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Wide-Scope Studies of LHD-Type Helical Reactors

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Abstract

The system optimization studies are carried out for the LHD(Large Helical Device)-type Helical Reactor, LHR, with continuous-coil or modular-coil system, which is characterized by the efficient closed helical divertor and the good plasma confinement. The physics and engineering optimization studies for LHR are carried out and the required machine parameters for DT ignition are clarified. Standard and compact reactor design candidates are selected, and the present cost analysis suggests the effectiveness of the compact design option. Preliminary ignition studies on D-^{3}He helical reactors are also discussed.

Keywords:

ignition reactor, Large Helical Device, modular coil, confinement scaling, system study, cost analysis

1. Introduction

Helical systems have remarkable advantages in steady-state operations of fusion reactors. To demonstrate this, the Large Helical Device (LHD) will start operation soon, and the $L=2$ LHD-type Helical Reactor (LHR) with continuos or modular coil system is under design[1] based on this LHD physics concept.

Helical devices with continuous helical coils such as LHD (Fig. 1(a)) provide with rather large space for divertor pumping to control fusion ashes and impurities. However, for reactors it is not easy to construct and maintain the large continuous coil system. Starting from the conventional continuous-coil Heliotron, the improved Modular Heliotron coil system (Fig. 1(b)) was proposed, and we confirmed the good magnetic surfaces almost similar to the optimized conventional Heliotron [1,2].

2. Ignition Projection

The physics properties of the LHD-type reactor configuration have been widely investigated. The standpoint of our reactor design is that the closed helical divertor configuration with tolerable neoclassical ripple loss might be essential for the improvement of edge confinement leading to the H-mode transition and for the pumping-out of plasma impurities and helium ash exhaust. Ignition conditions of D-T burning plasmas in LHR as functions of averaged temperature and density are studied using zero-dimensional power balance equations with profile corrections based on several empirical confinement scalings (LHD, gyro-reduced Bohm, Lackner-Gottardi or international stellarator (ISS) a scalings) and neo-classical ripple loss model. As shown in Fig. 2, without confinement improvement, the major radius for a DT helical ignitor should be greater than the major radius R of 20 m in the case of magnetic field strength B=6 T. When the confinement was improved more than twice, the neoclassical confinement with the helical ripple of 20% may not be neglected.

3. Engineering Design Constraints

The engineering designs of LHR are carried out using the helical design system code [3] including magnetic surface characteristics, ignition POPCON

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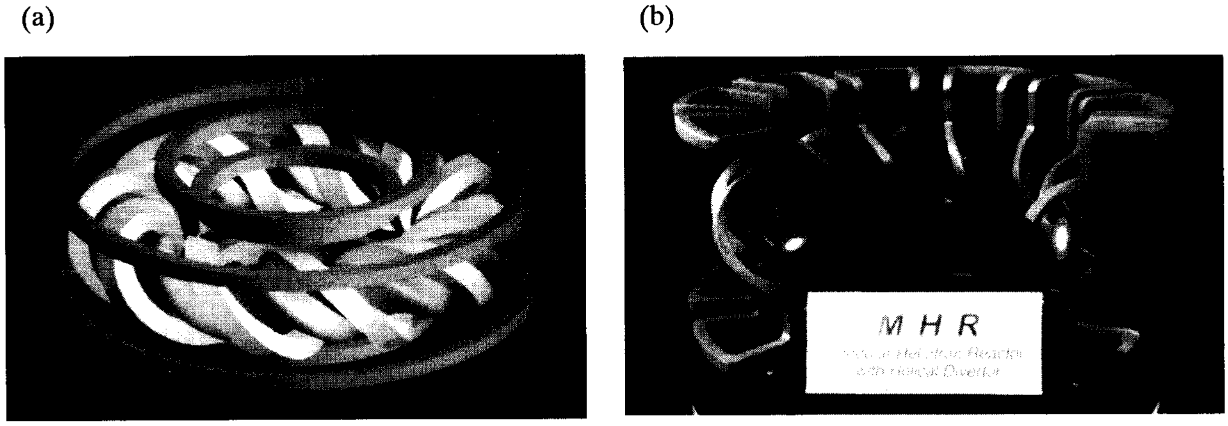

Fig. 1 Coil configurations of LHD-type Helical Reactors (LHR); (a) continuous coil design and (b) modular heliotron design. MHR: Modular Heliotron Reactor with Helical Divertor

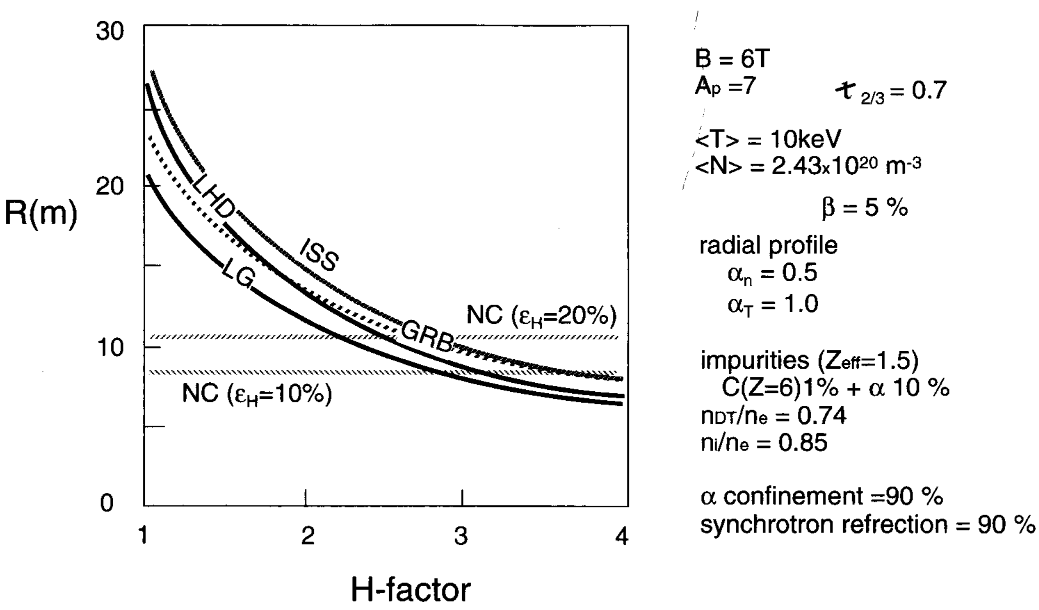

Fig. 2 Effects of anomalous loss reduction (H-factor) and neo-classical ripple transport on the size of D-T ignition reactors.

diagram, SC coil constraints, coil stress estimation, wall loading and so on, which gives rise to the design window for DT ignition reactors. Figure 3 denotes an optimized parameter window as functions of R and B for $L=2$, $m=10$ system with respect to neutron wall loading ($L_n < 3$ MW/m^2), fusion power output ($P_{fusion} > 1$ GW), divertor-coil clearance ($\Delta_{d-c} > 1$ m) for blanket space and so on. The confinement enhancement factor of 2 and density limit factor of 2 (during startup phase only) are assumed in the empirical ISS scaling. To reduce neoclassical ripple loss, the effective helical ripple should be less than 10%. As reference D-T reactors, the $m=10$ standard design (LHR-10S) with major radius of 16.5 m and magnetic field strength of 5 T is obtained. The $m=10$ compact system (LHR-10C) with major radius of 10.5 m and magnetic field strength of 6.5 T is evaluated by sacrificing the divertor clearance (Table 1).

4. Cost Analysis and Future Studies

The cost assessment for these DT designs based on the unit cost per weight is performed and clarifies the merit of compact design within several engineering constraints. The contours of direct cost and COE (Cost of

Table 1 Design parameters of L = 2/m = 10 LHR.

	LHR-10C (Compact Design)	LHR-10S (Standard Design)
Major Radius (m)	10.5	16.5
Average Plasma Radius (m)	1.62	2.54
Toroidal Field on Axis (T)	6.5	5.0
Maximum Field on Coils (T)	14.7	14.9
Averege Plasma Density <n> ($10^{20}m^{-3}$)	3.05	1.8
Average Plasma Temperature <T> (keV)	7.2	7.2
[T] (keV)	8.64	8.64
Volume Average Beta (%)	5.0	5.0
Energy Confinement Time (s)	1.47	2.46
LHD Scaling (fH=2)	2.10	3.21
NeoClassical (10% ripple)	4.97	10.58
Ignition Margin		
LHD Scaling (fH=2)	1.08	1.07
GRB Scaling (fH=2)	1.00	1.16
LG Scaling (fH=2)	1.28	1.49
ISS-95 Scaling (fH=2)	0.95	1.08

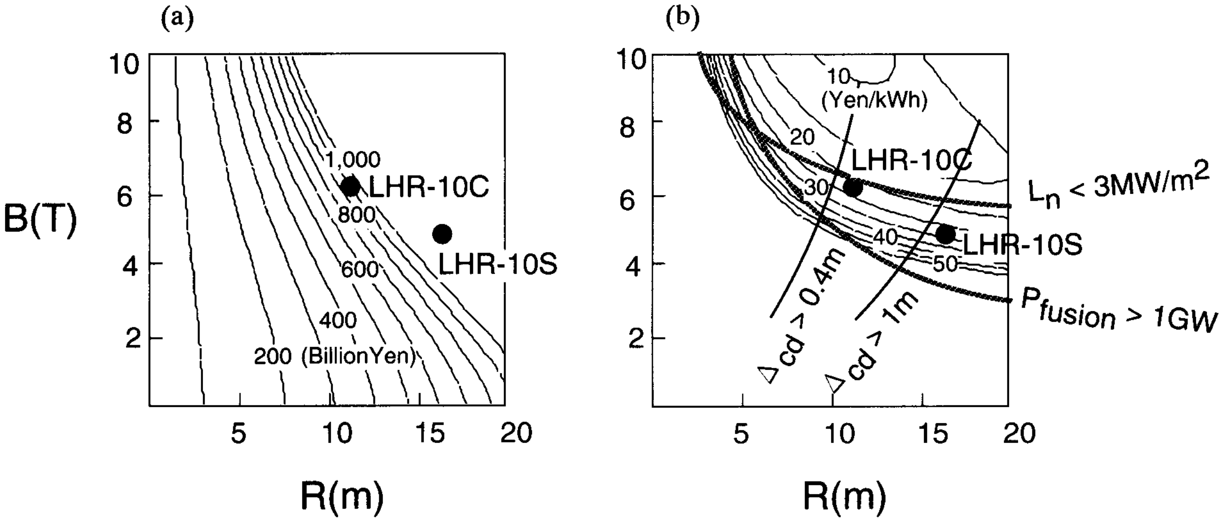

Fig. 3 Contours of direct cost (100 ~ 1,000 Billion Yen) and cost of electricity (COE, 10 ~ 50 Yen/kWh) as functions of major radius R(m) and magnetic field strength B(T).

Electricity) are shown in Fig. 3 in addition to other physics and engineering constrains, and the effectiveness of the compact machine is suggested.

The D-^{3}He reactor analysis is also carried out and the scale requirements of these reactors are clarified with the confinement enhancement factor of ~4, <3% helical ripple configuration and a 8% second stability configuration. This system analysis will be reported somewhere in the near future.

5. Summary

The physics, engineering and cost optimization studies have been carried out for LHD (Large Helical Device)-type Helical Reactor, LHR, with continuous-coil or modular-coil system. We came to the following conclusions:

(1) The merit of the L = 2 continuous coil design based on the LHD physics concept is clarified, and extend it to the Modular Heliotron Reactor system.

(2) One point transport model with profile correction suggests the requirement of appropriate reduction of both anomalous and ripple losses. The 3-dimensional equilibrium/1-dimensional transport simulation confirmed this result.
(3) The engineering design of LHR is carried out using the helical design system code, and clarified the design window for DT ignition reactors.
(4) The cost assessment based on the unit cost per weight is performed and clarified the merit of compact design.
(5) Preliminary study for D-^{3}He reactor design are shown and its survey will be continued.

The coming LHD experiment will clarify the future prospect of the LHD-type Helical Reactors, LHR.

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