COMPLETION OF THE FIRST ITER TOROIDAL FIELD COIL IN JAPAN

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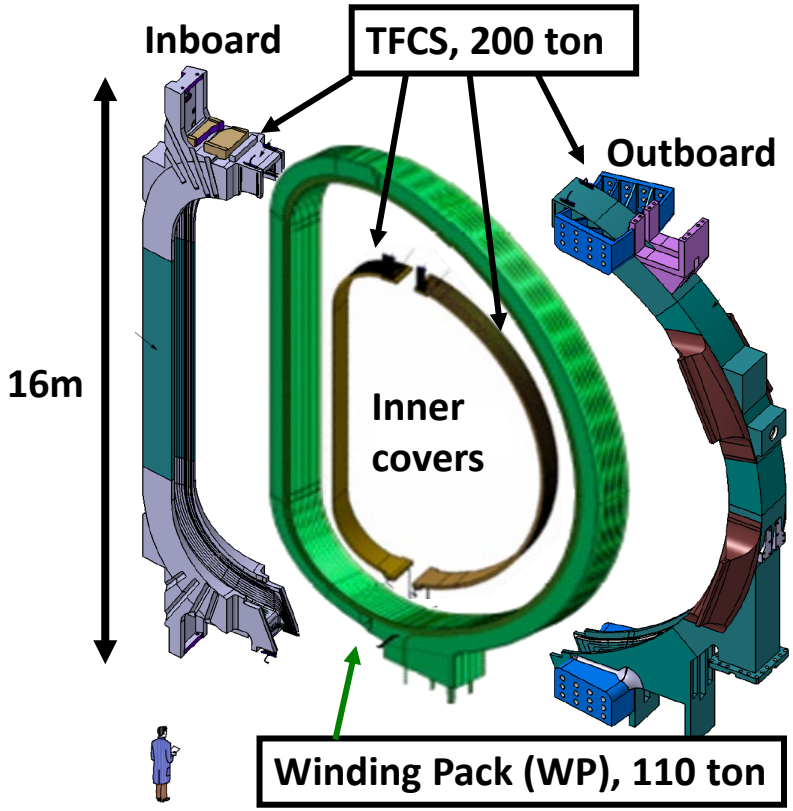
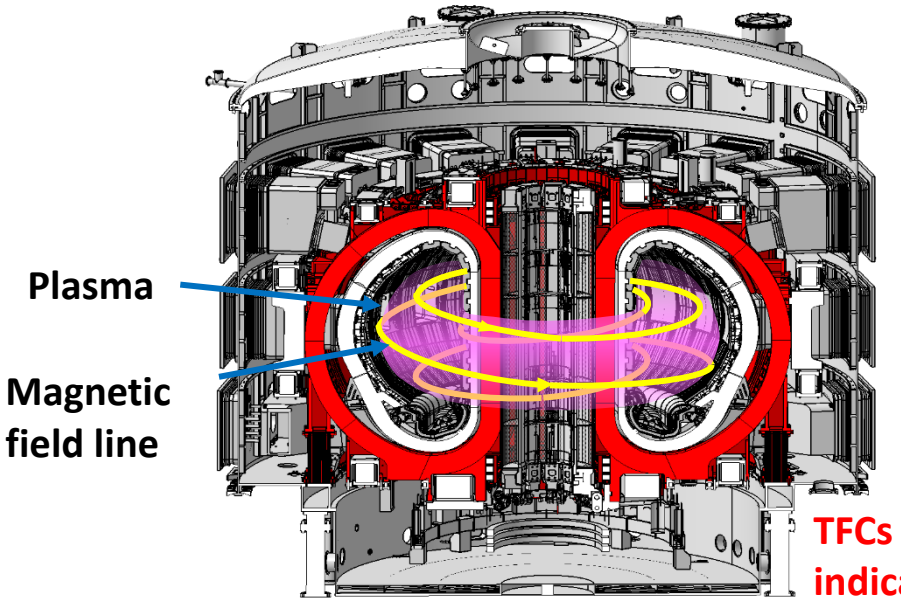
1.1 Introduction: TFC overview

- 18 Toroidal Field Coils (TFC) in ITER
- TFC Specifications
  - Peak magnetic field: 11.8 T
  - Total magnetic energy: 41 GJ
  - Conductor material: Niobium Tin (Nb_3Sn), with application temperature ~ 4 K
  - TFCS material: SS316LN – ITER grade to maintain the structural integrity at 4 K, not easy to control welding deformation.





TFCs are indicated in red.

- ITER TFC is the largest Nb_3Sn magnets in the world.
- Completion of the 1st-of-a-kind ITER TFC is an important milestone in the fusion energy research field.

1.2 Introduction: TFC requirements

Function of 18 TFC: to generate precise circular magnetic field in a vacuum vessel

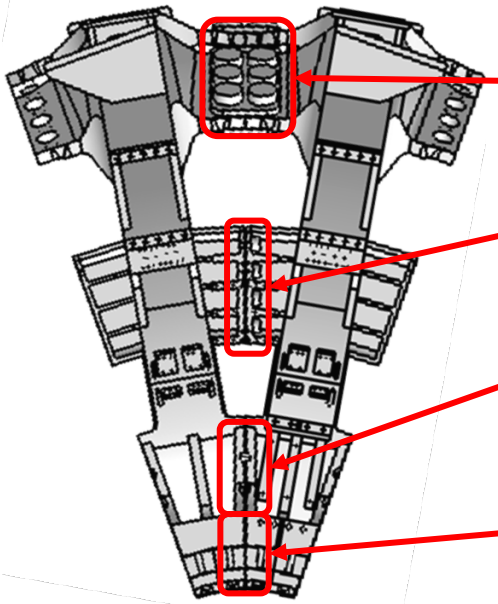
Assemblability: Precise positioning of 18 TFCs

Magnetic property: Common among TFCs

Magnetic property of whole TFC system

Magnetic property of each TFC

Interface tolerances



IOIS: 2 mm profile

OIS: 0.5 mm flatness

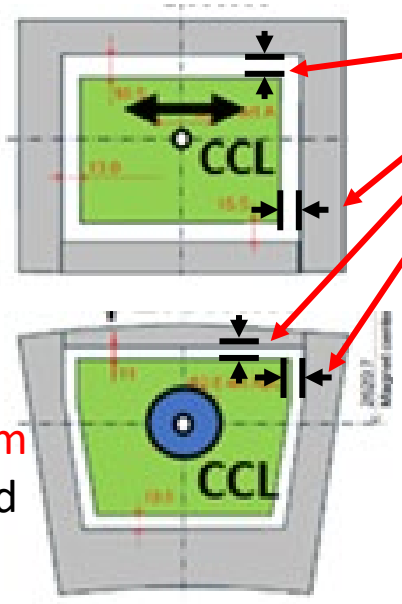
IIS: Φ2 mm positional

ILIS: 0.4 mm profile

CCL tolerances on each TFC

≤ ± 3 mm @ outboard

≤ ϕ2.6 mm @ inboard

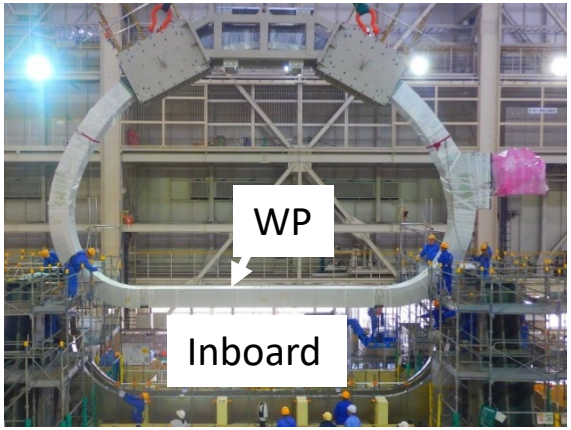


Min. Gap

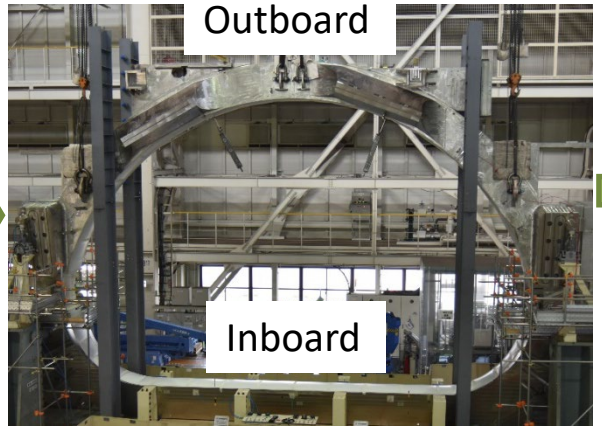
4 mm everywhere, for complete gap-filling

Control of deviations during assembly is necessary.

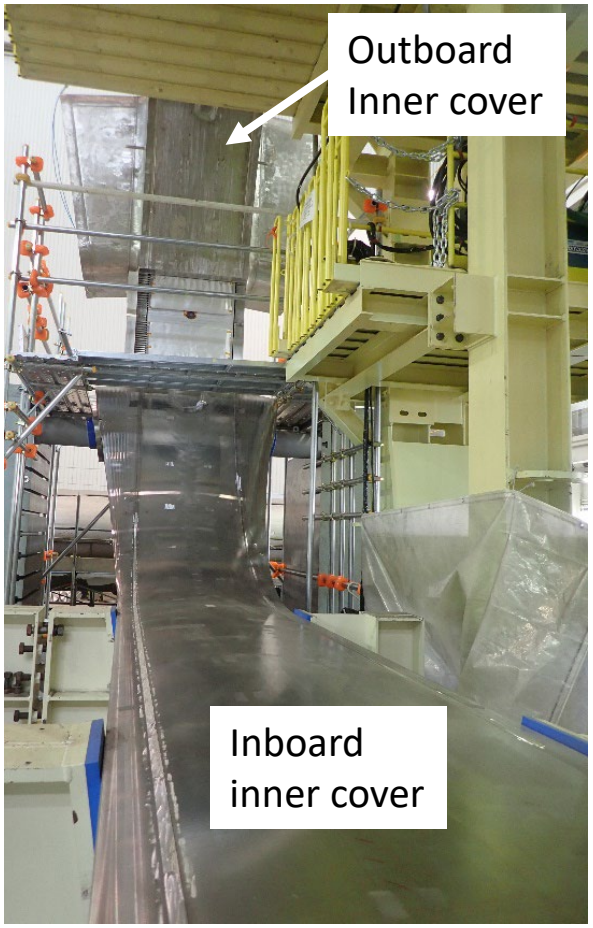
1.3 Introduction: TFC assembly steps



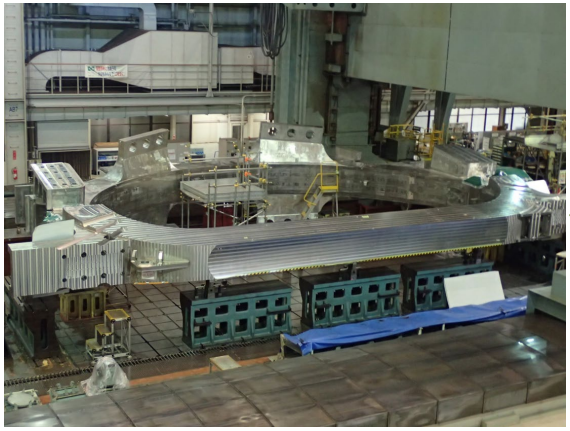
WP Insertion



Outboard Insertion



TFCS Welding



Final Machining

Final Inspection

Gap-filling

Any misalignments or welding deformations would be compensated by Final Machining.

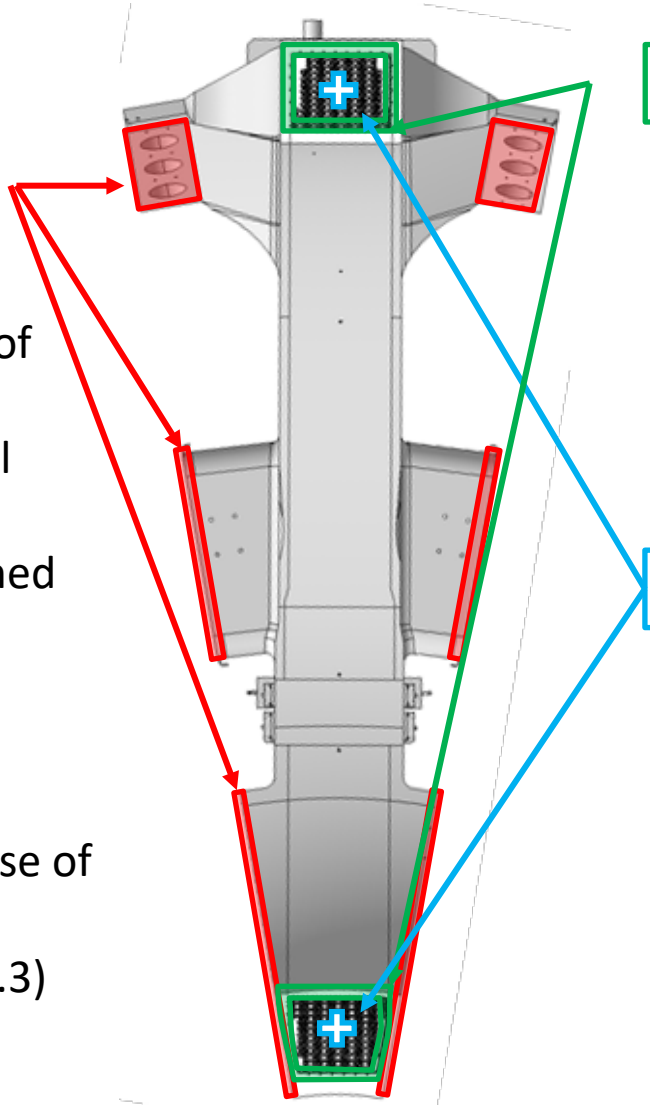
2. Technical challenges

A) Interfaces

Issue: **welding deformation control**

⇨ **Solution 1**: **In-advance estimation** of welding deformation (trials, FEM structural analysis) **& extra materials** to be finished at final machining (described in 3.1)

⇨ **Solution 2**: **Harmonization** as remedial action in case of large deformation (described in 3.2 & 3.3)



B) Gap

Issue 1: **High viscosity resin injection** into narrow gap (described in 4.1)

Issue 2: **Maintaining 4 mm gaps** through welding

⇨ **Solution**: **establishment of the resin injection method** into gaps < 4 mm (described in 4.2)

C) CCL

Issue 1: **Precise positioning of WP** within TFCS

Issue 2: **Maintaining WP shape/positions** through fabrication

⇨ **Solution 1**: **In-advance assessment** of target WP position **& monitoring** w/ laser tracker (described in 5.1)

Solution 2: **Traceability measurements & updating CCL information** (described in 5.2)

3.1. Interfaces: In-advance estimation

Welding qualification trials Local analysis

↓ Inherent strain parameters

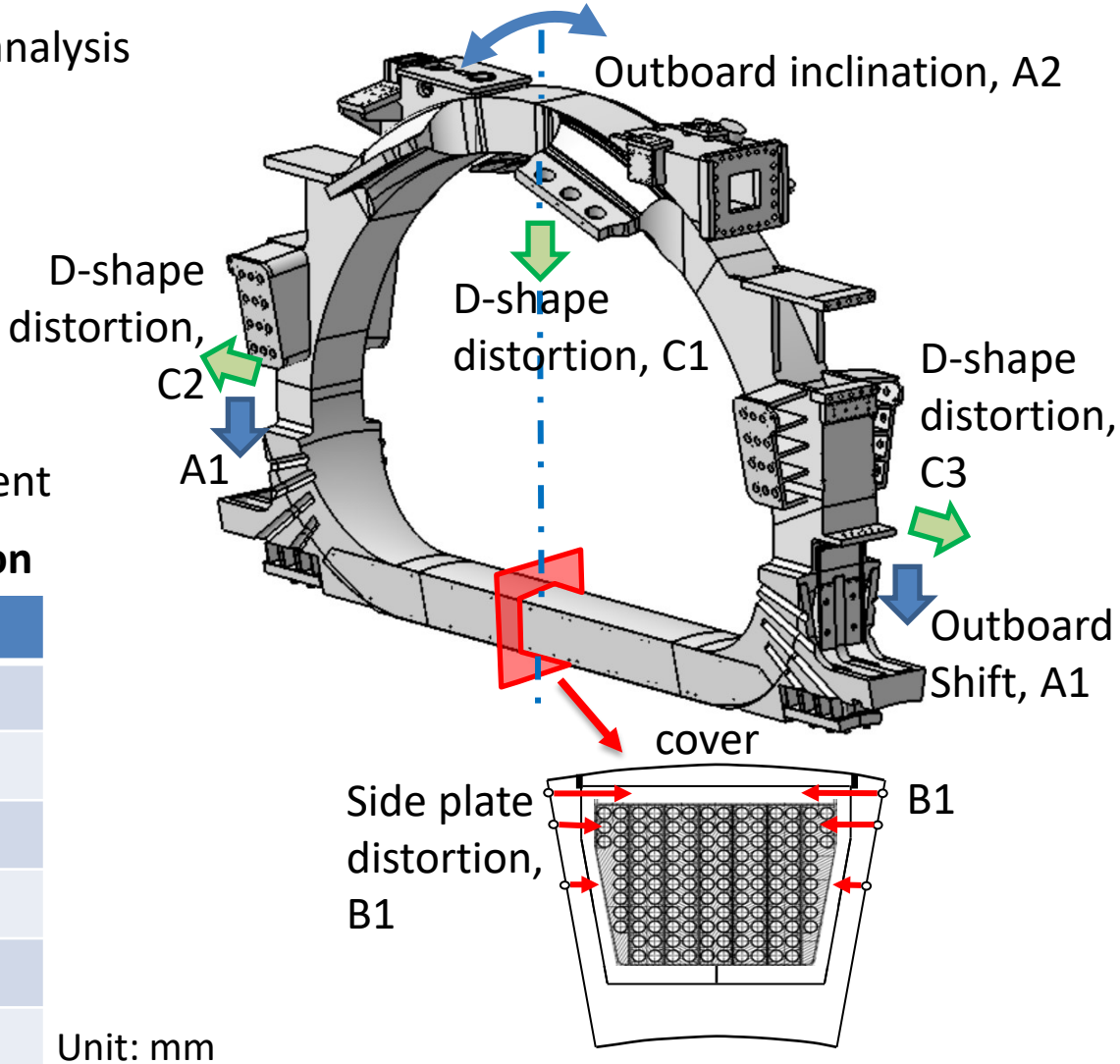
FEM analysis Global analysis

↓

Actual coil

Extra materials -> machined later

Laser tracker monitoring -> adjustment



Comparison of welding deformation

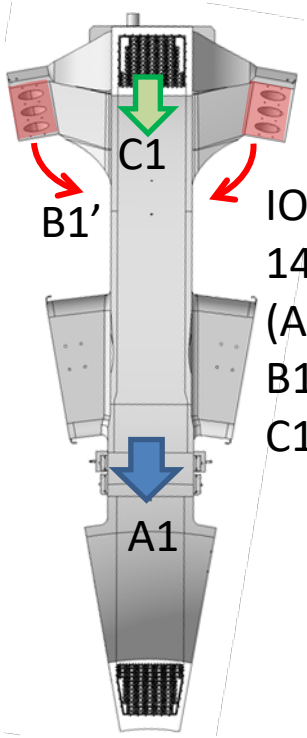
	Trial	FEM	1st coil
A1	8	5.6	6.9
A2	3.11	0	2.2
B1	4.4	4.0	5.0
C1	3.9	3.5	5.0
C2	3.6	2	1.8
C3	3.90	2	3.2

Unit: mm

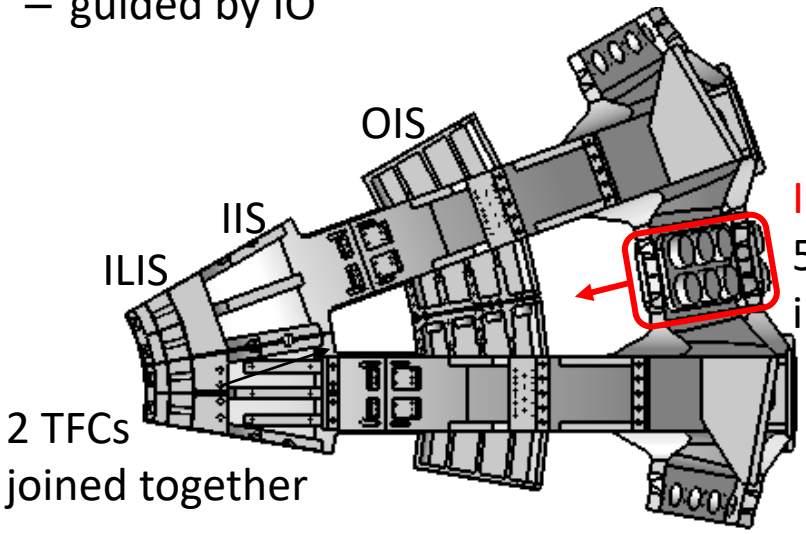
The distortions on interfaces were within the extra materials except at IOIS.

3.2. Interfaces: Harmonization

- **A few mm lack of materials** at IOIS interfaces on outboard.
  - 14.4 mm max. distortion
  - 10 mm extra materials + 2 mm profile tolerance
- **Comparison** to welding deformation results between EUDA's 1st coil & JADA's 1st coil:
  - **The common trends** were observed.
- **Harmonization**:
  - **18 TFCs can be assembled** if all have the same shape
  - **Global remedial action** to accept the welding deformation
  - guided by IO



IOIS distortion
14.4mm
(A1: 6.9 mm
B1': 2.5 mm
C1: 5.0 mm)

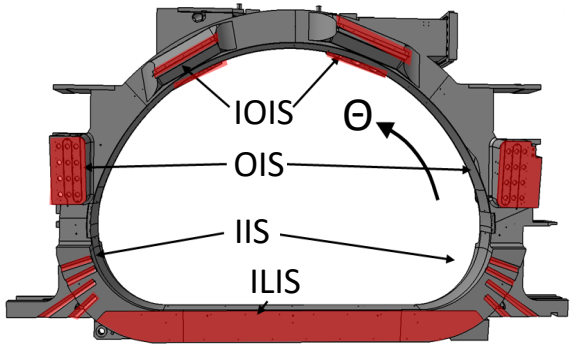


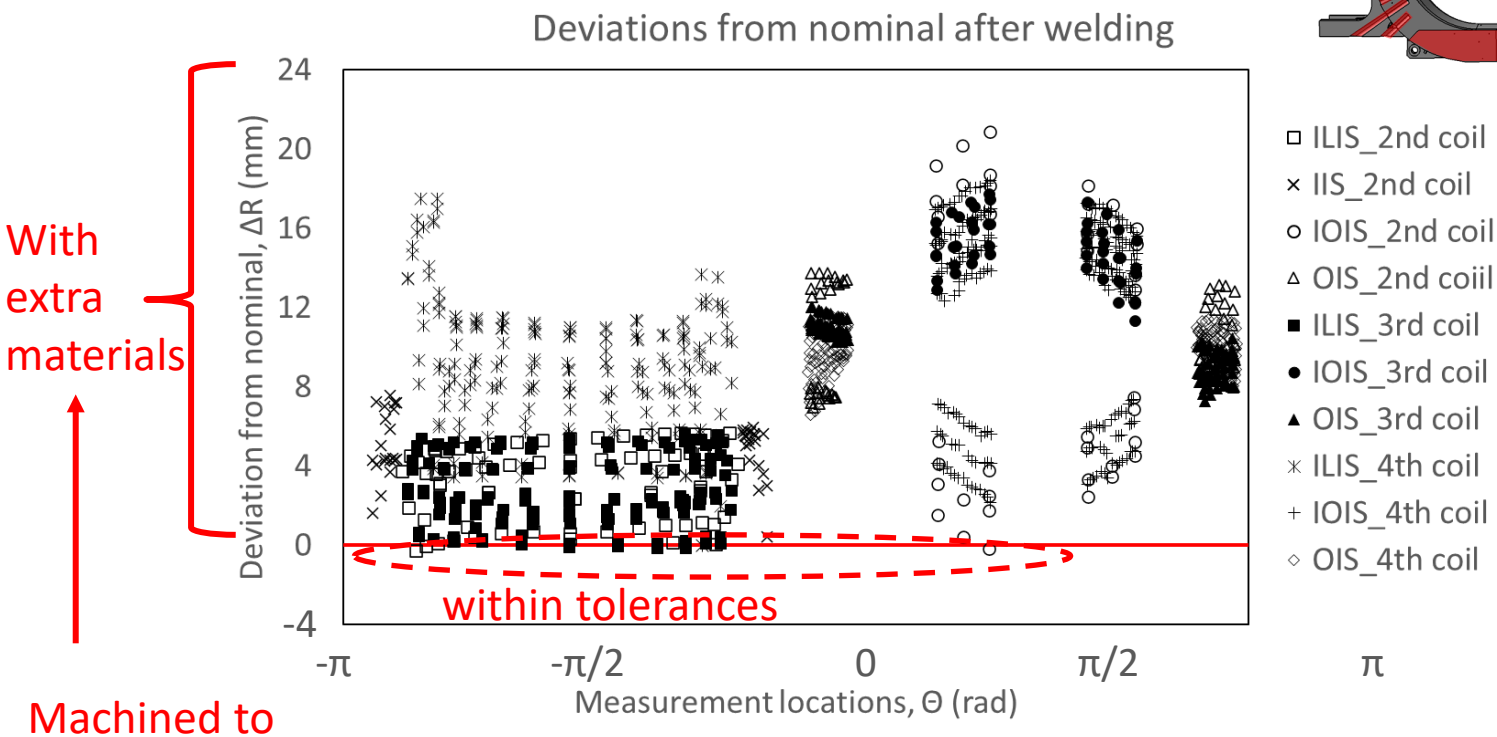
IOIS: shifting 5mm radially inward

All the interfaces satisfied the severe tolerances.

3.3. Interfaces: Harmonization effect

- Interface: sub-millimeter tolerances to secure assemblability of TFCs
- Interface measurement results of succeeding TFCs after welding:





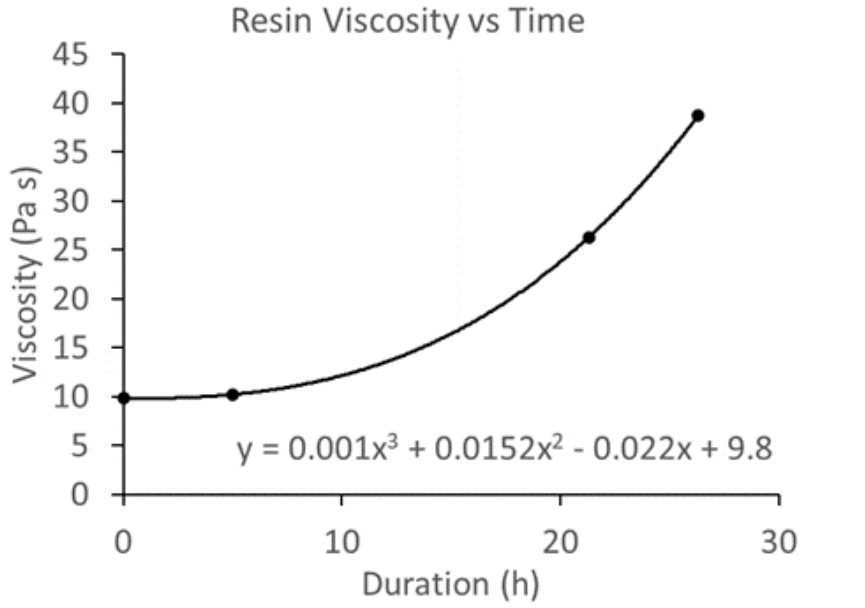
With extra materials

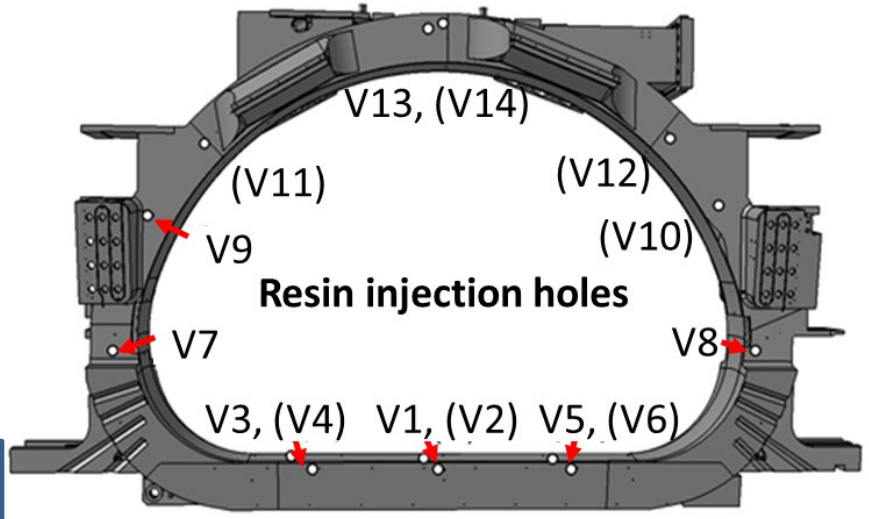
Machined to nominal during Final Machining.

For the 1st TFC,
- Interface tolerances: satisfied!
- Assemblability: ensured!

4.1. Gap: High viscosity resin injection

- Gap-filling:
  - **Structural integration** of a WP and a TFCS (compressive strength, integrated thermal contraction)
  - Satisfaction of structural requirements resulted in **High viscosity resin** (10 Pa·s for fresh mix, 26 Pa·s after 24 hrs)
  - **Fiberglass layer** on WPs
  - **Vaccum pressure impregnation** to prevent void formation (0.2MPa pressurization).
- **Min. gap:** 4 mm to ensure the complete filling of gap with high viscosity resin.
- **Fresh resin at the resin front**: to minimize void formation & valves for higher resin injection holes were opened as the resin level reaches the hole positions.

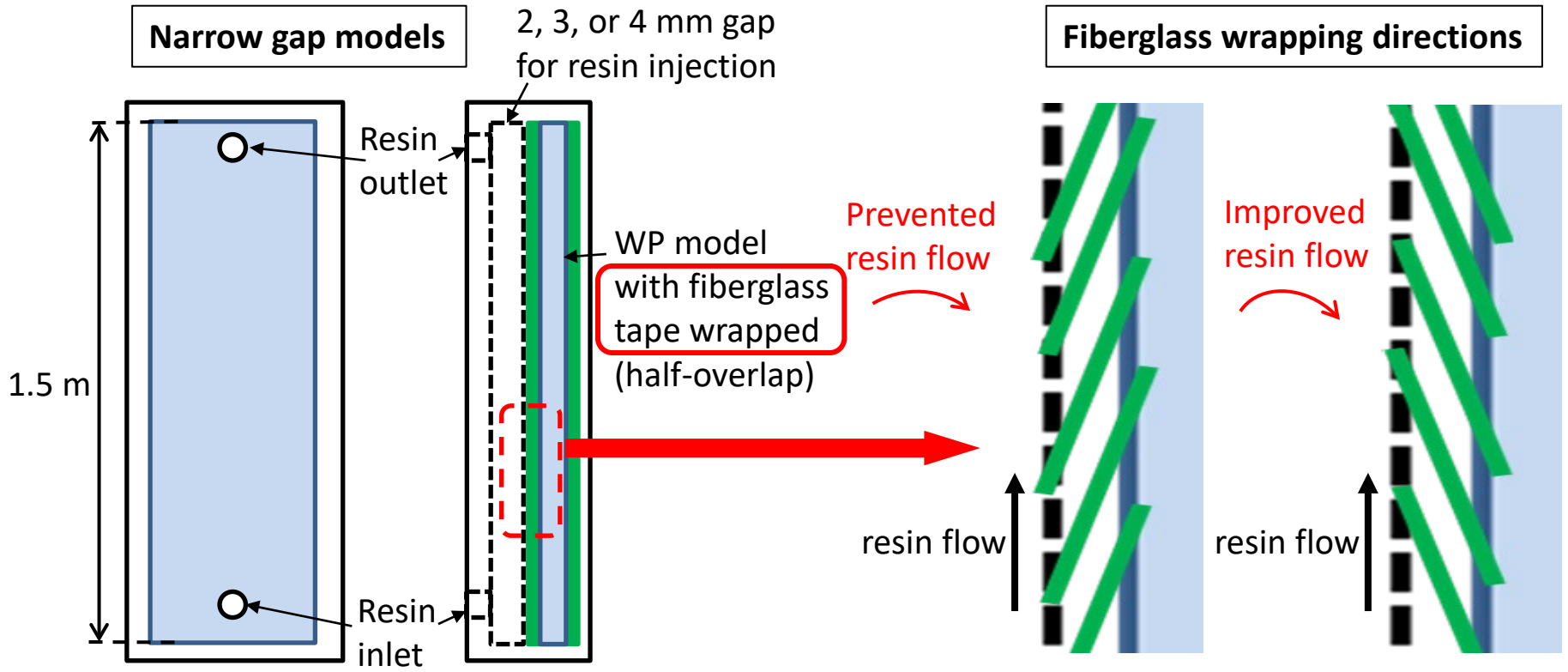




Verification of gap-filling procedure with those measures is necessary.

4.2. Gap: establishment of resin injection method

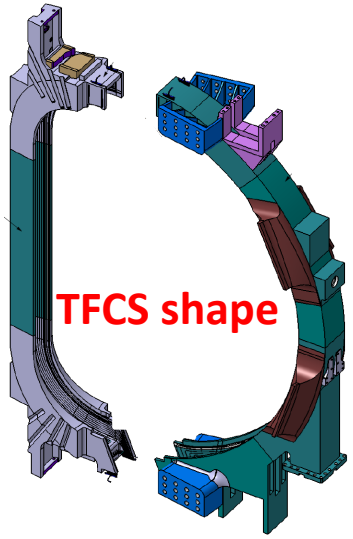
- **Resin injection trials to establish a resin injection method:**
  - High viscosity resin
  - for narrow gaps (<4 mm) due to larger welding deformation

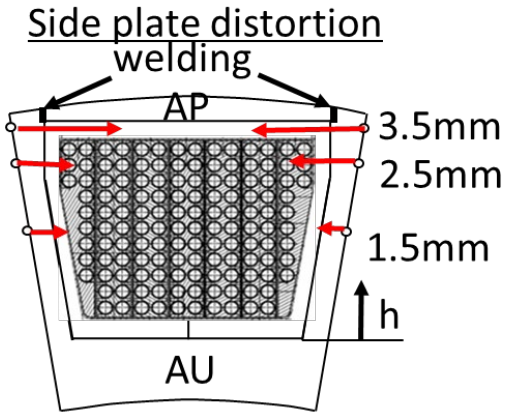


Local gap of 2 mm: Acceptable w/ improved procedure!

5.1. CCL: In-advance assessment

- **In-advance assessment of target WP position optimizing CCL positions while keeping 4 mm gap.**

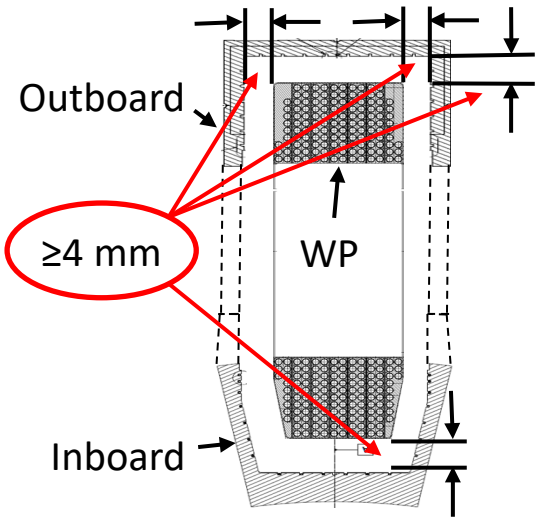




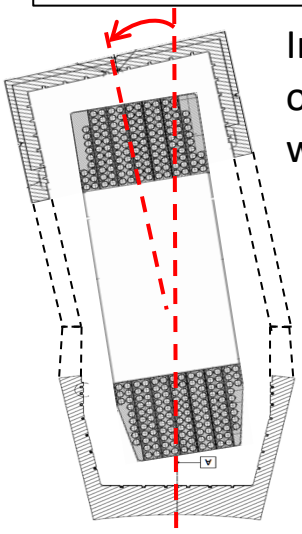
Welding deformation expectation

Gap analysis

Ideal case



Realistic case



Inclination of outboard during welding ≤±3 mm

WP tilt adjustment

⇨ gap ≥4 mm

- **Optimized WP target position from gap analysis**
- **Laser tracker monitoring for fine adjustment of 0.1mm order**

5.2. CCL: Traceability measurements

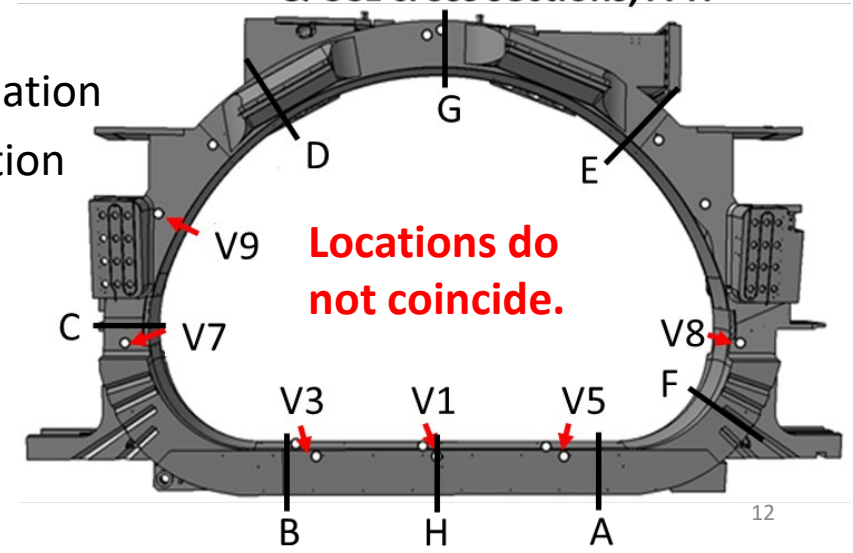
- **CCL traceability measurements** by laser tracker:
  - Frequent measurements ⇨ **minimize errors** during final machining
  - Repetitive measurements ⇨ **minimize uncertainties**
- **Original measurement plan**
  - up to cover installation of TFCS.
  - At CCL cross sections

A concern of welding deformation impact on WP shape/position from IO

- **Additional measurement plan**
  - Up to gap-filling
  - At resin injection holes after cover installation
  - Use of structural analysis for CCL calculation

Laser tracker measurement

Resin injection holes, V1-V9 & CCL cross sections, A-H

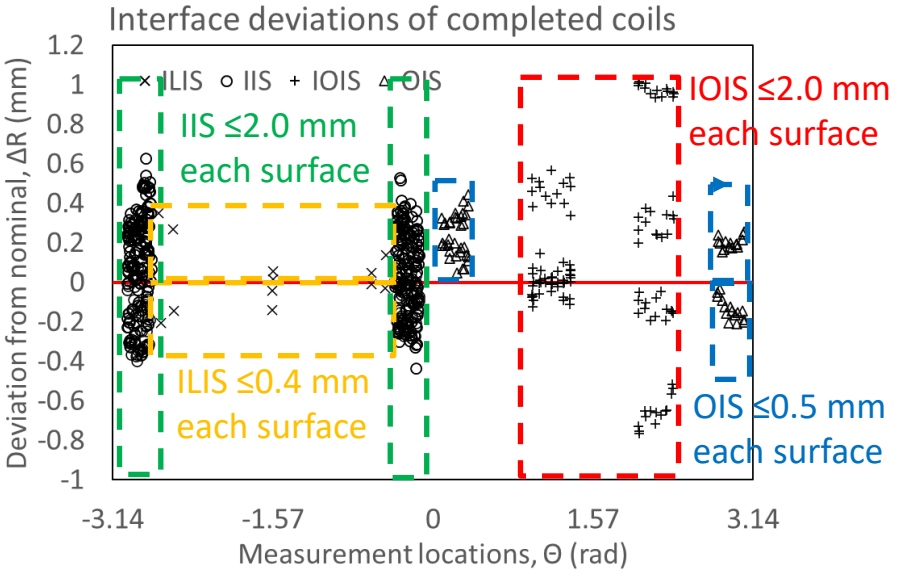


CCL deviations:
- **0.35 mm max. @ inboard**
- **1.46 mm max. @ outboard**

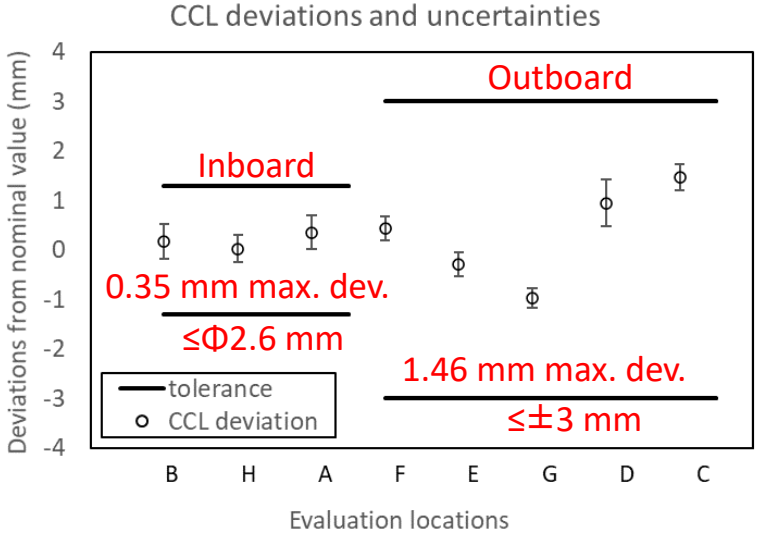
CCL requirements: satisfied!

6. Completion of the 1st coil

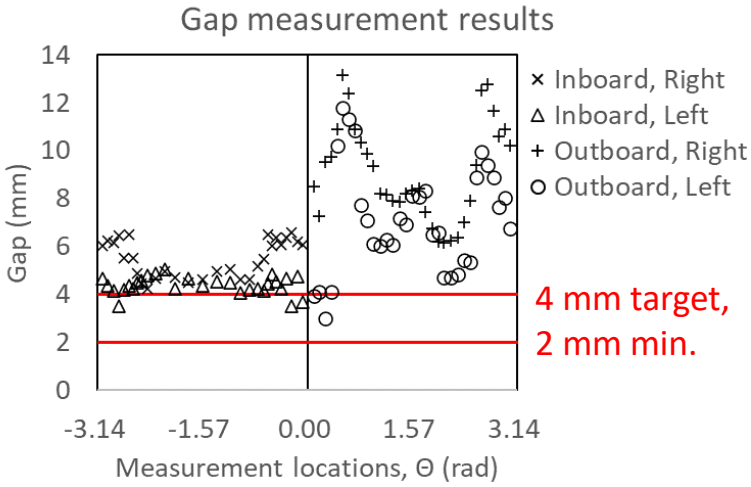
- **Interface requirement:** satisfied!
  (tolerances are indicated with dot-line boxes.)

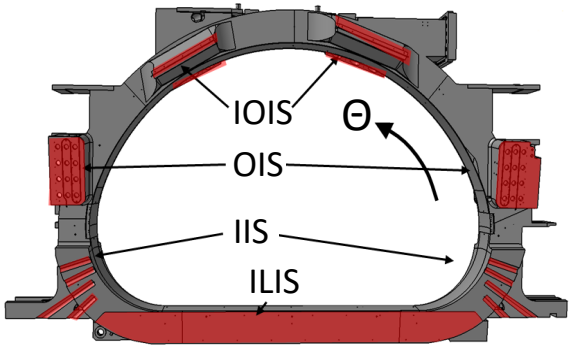


- **CCL position requirement:** satisfied!
  (uncertainty range is shown with bars.)



- **Min gap requirement:** satisfied!





For the 1st TFC,
- Magnetic property: achieved!
- Assemblability: achieved!

7. Conclusion

- The world's first ITER TFC was manufactured in Japan in January 2020, satisfying requirements.
- Completion of the 1st-of-a-kind was celebrated by holding a ceremony at MHI premises (Kobe, Japan).
- 3 TFCs from EUDA & 3 TFCs from JADA were delivered to ITER.

Thank you!