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Core Plasma Design for Helical Fusion DEMO Reactor FFHR-d1
ヘリカル型核融合原型炉FFHR-d1炉心プラズマの設計

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A conceptual design activity on the helical fusion DEMO reactor FFHR-d1 has been launched since 2010. FFHR-d1 is based on the core plasma design extrapolated from experimental data of LHD using the direct profile extrapolation (DPE) method. A confinement improvement effect due to the peaked heat deposition profile that is expected in the reactor has been included in the DPE method. Radial profiles of temperature and density in the reactor predicted by DPE make it possible to analyze detailed properties of the reactor core plasma, *e.g.*, MHD equilibrium, neoclassical transport, and alpha particle confinement.

1. Introduction

Since 2010, a conceptual design activity on the helical thermonuclear fusion reactor named FFHR-d1 has been started [1,2]. Technological feasibilities and safety together with the robustness of core plasma design are emphasized in FFHR-d1. Similar configuration of the superconducting magnet coils as LHD has been adopted in FFHR-d1 to make the best use of experiences in both fields of technology and plasma physics obtained so far in LHD.

In traditional fusion reactor design activities, radial profiles of density and temperature that determine the fusion output have been assumed to be, for example, parabolic. There remains a large degree of freedom in determining the profiles that causes a large ambiguity in the fusion output. Recently, the direct profile extrapolation (DPE) method has been developed to solve this problem [3]. In the DPE method, the radial profiles observed in the experiment are directly extrapolated to the reactor condition based on the gyro-Bohm model. Three enhancement factors for energy confinement, density, and plasma beta have been artificially given in the DPE method.

In this presentation, after introducing the device parameters provisionally adopted for FFHR-d1, a new method to estimate the energy confinement enhancement factor will be discussed. Preliminary results from theoretical analysis on MHD equilibrium and neoclassical transport in the reactor will be also shown.

2. Design parameters of FFHR-d1

FFHR-d1 is a heliotron device as LHD, where nested magnetic surfaces for plasma confinement are produced by two continuously wound helical coils. Except a pair of poloidal coils, FFHR-d1 is a large reproduction of LHD. Planar poloidal coils that generate the vertical magnetic field for plasma shaping and positioning are reduced from 6 in LHD to 4 in FFHR-d1, to secure large ports for maintenance. The device size is 4 times enlarged from LHD, *i.e.*, the major radius of the helical coil center, R_c, is 15.6 m, and the magnetic field at the helical coil center, B_c, is 4.7 T, in FFHR-d1. Due to the reduction of poloidal coils, the averaged plasma cross section becomes vertically elongated compared to the standard configurations in LHD.

To determine these device parameters, iterative discussions have been carried out between the core plasma, superconducting magnets, supporting structures, and blankets. Then, the device parameters have been fixed to keep the magnetic stored energy to ~160 GJ, the minimum distance from the blanket to the plasma to ~0.7 m. The self-ignition condition in FFHR-d1, where no auxiliary heating is needed, is foreseen by the DPE method with an assumed energy confinement enhancement factor of 1.3 [1]. More details about the device parameters will be found in [2].

3. Energy confinement enhancement factor

It has been often observed in LHD that the global energy confinement in the plasmas heated by neutral beam (NB) injection degrades at high-density. Qualitatively, this has been attributed to the shallow penetration of NB at high-density, *i.e.*, the NB heat deposition profile becomes peaked to flat to shallow as the density increases. This effect has been introduced to the DPE method using the energy confinement enhancement factor, γ_{DPE}, defined by

$$\gamma_{\mathrm{DPE}} \equiv \left(\frac{0.6}{(P_{\mathrm{dep}} / P_{\mathrm{dep1}})_{\mathrm{avg}}} \right)^{0.8}, \qquad (1)$$

where $P_{\mathrm{dep}} = P_{\mathrm{dep}}(\rho)$ is the volume-integrated NB power deposition profile as a function of normalized minor radius, ρ, $P_{\mathrm{dep1}} = P_{\mathrm{dep}}(1)$, and $(P_{\mathrm{dep}}/P_{\mathrm{dep1}})_{\mathrm{avg}}$ is the line-average of $P_{\mathrm{dep}}(\rho)/P_{\mathrm{dep1}}$ inside $\rho \leq 1$ that represents the peaking factor of the NB power deposition profile. The numerator of 0.6 in Eq. (1) is the assumed peaking factor of alpha heating in the reactor condition. The exponent of 0.8 in Eq. (1) is determined according to the regression analysis of a dataset obtained in LHD. Typical radial profiles in FFHR-d1 extrapolated from LHD using the DPE method coupled with Eq. (1) are depicted in Fig. 1.

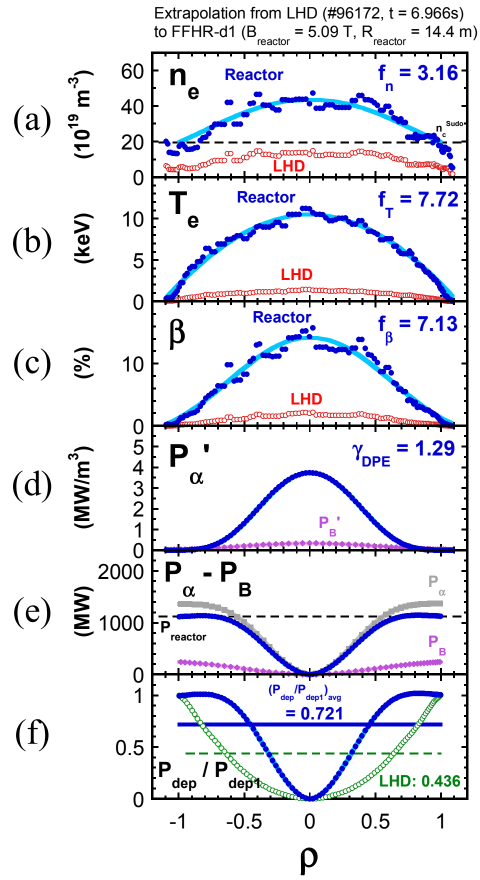

Fig. 1. Typical radial profiles in FFHR-d1, where (a) electron density, (b) electron temperature, (c) plasma beta defined by $100 \times 2n_eT_e/(B_0^2/(2\mu_0))$, in LHD (open circles) and reactor (closed circles), (d) alpha heating (birth profile) and Bremsstrahlung loss per unit volume in reactor, (e) the sum of volume-integrated alpha heating power and Bremsstrahlung loss in reactor, (f) normalized heat deposition profiles in LHD (open circles) and reactor (closed circles), are shown from top to bottom. Horizontal lines in (a), (e), and (f) denote the density limit of n_c^{Sudo} in reactor, the conduction loss in reactor, and $(P_{\mathrm{dep}}/P_{\mathrm{dep1}})_{\mathrm{avg}}$ in LHD (broken line) and reactor (solid line, deduced from the alpha birth profile shown in (d)). The enhancement factors of density, plasma beta, and energy confinement are assumed to be 3.16, 7.13, and 1.29, respectively.

4. Theoretical analysis

In the reactor, the MHD equilibrium will be different from that in the present experiment, at least in the cases with the beta enhancement factor, f_β, larger than 1. It will be also necessary to apply a vertical magnetic field to control the plasma position suffered from the Shafranov shift, which possibly causes degradation in the energy confinement and/or increase in the direct loss of alpha particles. Therefore, it is necessary to calculate the MHD equilibrium using the radial profiles given by the DPE method. Then, it becomes possible to concretely evaluate relevant physics quantities, such as the neoclassical and anomalous transport, and the heat deposition by alpha particles. Preliminary results on the MHD equilibrium reconstruction using the HINT2 code, the neoclassical transport analysis using the GSRAKE code, and the alpha particle transport analysis using the GNET code will be presented.

5. Summary

Typical profiles in the helical DEMO reactor FFHR-d1 are extrapolated from experimental data of LHD, using the DPE method and the confinement enhancement factor as a function of heating profile. It is already possible to design a helical fusion reactor without assuming unknown confinement improvement, although the discovery of it is still desired. Theoretical studies using the extrapolated profiles have been started successfully. Further endeavour to obtain better radial profiles for FFHR-d1 design is, on the other hand, still underway in LHD.

References

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