System Assessment of Helical Reactors in Comparison with Tokamaks

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Abstract. A comparative assessment of tokamak and helical reactors has been performed using equivalent physics/engineering model and common costing model. Higher-temperature plasma operation is required in tokamak reactors to increase bootstrap current fraction and to reduce current-drive (CD) power. In helical systems, lower-temperature operation is feasible and desirable to reduce helical ripple transport. The capital cost of helical reactor is rather high, however, the cost of electricity (COE) is almost same as that of tokamak reactor because of smaller re-circulation power (no CD power) and less-frequent blanket replacement (lower neutron wall loading). The standard LHD-type helical reactor with 5% beta value is economically equivalent to the standard tokamak with 3% beta. The COE of lower-aspect ratio helical reactor is on the same level of high-β_N tokamak reactors.

1. Introduction

Economically acceptable fusion reactors are anticipated as a future electric power plant, which requires steady-state and good-confinement plasma performances. At present with respect to the plasma confinement property the tokamak system is better than the helical system. However, the inefficient current-drive (CD) re-circulation power and the abrupt plasma current disruption events are worried from the standpoint of reactor economics. In contrast, the helical system is expected as a steady-state reactor [1], but it is supposed to be a rather big and expensive system. The comparative reactor study of tokamak and helical reactors had been carried out in Ref. [2-4] so far. After that period, much progress on physics and engineering databases has been performed [5]. To search for desirable helical reactors, it is worthwhile to carry out the system analysis of helical reactors by comparing with tokamak reactor designs. Moreover, using the common same-graded costing model we can clarify performance differences between helical and tokamak reactors.

2. Model of Helical and Tokamak Reactor Systems

System assessments have been done using newly arranged PEC (Physics, Engineering and Costing) code. The flowchart of this assessment for helical and tokamak reactors is shown in Fig.1. Several items are evaluated and optimized in physics design, engineering design and cost evaluations.

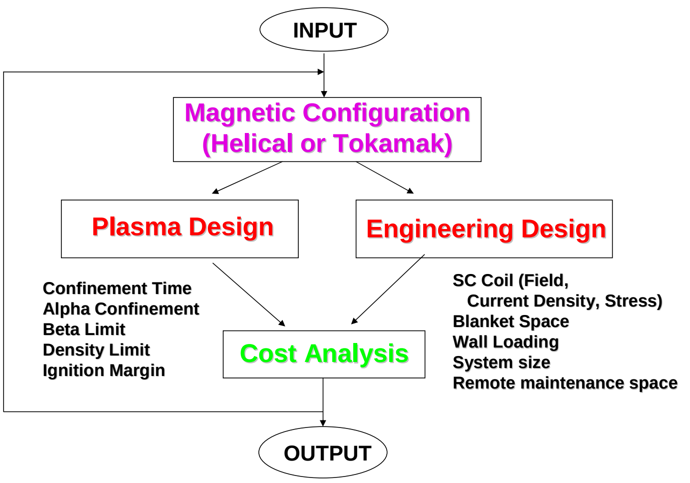

Fig.1 Flowchart of helical and tokamak system analysis

2.1 Magnetic Configurations

As for helical reactors several design concepts are studied here; the LHD (Large Helical Device)-type reactors (LHR) with continuous coil or Modular Heliotron Reactor (MHR) with modularized sector-coil systems [6] and quasi-axisymmetric modular helical reactor (QAR) based on the CHS-qa detailed design [7]. The LHR is characterized by the existence of enough plasma databases and the merits of sufficient spaces of helical divertor and remote maintenance. The plasma aspect ratio A_p is ~ 6.5 for the standard LHR with m=10 and γ=1.25 (m: helical period, γ: coil pitch parameter). The lower aspect ratio design with m=8 is also evaluated. The MHR was invented to solve the construction difficulties of large continuous superconducting coil systems of LHR. On the other hand, the N=2 QAR (N: toroidal period) with A_p ~3-4 is characterized by good confinement properties and compact design concept. In this design we need island divertor scenarios for helium ash exhaust. The tokamak reactors based on standard ITER-like designs (normalized beta: β_N ~3) [8] and higher beta compact designs (β_N ~4-5) [9] are also surveyed for the comparison with helical systems. The reactor models for both systems are shown in Fig.2. The system scale is determined by the radial-build of various system components. The plasma radius a_p and the coil thiskness t_c are deteremined by the plasma and engineering models.

2.2 Physics Model

Reactor plasma performances are determined by beta limits, confinement scaling laws and density limits. We checked several confinement scaling laws [1] including "New LHD" scaling laws. As for tokamak models the ITER Elmy H-mode confinement scaling [8] is used. The alpha-particle confinement fraction is assumed to be 0.9 for helical reactors and 0.95 for tokamaks.

The beta value of 5% is assumed for steady-state helical system without confinement degradation. Recent LHD experiments suggested the good operational regime of inward-shifted quasi-omnigenius configuration that is a target configuration of the LHR operation.

The density limit of the helical system (two times old LHD density scaling) is also considered [1] in comparisons with tokamak scaling laws (Greenwald limit). These plasma databases for both systems are checked comparatively [5]. In addition to simplified zero-dimensional power balance model with profile corrections, the TOTAL code predictive simulation [10] with empirical local transport coefficients has been carried out for the physics projections to the helical and tokamak reactors, which justified the simplified

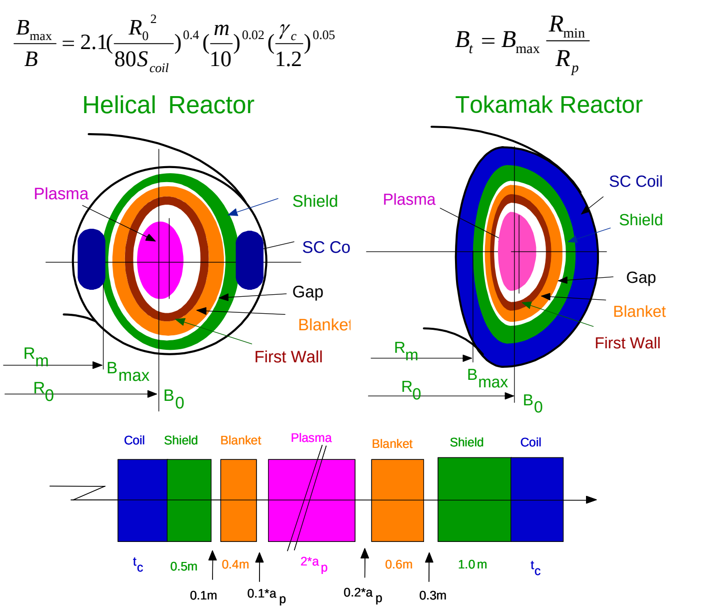

Fig. 2 Model of helical and tokamak reactor systems

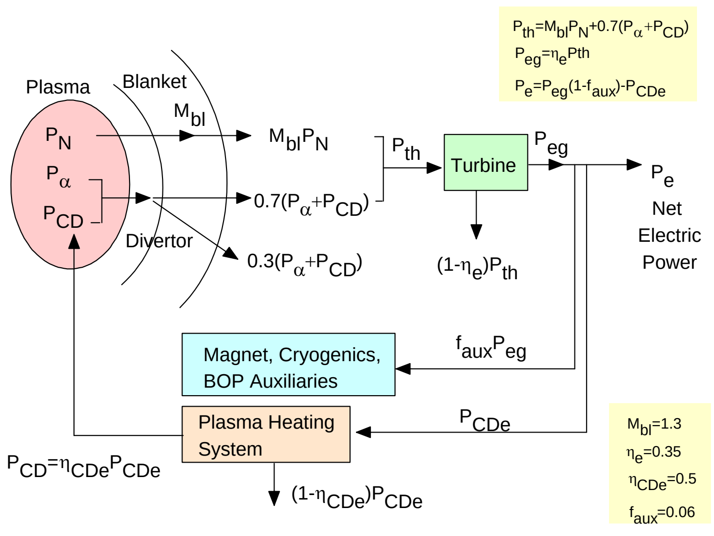

Fig.3 Power flow of fusion reactor

analysis.

2.3 Engineering Models

As for engineering design of helical and tokamak equivalent reactors, we assumed same thickness of blanket (inboard 0.5m, outboard 0.7m), shied (inboard 0.6m, outboard 1.0m) and relevant gaps (inboard 0.1m, outboard 0.3m) as shown in Fig.2. The reference magnet system is assumed made of Nb_3Sn conductor, and its maximum magnetic field strength is 12 Tesla. The superconducting coil engineering scaling for LHR/MHR is described in Ref. [11]. The coil current density, coil stress, wall loading and other engineering items are evaluated. These assumptions and relevant physics/engineering models determine the plasma-coil space and the scale of the reactor system. The thermal and electric power evaluated here is shown in Fig.3.

2.4 Costing Model

The cost analysis is mainly based on the unit costs per weight which values are mainly based on those of Refs. [12-14]. The unit cost of helical coil is assumed 25% higher than those of toroidal and poloidal coils. The main detailed values used here are shown in the Table 1. Here, Y is the normalized unit of cost (roughly 200Y~1US$).

TABLE I Unit Costs of System Components

	Unit Cost		Thickness(m)		Specific Weight	Remarks
	(U=100MY		inside	outside	(ton/m^3)	
Capital Cost						
Direct Cost						
Fusion Island						
Blanket	0.2	U/ton	0.45	0.6	4.8	Ferite.Be,Li2O
First Wall	0.1	U/ton	0.05	0.1	3.9	SS/Frite
Shield	0.04	U/ton	0.6	1	7.8	20% additional
TC Magnet	0.12	U/ton			7.9	Nb3Sn
PC Magnet	0.12	U/ton			7.9	25% of TF/HF Volume
HC Magnet	0.15	U/ton			7.9	Nb3Sn
Heating	2	U/MW				ICRF (50% efficiency)
Current Drive	4	U/MW				NNBI (50% efficiency)
Support	0.06	U/ton			6	50% of Coil Volume
Base	0.03	U/ton			6	25% of Coil Volume
Divertor	0.2	U/ton	0.05	0.1	6.9	2x10% of wall
Balance of Plant	2700	U*(Pf/4000)^0.6				6% addiditonal power
Indirect Cost	25% of Direct Cost					
time-related Cost	5% of Direct Cost					
Annual charge	10% of Capital Cost					
Operating Cost	4% of Capital Cost					
Component replacing						
Blanket	until maximum flux					10MW/m^2*year
Divertor	100% of Initial Cost					
Heating & CD	25% of Initial Cost					
Fuel	150	U/yr				
Waste disposal	0.2	Y/kWh				
Decomissioning	0.1	Y/kWh				
Electric conversisionnefficiency	35	%				
Availability	75	%				

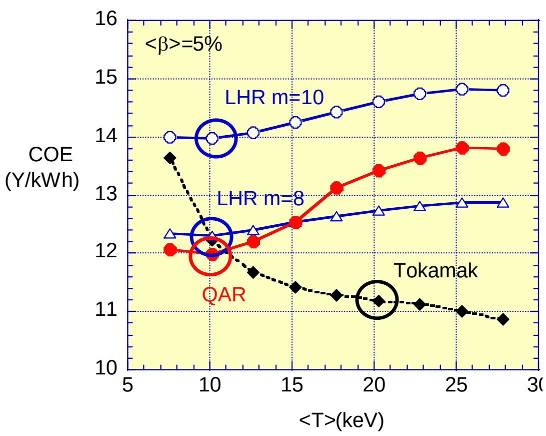

Fig.4 COE vs. averaged temperature.

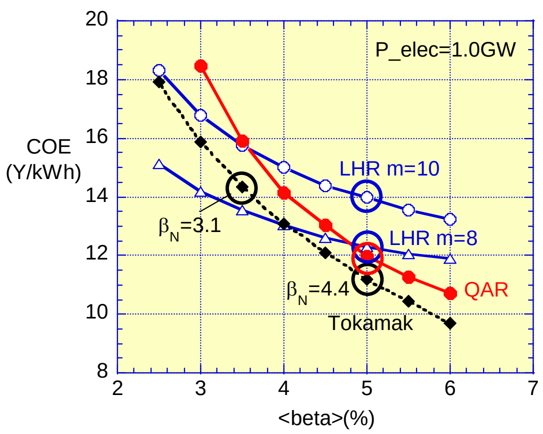

Fig.5 COE as a function of beta value.

3. Assessment Results

Figure 4 shows COE (Cost Of Electricity) as a function of average temperature <T>. High temperature plasma operation (<T>~20keV) is required in tokamak reactors to increase current drive (CD) efficiency and to reduce CD power. In contrast, rather low temperature operation (<T>~10keV) is feasible and desirable in helical system even to reduce helical ripple neo-classical transport. The density limit of helical systems is roughly two times higher than that of tokamaks. The effect of beta value is shown in Fig.5. If the tokamak operation with 5% averaged beta value (normalized beta: β_N =4.4) in the steady-state manner is not achieved, the helical system with 5% beta value will be one of target designs of future economical reactors.

The reference design points for both helical and tokamak systems are also plotted in these figures. The required confinement improvement factor is ~1.2 in these reference cases (see Table II). Figure 5 shows the plasma beta dependence of COE for helical (<T>=10keV) and tokamak (<T>=20keV) systems. In this figure, two tokamak design points are shown. The future reactor economics of tokamak reactors strongly depends on the attainable beta value in the steady-state operation.

The Fusion Island (FI) weight and FI cost of the standard LHD-type helical system are two times higher than those of reference tokamak design with same beta value and same net electric power, as shown in Table 1. However, no need of current drive (CD) power and the less-frequent replacement of blanket/heating equipments within the permissible neutron wall load (10MWyear/m^2) can contribute to the reduction in COE of helical reactor. Typically, for 1 GW plant, the wall load is ~1.5 MW/m^2 for large aspect ratio

Table II Typical Reactor Parameters (:input)*

Type	Helical			Tokamak	
	LHR m=10	LHR m=8	QAR N=2	Reference (β_N=3.1)	Reference (β_N=4.4)
R (m)	15.6	12.5	9.20	7.76	6.36
B (T)	4.5	4.6	4.7	7.0	6.62
Ap_avarage *	6.5	5.0	3.2	3.0	3.0
κ *	--	--	--	2.0	2.0
Vp (m^3)	1,773	1550	1,500	1.025	564
Ip (MA)	--	--	--	14.7	11.4
f_BS (%)	--	--	--	41	65
H_ISS95	2.75	2.54	2.21	--	--
H_NLHD1	1.28	1.15	0.95	--	--
H_ITER	--	--	--	0.908	1.17
<β> (%) *	5.0	5.0	5.0	3.5	5.0
β_N	--	--	--	3.1	4.4
Pwall (MW/m^2)	1.50	1.76	2.10	3.5	4.63
FI weight (ton)	33,870	26,760	23,690	20,814	14,550
FI cost (GY)	199	152	145	182	112
BOP cost (GY)	267	255	250	272	244
Capital (GY)	538	470	456	524	411
f_avail (%) *	75	75	75	75	75
P_thermal (GW)	3.04	3.04	3.06	3.89	3.44
P_elec (GW) *	1.0	1.0	1.0	1.0	1.0
COE (Y/kWh)	14.1	12.4	12.0	14.4	11.3

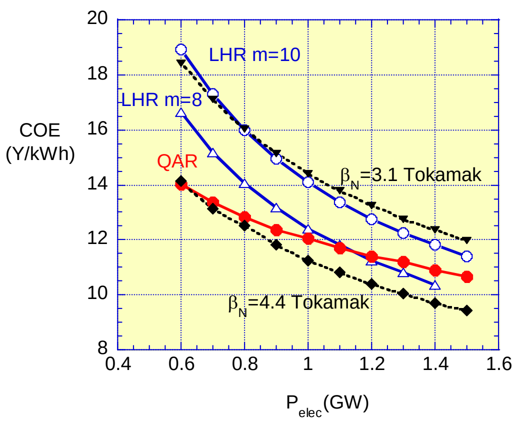

Fig.6 COE vs. electric power output

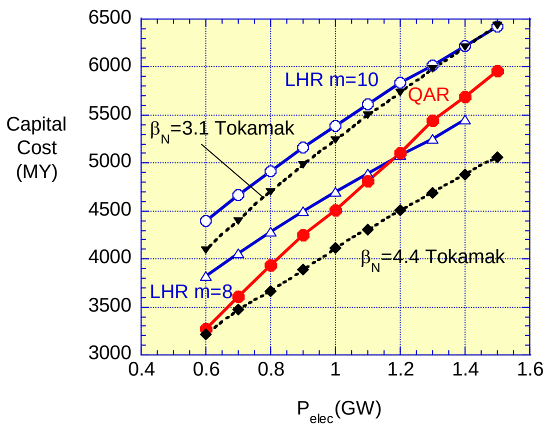

Fig.7Capital cost vs. electric power output helical reactor and ~4-5 MW/m^2 for reference tokamak reactors. Here the availability is assumed to be 75%. The increase in 10% of availability leads to decrease in 1.5Y/kWh of COE. This availability value should be determined by the easiness of remote maintenance and the probability of plasma disruptions.

The COE and capital costs for five reactor designs are given in Fig. 6 &7. The *m*=10 LHR with 5 % averaged beta value is economically on the same level of reference (β_N=3.1) tokamak reactors. The more compact helical reactor is more economical, and steady-state operations with higher plasma beta values are required in the future reactors.

The above-mentioned COE values critically depend on the unit cost of relevant equipments and operation scenarios of each reactor, and more detailed and careful assessments are required.

4. Summary

The system assessment of helical and tokamak reactors have been carried out using equivalent physics, engineering and costing models, and came to the following conclusions:

(1) High temperature operation is required in tokamak reactors to increase BS current fraction and to reduce CD power. In contrast, low temperature operation is feasible and desirable in helical system to reduce helical ripple transport.

(2) Capital cost of helical reactors is rather high, however, COE is almost same as that of tokamak reactors, because of smaller re-circulation power (no CD power) and less-frequent blanket replacements (lower neutron wall loading).

(3) The *m*=10 LHD type helical reactor with 5% beta value is economically equivalent to the standard tokamak with 3% beta value.

(4) The COE of lower-aspect ratio helical reactor (*m*=8 LHR, *N*=2 QAR) is on the same level of high-β_N (β_N~4) tokamak reactors.

(5) More compact, higher beta reactors operating in steady-state should be investigated for realization of future attractive fusion reactors.

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