Feasibility Study of Neutral Beam Injection on Chinese First Quasi-Axisymmetric Stellarator (CFQS)*)

Kunihiro OGAWA[1,2], Ryosuke SEKI[1,2], Hiroyuki YAMAGUCHI[1], Sadayoshi MURAKAMI[3], Mitsutaka ISOBE[1,2], Akihiro SHIMIZU[1], Shigeyoshi KINOSHITA[1], Shoichi OKAMURA[1], Haifeng LIU[4], Yuhong XU[4] and CFQS Team[1,2,4,5]

[1] *National Institute for Fusion Science, National Institutes of Natural Sciences, Toki 509-5292, Japan*
[2] *SOKENDAI (The Graduate University for Advanced Studies), Toki 509-5292, Japan*
[3] *Kyoto University, Kyoto 615-8540, Japan*
[4] *Southwest Jiaotong University, Chengdu, China*
[5] *Hefei Keye Electro Physical Equipment Manufacturing Co., Ltd, Hefei, China*

(Received 6 December 2018 / Accepted 4 March 2019)

Physics and engineering designs of Chinese First Quasi-axisymmetric Stellarator (CFQS) have been performed under the collaboration between National Institute for Fusion Science and Southwest Jiaotong University. To obtain high plasma parameter and to study the beam ion confinement in quasi-axisymmetric configuration, the installation of neutral beam (NB) injector is planned with CFQS. The feasibility study of NB injection of CFQS is performed by means of beam deposition calculation code (HFREYA) and the guiding center orbit following code (DELTA5D). The injection angle of 48 degrees is most favorable in terms of the deposition and beam ion confinement.

Keywords: CFQS, NBI, deposition, beam ion confinement, quasi-axisymmetric configuration

DOI: 10.1585/pfr.14.3402067

1. Introduction

High-temperature and high-density plasma has been achieved with additional heating by energetic ions created by neutral beam (NB) injections or ion cyclotron resonance frequency waves. In stellarator/helical devices, the research on energetic particle confinement is one of the key topics for obtaining better confinement by utilizing the flexibility of three-dimensional magnetic configurations. From 2017, the physics and engineering designs of Chinese First Quasi-axisymmetric Stellarator (CFQS) have been performed under the collaborative program NSJP (NIFS-SWJTU Joint Project) between National Institute for Fusion Science and Southwest Jiaotong University [1, 2]. The CFQS is classified as an advanced stellarator having a quasi-axisymmetry. The numerical study of confinement of quasi-axisymmetric stellarator was conducted for QAS [3, 4] by means of the guiding center orbit calculation code. The energetic particle confinement was surveyed in a variety of toroidal magnetic configurations with changing NB injection angles. It was reported that the diffusion coefficient of beam ions is at least two times larger than that of an equivalent-ripple tokamak. Subsequently, practical design studies were performed for CHS-qa [5] and NCSX [6] using the guiding center orbit code DELTA5D [7]. It was shown that the co-injection beam with low injection angle is favorable in the view point of beam energy losses during slowing down. Even though both quasi-axisymmetric stellarators were planned to be constructed, the creation of both CHS-qa and NCSX has not been implemented until now. The installation of the NB injector to the CFQS bring us the first opportunity to study the energetic ion confinement based on the experiment in the quasi-axisymmetric configuration. This paper reports the feasibility study on installing NB injector in the CFQS.

2. Setups for NB Calculation

Figure 1 shows the schematic drawing of the CFQS with NB injector. The major radius and the minor radius of the CFQS plasma is 1.0 m and ~0.22 m, respectively [1]. The toroidal magnetic field strength reaches up to as high as 1 T. From the consideration based on the CAD modeling including the coil case, the vacuum vessel, and the coil supporting structure, the possible range of NB injection angle is from 44 to 52 degrees (Fig. 1 (b)) [8]. Here, the injection angle is between a normal vector of CFQS and NB injection vector. The feasibility study of NB injection of CFQS is performed by means of the HFREYA code, which is the part of the FIT3D code [9] and the DELTA5D code [7]. The HFREYA code is the deposition calculation code using the Monte Carlo methods. The DELTA5D code is the

author's e-mail: kogawa@nifs.ac.jp

*) This article is based on the presentation at the 27th International Toki Conference (ITC27) & the 13th Asia Pacific Plasma Theory Conference (APPTC2018).

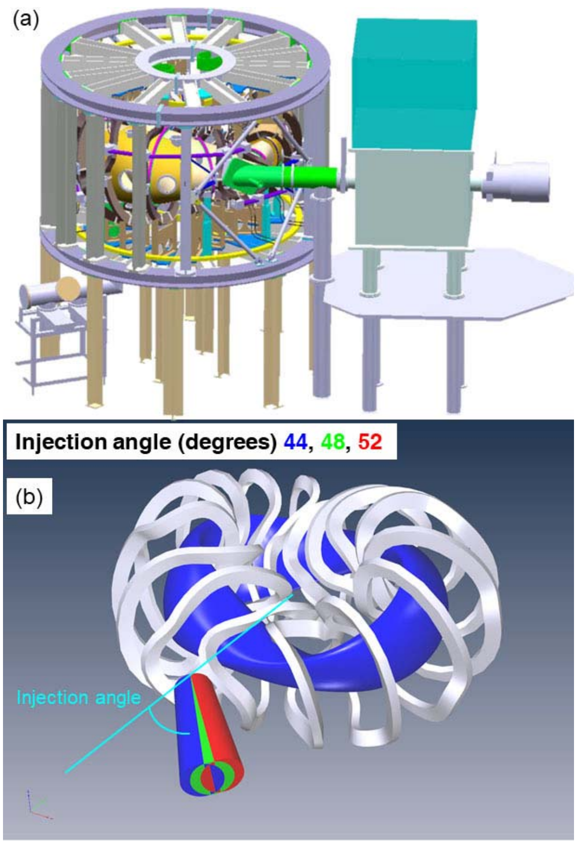

Fig. 1 (a) Design of CFQS with NB injector. (b) CFQS and possible NB injection lines.

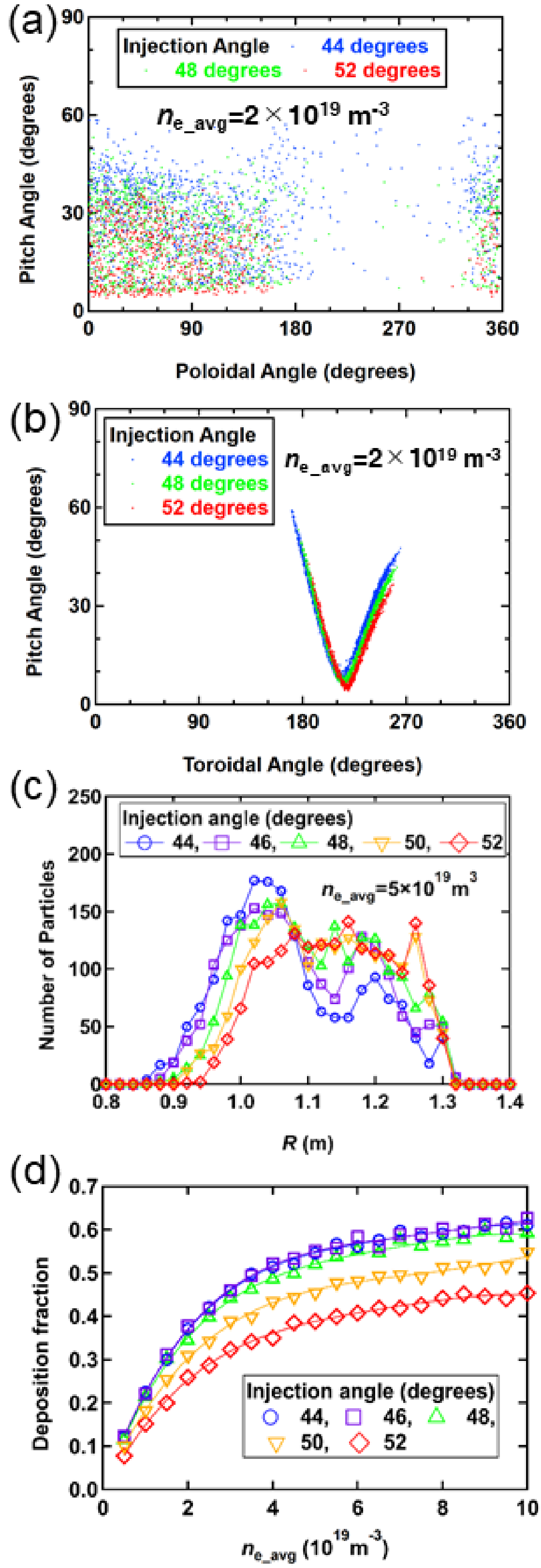

Fig. 2 Pitch angle distribution as a function of (a) the poloidal angle and (b) the toroidal angle. (c) Radial profile of beam ion deposition. (d) Deposition fraction of NB injection as a function of line averaged electron density.

guiding center orbit following models based on Boozer coordinates. The equilibrium is reconstructed by VMEC2000 code [10] with the fixed boundary mode. The plasma parameters used in this calculation are the central electron density n_{e0} of from $1.0 \times 10^{19}\mathrm{m}^{-3}$ to $10 \times 10^{19}\mathrm{m}^{-3}$ with $1.0 \times 10^{19}\mathrm{m}^{-3}$ steps with a profile of the electron density $n_e = n_{e0} \times (1-(r/a)^2)^2$ and a profile of the electron temperature $T_e = T_{e0} \times (1-(r/a)^2)^2$. The central electron temperature T_{e0} is given with $T_{e0} = 2.0/n_{e0}$ (10^{19} m^{-3}) in order to maintain the plasma stored energy. Note that the volume averaged plasma beta is 0.6 %. The plasma potential and the magnetic fluctuation are not considered in this calculation. The effective charge is assumed to be 1. Here, an NB injector operated in the Compact Helical System [11] with injection energy/power of 30 keV / 0.9 MW is used. The inner diameter of the injection port is around 260 mm ϕ according to the design of the vacuum vessel and the injection port.

3. Deposition Fraction of NB

We evaluate the deposition fraction and the initial pitch angle distribution of beam ions by changing the injection angle of the NB injector using HFREYA code. Figures 2 (a) and (b) shows the pitch angle distribution as a function of the toroidal and poloidal angles in the case of n_{e_avg} of 2×10^{19} m^{-3}. There is almost no clear relation between the pitch angle and the poloidal angle, whether there is the clear relation between the pitch angle and the toroidal angle. The clear dependence between the pitch angle and the toroidal angle is consistent with the relatively low magnetic shear. Note that the minimum pitch angle in the injection angles of the 44 degrees, the 48 degrees and the 52 degrees are the 9 degrees, the 7 degrees, and the 5 degrees, respectively. We compared radial deposition profile of beam ions in the 44 degrees to 52 degrees injection angles (Fig. 2 (c)). Here, we integrated all beam ions deposited inside the plasma. In this calculation, n_{e_avg} equal to 5.0×10^{19} m^{-3}. Innermost deposition position shifts outward with the increase of injection angles. Note that the moderate gradient appears due to the plasma density and the divergence of NB injector (1%). The deposition profile on the outer region (R of 1.2 m to 1.3 m) slightly shifts outward with the increase of injection angles in 44 to 48 degrees injection angles. However, the deposition profile in 50 degrees injection angle on the outer region is almost the same as that in 52 degrees injection angles. This means the deposition profile on the outer region is decided not by the injection angle but by the last closed flux surface in the case of 50 and 52 degrees injection angles; the part of the beams injected outside of the last closed flux surface. Figure 2 (d) shows the deposition fraction as a function of the plasma density in each case. The deposition fraction rapidly increases at n_{e_avg} of approximately 4×10^{19} m^{-3} and then increases slightly. The maximum deposition fraction in the case of the 44 degrees to the 48 degrees injection angle reaches around 60%, whereas fractions reach 55% and 45% in the case of the 50 degrees and the 52 degrees injection angles, respectively. The deposition fraction with the injection angle of 44 degrees to 48 degrees is better than that of with the injection angle of 50 degrees and 52 degrees because in 50 degrees and 52 degrees injection angles a part of the beams go directly to the vacuum vessel without passing through the plasma confinement region. It is found that the injection angle from 44 to 48 degrees is better than the injection angle from 50 and 52 degrees from the view point of deposition fraction.

4. Beam Ion Orbits Calculation and Evaluation of Beam Ion Confinement in CFQS

The beam ion orbit calculation is performed by the guiding center orbit code DELTA5D in order to evaluate the beam ion confinement. The typical guiding center orbit of beam ions calculated with non-collision mode by DELTA5D code is shown in Fig. 3 (a). The initial position of the beam ion is (r/a, θ, ϕ) of (0.6, 0, 0), where r/a, θ, and ϕ indicate the normalized minor radius, the poloidal angle, and the toroidal angle, respectively. The energy and the pitch angle of the beam ion are 30 keV and 22 degrees, respectively. Figures 3 (b) and (c) show the Poincaré plot of the co-passing transit and counter-passing transit beam ions in ϕ of 90 degrees and 180 degrees. The pitch angle of the co-passing transit ion and the counter-passing transit

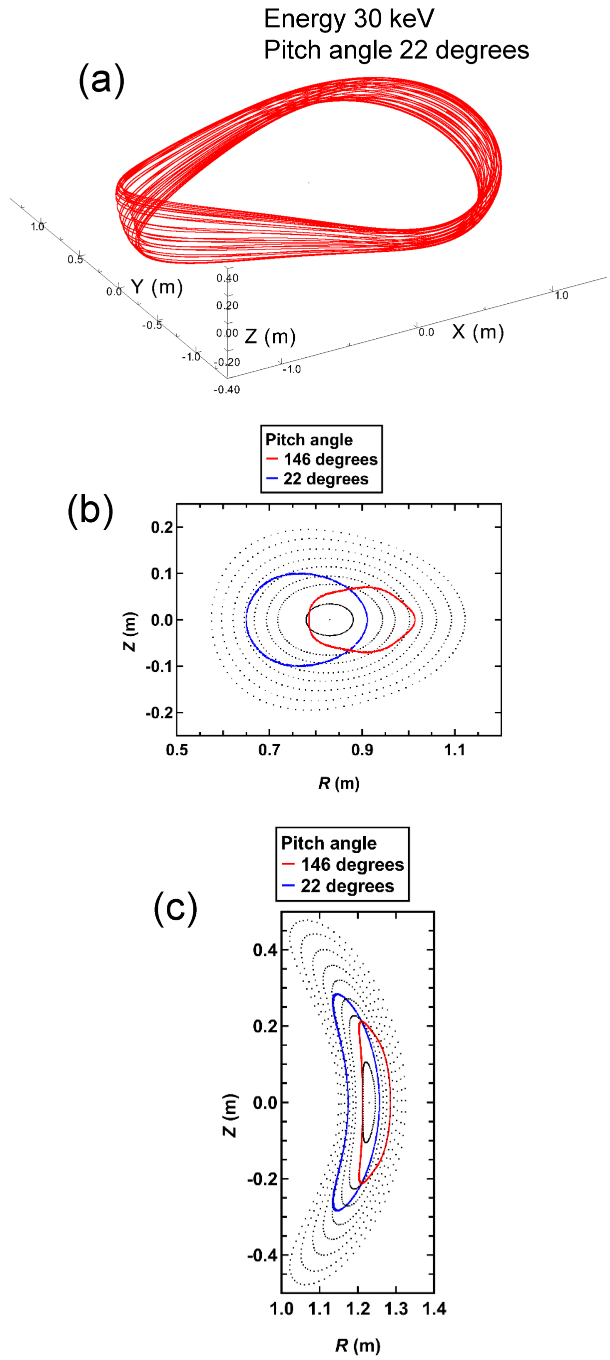

Fig. 3 (a) Typical collisionless orbit of co-going transit ion injected by NB. Poincare plot of co-going and counter-going transit beam ions at (b) ϕ of 90 degrees and (c) 180 degrees. Deviation of orbit from the flux surface is relatively large.

ion are 22 degrees and 146 degrees, respectively. The deviation of the orbit from the flux surface is relatively large due to the relatively low magnetic field and the relatively low rotational transform.

The evaluation of the beam ion confinement is performed using DELTA5D including the beam-plasma collision. Here, NB injects beam ions in co-direction. We randomly chose 1000 particles deposited inside the plasma and followed the orbit for 50 ms. Note that the orbit fol-

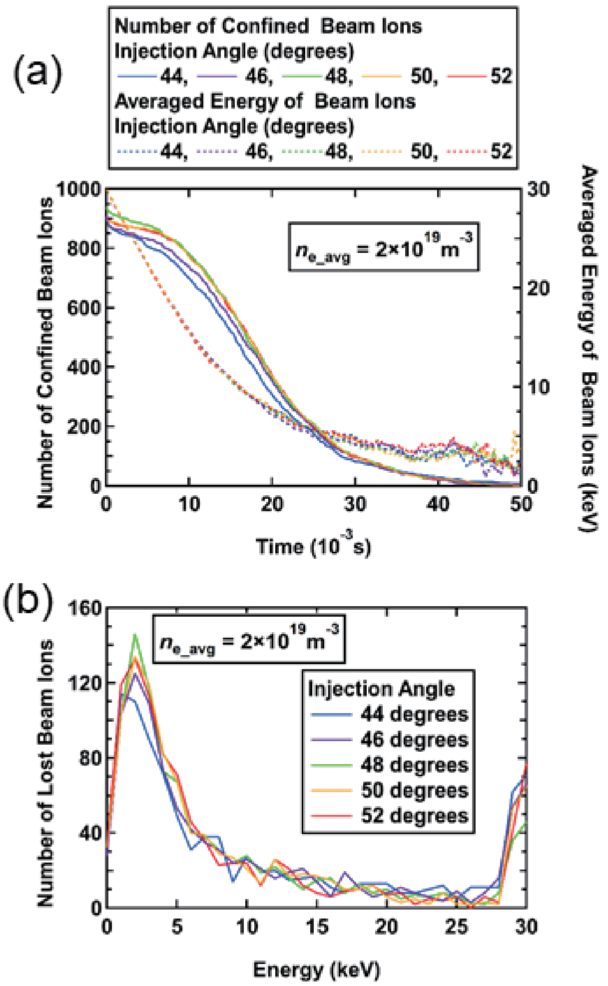

Fig. 4 (a) Time evolution of number of confined beam ions and averaged energy of beam ions. Beam ions are thermalized at t of 50 ms. (b) Energy distribution of beam ions lost from the plasma. There are two peaks corresponding to thermalized and prompt ions.

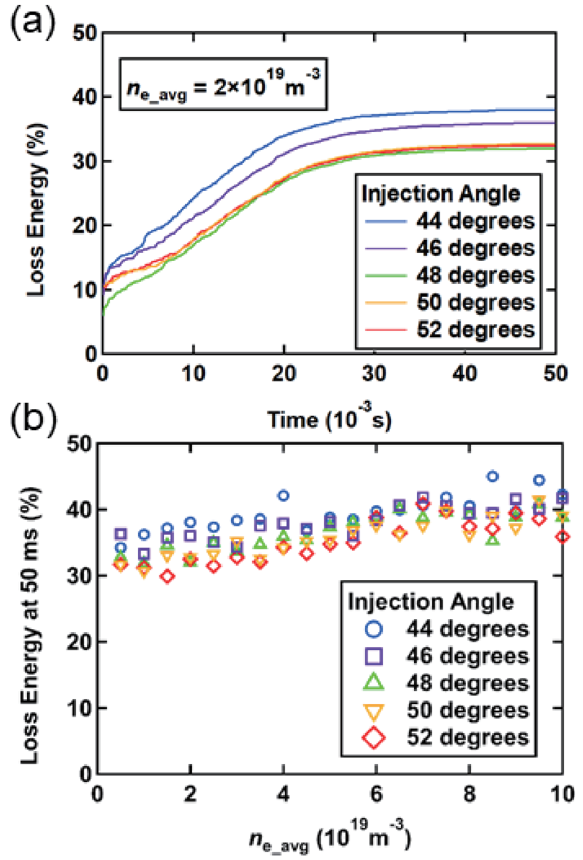

Fig. 5 (a) Time evolution of loss energy of beam ions. Loss energy increases at t < 25 ms and then saturated. (b) Loss energy at 50 ms as a function of line-averaged electron density. The loss energy slightly increases with the electron density.

lowing time 50 ms is decided by the formalization time of the beam ion. Figure 4 (a) shows the time evolution of the number of confined beam ions and the averaged energy of the beam ions with different injection angles at n_{e_avg} of 2×10^{19} m^{-3}. The number of confined particles rapidly drops at t < 1 ms, and then gradually decreases for up to 10 ms. The rapid drop of the number of confined particles appears from 10 ms to 30 ms, and again gradually reduces from 30 ms to 50 ms. The number of losses at the initial phase (t < 10 ms) is relatively small in the 48 degrees to the 52 degrees injection angles compared with the number of losses at the initial phase in the 46 degrees and the 44 degrees injection angles. In the low injection angle with relatively low density cases, some beam ions deposited in $R < R_{ax}$ region are lost from the plasma due to the outward shift of beam ion orbit from the flux surface as shown in Figs. 3 (b) and (c). The averaged energy of the particle decreases continuously and beam ions are thermalized at t of 50 ms. Figure 4 (b) shows the energy distribution of beam ions lost at the last closed flux surface. The energy distribution has two peaks in the energy of approximately 3 keV and 30 keV showing that the loss of beam ions mainly consist of thermalized ions and prompt loss ions. The energy distributions of lost-beam ions are not so different in all cases. The time evolution of loss energy of beam ions at $n_{e\_avg} = 2 \times 10^{19}$ m^{-3} is plotted in Fig. 5 (a). The loss energy increases with time until t = 25 ms, and then is almost saturated. In the 44 degrees and the 46 degrees injection angles, the loss energy is relatively high compared with the other cases. The initial loss energy (t < 7 ms) is relatively low in 48 degrees injection angles. Time evolutions of the loss energy are almost the same in 50 and 52 injection angles. The loss energy at 50 ms is lower in 48 to 52 degrees compared with that in 44 and 46 degrees injection angle. The loss energy at 50 ms is plotted as a function of n_{e_avg} (Fig. 5 (b)). The loss energy at 50 ms increases slightly with the increase of n_{e_avg}. The loss energy at 50 ms in 44 to 46 degrees injection angle is relatively higher in $n_{e\_avg} < 4 \times 10^{19}$ m^{-3}. This is because the fraction of beam ions deposited in smaller R region, where the confinement of co-passing beam ion seems to be worse due to the large outward deviation of orbit as shown in Figs. 3 (b) and (c), becomes larger with the decrease of the injection angle as shown in Fig. 2 (c). The loss energy becomes comparable in $n_{e\_avg} > 4 \times 10^{19}\,m^{-3}$ due to the shorter slowing down time in higher n_{e_avg} conditions. It is found that the beam ion orbit calculation result shows the injection angle from 48 to 52 degrees provides better confinement of beam ions compared with 44 and 46 degrees.

5. Summary

Feasibility study of CFQS NB injector is performed based on the beam deposition and guiding center orbit following calculations using HFREYA and DELTA5D codes. The evaluation of NB deposition fraction by changing the injection angle in different plasma density conditions is conducted using HFREYA code. Deposition fraction increases with the decrease of the injection angle and the increase of n_{e_avg}. Higher deposition fraction can be obtained with 44 to 48 degrees injection angle compared with that with 50 to 52 degrees injection angle. The confinement of beam ions is evaluated using the DELTA5D code including the beam-plasma collisions. The loss energy of beam ions slightly increases with the increase of n_{e_avg}. The lower loss energy of beam ions can be obtained with 48 to 52 degrees injection angle. It is found that the injection angle of 48 degrees is more favorable regarding deposition and beam ion confinement.

Acknowledgments

This work is performed with the support and under the auspices of the NIFS Collaboration Research Program (NIFS17KBAP034). Also, this work is partly supported by International collaborations with overseas laboratories (UFEX105) and Promotion of magnetic confinement research using helical devices in Asia (URSX401).

[1] L. Haifeng *et al.*, Plasma Fusion Res. **13**, 3405067 (2018).
[2] A. Shimizu *et al.*, Plasma Fusion Res. **13**, 3403123 (2018).
[3] M.H. Redi *et al.*, Phys. Plasmas **6**, 3509 (1999).
[4] M. Isobe *et al.*, J. Plasma Fusion Res. SERIES **6**, 622 (2004).
[5] H.W. Kugel, D.A. Spong, M. Majeski and M. Zarnstorff, Fusion Sci. Technol. **51**, 203 (2007).
[6] S. Murakami *et al.*, "Confinement of Energetic Particles in Quasi-axisymmetric Configurations", in Proceedings of International Symposium on Plasma Dynamics in Complex Electromagnetic Fields – for Comprehension of Physics in Advanced Toroidal Plasma Confinement– (1997) 137.
[7] D.A. Spong *et al.*, Phys. Plasmas **18**, 056109 (2011).
[8] S. Kinoshita *et al.*, Plasma Fusion Res. **14**, 3405097 (2019).
[9] S. Murakami *et al.*, Trans. Fusion Technol. **27**, 256 (1995).
[10] S.P. Hirshman and O. Betancourt, J. Comput. Phys. **96**, 99 (1991).
[11] K. Matsuoka *et al.*, Plasma Phys. Control. Fusion **42**, 1145 (2000).