JT−60SAの下側ダイバータの設計と開発

櫻井真治、JT−60SAチーム

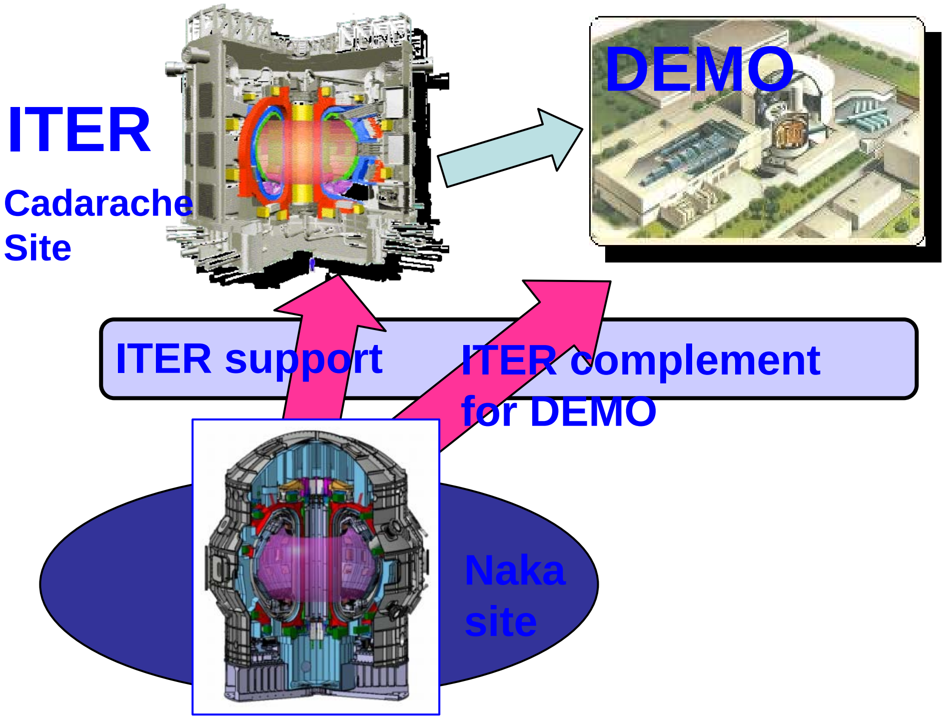
原子力機構

1. JT-60SAの概要（ミッション、特徴、運転計画）
2. 概念設計の進め方（目標、要求性能、コンセプトの検討）
3. 詳細設計、R&Dの進め方（技術要素の抽出と成立性の確認、全体設計の成立性の確認）
4. 物作りの進め方（製造手法の選択、量産向け試作試験、実機大試作試験）
5. まとめと若手の皆さんへの期待

Mission of the Project

The mission of the JT-60SA project is to contribute to the early realization of fusion energy by supporting the exploitation of ITER and research towards DEMO, by addressing key physics issues for ITER and DEMO.

Roles of JT-60SA contributing to ITER and DEMO



ITER

Cadarache Site

DEMO

ITER support

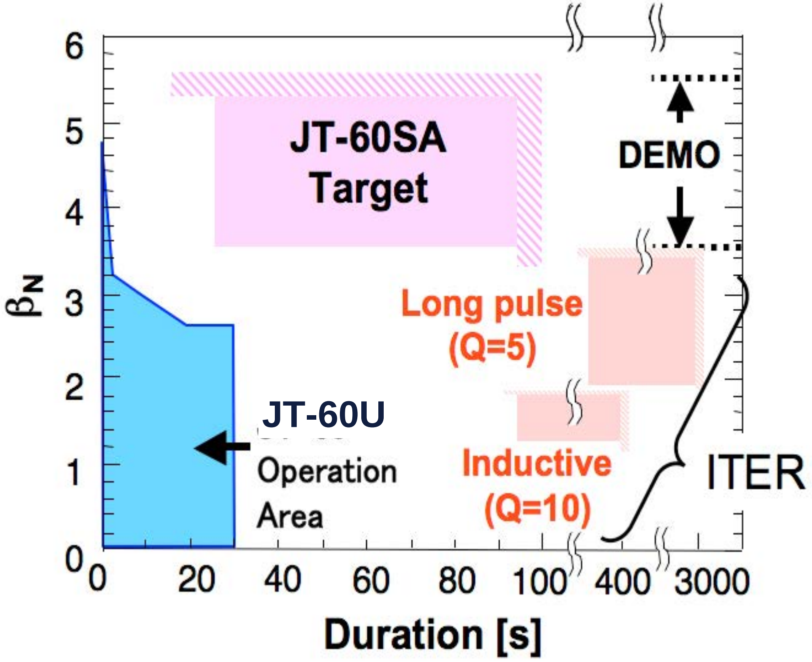
ITER complement for DEMO

Naka site

JT-60SA

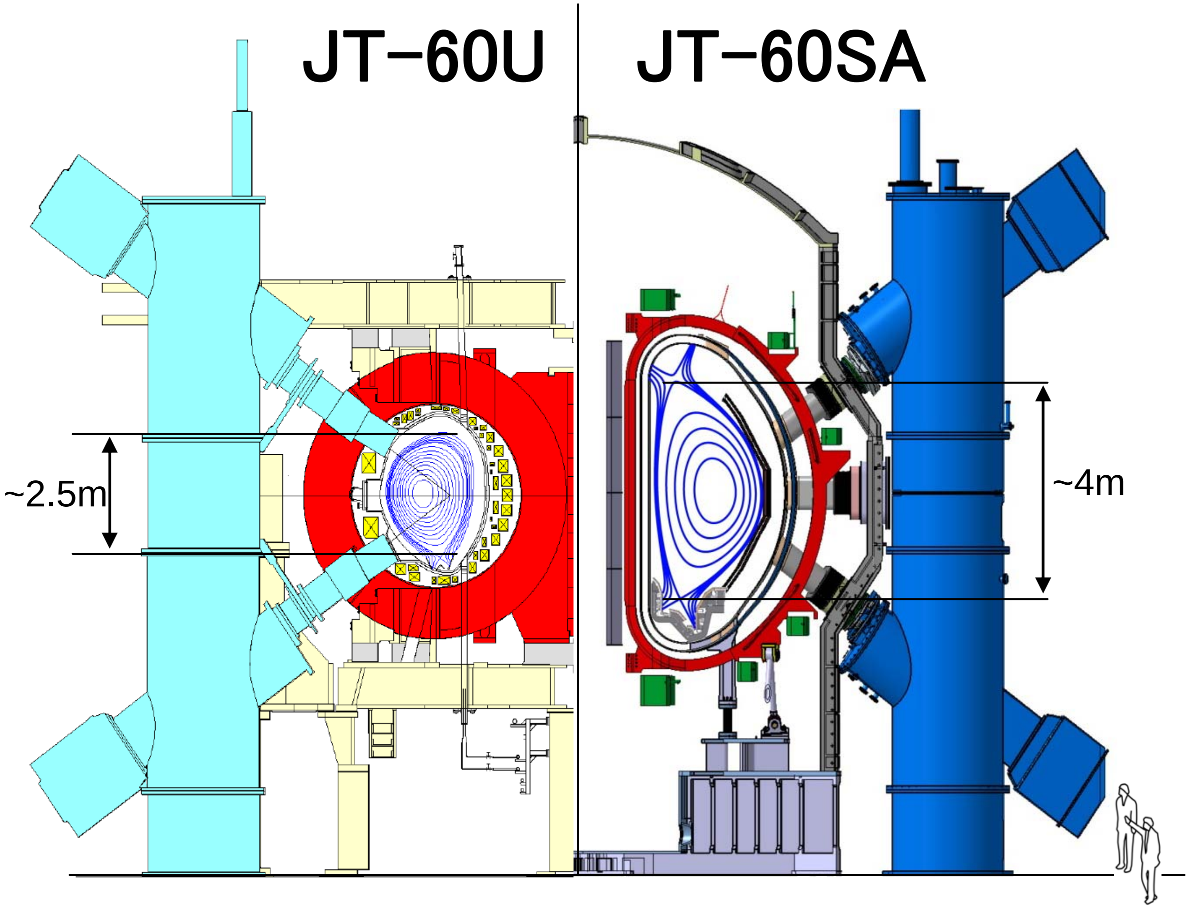
Target regime of JT-60SA

Higher-beta & Longer Duration are pursued on JT-60SA.

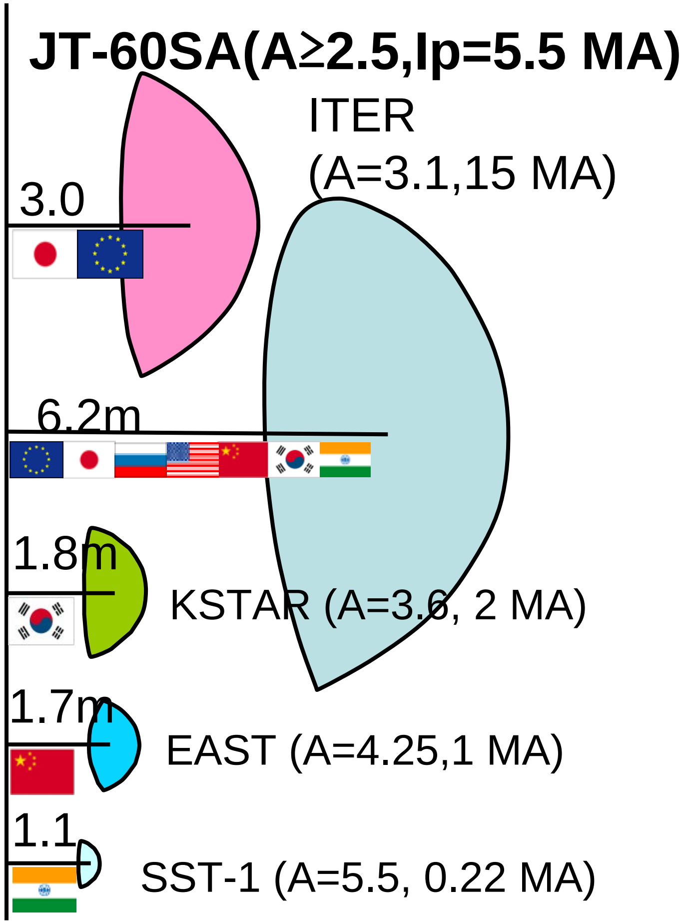


Larger & Highly Shaped Plasma

- JT-60SA has been designed to realize a large size of plasma configuration contributing the exploitation of ITER and DEMO with superconducting magnets and additional heating up to 41 MW for 100 s.



Superconducting Tokamaks



Phased Operation Plan

Divertor and remote handling (RH) system shall be upgraded according to “Phased Operation Plan”

Phase		Gas	Neutron (n/y)	RH	Divertor	Heating power	Divertor & RH improvement
Initial	I	H	-	R&D	LSN Partial^{*1} Mono-block	23MWx5s 21.5MWx100s^{*2}	Commissioning Improving and adding monoblock target Test of RH tools and endeffectors
	II	D	4E19			33MWx5s 31.5MWx60s^{*2} 21.5MWx100s^{*2}	
Integrated	I		4E20		LSN Full Mono-block	37MWx60s 27MWx100s	Test of RH system
	II		1E21	Use			Preparation for metal armor and upper divertor
Extended			1.5E21		DN	41MWx100s	

*1: Monoblock CFC targets will be installed 40 degree of outer target (1/9 of torus) at start of initial phase and added during initial phase.

*2: High power and long duration heating will be limited due to remaining bolted CFC divertor targets.

概念設計の進め方

１．目標を立てる。

２．要求を決める。

３．要求を満足するコンセプトを考えて
　有効性を確認する。

（形状、排気、熱負荷、除熱、モジュール化、
ダイバータカセット）

Objectives of divertor design

ITER support

- ✓ Enhancement of recycling and radiation by a private dome and “V-shaped” corner similar to ITER divertor geometry
- ✓ Particle and impurity control by divertor pumping
- ✓ Physics data base of plasma wall interaction in carbon and metal wall for ITER and DEMO
- ✓ Divertor geometry compatible with high beta plasma operation for DEMO

ITER complement for DEMO

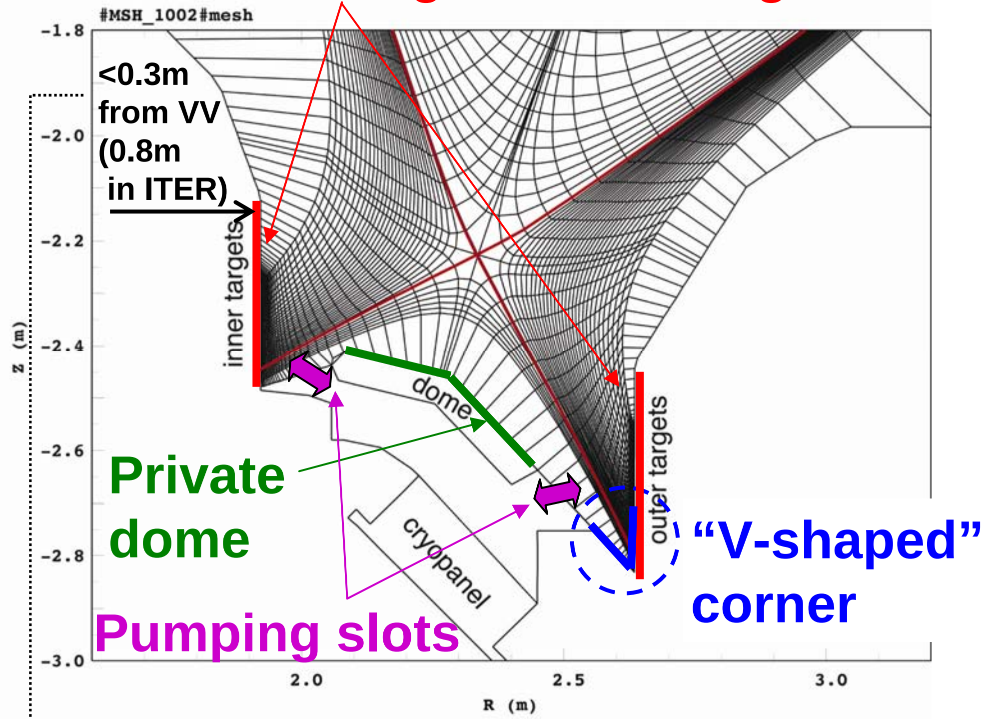
Cost reduction

Design Requirements

- ✓ Handling of 22-41 MW heating power during 100 seconds
- ✓ Remote handling maintenance compatibility to allow high performance long pulse plasma with large neutron yield
- ✓ Divertor pumping capability comparable to ITER divertor
- ✓ Allowing high κ and δ configuration with large volume
- ✓ Gradually upgradable design for PFCs to change plasma facing materials
- ✓ Compatibility with diagnostics
- ✓ Reliability and integrity for operation

Design Concepts - Geometry -

Vertical targets (VTs) compatible with ITER like and high δ & κ configurations

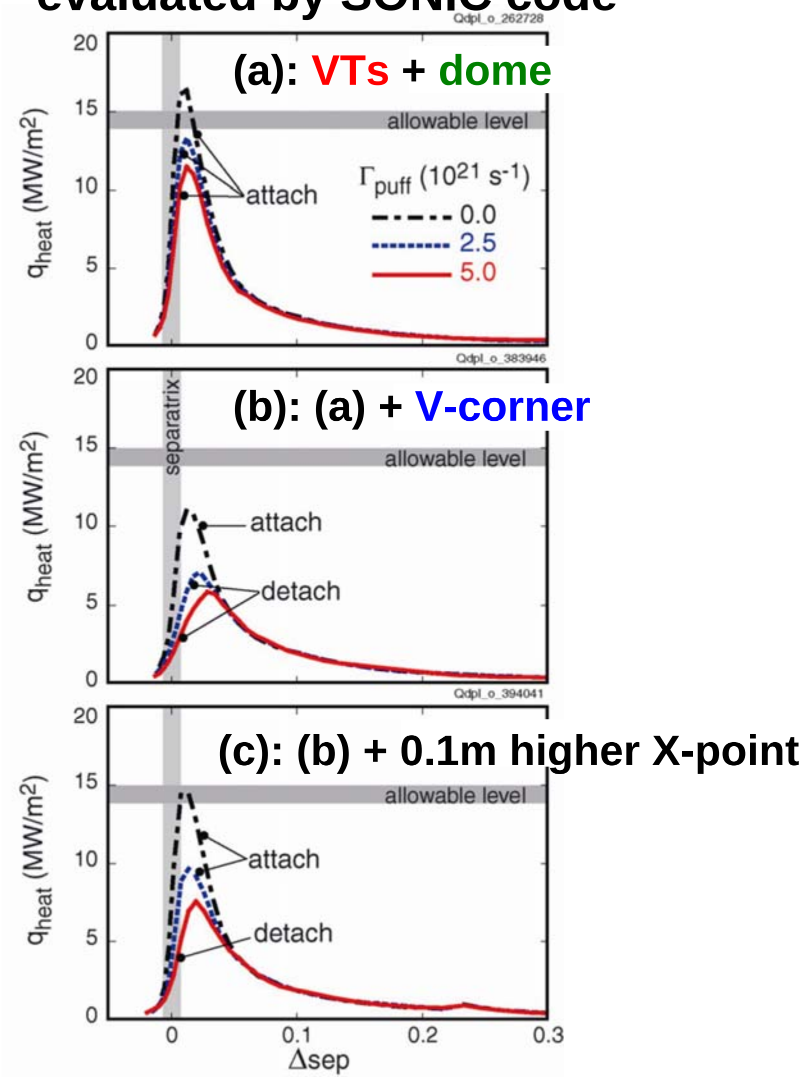


Space for structure (cassette, armor etc.) are strongly limited to achieve high δ & κ configuration at low aspect ratio.

"V-shaped" corner enhances recycling and radiation loss.

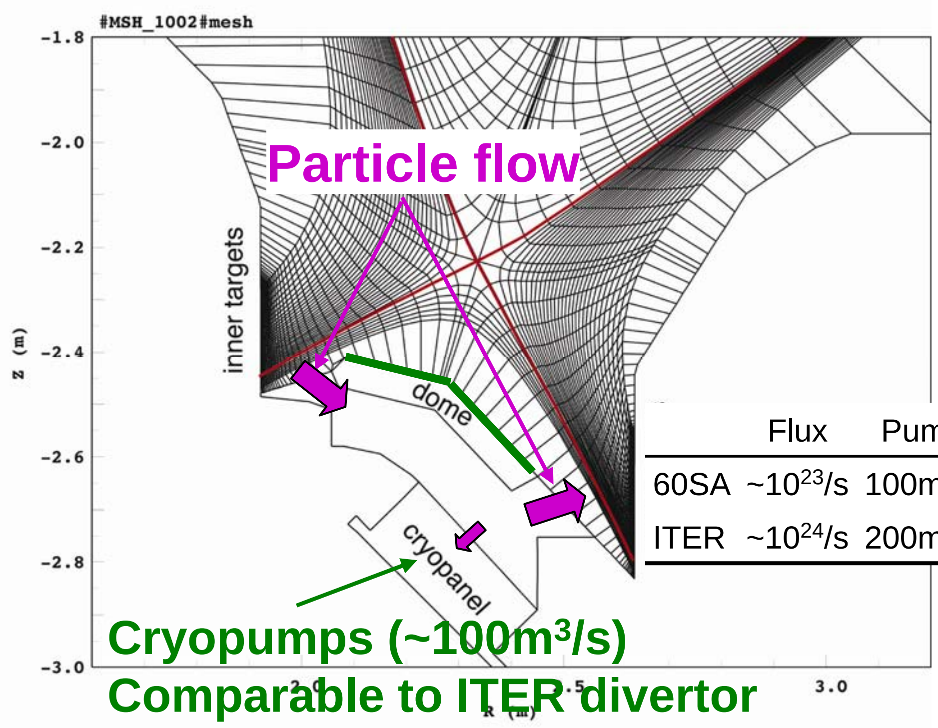
Height of dome and position of pumping slots were optimized.

Heat load on the outer target at 41 MW heating power evaluated by SONIC code



Ref. H. Kawashima and et al., Fusion Eng. Des., **83** (2008) 1643

Design Concepts - Pumping -



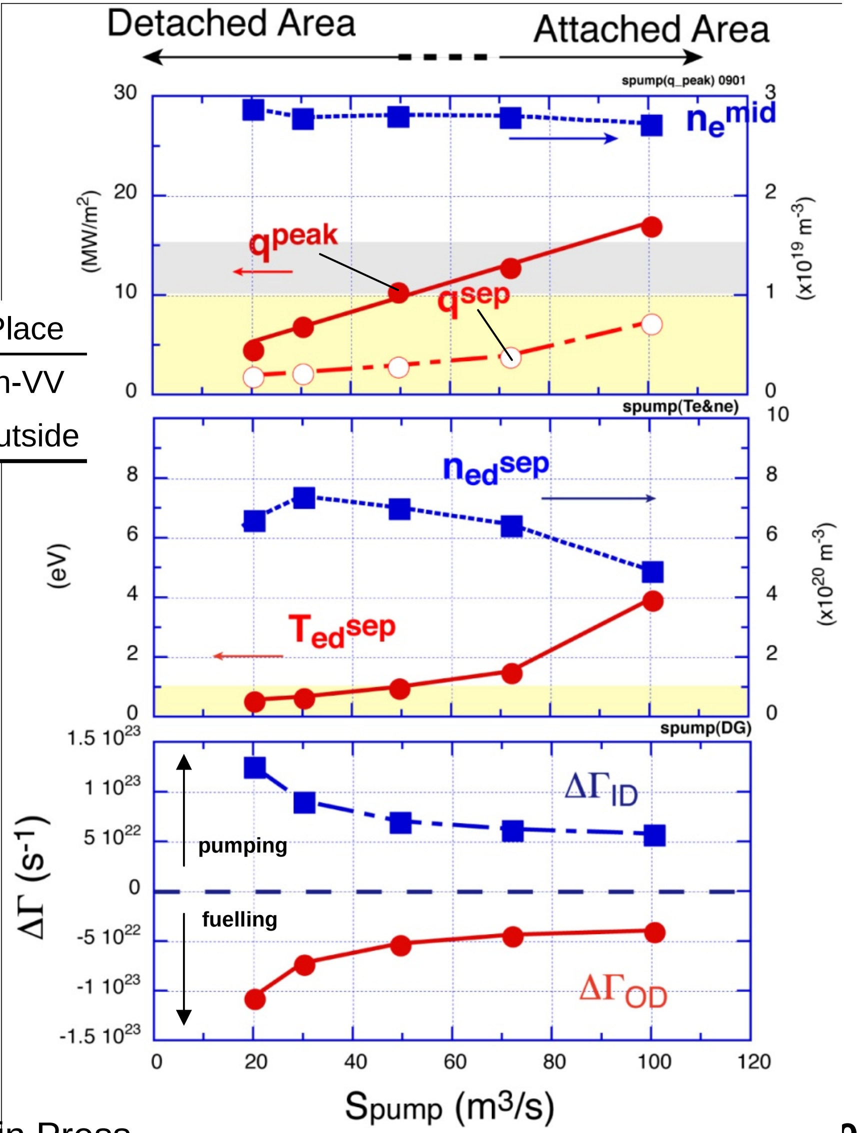
	Flux	Pump	Place
60SA	~10^{23}/s	$100m^3$/s	In-VV
ITER	~10^{24}/s	$200m^3$/s	Outside

Cryopumps (~$100m^3$/s)
Comparable to ITER divertor pumping (~$200m^3$/s)

9 cryopumps are installed behind the divertor for large and variable pumping speed.

Strike point plasma and peak heat load can be controlled by changing pumping speed with constant core edge density.

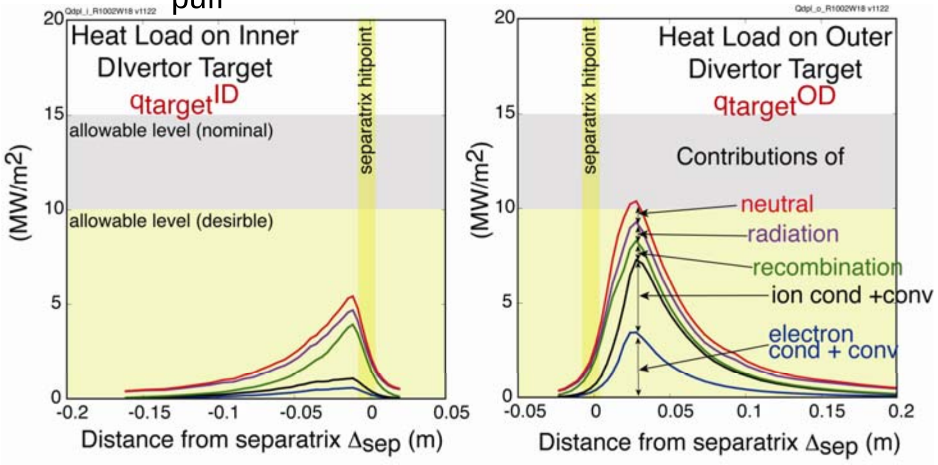
Pumping effects on the plasma parameters and heat flux



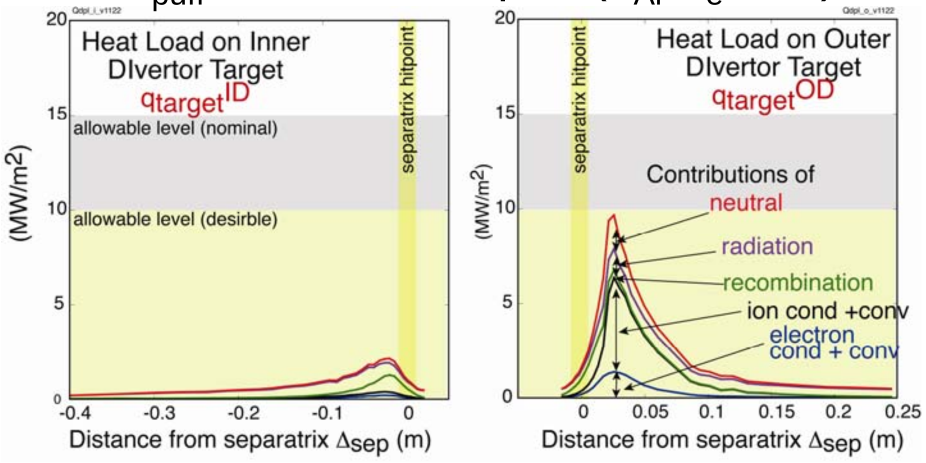
Ref. H. Kawashima and et al., J. Nucl. Mater. in Press

Design Concepts - Heat load -

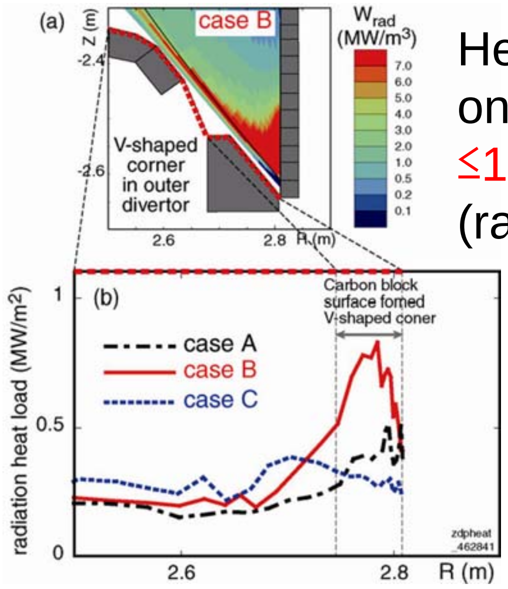
41MW heating, n_e^{ave} ~1E20/m^3, Γ_{puff}=15x10^{21}/s



41MW heating, n_e^{ave} ~5E19/m^3, Γ_{puff}=6x10^{21}/s, Ar puff (n_{Ar}/n_e=2%)



Heat flux on the vertical target ≤15 MW/m^2

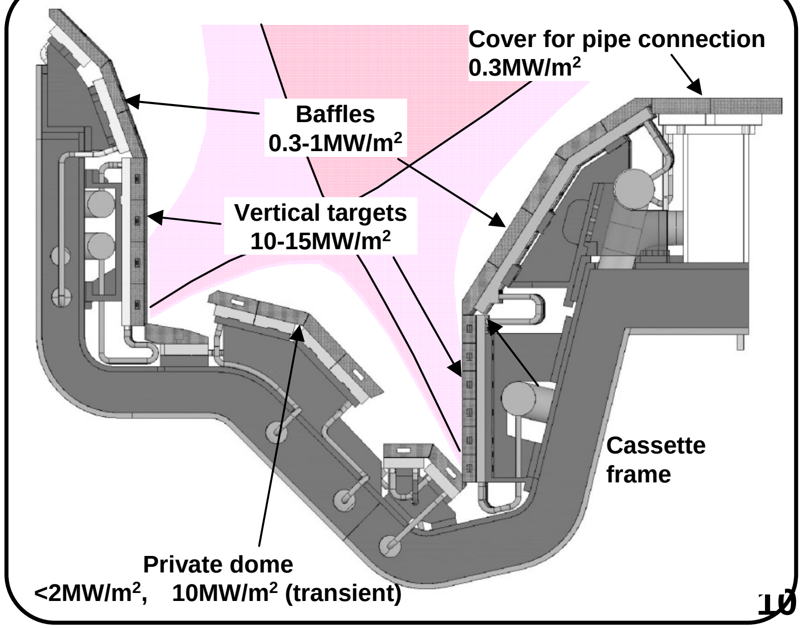


Heat flux
on the dome
≤1~2MW/m^2
(radiation+neutrals)

Ref. H. Kawashima and et al., Fusion Eng. Des., **83** (2008) 1643.

H. Kawashima and et al., J. Nucl. Mater., In Press.

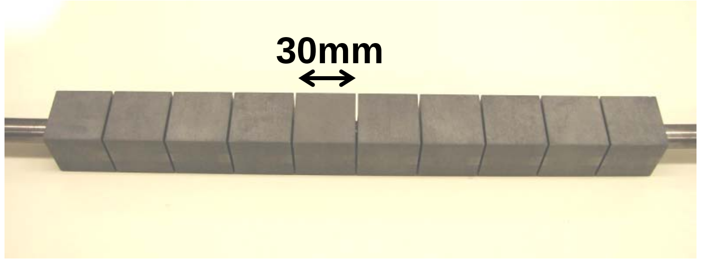
Heat load in the lower divertor



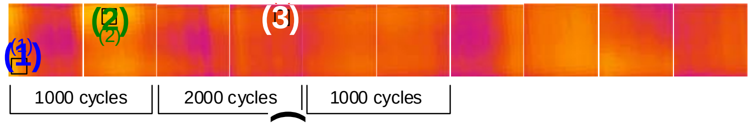
Design Concepts - Cooling -

All PFCs are fully water cooled for high power long pulse heating

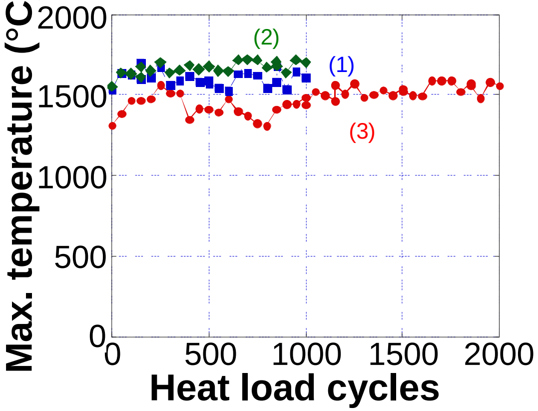
CFC monoblock target similar to ITER divertor are applied for 10~15 MW/m^2 x 100s



Full-size mockup of monoblock target

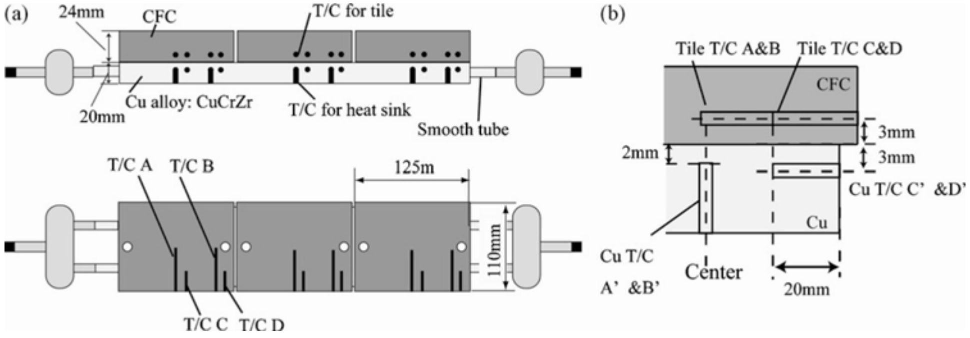


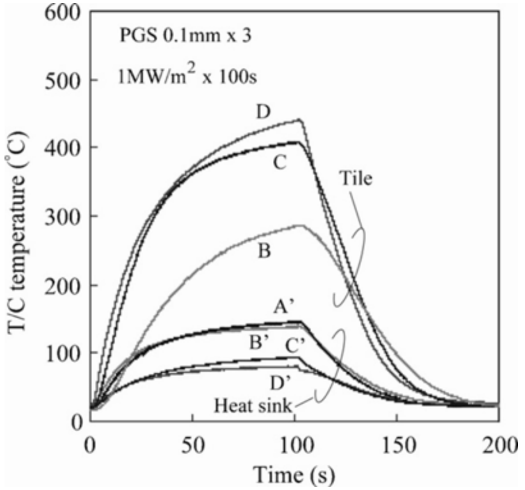
(1): existing the crack in the circumferential direction in CFC block
(2): the maximum temperature
(3): the representative at the monoblock receiving 2000 heat cycles



Ref. S. Higashijima and et al., Fusion Eng. Des., **84** (2009) 949.

Bolted armor tiles on cooled heatsink are applied for ≤2 MW/m^2(100s) and ~10MW/m^2(trans.).



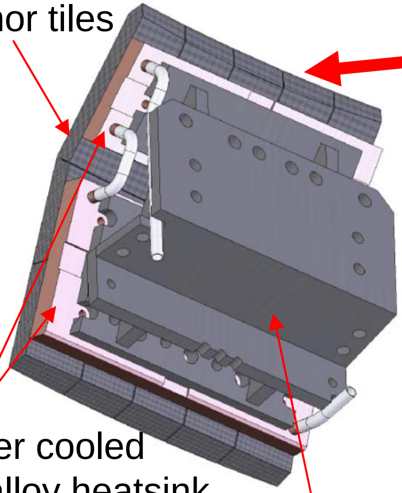


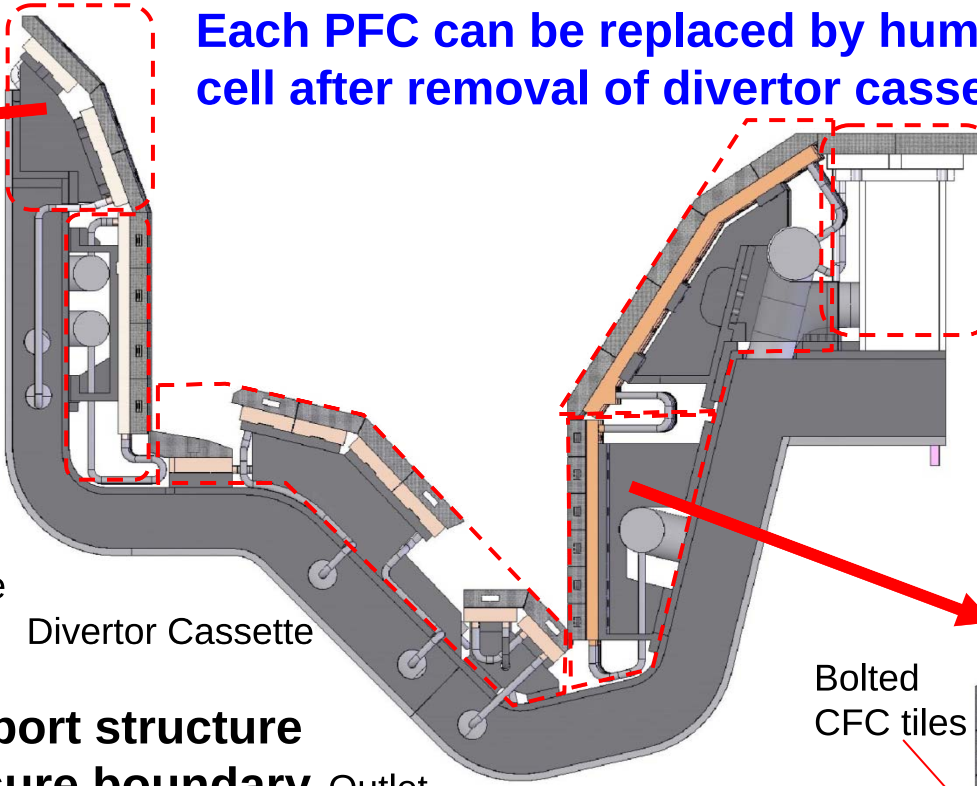
Ref. K. Masaki and et al., Fusion Eng. Des., **85** (2010) 1732

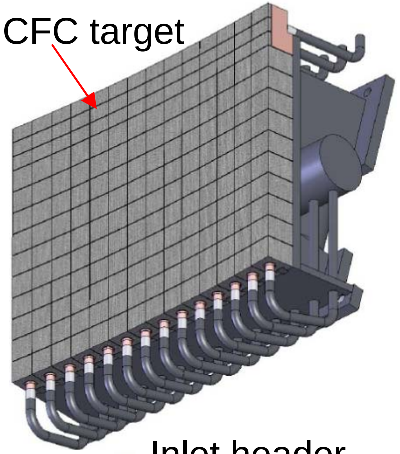
Design Concepts - modularized PFCs -

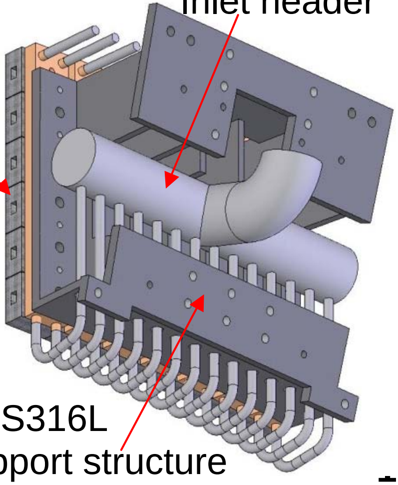
PFCs are modularized and mounted on a cassette frame to be upgraded and improved.

Each PFC can be replaced by human work in hot cell after removal of divertor cassette from VV.



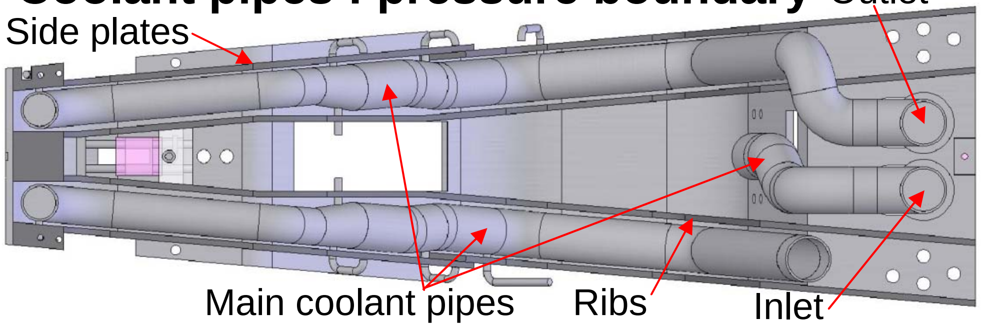






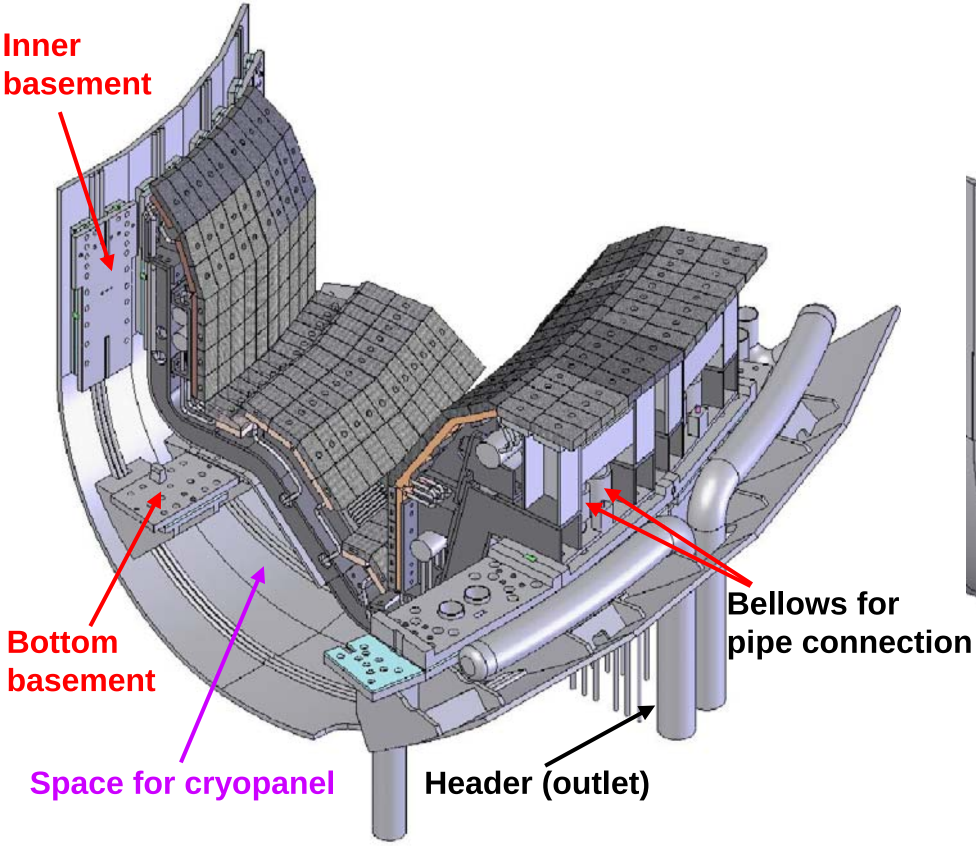
Cassette frame : support structure

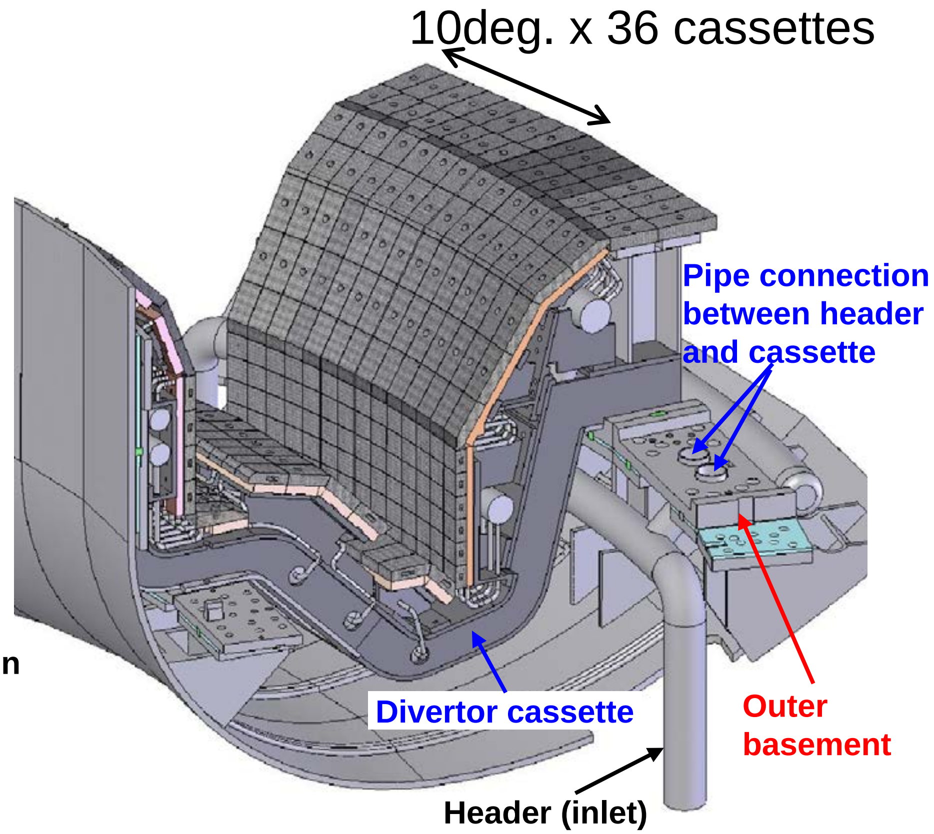
Coolant pipes : pressure boundary



Design Concepts - Divertor cassette -

- ✓**Coolant pipe connections** for the PFCs are integrated and **connected to in-vessel headers** at outboard side.
- ✓**Cassette shall be installed and replaced through a horizontal port (H1.8m, W0.6m) of vacuum vessel by remote handling system similar to that for ITER blanket.**





Ref. S. Sakurai and et al., Fusion Eng. Des., 85 (2010) 2187

詳細設計とR&Dの進め方

１．Keyになる技術要素を抽出する。

２．その技術要素の成立性を、詳細検討、試作試験などで確認する。

（モノブロックターゲット量産、遠隔保守）

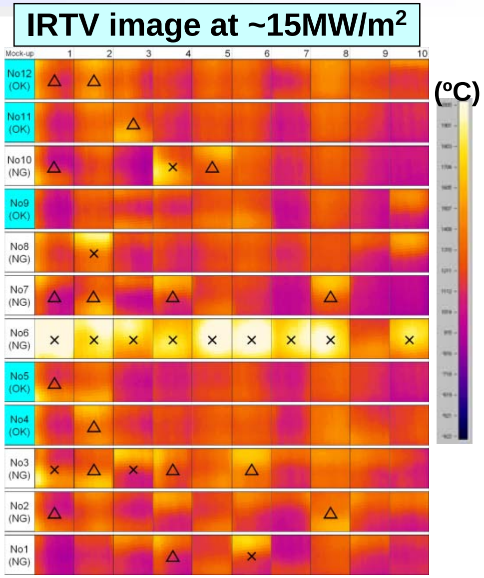
３．全体設計の成立性を確認する。

（電磁力解析、構造解析、*熱応力解析など*）

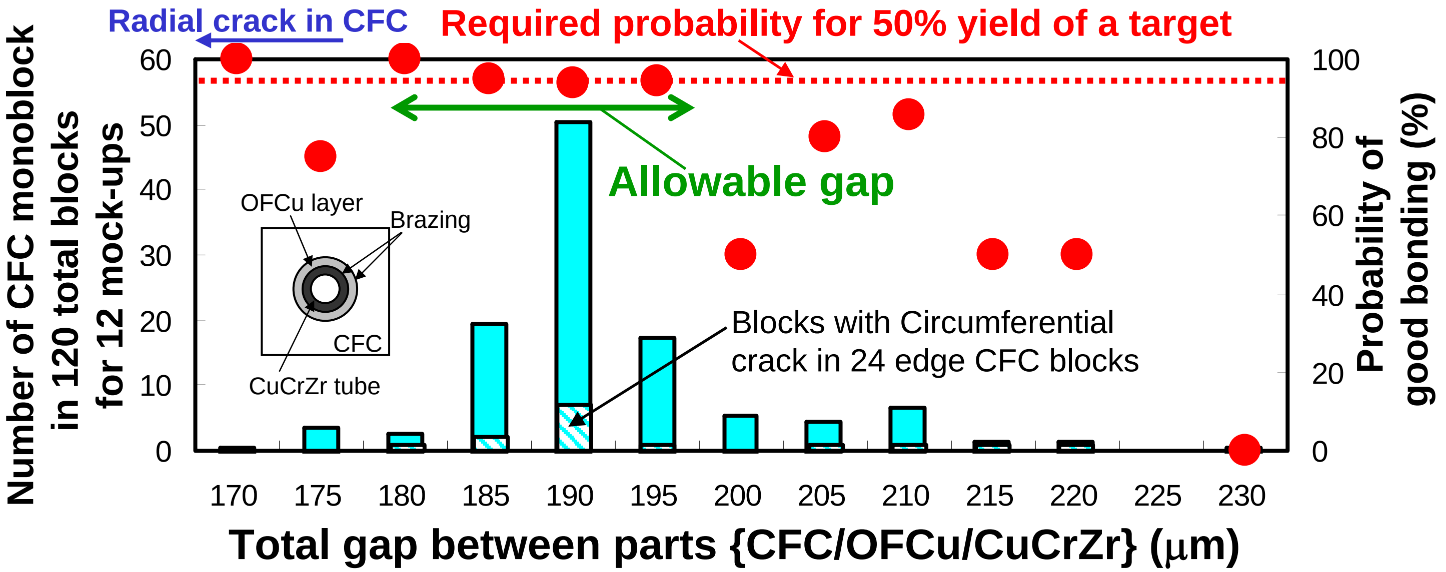
Key technology - Monoblock targets -

Metallization inside CFC blocks and careful control of gaps between CFC and Cu parts were introduced for good bonding.

12 full-size mockups were brazed in one furnace to check production yield.



Bonding performance of each blocks was tested by screening and cyclic heat load test.
Good : Max. surface temperature ≤1700°C



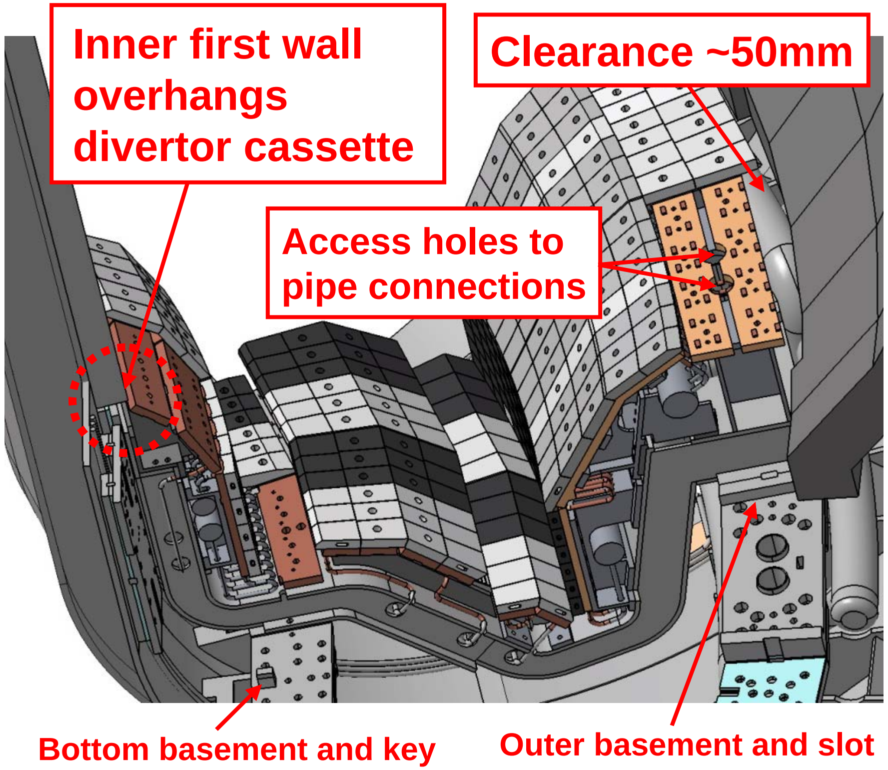
Total gaps were scattered due to scattering of metallization thickness.

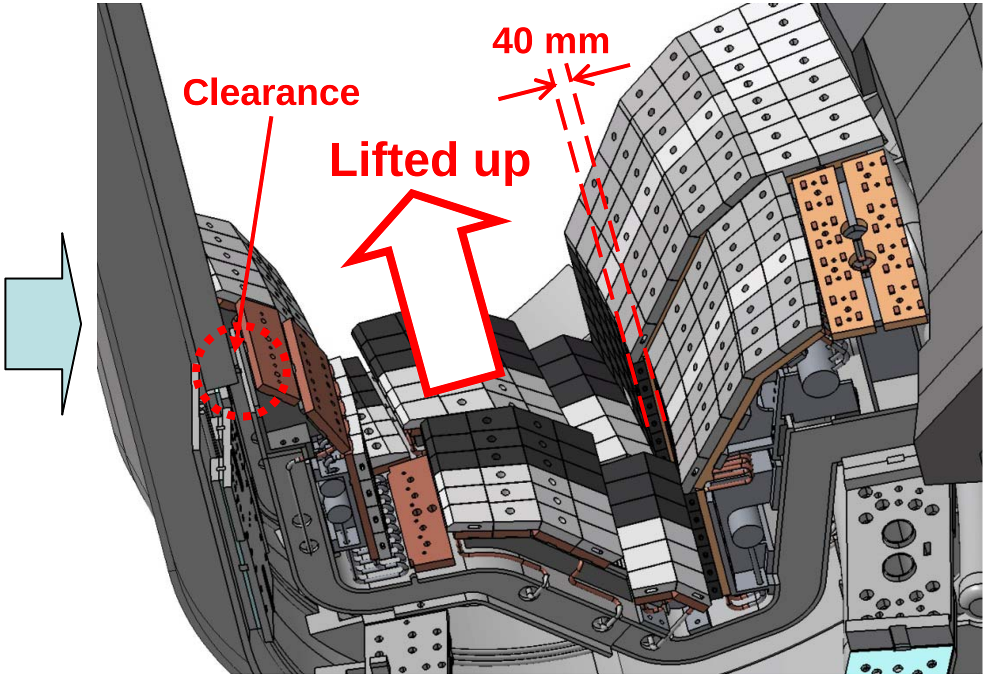
Total gaps shall be 180-195μm to obtain good reproducibility.

Key technology - Remote Handling - (procedure)

Tiles of inner baffle, inner part of private dome and cover for pipe connections are removed for tool access. Bottom tiles on stabilizing baffle plate are also removed to make clearance.

After cutting pipe connection and loosening fixing bolts and a key, divertor cassette is moved 40 mm outward to step aside inner first wall. Then a cassette is lifted up by RH manipulator.





Ref. S. Sakurai and et al., Fusion Eng. Des., **85** (2010) 2187

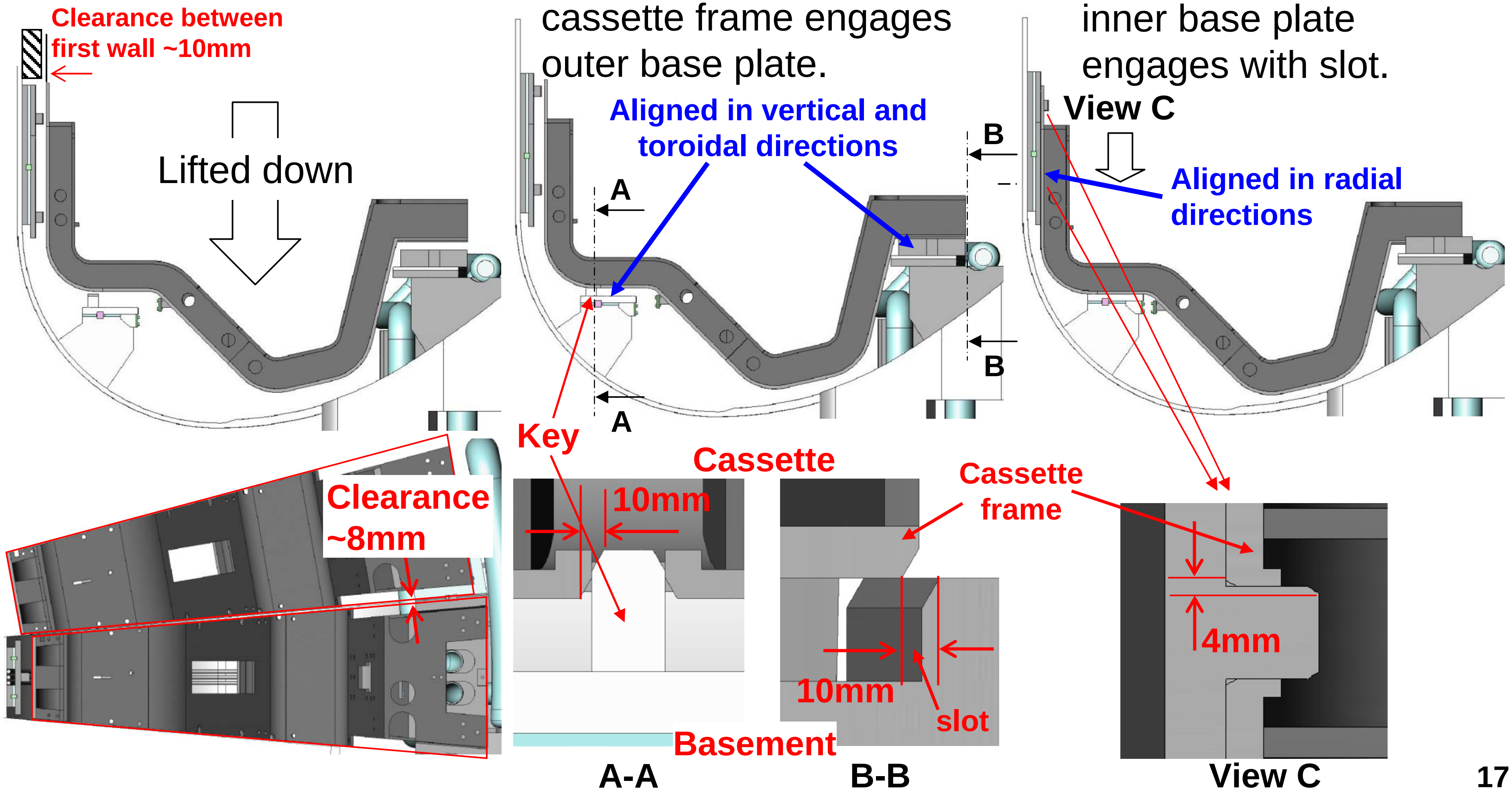
Key technology - Remote Handling - (Alignment)

Alignment in installation procedure

A cassette is lifted down at 40mm outside to step aside from inner first wall

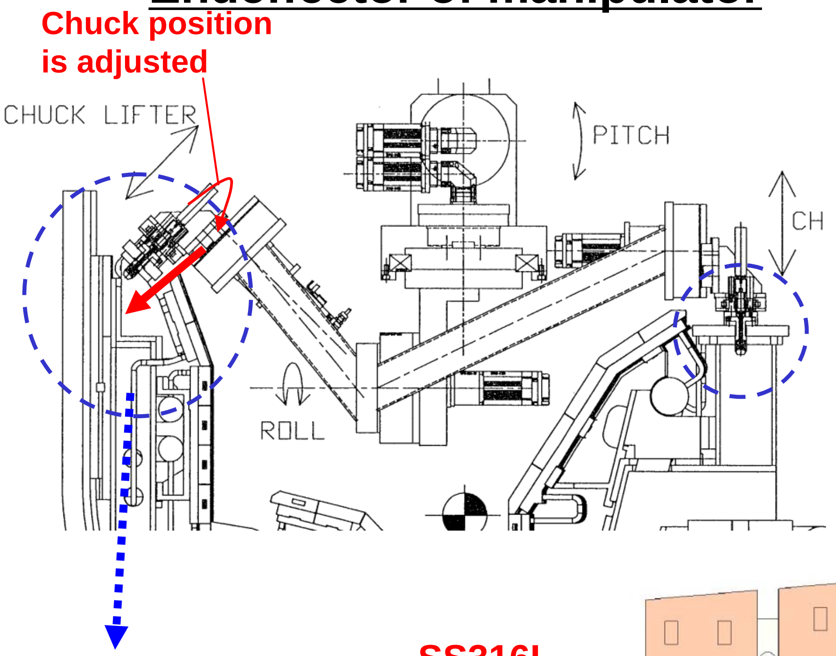
Key of bottom base plate engages with slot of a cassette at first. Then, cassette frame engages outer base plate.

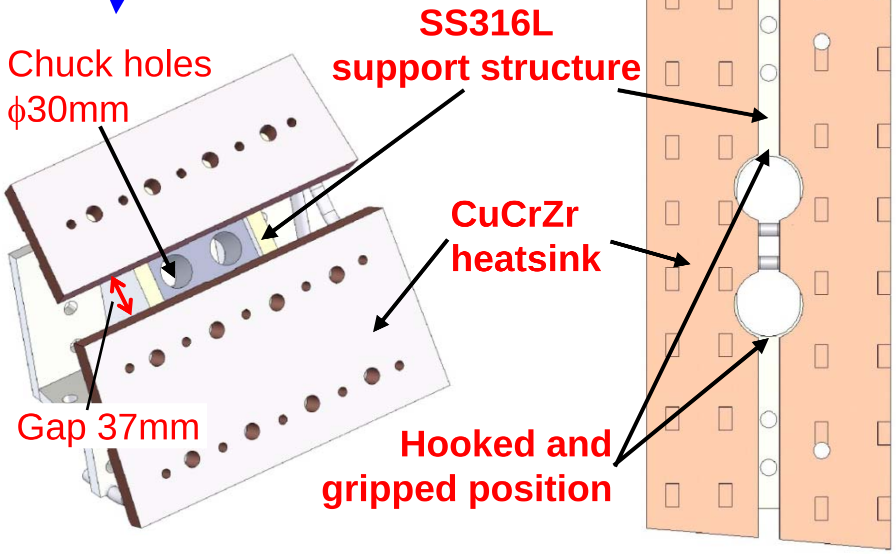
A cassette is moved inward to attach inner basement and key of inner base plate engages with slot.



Key technology - Remote Handling - (Handling tools)

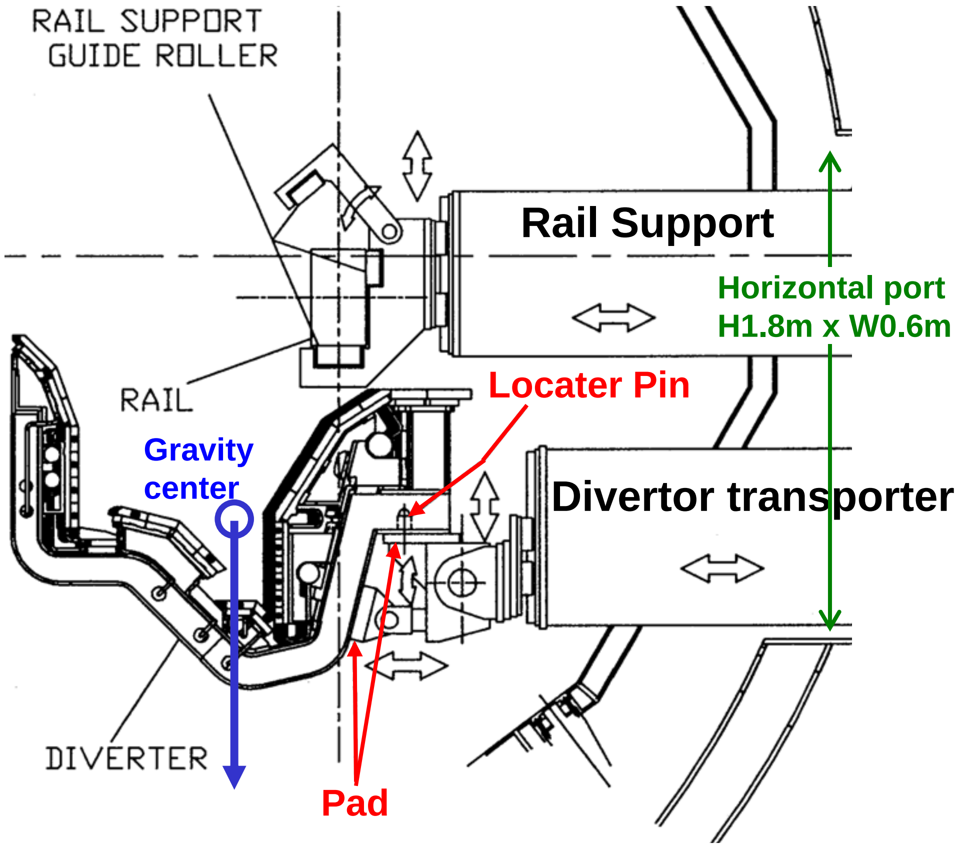
Endeffector of manipulator





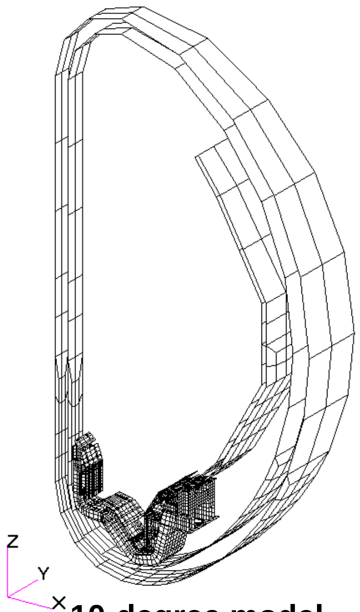
Allowable weight of cassette ~800kg

Divertor cassette has holding points for manipulator and transporter of RH system.

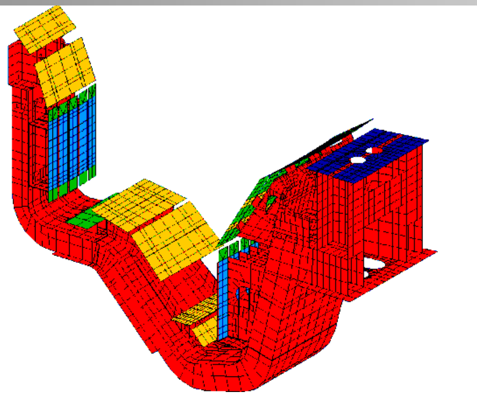


Ref. S. Sakurai and et al., Fusion Eng. Des., **85** (2010) 2187

Structural Integrity
Electromagnetic Force Analysis



10-degree model



Color	Material	Effective resistivity
🟥	SUS316L	7.70E-7 (Ωm)
🟩	Cu alloy	2.35E-8 (Ωm)
🟨	SUS 15mm + Cu 25mm	3.70E-8 (Ωm)
🟦	SUS 15mm + Cu 20mm	4.03E-8 (Ωm)
🟦	SUS 20mm + Cu 25mm	4.13E-8 (Ωm)

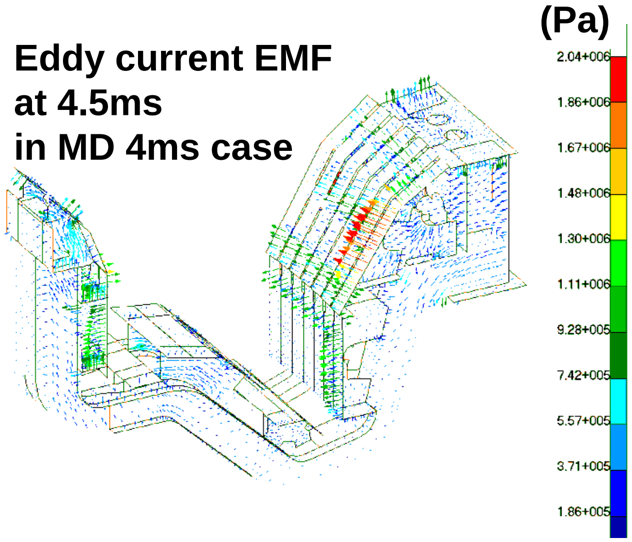
Plasma current decay and profile, Halo current waveform (DINA code: toroidal symmetry)

Eddy current and its EMF (EDDYCAL code:3D)

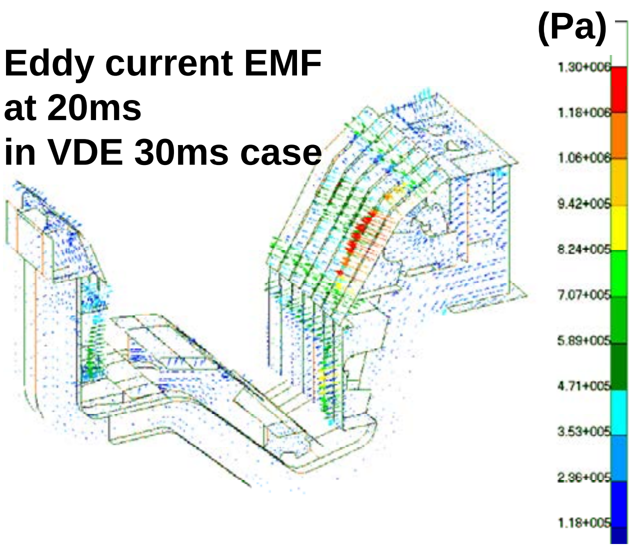
Max. halo current was normalized as $I_{halo}/I_{p}*TPF<0.5$. (ITER physics basis)
Inlet and outlet position of halo current were artificially provided.

Ref. S. Sakurai and et al., Fusion Eng. Des., **85** (2010) 2187

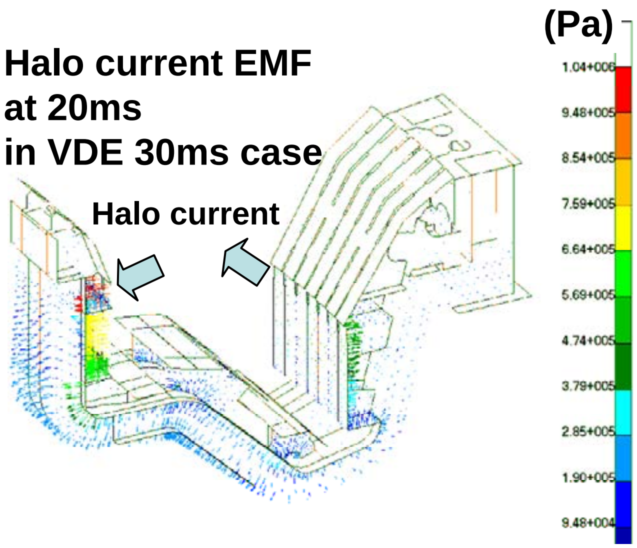
Eddy current EMF at 4.5ms in MD 4ms case



Eddy current EMF at 20ms in VDE 30ms case



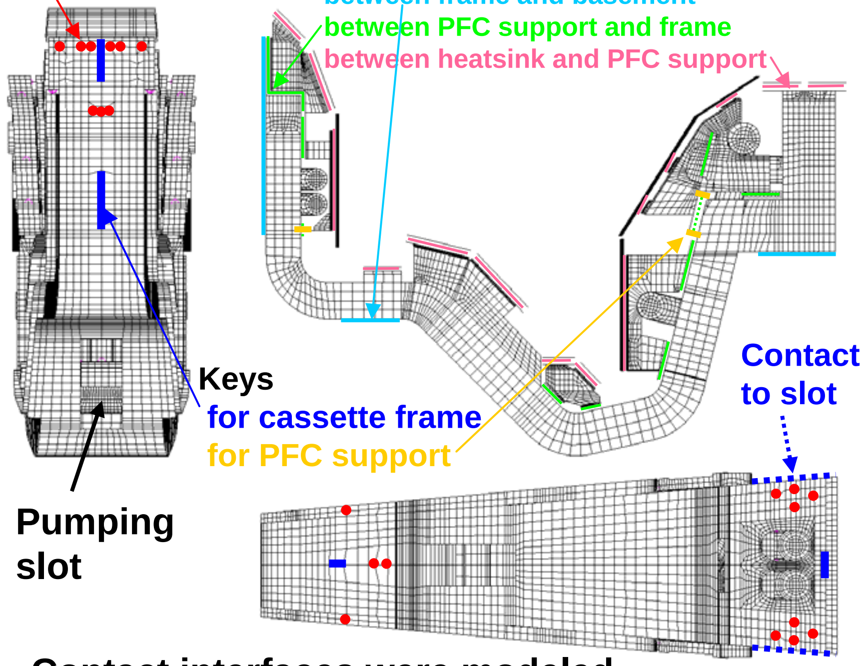
Halo current EMF at 20ms in VDE 30ms case



Eddy current on outer baffle, inner and outer targets cause overturning forces

Structural Integrity
Static Structural Analysis

FEM model



Bolts
for cassette frame

Contact
between frame and basement
between PFC support and frame
between heatsink and PFC support

Keys
for cassette frame
for PFC support

Contact
to slot

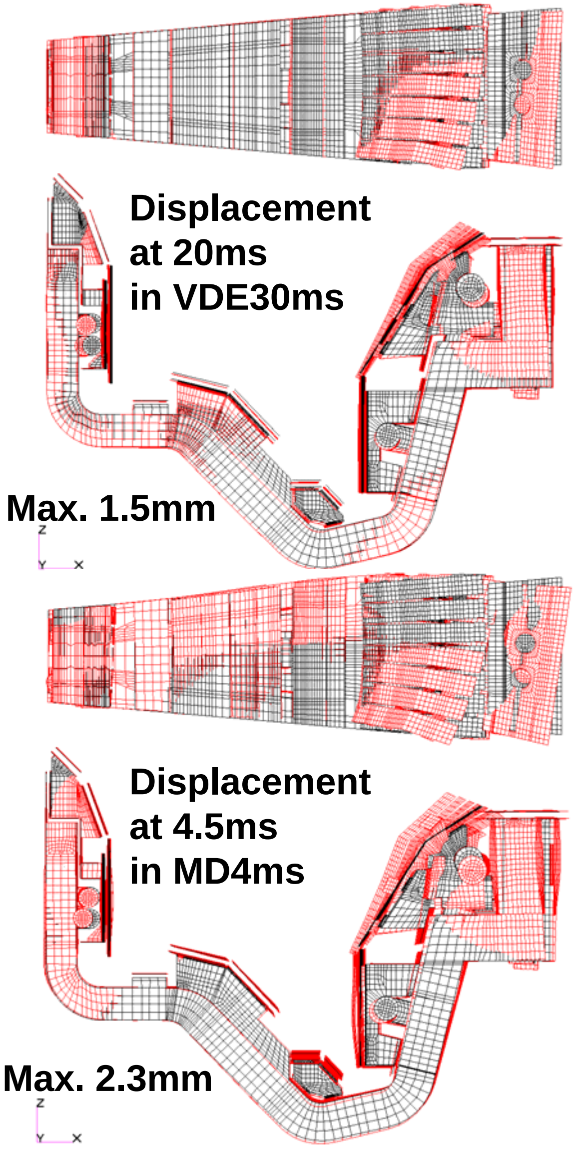
Pumping
slot

Contact interfaces were modeled with nonlinear spring elements

Concentrated overturning force on an outer baffle causes large displacement of support structure of outer baffle.

Ref. S. Sakurai and et al., Fusion Eng. Des., **85** (2010) 2187

Displacement due to dead weight, coolant pressure and EMFs



Displacement
at 20ms
in VDE30ms

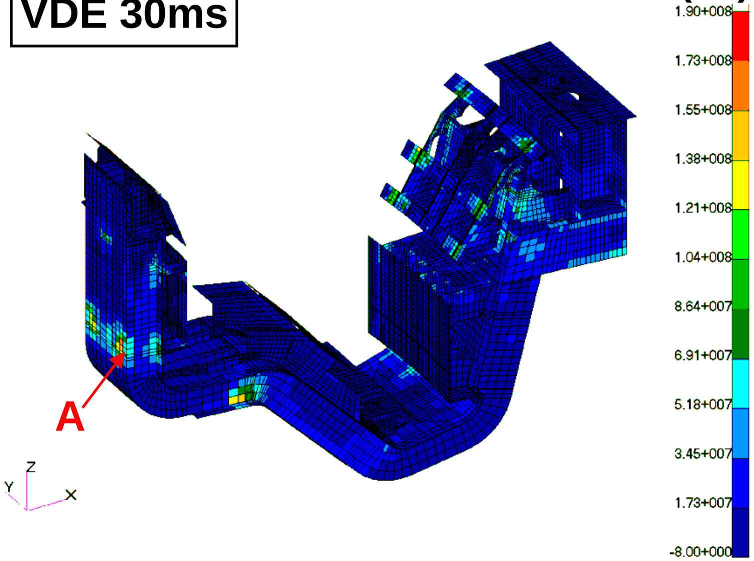
Max. 1.5mm

Displacement
at 4.5ms
in MD4ms

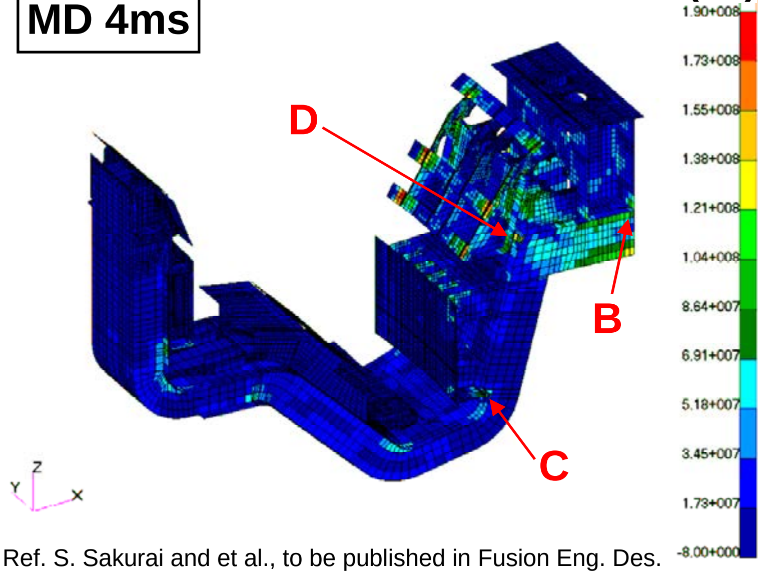
Max. 2.3mm

Structural Integrity
Stresses of frame and parts

VDE 30ms



MD 4ms



Ref. S. Sakurai and et al., to be published in Fusion Eng. Des.

Tresca stress of a cassette frame and support structure of PFCs are generally small (<0.5Sm).

Overturning force on an outer baffle causes large local stress in MD 4ms case.

Integrity of bolts and keys fixing a cassette

case	σ_t (MPa) for bolts			σ_s for keys (MPa)		
	Inner	Bottom	Outer	Inner	Bottom	Outer
VDE 30ms	14	-	30	5.4	8.1	7.8
MD 4ms	58	44	42	14	44	4.4

Local stress near the welding joint of cassette

A: σ_{m+b} =132MPa <1.5Sm (VDE 30ms)

B: σ_{m+b} =176MPa ~1.5Sm (MD 4ms)

Integrity of fixing bolts for PFC support

f_t(MPa) : 69(SUS316), 196(A-286),
300(SUS316L-HiMo class100)

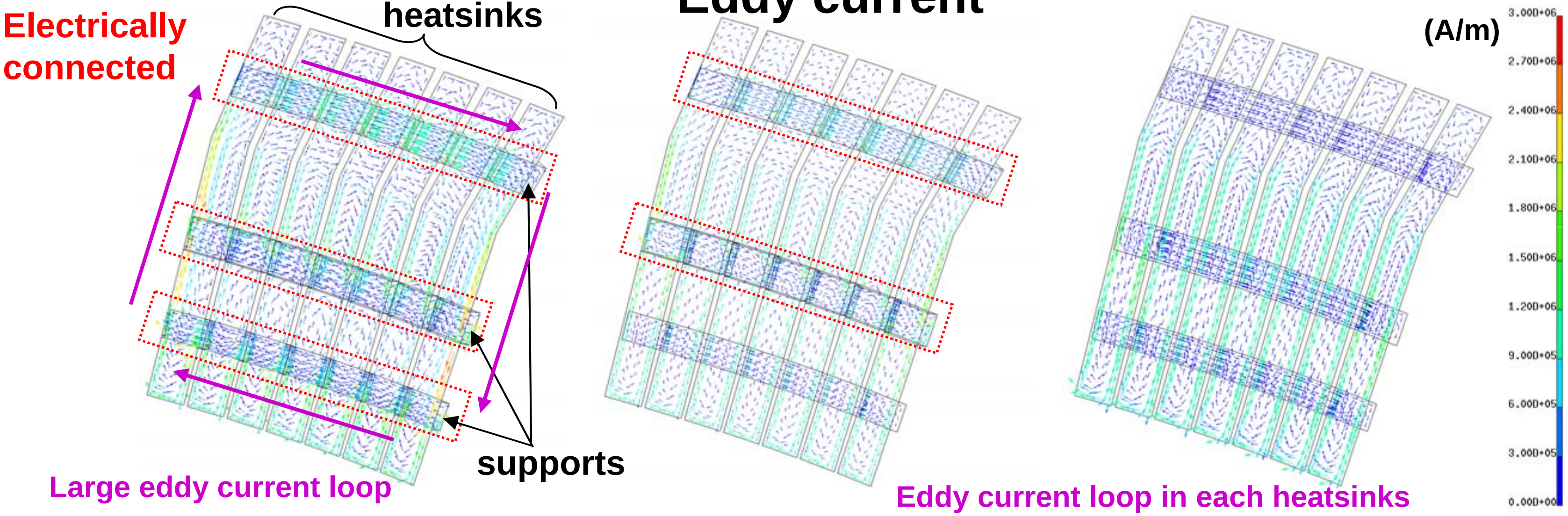
C: σ_t = 109MPa

D: σ_t = 142MPa

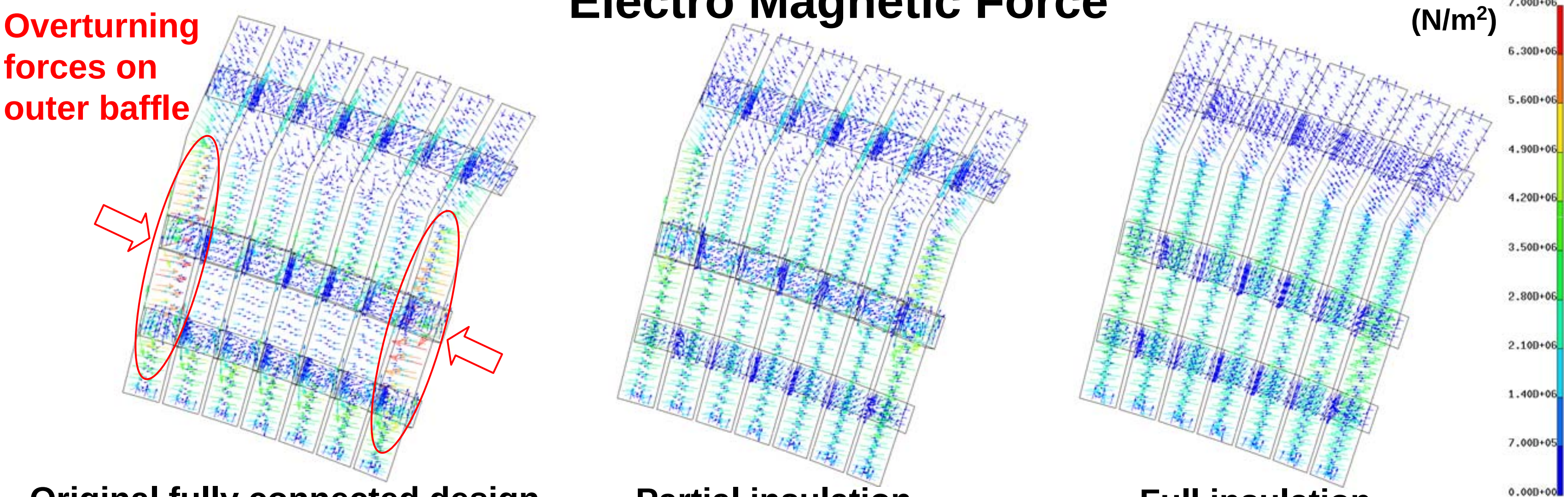
Outer baffle support structure shall be improved.

Improvement of outer baffle design
Insulation reduces eddy current EMF

Eddy current



Electro Magnetic Force



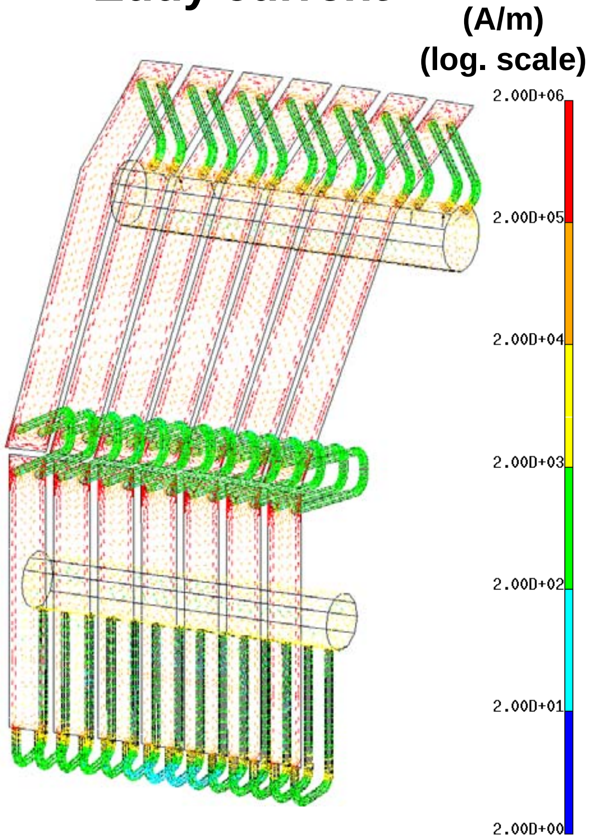
Original fully connected design **Partial insulation** **Full insulation**

Improvement of outer baffle design
EMFs on pipes and headers are small

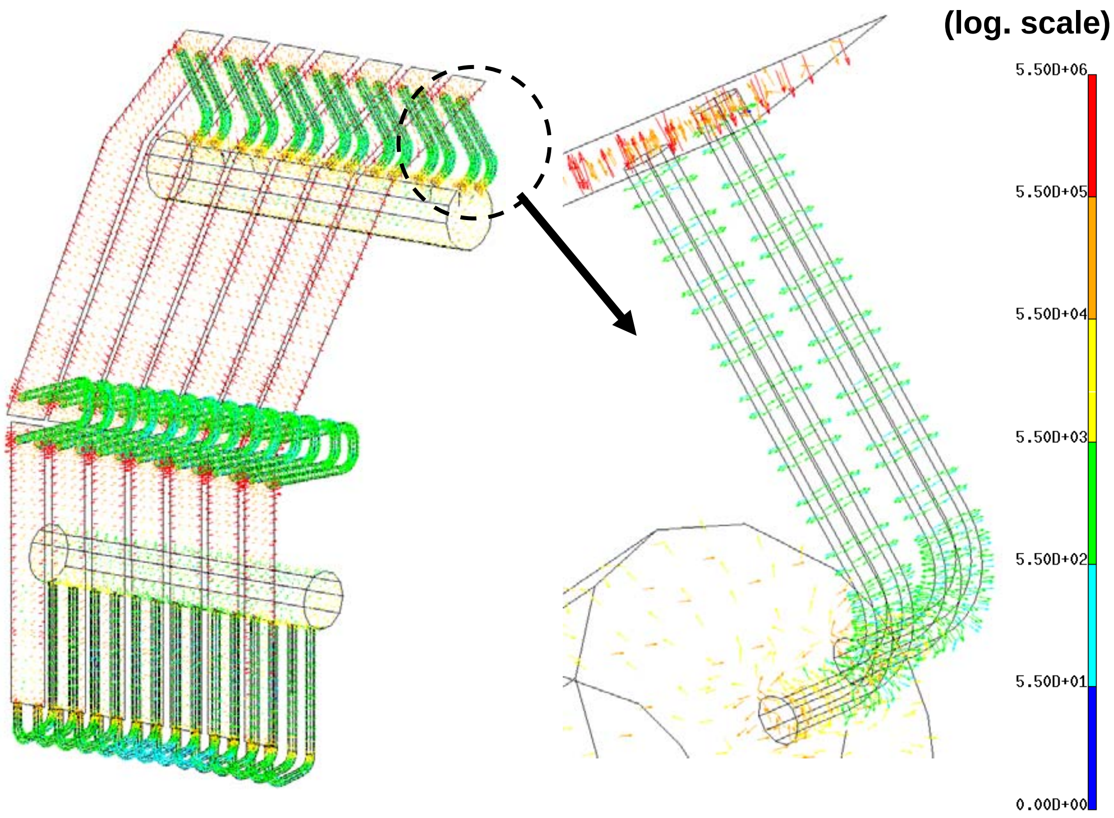
An eddy current loop closes in an each heatsink and does not make large loop through pipe connection and headers even for full insulation between heatsinks and their support.

Full insulation model in VDE 10ms case

Eddy current



EMF due to eddy current



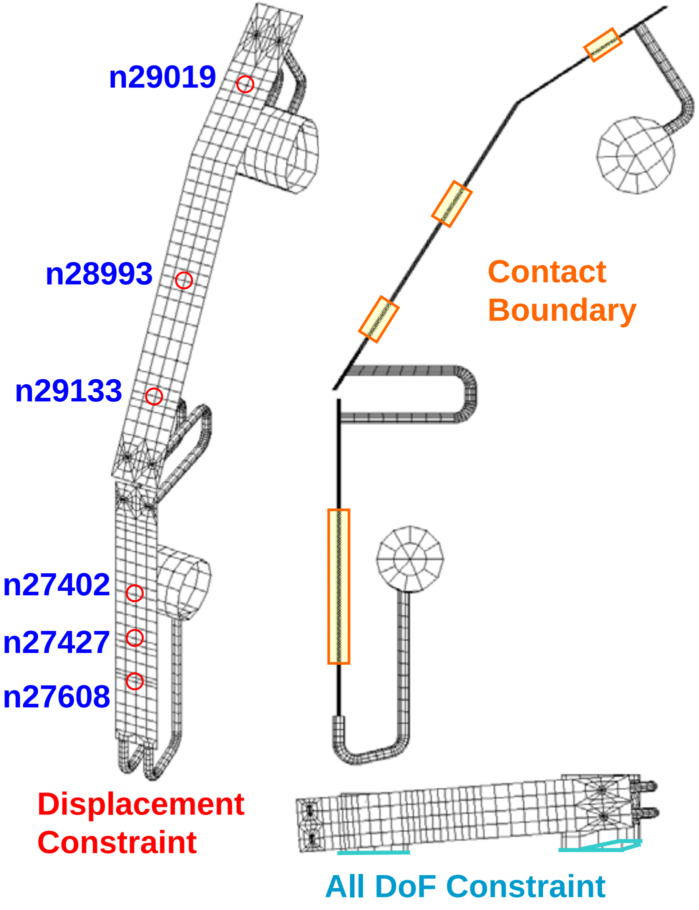
Improvement of outer baffle design
EM stress analysis of heatsinks and pipes

Maximum displacement and stress are within the design limit and will be reduced by optimizing bolt joint position of an outer target heatsink.

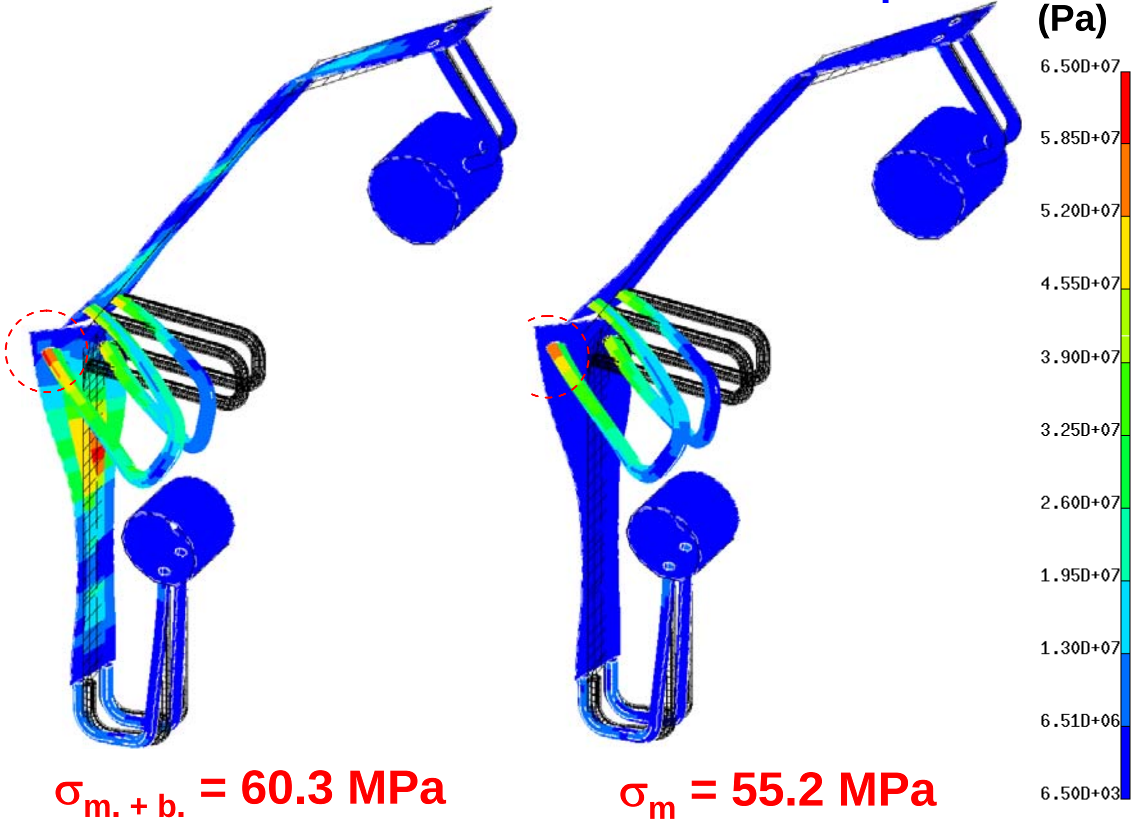
Structural Model focused to the channel at the edge

Torsion deformation induces displacement control load to the middle channel of the outboard heat sink

Bolt Joint **Contact and Boundary**



at 1.159sec, Scale Factor: 200 Max. Disp: 0.634 mm



$\sigma_{m.+b.}$ = 60.3 MPa

σ_{m} = 55.2 MPa

実際の物作りの進め方

１．予算、工期を考慮して製造手法を選択。

２．量産向け試作試験、実機大試作試験により
製造手法の妥当性を確認する。
（モノブロックターゲット量産、カセット配管系統、
ヒートシンク量産、遠隔保守ツール、カセットフレーム溶接）

３．製造工程、品質の監視。

量産技術の確立　モノブロックターゲット

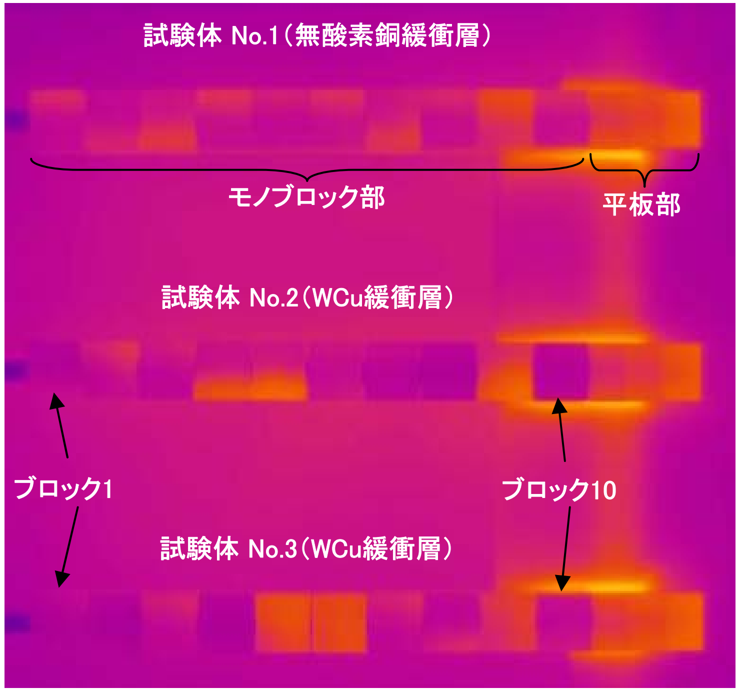
✓量産向けにCFCブロックへの前処理をTi/Cuメタライズ（手作業）からTiコーティングに変更

✓緩衝層を無酸素銅からWCuに変更

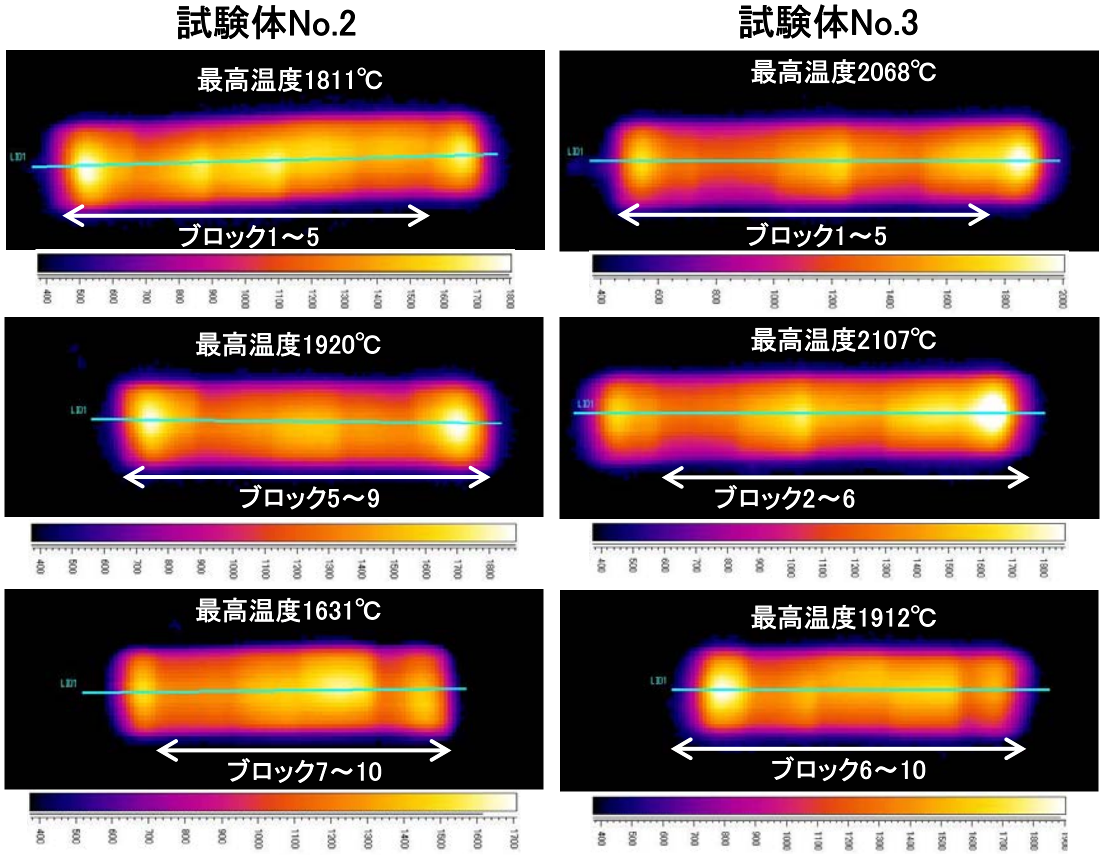
✓ロウ付け温度条件を若干緩和

サーモグラフィー試験

（95℃温水通水から、5℃冷水通水に
切り替えて温度応答を赤外カメラで測定）



温水冷水切替2秒後の表面温度分布



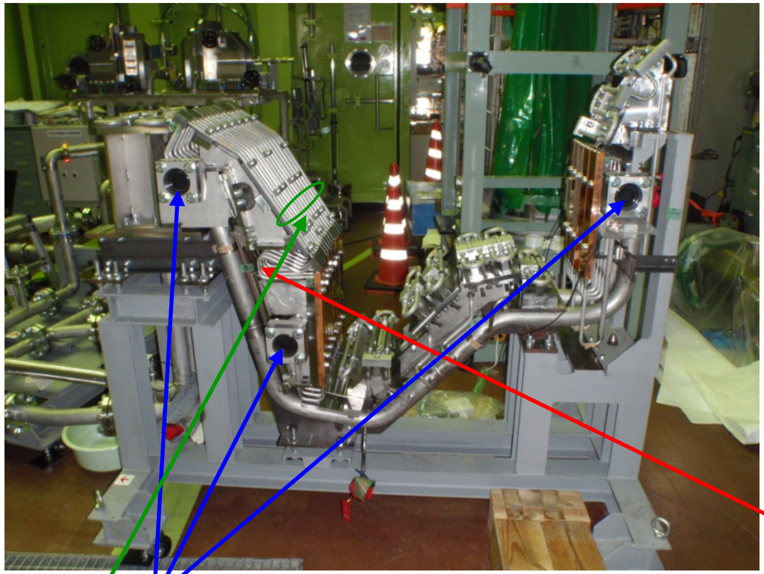
JEBIS熱負荷試験結果（～15MW/m^2、5秒後の表面温度）

若干のブロックで接合不良が生じているので、量産開始には更に最適化が必要。

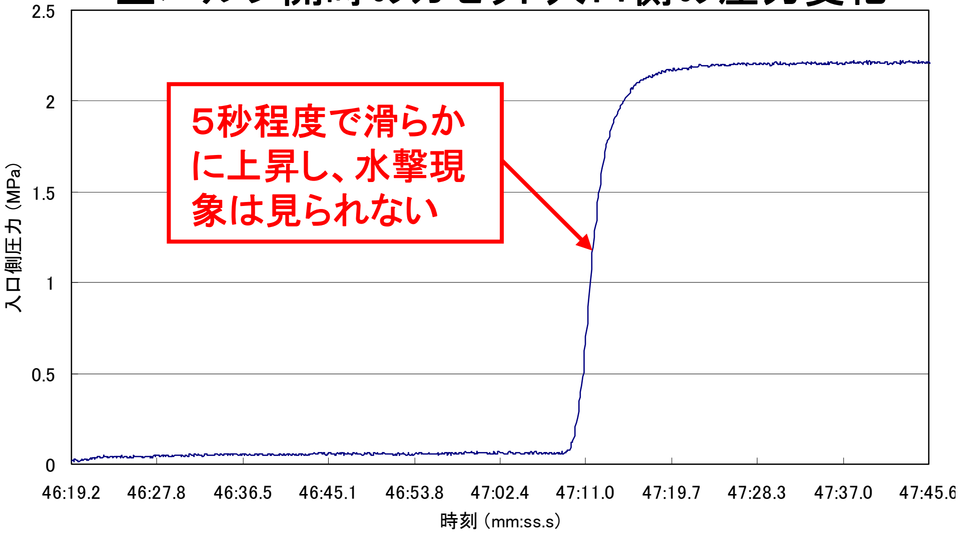
実規模大試作　カセット配管系統流動特性

カセット1体の配管系統を模擬する試験体に定格流量（750L/分＠2MPa）を通水して、圧力損失と流量配分、注排水手順とウォーターハンマーの有無、各部の異常振動の有無などを確認した。

ダイバータカセット配管系統模擬試験体

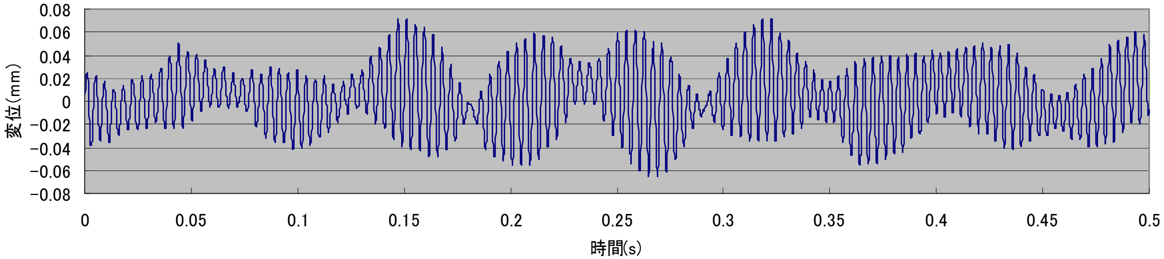


主バルブ開時のカセット入口側の圧力変化



5秒程度で滑らかに上昇し、水撃現象は見られない

レーザー変位計による配管の振動測定結果



最大振幅≦±50μm ⇒疲労は問題にならない

注水時の気泡、排水時の冷却水の残留は観察されず。

並列部の流量配分のばらつきは小。

全体の圧力損失は予想の1．5倍

⇒溶接の調整代確保のため
　接続部の形状が理想的でないため圧損増大

その他の量産向けおよび実機大試作試験

水冷ヒートシンク量産のための試作、試験

✓CuCrZr同士、CuCrZr/SUSのロウ付け条件最適化
（ロウ材、使用炉、温度、冷却条件など）
✓母材およびロウ付け部の強度試験
✓実機大ヒートシンクの試作と耐圧、リーク試験
✓実機大ヒートシンクの熱負荷試験、繰り返し曲げ疲労試験

を実施して、量産開始に必要なデータを収集した。

遠隔保守用配管切断ツールのプロトタイプ試作試験

管内から配管を切断するツールのプロトタイプを試作し、
再現性良く配管が切断できるか確認した。

カセットフレーム試作

溶接手順、溶接部強度、溶接変形の確認

⇒部分試作の溶接変形大のため溶接継手形状を変更、
現在、実機大試作を実施中。

まとめ

✓JT−60SAは高ベータ定常研究を主目的とする、ITERとDEMOに貢献する日欧共同のBA計画と国内計画の合同計画。

✓JT−60SAの下側ダイバータは、高ベータ化研究に適した配位で、ITERと同様の熱粒子制御研究が可能である。

✓工学的には、モノブロックターゲット、水冷ヒートシンクによる定常除熱、将来の遠隔保守に対応するためのダイバータカセット導入、部分的・段階的な改良が可能なモジュール化設計が基本コンセプト。

✓全体設計の成立性は、電磁力解析、構造解析、熱応力解析などで確認している。

✓実機量産開始に向けて、量産試作試験、実機大試作試験を実施中。

若手の皆さんへの期待

詳細設計、R&D、物作りは、ボトムアップ（材料、基本技術、量産技術などを順番に積み重ねる）が必要。

一方、概念設計、特に、目標設定はトップダウン（計画全体、装置全体の目的から各機器へ要請）で決まる。

材料や基本技術の研究開発には１０年単位の時間が掛かるが、目先の計画において、トップダウンで与えられる目標設定がそれよりも短い期間で変わってしまうことがある。

正しい方向に研究開発を積み上げていくためには、年寄りから与えられた目標設定を鵜呑みにしないで、より遠くのゴールを見据えて方向性を決める必要がある。

例えば、原型炉に向けた研究開発なら、各自が商用炉のイメージをしっかりと持つことが重要と思います。