REACTOR PLASMA DESIGN BASED ON LHD

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The overview of helical reactor concepts and related plasma designs based on the Large Helical Device (LHD) experimental database are described. Firstly, design requirements for helical reactors are clarified with respect to plasma confinement improvement, density limit and beta limit. Several new confinement scaling laws are derived using LHD database in addition to the previous medium-sized helical confinement database. In the previous LHD-type reactor designs two times better plasma confinement time than the conventional LHD scaling law was assumed, which has been already achieved experimentally as "New LHD" scaling laws. One and half times higher plasma density than the conventional helical density limit scaling law has been achieved. This condition is required at the start-up phase of reactors. Higher than half of beta value required in reactors is also achieved in the inward-shifted configuration in LHD experiment, which beta value is beyond the theoretical Mercier stability limit. This inward-shifted magnetic configuration satisfies high beta and low effective helical ripple operations required for reactors. Almost all these normalized requisites have been achieved in the LHD experiment. 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. As shown in Fig.1 Dr. L. Spitzer invented this concept in 1951, just 50 years ago. There were two helical research systems, planer axis and special axis systems. The former system consists of two concepts, so-called "Stellarator" concept (extended to C-Stellerator, Wendelstein 7-A) and

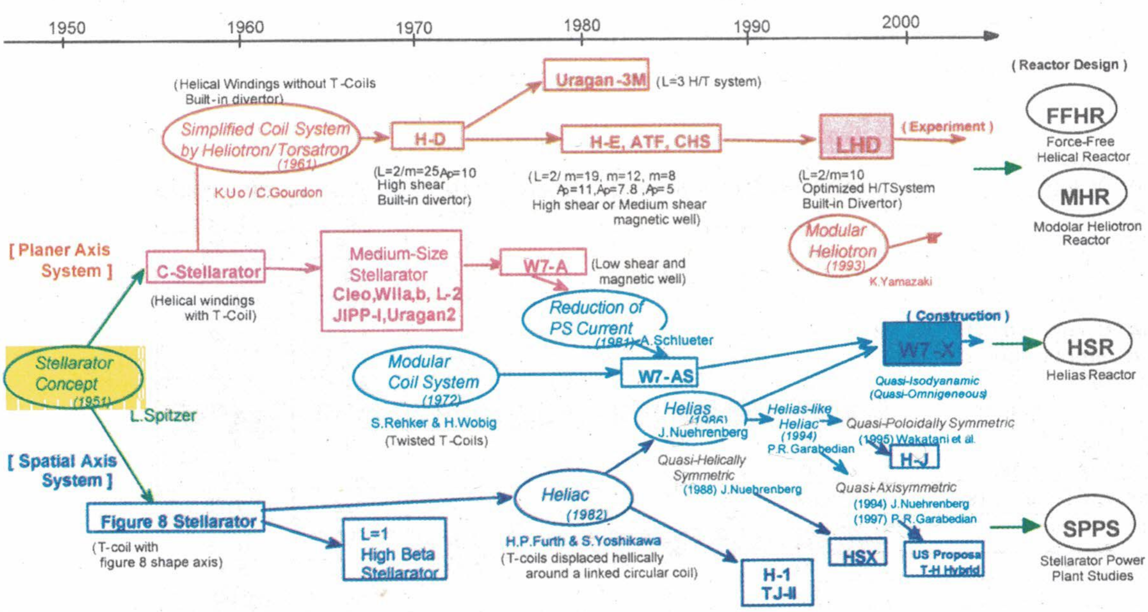

Fig.1 History of Helical system concepts

"Heliotron" concept (to Heliotron-D & E). On the other hand, the special axis system is created as the 8-Figure concept and later as the Heliac configuration.

Along these two systems, at present, there are two big helical experimental devices, the Large Helical Device (LHD, Fig.2) [1,2] and the Wendelstein 7-X (W7-X). The LHD had started experiments from April 1998, and the W7-X is now under construction. As an extrapolation of these experiments, several reactor designs (Table I) have been studied; MHR (Modular Heliotron Reactor, Fig.3) [3], FFHR(Force-Free-like Helical Reactor) [4], HSR(Helias Reactor) and SPPS(Stellarator Power Plant Studies).

Fig.2 Photo of LHD

In this overview paper, the Heliotron reactor design and related LHD experimental database are presented.

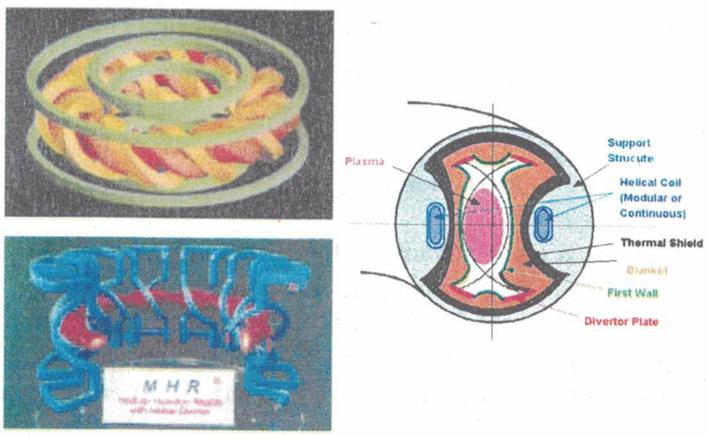

Fig.3 LHD-type plasma-coil systems with continuous coil (left up) or modular coil (left down), and reactor system (right).

TABLE I. Typical Helical Reactor Parameters

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 <n> ($10^{20}/m^3$)	2	3.4	1	1.4	1.33	1.46
Average Plasma Temperature <T> (keV	7.8	7.8	11	13.5	7.49	10
Volume Average Beta (%)	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 $_E$ (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

2. LHD Design and Experiment

The so-called Heliotron concept is characterized by simple continuous coil system, clean helical built-in divertor based on enough experimental databases from Japanese experiments. To demonstrate these merits of this concept, the Large Helical Device (LHD) had been constructed and started experiments from April 1998.

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 [5]. Three designs were compared as a function of axis-shift, and the slightly pitch-modulated coil configuration (case C in Fig.4) was decided as a final design of LHD. The magnetic surface of axis-position of R=3.75m is so-called standard design configuration. Inward shifted case is magnetic hill configuration. In this case particle orbit is improved like "omnigeneous" system (Fig.5).

Until now good confinement results are obtained in these inward-shifted configurations.

Table II shows experimental campaign of LHD and related hardware achievement. The 4th campaign has been conducted during last Japanese fiscal year, and the 5th experimental cycle will be started from September 2001. Table III shows maximum plasma parameters obtained in LHD so far. In the 4th cycle, plasma energy 1MJ and ~3% averaged beta value have been achieved.

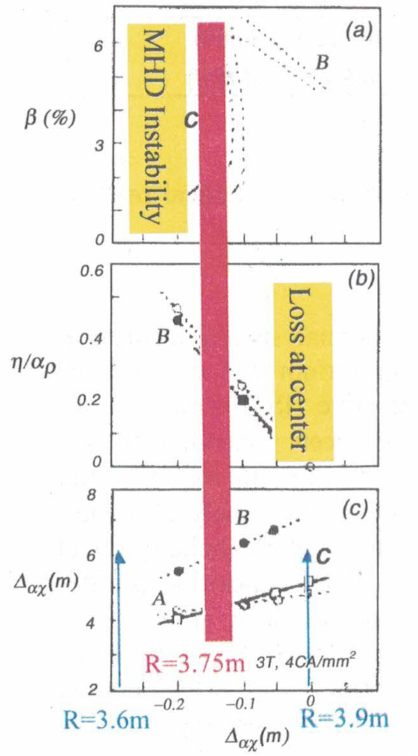

Fig. 4 Stability, particle loss, and divertor clearance vs. axis shift for LHD configuration

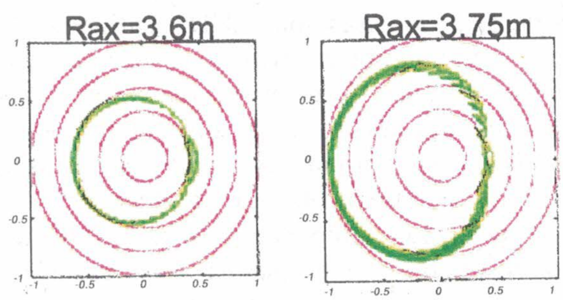

Fig.5 Deeply trapped particle orbit in LHD

TABLE II. Experimental Campaign of LHD

Exp. Campaign	2nd	3rd	4th	5th (Plan)
Period	Sep.16'98 - Dec.18'99	July 13 99 - Dec.14'99	Oct.2'00 - Feb.9'01	Sep.18'01 - Feb.15'02
Magnetic Field	1.5T	2.75T	2.8T	2.8T
ECH	0.4 MW	1 MW	1 MW	1.5 MW
ICRF		1.3 MW	2.7 MW	3 MW
NBI	3.5 MW	4.7 MW	5.2 MW	9 MW
Long Pulse (NBI)	22 s	80 s		
(ICRF)		68 s	2 min	

3. Confinement Database

TABLE III. Maximum achieved plasma parameters in LHD

	T_e	T_i	$_E$	n_e	P_{abs}
Electron Temperature	4.4 keV	2.7keV	0.06 s	$0.53 \times 10^{19} m^{-3}$	1.8 MW
Ion Temperature	3.3 keV	3.5 keV	0.09 s	$1.0 \times 10^{19} m^{-3}$	3.9 MW
Confinement time	1.1 keV		0.3 s	$6.5 \times 10^{19} m^{-3}$	2.0 MW
(Fusion Triple Product)	($n_i\ _E\ T_i = 2.0 \times 10^{19}\ m^{-3}$ s keV)				
Stored Energy	W_p = 1.03 MJ				
Average Beta	< > ~ 3 % (at B = 0.5 T)				
Line-Averaged Density	$n_e = 1.5 \times 10^{20}\ m^{-3}$				
Plasma Duration	$_{dur}$ = 80 s (at P_{NBI} = 0.5 MW) $_{dur}$ =120 s (at P_{ICRF} = 0.4 MW)				

As an extension of this LHD physics concept, the LHD-type helical reactors such as Modular Heliotron Reactor (MHR) and Force- Free-like Helical Reactor (FFHR) are under design. These reactors have been designed assuming improved plasma confinement nearly two times better than the conventional LHD scaling. The LHD experiments so far proved this assumption, which makes it possible to make helical reactors compact.

3-1. Transport Analysis Method

Transport analysis is required for two purposes, experimental data analysis and theoretical prediction simulation. For both purposes a 3-dimensional equilibrium / 1-dimensional transport code TOTAL was developed based on the previous predictive HSTR code [6]. By adding experimental data interface code PRE-TOTAL, it has been extended to the experimental data analysis code, and applied to the transient and steady-state experimental transport data analyses on LHD. Different from other experimental analysis codes, self-consistent equilibrium with experimental profile data, magnetic multiple-helicity effect and radial electric effects on neoclassical transport, time-varying NBI deposition profile, bootstrap current effects on equilibrium-transport, and so on are included (Fig.6). The self-consistent equilibrium has been treated with measured radial profiles by 11-channel FIR laser density measurements and 120-channel YAG Thomson scattering electron temperature measurements. Ion temperature is measured by charge-exchange spectroscopy and the radiation power loss from the plasma was measured by the bolometry.

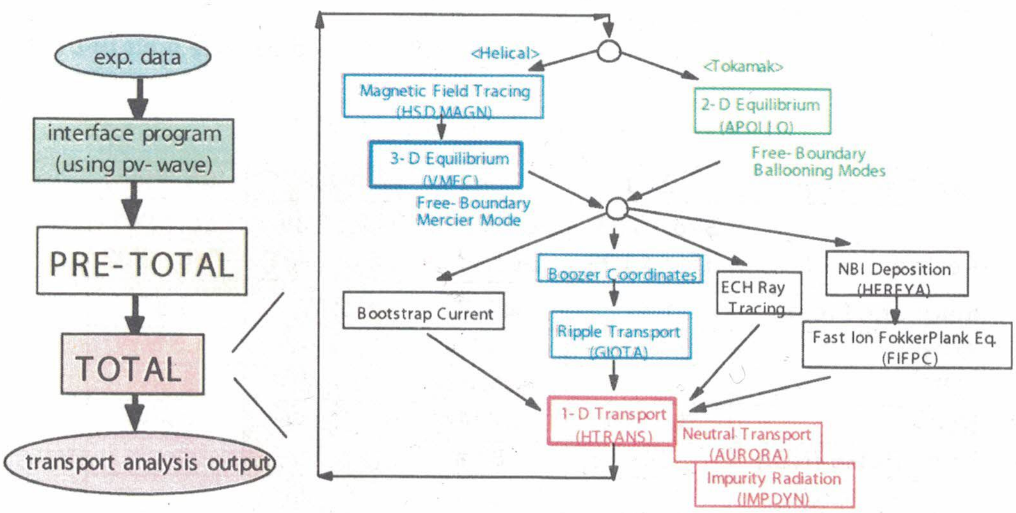

Fig.6 Flowchart of PRE-TOTAL and TOTAL code system for transport analysis

3-2. Global Scalings

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 [3]. 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 averaged helical ripple should be less than around 5 %,
(3) about 1.5 times higher plasma density than the helical density limit 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) are used. In the LHD experiment, we compared with conventional global confinement scaling laws for helical systems: LHD scaling (LHD), gyro-reduced Bohm scaling (GRB), Lackner-Gotardi scaling (LG) and International Stellarator Scaling (ISS95),

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

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

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

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

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 $\tau_E(s)$, $P(MW)$, $\bar{n}_e(10^{20}m^{-3})$, $B(T)$, $R(m)$, $a(m)$, 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.7(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:

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

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

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.7(b).

In the LHD experiments, the collisionality ν_{0*} regime relevant to reactors are already achieved, however, we should extrapolate the gyro-radius ρ_* effect to one order of smaller regime as shown in Fig.8. For this purpose, we applied analysis Kadomtev's dimensionl analysis technique. The obtained dimensionally-correct scaling laws are as follows;

$$\tau_{NLHD-D1} = 0.269 P^{-0.59} \bar{n}_e^{0.52} B^{1.06} R^{0.64} a^{2.58} \qquad (7)$$
$$\sim B^{-1} \rho_*^{-3.61} \nu_{0*}^{-0.17}$$

$$\tau_{NLHD-D2} = 0.115 P^{-0.64} \bar{n}_e^{\,0.54} B^{1.03} R^{1.04} a^{2.08} \qquad (8)$$
$$\sim B^{-1} \rho_*^{-3.41} \nu_{0*}^{-0.08} \beta^{-0.22}$$

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, which is different from previous conventional scaling laws (weakly gyro-Bohm) based on only medium-sized devices.

The density boundary used in these confinement scaling studies is ~ 1.5 times higher than the previous helical scaling laws, which condition fits the reactor core requirement.

As for beta value, a world highest beta value in helical systems (~3% in average) has been achieved in LHD. 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.

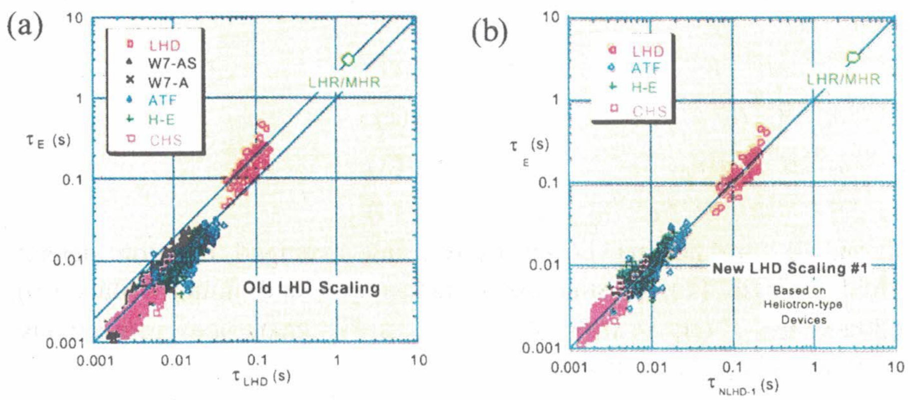

Fig. 7 Reactor plasma projection based on (a) old LHD scaling and (b) new LHD scaling NLHD-1

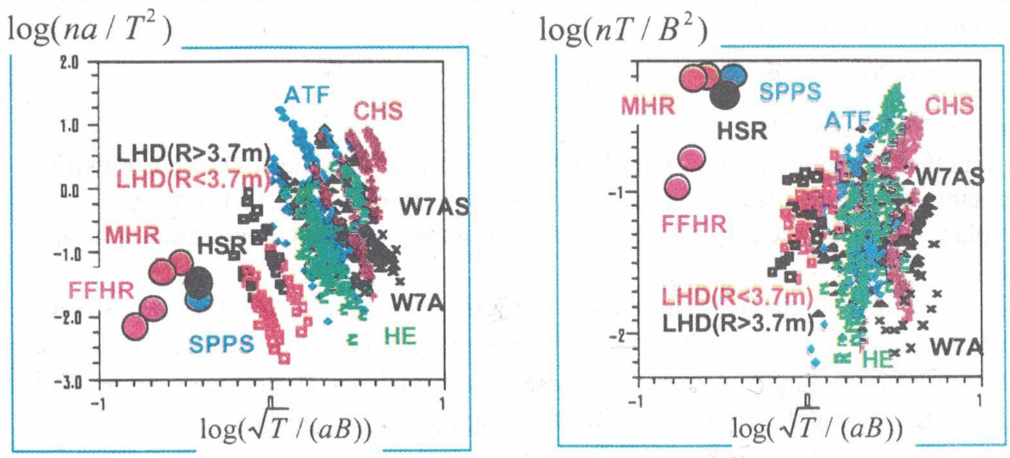

Fig. 8 Plasma regime as a function of ρ_* vs. ν_{0*} and ρ_* vs. β.

3-3 Local Scaling

Local transport analysis has been carried out and the effective thermal diffusivity χ_{eff} is defined as

$$\chi_{eff} = -(Q_{NBI}+Q_{RF}+Q_{OH} - dW/dt)/(2.5ndT/dr)$$

to avoid the uncertainty of ion temperature. Here, we use the following dimensionally normalized scaling:

$$\chi_E/(Ba^2) \sim 10^c \rho_*^{c_\rho} \nu_{0*}^{c_\nu} \beta^{c_\beta}.$$

The exponents of each parameter are obtained as a function of normalized minor radius by regression analysis as shown in Fig.9. It is found that the radial distribution is weak gyro-Bohm in the core and strong gyro-Bohm near the boundary. The global confinement feature is qualitatively consistent with strong gyro-Bohm-like local transport coefficient near the edge region.

Figure 10 shows a set of the diffusivities normalized by the neoclassical values for more than 50 discharges. Almost all data of this figure are in the ion-root negative-electric-field regime. The effective thermal diffusivity is same order of magnitude of neoclassical ion transport with the assumption of Ti = Te, especially agrees with them in the case of outward shifted case (R>3.7m) as shown in the right figure of Fig.10. On the other hand, in the case of inward-shifted configuration (R<3.7m) neoclassical transport is not dominant in the core region. According to the analysis of electron and ion diffusivities, the empirical electron thermal diffusivity is smaller than the neoclassical value, however ion diffusivity agrees well with neoclassical value. The radial electric field has been measured and roughly agrees with theoretical neoclassical values.

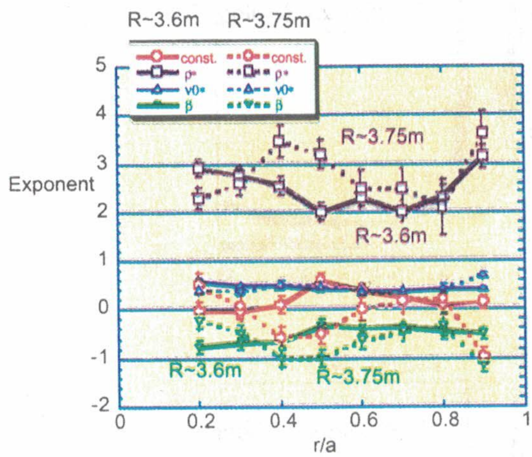

Fig.9Radial profile of dimensionless analysis

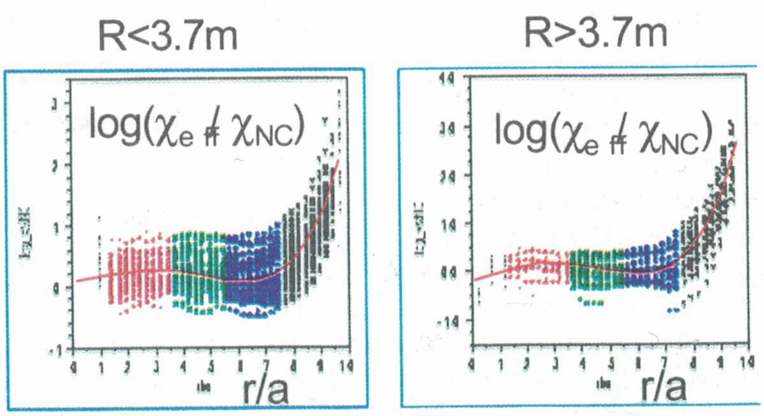

Fig.10 Comparisons with neoclassical transport and experimental values for a variety of discharges.

4. Reactor Plasma Projections and System Analysis

For reactor plasma projection, system code analysis (Fig.11) has been done. Using zero-dimensional plasma power balance model with radial profile corrections the POPCON plot is given in Fig. 12 with plasma confinement improvement factor of 2 or neoclassical confinement with edge helical ripple of 15% for R=15m, B= 5 T, m=10 LHD-type system. The real POPCON boundary is a combination of these two plots. In Figure 13 The "New LHD" scaling laws and other previous conventional scaling laws are compared as a function of confinement improvement factor. According to this new LHD scaling compact design is feasible without confinement improvement. 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.

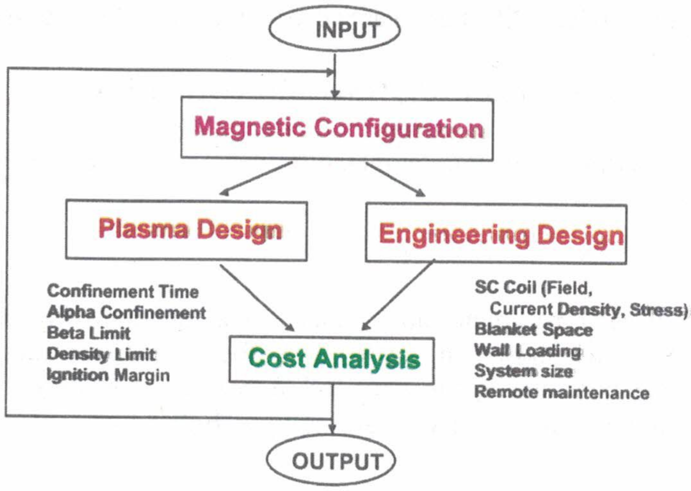

Fig. 11 Flowchart of Helical System Design

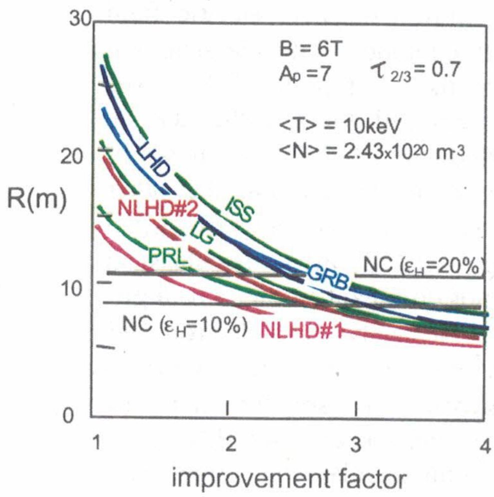

FIG.13 Reactor size vs. confinement improvement factor based on various helical confinement scaling laws in LHD-type helical reactors.

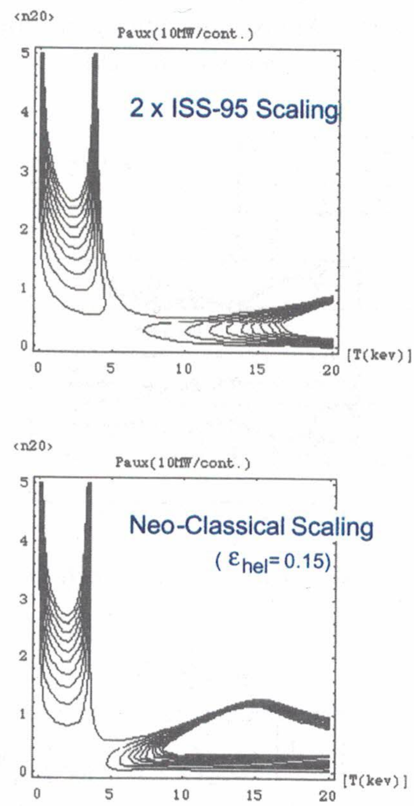

FIG.12 POPCON plot of helical reactor

Based on these plasma projection analyses, we made system design and cost analysis. Figure 14 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

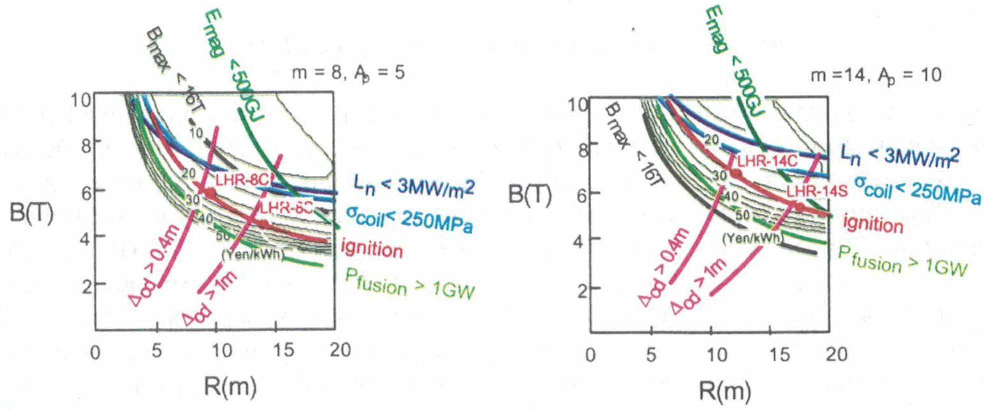

Fig. 14 Cost of Electricity of compact (left) and large (right) systems. Unit is Yen/kWh.

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.

5. Summary

This paper describes overview of helical concept features, present LHD experimental database and related reactor plasma design. Three design requirements for helical reactors are clarified: (1) confinement improvement , (2) plasma density regime and (3) beta limit, as follows.

(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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ПРОЕКТ ТЕРМОЯДЕРНОГО РЕАКТОРА, ЩО БАЗУЄТЬСЯ НА LHD

К. Ямазакі, Експериментальна група LHD

Зроблено огляд концепцій гвинтового реактора та пов'язаних із ним плазмових проектів, що базуються на базі експериментальних даних, отриманих на пристрої Large Helical Device (LHD). Спочатку було з'ясовано проектні вимоги до гвинтових реакторів щодо покращення утримання плазми, граничної густини та граничного бета. Потім на базі даних LHD було отримано декілька нових законів подібності утримання. У попередніх проектах реакторів типу LHD приймався час утримання плазми, який був удвічі кращим, ніж той, що відповідає звичайному закону подібності, і який нарешті, було досягнуто експериментально. Останній є відомим зараз як "Новий LHD-закон подібності". Було отримано густину плазми, яка в півтора рази перевищує граничну густину за стандартним законом подібності. Виконання цієї умови на початковій стадії реакторів є необхідним. В експерименті на LHD з магнітною конфігурацією зі зсувом усередину також досягнуто величину бета, яка є на 50 % більшою, ніж та, що потрібна для реактора, й яка знаходиться за межами граничного значення Мерс'є. Ця магнітна конфігурація із зсувом усередину забезпечує високе бета та малу ефективну гвинтову гофровку, які є необхідними для реакторів. Майже всі ці передумови отримано в експериментах на LHD. Сучасні експерименти на LHD можуть підтвердити майбутні перспективи гвинтового пристрою типу LHD як неперервно працюючого, ефективного й надійного реактора.