The free boundary equilibrium determination and optimization design of mega ampere configuration of HL-3 tokamak

Y.Y. Zhong [1], L. Xue [1], W.L. Zhong[1], J.X. Li[1], H.L.Du[1], T.Hoang[1], J. Garcia[2], J.F.Artaud[2], X. Song[1,3], Z.Yan[1], R.Ma[1], L.Liu[1], N.Wu[1], H. Heumann[4].

[1] *Southwestern Institute of Physics, China,*

[2]*CEA,IRFM,Saint-Paul-lez-Durance, F-13108, France*

[3]*Lehigh University, Department of Mechanical Engineering and Mechanics, Bethlehem, PA 18015, USA*

[4]*Universit´e Côte d'Azur, Inria, CNRS, Laboratoire J.A. Dieudonn´e, Nice,06108 Nice Cedex 02, France*

e-mail (speaker): Zhongyuanyun@swip.ac.cn

The free boundary equilibrium simulation, closely related to the tokamak poloidal magnet coil system, is frequently applied for operation scenario design, physical analysis, plasma magnetic control, etc. HL-3[1] is a new tokamak device that recently achieved plasma current over 1 MA in 2022, and achieved H-mode with 1 MA plasma current in 2023. It focuses on addressing critical physics and technology issues for ITER and next-step fusion devices, dedicated to the high-performance operation, tests and determination of high heat flux plasma-facing components. etc. One of its important missions is to develop the configuration research for various divertor configurations to explore plasma physics issues and scenarios in preparation for fusion reactors. This paper presents the free boundary equilibrium determination of HL-3 discharges[2] and the optimization of the configuration design with mega ampere plasma currents using code FEEQS [3,4].

Based on the finite element method and Newton iteration, FEEQS can utilize all non-linearities to accelerate convergence among other equilibrium codes for stable and accurate computations, as well as the ability to continuously solve for coil currents and eddy currents in the passive structure on a finite element mesh. Studies for plasma breakdown in WEST[5] and HL-3 by FEEQS are already done as the preliminary work for discharge.

In terms of the free boundary equilibrium determination of the experimental discharges, compared with the experimental diagnostic data from fast camera photos and saturated ion current signals.etc, various time evolution of plasma parameters are well reproduced, such as plasma shape, currents in the poloidal field(PF) coils, strike-point displacement[6]. It has been demonstrated that:

(i) The trend consistency of a and R_0 is fairly well, the mean relative error is less than 4%. The plasma boundary evolution of FEEQS can match the image of the fast camera and EFIT's reconstruction.

(ii)Time evolution of PF coil currents and the eddy current of the vacuum vessel are simulated, showing a good match with the experiment.

(iii) The overall time evolution trend of simulated strike points is consistent with the experiment. Although there exists the maximum intensity signals' location drift which may be caused by the effect of the EFIT magnetic reconstruction.

To explore the corresponding plasma operating space that supports the mega ampere plasma operation of HL-3 double null divertor configurations, the relationship between the safety factor q_{95} and the equilibrium configuration is established. Based on the region of larger q_{95}, the optimization direction of configuration design is pointed out. Then combined with the existing lower divertor structure, the first wall structure, and the reserved space of the upper divertor, the parameters of the double null divertor configuration that can be feasible for the HL-3 within 3 MA are clarified. Then, for the research needs-oriented to the closed divertor, further work is carried out for the conventional toroidal field B_T=2.2T, which can be operated with Ip=2MA. All the PF currents are within engineering limits.

These works lay the foundation for free boundary equilibrium integration simulation, providing significant support for HL-3 high-performance operation.

Reference

[1]Duan XR, Xu M, Zhong WL, et al. Progress of HL-2A experiments and HL-2M program[J]. Nuclear Fusion, 2022, 62(4): 042020.

[2]Zhong YY, Xue L, Zhong WL, et al. Free boundary equilibrium determination of HL-3 discharges[J]. Fusion Engineering and Design, 2024, 202: 114388.

[3]Blum J, Heumann H, Nardon E, et al. Automating the design of tokamak experiment scenarios[J]. Journal of Computational Physics, 2019, 394: 594-614.

[4]Heumann H, Blum J, Boulbe C, et al. Quasi-static free-boundary equilibrium of toroidal plasma with CEDRES++: Computational methods and applications[J]. Journal of Plasma Physics, 2015, 81(3): 905810301.

[5]Heumann H, Nardon E. An Automated Approach to Plasma Breakdown Design with Application to WEST[C]//44th EPS Conference on Plasma Physics. Belfast, United Kingdom, 2017. hal-01959686.

[6]Song X, Song XM, Li B, et al. Plasma initiation and preliminary magnetic control in the HL-2M tokamak[J]. Nuclear Fusion, 2021, 61(8): 086010.