Technology and Manufacturing of Plasma Facing Components

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Plasma Facing Component Technology Gr., Dept. of ITER project,
National Institutes for Quantum and Radiological Science and Technology(QST)

Contributed by

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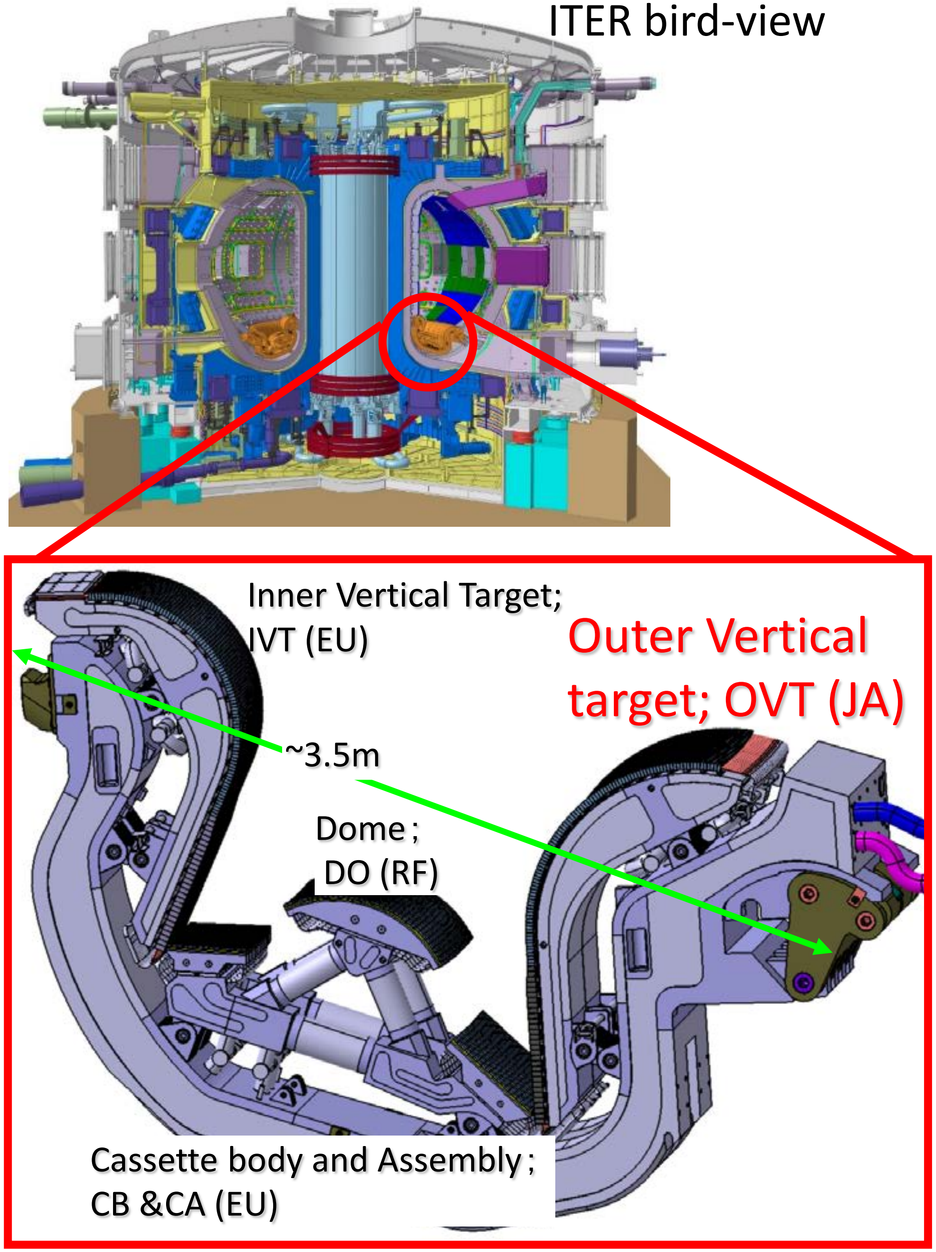
F4E IVT, CB team
RFDA, Dome team

Outlines

- Brief design review of ITER PFC, especially, Divertor Outer Vertical Target (OVT) and heat load specification
- How-to-Realize, Manufacture and Inspect ITER PFCs, esp. ITER OVT.
  - Joining Armor material to Heat Sink (Cooling tube), technology validation through high heat flux testing
  - Welding; cooling tube and steel support structure
  - Assembling
  - Other engineering topics
  - Inspection of PFCs

ITER Divertor

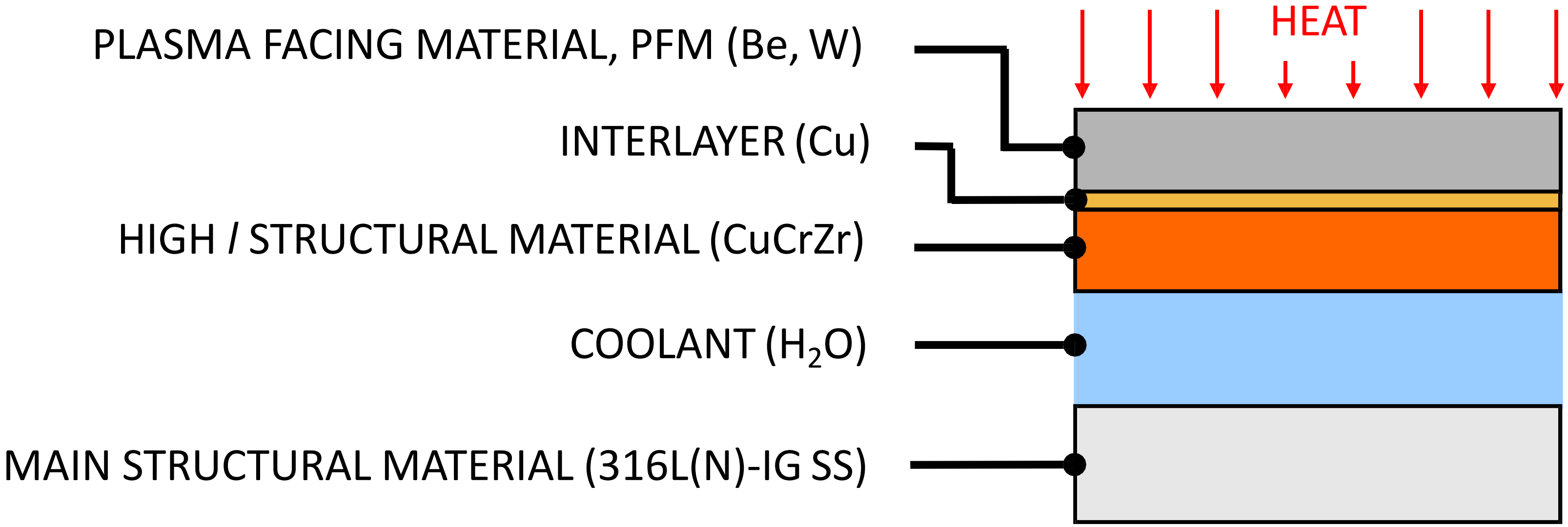


- **To absorb radiation and particle heat fluxes from plasma while allowing neutral particles to be exhausted to the Vacuum System**
- To minimize the influx of impurities to the plasma
- To provide shielding to reduce heat and neutron loads in the vacuum vessel and ex-vessel components
- To house diagnostics

One of 54 divertor cassettes
8.5 ton/cassette (W: 10 % of mass)
Three Parties (EU, RF and JA) are to supply PFC to ITER. JADA is to manufacture OVT

Basic Concept of Actively-Cooled PFC

- Long pulse (superconducting) → **active cooling**
  - **thermal conductivity**, *k* (W m^{-1} K^{-1}), is important material property (a function of temperature and neutron fluence)
  - **bonded components** that are welded to the cooling circuit



HEAT

PLASMA FACING MATERIAL, PFM (Be, W)

INTERLAYER (Cu)

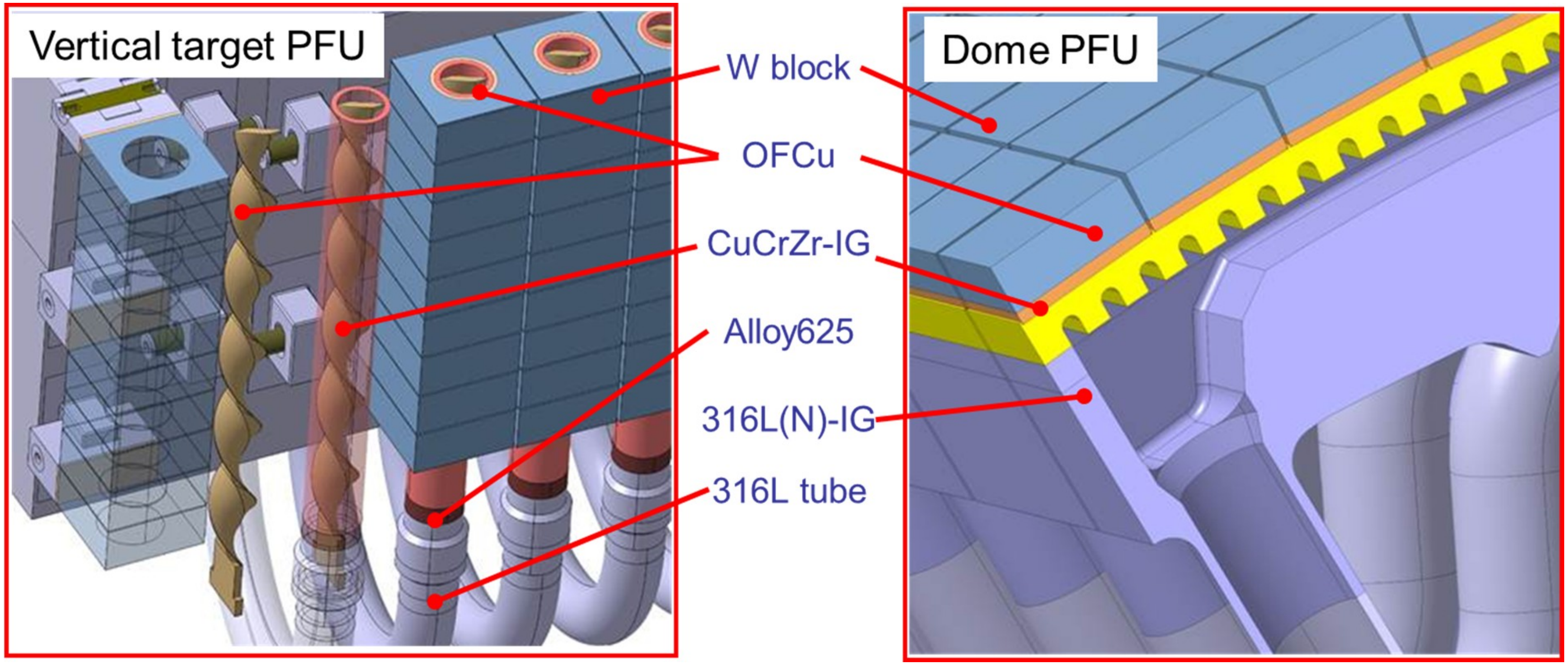
HIGH / STRUCTURAL MATERIAL (CuCrZr)

COOLANT (H_2O)

MAIN STRUCTURAL MATERIAL (316L(N)-IG SS)

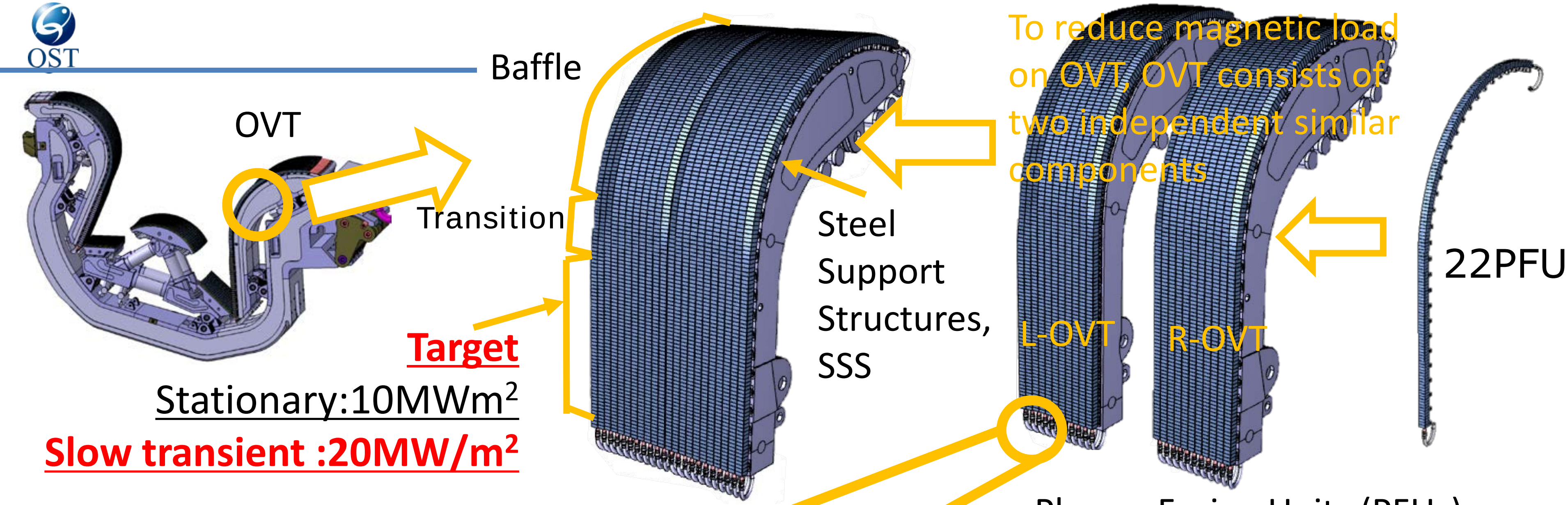
- ➢ Need: Metallurgical bonding between armor and heat sink: brazing, HIP, etc.
- ➢ Need: Connection to coolant circuit: welding
- ➢ the joints to be inspected

ITER Divertor Plasma-Facing Unit design



- **Vertical Target Plasma-Facing Unit**
  - **Monoblock** with **swirl tape** at high heat flux handing area
  - W armour/OFCu/CuCrZr-IG
  - Tube to tube joint CuCrZr-IG/ Alloy625/ 316L pipe
  - Twisted tape insertion
- **Dome Plasma-Facing Unit**
  - **W/Cu flat tile** with CuCrZr/316L(N)-IG **hypervapotron** coolant channel

PFC example: ITER Outer Vertical Target (OVT)



Baffle

OVT

Transition

Target

Stationary:10MWm^2

Slow transient :20MW/m^2

Steel Support Structures, SSS

To reduce magnetic load on OVT, OVT consists of two independent similar components

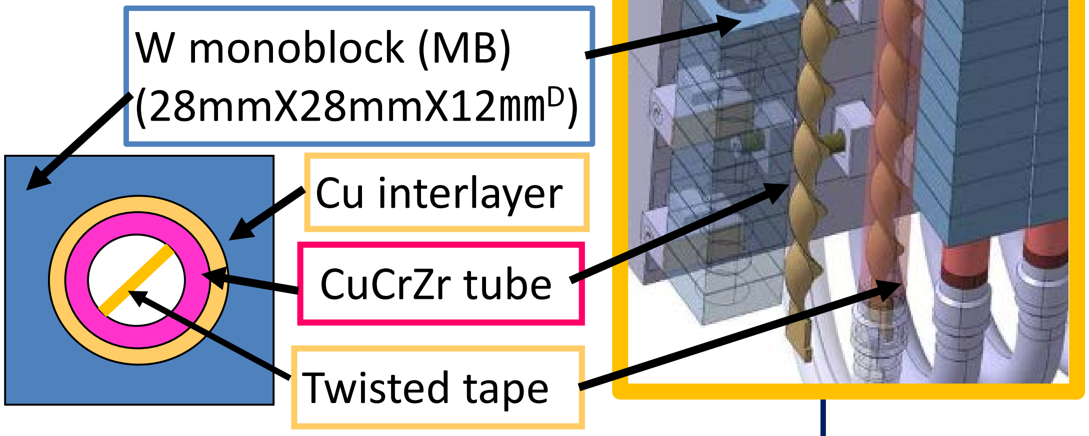
L-OVT

R-OVT

22PFU

Plasma Facing Units (PFUs):
x 11PFUs /L- + 11PFUs/R- OVT

PFU： W monoblock (MB) concept



W monoblock (MB) (28mmX28mmX12mm^D)

Cu interlayer

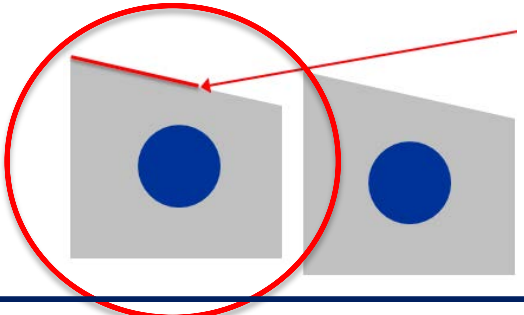
CuCrZr tube

Twisted tape

to augment heat removal capability of water flow

Leading Edges needs to be protected especially, at target by bevelled W-MB as explained by Pitts' presentation.

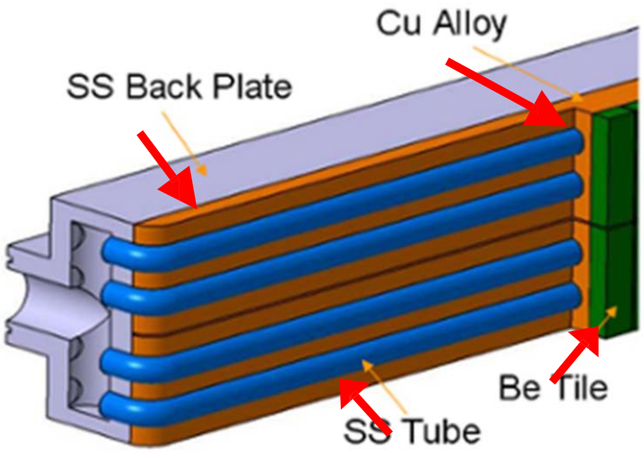
Chamfered MB

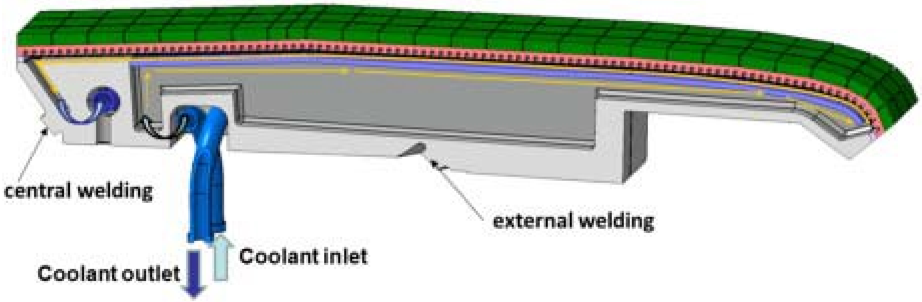


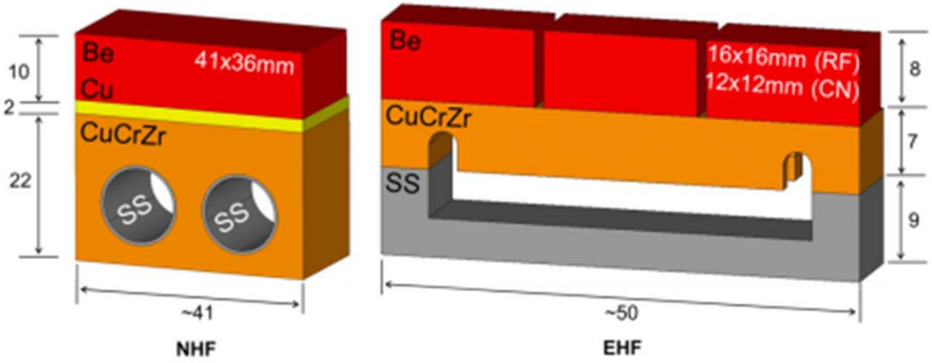
ITER First Wall Plasma-Facing Unit design

First Wall Normal Heat Flux Panel:
Steel Cooling Pipes

First Wall Enhanced Heat Flux Panel:
CuCrZr-IG plate with hypervapotron







Raffray A R et al 2014 Nucl. Fusion 54 033004

T. Hirai, et al., Phys. Scr. T167 (2016) 014072. (5pp)

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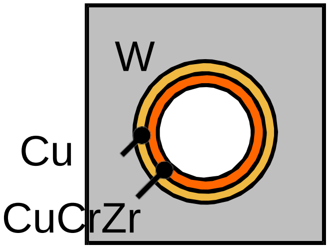
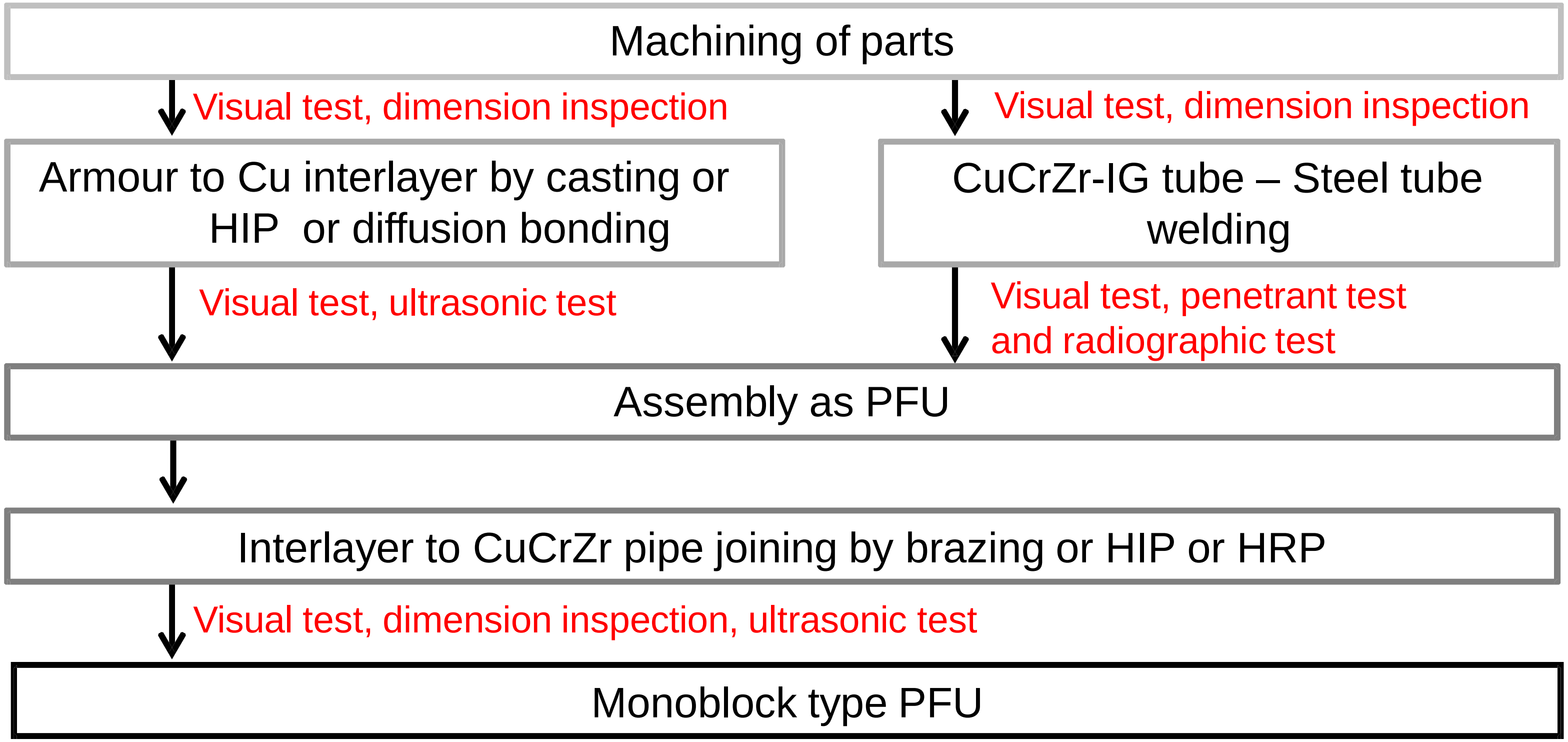
Monoblock type PFU Manufacturing and Inspection

❑ Monoblock type Plasma-Facing Unit



Reliable plasma-facing unit manufacturing routes and inspection plan shall be selected to ensure high acceptance rate



Machining of parts

- Visual test, dimension inspection → Armour to Cu interlayer by casting or HIP or diffusion bonding
  - Visual test, ultrasonic test
- Visual test, dimension inspection → CuCrZr-IG tube – Steel tube welding
  - Visual test, penetrant test and radiographic test

Assembly as PFU

Interlayer to CuCrZr pipe joining by brazing or HIP or HRP

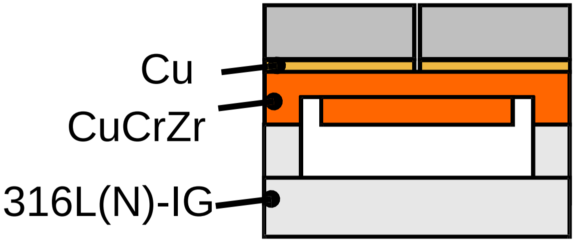
Visual test, dimension inspection, ultrasonic test

Monoblock type PFU

HIP: Hot isostatic pressing, HRP: hot radial pressing

Flat-tile type PFU Manufacturing and Inspection

❑ Flat tile Plasma-Facing Unit for dome, first wall enhanced heat flux



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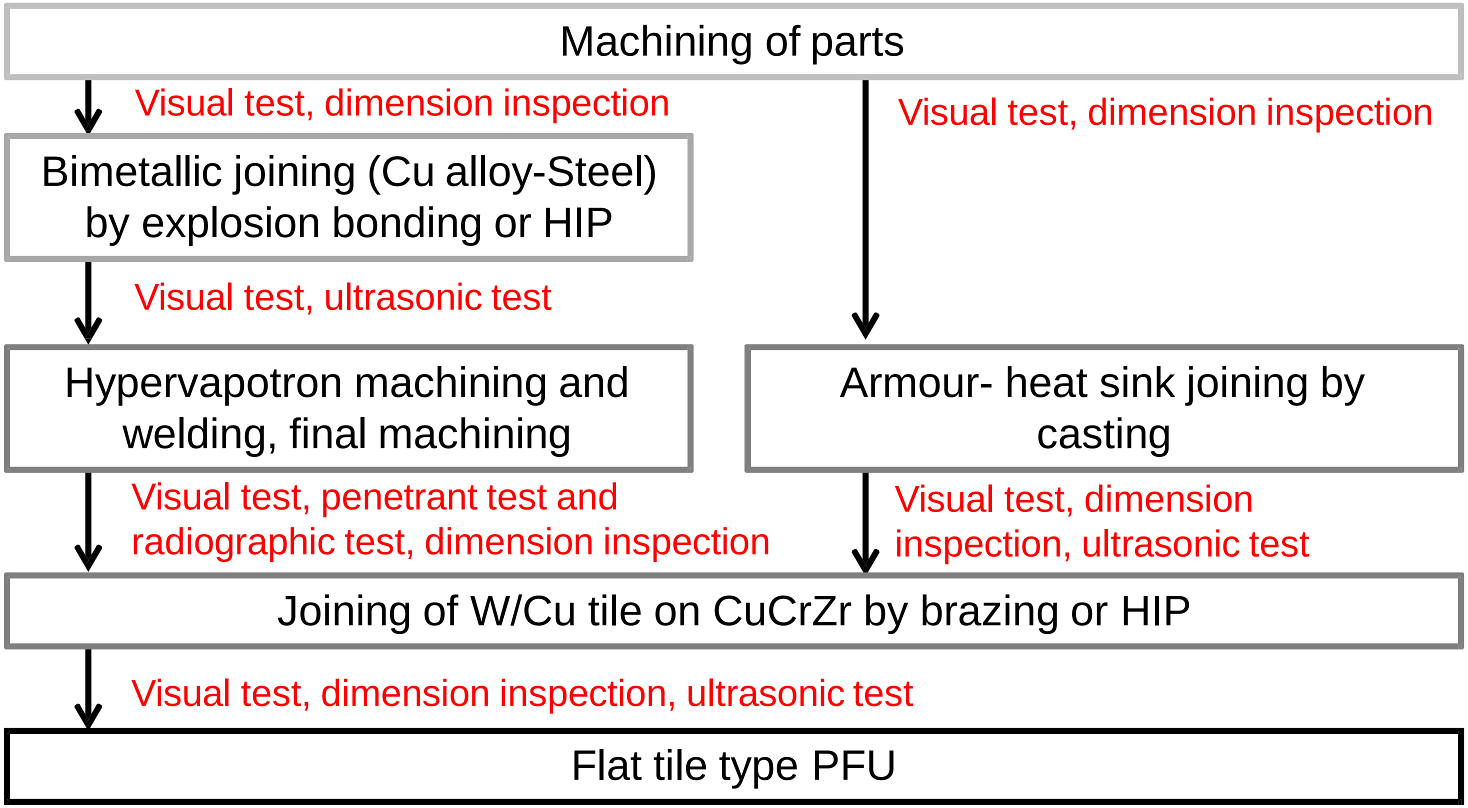


Machining of parts

Visual test, dimension inspection

Bimetallic joining (Cu alloy-Steel) by explosion bonding or HIP

Visual test, ultrasonic test

Hypervapotron machining and welding, final machining

Visual test, penetrant test and radiographic test, dimension inspection

Visual test, dimension inspection

Armour- heat sink joining by casting

Visual test, dimension inspection, ultrasonic test

Joining of W/Cu tile on CuCrZr by brazing or HIP

Visual test, dimension inspection, ultrasonic test

Flat tile type PFU

CuCrZr; difficult material

It reaches an optimum in strength after a thermo-mechanical treatment involving

1) first a solution annealing at high temperature (>950 ºC) to dissolve the alloying elements (Cr, Zr),
2) then a water quench to keep the alloying elements in supersaturated solid solution at room temperature,
3) and finally an ageing treatment at intermediate temperatures (475 C, 3 hrs) to decompose the supersaturated solid solution into a fine distribution of precipitates.

- PFU joining conditions need to be selected to recover or keep the mechanical properties of CuCrZr after heat treatments.

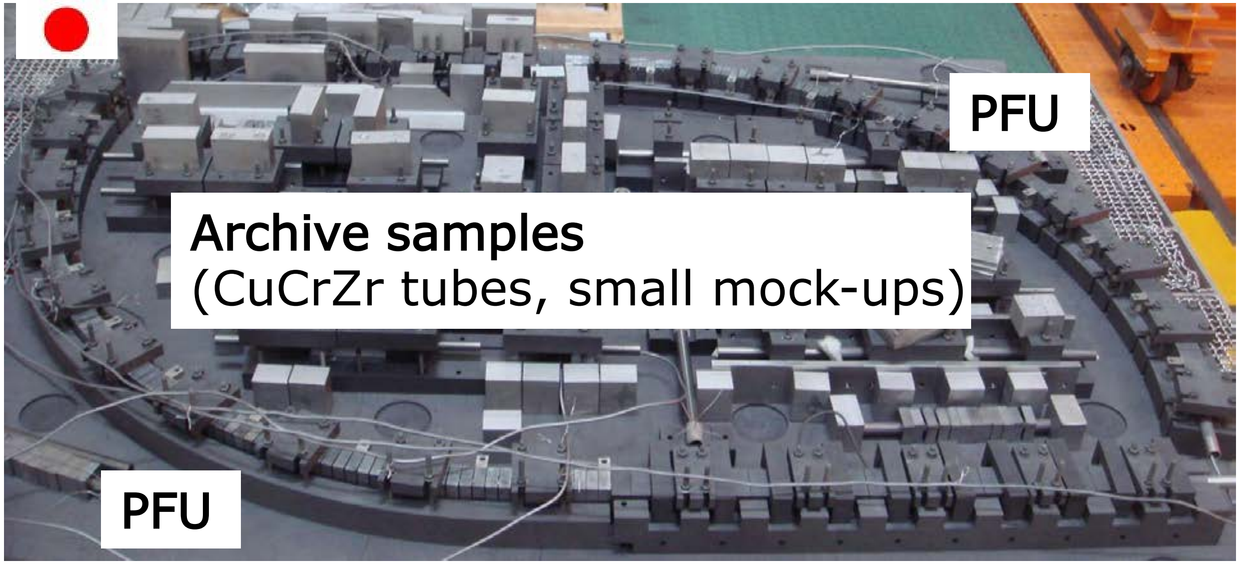
- Delivery conditions of CuCrZr tubes are linked to PFU joining conditions. Commercially available CuCrZr tubes may not fit the requirements.

Consideration of PFU joining conditions

- Filler inserted into joint interface is limited chemically. Elements that has higher vapor pressure (Zn and Cd, etc) and elements that is transmuted into higher-vapor-pressure elements (Ag, Au) are prohibited to use in joint process.
- High temperature joint vs low temperature joint
  - Brazing; joining conditions follows manufacturing condition of CuCrZr.
    1. Brazing at solution annealing temperature followed by gas-quenching with brazing filler (Ti, Ni, Cu-based alloy)
    2. ageing at 475^{o}C for 3hr.
    - Cooling rate of gas-quenching is key parameter. If low cooling rate, CuCrZr mechanical strength can not recovered.
  - HRP, HIP; intermediate temp. higher than ageing temp.
    - Need to prevent over-ageing leading deterioration.
- Assembly during joint need to be properly designed.
  - Thermal expansion
  - Gap controlling between tiles

Assembly for joint

Brazing of OVT (remove cover plate)

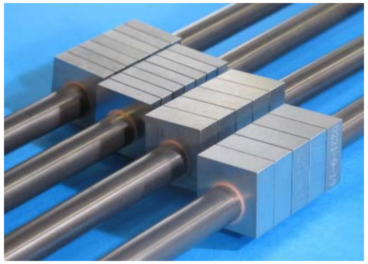


HRP assembly(IVT)

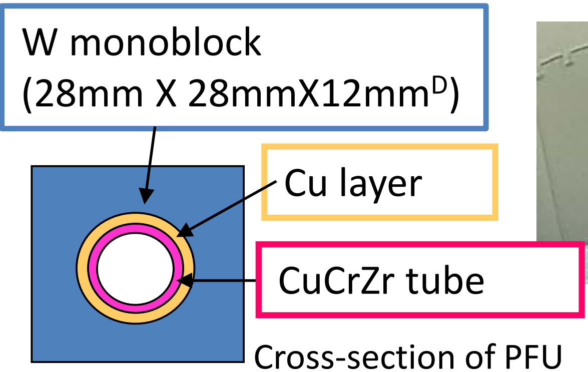
Flat tile joint (Dome)

Example of OVT
Manufacturing Full-length PFU prototypes

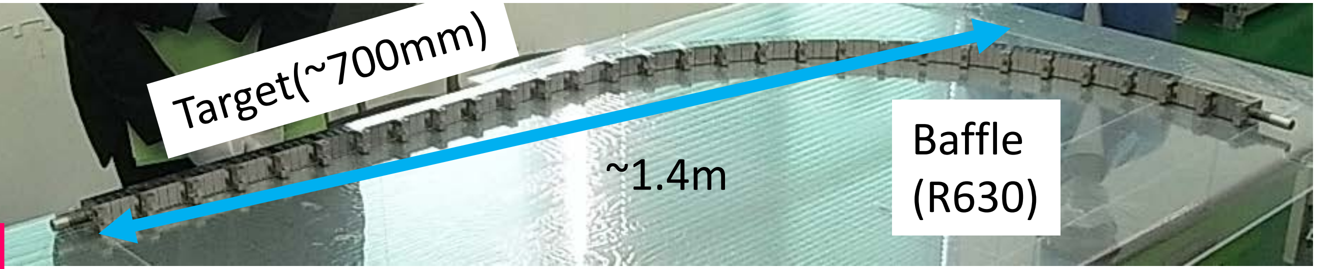
- W/Cu/CuCrZr joint: 2-step joining, 2-step inspection
  1. **W monoblocks/Cu layer: Direct Casting**
  2. **Ultrasonic Testing (UT) on W/Cu joint**
  3. Assembling PFU followed by bending Baffle part
  4. **Cu layer/CuCrZr: High temp. brazing** holding at 980°C followed by gas-quench and aging at 480°C to recover of CuCrZr mech. strength.
  5. **UT on W/Cu and Cu/CuCrZr**



Small scale mock-up with five W blocks



Cross-section of PFU

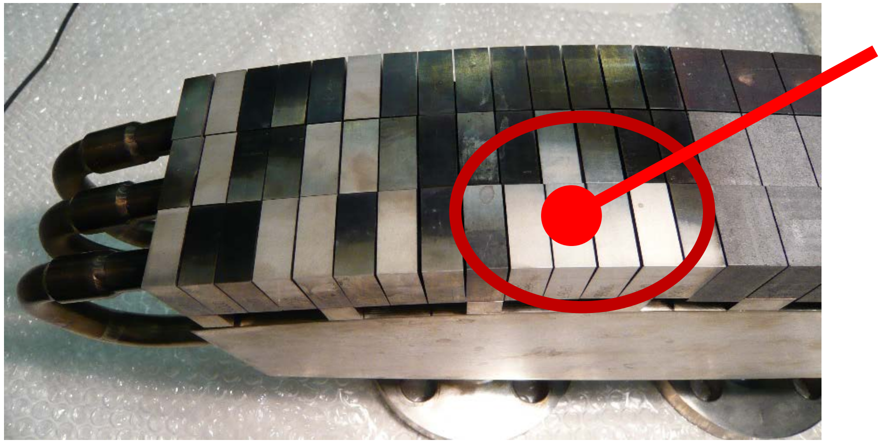


Full-length PFU prototype with 145 W monoblocks

Manufacturing technology of PFU prototypes with no harmful joint defect are available. These prototypes were tested in High Heat Flux Test facility, IDTF (ITER Divertor Test Facility).

Failure experience in manufacturing PFUs

- Using 1 step brazing of W/Cu/CuCrZr resulted in many joint defects.



White W tiles: recrystallized (higher surface temp. (more than 1300ºC) than those of tiles without defects)

→ 2 step joint of W/Cu and Cu/CuCrZr.

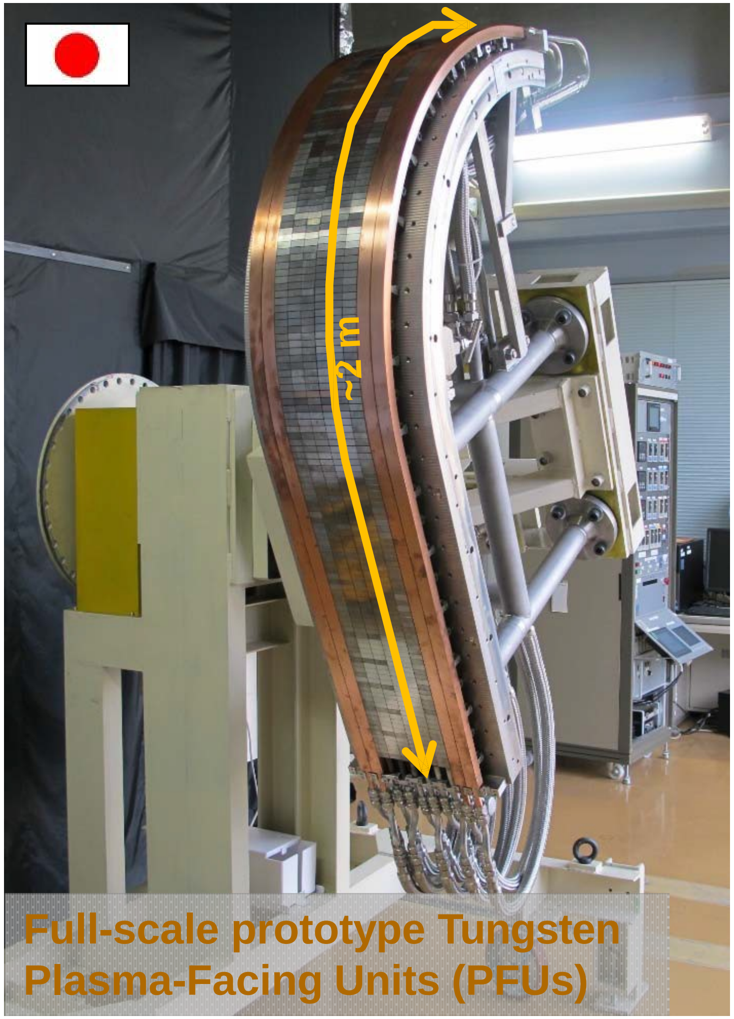
JADA VTQP after high heat flux testing

- Gap control between joint interface such Cu interlayer and CuCrZr tube are important. If fail, W will crack during high temperature heat treatment due to thermal expansion of tube.

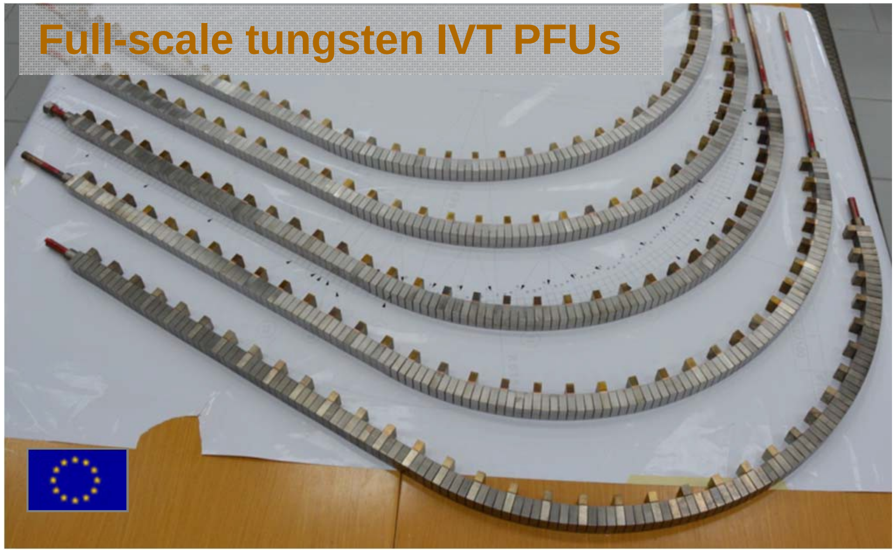
PFU joint process

- **Needs careful manufacturing route that can be scaled up to real size.**
- **Needs careful controls of gap and temperature**
- **Needs sophisticated jigs**

Divertor Prototype Plasma-Facing Units

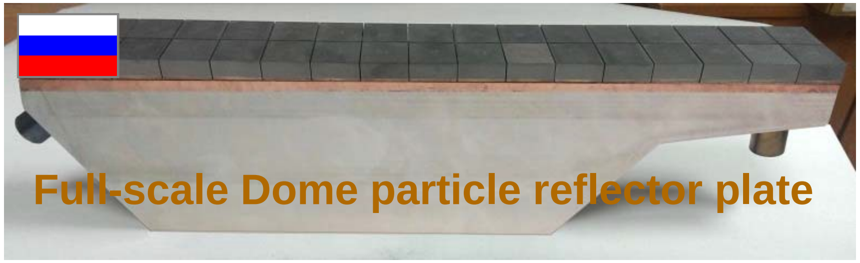


Full-scale prototype Tungsten Plasma-Facing Units (PFUs)



Full-scale tungsten IVT PFUs

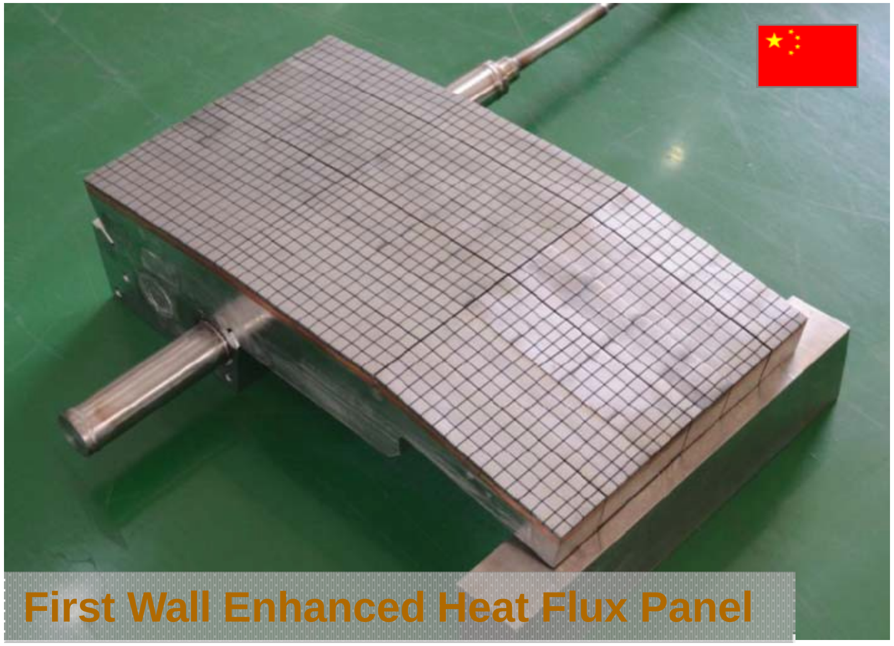
Full-scale Dome Umbrella



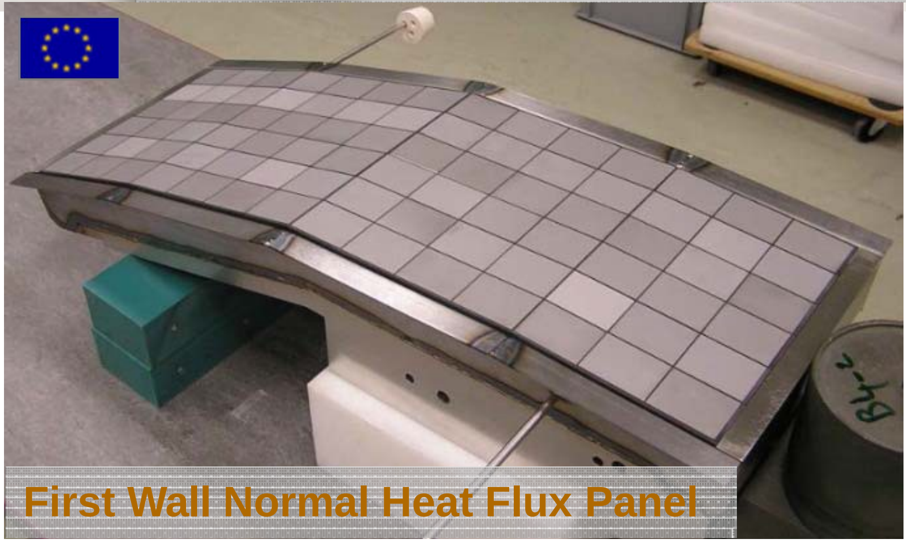
Full-scale Dome particle reflector plate

First Wall Semi-Prototype

First Wall Enhanced Heat Flux Panel



First Wall Enhanced Heat Flux Panel



First Wall Normal Heat Flux Panel

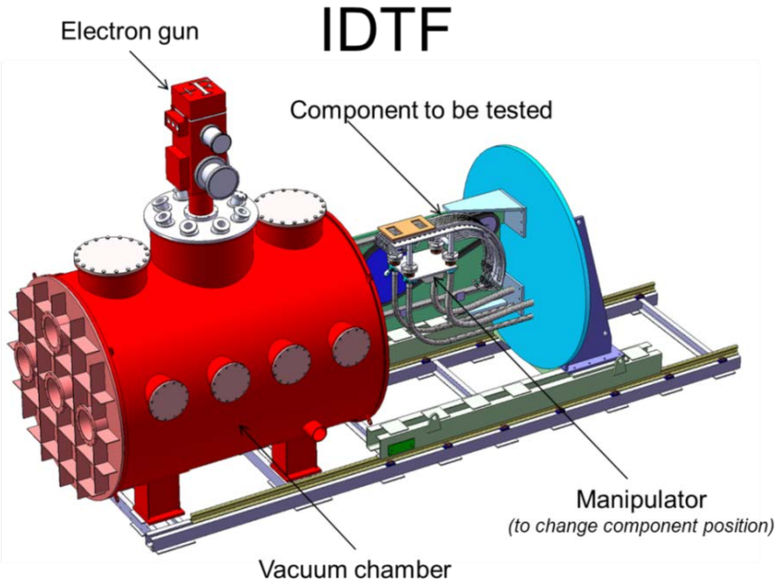
Enhanced Heat Flux, ≤ 4.7 MW/m2

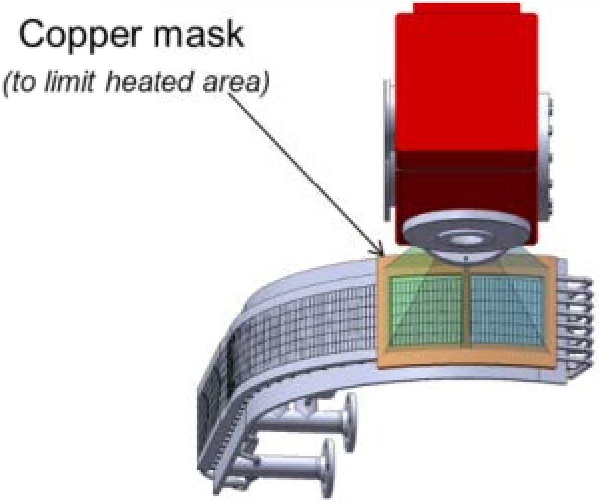
Normal Heat Flux, ≤ 2.0 MW/m2

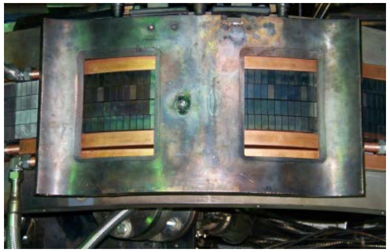
ITER Divertor Test Facility (IDTF)

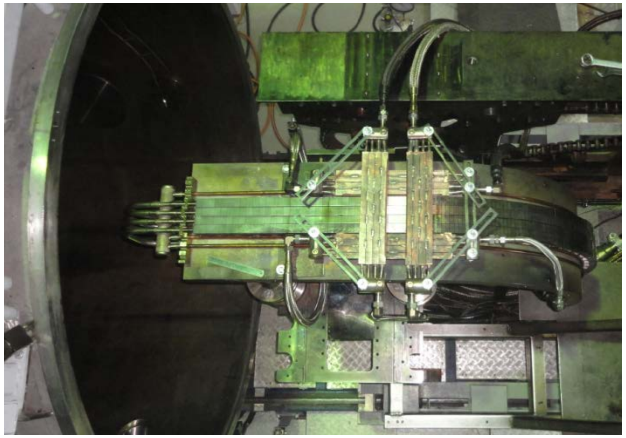
Objective: To qualify and check PFU thermal performance during series production (~20% PFU sampling)

- Location: Efremov Institute, St-Petersburg, RF
- Electron beam test facility
- Maximum electron beam power: 800 kW
- Maximum accelerating voltage: 60kV
- Cooling water parameters are ITER divertor relevant
- Dedicated system of diagnostics

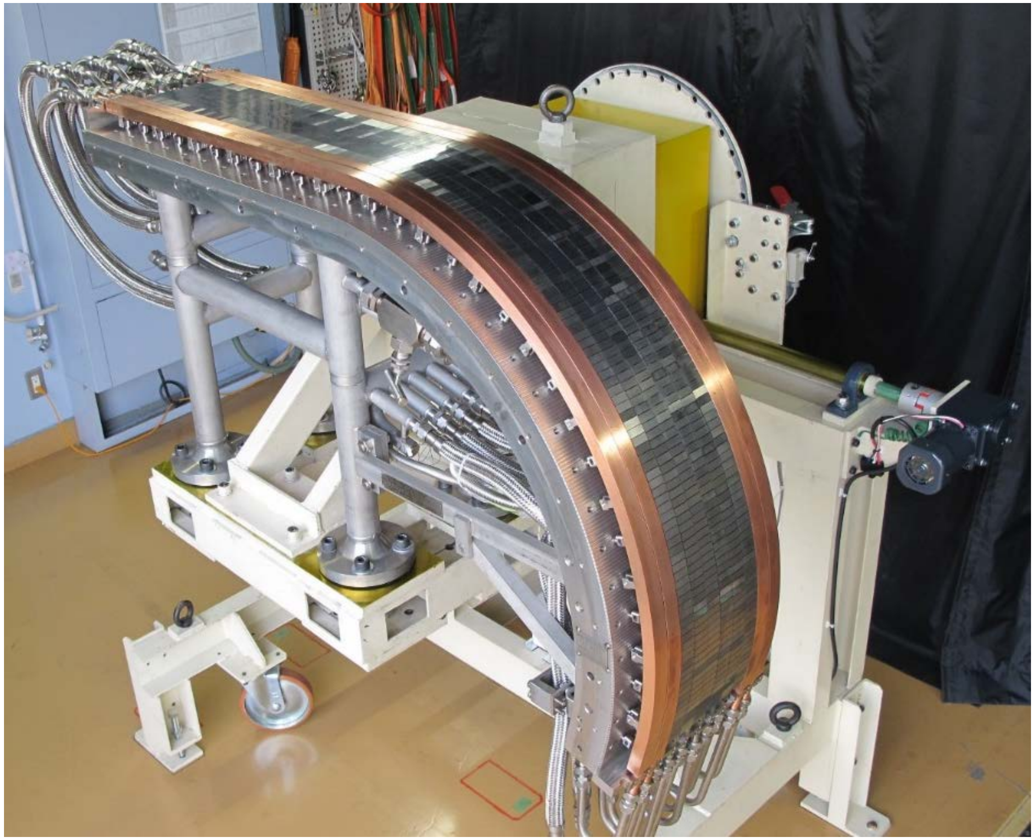


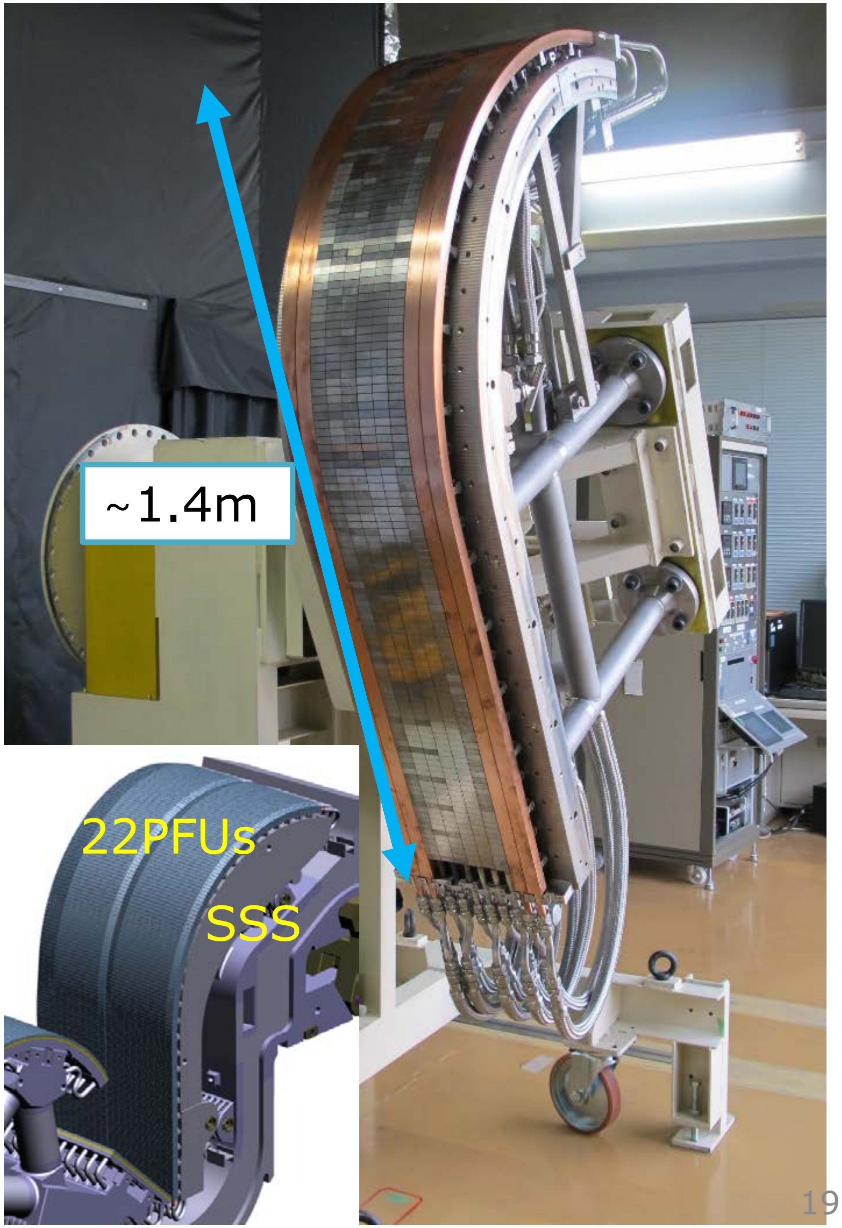






Full-length full-W OVT PFU prototypes

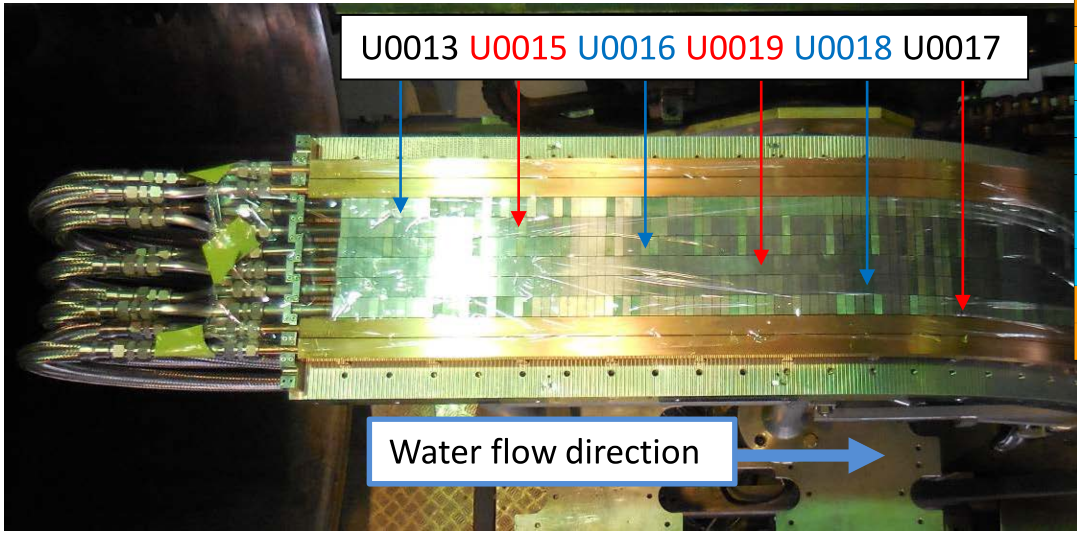




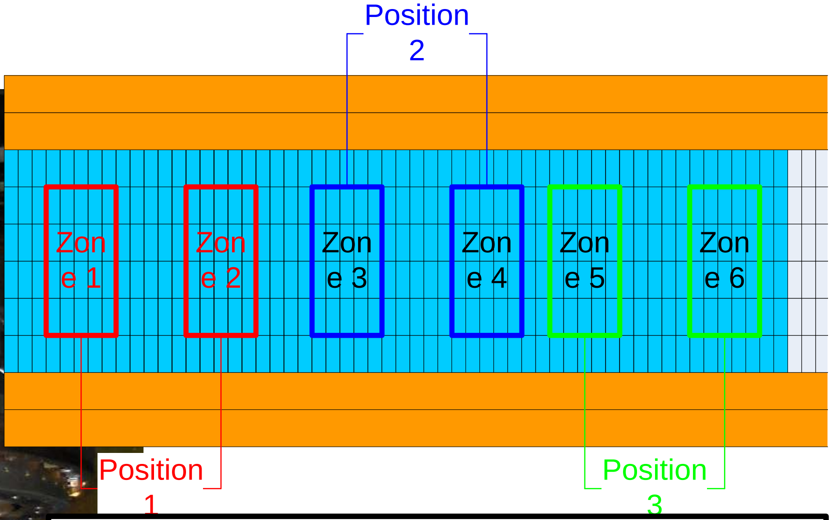
- ➢ 6 PFU prototypes were mounted on test frame resembling to SSS geometry as Test Assembly.
- ➢ Before HHF testing by RFDA and IO-CT, surface profile of prototypes was examined.

HHF testing on OVT PFU prototypes

- 4 prototypes mounted on test frame was tested at electron beam facility, IDTF (ITER Divertor Test Facility) operated by Efremov Inst. (RFDA). HHF testing was performed as qualification test for W monoblock technology by IO-CT.
- Heat load conditions on target part;
  - 10MW/m^2(10 sec)･5000 cycles,
  - 20MW/m^2(10 sec)･300 cycles (design requirement) + 700 cycles (additional)
  - Heating area: 5-6 W blocks/PFU (20-24 W blocks at once)
- Cooling cond. ：70^{o}C, 4MPa, 10m/s

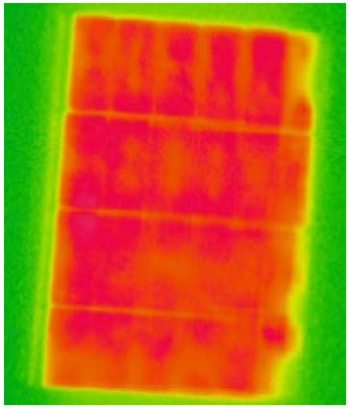


Test Assembly in IDTF

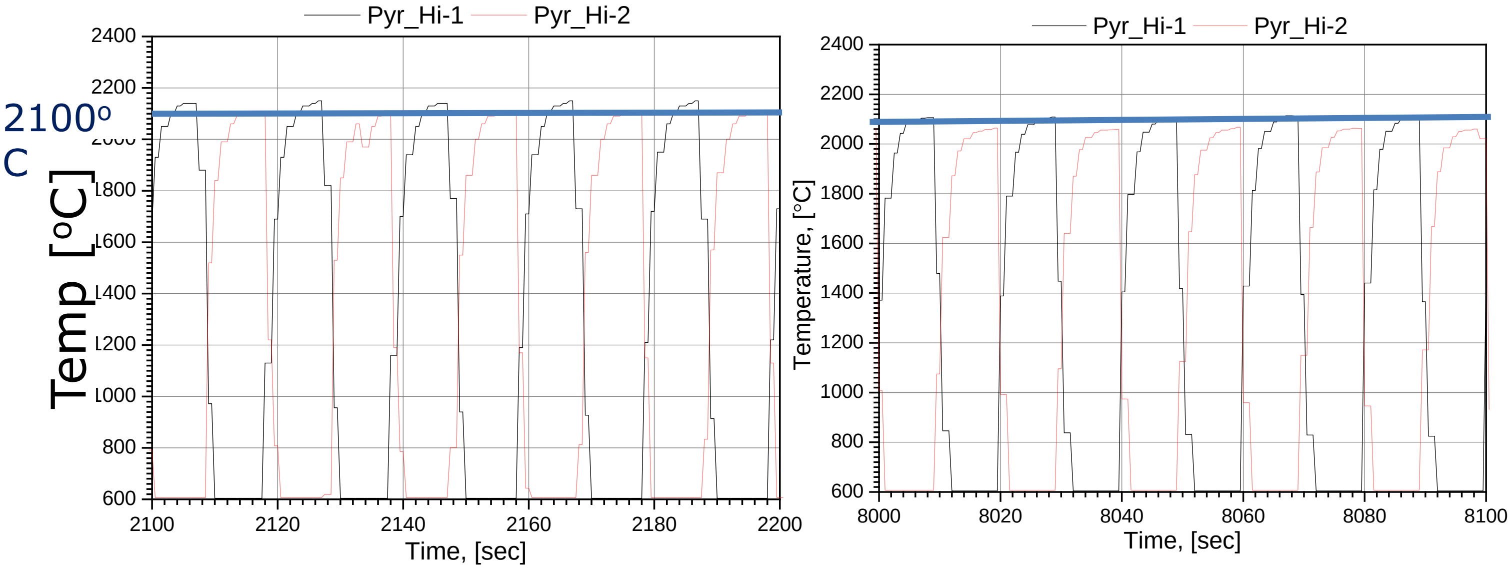


Test areas for 20MW/m^2 heating (performed onto central 4 prototypes)

HHF testing on PFU prototypes



IR image (20MW/m² · 1000th cycle)



(a) around 300th cycle

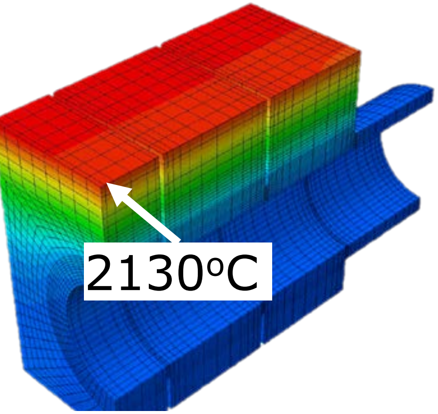
(B) Around 1000th cycle

Surface temperature evolutions of W monoblock under repetitive 20 MW/m² heat load exposure (area 3 and 4)

By courtesy of RFDA

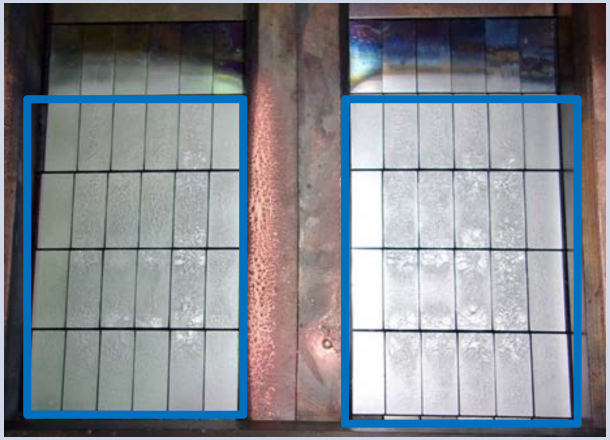
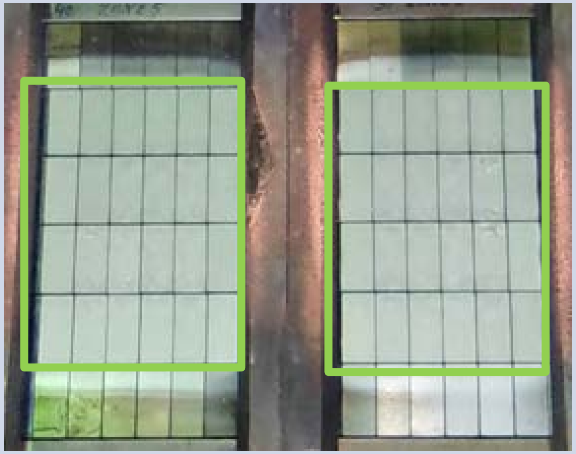
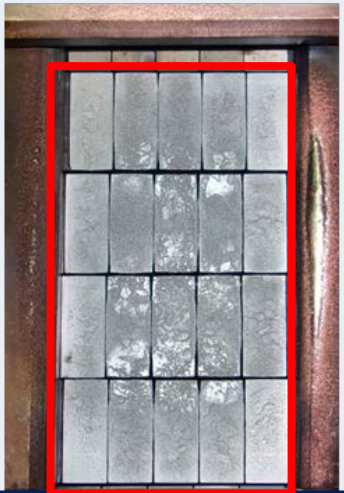
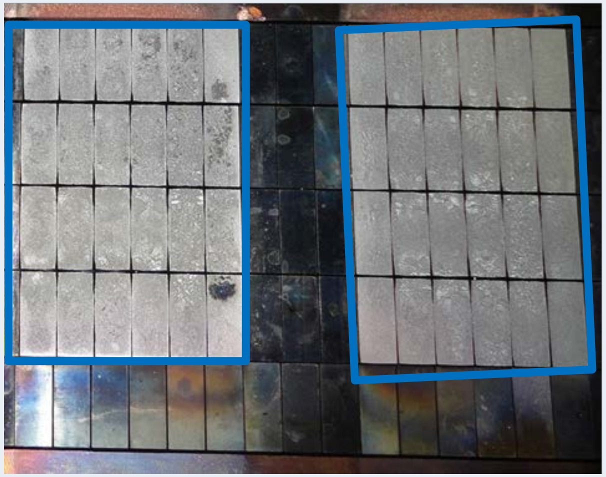
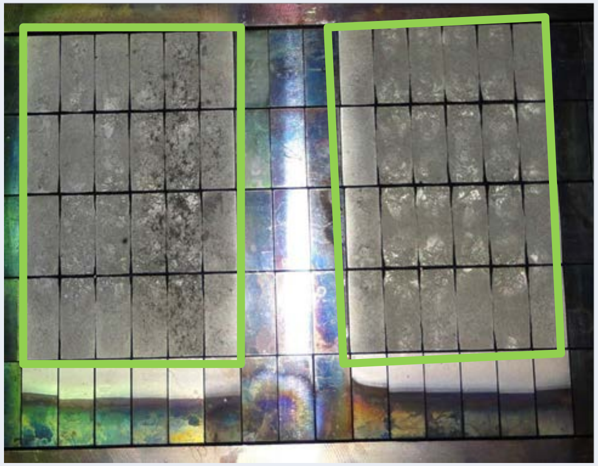
No degradation of heat removal capability and no water leak from cooling tube was observed in all of W monoblocks (116 blocks) exposed to 1000 cycle at 20MW/m².

***116 blocks = 4 PFU x (6 blocks x 4 area + 5 blocks x 1 area)**



Temp. contour under 20MW/m2 for 10s

W surface after 20MW/m^2 repetitive heat load exposure

Zone	2	3&4	5&6
After 300 cycles under 20MW/m^2			
After 1000 cycles under 20MW/m^2			

There was no macro-cracking at W surface after 1000 cycles under 20 MW/m^2, although large deformation of W monoblocks occurred.

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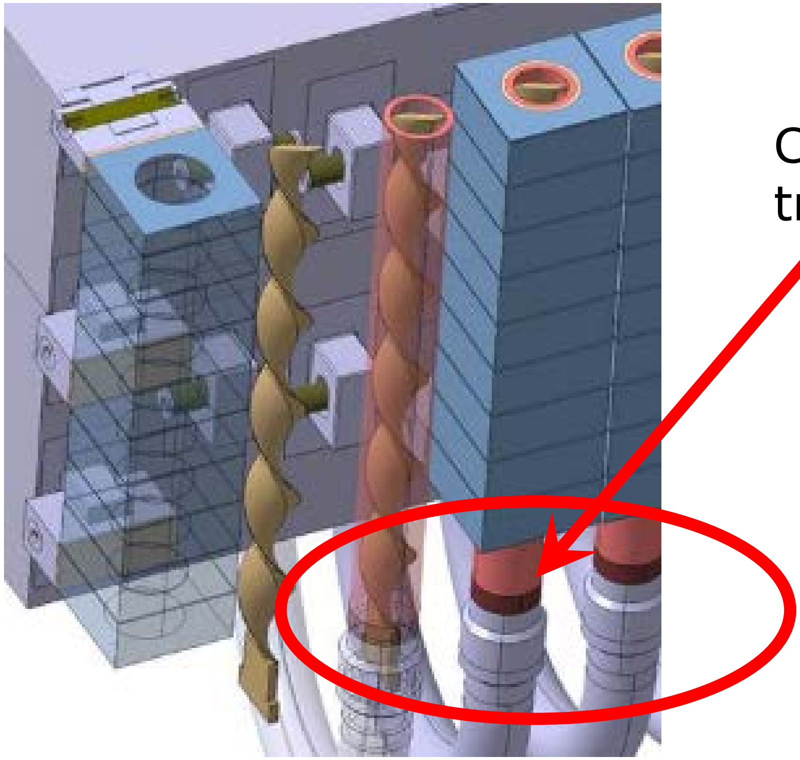
Welding: Heat sink (Cooling tube) and Steel Support Structure (thin wall)

- Vacuum Boundary Welding in Active cooled PFCs is critical to ensure availability of machine.
- They are subjected to 100% Non-Destructive Testing (NDT), i.e. Radiographic Testing.



CuCrZr cooling tube to 316L tube transition with 1.5mm^t

Lower part of Vertical Target

Welding: Heat sink (Cooling tube) and Steel Support Structure (thin wall)

- Cu-steel weld: Copper and iron have low solubility limit, and iron dissolved in copper by welding due to excessive penetration precipitates in the weld metal. This leads easily cracks at weld metal.
- CuCrZr/SS316L dissimilar tube-to-tube joint with transition of Ni-base alloy (Alloy 625) tube (1.5mm^t)
  - CuCrZr to Alloy 625: EBW(Electron Beam Welding)
  - Alloy 625 to CuCrZr: GTAW welding (GTAW: Gas-Tungsten Arc Welding; Orbital welder or manual)

EBW

GTAW Orbital welder

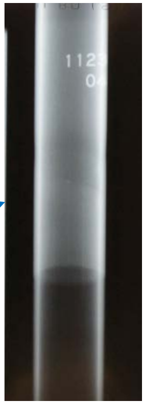
Manual GTAW

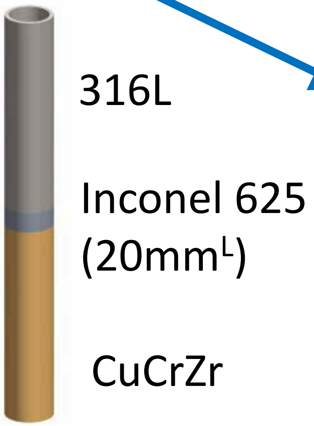
Welding of CuCrZr/316L tube-to-tube joint (Example of thin wall welding)

- CuCrZr/Inconel 625: EB welding
- Inconel 625/316L tube: GTAW welding
- Test specimens after PFU manufacturing heat cycle
- Welding qualification test resulted in;
  - NDT(VI, PT, RT); no defect was detected.
  - Tensile test at 150^{o}C (UTS > 200MPa)

ID	UTS [MPa]	$s_{0.2\%}$ [MPa]	Elong. [%]	Fracture location
TG001	236	119	2.4	CuCrZr
TG002	235	122	5.6	
TG003	245	124	8.8	
TG004	233	112	4.2	
	291	185	4.8	

  - Rotary bending fatigue test (incl. He leak test) and bending test satisfied IO' criteria.

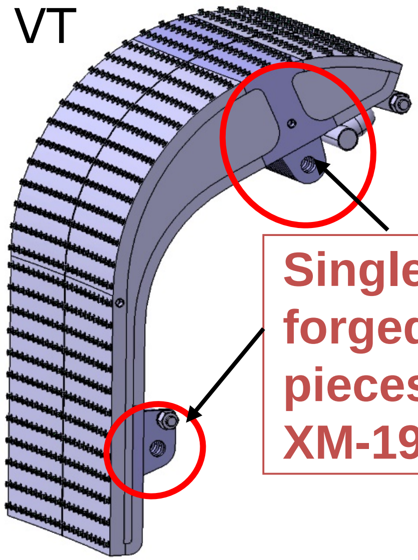




Tensile test specimen (Top: RT image, Right: After fracture)

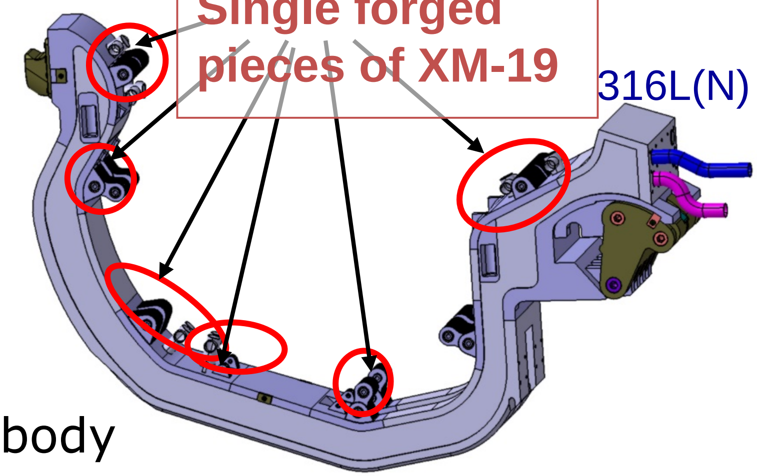
Welding of steel support structure (Example of Thick wall)

- Support Structure: Thick wall welding
  - 316L(N)-IG: GTAW, E-beam welding/Laser welding
  - XM-19: GTAW welding with filler
- Features
  - Distortions
    - Large and accurate structures
    - Lots of welding
  - Hot cracking of weld metal
    - Rigid structure
  - And naturally all the normal weld defects



Single forged pieces of XM-19

main body: 316L(N)-IG
Tubes: 316L



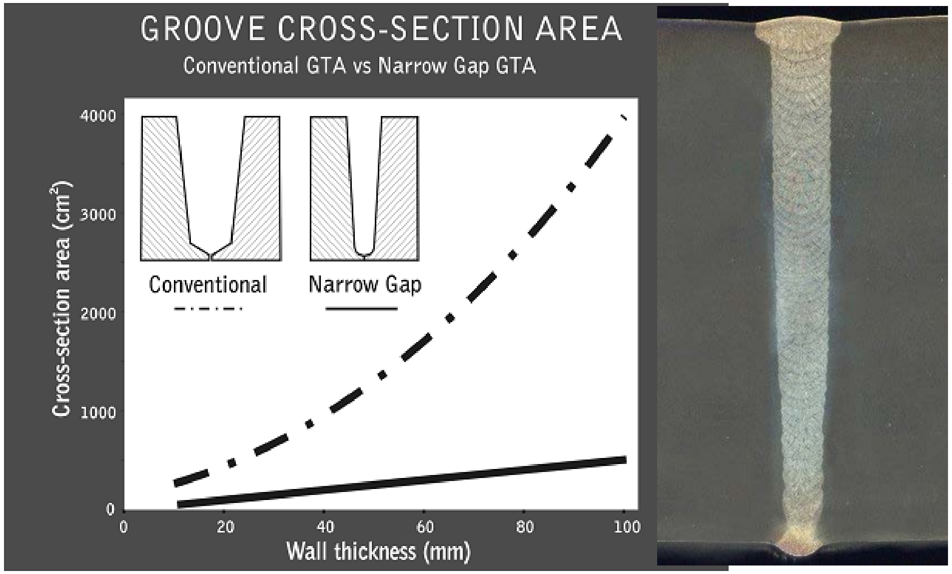
Single forged pieces of XM-19

316L(N) pipe

Casstte body

To avoid distortions of thick wall welding

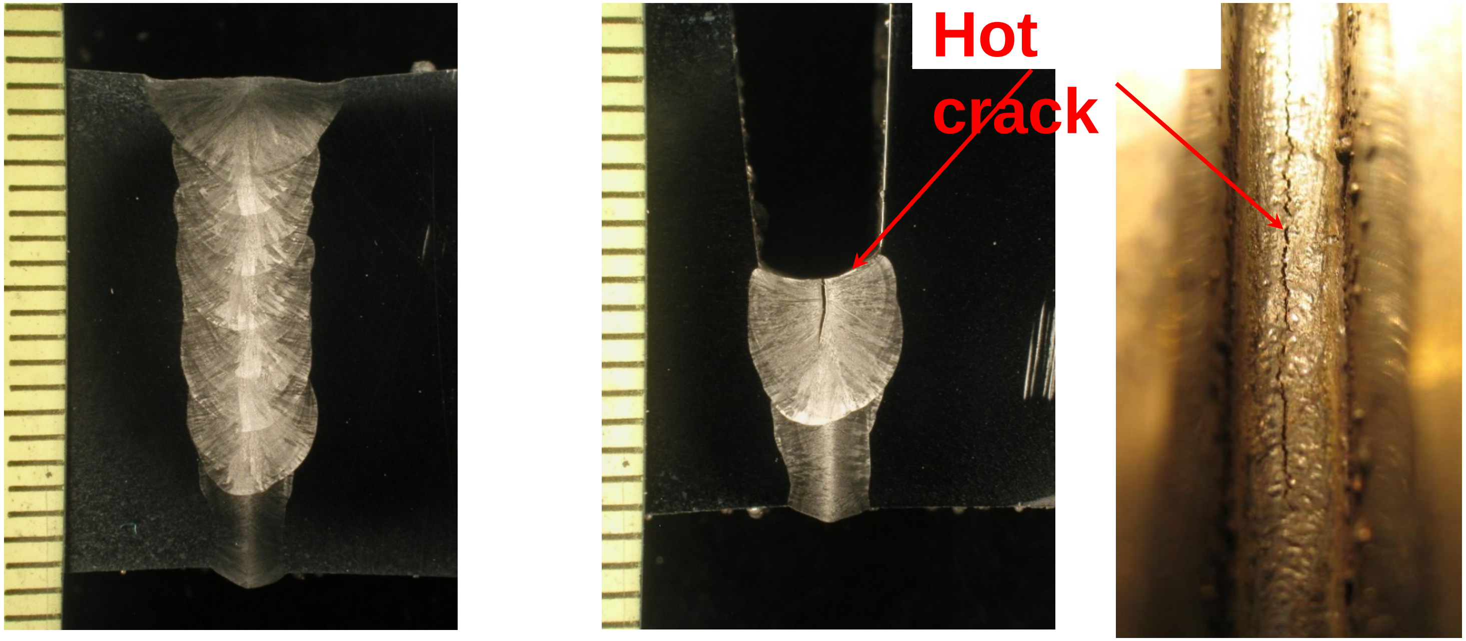
- “Best weld = No weld”; reduce of weld lines
- Welding sequence
- Jigs to fix welding piece right position
- Final machining to achieve surface profile with tight tolerances
- Balance welding i.e. welding from both sides
- Welding processes to minimize melted metal
  Narrow Gap welding
  Power beam processes; Power beam welding(electron, laser) or hybrid (beam+GTAW)



Conventional vs. Narrow Gap Grooves

Electron Beam welding

Defects in welding



Hot crack

- Hot cracking is coupled to Composition of welded material, Affect on weld solidification mode, impurity content (Phosphorus and Sulfur) and etc.
- Strains developed during solidification, high rigidity of welded structure promotes strains.
- Hot cracking can be hanled with filler material selection.

Qualifications of Welding Specification, Welder, Operator, and Inspector

❖ Welding requirements based on the pressure equipment standards

❑ Qualification of Welding Procedure Specification (WPS)

- WPS introduced EN ISO 15607 or EN ISO 15609-nn
- Preliminary WPS is qualified according to EN ISO 15614-nn
- Welding Procedure Qualification Record (WPQR)
- Acceptance criteria: quality level B of EN ISO 5817 for arc welding; quality level B of EN ISO 13919-n for power Beam welding;

❑ The welding qualification for Quality Class 1 components (including ITER-PFC) shall be witnessed by ITER recognized Independent Inspection Authority, e.g. Third Party Inspector.

❑ Welders, operators and NDT personnel shall be qualified (EN 287/ EN1418/ EN 473)

- *Other equivalent national or international standards and codes, and the updates may be acceptable subject to the IO's written acceptance. To this aim, the DA shall provide evidence that the proposed code and standard is equivalent to the corresponding one, which is specified.*

Weld Inspection – Non Destructive Test

- ☐ **Welding methods : GTAW, laser welding, electron beam welding**

- ☐ **Inspection**

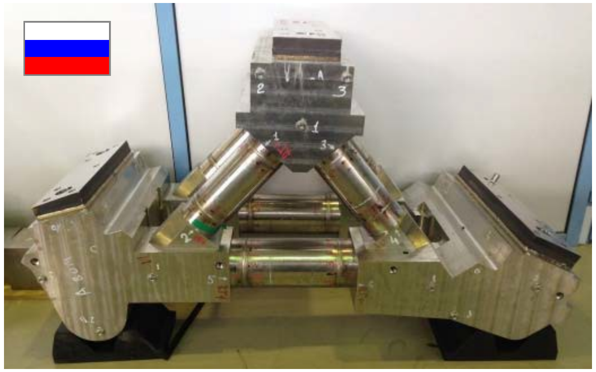
- **Surface crack examination (100%)**
  - **Visual Test for welds (EN 970)**
  - **Liquid Dye Penetrant Test for welds (EN 571)**
- N.B. ITER Vacuum Handbook requirement: use of qualified liquid penetrants
- **Volumetric examination (100%)**
  - **Radiographic test for welds (EN 1435)**
  - **Ultrasonic Test for welds (EN 22825)**

- **Acceptance Criteria**
  - Quality level B of EN ISO 5817/ EN ISO 13919; Pressure equipment relevant
  - **ITER Vacuum Handbook Attachment 1: Welding; Vacuum Components**

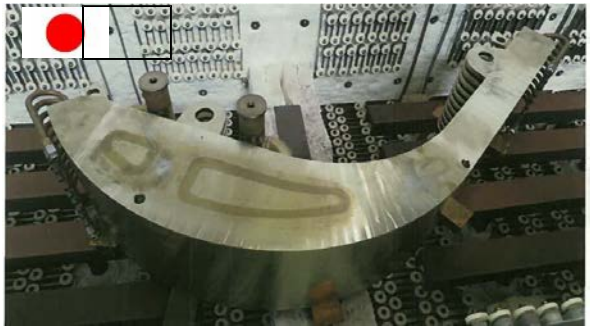
- *Other equivalent national or international standards and codes, and the updates may be acceptable subject to the IO's written acceptance. To this aim, the DA shall provide evidence that the proposed code and standard is equivalent to the corresponding one, which is specified.*

Consideration on Welding and Inspection

- Limited weld lengths and implementation plan to mitigate distortions
- Appropriate inspection plan to ensure 100% volumetric examination
- Well-established welding procedure specification (WPS) to mitigate imperfections in weld (hot cracking, lack of fusion, inclusion, etc)

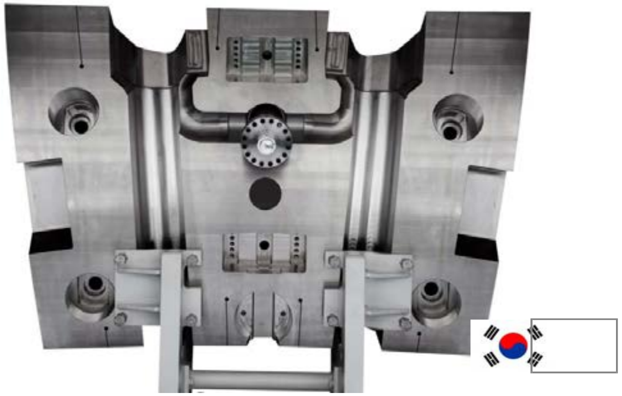


Divertor Dome full-scale prototype



Divertor Outer Vertical Target full-scale prototype

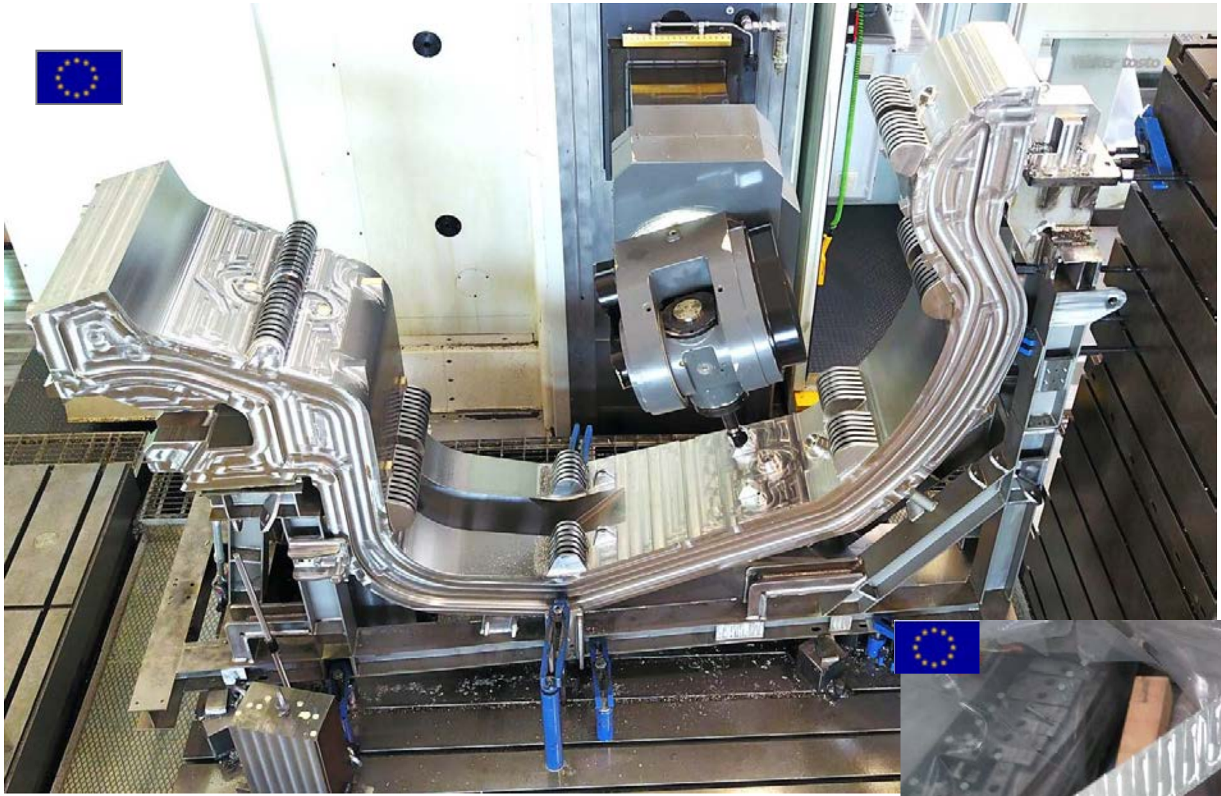
Shield Block Full-Scale Prototypes



Shield Block Full-Scale Prototypes

Divertor: Cassette Body & IVT

Full-scale Divertor Cassette Body Prototypes

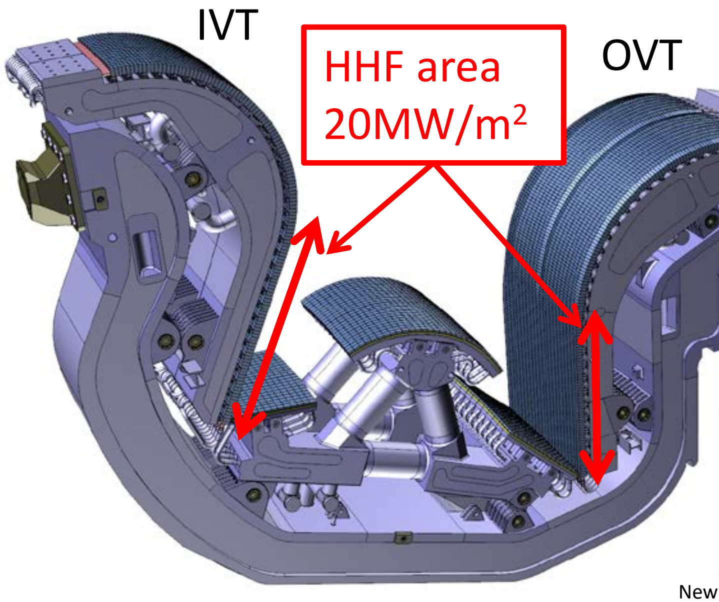


Divertor Inner Vertical Target full-scale prototype

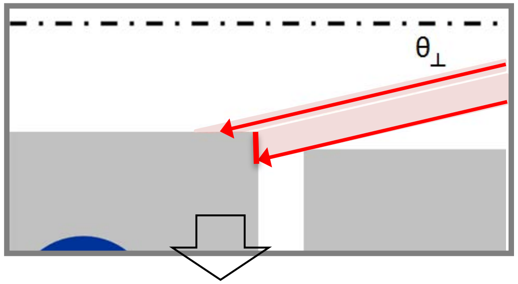
Topic

- Brief design review of ITER PFC, especially, Divertor Outer Vertical Target (OVT) and heat load specification
- How-to-Realize, Manufacture and Inspect ITER PFCs, esp. ITER OVT.
  - Joining Armor material to Heat Sink (Cooling tube), technology validation through high heat flux testing
  - Welding; cooling tubes and steel support structure
  - **Assembling**
  - other engineering topics
  - Inspection of PFCs

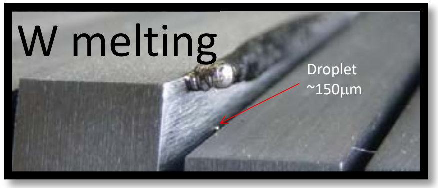
Strict control for surface profiles of W monoblocks to protect W monoblock leading edge



Leading edge Issue : Step of W monoblock causes increasing heat flux at leading edges.

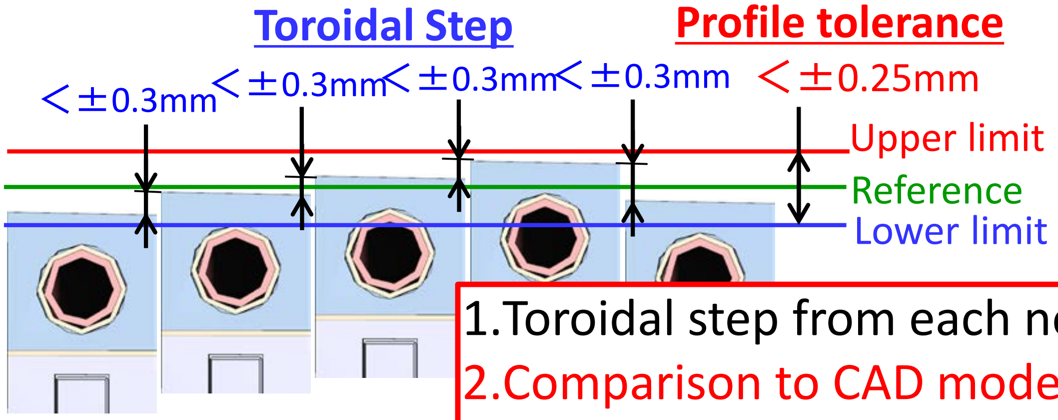


Two measures are taken for all W monoblocks to prevent the leading edges of the W monoblocks from over-heating.



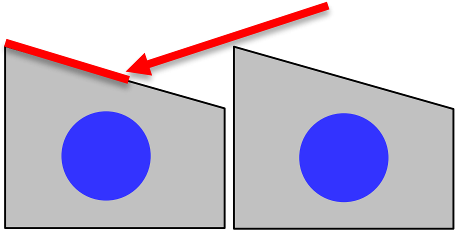
New high resolution images of W-melting in JET
[G. Matthews – PFMC 2015]

Measure 1：Strict tolerance



(Cross-section of PFUs：Exaggerated view)

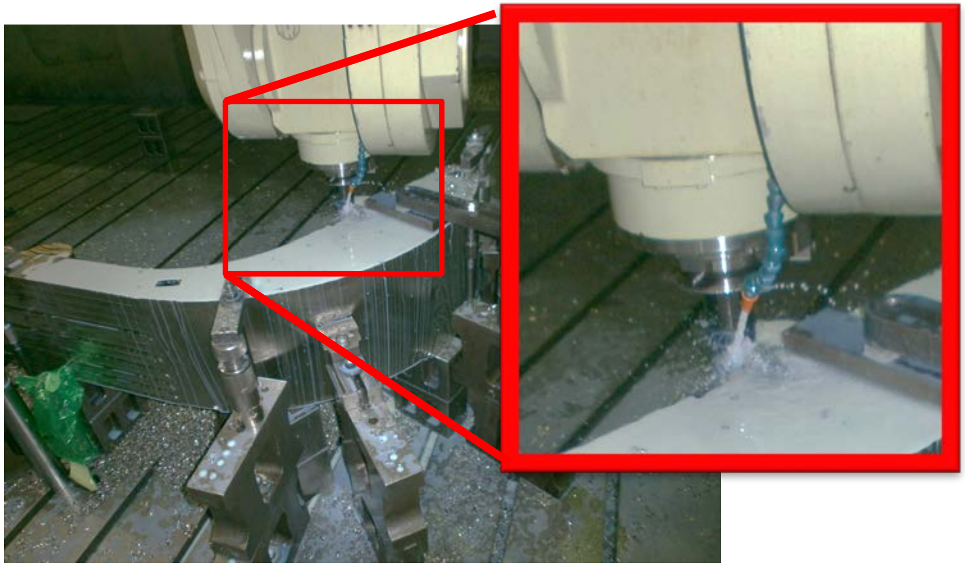
Measure 2：bevelled W monoblock



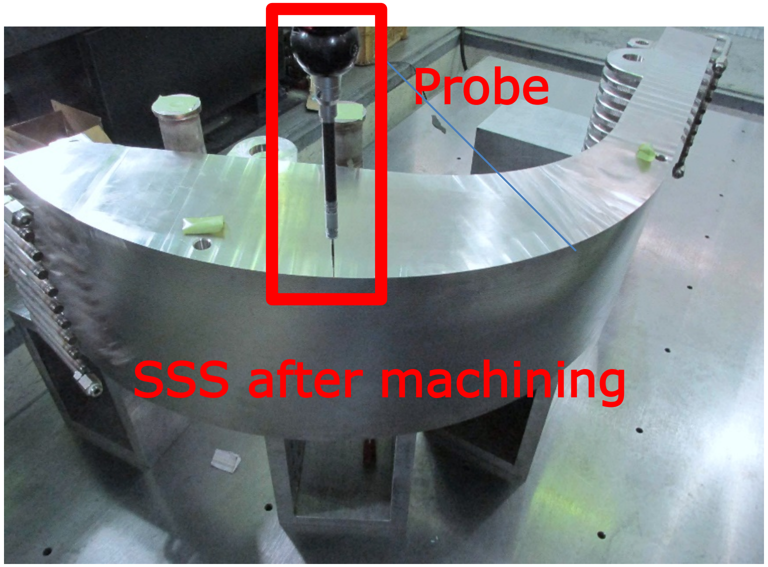
1. Toroidal step from each neighbouring W monoblock, ±0.3 mm
2. Comparison to CAD model：surface tolerance, ±0.25mm (demonstrated in the next slide)

How to achieve tight geometrical tolerances of surface profile of OVT

- Example; ITER OVT
- Evaluation of accumulating tolerances of OVT parts,
- Precise machining of Steel Support Structure (SSS) after welding and dimensional stabilized heat treatment,
- Precise machining of PFU parts, W monoblocks, support legs and plug, pin.
- Each part needs to be control with accurate dimensional inspection with low uncertainty in measurement.



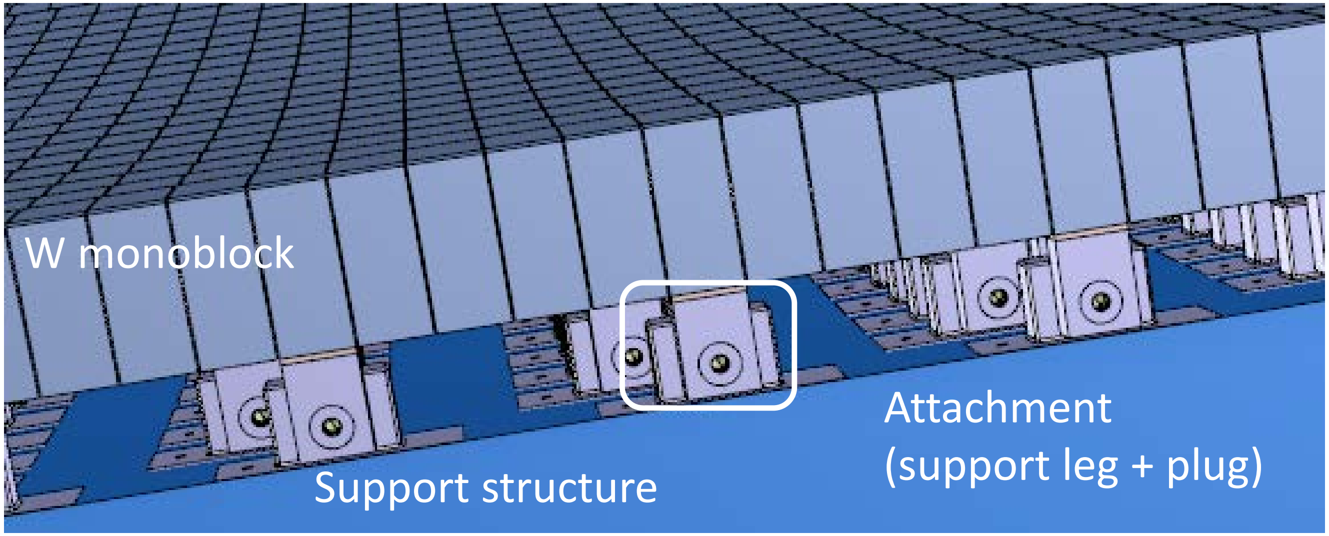
3D machining of SSS with 5-axis machine

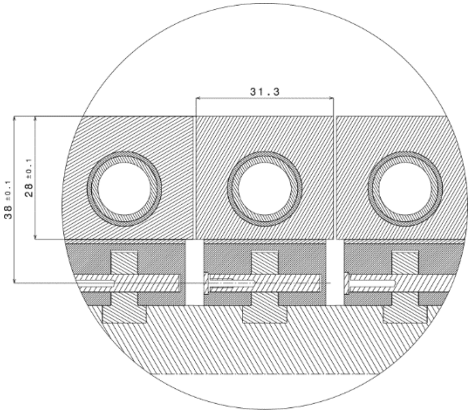


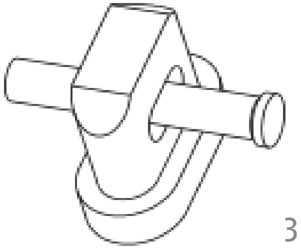
Dimensional control with 3D coordinate measuring machine

OVT case; PFU assemble to SSS

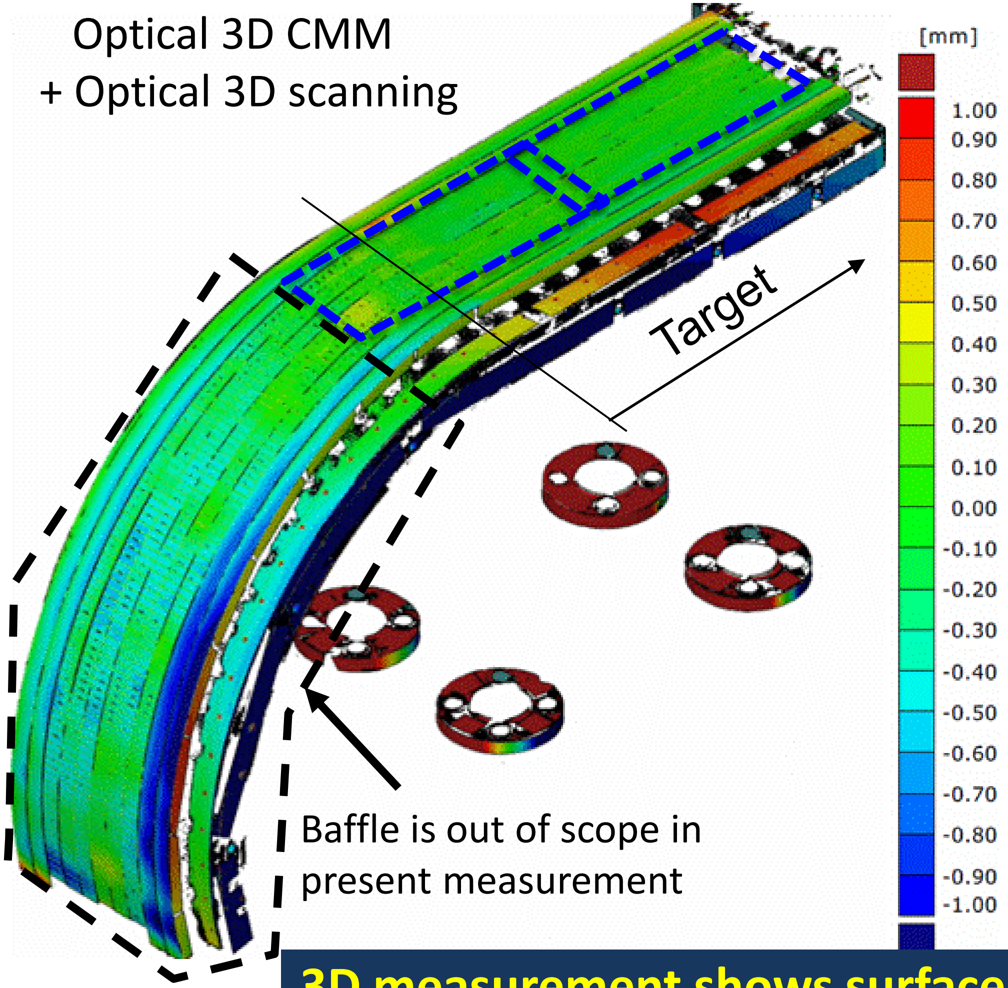
- PFUs in IVT and OVT need to expand along cooling tube axis during HHF loading to prevent excessive thermal stress in the cooling tubes leading thermal fatigue and failure of cooling tubes.
- Mechanical Leg – Plug attachment is applied to OVT to allow this movement.
- This is a dilemma between thermo-mechanical performance and surface profile of PFUs.





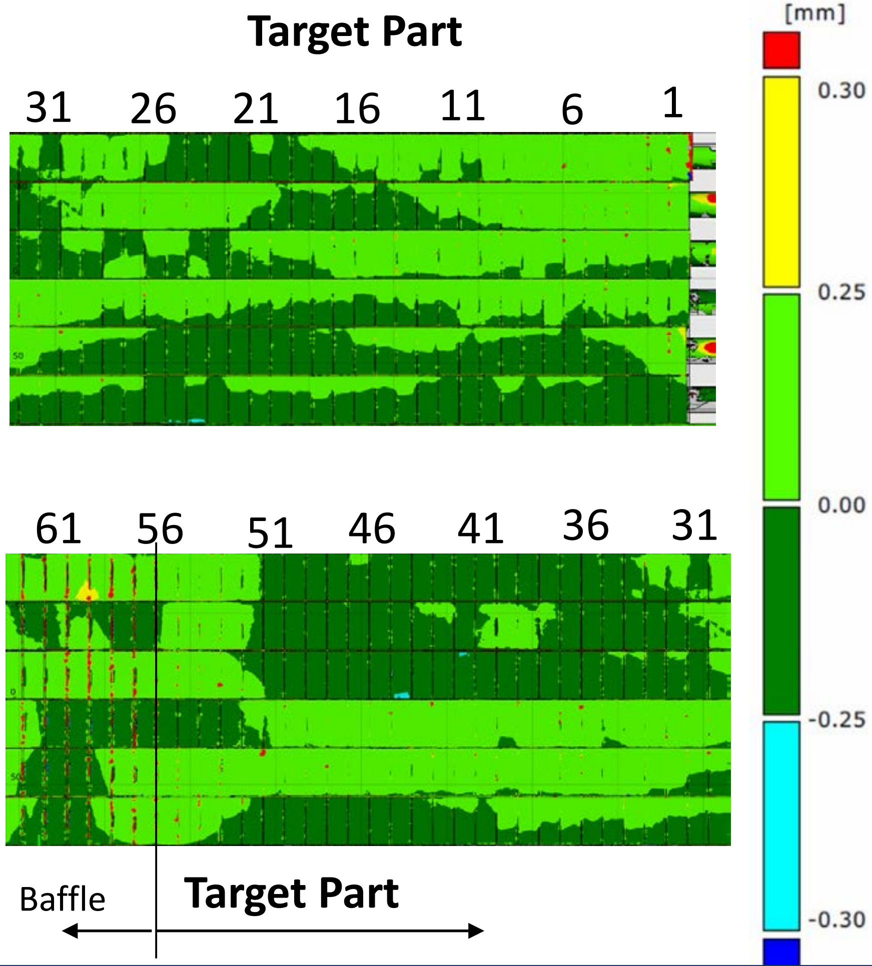


3D surface profile measurement of 6 PFU prototypes



Optical 3D CMM
+ Optical 3D scanning

Baffle is out of scope in present measurement

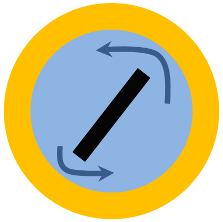


3D measurement shows surface profile of Target part satisfying the IO requirement (±0.25mm) is achievable.

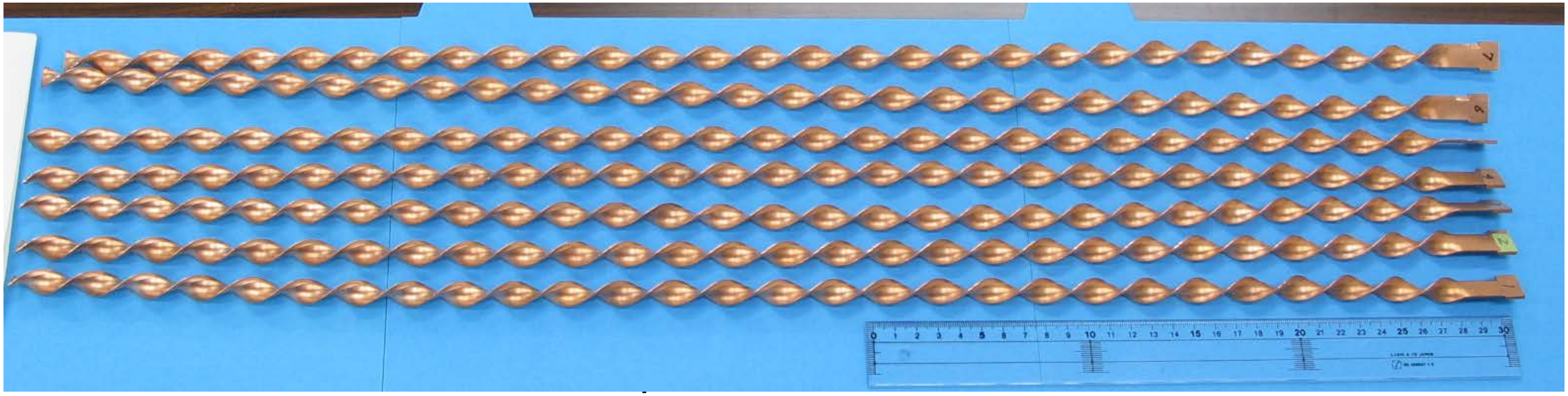
Flatness (gap between neighboring W blocks) within±0.3mm is planed to be demonstrated in the next OVT prototypes.

Tolerance between twisted tape and cooling tube

- To removal high heat load as high as 20MW/m^2, twisted tapes are inserted into PFU tube to enhance heat transfer performance and boiling limit.
- During operation, twisted tape can vibrate due to flow instability induced by high speed water flow in the gap between tape and the tube wall.



- If tape's vibration goes beyond threshold, the tube wall can be damage. In the worst case, the tube wall can be eroded and water leaks.



- To prevent the vibration and erosion of tape, tight tolerance controls of twisted tape and inner diameter of cooling tube are needed.

The other engineering topic;
Technical Challenges for OVT

A. Feasibility demonstration of OVT (⇒ full-scale prototyping)

A-1: Joint massive W monoblocks to cooling tube without joint

A-2: Surface profile of PFUs as OVT with high accuracy to protect leading edge

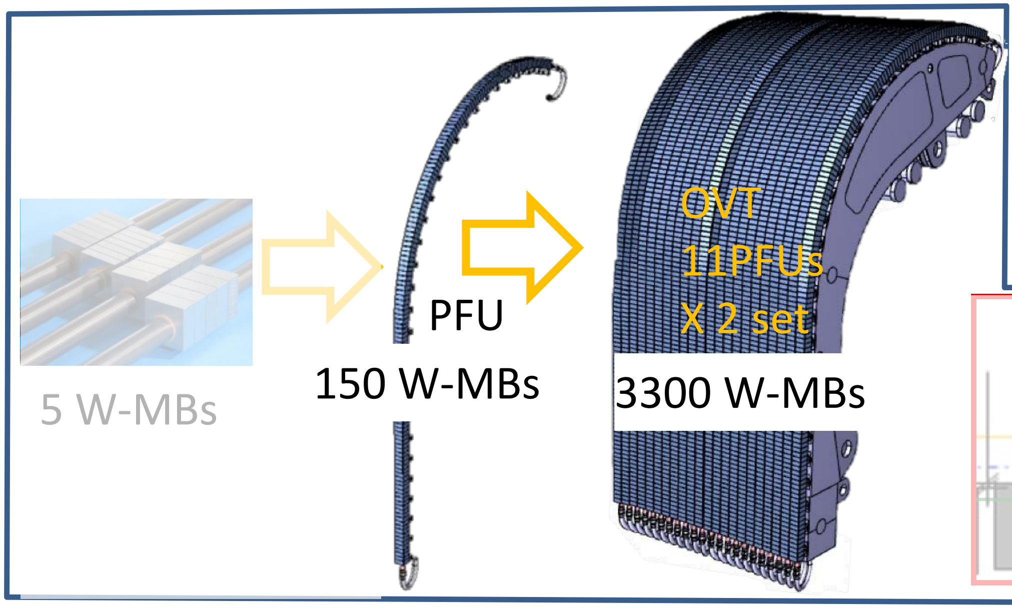
A-3: Uniformity of cooling water flow in parallel PFUs

B. Qualification for mass production of PFU

B-1: Mass production of W-MB with same high quality

150 W-MBs /PFU ⇒ 3300 W-MBs/OVT ⇒ 2x10^{5} W-MBs/58 OVTs

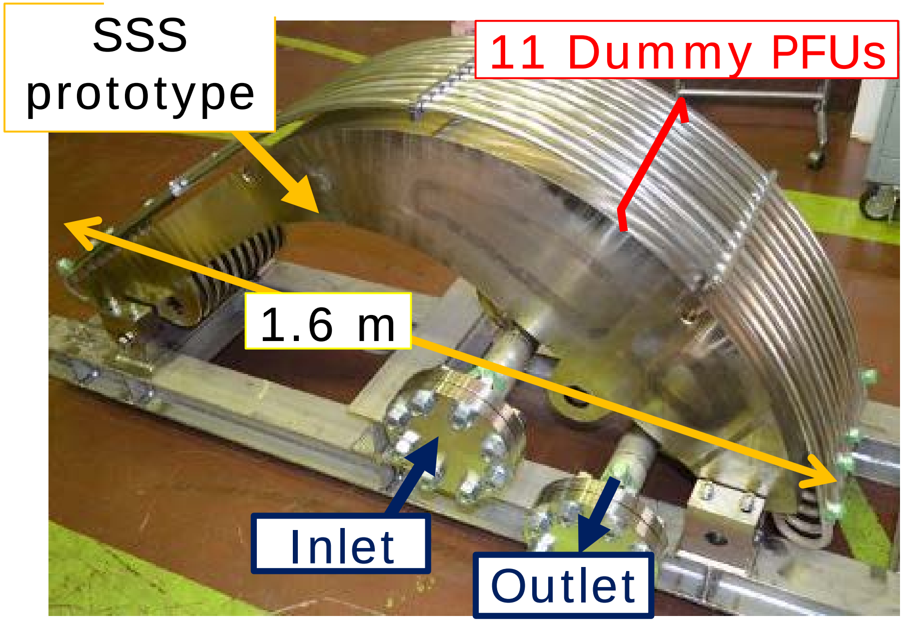
B-2: Mass production of PFU: 22 PFUs /OVT ⇒ 1300 PFUs/58 divertor cassettes



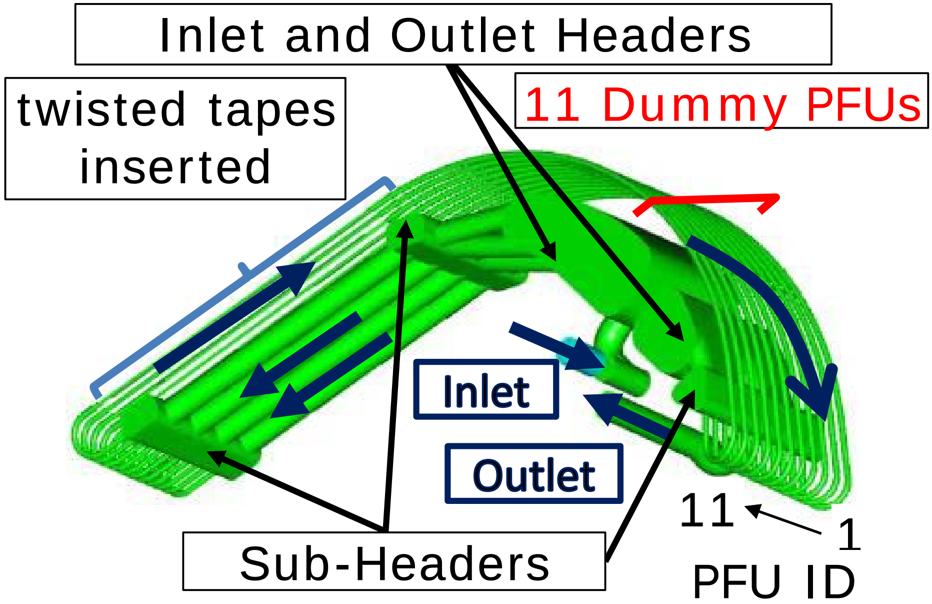
The other engineering topics
A: Uniformity of water flow rate in 11 parallel PFUs

- To remove the heat load of 20 MW/m^2, Uniformity of water flow distribution in 11 parallel PFUs is essential.
- Water flow test with OVT prototype (half-cassette size) was conducted to demonstrate that our design of SSS is suitable.

OVT prototype for flow test



SSS: steel support structure

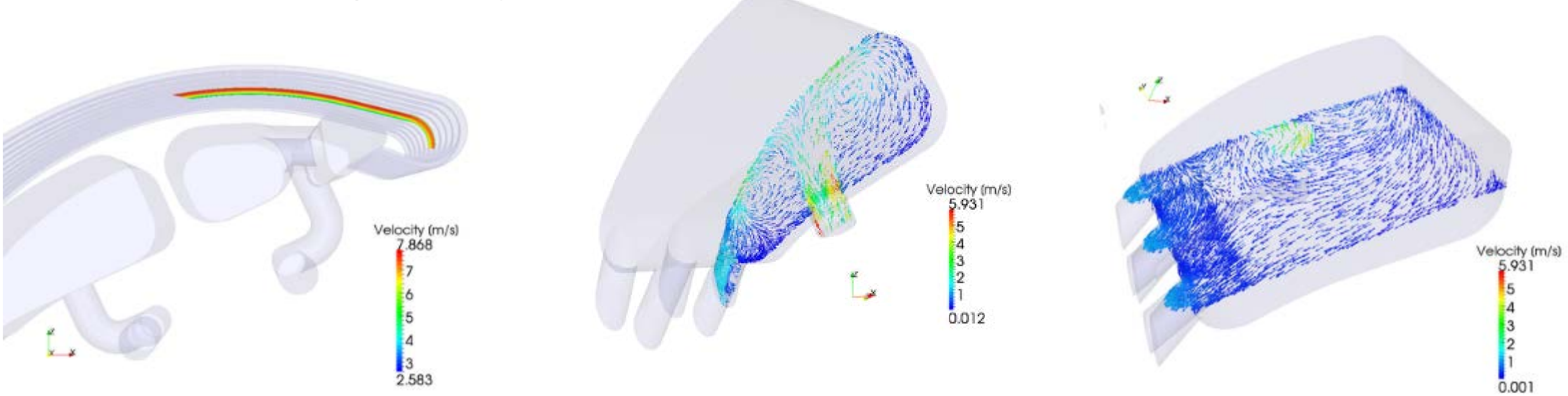


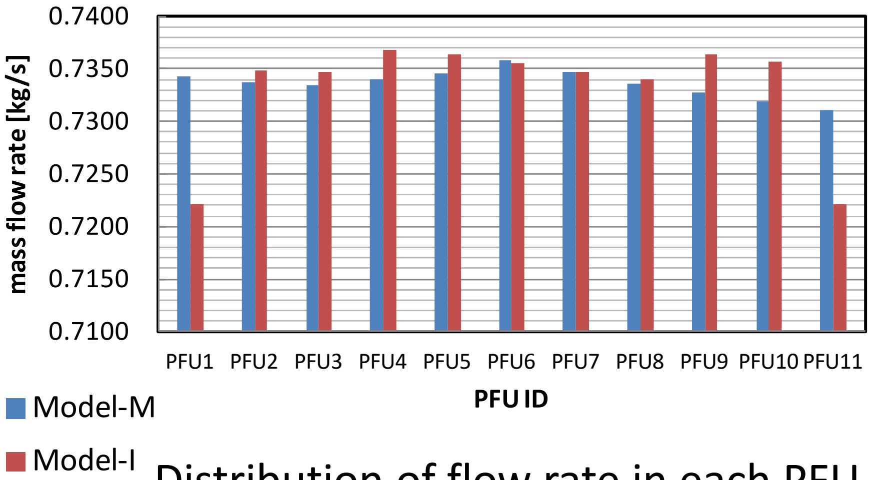
Flow channels of dummy PFUs and SSS internal structure.

Estimation method of turbulence model for flow distribution in OVT

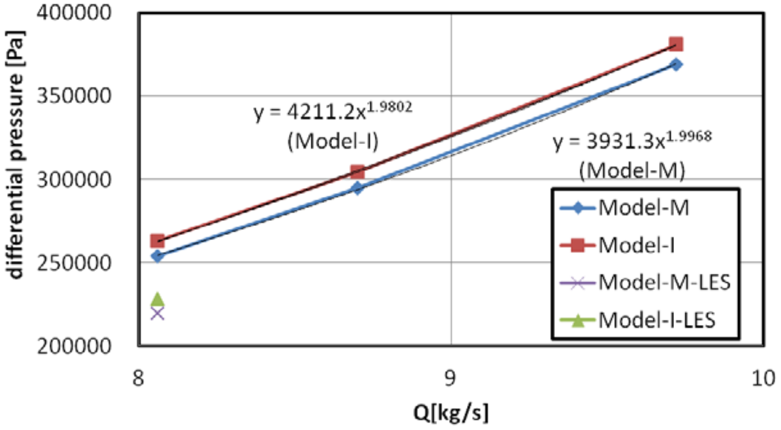
- Distribution of flow rate in each PFU and total pressure drop in half OVT were estimated by a numerical simulation (ANSYS) of flow distribution in SSS of CFC/W-OVT.

Results of CFD simulation (Larger-Eddy Simulation)



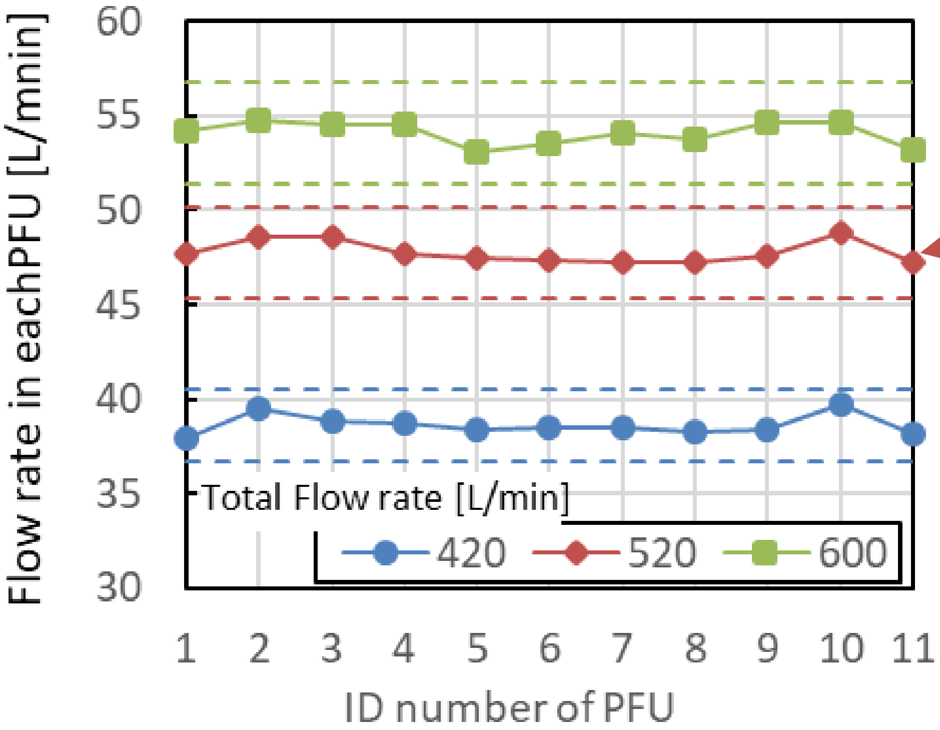


Distribution of flow rate in each PFU



Total pressure drop in half OVT

Results of water flow test of OVT prototype



- Condition: 2MPa, RT
- Design flow rate of half OVT :
  8.6 kg/s(516L/min)
- Exp. Rage: 7.0-8.6-10 kg/s in total
  (420-520-600 L/min)
- Average water flow rate in each PFU: 38.2- 47.3-54.5 L/min
- Flow rate measurement in each PFU: ultrasonic flow meter

➢ **Uniformity of flow rate distribution in 11 PFUs is demonstrated to range within ± 5%. The internal design of SSS is suitable for OVT.**

➢ **Complex flow pattern in headers inside of SSS affects on flow distribution.**

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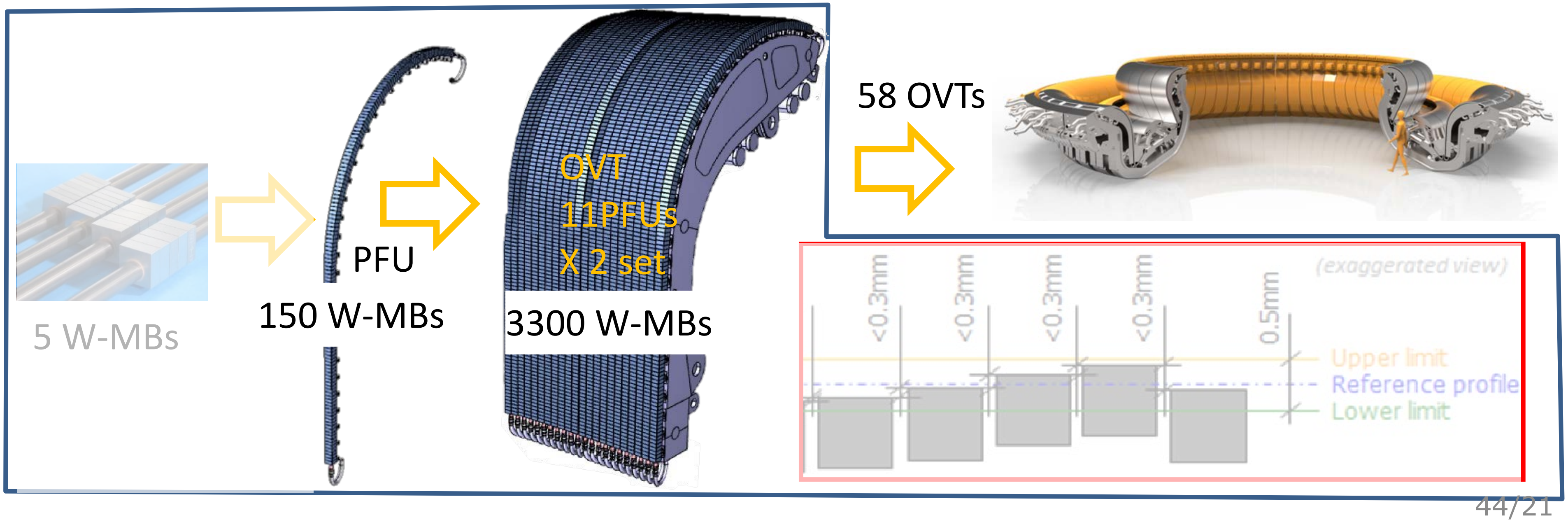
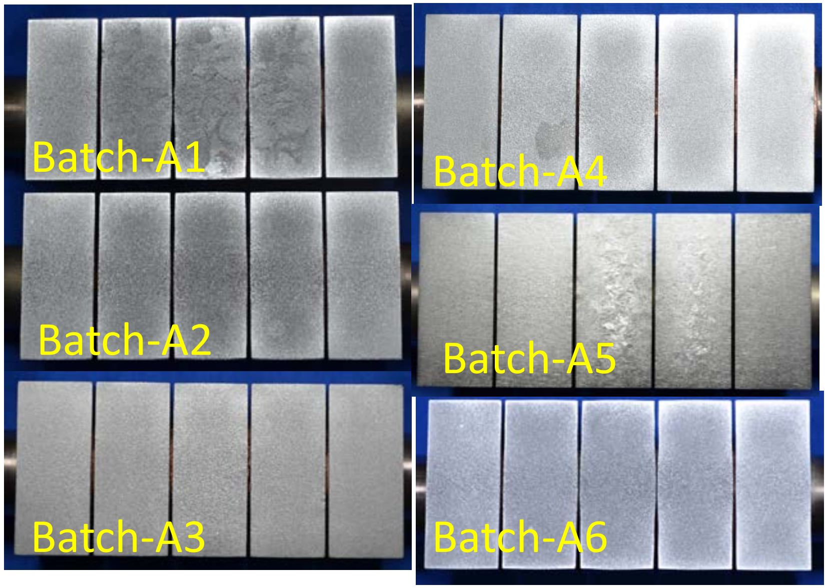


The other engineering topics
(B) Qualification for mass production of W monoblocks

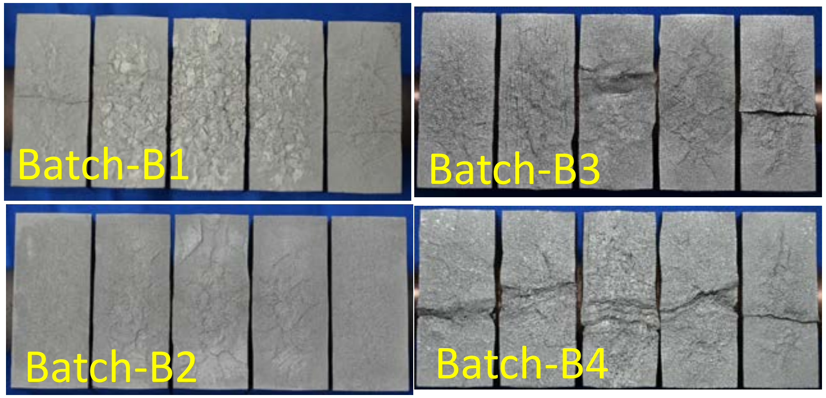
- Qualifications program for mass production of W-MBs was launched;
  - to check their quality deviations in different W plate lot, and
  - to confirm availability of new mass production facilities in potential suppliers.
- Many mock-ups with W-MBs from different W plate lot are being tested at 20MW/m^2 for 1000 cycles.

W-MB from Supplier(A)



No Macrocracking / stable quality

W-MB from Supplier (B)

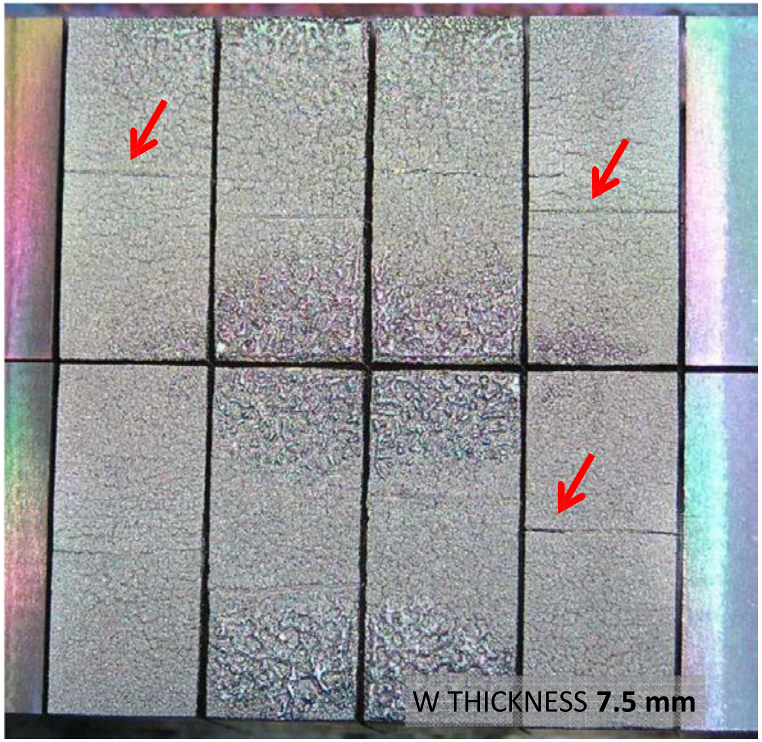


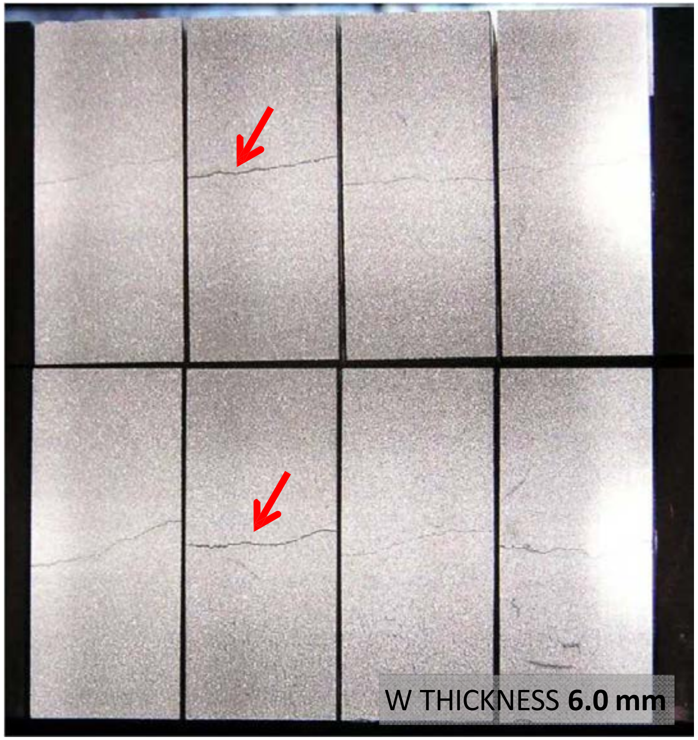
Macrocracking in some mock-ups

W surface after 20MW/m^{2}x1000cycles

ITER Divertor Test Facility for high heat-flux testing PFUs

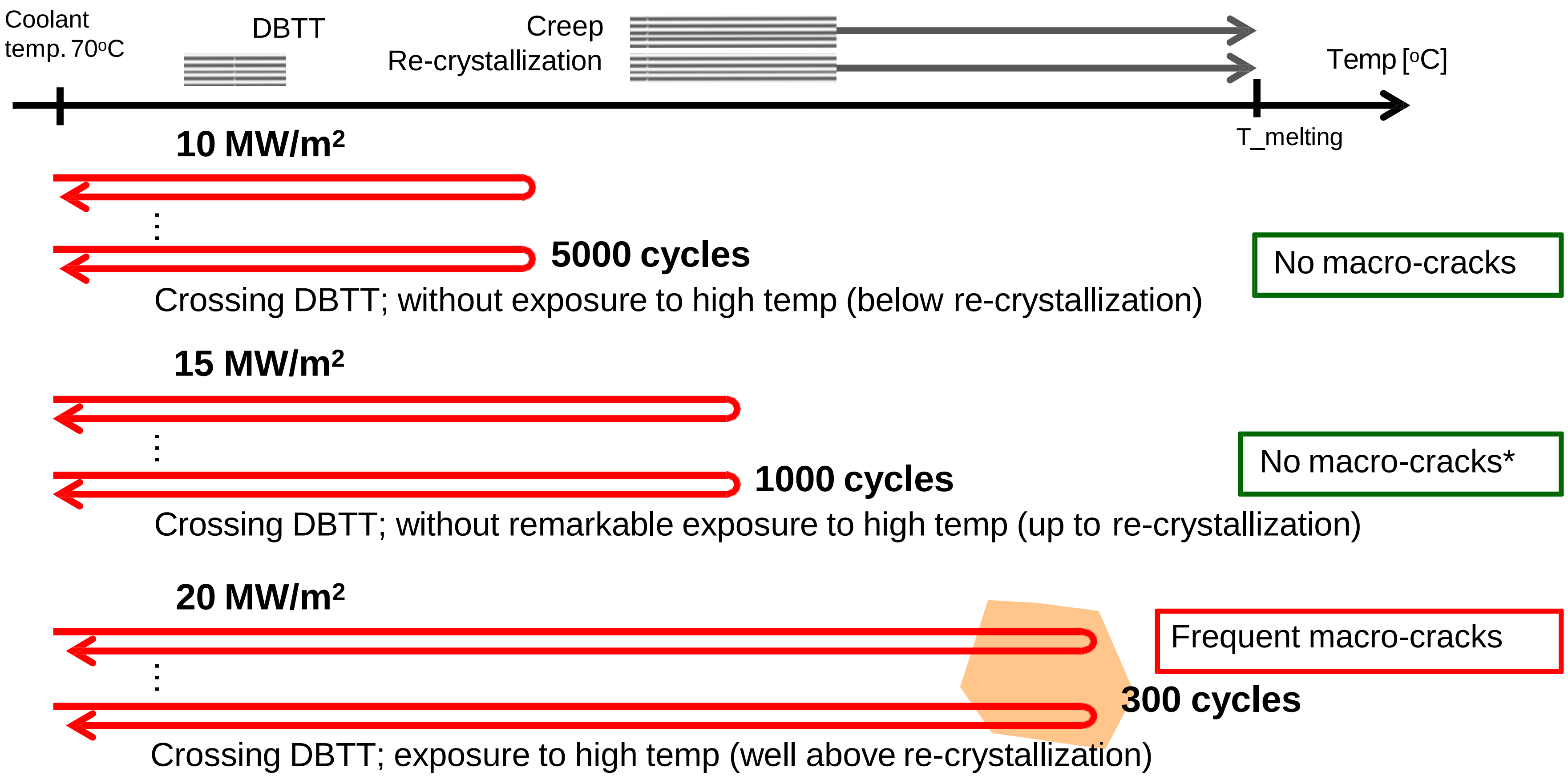
- W monoblock mockup High heat flux test at 20 MW/m^2 (in electron beam facility)
  - Macro-cracks observed in some W monoblocks
  - Acceptable in bonding technology qualification; should be mitigated for PFUs





T. Hirai, et al., J Nucl Mater 463 (2015) 1248–1251; T. Hirai, et al., Nucl Mater Energy 9 (2016) 616-622;
S. Panayotis et al., Nucl Mater Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.10.025

Macro-crack appearance at W Monoblock



Coolant temp. 70^{o}C

DBTT

Creep

Re-crystallization

Temp [^{o}C]

T_melting

10 MW/m^2

5000 cycles

Crossing DBTT; without exposure to high temp (below re-crystallization)

No macro-cracks

15 MW/m^2

1000 cycles

Crossing DBTT; without remarkable exposure to high temp (up to re-crystallization)

No macro-cracks*

20 MW/m^2

300 cycles

Crossing DBTT; exposure to high temp (well above re-crystallization)

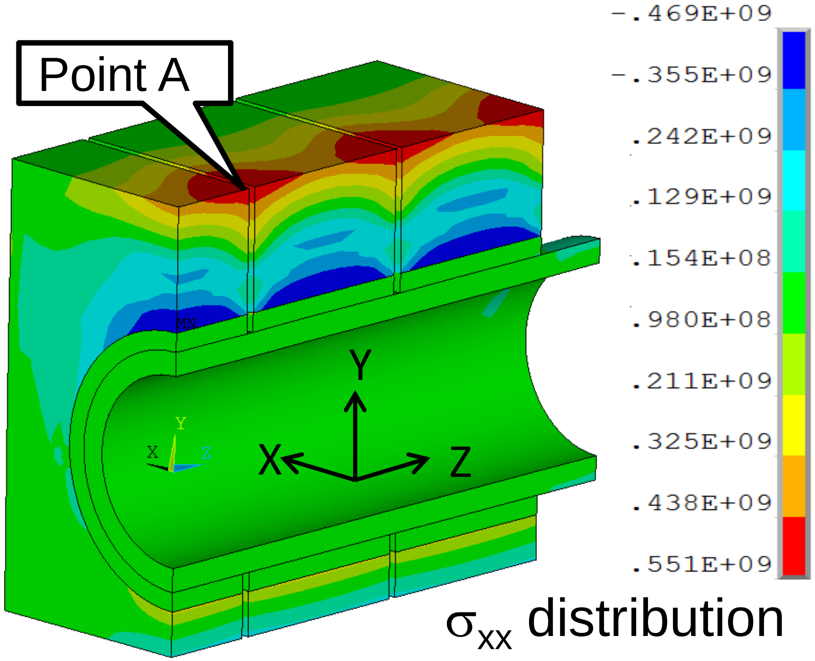
Frequent macro-cracks

* For mock-ups using W-plate materials

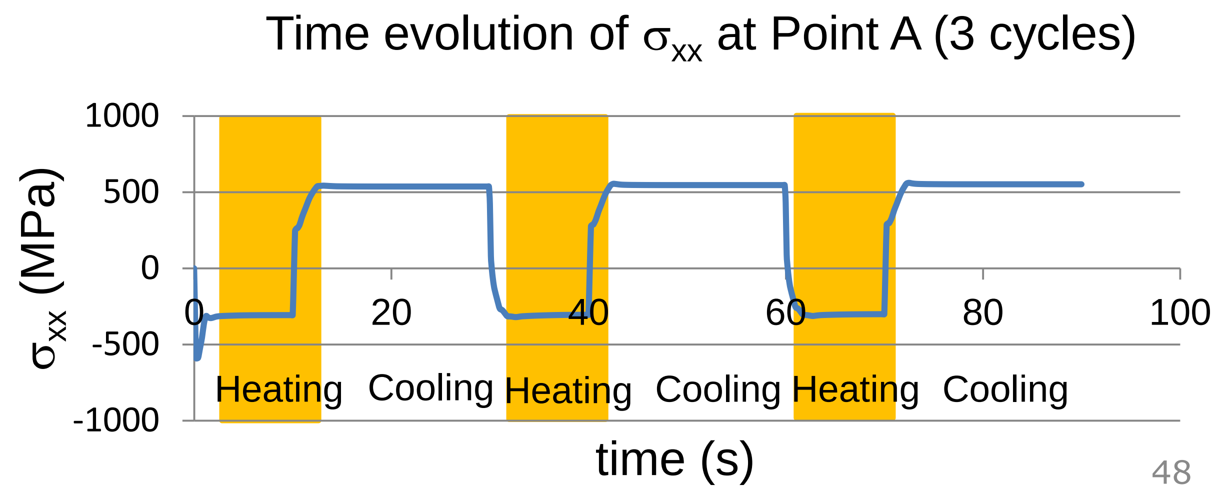
Appearance of Macro-cracks: Exposure to high temperature results in fatigue with plastic strain (low cycle fatigue), creep damage, progressive plastic deformation, degradation due to recrystallization

Why Macro-cracking occur?

- 3D elastoplastic stress analysis has been carried out to investigate the stress distribution of tungsten armor.
- More than 500MPa of normal stress along x-direction appeared at the central edge of the tungsten armor. The location where the maximum stress appeared is exactly the same as the cracked part in the small-scale mock-ups.
- The stress concentration will cause surface cracking since the heated surface of the tungsten armor has <u>fully recrystallized</u>. Further investigation of mechanical strength and ductility of fully recrystallized tungsten is necessary.



σ_{xx} distribution at the end of 3rd cycle (t = 90s)


Time evolution of σ_{xx} at Point A (3 cycles)

The other engineering topic; Technical Challenges for OVT

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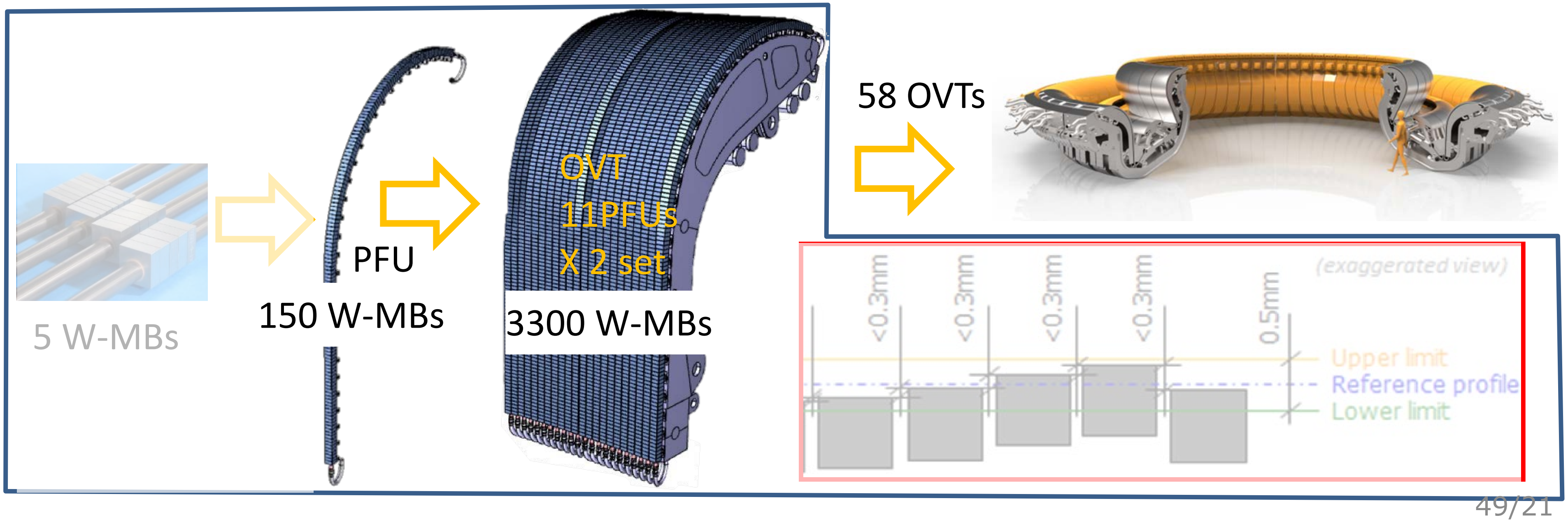
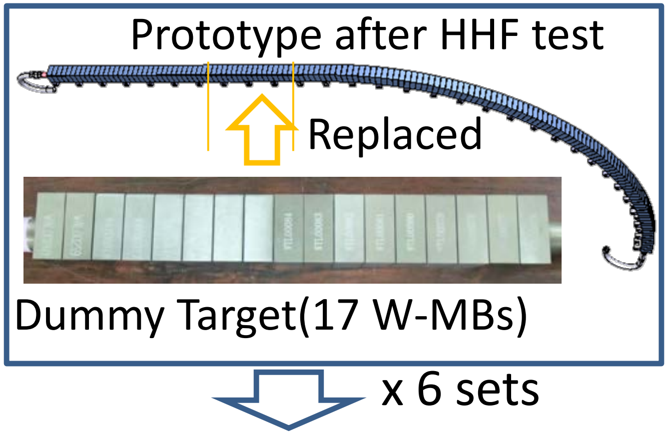
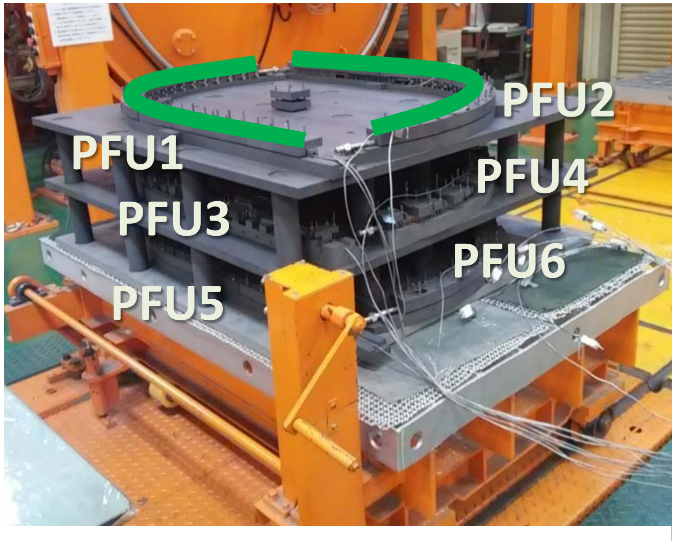


Challenge B-2: Brazing test to demonstrate series production of PFUs (1)

- Series production of PFUs; multiple PFUs in one joining heat-treatment batch.
- To demonstrate this process, brazing tests were carried out to manufacture 6 dummy PFUs simulating the target parts with 17 W monoblocks.
- The baffle part of the previous PFU prototypes were used to simulate the heat capacities in the furnace.
- Two items to be checked
  - Cooling rate after brazing temp. to recover mechanical properties of CuCrZr, and
  - Joint interface by Ultrasonic Testing (UT)

Dummy PFU for brazing test

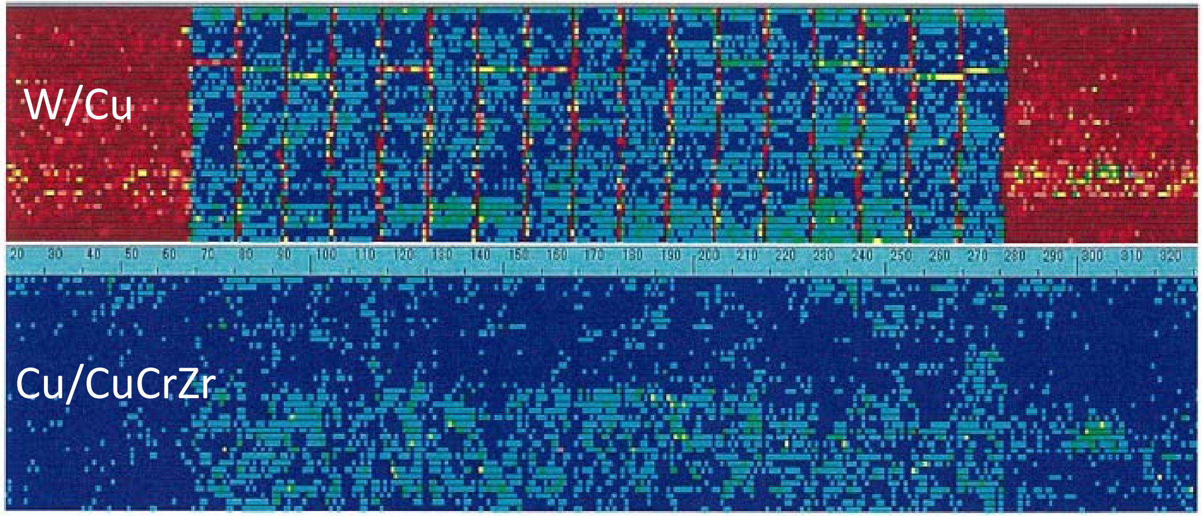




2 dummy PFUs on each stage
3-stage case was examined.

Challenge B-2: Brazing test to demonstrate series production of PFUs (2)

- The cooling rate after brazing temperature is as fast as 1K/s. This satisfies the target value to recover the mechanical properties of CuCrZr tube.



UT results of dummy target #6

- UT from inside of tube

Through the present brazing test, the manufacturing process of multiple PFUs in one brazing heat-treatment batch is promising to be applied in the series production.

Outlines

- Brief design review of ITER PFC, especially, Divertor Outer Vertical Target (OVT) and heat load specification
- How-to-Realize, Manufacture and Inspect ITER PFCs, esp. ITER OVT.
  - – Joining Armor material to Heat Sink (Cooling tube), technology validation through high heat flux testing
  - – Welding; cooling tubes and steel support structure
  - – Assembling
  - – Other engineering topics
  - – **Inspection of PFCs**

Inspection of ITER-PFCs

☐ **Dimension Inspection**

- **3D measurement to demonstrate meeting tight tolerances**
- Selection of appropriate tools and datums (reference points) for measurement
  - To meet tolerance requirements, Identify poor tolerance operation (joining (welding) and assembly) and recover tolerance budget by custom machining where possible

☐ **Inspection of heat sink joint Heat removal capability**

- Ultrasonic inspection to ensure metallurgical contacts at joints
- Use of appropriate calibration blocks and demonstration blocks
- Appropriate probes and geometry (frequency, size, focal length, etc)

☐ **Inspection of welds to ensure defect free welds**

☐ **Leak tightness**

- Mitigate leak path in materials – selection of re-melted steel products
- Mitigate leak path in vacuum boundary joints – 100% volumetric test
- Ensure leak tightness at component level – hot helium leak test

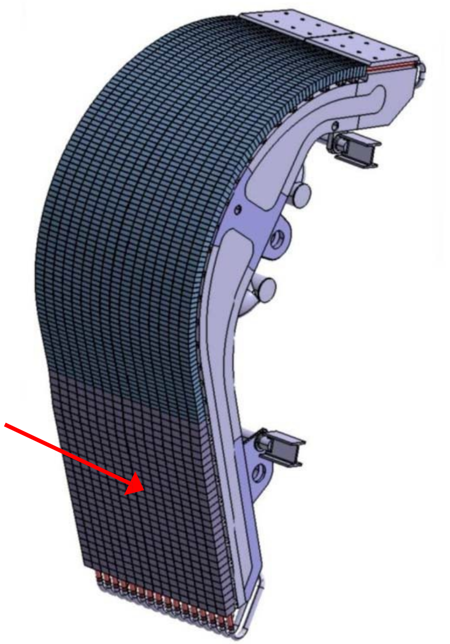
Dimension Inspection

❑ General Tolerances

ISO 2768-1:1989 class-c Tolerances for linear and angular dimensions … ISO 2768-2:1989 class-L Geometrical tolerances ...

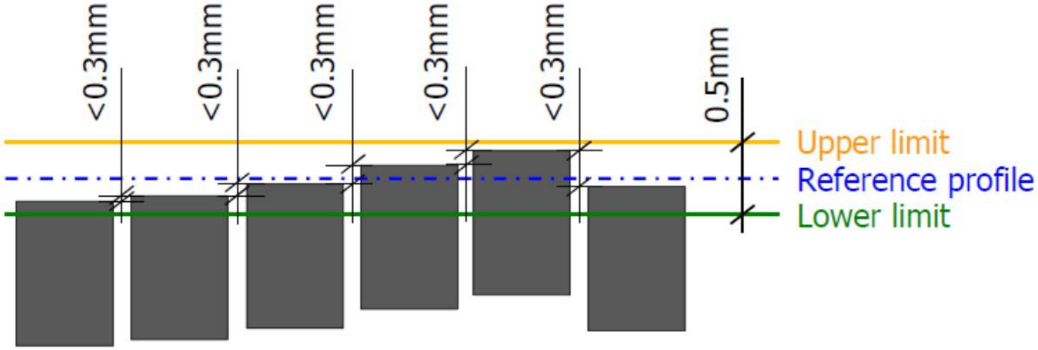
❑ Specific Tolerance - Priority on the Functionality

- Ensure mechanical and plasma operation performances
- Surface profile of PFC is critical. PFU in VT is allowed to expand in axial direction to reduce thermal stress during operation 10-20 MW/m^2.



Geometrical tolerances are specified considering operational requirements at global and local scales all monoblocks aligned within 0.5 mm range

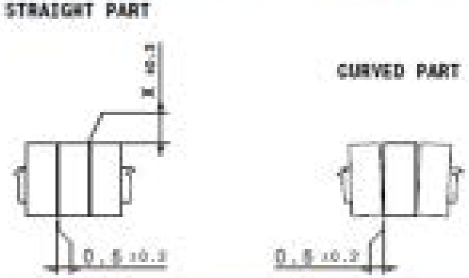
steps of neighbouring blocks smaller than 0.3 mm

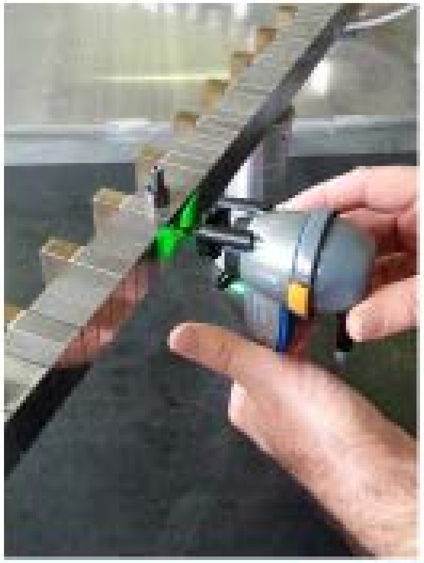


Manufacturing – PFUs NDEs (Dimensional control)

Control of the gaps and steps on individual PFUs:

- The control is done by GapGun (third dimension, www.third.com),
- The gaps and steps are measured on 3 positions on each pair of monoblock,
- The work was done by F4E metrology team.

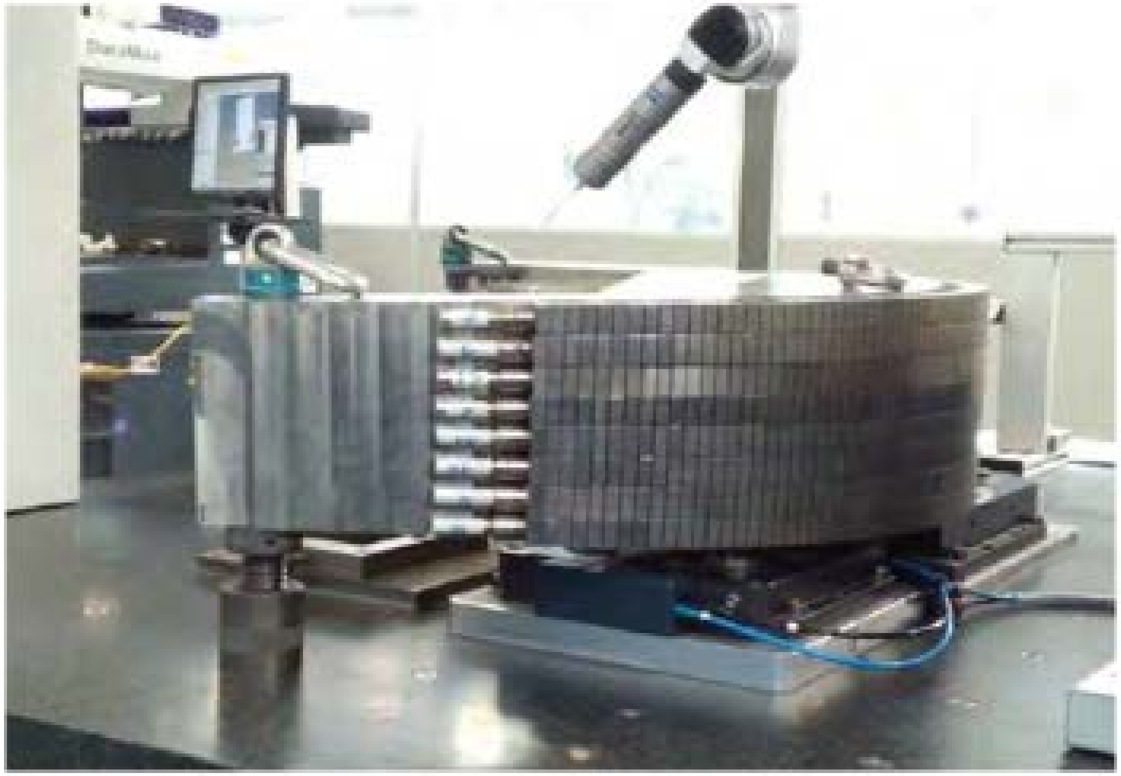




Manufacturing – IVT Prototype Dimensional control

CMM dimensional control of the Plasma facing surface,

Gap gun control of gaps and steps



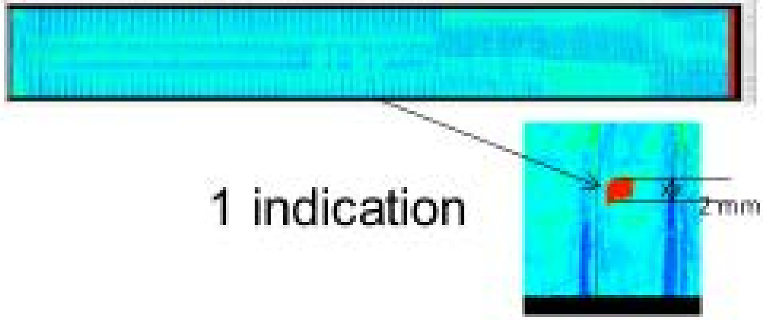
Manufacturing – PFUs NDEs (UT)

PFUs Non Destructive testing:

- Ultrasonic Testing: completed on the 1+2 additional units.

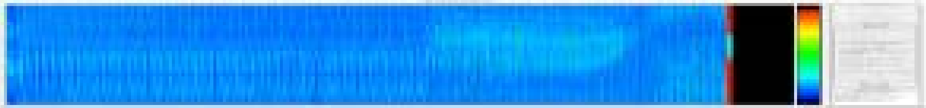
UT test bench at ENEA Frascati

U0001



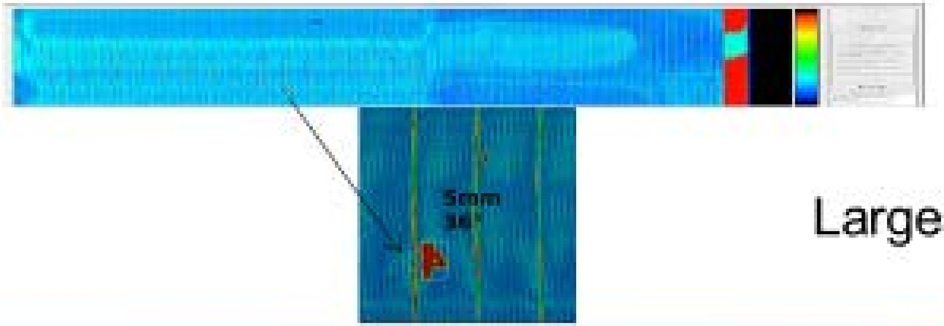
1 indication

U0002



No indication

U0003



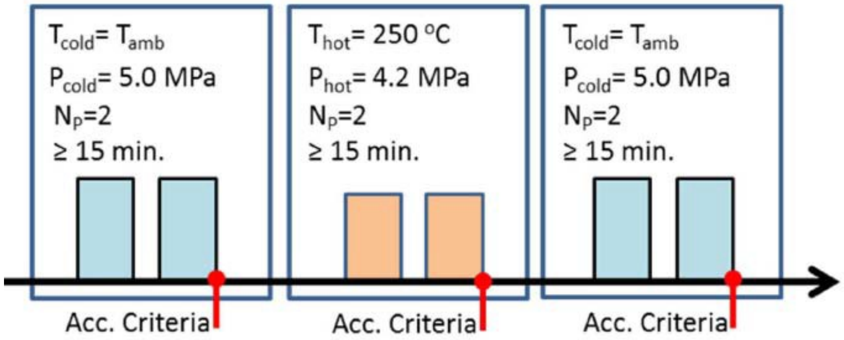
Several small indications

Largest indication θ=80° Δθ=36° L=5 mm

Leak tightness test - Hot Helium Leak Test

- ❑ Hot He leak test - combines a He leak test under

(1) stresses caused by temperature elevation and;
(2) membrane stresses caused by He pressure in the coolant channel.



ME60 test stand (5 m3) CEA

- ❑ Hot He leak tests were adapted in fusion devices for actively cooled components, e.g. Tore Supra, W7X, EAST, JET NB.

T. Hirai, et al., Phys. Scr. T170 (2017) 014045.

M. Chantant et al. Fusion Eng. Des. 98–99 (2015) 1250–1255.

- ❑ To be demonstrated: (i) **reach required sensitivity**, (ii) **efficient heating and cooling cycle for massive components**

1. Planned HHLT facility for Shield block

1) Heating and pumping system

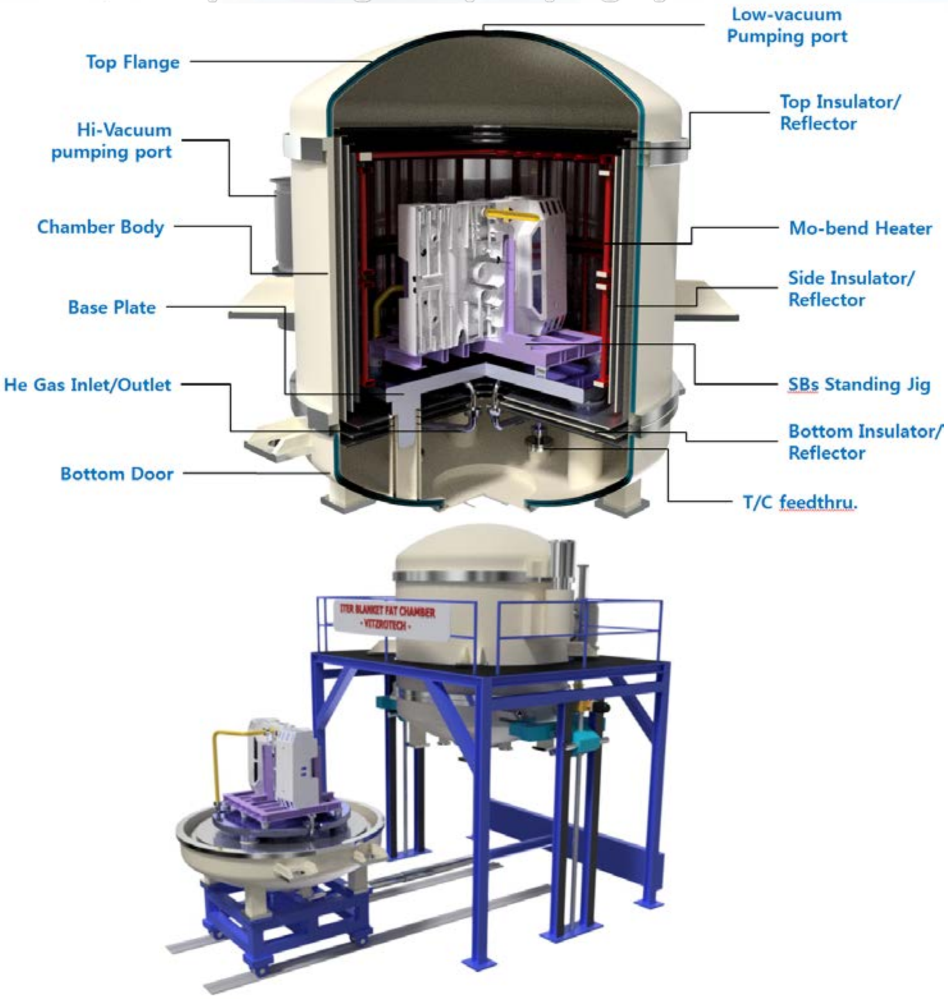


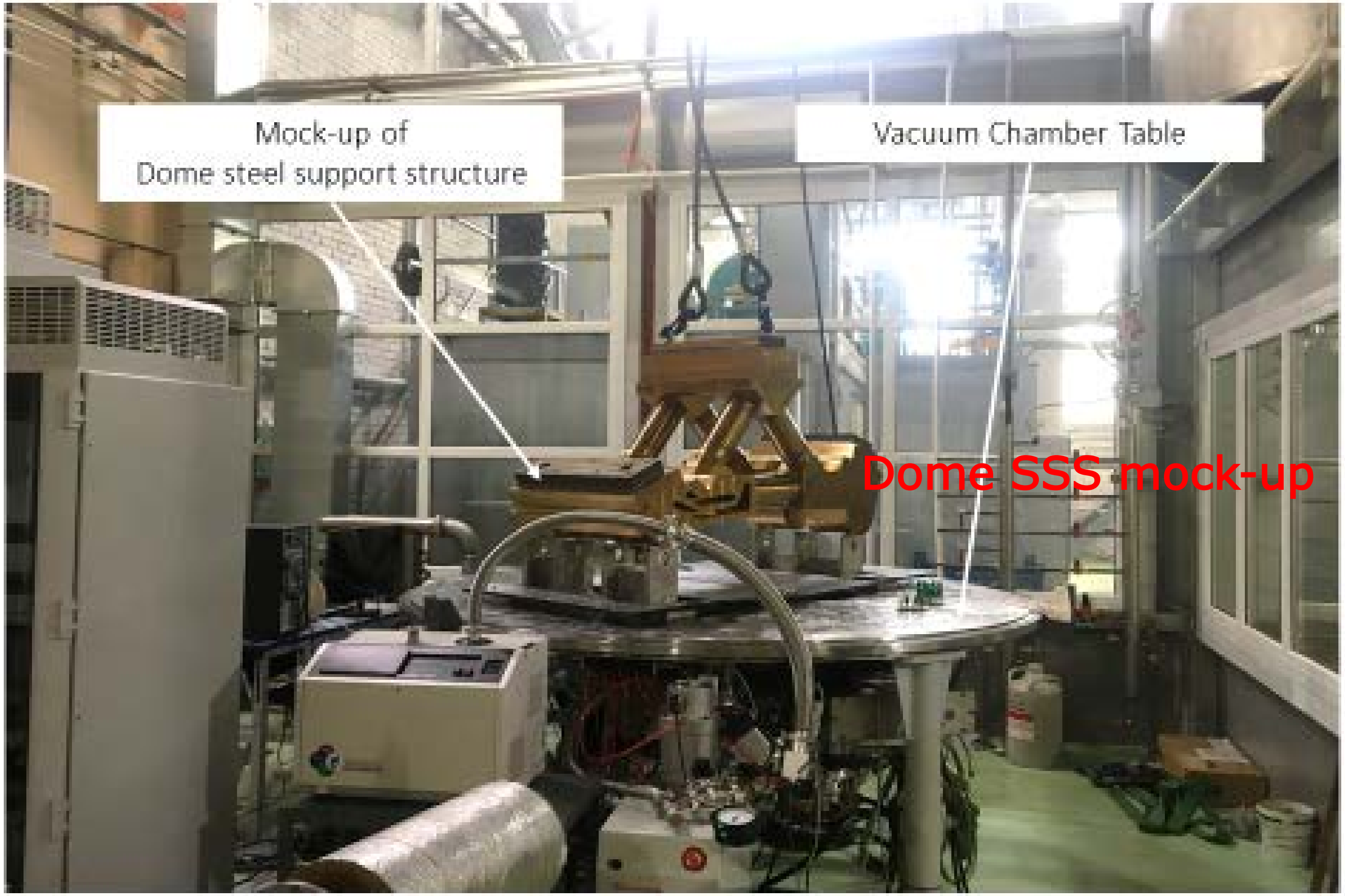
Fig.1 Schematic modeling of vacuum furnace

	Specification	Requirement
Facility	Hi-vacuum furnace for Hot He leak test	
Chamber Body	Stainless steel Dual jacket water cooling	
Loading Weight	Max. 7.0 ton	Max. 5.0 ton (Shield block)
Working Zone	ID2,100xH2,300(mm) (volume=11.2m^3)	1,725x1,300xH1,600 (Shield block+Jig)
Operating Temperature	Up to 600°C (Max. 700°C)	250°C
Heating Element	Moly[sheet type]	
Pumping System	Main pump : Cryopump Roughing pump : Dry pump	
Vacuum Level	Max : 6.7x10^{-4} Pa (expected)	1.0x10^{-1} Pa

Preliminary tests

To test the operation of the vacuum facility and test methods, preliminary tests were carried out

The object of preliminary tests



Since the first Dome (FSP) is expected only in the second half of 2019, the mock-up of Dome steel support structure was chosen as the object for preliminary tests

2. Brief introduction of SB HHLT facility

Electrical heating system in vacuum chamber

Standard leak

Vacuum chamber (9 m^3) and pumping system

Data acquisition & control center

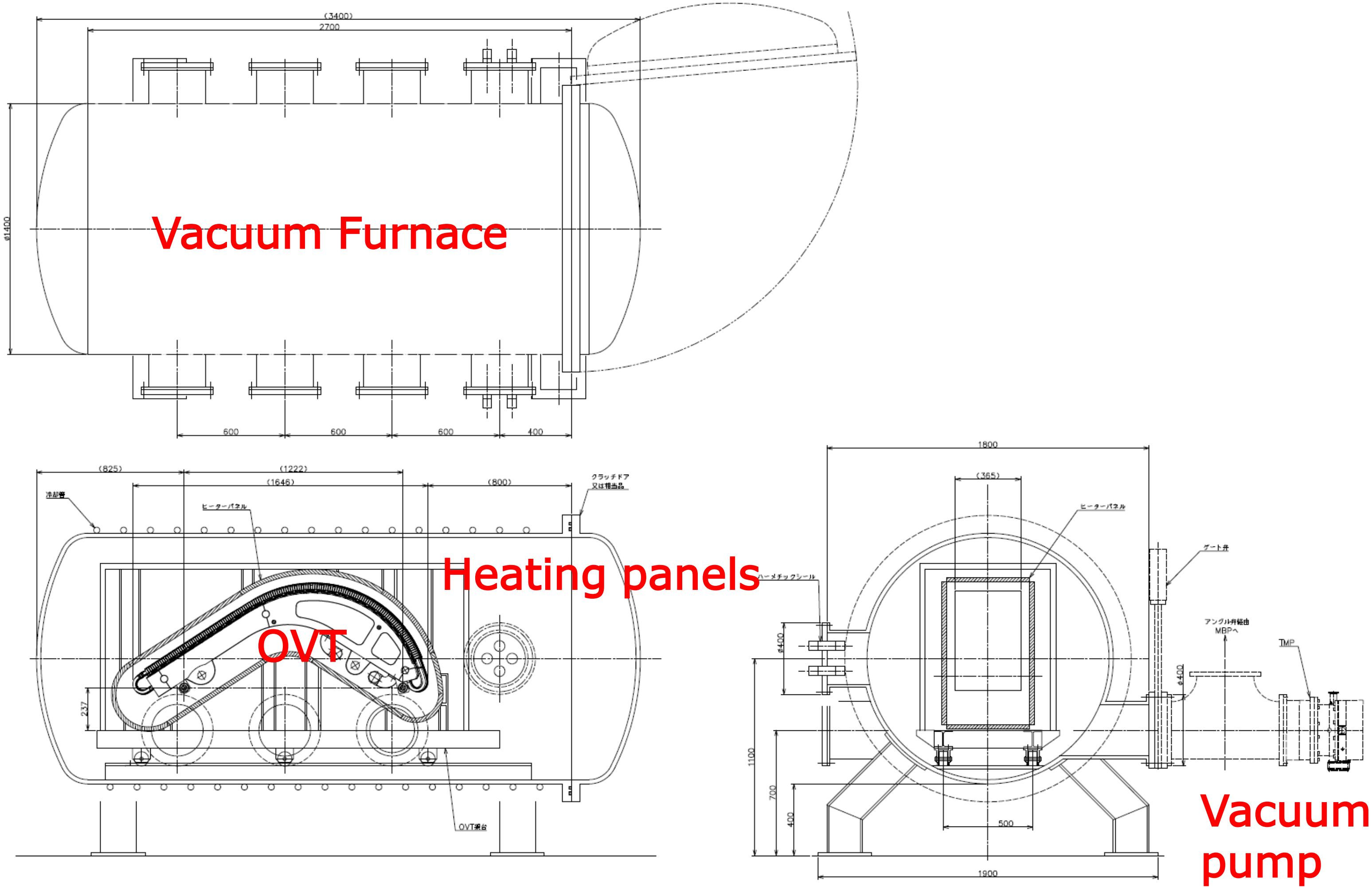
SB Hot Helium leak test facility

Installation & transfer system

High pressure He system

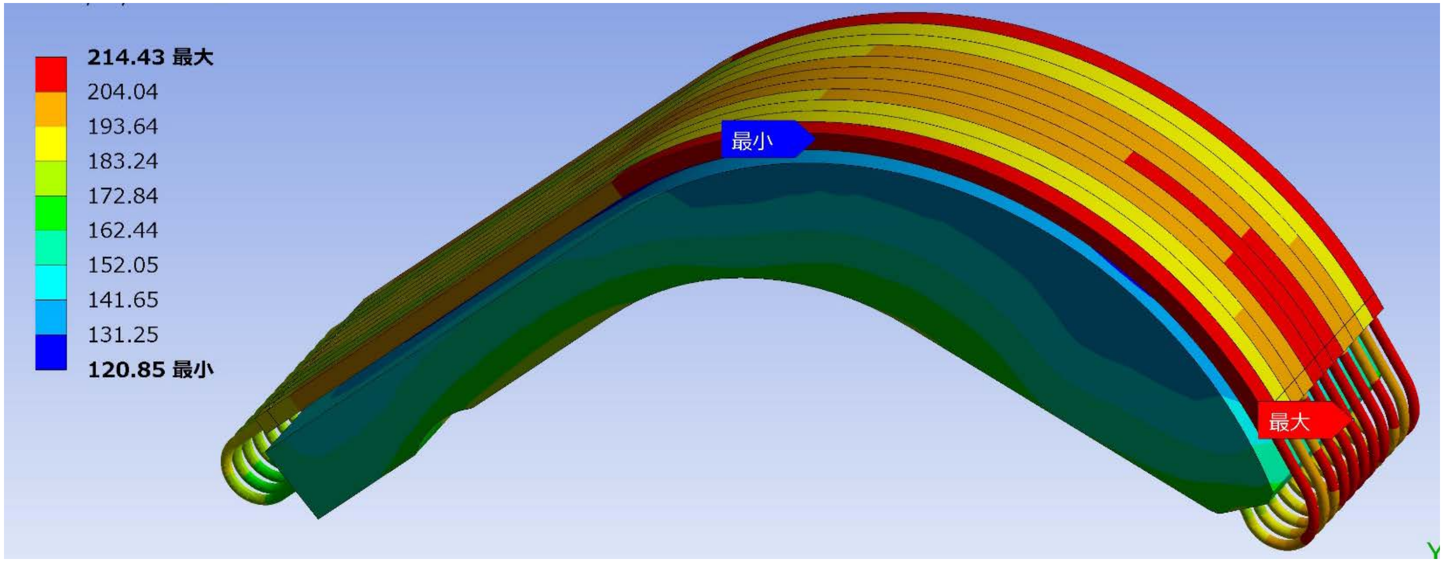
•Hot N_2 heating/cooling loop

Design of Vacuum vessel for OVT-HHLT



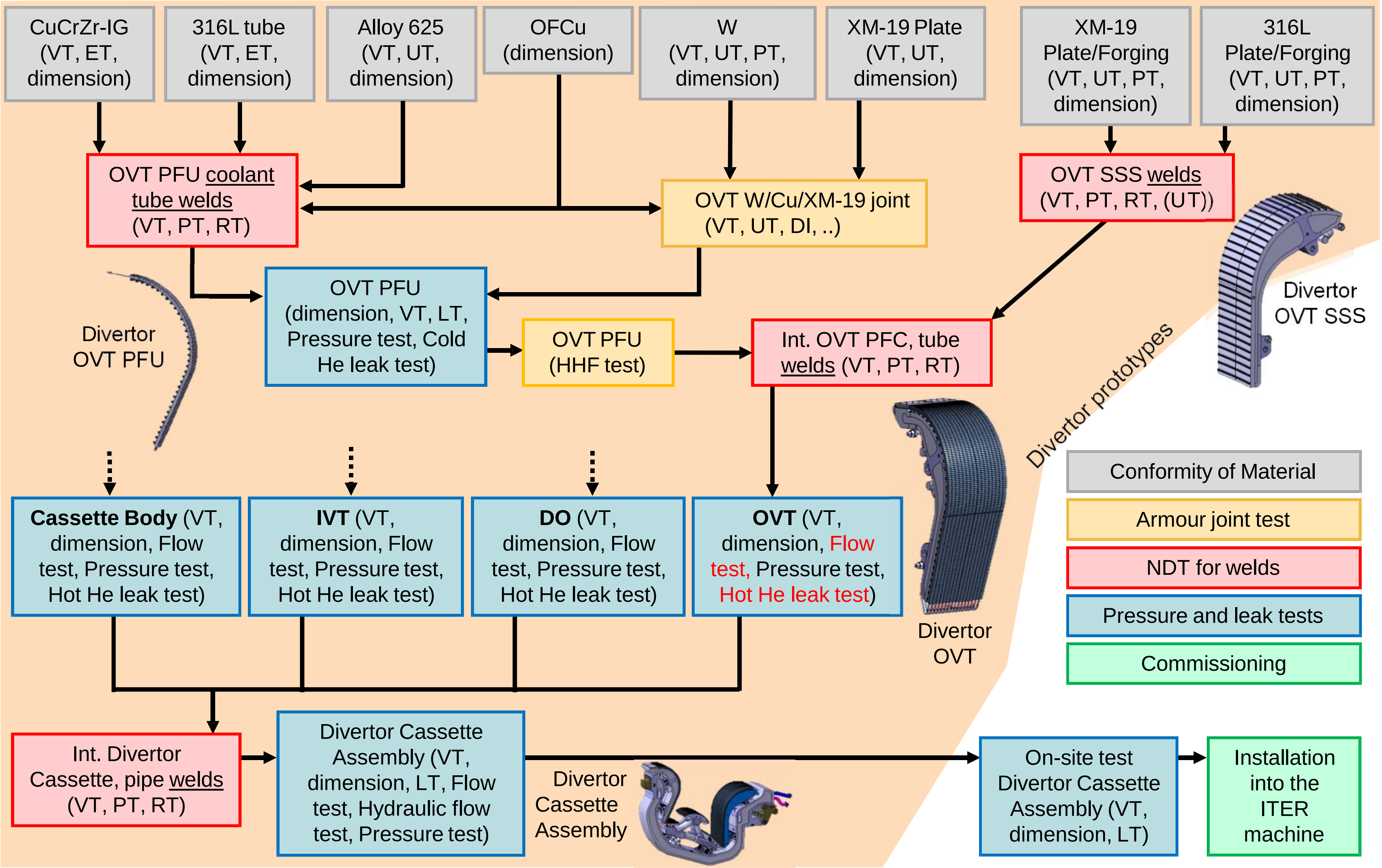
Issue: Heating panel design to heat up OVT uniformly

- OVT is consisted of three major parts with different thermal properties, i.e., W monoblocks, CuCrZr cooling tubes and Steel Support Structure (SSS).
- In design of Heating panel inside a vacuum chamber, thermal analyses were carried out to seek better solution of panel setting to heat OVT uniformly. CuCrZr cooling tube is easy to be heated up compared with the other parts.
- Each panel is needed to be controlled independently.



Example of analyses result of OVT during heating
(under optimization to get uniform temperature field)

Summary of Inspections/ tests for Divertor PFC/OVT



CuCrZr-IG (VT, ET, dimension)

316L tube (VT, ET, dimension)

Alloy 625 (VT, UT, dimension)

OFCu (dimension)

W (VT, UT, PT, dimension)

XM-19 Plate (VT, UT, dimension)

XM-19 Plate/Forging (VT, UT, PT, dimension)

316L Plate/Forging (VT, UT, PT, dimension)

OVT PFU coolant tube welds (VT, PT, RT)

OVT W/Cu/XM-19 joint (VT, UT, DI, ..)

OVT SSS welds (VT, PT, RT, (UT))

Divertor OVT PFU

OVT PFU (dimension, VT, LT, Pressure test, Cold He leak test)

OVT PFU (HHF test)

Int. OVT PFC, tube welds (VT, PT, RT)

Divertor OVT SSS

Divertor prototypes

Divertor OVT

Cassette Body (VT, dimension, Flow test, Pressure test, Hot He leak test)

IVT (VT, dimension, Flow test, Pressure test, Hot He leak test)

DO (VT, dimension, Flow test, Pressure test, Hot He leak test)

OVT (VT, dimension, Flow test, Pressure test, Hot He leak test)

Int. Divertor Cassette, pipe welds (VT, PT, RT)

Divertor Cassette Assembly (VT, dimension, LT, Flow test, Hydraulic flow test, Pressure test)

Divertor Cassette Assembly

On-site test Divertor Cassette Assembly (VT, dimension, LT)

Installation into the ITER machine

- Conformity of Material
- Armour joint test
- NDT for welds
- Pressure and leak tests
- Commissioning

Summary

- How-to-Realize, Manufacture and Inspect ITER PFCs, esp. ITER OVT.
  - Joining Armor material to Heat Sink (Cooling tube), technology validation through high heat flux testing
  - Welding; cooling tubes and steel support structure
  - Assembling
  - Other engineering topics
- Each PFC are ready to start prototyping and series production.

Thank you for your attention!!

Backup slides

Plasma-facing Material (PFM)

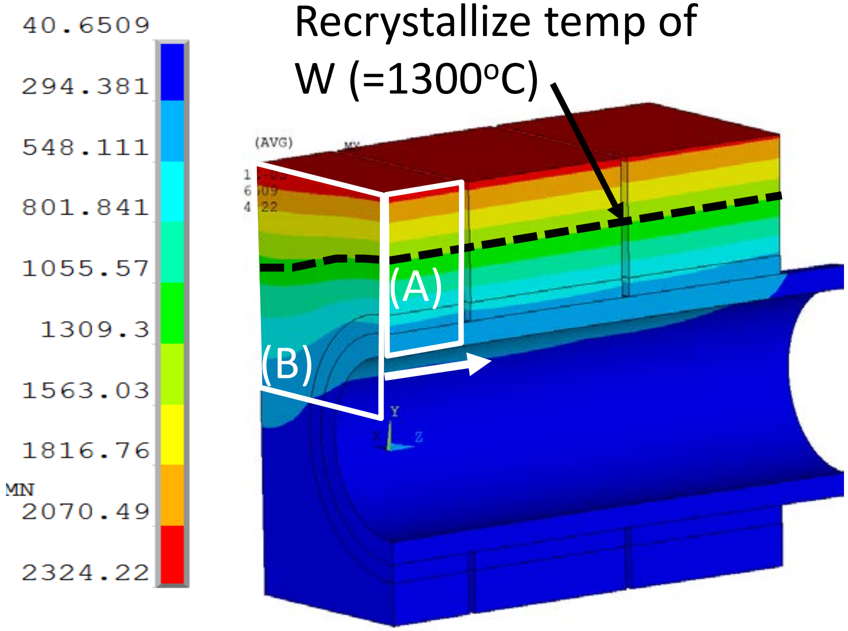
- High thermal conductivity
- High mechanical strength
- Low-Z material vs High-Z material

- PFM for ITER
  - First Wall: Beryllium
  - Divertor: Tungsten, Carbon

Cooling structure for PFC

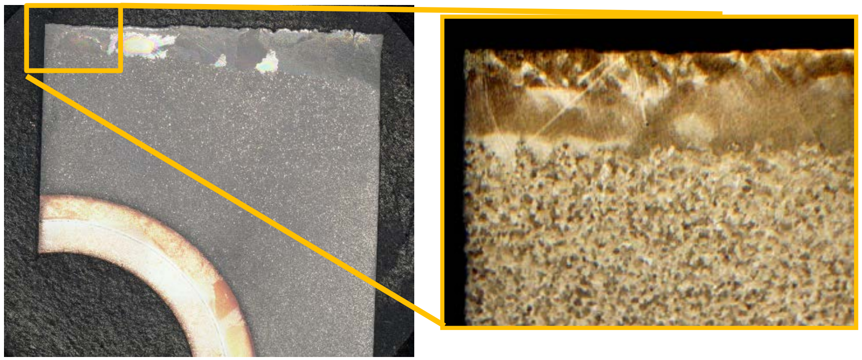
- Water cooling: ITER and the existing long pulse machines (Tora-Supra(WEST), EAST etc.)
  - CuCrZr tube and plate
  - Twisted tape insertion, hypervapotron, etc
- He-gas: ITER-TBM, DEMO-Divertor concepts
  - Impinging Jet Array with W/ODS-RFM
- Liquid metal (will covered by)

Post-mortem analysis of W monoblocks after HHF test of 20MW/m^2 for 1000 cycles

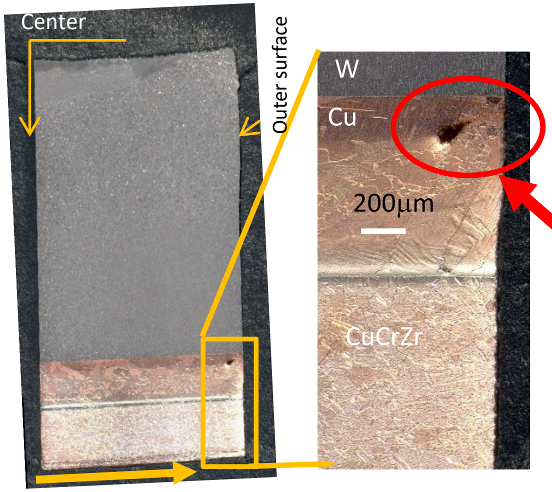


Recrystallize temp of W (=1300°C)

Cross-section (B) perpendicular to tube axis



Cross-section(A) parallel to tube axis



- No macro-cracking inside of W-MB, although large grain growth at surface due to recrystallization
- What is dominant characters to determine if macro-cracking occur is under investigation

Micro-crack in Cu interlayer (opening to outer surface) with 0.5 mm depth caused by thermal deformation of W during 20MW/m^2 heating for 1000 cycles.
This crack does not affect global heat removal capability.

Outline

- Design of ITER divertor and Outer Vertical Target (OVT)
  - Overall design, Shaping to protect leading edge
  - 5 Technical challenges JADA is struggling
- Recent achievements of JADA’s R&D activities,
  - Full-length Plasma-Facing Unit(PFU) prototyping and its High Heat Flux (HHF) testing
  - Water Flow Test on OVT prototype
- JADA’s qualification Programs for Mass Production
  - Mass production of W monoblock
  - Mass production of PFUs
- Summary and Near Future plan