34th Symposium On Fusion Technology, 21-25 September 2026, Aix-en-Provence

IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

Plasma-Facing Components in the COMPASS-U Tokamak

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[3]*CVUT, Faculty of Mecahnical Engineering, Prague, Czech Republic*

[4]*UKAEA, Culham, United Kingdom*

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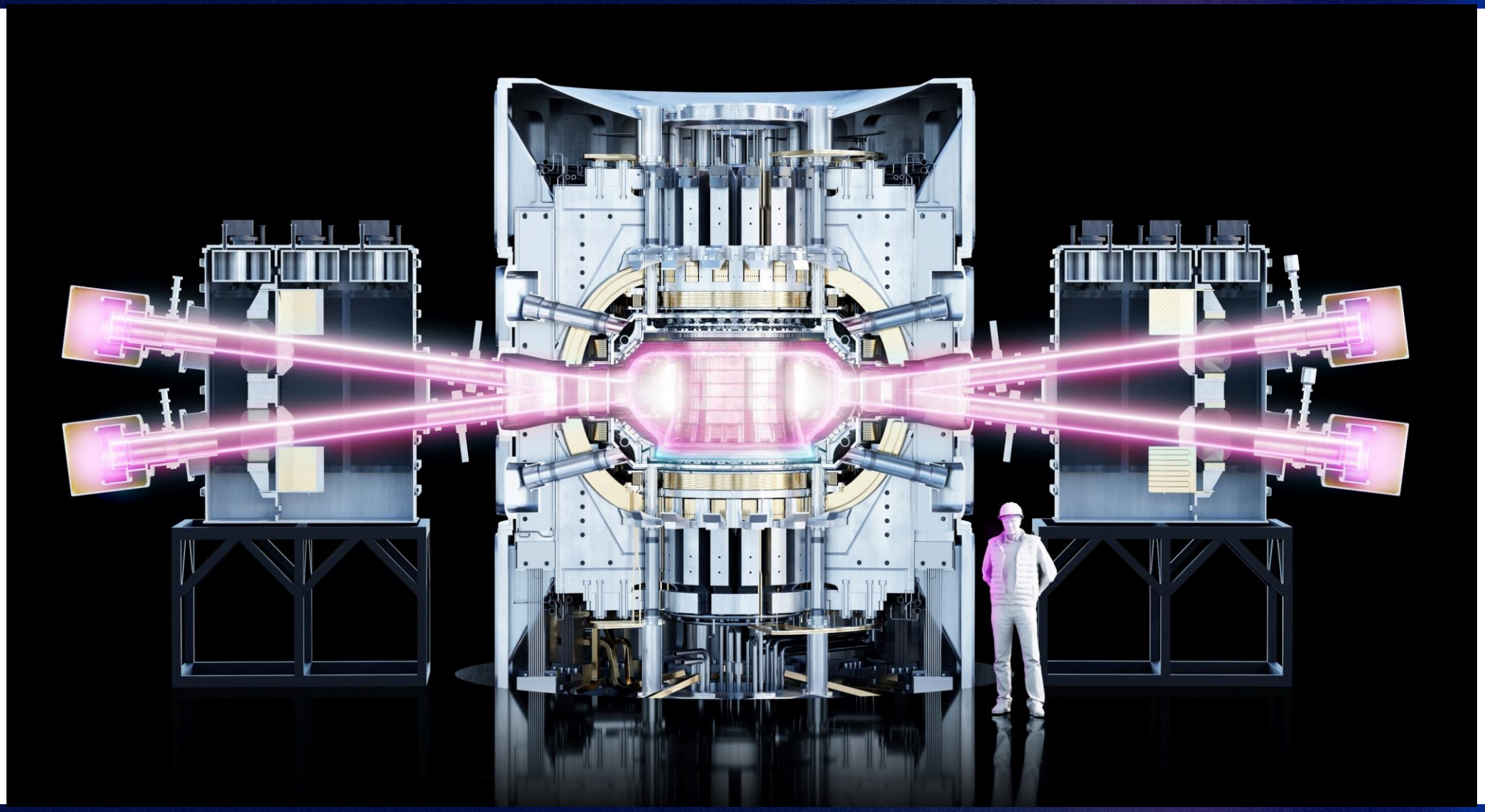
COMPASS-U

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

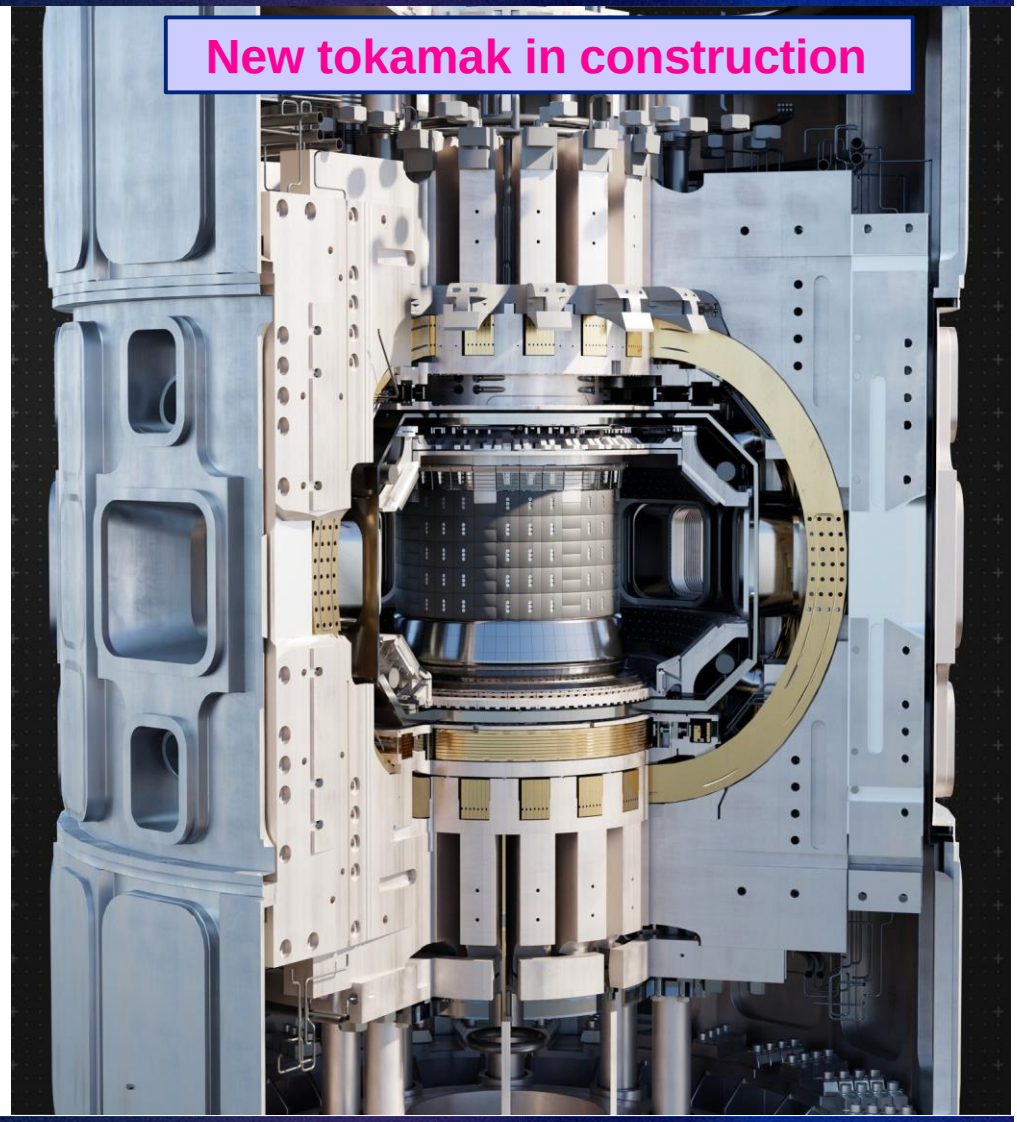
EUROfusion

IPP PRAGUE: COMPASS-U TOKAMAK



Main parameters

- **Toroidal magnetic field** — **$B_t \leq 5$ T**
- **Plasma current** — **$I_p \leq 2$ MA**
- Major radius — R = 0.90 m
- Minor radius — a = 0.27 m
- **VV operation temperature** — **RT – 500°C**
- **Short pulse plasmas** — **$t^{discharge} \leq 3$ s.**
  - **Passively cooled PFCs**



Want to know more about COMPASS-U construction status?

Invited presentation by P. Vondracek on Thursday 14:00 in Conservatoire

COMPASS-U PFC: OUTLINE

- General description & Materials choice
- Inner & Outer Wall limiters
- Lower Closed Divertor
- Divertor cassettes manufacturing



COMPASS-U PFC: GENERAL DESCRIPTION

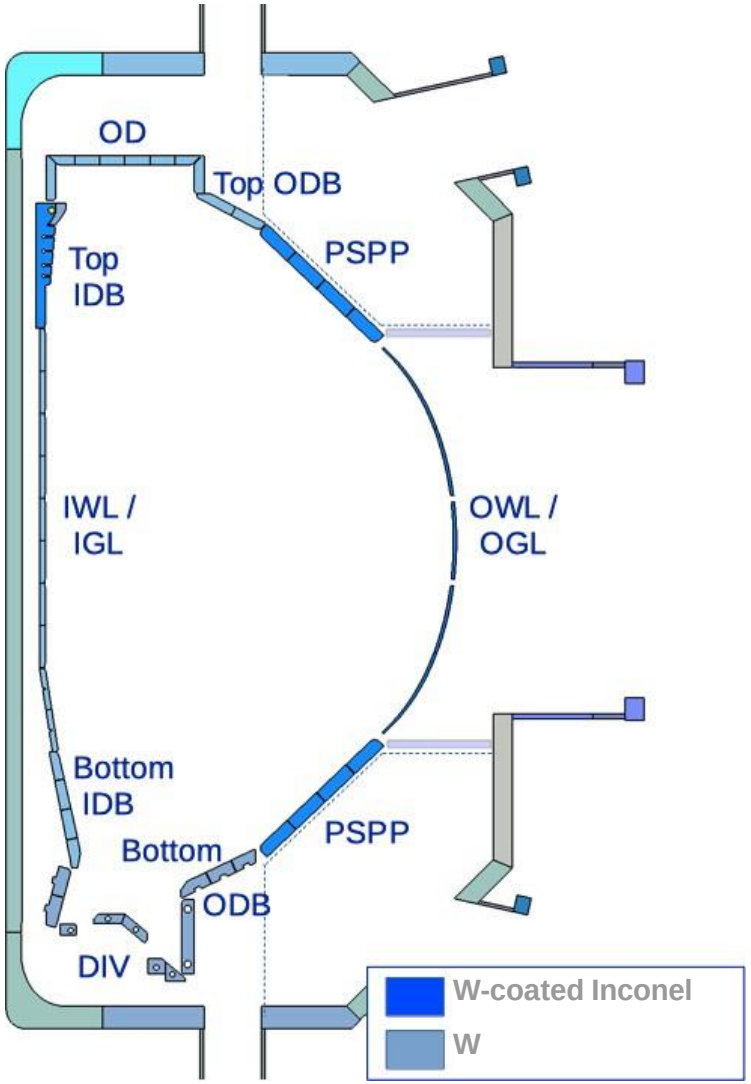
100% tungsten (W) coverage [1]

- **Bulk W for inertially cooled components in HHF regions:**
  - Lower closed (DIV) & upper open (OD) divertors
  - Inner (IGL) & outer (OGL) guard limiters
  - Total PFC area = 50 %

- **Elsewhere, Inconel 718 is used because of operation up to 500°C**
  - Inconel composition = Ni, Cr, Fe
  - Higher sputtering yields & lower sputtering thresholds (20-40 eV) than W

- **Solution = cover all Inconel components with thin W layer (PVD)**
  - W coating on Inconel not available on the market ⇒**in-house R&D programme**
  - Development with industrial partners [2]
  - Successful qualification under HHF tests [3] in GLADIS (steady state) & PSI-2 (transients)

Note: implementation of **full Liquid Metal Divertor ring** in the **future**



[1] R. Dejarnac, et al., FED 211 (2025); [2] J. Matejicek, et al., FED 42 (2025); [3] R. Dejarnac, et al., FED 42 (2025).

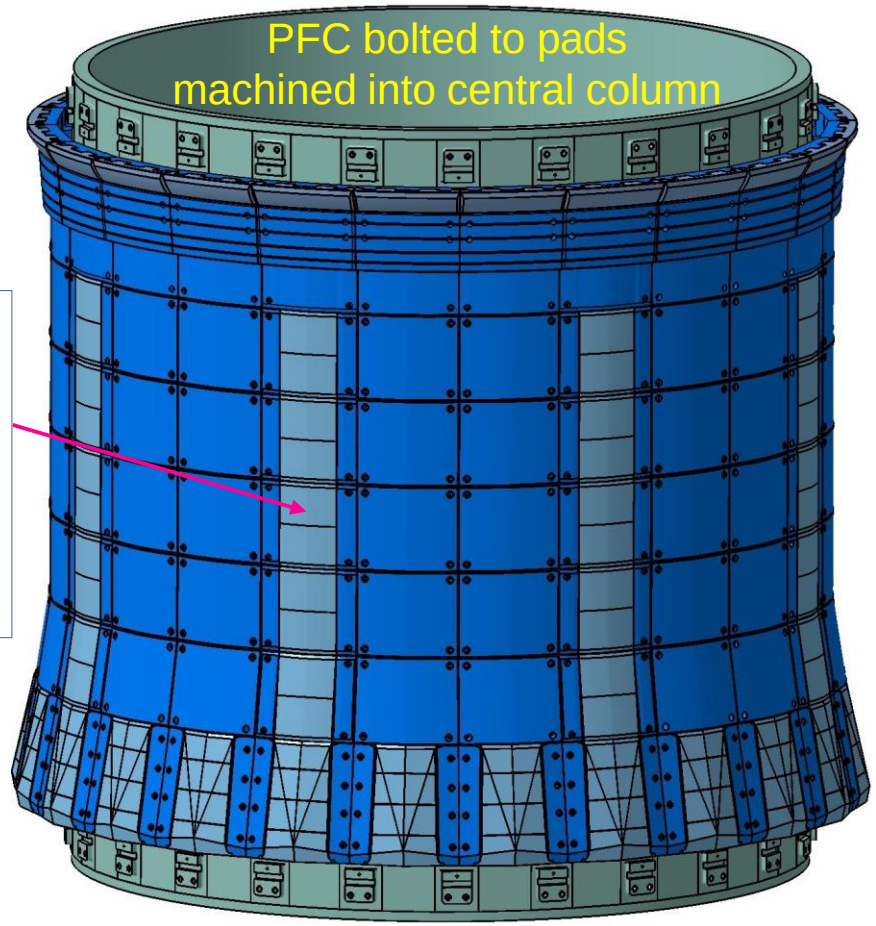
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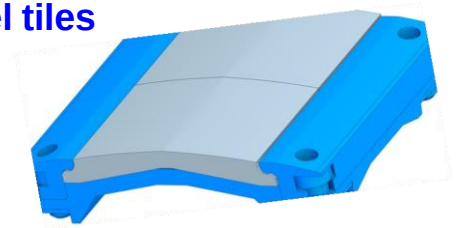


COMPASS-U PFC: INNER WALL LIMITER

24 columns of PFC – Full W coverage

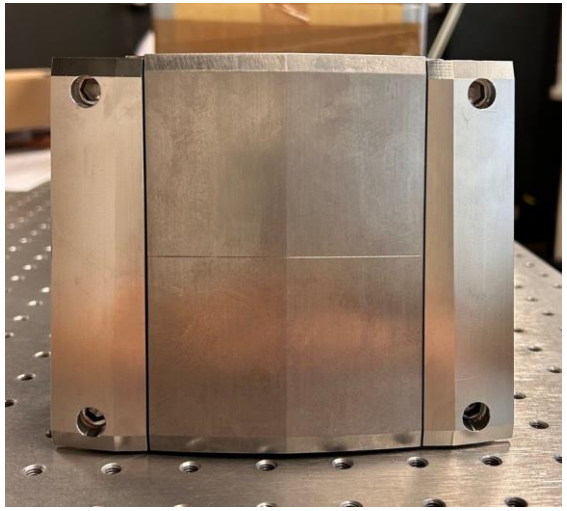


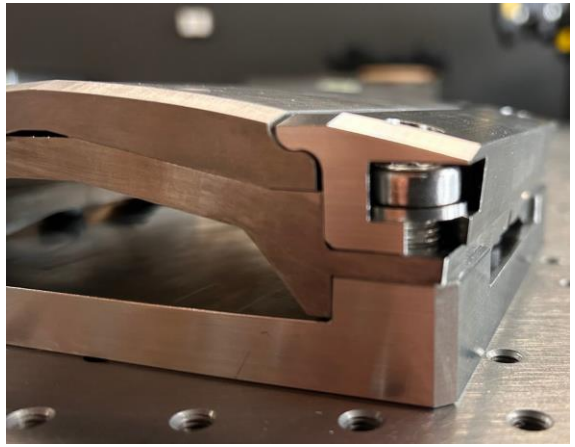
8x Guard Limiters (W) protruding by 1.5 mm wrt. **Inconel tiles**



⇒ **1 IGL = 2 W tiles** clamped from side

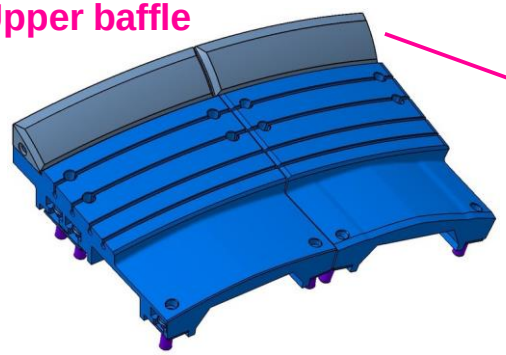
W
Inconel



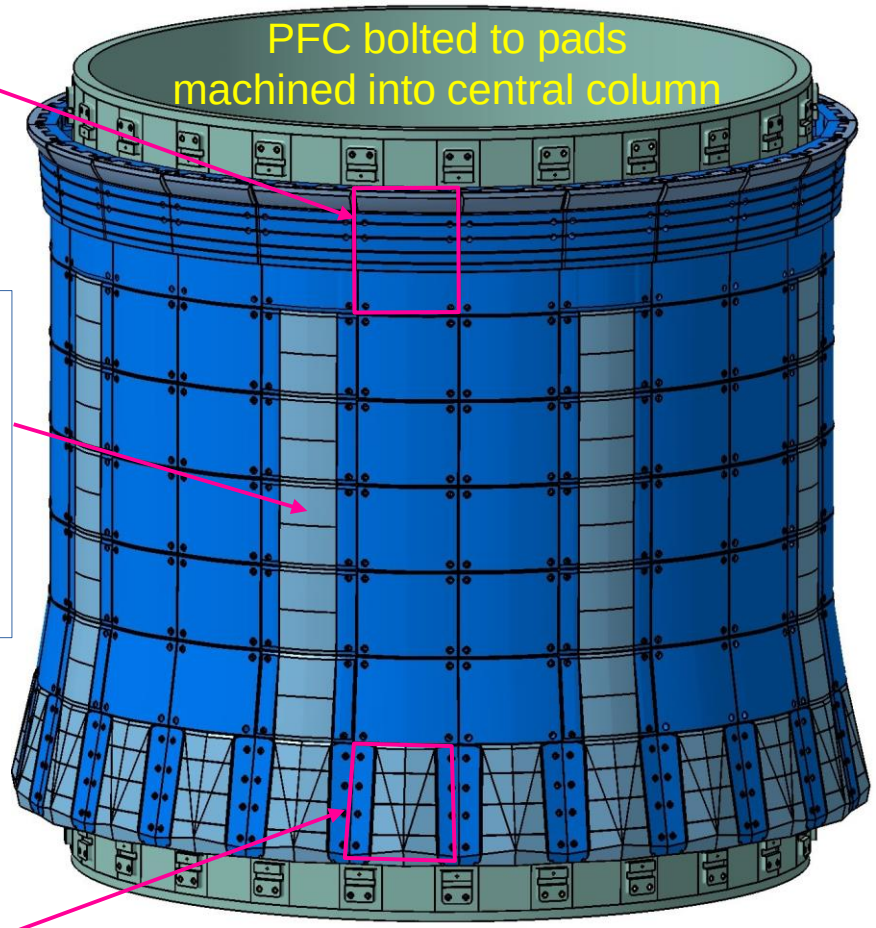


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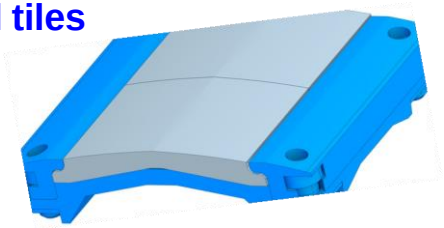
Upper baffle



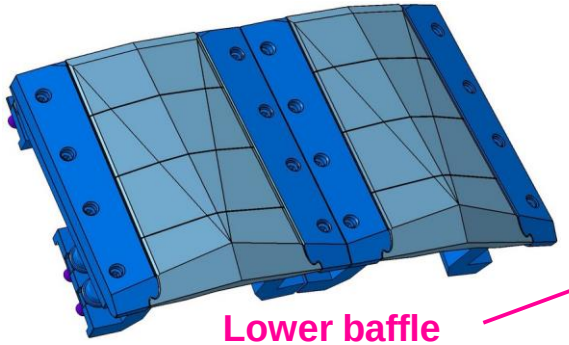
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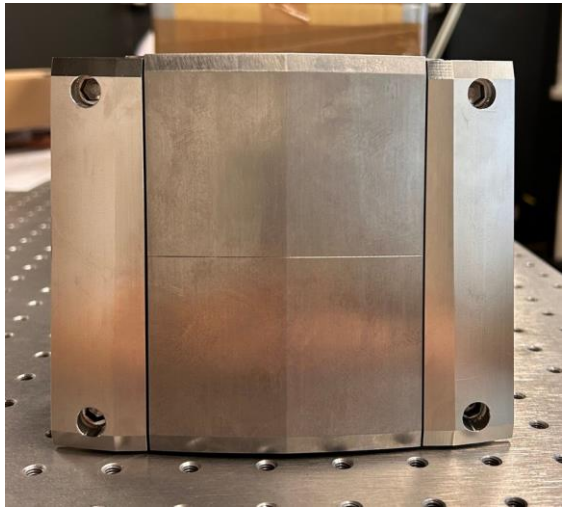


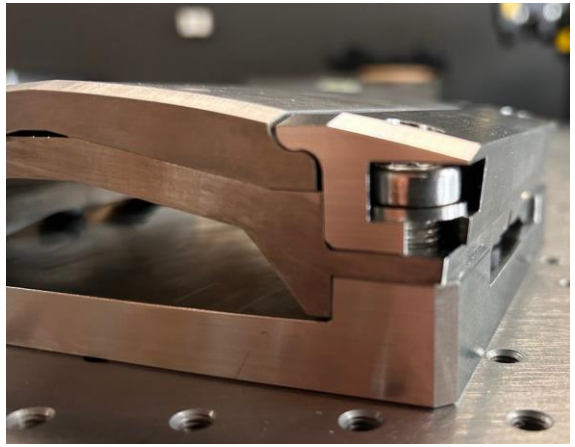
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Lower baffle

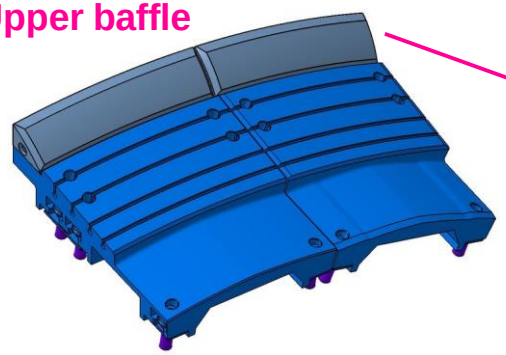
W
Inconel



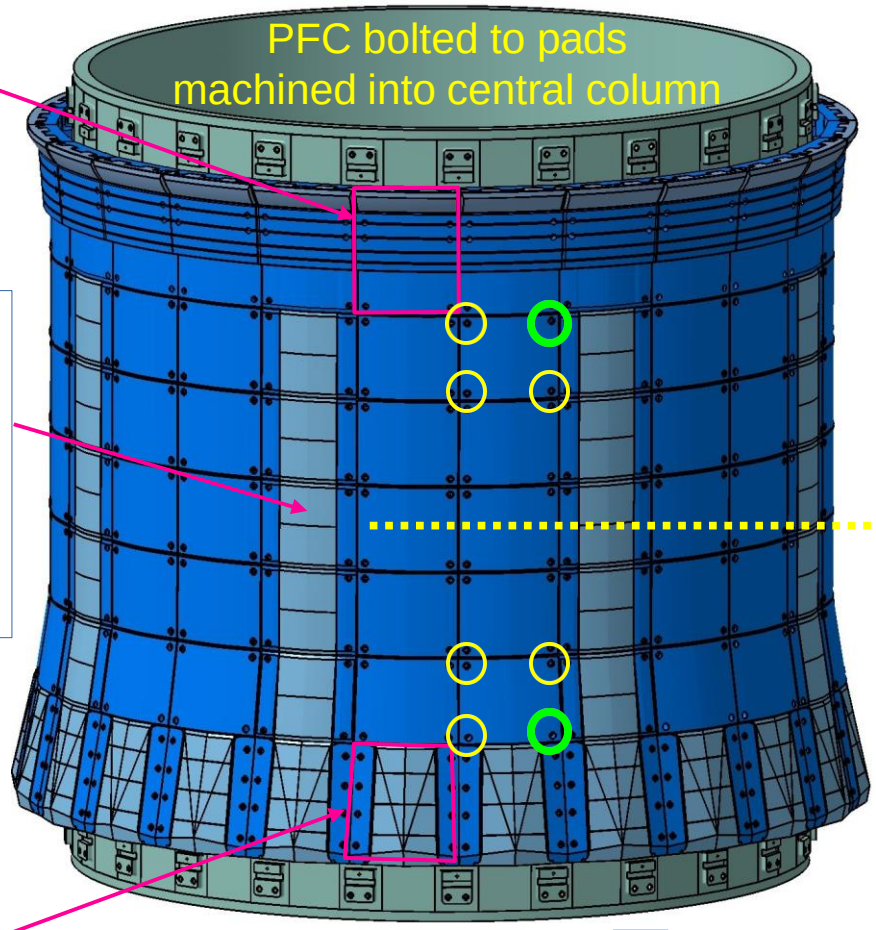


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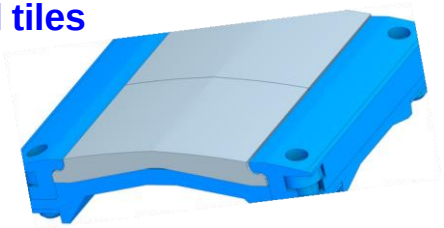
Upper baffle



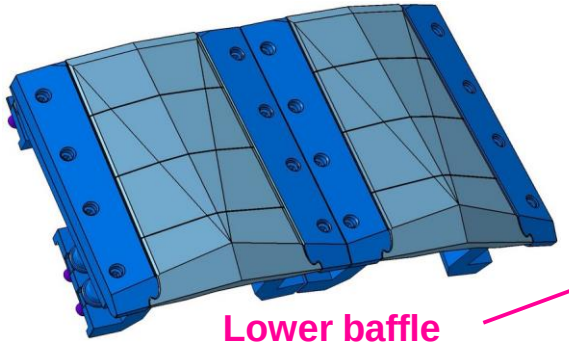
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8x Guard Limiters (W) protruding by 1.5 mm wrt. **Inconel tiles**



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Lower baffle

W
Inconel

Tiles are insulated at 3 corners

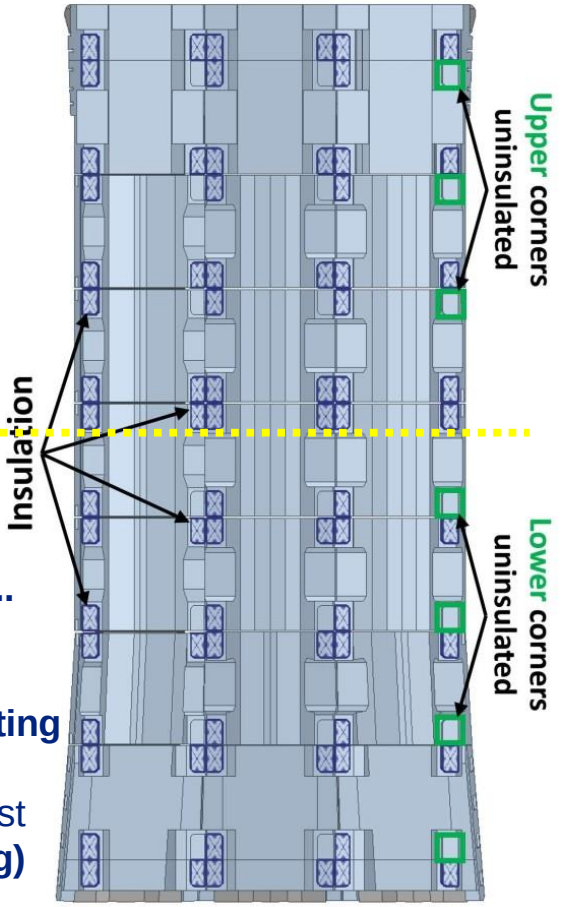
Z > 0:

Upper corner is **conductive**

Z < 0:

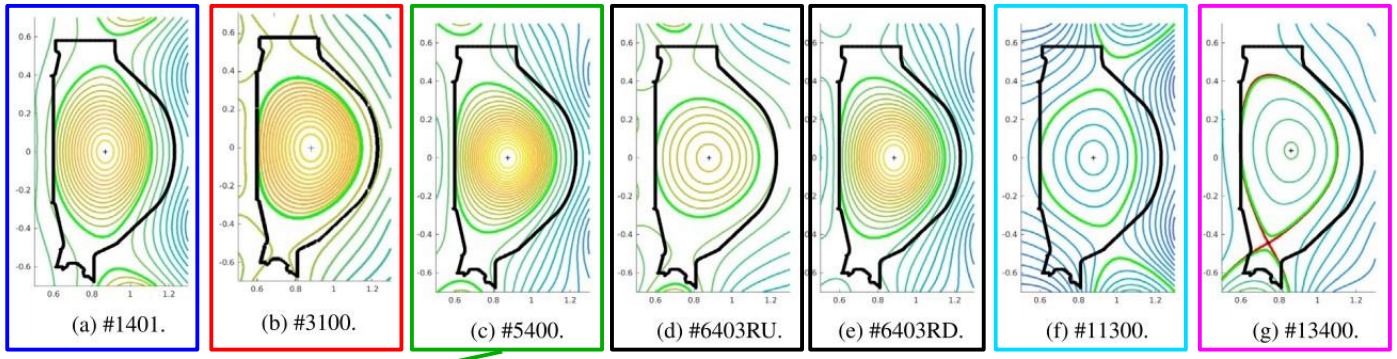
Lower corner is **conductive...**

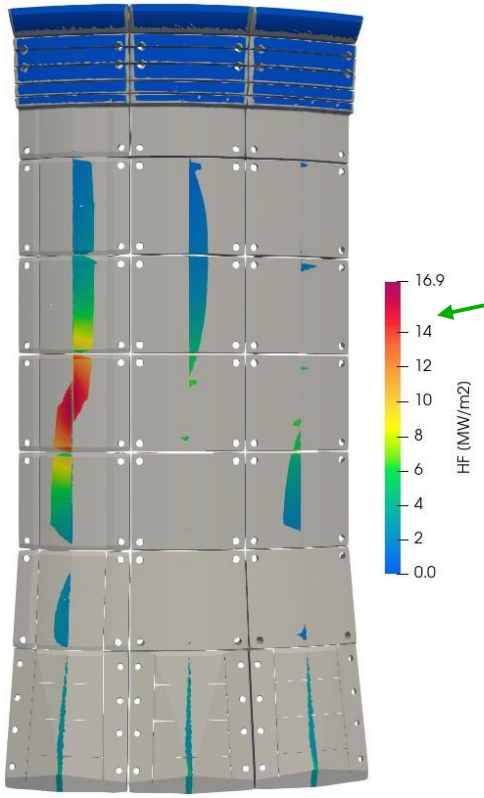
...so that **resulting EM forces** are **pushing** against VV **(not pulling)**

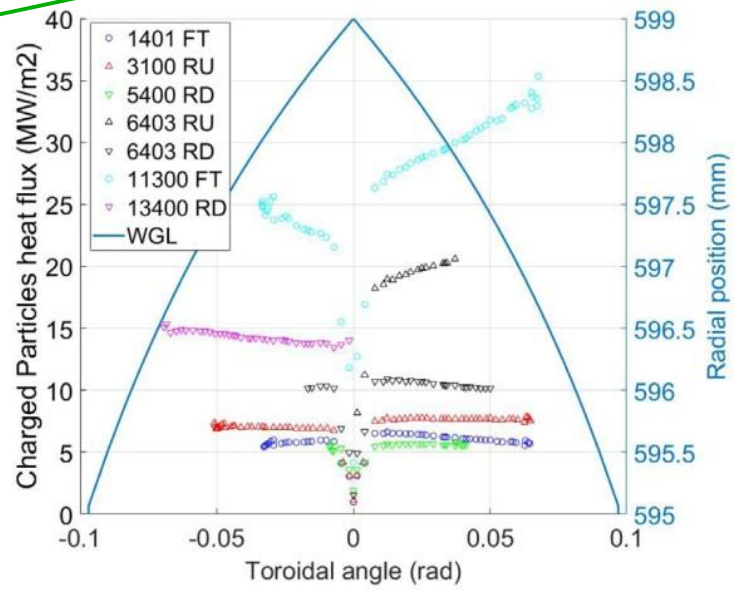


Front face shaping optimized by 3D field-line tracing code PFCflux [4]

- Accounting for **near-SOL**
- **7 workhorse scenarios**





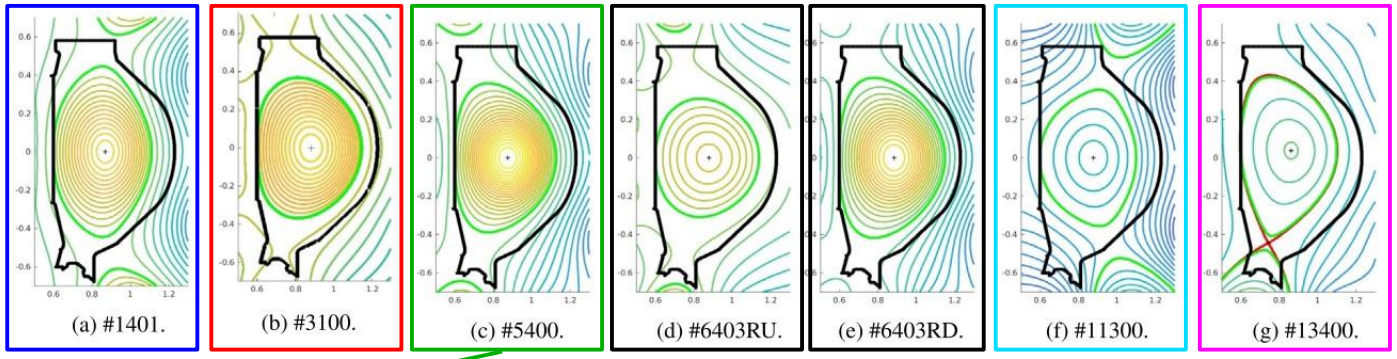


- **Heat loads spread** over a **maximum area**
- **Constant toroidal profiles**
- **Leading edges** are **protected** for shortwave misalignment up to 0.5 mm.

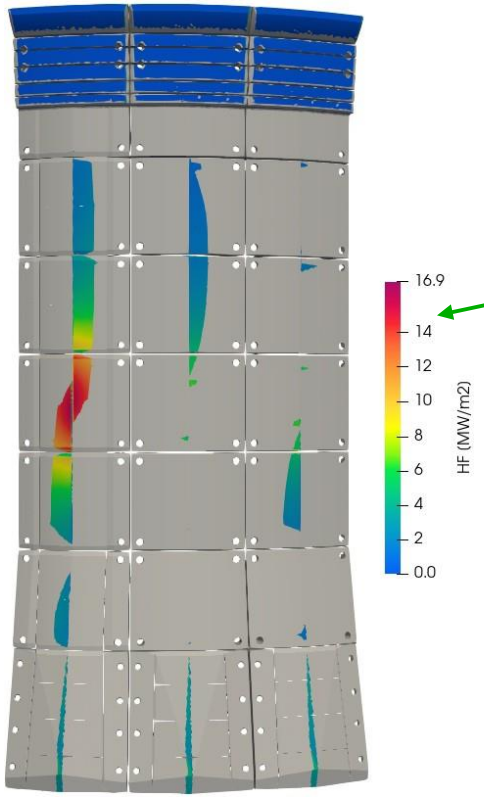
[4] J. Gerardin, et al., FED 194 (2023);

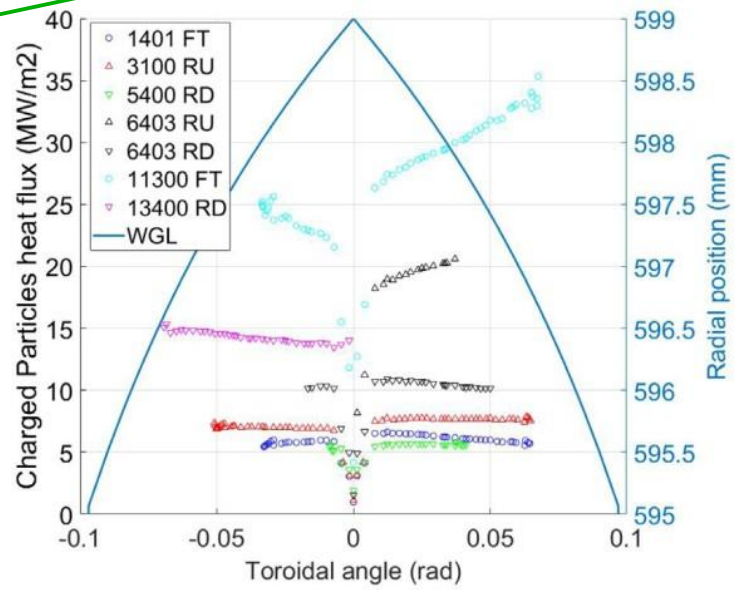
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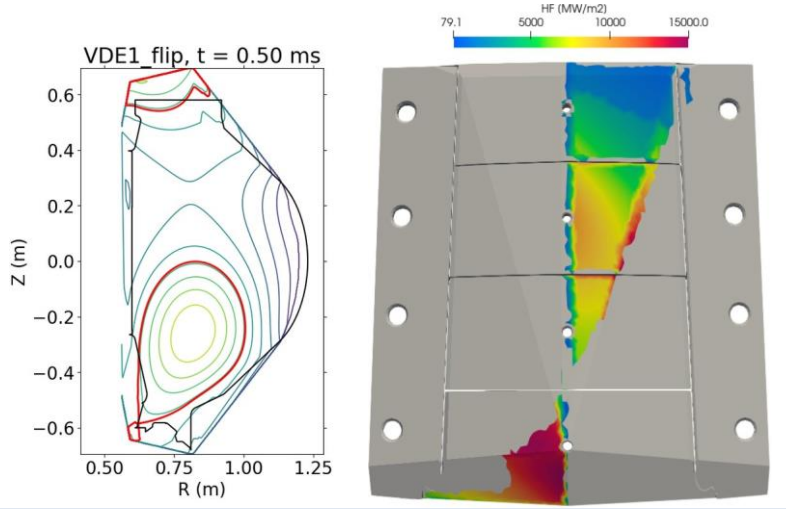
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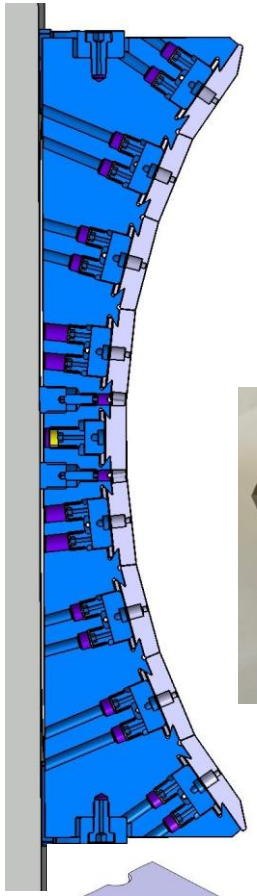
Disruption: heat loads on lower baffle

- Inconel clamps hidden, all flux on W



[4] J. Gerardin, et al., FED 194 (2023);

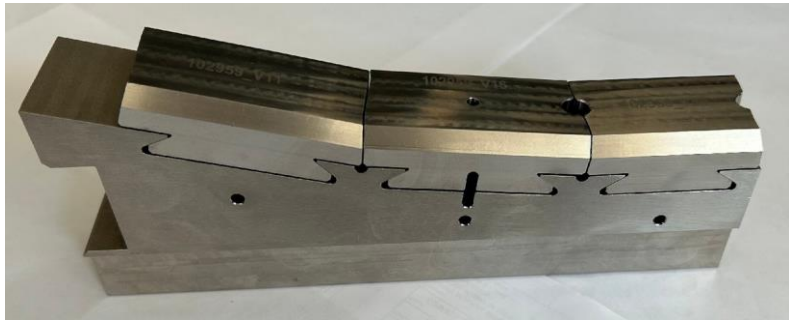
COMPASS-U PFC: OUTER WALL LIMITERS



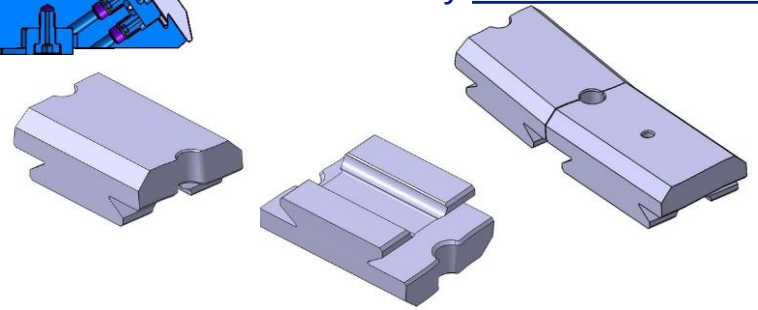
10 discrete, narrow outer wall limiters (large mid-plane ports) fixed to VV w/ welded nuts

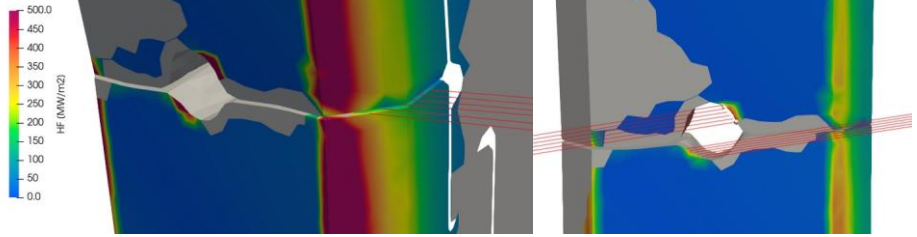
2 protruding OGL with **9 W tiles** each, protecting passive stabilizing coils bridge

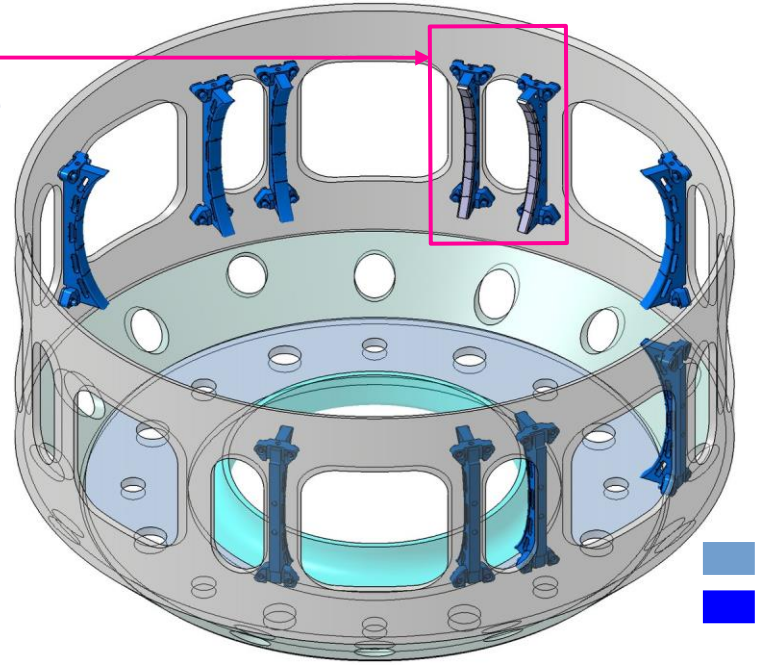
- **W tiles** with **dovetail shape,**
- fixed by **pushing stones / bolts**



- **Special shape to avoid toroidal gaps** validated by PFCflux simulations



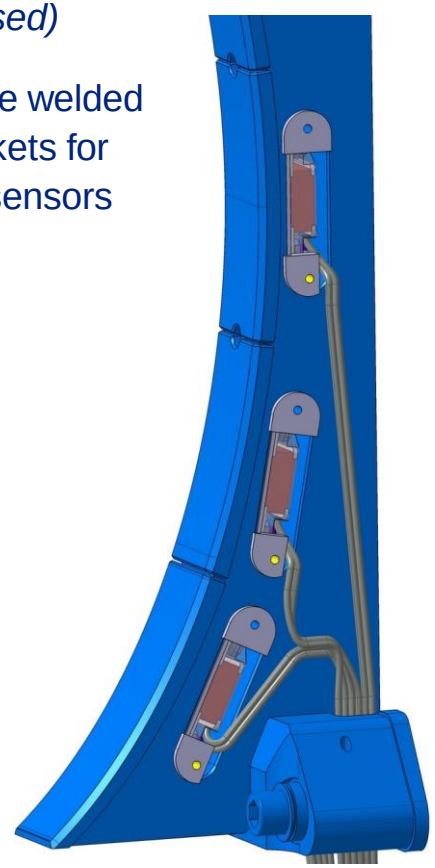




W
Inconel

8 OWL with **W-coated Inconel tiles**
(3 mm recessed)

- Tiles will be welded
- Large pockets for magnetic sensors



COMPASS-U PFC: OUTLINE

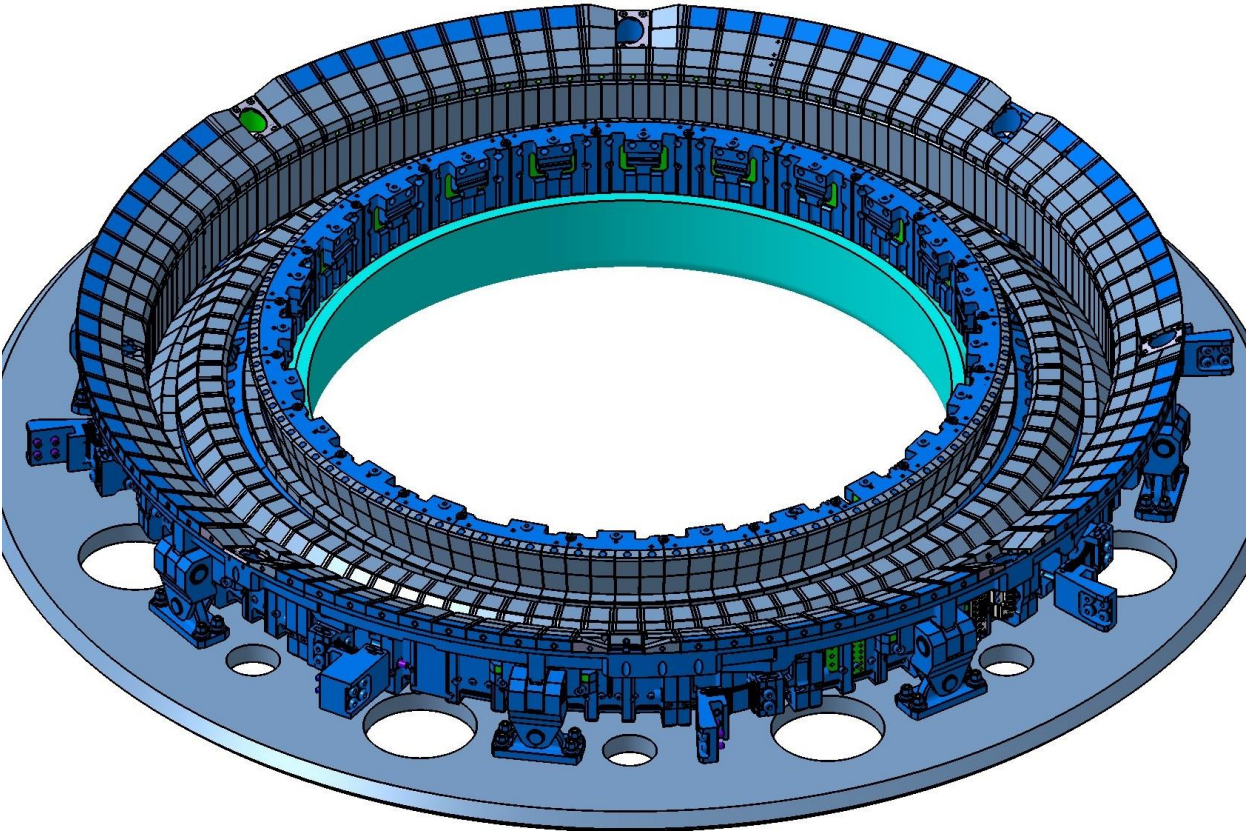
- General description & Materials choice
- Inner & Outer Wall limiters
- **Lower Closed Divertor**
- Divertor cassettes manufacturing

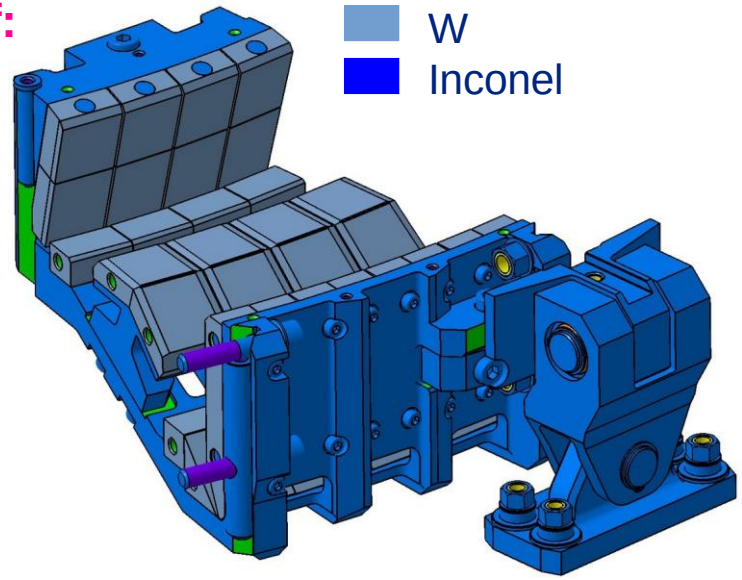


COMPASS-U PFC: LOWER CLOSED DIVERTOR

The COMPASS-U lower, closed divertor is composed of:

- **24 cassettes** fixed together to form a **stiff ring**.

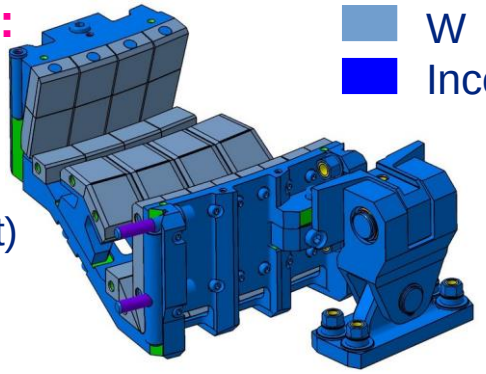


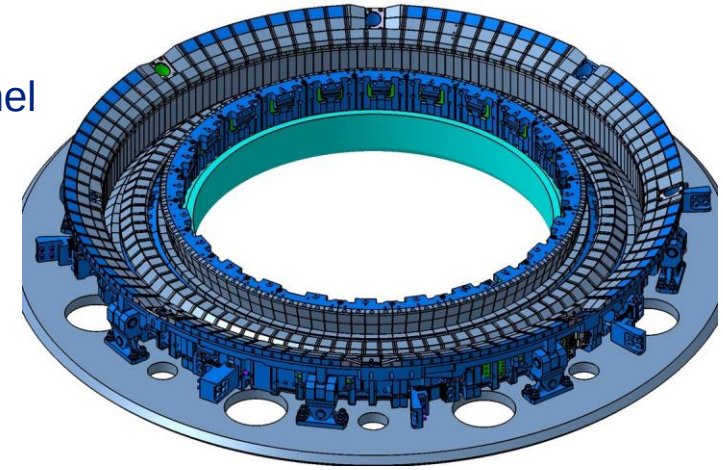


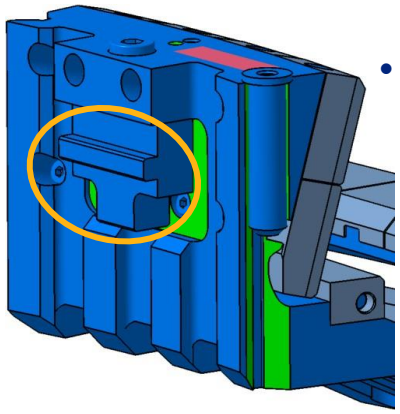
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- **Divertor ring fixed** at **HFS to VV central column**
  (each cassette → pad using a **shim plate** for radial/vertical alignment)
- During plasma operation, **OVT** (W) can possibly **heat up** to 2000°C and the **entire divertor expands radially by ≤ 6 mm.**

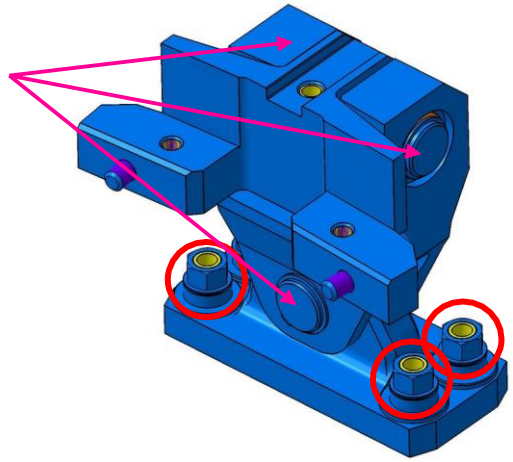






HFS connection with a shim plate

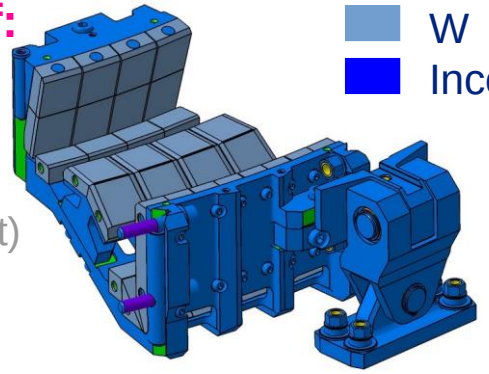
- At **LFS**, divertor ring lies on **8 flexible legs** fixed to VV using **4 welded studs** and **4 push bolts** to ensure horizontality.
  - A system of **3 spherical bearings** w/ **lubricant coating** (WS_2 or MoS_2) per leg accounts for **radial thermal expansion** and **keeping divertor ring horizontal.**

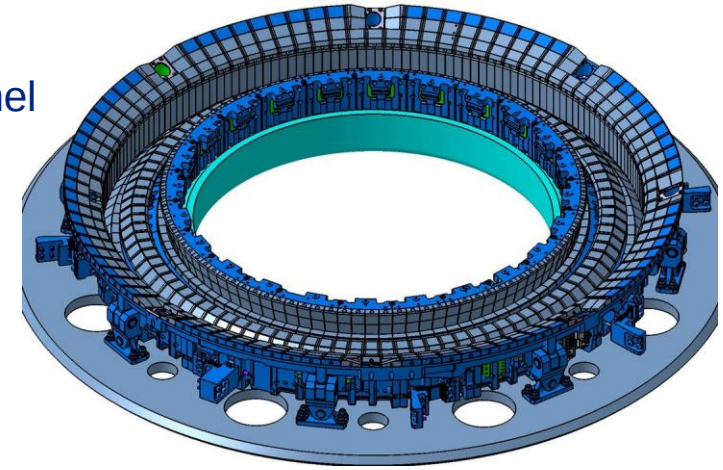


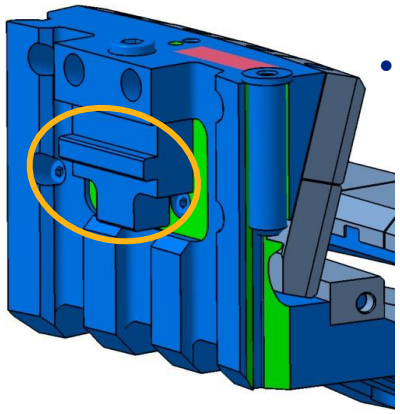
COMPASS-U PFC: LOWER CLOSED DIVERTOR

The COMPASS-U lower, closed divertor is composed of:

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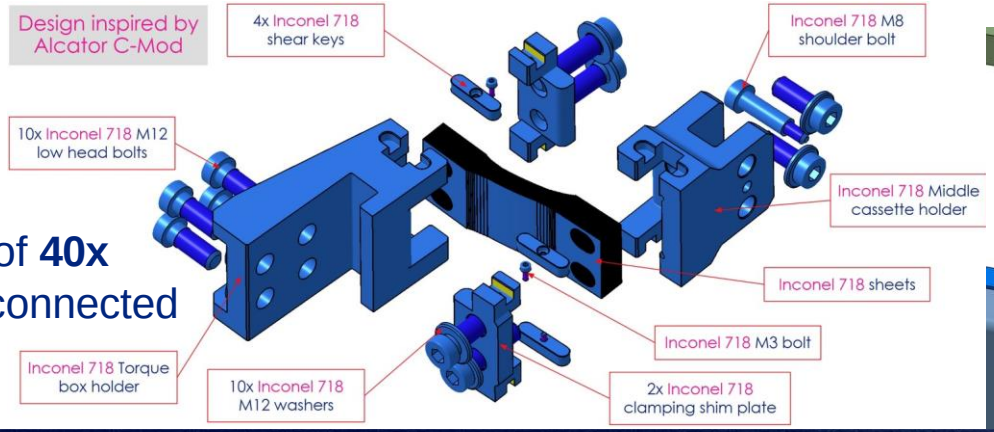


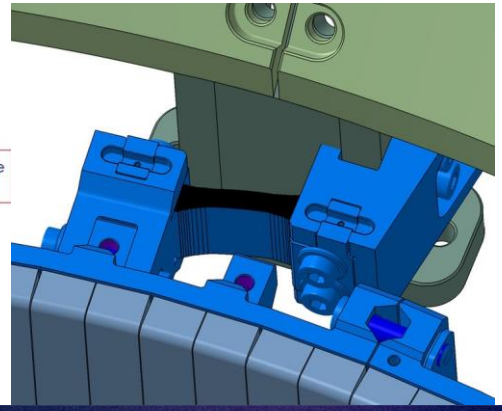


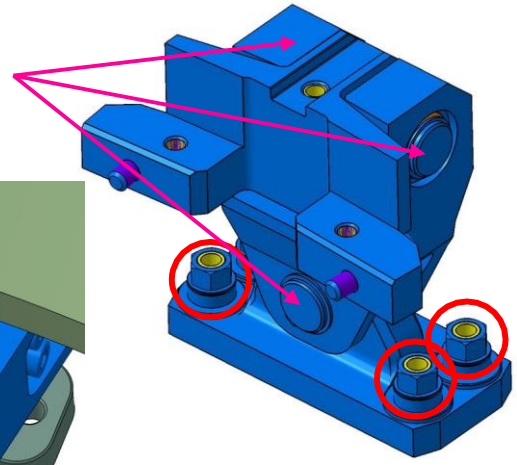


HFS connection with a shim plate

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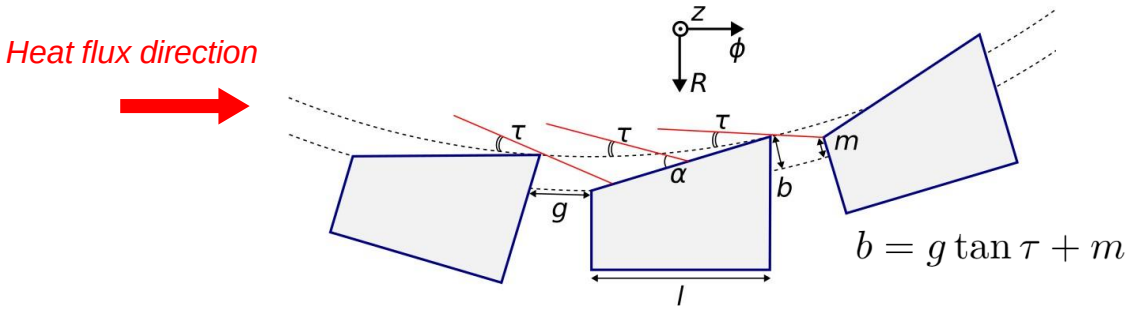
Halo straps & Flexible legs design based on Alcator C-Mod AOD concept [5]

- **8x halo current straps:** stack of **40x 0.25 mm Inconel 718 sheets**, connected to **VV** (torque box legs) to carry up to **187.5 kA** each.

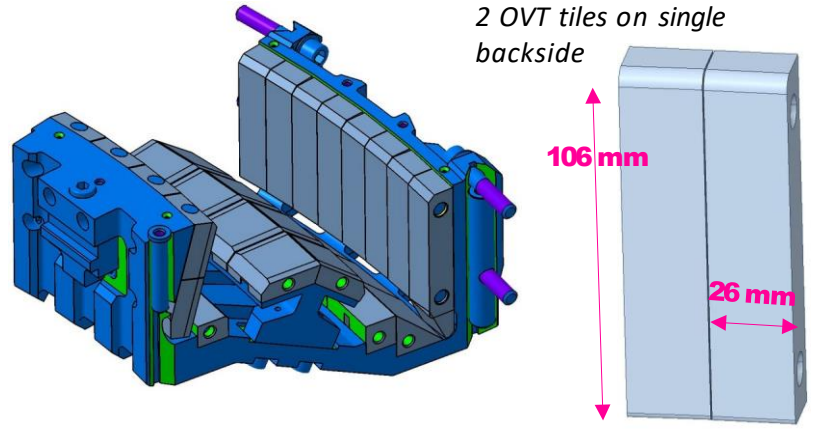
[5] S. Harrison, et al., Design, Engineering and Testing for the Alcator C-Mod Advanced Tungsten Divertor Upgrade, APS 2012;

Front face shaping of OVT tiles:

- **Special front face shaping** with a **toroidal bevel** to hide leading edges
- **Maximizing power exhaust** but allowing **only one helicity**

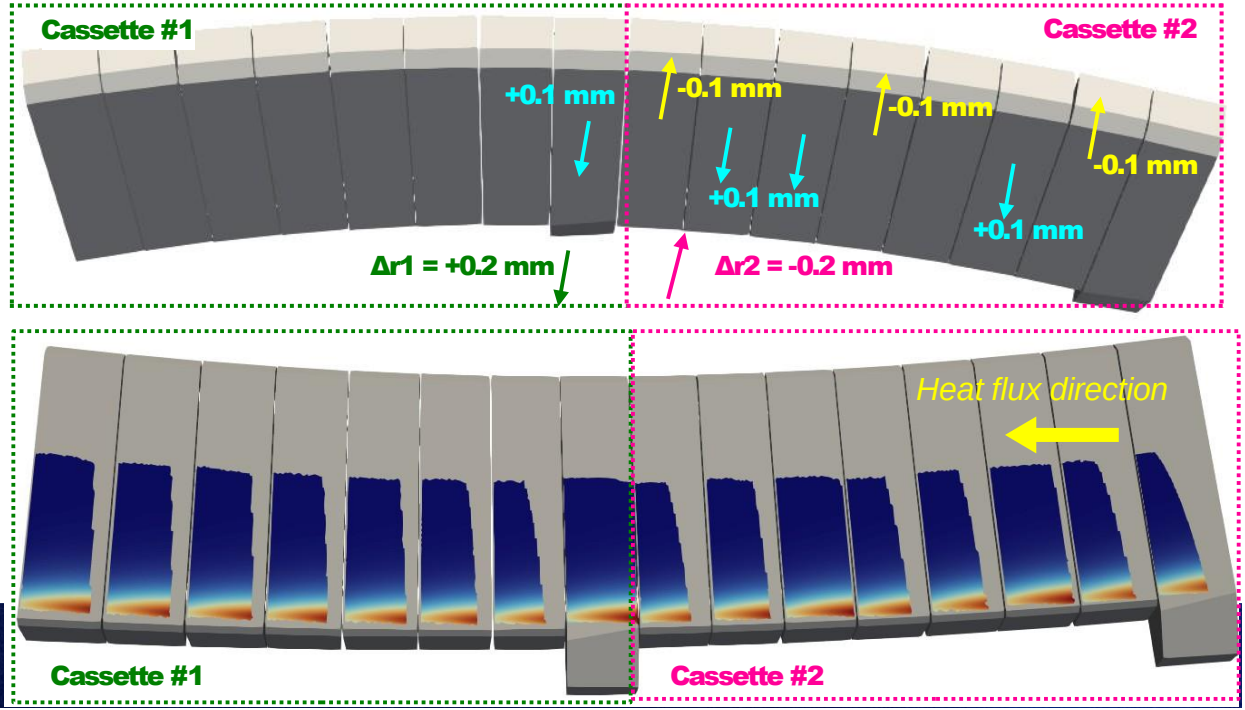


$$b = g \tan \tau + m$$



- **Intra-cassette, max. misalignment** is **small:** m = ± 0.1 mm
  (due to machining tolerances of W tiles and cassettes back side)
  ⇒**0.25 mm tor. bevel**
- **Larger misalignment** expected **between cassettes** m = ± 0.2 mm
  - **Backside** of **each pair of OVT tiles** is **machined** to **simulate a 0.1° tilt of cassettes**
- **Shaping validated** by **PFCflux simulations** of **worst case misalignment**

PFCflux simulations of heat flux pattern at OVT for worst misalignment



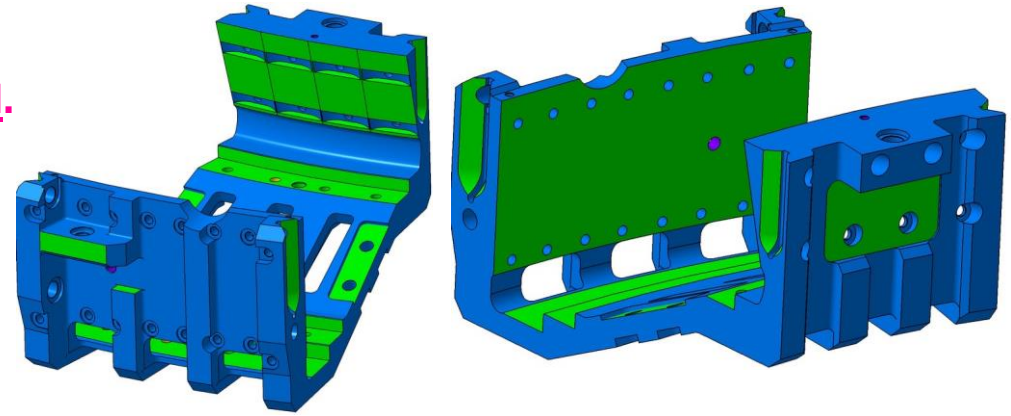
COMPASS-U PFC: OUTLINE

- General description & Materials choice
- Inner & Outer Wall limiters
- Lower Closed Divertor
- **Divertor cassettes manufacturing**



Divertor cassettes in Inconel 718

- **Manufacturing options: welding plates, milling billet** ($), **casting** ($$) & **AM.**
  - **Additive manufacturing (AM) very attractive because easier & cheaper**
  - **3D printing solution** *(also investigated: WAAM*, AFSD**, or CS***)*

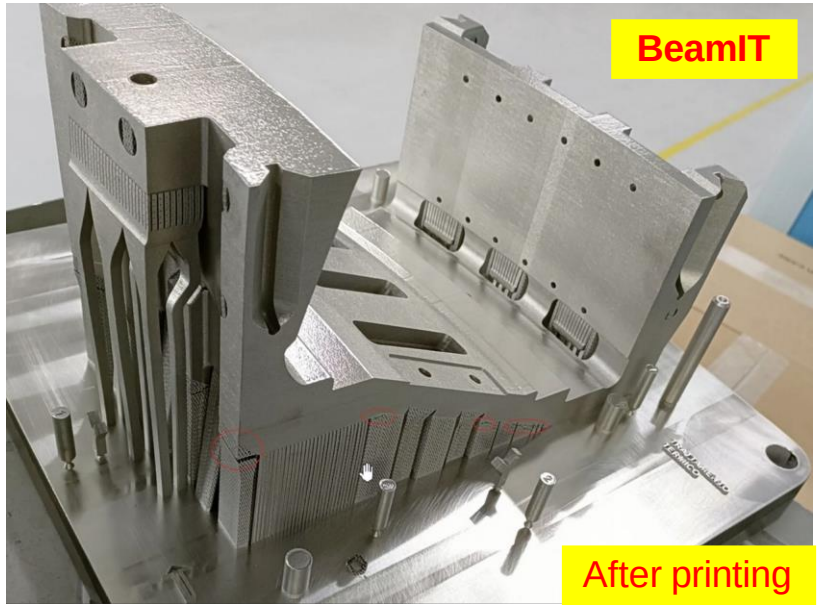


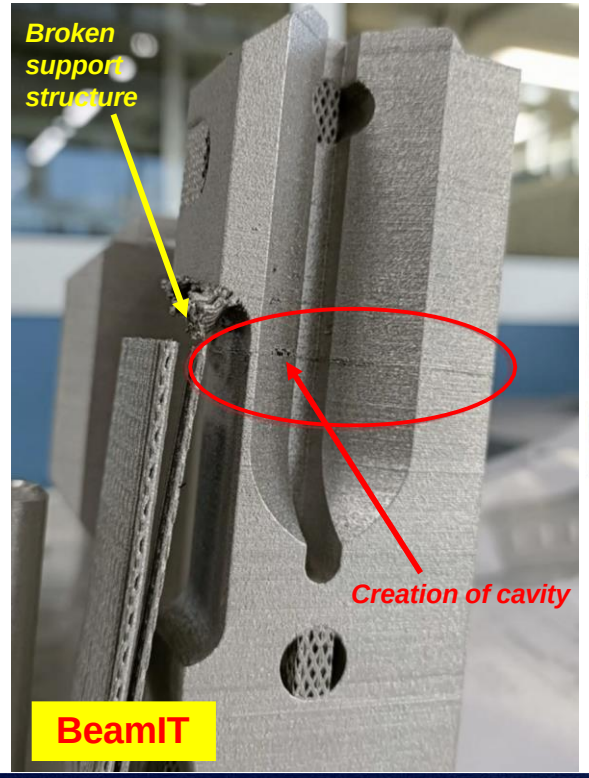
Required position accuracy *of* ***functional surfaces*** *after the machining is* ***0.1 mm***

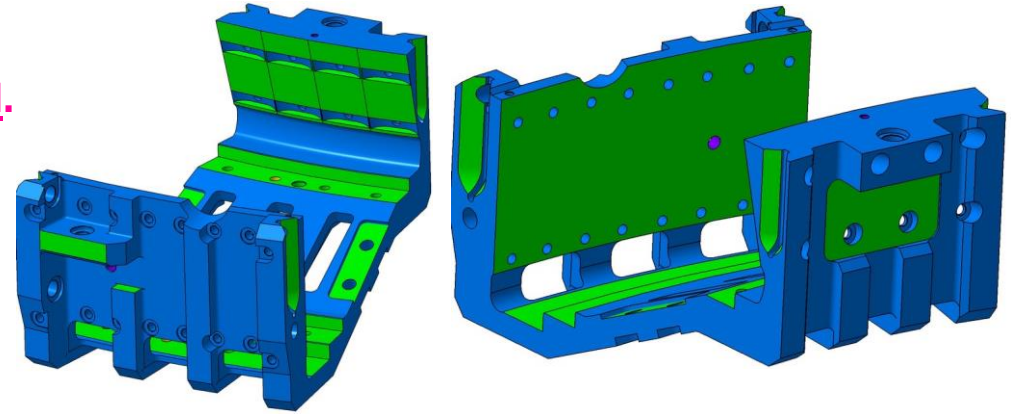
**Wire Arc Additive Manufacturing, **Additive Frictional Stir Deposition, ***Cold spray*

Divertor cassettes in Inconel 718

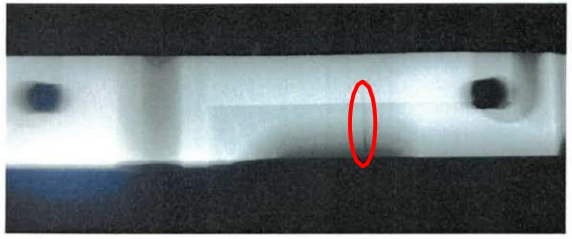
- **Manufacturing options: welding plates, milling billet** ($), **casting** ($$) & **AM.**
  - **Additive manufacturing (AM) very attractive because easier & cheaper**
  - **3D printing solution** *(also investigated: WAAM*, AFSD**, or CS***)*
- **2x prototypes** produced by **3D printing:**
  1) **BeamIT** (ITA)
  2) **Innomia a.s.** (CZ), 1st user of **EOS (GER)** industrial 3D printing systems.







Required position accuracy *of* ***functional surfaces*** *after the machining is* ***0.1 mm***



Defect (cavity) ***due to broken support*** *on X-ray picture, propagating 22mm deep inside bulk.*

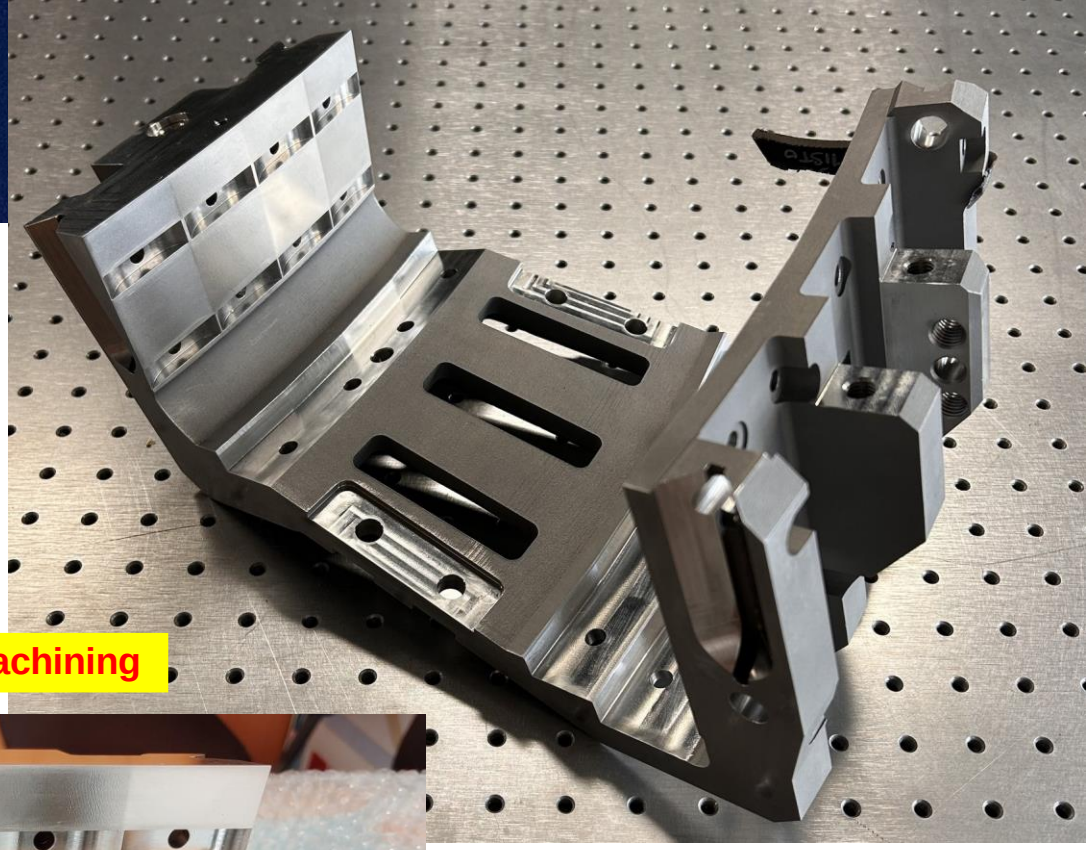
- **39 X-ray pictures** taken at **19 locations** and from **5 to 45 mm depth show no defect.**
- **A full volume ultrasound test** was performed, showing **no defect.**

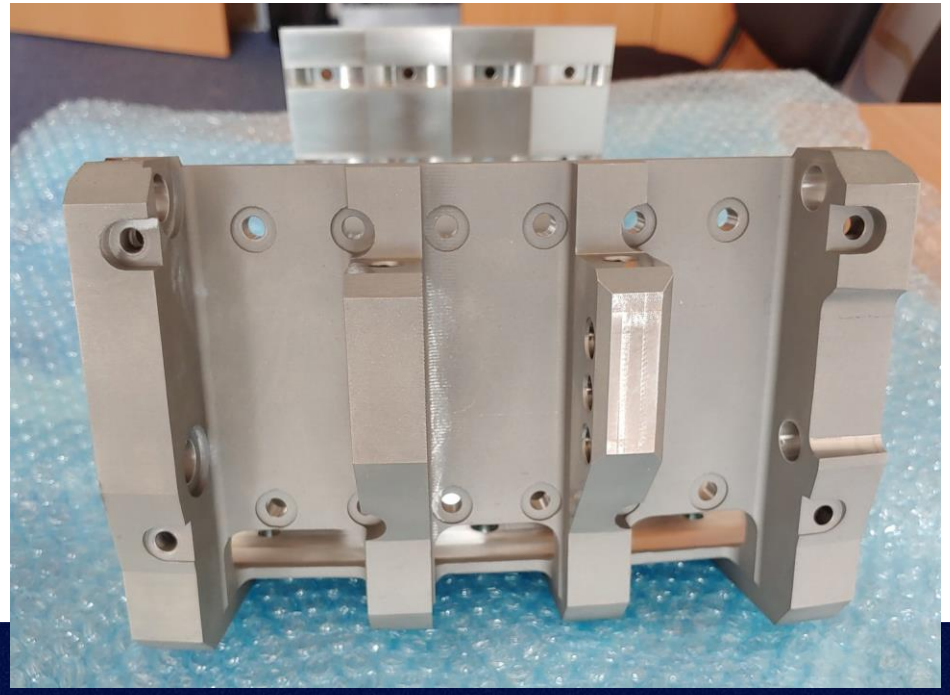
**Wire Arc Additive Manufacturing, **Additive Frictional Stir Deposition, ***Cold spray*

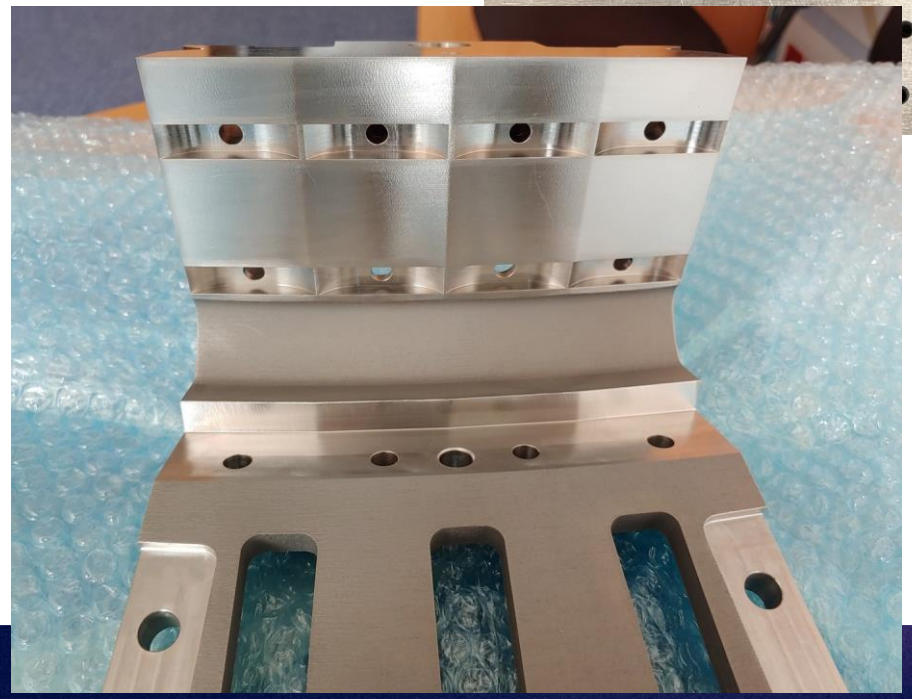


BeamIT

After HT *(hardening)* & **CNC machining**





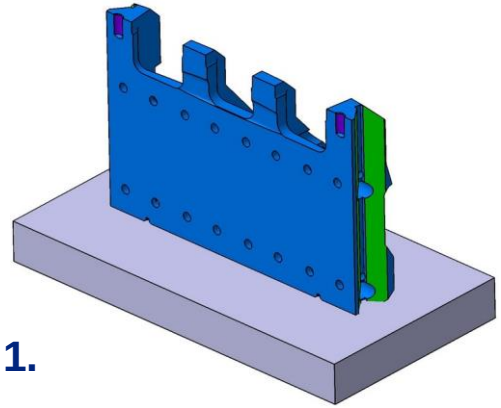


- **Machining protocole** developed to **secure tolerance** on the **alignment of 2 adjacent cassettes** (GO/NOGO approach)

Cassette manufacturing by 3D printing

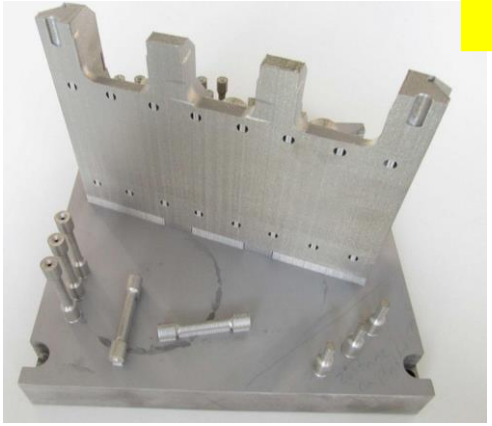
- **2nd prototype** (**Innomia a.s.**) made on **smaller printer ⇒develop a 2-step protocol:**

Step 1. Backside printed vertically, then



Step 1.

Innomia

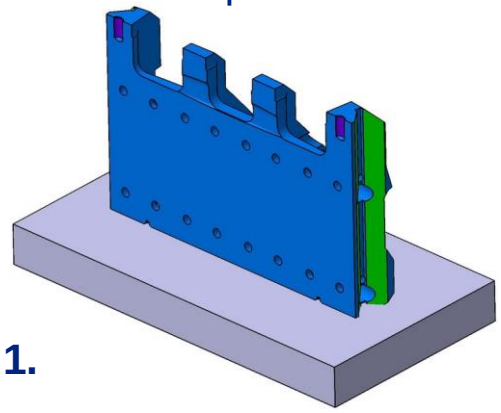




Cassette manufacturing by 3D printing

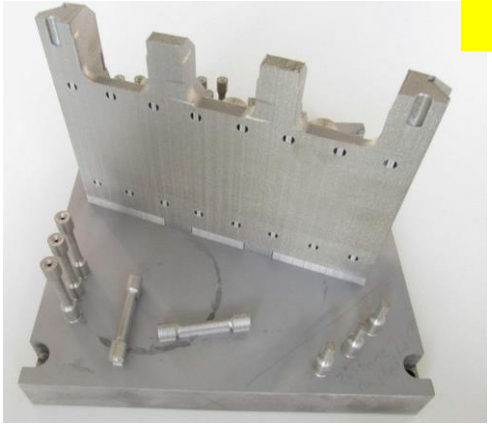
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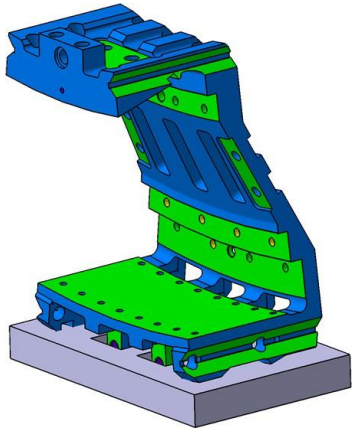
Step 1.

Innomia

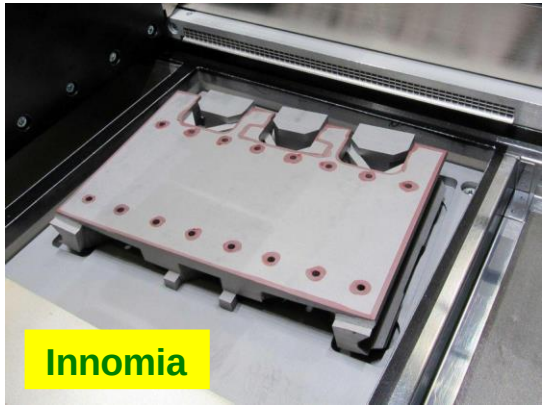




Step 2. building up the rest of cassette on the backside as horizontal base



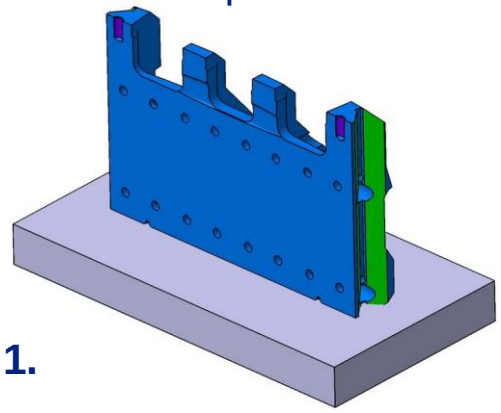
Step 2.



Cassette manufacturing by 3D printing

- **2nd prototype** (**Innomia a.s.**) made on **smaller printer ⇒develop a 2-step protocol:**

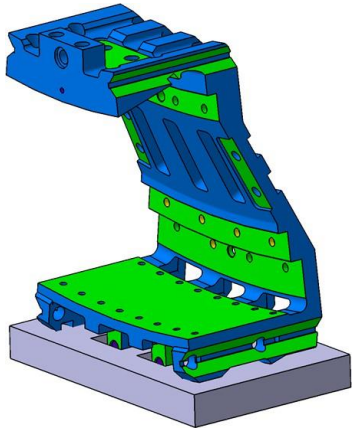
Step 1. Backside printed vertically, then



Step 1.

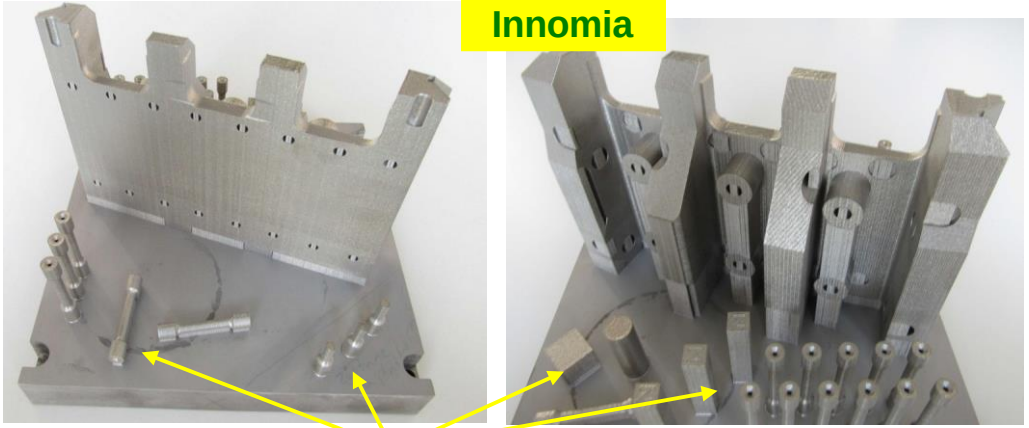
Special procedure to start print #2 in **same conditions** as at the end of print #1 *(temperature, etc.)*

Step 2. building up the rest of cassette on the backside as horizontal base

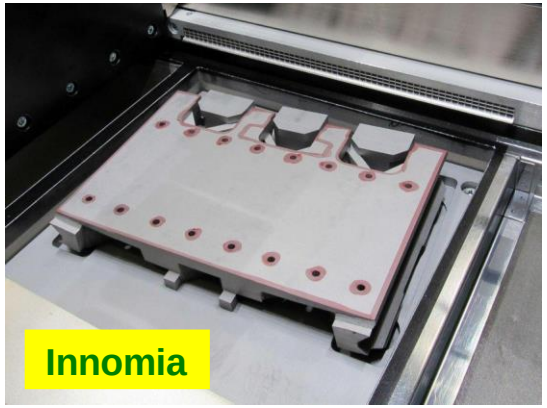


Step 2.

Innomia



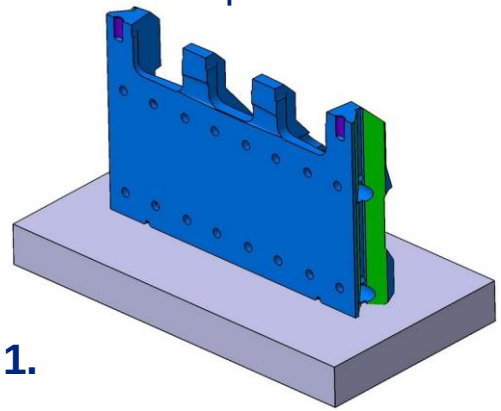
3D printed coupons / parts for material characterization



Cassette manufacturing by 3D printing

- **2nd prototype** (**Innomia a.s.**) made on **smaller printer ⇒develop a 2-step protocol:**

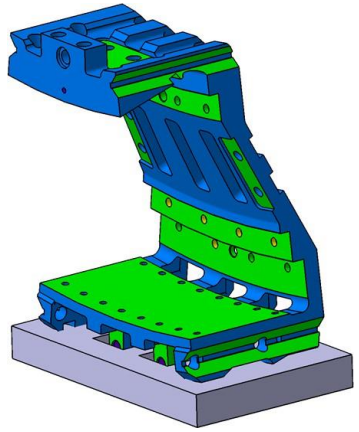
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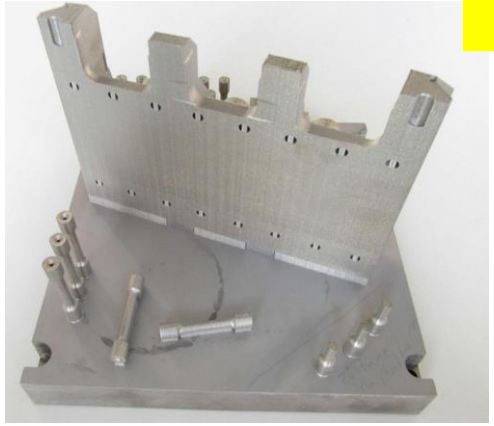
Step 1.

Special procedure to start print #2 in **same conditions** as at the end of print #1 *(temperature, etc.)*

Step 2. building up the rest of cassette on the backside as horizontal base

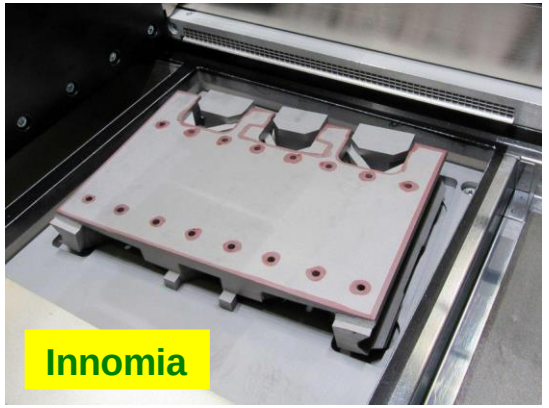


Step 2.

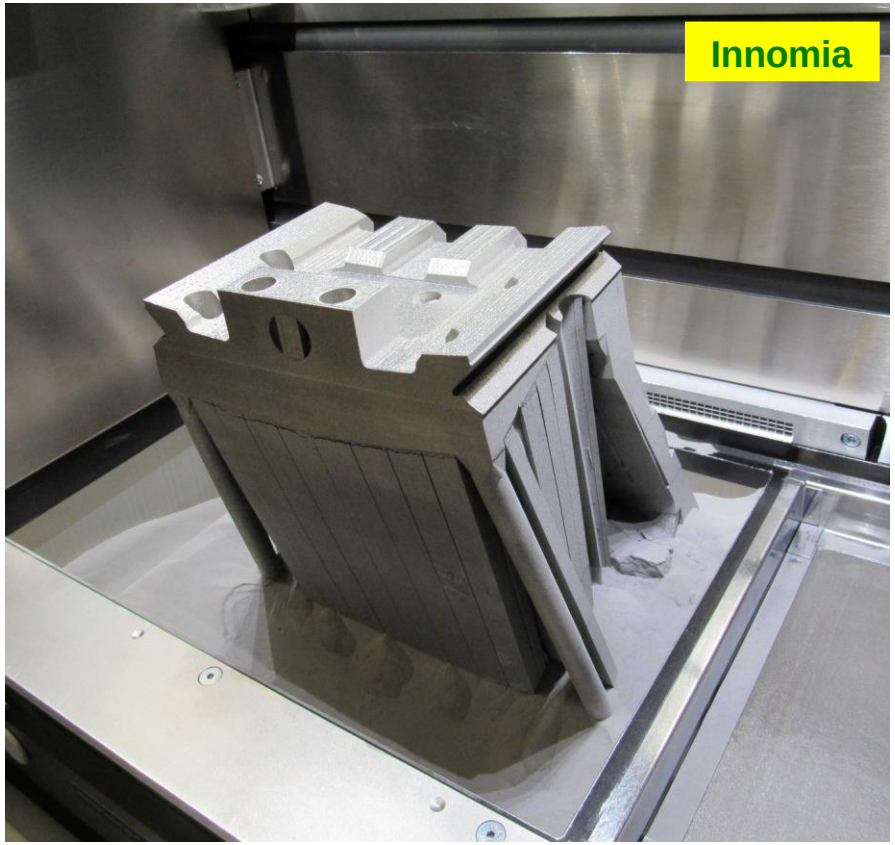


Innomia





Innomia

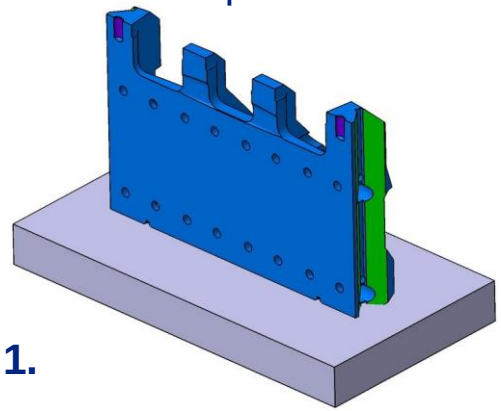


Innomia

Cassette manufacturing by 3D printing

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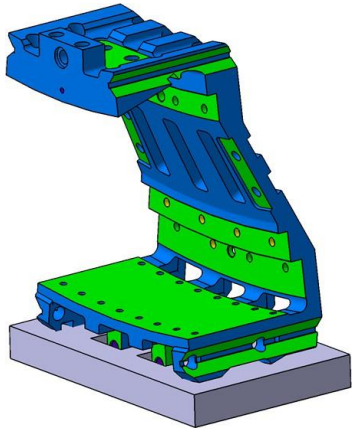
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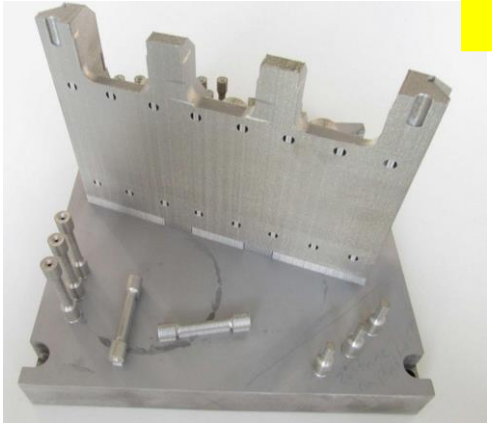
Step 1.

Special procedure
to start print #2 in
same conditions as
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(temperature, etc.)

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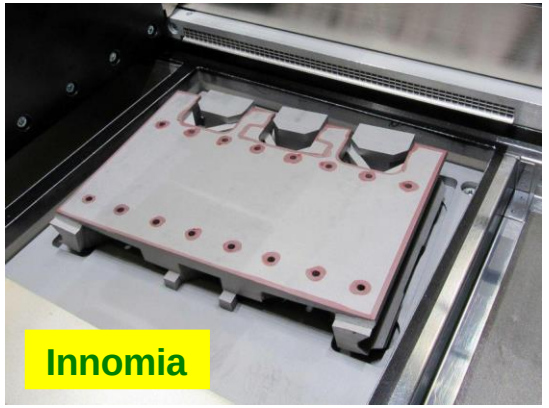


Step 2.

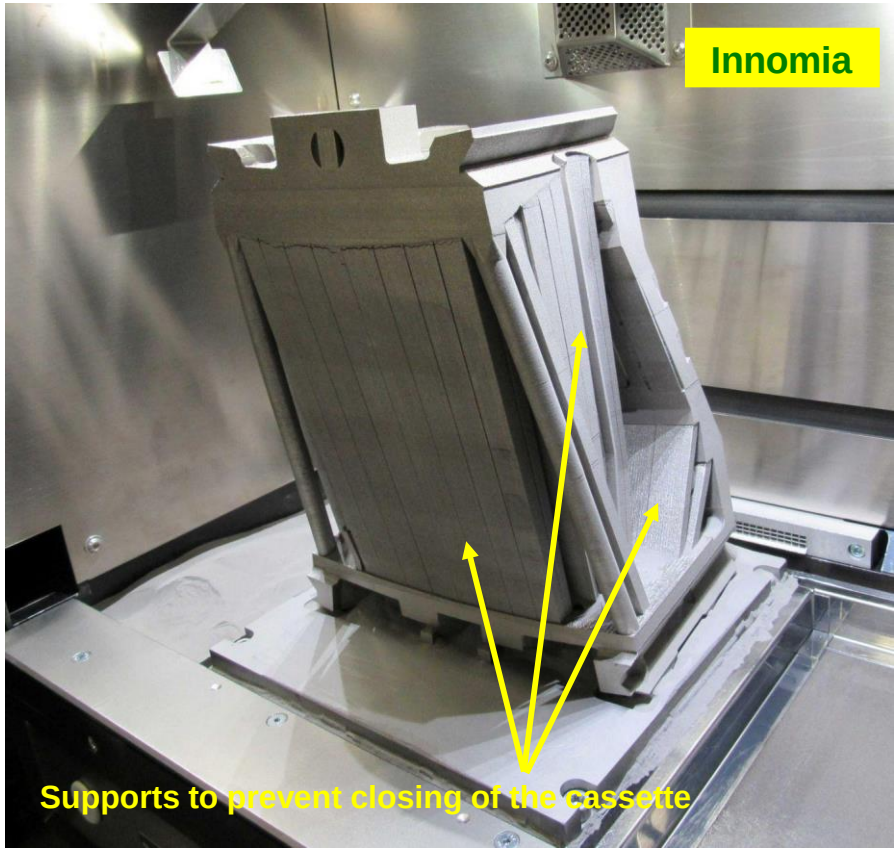


Innomia





Innomia



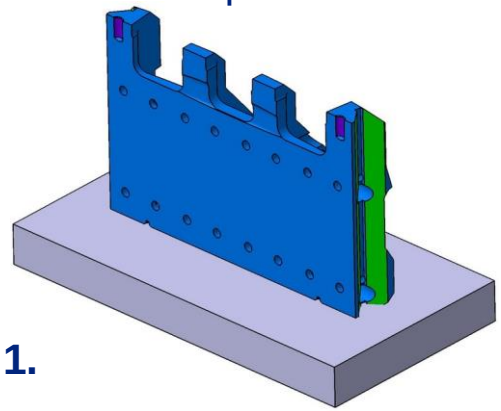
Innomia

Supports to prevent closing of the cassette

Cassette manufacturing by 3D printing

- **2nd prototype** (**Innomia a.s.**) made on **smaller printer ⇒develop a 2-step protocol:**

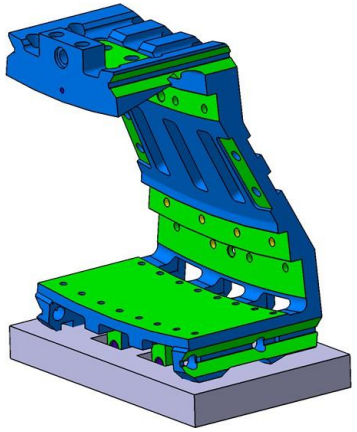
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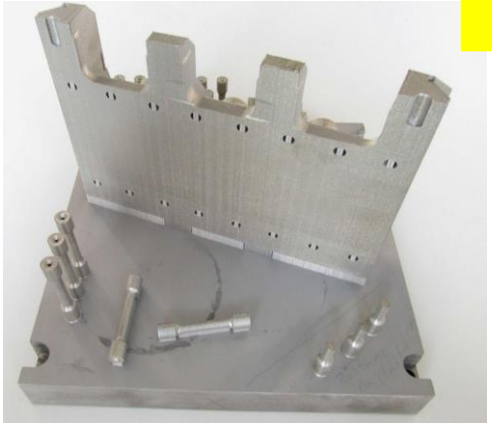
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Step 2. building up the rest of cassette on the backside as horizontal base

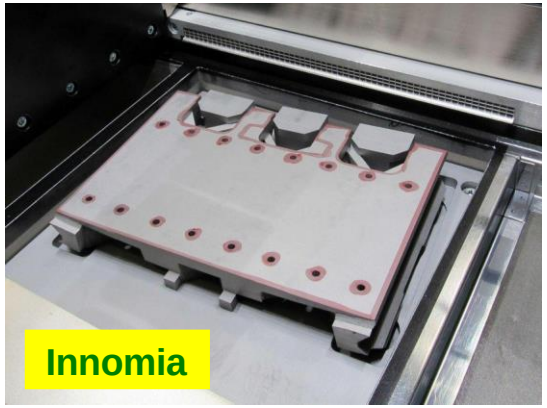


Step 2.



Innomia





Innomia

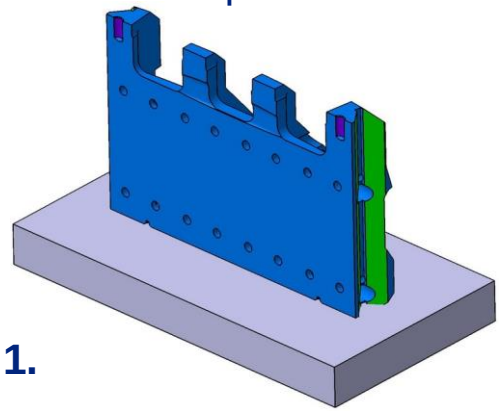


Innomia

Cassette manufacturing by 3D printing

- **2nd prototype** (**Innomia a.s.**) made on **smaller printer ⇒develop a 2-step protocol:**

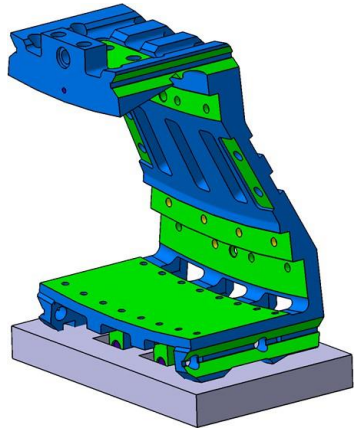
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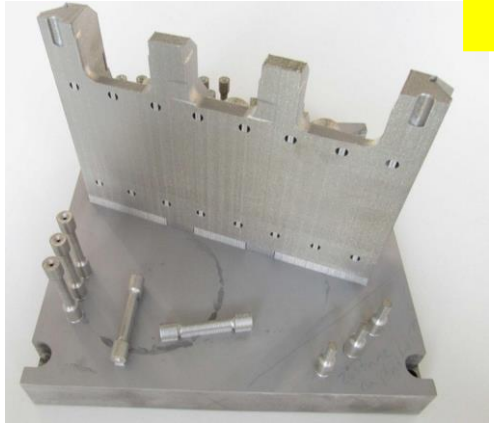
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Step 2. building up the rest of cassette on the backside as horizontal base

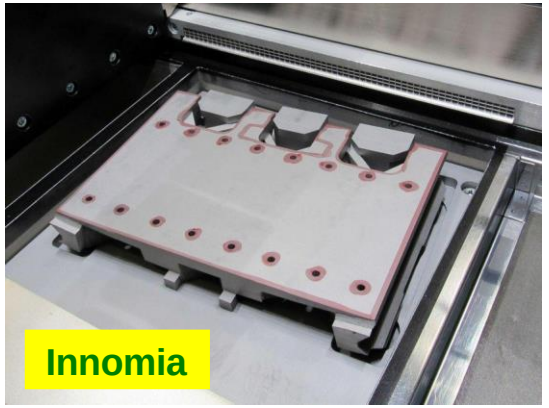


Step 2.



Innomia





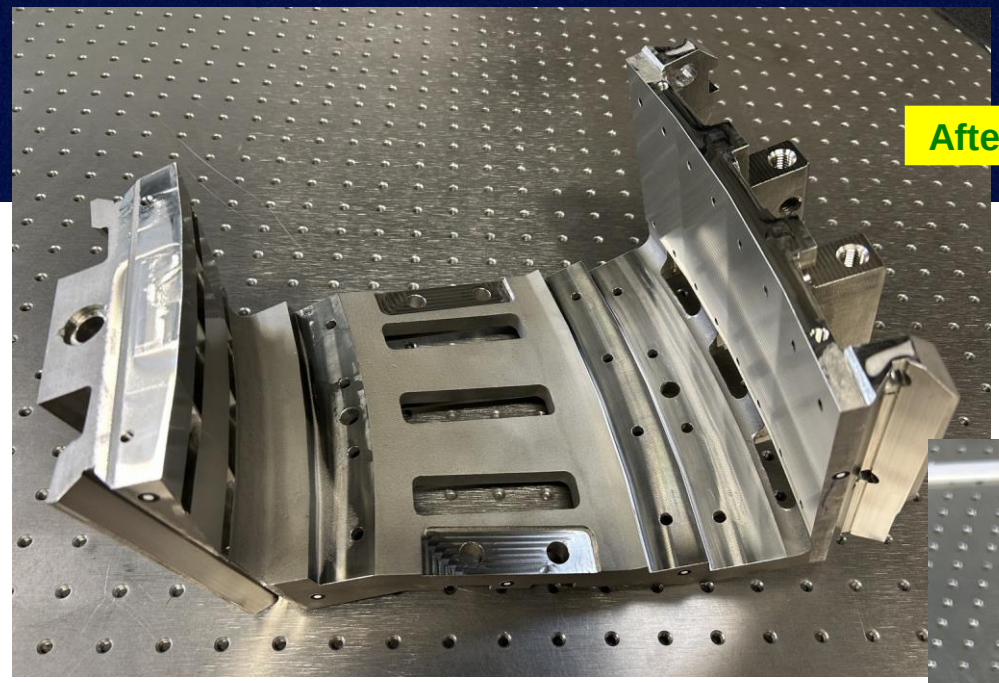
Innomia

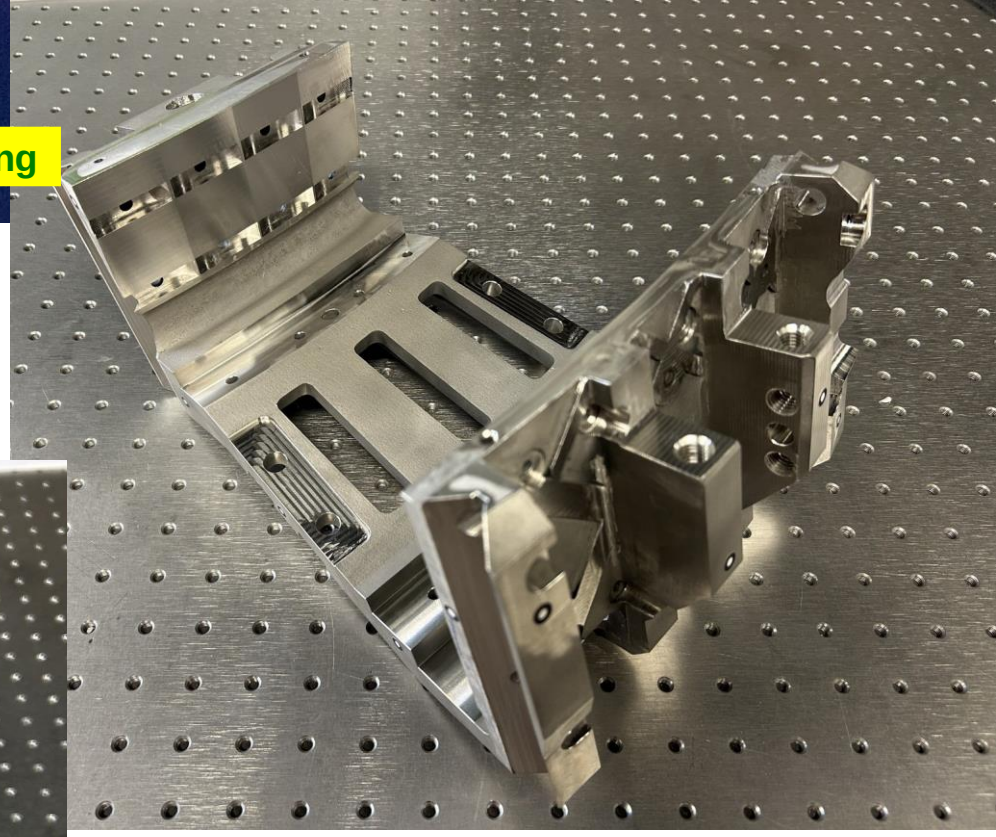


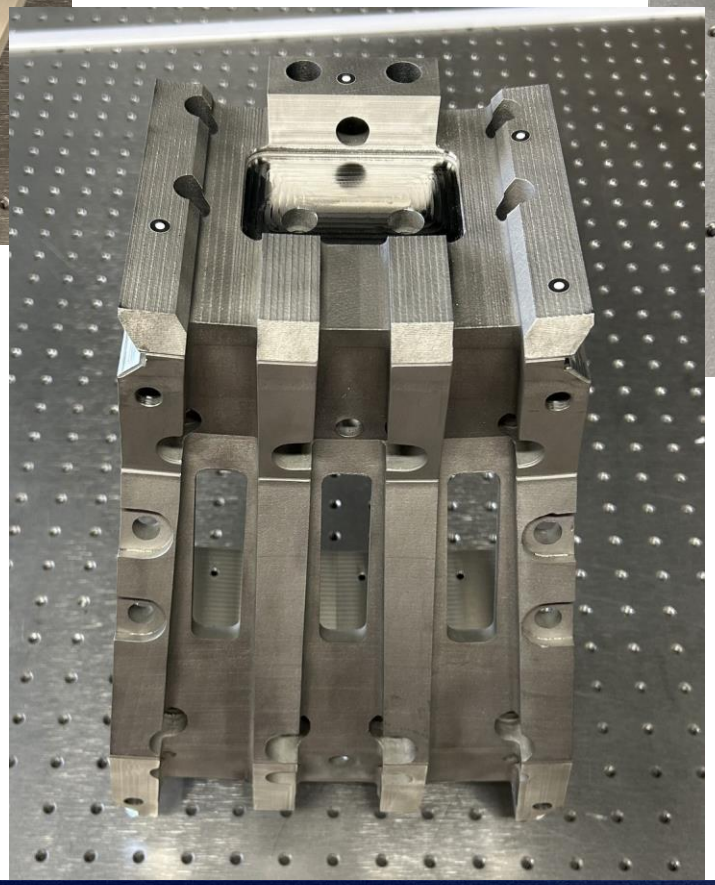
Innomia

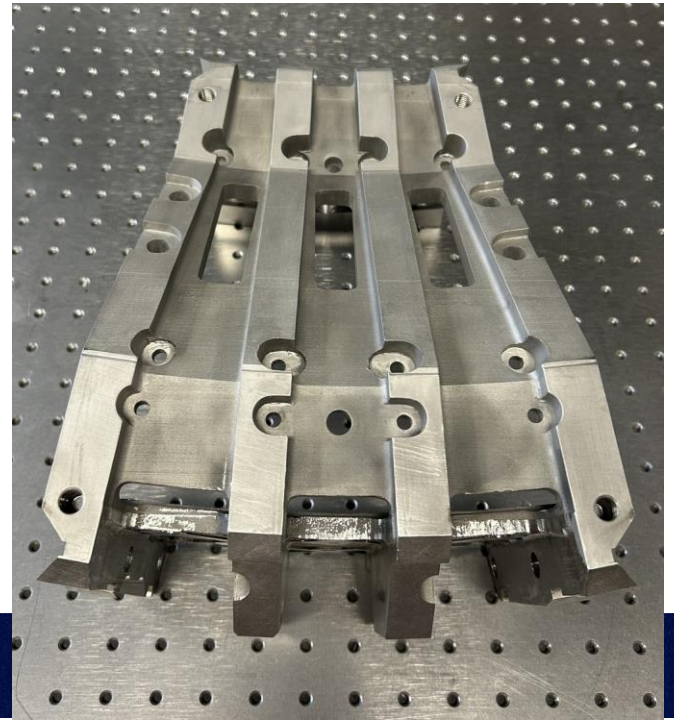
Innomia a.s.

After HT *(hardening)* & **CNC machining**









- **Both cassettes** are **vacuum compatible**
  (no significant trapped volumes,
  no significant outgassing visible)

Quality of 3D printed Inconel ?

- **Standard** for **3D printed Inconel 718** [ASTM F3055 (2021)] but **no acceptance criteria**, not for fusion application.
- **Important** is to ensure **no defects** & **good material properties:**
  - X-ray tests and ultrasound (large defects) performed on **BeamIT 3D printed cassette** showed **no defects**
  - Tensile tests (TT) performed a **RT** and **500°C** on coupons (**BeamIT** and **ATTL, China**) for **2 different heat treatments**
    - **RT:** $R_{p0.2}$ **= 964 MPa & 1115 MPa**
    - **500°C:** $R_{p0.2}$ **= 836 MPa & 958 MPa**
    - **Results** according to **SDC-IC:**

      $R_{p0.2}^{MIN}$ **= 1035 MPa (RT)**

      $R_{p0.2}^{MIN}$ **= 905 MPa (500°C)**

Tab. 2 Results of tensile tests at RT

Specimen	Temp. K	a_0 mm	b_0 mm	L_0 mm	$R_{p0,2}$ MPa	R_m MPa	A_g %	A %	Z %
V1_4	293	1,01	1,97	8,00	966	1271	22,6	28,8	40
V1_5	293	1,00	1,96	8,00	961	1272	23,7	29,9	38
V1_6	293	1,00	1,97	8,00	967	1274	24,1	30,3	41
V1_7	293	1,00	1,98	8,00	964	1268	23,7	29,6	37
V1_8	293	1,00	1,98	8,00	960	1269	24,0	31,1	38
Average					964	1271	24	30	39
V2_4	293	0,97	2,00	8,00	1102	1356	16,7	22,8	36
V2_5	293	1,01	1,98	8,00	1117	1376	16,8	21,0	20
V2_6	293	1,01	1,97	8,00	1120	1378	16,2	21,4	30
V2_7	293	1,01	1,96	8,00	1122	1377	15,8	20,9	29
V2_8	293	1,01	1,99	8,00	1116	1369	16,0	19,8	25
Average					1115	1371	16	21	28

Tab. 3 Results of tensile tests at 773 K

Specimen	Temp. °K	a_0 mm	b_0 mm	$R_{p0,2}$ MPa	R_m MPa	A_g %	A %	Z %
V1_1	773	1,00	1,97	838	1047	18,9	25,6	38
V1_2	773	1,00	1,96	829	1038	15,6	23,1	44
V1_3	773	1,00	1,96	842	1049	21,6	25,3	38
Average				836	1045	19	25	40
V2_1	773	1,01	1,97	890	1195	14,1	18,8	38
V2_2	773	0,99	1,97	990	1201	12,3	20,4	32
V2_3	773	1,02	1,96	994	1195	11,9	20,2	39
Average				958	1197	13	20	36

Quality of 3D printed Inconel ?

- **Standard** for **3D printed Inconel 718** [ASTM F3055 (2021)] but **no acceptance criteria**, not for fusion application.
- **Important** is to ensure **no defects** & **good material properties:**
  - X-ray tests and ultrasound (large defects) performed on **BeamIT 3D printed cassette** showed **no defects**
  - Tensile tests (TT) performed a **RT** and **500°C** on coupons (**BeamIT** and **ATTL, China**) for **2 different heat treatments**
    - **RT:** $R_{p0.2}$ **= 964 MPa & 1115 MPa**
    - **500°C:** $R_{p0.2}$ **= 836 MPa & 958 MPa**
    - **Results** according to **SDC-IC:**

      $R_{p0.2}^{MIN}$ **= 1035 MPa (RT)**

      $R_{p0.2}^{MIN}$ **= 905 MPa (500°C)**

Tab. 2 Results of tensile tests at RT

Specimen	Temp. K	a_0 mm	b_0 mm	L_0 mm	$R_{p0,2}$ MPa	R_m MPa	A_g %	A %	Z %
V1_4	293	1,01	1,97	8,00	966	1271	22,6	28,8	40
V1_5	293	1,00	1,96	8,00	961	1272	23,7	29,9	38
V1_6	293	1,00	1,97	8,00	967	1274	24,1	30,3	41
V1_7	293	1,00	1,98	8,00	964	1268	23,7	29,6	37
V1_8	293	1,00	1,98	8,00	960	1269	24,0	31,1	38
Average					964	1271	24	30	39
V2_4	293	0,97	2,00	8,00	1102	1356	16,7	22,8	36
V2_5	293	1,01	1,98	8,00	1117	1376	16,8	21,0	20
V2_6	293	1,01	1,97	8,00	1120	1378	16,2	21,4	30
V2_7	293	1,01	1,96	8,00	1122	1377	15,8	20,9	29
V2_8	293	1,01	1,99	8,00	1116	1369	16,0	19,8	25
Average					1115	1371	16	21	28

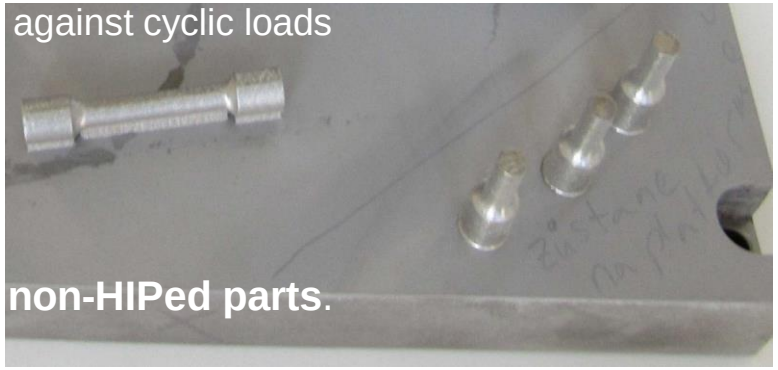
Tab. 3 Results of tensile tests at 773 K

Specimen	Temp. °K	a_0 mm	b_0 mm	$R_{p0,2}$ MPa	R_m MPa	A_g %	A %	Z %
V1_1	773	1,00	1,97	838	1047	18,9	25,6	38
V1_2	773	1,00	1,96	829	1038	15,6	23,1	44
V1_3	773	1,00	1,96	842	1049	21,6	25,3	38
Average				836	1045	19	25	40
V2_1	773	1,01	1,97	890	1195	14,1	18,8	38
V2_2	773	0,99	1,97	990	1201	12,3	20,4	32
V2_3	773	1,02	1,96	994	1195	11,9	20,2	39
Average				958	1197	13	20	36

Do we need HIPing of 3D printed Inconel ?

⇒ To remove possible defects in the bulk material to be more robust against cyclic loads

- **Innomia** has produced **3D printed parts** during the cassette manufacturing for **mechanical characterization** (LCF).
  - ⇒ ***1-step*** *&* ***2-step***
  - ⇒ ***two printing directions*** *= horizontal and vertical*
- Half of the part/coupons underwent **HIPing** for comparison with **non-HIPed parts.**
- Characterization in progress.





Great support from the entire fusion community

Special thanks to the teams of:

- **AUG** *(I. Zammuto, A. Herrmann, W. Zeider, ...)*
- **Alcator C-Mod** *(B. Lipschultz, J. Irby, R. Viera, ...)*
- **PPPL** *(P. Titus, H. Zhang, ...)*
- **WEST** *(M. Missirlian, R. Mitteau, M. Richou, E. Tsitrone, M. Firdaouss, ...)*
- **ITER** *(S. Carpentier, F. Escourbiac, Q. Deliege, ...)*
- **EUROfusion** [PMU, WP DIV, WP PWIE] *(J. Boscary, J-H. You, S. Brezinsek, ...)*
- **F4E** *(V. Tomarchio)*



- **Public tender** for purchase of **W components launched last week**

Want to know more about COMPASS-U closed divertor design challenges ? and/or FEM simulations for COMPASS-U PFC design ?

Poster BO.028 by M. Durovec on Tuesday 14:00 (EEG)

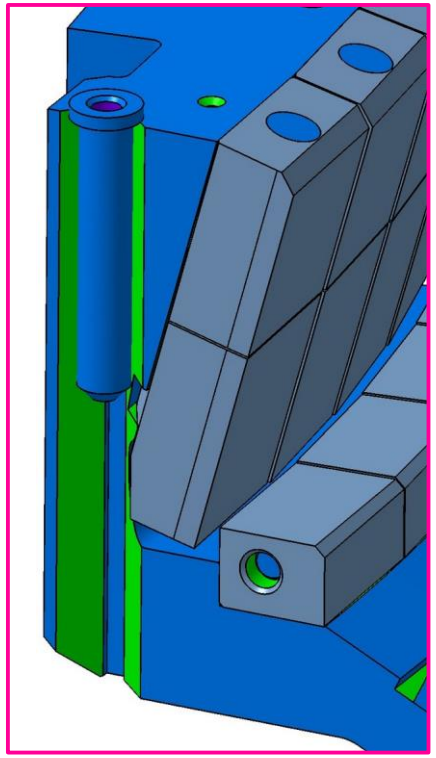
Poster BO.029 by O. Stukavec on Tuesday 14:00

BACK-UP SLIDES

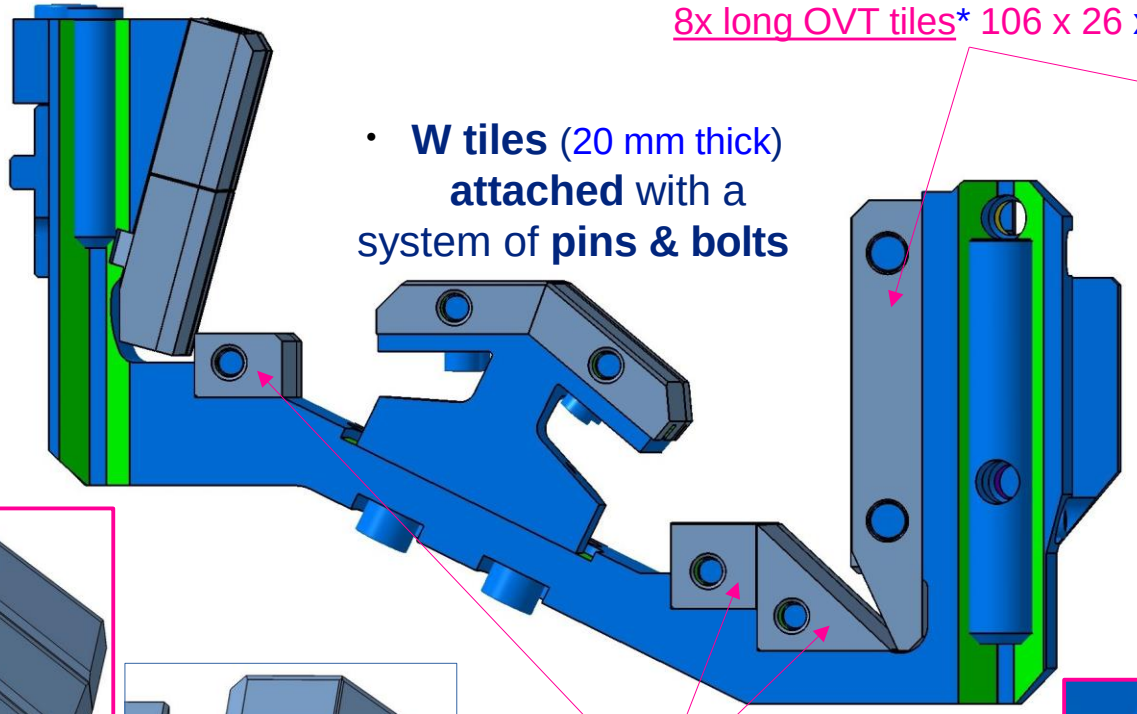


W tiles on each divertor cassette:

- **W tiles** mounted on **individual cassette outside tokamak** for precise alignment

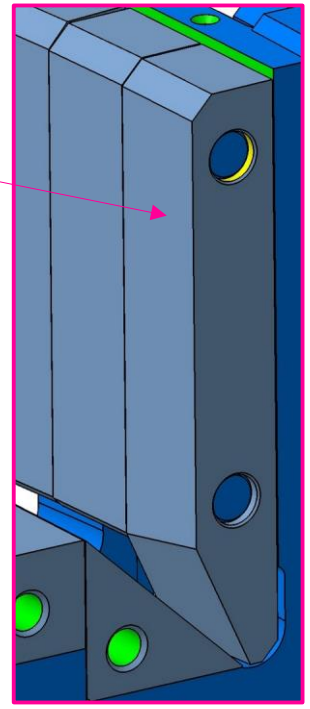


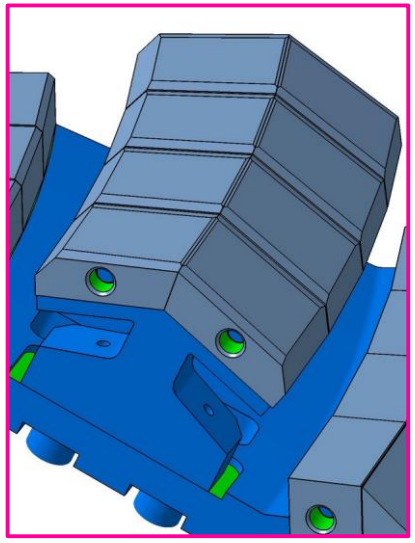
2 rows of 4x IVT*
40 x 45 x 20 mm

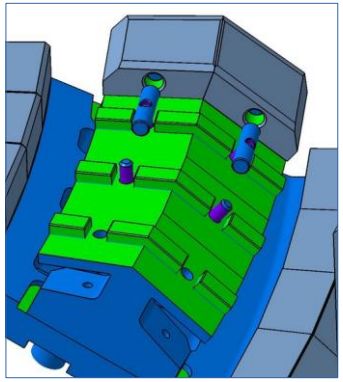


- **W tiles** (20 mm thick) **attached** with a system of **pins & bolts**

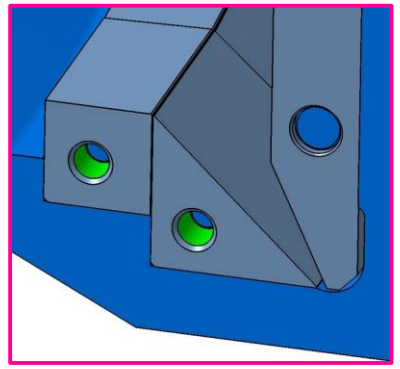
8x long OVT tiles* 106 x 26 x 20 mm







Inner / outer reflector tiles*

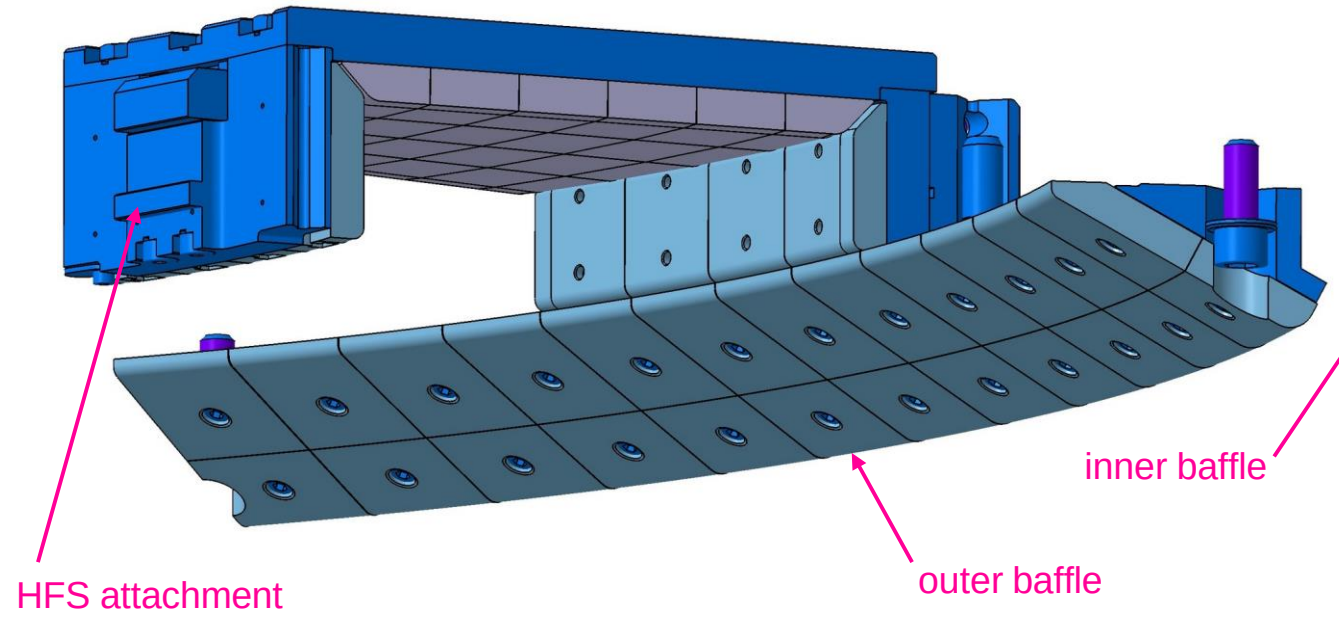


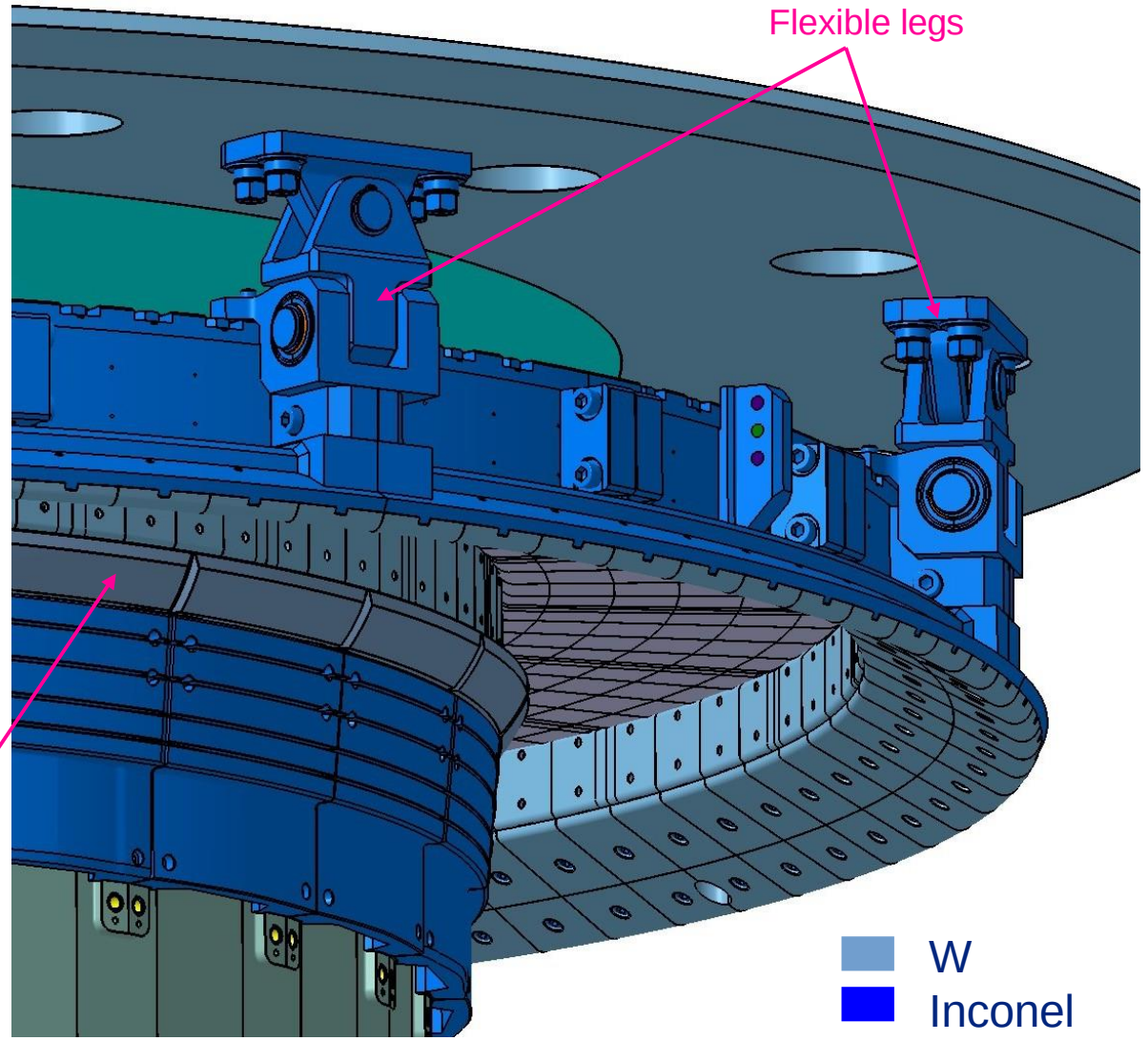
W
Inconel

**tiles with toroidal bevel*

Upper Open Divertor

- **Identical attachment to VV as lower divertor**
- **W tiles** mounted on **individual ring plates** (welded)
- **No bevel** to allow for **both helicity** ⇒> **double chamfer**
- **Preliminary design to be validated** against EM loads by structural analyses



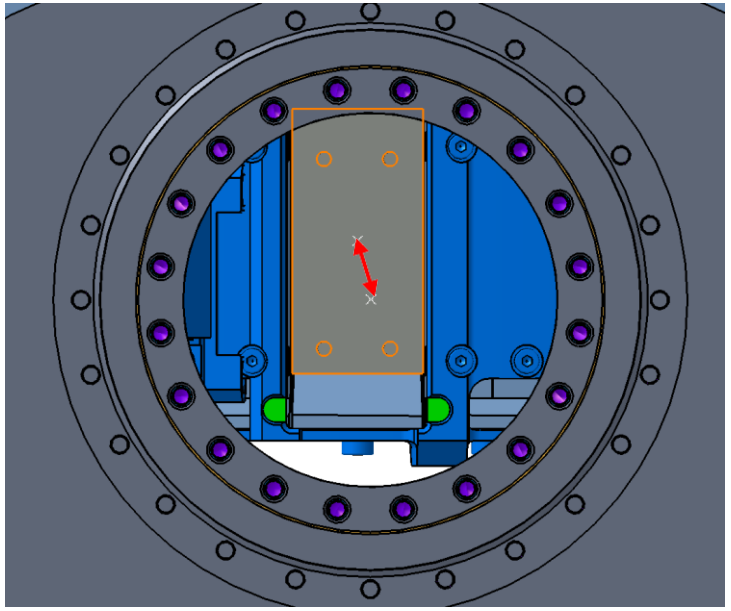


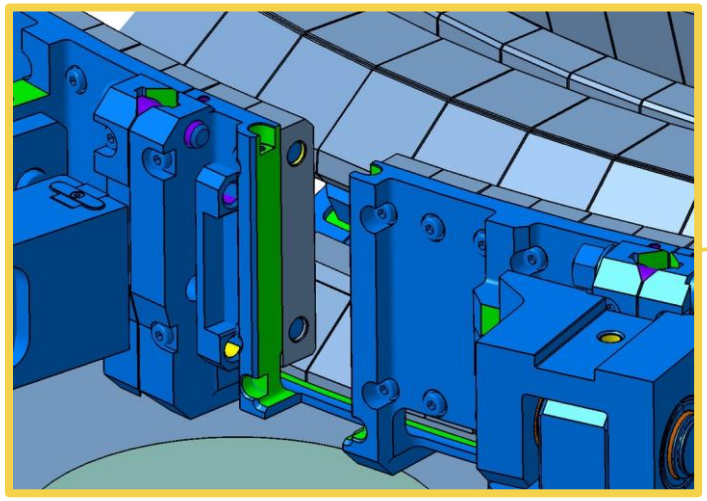
DIVertor ManipulaTor (DIVMAT)

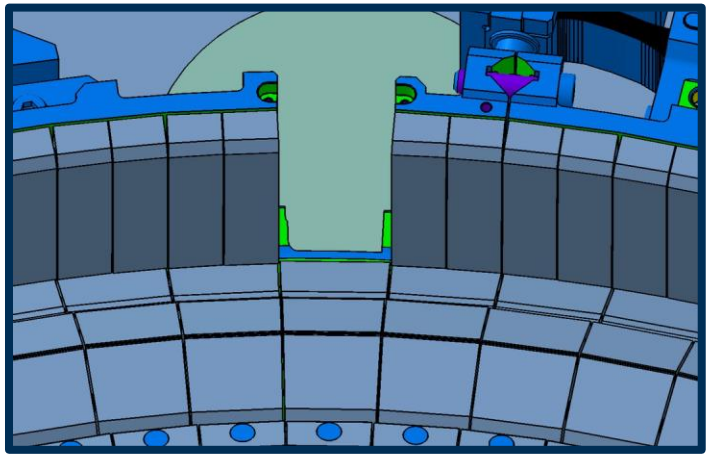
- **Replacing 2 OVT tiles =** area ~105 x 52 mm
- **Test new materials (liquid metals)**

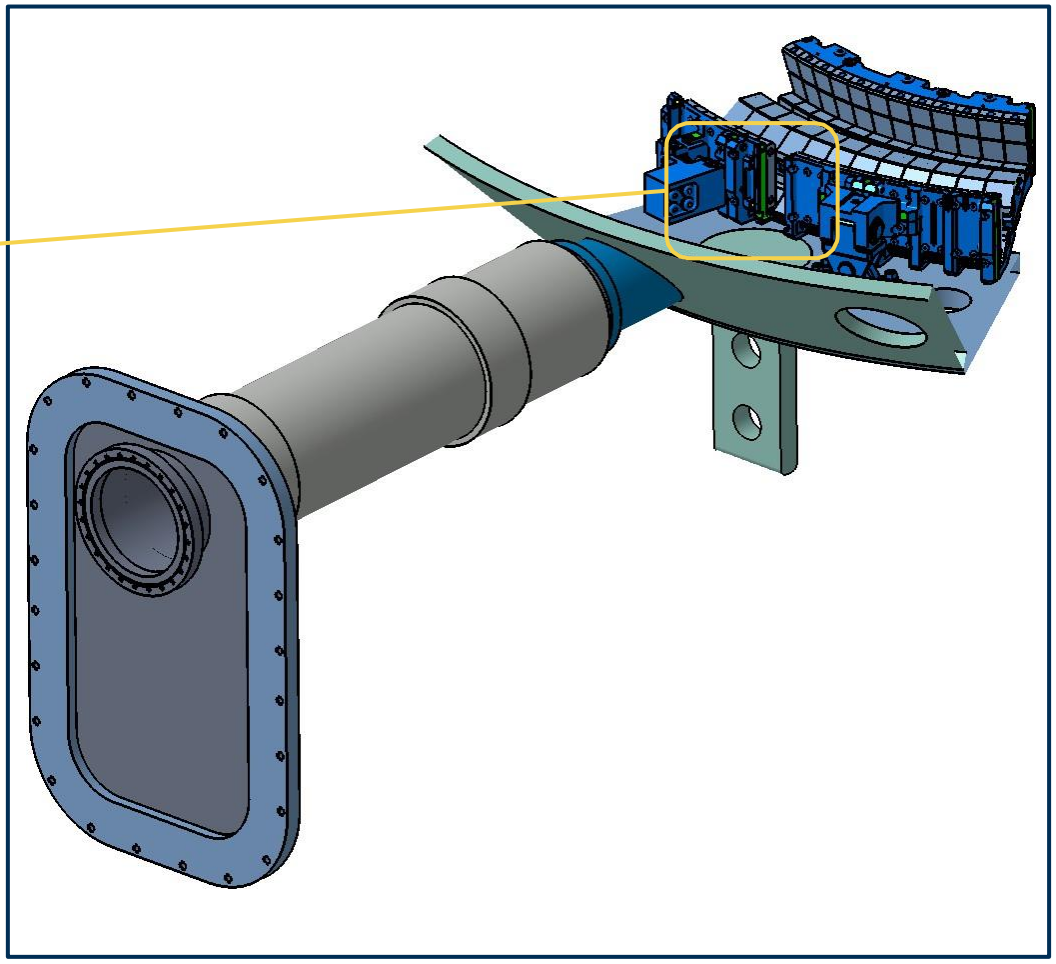
Tiles in **conflict** with **cryostat port + displacement** from **centre of port axis** to **centre of tile location**:

Δx = 5.4 mm; Δy = 23.5 mm



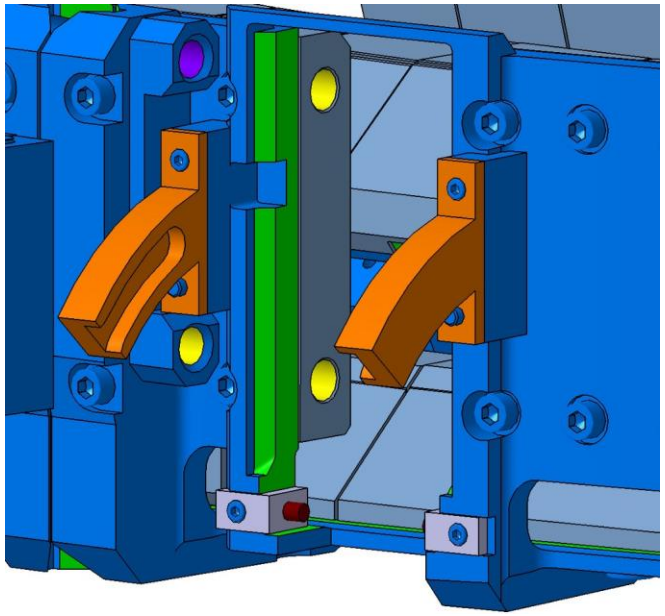


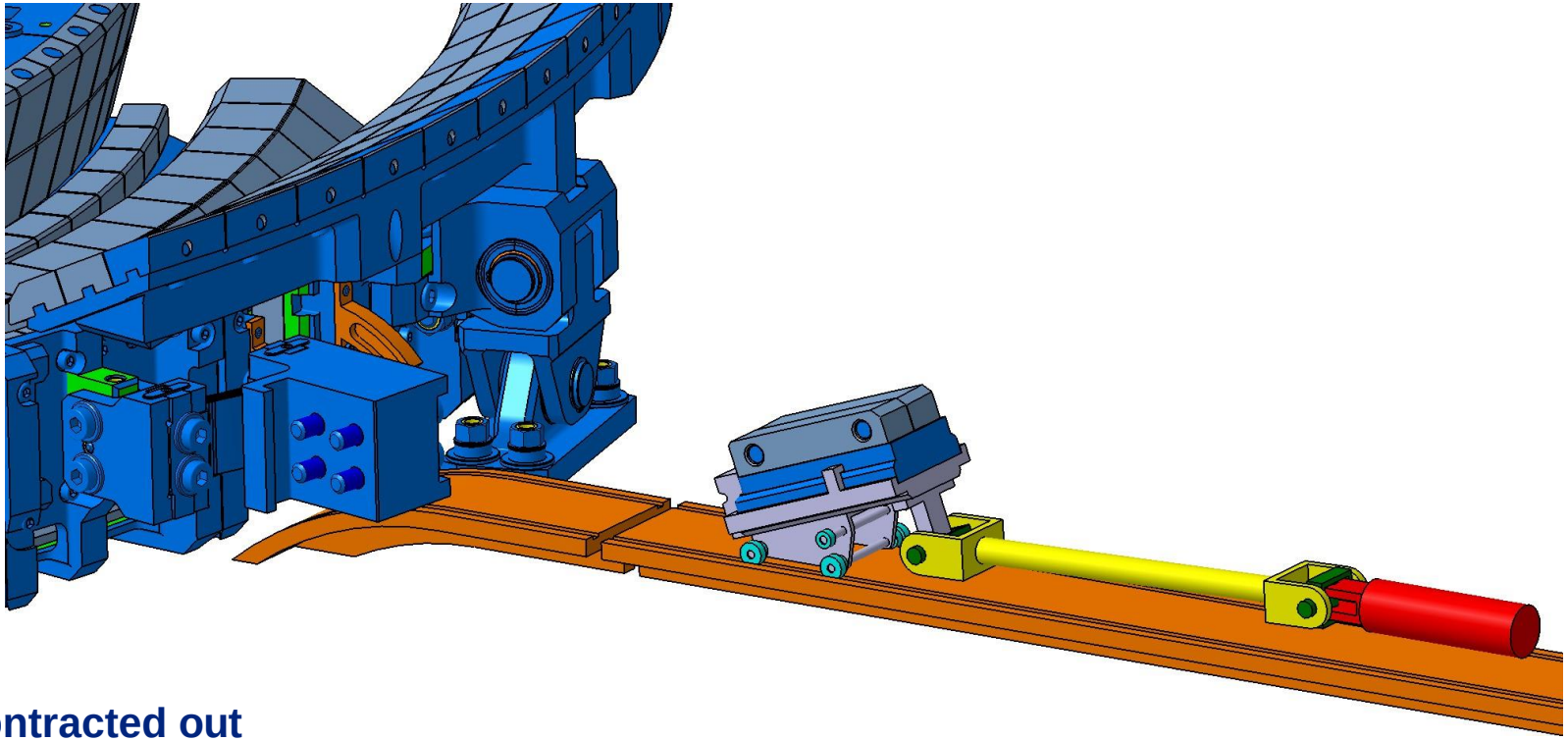




DIVertor ManipulaTor (DIVMAT)

- **Design strongly inspired** by **manipulator in AUG.**
- **Insert** the tiles in **“horizontal” position on rails**
- **Operate a rotation around a pivot** to install them in **final vertical position.**

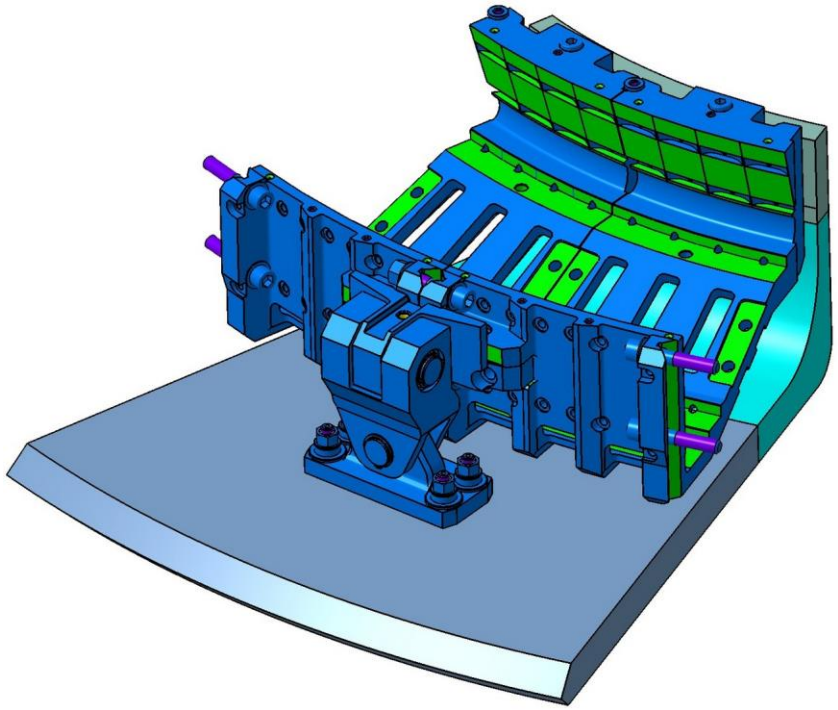


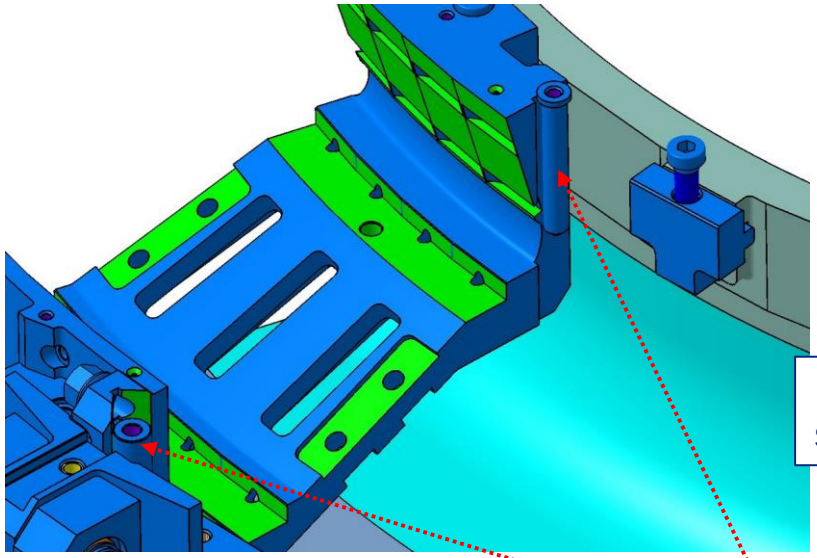


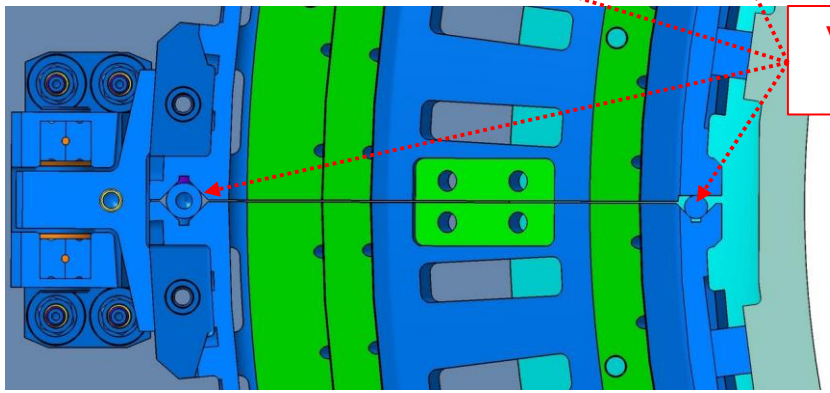
- **Mechanism feasibility was performed**
- **Preliminary design in-house, final design contracted out**

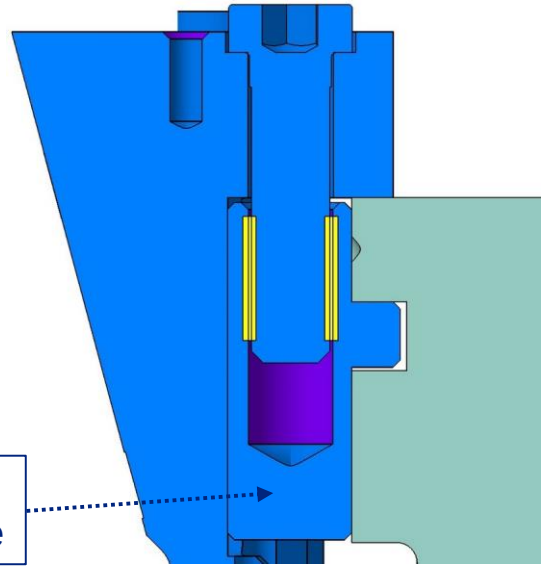
Divertor cassettes concept

- **Thick T-shaped shim plate** for connection between **HFS pad & cassette**
- Vertical bolts for attachment
- **Vertical pins** between cassette joints
- **Flexible legs at LFS** (see next slide)



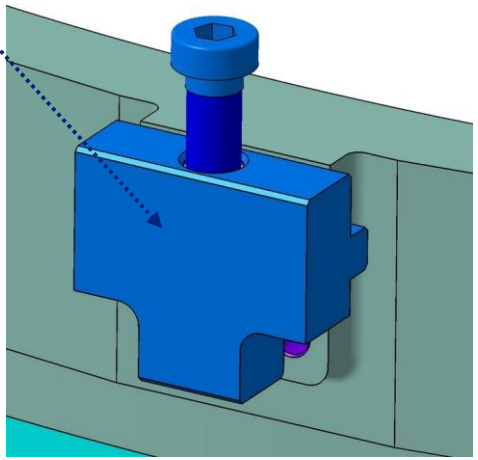






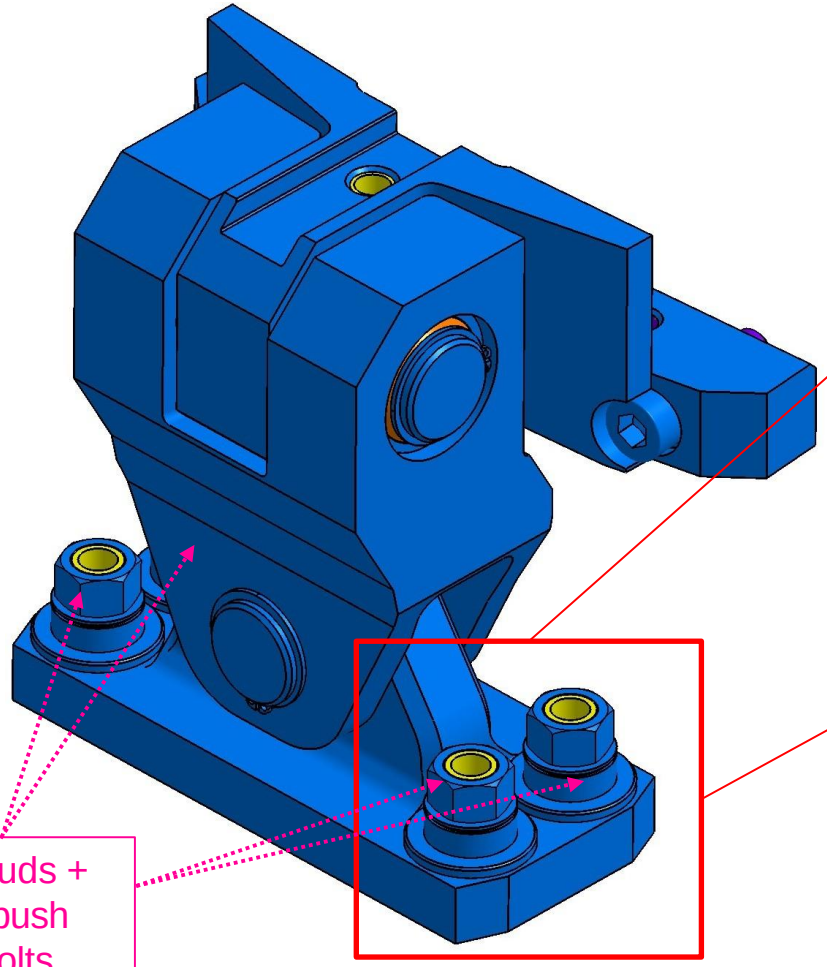
Thick shimplate

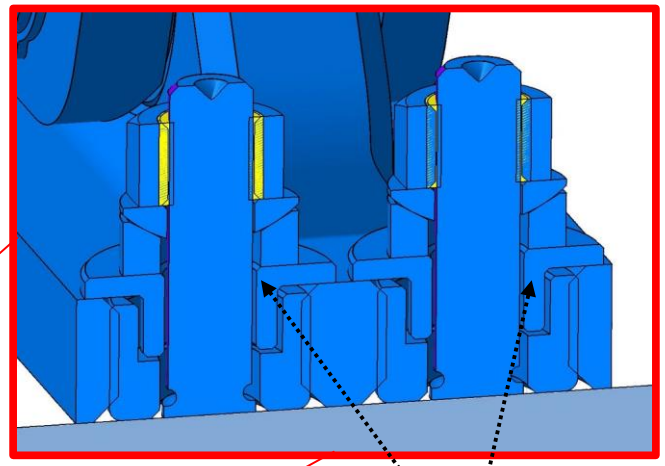
Vertical pins



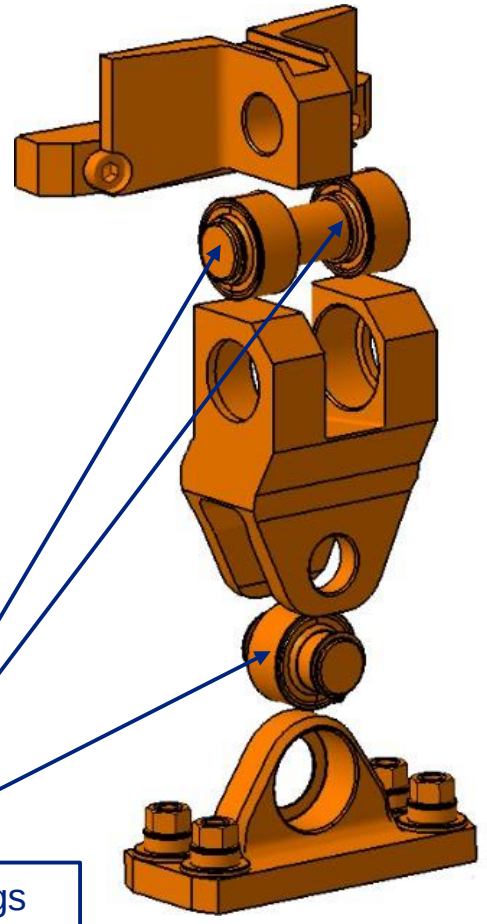
LFS flexible legs

- **Flexible legs** at LFS **fixed** to W using **4 welded studs** & **4 push bolts** for horizontality





4x Large flat washers



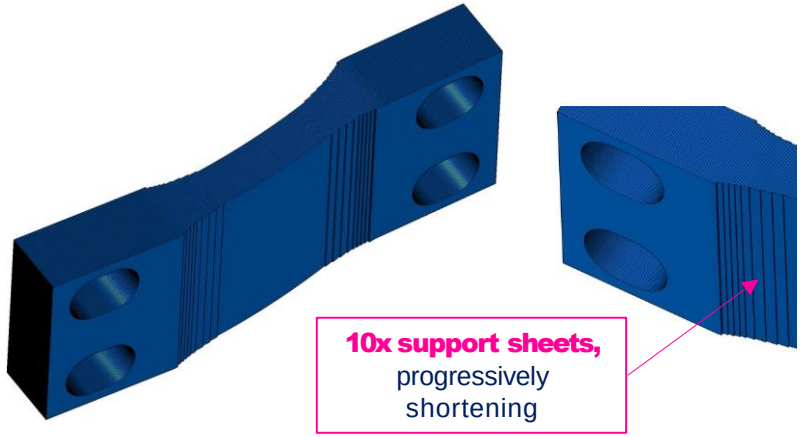
3x spherical bearings with lubricant coating (WS_2 or MoS_2)

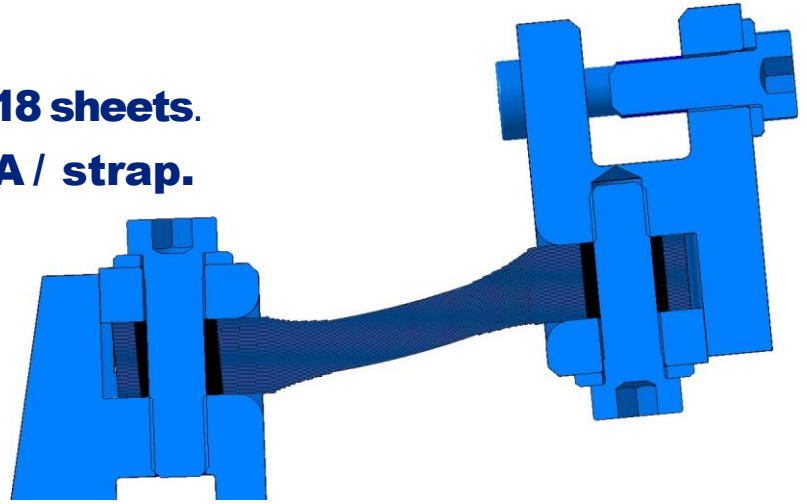
4 Studs + 4 push bolts

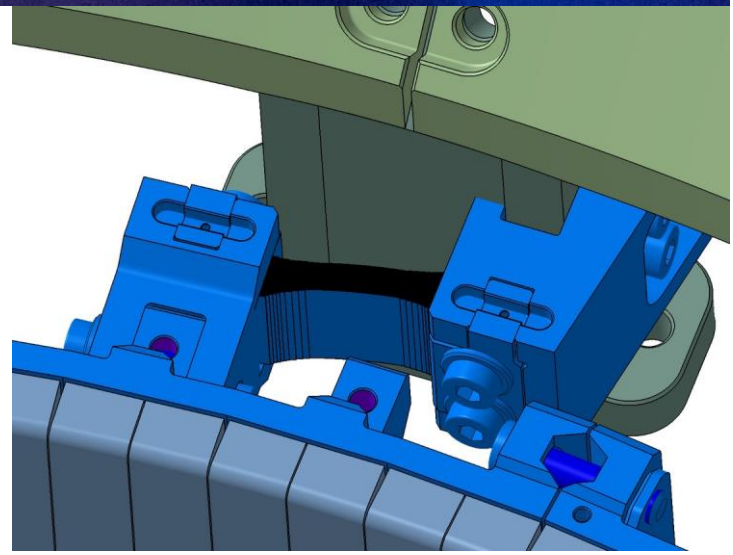
COMPASS-U PFC: DIVERTOR HALO STRAPS

LFS Halo straps

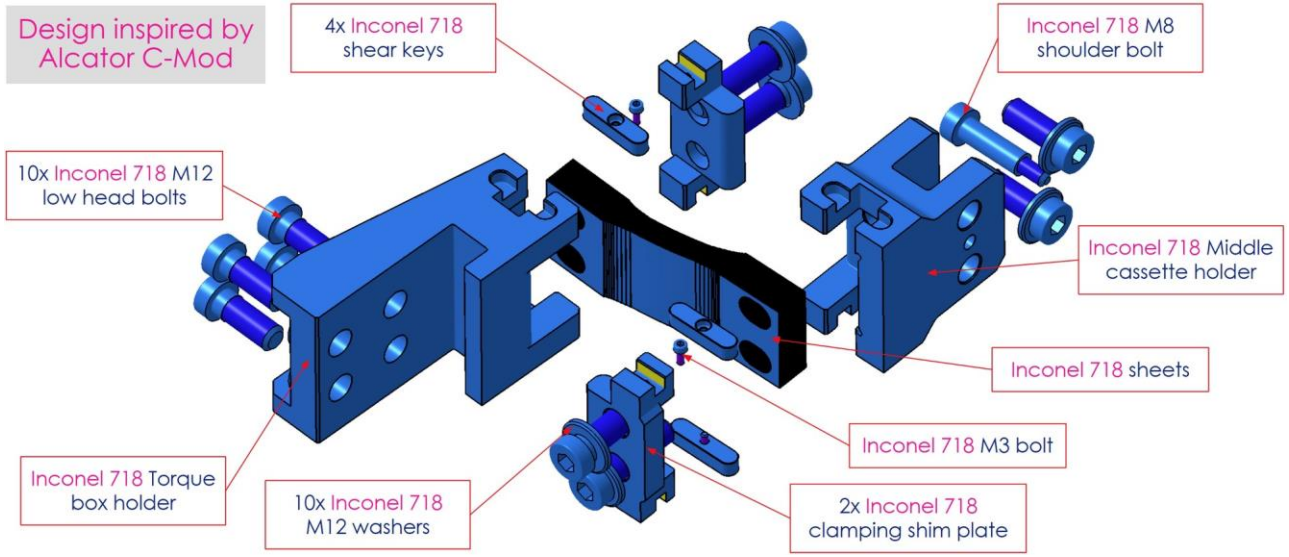
- Stack of **40x** flexible **0.25 mm Inconel 718 sheets**.
- **425 mm²** cross-section, **I_halo = 187.5 kA / strap.**







- Small **support sheets** around clamps to reduce stress.
- **8 halo current straps in total.**
- Each **end of strap** is **welded.**

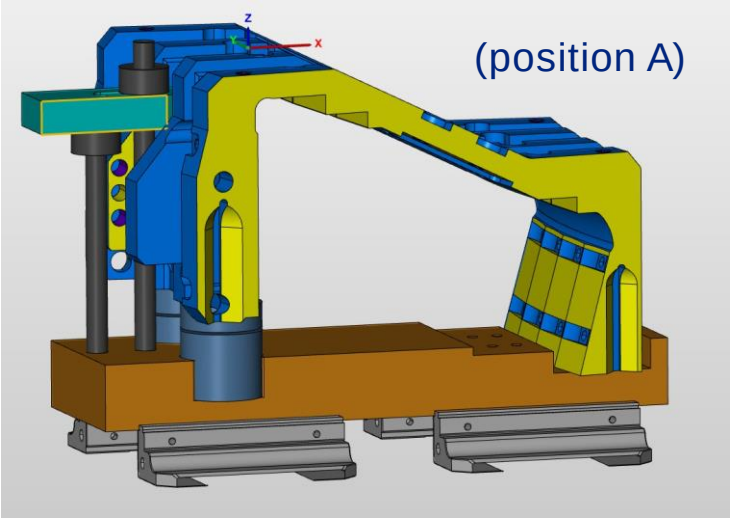


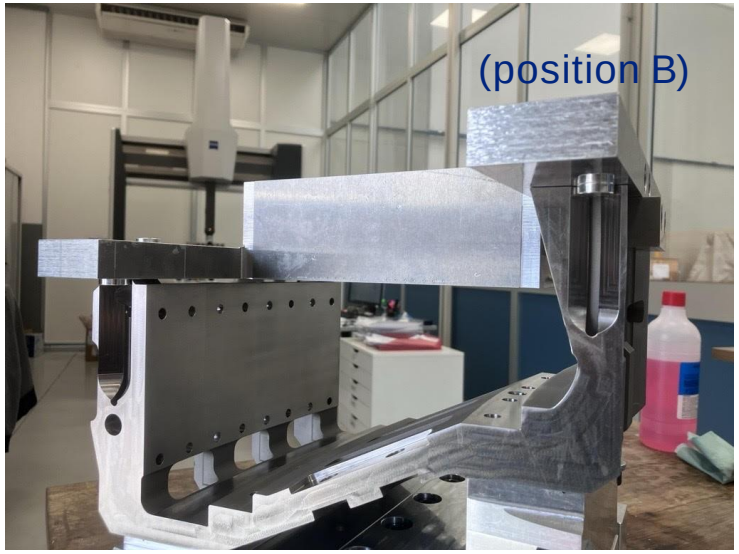
Forces

5mm radial + **2mm tor.** displacement (thermal exp.) **+ 20 kN** EM force when I_halo

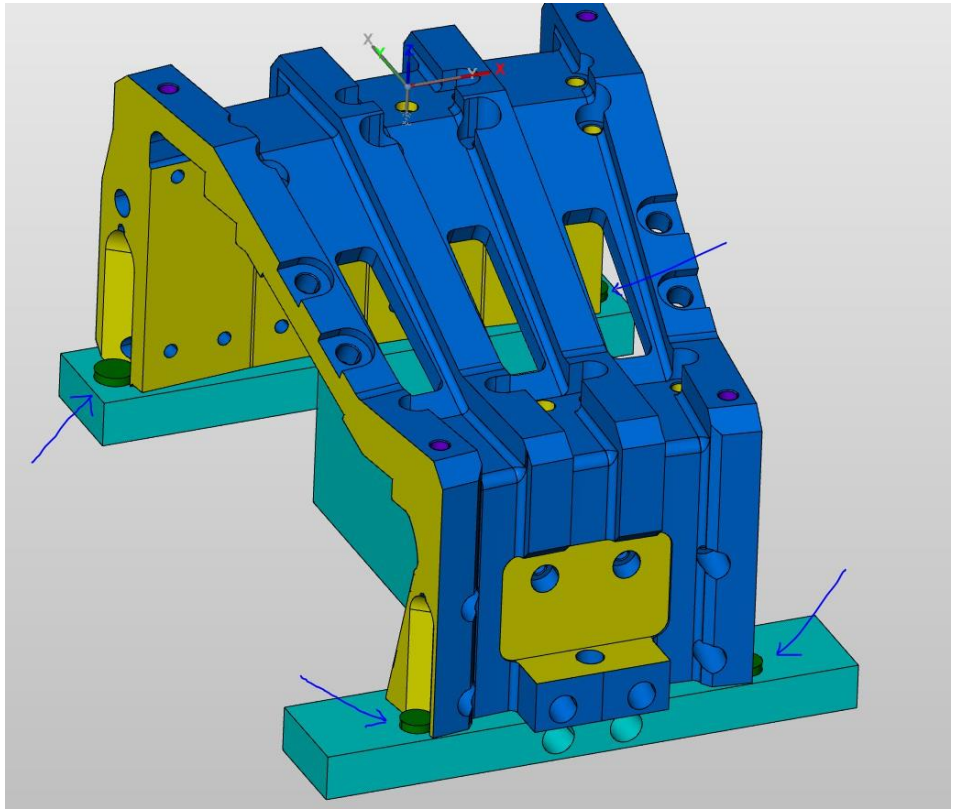
COMPASS-U PFC: MACHINING DIVERTOR CASSETTES

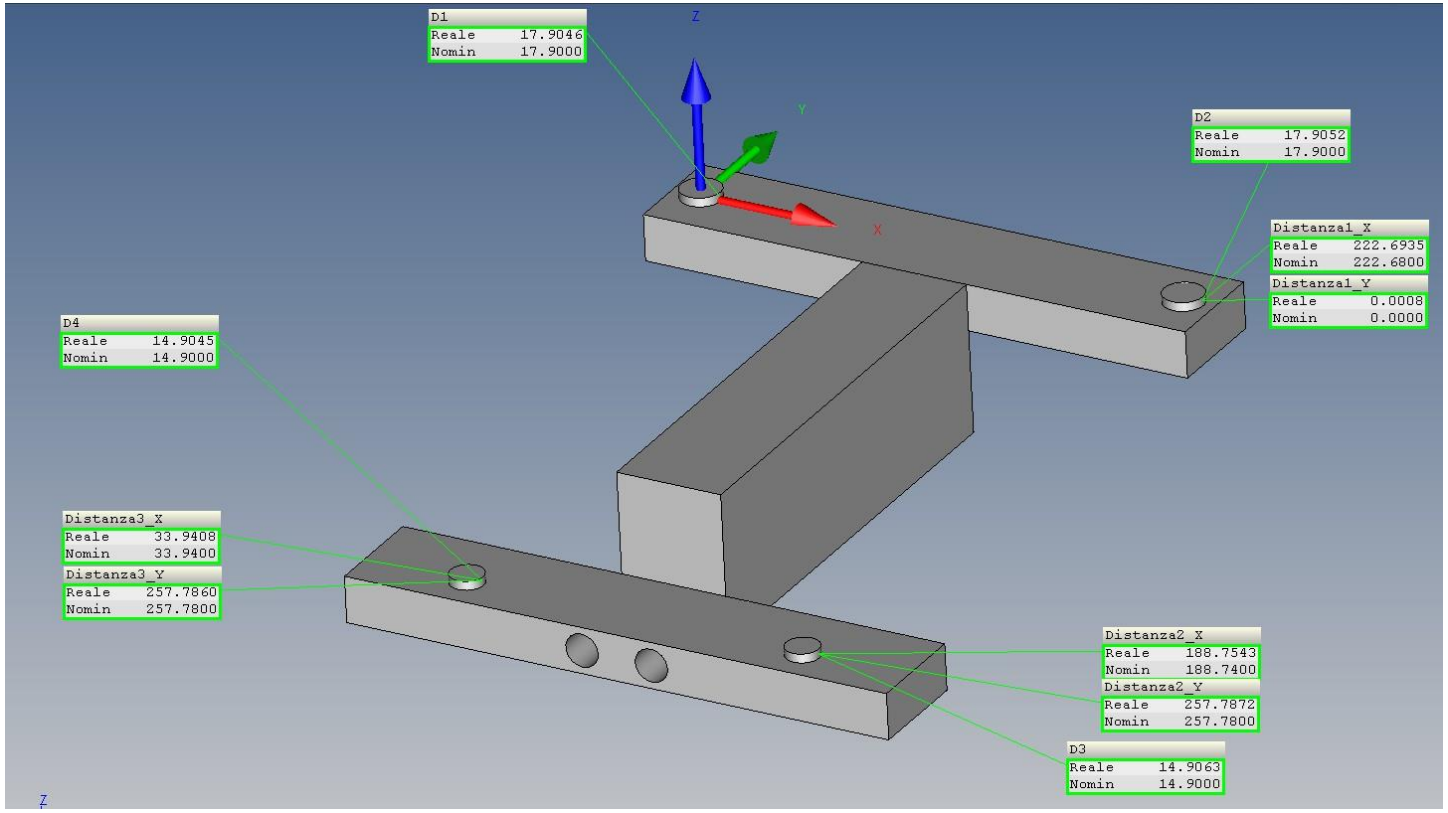
- **Raw cassette** was further **machined** on **5-axis CNC**
  - First, bottom of the cassette was machined + holes (position A).
  - Then the cassette was attached to the final jig (position B) using the elements done during the first machining.
  - All important surfaces were machined in this position.
  - **Position of vertical grooves** for alignment pins is then checked using **GO/NOGO approach** ⇒ if required, the grooves are remachined.



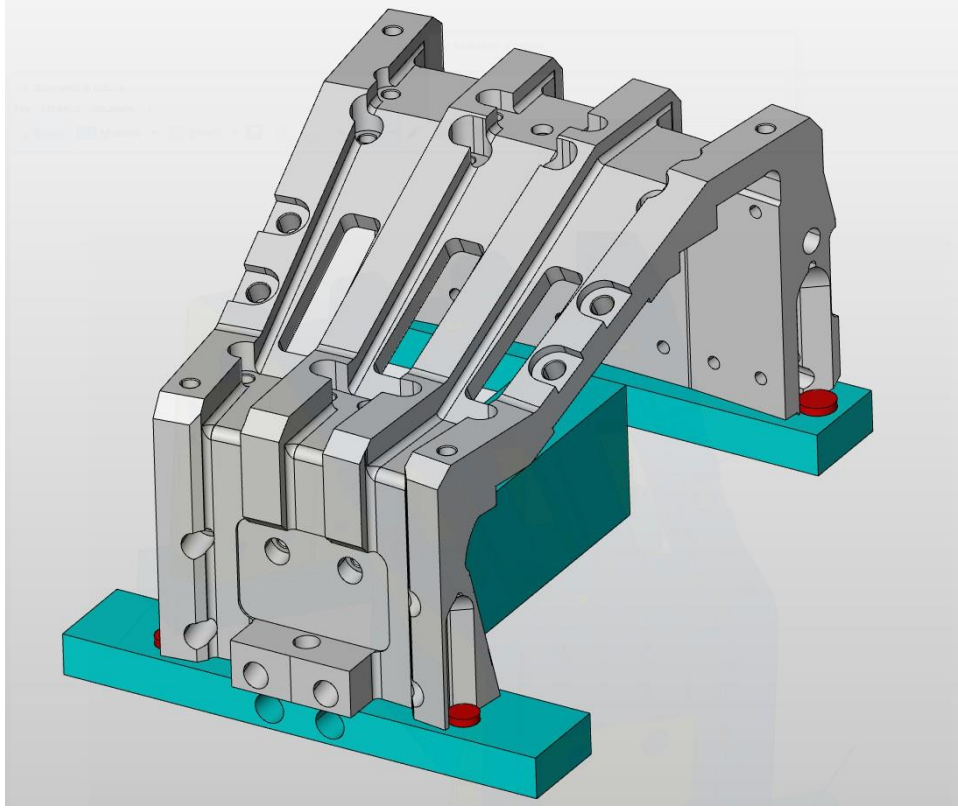


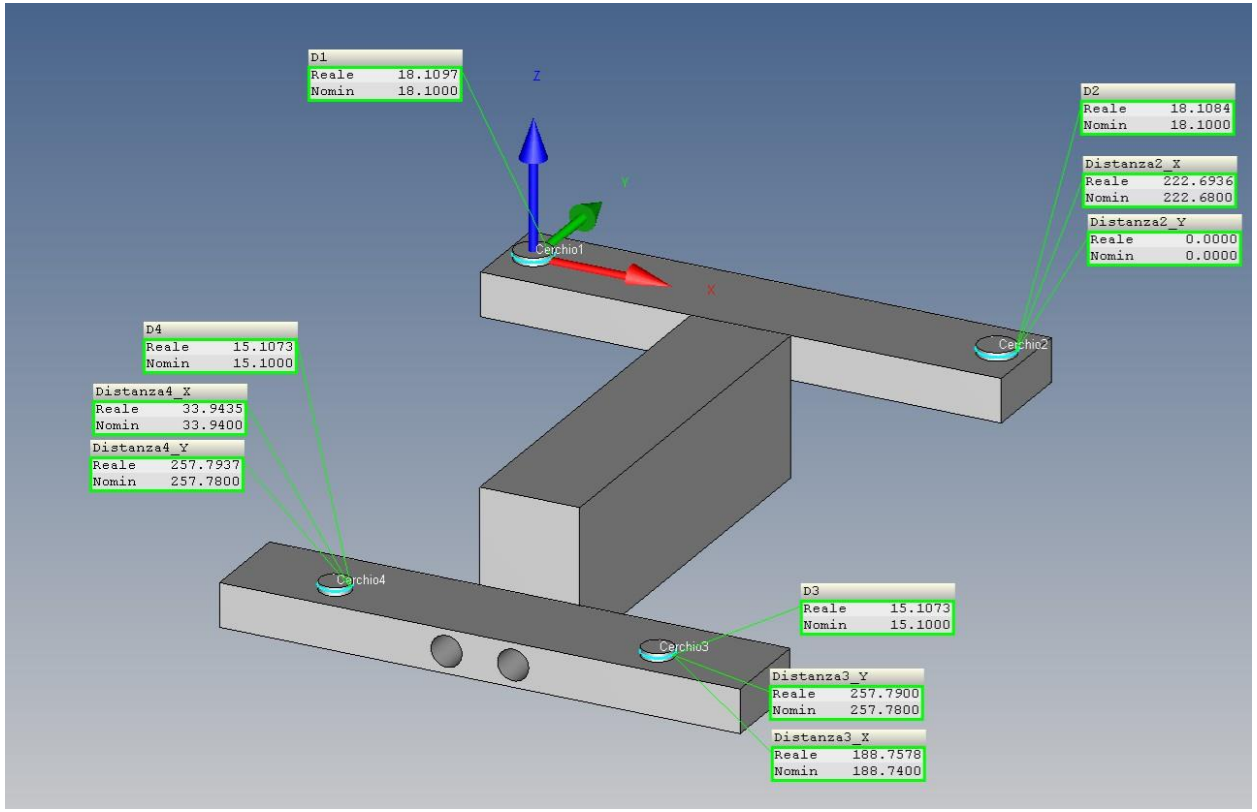
- **GO side**
  - Locating pins as close to the theoretically exact position as doable
  - Pins with **0.1 mm <u>smaller</u>** diameter (14.9/17.9 instead of 15/18)





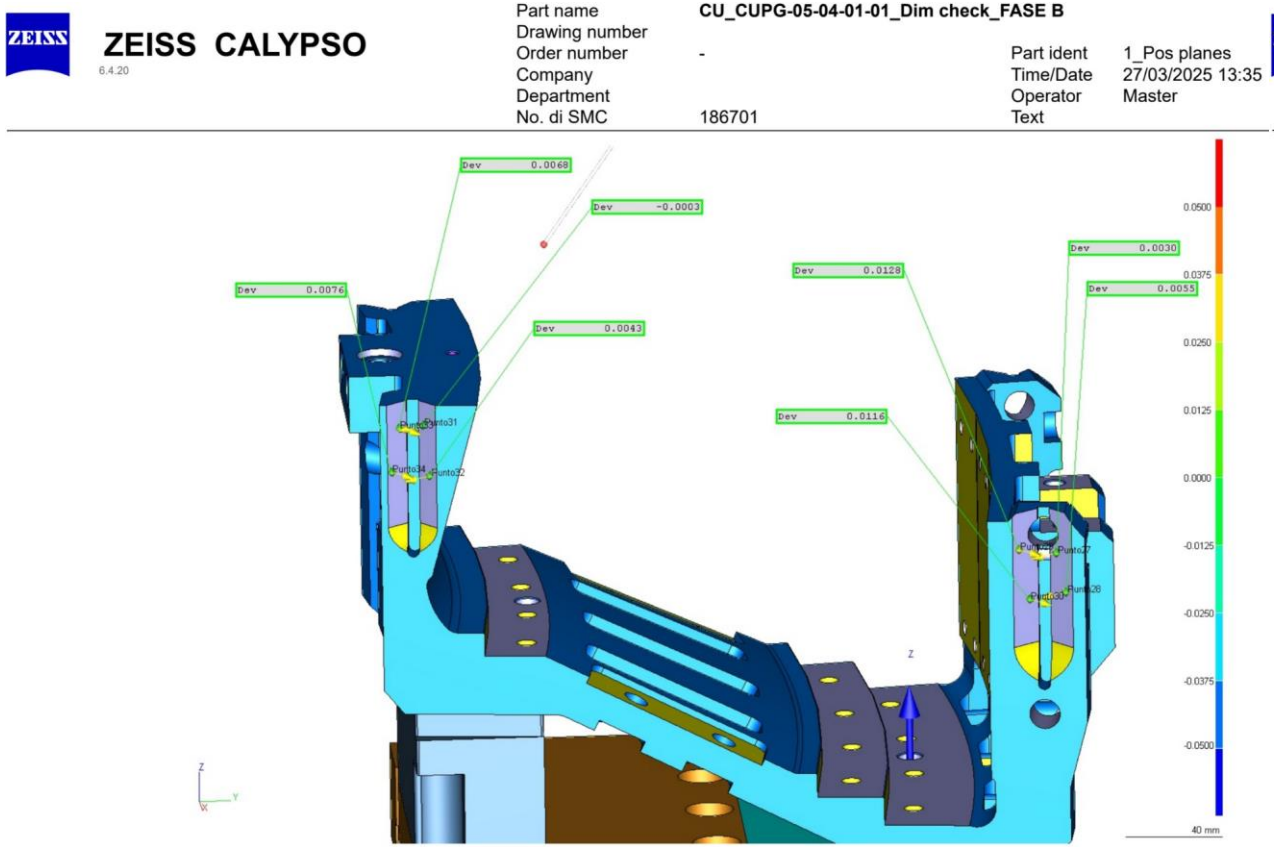
- **NOGO side**
  - Locating pins as close to the theoretically exact position as doable
  - Pins with **0.1 mm larger** diameter (15.1/18.1 instead of 15/18)

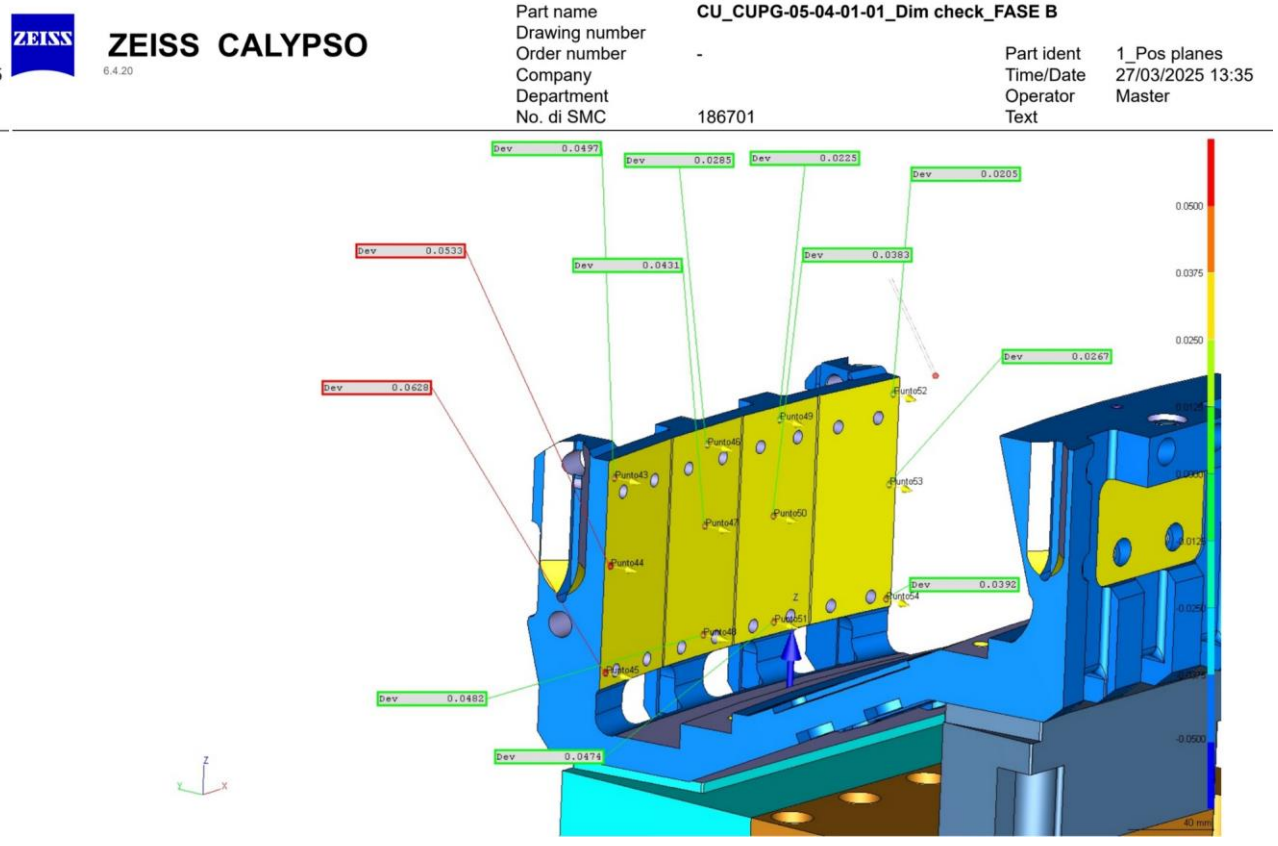




COMPASS-U PFC: MACHINING DIVERTOR CASSETTES

- **Using this approach**, **radial step** in **between 2 neighboring cassettes** should be **smaller than 0.1 mm.**
- **Vertical pins** in between the cassettes will be **individually machined** to achieve the correct full ring diameter.
- **After machining**, **required faces** were **within the required tolerances (BeamIT)**





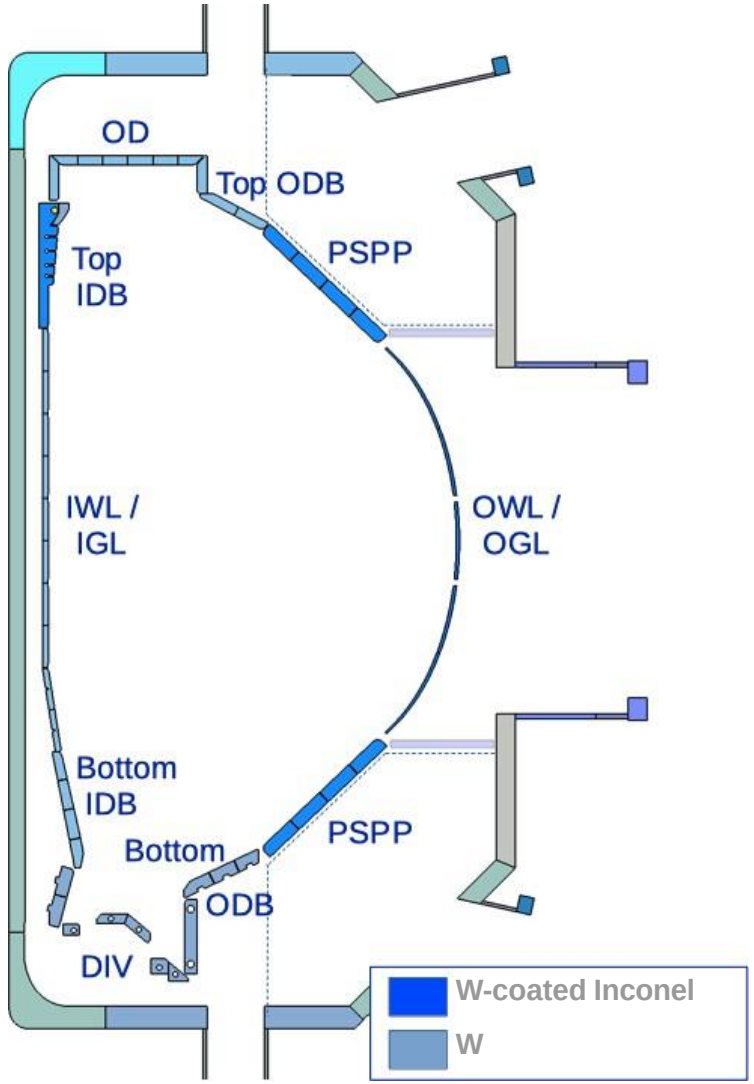
- **Materials qualification programme**



COMPASS-U PFC: GENERAL DESCRIPTION

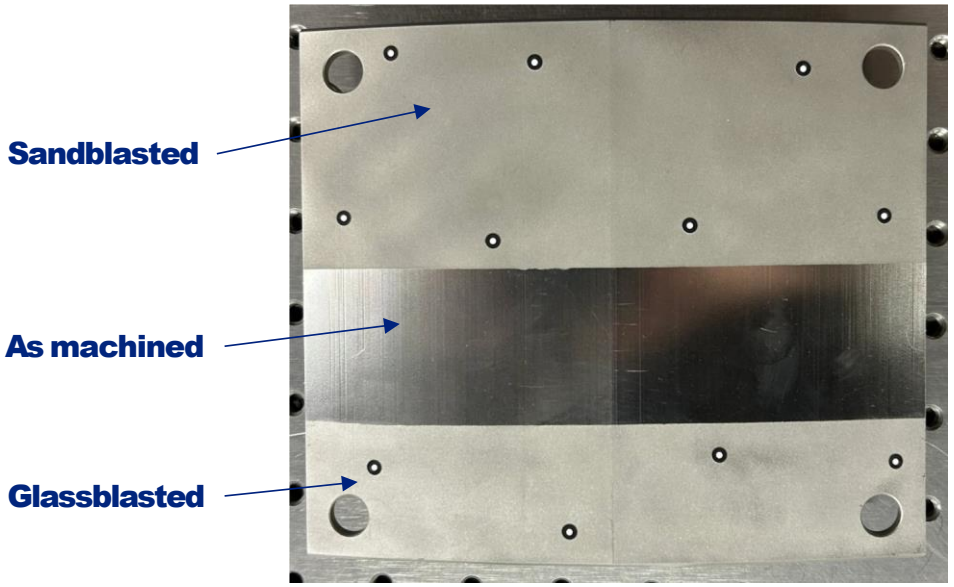
100% tungsten (W) coverage [1]

- **Bulk W for inertially cooled components in HHF regions:**
  - Lower closed (DIV) & upper open (OD) divertors
  - Inner (IGL) & outer (OGL) guard limiters
  - Total PFC area = 50 %
- **Use of Inconel 718 because of operation up to 500°C** *(higher mech. prop.)*
  - Inconel composition = Ni, Cr, Fe
  - Higher sputtering yields & lower sputtering thresholds (20-40 eV) than W
- **Solution = cover all Inconel components with thin W layer (PVD)**
  - Not available on the market, different CTE (x 3.5), hardened Inconel (550 HV)
  - In-house R&D programme to investigate feasibility of W coating on Inconel
- **Development with 3 industrial partners [2]:**
  - NILPRP, Romania *(JET, AUG, WEST, etc., on graphite)*
  - DEPHIS, France *(WEST, on CuCrZr)*
  - Czech Technical University, Prague
- **Successful qualification under HHF tests [3]:**
  - Steady state in GLADIS (MPG)
  - Transients (2-15 $MJ.m^{-2}.s^{-0.5}$) in PSI-2 (FZJ)



[1] R. Dejarnac, et al., FED 211 (2025); [2] J. Matejicek, et al., FED 42 (2025); [3] R. Dejarnac, et al., FED 42 (2025).

- **Machined Inconel tiles are like mirrors**
  - **Problem** for some **diagnostics** (reflections); **Problem** for our **metrology system** *(use of a spray is needed to mitigate reflections)*
  - We tried **sandblasting** and **glassblasting** of one **IWL tile prototype:**



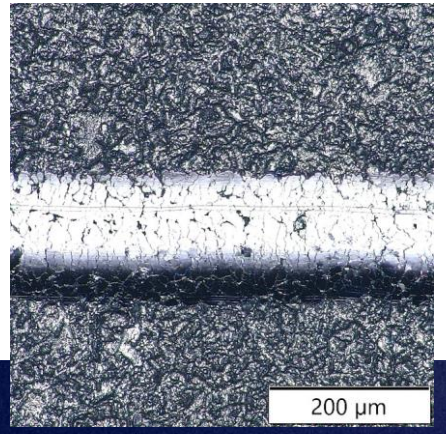
  - **Result is satisfactory** for <u>both blasting methods</u>, **Ra slightly increased** but **below requirement Ra 3.2 µm**, however...
  - **...SEM observations show a lot embedded particles.**
    - Is it a **problem** for **plasma operation?**
    - Is is a problem for **W coating?**

<u>*W coated tile*</u>



  - **W coating** was performed **on this tile**
  - **Reflectivity** is **mitigated**
  - **Adhesion** by scratch tests **is good on all 3 regions (95 N)**

<u>*Scratch test on sandblasted part*</u>



COMPASS-U PFC: BULK W QUALIFICATION

Activities under WP PWIE

- **D001: IPP.CR ⇒** Pre-characterization of **9 different W** materials
- **D002: CIEMAT ⇒** Fast transient heat loads by CW laser at **OLMAT**
- **D003: CU ⇒ Nanocracking detection** on exposed W
- **D004: DIFFER ⇒** HHF tests in **Magnum-PSI** = round robin w/ **HIVE**
- **D005: ENEA ⇒ Post-characterization** (Morphology + D_2 retention)
- **D006: FZJ ⇒** HHF tests in **PSI-2** and **JUDITH 2.**
  - i) Tests in PSI-2: **ELMs-like loading** [6 – 12 MJ.m^{-2}.s$^{0.5}$ (1 ms) x100 – x10,000]
  - ii) Tests (x2) in Judith 2: **(1) OVT-like samples** *(10 cycles)*
    (2) OVT *(100 cycles)* **& IGL tiles prototypes**
- **D007: IPPLM ⇒** Comparative **post-characterization**
- **D008: UKAEA ⇒** i) Round robin tests in **HIVE** (with Magnum-PSI)
  ii) **Tensile tests** at **elevated temperatures**
  [400°C – 500°C – 600°C]

