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Study on supporting structures of magnets and blankets for a heliotron-type fusion reactors

Shinsaku Imagawa, Akio Sagara

National Institute for Fusion Science

1. Introduction
2. Layout of magnets
3. Structural analysis of the magnets
4. Summary

1. Introduction

Advantages of Helical Fusion Reactor:

(1) no current-disruptions, (2) no current-drive

(3) constant coil-currents (owing to inherently current-less plasma)

Disadvantages:

(1) necessarily large major radius

to realize the self-ignition condition

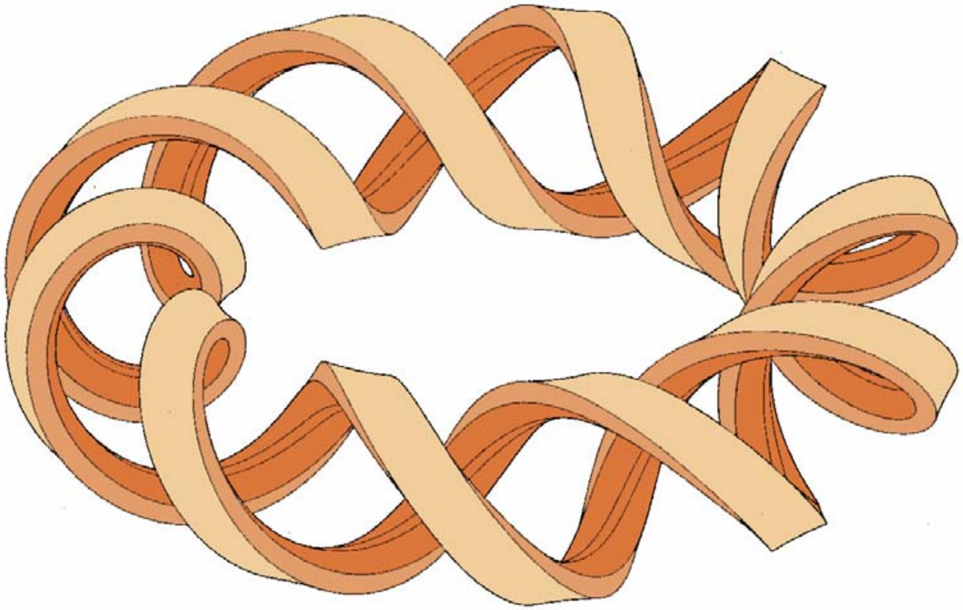
to produce sufficient space for blankets.

(2) difficulty of replacement of HCs

(3) difficulty of maintenance of blankets

–> SC magnets,especially the helical coils (HCs), must be simplified

for high reliability of them, good maintainability of blankets, and reasonable construction cost.



Objectives

(1) To survey the major parameters of the reactor with the blanket space > 1.1 m

(2) To optimize the position of poloidal coils

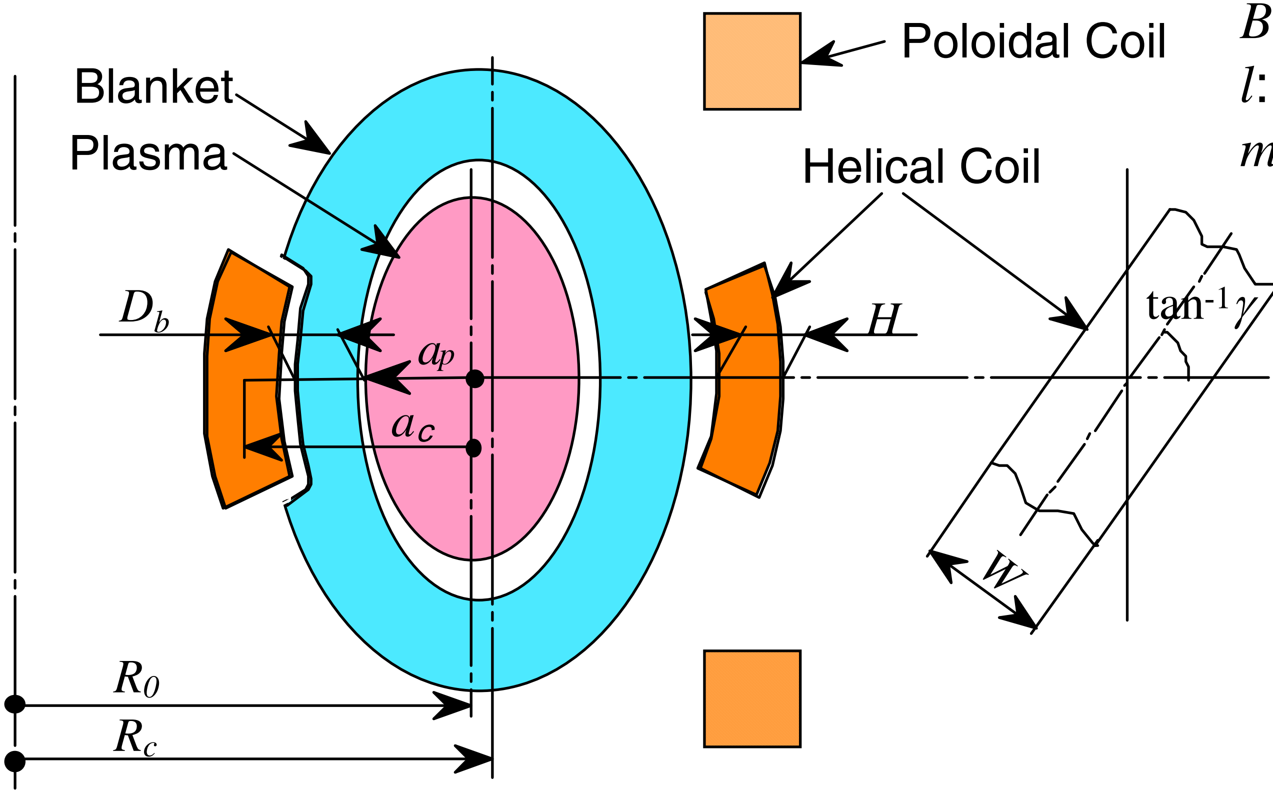
(3) To discuss the simplified supporting structure for SC magnets

(4) To estimate the mechanical feasibility by Finite Element Method.

Coordinate of Helical Coil

Pitch parameter : $\gamma = \dfrac{m}{\ell}\dfrac{a_c}{R_0}$, Coil current : $I = \dfrac{2\pi R_0 B_0}{\mu_0 m}$

Coil current density : $j = \dfrac{I}{W \cdot H} \propto \dfrac{B_0}{R_0}$ (when the shape is similar)



B_0: Central toroidal field
l: pole number
m: periodic number

Minimum gap for blanket D_b=Min(a_c-a_p) - H/2 - 0.1 [m]
(0.1 m is a space for thermal shield.)

Scale-up Effects for SC Magnets

In the case of similar shape (W and $H \propto R_0$),

(1) Stress is proportional to B_0^2 (not dependant on R_0).

Hoop force	: $V \propto f\, R_0 = (B_0\, R_0)^2$
Area of structures	: $A \propto R_0^2$
Stress	: $P_m = V/A \propto B_0^2$

(2) Maximum field B_{max} is proportional to B_0.

Coil current	: $I \propto B_0\, R_0$
Coil current density	: $j \propto B_0/R_0$
Maximum field	: $B_{max} \propto (I\, j)^{0.5} \propto B_0$

In the case that j is constant, B_{max} is proportional to $(B_0\, R_0)^{0.5}$

Plasma Parameter

<Scaling low of energy confinement time>

ISS95: $$\tau_E^{ISS95} = 0.079 a^{2.21} R^{0.65} P^{-0.59} \bar{n}_e^{0.51} B_t^{0.83} \iota_{2/3}^{0.4}$$

- P : Plasma heating power per unit volume
- n_e : Average electron density
- B_t : Central toroidal magnetic field
- ι : rotational transform

Under the condition that τ_E, P, n_e, and ι are constant,

$$\tau_E^{ISS95} \propto a^{1.03} R^{0.06} B_0^{0.83}$$

In the case of <u>similar shape</u>,

$$B_0 \propto R^{-1.31}$$ for constant τ_E

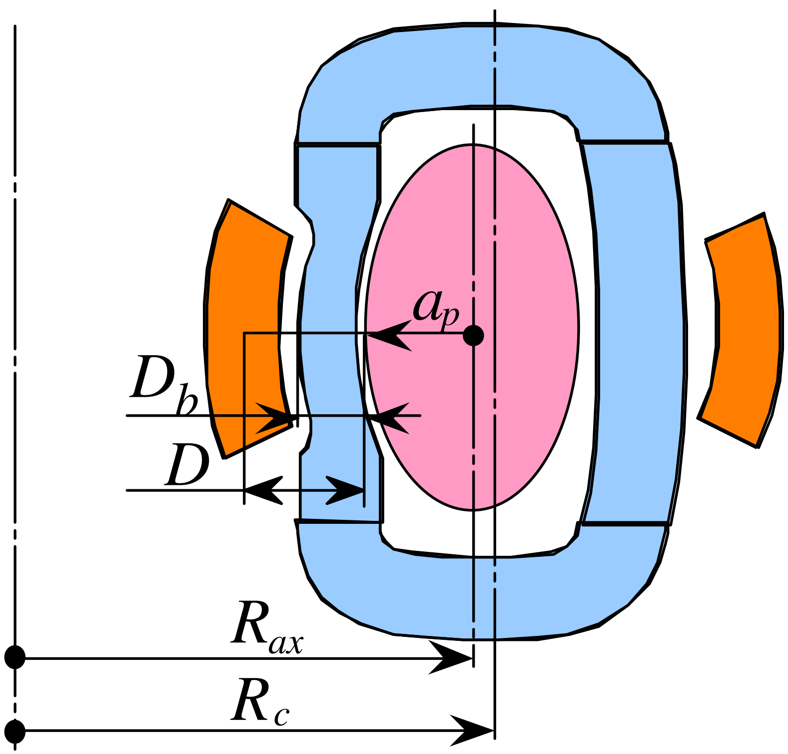
H factor to ISS95 < 2

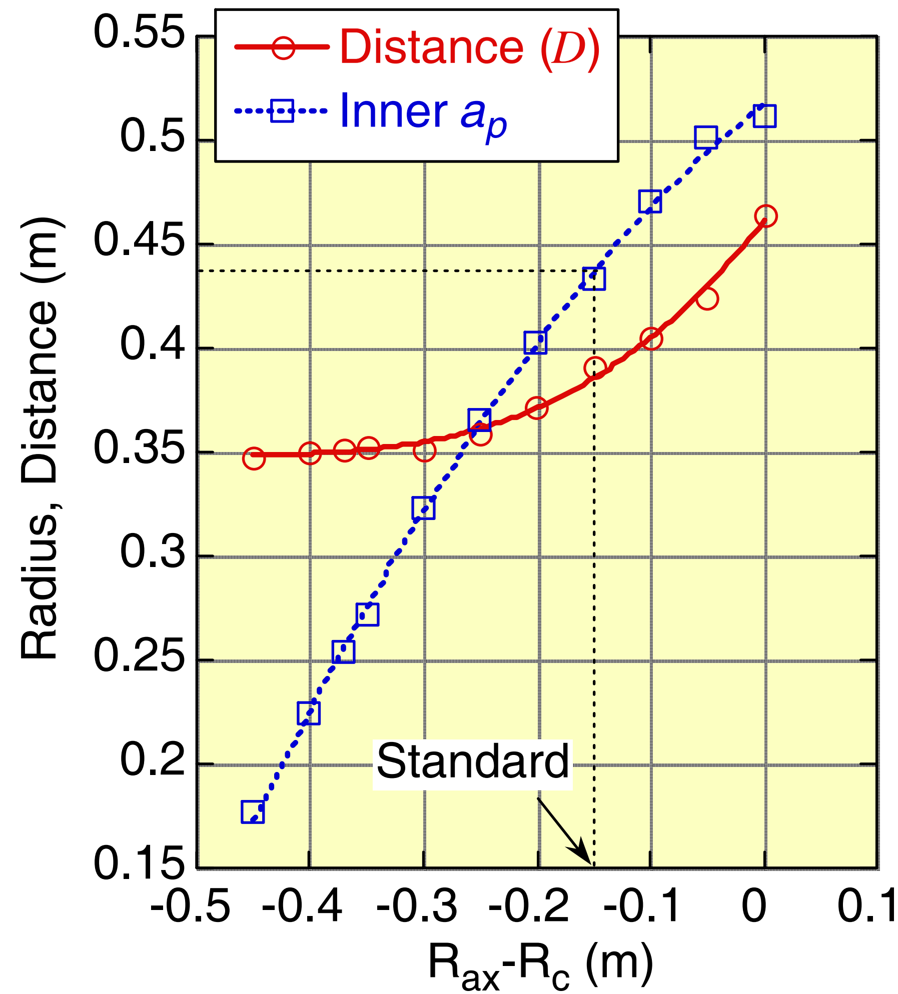
Blankets Space

Minimum space for blanket;

$$D_b = (a_c - a_p)_{\min} - H/2 - 0.1$$

0.1 m is distance for thermal shields





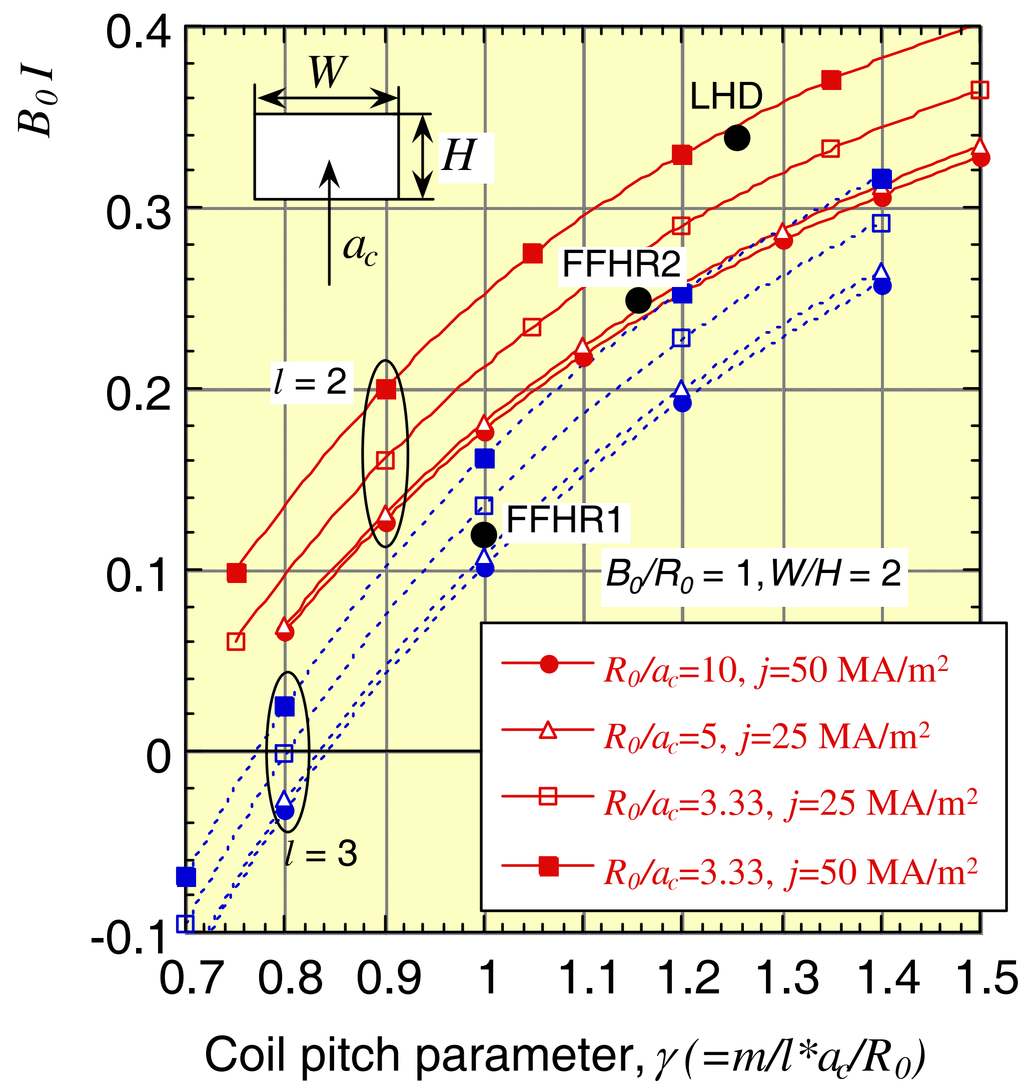
Minor radius at the vertically elongated cross-section of LHD.

Normalized Force of the Helical Coil

(1) The normalized forces become lower with the smaller γ.

(2) The 'force free' is attained at $\gamma = 0.6$ - 0.85.

(3) The curves are shifted in the positive y-axis with <u>the higher current density</u> or <u>the lower aspect ratio</u>. It depends on mainly the ratio of area occupied by the coils in the torus surface.

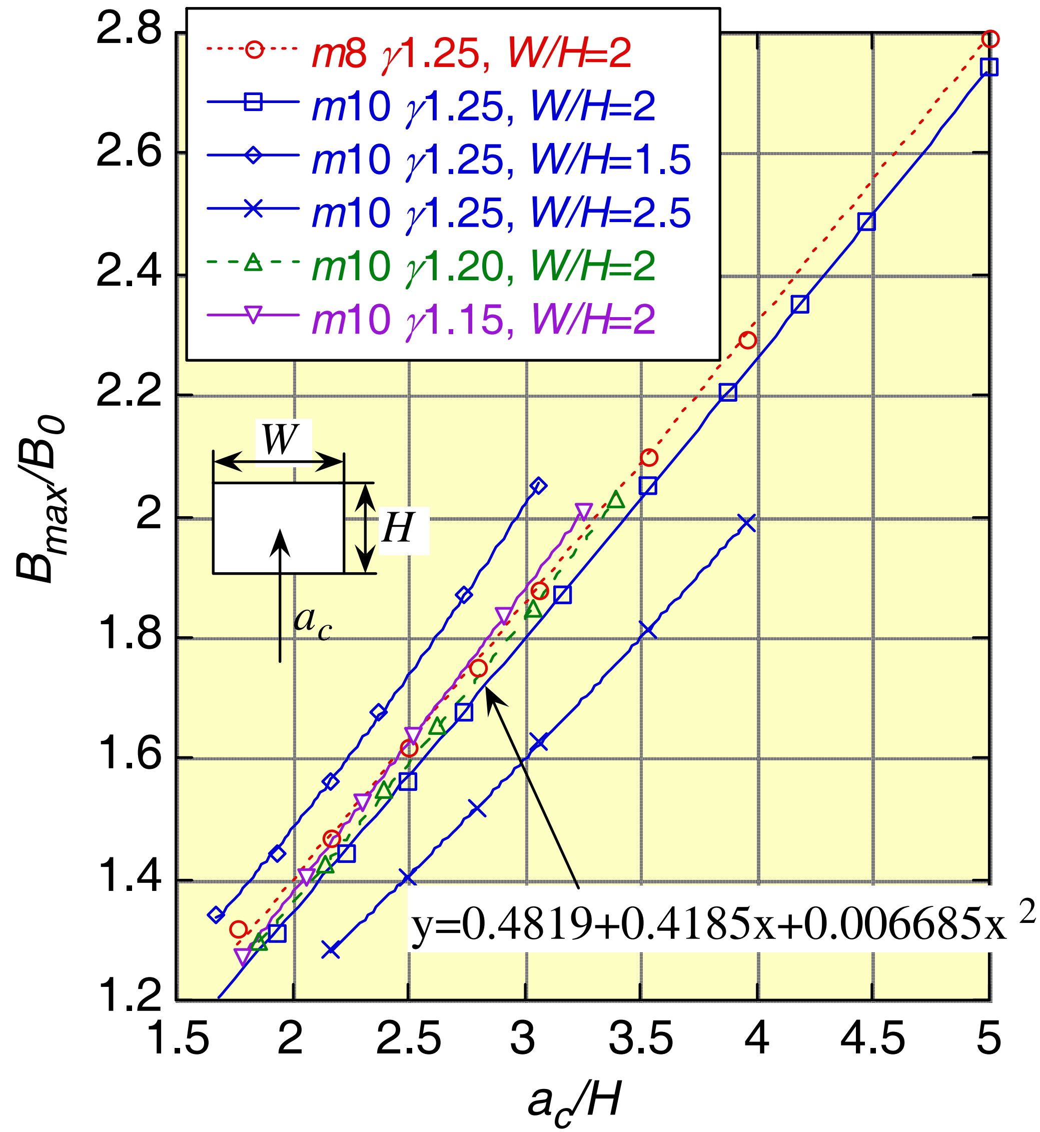


Transverse Magnetic Field in the Helical Coil

(1) B_{max} becomes higher at the lower R_0/a_c, owing to the increase of the current for the same B_0.

(2) B_{max} becomes gradually higher at the smaller γ, owing to the increase of the current.

(3) The maximum transverse field B_{max} in the helical coil is almost proportional to j^2.



Necessary Major Radius

For sufficient space for the blanket: D_b > 1.1 m

(1) High current density of the HC

j < 35 MA/m^2 due to cryogenic stability and mechanical support inside

B_{max} < 13 T as a conservative value for A15 superconductors

(2) Low γ; γ=1.15-1.25

Plasma confinement is comparable in 1.15 to 1.25. Low γ also reduces the electromagnetic force.

(3) Outward shift of plasma

Unfortunately, plasma confinement is not good in LHD. It should be improved.

(4) High ratio of W/H; W/H=2 as a moderate value

At higher ratio of W/H, D_b is enlarged and B_{max} is reduced.Nevertheless, it will bring problems for maintenance ports.

(5) Large major radius

Parameters of Heliotron-type Reactor

Items			FFHR2m1	FFHR2m2	FFHR2	LHD
Polarity / Field period	l/m		2/10	2/10	2/10	2 / 10
Coil pitch parameter			1.15	1.25	1.15	1.25
Coil major radius	R_c	m	14.0	17.3	10.0	3.9
Plasma major radius	R_p	m	14.0	16.0	10.0	3.75
Plasma radius	a_p	m	1.73	2.80	1.20	0.61
Plasma volume	V_p	m^3	831	2475	284	27.5
Magnetic field	B_0	T	6.18	4.43	10.0	4
Max. field on coils		T	13.3	13.0	13.0	9.2
Magnetic energy		GJ	120	142	147	7.85
Coil current density	j	MA/m^2	26.6	32.8	25.0	53
Min. Blanket space		m	1.20	1.10	0.70	0.12
Electron density	$ne(0)$	$10^{19}\ m^{-3}$	26.7	33.5	16.3	1.64
Temperature	$Ti(0)$	keV	15.6	15.6	18.7	
H factor of ISS95			1.96	1.8	1.9	
Average beta	$<\beta>$		2.84	3.56	4.06	
Fusion power (*1)	P_F	GW	1.90	3.00	3.00	
Neutron wall load		MW/m^2	1.50	2.37	1.31	

(*1) A heating efficiency is0.9, density fraction of He and O are 2% and 0.5%.
Density profile and temperature profile are parabolic.

2. Layout of Magnets

One set of poloidal coils (PCs) is necessary to adjust the major radius of the plasma, the quadruple field, and the stray field.

<Conditions from Plasma>

(1) $B_D = B_Z @ R_0$ (R_p): fixed

(2) B_Q (plasma shape): fixed

(3) Low stray field

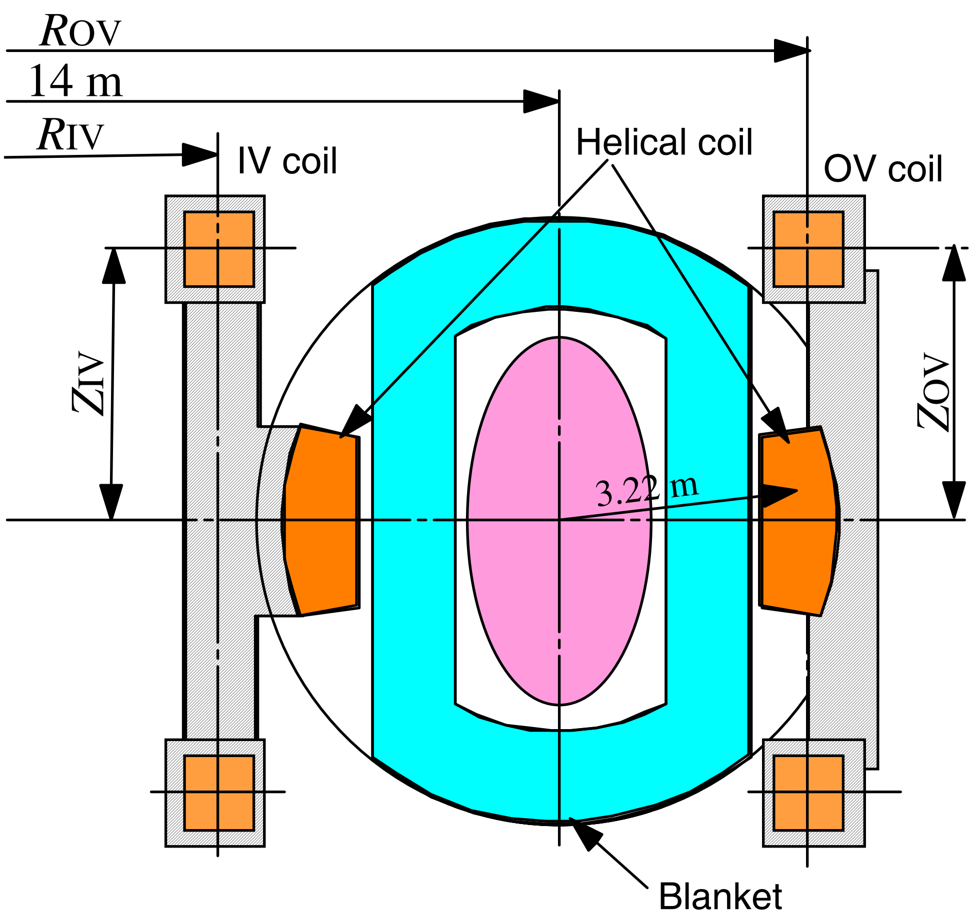
(4) Low field near the torus center

(5) Less stored energy

<Conditions from Coil Supports>

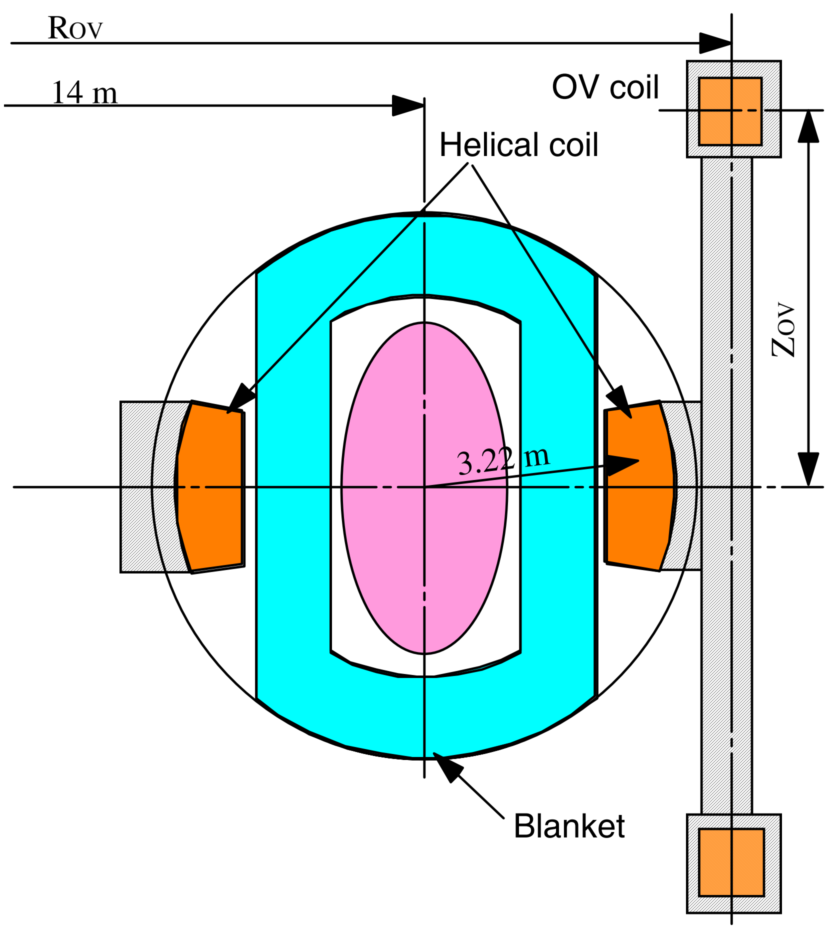
(1) Large ports are arranged at upper, lower, and outer side for maintenance of blankets.

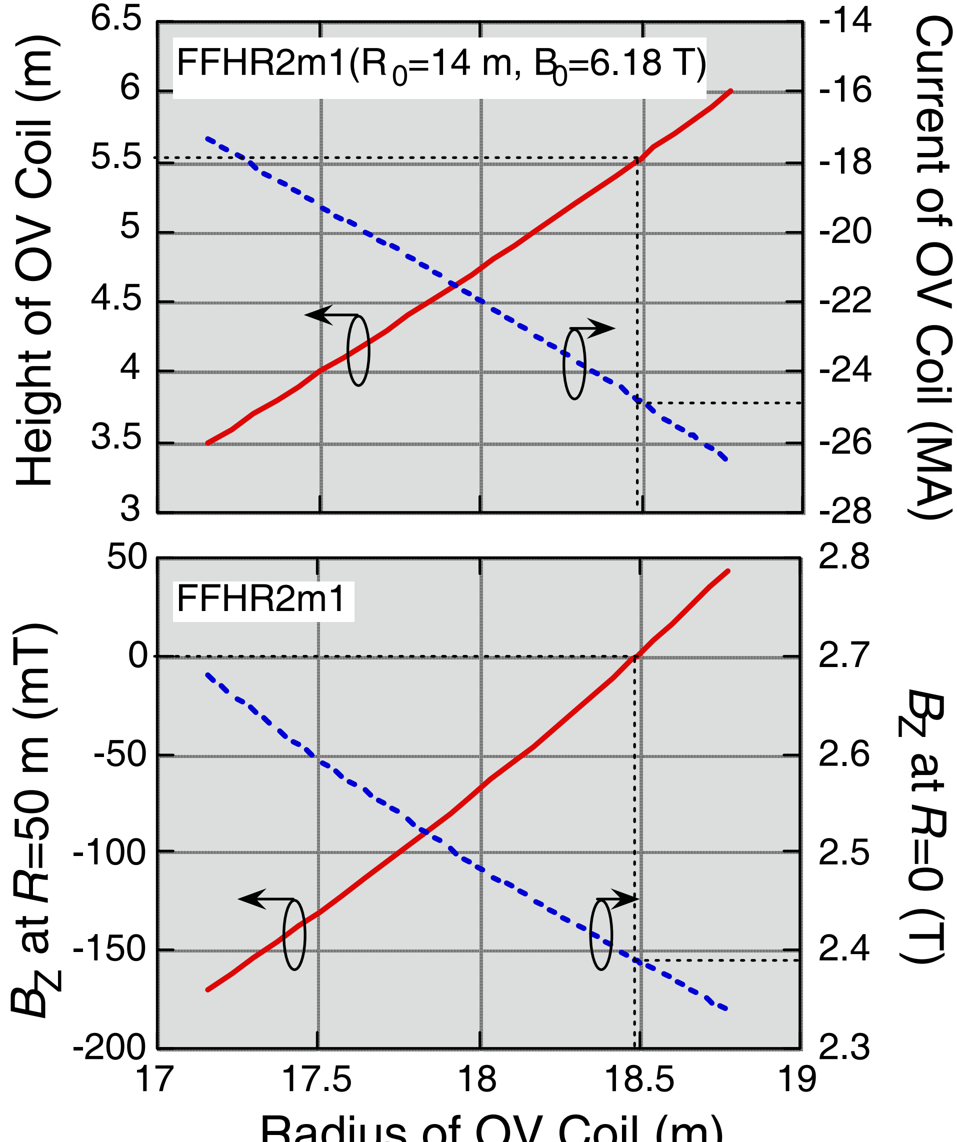
(2) Helical coil is supported from outside to enlarge the inner space.



B_0=6.18 T, $\langle a_p \rangle$=1.73 m

Layout of Magnets: Case 1(1 pair of PCs)





FFHR2m1 with one pair of PCs.

For B_Z=0 @R=50m

R_{OV}=18.49 m, Z_{OV}=5.52 m,

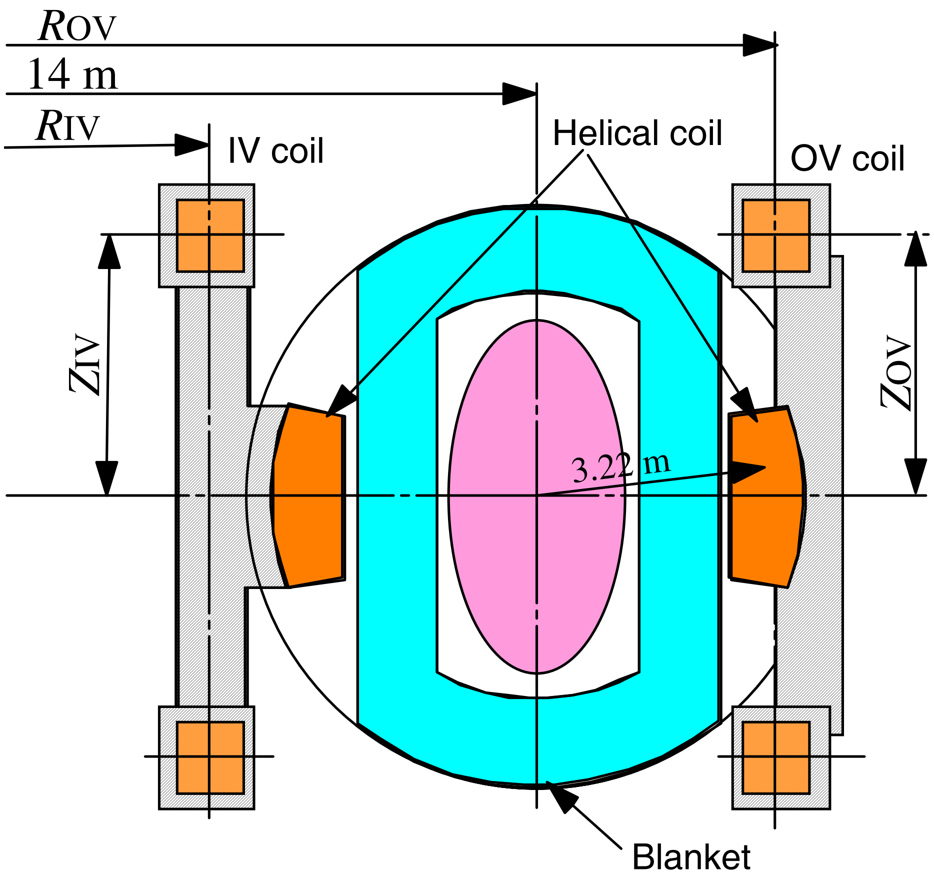
I_{OV}=-24.8 MA

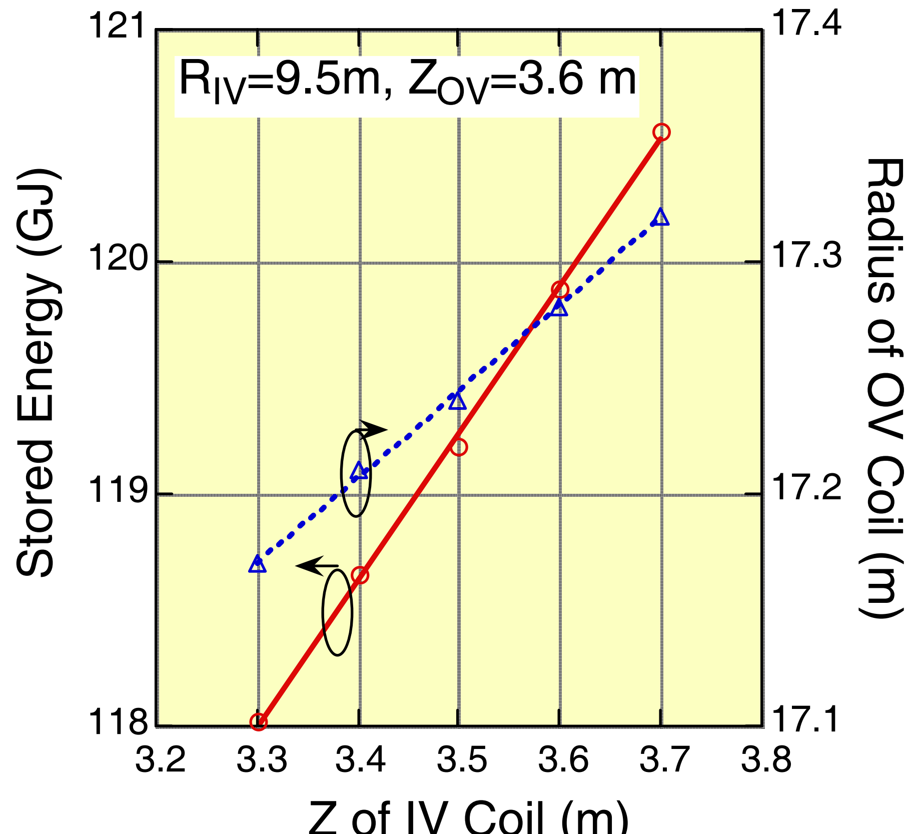
Wide outer space, but

W_B=152 GJ, B_Z(R=0)=2.4 T

Layout of Magnets: Case 2(2 pair of PCs)

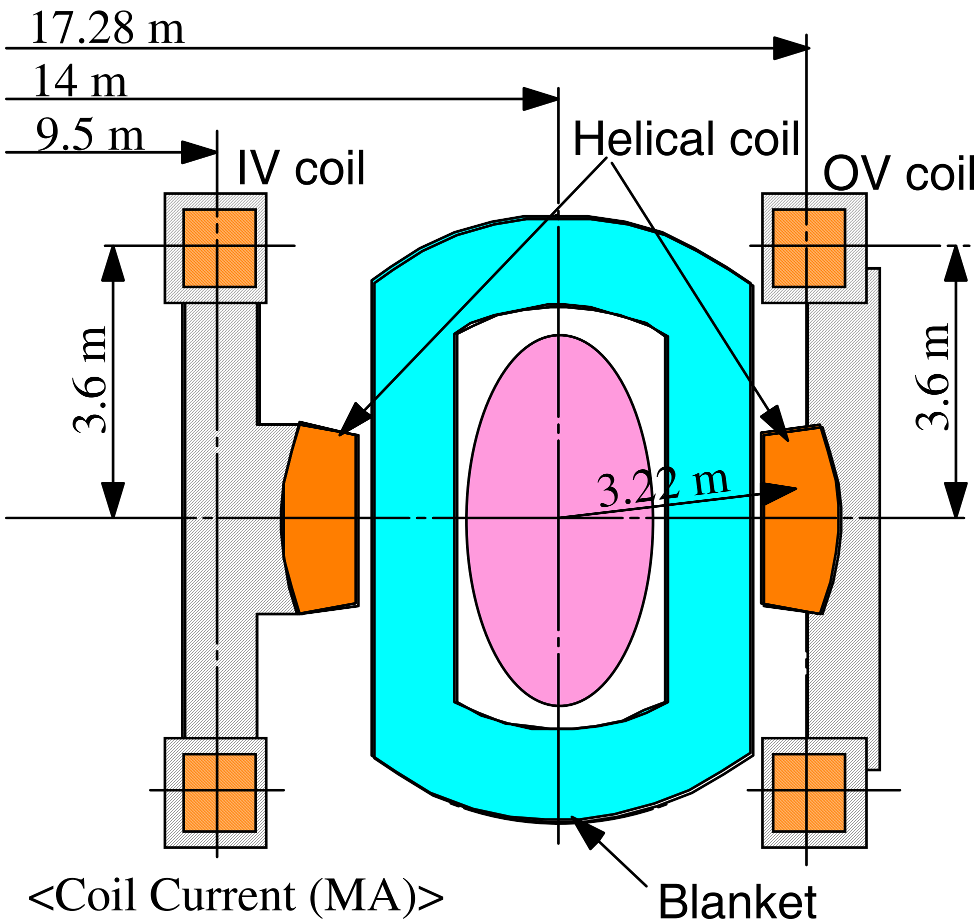
In the case of two pairs of PCs, the number of degrees of freedom is six. After minimizing the field near the center of the torus, two degrees are remained. The position of the coils can be optimized by considering the layout of the mechanical support.





FFHR2m1 with two pairs of PCs.

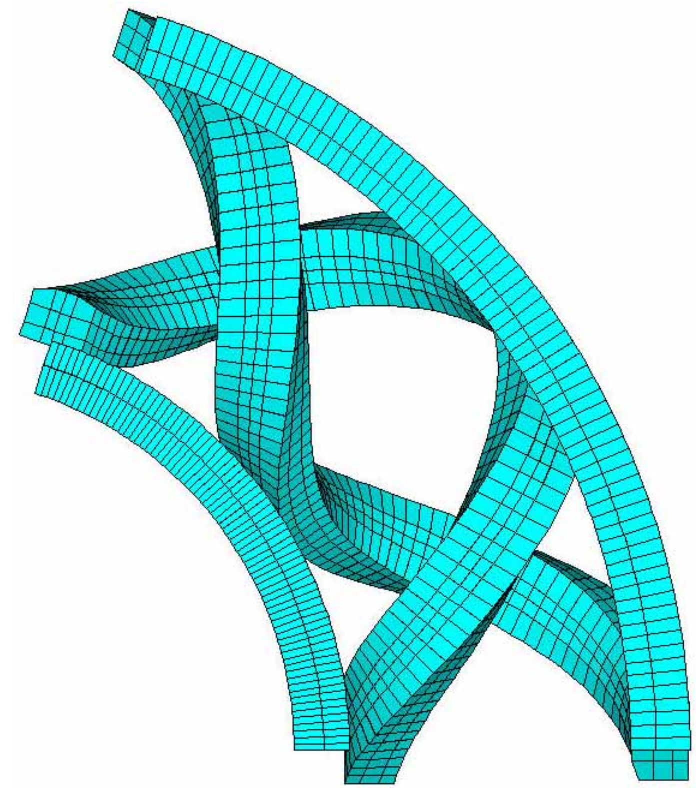
Layout of Magnets of FFHR2m1

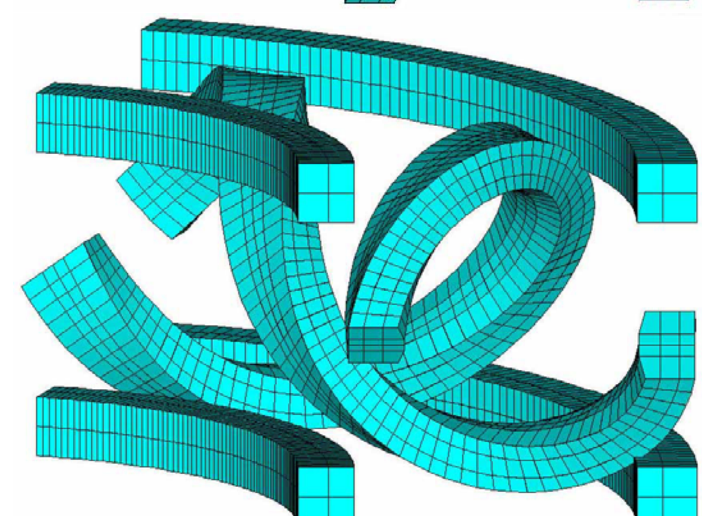


<Coil Current (MA)>

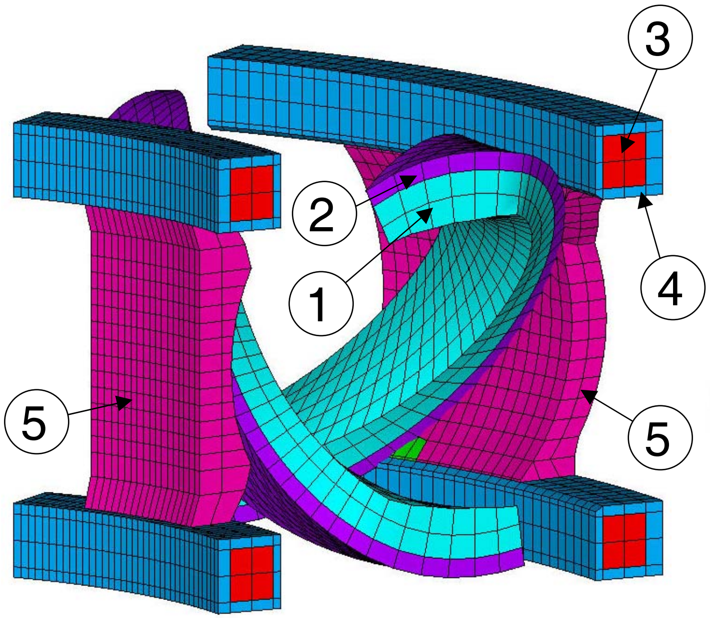
Mode	BD 100%	BD 105%
HC	43.257	43.257
OV	-21.725	-22.518
IV	-22.100	-21.601

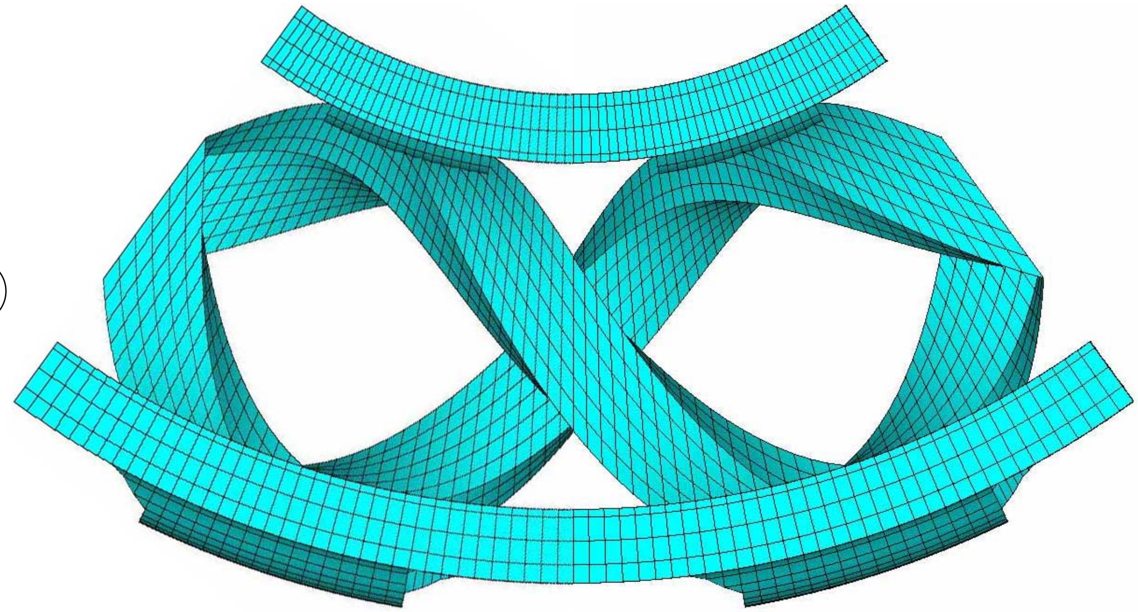
B_0=6.18 T



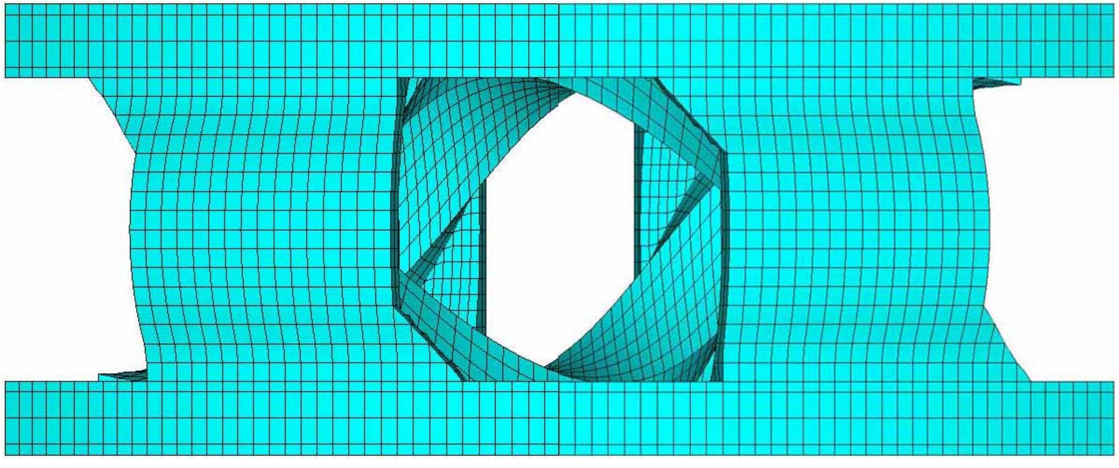


Layout of Coil Supports





1: HC winding (W/H=1.8/0.9 m, j=26.6 MA/m^2)



2: HC support (t=0.35m)

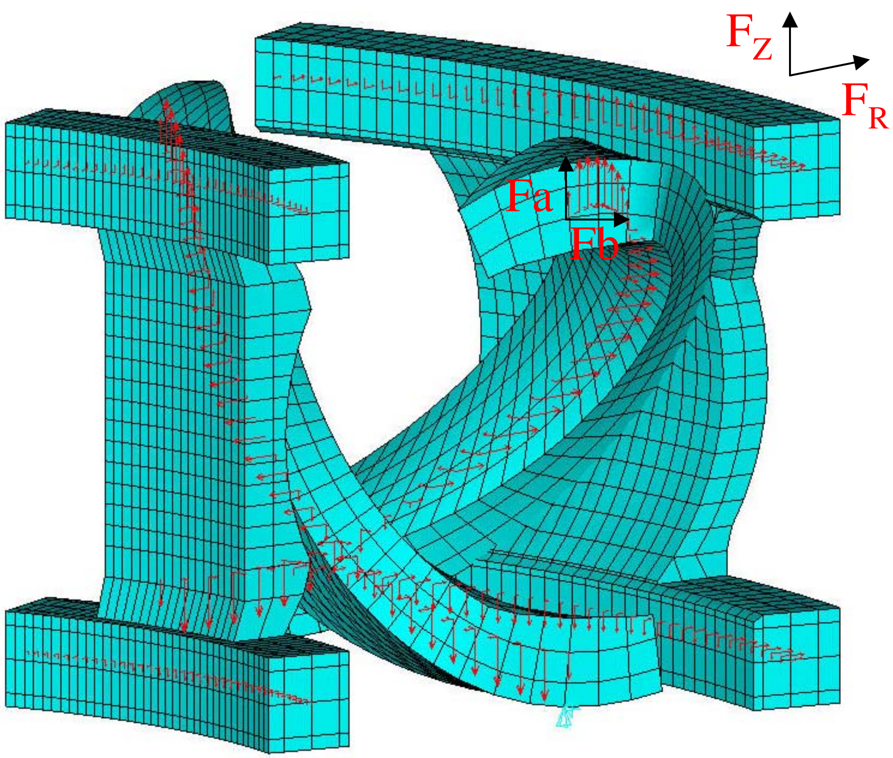
3: PC winding (j~25 MA/m^2)

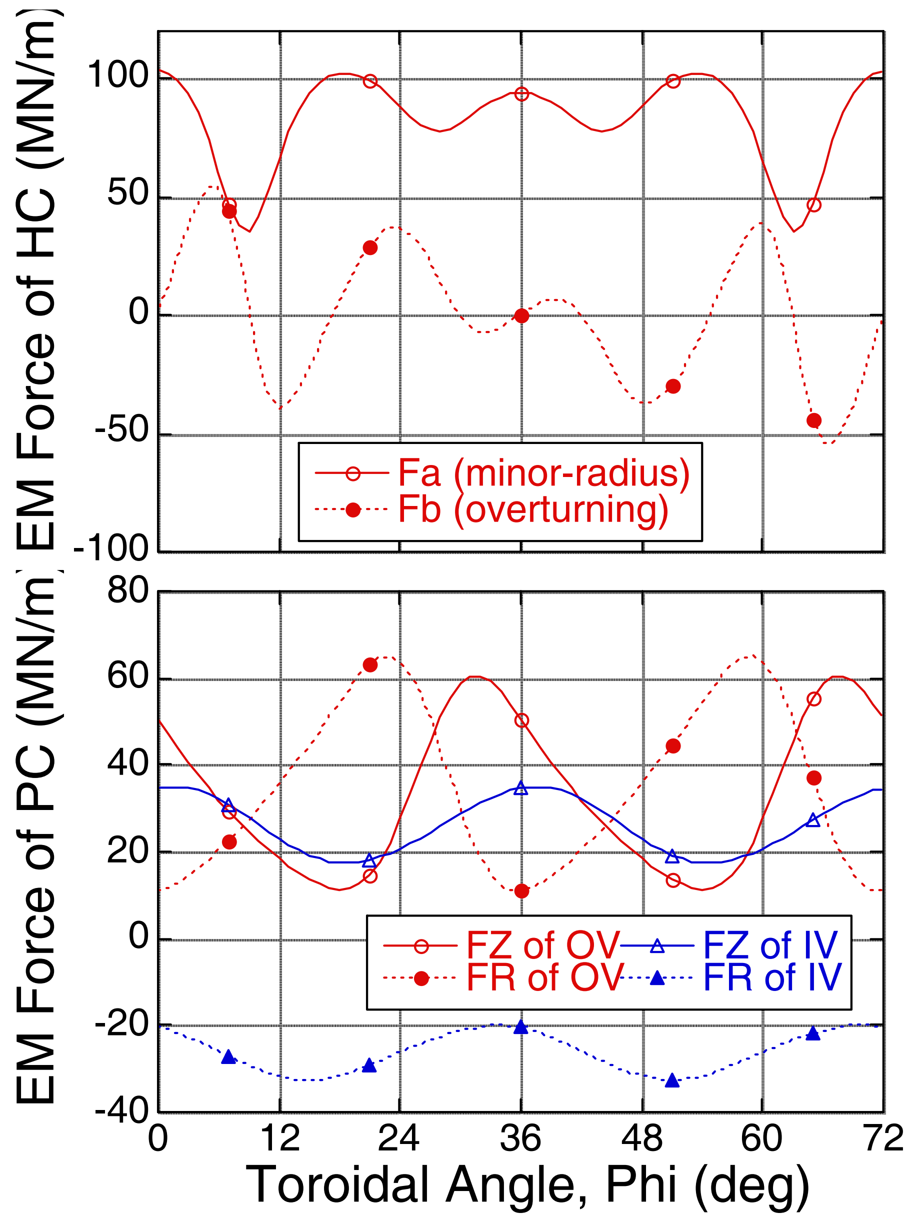
4: PC case (t=0.1-0.2m)

5: Inner and Outer support (t~0.5 m)

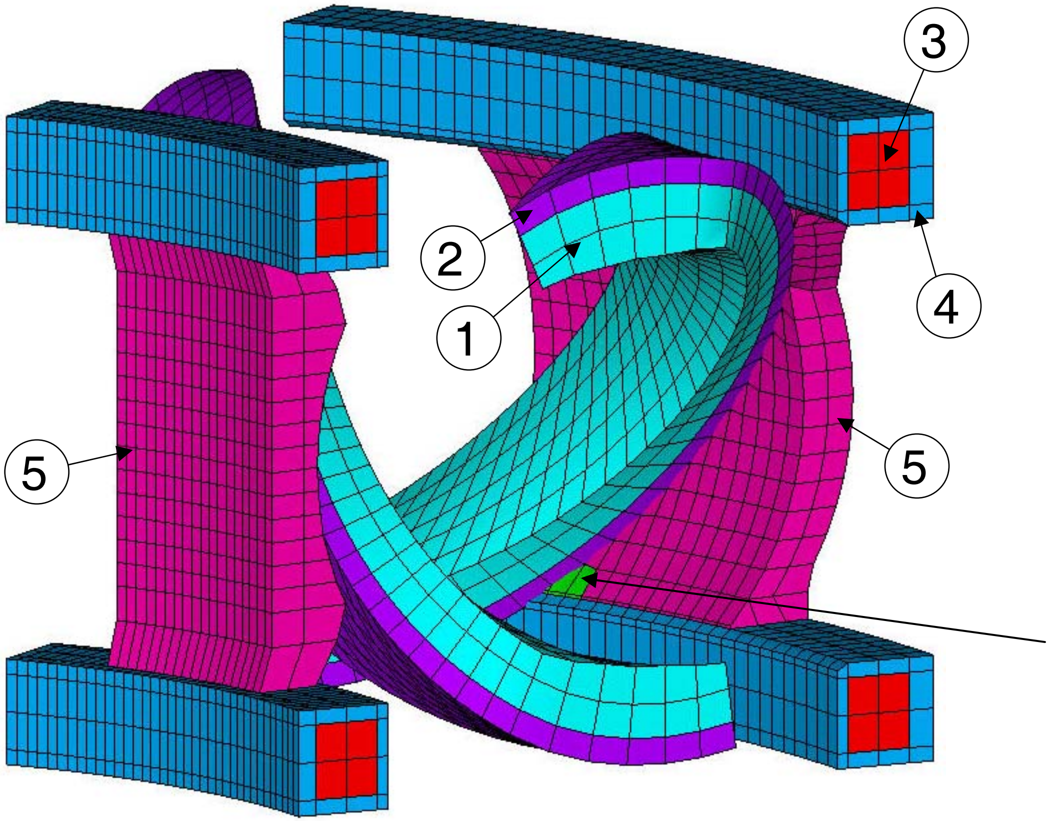
3. Structural analysis of the magnets

Software	: ANSYS
Analysis type	: Static
Element type	: 3-D solid, Elastic
Coupling	: Periodic symmetry
Joint type	: Rigid
Force	: EM force on nodes





Properties of Element



No	Material	Poisson ratio	Elastic modulus (GPa)
1	Cable+SS	0.3	150
2	SS	0.3	200
3	Cable+SS	0.3	150
4	SS	0.3	200
5	SS	0.3	200

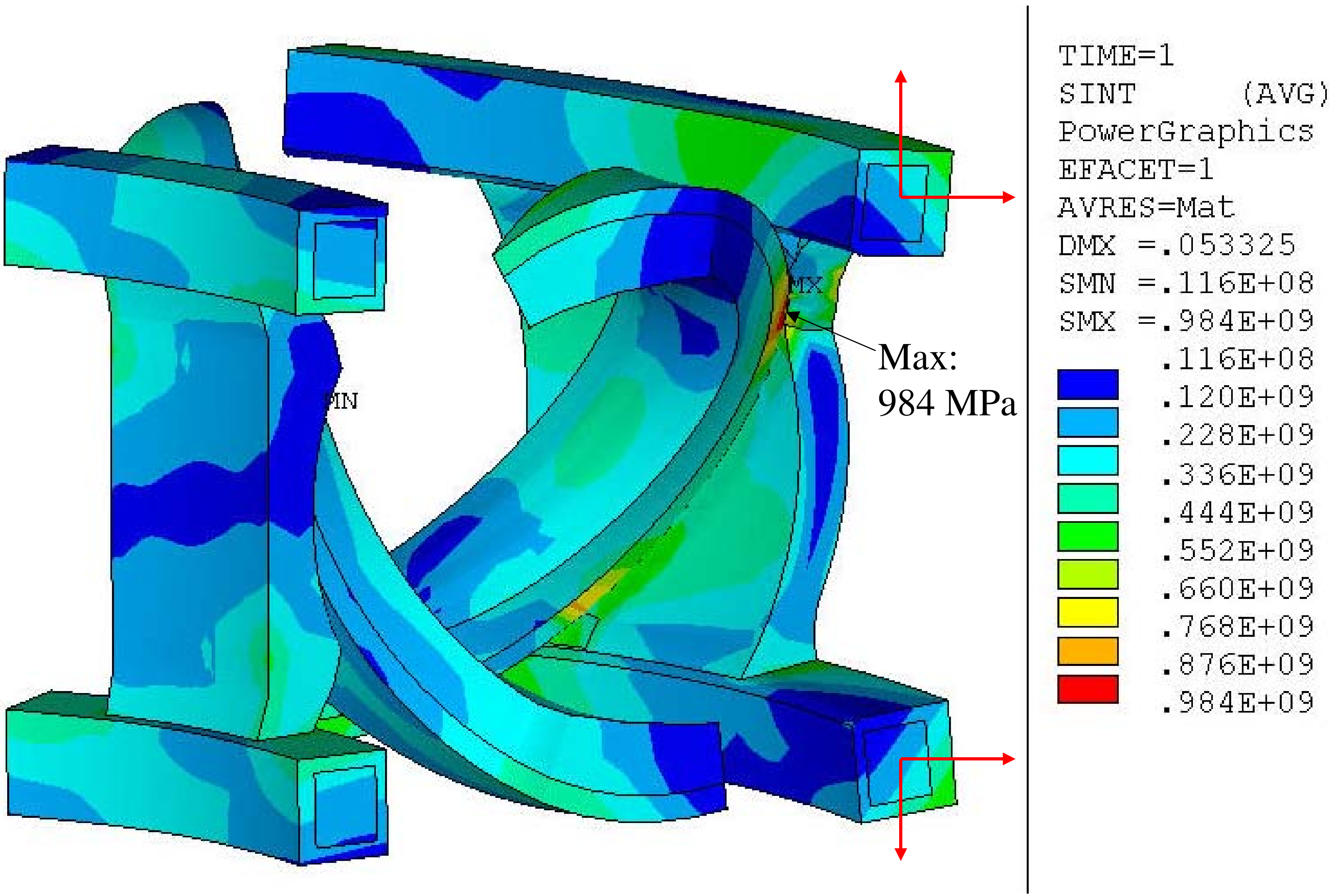
The modulus of support is partially reduced to relax the stress.

1: HC winding
2: HC support
3: PC winding
4: PC case
5: Inner and Outer support

The modulus of the real winding area is not isotropic. It depends on the design of the conductors and inner supports.

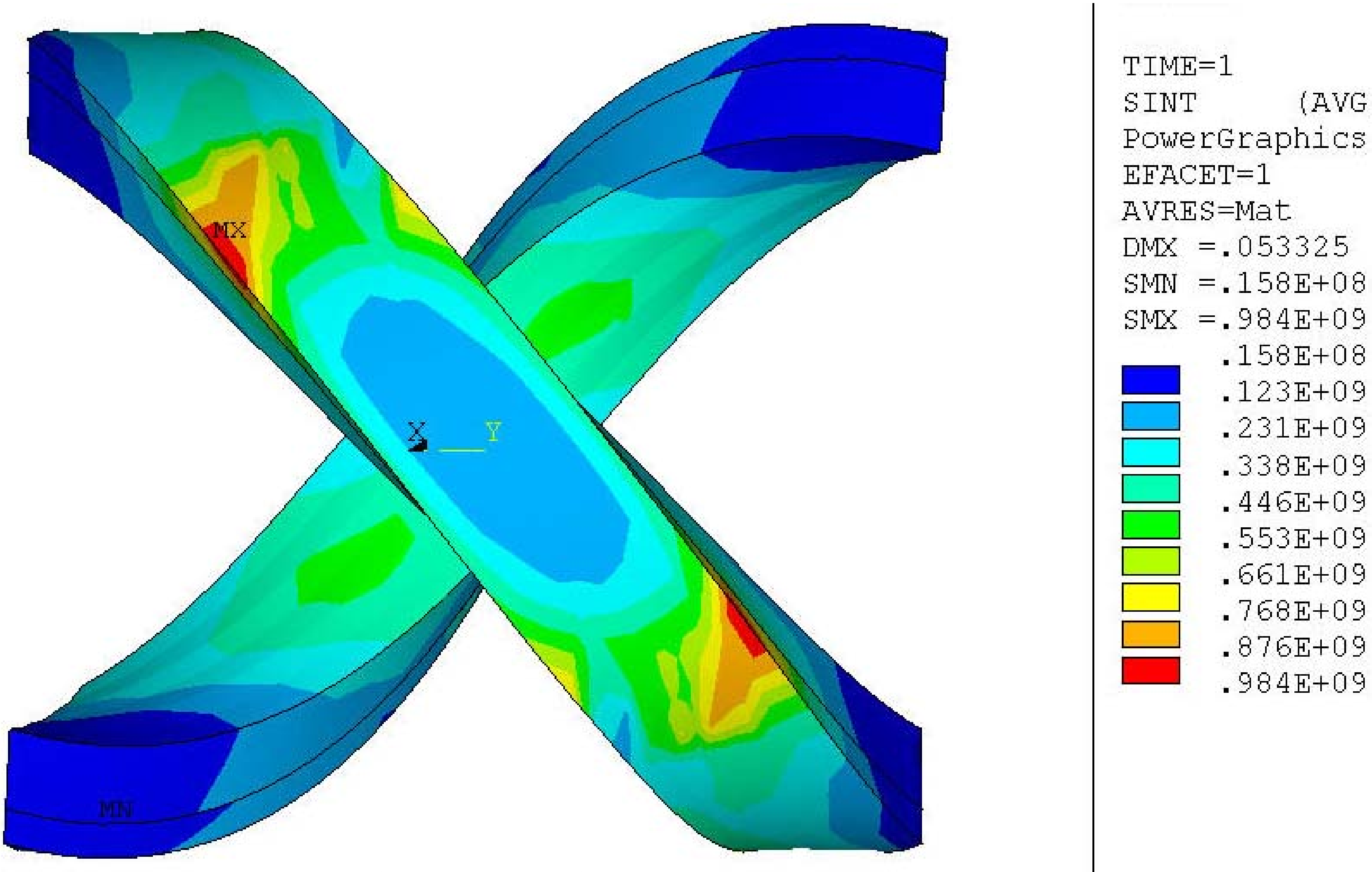
–> Future work

Results of Structural Analysis (1/4)



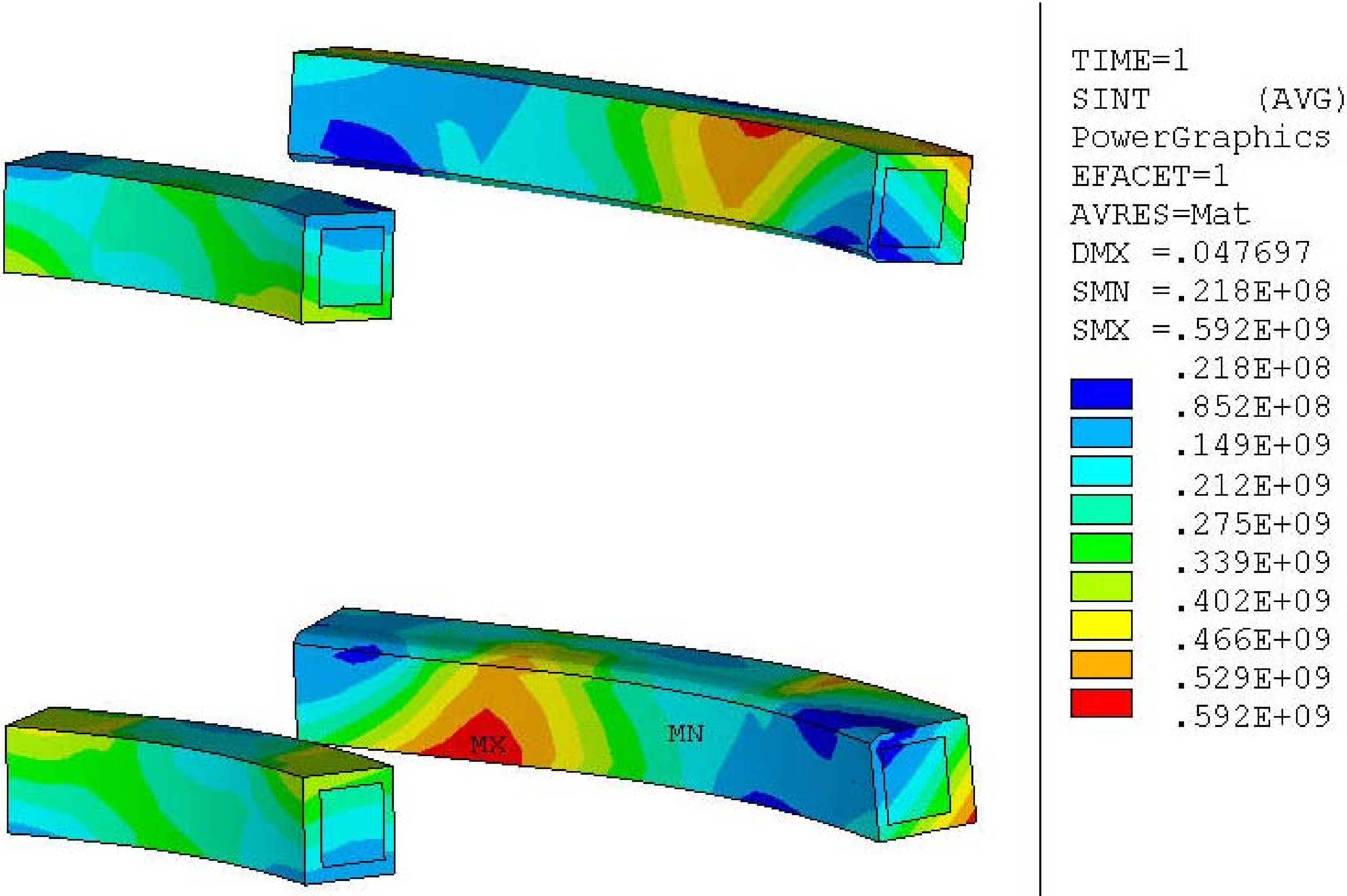
1,000 MPa is allowable for strengthened stainless steel at low temperature.

Results of Structural Analysis (2/4)



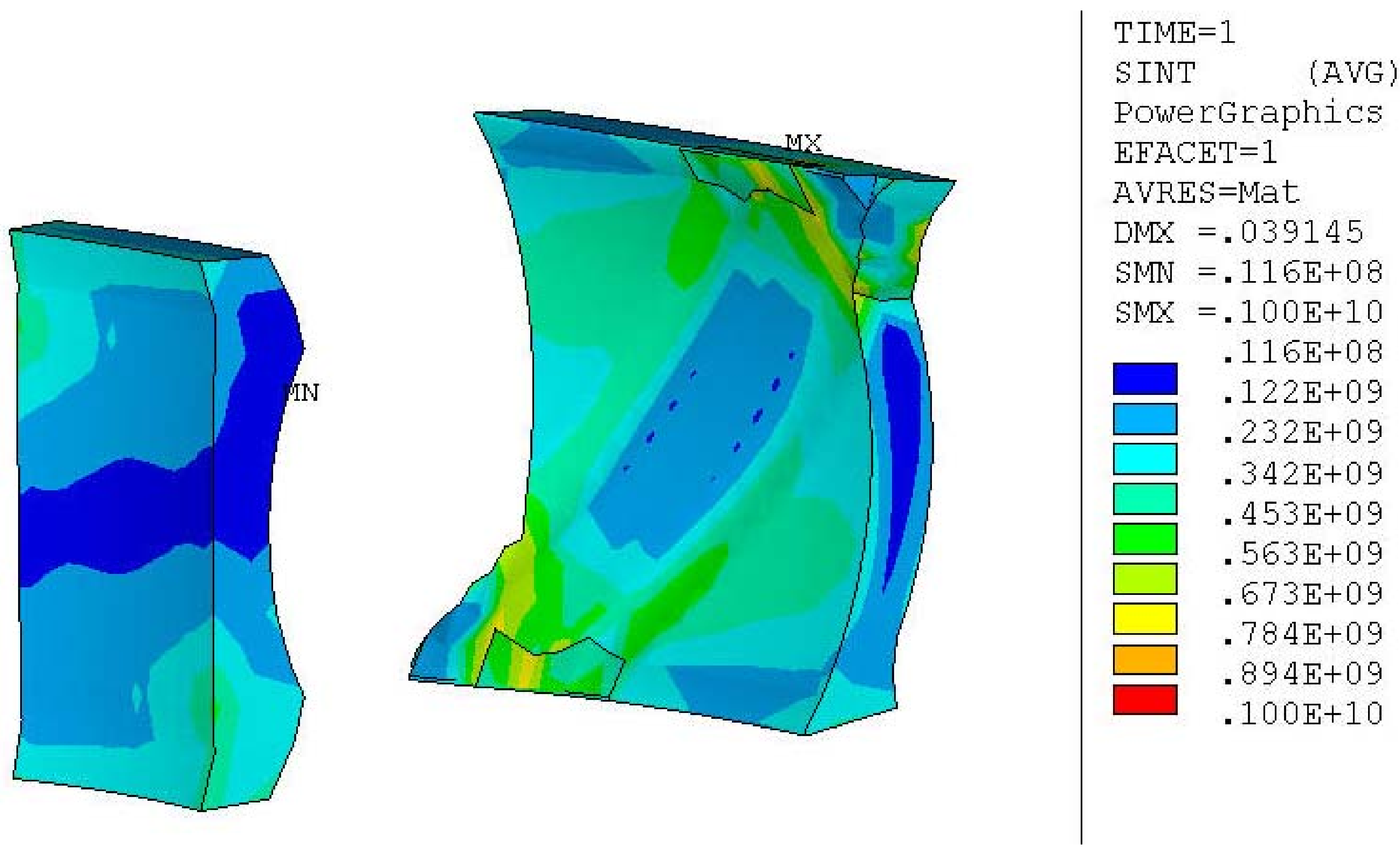
Stress in HC winding < 600 MPa

Results of Structural Analysis (3/4)



Stress in PC winding & PC case < 600 MPa

Results of Structural Analysis (4/4)



Peak stress is induced at the joint area to HC support. It can be reduced by modification of the shape.

Summary

(1) Two sets of poloidal coils (PCs) make it possible to reduce the magnetic field near the center and stored energy.

(2) The position of PCs is not optimized yet. Slightly larger radius of OV coils will reduce the peak stress.

(3) The supporting structure with wide ports at upper, lower, and outer area was proposed. The feasibility of this concept was confirmed by structural analysis.

(4) Future works are
new design of winding with high rigidity and strength,
further optimization of supporting structure (σ < 900 MPa),
and conceptual design of remote maintenance of blankets.