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Physics Analysis of Plasma Start-up of Helical Fusion Reactor FFHR
ヘリカル核融合炉FFHRのプラズマ立ち上げの物理解析

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Plasma start-up of the LHD-type helical reactor FFHR was examined using an integrated 1-D analysis code. A stable variation of the fusion power can be realized by feedback control of the pellet fuelling and the simple stepped variation of the external heating power with a small number of simple diagnostics (the line-averaged electron density, the edge electron density and the fusion power). Detailed physics assessment on MHD equilibrium and neo-classical energy loss was conducted by the integrated transport analysis code TASK3D. Although mitigation of the Shafranov shift is preferable to suppress the neo-classical energy loss in high beta conditions, a baseline operation control scenario of FFHR (plasma start-up and steady-state sustainment) for both self-ignition and sub-ignition conditions was established.

1. Introduction

Recently conceptual design of the Large Helical Device (LHD)-type helical reactor FFHR-d1 [1] has made a great progress. The direct profile extrapolation (DPE) method [2] improves predictability of the core plasma design and detailed physics analysis of the core plasma at the steady-state operation point has been carried out [3].

On the other hand, plasma start-up scenarios toward this steady-state operation point needs to be considered. For this purpose, 1D calculation code was developed and ignition access scenario by feedback control of the fuelling rate based on the measurement of the line-averaged electron density was proposed [4]. In this study, the examination of the control method of the external heating power and the detailed physics analysis for MHD equilibrium and neo-classical transport were conducted.

2. Calculation method

The developed calculation code adopts simple but valid models based on the LHD experimental observations [5]. The particle transport is calculated by solving a diffusion equation with the diffusion coefficient as the function of the power density ($D \propto (P_{abs}/\bar{n}_e)^{0.6}B^{-0.8}$). The particle source profile is assumed to be the same as the pellet ablation profile estimated by the NGS model. The thermal transport is estimated based on the gyro-Bohm-type parameter dependence ($p_e \propto n_e^{0.6}$), which is widely observed in the LHD experiment. These models were verified in terms that it can reproduce the waveform of typical pellet discharges of the LHD experiment. Consistency with MHD equilibrium and neo-classical transport was checked by coupling the 1D code with the integrated transport analysis code TASK3D [5].

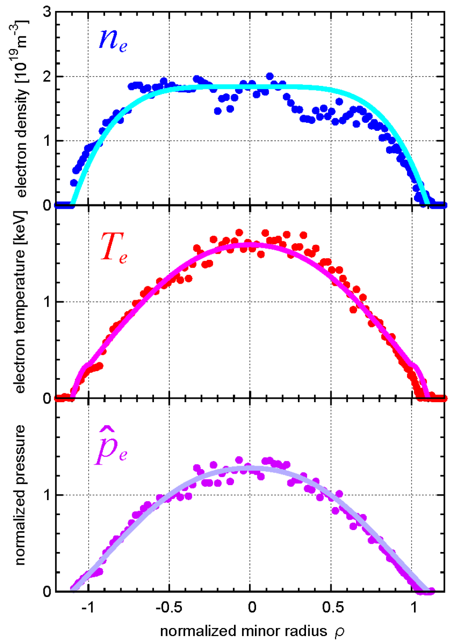

Fig.1. Radial profiles of (a) the electron density, (b) the electron temperature, and (c) the gyro-Bohm normalized electron pressure used in the calculation. The closed circles are experimental data and solid lines are the fitting curves.

3. Calculation result

Using the integrated 1D calculation code described the previous section, plasma start-up scenario of FFHR-d1 (the major radius of R_c = 15.6 m and the averaged toroidal magnetic field strength at $R = R_c$ of 5.6 T) was examined. In this study, the radial profiles obtained in LHD experiment with the magnetic configuration of the inward-shifted magnetic axis position (the ratio between the magnetic axis position R_{ax} and R_c is 3.55/3.9) and high plasma aspect ratio (A = 6.6) was used as the reference profile (Fig. 1). In order to find out the essential parameters need for a basic control algorithm as the first step, ideal conditions of the core plasma (complete absorption of the heating power, no impurity accumulation) were assumed. The electron density and pressure at the plasma boundary (corresponds to $\rho = 1.1$) were fixed to be zero. In the MHD equilibrium calculation, the pressure profiles of each time slice were used and the boundary shape of the last closed flux surface (LCFS) was fixed as that in the previous study [3]. In the calculation of neo-classical transport, pure deuterium plasma was assumed and ambipolar radial electric field was self-consistently solved so that the equality of the particle flux of ions and electrons is satisfied on every flux surface. For the pellet fuelling, the injection of a fixed size pellet (containing 2×10^{22} particles) was assumed with an injection velocity and the minimum injection interval of 1.5 km/s and 5 ms, respectively.

Figure 2 shows the time evolution of plasma and externally controlled parameters in the case of self-ignition operation. Smooth variation of the fusion power and steady-state sustainment with the fusion power of ~3 GW can be achieved by the feedback control of the fuelling rate based on the measurement of line-averaged electron density, which was confirmed in the previous study [3], and simple control of the external heating power: a staged increase on the condition that the ratio of the edge electron density (at $\rho = 1$) to the density limit reaches the pre-set value (0.7 in this case) and a staged decrease on the condition that the fusion power exceeds the target value. The outward shift of the magnetic axis due to Shafranov shift is observed but existence of the equilibrium is confirmed in the final state with the central beta value of ~ 8%. The neo-classical energy loss, however, is comparable to the absorbed power. Thus mitigation of Shafranov shift is preferable, otherwise the operation point moves to higher density region. The same control method is also applicable for sub-ignition operations (e.g., the fusion gain of Q ~ 20 with P_{fus} ~ 600 MW).

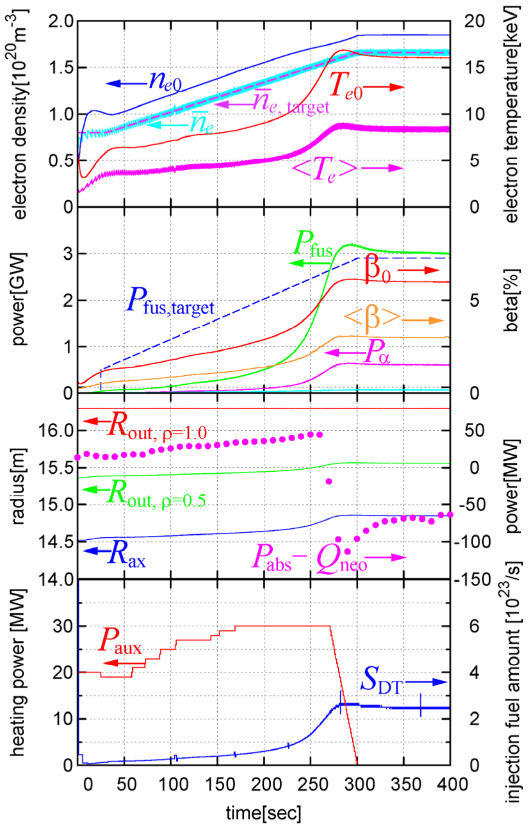

Fig.2. Time evolution of (a) the electron density and temperature, (b) the fusion power and beta value, (c) the magnetic axis position and the power balance (difference between the total generated power and neo-classical loss), and (d) the amount of the external heating power and the injected fuel in the case of the self-ignition operation.

4. Summary

Plasma start-up scenario of the LHD-type helical reactor FFHR-d1 was examined by the integrated 1-D analysis code. Although further detailed analysis (e.g., MHD stability, alpha particle confinement, energy transfer from electrons to ions) is needed, the controllability of the fusion power with a small number of simple diagnostics was confirmed. It indicates another merit of helical system with net-current-free plasma. This study also provides the baseline idea of further detailed physics analysis and engineering design of LHD-type helical reactors.

References

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