US-Japan WS, UCSD
Feb.23-24, 2010

Progress in Engineering Design of the SlimCS DEMO Reactor

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JAEA

Background of SlimCS

2000 | 2003 | FY2010

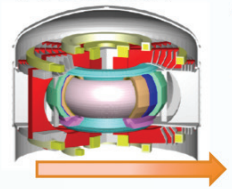
JAERI | **JAEA** | **JAEA**

Various concept study

Compact & low-A DEMO concept

BA DEMO-oriented
- Tech. requirements
- Eng. opt. Assess
- Design tools

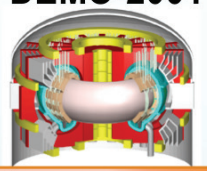
A-SSTR2



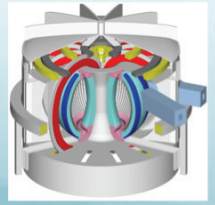
High field (23T)
→ CS-free tokamak

DEMO with SCW cooling
→ BLK concept

DEMO-2001



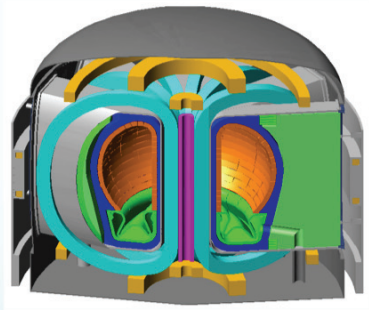
VECTOR



Supercond. low-A
→ Low-A, compact

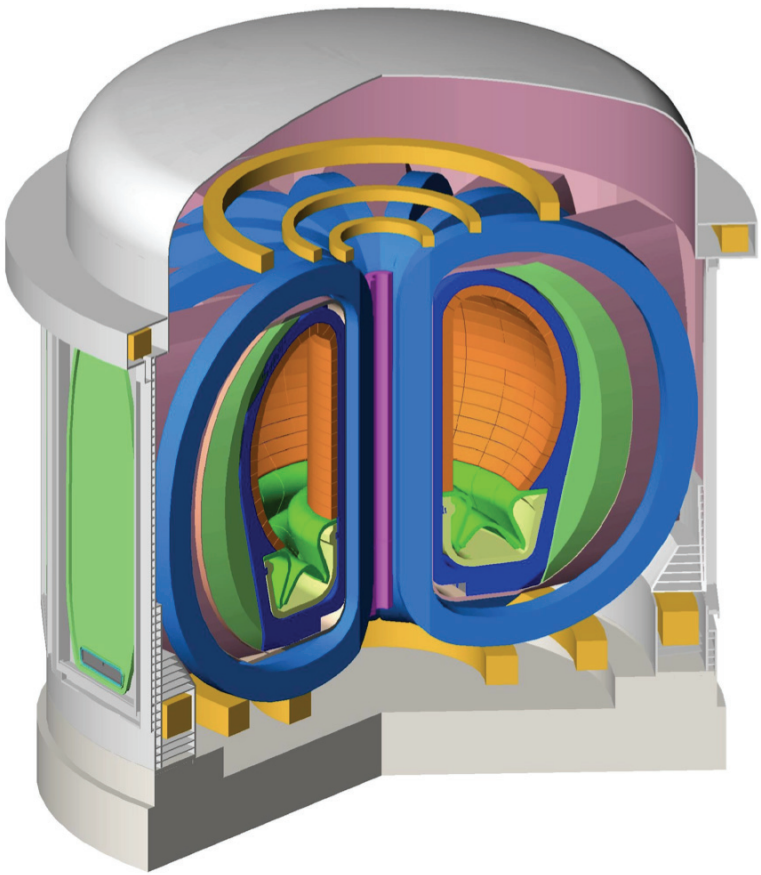
Lessons about CS and low-A

SlimCS



Final design rep

DEMO conceptual design, “SlimCS”



Major radius, R_p	5.5 m
Minor radius, a	2.1 m
Aspect ratio, A	2.6
Plasma current, I_p	16.7 MA
Toroidal field, B_T	6.0 T
Maximum field, B_{max}	16.4 T
Elongation, κ_{95}	2.0
Safety factor, q_{95}	5.4
Normalized beta, β_N	4.3
Density, $\langle n_e \rangle$	1.15×10^{20} m^{-3}
Normalized density, n_e/n_{GW}	1.0
Confinement enhancement, HHy2	1.3
Bootstrap current fraction, f_{BS}	~0.75
Current drive power, P_{CD}	60-100 MW
Fusion output, P_{fus}	2,950 MW
Neutron wall load, P_n	~3 MW/m^2

Foci of design activity in FY2009

Physics design

1. ■ Current drive efficiency of ECCD
   ■ Divertor simulation → Asakura

Engineering design

2. ■ Blanket
   Water-cooled solid breeder
   Water-cooled liquid breeder → Utoh
3. ■ Torus configuration
4. ■ Maintenance

1. CD efficiency of ECCD

K. Hamamatsu

Why ECCD efficiency?

Advantages:

- Readiness of maintenance
- Controllability of j(r)

↕

Yet, CD efficiency of ECCD is very low!

Motivation of study:
To find efficient ECCD conditions for DEMO parameters?

$\langle T_e \rangle \sim 20$ keV

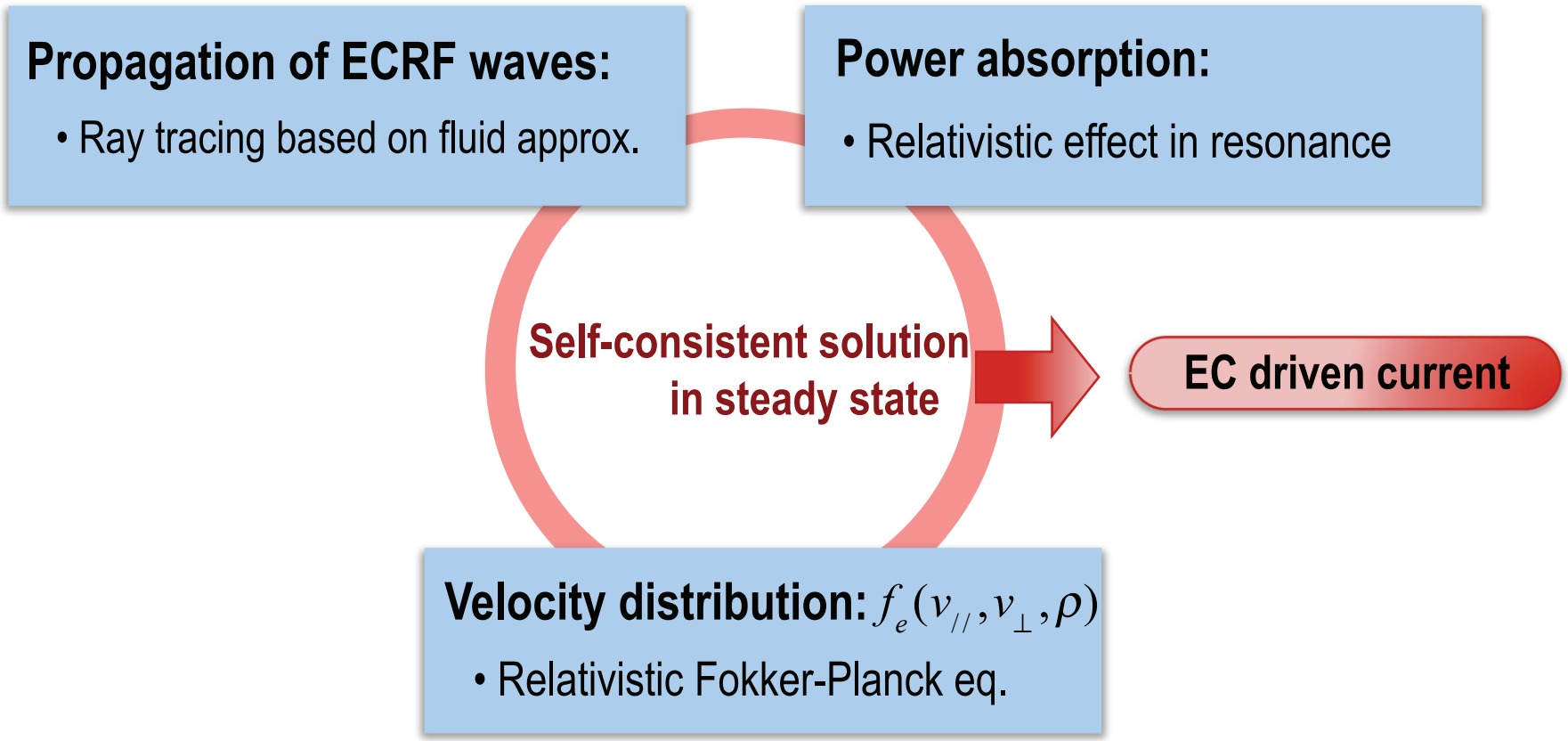
H&CD System	γ_{CD} $10^{20} AW^{-1}m^{-2}$	Deposition radius
NBCD	0.6 – 0.7	$\rho \geq 0$
LHCD	~ 0.3	$\rho > 0.8$
FWCD	0.3 – 0.4	$\rho \sim 0$
ECCD	~0.12	$\rho \geq 0$

Campbell et al. 21st IAEA Conf. (2006)

Problems of NBCD:

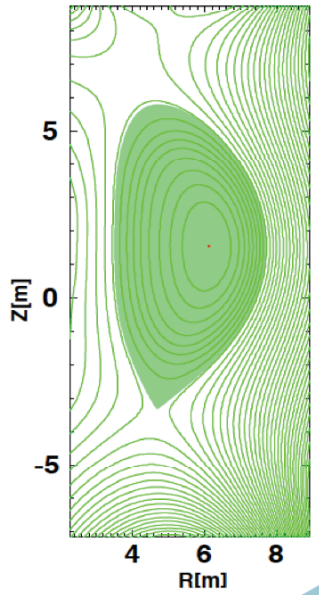
- Large ports (impact on maintenance and TBR)
- Central CD, difficult in DEMO
- Need to switch E_b to reduce shine-thru in I_p ramp phase (but low power $P_b \propto V^{5/2}$)
- Concern about AE modes for high E_b

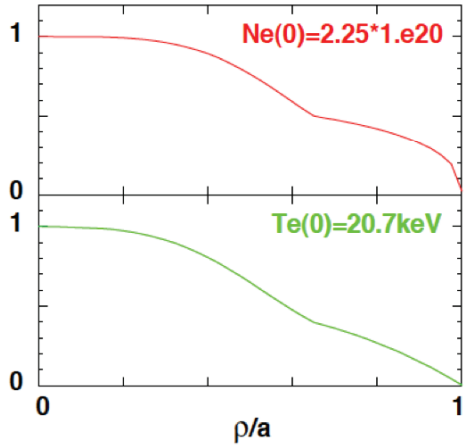
Analysis model



Conditions

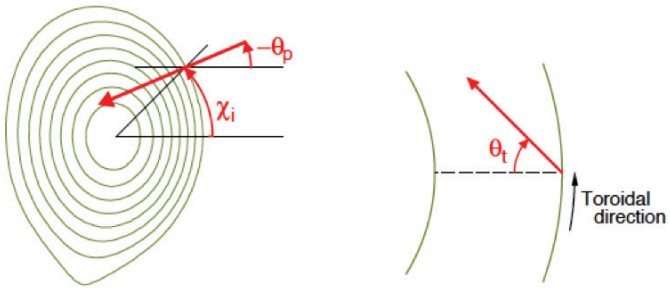
Reference profiles of SlimCS



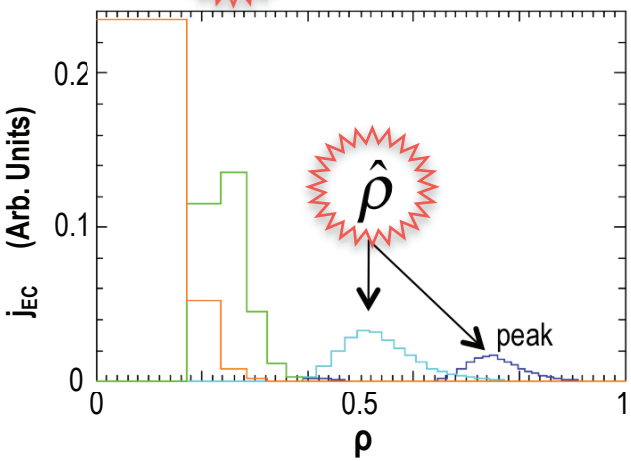


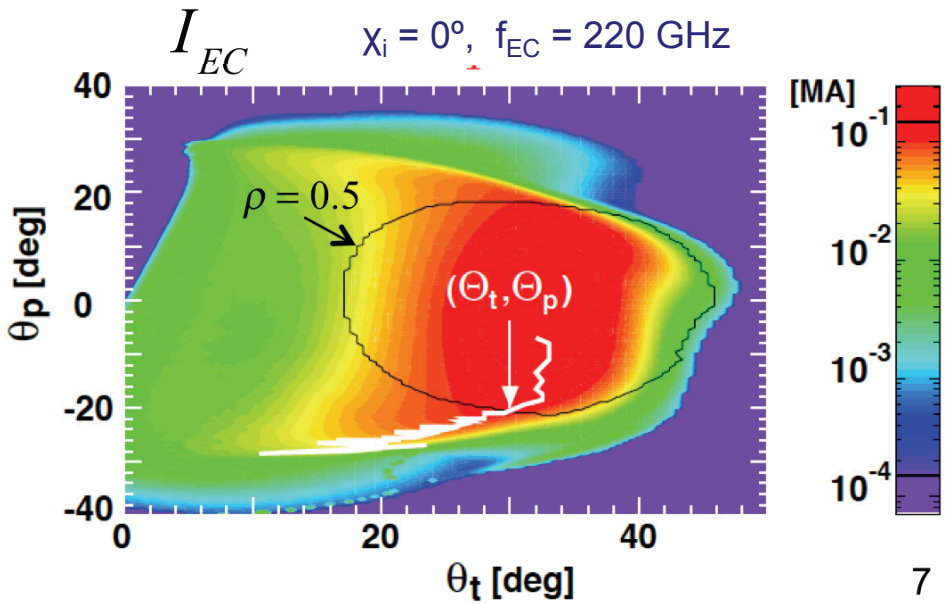
Injection position

- Change (χ_i, θ_t, θ_p) to find the optimal angles
- Change f_{EC} to find the maximum I_{EC}

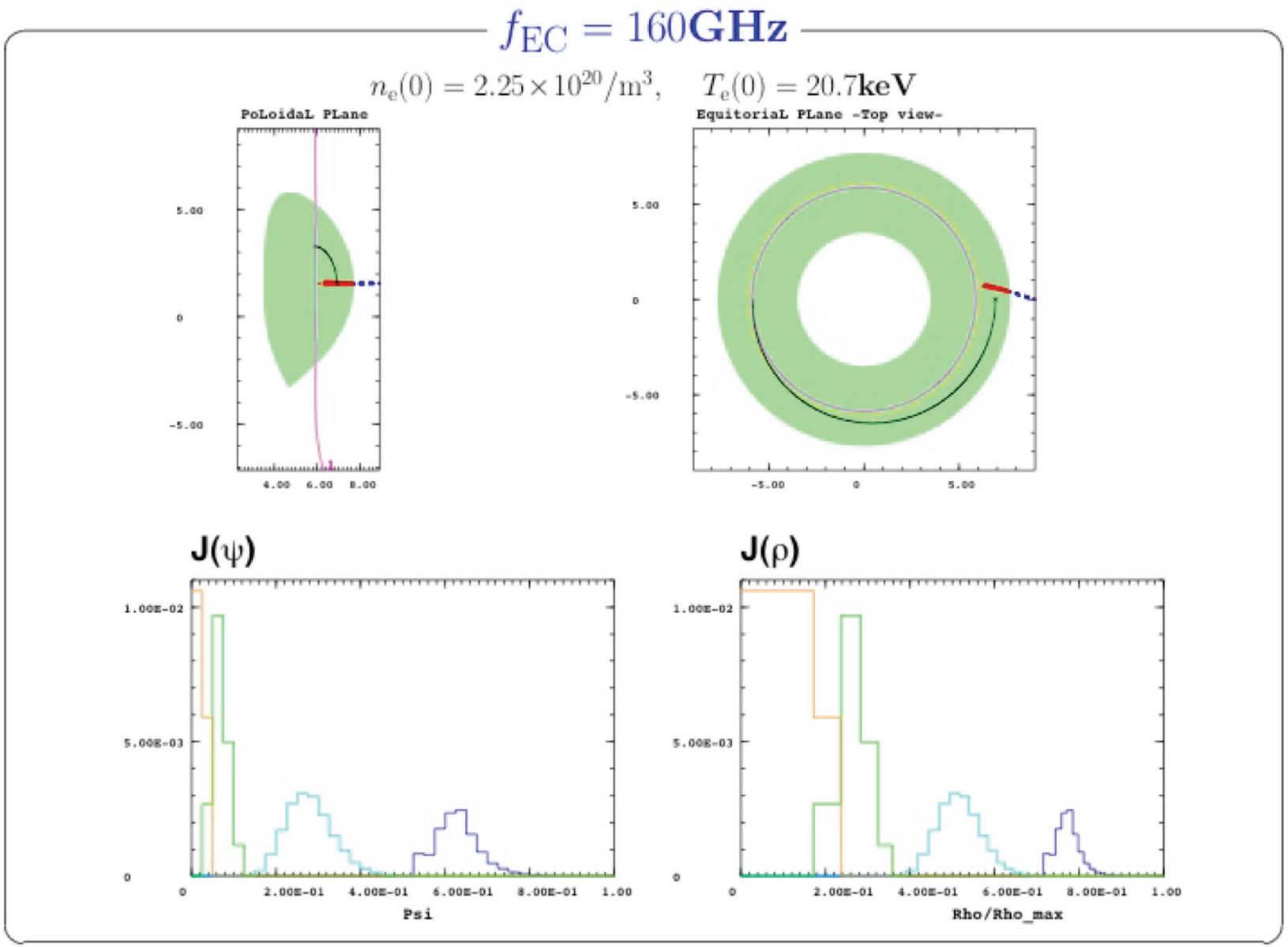


$$I_{EC} = 2\pi \int_0^1 \rho\, j_{EC}(\rho)\, d\rho$$



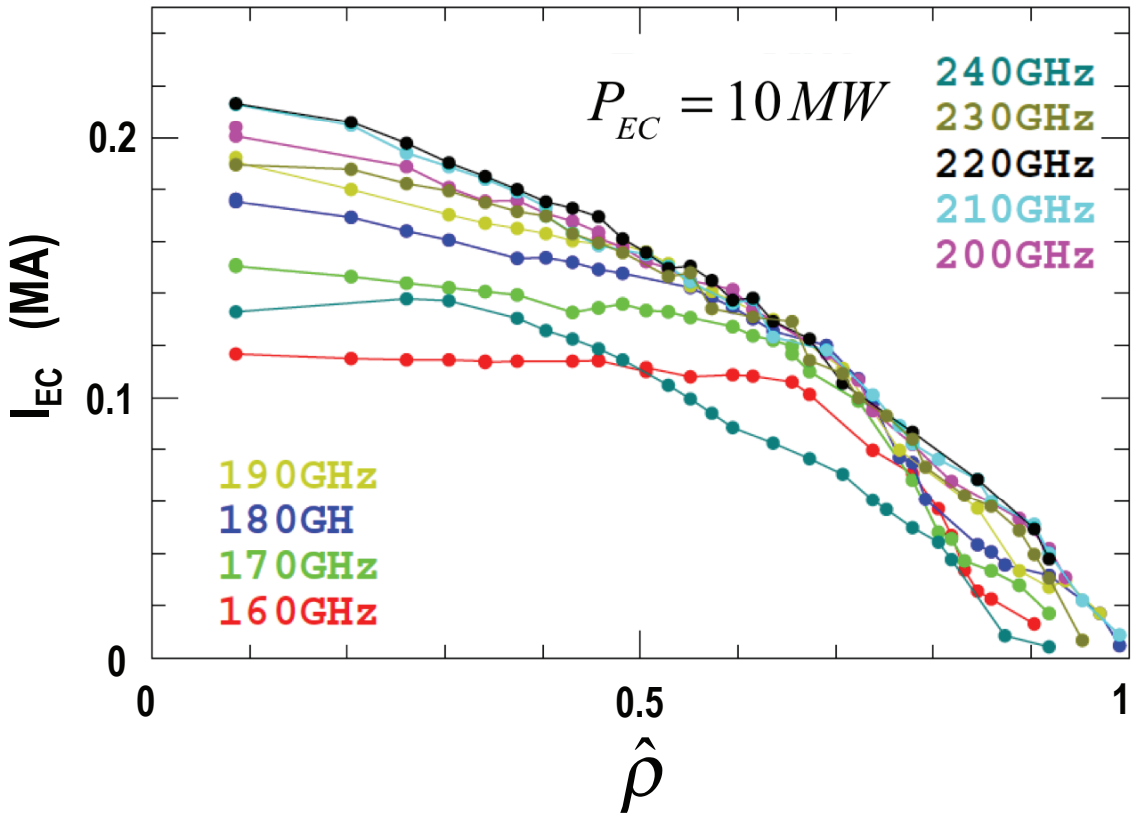


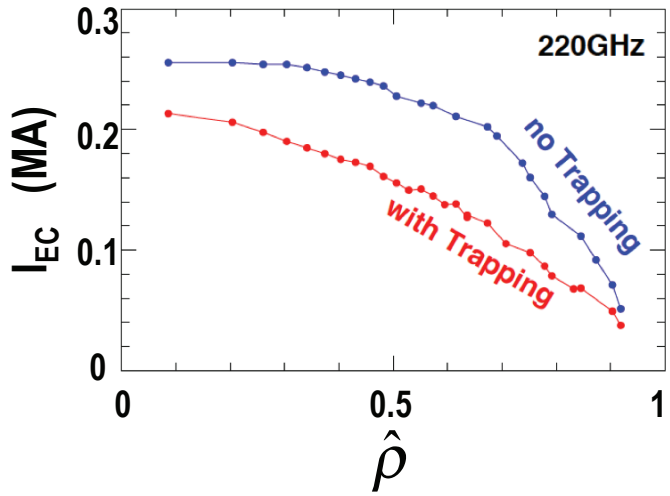
Result of f_{EC} scan (160-230 GHz)



Optimal frequency

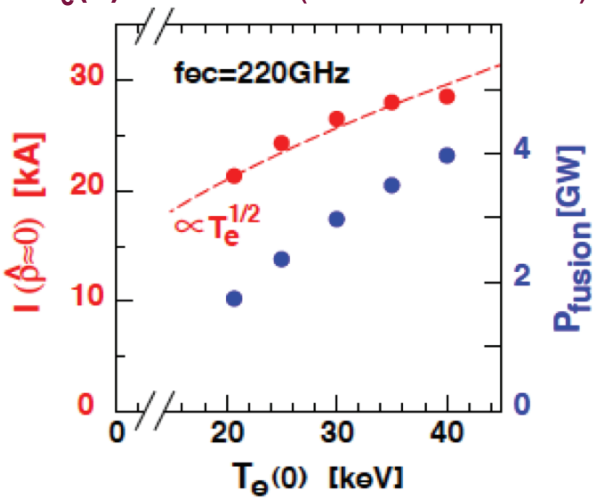
- The optimal frequency of ECCD for SlimCS, 210-220 GHz (f_{ce} = 170 GHz on axis)
- J profile control does not require f_{EC} change (single f_{EC} is OK!)



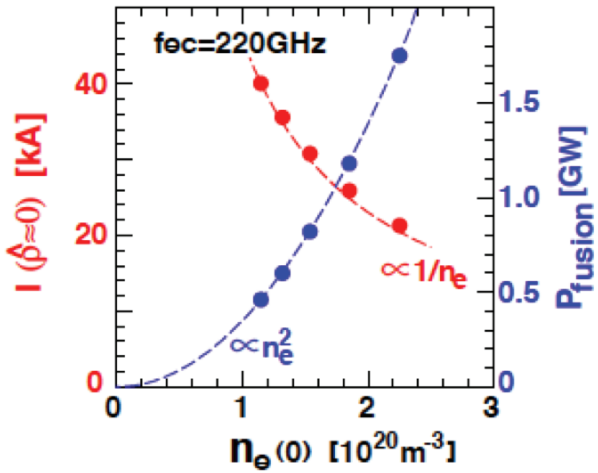


Parametric dependence of η_{CD}

$n_e(0)$ = const. (= 2.25×10^{20} m^{-3})



$T_e(0)$ = const. (= 20.7 keV)



- Parameter dependence of η_{CD} for ECCD

$$I_{EC} \propto T_e^{1/2} / n_e$$

$$\eta_{EC} = \frac{n_e R_p I_{EC}}{P_{EC}} \propto T_e^{1/2}$$

- η_{CD} is higher than a previous estimation, but still low compared with NBCD

Comparison of η_{CD}

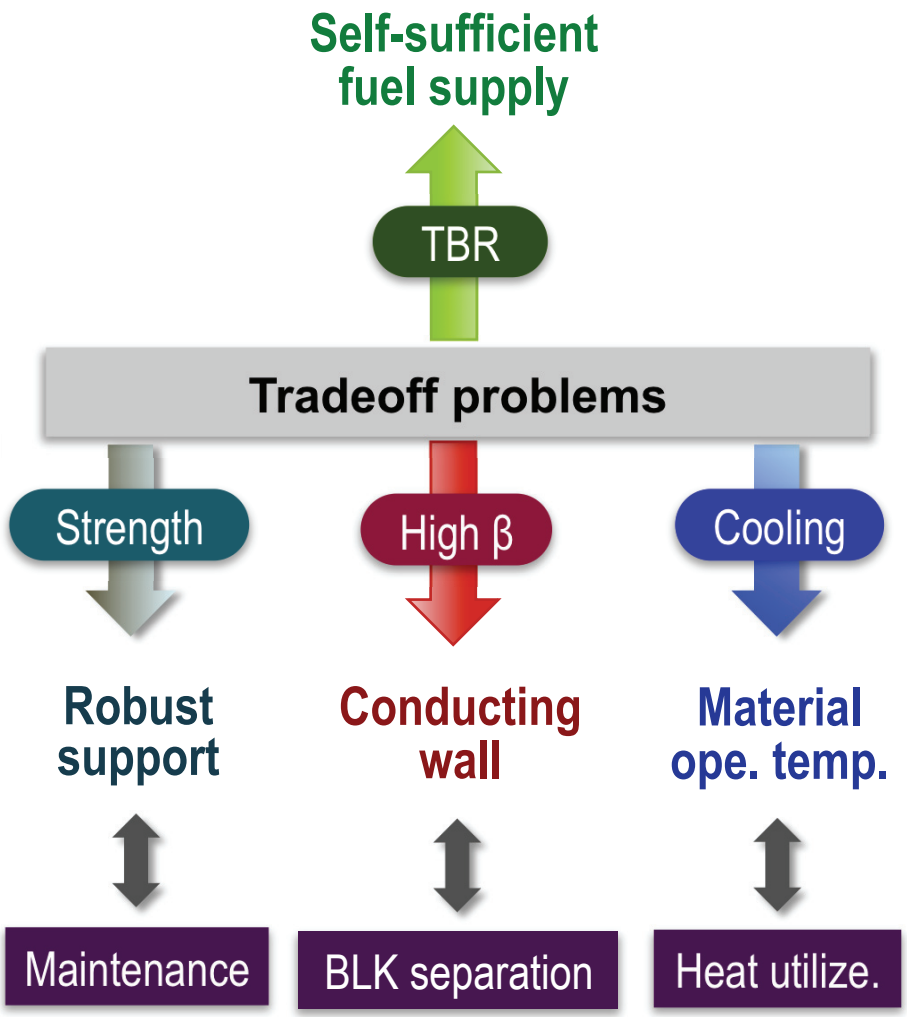
	This study <T_e> ~ 17 keV	Campbell <T_e> ~20 keV
ECCD	~0.2	~0.12
NBCD	~0.4	0.6-0.7

2. Blanket design

Requirements:

- Net TBR ≥ 1.05
- Withstand EM forces on disruption
- Allocate conducting shell

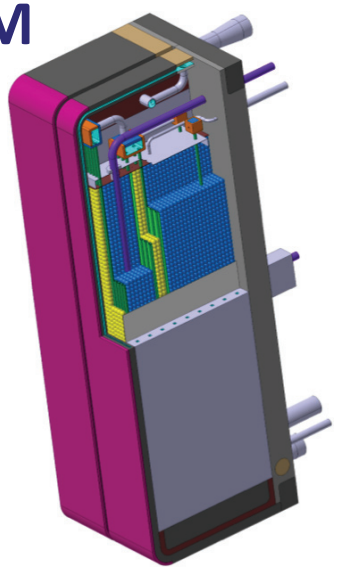
  Wall position: $r_W/a \leq 1.35$



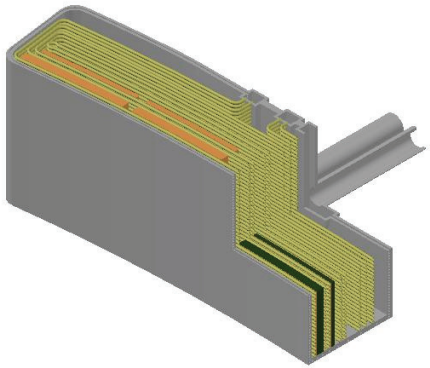
Continuity with ITER-TBM

ITER-TBM

JA concept



DEMO (SlimCS)



Structural material	RAFM (F82H)
Coolant	Water * 15 MPa, 280-325ºC
Neutron multiplier	Be or $Be_{12}Ti$
Tritium breeder	Li_2TiO_3 or other Li ceramics

RAFM (F82H)
Water ~23 MPa, 290-360ºC
Be or $Be_{12}Ti$
Li_2TiO_3 or other Li ceramics

* Another proposal:He gas -- 8 MPa, 300-500ºC

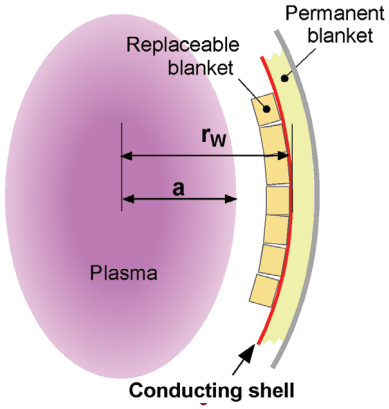
Blanket concept in view of torus configuration

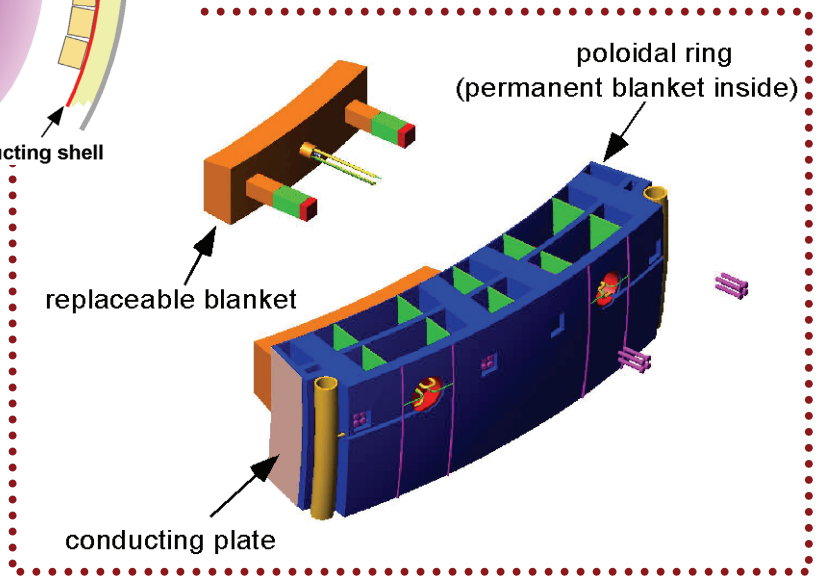
- Arrange conducting shell at $r_W/a \leq 1.35$
  - ✓Vertical stability
  - ✓High β

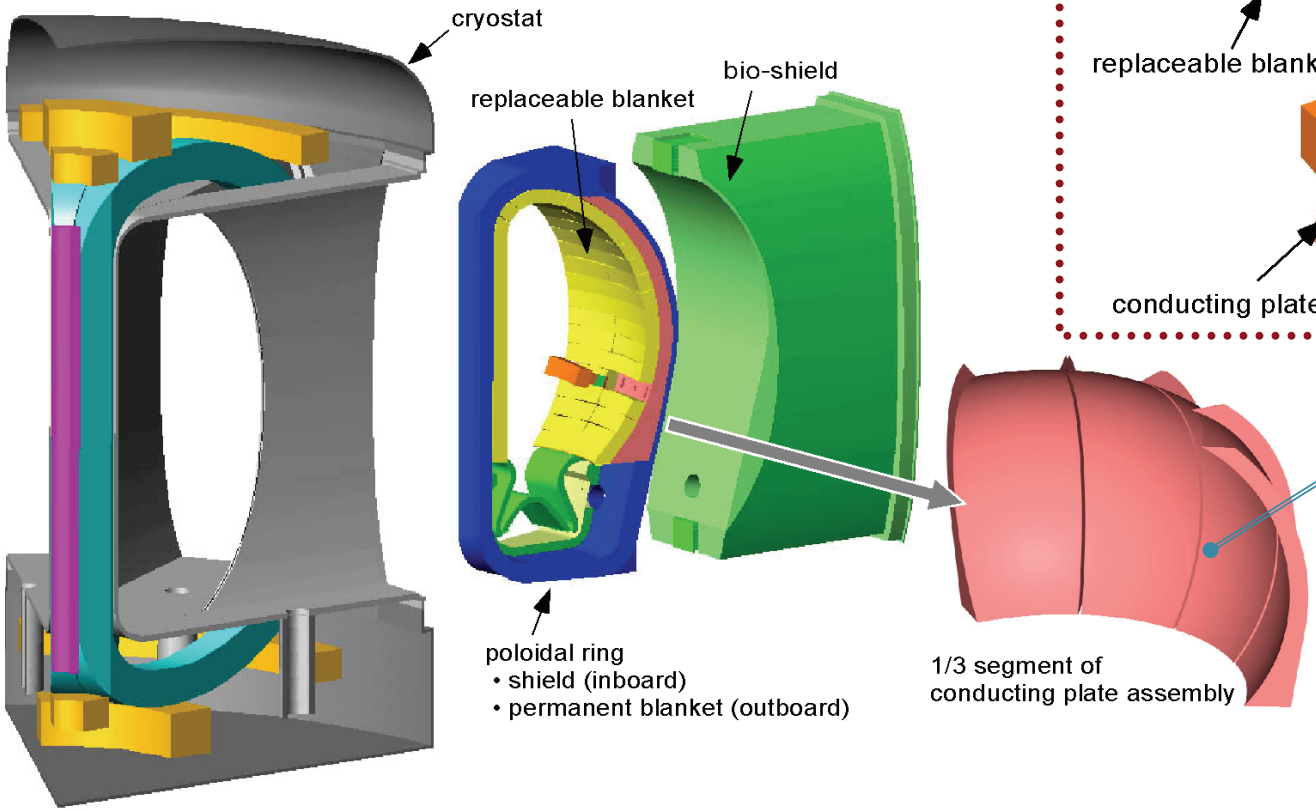
➡ Blanket separation

- Robust support & ease of maintenance

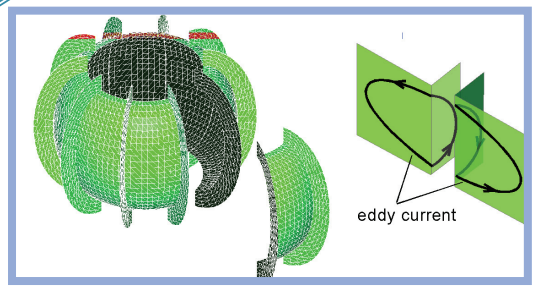
➡ Choose sector maintenance







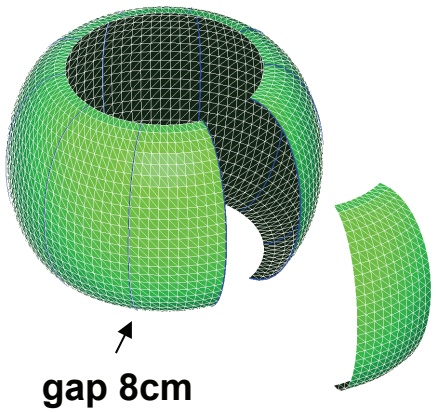
Conducting shell structure



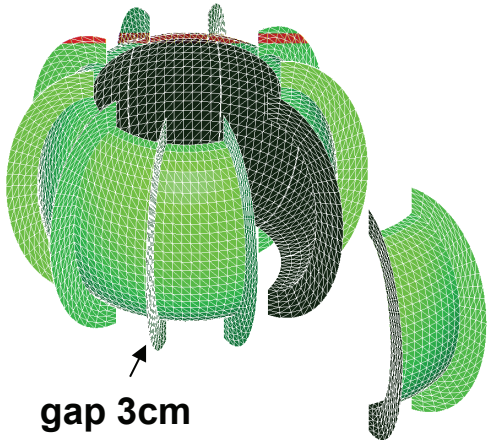
Impact of fins of conducting shell

Comparison of shell performance

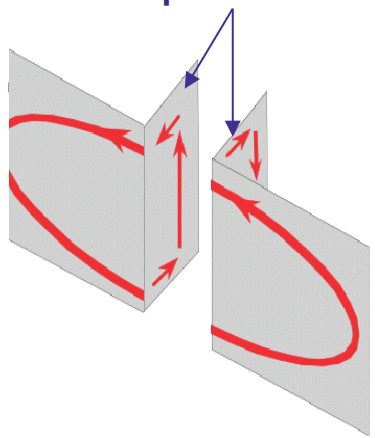
Simple cuts



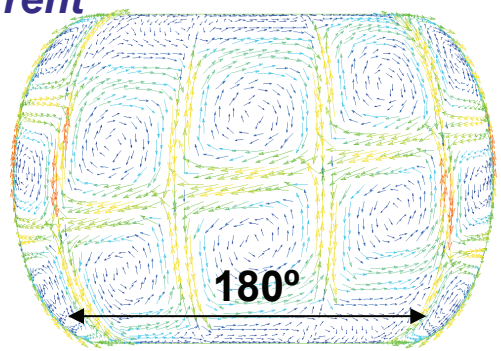
Shell with fins

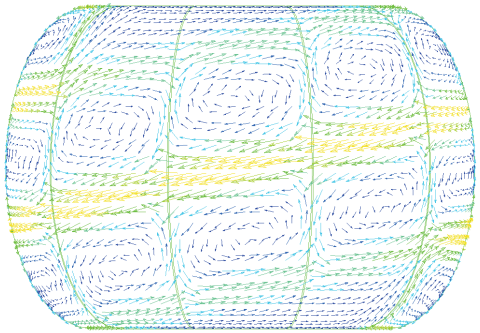


Harmful components cancelled

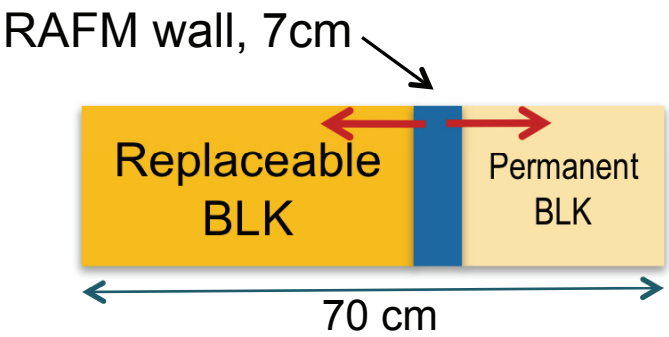


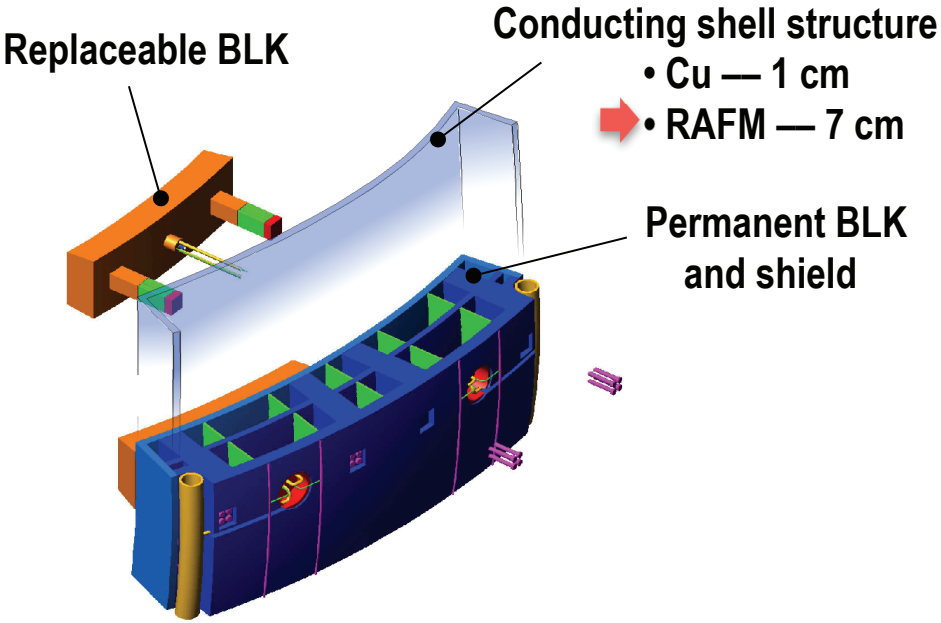
Eddy current on shell

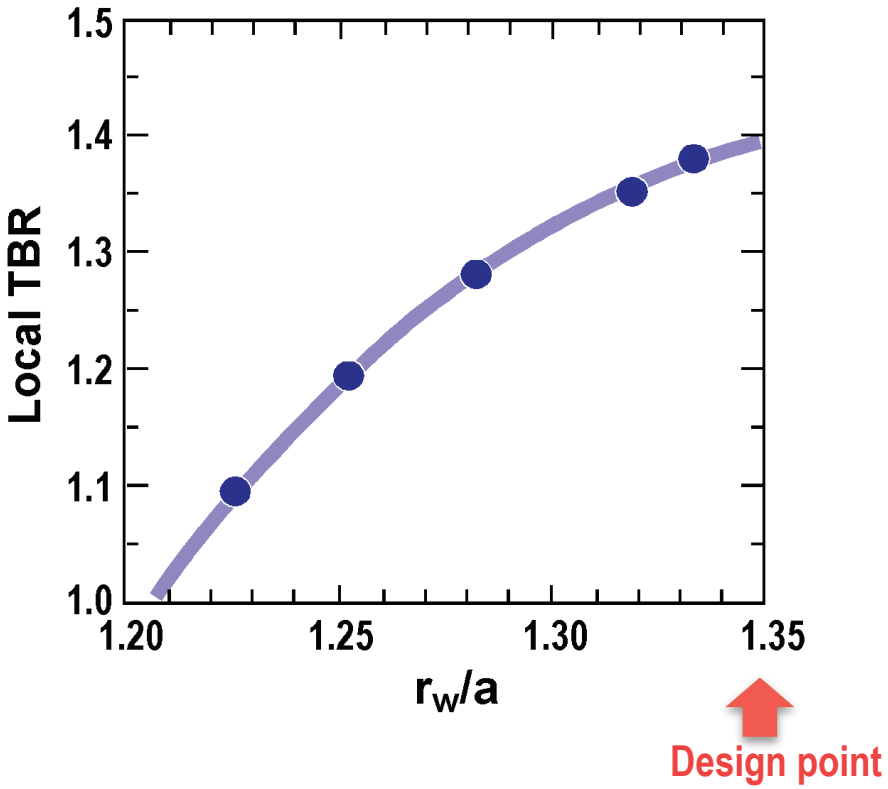


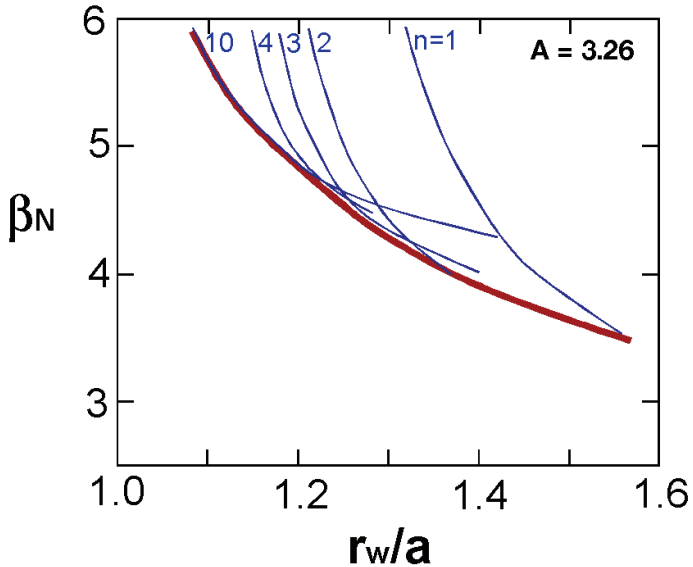


TBR versus r_w/a









Blanket interior design

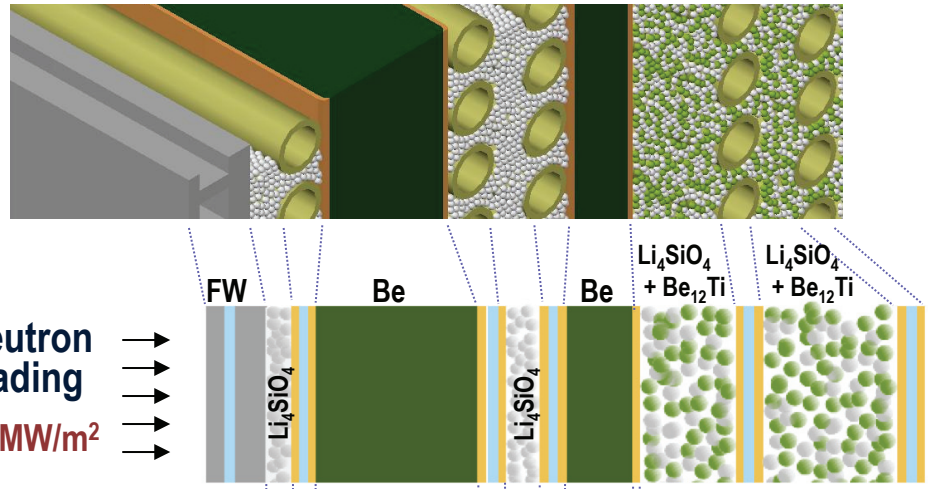
Interior Layout

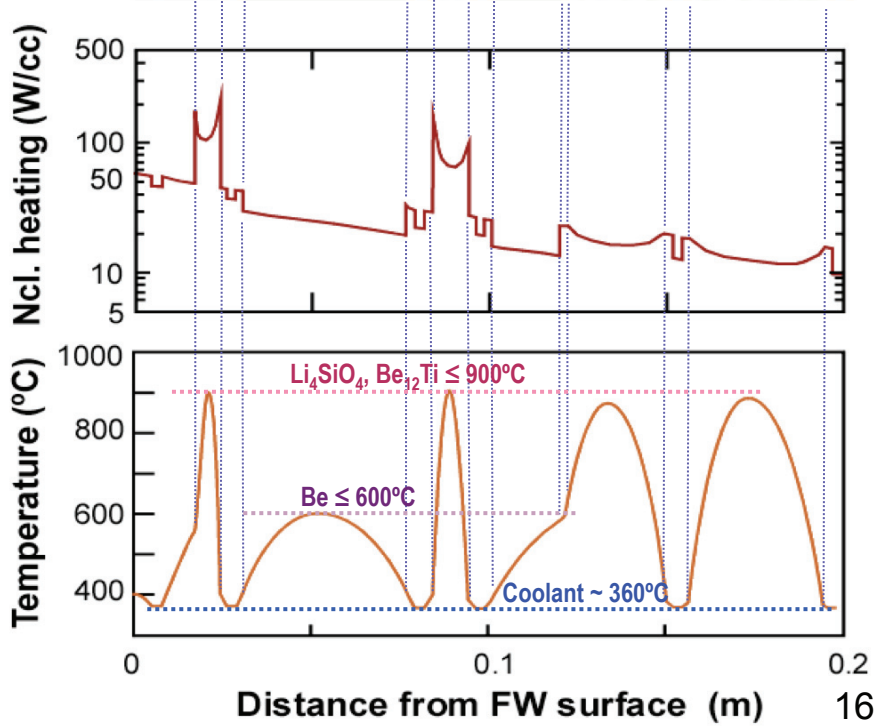
- Layered like ITER-TBM
- Material selections → design issue

How to optimize

- Evaluation function: TBR
- Conditions &constraints:
  - operating temp of materials
  - compatibility of materials

Peak P_n

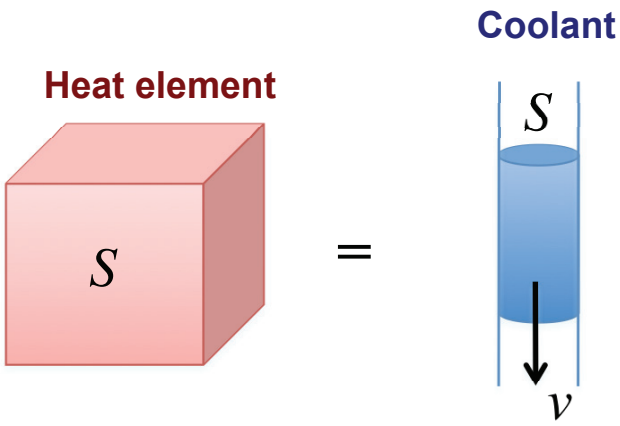




Materials considered

	Candidate	Note
Breeder	Li_2TiO_3 Li_4SiO_4 (Li_2O : chem. stability?)	^{6}Li- enrichment
n-multiplier	Be $Be_{12}Ti$	pebble / block
Coolant	water	Pressure, temp

Cooling water conditions



$$\int q dV = Sv \int_{\Delta T} \rho(T) C_p(T) dT$$

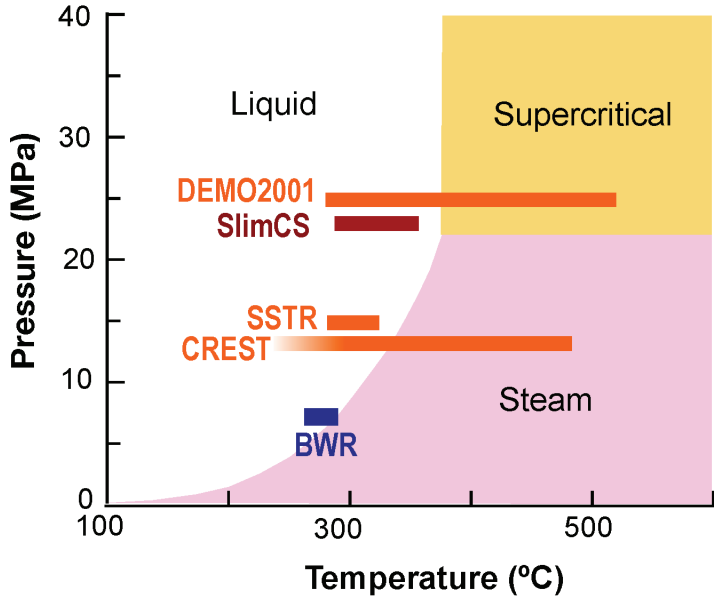
How to improve heat removal

How	Problem
S ↑	Decrease in TBR
v ↑	Enhance corrosions. Pressure drop
ΔT ↑	Compatibility with materials. Require R&D in heat engineering.

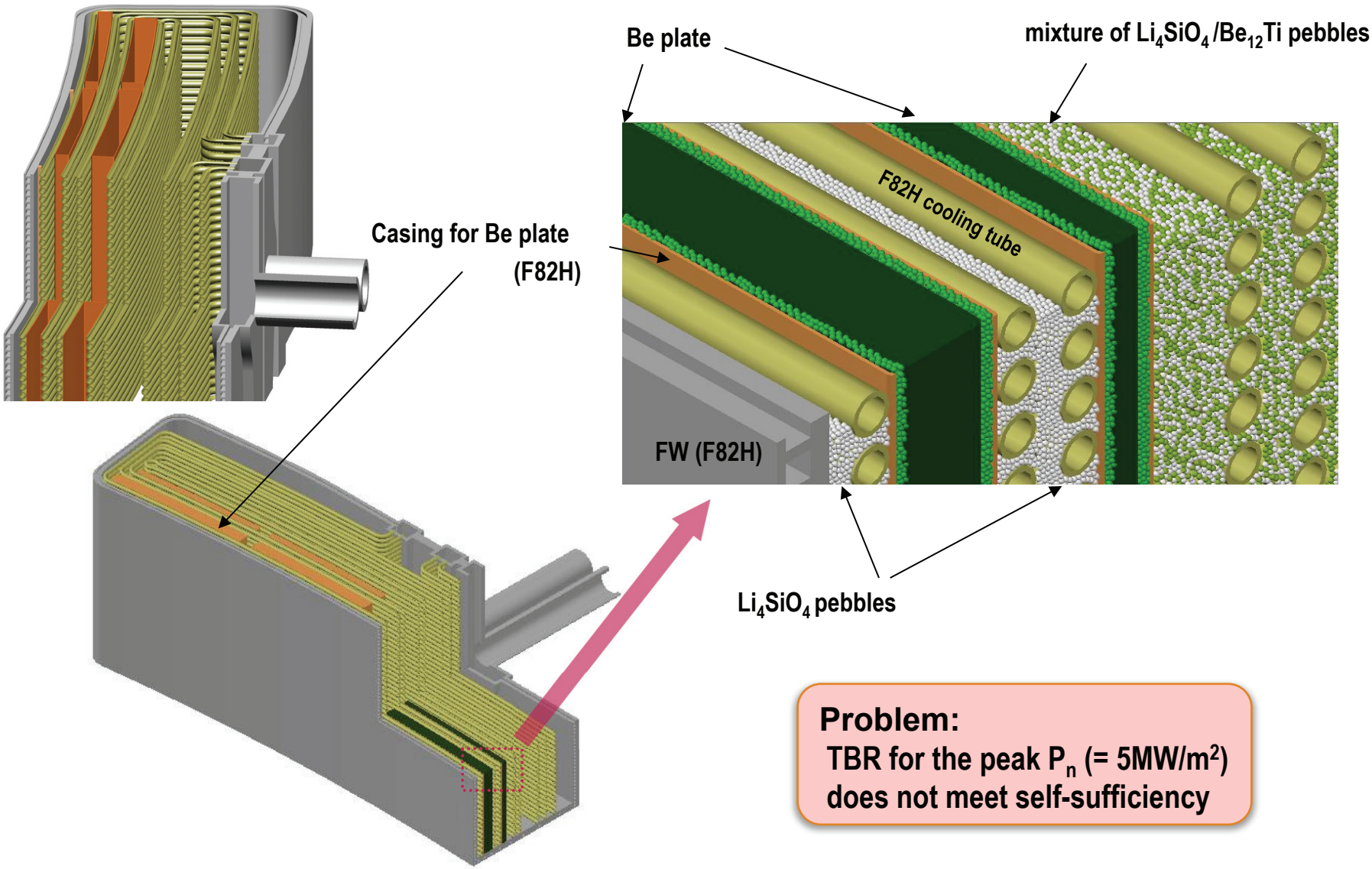
SlimCS:

23 MPa, 290-360ºC (ΔT = 70K)

Considering compatibility with
- **F82H**
- **TBR**
- **heat removal**

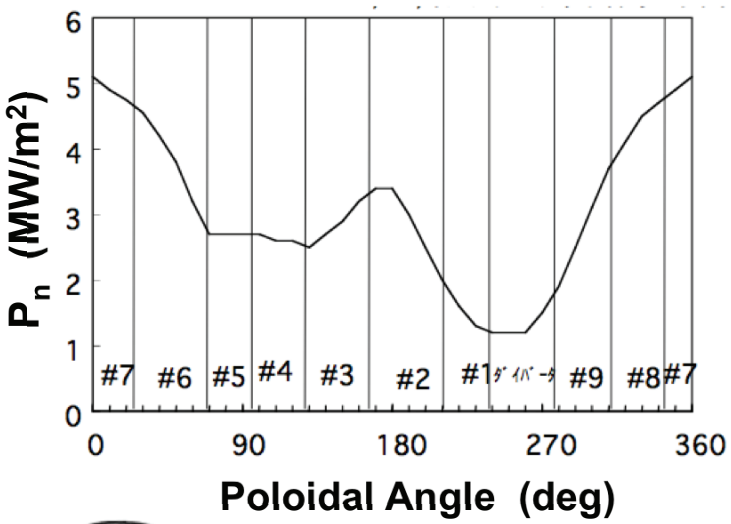


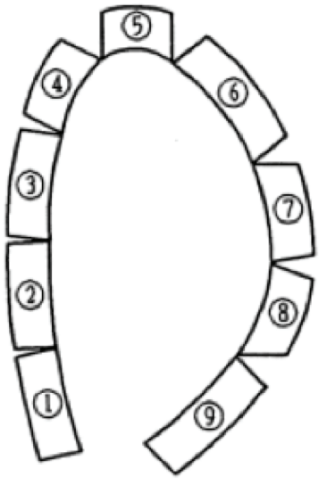
Latest interior design



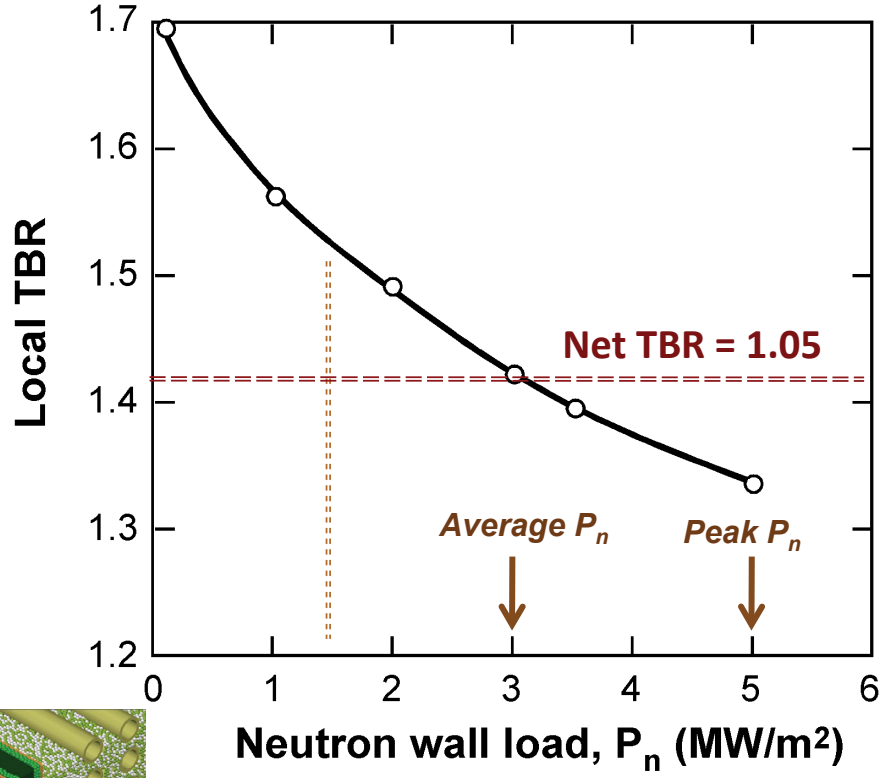
Problem:
TBR for the peak P_n (= 5MW/m^2) does not meet self-sufficiency

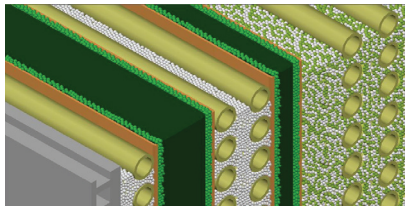
Impact of cooling channel optimization





Tritium self-sufficiency is marginally satisfied when cooling channel in BLK is optimized



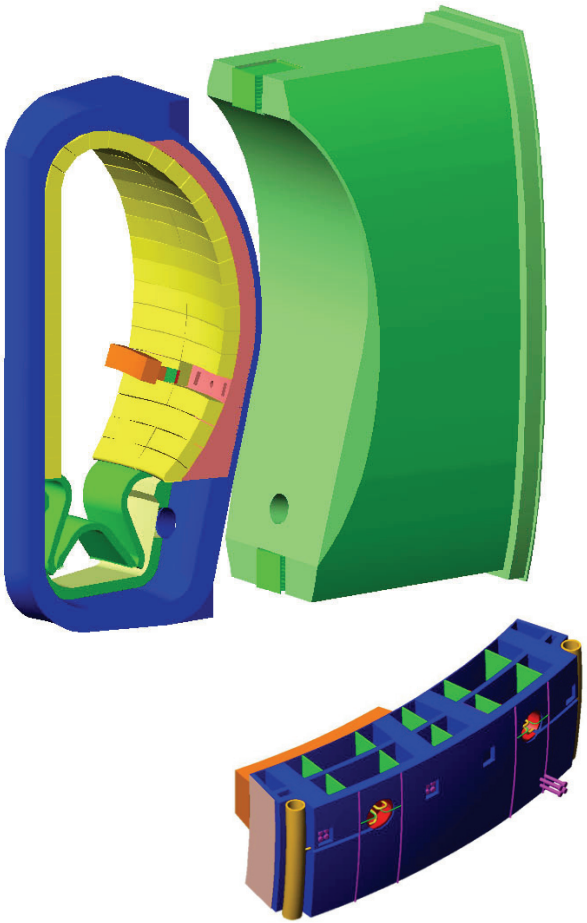


low P_n

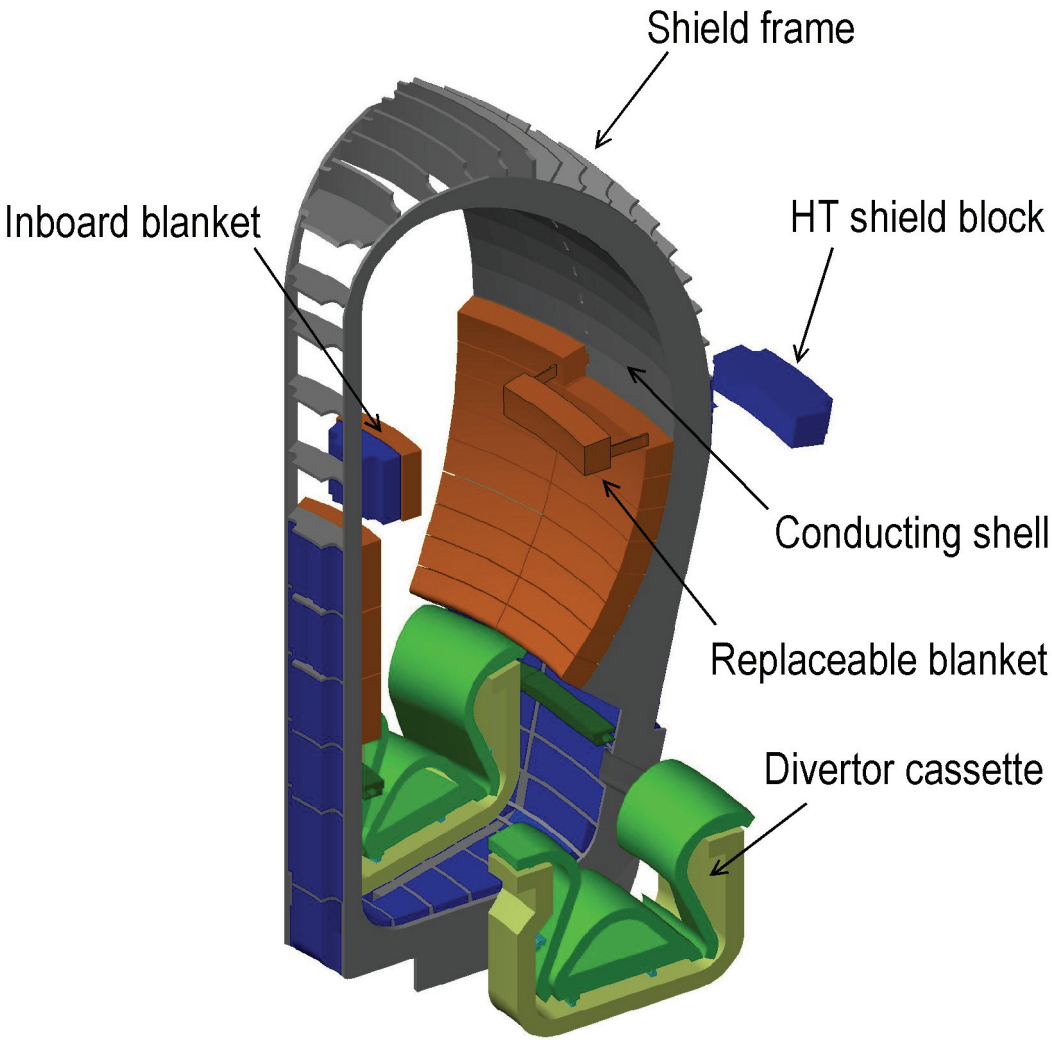
high P_n

For lower P_n, a wider distance between cooling channel layers

3. Torus configuration



Original design



Modified

High temperature shield

Requirements:

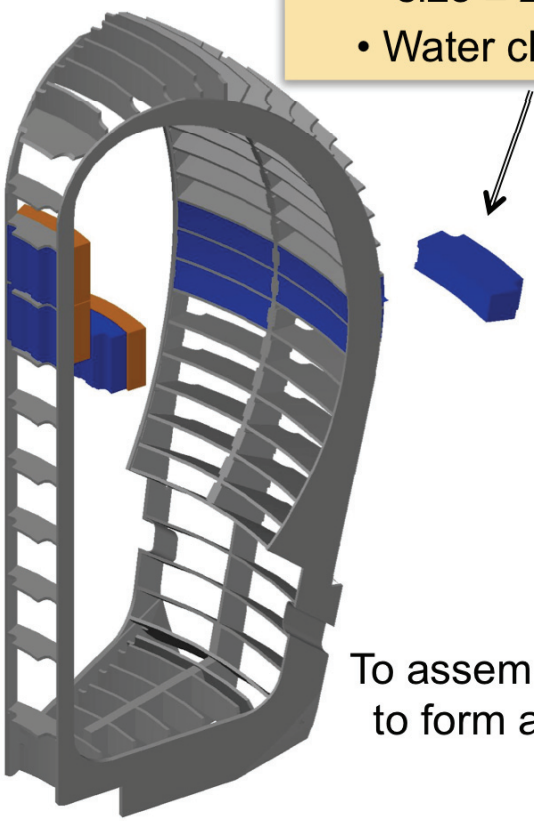
- RAFM : water = 0.7 : 0.3
- Water condition — 360ºC, 23 MPa

To use BLK outlet water for streamlined piping

Pressure-proof design for high-pressure water

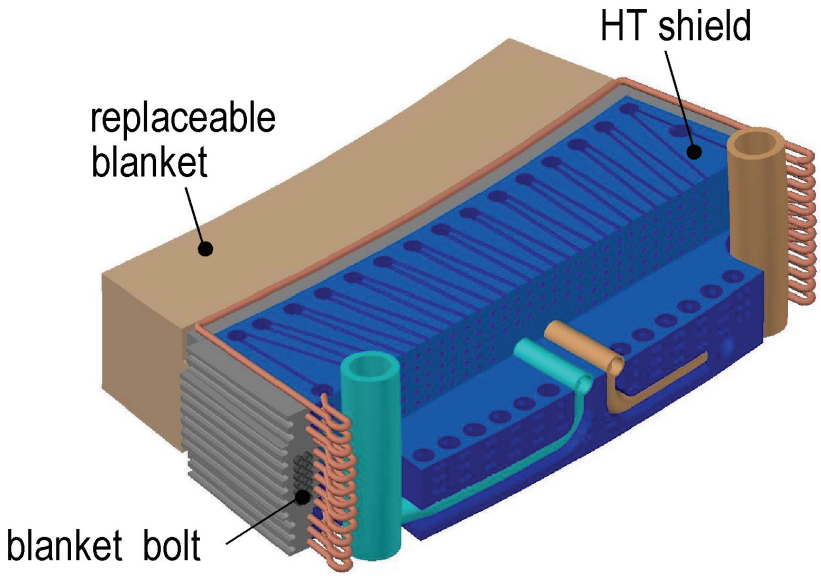
HT shield

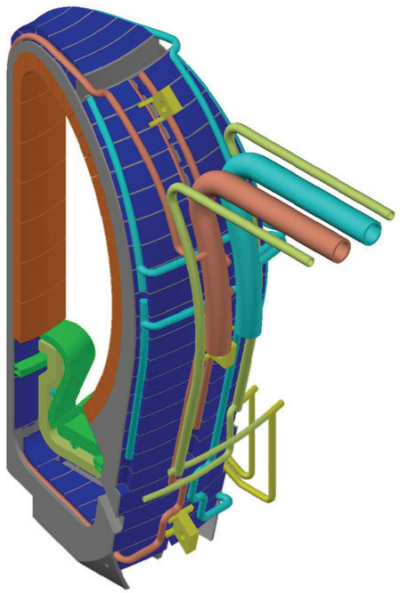
- Forged RAFM block, size ≤ 2 m for forging press
- Water channel by drilling

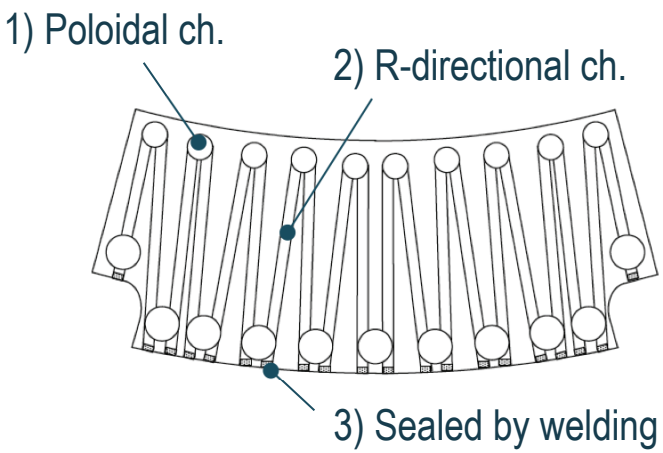


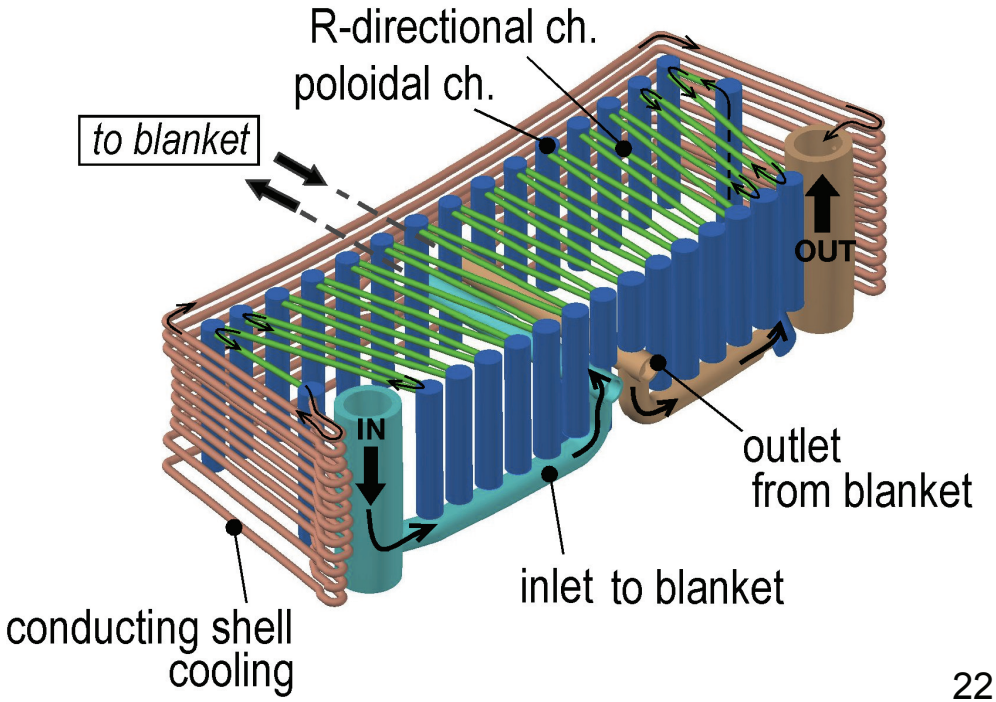
To assembly HT shield blocks to form a poloidal ring structure

Concept of HT shield





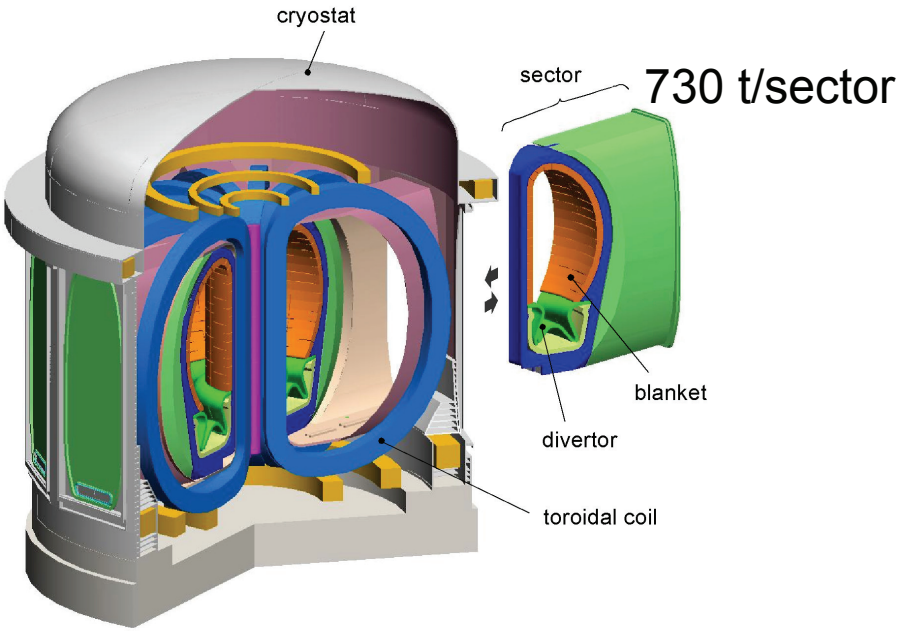




4. Maintenance scheme

Why “sector transport”?

- high plant availability
- flexibility to unexpected failures and events
- possibility of introducing advanced blanket



Main Design issues:

1) Transport of heavy sector

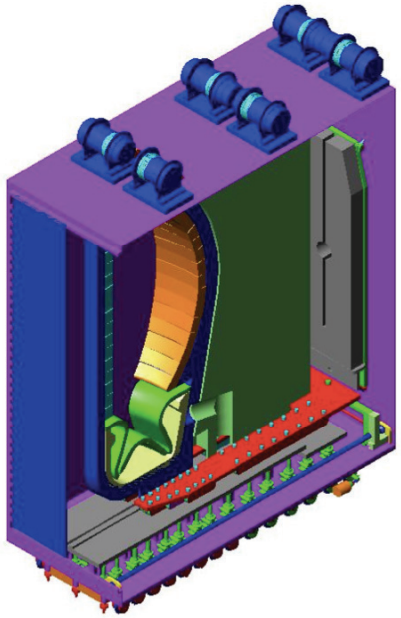
2) Support of TF turn-over force

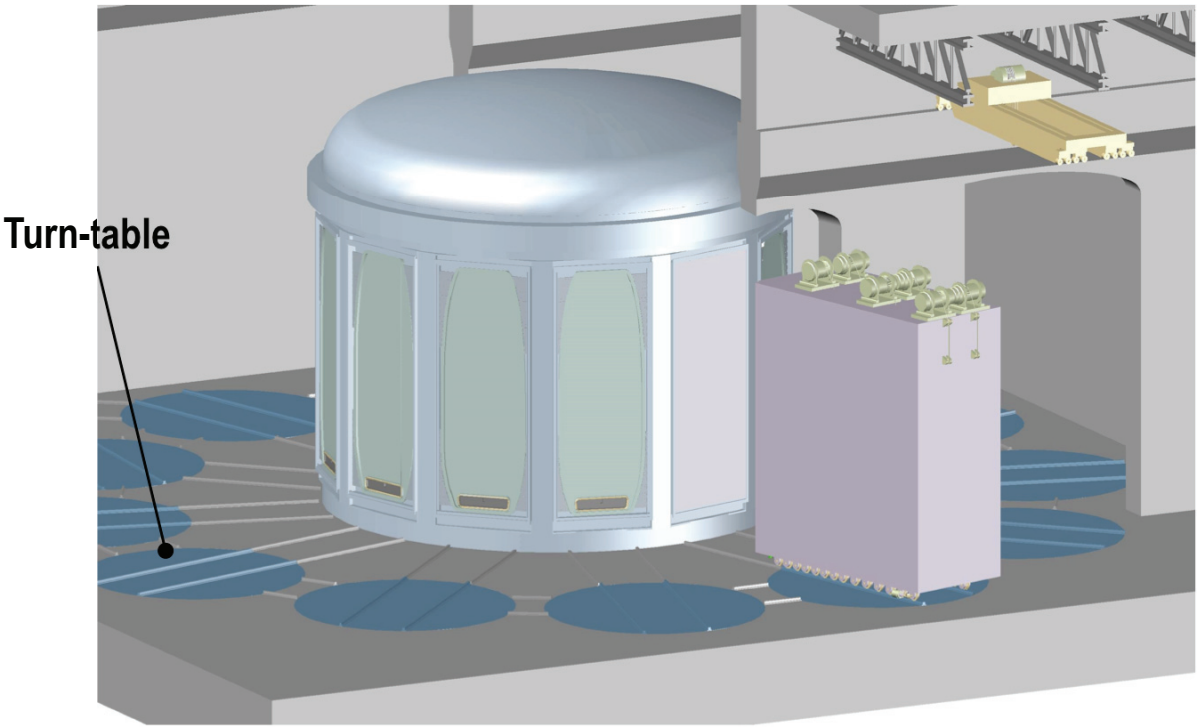
Original concept

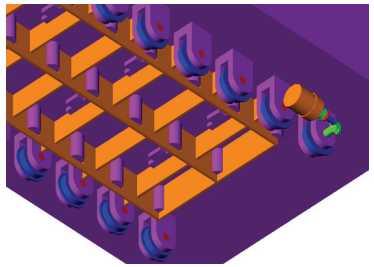
Transport

- Cask
- Turntable

Problem:
Difficult to load equally







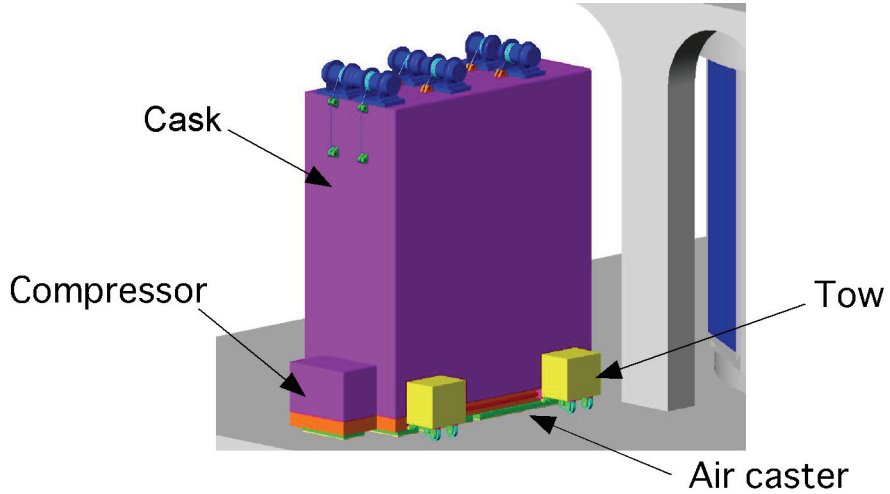
Wheel & roll bearing

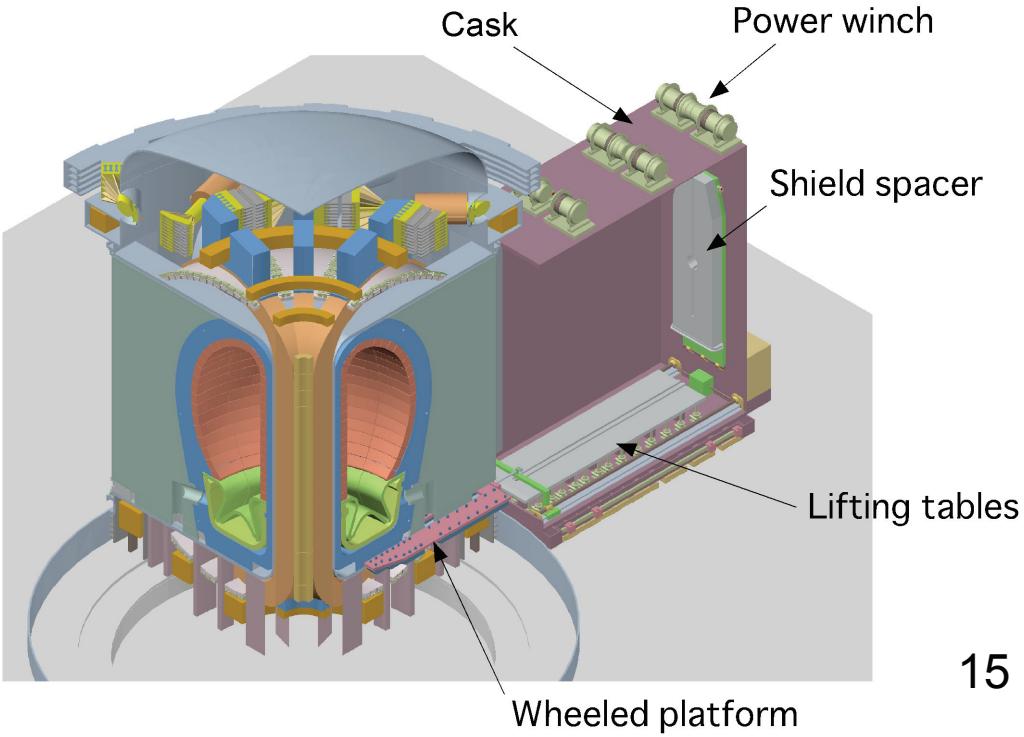
Modified concept

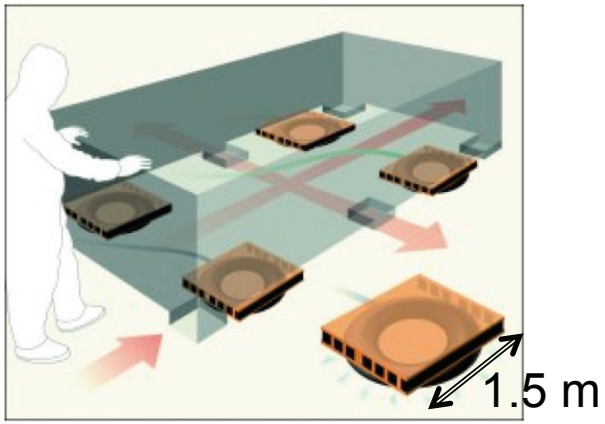
Transport

- Cask
- **Air caster**

→ **When lifted, cask can be moved with an equivalent power of moving 6t.**





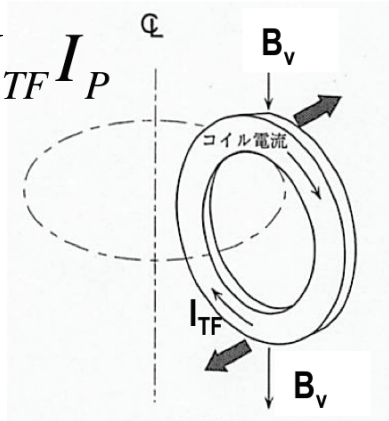


15 air casters with 1.5 m-dia can lift the cask

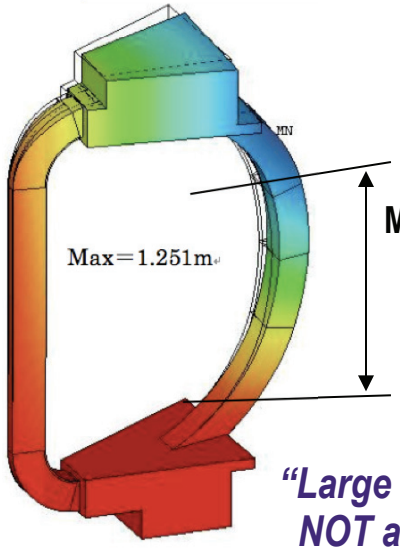
TF coil turnover force

Turnover force:

$$w \propto I_{TF} B_V \propto I_{TF} I_P$$



FEM analysis

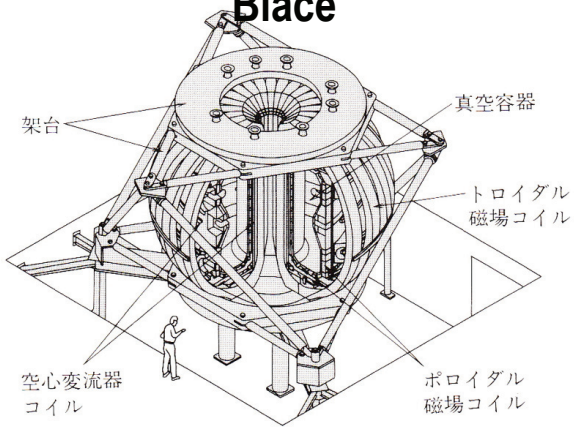


TO force: 10,000 tons/coil
Displacement: 1.25 m

Maintenance port
$\ell = 12\boldsymbol{m}$

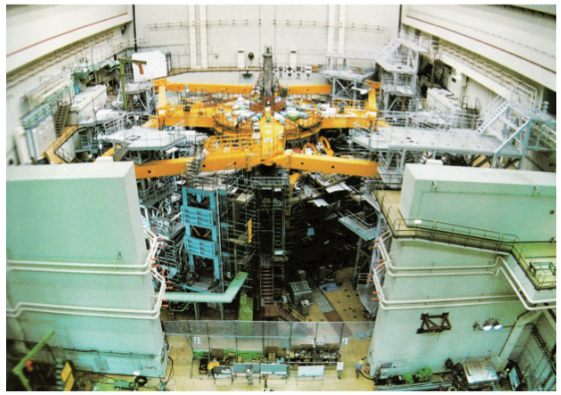
"Large port" for sector maintenance
NOT allow to setup inter-coil structure

Blace



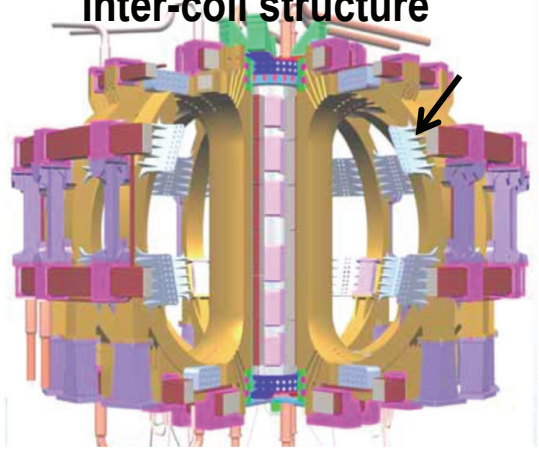
PLT, DIII-D

Support by building



JT-60

Inter-coil structure



ITER

Support of TF coil turnover force

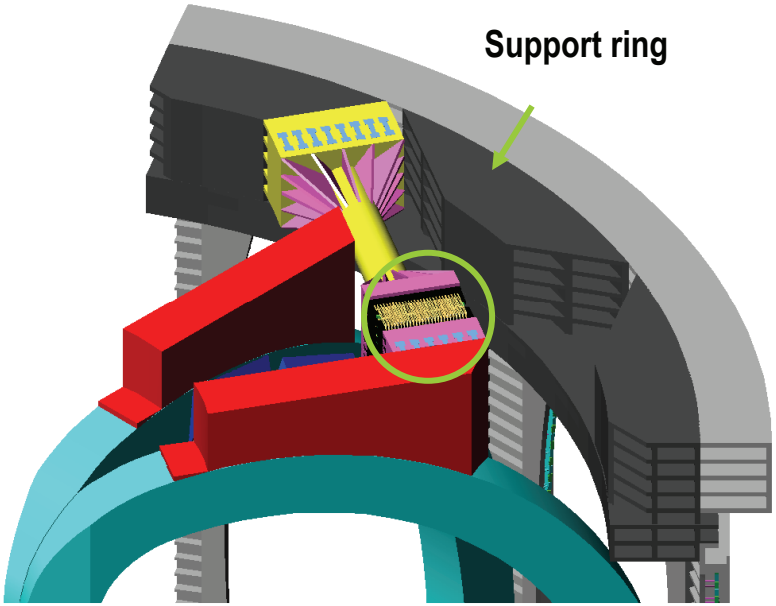
Supporting structure ← Cryostat

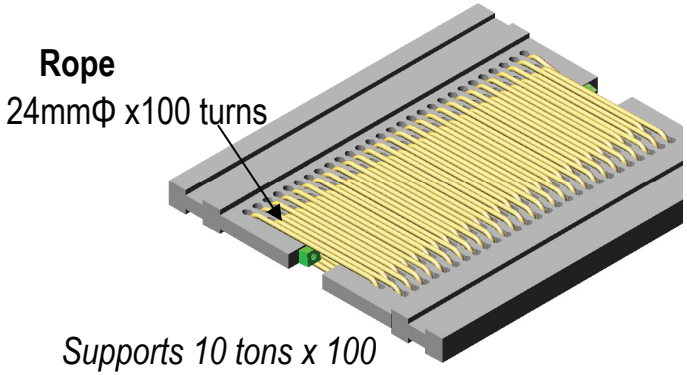
Load transfer ← "tension force" of ropes

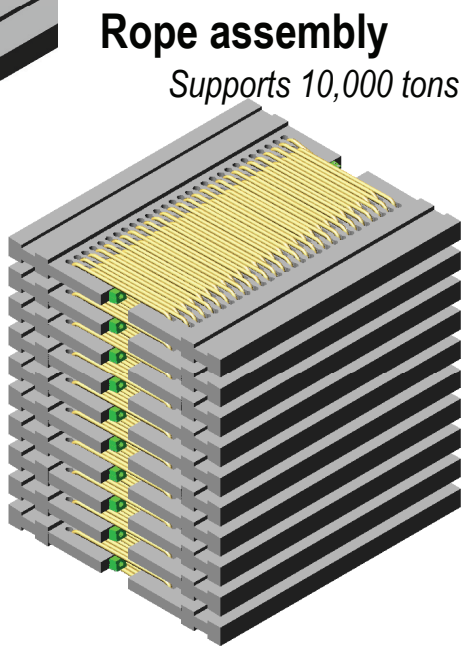
- Easy of length-tuning
- Balanced loading

Concern

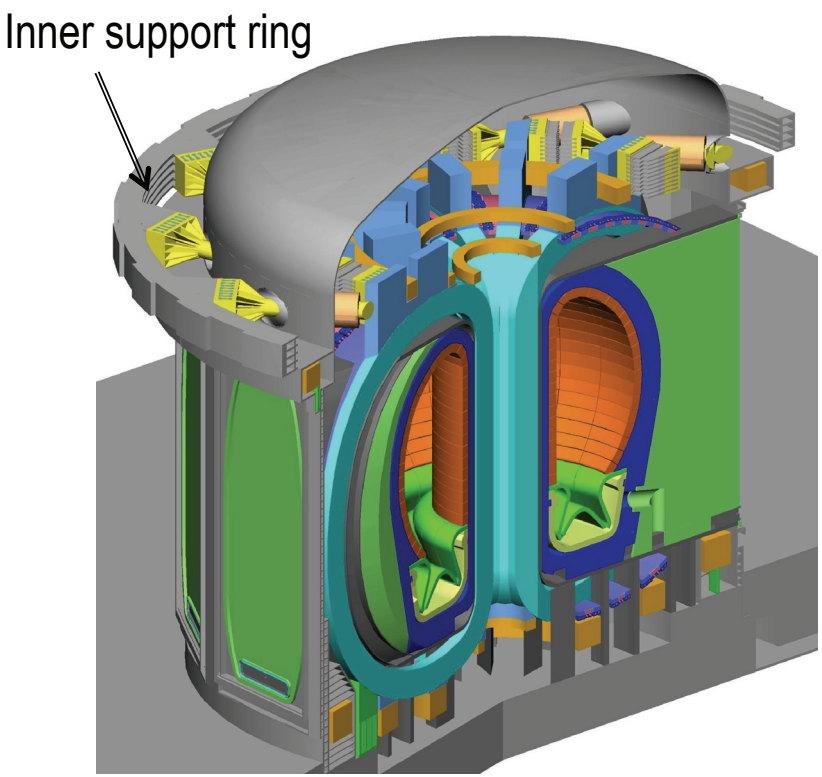
- torsional displacement of cryostat

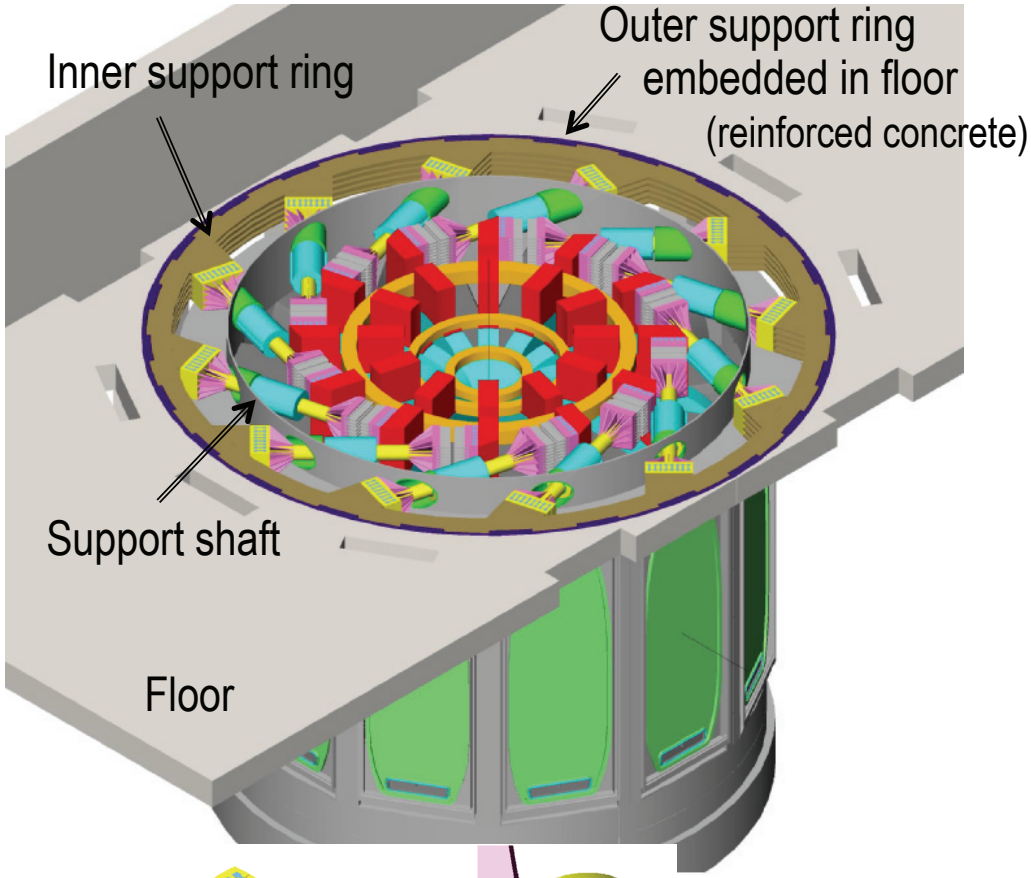


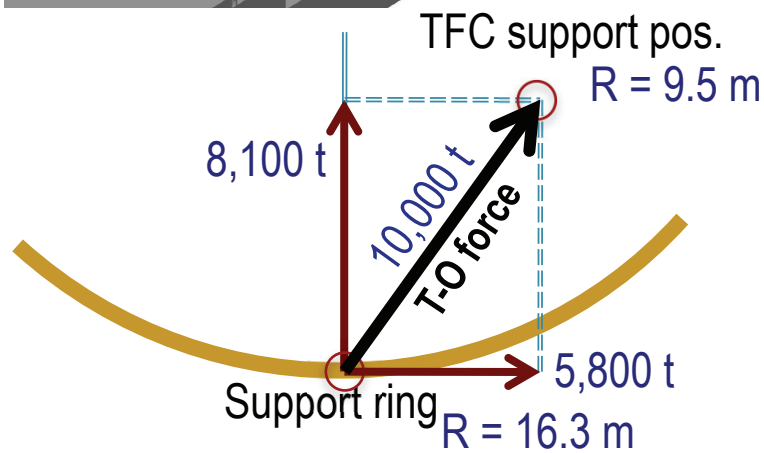


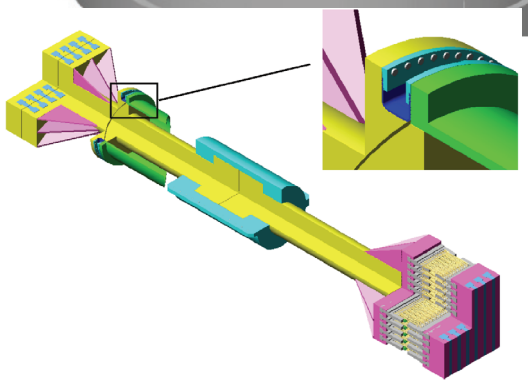


Modified concept









Summary

- JAEA has been completing the design study on a compact & low-A DEMO, SlimCS.
- Foci of FY2009 were ECCD, divertor, blanket, torus configuration and maintenance.
- After FY2010, the design study will be devoted to
  - Definition of DEMO requirements,
  - Development of DEMO design tool,
  - Assessment of Engineering choices.