§3. Economical Potential of LHD-type Helical Power Plants

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The design windows and economic analysis on LHD-type Helical Power Plants have been carried out based on the recent experiment results of LHD and the technology-cost basis of magnets developed for LHD and ITER. For searching design windows and discussing their potential as power plants, we have developed a mass-cost estimating model linked with system design code (HeliCos).

The design windows of helical reactors are discussed, considering not only the minimum B_0 and plasma size for required energy confinement time, but also the minimum reactor size getting enough blanket space for tritium breading. Searching the typical power plants of 3~ 4 GW fusion power we analyzed the standard LHD-type helical reactors, of which the basic geometry are similar to LHD, i.e. polarity l=2, field periods m=10, coil pitch parameter $\gamma=(m/l)/(R_c/a_c)=1.15\sim1.25$.

Table 1 shows the major design parameters of the typical helical power plants, given with the geometrically similar plasma to LHD and with the scaling law of ISS2004. The β of 5% for 4GW fusion power plants is expected, but for 3GW plants the smaller β (~4.4%) is yet manageable. With selecting adequate γ we can consider the wide range of design parameters, Rp=14.6~16.3 m, B_0=4.2~5.7 T, and W=122~144 GJ.

Table 1 Typical parameters of LHD similar helical power plants (Fusion power 3~4GW)

Design Parameters	Symbol (unit)	4GW standard plants β=5%, Hf=1.06-1.15			3GW β4.4%
Coil pitch parameter	γ	1.15	**1.20**	1.25	1.20
Coil major Radius	R_c (m)	15.91	**16.70**	17.63	16.69
Coil minor radius	a_c (m)	3.66	**4.01**	4.41	4.00
Plasma major radius	R_p (m)	14.69	**15.42**	16.27	15.40
Plasma radius	a_p (m)	1.78	**2.27**	2.85	2.27
Plasma volume	V_p (m^3)	916	**1565**	2604	1561
Magnetic field	B_0 (T)	5.74	**5.02**	4.42	5.00
Magnetic stored energy	W (GJ)	144	**131**	123	130
Energy confinement time	τ_{Er} (sec)	1.53	**1.95**	2.47	2.24
H factor to ISS04	Hf	1.064	**1.094**	1.151	1.150
Radiation loss	(GW)	0.13	**0.12**	0.11	0.09
Electron density $n_e(0)$	(10^{19}/m^3)	36.06	**25.77**	18.75	22.31
Line average density	(10^{19}/m^3)	28.32	**20.24**	14.73	17.52
Ion temperature	Ti(0)	14.68	**15.67**	16.69	15.69
Maximum field on	Bmax (T)	12.16	**11.91**	11.78	11.88
Coil current	I_{HC} (MA)	42.18	**38.67**	35.93	38.50
Blanket space	Δd (m)	1.10	**1.10**	1.10	1.10
Neutron wall loads	(MW/m^2)	2.9	**2.2**	1.7	1.7

We assessed the economical potential of helical power plants by estimating the weights and cost of key components (Table 2). As the conditions for calculating capital costs have been drastically changed in recent years, we should consider the rather low FCR~0.0578 (Fixed charge rate), which was used in the recent report of Japanese AEC for estimating nuclear power plants (with assumptions of 40 years life time and 3% discount rate). In estimating the cost of fusion power plants the operational cost of magnets should be taken special care for the inherent characteristics of long lifetime and a very high level of mean time between failures as these magnets should not fail. In regard to blanket, the blanket replacement frequency is a significant factor in the plant availability, which should be calculated depending on the neutron wall load.

The weight and costs of blanket and shield are estimated, 8,600~15,000 ton and 890~1,550 M$ with γ=1.15~1.25, basing on FFHR-2m1 blanket design studies [2]. The weight of blanket and shield are increased in proportion with the areas of the wall surface, although depending on the layout of the first walls and divertors.

We estimated the unit costs of magnet by using the cost basis of ITER and LHD experience [1]. In HeliCos code, we use the total magnet unit cost per magnetic stored energy, 1.59 BYen/GJ (14.4 M$/GJ) based on the magnet element unit costs per ton. The estimated total costs and weights of magnets for 3~4 GW power plants are 1,800 M$ (γ=1.25, 15,400 ton) to 2,080 M$ (γ=1.15, 18,000ton). Those magnet costs represent about 30% of the total plant cost, which can make the helical power plants of fusion power 3~4GW economically attractive.

We found that the economic characteristics of helical power plants is rather good as the cost of the large size helical coils is not so high in the conditions of β 5% plasma, because the lower magnetic field in the larger plasma volume makes the lower magnetic stored energy for the same fusion power.

Table 2 Economical potential of helical power plants estimated by the weights and cost of key components.

Plant Key Specs & Cost Item		Fusion Power 4GW			3GW
Net electric power	GW	1604	**1601**	1598	1194
Plant availability factor	f_A	0.680	**0.706**	0.726	0.727
Magnetic stored energy	GJ	144	**131**	123	130
Magnet (Weight and Cost*)	ton	18000	**16400**	15400	16200
	M$	2079	**1893**	1780	1875
	(%)	(34.6)	**(31.0)**	(28.0)	(33.7)
Blanket and shield (Weight and Cost*)	ton	8580	**11360**	14920	11340
	M$	889	**1177**	1546	1175
	(%))	(14.8)	**(19.3)**	(24.3)	(21.1)
Total construction cost	(M$)	7270	**7393**	7705	6735
Capital cost	*mill/kWh*	*44.0*	***43.2***	*43.8*	*51.2*
Operation cost	*mill/kWh*	*26.8*	***27.1***	*28.2*	*31.4*
Replacement cost	*mill/kWh*	*8.18*	***8.19***	*8.21*	*8.24*
Fuel cost	*mill/kWh*	*0.023*	***0.022***	*0.021*	*0.021*
COE (Cost of electricity)	*mill/kWh*	*79.0*	***78.5***	*80.3*	*90.9*

*The magnet costs, blanket and shield costs include the engineering indirect cost (2002 $).

1) Kozaki, Y. et al., 22nd IAEA Fusion Energy conf., FT/P3-18 (2008).
2) Sagara, A. et al., Fusion Eng. Design, 81(2006) 2703.
3) Dolan, T. J. et al., Fusion Science & Technology 47, 63 (2005)