Core Plasma Design of a Heliotron Reactor

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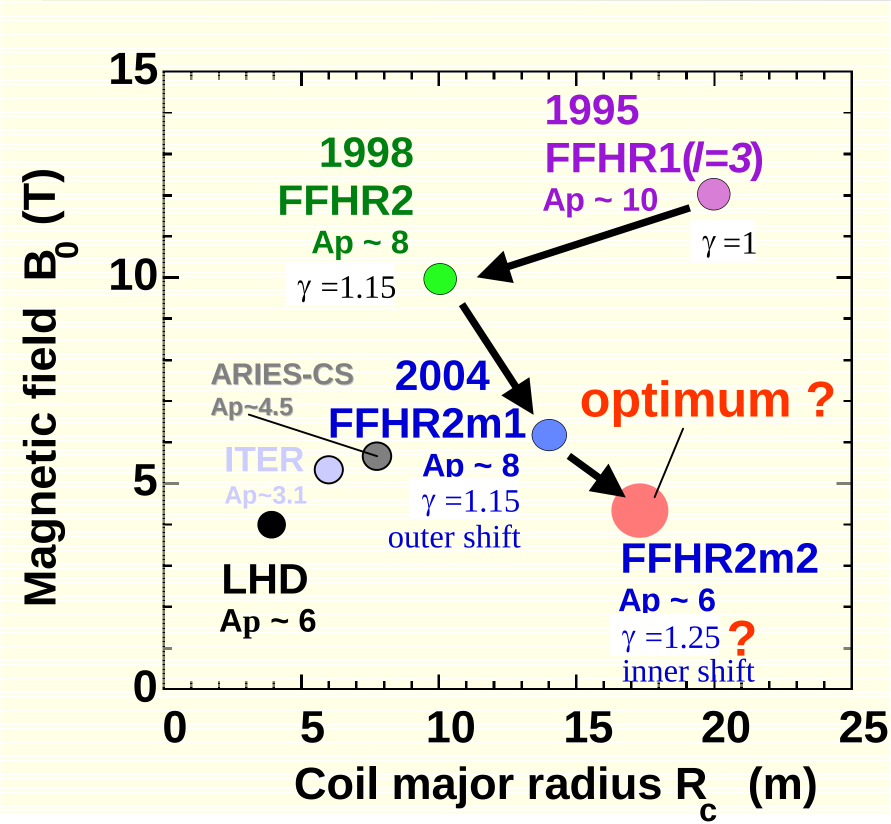
Outline

1. Introduction
2. Design point survey by a system design code
3. Finite-beta equilibrium calculation by VMEC
4. Summary

1. Introduction
Heliotron-type concept “FFHR”



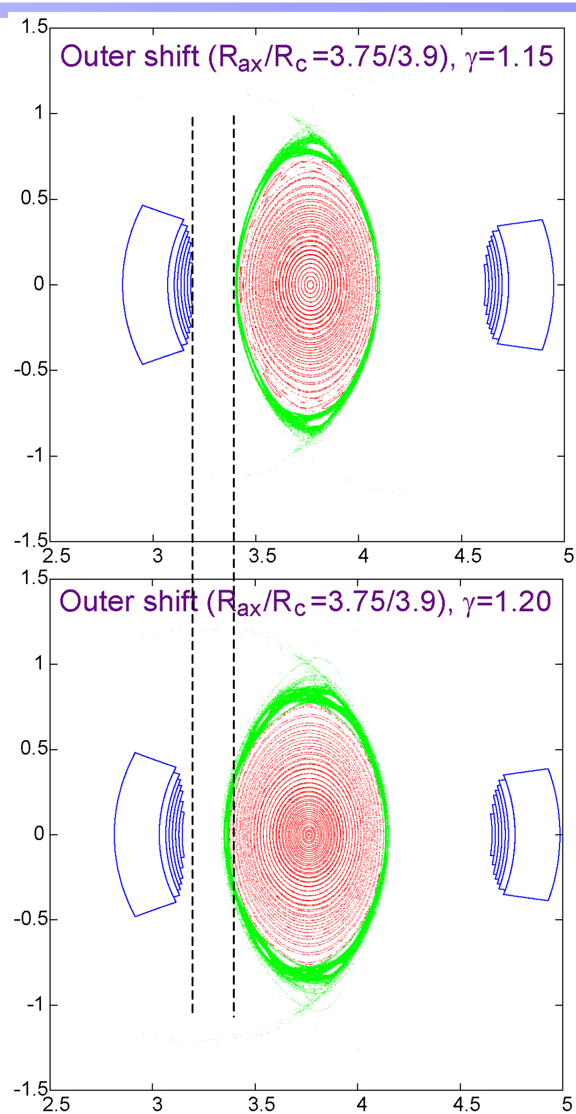


*Figure from A. Sagara *et al.*, *Proc. of 18th International Toki Conference (ITC18)*, Toki, Japan, Dec.9-12, 2008 I-33.

- Key design points are low neutron wall loading, low stored magnetic energy and sufficient blanket space.

Possibility of large size reactor design

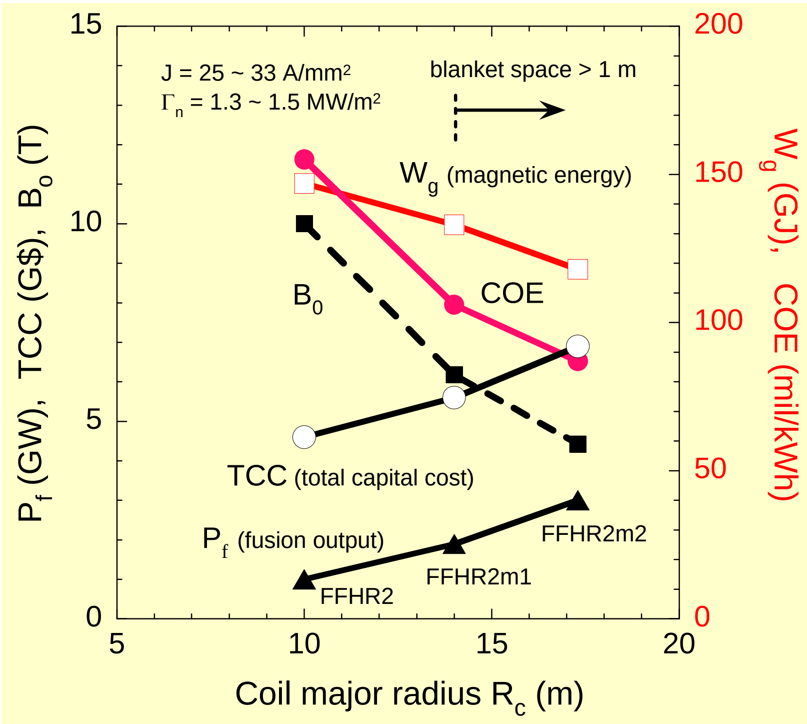
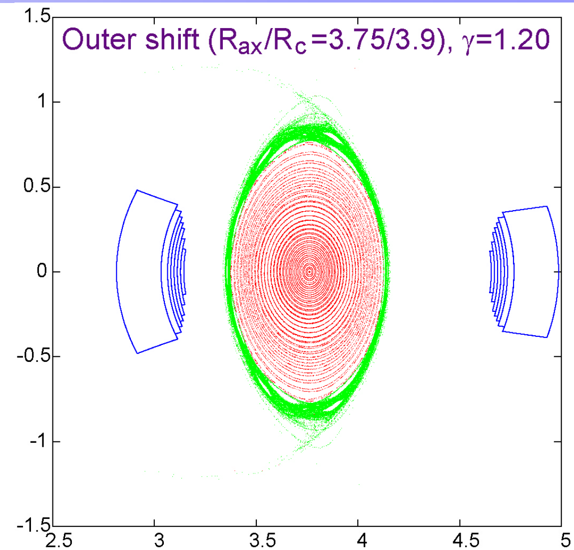
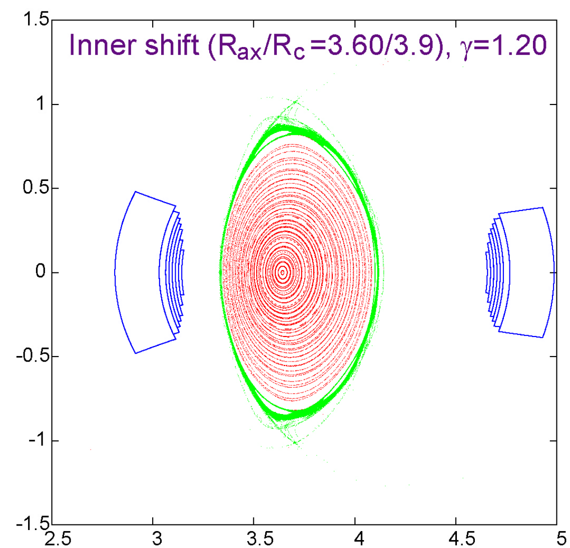


*Figure from A. Sagara *et al.*, FED **83** (2008) 1690..





- Increase in the reactor size is one possible solution!

  → Feasibility of design with larger γ (=1.2) and inward-shifted configuration has been investigated.

2. Design point survey

- Trade-off in design space
  - Physics vs. engineering constraints
  - Sufficient blanket space vs. suppression of stored magnetic energy

Magnetic field strength (low → high)		Reactor size (small → large)
high → low	required confinement improvement	high → low
high → low	required beta	high → low
low → high	stored magnetic energy	low → high
	wall load	high → low
wide → narrow	blanket space	narrow → wide

Development of system design code

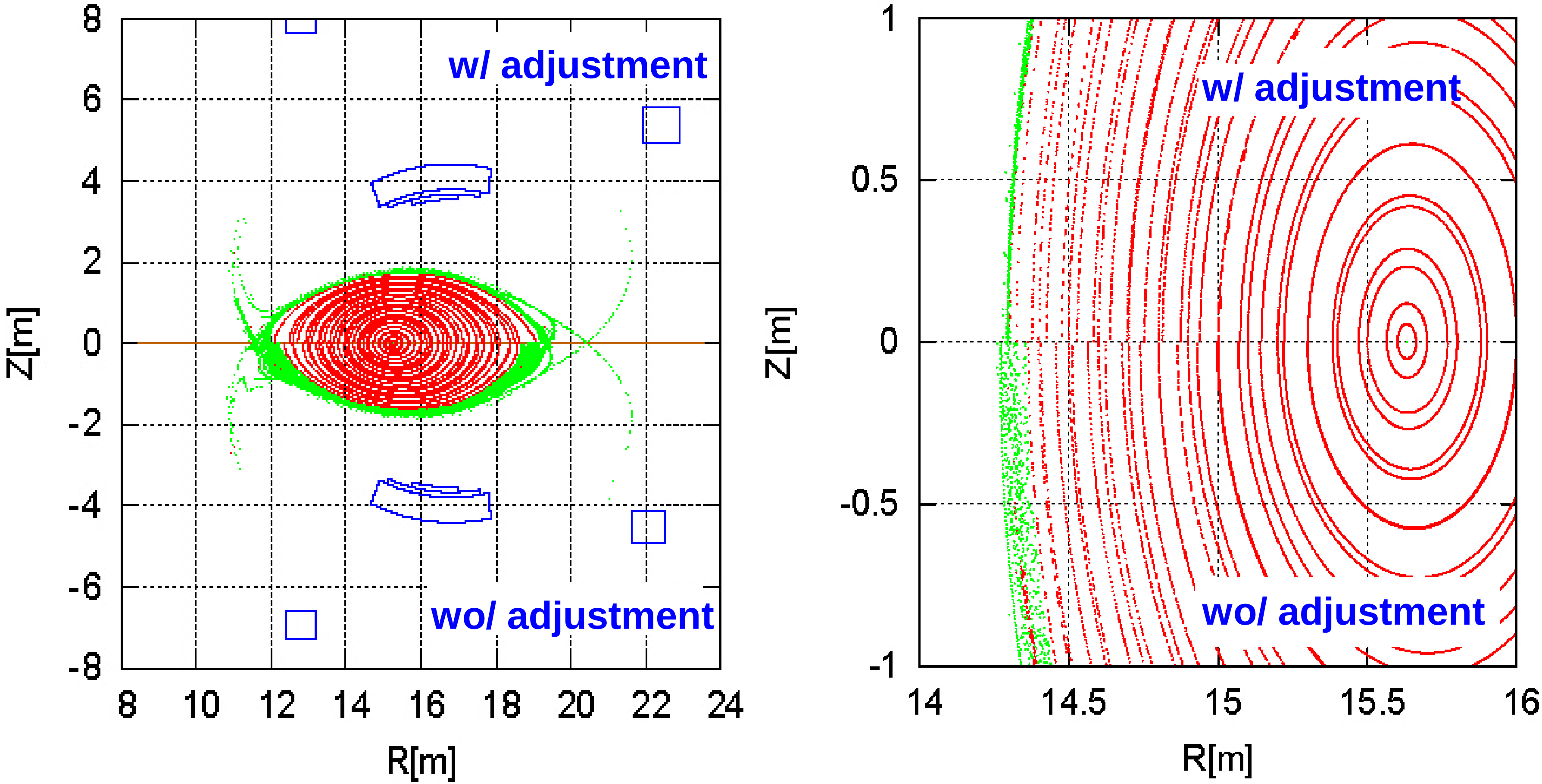
- Feasible design point was investigated through the parameter scan in the wide design space (R_c, B_t, $n(r)$, $T(r)$) by using the developed system design code
  - Calculate coil stored magnetic energy and blanket space with the actual helical and poloidal coil geometry
  - Plasma performance is estimated by a simple volume-averaged power balance model with power of parabolic density/temperature profile

$$n(\rho) = (1-\rho^2)^{\alpha_n},\ T(\rho) = (1-\rho^2)^{\alpha_T}$$

    and ISS04v3 energy confinement scaling.

- Coil and plasma geometries were fixed
  - a pair of γ=1.2 helical coils and two pairs of poloidal coils
  - Inner-shifted magnetic axis position (R_{ax}/R_c=3.6/3.9).

Adjustment of poloidal coil position



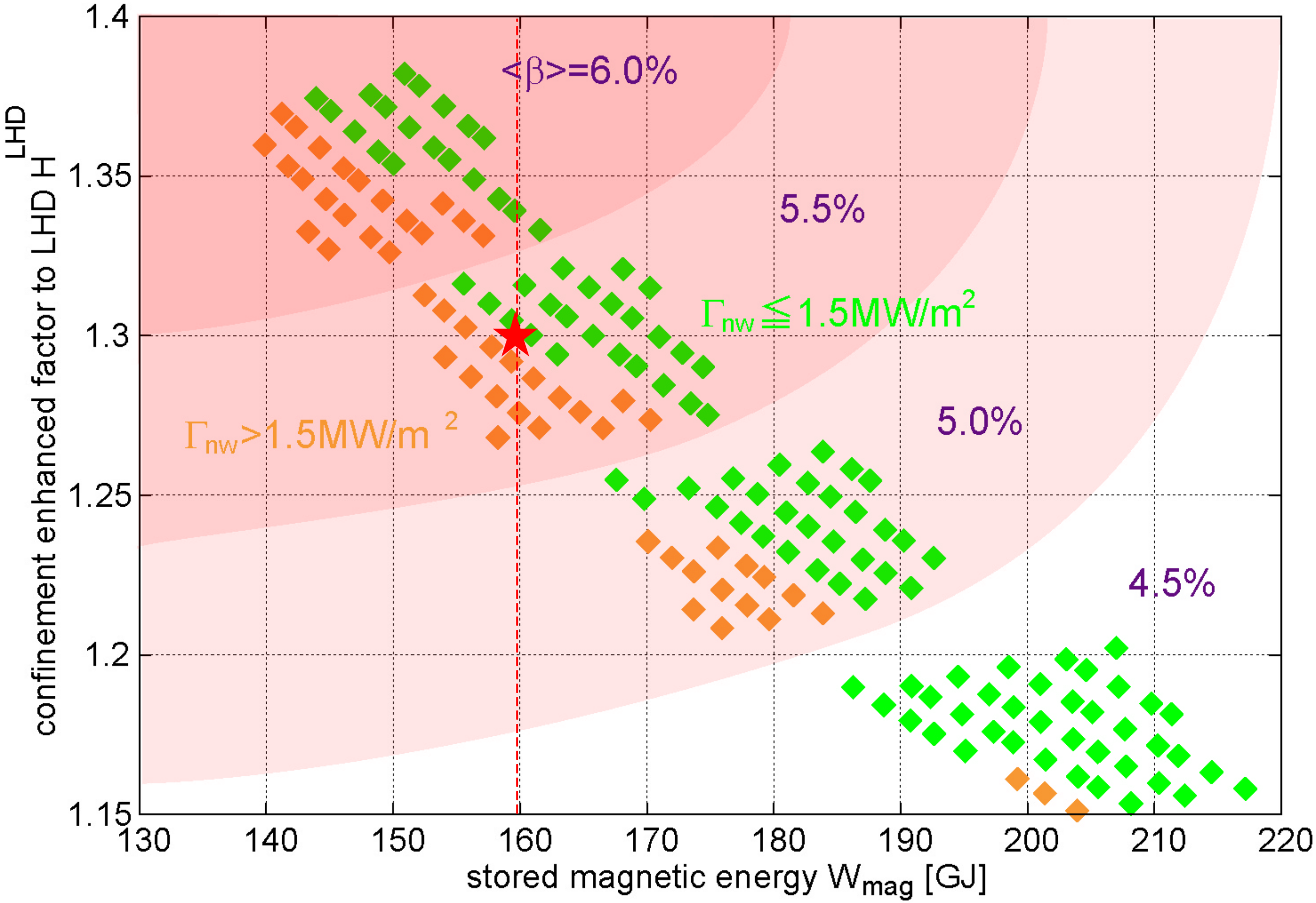
- Adjustment of poloidal coil position enables the increase of blanket space as well as increase of plasma volume (~22%) .

Prerequisite of design

- Physics:
  - Density : up to 1.5 times of Sudo density limit scaling (already achieved in past experiments)
  - Self-ignited plasma (no auxiliary heating power)

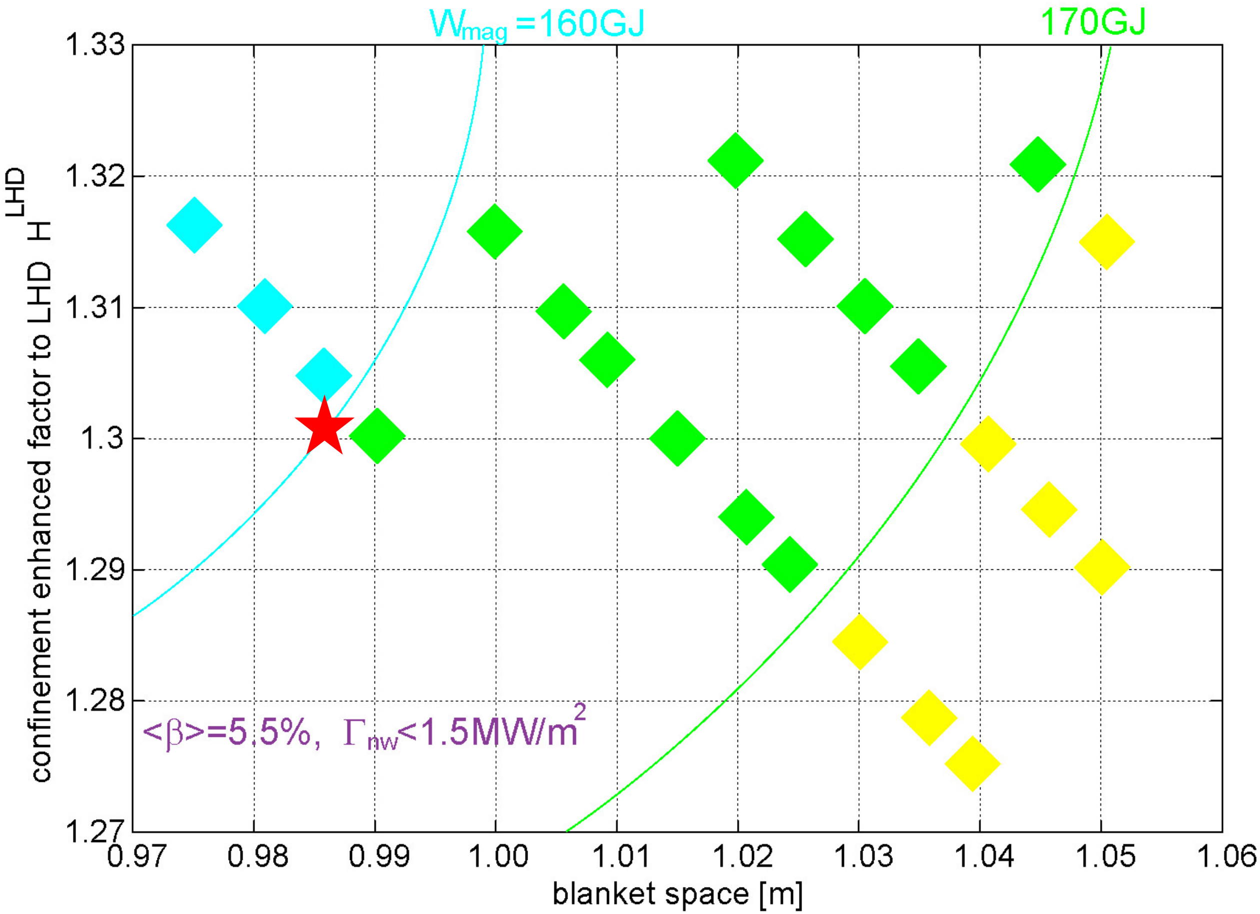
- Engineering:
  - Average neutron wall loading $<1.5 MW/m^2$
  - Blanket space ~1.0m
  - Stored magnetic energy <160GJ
  - Helical coil current density : $25 A/mm^2$
  - Fusion output : ~3GW

Effect of beta value



- In case of constant (~3GW) fusion output, beta value is limited by engineering constraints (stored magnetic energy, neutron wall load) and the required confinement enhancement factor.

Engineering constraints



- Blanket space with ~1m can be obtained with stored magnetic energy ~160GJ.

Design parameter

Parameter	LHD	Present Design
Pitch parameter γ	1.25	1.20
Coil major / minor radius R_c / a_c [m]	3.9 / 0.98	17 / 4.08
Plasma major / minor radius R_{ax} / $\langle a_p \rangle$ [m]	3.6 / 0.64	15.7 / 2.50
Plasma volume V_p [m^3]	30	1927
Toroidal magnetic field B_{ax} [T]	4	5.0
Fusion power P_{fus} [GW]		3.0
Averaged beta $\langle\beta\rangle$ [%]	5.0 (diamagnetic measurement)	5.5
Confinement enhanced factor to LHD / ISS4		1.3 / 1.2
Neutron wall load Γ_n [MW/m^2]		1.5
Divertor heat load Γ_{div} [MW/m^2]		2.2
Max. filed on coil B_{max} [T]	9.2	11.5
Coil current density j_c [A/mm^2]	53	25
Blanket space Δ [m]	0.12	**0.985**
Stored magnetic energy W_{mag} [GJ]	0.9	**160**

3. Finite-beta equilibrium calculation

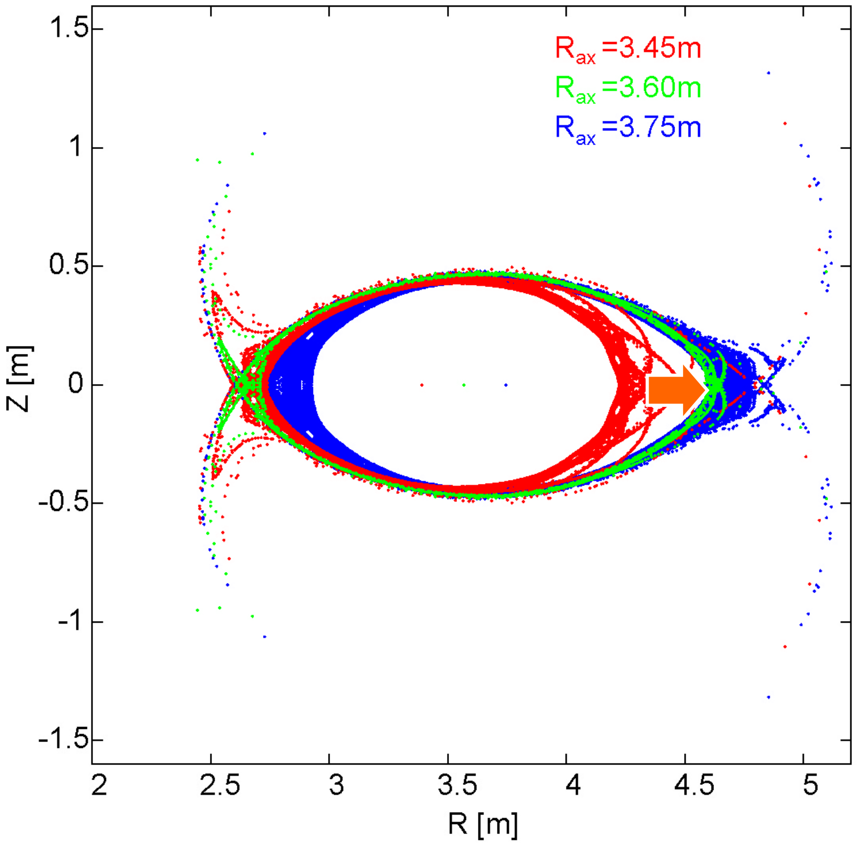
- The system code assumes plasma volume as large as volume enclosed by LCFS in vacuum equilibrium.
- Plasma volume shrinks with Shafranov shift.

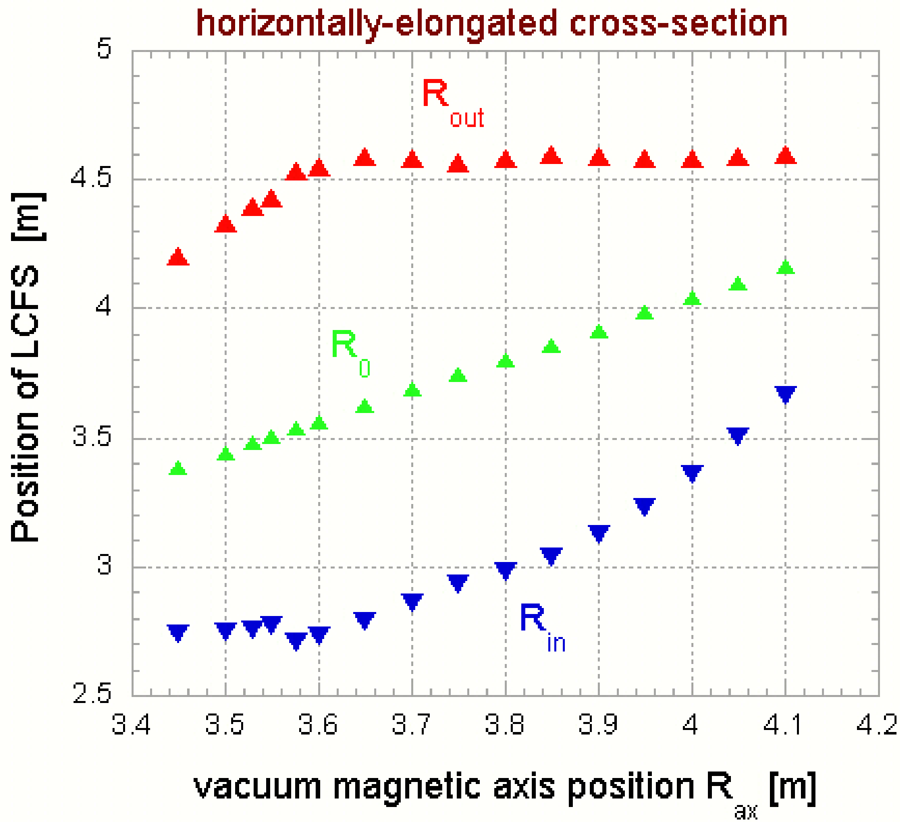
- In LHD experiments, control of magnetic axis during plasma discharge by changing poloidal coil currents has been demonstrated.

  → Shrinking of plasma volume due to Shafranov shift can be suppressed.

- Investigation of high-beta equilibrium consistent with point design by using numerical code VMEC
  – Demonstration of restoration of the volume of high-beta plasma by applying vertical field
  – Provision of base data for other analyses (stability, transportation, boot-strap current, etc.)

Separatrix position in LHD





- Outermost surface is considered to enlarge to the position that equivalent to R_{ax}=3.6m of LHD with the shift of magnetic axis by finite-beta effect from the further inward-shifted position.

Calculation condition

- Boundary condition：
  - Outward plasma boundary position in horizontally- elongated cross-section is fixed at the same position of LCFS for vacuum equilibrium.
- Pressure profile：
  - In reference to LHD high-beta operation,

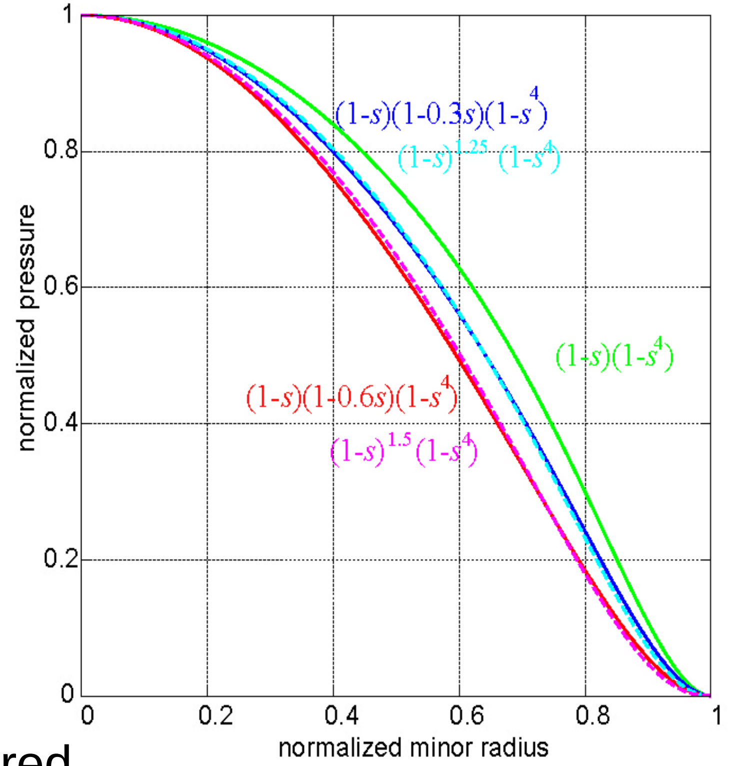
$$p=p_0(1-s)(1-s^4)$$

was adopted (s :normalized toroidal flux)

  - For more peaked profiles,

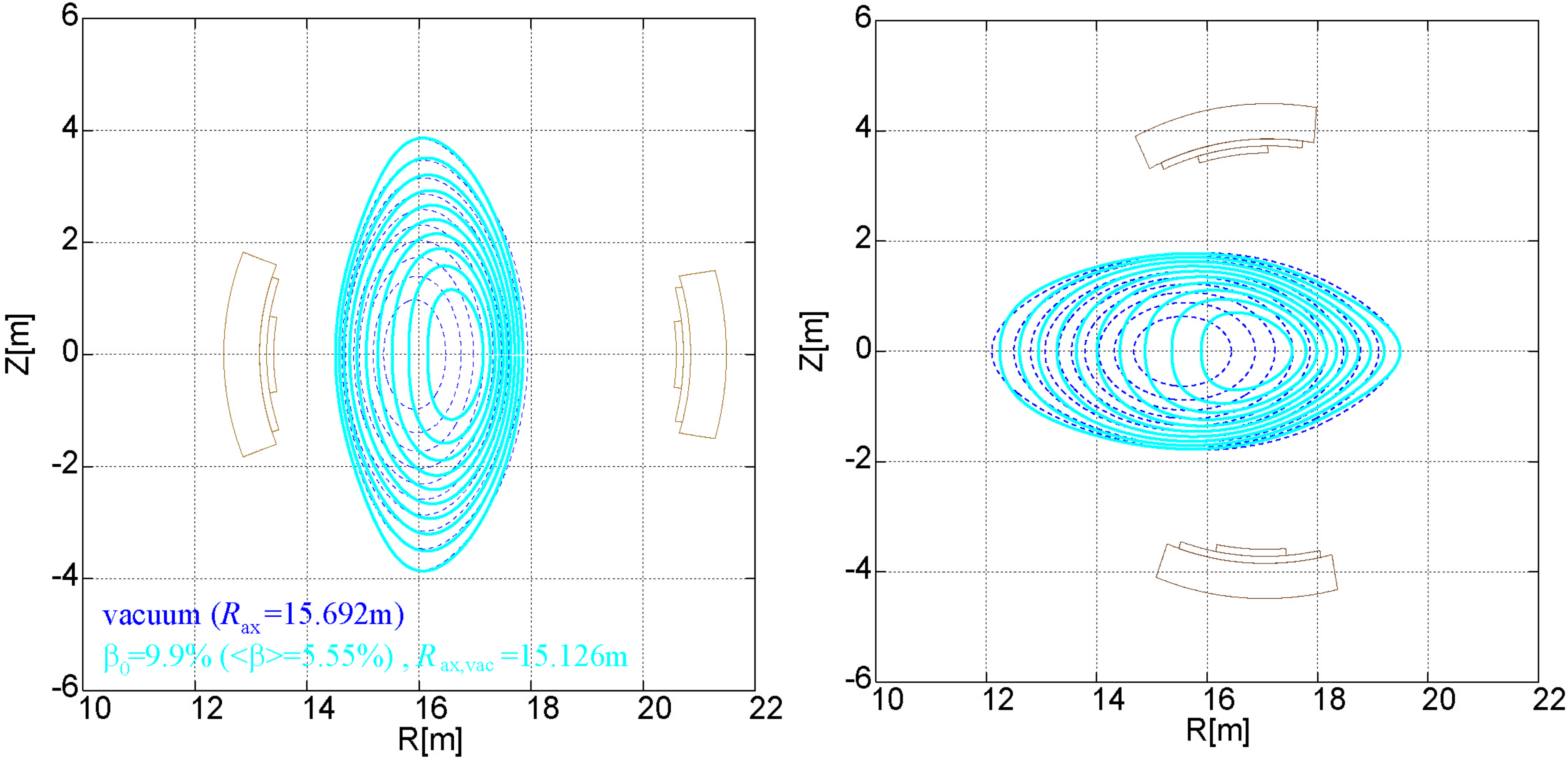
$$p=p_0(1-s)(1-0.3s)(1-s^4)$$
$$p=p_0(1-s)(1-0.6s)(1-s^4)$$

were used.



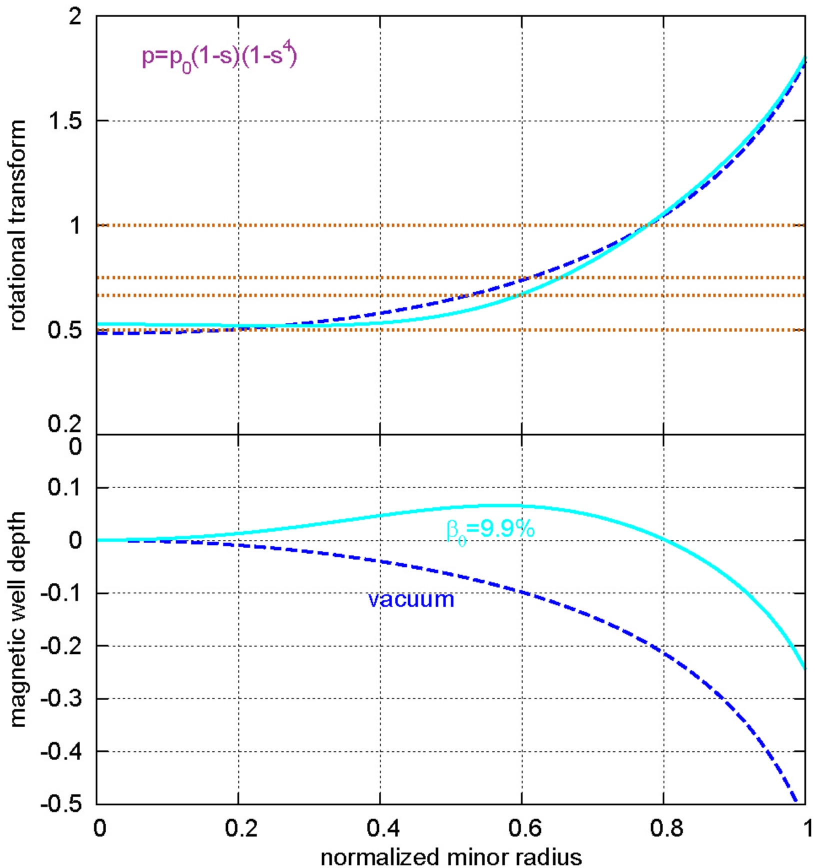
- Peak beta value：
  - Selected to achieve the same plasma stored energy as estimated by the system code.

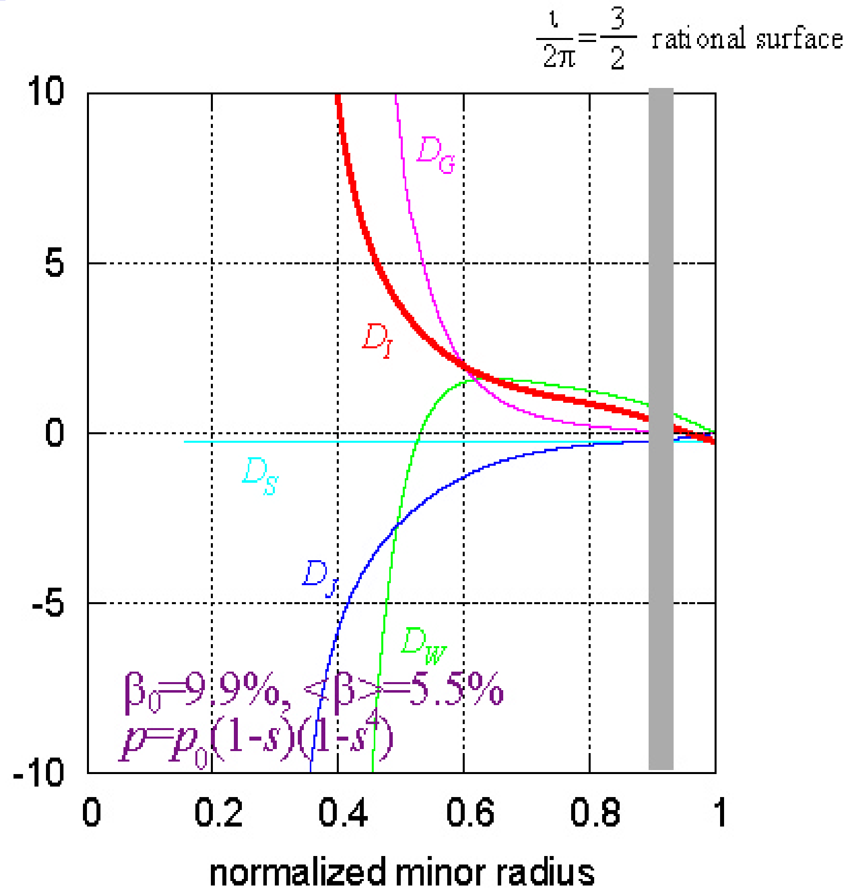
VMEC result (parabolic profile)



- Plasma volume as large as vacuum configuration with the sufficient plasma stored energy (~1300MJ) can be achieved.

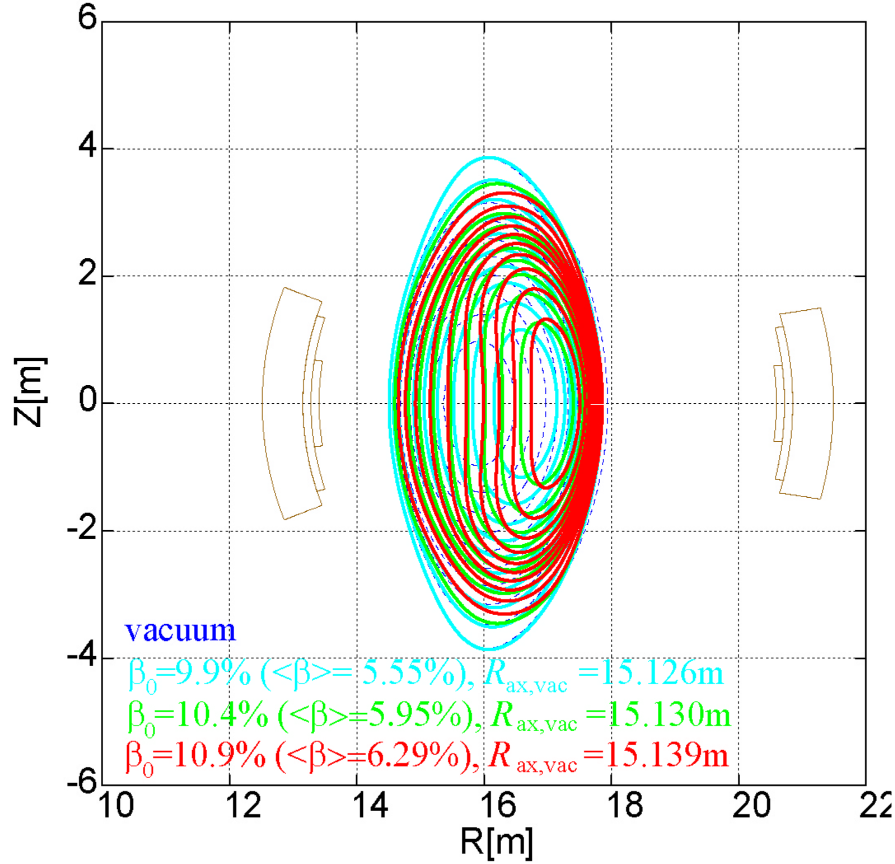
Mercier analysis (parabolic profile)

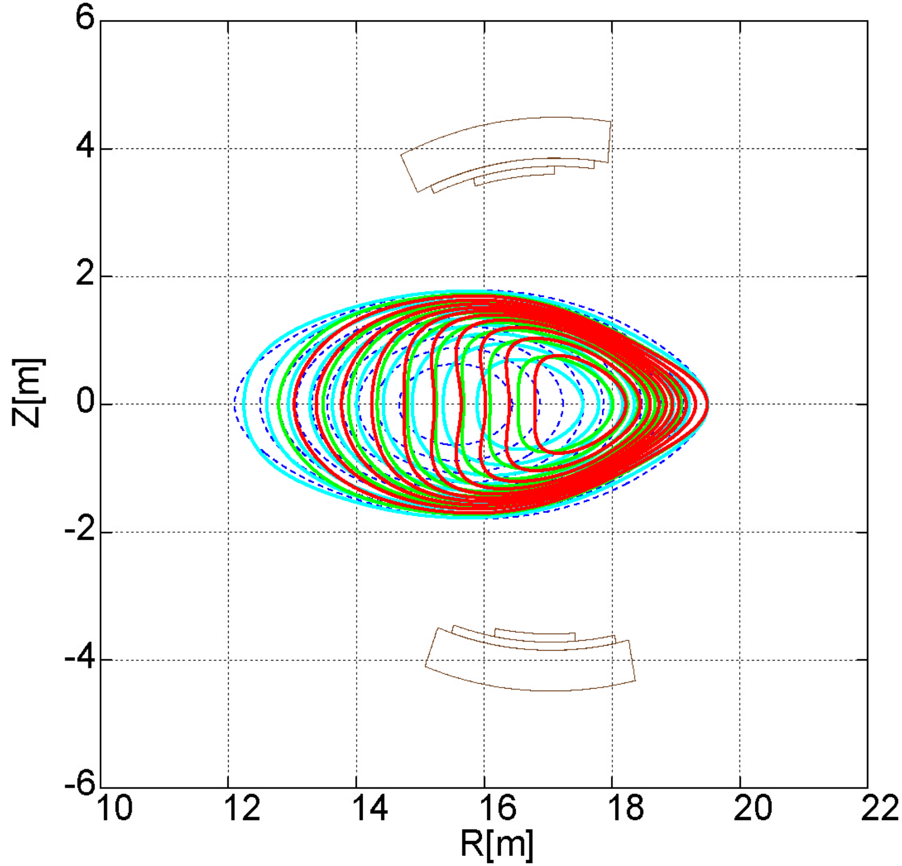




- In case of the configuration with the same volume as vacuum condition, all region is Mercier unstable.

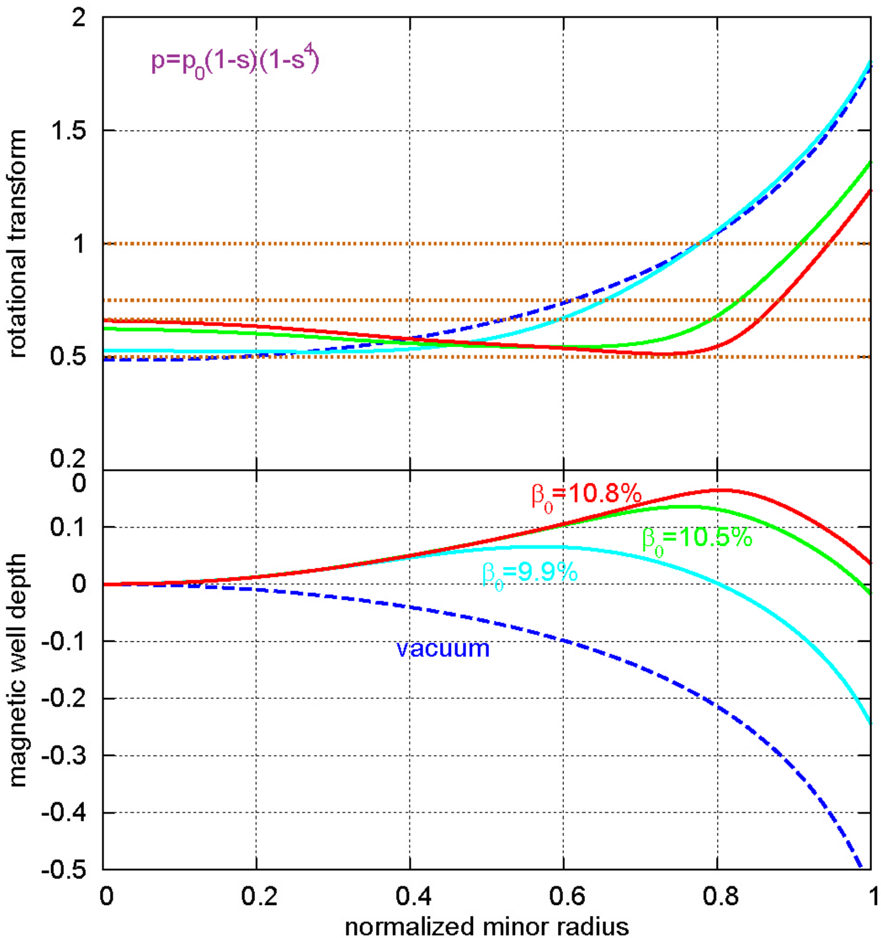
VMEC result (parabolic profile)

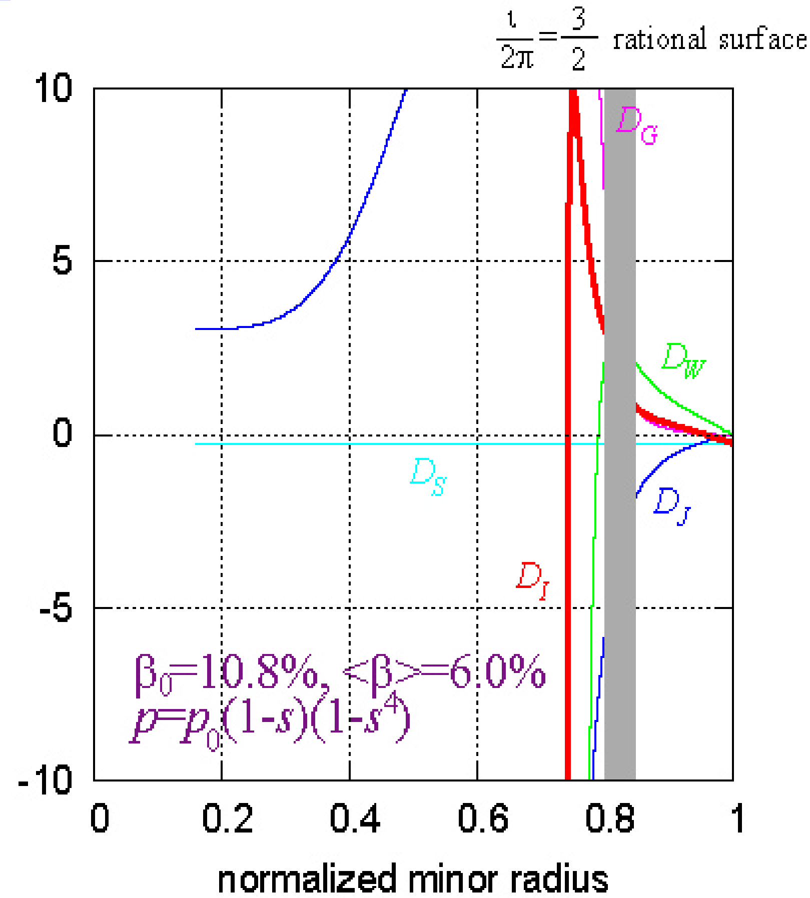




- The required plasma stored energy can be achieved with slightly outward-shifted configuration.

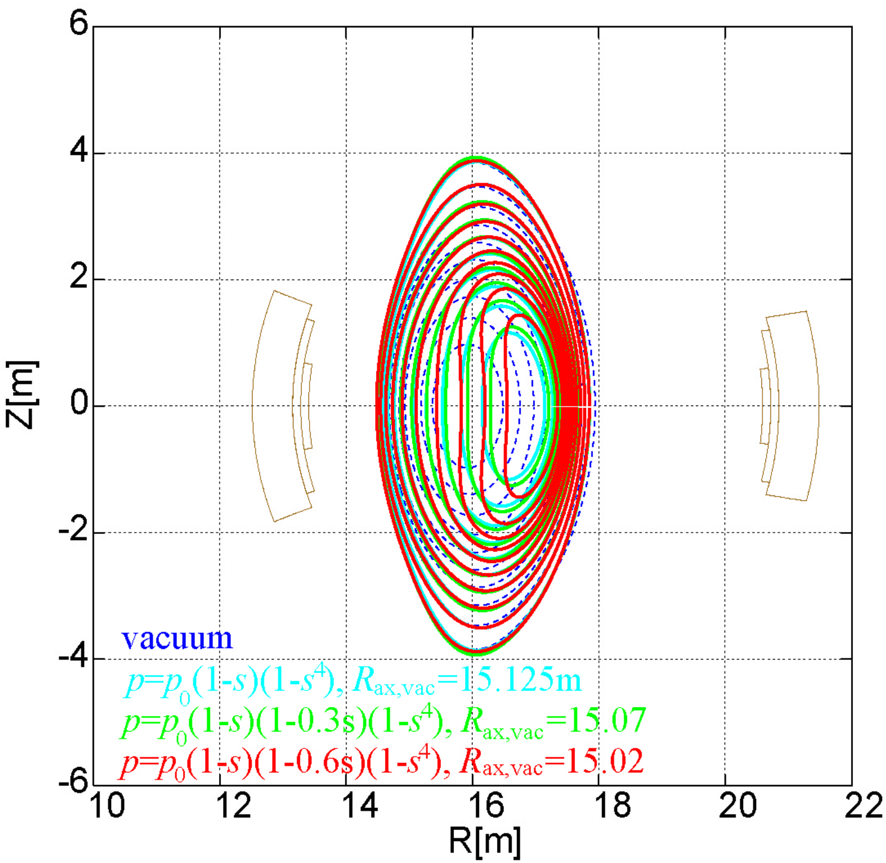
Mercier analysis (parabolic profile)

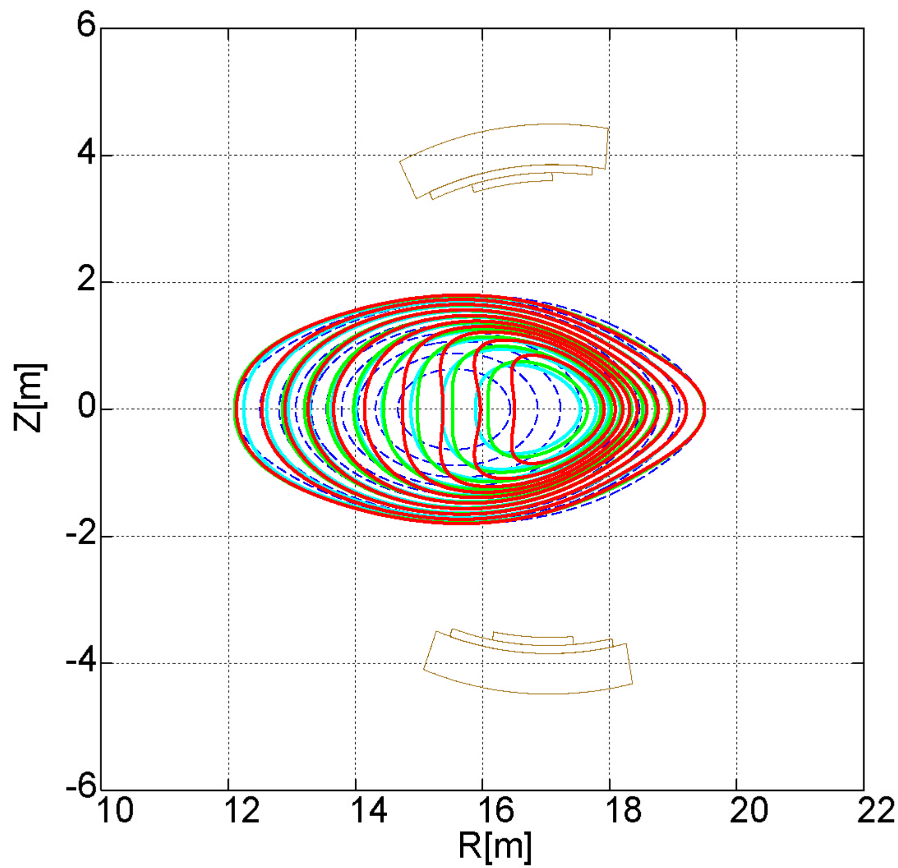




- Mercier stable region can be enlarged by moving the magnetic axis position slightly outward.

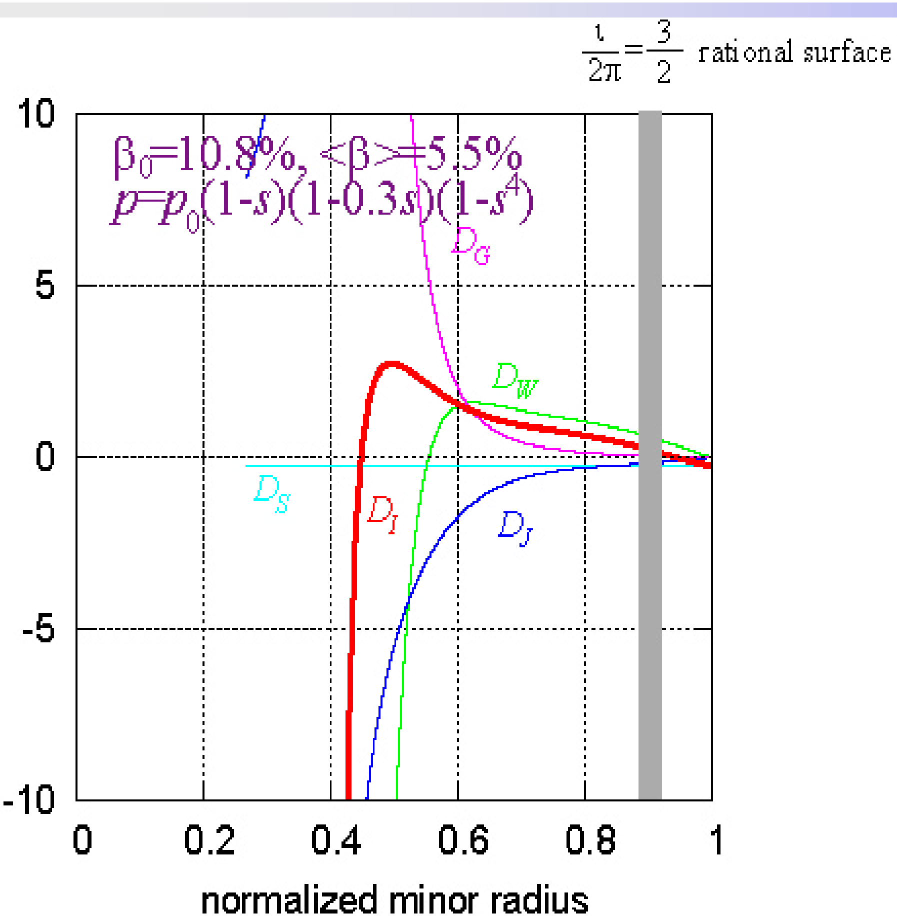
VMEC result (peaked profile)

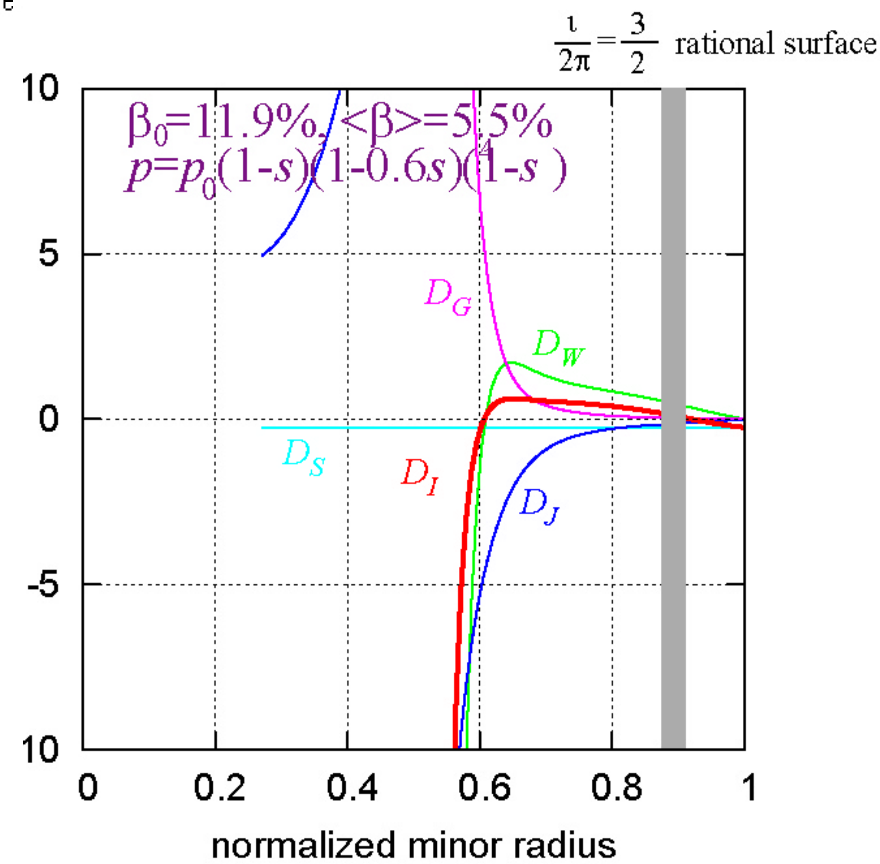




- High beta equilibrium for peaked profiles can be achieved with further high central beta value and vertical field strength.

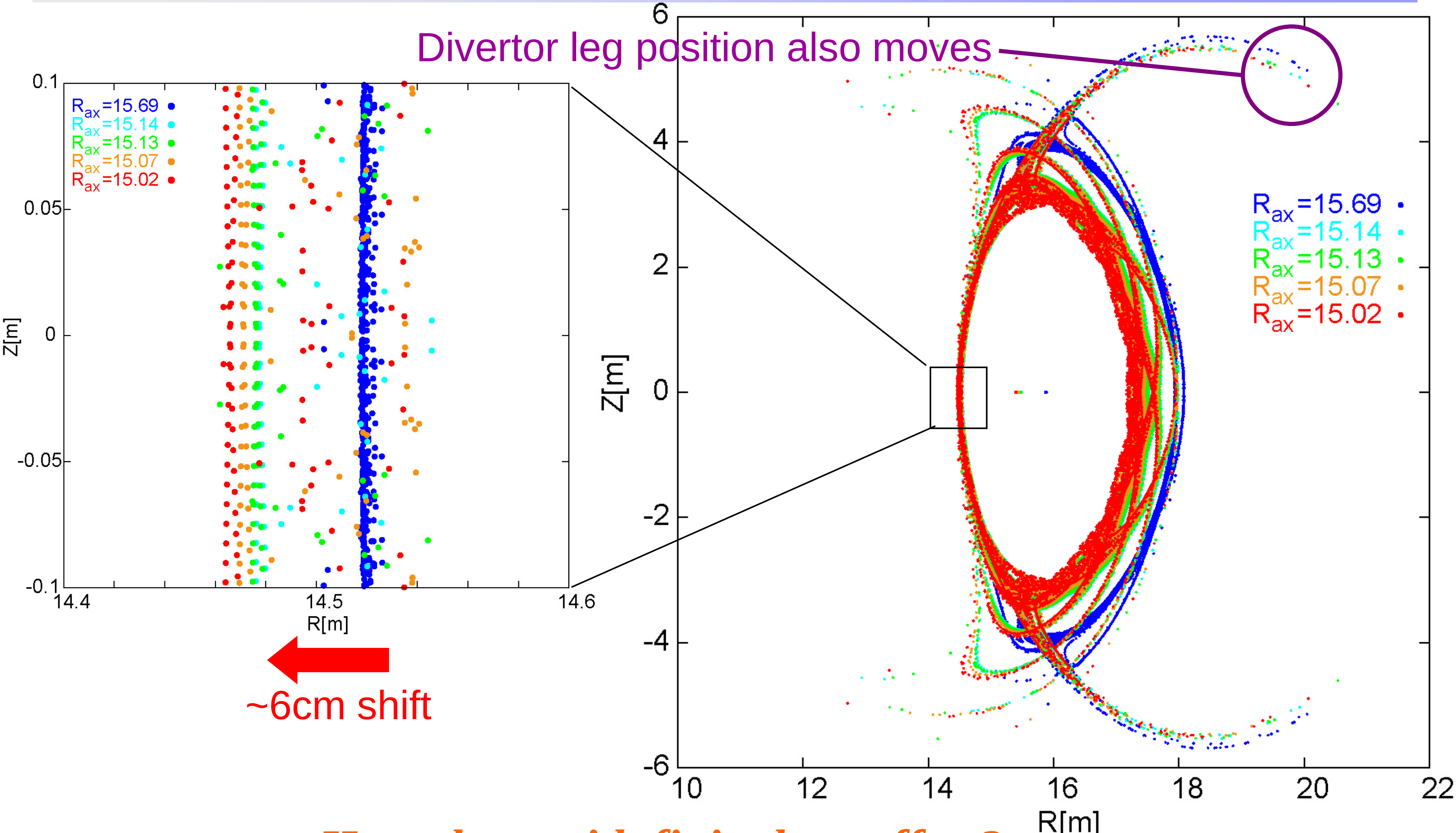
Mercier analysis (peaked)





- Relatively larger region becomes Mercier stable due to the larger Shafranov shift compared with the parabolic profile case.

Change in vacuum field



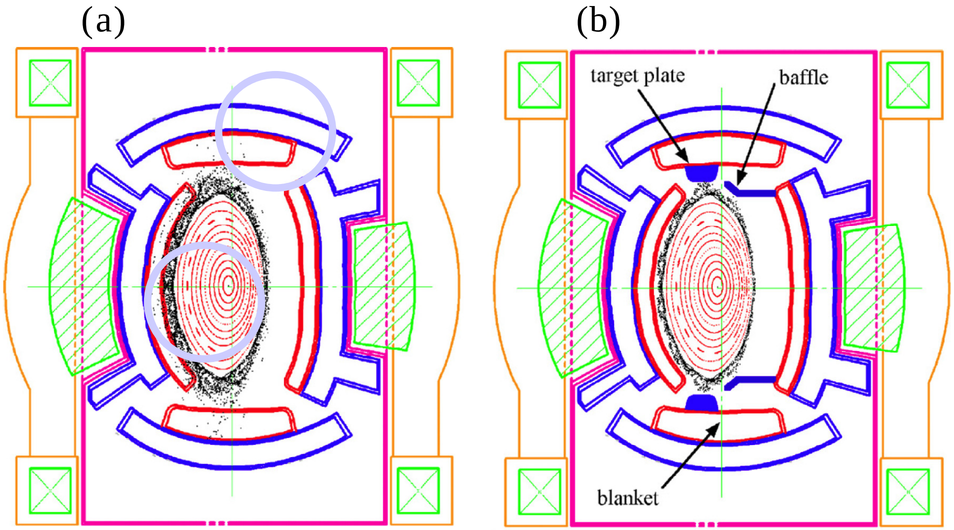
How about with finite-beta effect?

4. Summary and future work

- The design of core plasma with the LHD-type heliotron configuration has been advanced.
  - There exists a design window that satisfies engineering feasibility with the core plasma that can be extrapolated from the present achievement of LHD experiments.
  - Existence of equilibrium magnetic surface with sufficient volume and stored energy has been confirmed.

- For more reliable core plasma design, we need to
  - Check the magnetic surface structure including stochastic region (interference of inner ergodic layer with the first wall, change in effective plasma volume)
  - Evaluate the effect of boot-strap current
  - Evaluate the effect of the change in magnetic surface structure on alpha particle confinement property

Blanket space vs. Confinement property



Helical X-point Divertor (HXD)

A. Sagara *et al.*, FED **81** (2006) 2703.

T. Morisaki et al., FED **81** (2006) 2749.

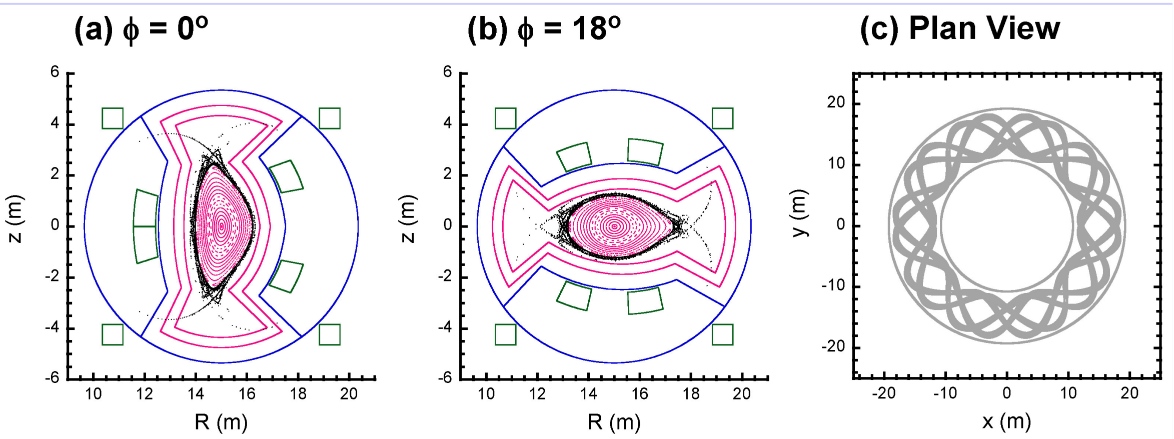
FFHR-2S Type-I

Proposed by N. Yanagi

$R_c = 15.0$ m, $a_c = 3.0$ m, $\gamma = 1.0$

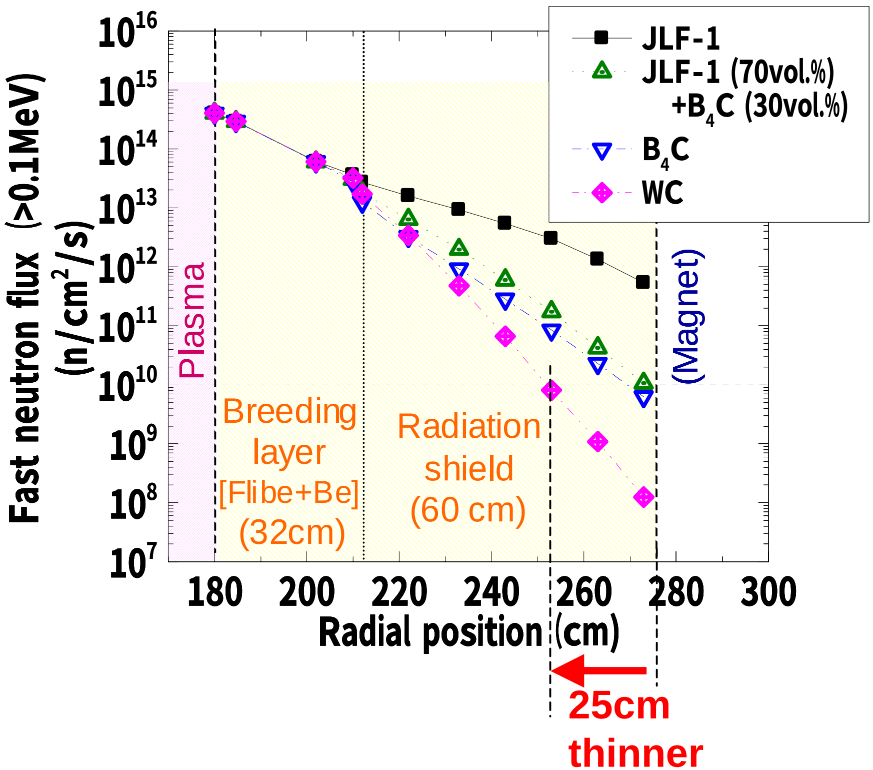
$B_{ax} = 6$ T, $a_p = 1.5$ m, $W = 143.2$ GJ

Smaller size and higher field with $\gamma = 1$ (reduction of total mass)



Design of FFHR-2m2 ~Trial to increase blanket space~

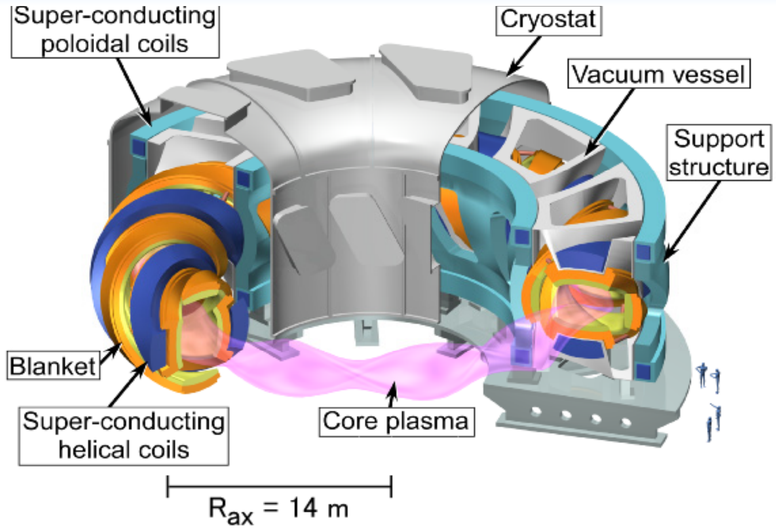
Effect of the Using of WC on inboard shielding thickness



*Figures from A. Sagara *et al.*, Fusion Engineering and Design **83** (2008) 1690.

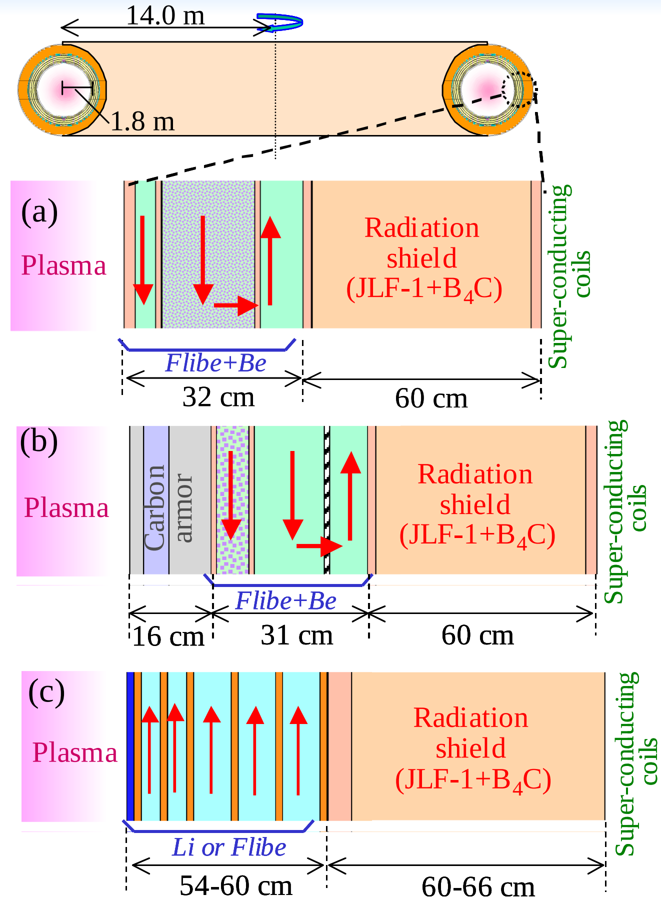
Thanks to Dr. T. Tanaka, NIFS

Advanced liquid blanket systems for FFHR2 (1)



Helical-type power reactor FFHR2m1.

- Four types of liquid blanket systems (Flibe-cooled and Li-cooled)
- Investigation of neutronics feasibility with simple torus geometry
- For design parameters of
  - Neutron wall load: 1.5MW/m^2
  - Blanket space: 1.2 m
  - Local TBR 1.2 - 1.3
  - Fast neutron flux at coils < 1.0x10^{10} n/cm^2/s



Structures of advanced liquid blanket systems proposed for FFHR2m.

(a)Flibe+Be/JLF-1 (b)Flibe cooled STB (Spectral-shifter and Tritium breeding Blanket) (c) Li/V-alloy, Flibe/V-alloy blanket systems

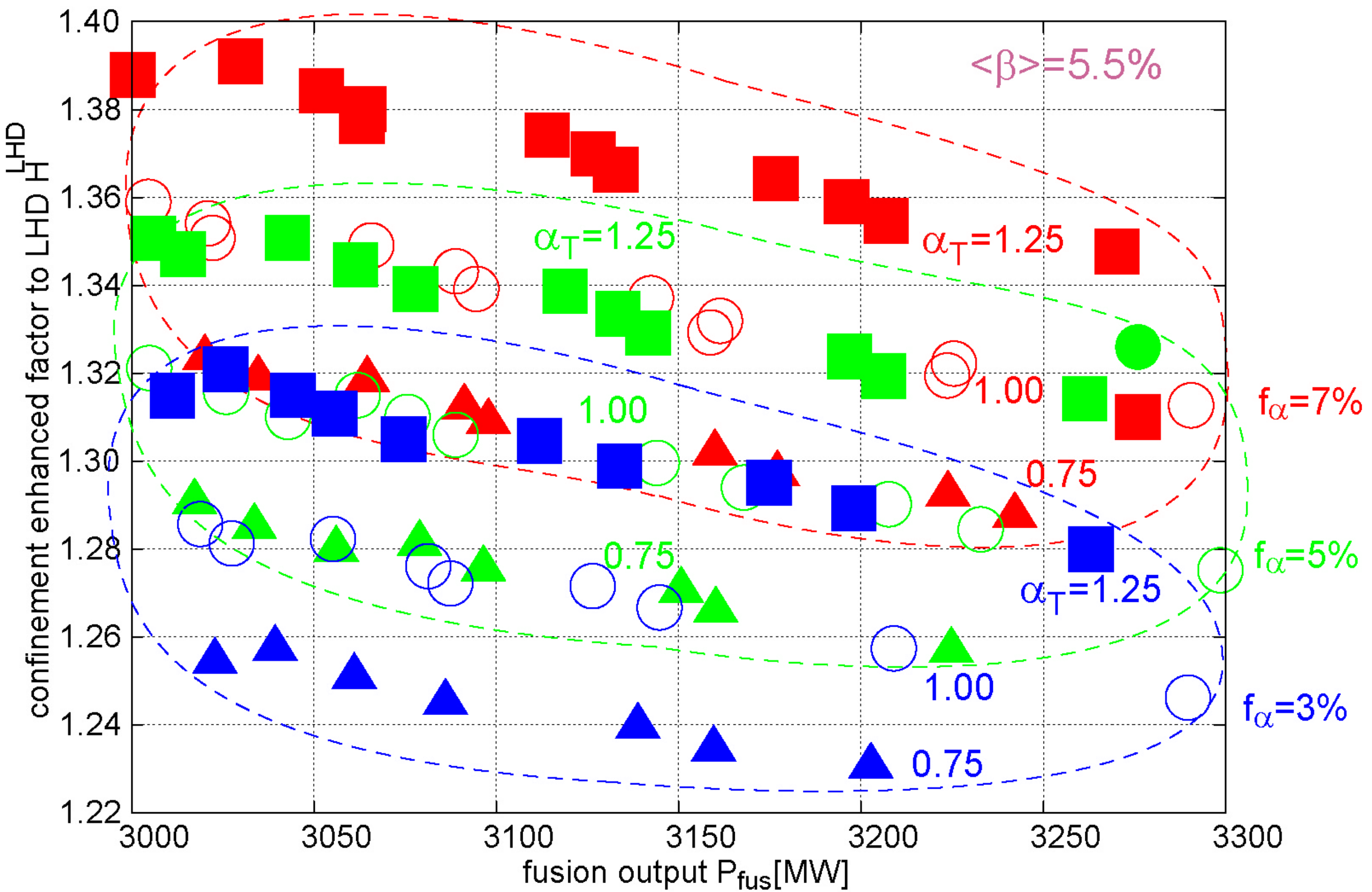
Thanks to Dr. T. Tanaka, NIFS

Advanced liquid blanket systems for FFHR2 (2)

Parameters and performance of self-cooled blanket systems for FFHR2

Blanket type	Flibe+Be/JLF-1	Flibe-cooled STB	Li/V-alloy	Flibe/V-alloy
Breeding coolant	Flibe (LiF:55 mol%, BeF_2: 45 mol%)	Flibe (LiF:55 mol%, BeF_2: 45 mol%)	Liquid lithium	Flibe (LiF:55 mol%, BeF_2: 45 mol%)
Structural material	JLF-1 (RAFS)	JLF-1 (RAFS)	V-4Cr-4Ti	V-4Cr-4Ti
Solid neutron multiplier	Be	Be	-----	-----
Enrichment ratio of ^{6}Li (%)	7.5	40	35	35
Thickness of Armor (cm)	-----	16	-----	-----
Thickness of breeding layer (cm)	32	31	54	60
Thickness of radiation shield (cm)	60	60	66	60
Local TBR	1.23	1.17	1.34	1.26
Fast neutron flux (>0.1 MeV) at outside of radiation shield (n/cm^2/s)	1.1×10^{10}	8.1×10^{9}	8.7×10^{9}	1.4×10^{9}

Effect of plasma profile



- Confinement degradation due to the increase in helium ash fraction can be cancelled out by the temperature profile peaking.