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The Design Windows and Economical Potential of Heliotron Reactors

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Abstract. The design windows analysis and economical evaluation on Heliotron reactors have been carried out based on the recent experiment results of LHD and the technology-cost basis of magnets developed for LHD and ITER. We found that the Heliotron reactors have the technically and economically attractive design windows, where the major radius is increased as large as for the sufficient blanket space, but the magnetic stored energy is decreased to reasonable level because of lower magnetic field with the physics basis of H factor near 1.1 to the ISS04 scaling and beta value of 5%.

Keywords: reactor design, heliotron, design windows, cost analysis, superconducting magnet

1. Inroduction

The Heliotron reactors are characterized by a pair of helical coils with large major radius but moderate aspect ratio, which give us different approaches for power plants from tokamak reactors.

For design studies on magnetic fusion reactors many integrating system design codes had been developed and guided design studies, such as Generomak (J. Shefield, 1986) and system design codes in ARIES design studies. Most of the previous studies showed the importance of the mass power density, and suggested the much higher beta value and the smaller reactor size is necessary to achieve economical fusion reactors. But as far as magnetic confinement fusion the direction for the compact reactor has become suffer from severe neutron wall loads, diverter heat loads, and tritium beading ratios. For practical fusion power plants, we should consider adequate size and mass power density.

To remove those misunderstandings on the necessity of compactness, we must investigate design windows with estimating the detail mass-cost relationships, especially on magnets and blankets. We have much experience on costs of fusion device through preparing ITER construction. Now we can discuss the costs of magnet and major facility with some reality with the ITER database.

2. The HeliCos code for system design

2.1 Major design parameters and relationships

The major relationships between plasma parameters and reactor parameters in the HeliCos code are identified as follows.

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1) Basic geometry of plasma and helical coils

The geometry of plasma and helical coils are similar to LHD, i.e. polarity l=2, field periods m=10, coil pitch parameter $\gamma=(m/l)/(R_c/a_c)=1.15\sim1.25$. We consider a_p, a_c (minor radius of plasma and coil) and a_{pin} (inner minimum plasma radius) are also similar to LHD inward shift plasma case. The plasma radius a_p is given by the LCFS (Last closed flux surface) of the LHD magnetic field calculations depending on γ. The larger plasma volume and the better plasma confinement conditions are discussed in the LHD inward shift cases. We should consider making the largest plasma volume given by optimizing the LCFS conditions, also with making the ergodic layer thin as possible.

We can describe the relationships between a_p and a_c, or R_p, as an equation of a linear regression and also an index regression only depending on γ, in the $\gamma=1.15\sim1.25$, based on LHD experiment.

$$a_p=a_c(-1.3577+1.603\times\gamma)$$

$$a_p=0.2904\times\gamma^{3.495}\,a_c=0.06292\times\gamma^{4.495}\,R_p$$

The plasma volume V_p is expressed by the R_p and γ.

$$V_p=2\pi^2 a_p^2 R_p=0.0841\times R_p^3\,\gamma^{8.87}$$

2) The space for blanket: Δd

The Δd is described with the configuration of plasma and helical coils as follows (Fig. 1),

$$\Delta d = a_c - (R_c-R_p) - a_{pin} - H/2 - \Delta t \quad \text{--------------(1)}$$

$$a_{pin}=(-1.2479+1.2524\,\gamma)\times(R_c/3.9)$$

$$H=(I_{HC}/(j\times W/H))^{0.5}$$

$$I_{HC}=R_P\,B_0/(2m)\times10$$

I_{HC}, j: helical coil current and current density,

H, W: height and width of helical coils,

Δt: thermal insulation space.

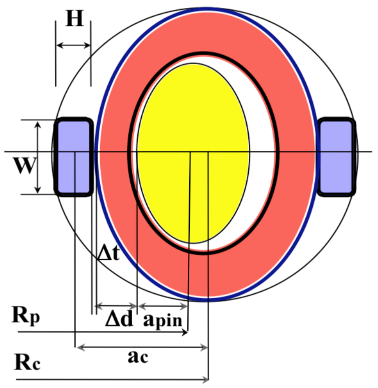

Fig.1 The profile of plasma, helical coil and blanket. The required blanket space constraints the minimum R_p.

The current density j depends on the B_{max}, which is given by the ratio of B_{max}/B_0,

B_{max}/B_0

$=(0.4819+0.41847(a_c/H)+0.0066851(a_c/H)^2)\times(R_p/R_c)$

The minimum blanket space Δd depends not only on the blanket-shield design but also the ergodic layer depth, of which optimization is one of the most important issues.

3) Fusion power given with B_0, β, and V_P

The fusion power is calculated by the volume integration of fusion power density p_f using the following reaction rate $<\sigma v>_{DT}$ and the plasma profile assumptions in the HeliCos code.

$p_f = n_T n_D <\sigma v>_{DT} V_p \times 17.58(\mathrm{MeV}) \times 1.6021\times10^{-19}$ (J/eV) $\times10^{-3}$ [GW]

$<\sigma v>_{DT}=0.97397\times10^{-22}\times\exp\{0.038245(\ln(Ti))^3 - 1.0074(\ln(Ti))^2 + 6.3997\ln(Ti) - 9.75\}(\mathrm{m^3/s})$

We might use a simple parabolic profile, index a_n for plasma density, and a_T for temperature to consider peaking factors. As we can calculate P_f easily by a good approximation, $<\sigma v>_{DT} \propto T_i^2$ for T_i~10keV to be well known, we use a following equation for sensitivity studies.

$P_f=0.06272/(1+2a_n+2a_T)\times n_e(0)^2 T_i(0)^2 V_p\times10^{-6} \propto \beta^2 B_0^4 V_P$ [GW], n_e:10^{19}/m^3, T_i : keV (2)

4) Power balance with the confinement scaling ISS04

The power balance is described using the required energy confinement time τ_{Er},

$P_\alpha f_\alpha - R_{loss}=W_p / \tau_{Er}$

($P_\alpha=0.2P_f$, f_α : α heating efficiency, R_{loss}:Radiation loss

W_p : plasma stored energy, $W_p \propto n_e(0)T_i(0)V_p$)

We use the energy confinement scaling ISS04, which can be expressed only with the R_p and γ as geometrical parameters [1].

τ_E(ISS04)

$=0.134\,(f_\alpha P_\alpha - R_{loss})^{-0.61} n_{el}^{0.54} B_0^{0.84} R_P^{0.64} a_p^{2.28} \iota_{2/3}^{0.41}$

$=6.23\times10^{-5} R_p^{1.09} \gamma^{2.98} (p_f(1- r_{loss}))^{-0.61} B_0^{0.84} n_{el}^{0.54}$

[ms]

($p_f= P_f / V_p$, $r_{loss}= R_{loss} /(0.2 f_\alpha p_f V_P)$,

r_{loss}: radiation loss rate)

The H factors are calculated using the density limit and density profile conditions as follows.

H_f (ISS04)= $\tau_{Er} / \tau_{E(ISS04)}$

$H_f =76.4\times f_{np}\times R_p^{-1.09} \gamma^{-2.98} p_f^{-0.16}(1-r_{loss})^{-0.66} B_0^{-1.11}$ (3)

f_{np} : density profile effect coefficient

(f_{np}=1.0 in the $n_{el}=1.2n_c$ and a_n=0.5 case)

$n_c=149.0\times p_f^{1/2} B_0^{1/2}$ [10^{19}/m^3], n_c : Sudo density limit

2.2 Major equations and calculation flow

We can calculate the major design parameters, B_0, R_p , γ, P_f , based on the three equations (1),(2),(3). Therefore the design points of the LHD-similar heliotron reactor are given with the cross points of the following three equations on the B_0-R_p plane.

1) The Δd-equation : $\mathbf{B_0(R_p, \gamma, \Delta d, j)}$ from eq.(1)

$B_0=(16j/R_p)((0.2633- 0.1312\,\gamma) R_p - 20.41(\Delta d +0.1))^2$ [T] (4)

2) The P_f equation : $\mathbf{B_0(R_p, \gamma, \beta, P_f)}$ from eq. (2)

$B_0=92.64\, P_f^{1/4} \beta^{-1/2} \gamma^{-2.22} R_p^{-3/4}$ [T] (5)

3) The H_f -equation : $\mathbf{B_0(R_p, \gamma, H_f, P_f)}$ from eq. (3)

The relationships between major equations, calculation flows and the issues to be considered are shown in Fig. 2.

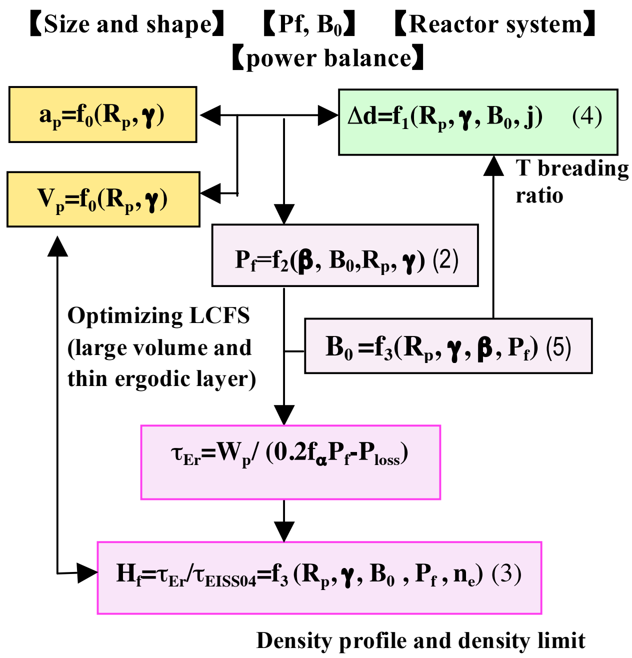

Fig.2 The major design parameters and calculation flows.

3 The design windows of Heliotron reactors

3.1 The constraints of design windows

In general the design spaces of magnetic fusion reactors are limited with following three constraints,

1) the Δd blanket space conditions necessary for tritium breading,
2) the B_0 and V_P conditions satisfying power balance with H factor limitation,
3) the upper magnetic stored energy (W) constraints for avoiding the difficulty of manufacturing.

Then the design space on the R_P-B_0 (or W) plane has the minimum R_P boundary given by the Δd constraints, the lower boundary of B_0 from H factor conditions, and the upper boundary of B_0 from the W constraints. With increasing γ the design points of helical reactors move to the larger R_P according to increasing plasma radius and much severe Δd constraints. For each γ Bo decreases with increasing Δ d, although W increases.

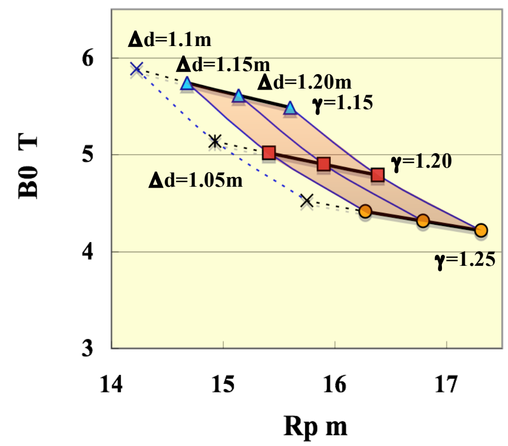

Fig. 3(a) Design windows on the R_p-B_0 plane.

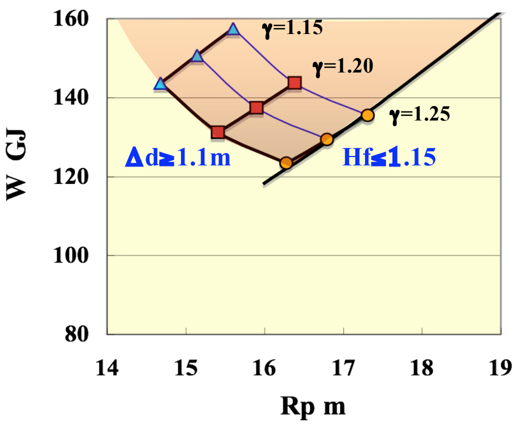

Fig. 3(b) Design windows on the R_p-W_0 plane.

Fig. 3(a), (b) Design windows are limited with the constraints of Δd≥1.1m, Hf≤1.15 and W<160G, depending on γ (β 5%, Pf 4GW case).

Though the minimum R_P increases with increasing γ, the B_0 decreases so much that the W also decreases with increasing the minimum R_P .

3.2 The design windows depending on γ and β

Searching for attractive fusion power plants a wide range of design options was investigated, β values from 3% to 5%, and fusion power P_f from 2GW to 4GW as shown in figure 4(1)~(3).

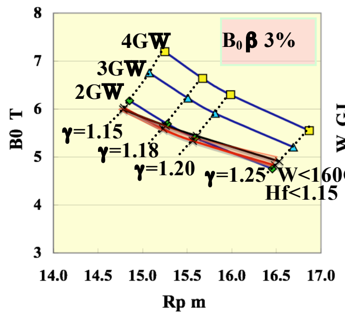

Fig. 4(1)(a) B_0 in β 3%

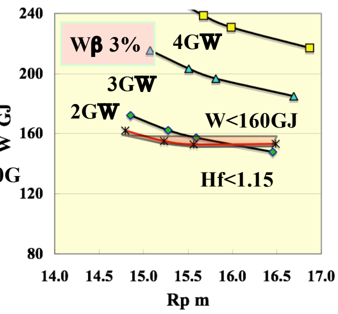

Fig. 4(1)(b) W in β 3%

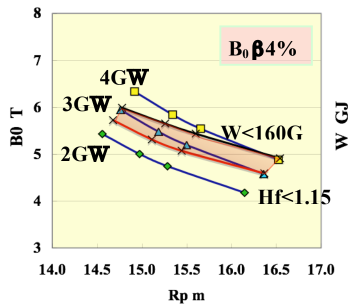

Fig. 4(2)(a) B_0 in β 4%

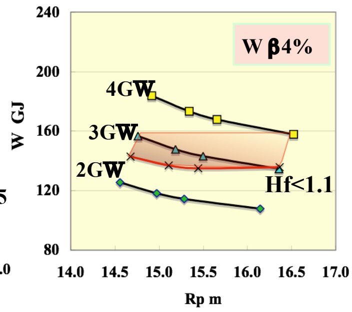

Fig. 4(2)(b) W in β 4%

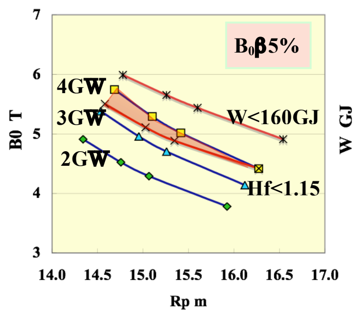

Fig. 4(3)(a) B_0 in β 5%

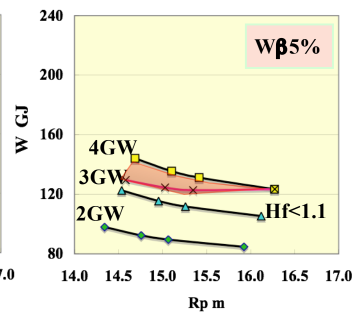

Fig. 4(3)(b) W in β 5%

Fig. 4(1)~(3) The design windows of Heliotron reactor strongly depend on γ and β, limited with the constraints of Δd=1.1m, H_f≤1.15, W<160GJ. The γ dependence are shown with the four points, γ=1.15, 1.18, 1.20, 1.25 on each line[4].

In the β 3% cases, even though in the smaller P_f plants, magnetic stored energy W is near upper boundary. In the β 4% cases, we can consider wide design space with B_0=5~6T, Pf=3~4GW, although W is rather large, ~150GJ.

In the β 5% cases, we can consider the optimum design windows of P_f=3.3~4GW plants with R_P=14.6~16.3m, B_0=4.4~5.5T, and W=125~140GJ

We should notice that the H factor conditions in β 5% are severe in the smaller P_f case and the larger γ case. Therefore in the H_f=1.10 case we must consider the minimum P_f is 3.8GW for γ=1.15, and P_f is 4.5GW for γ=1.25. We should also notice that the design windows must shift the larger R_p and the larger W in the large Δd case, as shown in figure 3.

4. Cost model

4. 1 Cost estimating methods

The COE (Cost of Electricity) is calculated with the general cost estimating method and the unit cost data and scaling lows for BOP (balance of plant) [5,6]. The cost of magnets and blanket -shield are estimated based on mass cost analysis. The capital costs are calculated using rather low FCR (~0.0578:Fixed charge rate) used in the recent report of Japanese AEC for estimating nuclear power plants (40 years life time and 3% discount rate).

The operation cost of magnet should be taken special care for the inherent characteristics of long lifetime and easy maintenance. In regard to blanket the periodic replacement is necessary, and the availability factors are estimated in changing with neutron wall loads.

4. 2 Magnet cost estimation

We estimated the unit cost of magnets to be related to weights and magnetic stored energy, thorough analyzing the cost factors of magnet systems based on the LHD construction, ITER construction and the FFHR-2m1 design studies [2]. In the FFHR2m1 design we considered a CIC conductor for helical coils based on the engineering base for ITER and the winding technology of LHD helical coils.

The cost factors are estimated in breakdown components such as super conducting strands, conduits, support structures, and winding process in each coil systems. The costs of the conductors and the winding occupy about 70% of the total magnet costs (Fig. 5).

The total weight 16,000 ton and the total cost 210 BYen are estimated for the total magnet systems of the 3GW Heliotron power plant, in which the magnetic stored energy is 133GJ [3].

Comparing the helical reactor magnets to ITER magnets, the magnetic stored energy is about three times, the weight is 1.6 times and the cost is about 2 times of ITER (ITER 2002 report, and FDR1999 report).

For the superconducting magnets having similar configuration we could consider the costs are

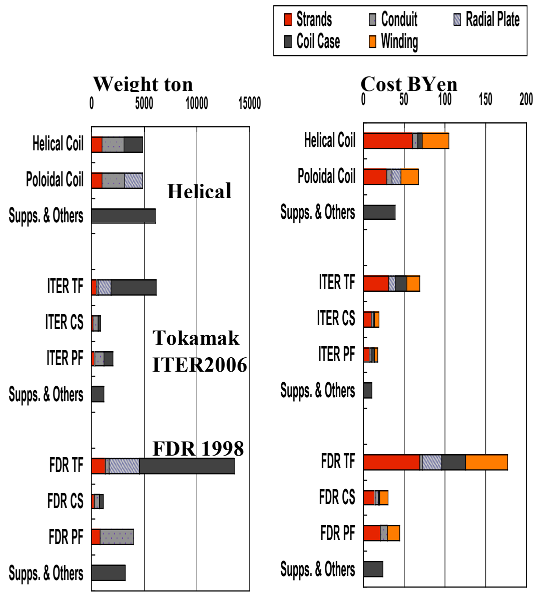

Fig. 5 The weight and cost of the magnets of the helical reactor (FFHR-2m1) and the tokamak reactor(ITER).

proportional to weights, which are approximately proportional to the stored energy. In HeliCos code we can use the above unit cost per ton that means the total unit cost is 1.59 BYen/GJ (14.4 M$/GJ).

5. Standard Heliotron power plants and economic analysis

5.1 Heliotron reactors of 3~ 4 GW fusion power

Table 1 shows the major design parameters and costs of typical Heliotron reactors. For 4GW fusion power plants β=5% 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, R_p=14.6~16.3 m, B_0=4.2~5.7 T, and W=122~144 GJ.

We could understand the reason why the difference of design parameters for different γ is so large, by comparing plasma volume, i.e., 920 m^3 in γ=1.15 versus 2600 m^3 in γ=1.25. The sensitivity of increasing V_P versus decreasing B_0 is very interesting. The optimization of the LCFS (V_p) might be one of the most important issues.

The major parameters in Table 1 are dominated with the simple relationships shown in 2.2. But there are remaining many uncertainties regarding power flows and mass flows, especially in the local heat load to the diverter. Those problems on optimizing LCFS, controlling ergodic layer and diverter plasma must be critical issues to be considered in the next design studies.

Table1. The major design parameters and mass-cost estimation of standard Heliotron reactors

Design Parameters	Symbol (unit)	4GW standard plants β=5%, Hf=1.06-1.15			3GW Hf=1.15
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
Inner plasma radius	a_{pin} (m)	0.78	**1.09**	1.44	1.09
Plasma volume	V_p (m^3)	916	**1565**	2604	1561
Magnetic field	B_0 (T)	5.74	**5.02**	4.42	5.00
Average beta	β	5.0	**5.0**	5.0	4.37
Fusion power	Pf (GW)	4.00	**4.00**	4.00	3.00
Energy confinement time (ISS95)	$\tau_{E(ISS95)}$ (msec)	0.84	**1.04**	1.25	1.14
Energy confinement time ISS04	$\tau_{E(ISS04)}$ (msec)	1.43	**1.78**	2.14	1.95
Required energy confinement time	τ_{Er} (msec)*	1.53	**1.95**	2.47	2.24
H factor to ISS04	Hf	1.064	**1.094**	1.151	1.150
Radiation loss **	Rloss (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	n_{el} ($10^{19}/m^3$)	28.32	**20.24**	14.73	17.52
Density limit	n_c ($10^{19}/m^3$)	23.6	**16.87**	12.27	14.61
Ion Temperature	Ti(0)	14.68	**15.67**	16.69	15.69
Iota 2/3	$\iota(2/3)$	0.904	**0.775**	0.641	0.775
Maximum field on coils	Bmax (T)	12.16	**11.91**	11.78	11.88
Coil current	I_{HC} (MA)	42.18	**38.67**	35.93	38.50
Coil current density	j (A/mm^2)	26.0	**26.0**	26.0	26.0
Helical Coil height	H (m)	0.90	**0.86**	0.83	0.86
Blanket space	Δd (m)	1.10	**1.10**	1.10	1.10
Neutron wall loads	f_n (MW/m^2)	2.9	**2.2**	1.7	1.7
Weight of Blanket and shield	Mbs (ton)	8580	**11360**	14920	11340
Magnetic stored energy	W (GJ)	144	**131**	123	130
Weight of magnets	Mmag (ton)	18000	**16400**	15400	16200
*Magnet cost (%)****	*Cmag*	*2079(34.6)*	***1893(31.0)***	*1780(28.0)*	*1875(33.7)*
*Blanket and shield cost (%)****	*Cbs (M$)*	*889(14.8)*	***1177(19.3)***	*1546(24.3)*	*1175(21.1)*
Total construction cost	*C (total)*	*7270*	***7393***	*7705*	*6735*
Net electric power	Pn (GW)	1604	**1601**	1598	1194
Total auxiliary power	Pa (GW)	109	**112**	115	91
Plant availability factor	f_A	0.680	**0.706**	0.726	0.727
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*

*Effective ion charge Zeff=1.32,

**Alpha heating efficiency 0.9, and profile index a_n=0.5,a_T=1.0.

*** The magnet costs, blanket and shield costs include the engineering indirect cost.

5. 2 Economic potentials of Heliotron reactors

We could consider the magnet cost and the blanket-shield cost are dominant cost factors in the magnetic confinement fusion reactor, as far as the normal steady operations are achieved with the reasonable recirculating power, and the sufficient plant availability factors without suffering from too high heat load or neutron load.

Using the magnetic stored energy and the unit cost mentioned in figure 5, we estimated the magnet costs shown in Ttable 1, which are 1800 M$ (γ=1.25, 15400 ton) to 2080 M$ (γ=1.15, 18000ton). Those magnet cost ratio to total plant cost are about 30%, which can make the Heliotron power plants of fusion power 3~4GW economically attractive.

In the LHD-similar-shape Heliotron reactors, when the major radius R_p and γ (i.e., a_p) increases, the magnetic field B_0 decreases much in the same β-P_f and Δd conditions as shown in figure 6(a). That is why the magnetic stored energy W decreases even if in the larger coil size. These characteristics between plasma volume (given with R_p, γ) and B_0, and magnet cost are shown in figure 6(a). The costs of blanket and shield (Cbs) are estimated basing on FFHR-2m1 blanket design studies [2] and are increased in proportion with $R_p a_p$. The sensitivity analysis regarding current density, plasma profile and density limit are carried out.

When the R_p and γ increase, the magnet cost decreases but the blanket-shield cost increases. Therefore the COEs of Heliotron reactors, depending on R_p, γ, show the bottom as the result of the trade-off between the magnet cost and the blanket-shield cost, i.e., B_0 versus plasma volume

The COEs of Heliotron reactors shown in figure 6(b) suggest us that the technically and economically attractive design windows exist in the rather wide area of the large R_p (15~16m), medium γ (~1.20) and β values (~5%), and the reasonable magnetic stored energy (~130 GJ).

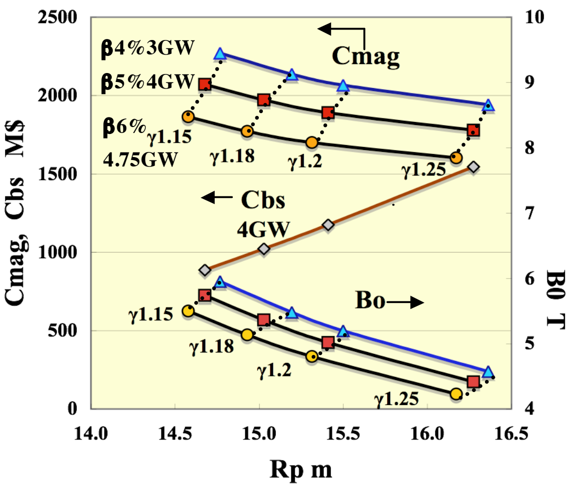

Fig. 6(a) The B_0, magnet cost (Cmag), and blanket Cost (Cbs) depend on R_p, γ and β. When R_p and γ increase, Cmag decreases but Cbs increases. Those plots on R_p (γ) are given with Δd=1.1m.

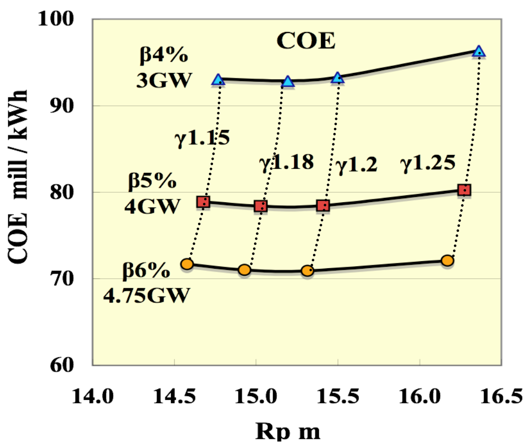

Fig. 6(b) The COEs of Heliotron reactors, which depend on plasma major radius R_p, coil pitch parameter γ and β, show the bottom near R_p=15~15.5m with blanket space condition Δd=1.1m.

6. Conclusions

We can summarize the results of analysis as follows,

1) LHD-type helical reactors have the attractive design windows in rather large plasma major radius of 15~16m, with the sufficient blanket space and the reasonable magnetic stored energy of 120~140 GJ based on the physics basis of H factor near 1.1 and β of 5%.
2) The β dependence is very important for selecting the optimum fusion power with reasonable magnetic energy, so that the confirming good confinement in the near β~5% plasma is the first priority of critical issues.
3) The γ dependence is essential in Heliotron reactors that is critically sensitive not only for optimizing LCFS (plasma volume) but for selecting the optimum blanket design.
4) There are many remaining subject to be studied, in especially, the problem of the particle and heat loads on the diverter are a critical issue to be considered in the next analysis.

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