대표10

Assembly of the Poloidal Field Coils in the ITER Tokamak

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***Abstract*—The ITER poloidal field (PF) magnet system is a set of six circular coils attached to the periphery of the toroidal field coil (TFC) structure. While the manufacturing of the PF coils is being launched in three different countries, the ITER Organization (IO) is looking ahead at assembly of PF coils in the tokamak. The PF coils can be grouped in three pairs with respect to their similarities in design and attachment to the TFC, which leads to preparation of different strategies and tooling for the transportation and assembly. The procedures shall also consider the integration, assembly sequence, and environment of the whole tokamak. For example, the two lower coils PF6 and PF5 must be brought in storage position in the tokamak pit and stay there until all the TFCs are assembled, before being attached to them. This paper presents the assembly scenario of the PF coils, including logistics, analysis of assembly tolerances, aligning strategy, and detailing the particularities of each PF coil, from the moment they are delivered to IO until they are connected to the feeder, waiting for the commissioning of the machine.**

***Index Terms*—Fusion, ITER, PF coil, magnet, tokamak assembly.**

I. Introduction

The ITER Poloidal Field (PF) magnet system consists of six PF coils (PF1 to PF6) procured by the European (EUDA) and Russian (RFDA) domestic agencies under separate procurement arrangements (PA). The RFDA will manufacture the PF1 coil in St Petersburg. The EUDA will manufacture the PF2, PF3, PF4 and PF5 coils in the building B55 located on the ITER site and the PF6 coil in Hefei (China). All coils use Niobium–Titanium (NbTi) superconducting cable-in-conduit conductor. The PF coil provides the position equilibrium of plasma current (i.e. the fields to confine the plasma pressure) and the plasma vertical stability.

The outer diameters of the coils vary between 8 and 24 m and weight between 140 and 320 tons (Table I). The six PF coils are attached to the Toroidal Field Coil (TFC) structures through PF supports [1]. To allow the radial deformations of the PF coil during cooldown or under the electromagnetic loads, the supports are constituted either of flexible clamps (PF2 to PF5) or sliding clamps (PF1 and PF6) [3].

The PF supports are already installed on the PF coils when they are delivered to the IO. The supports are the only allowed points where the PF coils can be handled or lifted.

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TABLE I
Size and Weight of the PF Coil

Coil	Mean radius (m)	WIDTH x HEIGHT (m x m)	WEIGHT without SUPPORTS(t)	WEIGHT with SUPPORTS (t)
PF1	3.955	0.98x1	144	201
PF2	8.310	0.6x0.73	143	184
PF3	12.028	0.72x0.98	324	388
PF4	11.999	0.66x0.98	299	361
PF5	8.416	0.83x0.97	253	316
PF6	4.347	1.6x1.13	279	380

In this paper, the design and function of the PF supports are explained since they are the main interface for the assembly and accurate positioning of the PF coil. Then the general workflow for the assembly is described. Finally, the paper details the difference of installation among the 6 PF coils.

II. PF Supports

The main functions of supports are: i) to hold PF coils in position on TFC structure, ii) to accommodate radial deformation of the PF coils with respect to the TFC, iii) to accommodate the operational TFC out of plane deformations, and iv) to allow the handling and lifting of the coils.

Each support includes a pair of bottom and top clamps that are mounted onto the winding pack with pre-tensioned tie-rods.

PF2 to PF5 are supported by 18 supports. The A286 tie-rods are highly preloaded at room temperature up to 75% of yield strength in order to block by friction the coil within the clamps and prevent the coils from sliding during plasma operation at 4K. One of the 2 clamps is bolted to the TFC structure. This clamp has a U-shape that can flex in the radial direction to allow the expansion and contraction of the PF coil with respect to the TFC under the Lorentz forces, or during cold down (Fig. 1).

PF1 and PF6 coil have 9 clamps because of their smaller radius. As the space is limited and vertical Lorentz forces are high in both upward and downward directions, sliding supports are provided instead of flexible plates. The sliding supports utilize a low friction material (MoS^2 coating) to allow radial displacement of the coil. In the vertical direction, PF1 and PF6 are maintained against the TFC by the TF support plates which are directly tightened to the TF.

One of the most critical items in the manufacturing and assembly procedure is the tolerances. To operate the plasma, highly tight tolerances are required for the shape of the as-built

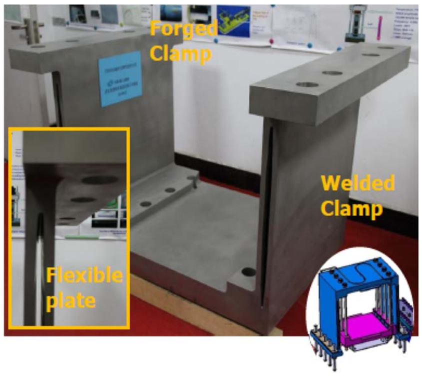

Fig. 1. PF5 U-shapes clamp with flexible plates (3-D model and prototype—courtesy of CNDA).

PF coils (3 to 4 mm on the height and radius), in regards of the coil size (up to 24000 mm diameter for PF3 or PF4), and the same accurate tolerances are required when assembling the PF coils on the TFC system (1 mm vertically and 2 mm radially) [2], [5]. These tolerances will be achieved by controlling the shape of the different components all along the manufacturing process and mitigated by the customization of shims during the assembly.

Since the TFC are massive welded structures, it is already known that the tolerances for the point where the PF supports are bolted to the TFC will be in the centimetre range, which is the result of manufacturing, measurement and positioning tolerances. The annular position of the circular PF coils is imposed by the terminal that will be connected to the feeder. To position the PF coil accurately radially and vertically, the assembly procedure of the coils relies, in complement of the assembly tools, on a survey of the as-assembled TFC in order to clamp the PF supports in the optimum position, on oversized bolt holes and on the customization of shims in the supports during the assembly.

III. General Assembly Workflow

A. Reception of the PF Coil by IO

According to the PA, the PF2 to PF6 coils produced by EUDA will be delivered to IO inside the building B55. The delivery of the PF1 coil by RFDA is planned to occur at the unloading area of the ITER site. However RFDA is considering performing the cold tests of PF1 in the EUDA cold test facility. In this case, the delivery of PF1 could also occur in B55.

IO will provide a transportation frame and self-propelled modular transporters (SPMT) to move the coils out of B55. EUDA will equip B55 with a gantry crane with the capacity of 400 tons. The loading of the coils on the vehicle is a joint activity between IO and the DAs, the details of which shall be agreed. Once loaded on the transportation frame, the ownership of the PF coils will legally be given to the IO, who is in charge of subsequent operations.

B. Storage

With the exception of PF3, the last coil to be manufactured, all the other coils shall be removed from B55 to leave space for the next coil to be produced. Once fixed on the transportation frame with IO ownership established, the coil will be driven to a storage area. Table II demonstrates the DA and IO schedule integration that would allow a closure of the cryostat in October 2024. Although the dates might not be the final yet, Table II shows that a storage area is unavoidable considering the time lag between the planned coil delivery dates to IO in B55 and when they are needed for the assembly in building B13. The location of the storage area on the site is not yet defined [4], but will probably be close to B55 and B13 to limit the transportation time. If there is no crane in this area, 3 different transportation frames shall be built and stay under the coil, or one frame shall be designed to be removed when the coils are unloaded.

TABLE II
Storage Duration of the PF Coils

Coil	Mean radius (M)	WIDTH x HEIGHT (m x m)	WEIGHT without SUPPORTS(t)	WEIGHT with SUPPORTS (t)
PF1	3.955	0.98x1	144	201
PF2	8.310	0.6x0.73	143	184
PF3	12.028	0.72x0.98	324	388
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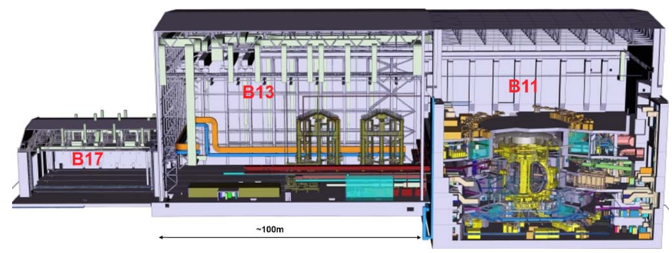

Fig. 2. Cleaning facility building (B17), assembly building (B13) and tokamak building (B11).

C. Assembly Hall

The details of the subsequent operations are jointly assessed by the IO Magnet (MAG) and Assembly (TAD) divisions. MAG is responsible for the technical requirements, procedures and specific assembly and is developing the related assembly and inspection plans (AIP). TAD is in charge of the major tooling, handling operation, general operations, access control and overall scheduling. They also prepare the corresponding construction work packages (CWP).

Before being moved to the tokamak pit, the PF coils will be driven with the SPMT through the cleaning facility B17 (Fig. 2) to be unpacked and cleaned, then to the assembly hall B13, to undergo the final preparation and checks, mainly consisting to the preparation for the lifting operation to the pit and of the terminal for the connection to the feeder in the pit. This stage is estimated to last for 20 days.

In building B13, lifting adapters will be fixed to the PF coil supports and the coils moved down by a 1500-ton crane to the

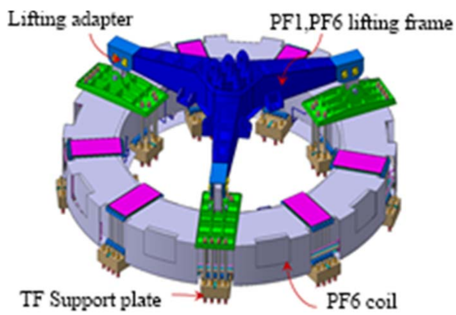

Fig. 3. PF6 coil with its lifting frame and adapters bolted to the TF support plates.

pit in building B11 and directly connected to the TFC, with the exception of the PF5 and PF6 coils. These 2 coils are located at the bottom of the tokamak and shall first be laid down on temporary supports before the TFC system is assembled above them. Then their installation can be completed. This explains the 3-year gap for the start of assembly between the PF5 and PF6 and the 4 other ones.

D. Tokamak Pit

The major steps for each PF coil in the pit are as follows:

- The installation of the PF coils into the TFC system consists in the survey of the TFCs, the lifting of the PF coils and supports, the survey of the PF coil position, the customization of almost 200 shims per coil in order to adjust the radial and vertical position of the PF coils to the millimeter range in regards to the as-assembled TFCs (see Section IV). The last step is the loading of the 180 M56 bolts of the supports of each PF coil. The estimated duration is 50 days.
- The connection to the feeders-welding of cryogenic pipes, assembly of the joint of the electrical superconducting busbars, the interconnection of high voltage (quench detection voltage taps) and low voltage instrumentation (temperature sensors) and applying insulation to withstand 30 kV on all HV components-will last for 70 days.
- Optimistically, five days will be needed to test the installed and connected PF coils—leak tightness, pressure drop, electrical continuity and correct labelling, dimensional survey and HV electrical test.
- For the safety of the workers who will operate at a few meters' height, in parallel to other activities where the simplest component weighs more than 10 kg, a minimum of 5 days are anticipated to install, secure and dismantle the working area.

IV. PF Coils Installation

A. PF6/PF1

PF6 and PF1 are the 2 smallest PF coils and their stiffness is high enough, basically a 8 m-diameter steel ring of 1 m $\times$ 1 m cross section to be handled, supported and lifted using only 3 points lifting (Fig. 3, [6]).

For PF1, the bottom clamp cannot be used because this area will land directly on the TFC. Lifting adapters will be directly bolted to the top clamp and the 200 tons of dead weight of PF1 is supported by 3 bottom clamps of 100 mm thickness and their eight 48-mm diameter tie-rods. For the fine positioning of PF1 in radial and toroidal directions, alignment units will be fixed to the 3 top clamps and guide PF1 against 3 alignment counterparts already fixed to the TFC (Fig. 4).

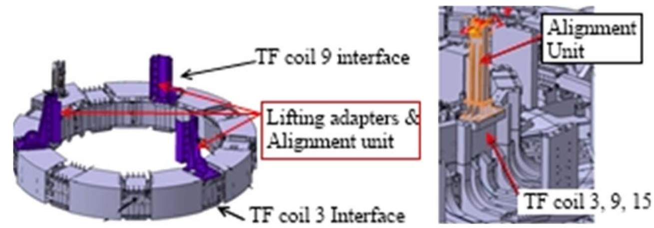

Fig. 4. PF1 coil equipped with the 3 alignment units (left picture), that will slide against the alignment units fixed on the TF (right picture).

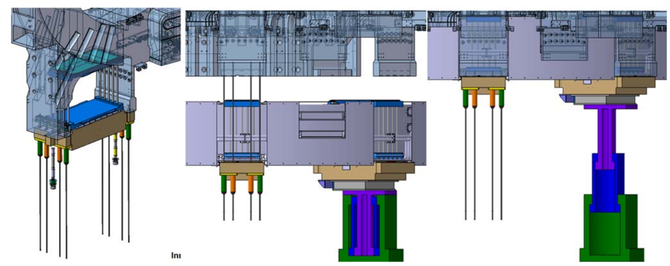

Fig. 5. PF6 lifting system. TF support plate, hollow jacks and TFC, PF6 hidden (left). PF6 coil ready for lifting, on the temporary support (center). PF6 in final position with the telescopic cylinders at full stroke (right).

For PF6, the TF support plates are tightened to the lifting adapters around the coil (Fig. 3) and PF6 is moved down on temporary supports installed in the pit (Fig. 6), waiting for about 3 years for the 18 TFC to be assembled above it. Then a hollow jack system is connected between the TFC and 6 of the 9 TF support plates, to pull up step by step the hanging PF6 coil along a 2 m path (Fig. 5). The PF6 coil is then secured in position by bolting the 3 remaining TF supports plates to the TFC and the hollow jack system is removed and replaced by the final bolts.

The support plates will be guided into position by a conical guiding cylinder screwed in the TFC. The radial and toroidal positioning of the PF6 coil in the tokamak relies then on the right alignment of PF6 coil to the TF support plate before lifting.

For securing the position of the coil during the lift, 3 temporary supports are based on double telescopic hydraulic cylinders with valves stopping any lowering. The telescopic cylinders follow the coil during lifting, and support the coil weight while the hollow jacks are repositioned. Each pile will have a second safety level with a shear pin to insert in the support at every step.

B. PF5/PF2

The same lifting methods and tools apply to PF5 and PF2. Like PF1, PF2 shall be lifted by the top. The lifting adapter shall be fixed to the upper flat clamp. For the alignment in the tokamak, the same type of alignment units as PF1 will be used.

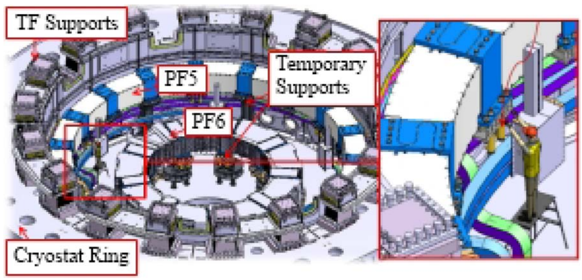

Fig. 6. PF5/PF6 in temporary position in the PIT, with a zoom on a worker.

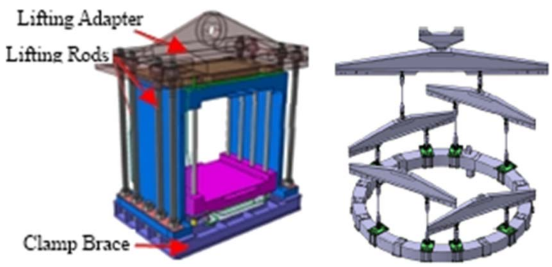

Fig. 7. PF5 with its lifting adapters bolted through the flexible clamp to the clamp brace (left). Configuration of the Spreaders beams connected to the lifting adapters.

Like PF6, PF5 will firstly rest on temporary supports (Fig. 6). The holes in the flexible U-shaped clamps will be used for the lowering down (Fig. 5) to the temporary supports [7] and later for the shifting up and auto-alignment to the TFC by a similar hollow jack system and conical guides as for PF6.

To limit the stresses in the insulation, there shall be a maximum of 80° between two clamps where PF5 is supported or lifted. Due to the different handling operations, constraints in the pit or crane configuration, the lifting points cannot be evenly separated. A specific arrangement of the spreader beams has been defined (Fig. 7) and analyzed [8] to use 3 hooks of the 1500-ton crane and guarantee an even loading of the 8 lifting points. To simplify the spreader, IO is also considering the option of 4 points with elastic absorber so as to ensure good load spreading. In any case, the same method of lifting will be used for PF2, PF3 and PF4 coils.

C. PF4/PF3

The specificity of PF3 and PF4 assembly is that they are commonly supported by 18 struts, forming a "squirrel cage" around the TFC (Fig. 8). A strut is a vertical beam bolted to one PF4 clamp at the bottom and one PF3 clamp at the top and connected to a TFC through a dowel. By rotating in regard to the TFC, the dowel keeps the struts vertical during the out-of-plane deformations of the TFC.

During assembly, the squirrel cage cannot be lowered into the pit in a single piece. PF4 is installed and precisely positioned first on a few temporary brackets (onto jacking system), and then the struts are lowered, inserted radially into the TFC by their dowel and secured to prevent them from falling. Shims between PF4 supports and the dowels are installed and the PF4 is bolted to the struts. Then PF3 is lowered, shimmed and bolted to complete the squirrel-cage.

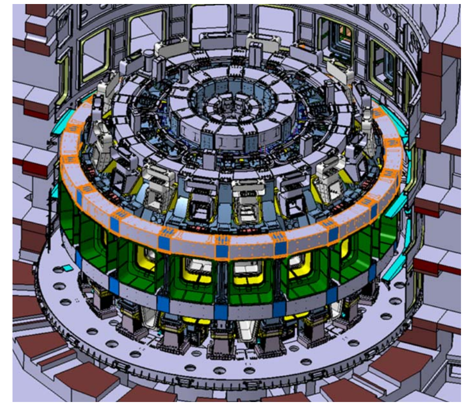

Fig. 8. Squirrel cage of the PF3 and PF4 coils with their struts.

One of the difficulties in the process is the tight space around PF3/PF4. For instance, the Side Corrections coils (SCC) are installed between the TFC and PF3 and PF4. Despite an optimized and individualized design of the SCC supports, there is only a nominal gap of 30 mm between these SCC supports and the 2 PF coils.

V. Conclusion

The assembly procedures and definitions of the tooling are already quite advanced. Sequences and durations of activities have been defined considering the overall assembly schedule in the pit, the availability and interferences with the other components of the ITER tokamak. MAG and TAD shall continue to define the assembly procedures down to the minutest detail and refine the assembly schedule to include all the logistics before the components are ready for lowering into the pit, the possibilities for overlapping activities, the bottlenecks such as the available time for the 1500-ton crane and, last but not least, ensuring the safety of the workers during this exciting period.

Disclaimer

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

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