Integrated Physics Analysis of Helical Fusion Reactor

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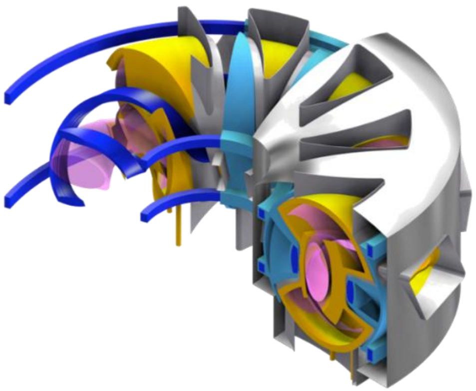
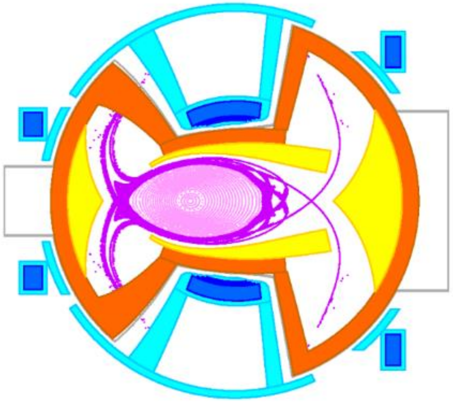
Advantage of LHD-type helical fusion reactor

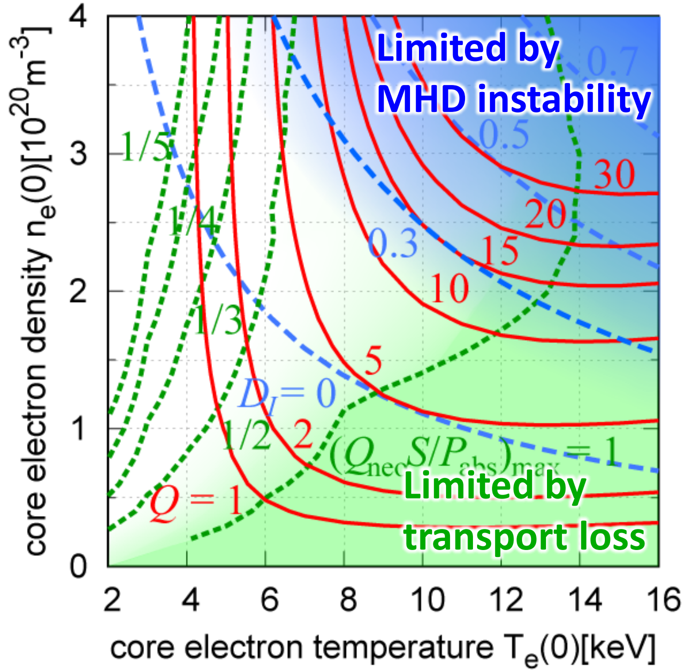
- LHD-type helical fusion reactor has several advantages as a power plant
  - Steady-state operation capability with a low recirculation power (common with helical system)
  - Highly reliable core plasma design based on plenty of LHD experimental data & numerical tools verified by LHD experiment
  - Coil with a small curvature variation
  - Robust divertor field structure
  - Large aperture for the maintenance of in-vessel components



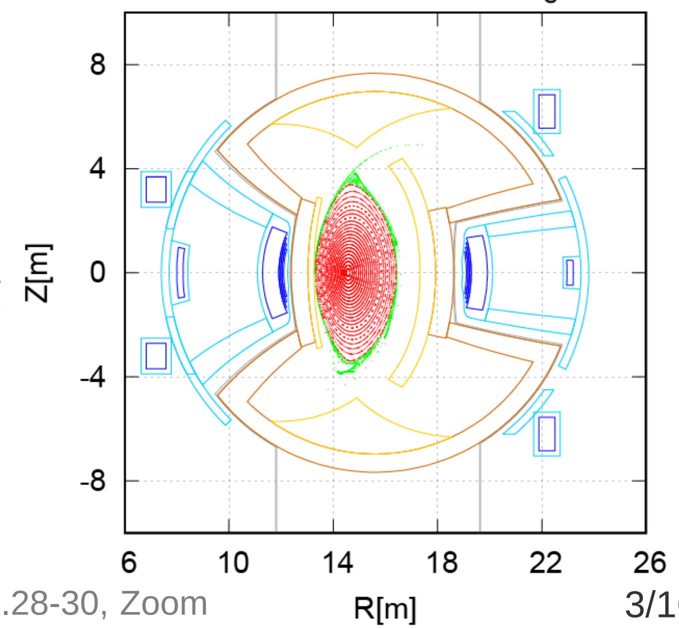


Two major Issues in LHD-type reactor design

- **Physics issue**
  - Trade-off btw. MHD stability and energy confinement property
  - Achievable fusion gain is limited to ~10 if there is no improvement in plasma performance from present LHD experimental results

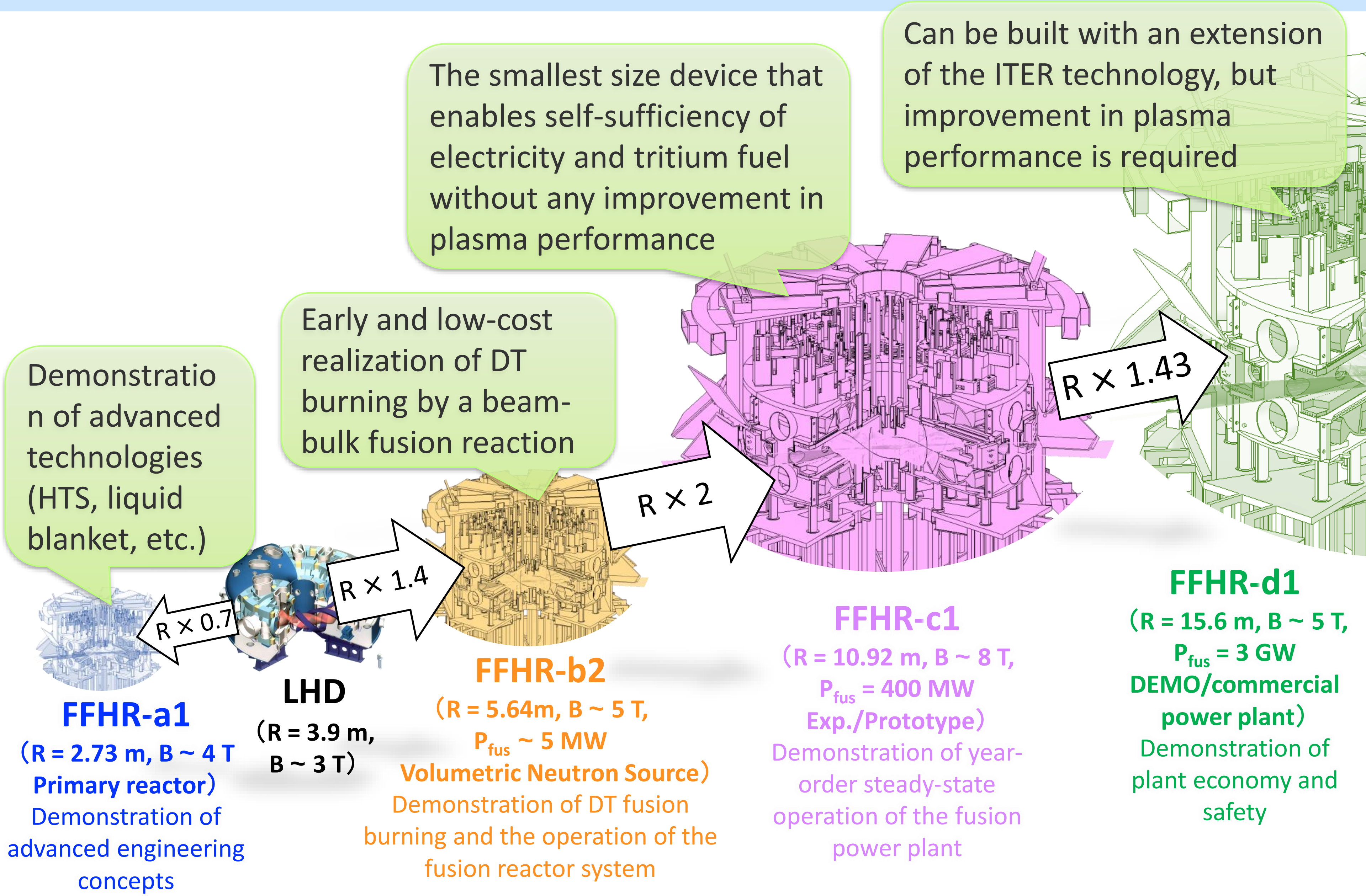


- **Engineering issue**
  - Limited space btw. the plasma and the helical coil
  - Reduction of the reactor size is difficult due to the insufficient neutron shielding performance and tritium breeding ratio

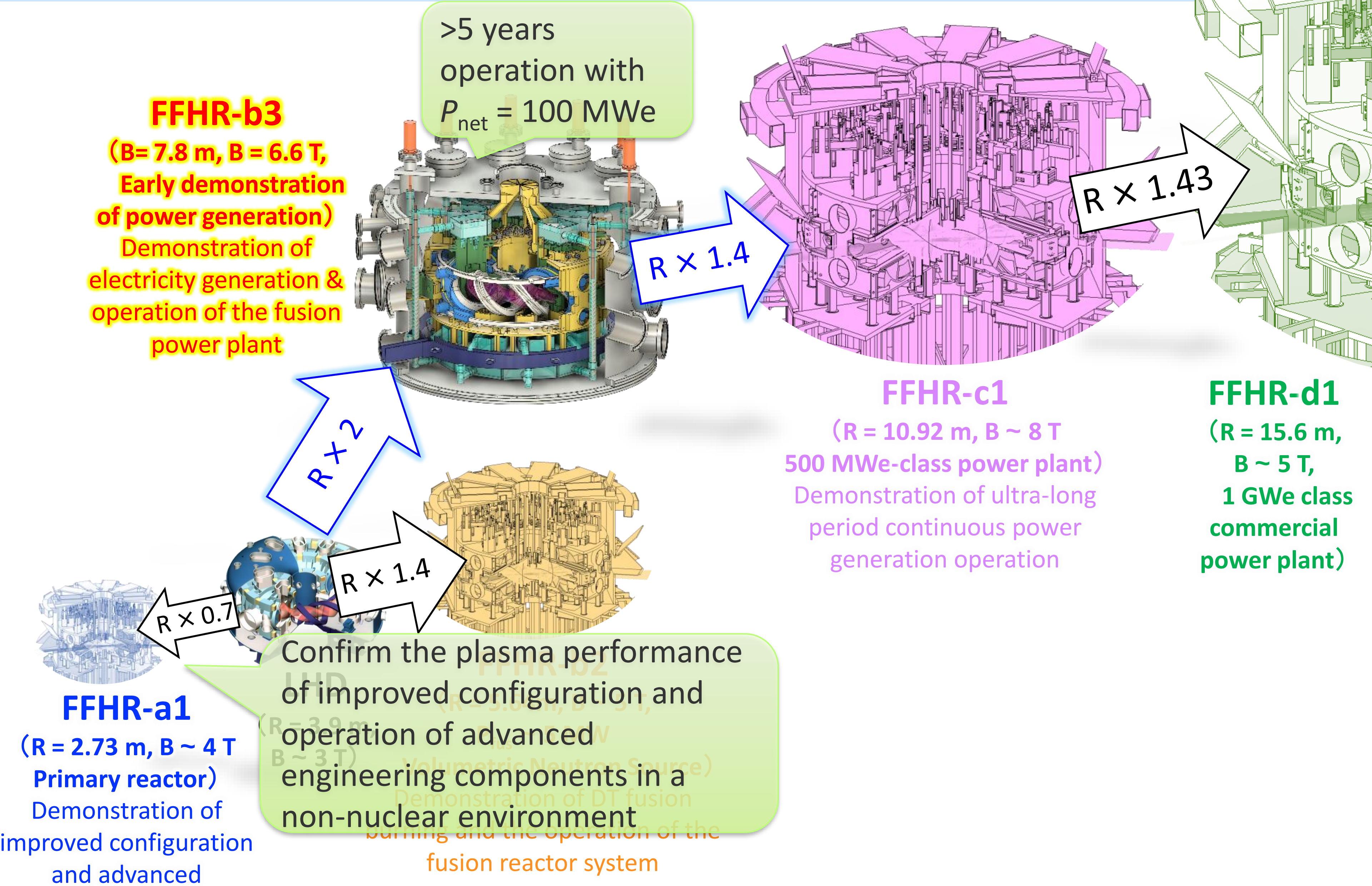


- Reactor design with a high power density is difficult to achieve.

“Original” development strategy of helical fusion reactor



“New” development strategy of helical fusion reactor

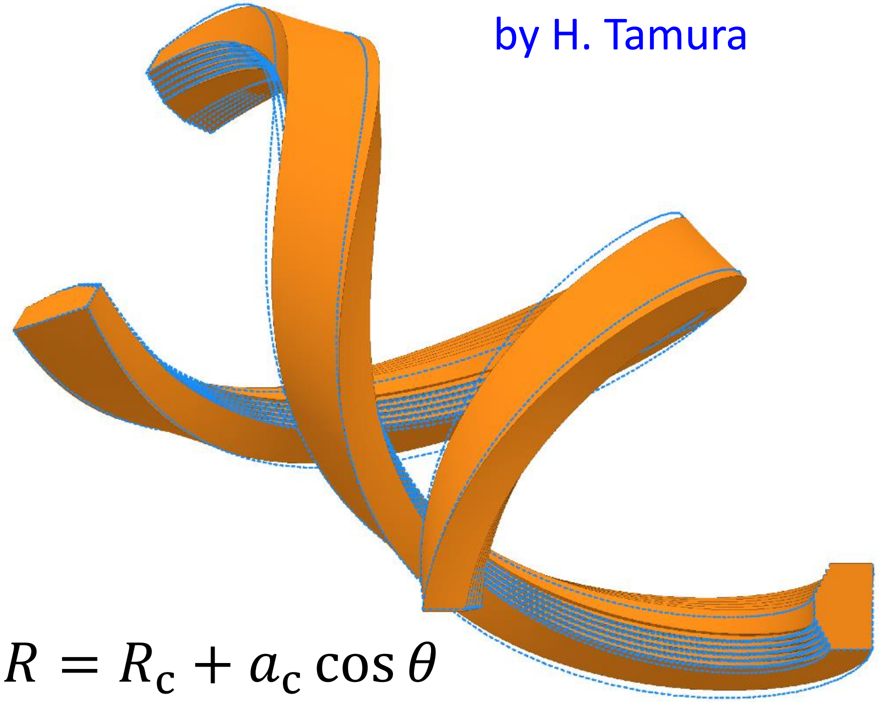


Changes in the design prerequisites

	Previous designs	FFHR-b3
Plasma temperature	≤ 9 keV (neoclassical transport calculation)	≤ 11.7 keV (optimum value from the viewpoint of plasma power balance)
Beta value	≤ 3.0% (linear MHD stability analysis)	≤ 5.0% (expected value by configuration optimization)
Confinement improvement	1.0 (direct extrapolation from LHD)	1.3 (deterioration due to the increase of plasma beta is considered)
Helium ash fraction	5%	3% (configuration optimization)
Alpha particle loss	15% (orbit calculation)	5% (configuration optimization)
HC current density	≤ 48 A/mm^2	≤ 80 A/mm^2 (development target)
Enlargement of the space between helical coil and plasma	~15% (supplemental coils)	~25% (supplemental coil + optimization of HC winding law)
Attenuation of fast neutron flux in breeding zone	1 order atten. by 30 cm	1 order atten. by 20 cm (optimization of material selection and layout)
Divertor heat recovery	20%	30% (by design optimization)
Thermal efficiency	42%	50% (S-CO_2 gas turbine)
Total efficiency of heating system	50%	66% (target of JA-DEMO)
Cryogenic efficiency	1.5% (20 K operation)	2.0% (by design optimization)

Room for optimization of the shape of helical coils

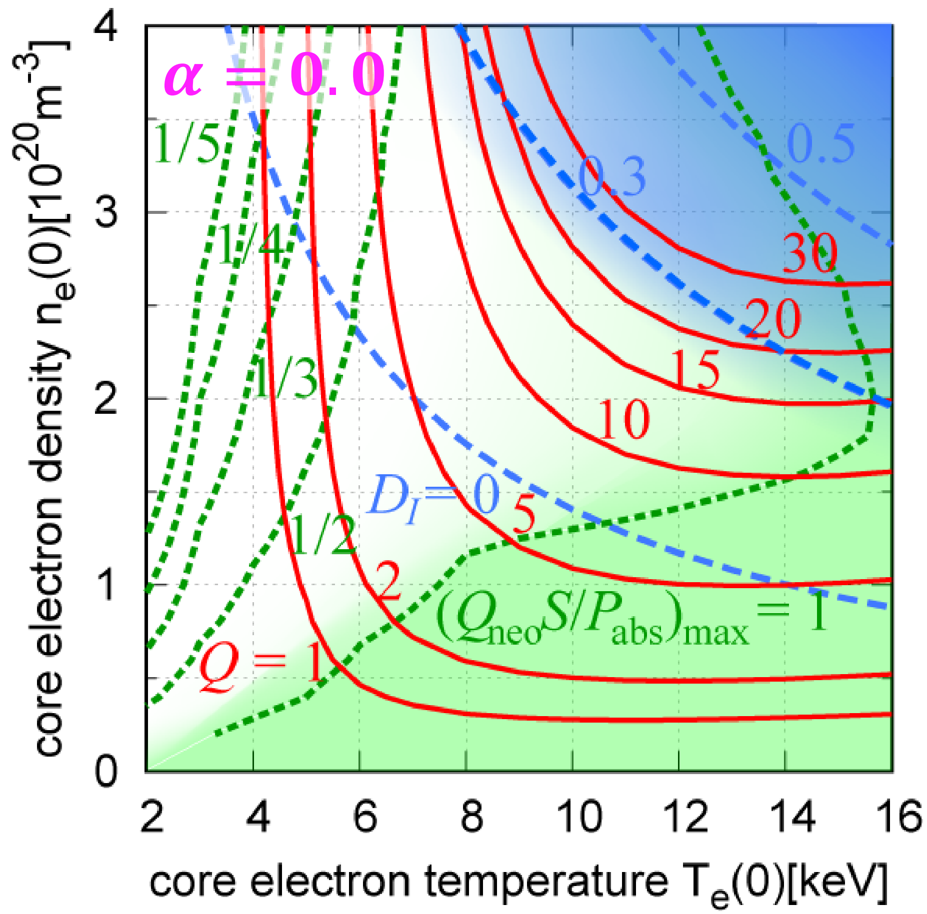
by H. Tamura



$$R = R_c + a_c \cos\theta$$
$$Z = a_c \sin\theta$$
$$\theta = -\frac{m}{\ell}\phi - \alpha \sin\left(\frac{m}{\ell}\phi\right)$$

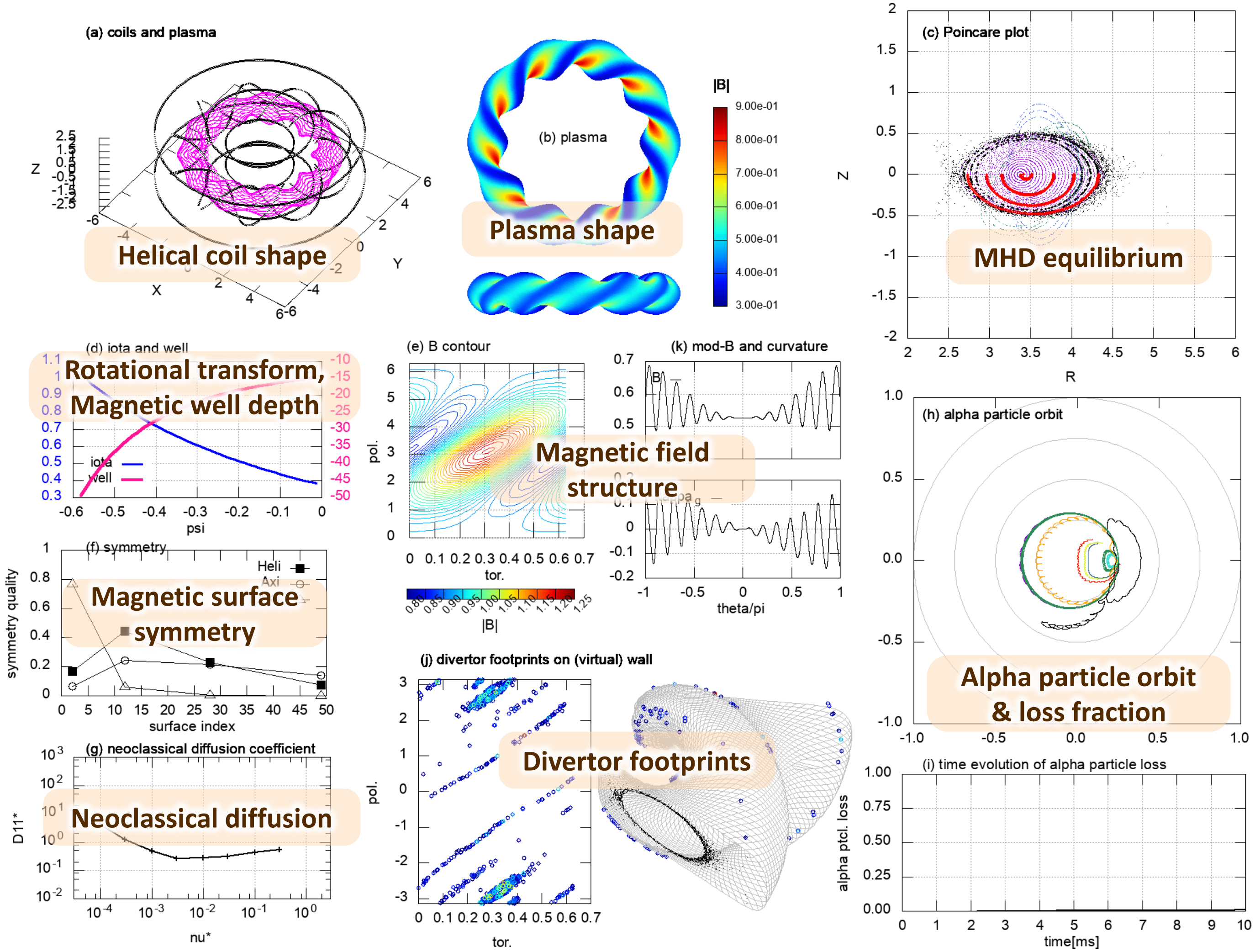
solid: $\alpha = 0.0$, broken: $\alpha = 0.1$ (LHD)

T. Goto et al., Plasma Fusion Res. **16** (2021) 1045085.



- Slight change in the pitch modulation α (0.1→0.0) enables simultaneous improvement of MHD stability and energy confinement. However, the blanket space decreases.

Helical coil optimization code “OPTHECS”

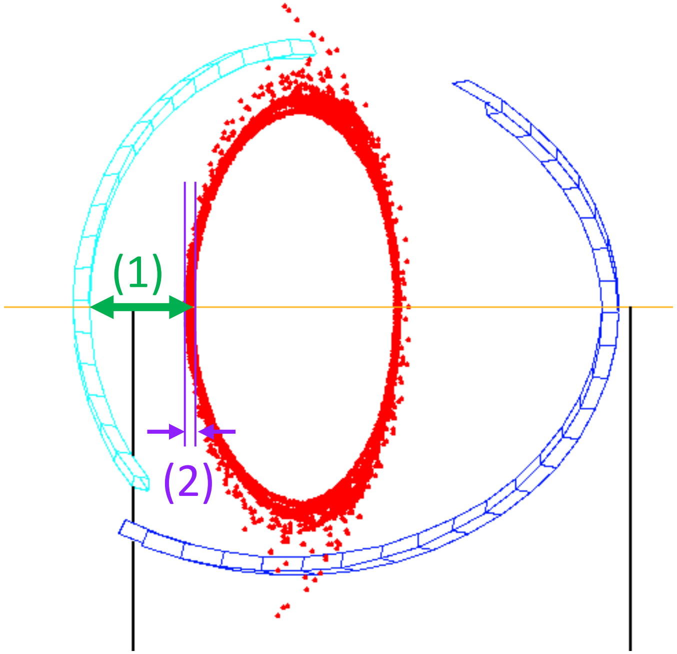


H. Yamaguchi,
ITC-28, 2019, O1-4

- Optimization of the coil shape and current by considering overall plasma performance has become possible.

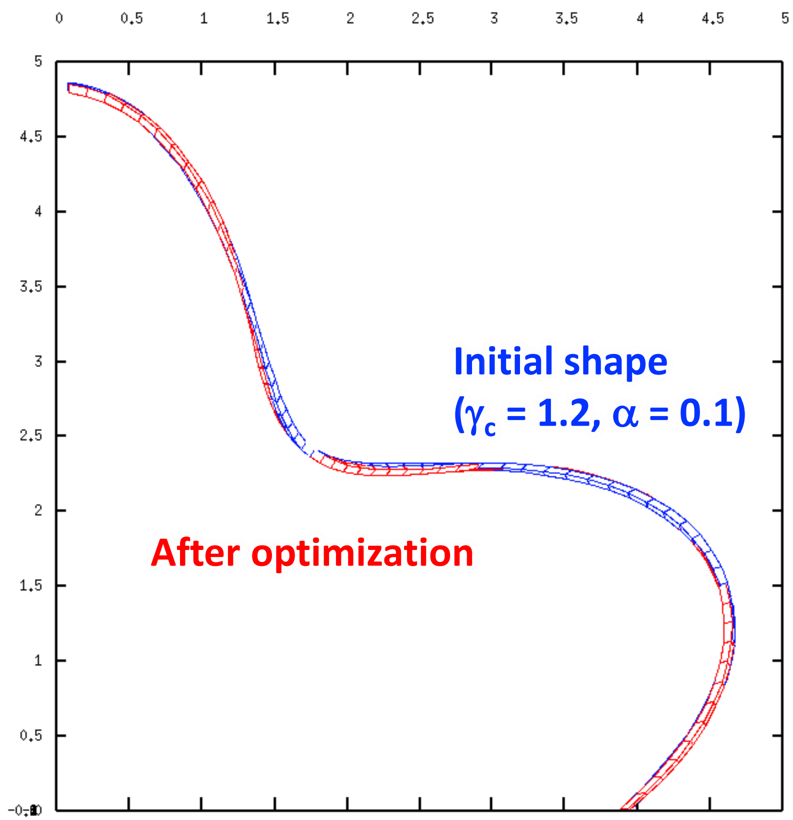
Optimization including the blanket space

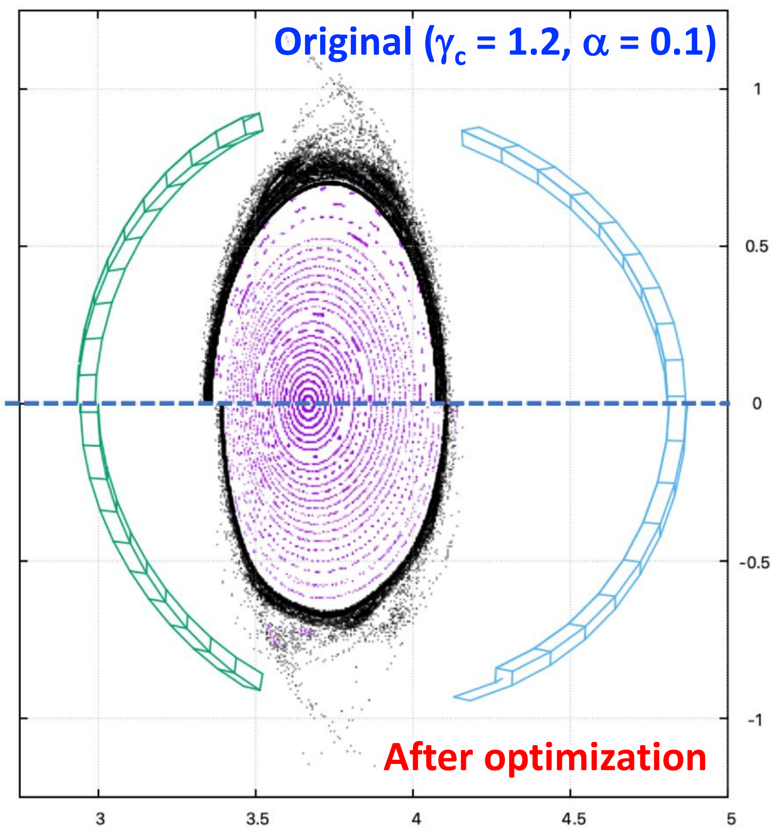
- Optimization targets regarding the blanket space have been added
  - coil-to-LCFS distance (1)
  - thickness of ergodic layer (2)
- Coil shape is freely given with a b-spline curve (beyond the conventional winding law)



- Optimization with following conditions was conducted
  - Increase the coil-to-LCFS distance
  - Decrease the thickness of ergodic layer
  - Decrease the neoclassical particle diffusion coefficient
  - Keep plasma volume (within ~15% variance)

Optimization result – coil shape and blanket space





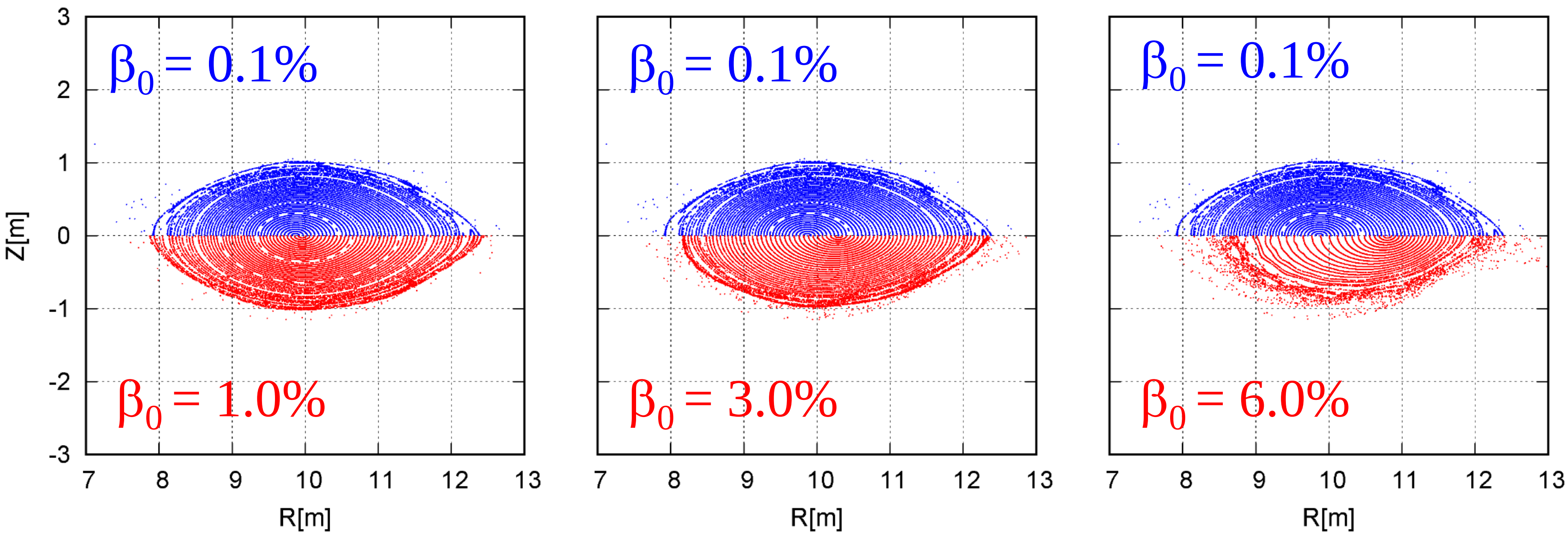
- ~10% increase in the blanket space is achieved by only a slight change in the helical coil shape

  ➔ **Initial candidate configuration**

Integrated physics analysis

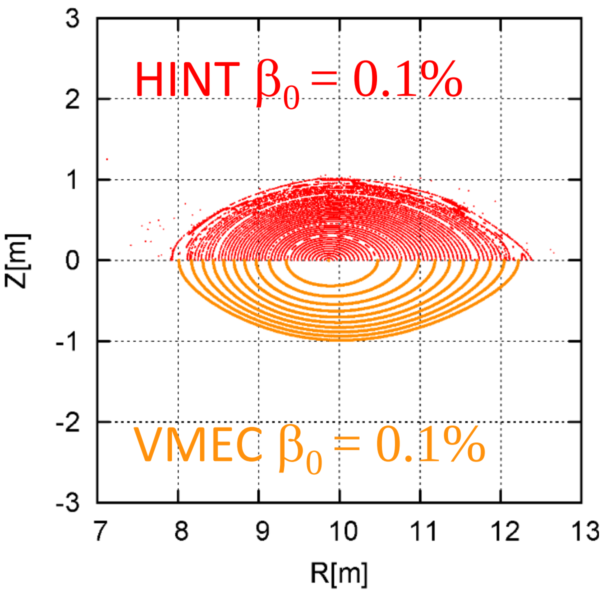
- The plasma performance of the initial candidate configuration is examined and compared with those of the reference configurations ($\alpha = 0.1$ in the previous design and $\alpha = 0.0$, which is the optimum point in the range of the conventional winding law).
- Following calculations were conducted:
  - 3D MHD equilibrium calculation (HINT)
  - Linear MHD stability analysis (KSPDIAG)
  - Neoclassical transport calculation (GSRAKE)
- Calculation conditions:
  - Reactor specifications equivalent to FFHR-c1 : $R_c = 10.92$ m, $B_c = 7.3$ T, $n_{e0} = 2.8\times10^{20}$ m^{-3}, $T_{e0} = 9$ keV

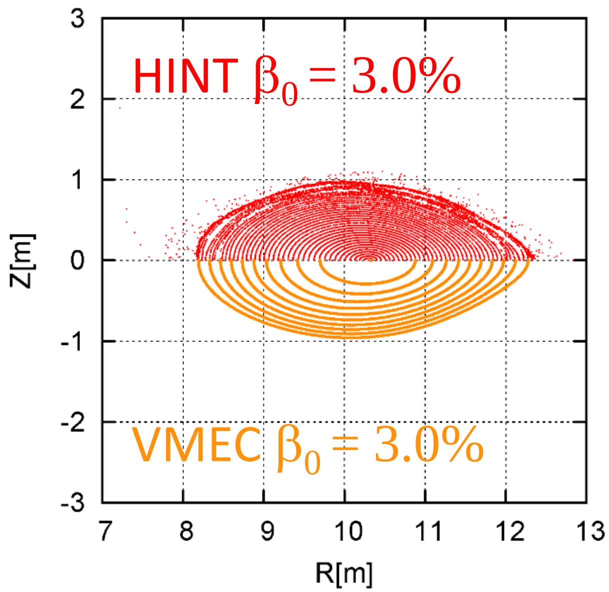
Calculation result – MHD equilibrium (HINT)

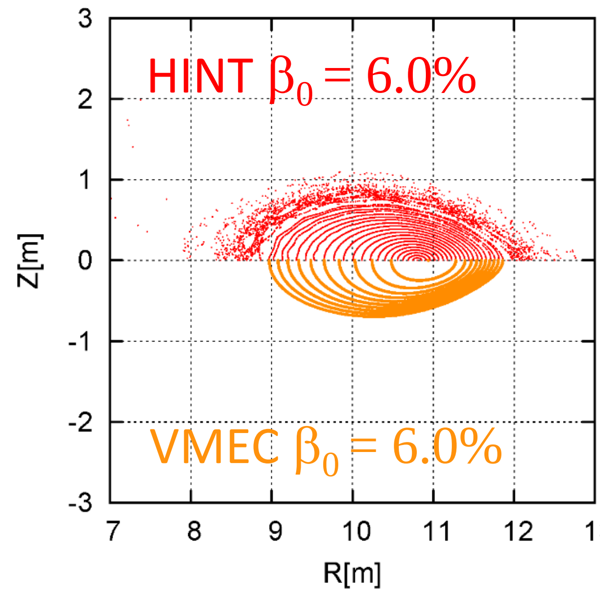


- Magnetic axis position shifts outward with increasing beta.
- Intense ergodization of the peripheral magnetic field when $\beta_0 \geq 5\%$ (Adjustment of the magnetic axis position by controlling vertical field may be needed)

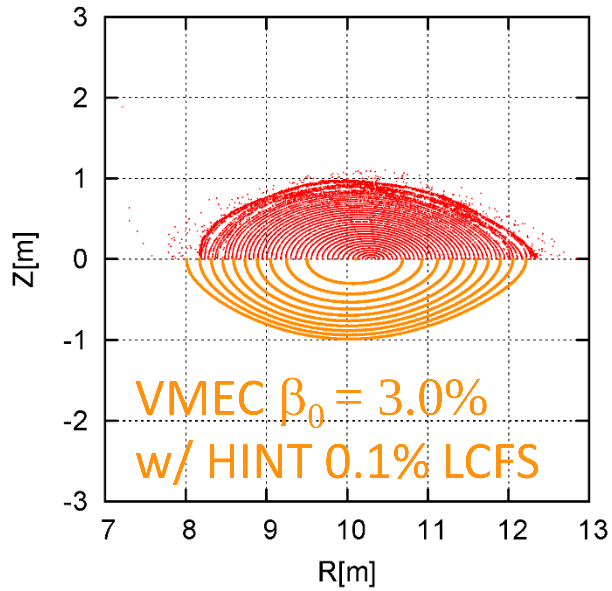
Calculation result – MHD equilibrium (VMEC)

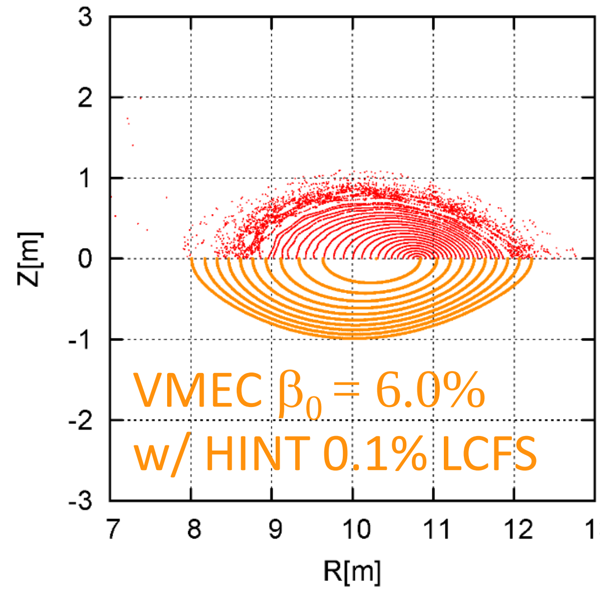




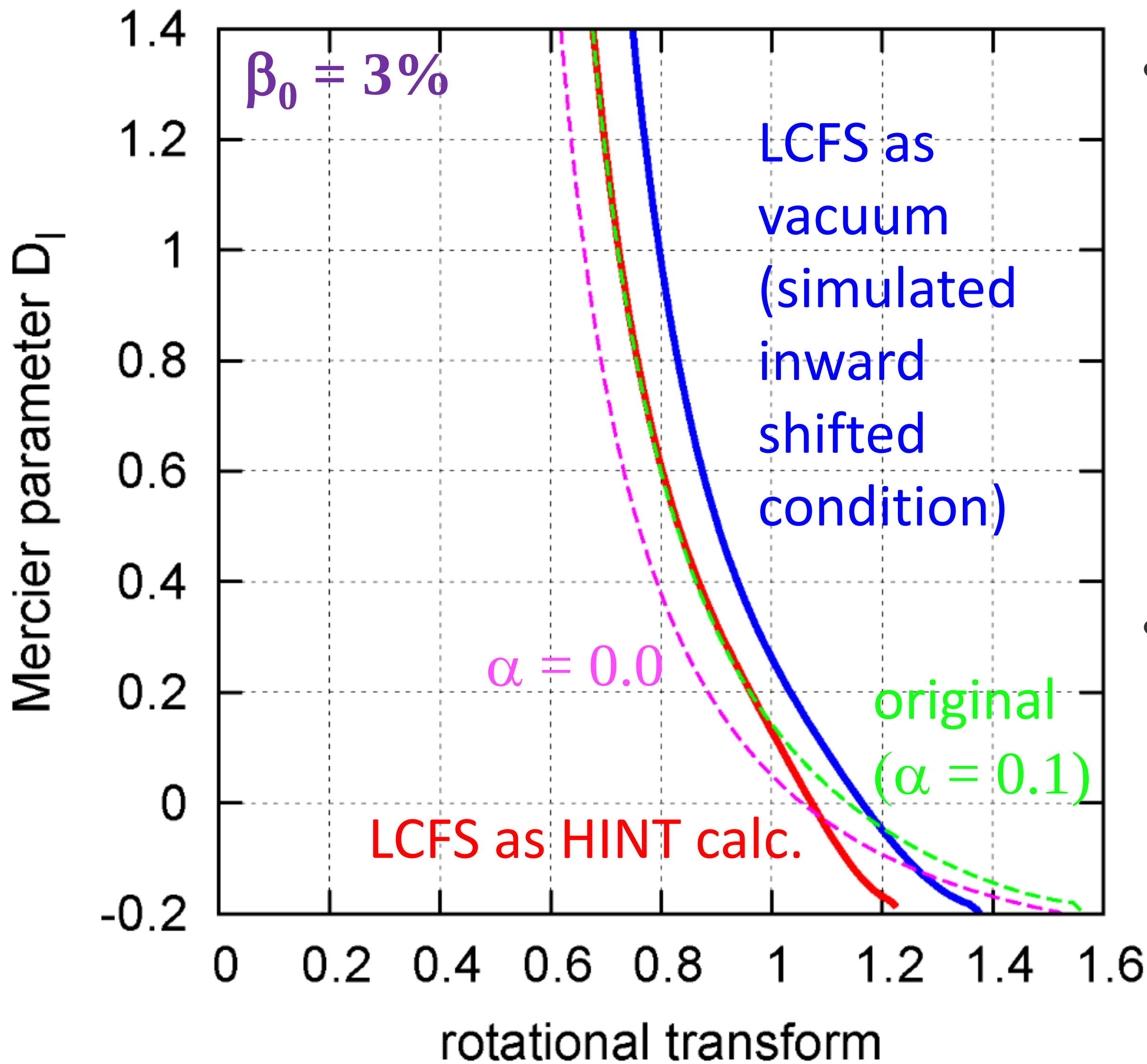


- Use LCFS shape calculated by HINT
- Good agreement with HINT results



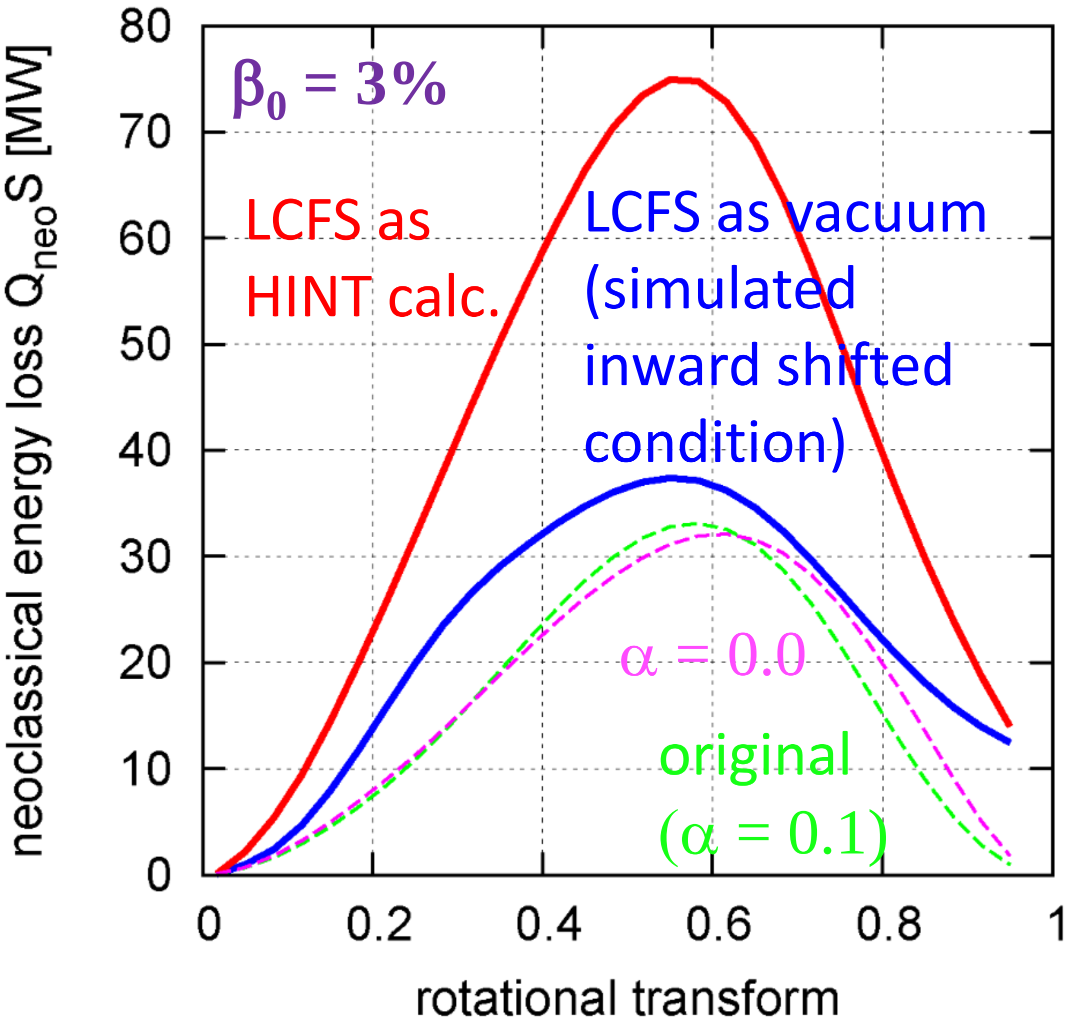


Calculation result – MHD stability (KSPDIAG)



- D_I at $m/n = 1/1$ rational surface is an index for the MHD stability.
  - In LHD experiment, stable discharges are obtained with $D_I < 0.3$
- Magnetic axis position with HINT equilibrium (red) shifts more outward than other cases.

Calculation result – Neoclassical transport (GSRAKE)



- Neoclassical energy loss is larger than reference cases.
- If the shift of the magnetic axis position is suppressed, neoclassical energy loss can be reduced to the same extent as the reference cases.

- Plasma performance is slightly inferior to the reference cases, but **comparable performance is obtained with a larger blanket space.**

Summary and future work

- **OPTHECS has greatly advanced the configuration optimization study for the LHD-type helical reactors.**
  - Helical coil shape beyond the conventional winding law
  - Overall optimization on physics & engineering design conditions
- **Integrated physics analysis for the initial candidate configuration has been conducted**
  - Comparable (slightly inferior) performance as the reference case (LHD-like) is obtained w/ ~10% increase in the blanket space.
- **Further optimization will be conducted**
  - OPTHECS w/ finite-beta equilibrium & turbulent model
  - Neoclassical transport analysis by KNOSOS
  - Target : ~20% increase of the blanket space, MHD stability at $\beta_0 = 5\%$ and 1.3 times confinement improvement to realize the target design ($P_{\mathrm{net}} = 100$ MWe with 2 × LHD size reactor, FFHR-b3)