A Double Check Process for CCL Positional Plates in ITER TF Coil Integration*)

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A current center line (CCL) was precisely controlled with markers called "CCL positional plates (CCLPPs)" during the ITER toroidal filed (TF) coil integration. CCLPPs with the same x and y coordinates (CCLPP pair) are attached on both sides of the TF coil Winding Pack (WP). The CCLPP insufficiently fixed has to be replaced with new one to ensure the accuracy of CCL. On the other hand, the replacement possibly leads to some issues, such as, dropping the CCLPP into the CC and damaging the WP. Thus, unnecessary replacement should be avoided. We have therefore implemented a double check process to confirm soundness of the CCLPPs. First, change of the distance of CCLPP pair ($\Delta W_{\mathrm{CCLPP}}$) is evaluated (Check A). However, $\Delta W_{\mathrm{CCLPP}}$ would be influenced by the WP deformation. Thus, the Check A possibly judges the fixing condition of the CCLPP as "unusual" even if it has no issue. This may lead to the unnecessary replacement of the CCLPP. To avoid the unnecessary replacement, the local displacement of each CCLPPs ($\Delta r_{\mathrm{CCLPP}}$) is also evaluated (Check B). In this paper, we define the criteria for "unusual" $\Delta W_{\mathrm{CCLPP}}$ and $\Delta r_{\mathrm{CCLPP}}$ based and verify its validity for the TF coil integration by considering the measurement error and geometrical configuration of the CCLPPs. In the case of one Toshiba TF coil, the double check process confirmed that CCLPPs were insufficiently fixed, and they were successfully replaced to the new ones. Thus, it was demonstrated that the proposed criteria indicated the appropriate action to keep the CCLPP soundness. The method proposed in this paper would be powerful tool to inspect the soundness of the CCLPP which is important for the CCL control not only in the ITER TF coil, but also in the future fusion magnets.

Keywords: ITER, toroidal filed coil, winding pack, superconducting magnet, current center line

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1. Introduction

The ITER magnet system has 18 Toroidal Field (TF) coils for plasma confinement. National Institutes for Quantum Science and Technology (QST), as the Japan Domestic Agency (JADA), is responsible for the procurement of 9 ITER TF coils and 19 TF coil cases (CCs) [1–6]. Figure 1 illustrates a winding pack (WP) and CC of the TF coil. The WP with 7 pancake coils made of 68 kA class Nb_3Sn conductors is integrated into the CC withstanding several-hundred-MN electromagnetic forces. Procedure of the TF coil integration [4] is as follows, (1) half of CC with opened surface is placed on the floor with its inner board facing down, (2) WP is inserted into the CC, (3) another half of the CC with opened surface is placed over the WP, (4) interface of the two halves of CC is welded, (5) opened surface of the CC is closed with plates (closure welding), (6) the gap between CC and WP is filled with epoxy resin (gap filling). During the TF coil integration process, current center line (CCL) is controlled with accuracy of 1.3 - 3.0 mm [4, 7]. It is possible to geometrically track the CCL location by using CCL markers on the WP in the processes (1) - (5) [4]. However, the CCL markers are not visible after the closure welding. Thus, we use additional markers on the WP (CCL positional plates, CCLPPs) to calculate the CCL location. The CCLPPs are attached on both sides of the WP, and some of them have the same x and y coordinates (CCLPP pair) as shown in Fig. 2. Notably, the CCLPPs can be seen through the gap-filling port even at the closure welding. The CCL location is calculated with geometrical relationship between the CCL and CCLPP. Thus, it is important to check the fixing condition of the CCLPP. The CCLPP insufficiently fixed has to be replaced with new one to avoid the change of the geometrical relationship of the CCL and CCLPP. On the other hand, the replacement possibly leads to some issues, such as, dropping the CCLPP into the CC and damaging the WP. Thus, unnecessary replacement should be avoided.

In this paper, we propose a double check process to check the fixing condition of the CCLPPs. This process allows to keep the soundness of the CCLPPs without their unnecessary replacement during the TF coil manufacturing. Then, the reasonable criteria for the proposed process

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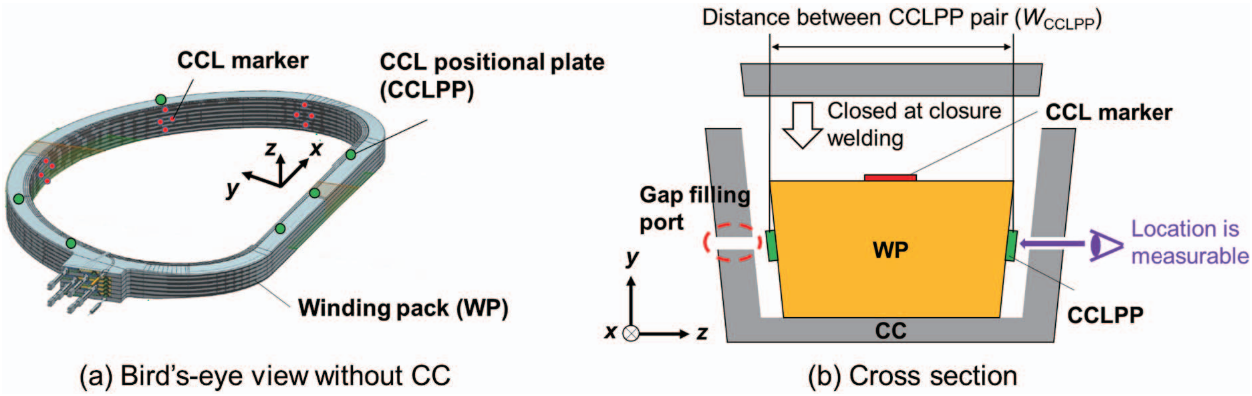

Fig. 1 The WP, CC, and markers used for the ITER TF coil integration.

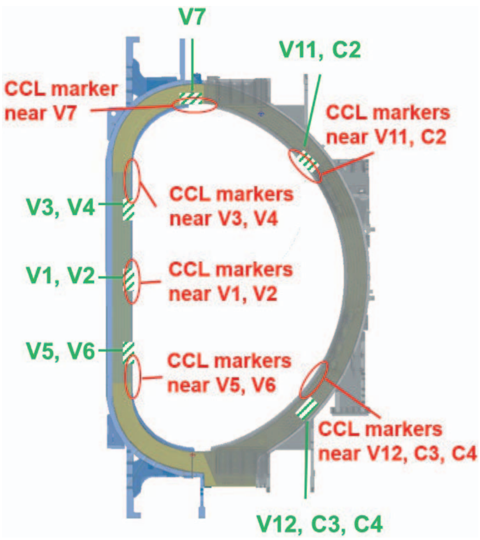

Fig. 2 Location of the CCL markers and CCLPPs.

are defined with a numerical analysis to correctly identify the insufficiently fixed CCLPPs. Then, we verify its validity in the actual TF coil integration. Section 2 describes the CCL calculation method at the closure welding in terms of the necessity of the CCLPPs. Section 3 describes the principle of the proposed double check process for the soundness of the CCLPPs. Section 4 presents criteria of the double check process. Discussion on applicability of the proposed method with an actual example of TF coil integration is shown in Section 5, followed by a conclusion in Section 6.

2. CCL Calculation at Closure Welding

As describe in the Section 1, the CCLPPs on the WP are used to calculate the CCL location at the closure welding, which can be observed from the gap filling ports. We confirm the positional relationship among the CCL and CCLPPs before the closure welding, and the CCL location is traceable. Here is the example; when the CCL at a certain measurement point (local CCL) moves from the last measurement, the CCLPPs close to that point should move as well. Thus, the location of the local CCL at present measurement ($\boldsymbol{x}'_{\mathrm{CCL}}$) can be calculated as

$$\begin{aligned} \boldsymbol{x}'_{\mathrm{CCL}} &= \boldsymbol{x}_{\mathrm{CCL}} + \delta\boldsymbol{x}_{\mathrm{CCL}} \\ &\sim \boldsymbol{x}_{\mathrm{CCL}} + \delta\boldsymbol{x}_{\mathrm{CCLPP}}, \end{aligned} \tag{1}$$

where the vectors of $\boldsymbol{x}_{\mathrm{CCL}}$, $\delta\boldsymbol{x}_{\mathrm{CCL}}$, and $\delta\boldsymbol{x}_{\mathrm{CCLPP}}$ are the location of CCL at the last measurement, and the displacement of the CCL and CCLPP, respectively. Notably, CCL and CCLPP are assumed to be sufficiently close so that the difference between $\delta\boldsymbol{x}_{\mathrm{CCL}}$ and $\delta\boldsymbol{x}_{\mathrm{CCLPP}}$ is negligible. To ensure the accuracy of $\boldsymbol{x}'_{\mathrm{CCL}}$, fixing condition of the CCLPP must be checked before the closure welding.

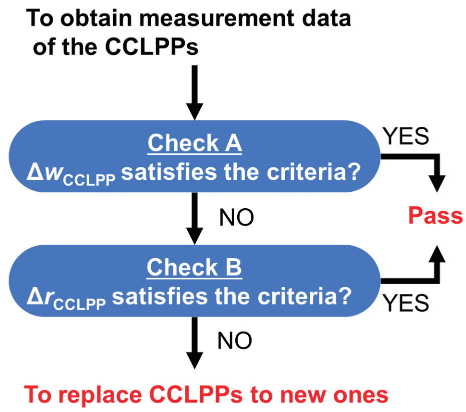

Fig. 3 Flow chart of the double check process.

3. Double Check Process for CCLPP

We have implemented a double check process to confirm if the CCLPPs are fixed firmly as follows. Figure 3 illustrates the flow chart of the double check process.

Check A: Distance between CCLPPs pair

In a first process of the double check process (Check A), change of the distance between the pairs of two CCLPPs ($\Delta W_{\mathrm{CCLPP}}$) are checked. This process does not

Table 1 CCLPP pair.

CCLPP pair	CCLPPs
I	V1, V2
II	V3, V4
III	V5, V6
IV	C3, C4

need the complex calculation, and it allows the quick check of the CCLPPs. Table 1 shows the combination of the CCLPPs whose x-y coordinates are almost same (CCLPP pair). Large $\Delta W_{\mathrm{CCLPP}}$ indicates the "unusual" movement of CCLPPs. However, $\Delta W_{\mathrm{CCLPP}}$ would be influenced by the WP deformation. Thus, the Check A possibly judges the fixing condition of the CCLPP as "unusual" even if it has no issue. This may lead to the unnecessary replacement of the CCLPP. Considering the risk of replacement of CCLPPs, such as damage on the WP and drop of the CCLPP, it is desirable to avoid the unnecessary replacement. Thus, "Check B" is also used to check the CCLPPs to avoid the unnecessary replacement.

Check B: Displacement of the CCLPPs

We propose the secondary process to check the displacement of the CCLPPs to avoid the unnecessary replacement of the CCLPPs. The proposed process utilizes the similar method used for CCL calculation with CCL markers [8]. The principle is as follows. First, the set of the CCLPPs and "three" CCL markers which are close to the selected CCLPPs are prepared, and their locations are measured. Then, the positional vector of the CCLPP with respect to the CCL markers ($\boldsymbol{r}_{\mathrm{CCLPP}}$) is expanded as

$$\boldsymbol{r}_{\mathrm{CCLPP}} = a\boldsymbol{\alpha} + b\boldsymbol{\beta} + c\boldsymbol{\gamma}, \tag{2}$$

$$\boldsymbol{\gamma} = \frac{\boldsymbol{\alpha} + \boldsymbol{\beta}}{|\boldsymbol{\alpha} + \boldsymbol{\beta}|}, \tag{3}$$

where a, b, and c are the constants, and they are calculated with the measured coordinates of CCL markers and CCL PP. Figure 4 illustrates the positional relationship among the vectors, CCLPP (green mark), and CCL markers (red marks). Then, the CCL markers are measured again when the fixing condition of the CCLPP should be confirmed. The updated $\boldsymbol{r}_{\mathrm{CCLPP}}$ ($\boldsymbol{r}_{\mathrm{CCLPP}}'$) is calculated by equation (2) where a, b, and c have already determined in previous step. Notably, this holds with the assumption where the close CCL markers and CCLPPs move in the same way. It is possible to identify the CCLPPs with insufficient fixing condition by checking the difference of $\boldsymbol{r}_{\mathrm{CCLPP}}$ and $\boldsymbol{r}_{\mathrm{CCLPP}}'$ ($\Delta\boldsymbol{r}_{\mathrm{CCLPP}} \equiv \boldsymbol{r}_{\mathrm{CCLPP}}' - \boldsymbol{r}_{\mathrm{CCLPP}}$). In practice, the norm of $\Delta\boldsymbol{r}_{\mathrm{CCLPP}}$ ($\Delta r_{\mathrm{CCLPP}}$) is used in this process. We always have four ($= {}_4\mathrm{C}_3$) values of $\Delta r_{\mathrm{CCLPP}}$ with different sets of "three" CCL markers. Thus, $\Delta r_{\mathrm{CCLPP}}$ indicates the mean of its four values in the following of this paper. Although the Check B takes more process than the Check A, it directly shows the movement of CCLPPs with less influence of the WP deformation.

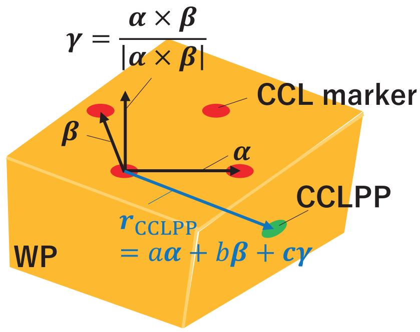

Fig. 4 Calculation of $\boldsymbol{r}_{\mathrm{CCLPP}}$ in check B.

4. Criteria for the Double Check Process

The criteria for both unusual $\Delta W_{\mathrm{CCLPP}}$ and $\Delta r_{\mathrm{CCLPP}}$ should be defined by considering the measurement accuracy and geometrical configuration of the CCL markers and CCLPPs. In check A, $\Delta W_{\mathrm{CCLPP}}$ would be influenced by the accuracy of measurement instrument. The instrument used in the TF coil integration is the laser absolute tracker manufactured by Leica, and its measurement error (deviation) is less than 0.1 mm. Thus, the criterion for "unusual" $\Delta W_{\mathrm{CCLPP}}$ was set to be 0.1 mm. Similarly, $\Delta r_{\mathrm{CCLPP}}$ in Check B would be influenced by the measurement accuracy. The error in $\Delta r_{\mathrm{CCLPP}}(\varepsilon_{\mathrm{CCLPP}})$ due to the ~0.1 mm measurement error should be larger with longer distance between the CCLPP and closest CCL markers (r_{CCLPP}). Thus, the expected $\varepsilon_{\mathrm{CCLPP}}$ considering this effect was calculated to determine the criterion for $\Delta r_{\mathrm{CCLPP}}$. Assuming up to three CCL markers have the measurement error, we calculated the expected $\varepsilon_{\mathrm{CCLPP}}$ for all the CCLPPs by using the equation (2). The assumed measurement error was ±0.1 mm in x, y, or z components of the CCL markers' coordinates. Notably, the designed coordinates of CCL markers and CCLPPs were used to obtain the equation (2). Figure 5 shows the calculation results; the x axis is r_{CCLPP}, and the y axis is the expected $\varepsilon_{\mathrm{CCLPP}}$. The larger r_{CCLPP} leads to the larger $\varepsilon_{\mathrm{CCLPP}}$ as expected, and their relationship looks nearly proportional. The equation for linear approximation of r_{CCLPP} and $\varepsilon_{\mathrm{CCLPP}}$ is yield to

$$\varepsilon_{\mathrm{CCLPP}}(r_{\mathrm{CCLPP}}) = 5.56 \times 10^{-4} r_{\mathrm{CCLPP}}. \tag{4}$$

We use this $\varepsilon_{\mathrm{CCLPP}}(r_{\mathrm{CCLPP}})$ for the criterion of $\Delta r_{\mathrm{CCLPP}}$, which is $\Delta r_{\mathrm{CCLPP}} \leq 5.56 \times 10^{-4} r_{\mathrm{CCLPP}}$. Table 2 summarizes the criteria for the double check process.

5. Evaluation of the Displacement of CCL Positional Plates of the ITER TF Coils

Displacement of the CCLPP of the ITER TF Coils just before the closure welding was evaluated with the dou-

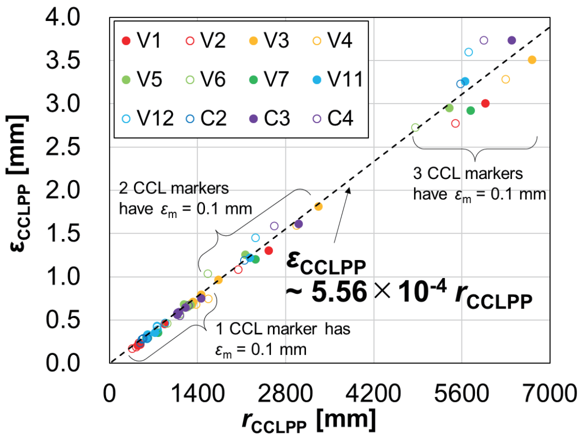

Fig. 5 Results of the error analysis.

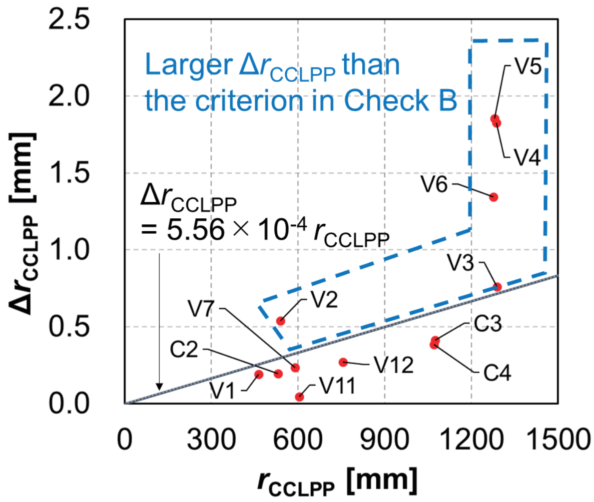

Fig. 6 Results of the error analysis.

Table 2 Criteria for the double check process.

Check	Criteria
A	$\Delta w_{CCLPP} \leq 0.1$ mm
B	$\Delta r_{CCLPP} \leq 5.56\times10^{-4}\, r_{CCLPP}$ [mm]

ble check process. Targets in this section are TF10/JA03, TF16/JA07, and TF15/JA08, which are manufactured by Toshiba Energy Systems & Solutions Corporation, Japan.

First, ΔW_{CCLPP} were estimated in Check A. The locations of CCLPPs after AU-BU welding and just before the closure welding were used to calculate ΔW_{CCLPP}. All the CCL pairs satisfied the 0.1 mm criterion in the TF10/JA03 and TF16/JA07, which were less than 0.05 mm. On the other hands, some CCL pairs in the TF15/JA08 (V3 - V4 and V5 - V6) showed $\Delta W_{CCLPP} > 0.16$ mm, which was larger than 0.1 mm. However, this was possibly caused by the WP deformation as mentioned in the Section 3. Thus, the process went to the Check B to check the necessity of their replacement. In the Check B, the equation (2) was obtained with the measurement data at the start of coil integration. Then, location of all the CCL markers were measured, Δr_{CCLPP} was calculated with the equation (2) just before the closure welding. Figure 6 shows the calculation results of Δr_{CCLPP} with respect to r_{CCLPP}. The line of the criterion is also shown in the figure. Δr_{CCLPP} of V1, V7, V11, C2, C3, and C4 are smaller than the criterion. This result is reasonable because ΔW_{CCLPP} satisfied the criterion in the Check A as described before. On the other hand, Δr_{CCLPP} of V2 - V6, which are the CCLPPs in the inner board region, is larger than the criterion and not acceptable. Since the fixing condition of V2 - V6 was judged as “unusual” by the double check process, V2 - V6 were removed and visually checked. As the results, it was confirmed that the fixing of V2 - V6 was not sufficient due to lack of the glue and successfully replaced to the new ones.

Conclusively, the Check A could roughly estimate the behavior of the CCLPPs. Then, the Check B could accurately identify the CCLPPs with insufficient fixing condition with a proposed criterion. These results demonstrate that the double check process and its proposed criteria can keep the soundness of the CCLPPs to manage the CCL accurately. This method would be useful tool to manage the CCL control not only in the coming TF coils, but also in the manufacturing of future fusion magnets.

6. Conclusion

In this paper, a double check process used to check the soundness of the CCLPPs of the ITER TF coil during its integration was proposed and its applicability for the TF coil integration was verified with the actual TF coil. The highlights are as follows:

- The double check process to judge the fixing condition of the CCLPPs was proposed.
- The appropriate criteria for the double check process were proposed by the numerical analysis considering the measurement error and geometrical configuration of the markers.
- The double check process indicates “unusual” behavior of some CCLPPs of TF coil TF15/JA08, and it was confirmed that fixing condition of the CCLPPs was insufficient. Those were successfully replaced to new ones. Thus, it was demonstrated that the proposed process is applicable for the inspection of soundness of the CCLPPs at ITER TF coil integration.

The method proposed in this paper would be powerful tool to inspect the soundness of the CCLPP which is important for the CCL control not only in the ITER TF coil, but also in the future fusion magnets. JADA is going to apply this method also for the coming ITER TF coils and target the completion of accurate manufacturing of them.

Acknowledgement

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