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Bootstrap current fraction scaling for a tokamak reactor design study

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HIGHLIGHTS

- New bootstrap current fraction scalings for systems codes were derived by solving the Hirshman–Sigmar model.
- Nine self-consistent MHD equilibria were constructed in order to compare the bootstrap current fraction values.
- Wilson formula most successfully predicted the bootstrap current fraction, but it requires current density profile index.
- The new scaling formulas and IPDG accurately estimated the fBS values for the normal and weakly reversed shear tokamaks.

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ABSTRACT

We have derived new bootstrap current fraction scalings for systems codes by solving the Hirshman–Sigmar model, which is valid for arbitrary aspect ratios and collision conditions. The bootstrap current density calculation module in the ACCOME code was used with the matrix inversion method without the large aspect ratio assumption. Nine self-consistent MHD equilibria, which cover conventional, advanced and spherical tokamaks with normal or reversed shear, were constructed using numerical calculations in order to compare the bootstrap current fraction values with those of the new model and all six existing models. The Wilson formula successfully predicted the bootstrap current fraction, but it requires current density profile index for the calculation. The new scaling formulas and IPDG accurately estimated the bootstrap current fraction for the normal and weakly reversed shear tokamaks, regardless of the aspect ratio. However, none of the existing models except the Wilson formula can accurately estimate the bootstrap current fraction for the reversed shear tokamaks, which is promising for the advanced tokamak operation mode.

1. Introduction

For future steady-state fusion reactors [1–3], a high bootstrap current fraction will be desirable to ensure sufficient energy gain and to reduce auxiliary non-inductive current drives. Extensive parameters scans using systems codes [4–6] are generally conducted to determine the operation points for the reactor design study. The systems codes consist of a zero dimensional energy balance, current balance, and particle balance equations containing plasma physics and reactor engineering modules. For the broader approach (BA) DEMO design, the systems codes have been developed/improved by benchmarking the following systems codes: TPC/TOPPER (Japan) and PROCESS (EU) [7].

In the systems codes, the bootstrap current is in a scaling formula form, i.e., f_{BS} (=I_{BS}/I_p), where f_{BS} is the bootstrap current fraction, I_{BS} is the bootstrap current, and I_p is the total plasma current. Accurate calculations of the bootstrap current fraction are essential in performing a precise analysis of the self-consistent parameter sets obtained from the extensive parameters scan of the systems codes. If the bootstrap current fraction cannot be accurately estimated, then the errors of other important evaluation-standard parameters such as the confinement enhancement factor HH_{y2} and Greenwald density fraction f_{GW} are increased, thereby adversely affecting the optimization of the operation point.

The bootstrap current is the current parallel to the magnetic field caused by the anisotropy in the electron pressure tensor. Among the models describing the bootstrap current, the Hirshman–Sigmar model [8,9] provides the most complete treatment for tokamaks. The Hirshman–Sigmar model consists of balanced equations for the fluid flow and heat flux in a matrix form, which is valid for arbitrary aspect ratios, multi-ion species, and arbitrary collision conditions.

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As for the bootstrap current fraction scaling, Wilson [10] deduced an empirical formula that is a function of the pressure, temperature, and total current profiles as well as the poloidal beta and aspect ratios. However, this formula cannot be used in the TPC code [4] because the total parallel current density is expressed as a simple parabolic expression of the poloidal flux function using the current profile index a_J, which is not included in the TPC code. Therefore, another scaling formula is required.

In this study, we solve the Hirshman–Sigmar model using the matrix inversion method and derive bootstrap current fraction scaling formulas that are described by explicit variables in the TPC code. Then, the bootstrap current fraction values of the self-consistent current and magnetohydrodynamics (MHD) equilibria are compared with those of the new scaling formula and existing models.

This paper consists of the following sections. In Section 2, we shall explain the scan methodology and variables for the bootstrap current fraction scaling. The scan results and derivation of the scaling formulas are shown in Section 3. Meanwhile, Section 4 discusses the self-consistent current and MHD equilibria as well as compares the numerical-experimental bootstrap current fraction values of the equilibria with the ones calculated from the f_{BS} formulas. Finally, a summary is provided in Section 5.

2. Scan methodology

We created a database for the bootstrap current fraction using the bootstrap current density calculation module in the ACCOME code [11]. The bootstrap current density of the initial equilibrium is calculated without using the iterative calculations of the current drive and equilibrium modules in this scan. Note that the equilibrium constructed here is not self-consistent and includes a few errors from the bootstrap current fraction value. However, because we did not use an iterative calculation, we can have a large number of parameters. We solved the Hirshman–Sigmar model using the matrix inversion method without the large aspect ratio approximation.

Table 1
The scan parameters and ranges for the bootstrap current fraction scaling.

Parameter	Range		Points
Major radius	R_p (m)	5.0	1
Aspect ratio	A	1.3, 1.5, 1.7, 2.0, 2.2, 2.5, 3.0, 3.5, 4.0, 5.0	10
Elongation	κ	~2	1
Triangularity	δ	~0.3	1
Density profile index	a_n	0.1–0.8	8
Temperature profile index	a_t	1.0–3.0	11
Effective charge	Z_{eff}	1.2–3.0	10

Table 1 shows the scan parameters and ranges for the bootstrap current fraction scaling. The plasma major radius is fixed at R_p = 5.0 m, and aspect ratio A consists of 10 points that are varied from 1.3 to 5.0 in order to cover the conventional and spherical tokamaks (STs). The elongation and triangularity are set to be $\kappa \sim 2$ and $\delta \sim 0.3$, respectively. The parabolic profiles of the density and temperature that are used in the systems codes are respectively

$$n(\rho) = n_0(1-\rho^2)^{a_n} \quad (1)$$

$$T(\rho) = T_0(1-\rho^2)^{a_t} \quad (2)$$

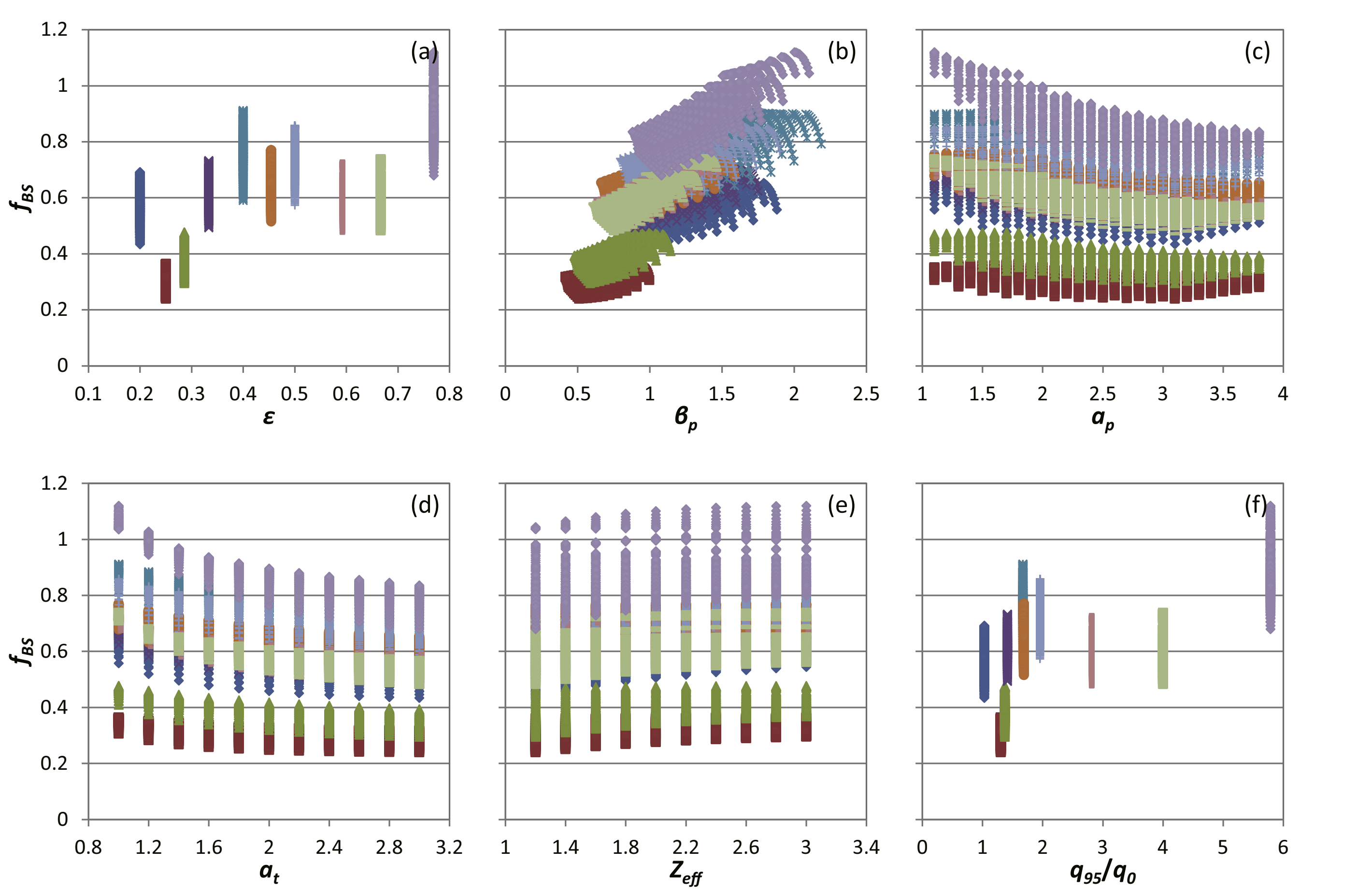

Fig. 1. Dependences of bootstrap current fraction f_{BS} on the (a) inverse aspect ratio ε, (b) poloidal beta β_p, (c) pressure profile index a_p, (d) temperature profile index a_t, (e) effective ion charge Z_{eff}, and (f) safety factor ratio q_{95}/q_0, which are obtained from the parameters scan.