Current Centre Line control, results and comparison after the manufacturing of the ITER Toroidal Field Coils

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***Abstract*— In 2021, seven Toroidal Field Coil (TF) are already built by European industries and delivered to the ITER Organization (IO). The TF are composed mainly by a superconducting Winding Pack (WP), and the enclosing Coil Cases (TFCC).**

One of the main parameters characterizing the TFCs is the Current Centre Line, defined as the barycentre of the WP conductors. The CCL has been initially calculated for all the TFCs, and Fusion for Energy (F4E) developed a methodology to monitor and control the CCL during the subsequent manufacturing processes, including WP insertion, TFCC welding, preparation for machining and final measurements. The method is based on detailed laser measurements, CAE models and data processing, and it provides one of the main inputs to be considered when defining the final machining of the component. The final CCL position after machining can be further used as input parameter during the machine assembly and it is useful to understand important aspects for the operation of ITER reactor such as the Error Field.

This paper presents the results of the abovementioned strategy for the coils completed so far, during the different manufacturing phases, and the intermediate results of the remaining coils under construction. It focuses on the similarities and differences obtained comparing the TFs, and it assesses the correspondence of the CCL data with other parameters related to the magnet.

Index Terms— ITER, Magnets, magnetic characterization, Current Centre Line, Error Field

I. Introduction and Objectives

The ITER project has the objective to build a Tokamak type fusion reactor. For its operation, super-conducting magnets are required [1]. The ITER magnet system is mainly composed by the Central Solenoid (CS), Poloidal Field Coil (PF) and Toroidal Field Coil (TF) systems. The TF system is formed by 18 D-shape coils, and each coil involves a winding pack (WP) within an exterior SS316LN stainless steel coil case (TFCC). The WP is built from 7 "Double Pancake" windings (DPs) which are stacked together before insulating and impregnating to form a single unit. The WP contains a total of 134 turns of superconducting Nb_3Sn cable-in-conduit conductor. While the WP is the superconducting core of the magnet, the TFCC provide the necessary structural integrity to withstand operating loads and interface areas with the rest of components of the ITER machine.

The Current Centre Line (CCL) is defined as the geometric barycenter of the 134 turns of conductors, and it represents 'As-built' information of the magnet. It should be calculated in 30 sections of the TF coil and one of its uses is to characterize the magnetic field of the 'as-built' magnet. Manufacturing stages can be optimized to recover previous deviations, since proper CCL positioning is key to minimize Error Field during operation.

Systematic deviations from the TF coils supplied by Europe and Japan will negatively affect the Error Field. For this, IO has defined a tolerance of ϕ2.6 mm on the CCL positioning in the TF inboard straight area, known as the Straight Leg (SL) and the three parties have set a harmonization the strategy for WP

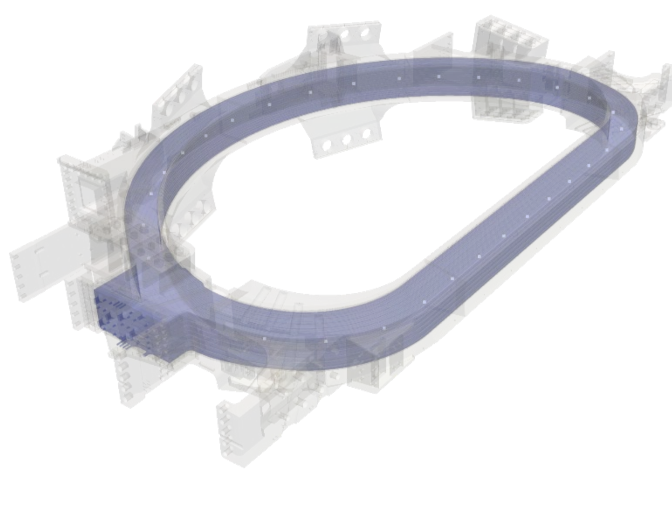

Fig. 1. ITER TF Coil. TFCC are shaded in gray, Winding Pack in blue and the 20 CCL calculation points along its circumference are in white.

The work leading to this publication has been funded by Fusion for Energy under the contract F4E-OPE-053 and F4E-OPE-414. This publication reflects the views only of the author, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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insertion and final machining of the TFCC, in order to have each final TF as similar as possible.

From 2019 to 2021, F4E implemented a process to execute CCL strategy harmonization while maintaining Quality Assurance, Configuration and Control of the Data. This paper shows the results of the implementation during these three years for the different manufacturing phases. It focuses on the similarities and differences obtained comparing the CCL of the TFs and the potential correspondence of the CCL data with other parameters related to the magnet. The paper starts with a global process overview, and continues providing results of the method implementation, further work, and conclusions.

II. Process Overview

The process defined by F4E to integrate the CCL calculation and control into the TF manufacturing contains the main phases shown in Fig 2. The method is based in processing dimensional measurements and manufacturing data for the creation of Computer Assisted Engineering (CAE) models, as explained in detail in the paper dedicated to the method explanation [2]. The Final CCL data is given to the IO for the machine assembly and it is used by F4E to assess the Error Field.

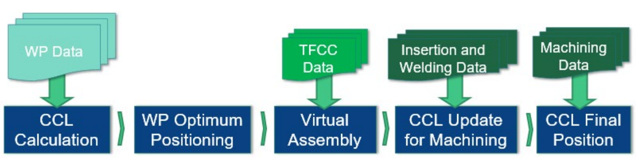


Fig. 2. Process overview to obtain the CCL in its final position considering in each step of the TFC manufacture. Manufacturing data is feed into the process at several steps to try to correct CCL deviations.

The first phase is the calculation of the CCL. The calculation method is based in DI and manufacturing data, mainly a laser scan of the full WP external surface and a detailed interlayer mapping for the DP stacking. Details on the WP manufacturing and associated dimensional inspection process are given in [3][4]. The second phase deals with obtaining the optimum position of the WP inside the TFCC in order to minimize the CCL deviations from their reference nominal position. With the WP in virtual position, a virtual assembly is built considering also TFCC manufacturing data provided by their suppliers. This model allows the verification of the gap between components. Later on, the CCL position is updated during insertion and welding and the final machining strategy is defined to minimize deviations in the SL. After the machining, dimensional data is used to calculate the final CCL position. The final position of the points of the CCL in Tokamak Global Coordinate System (TGCS) is used by F4E to calculate the Error Field assessment [5] of the completed Tokamak. This is also used by IO to provide data for the optimum coil position and alignment for the assembly of the machine. The following section provides results of each step of the process implementation for the coils manufactured so far.

III. Results of Process Implementation 2019 to 2021

A. CCL Calculation

The CCL for all the TF WP have been calculated, as shown in in Fig.3.

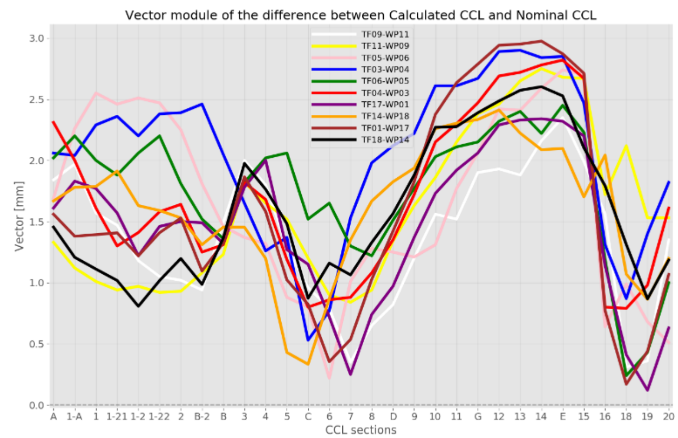


Fig. 3. CCL deviation considering WP dimensional inspection results. Sections A to B are in the SL inboard, while section G is located in the equatorial plane of the D shape.

These deviations are then reduced in the SL area optimizing the position of the WP inside the TFCCs, with the results shown in the next section.

B. CCL Optimization

The deviation of the CCL calculated during the WP manufacture can be reduced in the SL by defining an optimum position of the WP inside the TFCC. These results are depicted in Fig.4.

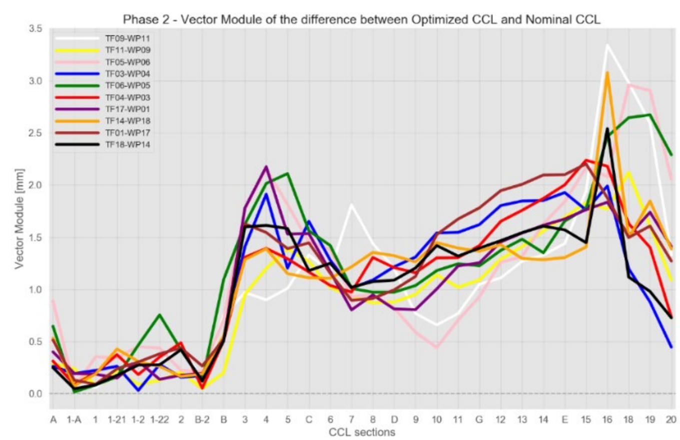


Fig. 4. CCL deviation considering WP optimum position inside CC

C. Gap Check with the virtual assembly.

The new position defined for the WP minimizes the deviation of the CCL once it is inserted in the TFCC, but the remaining gap between components needs to be verified using a virtual assembly, as shown in Fig.5. The virtual assembly is built in

Polyworks ® software using the WP scan in its optimum position and the TFCC dimensional data points of the inner surfaces provided by Japanese manufacturers.

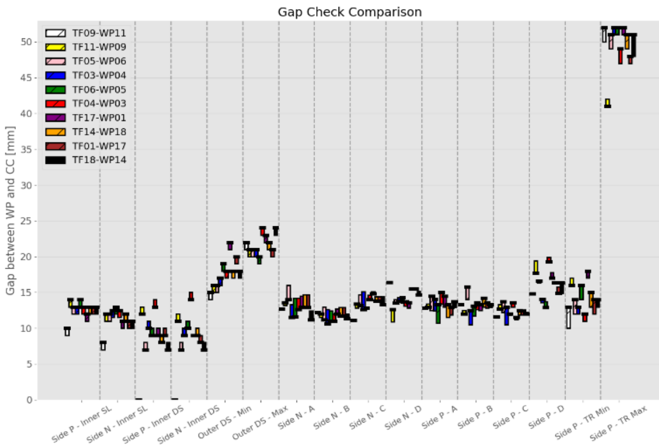


Fig. 5. Gap values in different areas around the TF. Black line defines the initial gap before optimization and bar end defines the final gap.

The virtual assembly of all TFs allowed the requirement for a minimum gap (4 mm) between the WP and TFCC to be verified prior to assembly. This requirement has been respected on all TFs produced, with gap values ranging from 7-15mm in the SL critical area and well above 10 mm in the rest of the controlled areas distributed along the coil perimeter.

D. Control during insertion, welding, and machining definition

During the insertion and welding process, the WP position is measured with a laser tracked controlled probe through eight access holes in the TFCC. In this way, the CCL position can be updated with the WP DI data acquired and compared to the optimum required position. The deviation of the WP Fiducial Points with respect to their optimum position is shown in Fig. 6 (top). Fiducials AU 1 to 5 are located in the inboard SL. In order to further reduce their deviation with respect to the optimal position, the final machining of the TFCC interfaces is modified thanks to the presence of excess material. This allows the final alignment of the CCL to be adjusted, resulting the values shown in Fig. 6 (bottom).

In this way, the CCL errors in SL inboard area are reduced to well below the requirement of 2.6 mm, with an average, to date, of <0.5mm. This can be at the expense of higher errors in other areas of the coil (i.e. outboard features).

It is worth noting the similarity between all the coils welded to far, even after the effects of a high variability process such as the GTAW welding of high thickness structures, in which there is a large proportion of manual welding. This is a positive outcome of the preliminary work on to study and validate the welding sequence and measurement campaign [6].

After final machining, the DI data of coil features and fiducial points is processed to obtain the deviation of internal WP fiducials, using best-fit methods on measured points. More details on the TF production and metrology global strategy are available in [7][8].

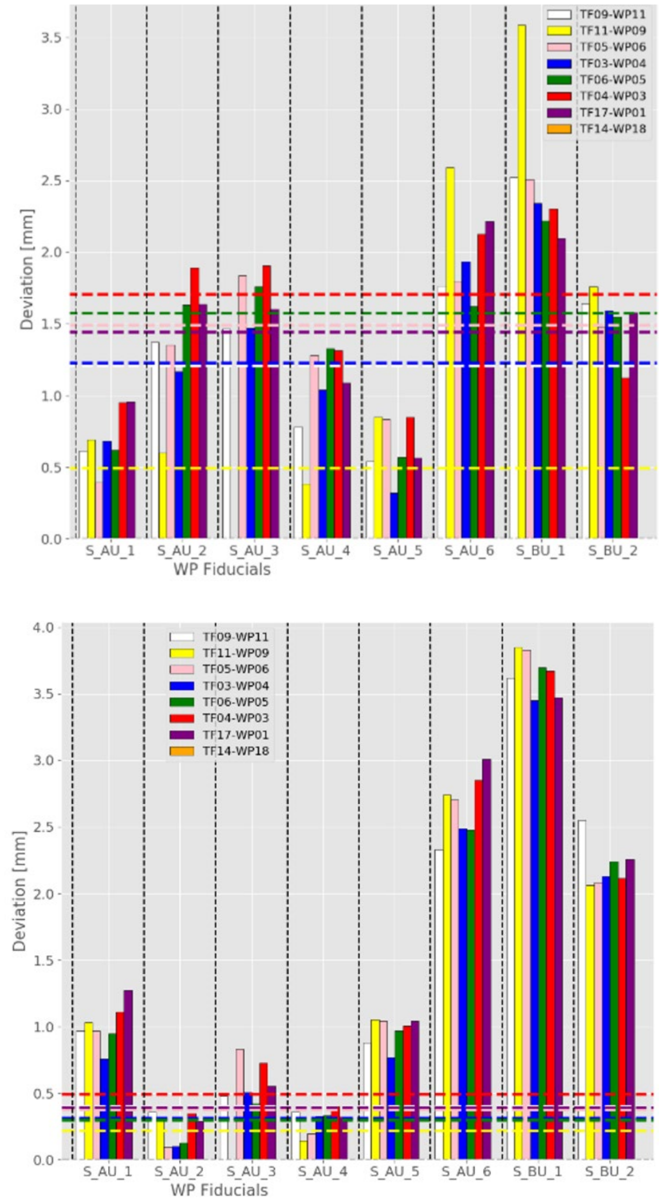
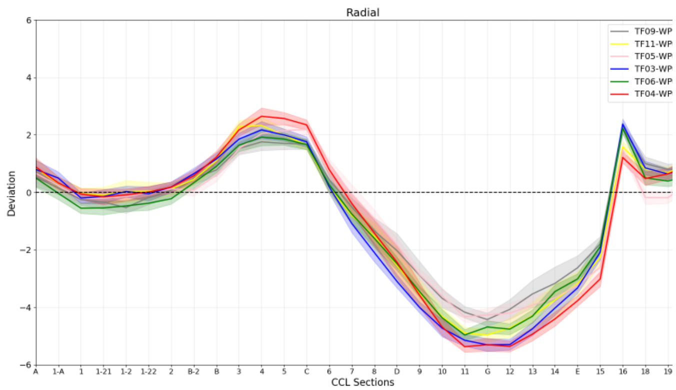


Fig. 6. Deviation of WP Fiducial Points measured after the welding process, before (top) and after (bottom) optimization alignment for machining. Dashed line indicates average value of the SL inboard fiducials, which is highly reduced after the optimization for all coils.

E. Final CCL values

The final position of WP Fiducial points is then used to calculate that of the 30 CCL points. In the next page, Fig.8 shows the final deviation of the CCL in the radial and vertical directions of the European TF Coils completed so far. The vertical direction is defined as the out-of-plane axis of the WP, while, while the radial direction corresponds to the perpendicular direction of the CCL in the WP plane. The radial deviations are very similar for all the TF coils, and close to zero average in the SL area (sections A to B), following the optimization works, and they present a global deformation near equatorial G section, which is thought to be due to closure welding deformation. In the out-of-plane direction, results show a higher dispersion, but with generally lower deviation values and always oscillating around zero value. This difference is probably due to the manual distribution of interlayer insulation shims between DP during the stacking phase, which is more difficult near the terminal region area (sections 16 - 19).



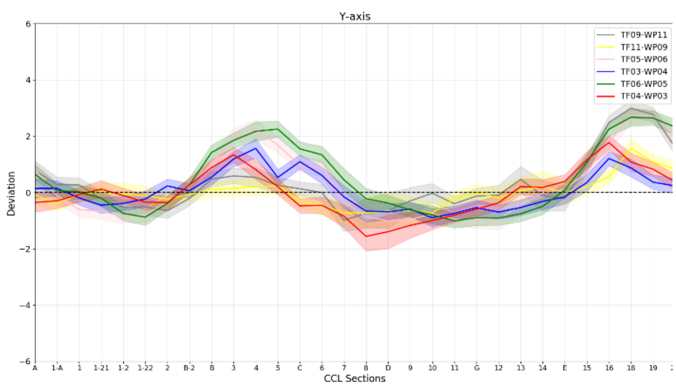


Fig.8. Final CCL radial and vertical deviations of TF coils with bands of uncertainty (at 2σ) from measurements and calculation method.

Again, it is worth to note the high degree of similarities for all the coils produced to date, which is a very positive outcome for the subsequent part processing at IO in the assembly phase and good starting point for the evaluation of the Error Field assessment.

F. Further work

The CCL data is further used in F4E's Error field analysis and to study potential relationship with other magnet's parameters. On the former, it follows previous work [5], and the calculations includes CCL from European and Japanese TF and PF coils. PF CCL is obtained using the same calculation method based on DI and manufacturing data, slightly adapted to the specificities of the PF architecture (e.g lack of radial plates). Details of the PF CCL calculations are presented in [9]. The CCL data is processed to include in the Error Field analysis not only manufacturing effects, but also operation load effects of Gravity, Preload, Cool Down, and Coil Energization, which are obtained by Finite Element analyses [10]. Three different plasma scenarios are considered, and calculation model is benchmarked against independent analysis. Preliminary results for the TF and PF considered so far, at their respective manufacturing and assembly stages at March 2021 are reported in Table 1 below, and they show contribution to Error Field well below required thresholds. Work is ongoing and will need CCL results for the whole ITER Magnet System. It is worth to mention that the results show satisfactory agreement with other parallel studies developed independently at IO.

mT	Plasma Sc. 1	Plasma Sc. 2	Plasma Sc. 3
n=1	97.26	37.53	11.24
Limit	420	250	80

Table 1. Error field values for each plasma scenario under study, for mode 1 (n=1), considering as-built CCL values.

Besides the data regarding the CCL, other data collected during the manufacturing and testing of the TF is collected and processed by F4E. Work is ongoing to analyze the data available, in order to extract information and potential insights, such as a potential relationship between CCL results and magnetic measurements of the WP. These measurements were taken using Hall probes assembled with laser tracker probes to map the magnetic field around the WP with 200A DC current, and the preliminary work on going indicates very similar magnetic behavior of the WPs, in line with the outcomes of CCL calculations based on pure geometrical measurements.

IV. Conclusions

F4E created CAE models and methods to manage the CCL position throughout the TF manufacturing, using suppliers' DI and manufacturing data from EU and Japan. The standardized and controlled procedure collects, processes, and stores all the technical data maintaining configuration and traceability. The priorities defined jointly between the IO, JADA and F4E are considered to meet the requirements of CCL positioning and tolerances check, and to increase the degree of harmonization between Japanese and European TFs. All outputs obtained so far suggest very stable manufacturing and allow the EU TF magnets to be considered as a coherent set of components. All CCL related data is further used by F4E and IO for Error field Analysis and relationships with other magnet's parameters are also under study (e.g. warm magnetic measurements). The low contribution of CCL position to Error Field will allow IO to focus their efforts on the foreseen assembly operations without having to consider corrective realignment of the coils, either with respect to each other or to other components in the machine.

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