TEMO: a comprehensive and versatile equilibrium modelling toolbox for tokamak operations

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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 function, 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. The overall structure of TEMO can be seen in Fig. 1 and the following is a brief introduction to the main classes and their associated features:

1. The *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. The computation of Green's functions is also performed within this class. 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.

2. The *Tokamak Start Up* (TSU) class. This class is designed for startup research, utilizing the global optimization algorithm as its core numerical solution method. This class enables the calculation of static and dynamic null field, which can be single or double null configurations. Typical applications include compensation coil design and breakdown waveform optimization.

3. The *diagnostic* class. This class is primarily used for downloading experimental data. All diagnostic channel information associated with gain factor is stored in a YAML file. Additionally, this class supports vacuum field analysis. It can also validate flux loops and magnetic probes by comparing measured signals with simulated ones[1].

4. The *free boundary equilibrium* (FBE) class. The core numerical algorithm of this class is the Picard iteration. And this class includes three types of problems, including equilibrium reconstruction[2], coil current reconstruction and forward free boundary calculations. 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.

5. The *wave design* class. This class can be used to carry out rapid full-pulse scenario design including breakdown and plasma phases. It offers two calculation modes: a fast mode, which neglects eddy currents, and a detailed mode, which computes the discharge waveform step by step, evolving self-consistently with equilibrium and eddy currents at each time step.

6. The *free boundary equilibrium evolve* (FBEE) class. This class self-consistently solves the plasma dynamic system coupled with surrounding passive and active conductors. Its core algorithm, Jacobian-Free Newton-Krylov (JFNK) method, achieves rapid convergence within 2 to 10 seconds. FBEE can be used to train AI-based plasma controllers via reinforcement learning.

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 null-field 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.

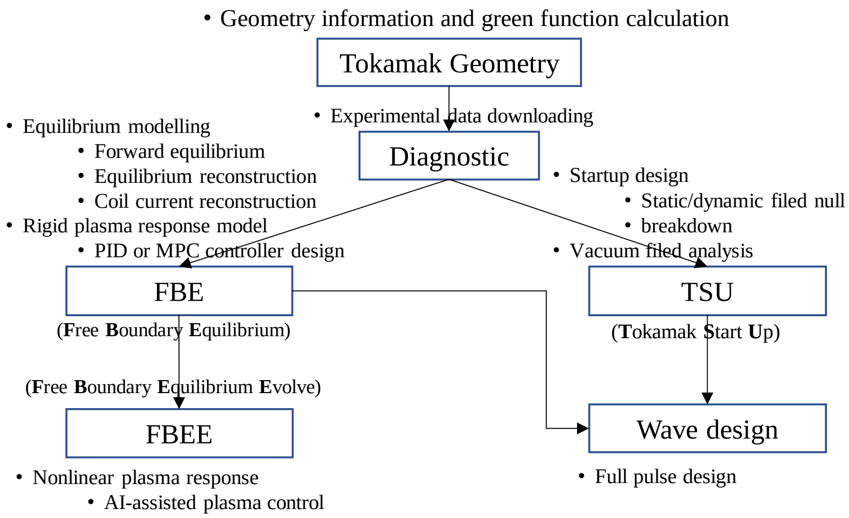

Fig. 1. The overall structure of TEMO. The arrow denotes that the previous class is an attribute of the next.

1. Zhengbo Cheng, Yi Tan, Zhe Gao, 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).
2. Zhengbo Cheng, Yanzheng Jiang, Long Zeng, et al. Equilibrium reconstruction in the Sino-United spherical tokamak[J]. Fusion Engineering and Design, 2025, 213: 114871.