current density profile

Initial $\iota/2\pi$:

- ➢ Under the configuration of CFQS, $\iota=\iota_{vac}+\Delta\iota_{curr}$, where ι_{vac} is the rotational transform created by magnetic coils and $\Delta\iota_{curr}$ is the contribution to the rotational given by toroidal current.

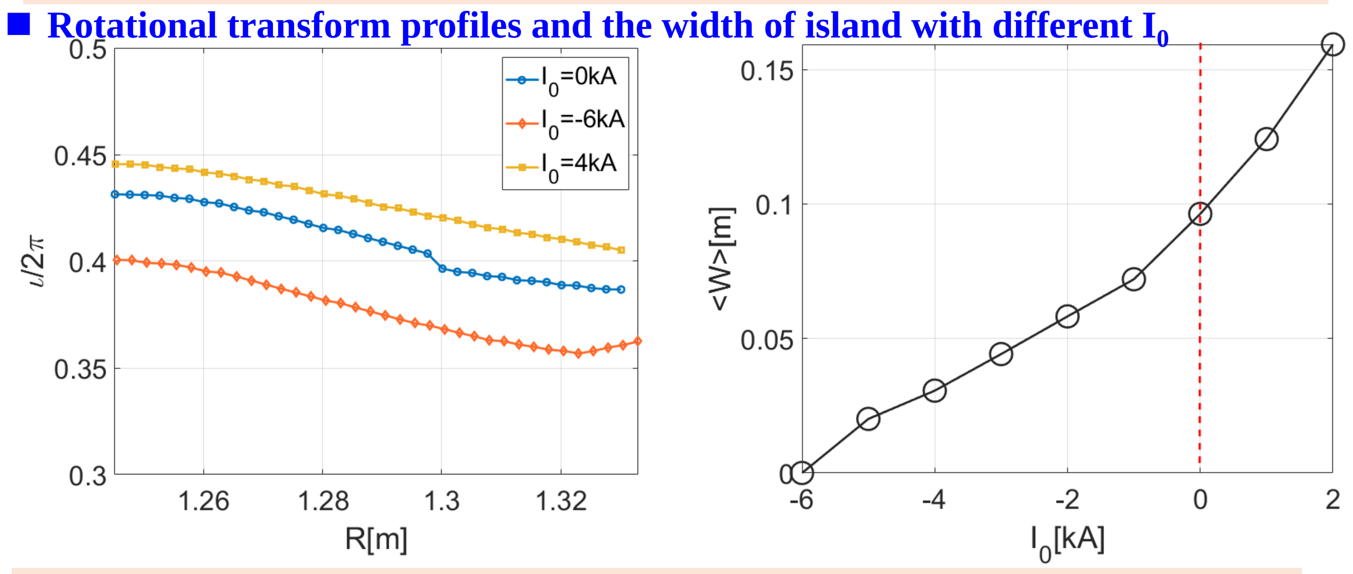
3.1 Effect of the flat current density profile on islands

■ Poincaré plots corresponding to different constant currents



- ➢ (a) The poincaré plots of magnetic surfaces with $I_0=4kA$
- ➢ (b) The poincaré plots of magnetic surfaces with $I_0=-6kA$

■ Rotational transform profiles and the width of island with different I_0

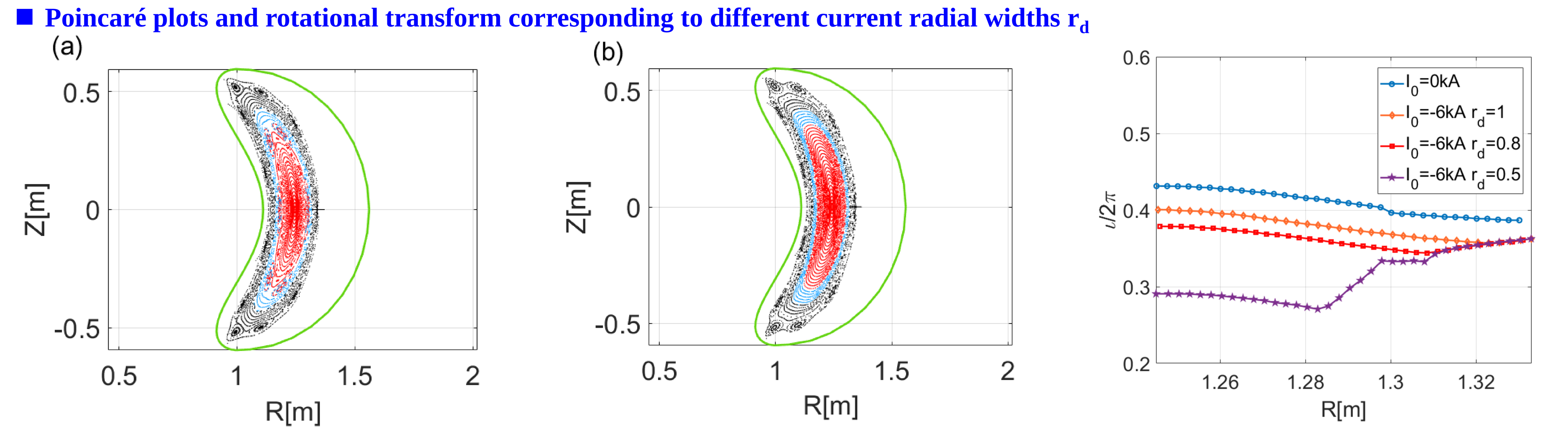


- ➢ For counter toroidal direction, the more significant the current the smaller width of the islands. For same toroidal, when the amplitude of current increase, the width of islands increases.

III. Simulation Results

3.1 Effect of the flat current density profile on islands

■ Poincaré plots and rotational transform corresponding to different current radial widths r_d

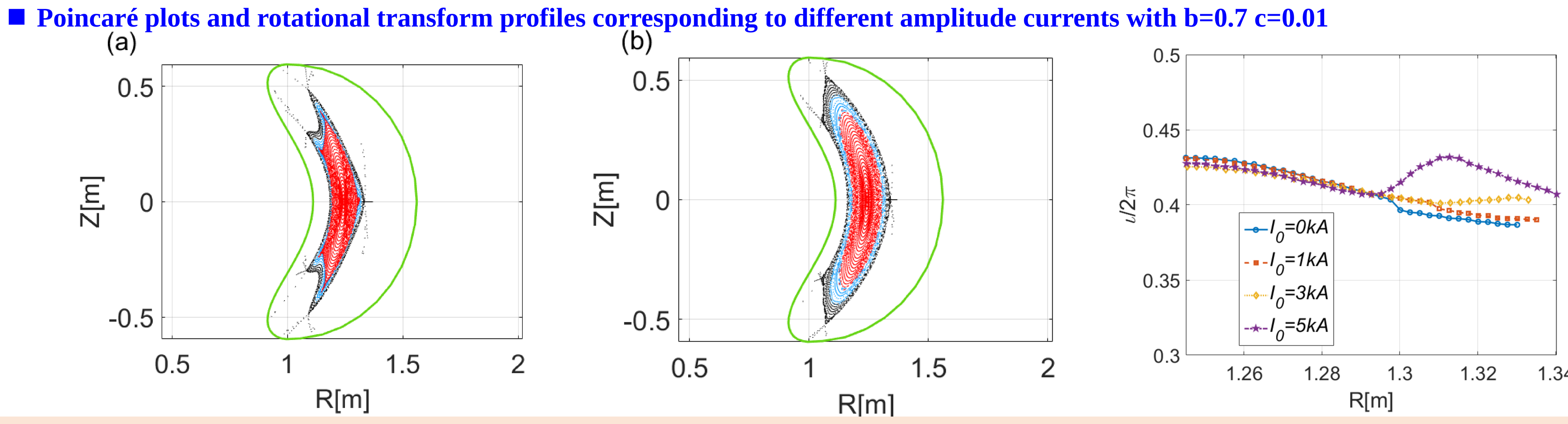


- ➢ Figure (a),we can see that when r_d=0.5, the m/n=6/2 islands appeared in the plasma confinement of the plasma. However, figure (b), when r_d=0.8, similar to r_d=0.5, the 4/11-island chain appeared on the boundary. It has little effect on plasma confinement.
- ➢ The rotational transform profiles with different current radial width have to pointed out that when the current radial width is narrow, rotational transform of the plasma core varies greatly. This situation can lead to more rational surface existence, which can cause the different model number of magnetic islands to appear. These results suggest that the current radial width cannot be too narrow in the CFQS.

3.2 Effect of the Gaussian current density profile on islands

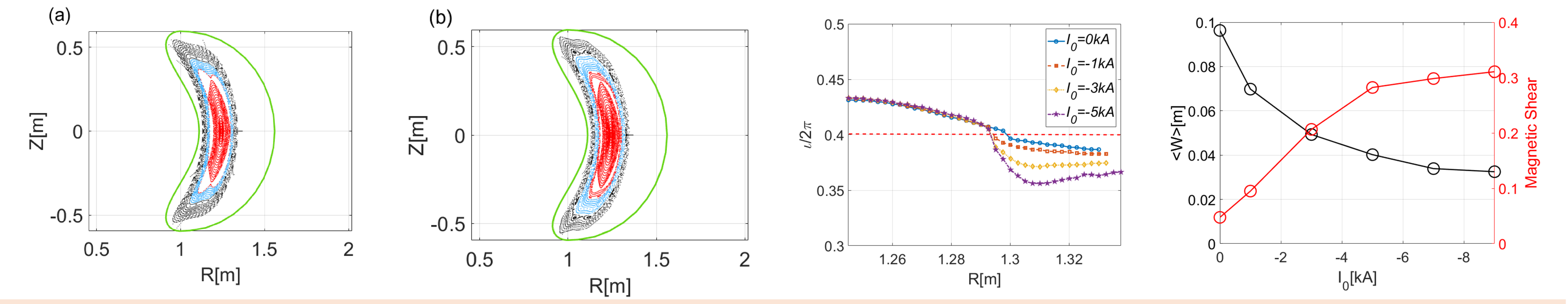
- ➢ To gain insight into the dependence of the CFQS equilibrium islands on the toroidal current, the CFQS equilibrium is calculated with Gaussian current density profiles by HINT codes. In the present case, we provide a Gaussian current density profile given as $j(r)=e^{(-(\sqrt{\psi}-b)^2/c)}$, for starting the HINT computation with $\langle\beta\rangle=0.5\%$, where *b* is peak radial location, *c* is radial width.

■ Poincaré plots and rotational transform profiles corresponding to different amplitude currents with b=0.7 c=0.01



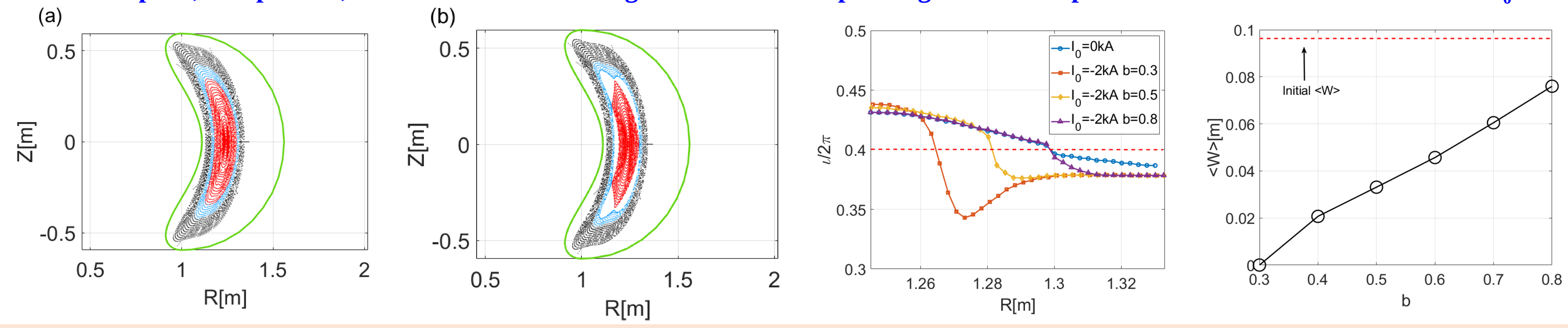
- ➢ Figure (a) , I_0=3kA, island moved to the boundary and the magnetic surface changes significantly. When the amplitude of current increases to 5kA, the magnetic surface of the core confinement area is relatively good.

■ Poincaré plots, iota profiles, width of islands and magnetic shear corresponding to different amplitude of opposite currents with b=0.7 c=0.01



- ➢ Figure (a) I_0=-1kA , figure (b) I_0=-5kA. We can see that m/n=5/2 islands width are decrease. The reasons can be explained as follows: The increase of current I_0 induces changes in the iota profile, which change magnetic shear at the m/n=5/2 rational surface.

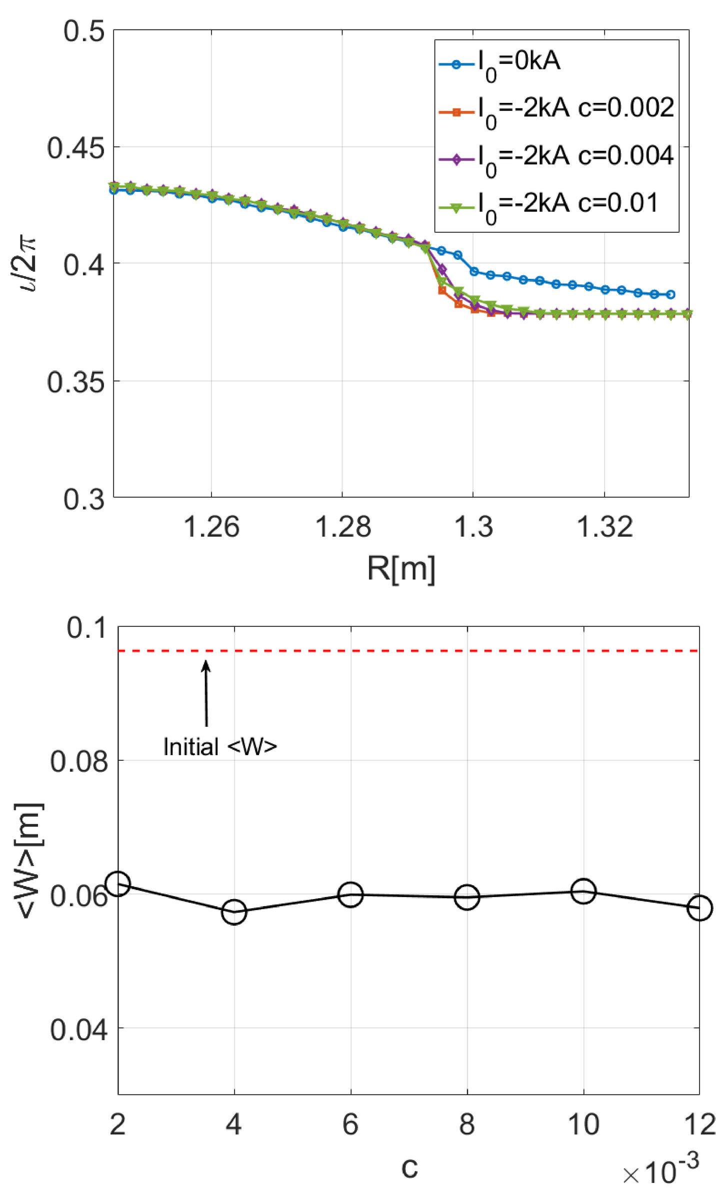
■ Poincaré plots, iota profiles, width of islands and magnetic shear corresponding to different peak radial locations b with c=0.005 I_0=-2kA



- ➢ Figure (a) b=0.3 figure (b) b=0.8. If the injection location close to the plasma boundary, the islands width will increase. It shows that the peak radial location is important for CFQS equilibrium with ECCD.

3.2 Effect of the Gaussian current density profile on islands

■ Rotational transform profiles and width of islands with different radial width c



- ➢ It is clear that the magnetic islands width corresponding to different radial widths of ECCD with I_0=2kA is almost unchanged.

IV. Summary

- ■ For the flat current density profiles, the magnetic islands are suppressed and when amplitude of current I_0 > 6 kA (counter direction) or I_0 > 2 kA (positive direction), the m/n=5/2 magnetic islands are completely healed. In different current radial width case, we found that width should not be too narrow to avoid more rational surface existence.
- ■ For the same toroidal direction, the magnetic islands are suppressed and the nested flux surfaces can be relatively well maintained due to removing m/n=5/2 rational surface. Reduction of magnetic island width by shear enhancement with the counter toroidal direction.
- ■ The simulation of different peak radial location *b* for the magnetic islands indicates that the rational surface location close to the plasma core and reduce the magnetic islands width with *b* to the core.
- ■ We consider the radial width *c*, it is found that magnetic islands width remains same as a function of radial width. But the larger width can suppress the island-chain in the edge region.

Email: suxiang@my.swjtu.edu.cn
xianquwang@swjtu.edu.cn