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Progress of plasma experiments and superconducting technology in LHD

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Abstract

The large helical device is a heliotron device with $L = 2$ and $M = 10$ continuous helical coils and three pairs of poloidal coils, and all of coils are superconductive. Since the experiments started in 1998, the development of engineering technologies and the demonstration of large-superconducting-machine operations have greatly contributed to an understanding of physics in currentless plasmas and a verification of the capability of fully steady-state operation. In recent plasma experiments, the steady state and high-beta experiments, which are the most important subjects for the realization of attractive fusion reactors, have progressed remarkably and produced two world-record parameters, i.e. the highest average beta of 4.5% in helical devices and the highest total input energy of 1.6 GJ in all magnetic confinement devices. No degradation has been observed in the coil performance, and stable cryogenic operational schemes at 4.4 K have been established. The physics and engineering results from the LHD experiment directly contribute to the design study for a D-T fusion demo reactor FFHR with a LHD-type heliotron configuration.

Keywords: LHD; Superconductive; Steady-state; High-beta; LID; FFHR

1. Introduction

The large helical device (LHD) is a large-scale superconducting heliotron device with a set of $L = 2/M = 10$ continuous helical coils and three pairs of poloidal coils [1]. The major and minor radii are 3.9 and 0.6 m, respectively. The available toroidal magnetic field is up to 2.9 T. LHD has the intrinsic abilities to realize high-beta and steady state operation because of its disruption-free configuration and its superconducting coils. In addition, a double-null divertor, which is suitable for edge heat and particle control in order to sustain plasmas for a long time, is naturally built in a heliotron configuration. Since the experiments started in 1998, an extension of the operational regime due to an increment of the heating power, in addition to a wide

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flexibility in the magnetic configuration has greatly contributed to the understanding of physics in currentless plasmas. Especially, expansion of the high-beta regime and realization of high-performance steady-state operation, which are major subjects for realization of helical fusion reactors, have been energetically investigated recently and have updated the capability of the plasma performance [2–5]. Also, an advanced divertor scenario, that is, the local island divertor (LID) experiment, has been performed to achieve the confinement improvement via its effective edge plasma control, and its applicability is being verified [6].

These important results have been provided by the reliability of the superconducting technology and its development. After intensive physics design studies in the 1980's, the necessary programs of superconducting (SC) engineering R&D were carried out, and as a result, LHD fabrication technologies were successfully developed [7]. The fact that a long-term continuous operation of LHD has been realized is indeed proof of not only the soundness of the systems but also the engineering base for large SC systems.

In this paper, recent results of the LHD experiments, especially on high-beta, long-pulse and LID operation are described. Results of SC operation and recent progress of R&D are indicated. The conceptual design studies on LHD-type D-T helical reactors have been carried out by introducing physics and engineering results obtained in the LHD project with collaboration works in wide research areas on fusion science and engineering in the universities of Japan. Finally, the present status of the reactor design work is given briefly.

2. Plasma experiments

2.1. High-beta experiments

High-beta plasma production is a common subject in magnetic confinement systems for the realization of an economical fusion reactor, and an understanding of magneto-hydrodynamic (MHD) characteristics concerning beta-limit is the most important issue. Characterization of pressure-driven instabilities and control of them in the high-beta regime are one of the crucial issues towards a helical fusion reactor. Since the heliotron has the configuration with weak magnetic shear in the core region, and high shear and magnetic hill in the periphery, it is predicted that activities of ideal or resistive interchange instabilities are major key issues for high-beta plasma production. Especially, the understanding of peripheral modes excited by a steep pressure gradient in the magnetic hill region is a subject common to helical device and tokamaks.

In recent high-beta experiments, control of the pitch parameter of the helical coil, γ_c (=$M/2\ a_c/R_0$) from 1.254 to 1.13 was mainly performed for producing higher-β plasma and investigating the configuration dependence of MHD characteristics [3], where a_c and R_0 are helical coil's minor and major radii, respectively. A reduction of γ_c brings out an increase in the central rotational transform and restricts the Shafranov shift. It is favourable for heating efficiency and transport because the outward shift of the magnetic axis leads to an increase in the helical ripple loss of particles. Also, it is suitable for raising the equilibrium beta-limit. However, a reduction of the plasma shift restricts spontaneous formation of the magnetic well, and a reduction of γ_c reduces the magnetic shear and enhances the magnetic hill [8].

Fig. 1 shows the central rotational transform, plasma aspect ratio and achieved volume averaged beta value

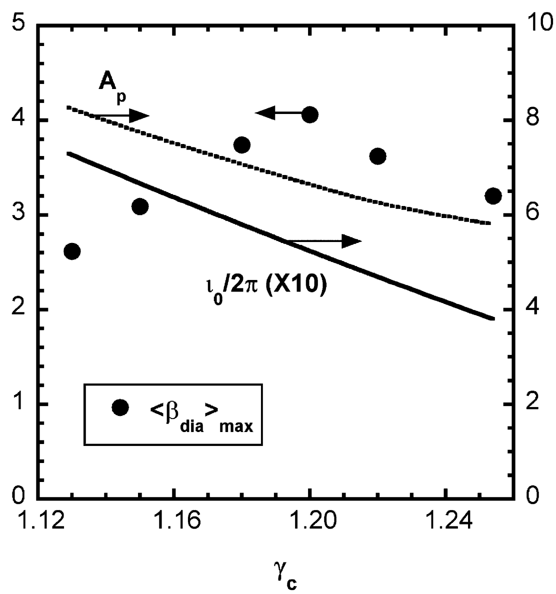

Fig. 1. Variation of plasma aspect ratio, central rotational transform and achieved beta value as a function of γ_c.