Comparison of FEM Predicted and Measured values of the TF coil closure welding distortion

FUSION FOR ENERGY

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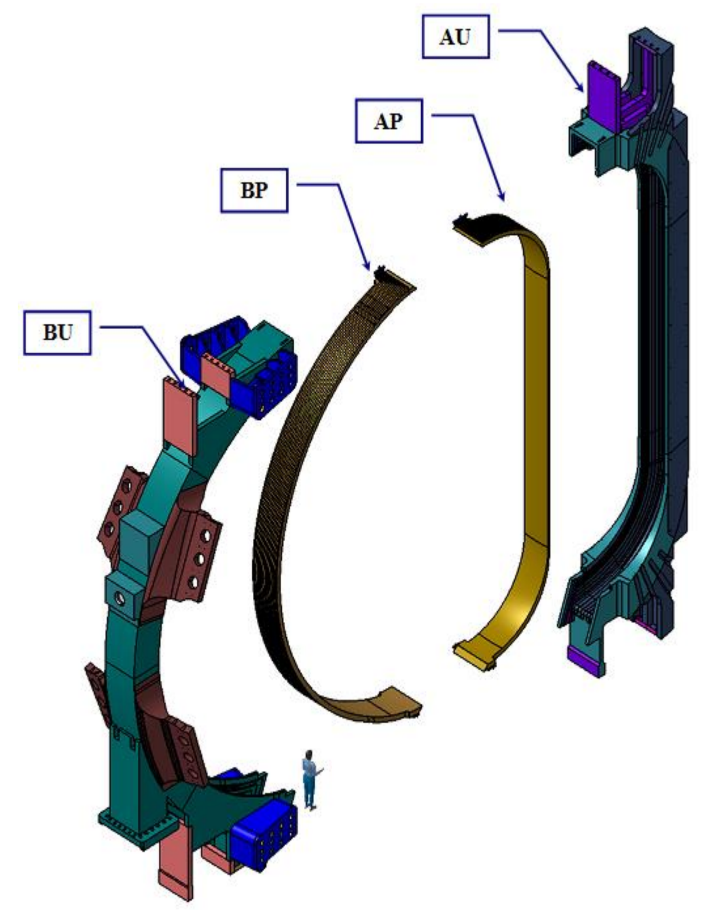
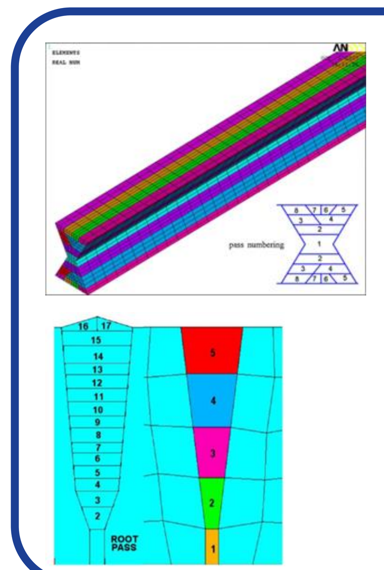
1. Introduction

- **Toroidal Field Coils Cases (TFCC)** are SS316LN structures, which have to withstand strong magnetic fields (around 12 T) in order to confine the high temperature plasma (150M C°)
- **Welding distortions** can compromise the final shape of the assembly, generating out-of-tolerances in the interface areas that cannot be recovered by the extra-material foreseen.
- A **Finite Elements Model** has been developed by Enginsoft S.p.A in collaboration with SIMIC and F4E.
- In July 2019 the welding phase of TFC09 has been completed, monitoring the case deformation by fiducial points along the whole process.



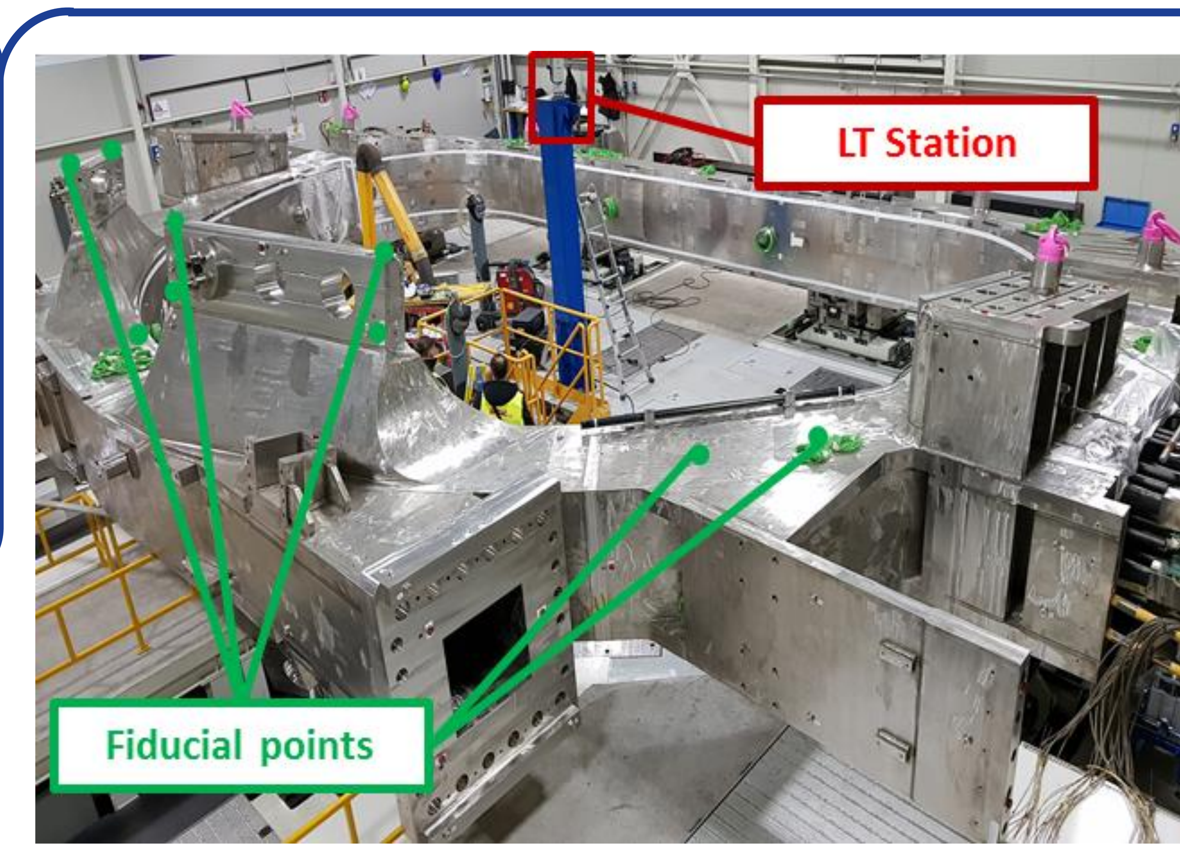
2. FEM model definition and survey setup

- **Theoretical and technical methods** applied to the model:
  - **Quasi-steady state analytical solution** (Rosenthal) to de-couple the thermo-mechanical analysis.
  - **'Birth' and 'death' technique** to simulate material deposition during weld.
  - **Clustering technique** of the weld passes to achieve mesh reduction maintaining as much as possible the real sequence in the material deposition.
- **Tuning of the model** through experimental campaign:
  - First stage: welding of six **qualification coupons**. Measured displacements and temperatures have been used **as calibration parameters** (cut-off temperatures and cooling law, chord mesh size and coefficient of thermal expansion (CTE) of chord material). A blind test on a coupon has been carried out to final validate the model.
  - Second stage: more refined tuning of the parameters on three **TFCC full scale mockups**, reproducing three zones of the case.
- Deformation of the TFCC structure has been monitored approximately every 25mm of deposited material by **laser tracking survey**. The system accuracy depends on the distance from the target, the number of fiducials and the number of position of the LT used. The uncertainty of the measurement evaluated is about 0.2 mm. Quick surveys on **45 accessible fiducial points** on the case with high repeatability.



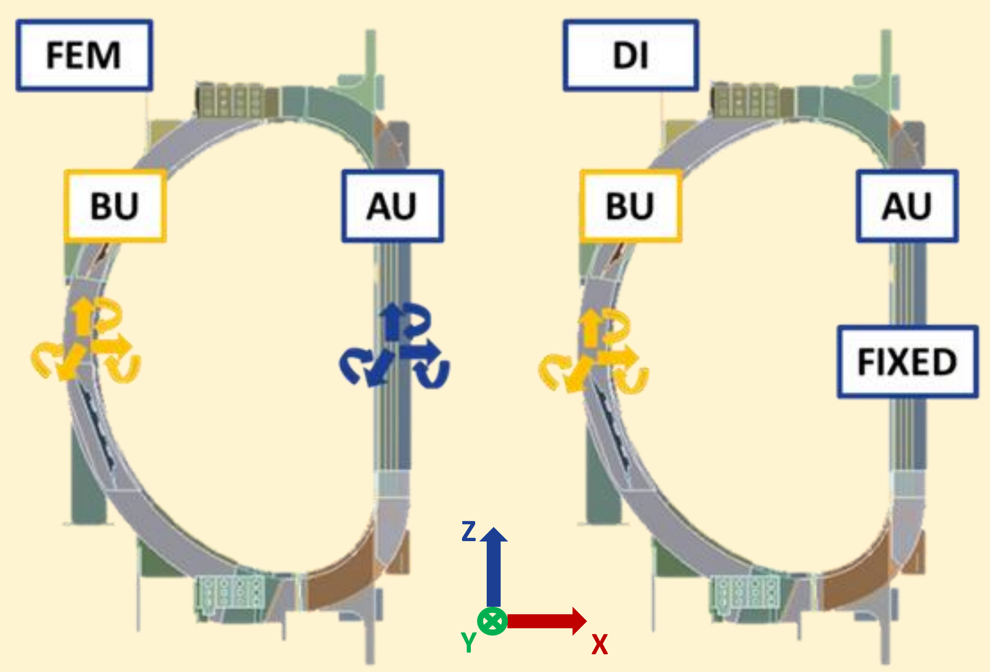
FEM techniques

Fiducial point



Survey setup

3. Results comparison



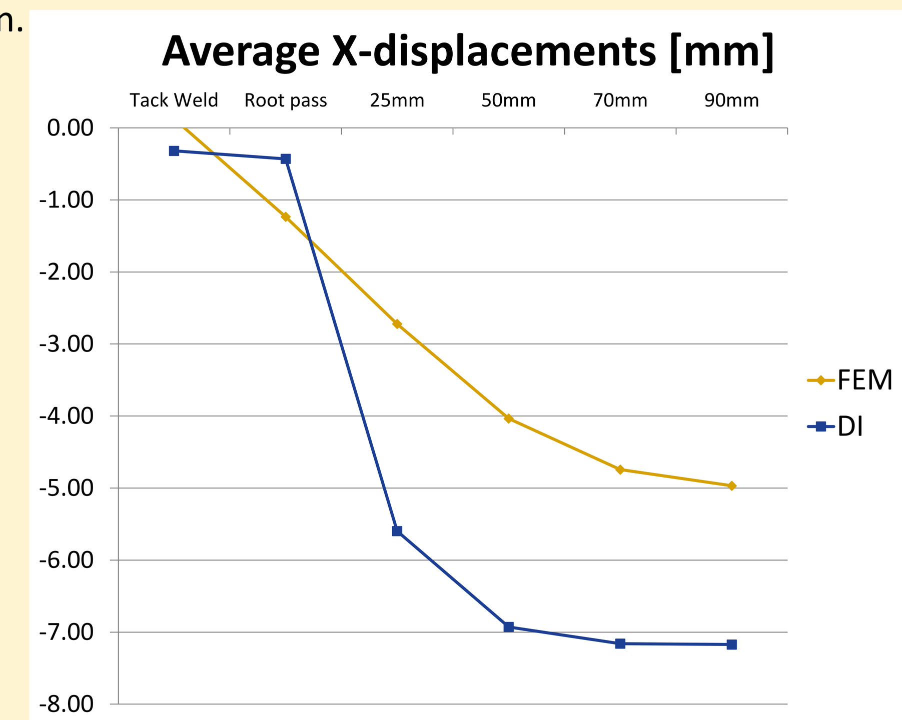
- The TFCC full model (190k elements) includes all the steps of the real welding sequence, **tack weld**, **butt weld**, **poloidal weld** and **splice plates weld**.
- **FEM boundary conditions** allows all the DOF of the support with minimum reaction forces. The real support configuration only allows BU case to move, while AU remains fixed along the process. FEM deformations have been filtered with the average values of the displacements of the AU fiducials points in order to achieve the same configuration of the DI.

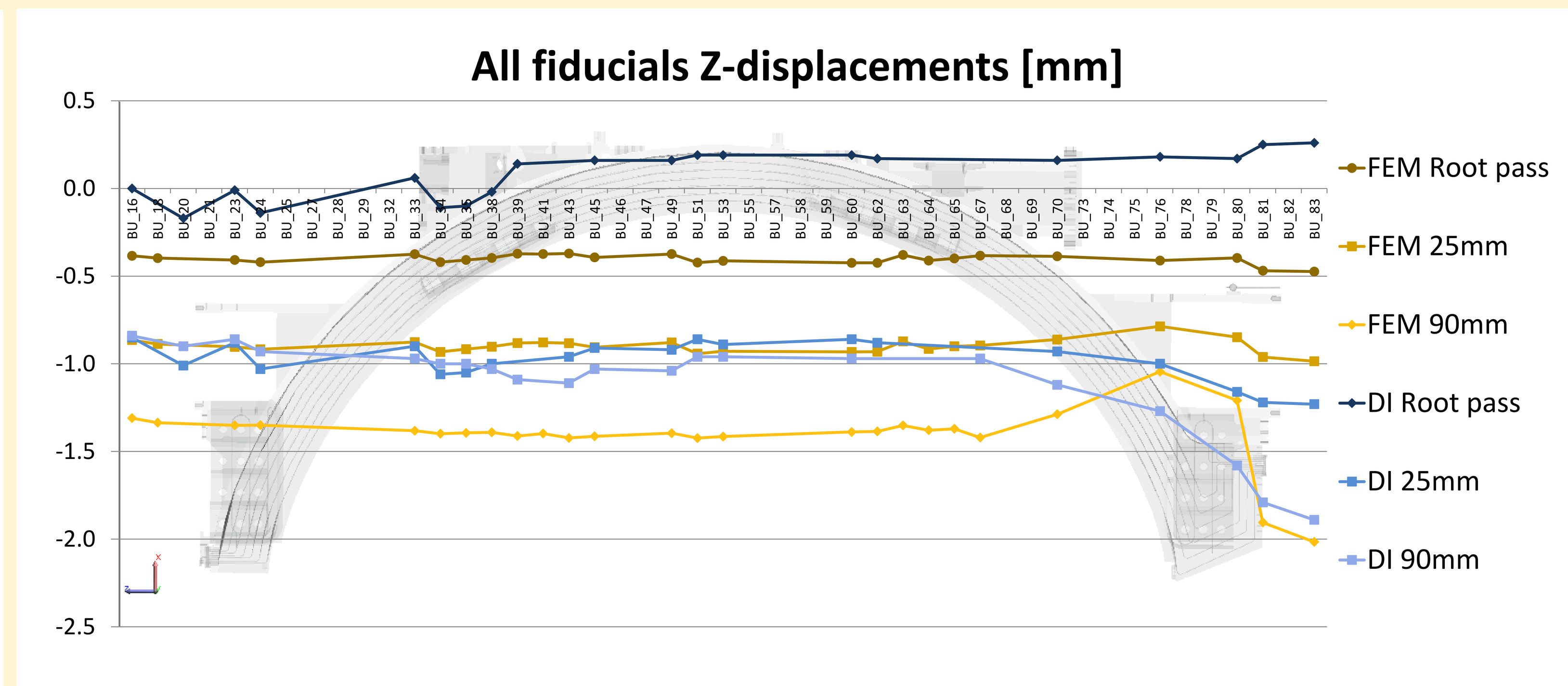
Steps comparison

		Analysis step	Bevel fill [mm]
Tack Weld		1	-
Butt Weld	Root Pass	8	6
	25%	12	25
	50%	15	50
	75%	18	70
	End	21	90
Poloidal Weld	Root Pass	31	6
	50%	73	55
	End	54	110
Splice Plates Weld	Root Pass	57	6
	25%	58	25
	50%	59	50
	End	61	90

3a. Butt weld phase

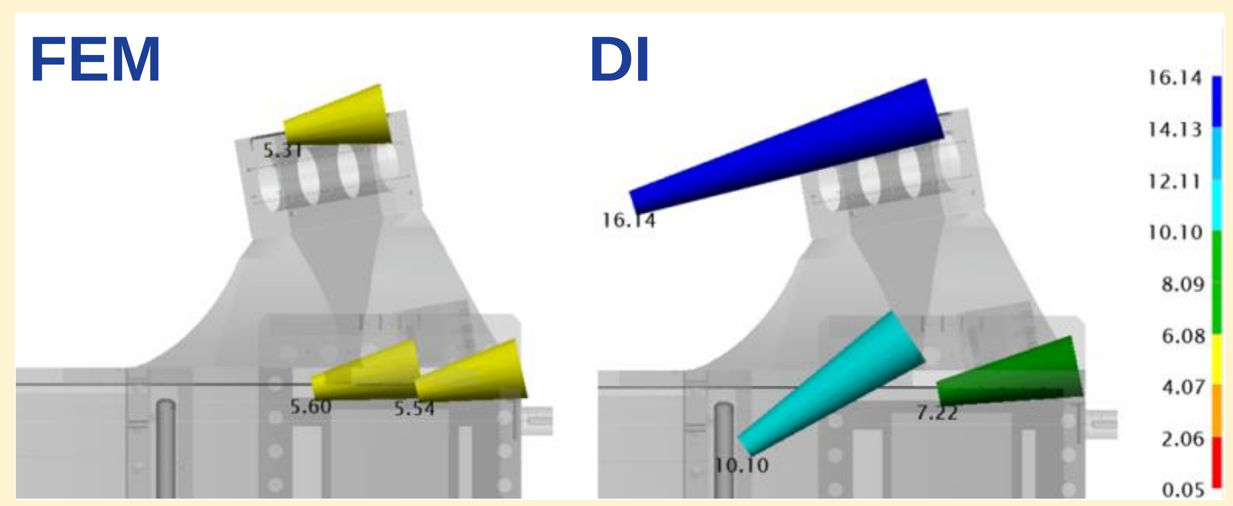
- The FEM model foresees the AU-BU **gap to reduce** uniformly with time of **~5mm** along the radial (X in the TGCS reference frame) direction, and **a global misalignment** between the two sub-components of **1.4mm** along the vertical direction. No out of horizontal plane (Y axis) displacements are predicted.
- The DI reported ~6mm of average closure after the first 25mm of material deposition in the chamfer, achieving at the end of the weld an average **7mm closure** between parts.
- The cases **misalignment** along the vertical direction has been verified by the DI data. The measurements show the same order of magnitude, but the real component present a higher degree of misalignment **localized in the termination area**.

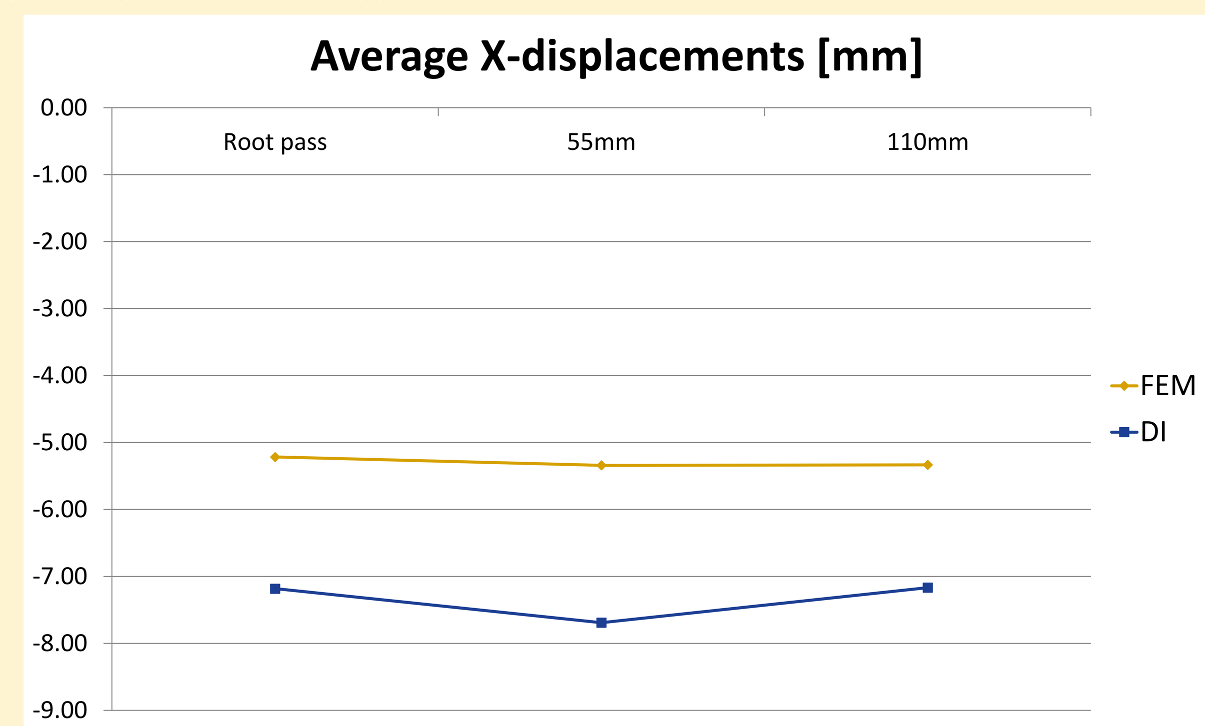




3b. Poloidal weld phase

- Only AP and BP plates have been foreseen to deform under the welding loads. The FEM model predicts **negligible deformations** on the rest of the case.
- The FEM prediction is localized in the bevel zone, while the DI demonstrated to be extended to the case sides. This caused the fiducials on the IOIS interfaces to rotate according to the cases sides angular deformation.
- By taking into account only the fiducials not affected by the angular deformation, the **average X displacements** reported from the DI **are in line with the model.**





4. Conclusions and future activities

Globally, the model reproduces the with **good fidelity** the TFCC deformation, in terms of behavior of deformations and order of magnitude of the displacements. Further work is foreseen in order to **improve the prediction of deformation in specific areas** (IOIS), while maintaining the global coherence. Increasing the structure stiffness, fine-tuning of material properties are foreseen as possible solutions to improve the model prediction capabilities.