



30th IAEA Fusion Energy Conference

Recovery of ITER Sector Modules from Critical Issues

Chang Hyun NOH, A. Bonito Oliva, N. Koizumi, and E. Rodilla Hoyo

ITER Organization

15 Oct. 2025



china eu india japan korea russia usa

ITER Sector Module

- ITER Tokamak chamber consists of nine 40-degree sector modules (SM)
- Each SM composed of one 40-degree VV sector, sub-assembly of 40-degree VVTS and two TFCs

Vacuum Vessel (VV) (373 Kelvin, 100°C)

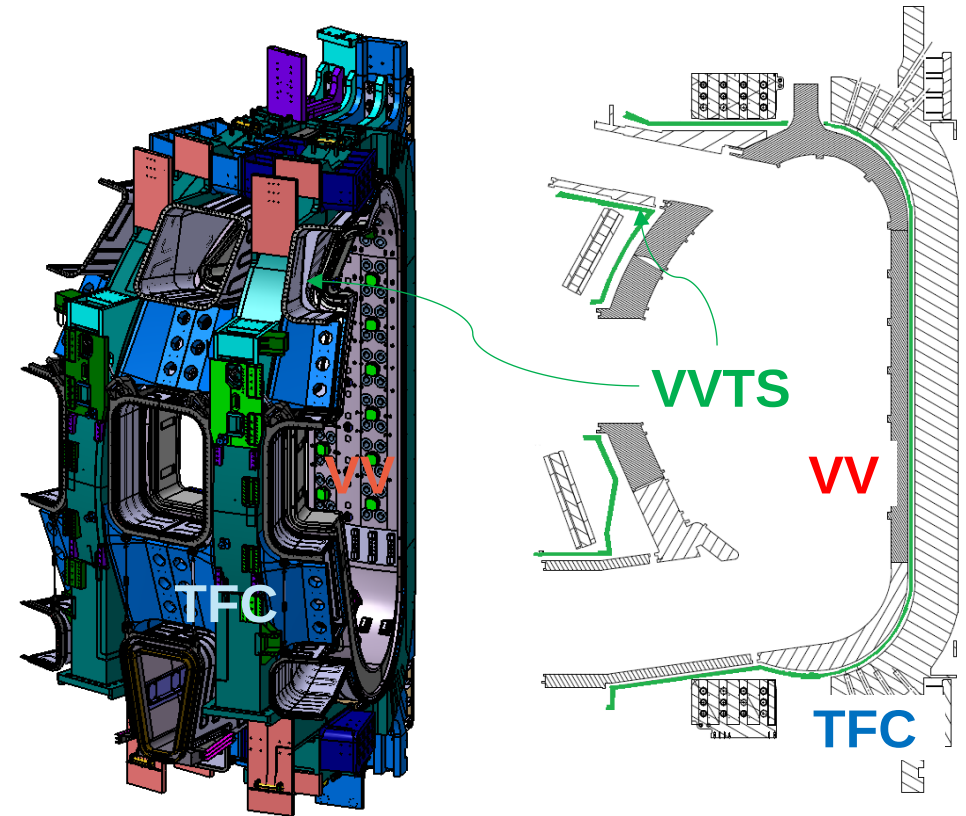
- ✓ Provide **High Vacuum** for Plasma
- ✓ **Support** the In-Vessel Components

Vacuum Vessel Thermal Shield (VVTS) (80 Kelvin, - 196°C)

- ✓ Minimize radiation heat loads from VV to TFCs

Toroidal Field Coils (TFC) (4 Kelvin, - 269°C)

- ✓ Confine the plasma particles



Introduction of Critical issues discovered in 2022 and its Recovery

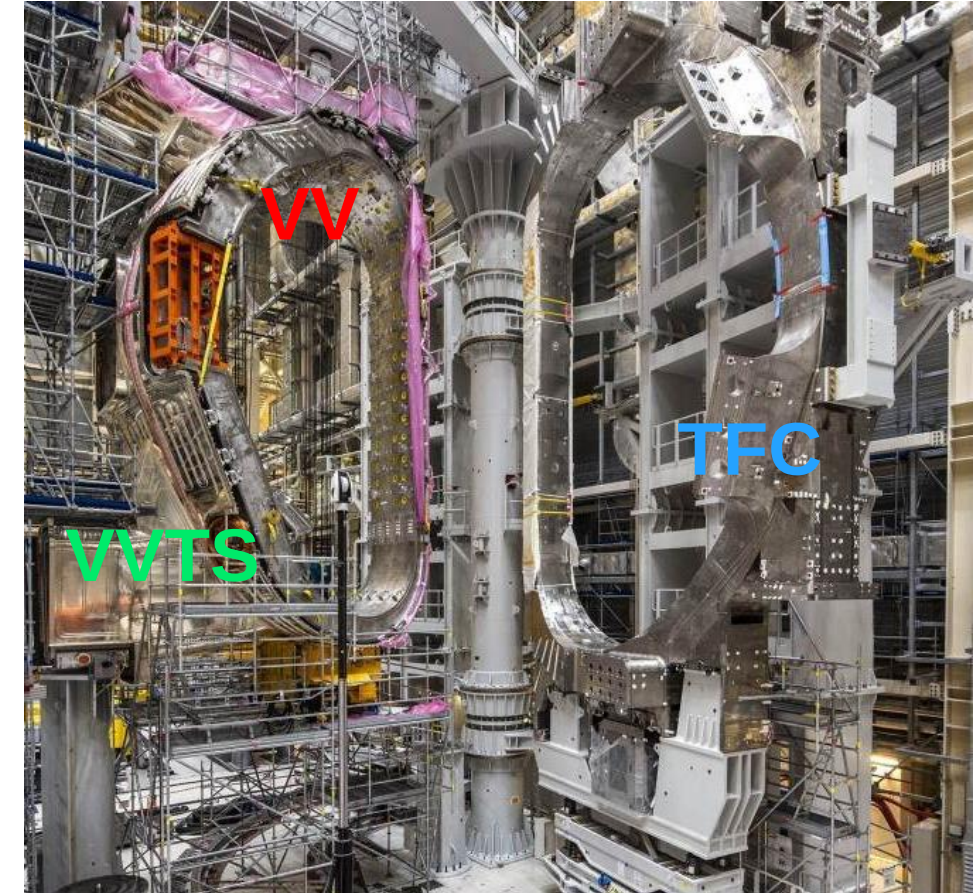
Vacuum Vessel Thermal Shield (VVTS)

- ✓ During the site acceptance test of TS components, leakage was detected on the VVTS equatorial port shroud
- ✓ Root cause analysis: intergranular crack on cooling pipe caused by stress corrosion cracking (SCC)
- ✓ Remedial action: Replacement of cooling pipes with new ones

Vacuum Vessel (VV)

- ✓ Significant geometrical deviation were detected at the bevel joint for VV sector welding
- ✓ Root cause analysis : welding bevel machined at segment level of VV and welding shrinkage was not compensated during segments welding.
- ✓ Remedial action : repair by build-up welding and machining

This presentation describes the critical issues identified in both the VVTS and VV, recovery strategy, the repair process and lesson learned.

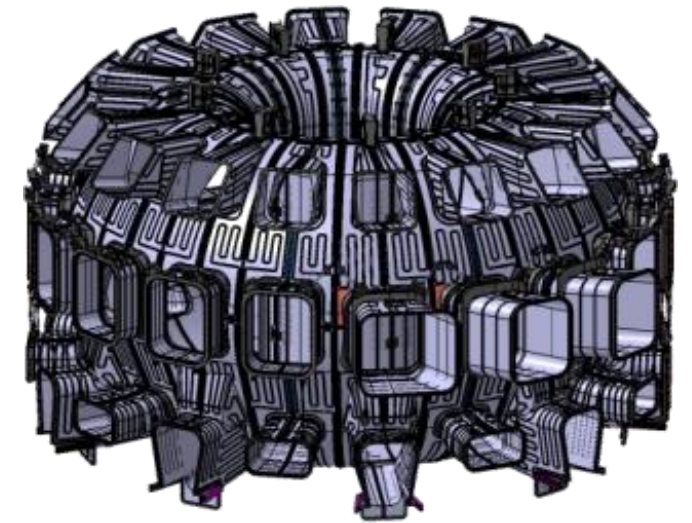
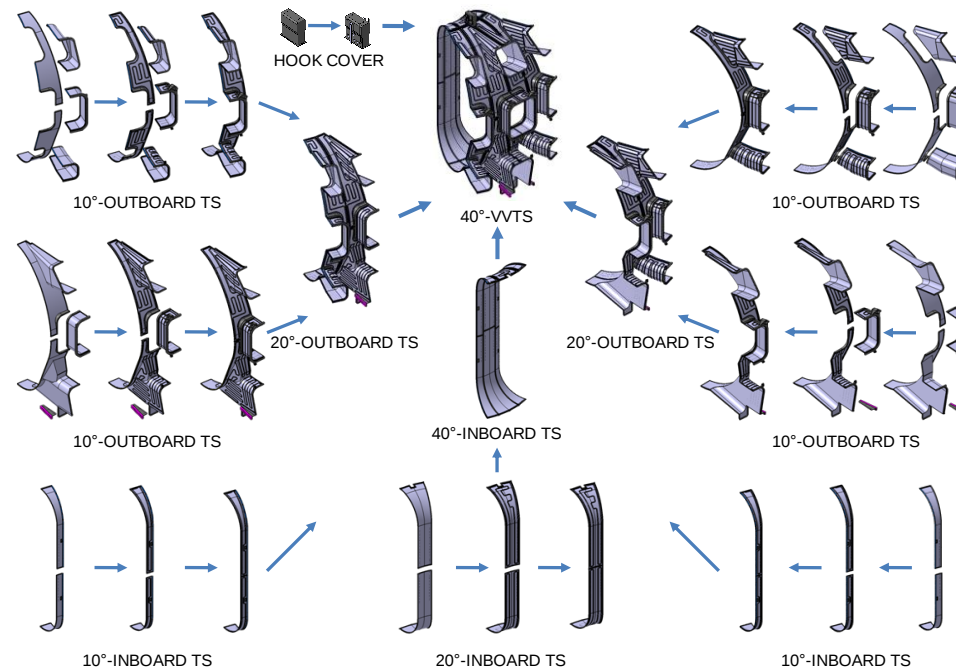
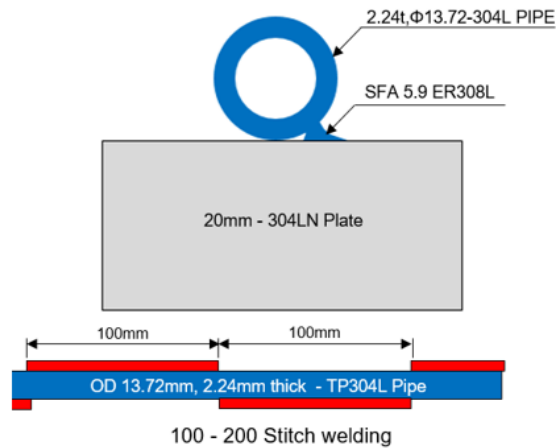


Sector Module Assembly on the ITER SSAT
(Sector Sub-Assembly Tool)

Vacuum Vessel Thermal Shield

VVTS

- ✓ Composed of approximately 200 panels and each panels are assembled together by bolting.
- ✓ Cooling circuit (DN80, stainless steel pipes, 80K 1.8 gaseous helium flow) attached on the panel by stitch welding.



Full VVTS

VVTS 40 deg. sector and its fabrication flow

Vacuum Vessel Thermal Shield

Issue

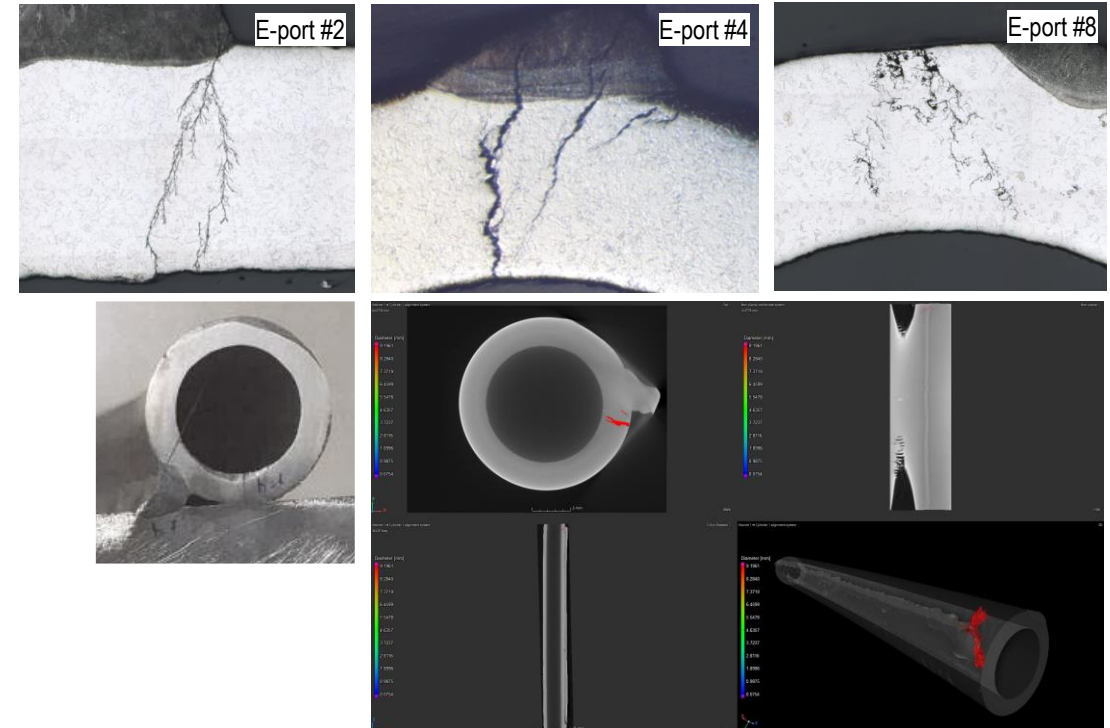
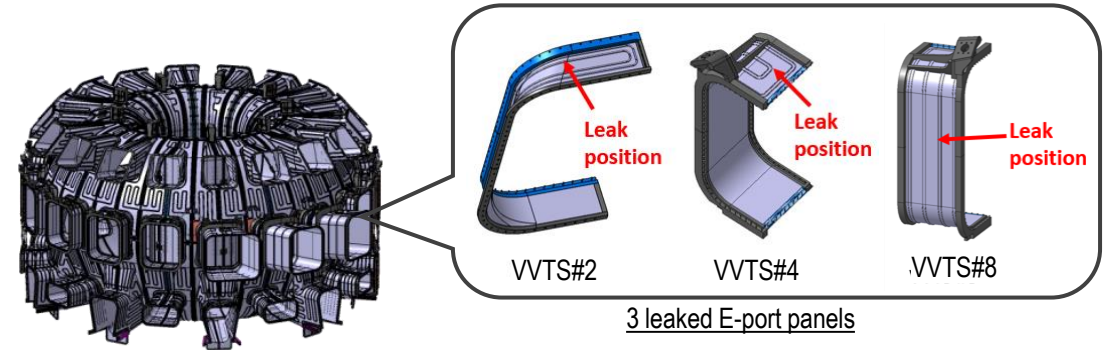
- ✓ Leak detected on the three EQ shroud panels during site acceptance test
- Total number of TS panels : VVTS 200 pcs, CTS 320 pcs

SCC on pipes

- ✓ Intergranular crack observed by metallographic examination
- ✓ High contents of chloride detected on the pipe surface (chemicals from **Ag coating*** process became trapped underneath of the pipe weld)
- ✓ Residual stress due to pipe bending and pipe welding

*Ag coating on the TS surface

- ✓ To achieve good thermal radiation emissivity : less than 0.05 of emissivity of silver coated surface
- ✓ HCl was used for activation process and nickel strike process during Ag coating which are mandatory process for the Ag coating on stainless surface



Thermal Shield : Recovery

Repair strategy

Repair vs re-manufacturing

✓ Soundness of pipe and panel

A detailed study was carried out on samples from several different panels stored under various conditions such as drying duration after Ag coating, storage duration etc.

Cooling pipe : SCC propagation was observed in most of the examined samples.

→ Replacement of pipes in all thermal shield panels

Panel : SCC propagation was detected only in the leaking panel.

Luminescent PT and Metallographic test on the panel-to-panel weld joint (considered susceptible to SCC) : no crack observed.

→ Remanufacturing of EQ shroud and repair of other panels.

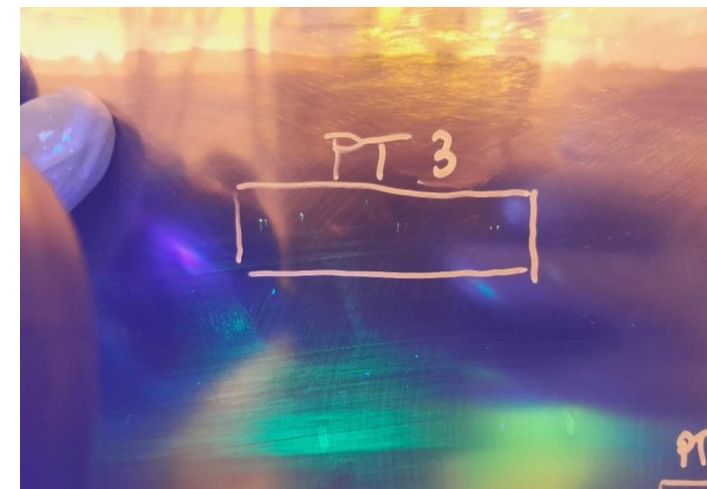
✓ Risk of panel deformation

Re-welding of pipes can cause welding deformation, and VVTS required tight tolerance in manufacturing due to its confined position between VV and TFC.

→ Re-manufacturing two sectors in parallel with repair.

(new manufacturing requires one year or more due to material procurement & panel forming)

→ During repair, rigid welding jig/correction was applied. and deformation was estimated through mock-up testing and FE analysis



Luminescent PT

Thermal Shield : Recovery

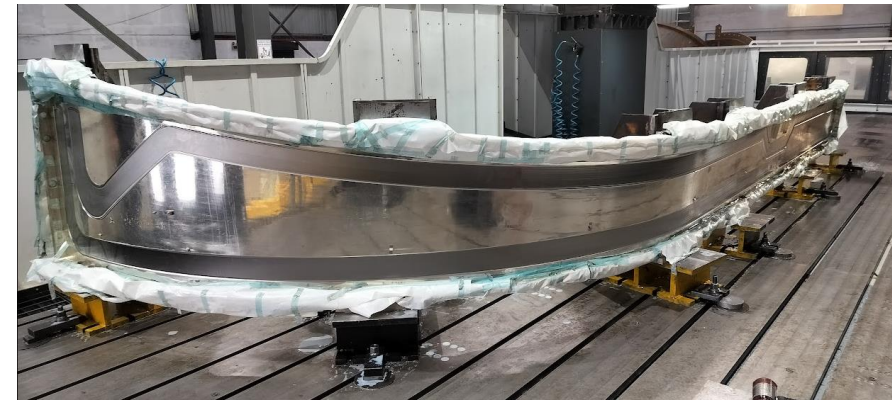
Repair strategy

Repair to eliminate risk of SCC

- ✓ Presence of chloride and SCC crack
 - Systematic visual inspection to find relatively clean panel and FPT were conducted to confirm the absence of SCC on the panel
 - Particularly targeted the pipe welded area and welding joint between panels (high initial stress region)
- ✓ Grinding can't guarantee perfect removal of chloride
 - Panel 2 mm thick layer in the vicinity of the pipes
- ✓ Potential risk of SCC caused by residual chloride and corrosion during sea transportation and long-term storage
 - Use of 316L grade pipe and ER317L Mn Mod filler
 - Low carbon and high molybdenum content, provides enhanced resistance to pitting, crevice corrosion, and stress corrosion cracking



Systematic visual inspection & FPT



Panel 2 mm thick layer removal by machining

Thermal Shield : Recovery

Repair strategy

New Problem in VVTS during repair and its recovery

- ✓ Numerous corrosion spots were observed in two VVTS panels that had been shipped to the supplier for repair.
- ✓ Upon investigation, TS panel working group confirmed that galvanic corrosion happened due to
 - presence of Chloride under Ag coating,
 - defects of Ag coating (pin-hole, scratch, etc.) resulting from thin Ag coating (3mm thickness instead of 5-10mm), and
 - high humidity during shipping and/or by opening package at Indian custom at port.

→ Ag coating removal and surface buffing with $R_a < 0.1 \mu\text{m}$

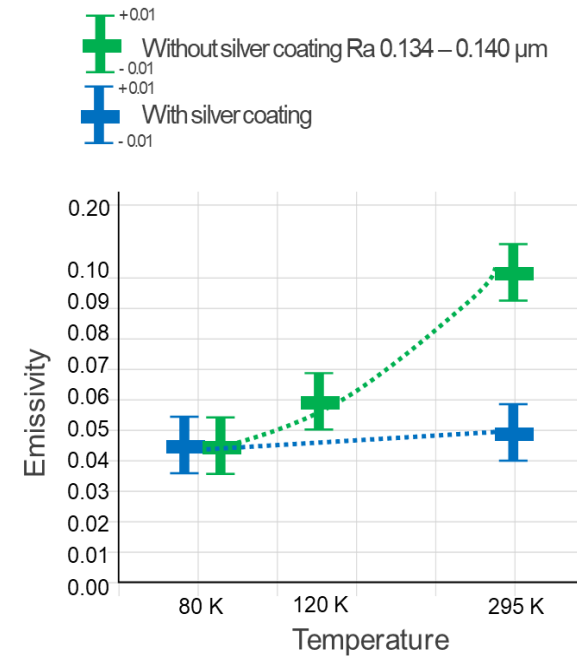
Polished stainless steel with a surface roughness of less than $0.2 \mu\text{m}$ can exhibit emissivity comparable to that of a previously silver-coated surface



Galvanic corrosion in two panels



Panel polishing with $R_a < 0.1 \mu\text{m}$



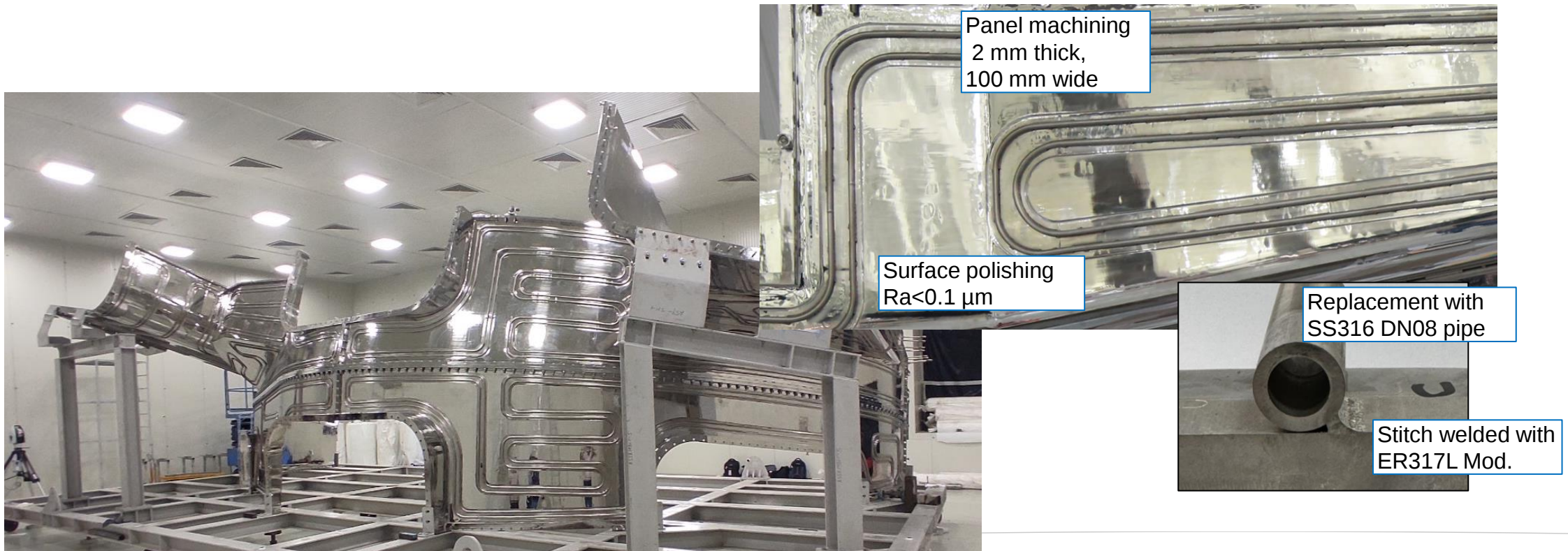
Emissivity test result

Thermal Shield : Recovery

Repair strategy

Completion of Repair

- The success of repair was confirmed geometrically by the pre-assembly test and survey.
- Thermal shield repair approach shortened the time of recovery from the critical issue of thermal shield as mentioned previously.

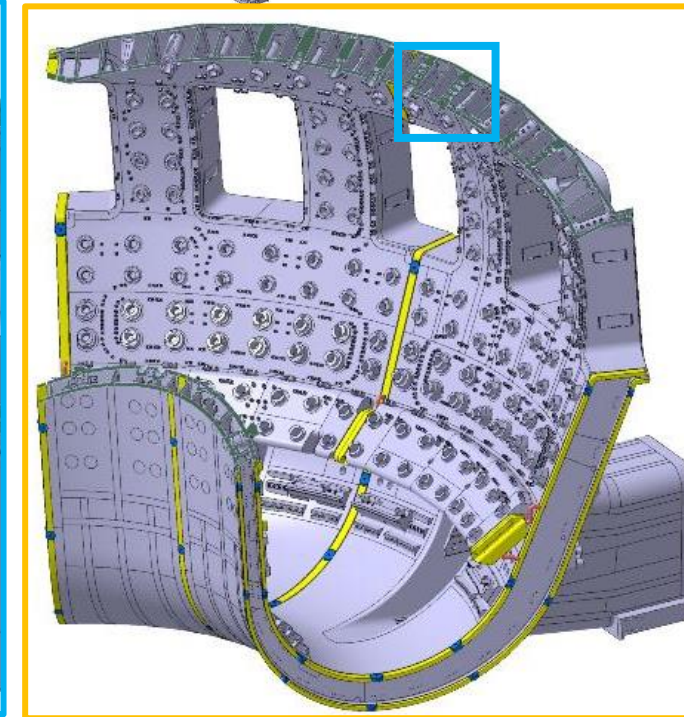
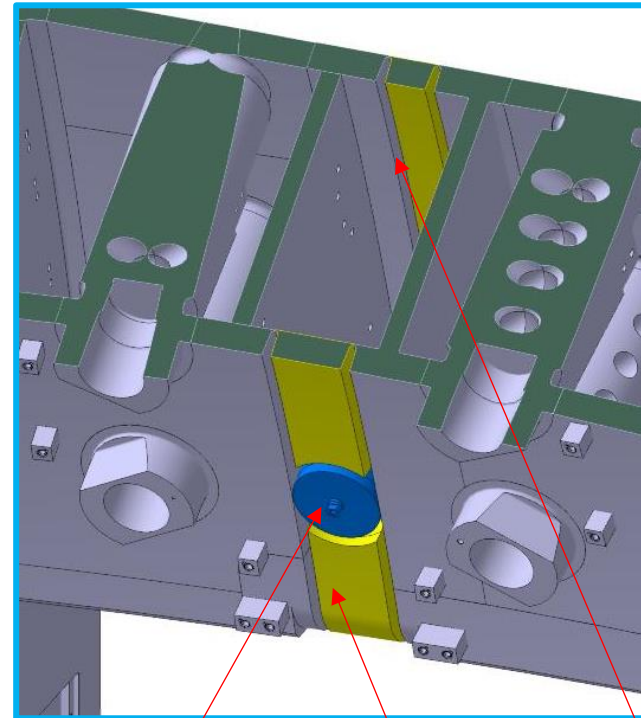
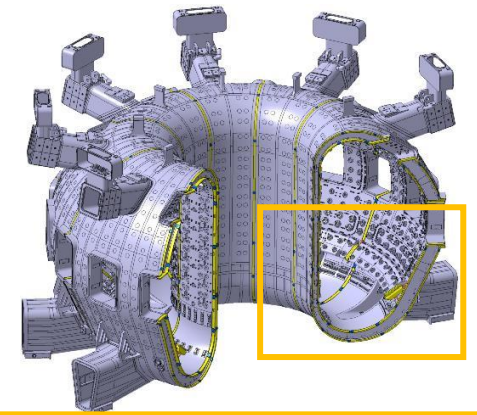


VVTS Outboard right-hand segment repair completion and key element of repair

Vacuum Vessel Sector welding

Vacuum Vessel Sector Field Joint Assembly Welding:

- ✓ Welding of the **9 Vacuum Vessels**
- ✓ Austenitic Steel 316L(N)-IG, **60 [mm] thick**
- ✓ Total **welding length** ≈ 1 [km]
- ✓ Total **welding mass** ≈ 10 [t]
- ✓ **Splice Plate** (SP) are to accommodate manufacturing and assembly tolerances with widths around 100 [mm] and 160 [mm] for outer shell and inner shell respectively (customization for each assembly)
- ✓ **Biscuits** are intermediate circular plated whose function is to access to the backside of splice plates (let the root access, avoid cross welding & allow NDE)

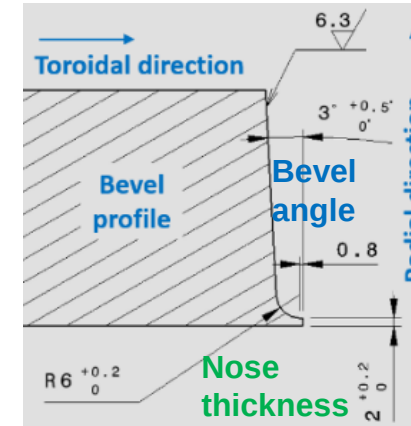


Biscuit Inner Shell Field Joint / Splice plate Outer Shell Field Joint / Splice plate

Issue on Vacuum Vessel

Issue

- ✓ Deformations on the VV Sector field joint bevels during sector manufacturing not compatible with the VV Sector welding requirements.



VV Field Joints bevel tolerances accuracy (especially for automatic system)

Geometrical deviation on VV welding bevel due to

- ✓ Toroidal welding shrinkage from manufacturing process* in consequence, radial/toroidal waviness, slope in bevel profile

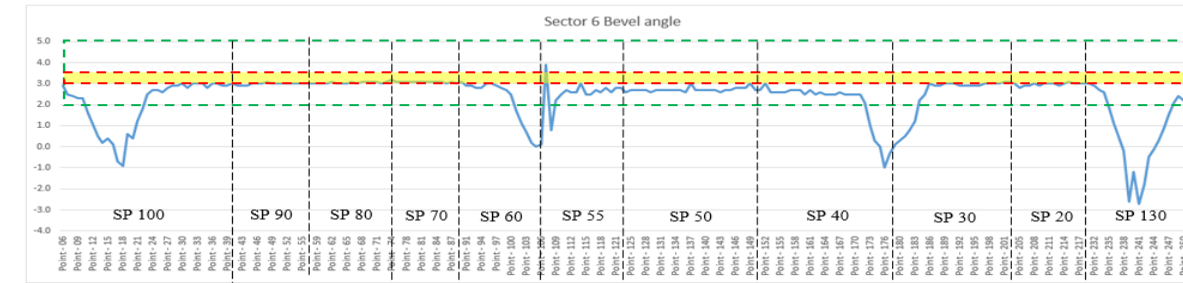
*Manufacturing process VV sector

- ✓ Final machining at Segment level
- ✓ Segment installed on Assembly Jig and Welded together
- ✓ Welding shrinkage not compensated.

Bevel angle

Acceptable range (IO)

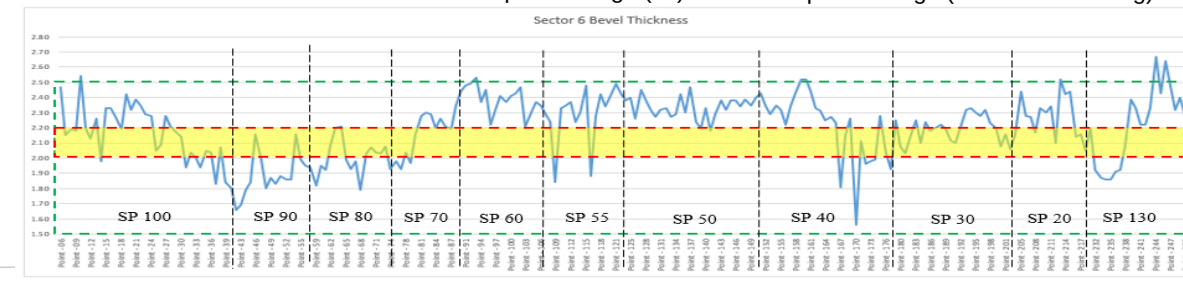
Acceptable range (automatic welding)



Nose thickness

Acceptable range (IO)

Acceptable range (automatic welding)

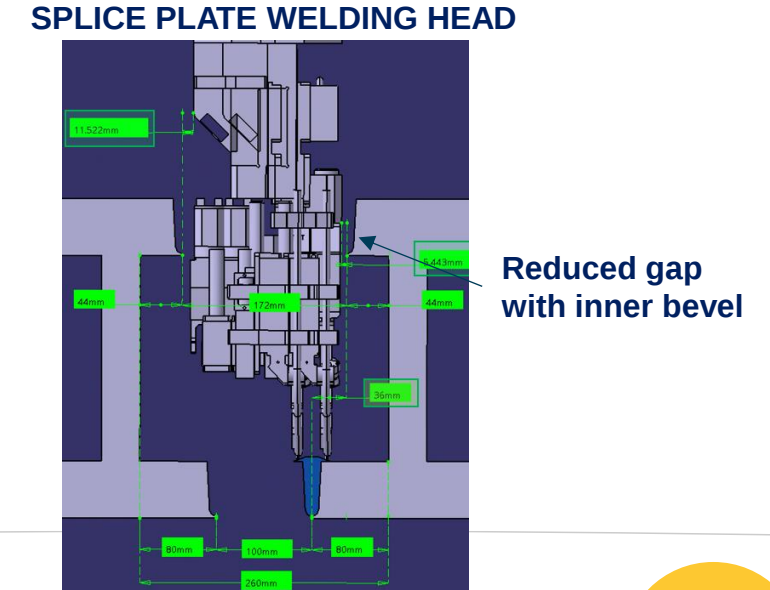
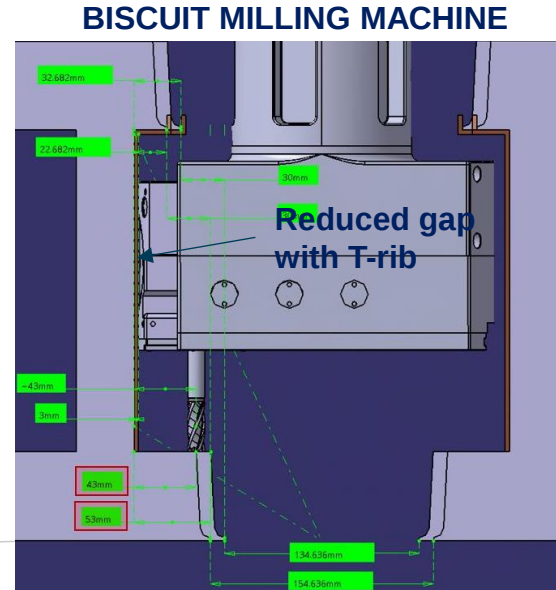
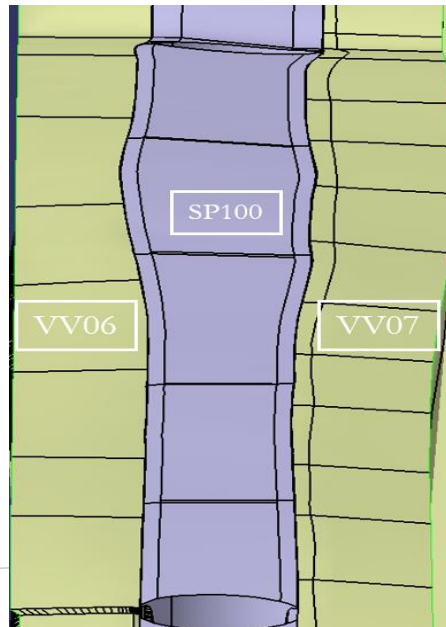
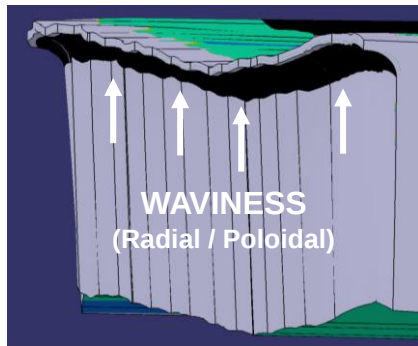


Issue on Vacuum Vessel

Consequences of bevel dimensional deviations

- ✓ Difficulties in adapting the welding machine to trajectory changes
- ✓ Difficulties in splice plate customization and alignment
- ✓ Potential variability in welding parameters depending on position: Irregular bevel profile due to deviations in nose thickness
- ✓ Potential clashes with welding machining and NDE tooling

→ To Repair VV Sector bevel as built dimensions to meet the dimensional requirements for field joint welding and Non-Destructive examination.

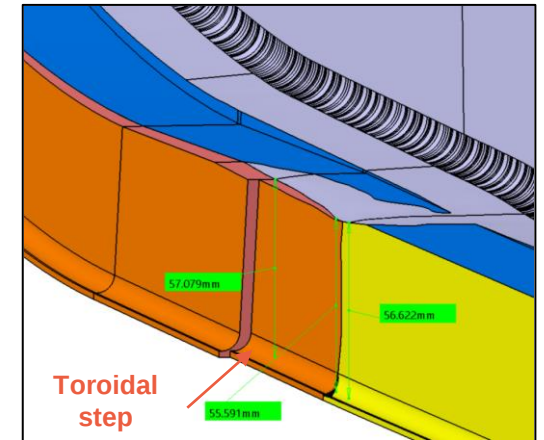
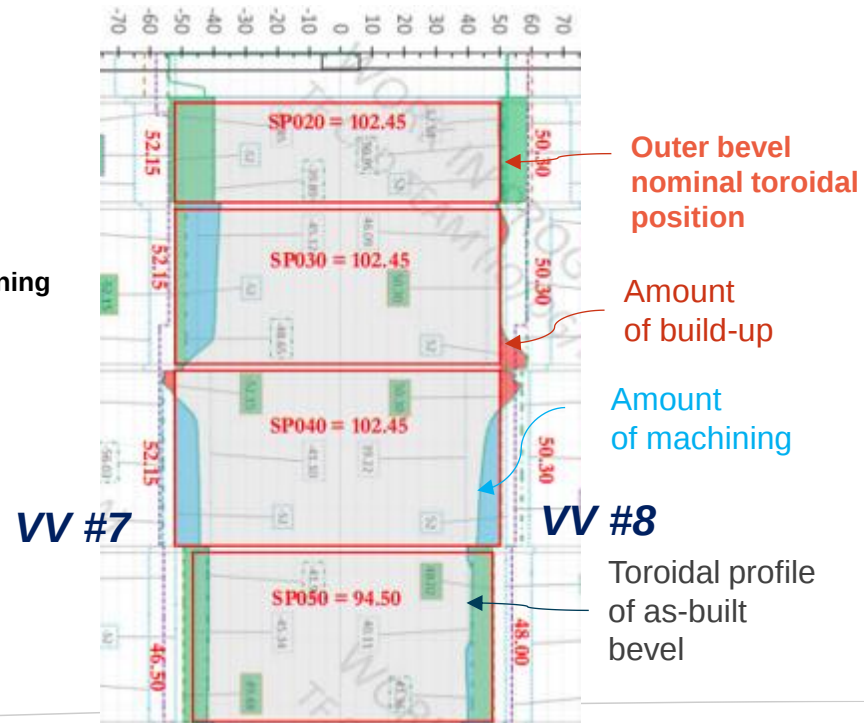
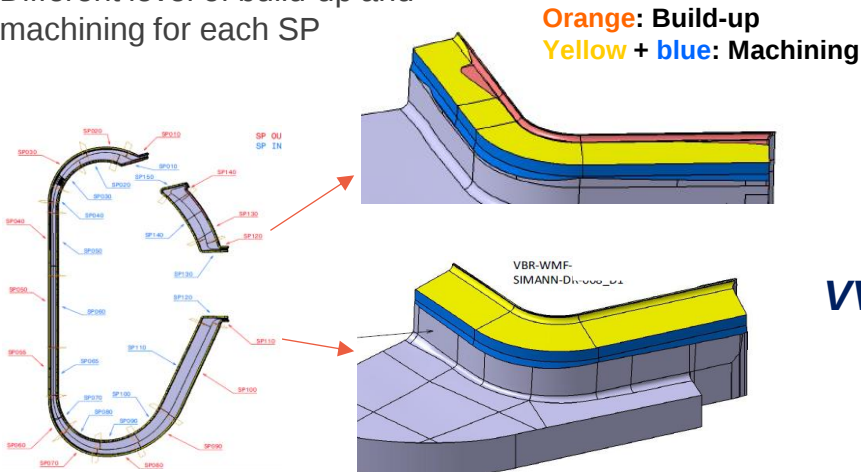


Recovery of VV : Repair Strategy

Optimized combination of build-up and machining: Less build-up than machining

- ✓ Build-up: to recover material in toroidal dir. (mostly outer bevel)
- ✓ Machining: to remove excess of material in toroidal dir. (mostly inner shell) and to get final bevel shape
- ✓ Customized solution for each Splice Plate adapted to each field joint.
- ✓ Development of metrology process for identification, monitoring and validation of areas to be repaired

Different level of build-up and machining for each SP



Different toroidal position for bevel nose for each SP

Example (FJ #15, S7-S8):

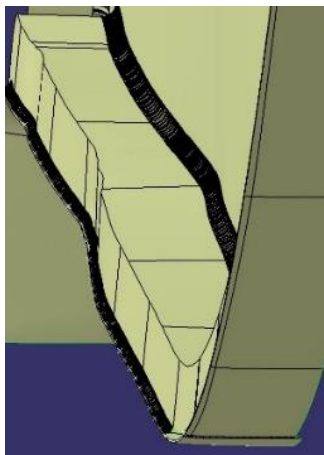
30th IAEA FEC Oct. 13-18 2025
Recovery of ITER Sector Modules from Critical Issues
Chang Hyun NOH

Recovery of VV : Repair Strategy

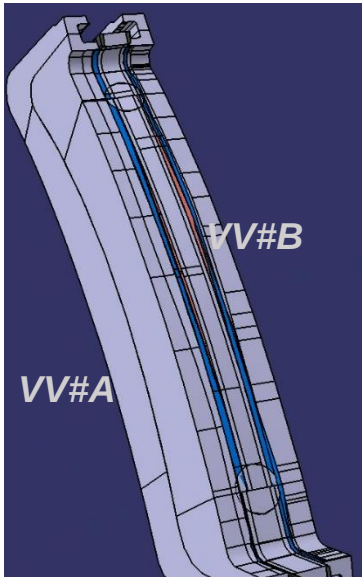
Bevel repair : from as-built deviation to repaired bevel



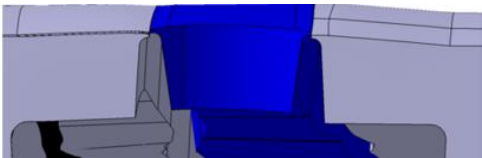
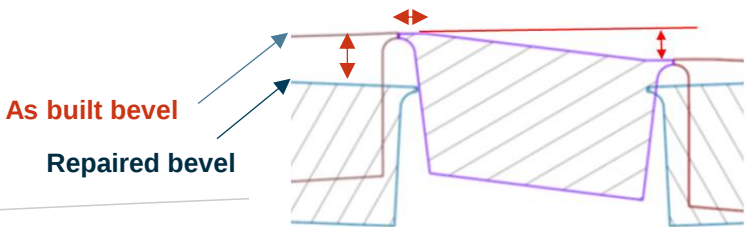
Accurate scanning of as-built bevel



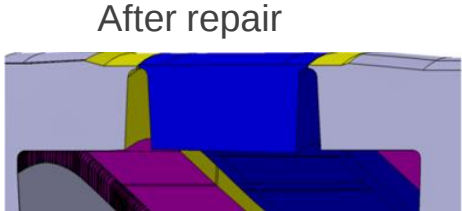
Re-Construction of as-built bevel 3D model



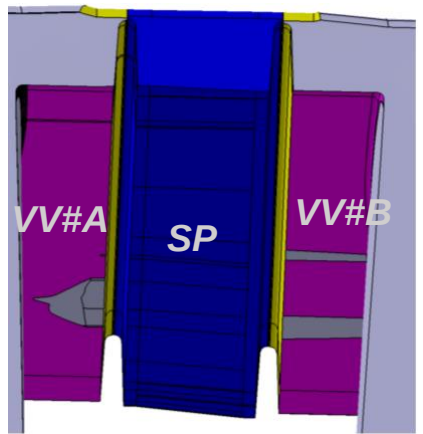
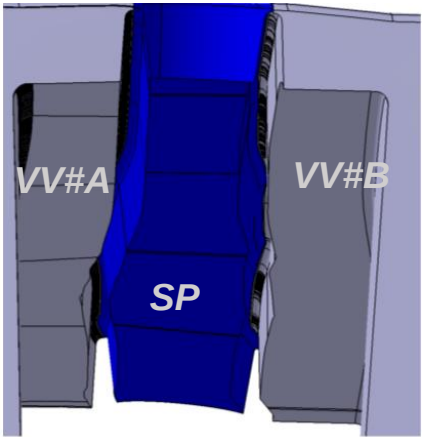
Construction of 3D model for repair : build-up and machining



Before repair



After repair



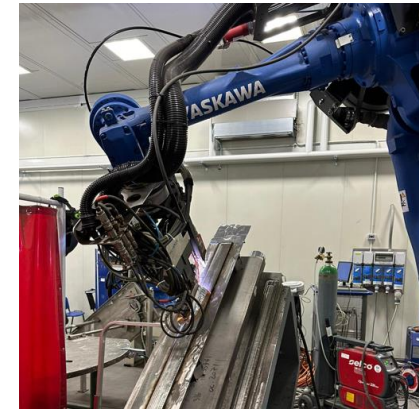
Recovery of VV : Repair Strategy

Challenge and Resolution by qualification program

- ✓ Feasibility of build-up in different welding positions / Need of significant level of build-up / Demonstration of mechanical properties of build-up / Dedicated UT qualification of the build-up area / Metrology validation of achieved tolerance
 - Demonstrated with specific qualification through dedicated representative build-up welding coupons in different positions for both manual tig and mechanized tig. NDE and Mechanical test of build-up coupon. All process followed in accordance with RCC-MR code.
- ✓ To limit the distortions induced by the deposited weld build-up material:
 - An “Optimized” repair solution combining local build-up (minimization) and machining of bevels.
- ✓ Machining process
 - Portable milling machines were proposed having customized design to adapt the shape of the VV Sector and demonstrated for the feasibility of machining within required tolerances with dedicated mock-up
- ✓ Assessment of Schedule, logistics and peripheral potential impacts



Manual tig representative coupon



Mechanized tig representative coupon

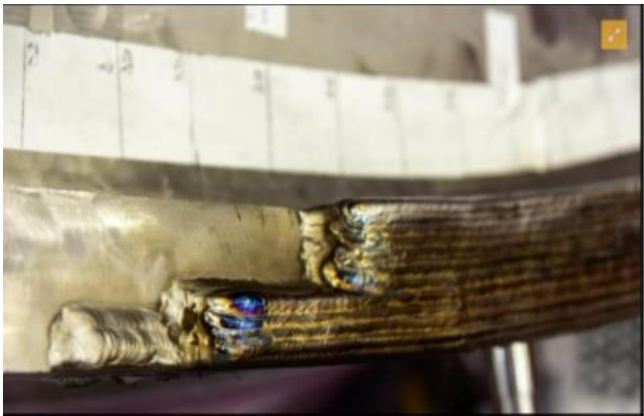
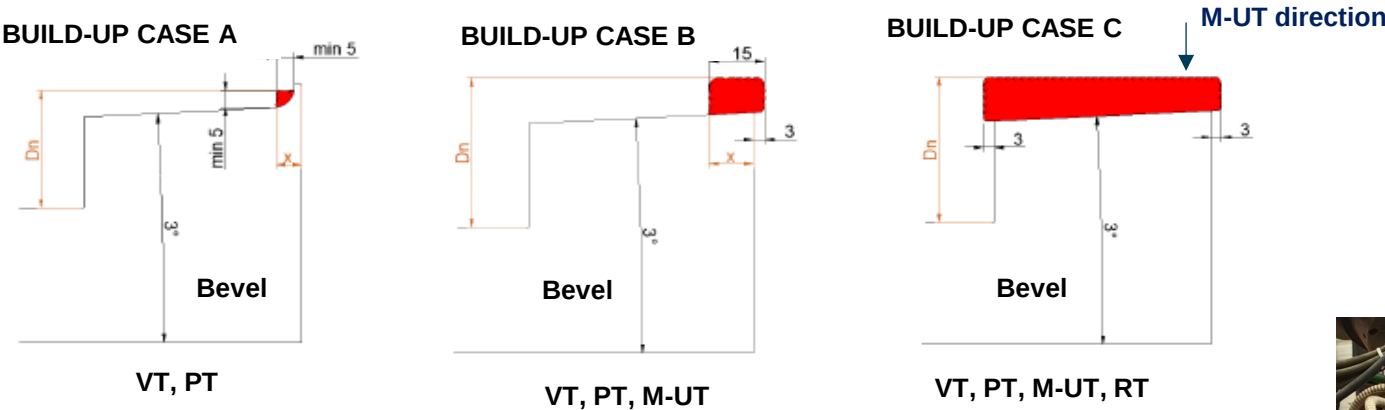


Machining and Metrology qualification mock-up

Recovery of VV : Repair Strategy

Repair process

✓ **Build-up and NDE** : three different cases depending on the level of material to be recovered



Manual build-up



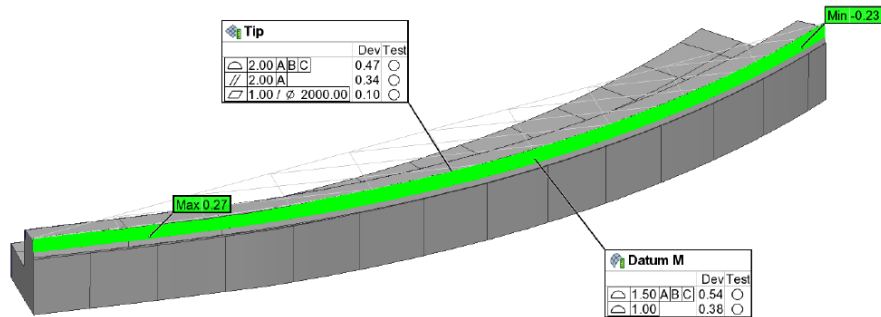
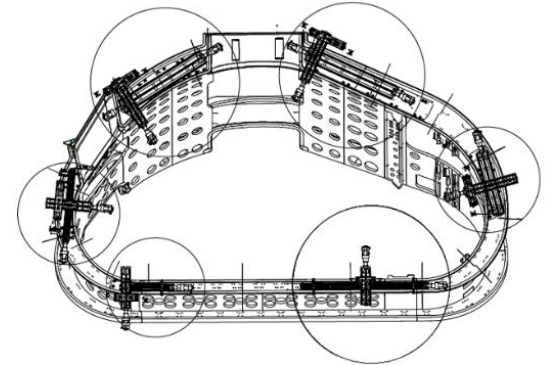
Mechanized build-up

Recovery of VV : Repair Strategy

Repair process

✓ Bevel machining and Metrology

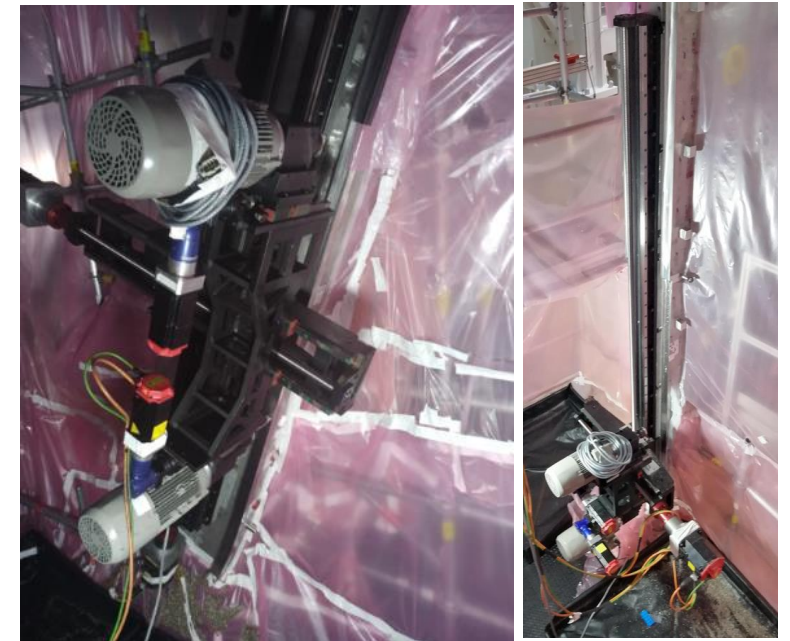
- Portable milling machine fixation by bolting to the Sector T-rib
- Different set up and 5 machine configurations to adapt to different position of splice plate.
- Machines alignment to the Sector bevels by temporary metrology network
- Final machined bevel inspection by VT, PT.
- 3D scanning after final bevel machining to validate of achieved tolerances.



Scanning



Machined bevel



Portable milling machine bolted to the T-rib

Recovery of VV : Repair Strategy

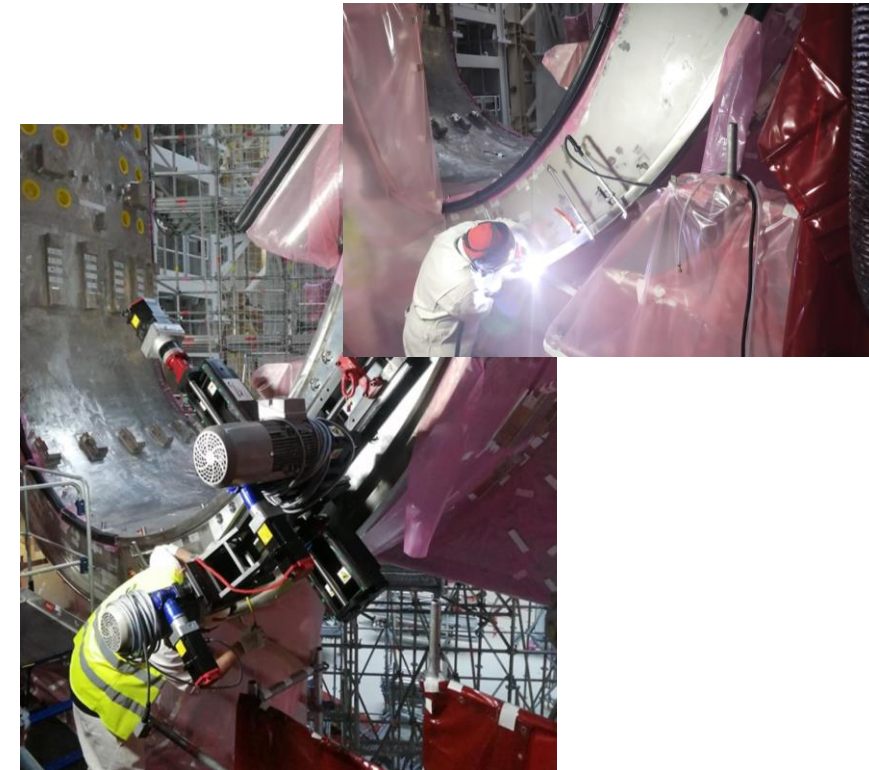
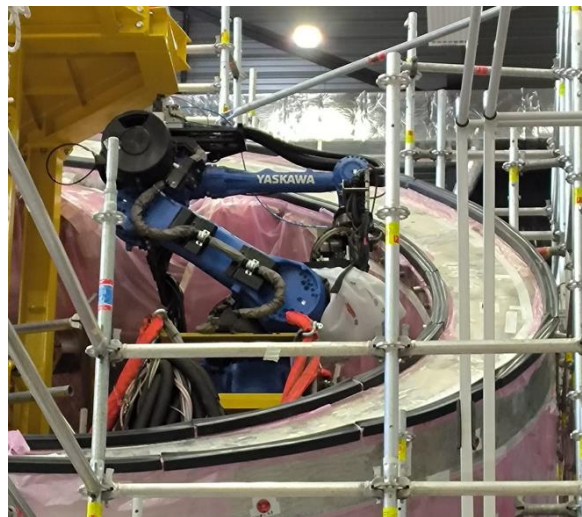
Repair process

✓ Sector configuration during repair

- Sector 6 and Sector 7 were repaired in vertical (SSAT)
- Sector 8 and Sector 1 were repaired in horizontal. Welding robots for mechanized tig are supported by a dedicated platform installed at the inside of the Sector



Sector repair in horizontal position



Local build up / machining in vertical position on the SSAT

Achievement and Lesson Learned

Achievement

- ✓ Five VVTS and Four VV sectors have been successfully repaired by mid of 2025.
- ✓ Sector Module #6 and #7 have been assembled in their respective SSAT and transferred to pit.
- ✓ After approximately three years, the recovery from the critical problem has been successfully accomplished, preventing further delays by removing technical risk in the ITER project.

Lesson Learned

VVTS

- ✓ Silver coating on the pipe stitch welding should be avoided due to potential risk of residual chlorides from the coating process.
- ✓ For ensuring the long-term reliability of the cooling circuit, high corrosion-resistance material should be selected
- ✓ At cryogenic temperatures, a well-polished stainless-steel surface can provide favourable thermal radiation emissivity. Therefore, rather than applying silver coating, which carries the risk of SCC, enhancing the cooling performance through polished stainless steel can also be considered a practicable alternative.

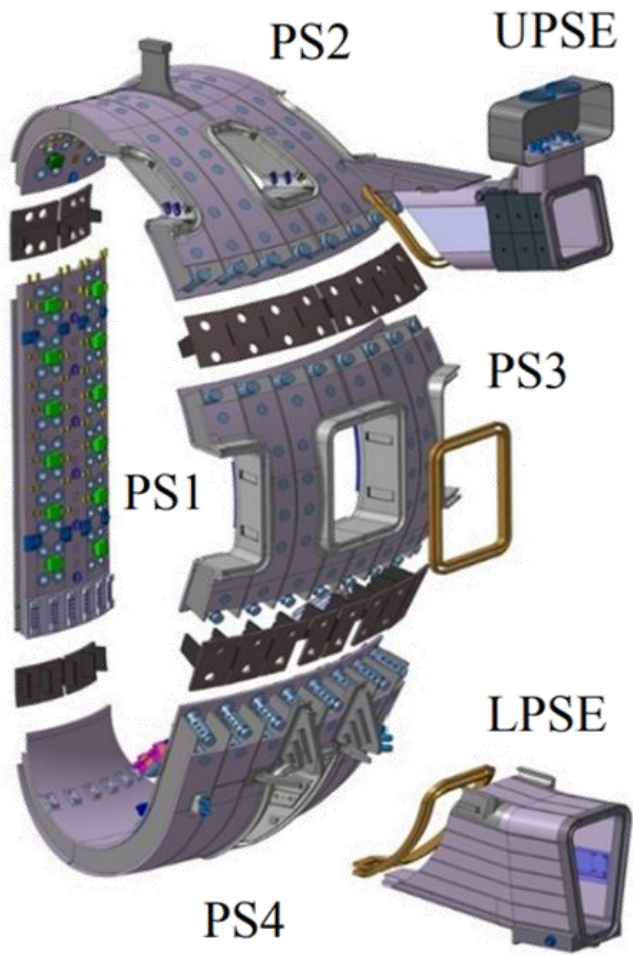
VV

- ✓ Narrow gap welding required tight tolerance. Bevel machining shall be carried out at the last stage of manufacturing process.
- ✓ Tight tolerances on field joint bevels must be achieved by machining. If the use of a fixed machine is not feasible, using a portable machine is a suitable alternative.
- ✓ It has been demonstrated that a significant level of build-up can be applied to recover lost material without defects satisfying specified quality requirements.
- ✓ Key factors for success are: accurate analysis of as-built deviations, qualified welding & machining process, preliminary trials through dedicated mock-up, and skilled, experienced welders and operators.

Thank you!



Appendix : VV Fabrication – sector assembly



Manual welding accessibility

In the figure below it is reported the detail of the area of the outer shell that can be accessible for manual weld, area in blue. All the inner shell is accessible by hand

(IO input FJ#05&07 (marc le rest))			Theoritical Distance (mm) between Inner & Outer = normal to the edges of the outer noses + 60 (inner shell) (IO input FJ#05&07 (marc le rest))				Manual considered (study)					
N° Splice plate	Length of the SP (m)	Start	Middle	End	Triangular support	Welding Position	Welding process (defined since the begining)	Direct Manual welding <470mm	% Lenght achievable	Lenght achievable (m)	Indirect Manual welding >470mm (Position PE excluded)	
Outer	10	0,778	203,18	294,4	294,4	No	PE	Manu	Possible	100%	0,778	/
	20	1,624	557,76	530,97	502,29	No	PE	Auto	No	0%	0,000	/
	30	2,485	502,29	458,12	350,44	No	PF + PE	Auto	Possible	50%	1,243	/
	40	2,790	350,44	338,1	338,1	No	PF	Auto	Possible	100%	2,790	/
	50	2,700	338,1	338,1	338,1	No	PF	Auto	Possible	100%	2,700	/
	60	1,800	338,1	338,1	338,1	No	PF	Auto	Possible	100%	1,800	/
	70	1,613	338,1	412,75	483,78	No	PF	Auto	Possible	90%	1,452	Possible
	80	1,521	483,78	531,64	555,73	No	PA + PF	Auto	No	0%	0,000	Possible
	90	1,706	555,73	589,36	632,36	No	PA + PF	Auto	No	0%	0,000	Possible
	100	1,706	632,36	680,68	730,7	Yes	PF	Auto	No	0%	0,000	Possible
	110	3,671	730,7	729,74	705,92	No	PF	Auto	No	0%	0,000	Possible
	120	3,046	705,92	755,19	707,21	No	PF	Auto	No	0%	0,000	Possible
	130	1,903	707,21	707,28	707,28	No	PF/PE	Auto	No	0%	0,000	Difficult
	140	0,334	203,18	203,18	203,18	No	PE + PA	Manu	Possible	100%	0,334	/
27,679												
										40,09%	11,097	

