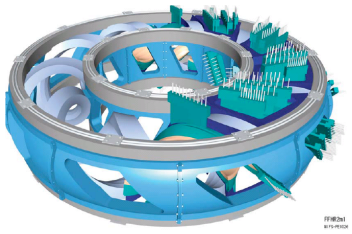
Design-based System Optimization on LHD-type Reactor FFHR



Akio SAGARA

with contributions from

O. Mitarai[1)], T. Mito, S. Imagawa, T. Morisaki, T. Tanaka, N. Mizuguchi, J. Miyazawa, H. Chikaraishi, S. Yamada, K. Seo, R. Sakamoto, S. Masuzaki , T. Muroga, H. Yamada, S. Fukada[2)], H. Hashizume[3)], K. Yamazaki[4)], O. Kaneko, T. Mutoh, N. Ohyabu, N. Noda, A. Komori, S. Sudo, O. Motojima and FFHR Design Group

National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

1) Kyushyu Tokai University, 9-1-1 Toroku, Kumamoto 862-8652, Japan

2) Kyushyu University, Fukuoka 812-8581, Japan

3) Tohoku University, Sendai 980-8579, Japan

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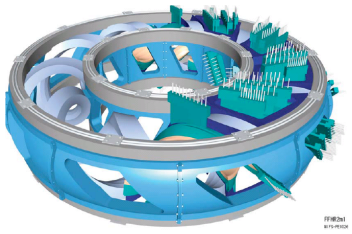
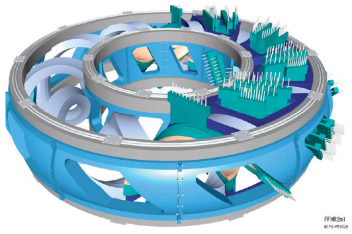
US-J Workshop on Power Plant Studies and Related Advanced Technologies with EU Participation, Jan.24-25, 2006



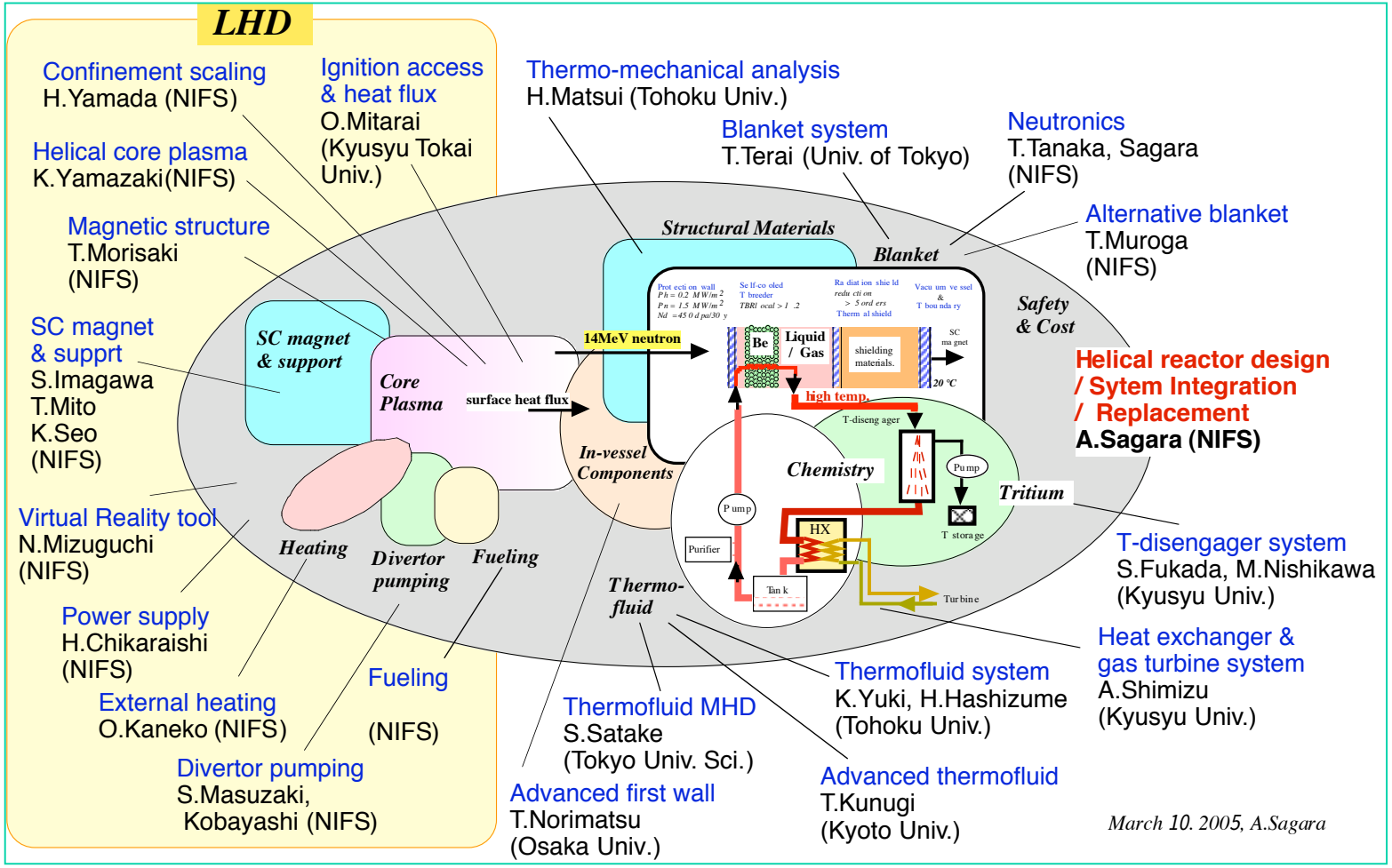
Presentation Outline

1. Design Activities
2. Design Scenario
3. Recent Progress
   - (1) Reactor size optimization
   - (2) New proposal of long-life blanket
   - (3) Replacement scenario
4. Design Methodology
   - (1) PC simulator of power plant operations
   - (2) Virtual reality for 3D design assisting
5. Summary

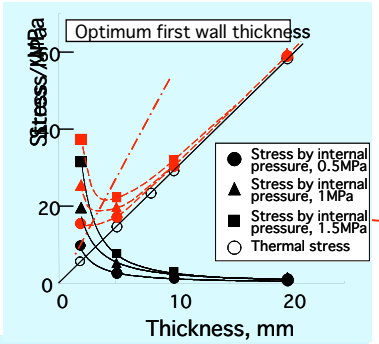
Design Activities



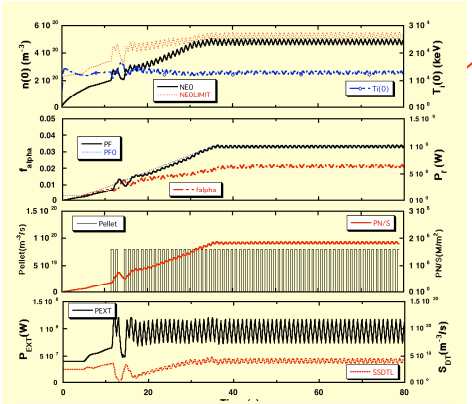
From 1993, collaboration activities on LHD-type reactor-system designs have developed with connecting wide research areas on fusion science and engineering (Fusion Research Network) in the universities in Japan.



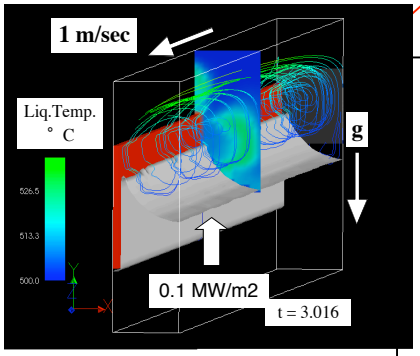
Collaborations on Key R&D Issues



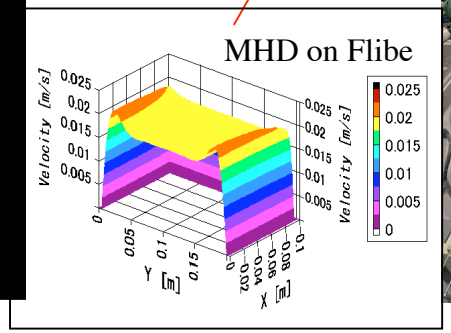
ブランケット板厚の熱構造解析



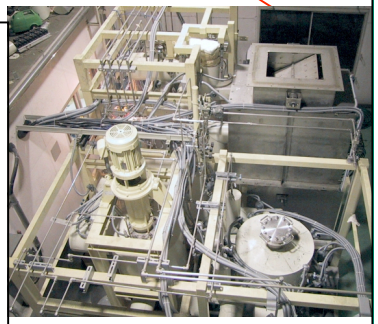
自己点火運転制御



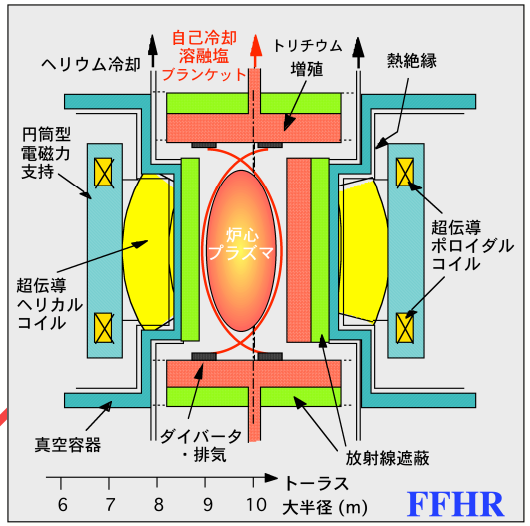
液体自由表面支持の新提案

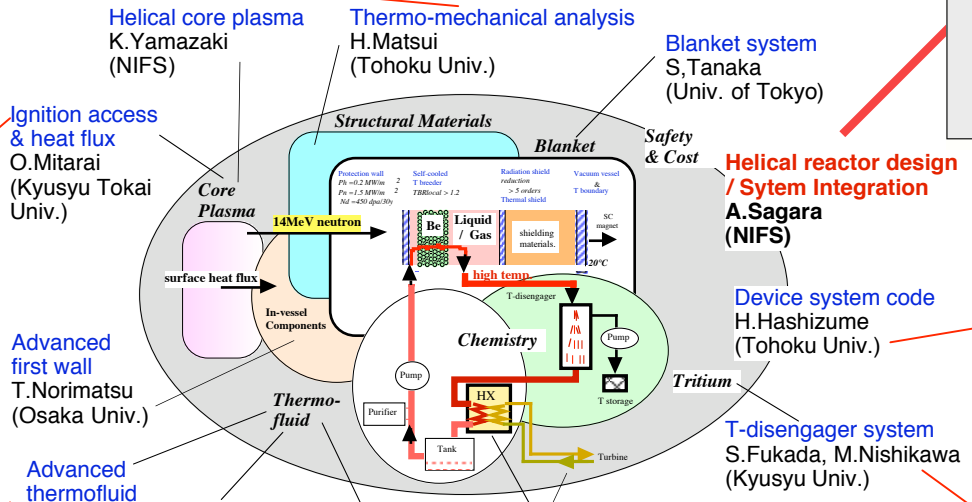


溶融塩での電磁流体効果



高温融体伝熱 TNT Loop構築
: Max.20L/min @ 600°C





Helical core plasma
K.Yamazaki
(NIFS)

Thermo-mechanical analysis
H.Matsui
(Tohoku Univ.)

Blanket system
S,Tanaka
(Univ. of Tokyo)

Ignition access & heat flux
O.Mitarai
(Kyusyu Tokai Univ.)

Helical reactor design / Sytem Integration
A.Sagara
(NIFS)

Device system code
H.Hashizume
(Tohoku Univ.)

Advanced first wall
T.Norimatsu
(Osaka Univ.)

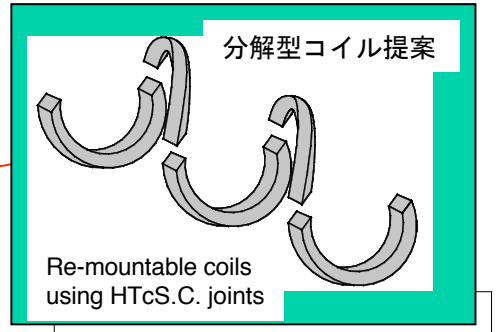
T-disengager system
S.Fukada, M.Nishikawa
(Kyusyu Univ.)

Advanced thermofluid
T.Kunugi
(Kyoto Univ.)

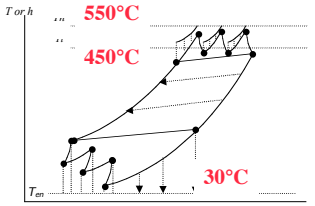
Thermofluid MHD
S.Satake
(Tokyo Univ. Sci.)

Thermofluid system
K.Yuki
(Tohoku Univ.)

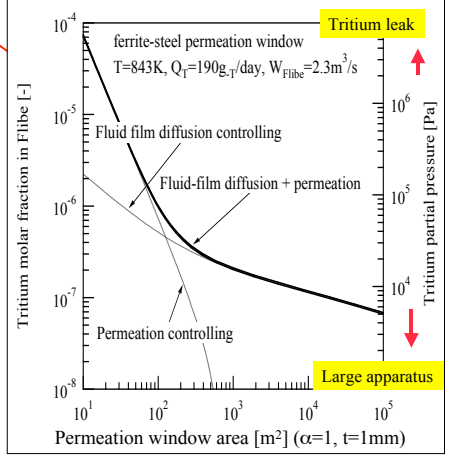
Heat exchanger & gas turbine system
A.Shimizu
(Kyusyu Univ.)



Closed He gas turbine cycle with three-stage compression/expansion

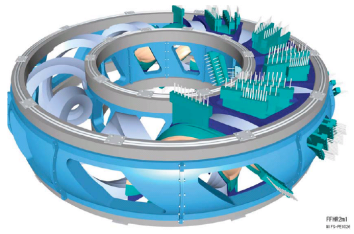


多段ブライトンサイクルの新提案



透過窓式T回収の最適化設計

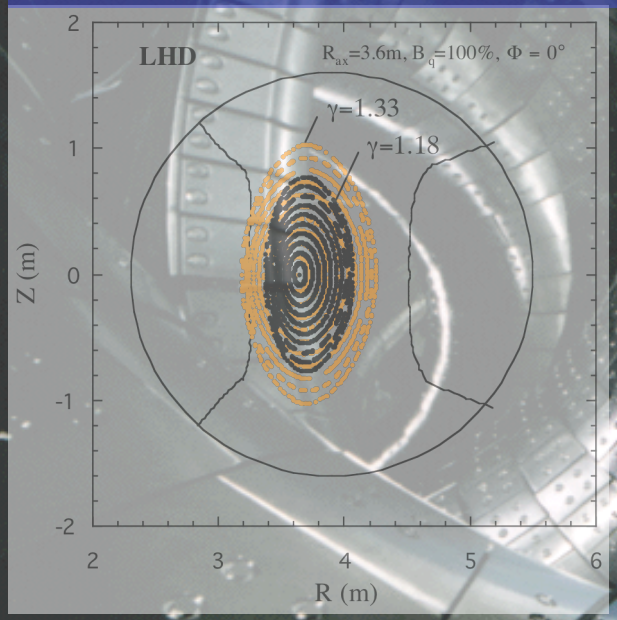
Design Scenario



(1) The coil pitch parameter γ of continuous helical winding has been adjusted

- to reduce the magnetic hoop force (Force Free Helical Reactor: FFHR),
- to expand the blanket space

By Selecting lower value of $\gamma = \left(\frac{m}{l}\frac{a_c}{R}\right)$



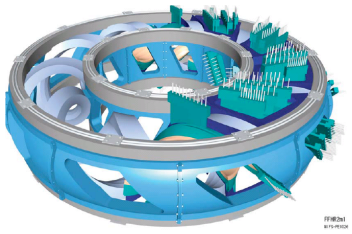
γ=tanθ

(2) Self-cooled liquid Flibe (BeF_2-LiF) blanket has been proposed, due to

- low MHD pressure loss,
- low reactivity with air,
- low pressure operation,
- low tritium solubility.

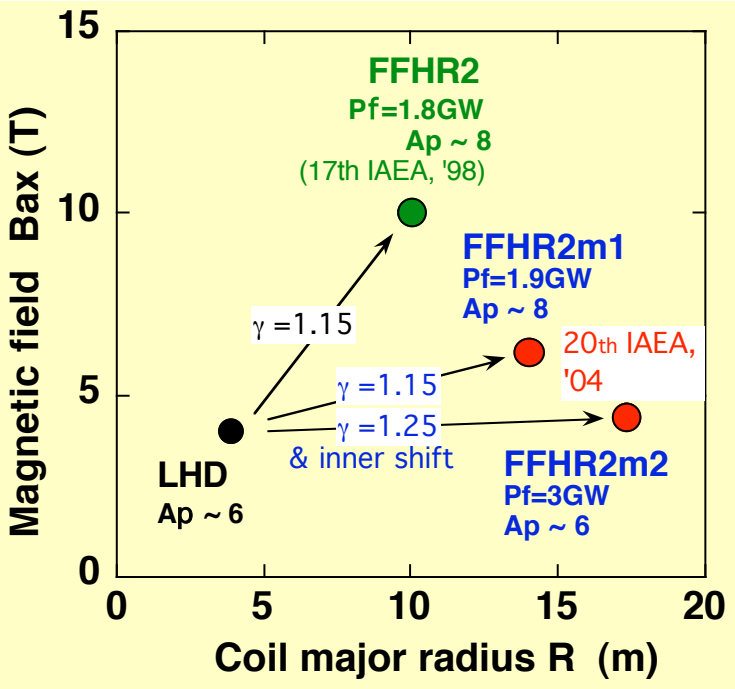
Recent Progress

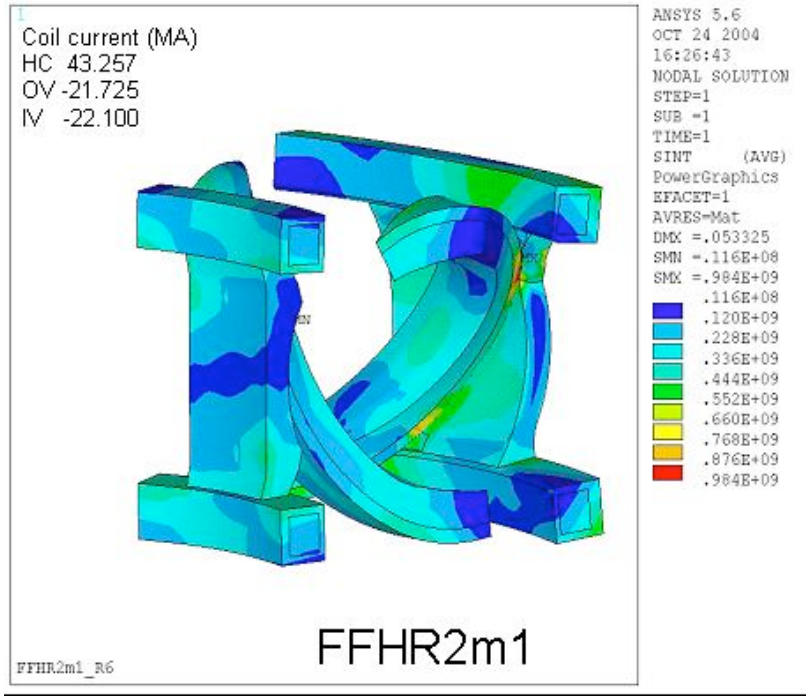
(1) Reactor size optimization



Under engineering requirements, design parameters of FFHR have been modified with increasing the major radius R and reducing the B_0 within B_{max} of 13T

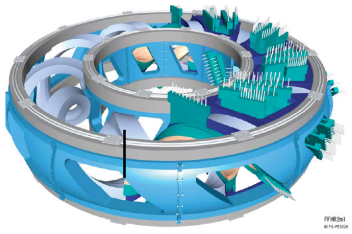
- **to expand the blanket space ~ 1.2m**
- **to simplify the coil-supporting structure (stress<1.5Sm) for large size maintenance ports.**





Recent Progress

(1) Reactor size optimization



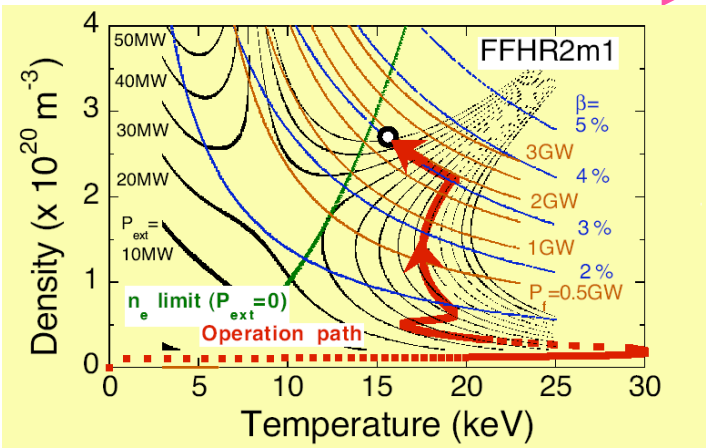
Design Parameters

Improved input

Expanded Blanket space

Reduced Wall loading

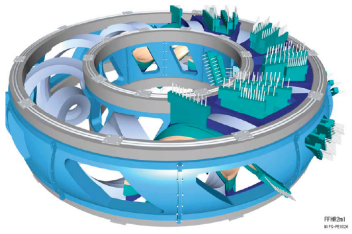
Design parameters			LHD	FFHR2	FFHR2m1	FFHR2m2
Polarity	l		2	2	2	2
Field periods	m		10	10	10	10
Coil pitch parameter	γ		**1.25**	**1.15**	**1.15**	**1.25**
Coil major Radius	Rc	m	3.9	10	14.0	17.3
Coil minor radius	ac	m	0.98	2.3	3.22	4.33
Plasma major radius	Rp	m	**3.75**	**10**	**14.0**	**16.0**
Plasma radius	ap	m	0.61	1.2	1.73	2.80
Blanket space	Δ	m	0.12	**0.7**	**1.2**	**1.1**
Magnetic field	B0	T	**4**	**10**	**6.18**	**4.43**
Max. field on coils	Bmax	T	9.2	13	13.3	13
Coil current density	j	MA/m2	53	25	26.6	32.8
Weight of support		ton	400	**2880**	**3020**	**3210**
Magnetic energy		GJ	1.64	147	120	142
Fusion power	P_F	GW		**1.77**	**1.9**	**3.0**
Neutron wall load		MW/m2		**2.8**	**1.5**	**1.3**
External heating power	Pext	MW		100	80	100
α heating efficiency	ηα			0.7	0.9	0.9
Density lim.improvement				1	1.5	1.5
H factor of ISS95				**2.53**	**1.92**	**1.68**
Effective ion charge	Zeff			1.32	1.34	1.35
Electron density	ne(0)	10^19 m-3		28.0	26.7	19.0
Temperature	Ti(0)	keV		27	15.8	16.1
<β>=2*n*T/(B^2/μ) (parabolic distribution)				**1.8**	**3.0**	**4.1**
COE	Yen/kWh			**21.00**	**14.00**	**9.00**



A. Sagara et al., Nuclear Fusion 45 (2005) 258-263.

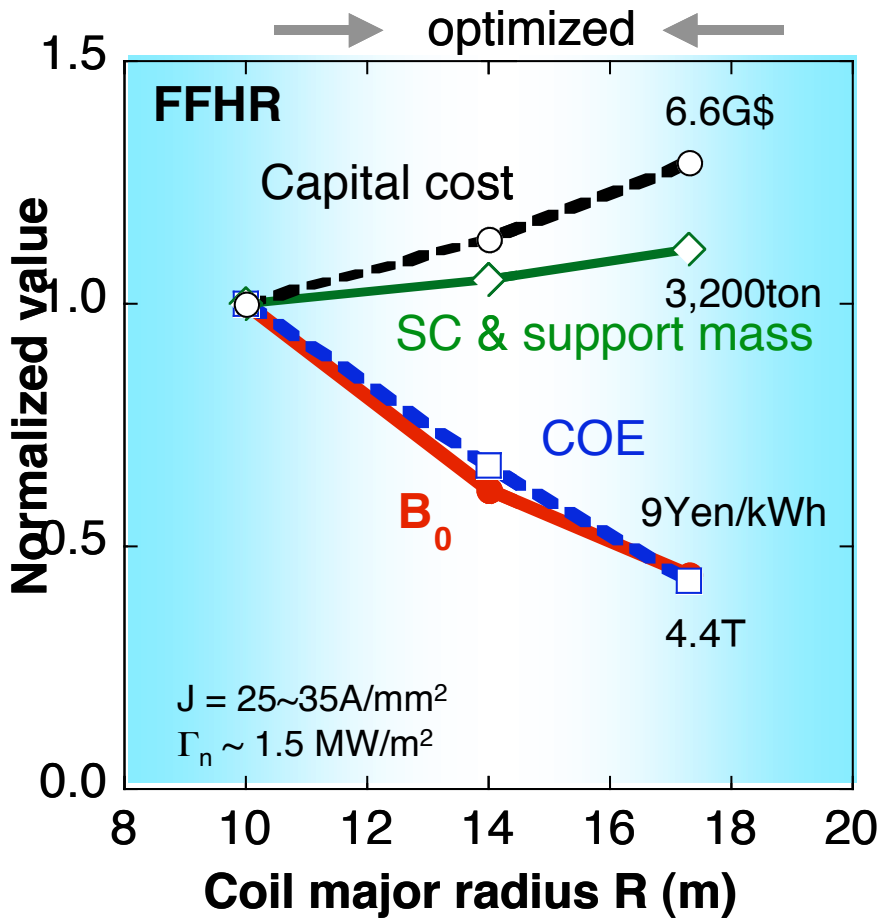
Recent Progress

(1) Reactor size optimization



under the constraints of

- **SC J=25~35A/mm^2**
- **neutron wall loading Γ_n=1.3~1.5 MW/m^2**



Key issues:

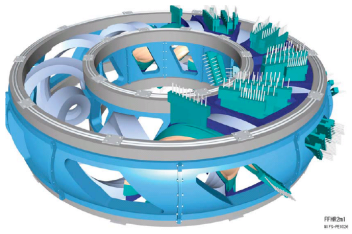
- **Physics on γ and R_{ax}**
  → LHD experiments

New targets based on LHD:

- **Large scale SC magnet**
- **SC magnet of high J**

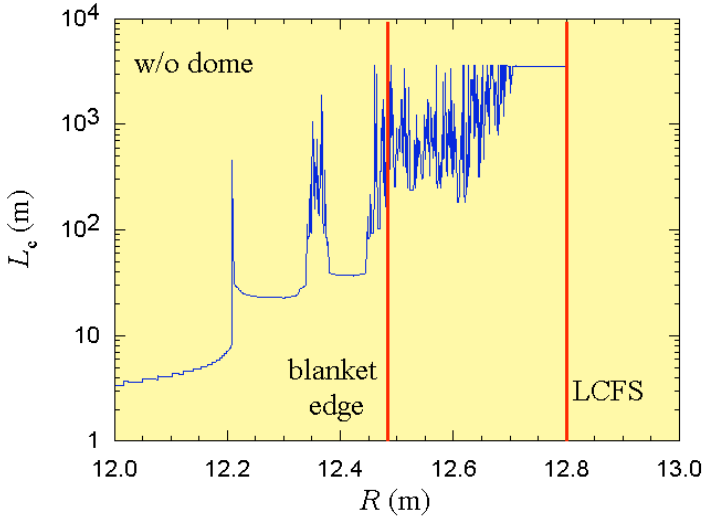
Recent Progress

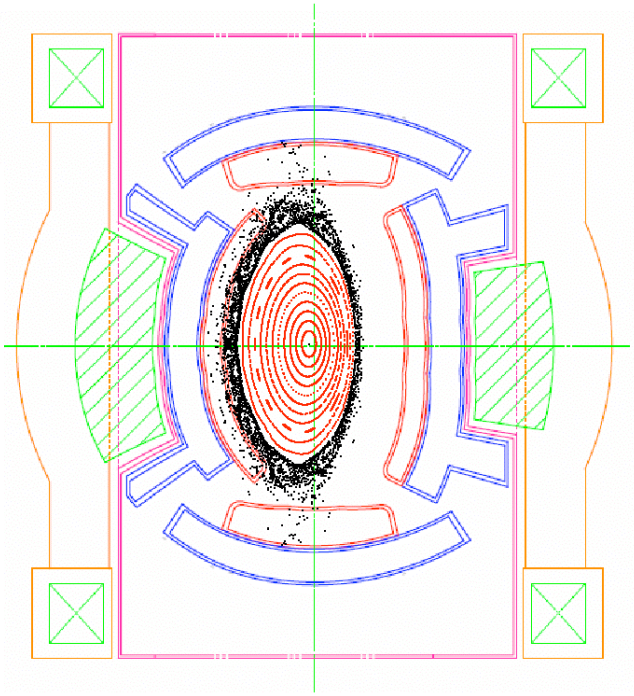
(1) Reactor size optimization

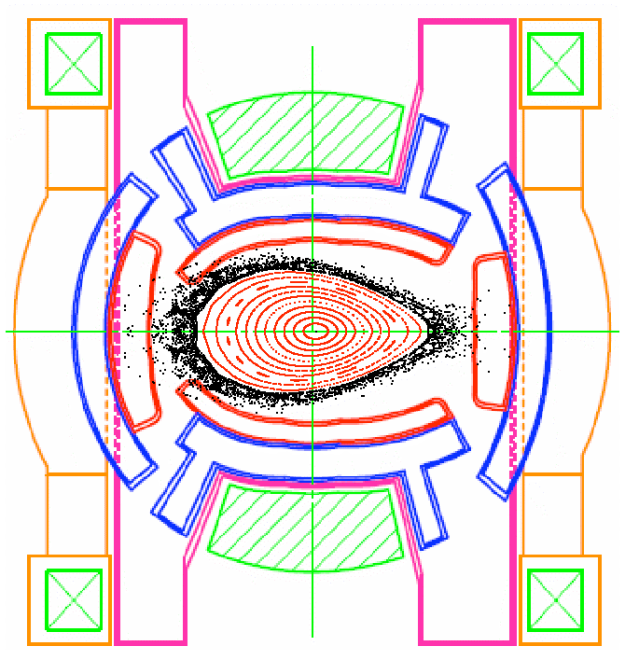


FFHR2m1 Magnetic configuration (ITC-15 / T. Morisaki)

First version

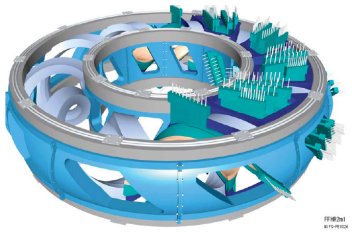






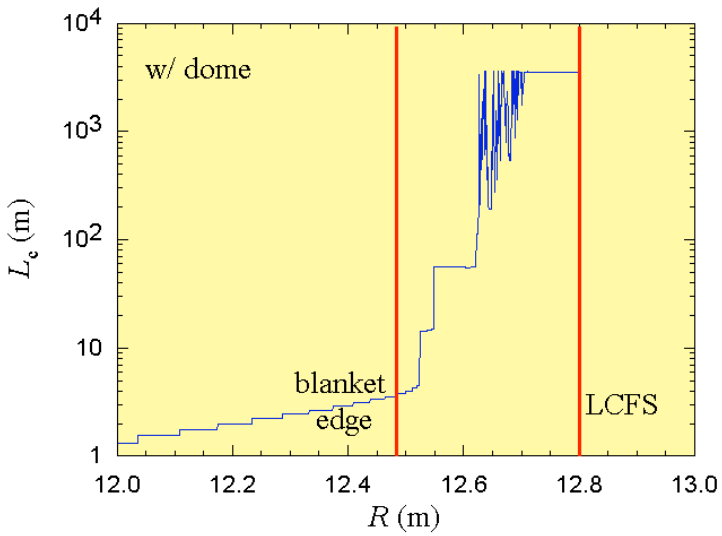
Recent Progress

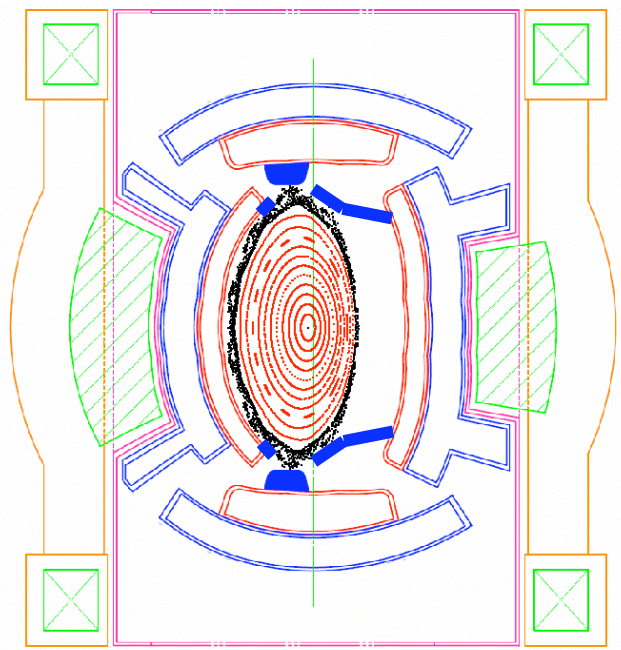
(1) Reactor size optimization

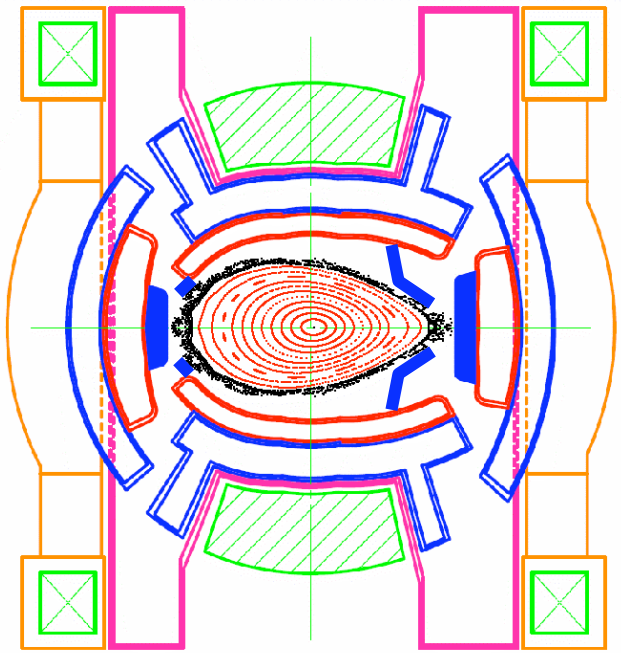


FFHR2m1 Magnetic configuration (ITC-15 / T. Morisaki)

Modified version



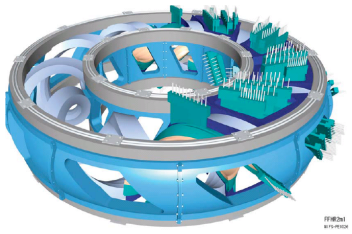




Further shaping of blanket & divertor is the next step.

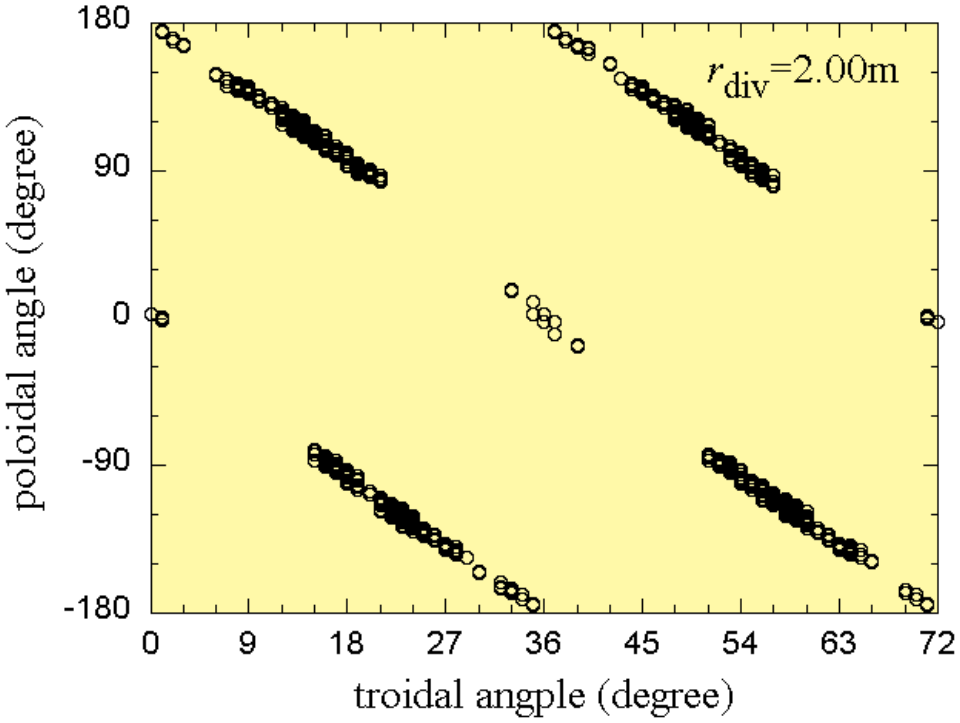
Recent Progress

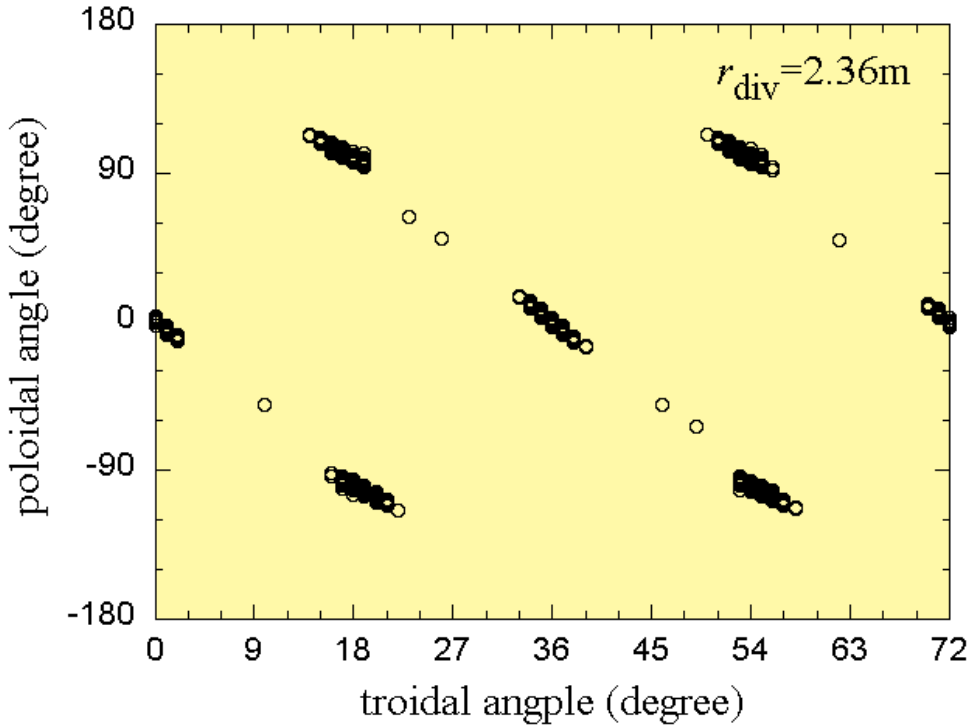
(1) Reactor size optimization



FFHR2m1 Magnetic configuration (ITC-15 / T. Morisaki)

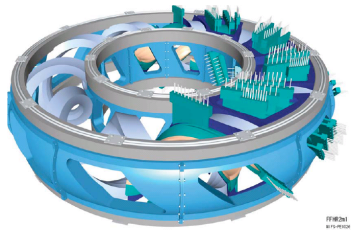
Distribution of divertor magnetic flux



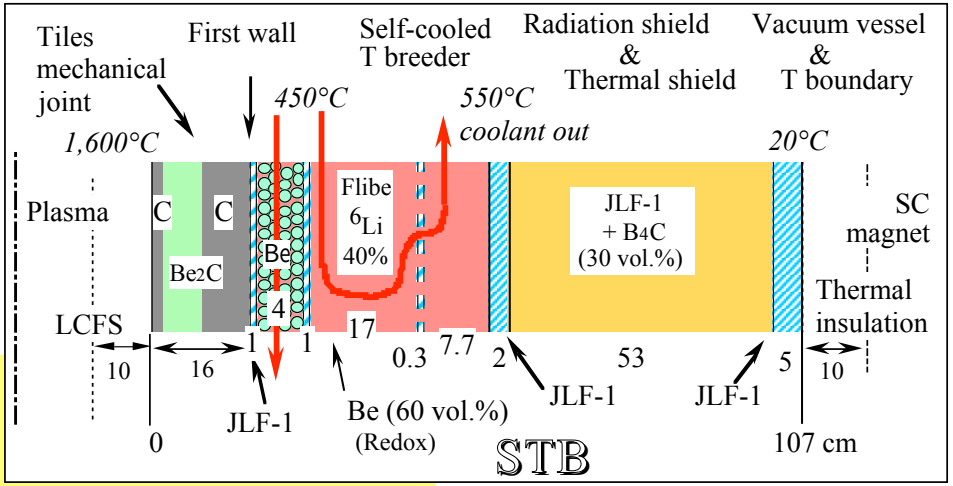


Recent Progress

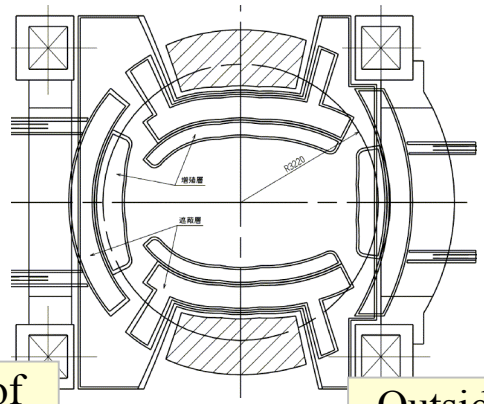
(2) New proposal of long-life blanket



Under the reduced wall loading of 1.5MW/m², Long-life blanket STB (Spectral-shifter and Tritium Breeder) has been newly proposed, resulting in



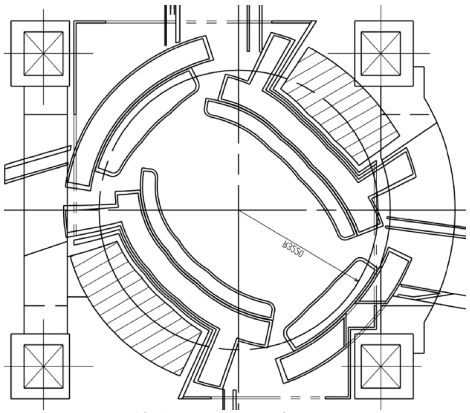
- **Replacement-free** of breeder units
  < 100dpa in the full-life of 30years
- **Improved nuclear shielding** for SC magnets
  ~ 5×10^{22} fast n/m² in 30years



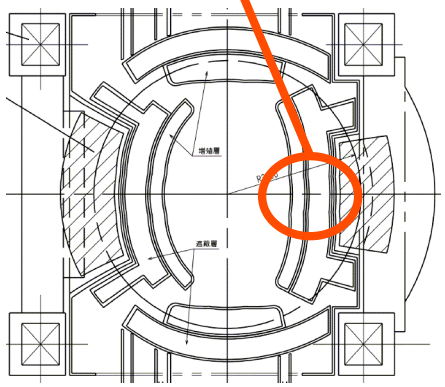
Inside of torus

Outside

(a) 0 deg.

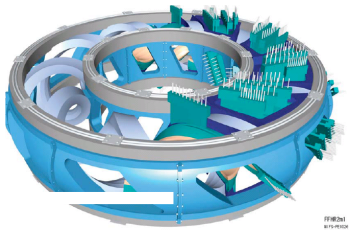


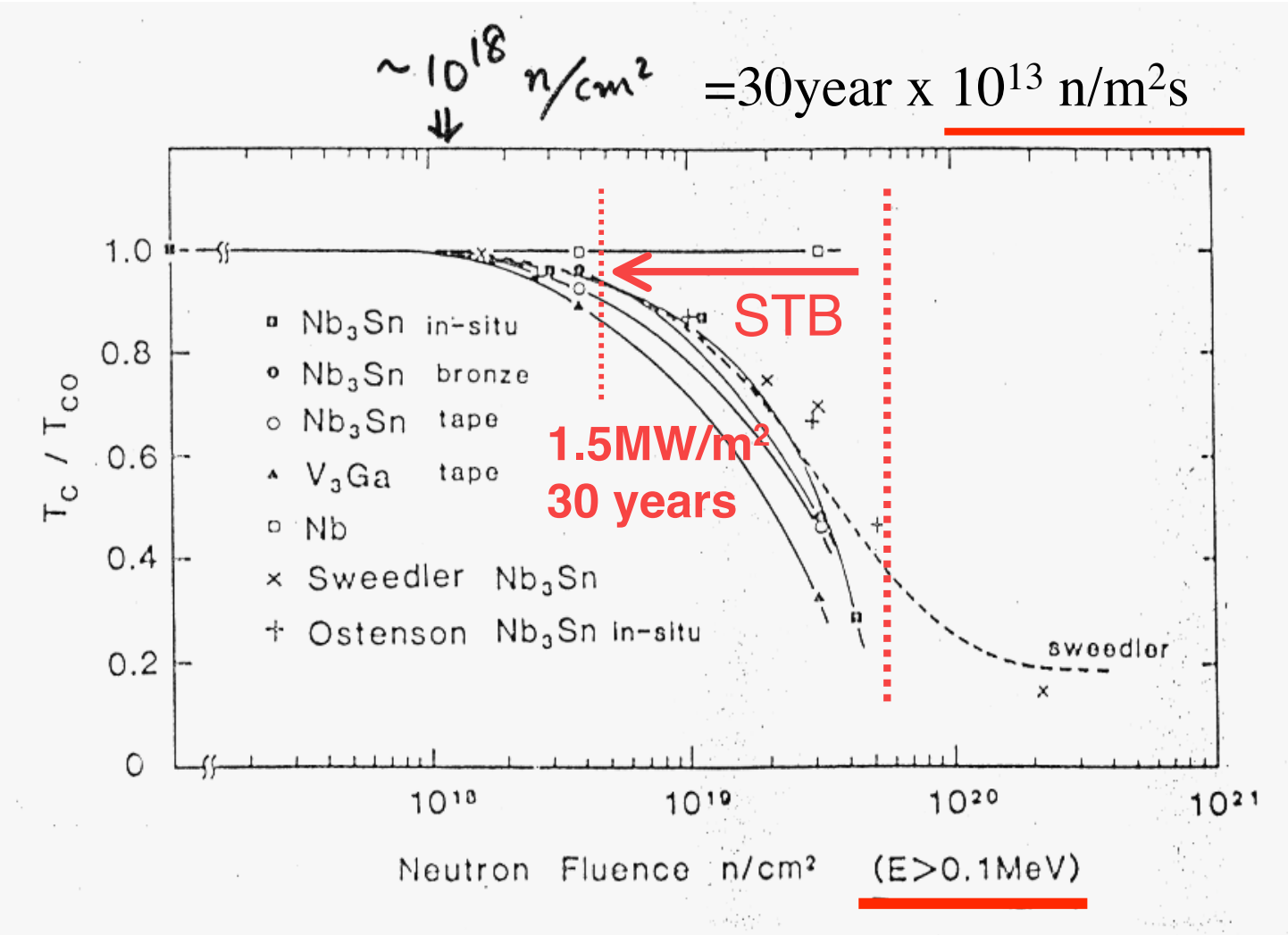
(b) 45 deg.



(c) 90 deg.

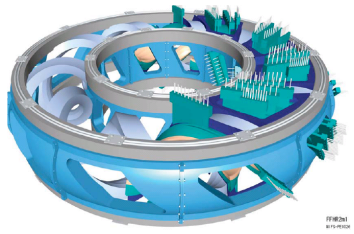
Dose effects of fast neutrons on SC magnets



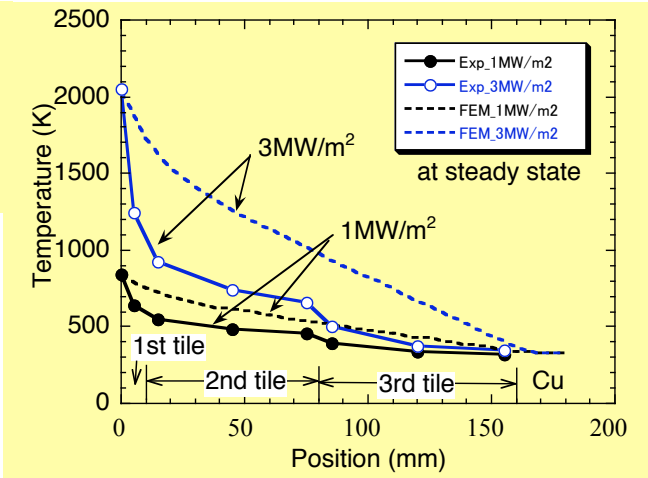


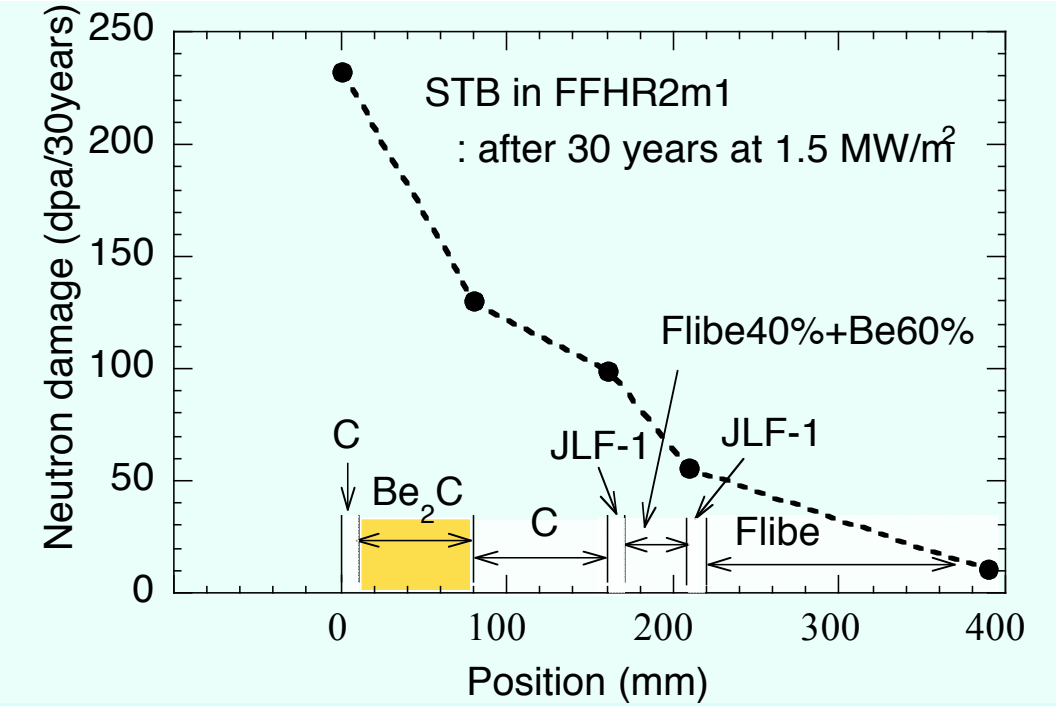
Kodama et al., JNM(1985) 819.

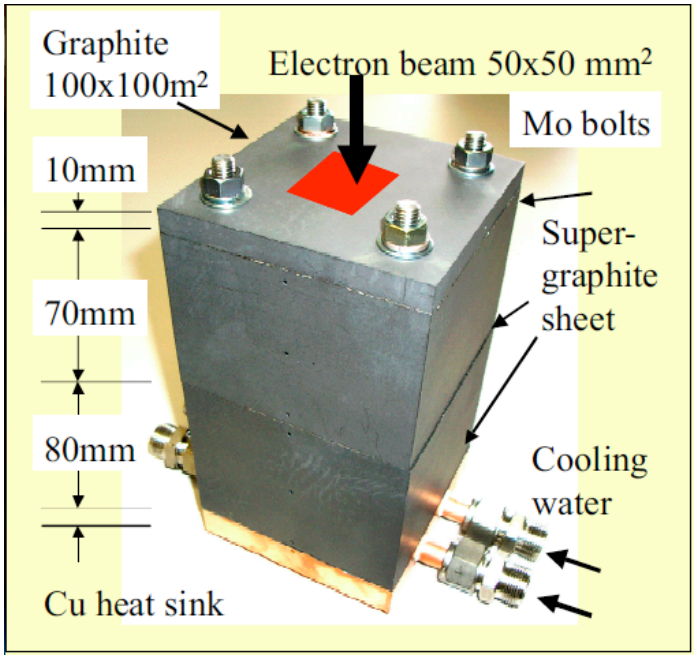
(2) New proposal of long-life blanket



It has been experimentally demonstrated that STB tiles can be below 2,000K by optimizing the first metal-wall thickness.

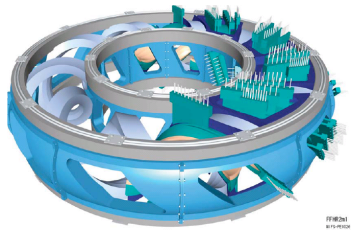






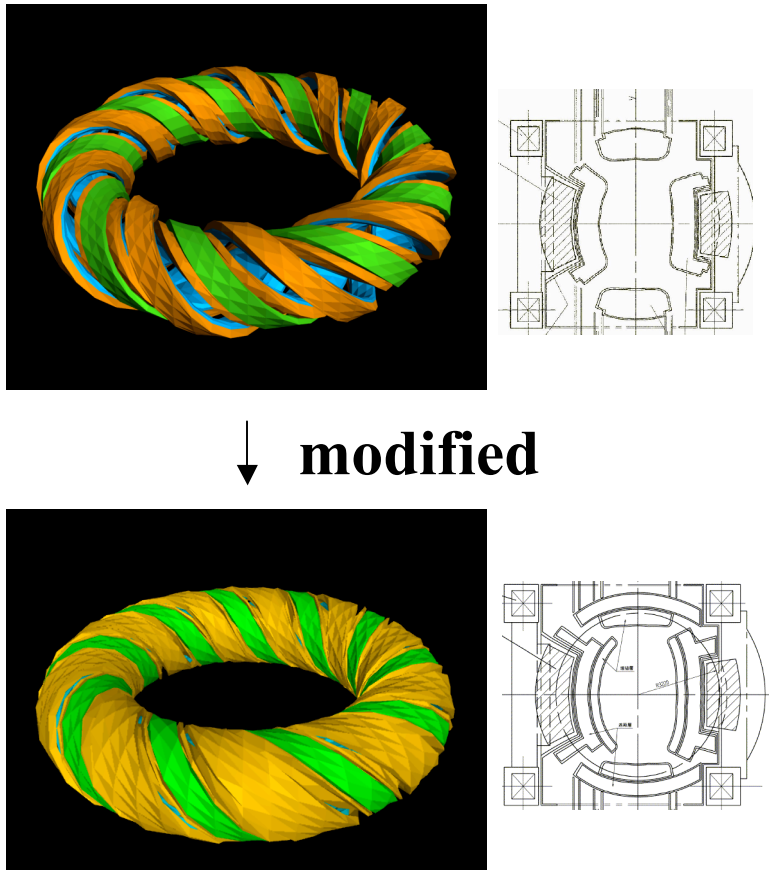
Calculated damage is below 100dpa after 30 years for the STB RAFS structure

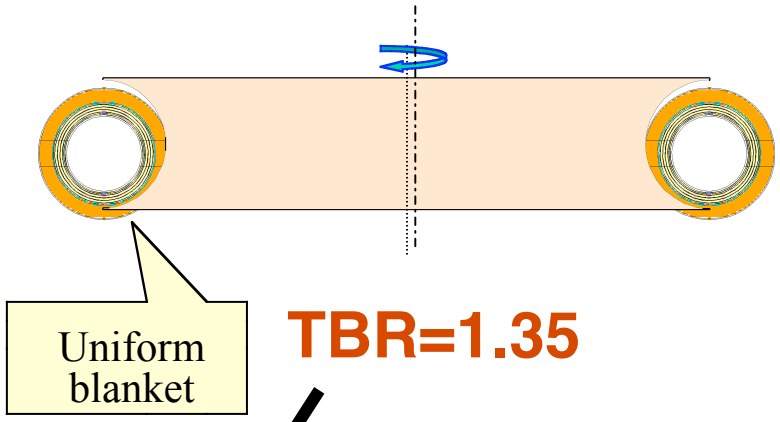
(2) New proposal of long-life blanket



Neutronics with CAD-base MCNP on helical shaped system

(ITC-15 / T. Tanaka)





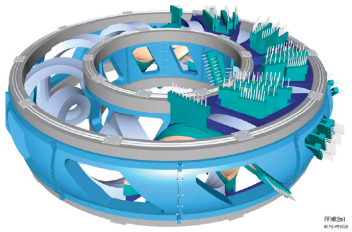
TBR=1.35

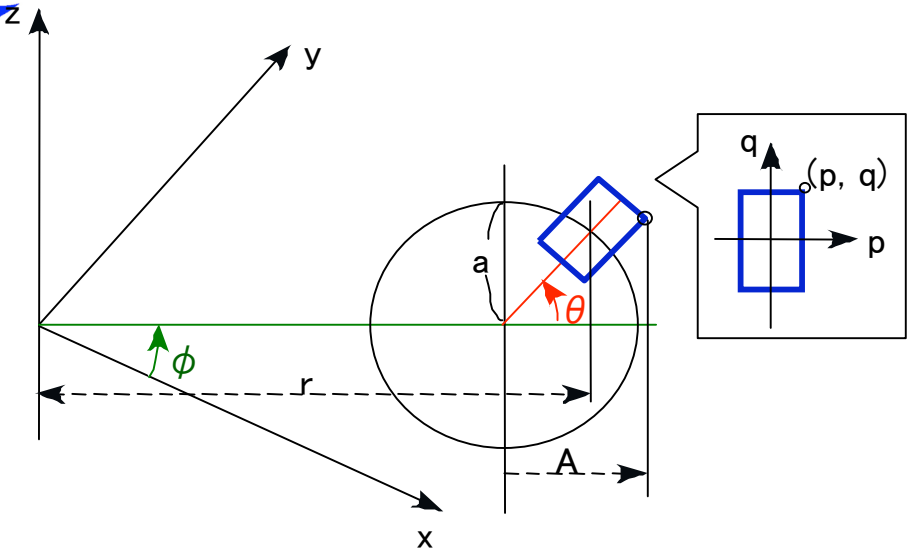
20% loss of neutrons

TBR=1.09

Further improvements are needed

Equations for helical structure





Polarity	$\ell=2$
Field periods	m=10
Coil pitch parameter	$\alpha^*=0.1$
Major radius	$R_0=14$m
Minor radius	$a_c=3.22$m

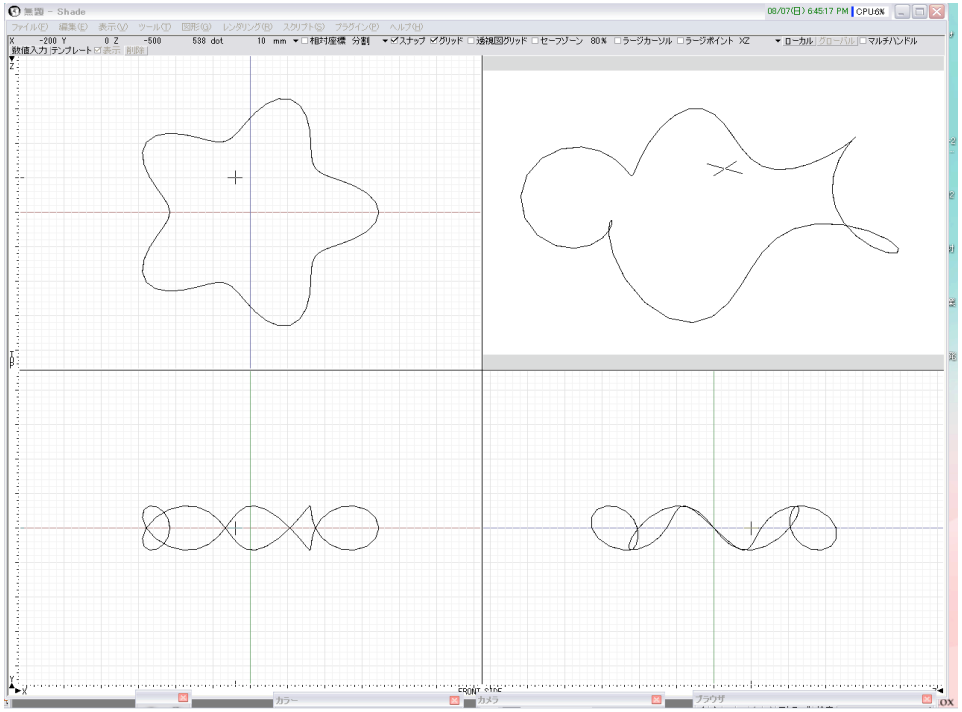
$$\theta=m/\ell\varphi+\alpha^*\sin(m/\ell\varphi)$$

$$A=(a+q)\cos\theta+P\sin\beta\sin\theta$$

$$\tan\beta=\frac{rd\phi}{ad\theta}=\frac{\frac{R}{a}+\cos\theta}{\frac{m}{l}\left\{1+\alpha^*\cos\left(\frac{m}{l}\phi\right)\right\}}$$

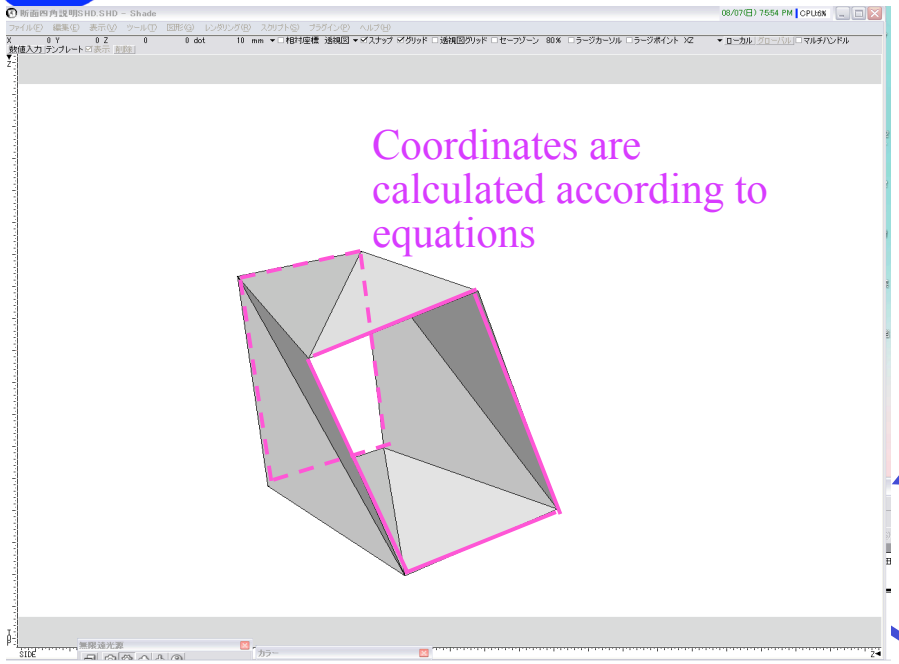
$$\begin{cases} x=(R+A)\cos\varphi-P\cos\beta\sin\varphi \\ y=(R+A)\sin\varphi+P\cos\beta\cos\varphi \\ z=(a+q)\sin\theta-P\sin\beta\cos\theta \end{cases}$$

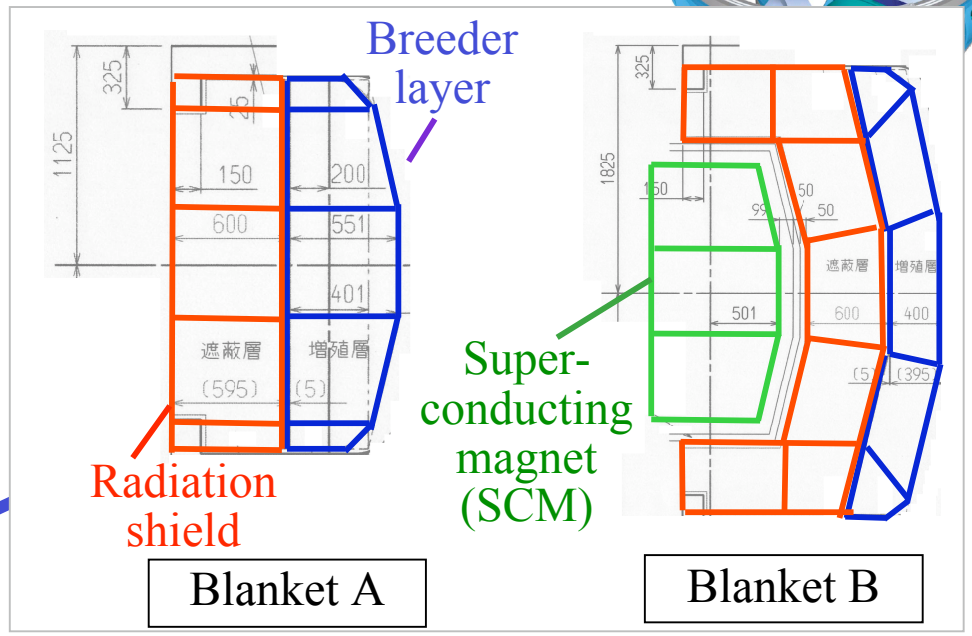
Equations for helical structure



Trajectory according to equations
(p, q) = (0,0)

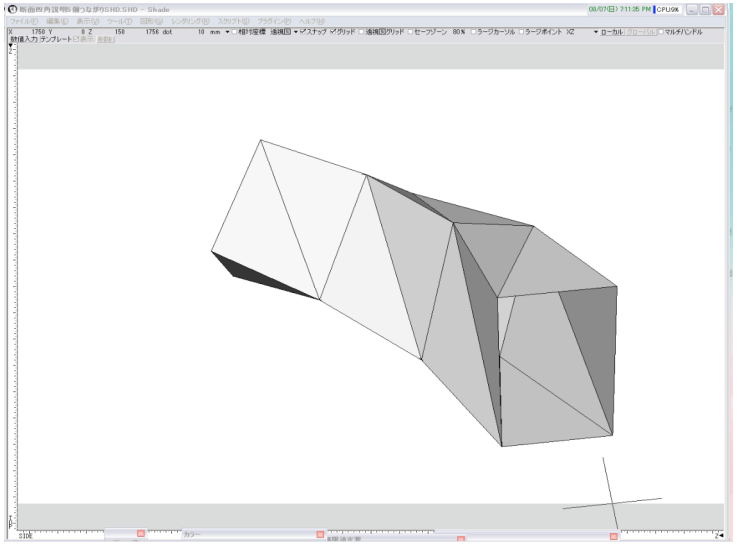
Division of cross-sections and making of input data





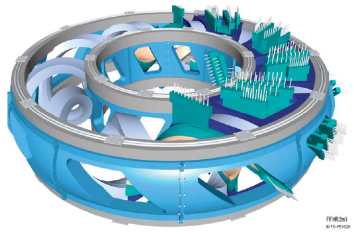
- Divide blanket and coil cross-sections into quadrangles
- Proceeding spirally according to equations

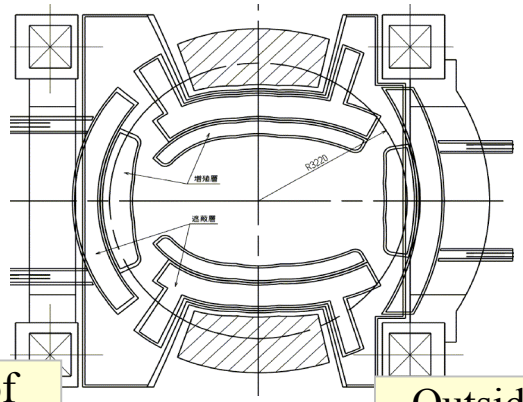
→ Side surfaces are divided into triangles (blanket and coil surfaces)



Making of geometry data for MCNP code

Cross-section of FFHR2 blanket (modified)

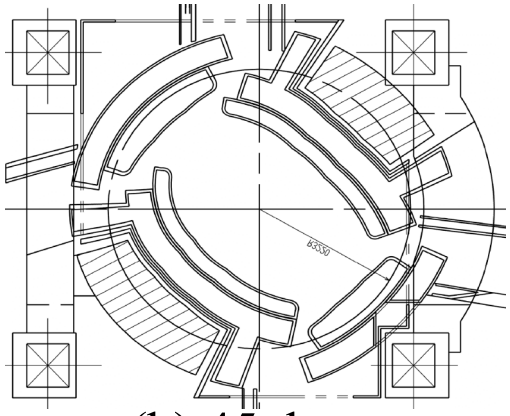




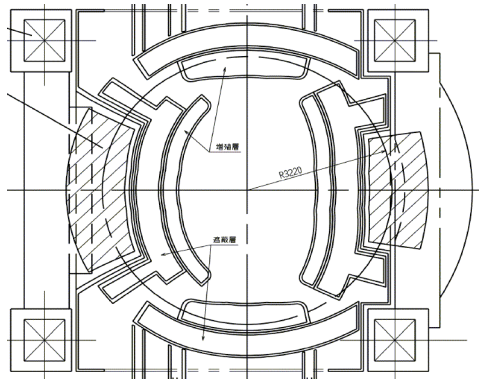
Inside of torus

Outside

(a) 0 deg.

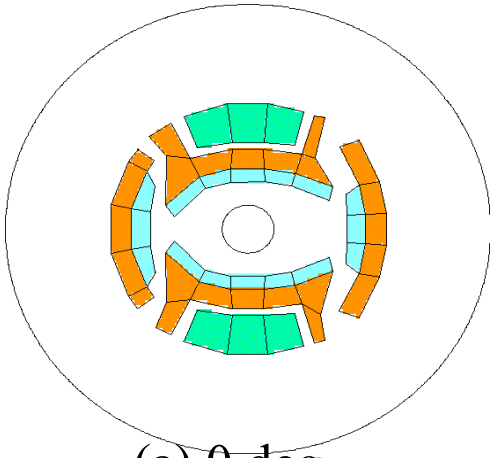


(b) 45 deg.

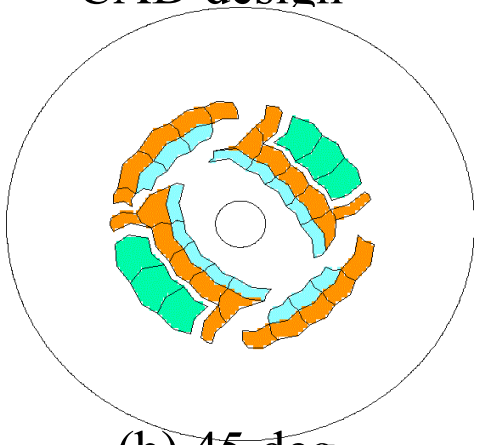


(c) 90 deg.

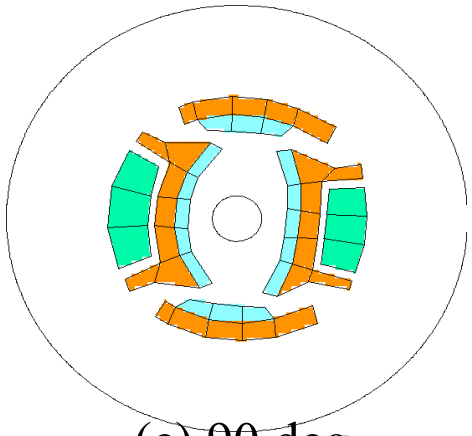
CAD design



(a) 0 deg.



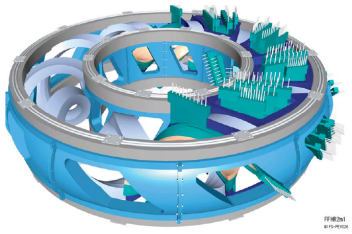
(b) 45 deg.



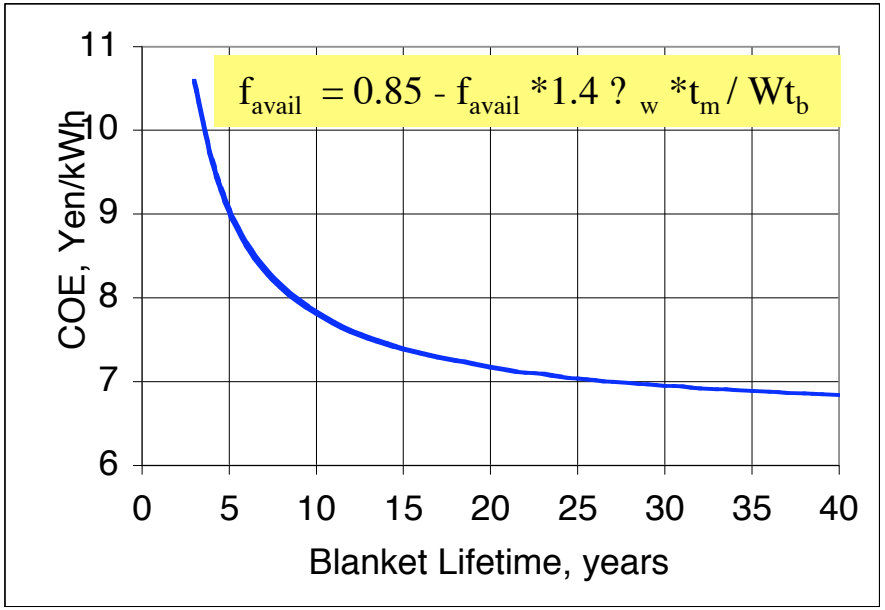
(c) 90 deg.

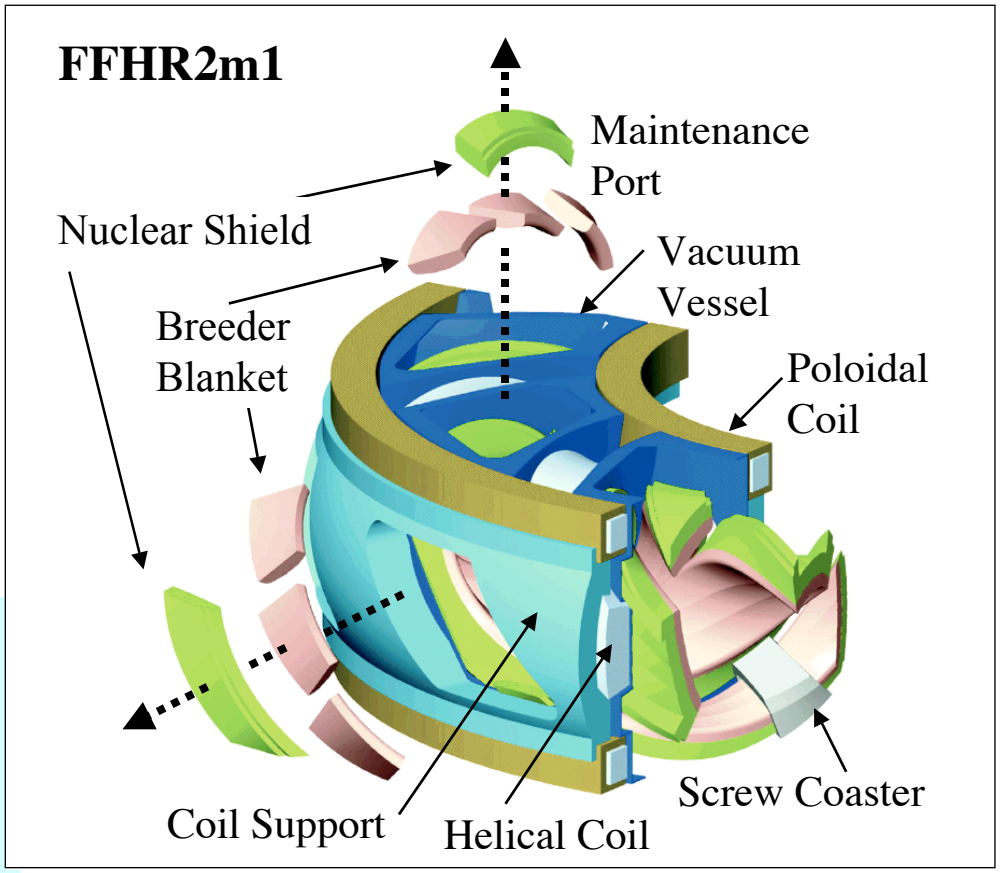
Input data for neutronics calculation

(3) Replacement scenario



- **Long-life for 30years, then the COE reduced 30%**

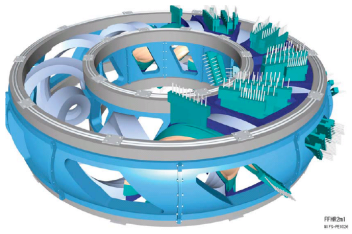


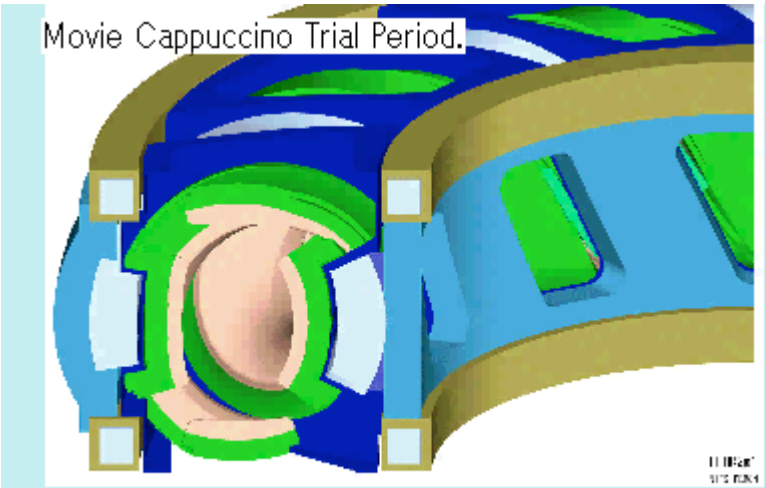


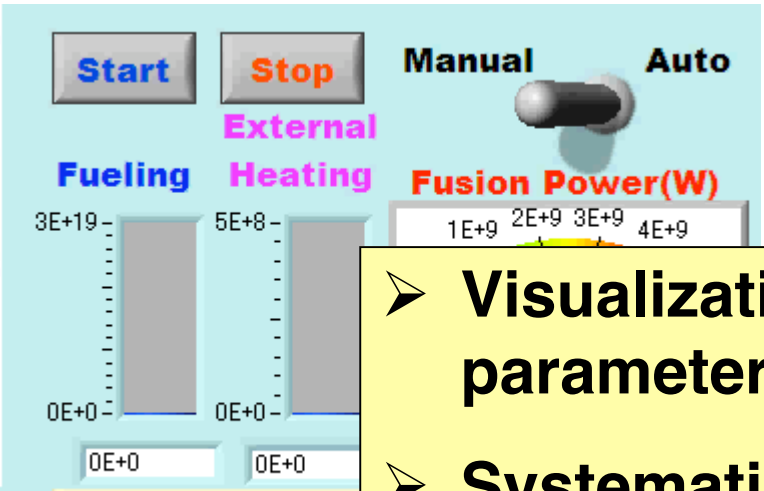
- **Only STB tiles are replaced with "screw coasters"**
- **<u>If needed,</u> breeder units are replaced through large maintenance ports**

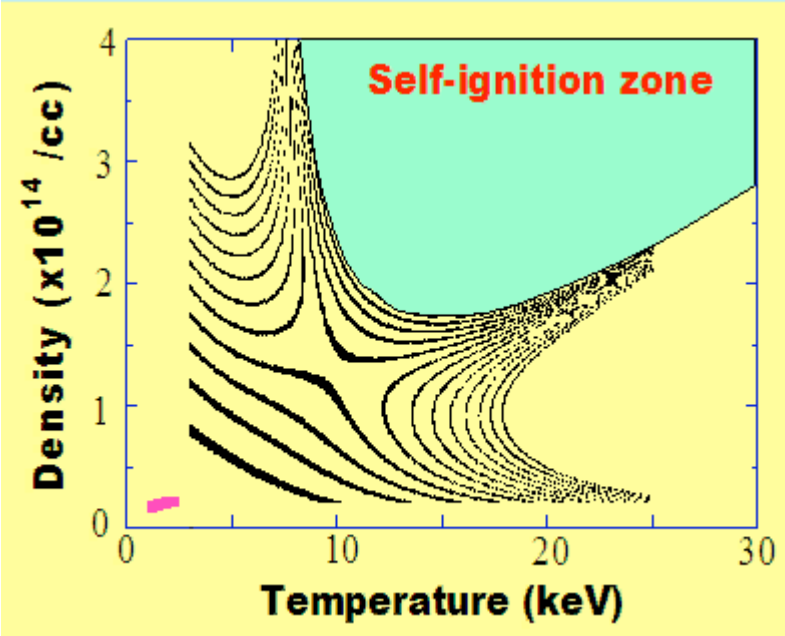
Design methodology

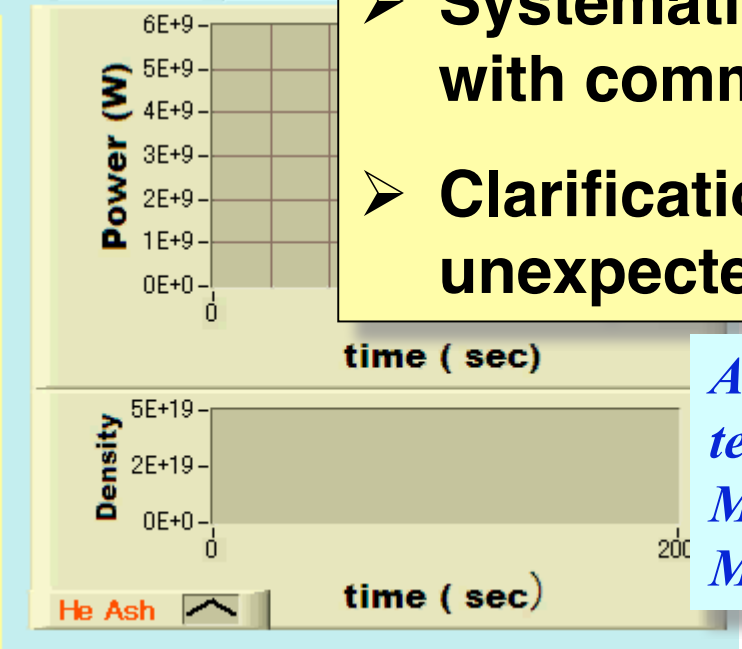
(1) PC simulator of power plant operations









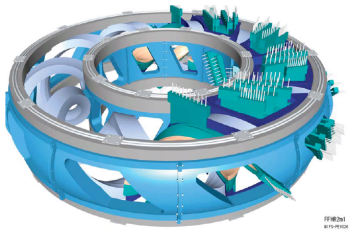


- Visualization of parameter sensitivities
- Systematic designing with common images
- Clarification of unexpected behaviors

Acknowledge to technical supports by Mr.T.Inoue and Mr.H.Ogawa.

Design methodology

(2) Virtual reality for 3D design assisting



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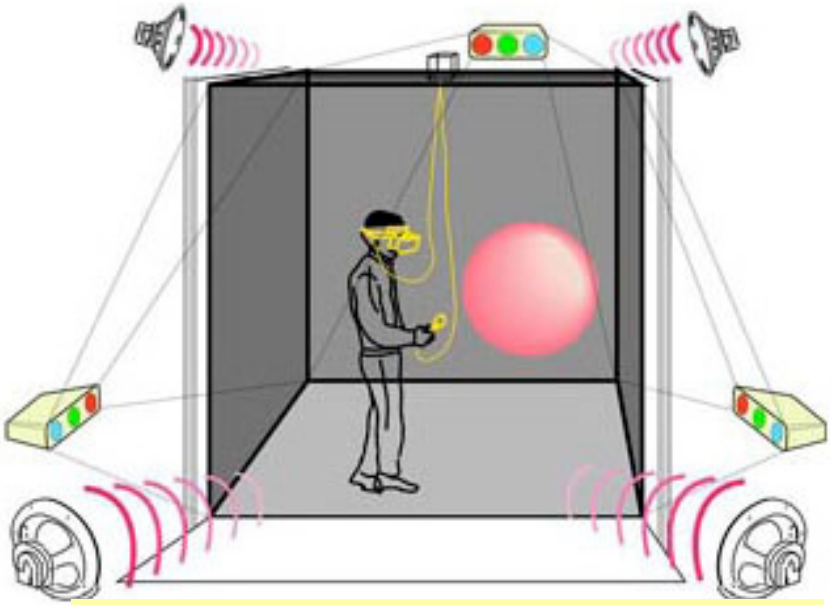
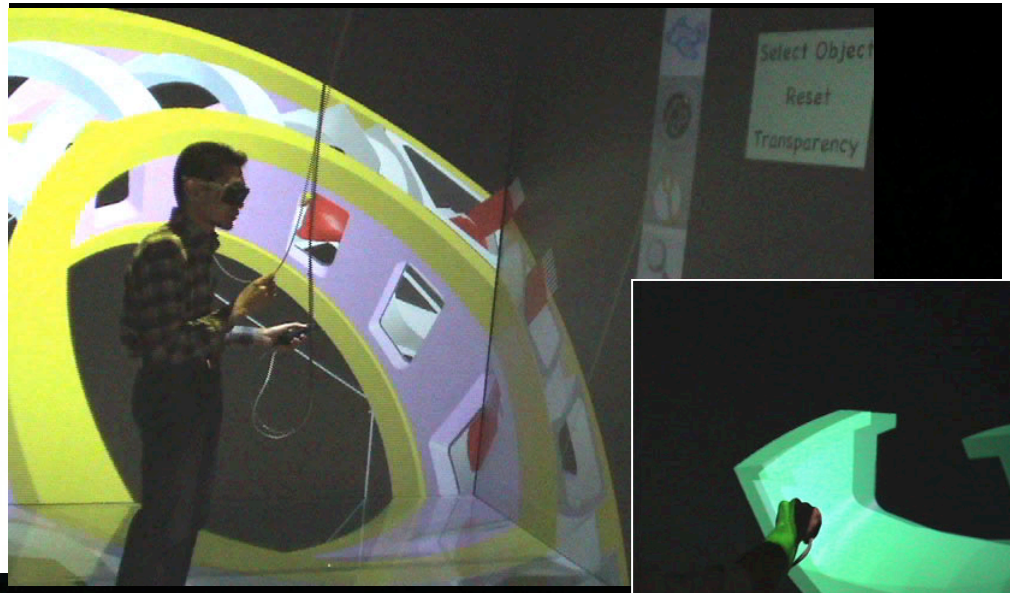
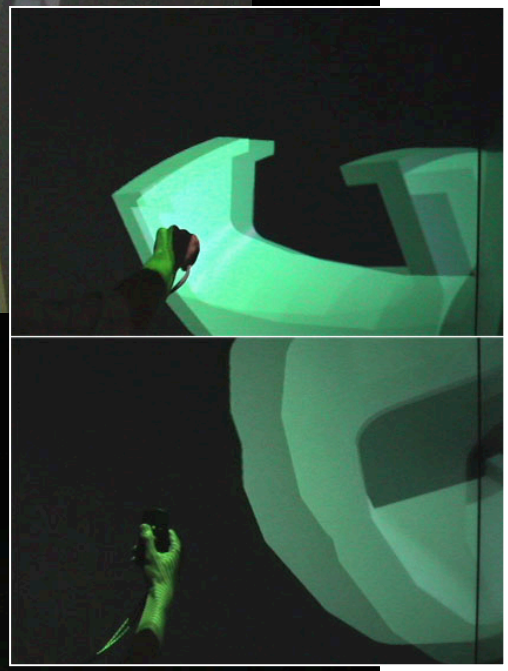


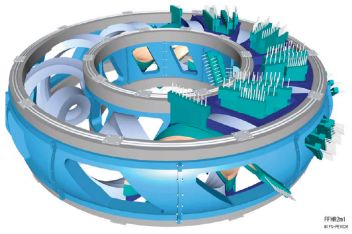




" CompleXcope"
- an integrated VR system -

- 4 wall screens
- stereo shutter glasses
- Wanda / tracker
- graphic workstation
- 3D-stereo sound system

The "fork" tool
- an intuitive interface for manipulation of VR object -



Summary

1. Design-based system optimization has been studied on LHD-type reactor FFHR, under the collaboration activities on wide research areas in the Fusion Research Network in Japan.

2. There have been much progress on Reactor size optimization, New proposal of long-life blanket, and Replacement scenario with making clear key physics / engineering issues and new research targets.

3. Design methodology has been newly proposed on PC simulator of power plant operations and Virtual Reality for 3D design assisting.