Seventh International Symposium on Fusion Nuclear Technology (ISFNT-7)
May 22 - 27, 2005, Tokyo, Japan

IMPACT OF PLASMA, MAGNET AND WALL PERFORMANCES ON TOKAMAK AND HELICAL REACTOR ECONOMICS

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2. Assessment Models
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   (2) Engineering Model
   (3) Cost Model
3. Benchmark of Model
4. Assessment Results
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Why tokamak vs. helical systems?

For Future Reactors, Steady-State and Good Confinement Compact System is Required

Tokamak : Good-Confinement

=> CD required and inefficient?

Helical : Steady-State

=> Large & Expensive?

Comparative system evaluations are helpful.
Related to physics, engineering and economics, comparative assessment will clarify the optimized target and limitations of both systems.

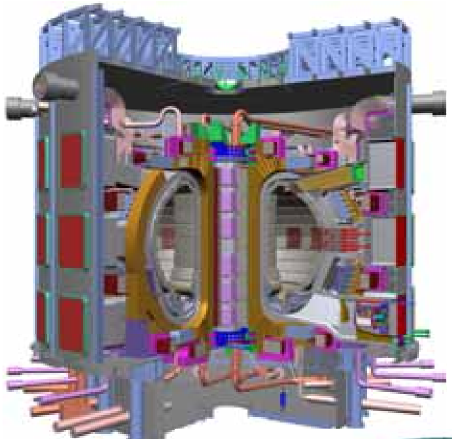
Tokamak Reactor

ITER-like Reactor

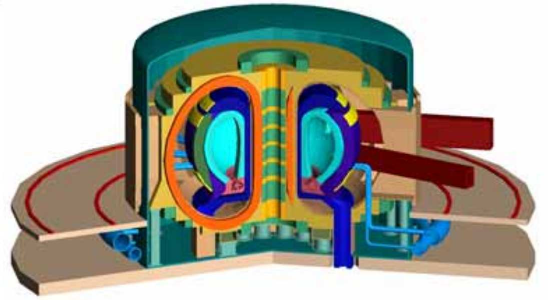
$\beta_N \sim 3$

High Beta Compact Reactor

$\beta_N \sim 5$



ITER-like



Advanced Design
(Example: CREST)

Helical Reactor

Heliotron $\langle \beta \rangle \sim 3\%,5\%$

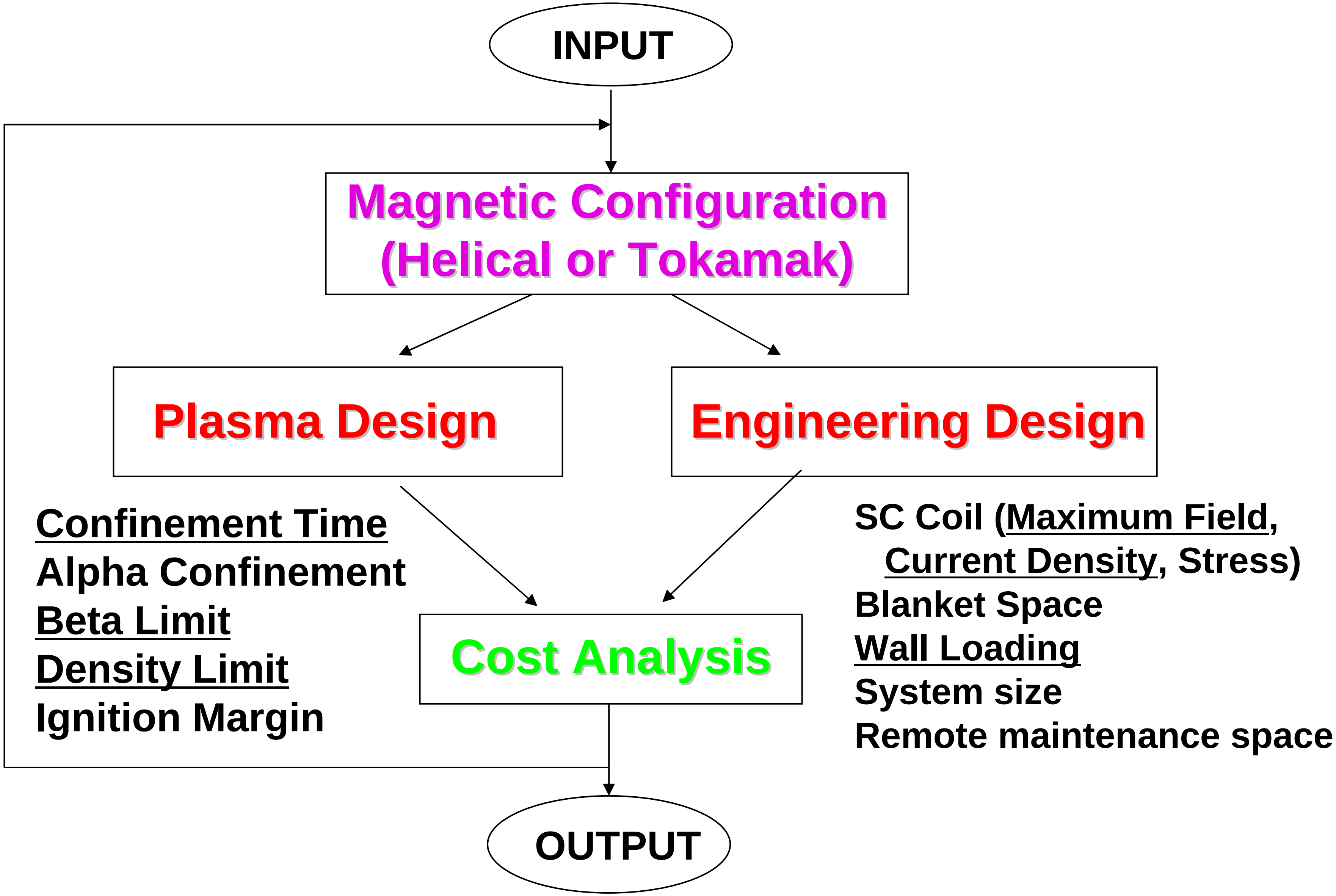
Modular Heliotron

Modular Stellarator

LHR/MHR

CHS-qa like

System Analysis Flow Chart



INPUT

Magnetic Configuration
(Helical or Tokamak)

Plasma Design

Engineering Design

Confinement Time
Alpha Confinement
Beta Limit
Density Limit
Ignition Margin

Cost Analysis

SC Coil (Maximum Field,
Current Density, Stress)
Blanket Space
Wall Loading
System size
Remote maintenance space

OUTPUT

Physics Models

Tokamak

Confinement

$$\tau_E^{ELMY} = 0.0365 R^{1.93} P^{-0.63} \bar{n}_e^{0.41} B^{0.08} \varepsilon^{0.23} I^{0.97}$$

Density limit

$$n_{20\_GR} = \frac{I_{MA}}{\pi a_m^2}$$

Beta limit

$$\beta_N / \frac{I_{MA}}{B_T a_m} = 3 \sim 5$$

Helical

$$\tau_E^{NLHD-1} = 0.263 a^{2.59} R^{0.64} P^{-0.58} \bar{n}_e^{0.51} B^{1.01}$$

$\tau_E(s), a(m), R(m), P(MW), \bar{n}_e\ (10^{19} m^{-3}), B(T), \iota_{2/3}$

$$n_{20\_hel} = 2 \cdot Min\left\{0.25\sqrt{\frac{P_{MW} B_T}{R_m a_m^2}}, 0.35\frac{P_{MW}}{R_m a_m}\sqrt{B_T}\right\}$$

Based on Recent Scaling

$$\langle \beta \rangle = 5\%$$

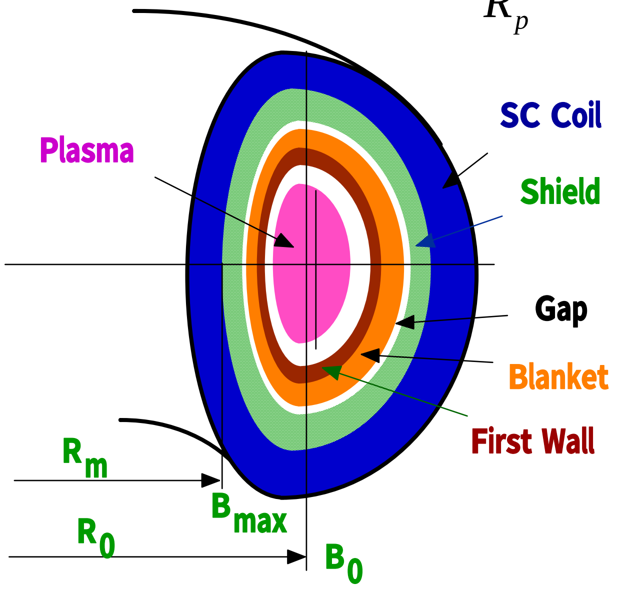
Depending on Configurations

Transport Simulation for Both Systems Using TOTAL code.

Engineering Models

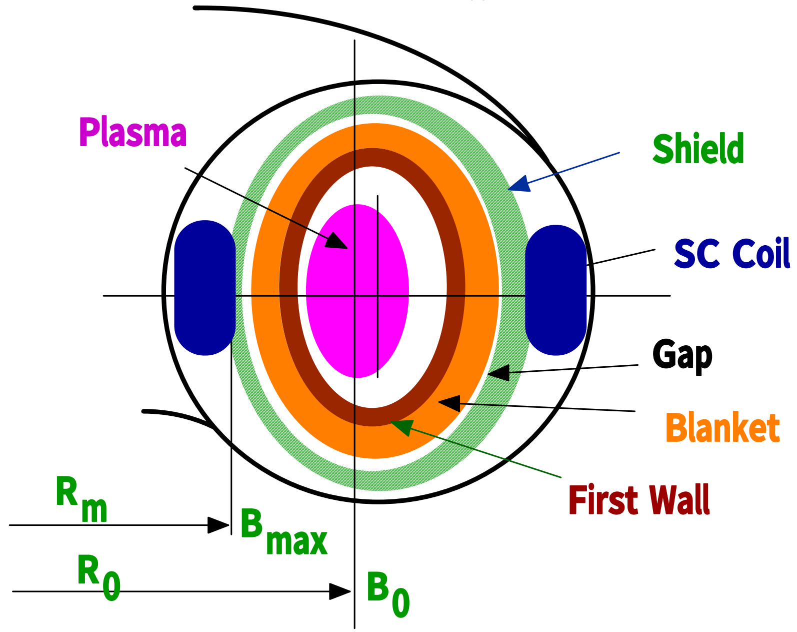
Tokamak

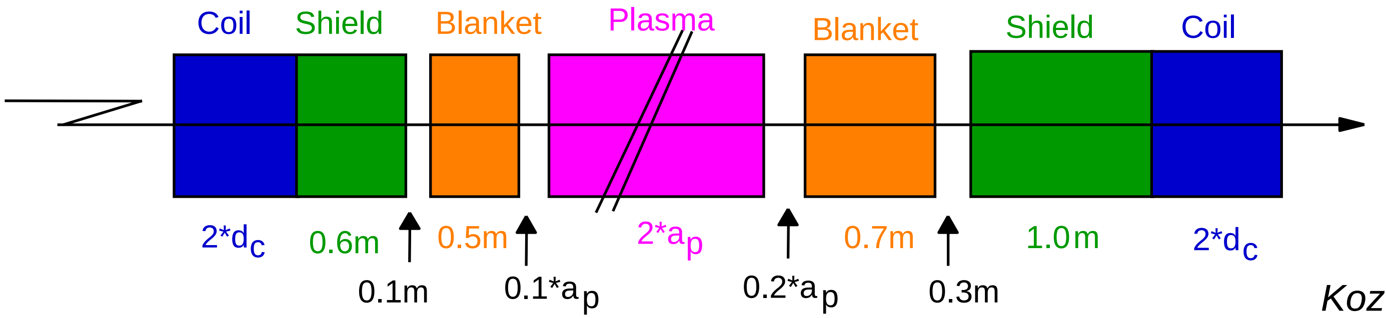
$$B_t = B_{\max}\frac{R_{\min}}{R_p}$$



Helical

$$\frac{B_{\max}}{B} = 2.1\left(\frac{R_0^{\,2}}{80S_{coil}}\right)^{0.4}\left(\frac{m}{10}\right)^{0.02}\left(\frac{\gamma_c}{1.2}\right)^{0.05}$$



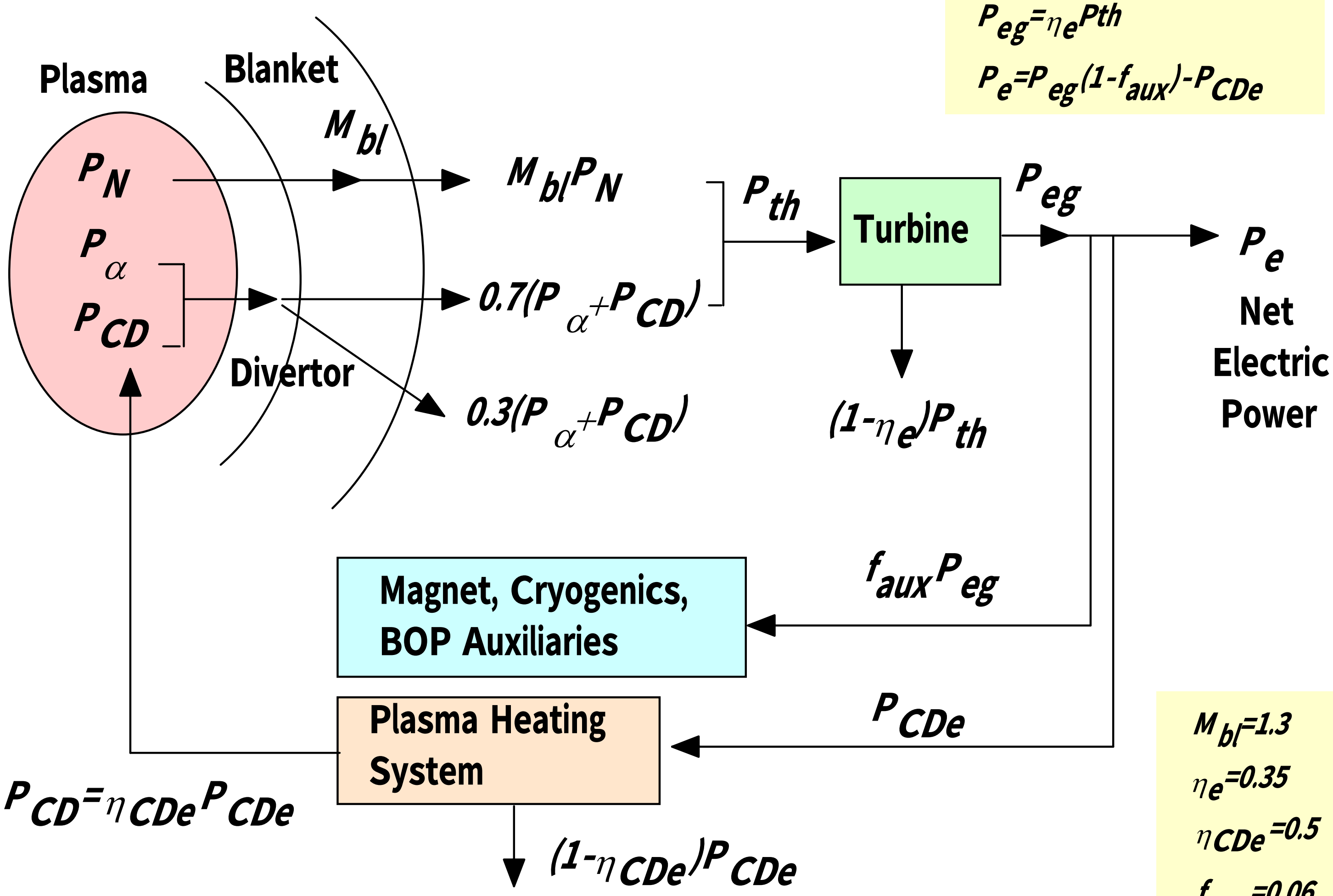


Reactor Power Flow

$P_{th}=M_{bl}P_N+0.7(P_{\alpha}+P_{CD})$

$P_{eg}=\eta_e P_{th}$

$P_e=P_{eg}(1-f_{aux})-P_{CDe}$



Plasma

Blanket

M_{bl}

P_N

P_{α}

P_{CD}

Divertor

$M_{bl}P_N$

$0.7(P_{\alpha}+P_{CD})$

$0.3(P_{\alpha}+P_{CD})$

P_{th}

Turbine

$(1-\eta_e)P_{th}$

P_{eg}

P_e

Net Electric Power

$f_{aux}P_{eg}$

Magnet, Cryogenics, BOP Auxiliaries

P_{CDe}

Plasma Heating System

$P_{CD}=\eta_{CDe}P_{CDe}$

$(1-\eta_{CDe})P_{CDe}$

$M_{bl}=1.3$

$\eta_e=0.35$

$\eta_{CDe}=0.5$

$f_{aux}=0.06$

Cost Analysis Models

	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	%				

Base Case Designs

Tokamak

$A_{av}=3.0$, $\kappa=2.0$, $\delta=0.5$
$q_0=1.0$, $q_a=3.5$
$f\alpha=0.95$

$$I_p = 5\frac{{a_p}^2 B_t}{R_p q_*} f$$

$$f \equiv \frac{\{1+\kappa^2(1+2\delta^2-1.2\delta^3)\}}{2}$$

$$f_{BS} = \frac{I_{BS}}{I_p} = [1.32-0.235\frac{q_a}{q_0}+0.0185(\frac{q_a}{q_0})^2](\sqrt{\varepsilon}\beta_p)^{1.3}$$

$$P_{CD} = \frac{n(I_p - I_{BS})R_p}{0.5}$$

Helical

$A_{av}=6.0$, $L=2$, $M=10$, $\gamma=1.25$
$\varepsilon_H=0.05*(1/10)^{2/3}$
$f\alpha=0.90$

$$\frac{B_{\max}}{B} = 2.1(\frac{{R_0}^2}{80S_{coil}})^{0.4}(\frac{m}{10})^{0.02}(\frac{\gamma_c}{1.2})^{0.05}$$

$$I_{coil} = 5\frac{R_p B_t}{m}$$

$$j_{coil} = \frac{I_{coil}}{S_{coil}} = 1.5\frac{(9.6-0.6B_{\max})^{10}}{(1.+(B_{\max}/12)^{1.5})}$$

$$\Delta = 0.14\frac{R_0}{4.0}\{1.5(\frac{j_{coil}}{40}\frac{R_0}{B_t}\frac{10}{m})(\frac{1.2}{\gamma_c})^{3.5}-0.5\}^{0.6}$$

B_{max} =13 T
impurity(Z=6) 1%, alpha 5%, Z_{eff}=1.5
$T\sim(1-x^2)$, $n\sim(1-x^2)^{0.5}$
Beta = 5%, P_{elect} = 1GW

Base Case Designs

	Base Case Tokamak Reactor		**Base Case Heliotron Reactor**	
	TR-1	**TR-2**	**HR-1**	**HR-2**
P_electric [GW]	**1**	**2**	**1**	**2**
T0 [keV]	30	30	20	20
<beta>[%]	**5**	**3**	**5**	**3**
beta_N	4.7	2.8	**-**	**-**
B_max [T]	13	13	13	13
F_wall [MWy/m^2]	15	15	15	15
R_p [m]	**5.20**	**8.10**	**12.5**	**14.4**
B [T]	**7.06**	**8.09**	**4.60**	**6.35**
Ip [MA]	9.3	16.6	-	-
f_BS [%]	69	35	-	-
P_fusion [MW]	2.69	6.28	2.32	4.64
L_wall [MW/m^2]	4.91	4.90	1.43	2.17
H-factor	1.17 (ITER)	0.65 (ITER)	2.68 (ISS) 1.35(NLHD1)	1.68 (ISS) 0.75(NLHD1)
F.I. Mass [kt]	**5.0**	**11.2**	**12.2**	**23.8**
Capital Cost [M$]	**4,140**	**7,270**	**5,020**	**8,010**
COE [Yen/kWh](2003)	**8.27**	**7.33**	**9.52**	**7.48**

$\kappa = 2.0$

$\delta = 0.5$

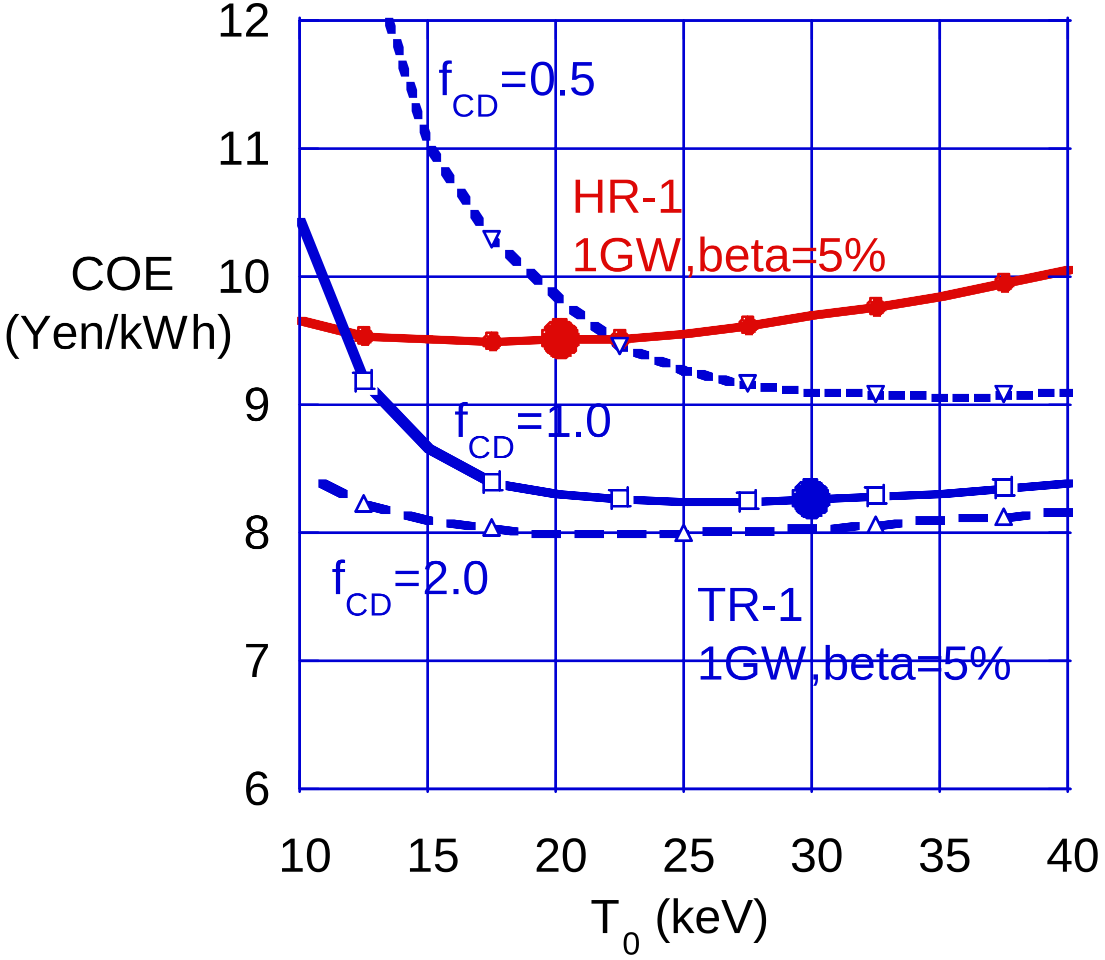
$R_p / \langle a_p \rangle = 3.0$

$L = 2$

$m = 10$

$R_p / \langle a_p \rangle = 5.7$

Effects of CD Efficiency



$$I_p = 5\frac{a_p{}^2 B_t}{R_p q_*} f$$

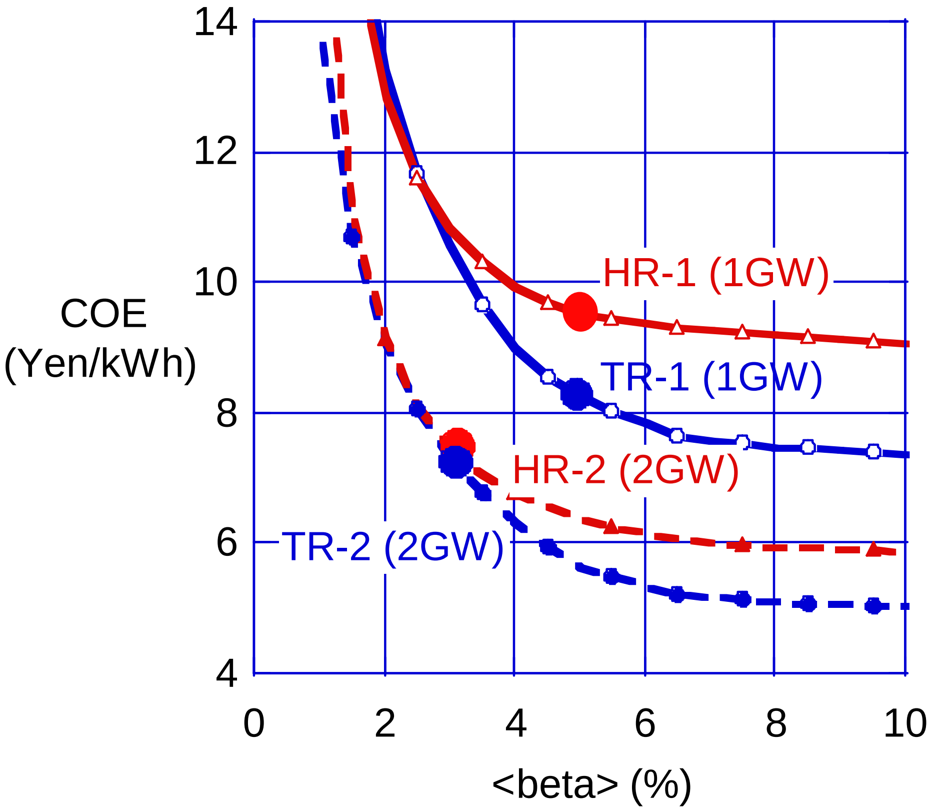
$$f \equiv \frac{\{1+\kappa^2(1+2\delta^2-1.2\delta^3)\}}{2}$$

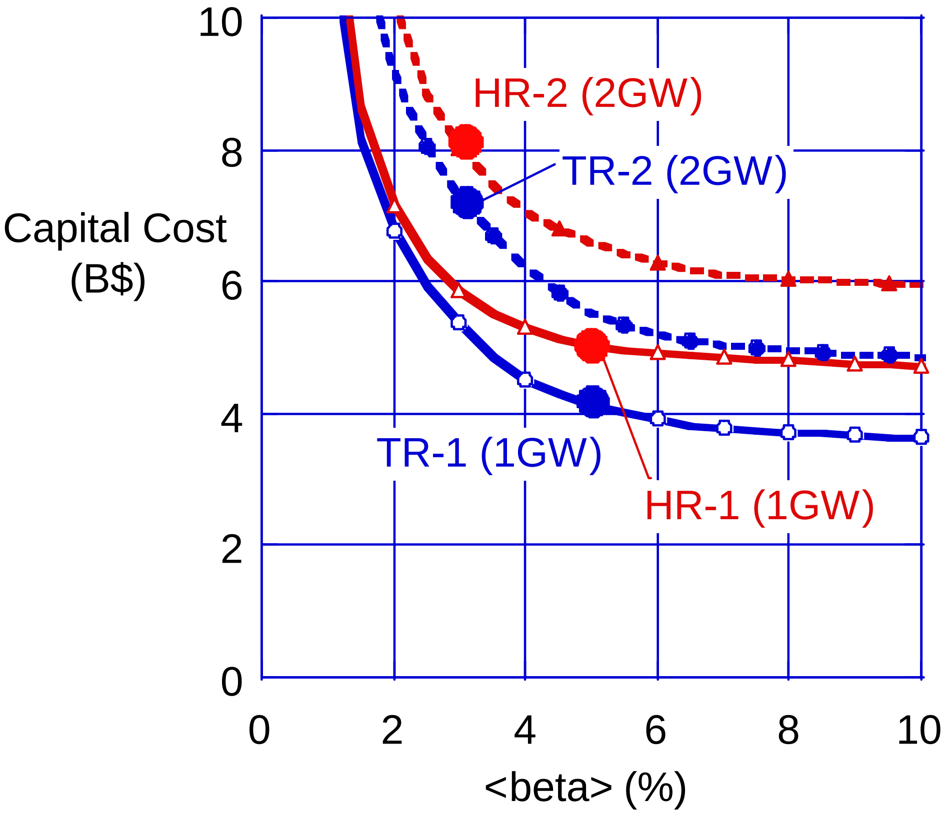
$$f_{BS} = \frac{I_{BS}}{I_p}$$

$$= [1.32 - 0.235\frac{q_a}{q_0} + 0.0185(\frac{q_a}{q_0})^2](\sqrt{\varepsilon}\beta_p)^{1.3}$$

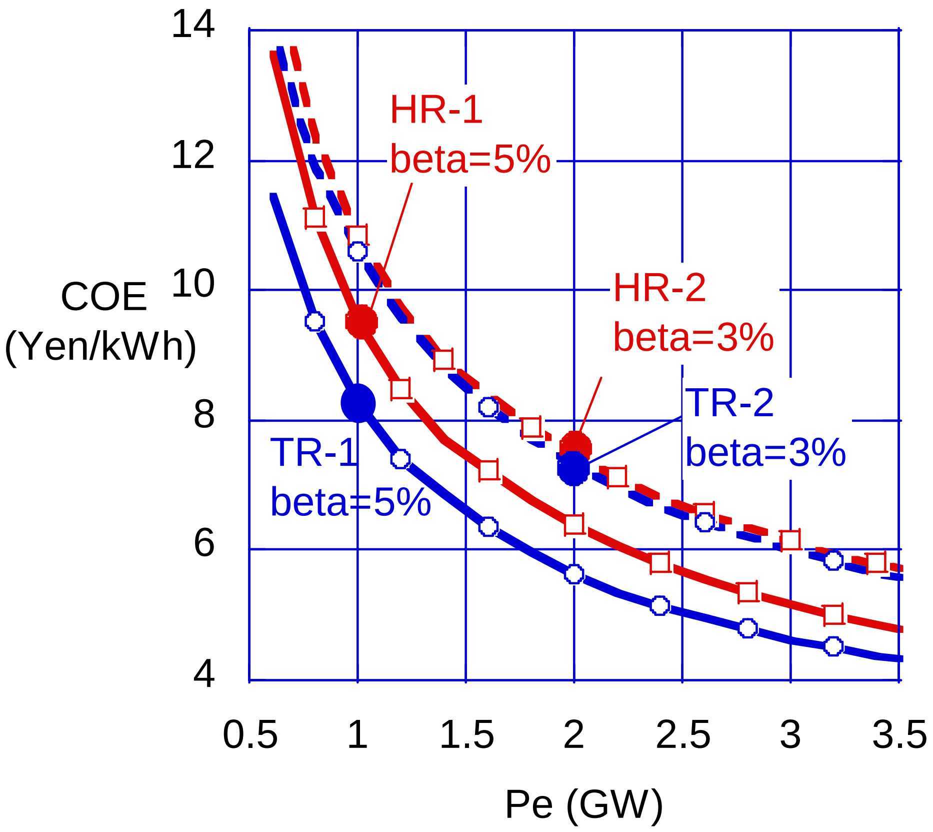
$$P_{CD} = \frac{n(I_p - I_{BS})R_p}{0.5} / f_{CD}$$

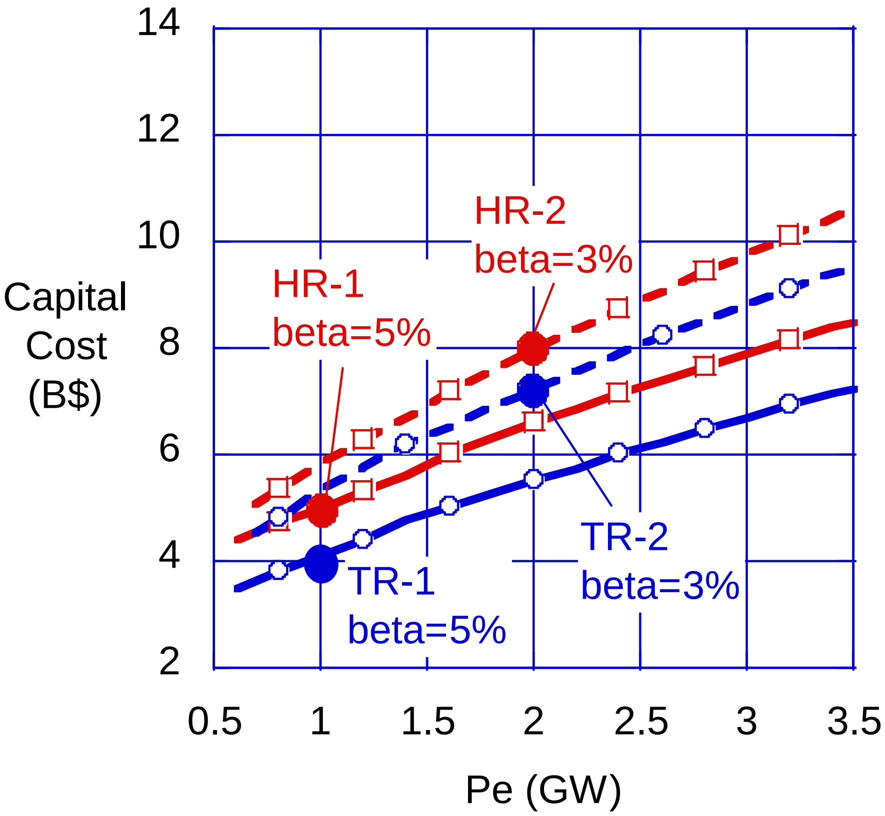
COE, Capital Cost vs. Plasma Beta



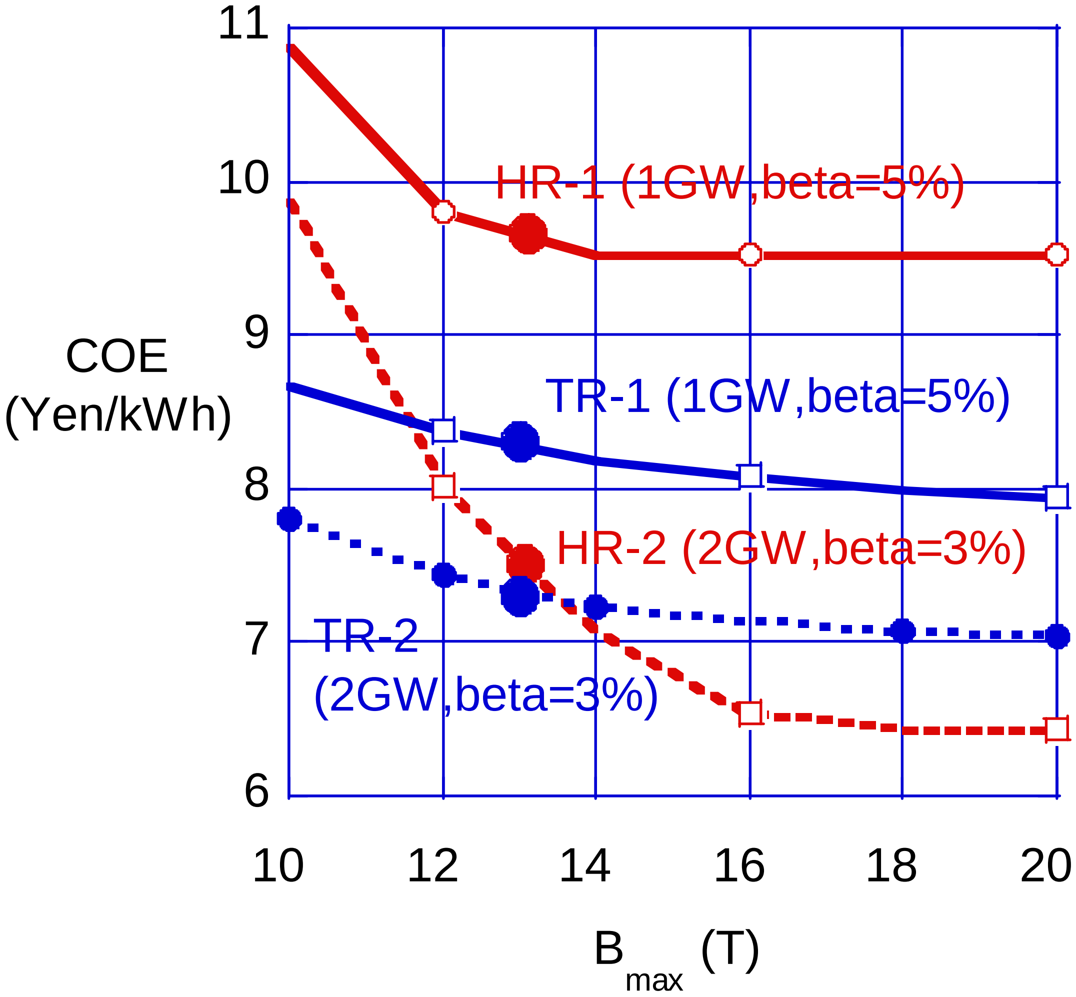


COE, Capital Cost vs. Electric Power Output





Effects of Maximum Field Strength



HR

$$\frac{B_{\max}}{B} = 2.1\left(\frac{R_0^{\ 2}}{80S_{coil}}\right)^{0.4}\left(\frac{m}{10}\right)^{0.02}\left(\frac{\gamma_c}{1.2}\right)^{0.05}$$

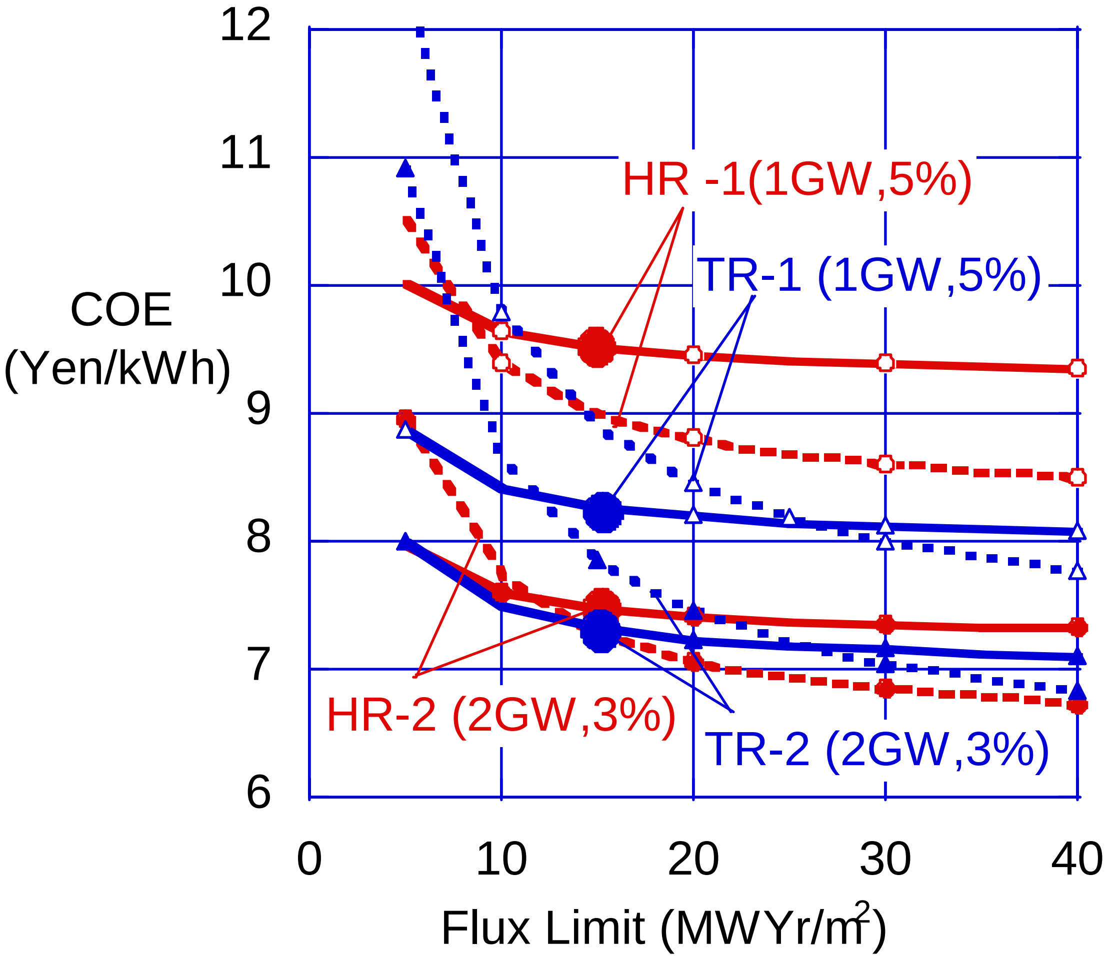
TR

$$B_t = B_{\max}\frac{R_{\min}}{R_p}$$

$$j_{coil} = \frac{I_{coil}}{S_{coil}} = 1.5\frac{(9.6-0.6B_{\max})^{10}}{(1.+(B_{\max}/12)^{1.5})}$$

$$or \qquad = 30MA/m^2$$

Effects of Neutron Flux Limit and Availability



Solid line:

$$f_{avail} = 0.75$$

Dotted lines:

$$f_{avail} = 0.85/(1 + f_{peak}\Gamma_W t_m / \Phi_w)$$

f_{peak} : Peak factor (1.4)

t_m : Maintenance time(0.5Yr)

Γ_w : Neutron wall flux (MW/m^2)

Φ_w : Flux Limit (MW-Yr/m^2)

Summary

(1) High temperature, thermally stable operation with high BS current fraction is preferred in tokamak reactors 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 engineering improvement of increasing maximum magnetic field strength leads to the compact designs. However, it does not mean the strong reduction of COE because of the increase in the wall neutron load.

(4) The system availability might be affected by this wall lifetime and the blanket maintenance time. A rather-compact, high-availability and steady-state reactor should be explored for the realization of future economical and attractive fusion power reactors.