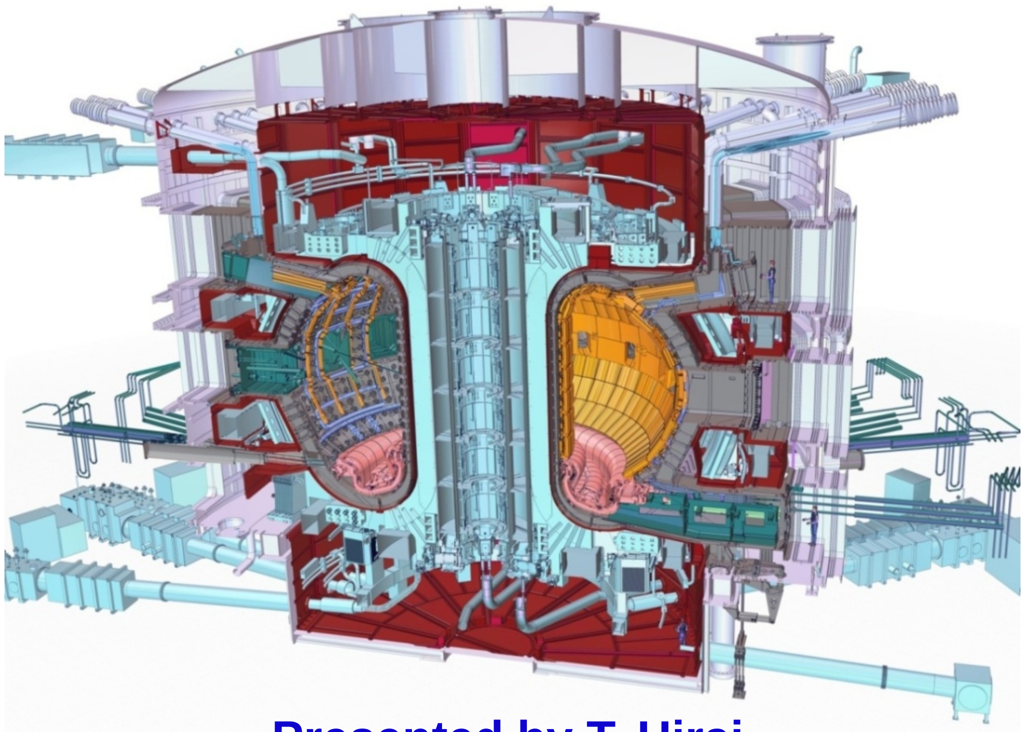
ITER full W Divertor Design and Progress of Technology R&D



Presented by T. Hirai

Tungsten Divertor Section, ITER Organization

On behalf of Tungsten Divertor Task Force at IO

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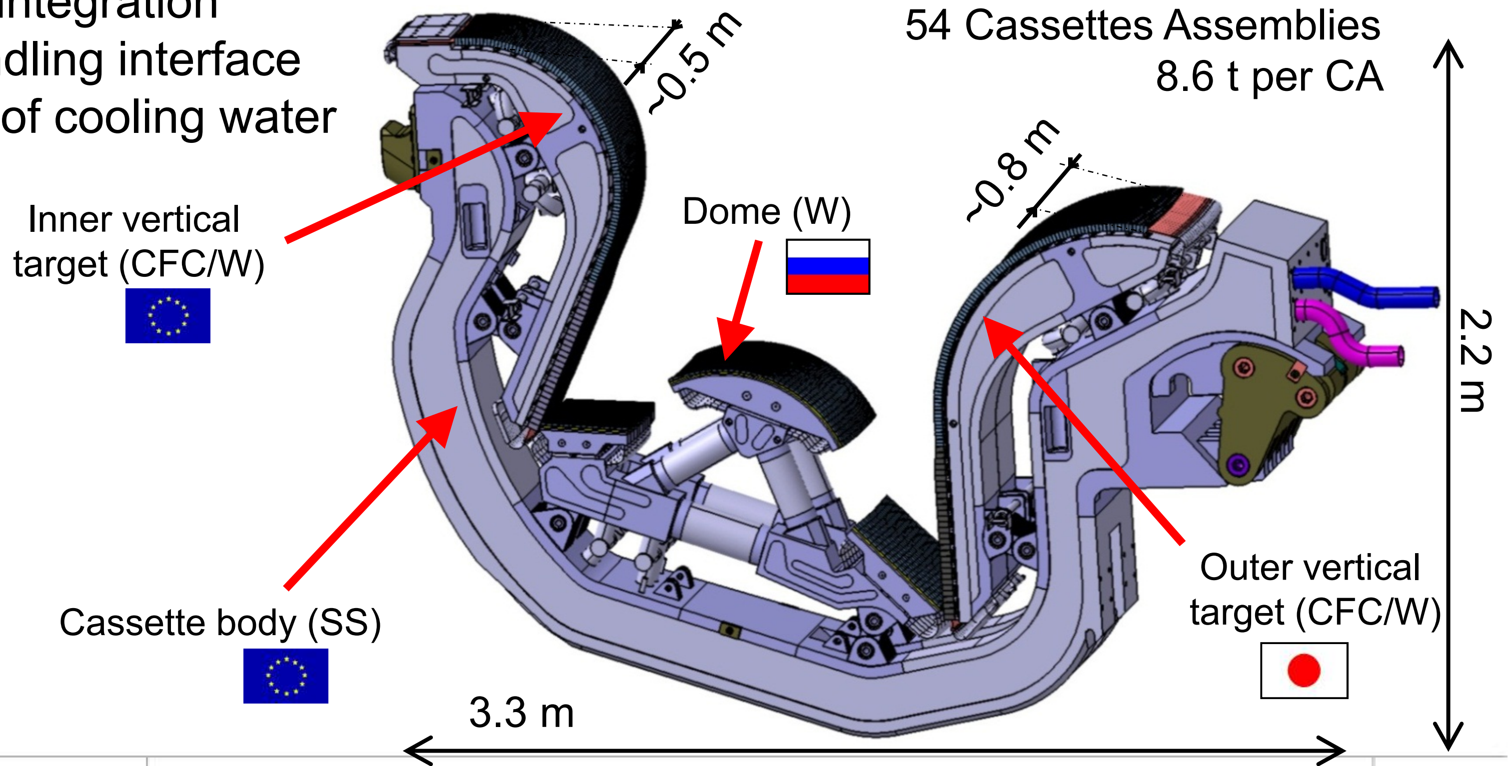
Divertor Cassette assembly

1. 54 Divertor Cassettes + 6 spare Cassettes
2. 3 Plasma-Facing Components (PFCs) on a cassette
3. Outer/Inner Vertical Targets, Dome (Umbrella and Reflector Plates)
4. Plasma-Facing Units (monoblock for VT PFUs and flat tile concept for Dome PFUs)
5. Plasma-facing Unit Attachments (plug and support leg)
6. Plasma-facing Component Attachments (Pin and multilink)
7. Divertor Cassette Attachments (Nose and Knuckle)
8. Diagnostics integration
9. Remote Handling interface
10. Circulation of cooling water

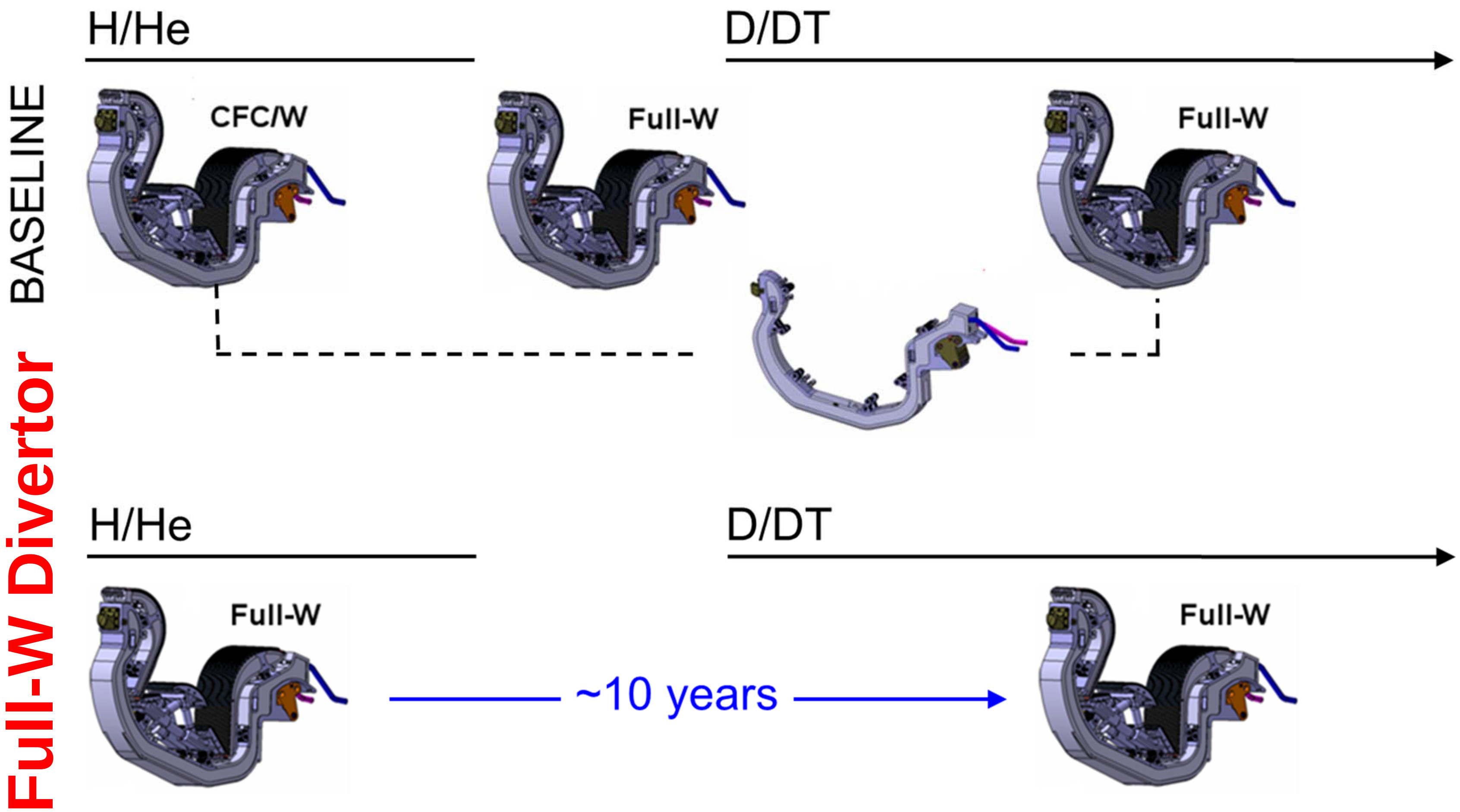


Background of Full-W Divertor Activity

- **New ITER divertor strategy**
  - From MAC-12 (Oct. 2011) [ITER_D_6SR5F7]: "[…] for budgeting purposes, the MAC supports the DG recommendation to de-scope to a single divertor during construction and initial five years of operation".[…] "As to the specific choice of divertor, MAC recommends delaying the decision for up to two years.
  - These recommendations were adopted by the ITER Council during its ninth meeting in Nov. 2011 so that IO started to investigate the possibility of beginning operation with a full-W armoured divertor.

Divertor Maintenance strategy

- **Extension of Lifetime**



Outline

1. Design constrain/input
2. Detailed divertor PFC Design
3. Design Validation
4. Technology R&D requirements
5. Progress of technology R&D in EU and JA
6. Conclusion/Schedule

W Divertor Design – Requirements/ Input

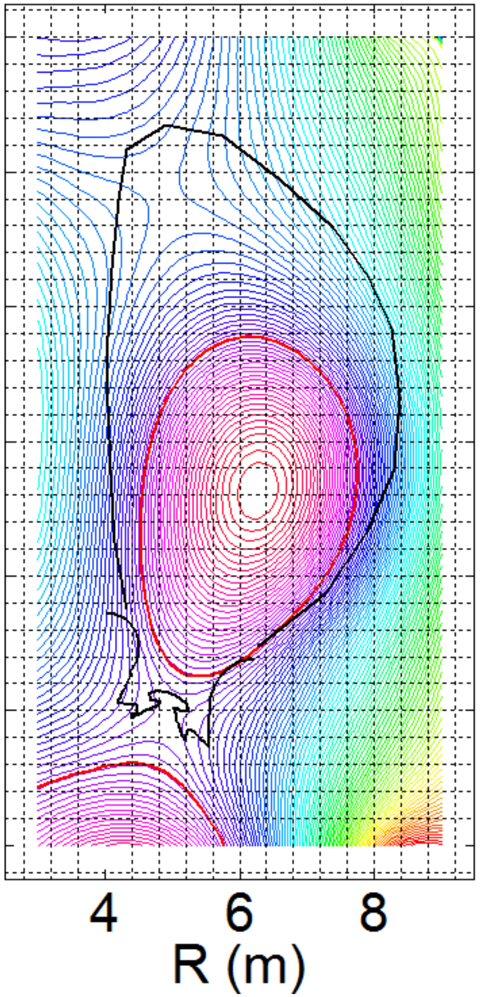
- **Structural Design**
  - Load Specification for the ITER Divertor *(C9RF33)*
  - Structural Design Criteria – In-vessel Component (SDC-IC) *(222QGL)*

- **Plasma-Facing Unit Design**
  - Heat Load Specification for ITER Tungsten Divertor:
    (1) Power density and number of cycles on the Vertical Target *(7GFMB6)*
    (2) Poloidal conductive/convective surface heat loads *(HDB7NZ)*

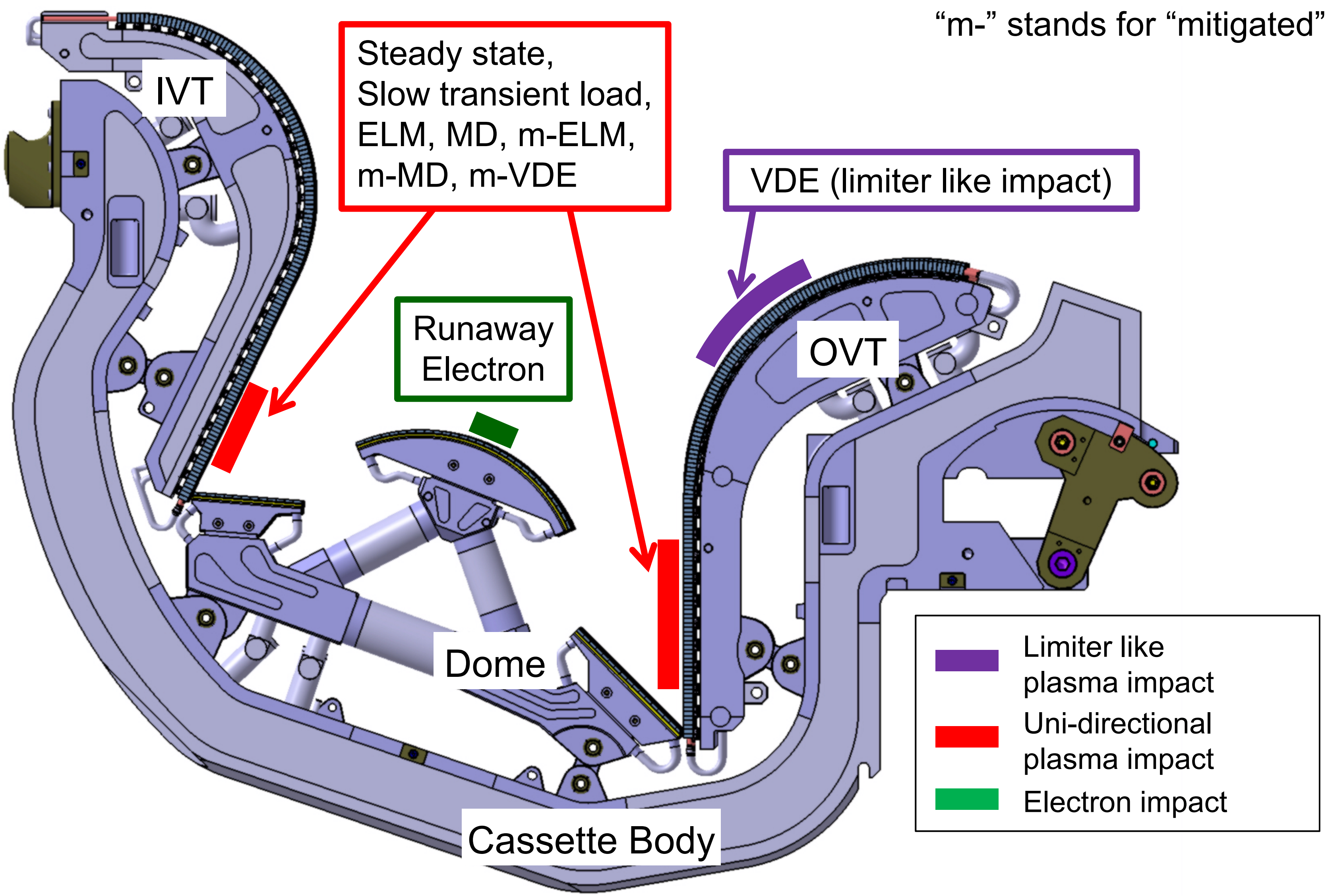
- **Tolerances**
  - Assembly tolerances between Cassettes (20mm gap) : step ±2 mm *(Divertor Plasma Facing Surfaces Position and Shadowing Tolerances Build Up (764MGY), and margin)*
  - Assembly tolerances between two halves of VT PFCs (3mm gap) : step ±0.3 mm *(in 2D drawings)*
  - Assembly tolerances between VT PFUs (0.5mm gap): step ±0.3 mm *(in 2D drawings)*

W Divertor Design: Design Constrains/ Assumptions

1. Single coolant tube for a PFU to limit impact on CB design, diagnostics procurement, assembly plan, other interfaces (splitting target and baffle is not considered)
2. Dome design is retained as long as neutronics analysis confirms
3. Materials for Tungsten Divertor remain same except (a) exchange of CFC by W and (b) updated radioprotection requirements
4. Monoblock concept is retained
5. PFU attachment concept (PFU to the steel support structure) is retained.
6. DW VDE (limiter configuration) contact only at OVT baffle according to the recent DINA analysis (ITER_D_765S86).



Thermal Event Impact at Plasma-Facing Surfaces



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Divertor Shaping Strategy

Objective:

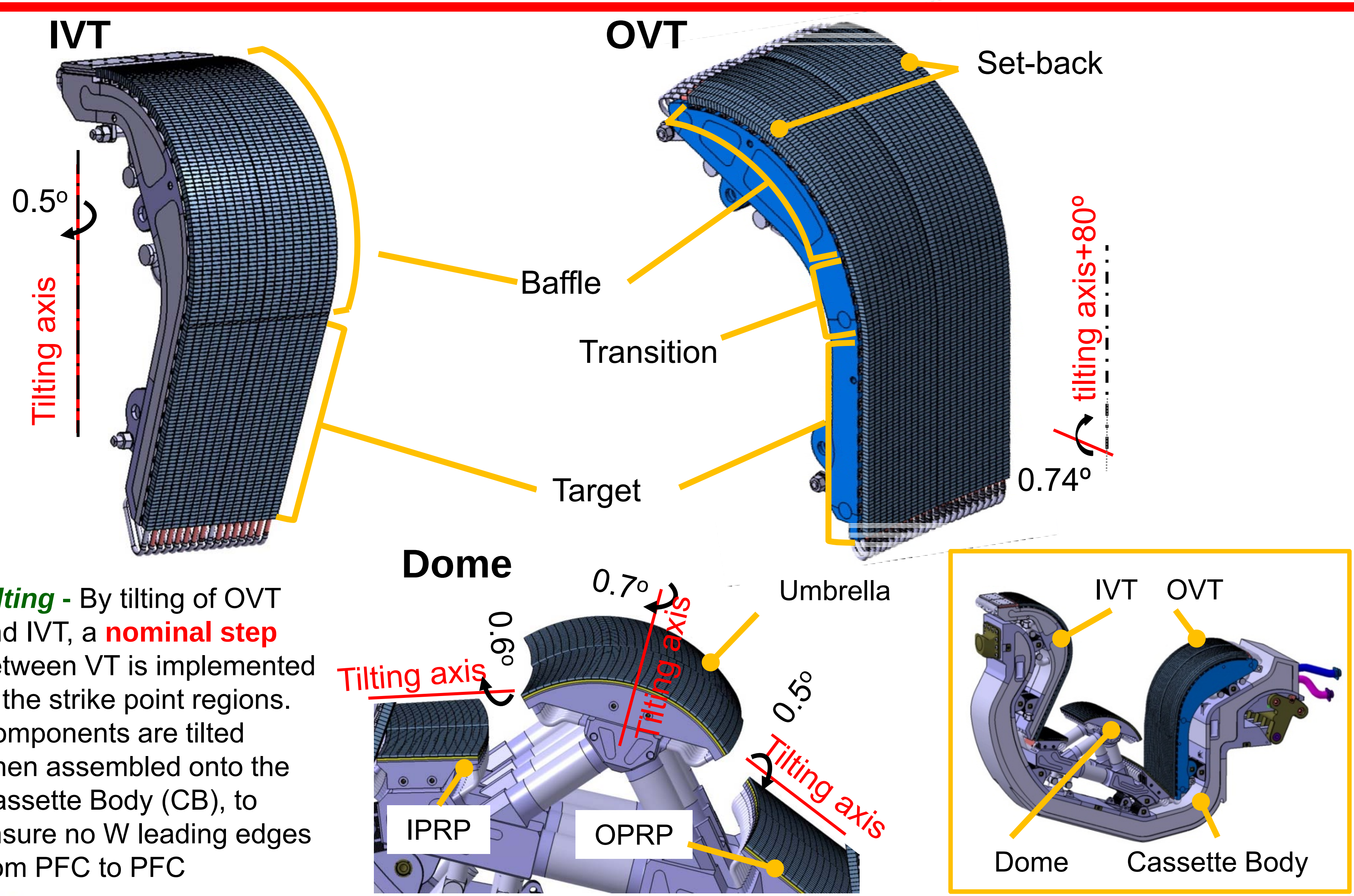
To avoid melting due to leading edge exposure during steady-state and slow transient and to minimize the melting under off-normal events – **full edge-shadowing in high heat flux handling areas**

1. Tilting of each Divertor Plasma-Facing Component

2. Toroidal-Roof-shaping and Outer Vertical Target chamfer

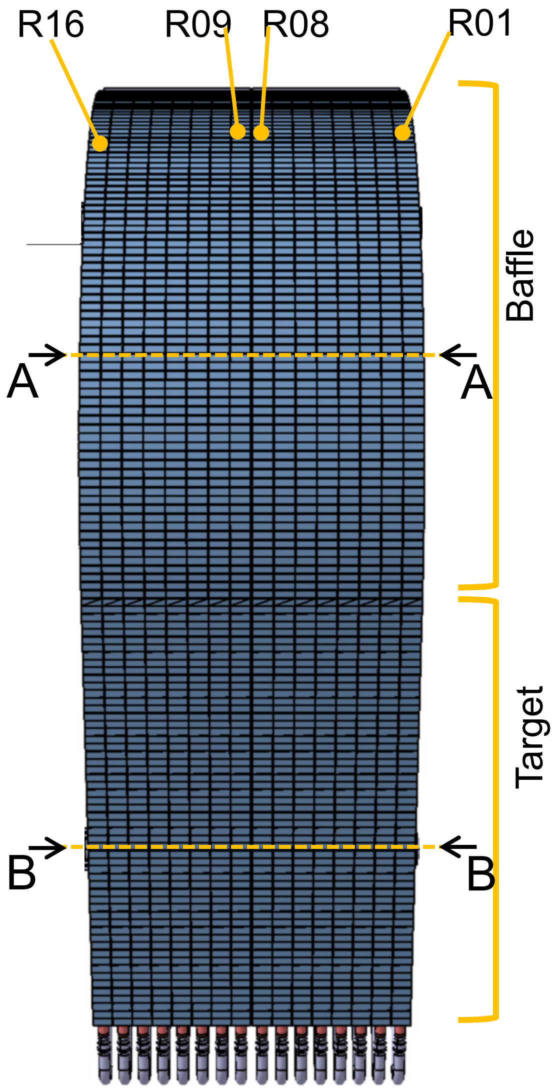
3. Monoblock toroidal chamfer

Tilting Scheme for OVT, IVT and Dome

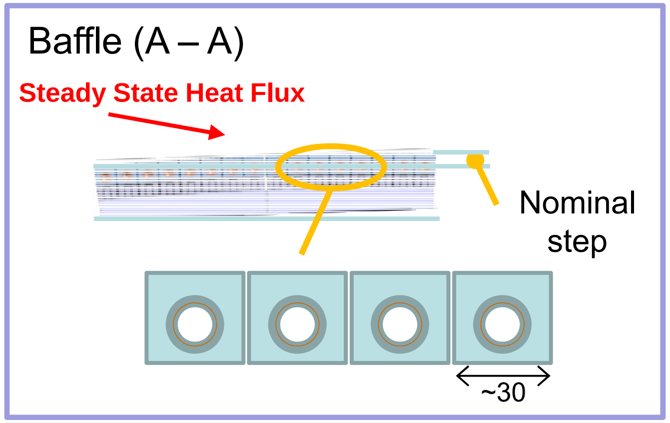


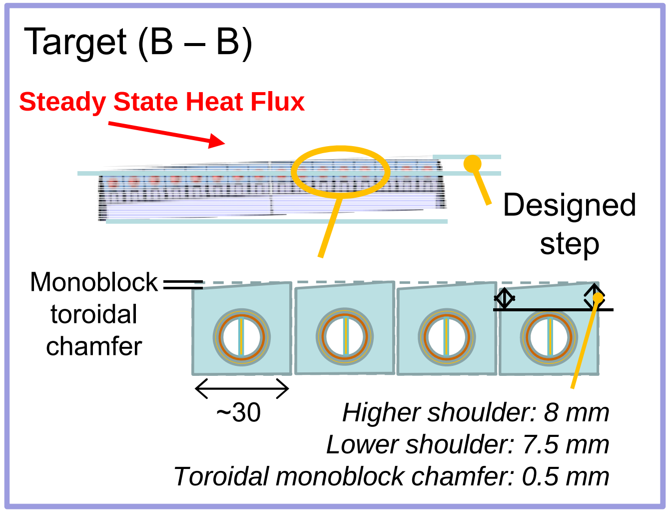
Tilting **-** By tilting of OVT and IVT, a **nominal step** between VT is implemented at the strike point regions. Components are tilted when assembled onto the Cassette Body (CB), to ensure no W leading edges from PFC to PFC

IVT design – Monoblock toroidal chamfer at target



PFU variant: R01=R02…R16 (Reference PFUs)

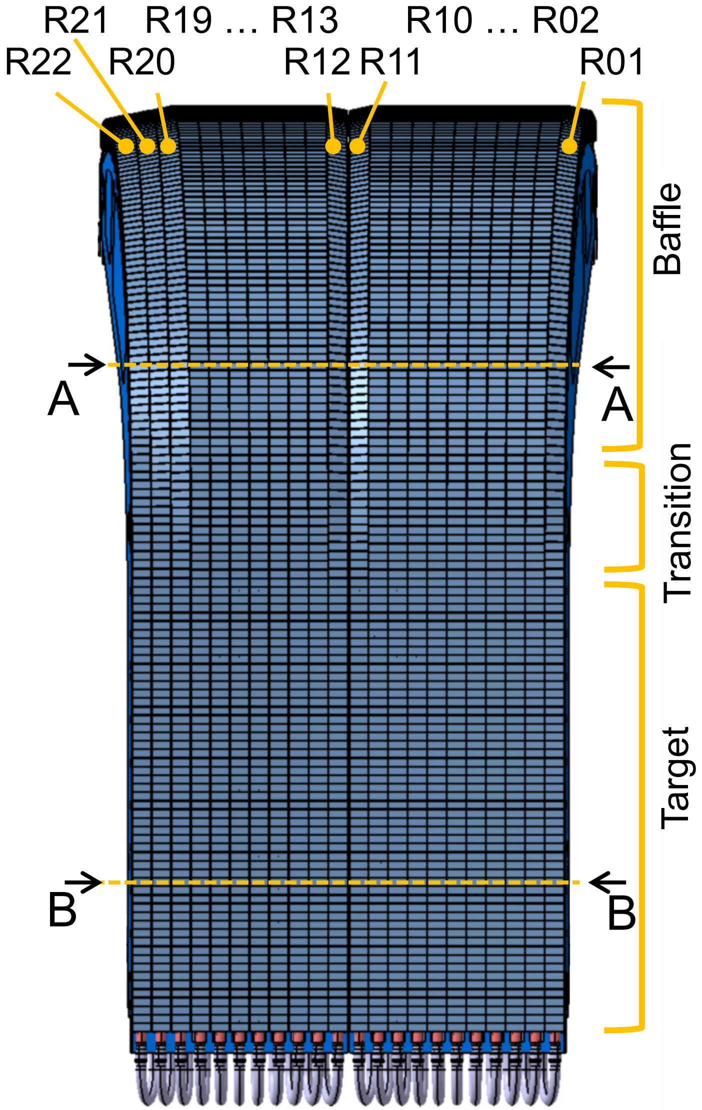


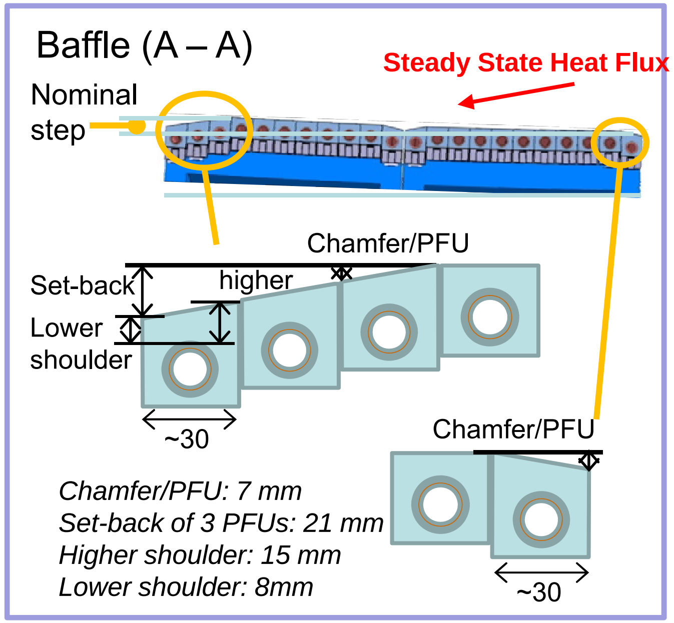


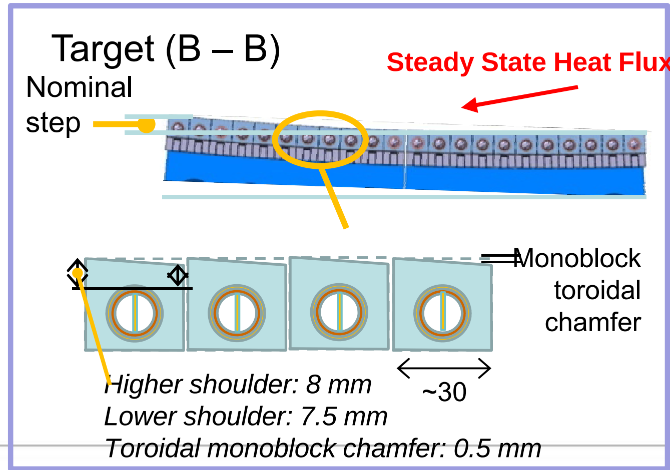
Monoblock toroidal chamfer to protect edge from 0.3 mm deviation → 0.5 mm toroidal monoblock chamfer

OVT design: PFC chamfer + monoblock chamfer

PFU variants: R01=R12; R11=R20;
R02= R03…R10, R13…R19 (reference PFUs)

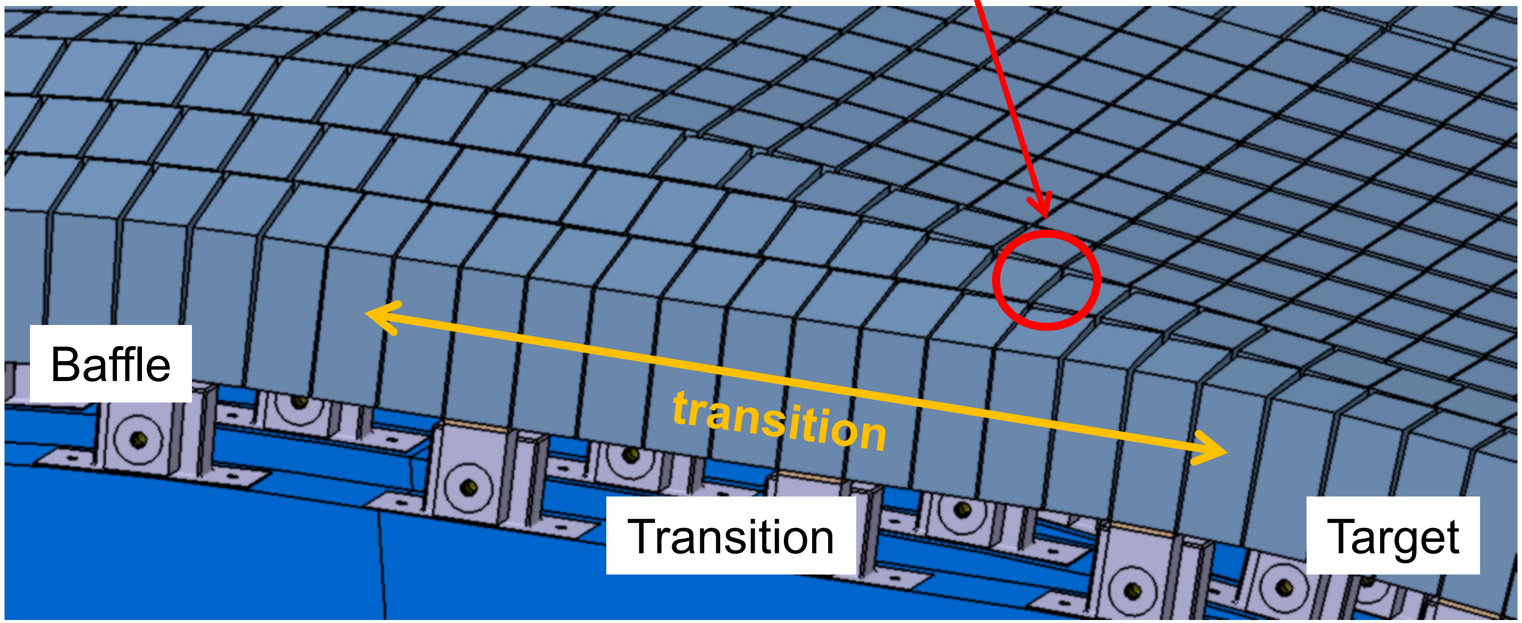






OVT design – Transition from target to baffle

- **Transition: (1) monoblock thickness; (2) monoblock toroidal chamfer; (3) PFU profile**
  - Monoblocks have simple chamfers at plasma facing side
  - Location of transition: away from the VDE impact area – steady state loading area
  - Poloidal edge: exposed toward bottom direction

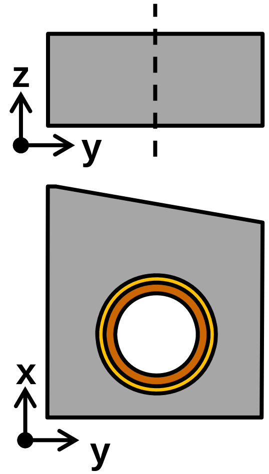


Manufacturing of W monoblock and PFU

- **W Monoblock**
  - Monoblocks consist of simple chamfer or double chamfer at plasma facing side (No complicated 3D profile)

  → Monoblocks can be manufactured by conventional operations such as:
    - EDM wire cut operation (no need of milling)
    - Grinding operation
    - Conventional cleaning process

  → Inspection i.e. dimension control, to be defined in NDT protocol



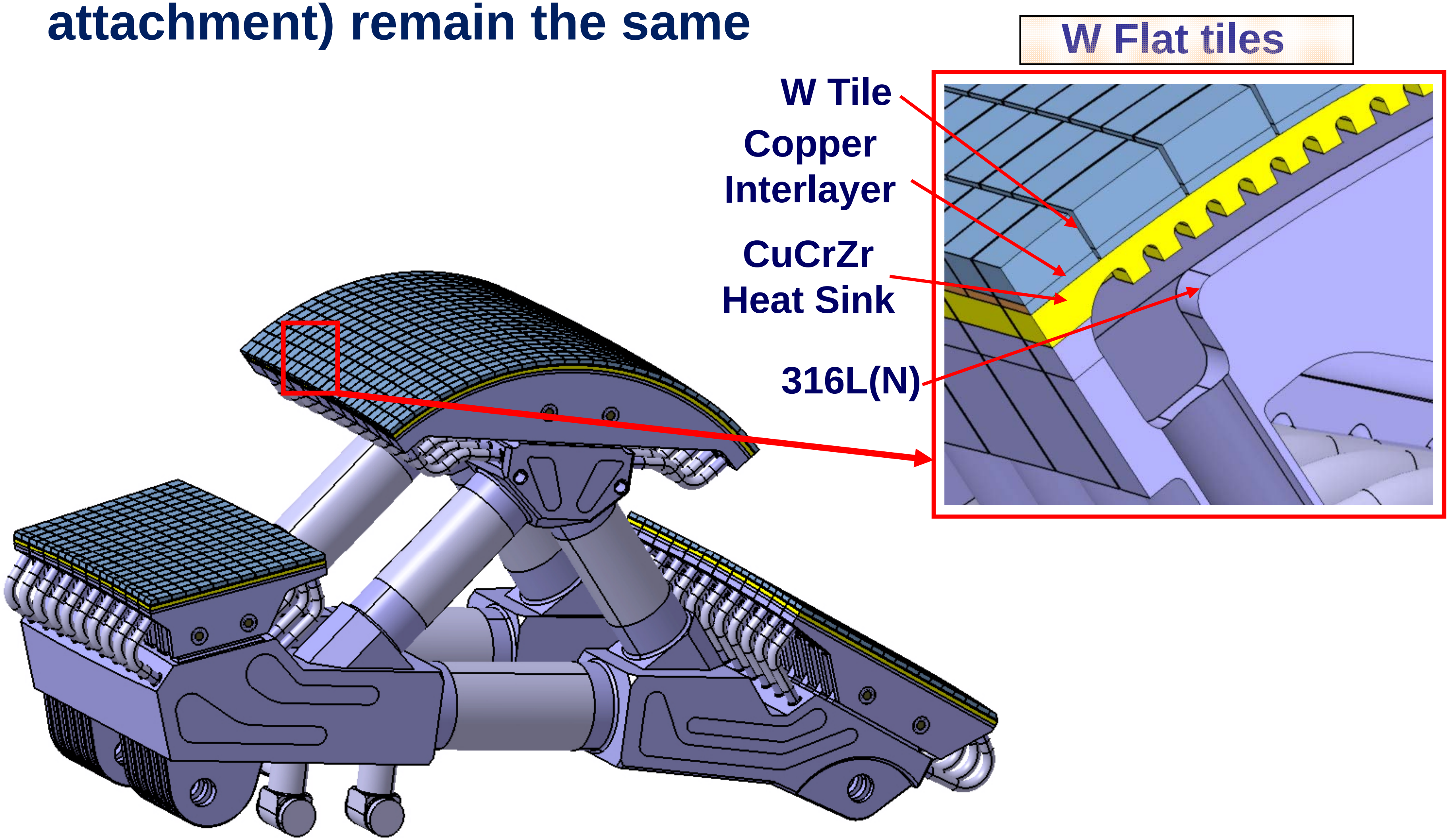
- **PFU**
  - **OVT: only 5 variants**

  Reference OVT PFU R2 = R3-R10 = R13-R19;
  Toroidal roof shaping OVT PFUs R1=R12; R11=R20; R21; R22

  - **IVT: only 1 variant**

Dome cooling structure and PFU attachment

- **Dome design (cooling structure & PFU attachment) remain the same**



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Design Validation by analysis

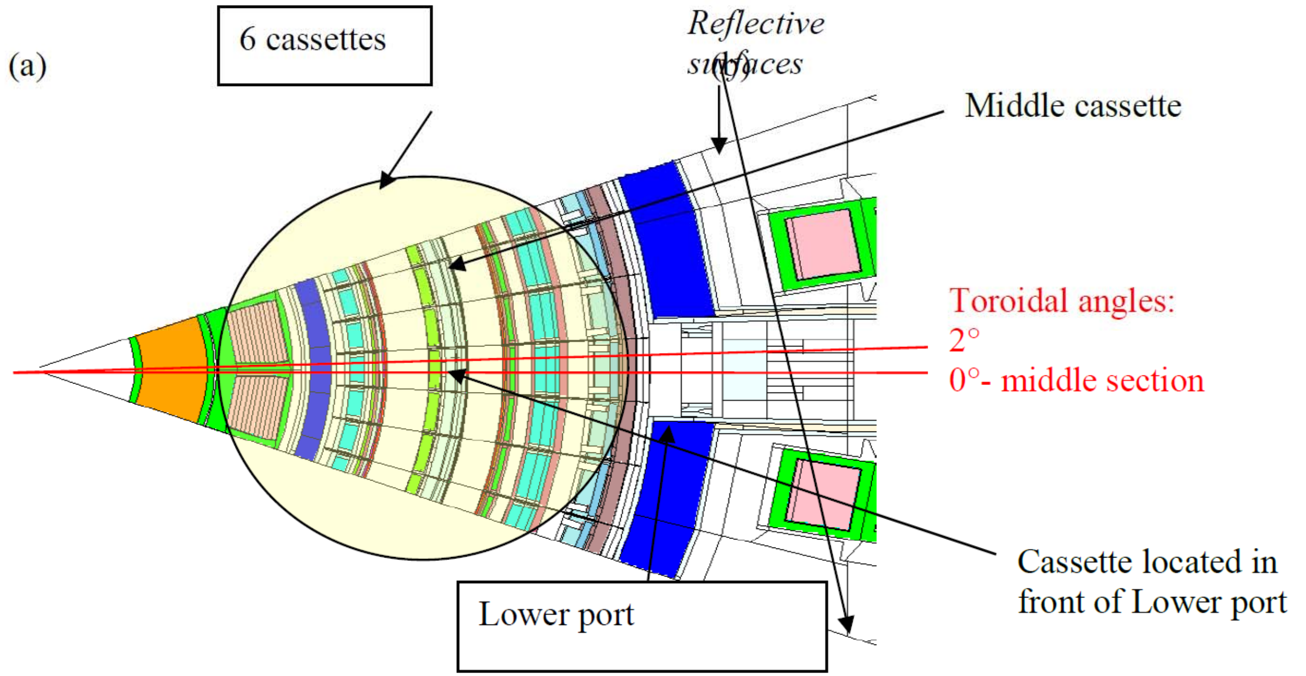
1. Neutronic analysis
2. Design Supporting analysis (thermo-mechanical and EM analysis)
3. Heat Load distribution Study – PFC and monoblock level

Nuclear Analysis for ITER W Divertor

Model: Neutronic analysis by means of the latest ITER MCNP-5 Monte Carlo Code for 3D model (MCNP ITER 40° model B-lite v-2)

Assumption: 18% of the cumulated $3x10^{27}$ neutrons (End of Life) during first divertor (up to end of the first full DT campaign)

Aim: Evaluate nuclear heating, radiation damage and helium production



Nuclear Analysis Results – damage (dpa)

Villari - Neutronic Analysis (ITER_D_HQZHC5)

Maximum dpa at ITER EOL (permanent)			
Component	**W**	**Cu/CuCrZr**	**SS**
IVT PFU	0.51	2.37	1.28
OVT PFU	0.54	2.50	1.52
Dome Umbrella PFU	0.48	2.11	1.31
CB plate below Dome			0.14
Maximum dpa after 4 years of ITER nuclear phase (first cassette)			
Component	**W**	**Cu/CuCrZr**	**SS**
IVT PFU	**0.089**	**0.41**	**0.22**
OVT PFU	**0.095**	**0.44**	**0.27**
Dome Umbrella PFU	**0.084**	**0.37**	**0.23**
CB plate below Dome			**0.025**

Design supporting analysis

Input:

Defined Load combinations in Load Specification for the ITER Divertor (C9RF33)

Aim:

Validate structural integrity under the following loads and load combinations by FEM

- Inertial loads (associated with gravity and seismic events);
- Hydraulic pressure loads,
- Electromagnetic loads,
- Thermal loads (due to nuclear heating and surface heat fluxes), and
- Assembly loads (typically due to preloads imposed on the CB during assembly and preload of the bolts).

Design supporting analysis – Load Combinations

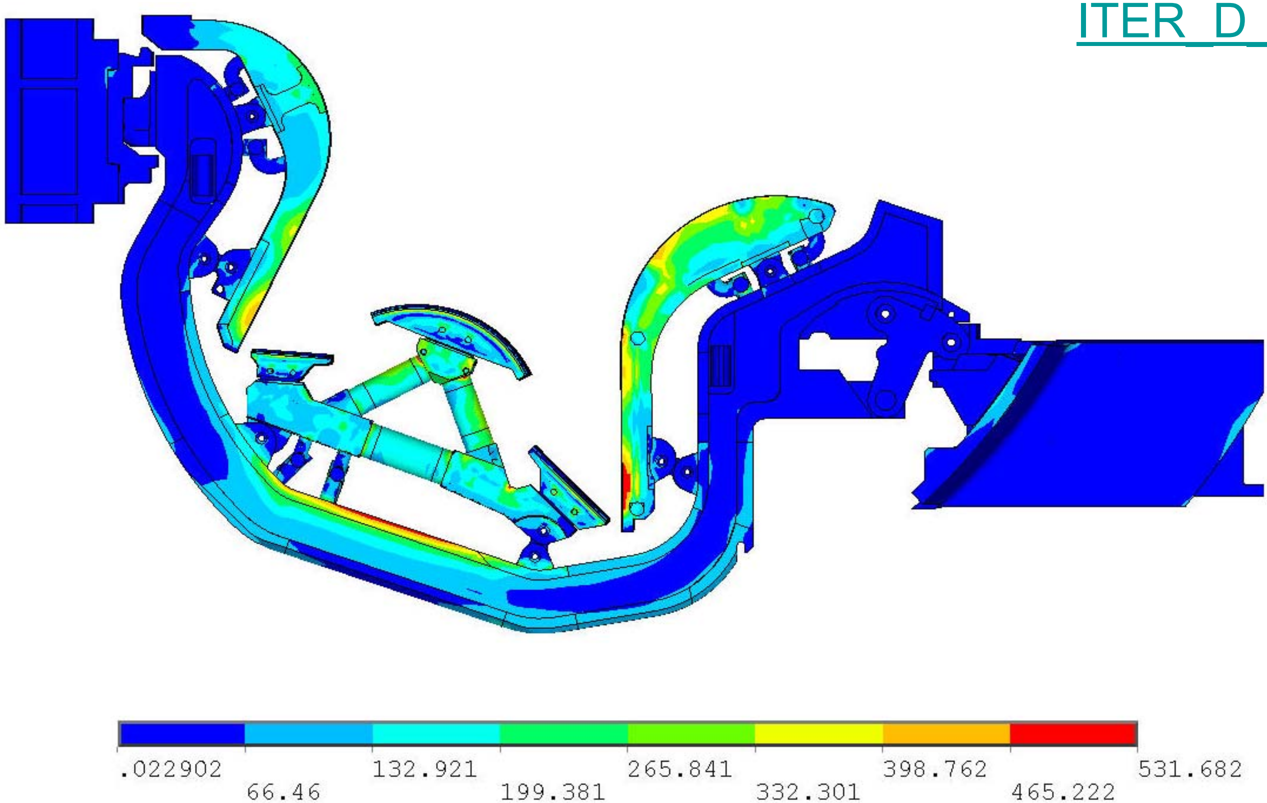
	Individual events in ITER tokamak			Additional loads specific to divertor	Category	Number of events[1]
	Seism	Plasma[3]	Magnet			
1		Testing regime		DW, Hydr. test pressure,	Test	1
2		Baking regime[2]		Preload, DW, CP, TH	I	200 at 240 C 4.4 MPa 200 at 350 C at 1 MPa
3		Normal operation		Preload, DW, CP, TH	I	Only for thermal loads: 5000 for PFCs and CB @ 10 MW/m^2 300 for PFCs and CB @ 20 MW/m^2 30,000 for rails
4		SDVDE-II 50-100 ms		Preload, DW, CP, TH	II	150
5		FDVDE-II 36 ms		Preload, DW, CP, TH	II	150
6		MD-I 50 ms	MFD-II	Preload, DW, CP, TH	II	3000
7	SL-1[3]		MFD-II	Preload, DW, CP, TH	II	1
8		SDVDE-III (>200ms)		Preload, DW, CP, TH	III	1
9		FDVDE-III 36 ms		Preload, DW, CP, TH	III	1
10	SL-1[3]	SDVDE-II 50-100 ms	MFD-II	Preload, DW, CP, TH	III	1
11	SL-1[3]	FDVDE-II 36 ms	MFD-II	Preload, DW, CP, TH	III	1
12	SL-2[3]			Preload, DW, CP, TH	IV	1
13		SDVDE-IV slow-fast		Preload, DW, CP, TH	IV	1
14		“Rotating Asymmetric VDEs”		Preload, DW, CP, TH	IV	1
15	SL-2[3	Baking regime		Preload, DW, CP, TH	IV	1
16	SL-2[3	Maintenance		DW	IV	1

Load Specification for the ITER Divertor System (C9RF33)

Design Supporting Analysis Results

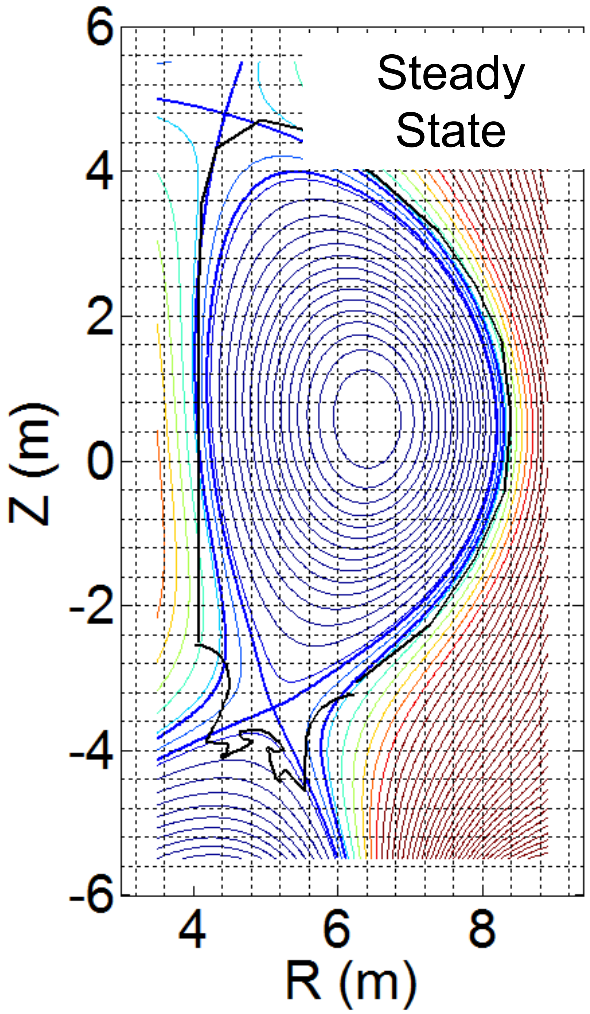
Stress intensity (MPa) at 2nd load combination: CB preload + DW+ CP + Temperature

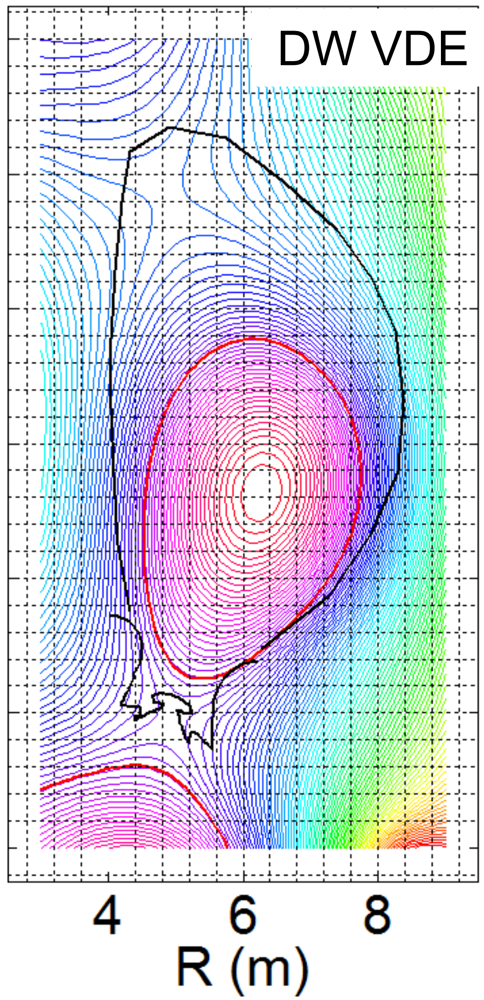
ITER_D_HR2ZCU



- Primary stresses are within allowable limits for the analysed load cases (DW, Pressure test, Coolant pressure, EML)
- Cyclic strength criteria (no ratcheting) are satisfied for the SSS of the PFCs, Dome PFUs and CB.

Heat Load distribution study – PFC level





Input:
- Plasma configurations
- Heat load specification
- Max misalignment at gap
- Plasma-facing surface envelop

Tool:
PFCFLUX – 3D field line tracing code

Aim:
Validate full edge shadowing during Steady State and VDEs

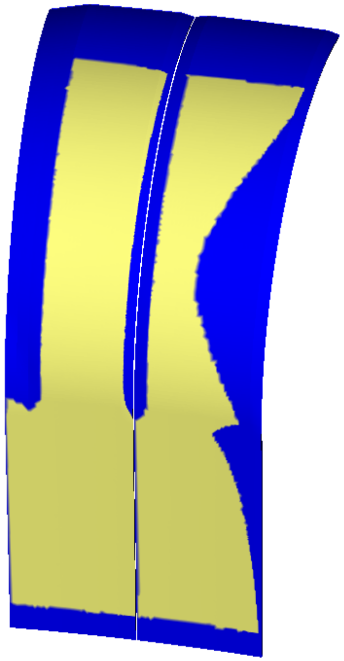
Key component: OVT

Heat Load Distribution Analysis Results

- **Examin 5 (I_P, B_T) steady-states**

→ No leading edges

15MA, 5.3T

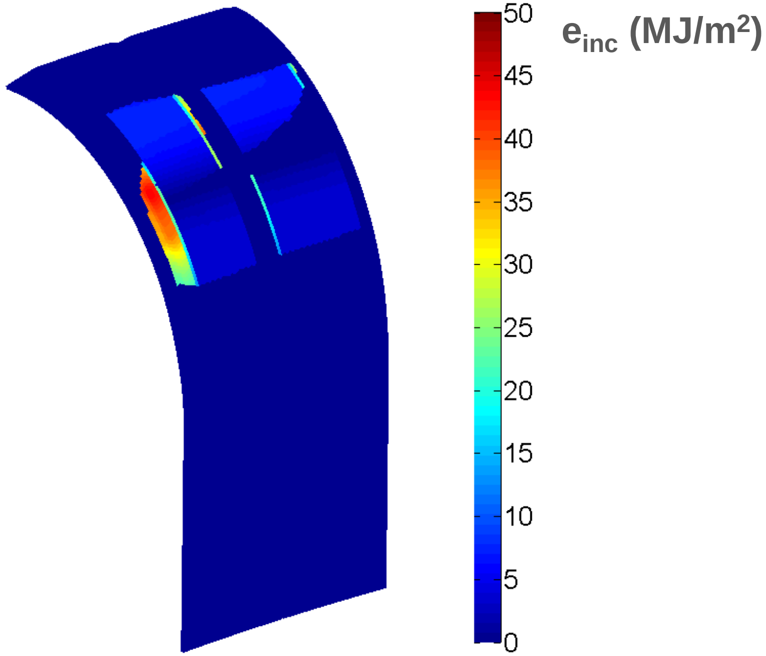


Wetted area at OVT surface

With worst misalignment

- **Examine Analysis of ~75 DINA time sequences → no leading edges**

'DW VDE, init li = 0.6, 675 ms'



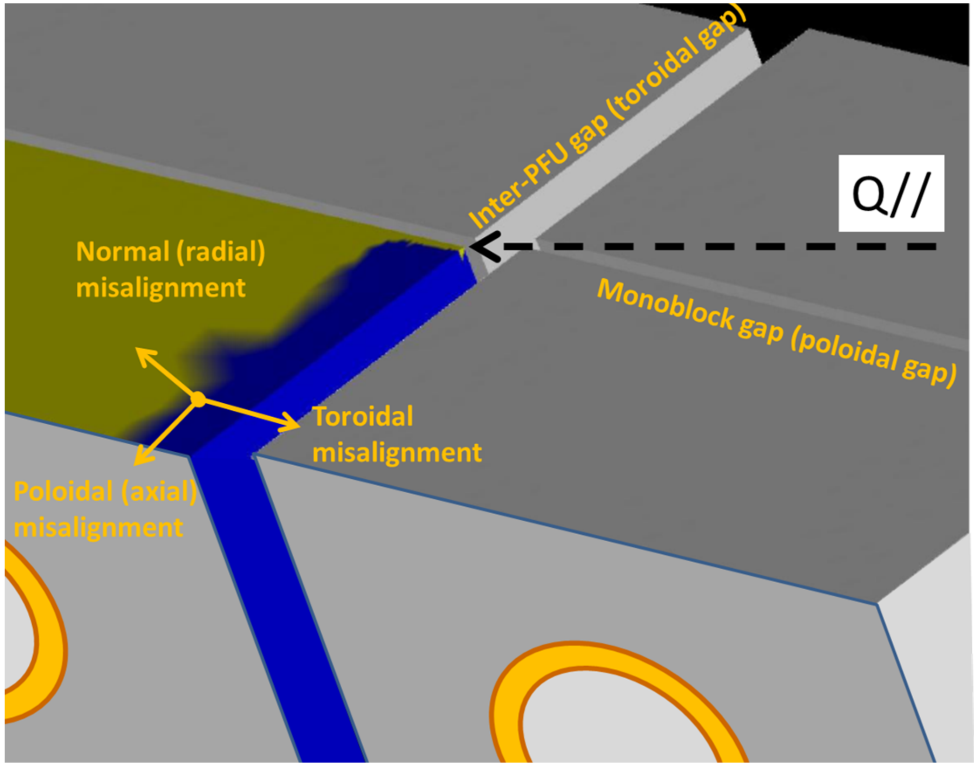
Energy density at OVT surface

With worst misalignment

- Demonstrates OVT shaping design could avoid leading edges

Heat Load distribution study – monoblock level

Monoblock (axial 12 mm; toroidal 28 mm) edges could be exposed to flux tubes penetrating through the monoblock gaps (nominal width 0.5 mm).



Input:

- Plasma configurations
- Heat load specification
- Max misalignment at gap
- Monoblock geometry

Tool:

1. PFCFLUX:

Field tracing analysis (optical)

2. Monte Carlo test particle simulation:

Ions with random perpendicular velocities (Maxwellian distribution) in magnetic field

Aim:

Validate full edge shadowing at HHF area at monoblock level

Under final tuning: double chamfer

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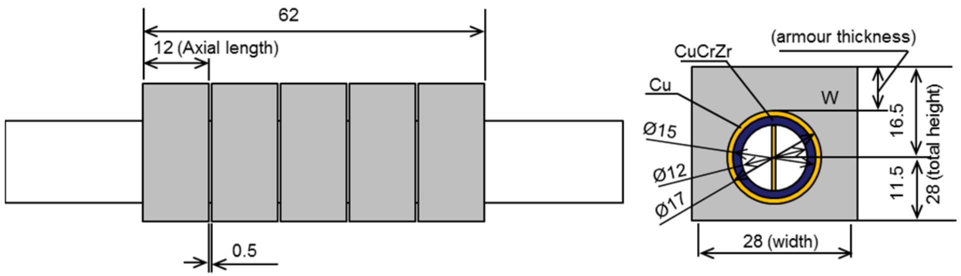
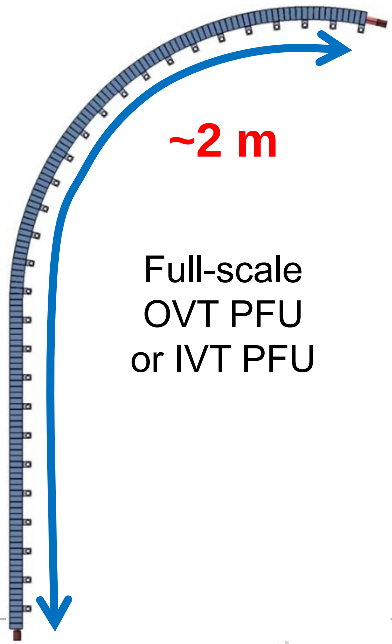
Full-W Divertor Qualification Program

2 steps in the program

(1)Technology Development and Validation : Demonstration of the *fitness-for-purpose* of the proposed technology, full-W small-scale mock-ups manufacturing and High Heat Flux testing

(2) Full-scale demonstration : Demonstration of the technology via full-scale-prototype PFU manufacturing and testing in IDTF; Compliance with IO procurement quality requirement





1st step: Technology Development and Validation

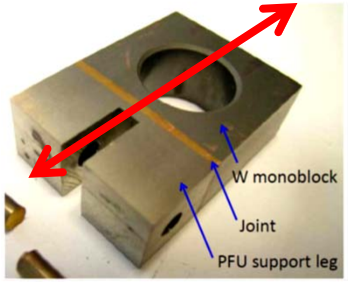
- **PFU attachment joint**

(1) Uniaxial tensile test at RT (at least 5 samples; Load speed 20-60 N/s)

Acceptance Criteria: >8 kN for OVT and >10 kN for IVT (attachment/5monoblocks)

(2) Cyclic zero-pull fatigue test at RT cycle number 15k cycles (<1 Hz) 0-8 kN (0-10kN) OVT (IVT) PFU leg (attachment/5monoblocks)

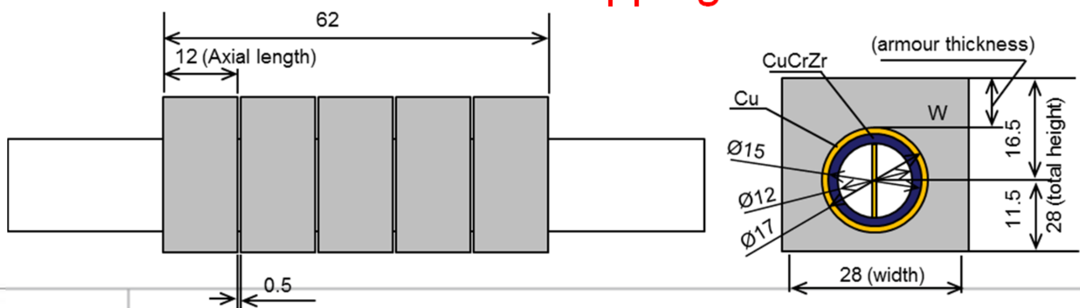
Acceptance Criteria: deformation along the loading axis < 0.3 mm



- **W monoblock armor to heat sink joint**

HHF test 5000 cycles at 10 MW/m^2 and 300 cycles at 20 MW/m^2

Acceptance Criteria: No trace of substantial melting by Visual Inspection / No water leak / No detachment of any armour block / No appearance of any "hot spot" during fatigue cycling / no variation of max T_{surf} (°C) exceeding 20% increase between initial and final thermal mapping



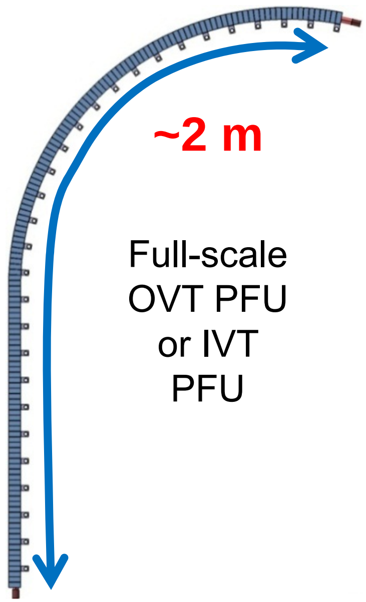
2nd step: Full-scale demonstration

- **Tube to tube joint qualification**

(1) Welding qualification test in accordance to EN ISO 15614-1
Acceptance Criteria: Quality class B as defined in EN ISO 5817 or EN ISO 13919-1, and ITER Vacuum Handbook Attachment-1
(2) He leak test after rotary bending fatigue test 0.1% strain,10k cycles (<1Hz) at RT
Acceptance Criteria: He leak rate ≤ 10^{-10} Pa m^3/s
(3) Tensile test at 150^{o}C
Acceptance Criteria: > 200 MPa

- **PFU W monoblock armor to heat sink joint**
  - HHF test 5000 cycles at 10 MW/m^2 and 300 cycles at 20 MW/m^2 at straight part
  - HHF test 5000 cycles at 5 MW/m^2 at curved part

Acceptance Criteria: No trace of substantial melting by Visual Inspection / No water leak / No detachment of any armour block / No appearance of any "hot spot" during fatigue cycling / no variation of max T_{surf} (^{o}C) exceeding 20% increase between initial and final thermal mapping

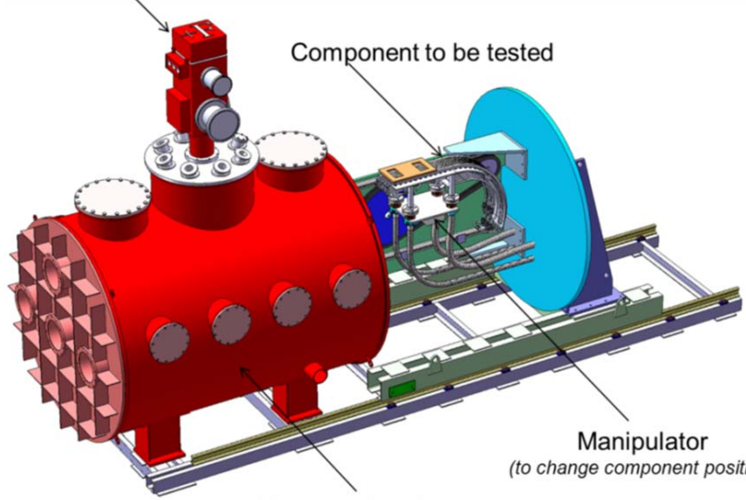


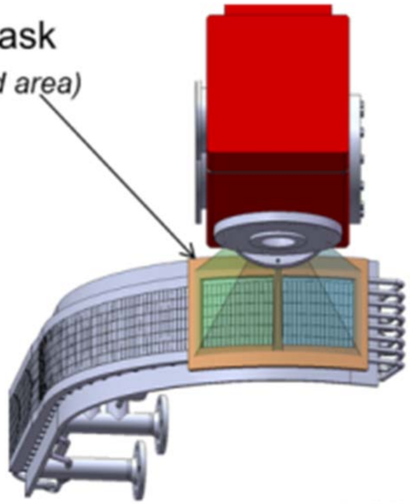
- **Compliance with ITER Procurement Quality Requirements**

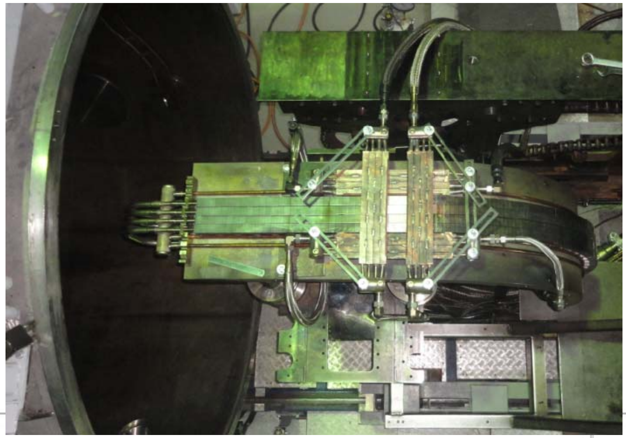
ITER Divertor Test Facility (IDTF)

IDTF that commissioned in frame of Divertor PA

- Built within Procurement Arrangement 17P2D
- 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







Task Agreements to support technology R&D

- **Objectives:**
  - Deliver results of technology validation timely for the decision of the armour material (end 2013)
  - Support demonstration by the full-scale prototypes activities

- **3 TAs with DAs**
  - With JA DA: for the manufacturing of OVT small-scale mock-ups and full-scale prototype PFUs
  - With EU DA: for the manufacturing of IVT small-scale mock-ups (full-W full-scale PFU manufacturing already planned in the PA for IVT)
  - With RF DA: for the HHF testing of the above component s at the ITER Divertor Test Facility (IDTF)

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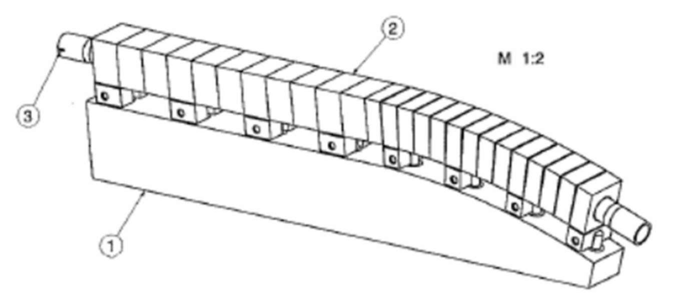
EU HHF Test Results 2009-2011

HHF tests were performed on the FE200 facility at AREVA. Tungsten monoblock mock-ups armouring CuCrZr cooling pipes were successfully tested up to 15 MW/m^2 for 1000 cycles and 20 MW/m^2 for 300 cycles [1].



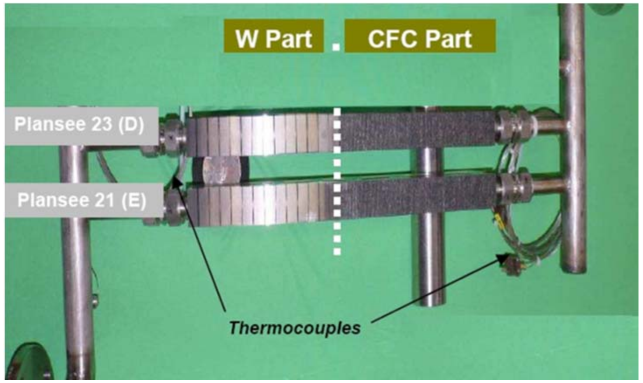


Table summarizes the main results on the tested tungsten mock-ups [2]

1000 cycles at 10 MW/m^2	1000 cycles at 15 MW/m^2	300 cycles at 20 MW/m^2
No significant visible effect	Surface modification but no melting trace	Self-castellation ; No debonding of tile ; no substantial melting

Results fulfil the IO acceptance criteria, and indicate that W monoblock technology is acceptable for the requirements of the full-W vertical target

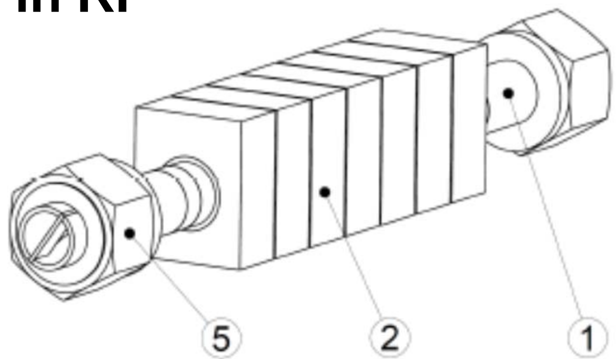
[1] P. Gavila et al, Fus. Eng. & Des. 86 (2011) 1652-1655
[2] P. Lorenzetto et al, 24th IAEA-FEC 2012

EU HHF test results in 2013

EU DA campaign: on 12 mock-ups in IDTF in RF

HHF Testing program:

- step 1 : 5000 cycles at 10 MW/m²
- step 2 : 300 (+700 cycles) at 20 MW/m²
- step 3 : critical heat flux



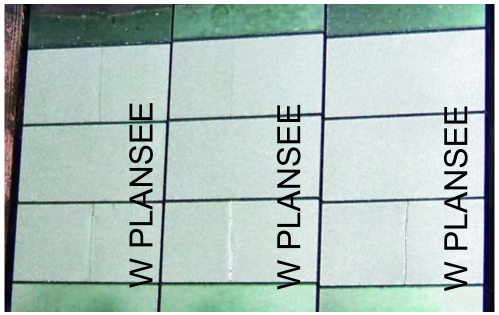
HHF results @ 20MW/m^2 obtained on **first set** of 6 mock-ups.

- No traces of melting on the loaded surface
- Cracking development

Ansaldo 20MW/m^2 after 75 cycles

with 6 mm of W thickness

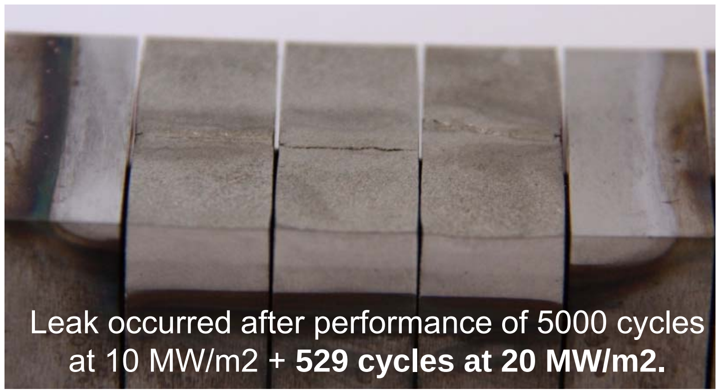
Plansee 20MW/m^2 after 75 cycles



with 7.5 mm of W thickness

Self-castellation was observed

Second set of HHF testing program with 6mm of W thickness was recently stopped.

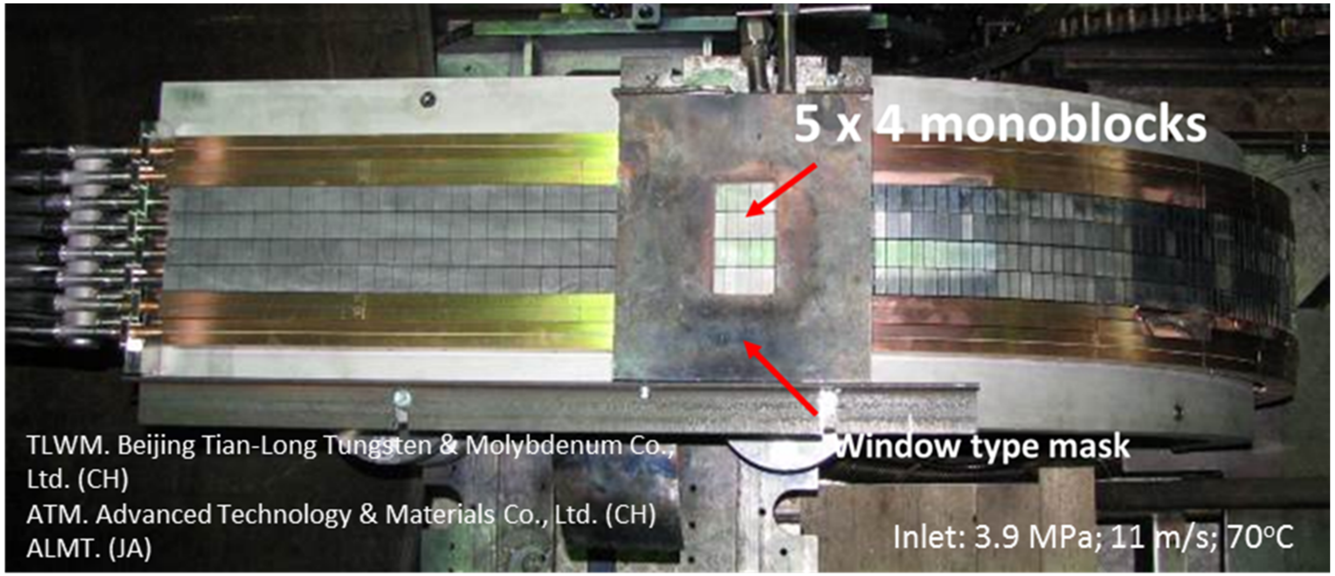


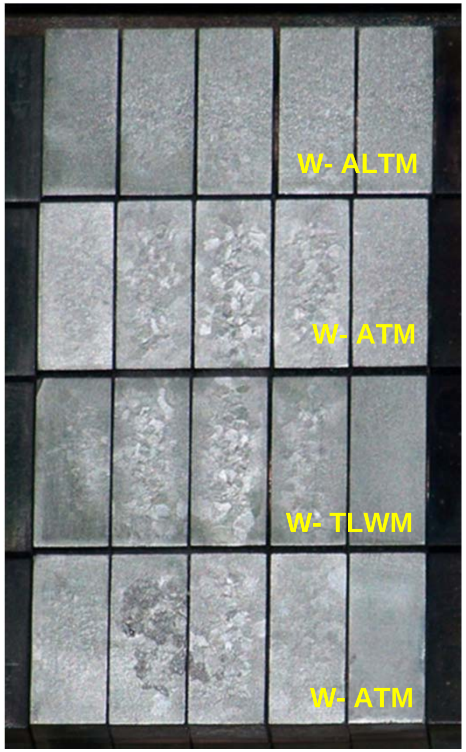
JA HHF results in 2012

JA DA campaign: OVT CFC/W Full-Scale PFUs

Straight W part of PFUs subjected to the HHF tests -- *5000 cycles at 10 MW/m² and 1000 cycles at 20 MW/m²*

20 monoblocks of 12mm (axial) x 28mm (poloidal) x 7.5 mm (W thickness at the top of the tube).



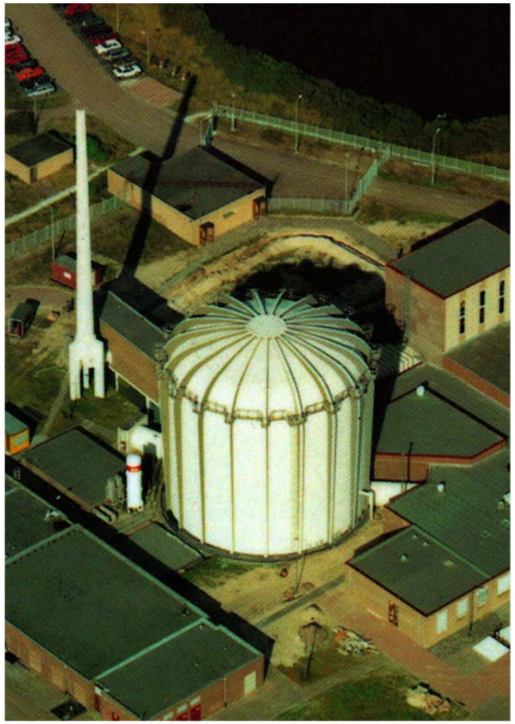


Results fulfil the IO acceptance criteria, and indicate that W monoblock technology is acceptable for the requirements of the full-W vertical target

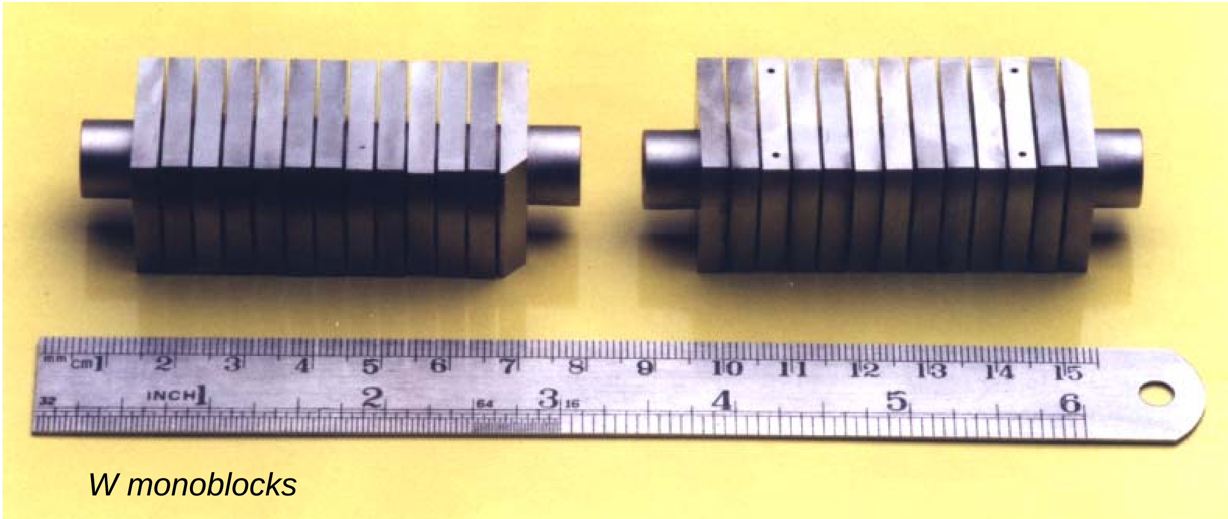
Small scale mockups will be tested in IDFT 24-26 Sep 2013

Effects of Irradiation on Performance

The effects of irradiation on the performance of the W monoblock have been assessed by experiments – PARIDE 3 and PARIDE 4 [4].



High Flux Reactor Petten, Netherlands



W monoblocks

Neutron-Irradiation campaign:

PARIDE 3: 0.1 dpa at 200 °C // PARIDE 4: 0.6 dpa at 200 °C

Irradiated W mock-ups (0.6 dpa at 200°C) sustained thermal fatigue testing at 18 MW/m^2 for 1000 cycles

Post irradiation testing of samples from the irradiation experiments PARIDE 3 and PARIDE 4, M. Roedig et al., JNM 329–333 (2004) 766–770

Outline

1. Design constrain/input
2. Detailed divertor PFC Design
3. Design Validation
4. Technology R&D requirements
5. Progress of technology R&D in EU and JA
6. **Conclusion/Schedule**

Schedule for full-W Divertor Decision

- Final Design Review of Tungsten Divertor (26-28 June 2013)
  - ✓ Full-W Divertor design
  - ✓ Full-W Divertor technology qualification programme
- Physics Assessment
  - ✓ Report from ITPA Topical Groups to STAC-14 (May 2013) giving a physics/operational opinion on a full-W divertor start for ITER
  - ✓ JET misaligned lamella melt experiment: summer 2013
- **STAC-15 (Oct 2013) to take note** of the Design and Physics outcome and provide recommendation
- **ITER Council-13 (Nov 2013) to endorse the STAC/ MAC recommendation on this topic**
- **Implementation of the decision into the baseline** via a PCR (end-2013, *SMP.0116.001032 milestone*) **if selected**

Thank you very much for your attention