Japan-US Workshop on
Fusion Power Plants and Related Advanced Technologies March 5-7, 2008
UCSD, La Jolla, CA, USA

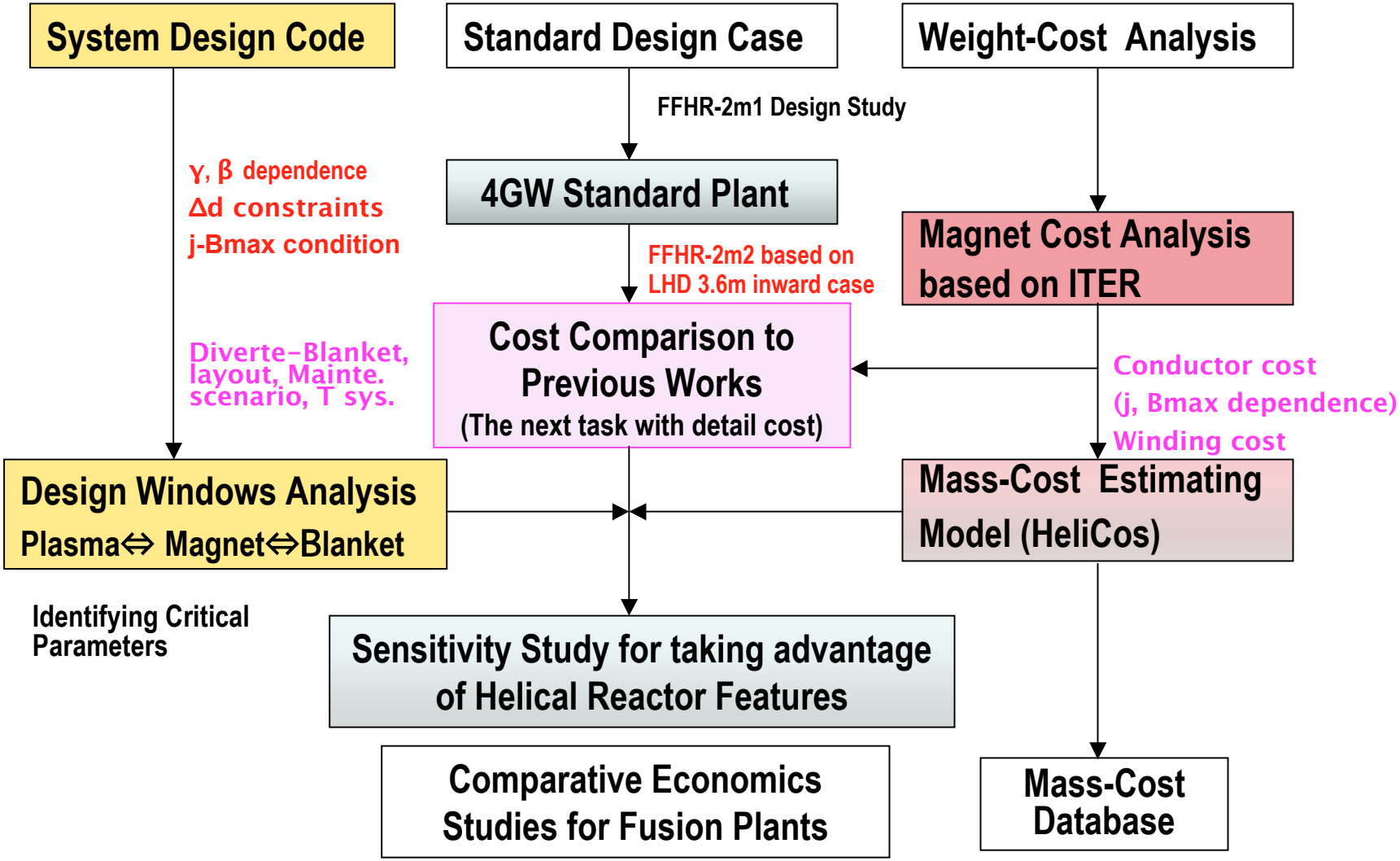
Design Windows and Cost Analysis on LHD-type Helical Reactor

Yasuji Kozaki, NIFS

Outline

- Introduction What is LHD-type? Why Heliotron shows so good performance?
- A System Design and Cost Estimation Code on LHD-type Helical Reactor HeliCos → Major design parameters and their relationships.
- The reactor size and magnet conditions depending on γ and β (large size but low B, slender or fat) → It is not correct that small is always economical.
- Blanket space Δd determines the minimum major radius depending on γ.
- Design windows are mainly restricted by 1) Δd, 2) the upper limit of stored energy W, 3) the lower limit of B_0 for plasma confinement (H factor).
- The magnets cost analysis based on the ITER and LHD construction data.
- The sensitivity study on current density.
- Summary

System Design and Mass-Cost Estimating Model (HeliCos)
-Tasks for developing methodology and studying design windows-



Major design parameters, their relationships, and conditions

1) Power balance

- $P_\alpha / h_\alpha = Wp / \tau_E + P_r$, $P_\alpha = Pf / 5$ (Radiation loss $P_r = P_{brm} + P_{syn} + P_{li}$)
- $Pf = f_p\, n_T\, n_D \langle\sigma v\rangle_{DT}\, Vp \times 17.58(MeV) \times 1.6021\times10^{-19}\,(J/eV) \times 10^{-3}$ [GW]
- f_p: Density and temperature profile (Parabolic: Index a_n, a_T)

2) Energy confinement scaling ISS95 and H_f factor

$\tau_E = 0.26\,(P_\alpha/h_\alpha - P_r)^{-0.59} n_e^{0.51} B_0^{0.83} R^{0.65} a^{2.21} \iota_{2/3}^{0.4}$ (ISS95) , H_{iss}~1.5 attained experimentally

$\tau_E = 0.134\,(P_\alpha/h_\alpha - P_r)^{-0.61} n_e^{0.54} B_0^{0.84} R^{0.64} a^{2.28} \iota_{2/3}^{0.41}$ (ISS04)

H_f =(Required τ_E / τ_E), Required $\tau_E = Wp / (P_\alpha/h_\alpha - P_r)$ (h_α : alph heating efficiency)

3) Geometry and Magnet Design (γ and a_p, B_{max} , j, blanket space Δ d)

- Coil pitch parameter γ=1.15~1.25 (Polarity l=2, Field periods m=10, 3.6m LHD inward shift)
- $a_p = a_c\,(-1.3577 + 1.603 \times \gamma)$
- $B_{max}/B_0 = (0.4819 + 0.41847(a_c/H) + 0.0066851(a_c/H)^2) \times (R_p/R_c)$
- $I_{HC} = (R_P / B_0)/(2m) \times 10$, $H = (I_{HC} / (j \times W/H))^{0.5}$ (W: width of HC, H: height of HC)

4) Blanket space $\Delta d = a_c - (R_c - R_p) - a_{pin} - H/2 - 0.1 \geqq 1.1$ m +0.05 (0.05:ergodic layer depth)

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

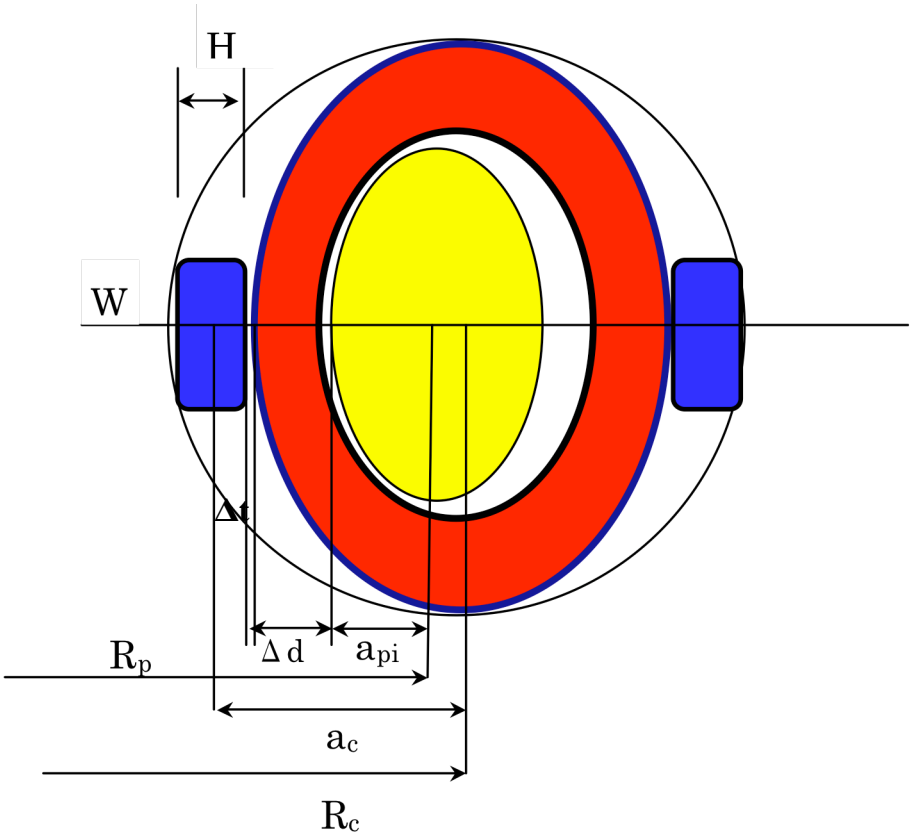
The Basic size and layout of magnets and blankets

・Magnet design conditions

$$B_{max}=(0.4819+0.41847(a_c/H)+0.0066851(a_c/H)^2)\times B_0\,(R_p/R_c)$$

$$I_{HC}[MA]=\frac{R_p\times B_0}{2\times m}\times 10$$

$$H=\left(\frac{C_I}{j\times r_{(W/H)}}\right)^{0.5}$$



・Blanket design conditions

$$(a_c-a_p)_{min}=a_c-(R_c-R_p)-a_{pin}$$

$$\Delta d=(a_c-a_p)_{min}-\frac{H}{2}-0.1$$

(Δt= 0.1 m : distance for thermal shields)

Design windows of Heliotron reactor(Pf=3GW,4GW) (Δd≤1.1m, Hf≤1.16, W<160G)

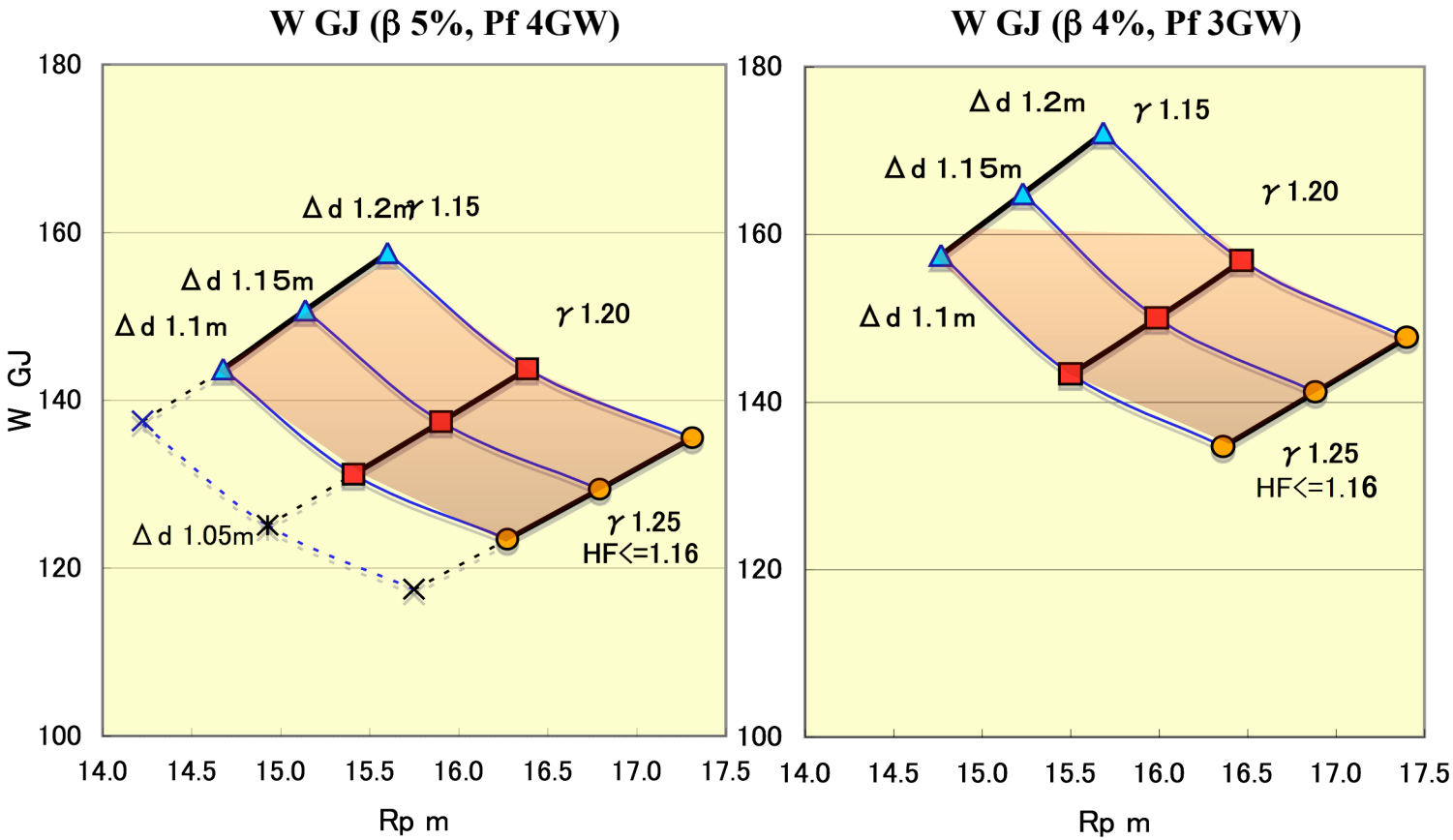


Fig.1 The design windows limited with Δd≥1.1m, Hf≤1.16, W<160G, depending on γ and β (Two β-Pf cases are shown, β 5%, Pf 4GW, and β 4%, Pf 3GW). Hf=1.16 means the 1.2 times value achieved in LHD experiment [1]. j=26A/mm^2 premised.

Design windows of Heliotron reactor(β 4%)
(B_0 - Pf, W, COE ; Δd≤1.1m, Hf≤1.16, W<160G)

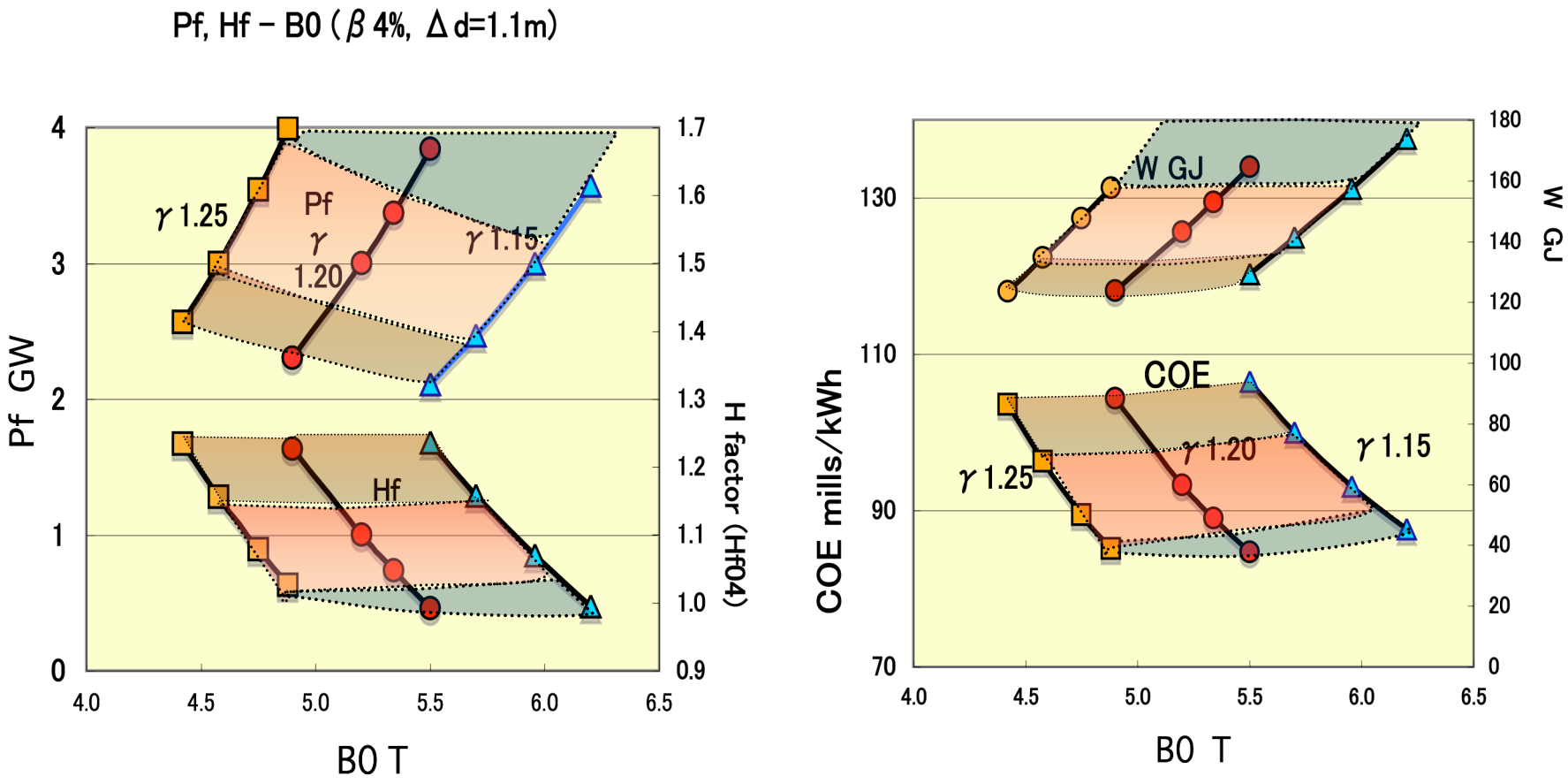


Fig.4-1 The design windows limited with Δd≥1.1m, Hf≤1.16, W<160G, depending on γ and β (β 4%case, j=26A/mm^2).

Design windows of Heliotron reactor(β 5%)
(B_0 - Pf, W, COE ; Δd≤1.1m, Hf≤1.16, W<160G)

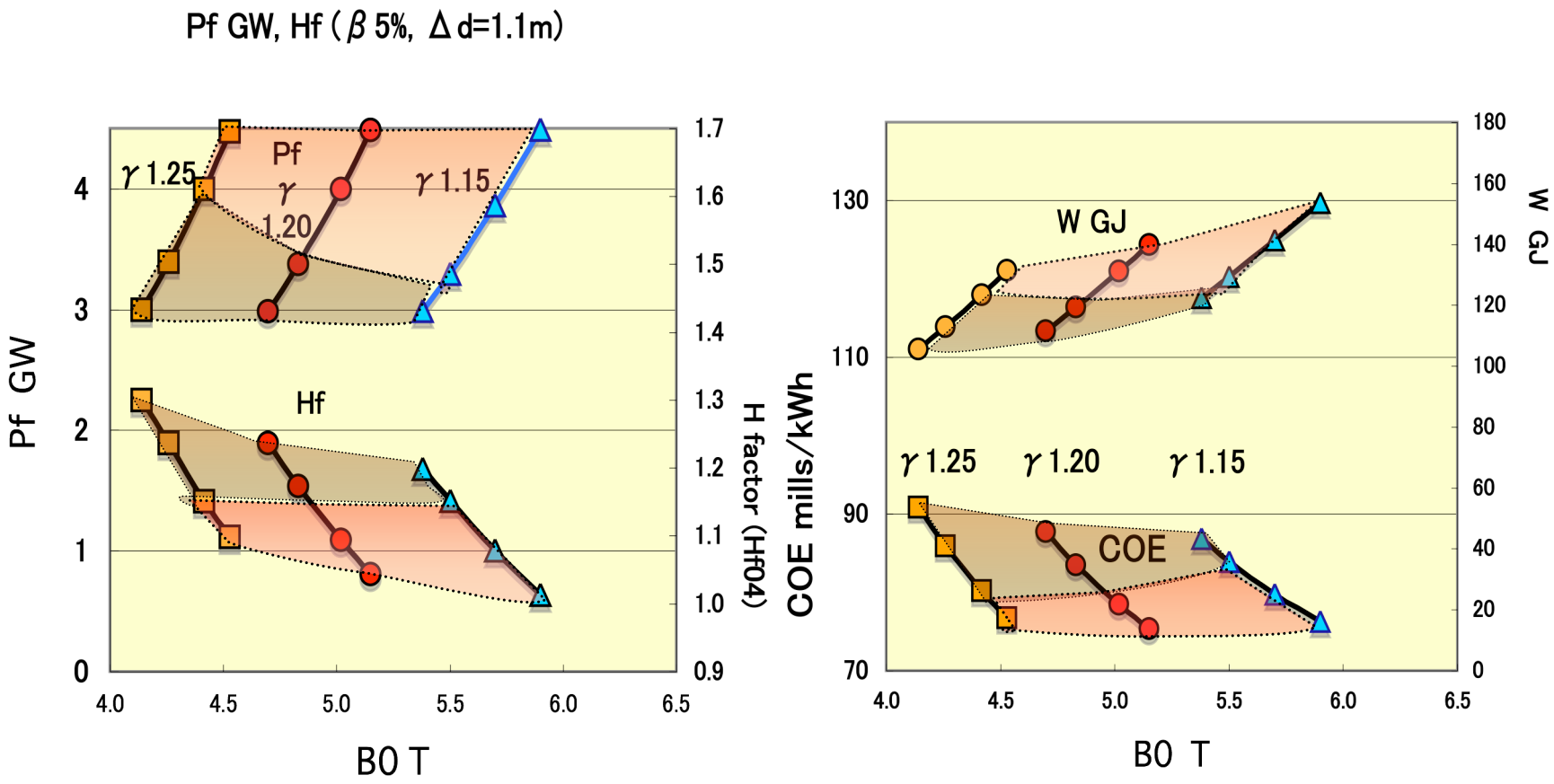


Fig.4-2 The design windows limited with Δd≥1.1m, Hf≤1.16, W<160G, depending on γ and β (β 5%case, j=26A/mm^2).

Design windows of Heliotron reactor(β 6%)
(B_0 - Pf, W, COE ; Δd≤1.1m, Hf≤1.16, W<160G)

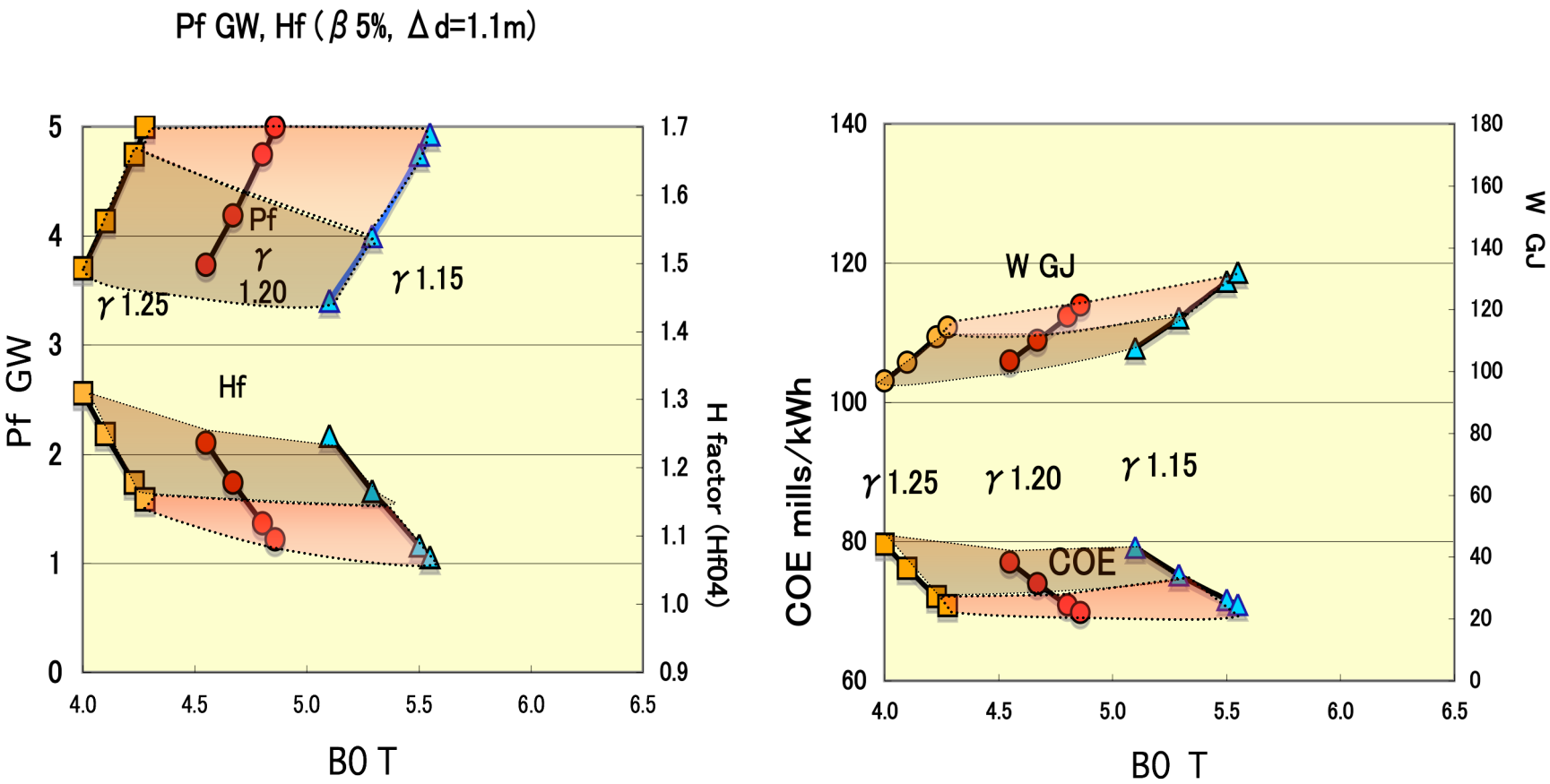


Fig.4-3 The design windows limited with Δd≥1.1m, Hf≤1.16, W<160G, depending on γ and β (β 6%case, j=26A/mm^2).

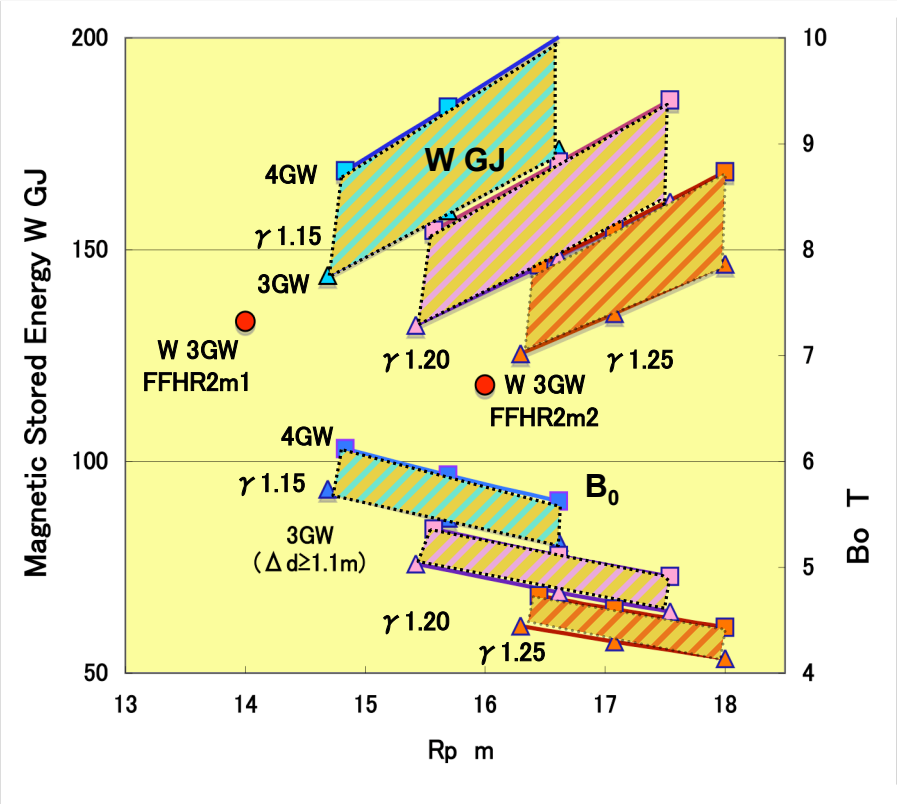
Design Parameters of Heliotron Reactor (LHD similar: l=2, m=10)

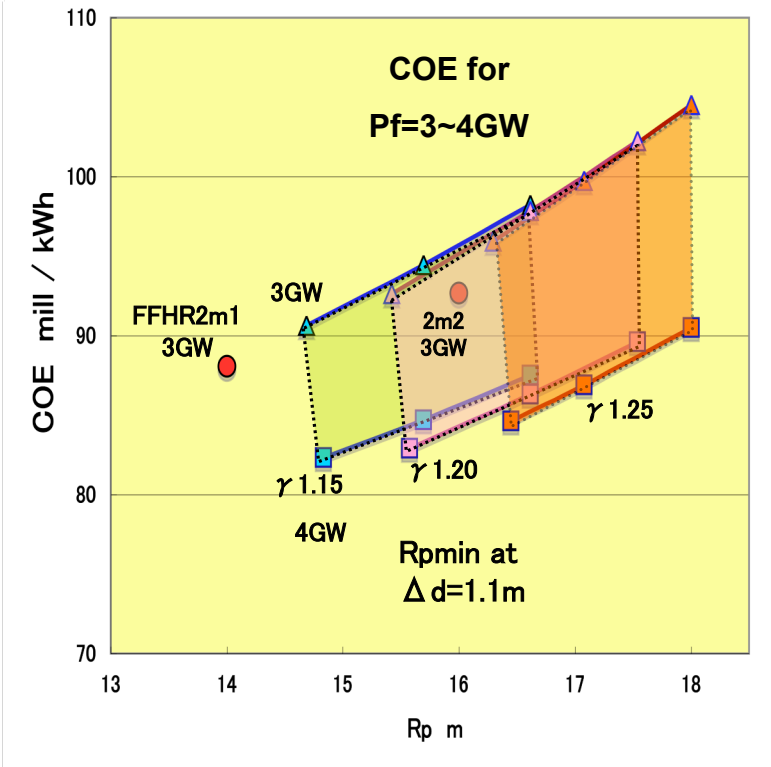
Items			LHD	FFHR2m1	2m1-3GW	2m2-3GW**	2m2-4GW**
Fusion power *	P_F	GW	-	1.9	3.0	3.0	4.0
Average beta	$<\beta>$	%		2.84	3.56	4.0	5.0
Coil pitch parameter	γ		1.25	1.15	1.15	1.18	1.20
Coil major radius	R_c	m	3.9	14.0	14.0	16.5	16.7
Coil minor radius	a_c	m	0.975	3.22	3.22	3.88	4.01
Plasma major radius	R_p	m	3.75	14.0	14.0	15.2	15.4
Plasma radius	a_p	m	0.61	1.73	1.73	2.07	2.27
Plasma volume	V_p	m^3	27.5	831	831	1290	1564
	τ_{E04}	s		1.65	1.40	1.91	1.78
H factor of ISS04	H_{04}		0.93	1.11	1.03	1.09	1.09
Electron density	$ne(0)$	10^{19} m^{-3}		26.7	33.0	25.7	25.8
Temperature	$Ti(0)$	keV		15.6	15.8	15.0	15.7
Magnetic field	B_0	T	3	6.2	6.2	5.5	5.02
Max. field on coils	B_{max}	T	6.9	13.3	13.3	12.3	11.9
Coil current	I_H	MA	5.9	43.3	43.3	41.7	38.7
Coil current density	j	MA/m^2	53	26.6	26.6	26	26.0
Magnetic energy	W	GJ	0.92	133	133	148	131
Min. Blanket space	Δd	m	0.118	< 1.1	< 1.1***	1.1	1,1
Neutron wall load	f_n	MW/m^2	-	1.5	2.4	2.2	2.2

***α heating efficiency: 0.9, density fraction of He: 3%,Oxygen 0.5%, density and temperature profile: parabolic.**
****plasma inward shift case (3.6m/3.9m LHD)**
***** Blanket space is restricted with broad ergodic layer for decreasing α loss in R_p=R_c case .**

Design Windows Analysis for Helical Power Plants

- B_0, Magnetic Stored Energy W and COE for fusion power 3GW~4GW -

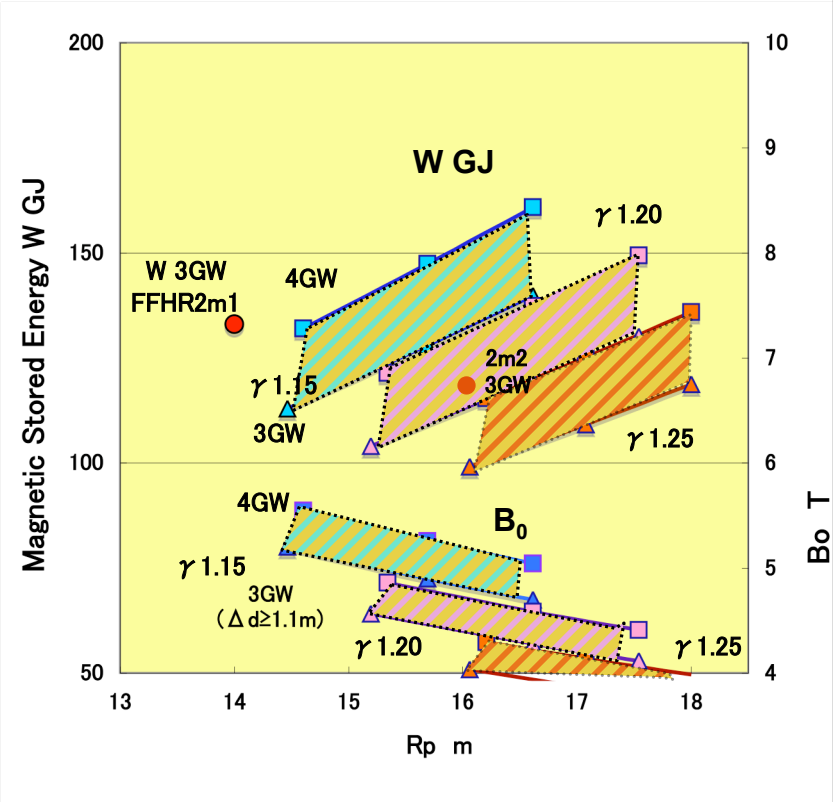


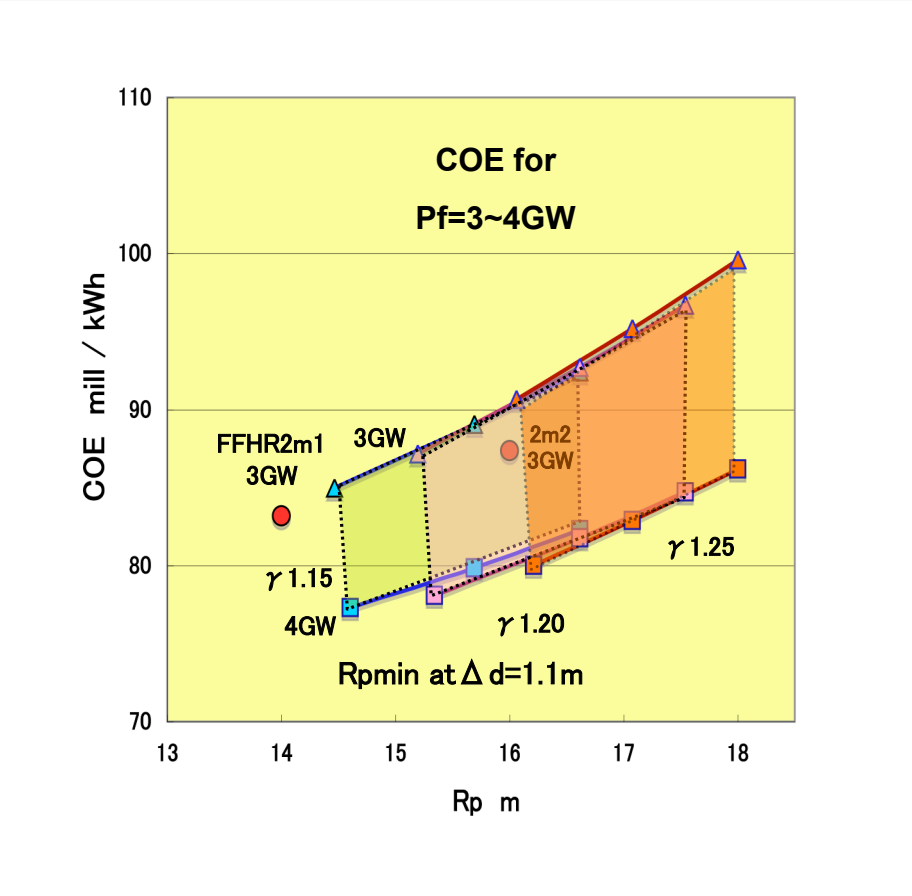


(β= 4% , Δd≥1.1m, γ= 1.15, 1.20, 1.25 case)

Design Windows Analysis for Helical Power Plants

- B_0, Magnetic Stored Energy W and COE for fusion power 3GW~4GW -





(β= 5% , Δd≥1.1m, γ= 1.15, 1.20, 1.25 case)

Table 1. Analysis on Weight and Cost of Magnet Systems based on ITER (1kIUA=144Yen)

TOKAMAK Coil Systems	Elements		ITER Report 2002			ITER FDR 1999		
			Weight ton	Unit Cost Myen/ton	Cost MYen	Weight ton	Unit Cost Myen/ton	Cost MYen
C1.TF coil Nb3Sn/Cu (Cu ratio:1)	Conductor	Strands	483	63.3	30,564	1280	54.0	69,099
		Conduit	137	2.9	396	380	8.1	3,064
			620	50.0	30,960	1660	43.5	72,163
	Radial Plate		1212	6.5	7,854	2900	8.1	23,579
	Winding (Weight)		(1832)	8.9	16,266	(4560)	11.3	51,434
	Coil Case		4289	3.3	14,184	9000	3.3	29,539
			6120	10.0	59,335	13560	13.0	176,715
C2. CS Coil Nb3SnCu Cu ratio:1	Conductor	Strands	149	62.9	9,387	273	52.5	14,323
		Conduit	441	8.1	3,573	457	8.1	3,685
			590	22.0	12,960	730	24.7	18,008
	Radial Plate		0			0		0
	Winding (Weight)		(590)	8.3	4,879	(730)	14.2	10,365
	Coil Case		250	3.3	824	400	4.6	1,852
			840	22.2	18,662	1130	26.7	30,225
C3. PF coil NbTi/Cu Cu ratio: 1	Conductor	Strands	278	28.9	8,041	814	25.1	20,398
		Conduit	902	2.9	2,615	3174	2.9	9,141
			1180	9.0	10,656	3988	7.4	29,539
	Radial Plate		0			0		
	Winding (Weight)		(1180)	3.6	4,298	3988	3.8	15,288
	Coil Case & Support		862	2.9	2,499	0		
			2042	8.5	17,453	3988	11.2	44,827
C4. Coil Supports			1164	2.9	3,377	3200	5.6	18,008
C5. Other Systems (Feeders etc.)					6,739			5,571
Total Weight & Direct Cost			10166	10.6	107,641	21878	12.6	275,346

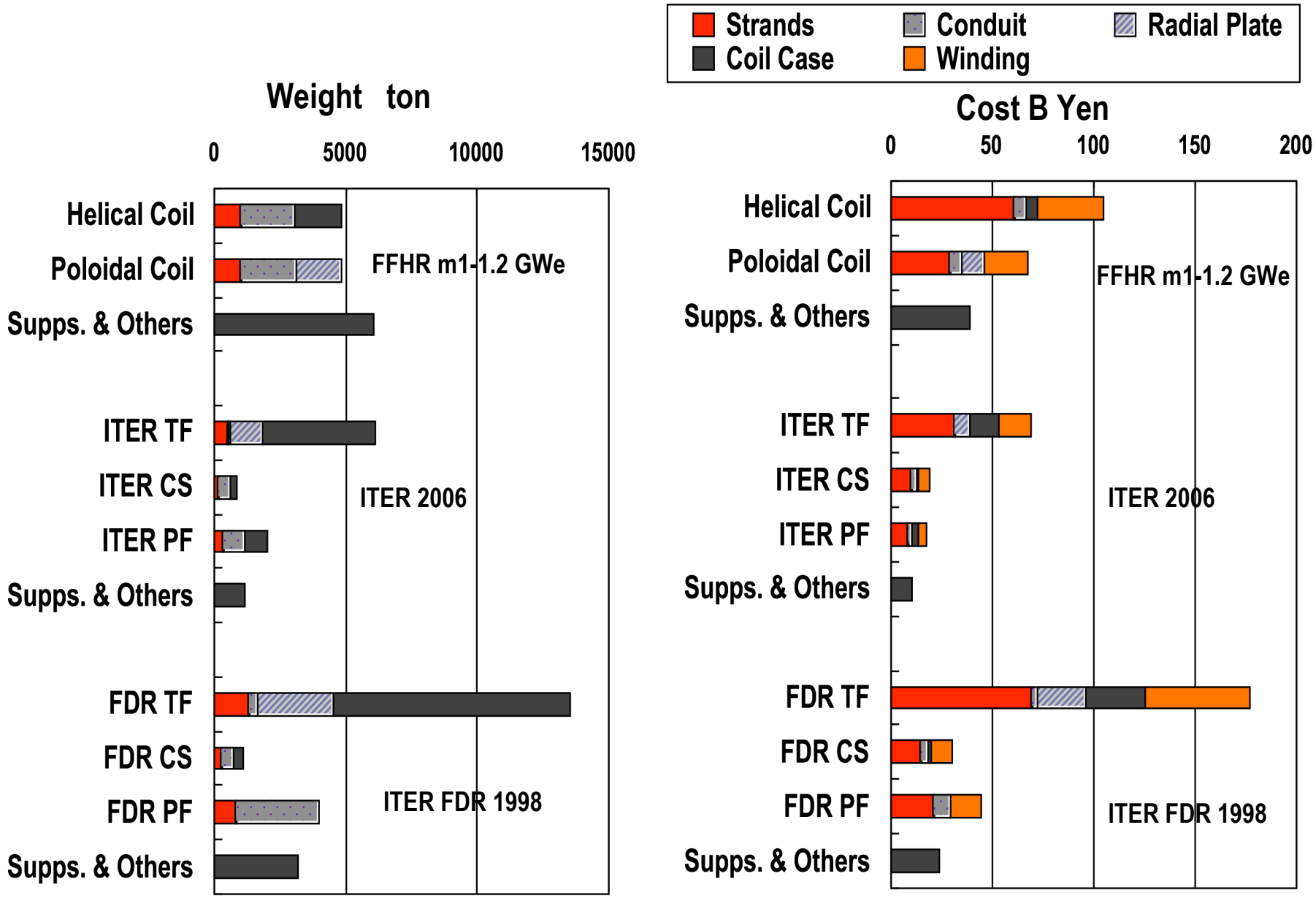
The weights of coil system elements are calculated based on the technical design data. Cost values in italic are calculated by using the cost data those of the ITER Report, the FDR costs and the unit cost data by Mitchell 1999.

Table 2. Estimation on Weight and Cost of Helical Reactor Magnet Systems based on FFHR-m1 Design Study and ITER Magnet Cost

Coil Systems	Elements		Weight ton		Unit Cost Myen/ton	Cost MYen
C1. Helical Co i l Nb3Al/Cu (Cu ratio: 1)	Conductor	Strands	960		63.3	60,723
		Conduit	2,077		2.9	6,023
			3,037		*22.0*	66,747
	Winding			3,037	10.7*	32,431
	Coil Case		1,770		3.3	5,809
				4,807	*21.8*	104,987
C2. Poloidal (OV& IV)Coil NbTi/Cu (Cu ratio: 3)	Conductor	Strands	1,001		28.9	28,929
		Conduit	2,092		2.9	6,067
			3,093		*11.3*	34,995
	Radial Plate		1,717		6.5	11,163
	Winding			4,810	4.4*	21,165
	Coil case		0			
				4,810	*14.0*	67,324
C3. OV& IV Coil Support				6,085	3.3	20,081
C4. Other Coil systems 0.1*Sum(C1:C3)						19,239
Total Weight & Direct Cost				15,702	*13.5*	211,631

*We consider winding unit cost of Helical Coil is 1.2 times that of Tokamak Coil, and Poloidal Coil is 1/2 as same.

Magnets Weight and Cost of Tokamak and Helical Reactor



Comparison of Weight and Cost between Helical and Tokamak Reactor

	Helical Reactor	Tokamak	
		ITER	SSTR
Magnetic stored energy	120-135 GJ ~ 2 times(ITER)	50 GJ	140GJ
Weight	15.7 k ton ~ 1.5 times	10 k ton	11.2 k ton * (under estimated)
Cost	210 Byen ~ 2 times	110 Byen	140 Byen ** (depend on estimated weight)

Design Parameters of Heliotron Reactor (LHD similar: l=2, m=10)

Items			LHD	FFHR2m1	2m1-3GW	2m2-3GW**	2m2-4GW**
Fusion power *	P_F	GW	-	1.9	3.0	3.0	4.0
Average beta	$<\beta>$	%		2.84	3.56	4.0	5.0
Coil pitch parameter	γ		1.25	1.15	1.15	1.18	1.20
Coil major radius	R_c	m	3.9	14.0	14.0	16.5	16.7
Coil minor radius	a_c	m	0.975	3.22	3.22	3.88	4.01
Plasma major radius	R_p	m	3.75	14.0	14.0	15.2	15.4
Plasma radius	a_p	m	0.61	1.73	1.73	2.07	2.27
Plasma volume	V_p	m^3	27.5	831	831	1290	1564
	τ_{E04}	s		1.65	1.40	1.91	1.78
H factor of ISS04	H_{04}		0.93	1.11	1.03	1.09	1.09
Electron density	$ne(0)$	10^{19} m^{-3}		26.7	33.0	25.7	25.8
Temperature	$Ti(0)$	keV		15.6	15.8	15.0	15.7
Magnetic field	B_0	T	3	6.2	6.2	5.5	5.02
Max. field on coils	B_{max}	T	6.9	13.3	13.3	12.3	11.9
Coil current	I_H	MA	5.9	43.3	43.3	41.7	38.7
Coil current density	j	MA/m^2	53	26.6	26.6	26	26.0
Magnetic energy	W	GJ	0.92	133	133	148	131
Min. Blanket space	Δd	m	0.118	< 1.1	< 1.1***	1.1	1,1
Neutron wall load	f_n	MW/m^2	-	1.5	2.4	2.2	2.2

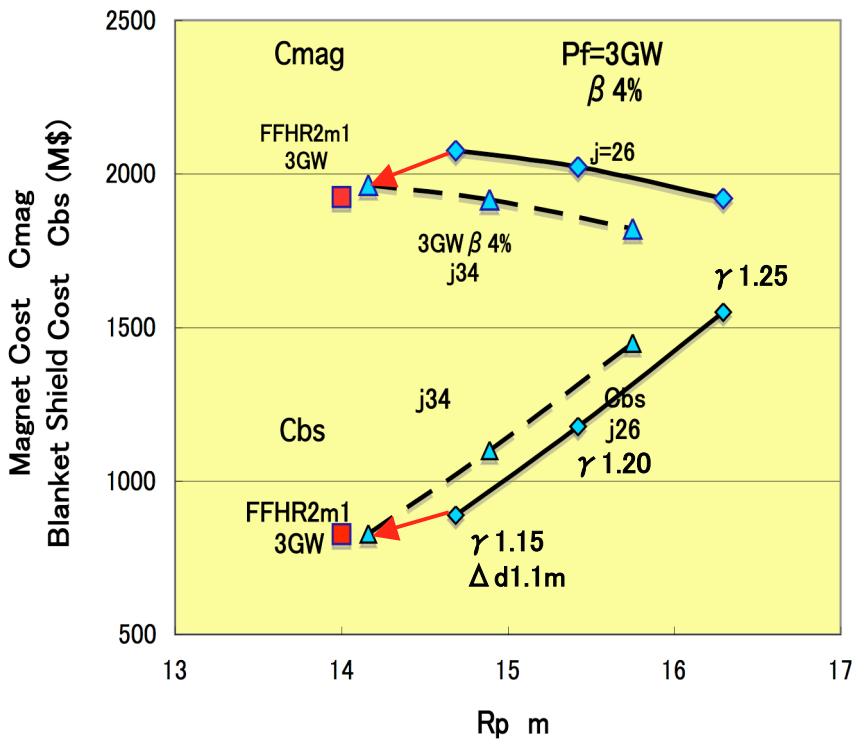
***α heating efficiency: 0.9, density fraction of He: 3%,Oxygen 0.5%, density and temperature profile: parabolic.**
****plasma inward shift case (3.6m/3.9m LHD)**
***** Blanket space is restricted with broad ergodic layer for decreasing α loss in R_p=R_c case .**

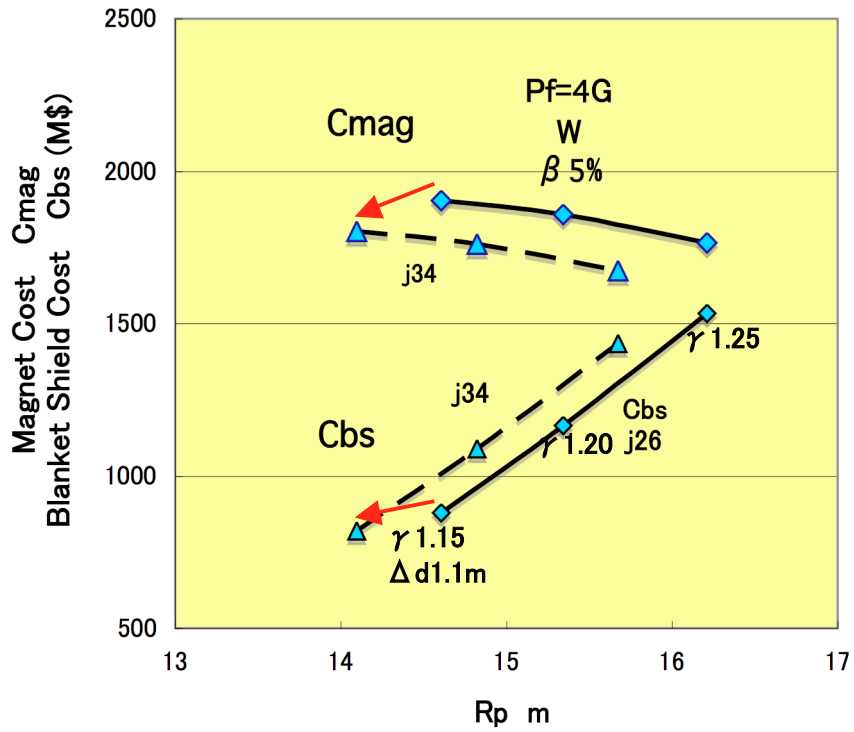
Construction Cost and COE of Heliotron Reactor (LHD similar: l=2, m=10)

	FFHR2m1-1.9GW	2m1-3GW	2m2-3GW	2m2-4GW
20 Land & land rights	12.70	12.70	12.70	12.70
21 Structures and Site facilities	264.52	359.25	359.21	435.61
22 Reactor Plant Equipment	3433.16	3677.37	4128.28	4190.57
221 Fusion Reactor Equipment	3035.89	3137.85	3588.81	3536.36
2211 Blanket & shield	827.60	827.60	1064.58	1175.87
2213 magnets	1923.62	1923.64	2137.66	1891.70
2214 heating	31.58	42.88	42.88	52.00
2215-2218 structure & others	253.10	343.73	343.69	416.80
222 Main heat transport system	293.50	398.60	398.56	483.33
223-227 Fuel handling etc.	103.76	140.92	140.91	170.88
23 Turbine Plant Equipment	211.52	311.54	309.85	395.19
24-27 Electric Plant Equipment & etc.	259.15	323.04	322.54	371.22
90 Total Direct & engineering Cost #1	4181.06	4683.90	5132.57	5405.29
91-97 Indirect Cost (without #1 indirect cost	1410.21	1690.18	1789.55	1986.33
99 Total Plant Capital Cost	5591.26	6374.08	6922.12	7391.62
Plant availability factor A ##	0.734	0.700	0.72	0.71
Capital cost * (mill/kWh)	66.65	49.93	53.07	43.14
Operation cost **	38.13	29.92	31.56	27.12
Replacement cost ***	8.26	8.16	8.23	8.19
Fuel cost	0.021	0.022	0.02	0.02
COE (Cost of Electricity) (mill/kWh)	113.06	88.03	92.88	78.47

#1Cmag2213,Cbs2211:involving indirect cost without owner's cost. *FCR (Fixed chrge rate)=0.0578(discout rate3%, life time40years)
**Operation cost:4.58% of Construction cost (Magnet:1.53%), ***Blanket replace cost: Cbrep=363.1*(S/1618.3)/Lm*(fn*fA)
Plant availability factor : fA＝0.8*Lm/(Lm+fn*tr), Lm; life time of material, tr; replace time.

Magnet costs and blanket costs are decreased with increasing current density (current density j=26, 34 A/mm² , Pf 3GW, β=4% and Pf 4GW, β=5% cases)



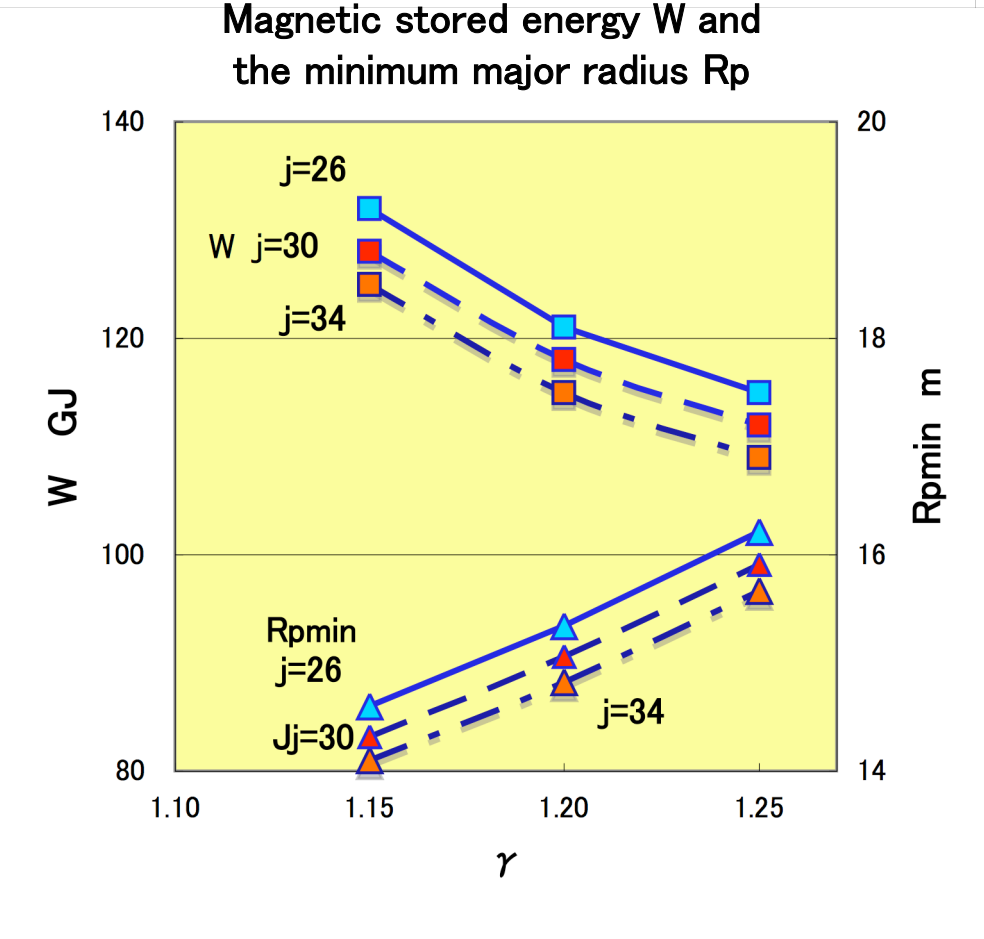


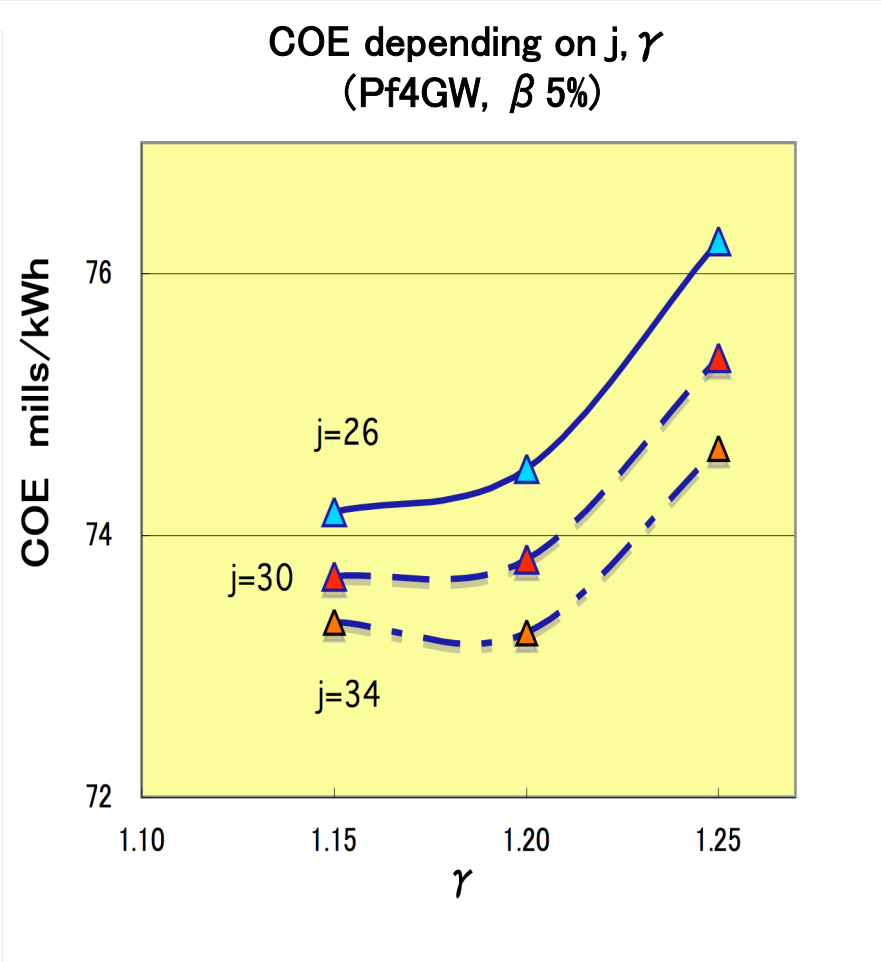
- When current density increase a coil thickness H can be decreased, then the wider space for blanket can make the major radius much smaller .

→ Strongly decreasing magnet and blanket costs.

- Magnet cost down also can be expected with decreasing the weight of super conducting strands in high current density.

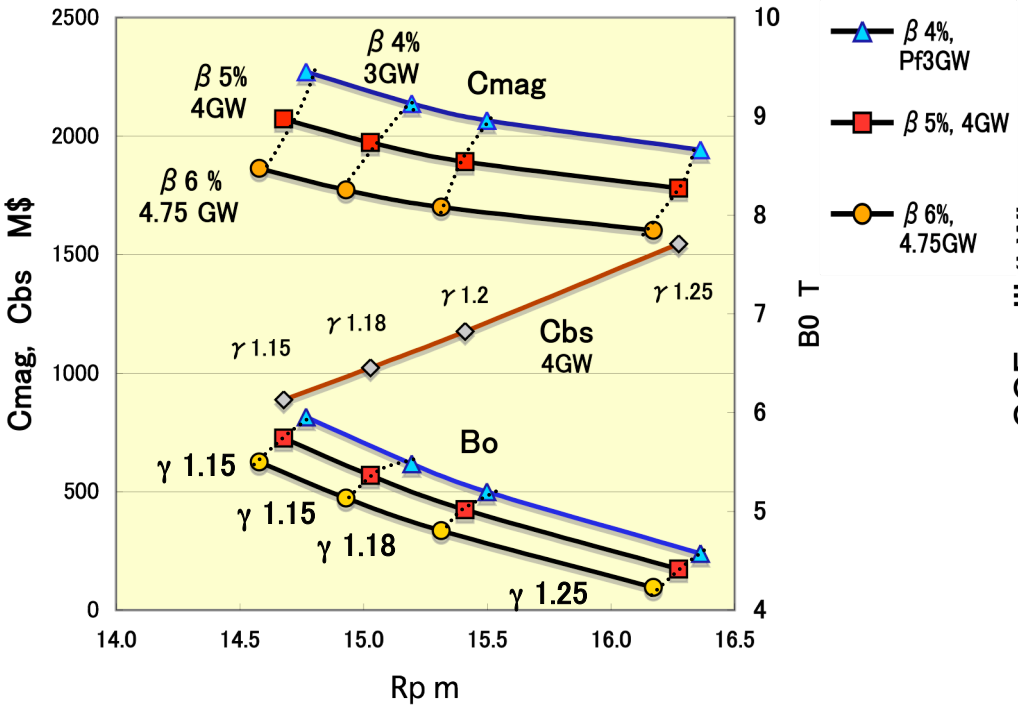
The magnetic stored energy W and COE are reduced effectively by the higher current density (shown in the dependence on γ).





The magnetic stored energy W, the minimum major radius Rp, and COE decrease in the higher current density, depeding on γ. (j=26, 30, 34 A/mm^2, Δd=1.1m constraints)

Magnet cost, blanket cost, and COE(Pf= 3~4.75 GW)
(Rp: minimum Rp at each γ with Δd=1.1m)



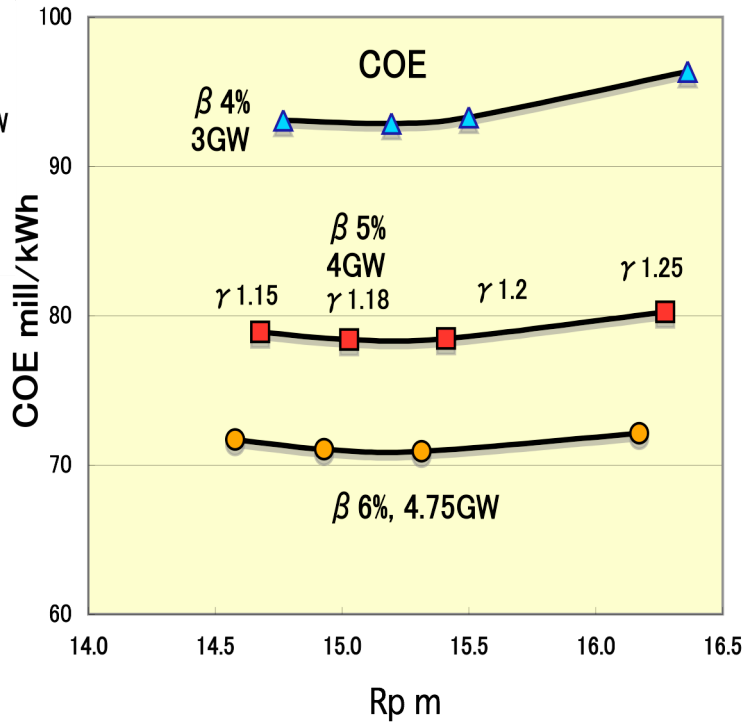


Fig. 2 B0 and Magnet cost (Cmag) depending on γ and β. The magnet costs decrease with increasing Rp and γ, while the blanket Cost(Cbs) increasing. The Rp plot at each γ is given by the minimum Rp limited with Δd≥1.1m constraints such as Fig. 2.

Fig.3 The COEs of Helical reactor, which depend on β (giving B0- Pf) and γ, show the bottom as the result of the trade-off between Cmag and Cbs (B0 versus Plasma volume Vp for the same fusion output)

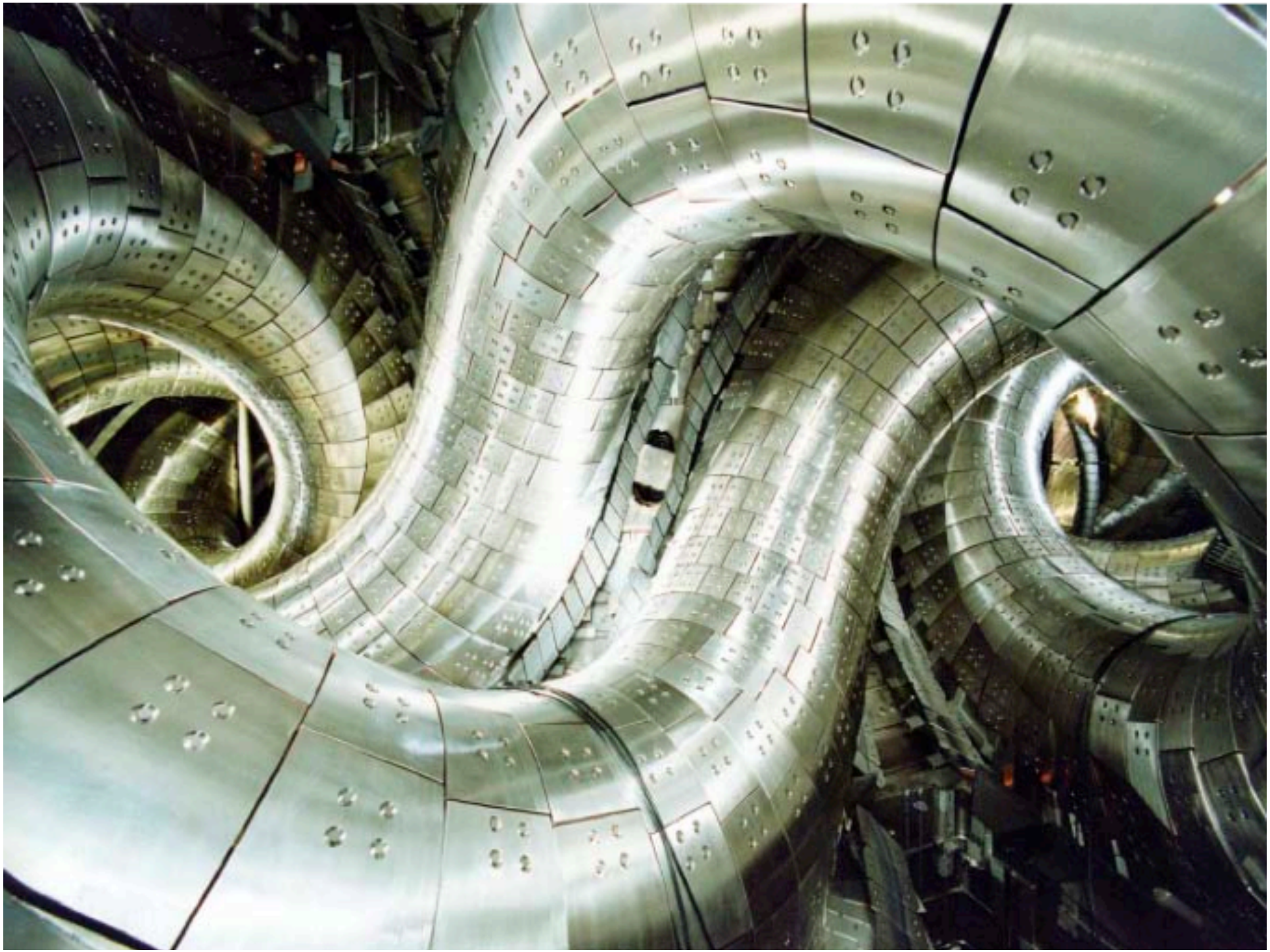
Summary

1. Using HeliCos code based on LHD experiments and the recent magnet cost data, we identified the basic features of desin windows of LHD-type Helical reactor, which are restricted by the blanket space, the upper limit of magnetic stored energy, and the lower limit of B0 for plasma confinement (H factor).

2. We can select the economically attractive reactor size and magnet conditions depending on γ and β, i.e., Rp= 15~17m, B_0 = 4.5~5.5T, W=120~140GJ at β = 5 %.

→ It is misunderstanding that the large size reactor is always uneconomical.

3. We estimated the magnet costs based on the construction data of LHD and ITER, which show the similar cost between Helical and Tokamac conventional reactors (The costs of strands and winding occupy about 70% of total magnet cost) .

4. We should select the γ (index of slender or fat) considering the trade off between the lower magnet cost and the larger blanket cost in the larger γ . The lower neutron and heat load, the better maintenance conditions in the larger reactor size also should be considered.

5. The detailed sensitivity studies on current density, plasma density limit, and density profile are necessary. In the next design studies we think the diverter design and the maintenance scenario of blanket considering the layout of magnet support are critical issues.