Helical Reactor Design Studies Based on New Confinement Scalings

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Abstract The design requirements for helical reactors are investigated on plasma confinement, density regime and beta limit, comparing with recent LHD (Large Helical Device) experimental data. Several new confinement scaling laws are derived using LHD database in addition to the medium-sized helical system database. In the previous reactor designs two times better plasma confinement than the conventional LHD scaling law was assumed, which has been achieved experimentally as “New LHD” scaling laws. One and half times higher density than the conventional helical density limit scaling laws has been achieved, which condition is required at the start-up phase of reactors. Half of beta value required in reactors is achieved in the inward-shifted configuration in LHD experiment, which value is beyond the theoretical stability limit. This magnetic configuration satisfies the high beta and low effective helical ripple operation required for reactors. Almost these normalized requisites have been achieved in the LHD experiment Based on new LHD scaling laws the reactor system design has been carried out. The COE (cost of electricity) value of large reactor system is not so high in comparison with that of compact design, however the compact reactor has advantage of rather lower direct cost. The present LHD experiment can justify the future prospect of the LHD-type helical devices towards a steady-state efficient and reliable reactor.

1. Introduction

Helical confinement system has a great advantage for sustaining current-disruption-free steady-state fusion plasmas by external helical magnetic field with built-in divertor. To demonstrate this concept, the Large Helical Device (LHD) had started experiments from April 1998 [1,2]. This configuration has been determined by optimizing (1) particle confinement without loss cone at one-third of plasma minor radius, (2) >5% plasma beta achievement and (3) clean divertor configuration formation [3]. As an extension of this LHD physics concept, the LHD-type helical reactors (Fig.1) such as Modular Heliotron Reactor (MHR) and Force-Free-like Helical Reactor (FFHR) are under design [4,5]. These reactors have been designed assuming improved plasma confinement nearly two times better than the conventional LHD scaling. The LHD experiments [1,2] so far proved this assumption, which makes it possible to make helical reactors compact. Using LHD experimental database in addition to medium-sized helical database, several new confinement scaling laws (New LHD scaling Laws) are introduced and applied to scooping studies of helical reactors.

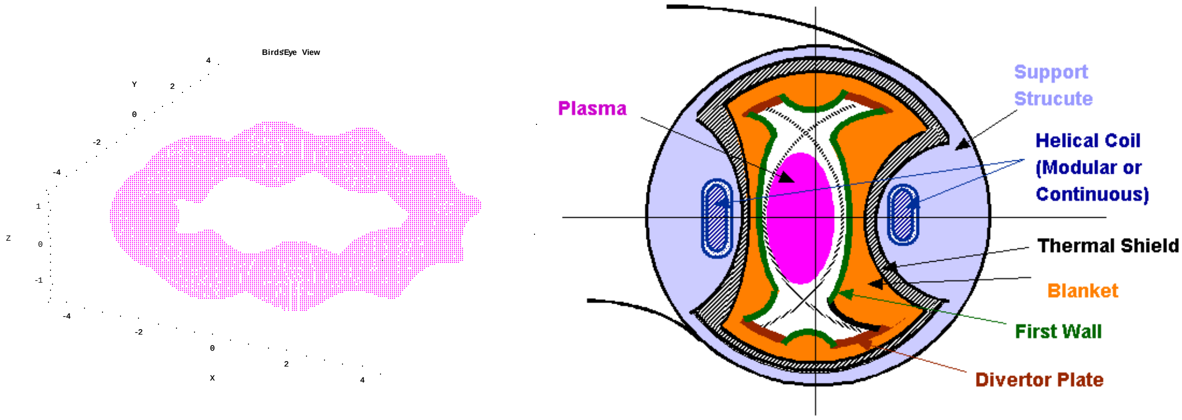

FIG.1 LHD-type helical plasma and reactor core system

2. Reactor Plasma Requirements and Experimental Database

In the design of helical reactor core plasmas, the plasma confinement scaling laws (anomalous and neoclassical confinement), density limits and beta limits are crucial, and their requirements have been investigated for helical reactors [4]. Our final requisites for LHD-type helical reactors, especially Modular Heliotron Reactors, are as follows:

(1) about two times higher plasmas confinement than the old LHD scaling is required,
(2) effective helical ripple should be less than around 5 %,
(3) about 1.5 times higher density than the helical density limits is required in the start-up phase of reactor operation, and
(4) around 5% beta value is required.

The precise projection of the present LHD experimental data to the reactor regime, the experimental transport analysis and the predictive simulation using 3-dimensional equilibrium / 1-dimensional transport code TOTAL (Toroidal Transport Analysis Linkage) [6] have been performed for the NBI-heated LHD plasmas compared with neoclassical ripple transport as well as anomalous transport (empirical or drift turbulence theory). In addition to LHD experimental data, previous database from the medium-sized helical devices (Heliotron-E, ATF, CHS, Wendelstein-A, Wendelstein-AS) [7] are used. In the LHD experiment, we compared with conventional global confinement scaling laws for helical systems: LHD scaling (LHD)[8], gyro-reduced Bohm scaling (GRB), Lackner-Gotardi scaling (LG) and International Stellarator Scaling (ISS95) [7],

$$t_{LHD} = 0.17 P^{-0.58} \bar{n}_e^{\,0.69} B^{0.84} R^{0.75} a^{2}, \qquad (1)$$

$$t_{GRB} = 0.25 P^{-0.6} \bar{n}_e^{\,0.6} B^{0.8} R^{0.6} a^{2.4}, \qquad (2)$$

$$t_{LG} = 0.17 P^{-0.6} \bar{n}_e^{\,0.6} B^{0.8} R a^{2} \bar{\iota}_{2/3}^{\,0.4}, \qquad (3)$$

$$t_{ISS95} = 0.26 P^{-0.59} \bar{n}_e^{\,0.51} B^{0.83} R^{0.65} a^{2.21} \bar{\iota}_{2/3}^{\,0.4}, \qquad (4)$$

where P, $\bar{n}_e$, B, R and a are heating power (MW), line-averaged electron density (10^{20}m^{-3}), magnetic field strength (T), plasma major radius (m) and minor radius (m), respectively. Units used here are $t_E(s)$, $P(MW)$, $\bar{n}_e(10^{20}m^{-3})$, $B(T)$, $R(m)$, $a(m)$, respectively. These are based on medium-sized helical experiments.

We confirmed that the global confinement of the LHD plasma is ~ 2 times higher than the LHD scaling law (Fig.2(a)), and ~ 1.5 times higher than the ISS95 scaling laws. Here we derived several new global scaling laws using log-linear regression analysis. Two "New LHD" scaling laws based on only heliotron-type experiments (NLHD-1) and all helical experiments (NHD-2) are as follows:

$$t_{NLHD-1} = 0.263 P^{-0.58} \bar{n}_e^{\,0.51} B^{1.01} R^{0.64} a^{2.59} \qquad (5)$$

$$t_{NLHD-2} = 0.115 P^{-0.64} \bar{n}_e^{\,0.54} B^{0.85} R^{1.02} a^{2.09} \qquad (6)$$

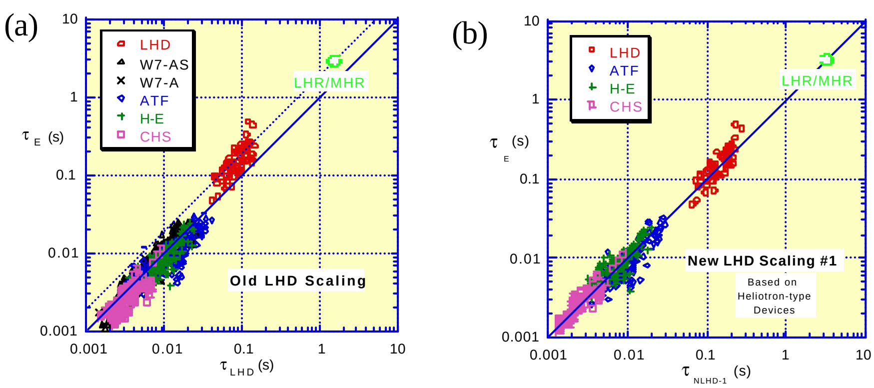

FIG.2 Reactor plasma projection based on (a) old LHD scaling and (b) new LHD scaling NLHD-1

The rotational transform is not included because it is confirmed that the rotational transform makes no dominant effects on these scaling laws. Based on these new LHD scaling we can extrapolate the plasma confinement to the reactor regime without enhancement assumption, as shown in FIG.2(b).

In the LHD experiments, the collisionality n_{0*} regime relevant to reactors are already achieved, however, we should extrapolate the gyro-radius r_* effect to one order of smaller regime as shown in Fig.3. For this purpose, we applied analysis Kadomtev's dimensionl analysis technique. The obtained dimensionally-correct scalings are as follows;

$$t_{NLHD-D1} = 0.269\, P^{-0.59} \bar{n}_e^{\,0.52} B^{1.06} R^{0.64} a^{2.58} \sim B^{-1} r_*^{-3.61} n_{0*}^{-0.17} \quad (7)$$

$$t_{NLHD-D2} = 0.115\, P^{-0.64} \bar{n}_e^{\,0.54} B^{1.03} R^{1.04} a^{2.08} \sim B^{-1} r_*^{-3.41} n_{0*}^{-0.08} b^{-0.22} \quad (8)$$

Again, NLHD-D1 scaling is based on only heliotron-type devices, and NLHD-D2 is obtained from all databases. These global scaling laws suggested the strong gyro-Bohm-like features [9], which is different from previous conventional scaling laws (weakly gyro-Bohm) based on only medium-sized devices.

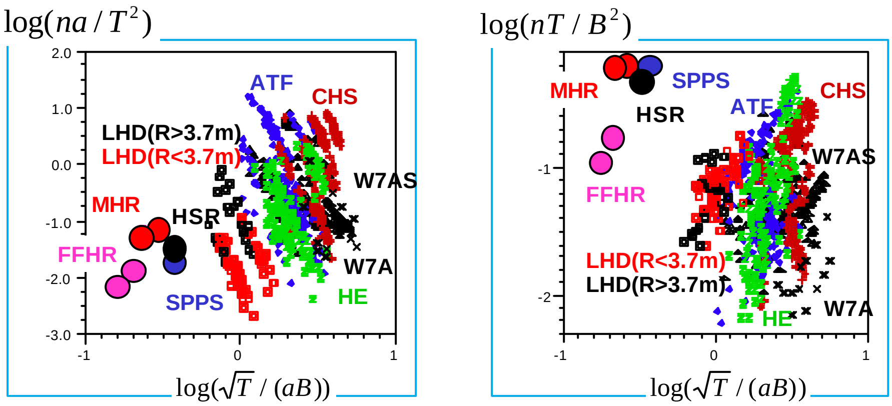

FIG.3 Plasma regime as a function of r_* vs. n_{0*} and r_* vs. b.

The density boundary used in these confinement scaling studies is ~ 1.5 times higher than the previous helical scaling laws [8] as shown in FIG.4, which condition fits the reactor core requirement.

As for beta value, a world highest beta value in helical systems (2.4 % in average) has been achieved in LHD [1]. This beta value is still half of the required value for reactors; however, the experimental value exceeds the theoretical limits in the inward-shifted case (~15cm inward shift from the standard configuration R=3.75m). This configuration leads to the strong reduction of neoclassical transport values due to the good magnetic helicity spectrum, and typically its ripple transport diffusivity is ~5-10 times smaller than that of the standard configuration. The effective helical ripple at the core (at half minor radius) is less than 5% as small as reactor start-up requisite.

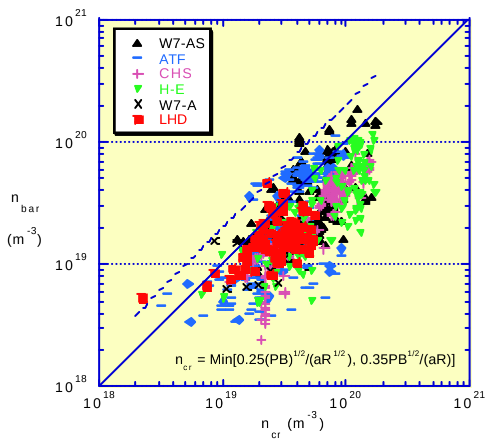

FIG.4 Density regime used for confinement scaling database

3. Reactor Plasma Projection

. Using zero-dimensional power balance model with profile corrections and above-stated new scaling law NLHD-1, the POPCON plot is given in FIG. 5 without confinement improvement for R=15m, B= 5 T, m=10 LHD-type system. The reactor operation domain was bounded by plasma confinement limit, density limit and beta limit. Using old LHD scaling with confinement improvement factor of 2, we can obtain almost same contour as FIG. 5. These "New LHD" scaling laws and other previous conventional scaling laws are compared as a function of confinement improvement factor in FIG.6. The design values of various reactor systems and predicted confinement times are listed in Table 1.

The detailed physics projection to the LHD-type helical reactors is also carried out by TOTAL code simulation predictions with new empirical local transport coefficient. These are shown later somewhere.

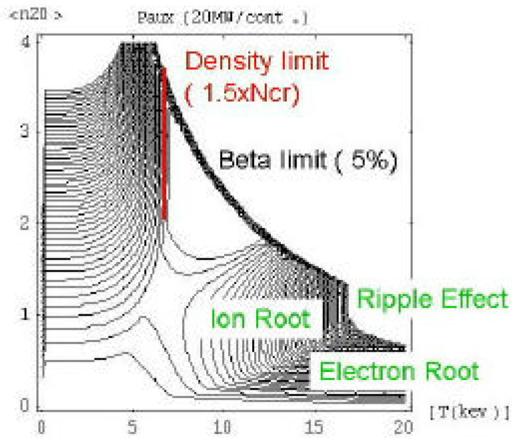

FIG.5 POPCON plot of helical reactor

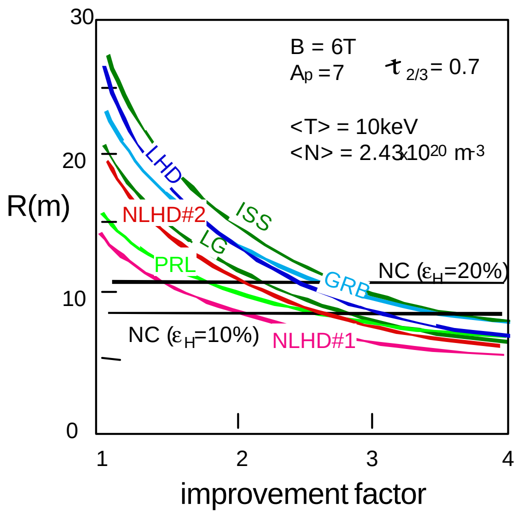

FIG.6 Reactor size vs. confinement improvement factor based on various helical confinement scaling laws in LHD-type helical reactors.

TABLE I Helical Reactor Parameters and Requirement of Confinement Improvement

Name of Reactor Design	LHR/MHR-S	LHR/MHR-C	FFHR-1	FFHR-2	HSR	SPPS/MHHR
Major Radius R (m)	16.5	10.5	20	10	19.5	13.95
Average Plasm Radius a (m)	2.4	1.5	2	1.7	1.6	1.63
Toroidal Field B (T)	5	6.5	12	10	5	4.94
Maximum Coil Field B_{max} (T)	14.9	14.7	16	13	10.7	14.5
Average Plasma Density $\langle n \rangle$ ($10^{20}/m^3$)	2	3.4	1	1.4	1.33	1.46
Average Plasma Temperature $\langle T \rangle$ (keV	7.8	7.8	11	13.5	7.49	10
Volume Average Beta β (%)	5	5	0.7	0.59	4.57	5
Enhancement Factor Designed	2 (LHD)	2 (LHD)	1.5 (LHD)	2.5 (LHD)	1 (LG)	2.3 (LG)
Thermal Power P_{FT} (GW)	3.8	2.8	3	1	3	2.29
Effective Heating Power (MW)	600	400	200	400	300	200
Energy Confinement Time τ_E (s)	2.67	1.5	3.7	1.8	1.2	1.75
LHD scaling (s)	1.24	0.79	2.46	0.76	0.71	0.76
GRB scaling (s)	1.30	0.69	2.42	0.75	0.64	0.74
LG scaling (s)	1.66	0.89	3.58	0.90	1.03	1.02
ISS95 scaling (s)	1.20	0.66	2.52	0.76	0.67	0.74
New LHD-1 (heliotron-type) (s)	2.70	1.30	6.13	1.71	1.28	1.42
New LHD-2 (all helical) (s)	1.62	0.87	4.64	1.04	1.03	1.02

4. System Analysis

Based on these plasma projection analyses, we made system design and cost analysis. Figure 7 shows the COE (Cost Of Electricity) values of m=8 compact design and m=14 larger-sized design. In this figure, 10 keV temperature and 5% beta value are assumed. The engineering constraints on superconducting condition ($j_{coil}<j_{cr}$), mechanical stress (<250MPa), neutron wall loading (<3MW/m^2), reasonable magnetic energy (<500GJ) etc. are also added and evaluated in these figures. The COE value of large system is not so high in comparison with compact design, however the compact design has definite advantage of rather lower direct cost.

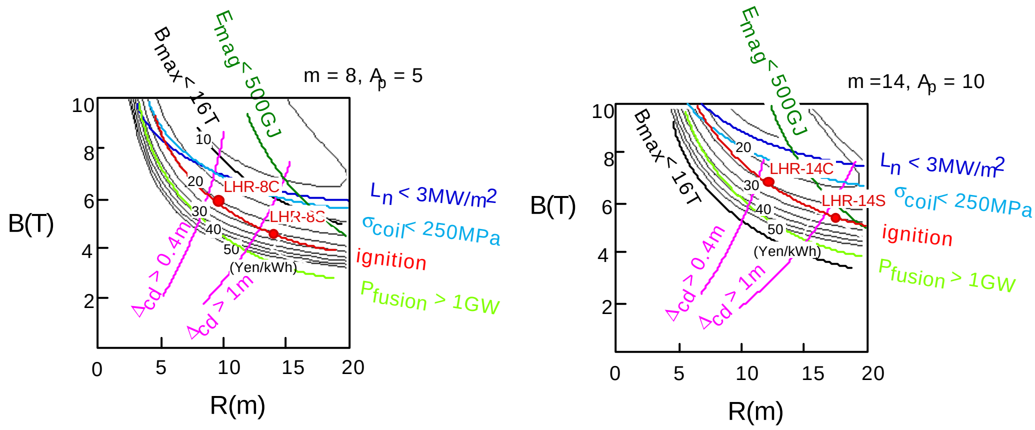

FIG.7 Cost of Electricity of compact (left) and large (right) systems. Unit is Yen/kWh.

5. Summary

The design requirements for helical reactors are investigated on (1) confinement improvement and effective helical ripple reduction, (2) plasma density regime and (3) beta limit, comparing with recent LHD (Large Helical Device) experimental data.

(1) Four new LHD confinement scaling laws are derived using LHD database in addition to the medium-sized helical system database. In the previous reactor designs two times higher plasma confinement than the conventional LHD scaling law was assumed, which has been achieved experimentally as “New LHD” scaling laws. (2) One and half times higher density than the conventional helical density limit scaling has been achieved, which condition is required at the start-up phase of reactors. (3) Half of beta value required in reactors is achieved in the inner-shifted configuration in LHD experiment, which value is beyond the theoretical limit. This configuration satisfies the high beta (~5%) and low effective helical ripple (<5%) operation required for reactors.

Based on these new scaling laws the reactor system design has been carried out. The COE (cost of electricity) value of large reactor system is not so high in comparison with that of compact design, however the compact reactor has advantage of rather lower direct cost.

The present LHD experiment can justify the future prospect of the LHD-type helical devices towards a steady-state efficient and reliable reactor.

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