The Design Windows and Economical Potential of Heliotron Reactors

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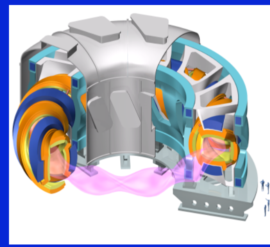


ITC-18, Toki, 2008.12.12 .

Outline

- Background and Objectives
- HeliCos code - Basic equations and calculation flow
- The design windows boundary and β, γ dependence
- Estimating magnet cost based on ITER data
- Economical potential of heliotron reactors
- Conclusion

Background

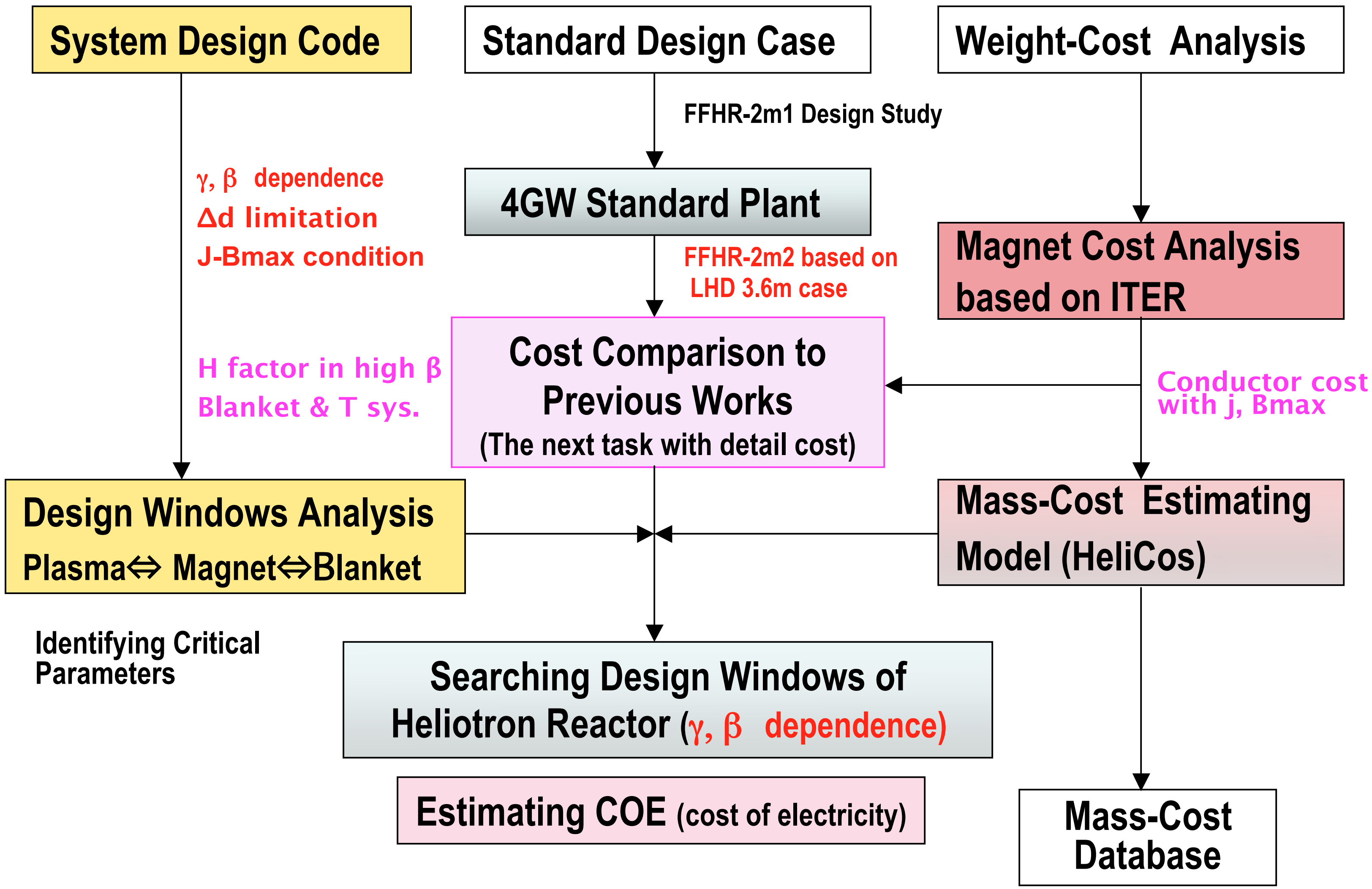
1) Many studies on system designs and economic evaluations of magnetic fusion reactor had been carried out such as the Generomac by Sheffield and the ARIES design studies. The most had concluded the smaller reactor with high beta was necessary for attractive fusion reactors from the point of view of mass-power density.
→ But with high beta we should consider decreasing magnetic field, on the other hand enlarging reactor size to ensure enough blanket space and to avoid too much heat flux and neutron loads.

2) As we have much experience of large size superconducting magnet from LHD and ITER construction, we should estimate the magnet cost based on some realistic database.

Objectives

1) To identify the equations dominating the design windows, and to develop the system design code linked with cost model.
2) To search the design windows and to estimate the economical potential of heliotron reactors.

System Design and Mass-Cost Estimating Code (HeliCos)
- Major tasks and methodology-



HeliCos code - Major design parameters and relationships (1)

1) Basic geometry of plasma and helical coils given with Rp, γ, and Δd

→ The fat plasma increases plasma volume but decreases blanket space.→ It depends on γ.

→ We can consider the similar shape of the LHD 3.6m inward shift cases for the high performance of plasma with variable γ (LHD → polarity l=2, field periods m=10, coil pitch parameter γ =(l/m)/(Rc/ac) is corresponding aspect ratio, γ=1.15~1.25 variable in LHD experiment)

→The a_p and a_{pin} are given by the equations of regression of LHD data.
(a_p, a_c : minor radius of plasma and coill, a_{pin} : inner minimum plasma radius)

$$a_p = a_c\,(-1.3577 + 1.603 \times \gamma) = 0.06292 \times \gamma^{4.5} R_p \rightarrow \tau_E$$

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

→Blanket space

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

Δt : thermal insulation space (Δt =0.1 m)

H : The coil thickness depending on the I_{HC} and j

(I_{HC}, j :current and current density of helical coils)

→ $I_{HC} = (R_P / B_0)/(2m) \times 10$

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

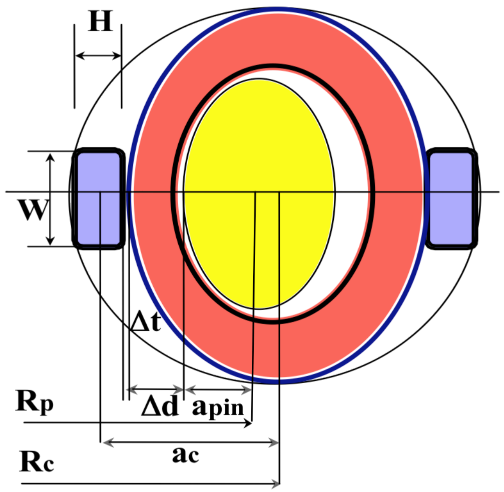


FIG.1 The profile of plasma, helical coil and blanket. The required Δd gives the minimum Rp

Major design parameters and their relationships (2)

2) 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 $<\sigma v>_{DT}$ and the plasma profile assumptions in the HeliCos code.

$$p_f = n_T\, n_D <\sigma v>_{DT}\, Vp\times 17.58(\mathrm{MeV}) \times 1.6021\times 10^{-19}\,(\mathrm{J/eV}) \times 10^{-3}\ [\mathrm{GW}]$$

$$<\sigma v>_{DT}=0.97397\times 10^{-22}\times \exp\{0.038245\,(\ln(Ti))^3 - 1.0074\,(\ln(Ti))^2 + 6.3997\,\ln(Ti) - 9.75\}(\mathrm{m^3/s})$$

→ parabolic profile index a_n : plasma density, a_T : ion temperature

→ a good approximation $<\sigma v>_{DT} \propto T_i^2$ for T_i-~10keV using for sensitivity studies.

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

3) Power balance conditions given with scaling low ISS04 in H factor equations

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

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

($P_\alpha = 0.2P_f$, f_α :α heating efficiency, R_{loss}:Radiation loss
W_p : plasma stored energy, $W_p \propto n_e(0)T_i(0)V_p$)

$$\rightarrow \quad \tau_E(\mathrm{ISS04}) = 0.134\,(f_\alpha P_\alpha - R_{loss})^{-0.61}\, n_{el}^{0.54}\, B_0^{0.84}\, R_P^{0.64}\, a_p^{2.28}\, \iota_{2/3}^{0.41}$$
$$= 6.23\times 10^{-5}\, R_p^{1.09}\, \gamma^{2.98}\, (p_f(1-r_{loss}))^{-0.61}\, B_0^{0.84}\, n_{el}^{0.54} \quad [\mathrm{ms}]$$

(Expressed only with the R_p γ, B_0, $p_f = P_f / V_p$, $r_{loss} = R_{loss}/(0.2\, f_\alpha\, P_f)$, r_{loss}: radiation loss rate)

$$H_f\,(\mathrm{ISS04}) = \tau_{Er} / \tau_{E(\mathrm{ISS04})} = 76.4 \times f_{np} \times R_p^{-1.09}\, \gamma^{-2.98}\, p_f^{-0.16} B_0^{-1.11}\, (1 - r_{loss})^{-0.66} \quad (3)$$

Design points given with the cross points of the three basic equations

1)The function $B_0(R_p, \gamma, \Delta d, j)$ from the Δd-equation (1)

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

2) The function $B_0(R_p, \gamma, \beta, P_f)$ from the P_f-equation (2)

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

3) The function $B_0(R_p, \gamma, H_f, P_f)$ from the H_f-equation

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

We can calculate the major design parameters, B_0, R_p, γ, P_f, based on the three equations (1),(2),(3).

→ The cross points of the three equations on the B_0-R_p plane.

Figure 2 shows a cross point of those three equations, with the common assumptions of γ=1.2, Pf=4GW, a_n=0.5, a_T=1, j=26 A/mm^2, and with the constant key parameters in each equation, H_f=1.09 in (3), β=5% in(5) and Δd=1.1m in(4).

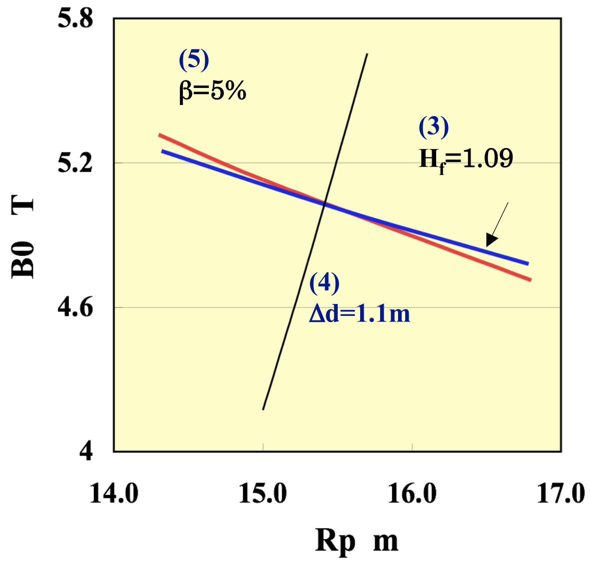


FIG.2 Design points given by the cross points of the three basic equations

Guidelines for analysis on the Design Windows

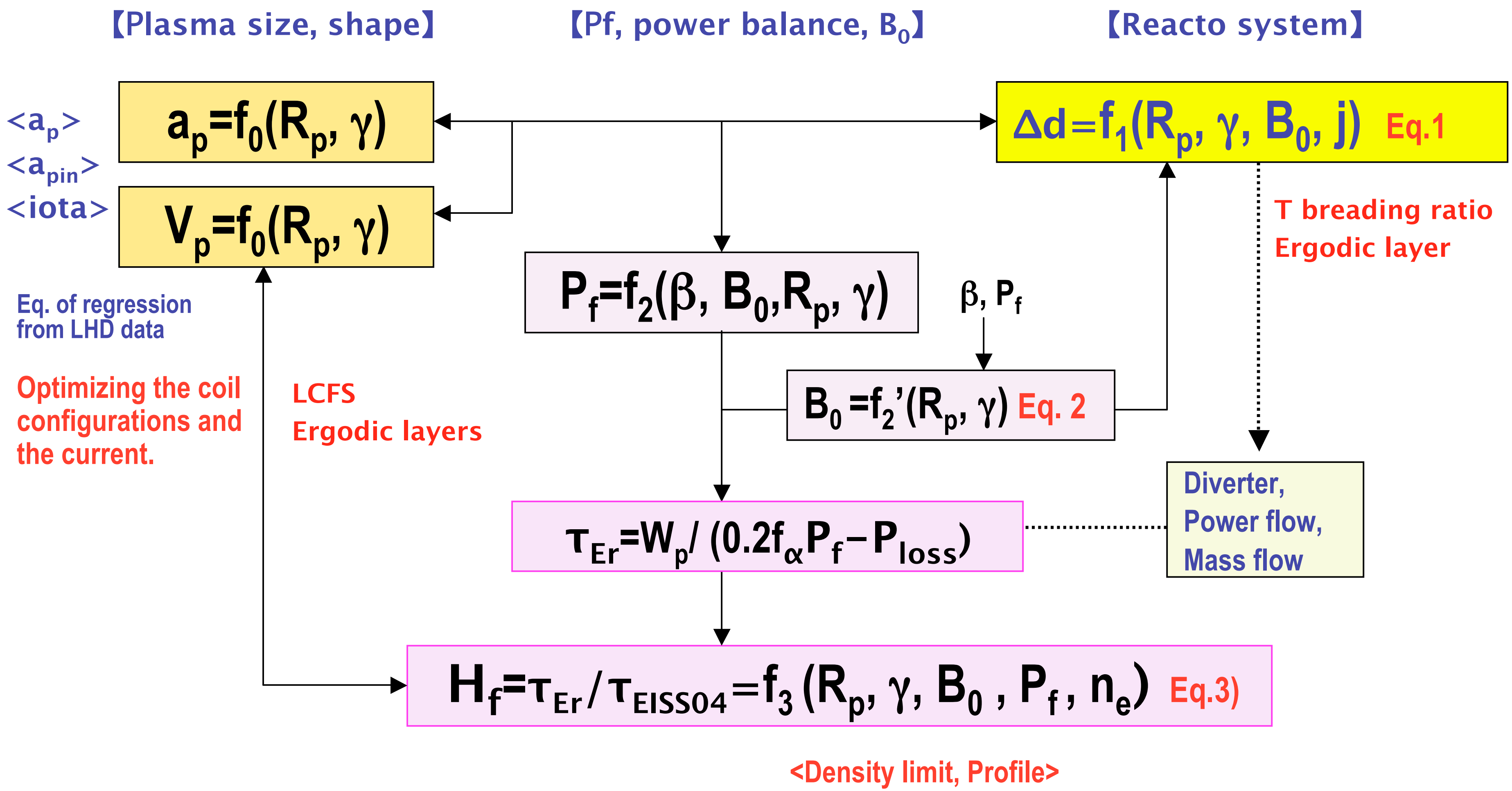
1) Logical results
→from basic equations with the clear preconditions

2) Self consistent
→with comprehensive view of plasma, magnets and reactor

3) Reasonable and affordable
→Don’t design on the cliff
→To open the design windows wide

→ Searching design windows logically with clear conditions

Major design parameters and calculation flows



Identifying Critical Parameters

The minimum Rp is given with Δd constraints for each γ

-How to get design points of 4GW-β 5% plants with Δd1.1m-

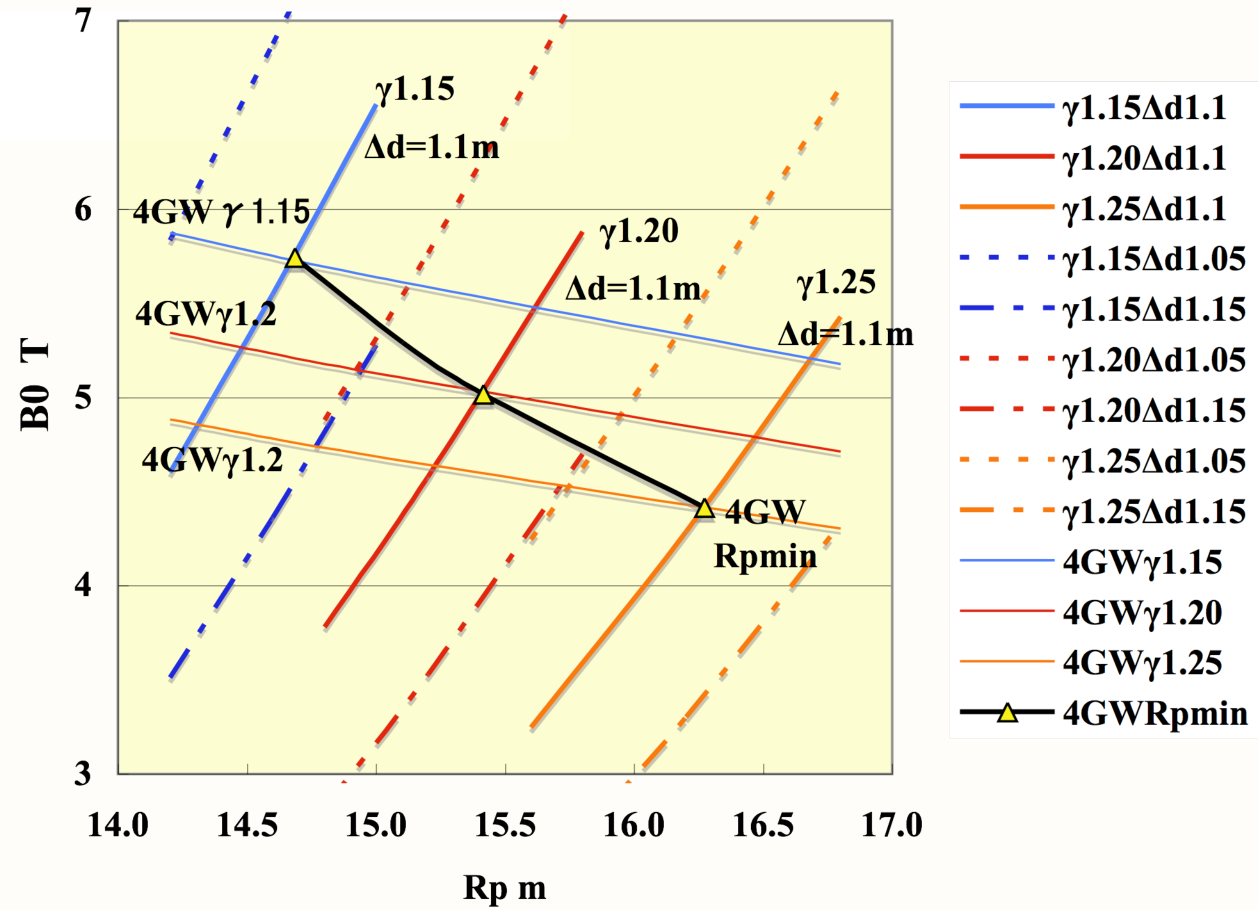


Fig.2-3 The B_0-R_p relationships depending on γ and Δd [The minimum R_p line is given by the cross points of the Pf=4GW lines and Δd=1.1m lines for each γ.]

Design windows limited by the constraints of Δd and H factor

1) Δd constraints give the lower boundary of R_p (increasing γ, a_p →enlarging R_p)
2) H factor constraints give the lower boundary of B_0 (larger R_p , γ→decreasing B_0)
3) The constraints of magnetic stored energy W give the upper bounds of B_0
→ Serching with the constraints of Δd≥1.1m, H_f≤1.16, W<160G

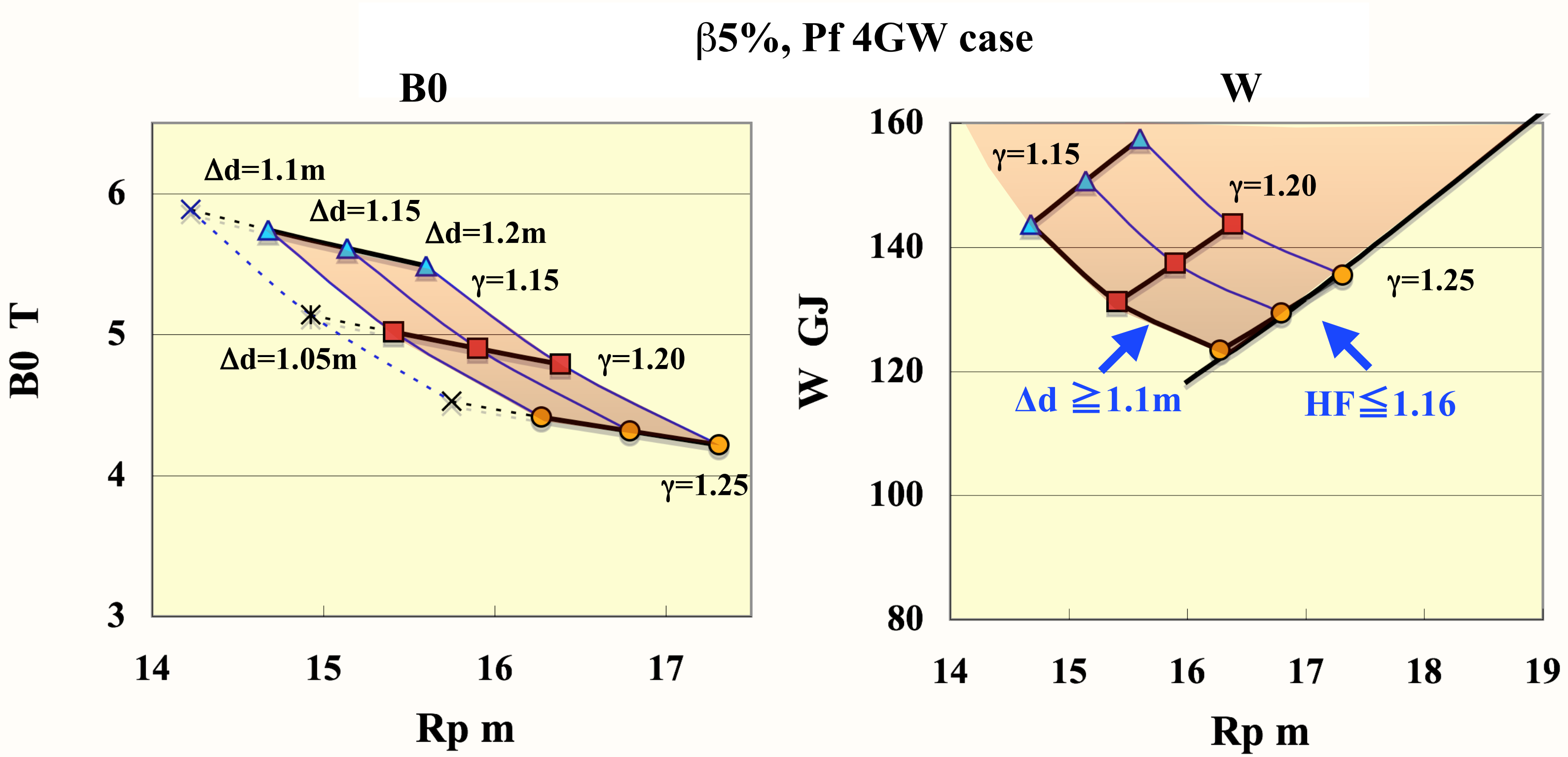


Fig.4 The design windows limited with Δd≥1.1m, Hf≤1.16, W<160G, depending on γ (β 5%, Pf 4GW).
Hf=1.16 means the enhancement factor of 1.2 to LHD experiment [1]. j=26A/mm^2 precondition.

The heliotron reactor design windows depending on γ and β

The design windows on R_p-B_0 plane limited with Hf<1.15 and W<160 GJ (Δd=1.1m).

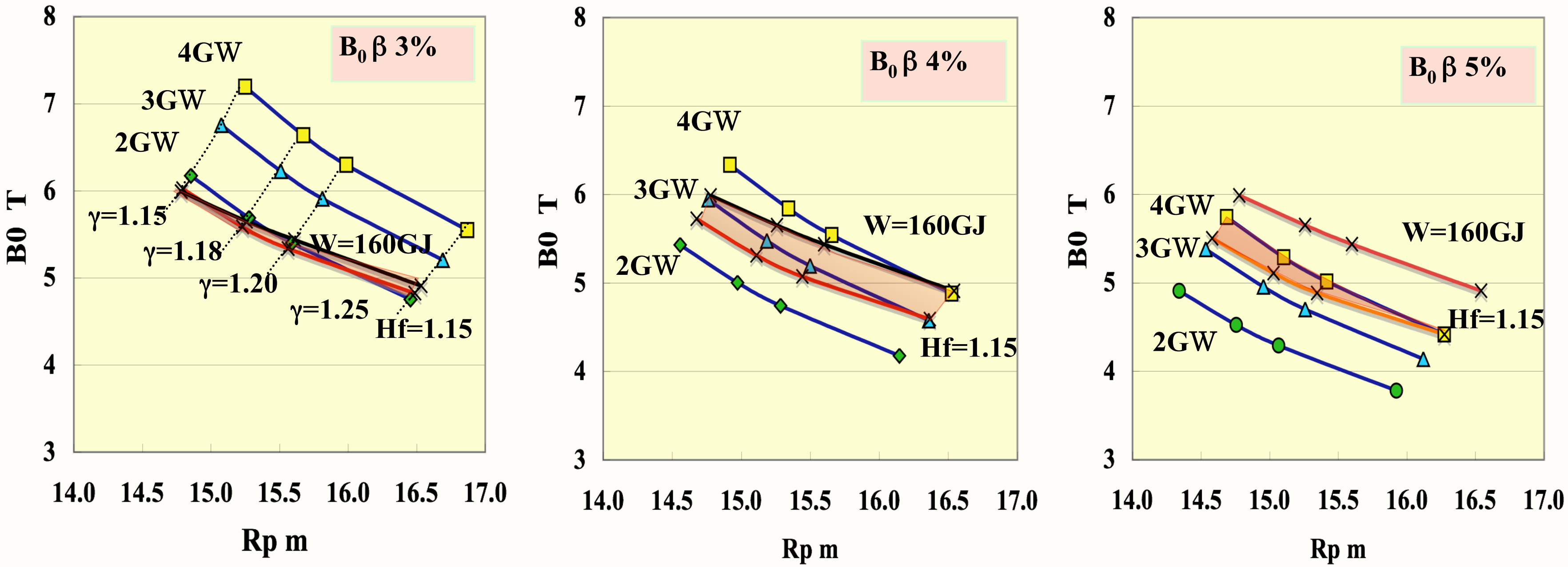


Fig. 5-1 The design windows of 2~4GW fusion power plants limited with the constraints of Δd=1.1m, H_f≤1.15, W<160GJ. The γ dependence are shown with the four points, γ=1.15, 1.18, 1.20, 1.25 on each line.

The low β(~3%) conditions severely limit the fusion power less than Pf=2GW.
In the high β(~5%) conditions the large fusion power (~4GW) plants are not limited by W, but H factor constraints restrict the small fusion power plants.

The heliotron reactor design windows strongly depending on β

The design windows clearly shown on R_p-W plane limited with Hf<1.15 and W<160 GJ)

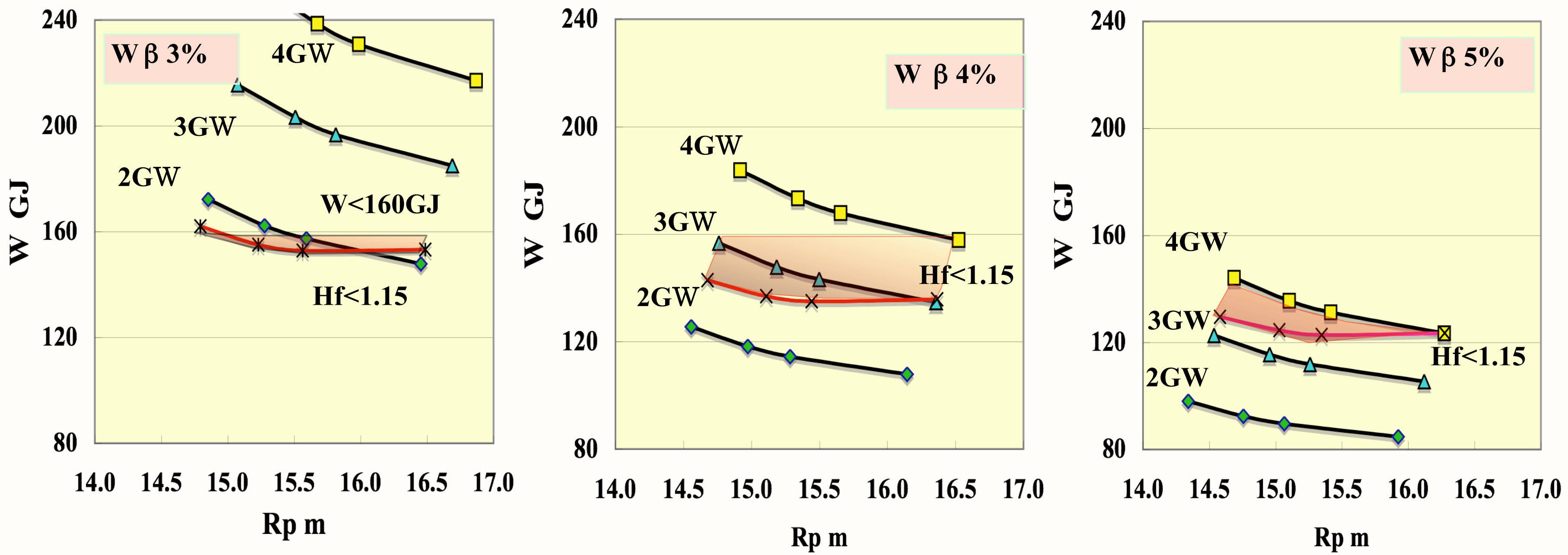


Fig. 5-2 The design windows of 2~4GW fusion power plants limited with the constraints of Δd=1.1m, H_f≤1.15, W<160GJ. The γ dependence are shown with the four points, γ=1.15, 1.18, 1.20, 1.25 on each line.

β3% → only P_f=2GW in W~160GJ

β4% → B_0=4.5~6T→P_f=3~4GW, although W =140~150GJ

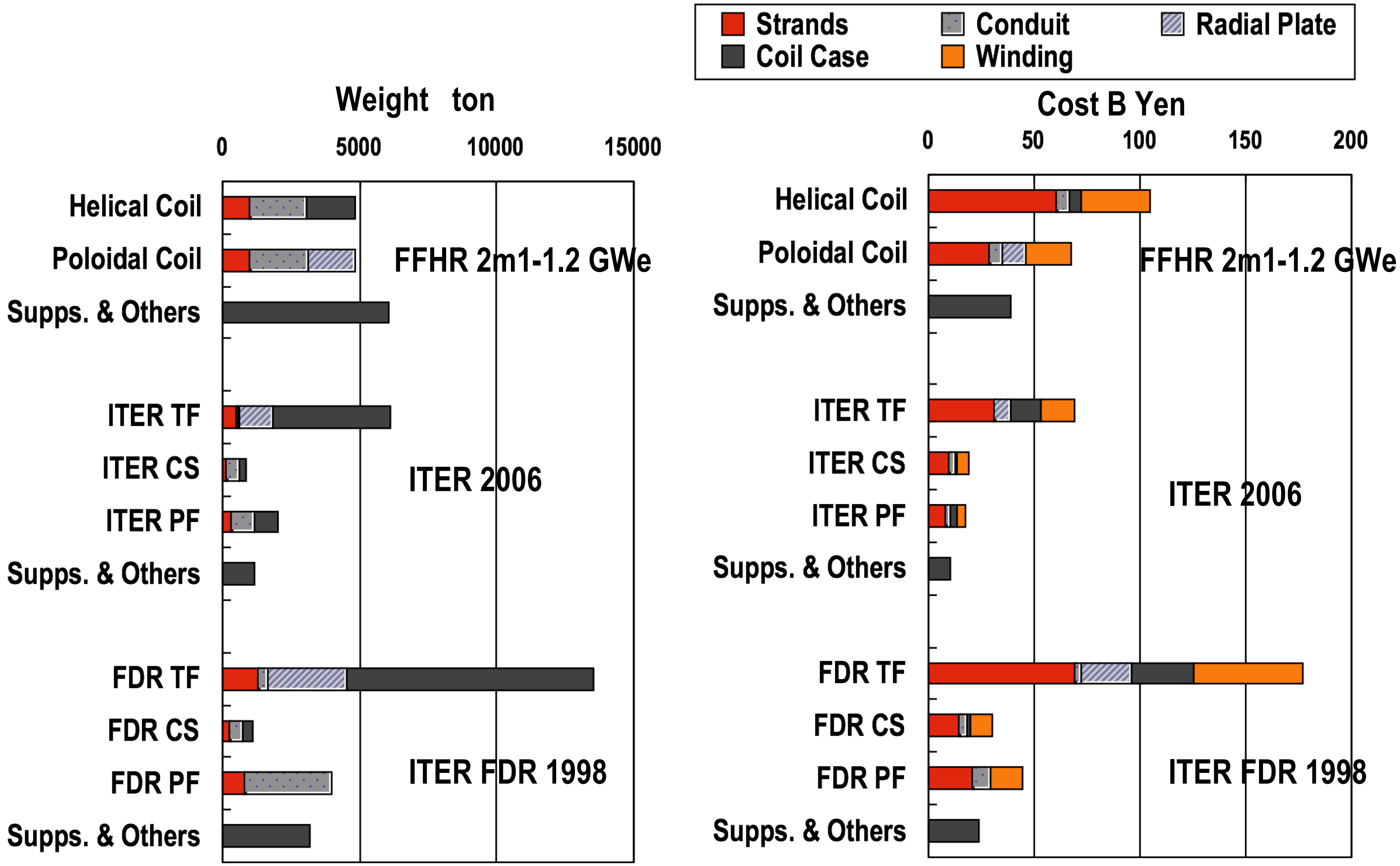
β5% → We can consider the optimum design windows of P_f=3.3~4GW plants with R_P=14.6~16.3m, B_0=4.4~5.5T, and W=125~140GJ

Table 1 The Standard helical reactors of 3~4 GW Fusion Power(1)

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
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
H factor to ISS04	H f	1.064	**1.094**	1.151	1.150
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
Magnetic stored energy	W (GJ)	144	**131**	123	130

***Effective ion charge Zeff=1.32, **Alpha heating efficiency 0.9, and parabola profile index a_n=0.5,a_T=1.0.**

Magnets Weight and Cost of Tokamak and Helical Reactor



	Helical Reactor		Tokamak Reactor ITER	SSTR*
Magnetic stored energy	135 GJ	2.5 times(ITER)	50 GJ	140 GJ
Weight	15.7 k ton	~ 1.6 times	10 k ton	11.2 k ton
Cost	210 B yen	~ 2 times	110 B yen	140 B yen

* estimated with the first version

Table 2 The Cost Comparison of Helical Power Plants (Fusion Power 3~4 GW)

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
Fusion power	Pf (GW)	4.00	**4.00**	4.00	3.00
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(M$)*	*2079(34.6)*	***1893(31.0)***	*1780(28.0)*	*1875(33.7)*
*Blanket and shield cost (%)****	*Cbs (M$)*	*889(14.8)*	***1177(19.3)***	*1546(24.3)*	*1175(21.1)*
Total construction cost	*C total (M$)*	*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/kW h*	*44.0*	***43.2***	*43.8*	*51.2*
Operation cost	*mill/kW h*	*26.8*	***27.1***	*28.2*	*31.4*
Replacement cost	*mill/kW h*	*8.18*	***8.19***	*8.21*	*8.24*
Fuel cost	*mill/kW h*	*0.023*	***0.022***	*0.021*	*0.021*
COE(Cost of electricity)	*mill/kWh*	*79.0*	*78.5*	*80.3*	*90.9*

\# **The major assumption for calculating COE are FCR (Fixed charge rate); 5.78%, with 40 years plant life time and 3% discount rate, the ratio of operation and maintenance cost to construction cost; 4.5 % for the conventional components, but 1.5% for magnets considering the inherent characteristics of super conducting magnets.**

\## **Availability factor is calculate as a function of neutron wall load.**

The magnet cost, blanket-shield cost, and the COE

1) With increasing R_p and γ, the blanket-shield cost increases but the magnet cost decreases, as B_0 decreases much with increasing γ ($\sim V_p$)

2) The COE decreases strongly with increasing β from 3% to 5%.

3) We should select the size (R_p, γ) and B_0 with considering the trade-off between magnet cost and blanket cost, and also plant availability.

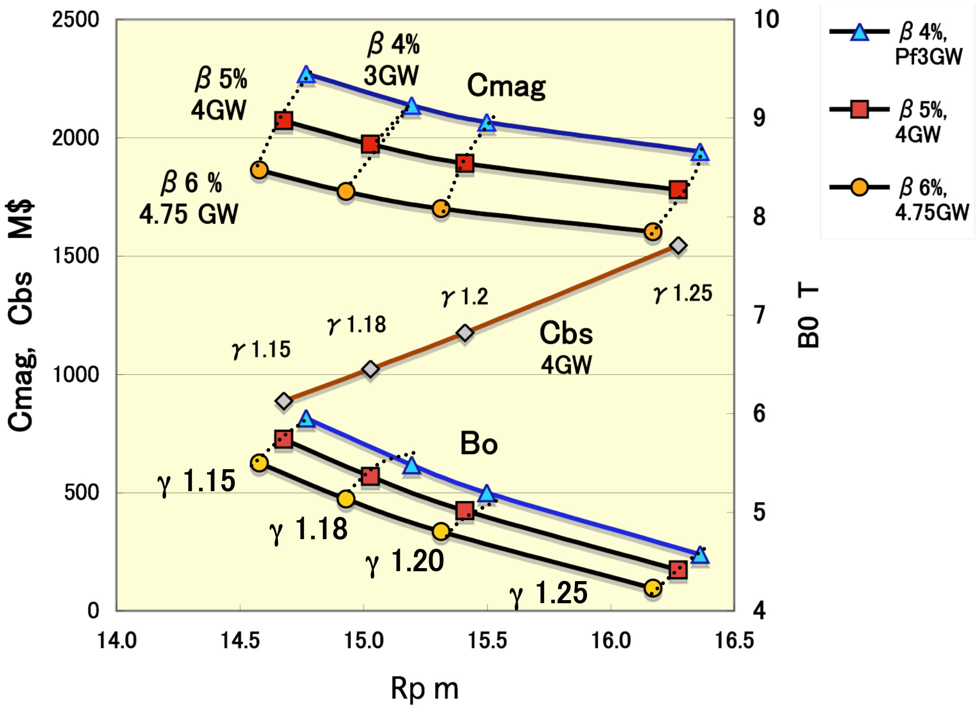
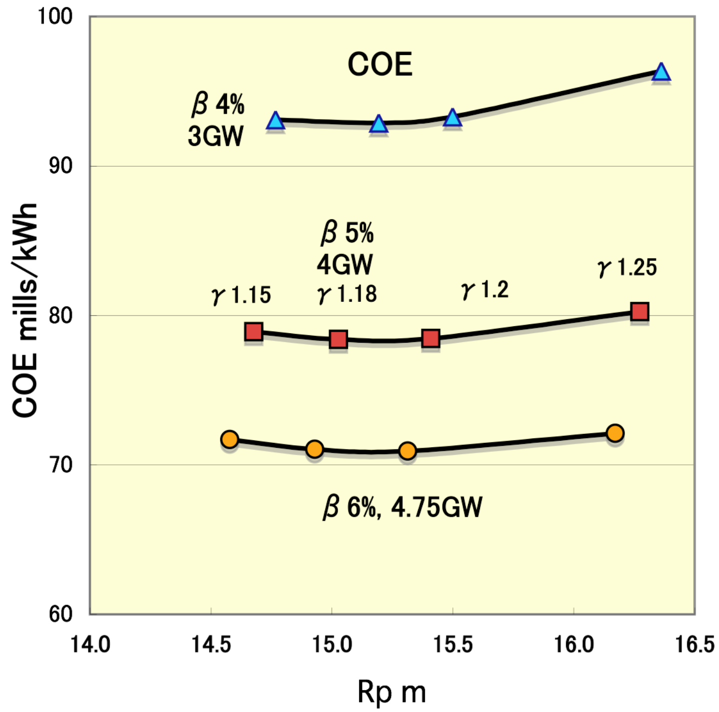


Fig. 2 . The B_0, magnet cost (Cmag), and blanket Cost (Cbs) depend on R_p, γ and β. When R_p and γ increase, Cmag decreases but Cbs increases. Those plots on R_p (γ) are given with Δd=1.1m.



The COEs of helical reactors, which depend on R_p, γ and β, show the bottom as the result of the trade-off between the Cmag and Cbs, i.e., B_0 versus plasma volume.

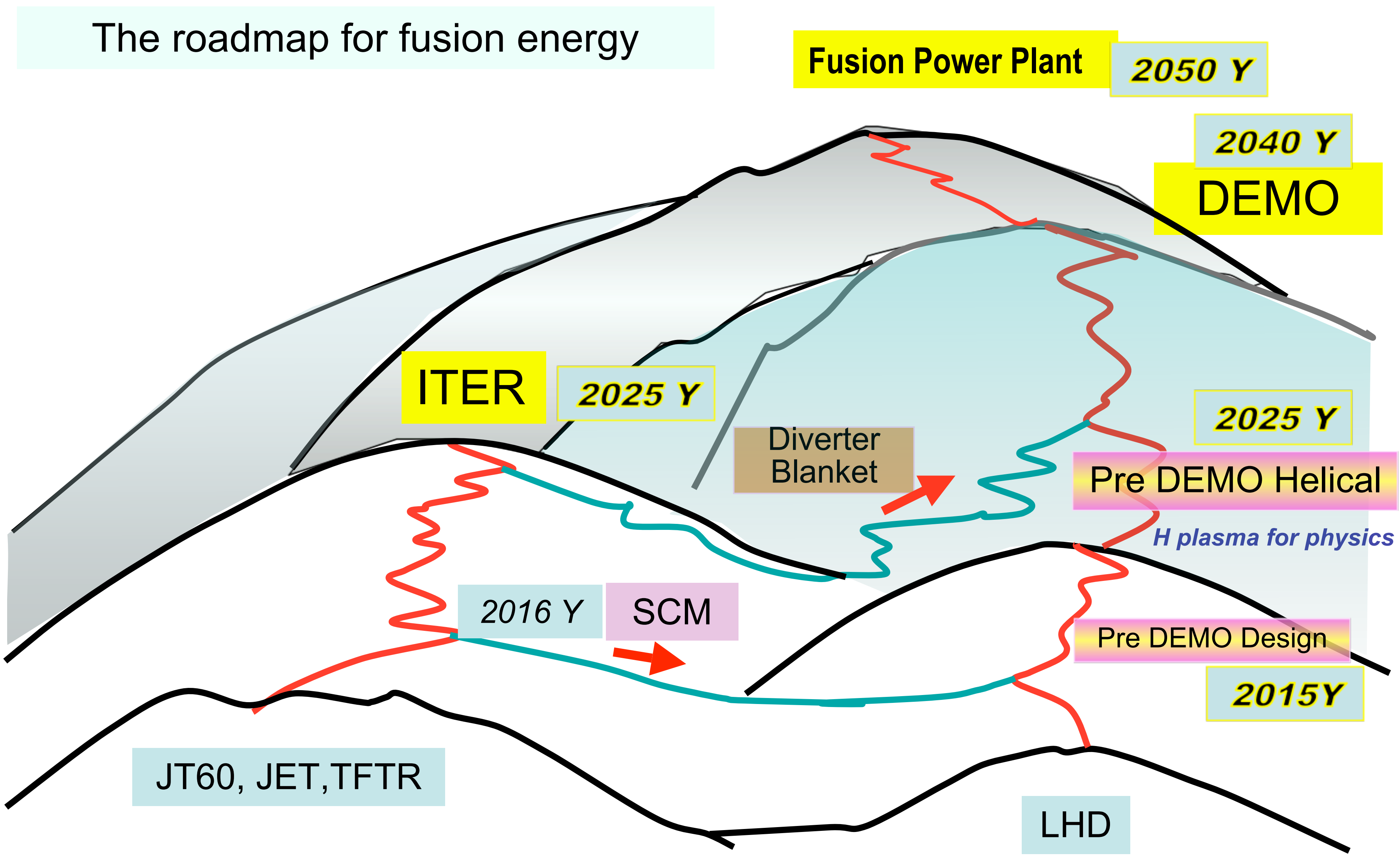
Conclusions

1) LHD-type helical reactors have the attractive design windows in rather large size of R_p = 15~16m, with the sufficient blanket space and the reasonable magnetic stored energy of 120~140 GJ based on the physics basis of H_f~1.1 and β~5%.

2) The β dependence is very important for selecting the optimum fusion power with reasonable magnetic stored 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 is a critical issue to be considered in the next analysis.



The roadmap for fusion energy
Fusion Power Plant
2050 Y
2040 Y
DEMO
ITER
2025 Y
Diverter
Blanket
2025 Y
Pre DEMO Helical
H plasma for physics
2016 Y
SCM
Pre DEMO Design
2015Y
JT60, JET,TFTR
LHD

Demonstrating the required β ~5% plasma in the next LHD experiment and the Pre-DEMO experiment is one of the most critical issues.

-The LCFS of LHD is very beautiful and it is also expected in the β ~5% heliotron reactor plasma

- The LCFS volume could change largely depending on γ and controlling poloidal coil currents, as shown by Tsuguhiro Wtanabe. The LCFS plasma volume could be enlarged about 20% by optimizing the quadrupole component with removing the conditions of minimizing the leakage flux.
It means the potential of decreasing magnetic stored energy from 130GJ to 110GJ.

- Even if in the high β plasma largely affected with shafranov shift, It is expected the high β heliotron plasma could be achieved with selecting the γ and controlling coil currents. That is critically sensitive not only for optimizing the LCFS but also for selecting the optimum blanket design.

Acknowledgements

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