CONFERENCE PRE-PRINT

TEMO: A COMPREHENSIVE AND VERSATILE EQUILIBRIUM MODELLING TOOLBOX FOR TOKAMAK OPERATIONS

Zhengbo Cheng[1], Yunxiao Wei[2], Zichong Song[2], Gang Yin[1], Zhengrong Liu[1], Ximan Li[2], Binbin Wang[2], Shouzhi Wang[1], Rui Chen[1], Yi Tan[2]

1) Shaanxi Startorus Fusion Technology Company Limited, Shaanxi, 710000, China
2) Department of Engineering Physics, Tsinghua University, Beijing, 100084, China

Email: chengzb292@gmail.com

Abstract

A novel Tokamak Equilibrium Modelling toolbox for Operations (TEMO) is developed in the MATLAB environment. TEMO is developed using object-oriented programming, making it highly extensible. And with the axisymmetric equilibrium and magnetic field null calculations as the core functionality, it has extended many applications, such as linear and nonlinear plasma response model analysis, feedforward discharge waveform design and feedback controller design, etc. Each application corresponds to a specific class in the code, and all these classes share the same low-level routines. This paper presents a comprehensive description of the TEMO suite, including the overall structure of the code, and its main modules. Illustrative examples are also provided, demonstrating its application to the analysis of experimental discharges and the development of new scenarios.

1. INTRODUCTION

For both the design and operation of a tokamak device, the optimization of magnetic null field and equilibrium configurations is a fundamental requirement. The magnetic null field is a necessary condition for plasma initiation, while the evaluation of equilibrium configurations provides essential guidance for achieving specific plasma shapes during discharges. For instance, during the design phase of the Sino United Spherical Tokamak-2 (SUNIST-2) device [1], we were confronted with a series of challenges, including how to design the ohmic compensation coils positions and currents, how to compensate stray fields generated by eddy currents during breakdown, how to achieve various plasma configurations, and how to design discharge scenarios. In particular, one of the scientific objectives of the SUNIST-2 device is to realize double ring startup and discharges, which are rarely addressed by conventional codes such as EFIT [2-5] and SE [6], since they lack dedicated modules for such cases. In view of these practical demands, we have developed TEMO, with magnetic null field and equilibrium calculations as its core functionality, further extended by versatile modules, including vacuum field analysis, plasma response model and discharge scenario design, etc. And all of these functions are implemented through dedicated classes. As each module is designed to solve engineering problems arising in practical applications, delivering results directly usable in tokamak design and experimental discharge. Besides, the toolbox has achieved a high degree of completeness, effectively addressing the main operation related physical problems associated with conventional ohmic discharges in tokamaks.

The paper is organized as followings. Section 2 gives an overall structure of TEMO. Sections 3 and 4 offer a systematic introduction to the major functionalities, introducing them sequentially. Sections 3 focuses on plasma-less models, including Section 3.1 on *geometry* classes, Section 3.2 on *vacuum* classes, and Section 3.3 on *Tokamak Start Up* (TSU) classes. Section 4 is devoted to models with plasma, with Section 4.1 on *Free Boundary Equilibrium* (FBE) classes for static forward and inverse calculations, Section 4.2 on *Free Boundary Equilibrium evolve* (FBEE) classes responsible for nonlinear and deformable plasma response model dedicated to plasma control, and Section 4.3 on *wave design* classes for discharge scenario design. Finally, Section 5 concludes with a summary and presents the upgrade plans for future development.

2. DESIGN AND ORGANIZATION OF THE CODE MODULES

TEMO is fully organized in an object-oriented programming paradigm, where different modules are organized into classes following the logical hierarchy. Some fundamental classes serve as members of higher-level classes. The overall structure of all these classes and their respective functionalities are illustrated in Fig. 1. Among them, the Geometry class is the most fundamental one, responsible for defining the geometric structure and computing Green's functions, and thus serves as a member of all other classes. Another relatively fundamental class is the

Diagnostics class, which is not shown in the figure and is used for interaction with experimental data. For modules without plasma, the Vacuum class is in charge of all calculations related to vacuum magnetic fields, electric fields, and eddy currents in the vessel, while the TSU class is responsible for optimizing either the static coil currents or the dynamic eddy-current compensation coil currents, thereby maintaining the experimental conditions required for plasma breakdown. In modules with plasma, the FBE class is responsible for static equilibrium calculations and supports three computational modes: forward free boundary, coil current reconstruction, and equilibrium reconstruction. The FBEE class handles equilibrium evolution, ensuring that successive equilibria satisfy the current diffusion equation. More comprehensive classes include the Wave Design class, which is used for experimental preparation prior to discharges. The members of this class encompass almost all of the aforementioned classes. Finally, all classes share the same low-level subroutines.

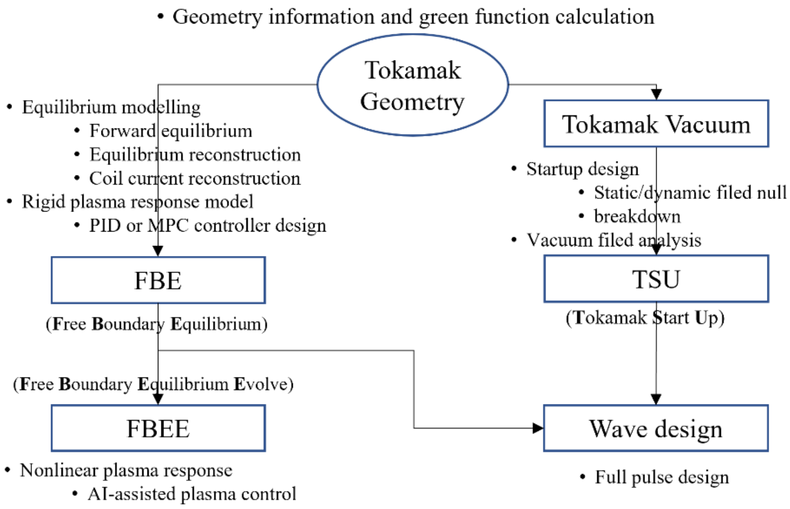

FIG. 1. The overall structure of TEMO. In which the arrow direction indicates a membership relationship, where the class at the starting point is a member of the class at the endpoint.

3. PLAMA LESS MODELUES

One of the key functionalities of TEMO is plasma less analysis. This capability serves, on the one hand, to validate system parameters—such as passive conductor models and diagnostics—primarily through comparisons between simulated and measured signals. On the other hand, it facilitates startup waveform optimization via vacuum field calculations, and supports experimental interpretation through vacuum field analyses.

3.1. Geometry class

This class is an essential component of almost all other classes. It defines the device geometry, including the positions of coils and passive conductors, as well as the shape of the vacuum vessel. Since TEMO is a two-dimensional code based on the toroidal symmetry of the tokamak, all computational elements are represented within a single poloidal plane. Notably, the coil definition in the geometry class supports the specification of non-standard coil shapes, as well as positive and negative series connections and power grouping, ensuring compatibility with diverse device configurations. The computation of Green's functions is also performed within this class and all Green's functions are constructed as weighted linear combinations of point-to-point Green's functions, rather than being computed individually.

3.2. Vacuum class

The Vacuum class is primarily responsible for computing vacuum magnetic and electric fields and is typically used in conjunction with the Diagnostics class. Once the active coil currents are obtained, the Vacuum class solves ordinary differential equations to calculate eddy currents, thereby determining the resulting vacuum fields. This, in turn, allows for direct comparison between the measured and the simulated signals. An example of such a calculation is presented below in Fig. 2. As illustrated in the figure, the vacuum field at this moment exhibits good agreement with the high-speed camera measurements, revealing a distinct breakdown region on the low-field side.

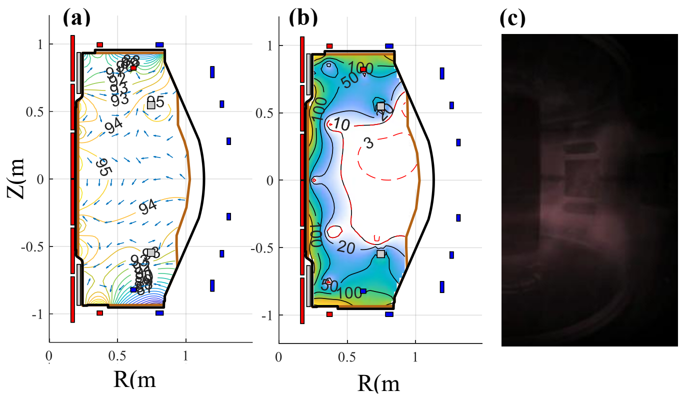

FIG. 2. (a) flux map, (b) magnetic null field configuration and (c) fast camera picture of shot250816033 @561.5ms in SUNIST-2

3.3. TSU class

This class is designed for startup research, utilizing the global optimization algorithm as its core numerical solution method. It enables the calculation of static and dynamic magnetic null field, which can be single or double null configurations. For the dynamic null field, TSU determines the current waveforms required for ohmic breakdown, which must generate a sufficient toroidal electric field while simultaneously maintaining the magnetic null field condition [12, 13]. To accomplish this, TSU compensates sequentially for the CS coil current and for the eddy currents induced by the ramp-down of the CS coil current. Typical applications include compensation coil design and breakdown waveform optimization. Examples of static single null and double null configurations designed by TSU is presented in Fig. 3.

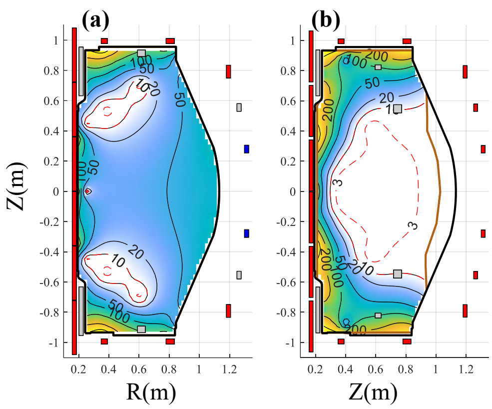

FIG. 3. (a) double and (b)single null magnetic field configurations designed by TSU class

4. MODELUES WITH PLASMA

For modules that include plasma, TEMO is designed to perform equilibrium analysis, linear and nonlinear response modelling, controller design, and discharge scenario development.

4.4. FBE class

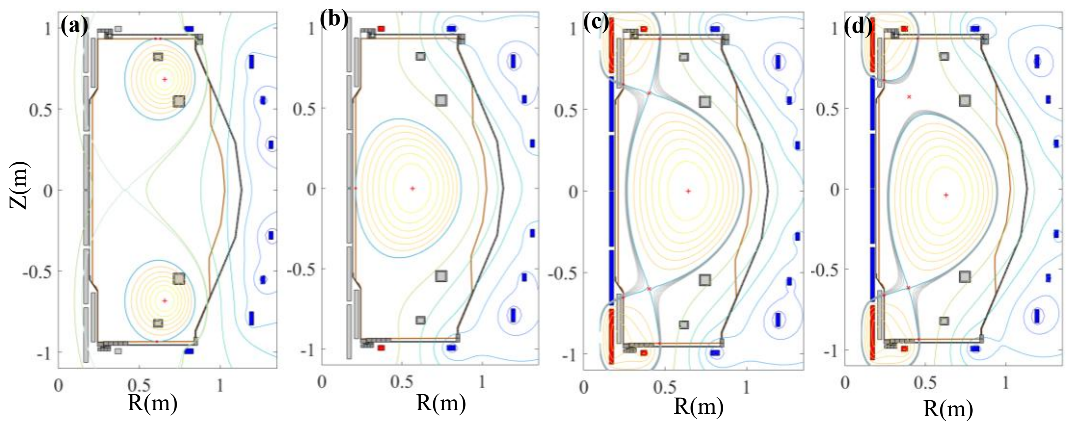

FIG. 4. (a) droplet, (b) limiter, (c) double null divertor and (d) single null divertor configurations designed FBE class

This class is the designed for the free boundary equilibrium calculation. The core numerical algorithm of this class is the Picard iteration. And this class handles three types of problems, including equilibrium reconstruction, coil current reconstruction and forward free boundary equilibrium calculations. The first two problems are inverse and the third is forward. Notably, this class supports both singlet and doublet equilibrium configurations. Once the equilibrium is obtained, this class can also be used to get the rigid plasma response model for plasma controller design. The different configurations designed by FBE can be seen in Fig. 4.

4.5. FBEE class

FBEE is the free boundary equilibrium evolve class. This class self-consistently solves the plasma dynamic system coupled with surrounding passive and active conductors. All of these equations are reformulated as a root-finding problem for numerical solution. Consequently, the class incorporates a deformable, nonlinear plasma response model. Its core algorithm, the Jacobian-Free Newton–Krylov (JFNK) method, achieves rapid convergence within 2 to 10 seconds. The inputs to the code are the coil currents and voltages, while the output is the plasma equilibrium state at the next time step. Finally, FBEE, serving as a fast and flexible physics simulator, together with external magnetic signals, can facilitate subsequent neural network training to learn control strategies [7-9].

The following example demonstrates a PID control simulation conducted with FBEE. Fig. 5(a) shows the initial equilibrium, while Fig. 5(b)–(d) illustrate the control results. In this simulation, the objective is to regulate the plasma current to 145 kA and maintain the vertical displacement at 0 mm. Therefore, there are two PID controllers in total. The modulation modes of the active coils for vertical displacement and plasma current are decoupled from that for horizontal displacement. As shown in the figure, the designed controller effectively regulates the plasma current as well as the horizontal and vertical displacements. It is worth noting that in this simulation the plasma is modelled as a deformable system, which distinguishes it from the RZIP model [10-11].

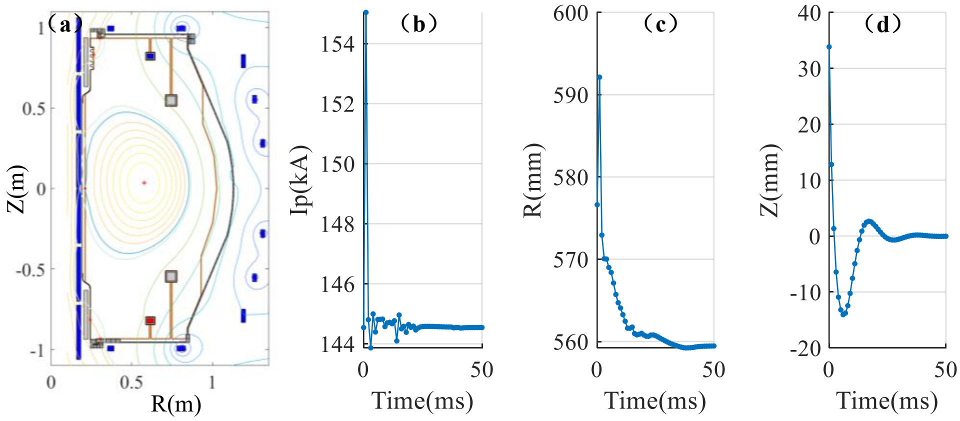

FIG. 5. (a) plasma equilibrium configuration, (b), (c) and (d) are the plasma current, horizontal, and vertical displacements

4.6. Wave Design class

The wave design class can be used to perform rapid full-pulse scenario design, covering both the breakdown and plasma phases. It provides two calculation modes: a fast mode, which neglects eddy currents, and a detailed mode. In the fast mode, to improve computational efficiency, equilibrium are computed only at key time points—typically those where significant changes in plasma conditions occur, such as before and after configuration transitions or at inflection points of the plasma current—while plasma equilibrium parameters at intermediate times, such as plasma inductance and current, are obtained by linear interpolation. This treatment is consistent with that adopted in [6]. Furthermore, plasma-induced eddy currents are neglected, whereas eddy currents generated by the ohmic solenoid throughout the discharge are explicitly subtracted, allowing accurate modelling of equilibrium evolution and volt-second consumption estimation without sacrificing computational efficiency. In contrast, the detailed mode computes the discharge waveform step by step, evolving self-consistently with the equilibrium and eddy currents at each time step. Overall, the wave design class is a highly integrated module: it employs the TSU class for null-field and breakdown calculations, and the FBE class for equilibrium computations.

Below is an illustrative case study of an innovative operational scenario designed with the Wave Design class. For ohmic discharges in spherical tokamaks, the pulse length is strongly constrained by the available volt-seconds, with nearly half of them potentially consumed during the breakdown and current ramp-up phases. To conserve volt-seconds as much as possible, this example proposes a discharge scheme in which a plasma current of –40 kA (negative polarity) is initiated already during the initial magnetization phase as shown in Fig. 6. And in Fig. 8 is the designed magnetic null field configuration and breakdown area for this. After that is the normal discharge, with the final designed plasma current set at 250 kA. By subsequently switching the loop voltage, the plasma current is reversed from negative to positive, thereby reducing the volt-second consumption in breakdown and ramp-up and ultimately enabling more efficient utilization of the available volt-seconds. The waveforms of the poloidal field coil currents can be seen in Fig. 7。

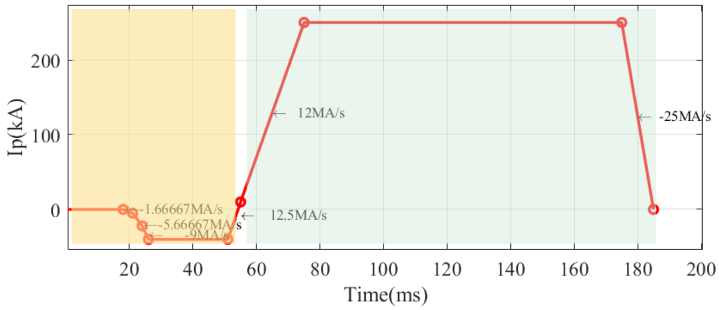

FIG.6. The designed plasma current waveform

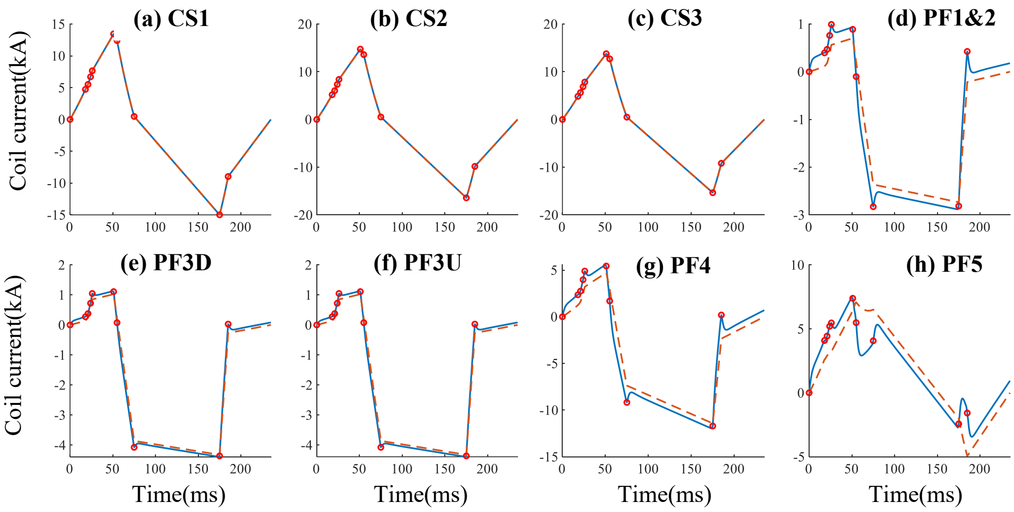

FIG. 7. The designed poloidal field current waveforms. The red dashed lines represent the currents before eddy-current compensation, while the blue solid lines indicate the PF coil currents after accounting for eddy-current compensation. Red circles mark key time points, at which the detailed equilibrium parameters are examined.

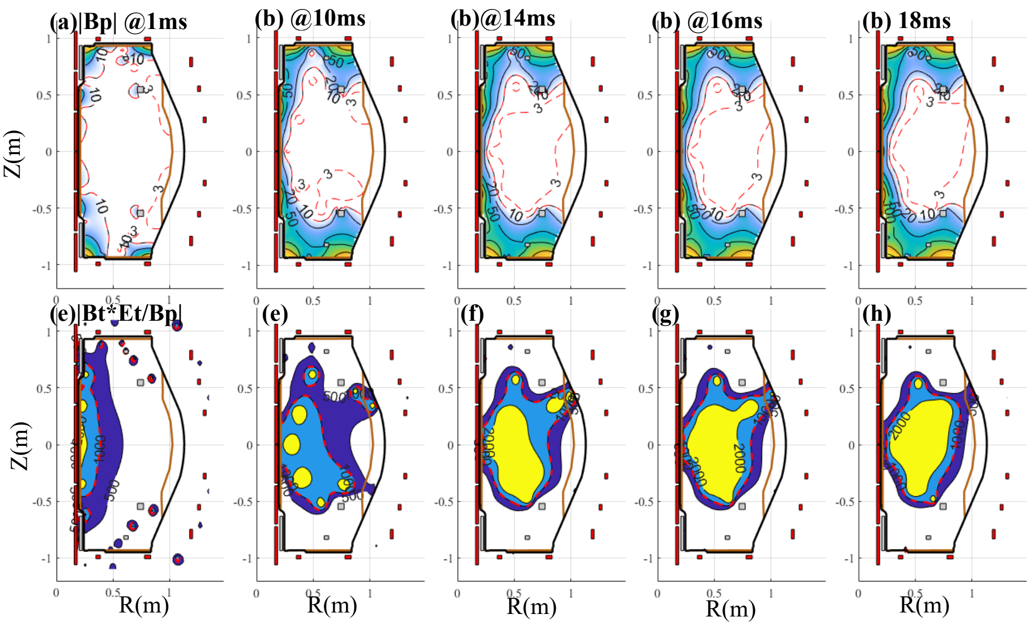

FIG. 8. The designed magnetic null field configuration and breakdown area.

5. CONCLUSION

Based on the aforementioned classes, TEMO can provide strong support for both the design and operation of tokamak devices. During the design phase, it facilitates the optimization of ohmic compensation coils, equilibrium field coils, and vertical displacement control (VDE) coils. In the operation phase, it is capable of executing feedforward control for the full pulse design, from breakdown to plasma formation, performing equilibrium reconstruction, and computing both linear and nonlinear response models for plasma feedback control. In summary, TEMO is a powerful and versatile equilibrium modelling toolbox that integrates design optimization, real-time control, and equilibrium analysis, making it well suited for tokamak operations.

In the future, TEMO will be extended in several aspects. Firstly, a double ring plasma evolution module will be developed to support reinforcement-learning-based controller studies for double ring configurations. Secondly, FBEE with energy transport will be incorporated, thereby eliminating the need for manually specifying pressure profiles and internal inductance. In addition, a new control class will be implemented to design controllers based on plasma response models, enabling seamless integration with our (Plasma Control System) PCS system. Finally, the existing vacuum, diagnostic, and equilibrium classes will be integrated into a comprehensive tokamak analysis module dedicated for experimental applications.

ACKNOWLEDGEMENTS

The author gratefully acknowledges Startorus Company and the SUNIST-2 Group.

REFERENCES

[1] Zou C , Xu H , Tan Y ,et al. The Preliminary design of SUNIST-2:A Spherical Tokamak[J].Fusion Engineering and Design, 2025, 212(000).DOI:10.1016/j.fusengdes.2025.114865.

[2] Lao L L , St. John H , Stambaugh R D ,et al. Reconstruction of current profile parameters and plasma shapes in tokamaks[J].Nuclear Fusion, 2011, 25(11):1611.DOI:10.1088/0029-5515/25/11/007.

[3] Lao L L , St. John H E , Peng Q ,et al.MHD Equilibrium Reconstruction in the DIII-D Tokamak[J].Fusion Science & Technology, 2005, 48(2):968-977.DOI:10.1016/j.fusengdes.2005.07.001.

[4] Lao L L , John H S , Stambaugh R D ,et al.Separation of bar betap and ℓi in tokamaks of non-circular cross-section[J]. 1985.

[5] Lao L L , Jensen T H .Magnetohydrodynamic equilibria of attached plasmas after loss of vertical stability in elongated tokamaks[J].Nuclear Fusion, 1991, 31(10):1909.DOI:10.1088/0029-5515/31/10/009.

[6] Song X M , Li J X , Leuer J A ,et al. First plasma scenario development for HL-2M[J].Fusion Engineering and Design, 2019, 147:111254.DOI:10.1016/j.fusengdes.2019.111254.

[7] Degrave J , Felici F , Buchli J ,et al. Magnetic control of tokamak plasmas through deep reinforcement learning[J].Nature, 2022(602-Feb.17 TN.7897).DOI:10.1007/978-3-031-04420-5_11.

[8] Hofmann F .FBT - a free-boundary tokamak equilibrium code for highly elongated and shaped plasmas[J].Computer Physics Communications, 1988, 48(2):207-221.DOI:10.1016/0010-4655(88)90041-0.

[9] Cheng Z , Tan Y , Gao Z ,et al. Development of a thin high-frequency and high-precision magnetic probe array in Sino-United Spherical Tokamak[J].Review of Scientific Instruments, 2021, 92(5):053518-.DOI:10.1063/5.0043631.

[10] Walker M L , Humphreys D A .Valid Coordinate Systems for Linearized Plasma Shape Response Models in Tokamaks[J].Fusion Science & Technology, 2006, 50(4):473-489.DOI:10.13182/FST06-A1271.

[11] Humphreys D A , Walker M L , Leuer J A .Minimal Plasma Response Models for Design of Tokamak Equilibrium Controllers with High Dynamic Accuracy[J].APS Division of Plasma Physics Meeting Abstracts, 1999.

[12] Leuer J A , Eidietis N W , Ferron J R ,et al.Plasma Startup Design of Fully Superconducting Tokamaks EAST and KSTAR With Implications for ITER[J].IEEE Transactions on Plasma Science, 2010, 38(3):333-340.DOI:10.1109/TPS.2009.2037890.

[13] Leuer J A , Xiao B J , Humphreys D A ,et al.Tokamak Start-Up Modeling and Design for EAST First Plasma Campaign[J].Fusion Science & Technology, 2010, 57(1):48-65.DOI:10.1016/j.fusengdes.2009.08.007.