Status of the project: New Upper Divertor with coils in ASDEX Upgrade

I. Zammuto, A. Herrmann, M. Weißgerber, V. Brack, V. Rohde, G. Schall, M. Teschke, T. Vierle, S. Vorbrugg, B. Petzold, W. Zeidner, Paolo Badino, Marco Dani, the ASDEX Upgrade Team

Abstract— **ASDEX Upgrade (AUG) is the German mid-size Tokamak with the aim to exploit the physics baseline of the future fusion devices. Since August 2022 AUG is in maintenance phase to allow, among others, the installation of the new upper divertor including two concentric coils.**

Theoretical detachment studies have shown a mitigation of the exhaust power problem with alternative divertor configurations, realized with two coils positioned in the outer strike line of the divertor. The coil conductor has been custom-made for our application and has been extensively tested and stressed in previous years. The main peculiarity of these coils is that they are wound from a single unit length of conductor without any internal electrical joint to reduce the risk of failures. This design choice involves a considerable effort to wind the coils inside the much-populated vessel of an experimental machine. A complex bending procedure has devised considering the tight space available inside the AUG vessel. The procedure is based on the deployment of a fully automated winding machine and only for the realization of the termination manual bending will be adopted, assisted by accurate metrology.

To mitigate the risks and to train the work-force, the winding machine is commissioned using a 1:1 mechanical twin of the AUG vacuum vessel. This mock-up has been built by reverse engineering of the existing experimental vessel. Currently, the commissioning of the system is ongoing. The present paper provides a description of the processes involved and reports the current status of the activities.

Index Terms— **ASDEX Upgrade, Divertor, In-vessel coils Snowflake divertor; advanced divertor configuration.**

I. INTRODUCTION

Controlling and removing the excess heat, known as power exhaust, is decisive for ensuring the stability and safety of a fusion reactor. If not properly managed, this heat and particle flux can damage the reactor's walls, divertors, and other crucial components, limiting its efficiency and potentially leading to disruptions. Different approaches are under exploitation in the fusion experiments to address this problem, hoping to provide a wide range of solutions for the next fusion reactor (DEMO). In ASDEX Upgrade (AUG) the advanced divertor design is proposed, namely improving the divertor configuration to spread the heat load over a larger area and reduce the impact on specific components. It includes the use of radiative divertors, super-X divertors, and snowflake divertors. The novel and advanced divertor configurations [1][2], requires the installation in AUG of two concentric coils in the region of the null point of the upper divertor.

In 2017, the design phase of the coil project began [3] and over the year the design was finalized [4][5][6][7]. The upper divertor was redesigned to accommodate two coils and cryo-pumps, enabling helium pumping capability as well (Fig. 1). Since July 2022, AUG is in maintenance phase to implement the new divertor, with its numerous new diagnostics. Furthermore, since many components need to be disassembled to accommodate the tools used for the bending, the opportunity is being seized to dismantle almost all in-vessel components and to refurbish the water cooled in-vessel component of AUG, to enhance its future reliability.

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Irene Zammuto, Albrecht Herrmann, M. Weißgerber, V. Brack, G. Schall, V. Rohde, M. Teschke, T. Vierle, S. Vorbrugg, B. Petzold and W. Zeidner, are with the Max Planck Institut fuer Plasmaphysik, D-85748, Garching, Germany. Marco Dani and Paolo Badino are both with the Sea Alp, I-16152, Genoa, Italy.

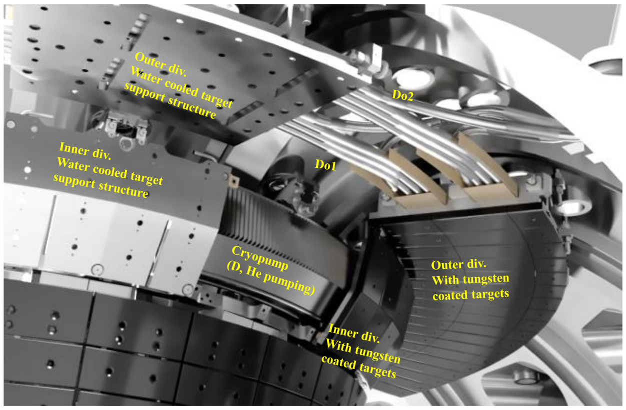

Fig. 1 Main components of the new upper divertor that will be in operation at the end of 2024.

The divertor coils are designed with the aim of preventing any electrical faults within the vessel, as such faults could potentially jeopardize the integrity of the machine. A Tefzel insulated conductor (TIC) has been developed. Consequently, a solution was chosen in which the copper conductor (ID=8mm; OD=18mm) is protected by a stainless-steel jacket, while the electrical insulation was provided by 2.5 mm thick extruded Tefzel HT 2183 layer (Fig. 2). The coils have 4 turns each and will operate with a maximum current of 13 kA for 4 seconds, of which 3 seconds of flattop and 0.5 seconds for ramp up and ramp down. The constraint here is given by the heating of the conductor that was limited to 60°C. The operational voltage is up to 300 V but during the disruption it can reach 5 kV. The coils are powered in opposite directions, allowing only a small difference in terms of current. Details on the conductor qualification can be found in [8], while considerations on the handling of overvoltage during disruption are given in [9].

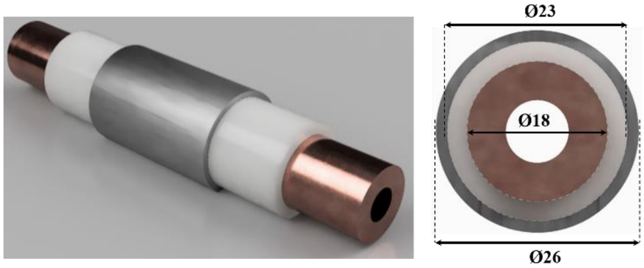

Fig. 2 Conductor parameters with the size reported in mm.

The coils are embedded within the outer divertor plate, inside of which they are free to move radially on insulating supports. This allows the coils to expand due to thermal deformation during operation and baking.

This paper describes the winding procedure developed to bend the coils inside the vacuum vessel. The boundary conditions of the activities are described in the second paragraph, together with a description of the AUG dummy on which the first coil protypes were realized. In the next paragraph, the hardware that has been designed is described. In the fourth paragraph the experience collected and the outcome of the prototyping phase is reported. Finally, conclusion and outlook are given in the last paragraph.

II. BOUNDARY CONDITIONS AND MECHANICAL TWIN OF AUG

To ensure a safe operation and the structural integrity of the machine, a design without electrical joints has been chosen. This means that about 45 m of conductor are bent in a single pass to form each coil. This solution is possible thanks to the presence of an oblique port of the vessel, which allows the bending of the coil turns on a horizontal plane and the insertion of both coil terminations inside the upper port. The vacuum barrier of the coil is on the port flange where to each coil termination is orbital welded a CF35 flange with a bellow on the stainless-steel jacket. To prevent damage to the underlying electrical insulator, a 1 mm layer of Tefzel below the stainless steel is removed, and before welding, a protective bushing is inserted to shield the remaining insulator from the welding heat. Extensive welding qualifications have been carried out. Thanks to a right-handed threading, the copper tube is connected to the power line through a threaded element into which multi-contact elements are inserted (Fig. 3).

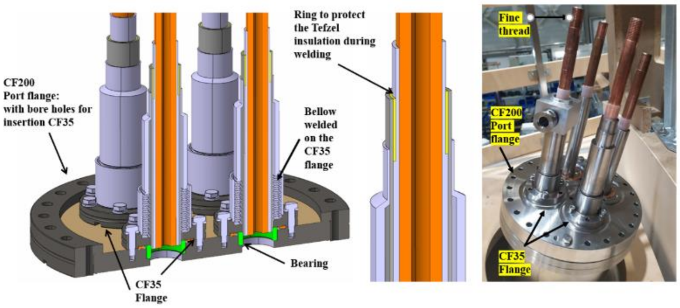

Fig. 3 CAD model of the coil feedthrough is illustrated on the left-hand side; on the right-hand side the prototyping in the test mockup is shown.

Due to limited space, some terminations need to be bent prior to the coil winding, and some even before accessing the vessel. This implies that during the winding process, the coil will rotate within the vessel with the first termination already vertically bent. This configuration constrains significantly the maximum winding plane at a distance of about 324.5 mm below the vessel horizontal mid-plane, to ensure no interference between the rotating conductor and the in-vessel components. The integration of such coils required an enormous effort to design and install the required bending machine, tools and ancillary system in the tight space available inside the vacuum vessel, in the torus hall and for the tight tolerance required for the in-vessel components and the coil itself. A close collaboration with a specialized company in winding machine manufacturing (Sea Alp) has been established to develop ad hoc procedures, bending machines and tools compatible with the room available, while the bending of the termination has been taken in charge by highly specialized IPP personnel.

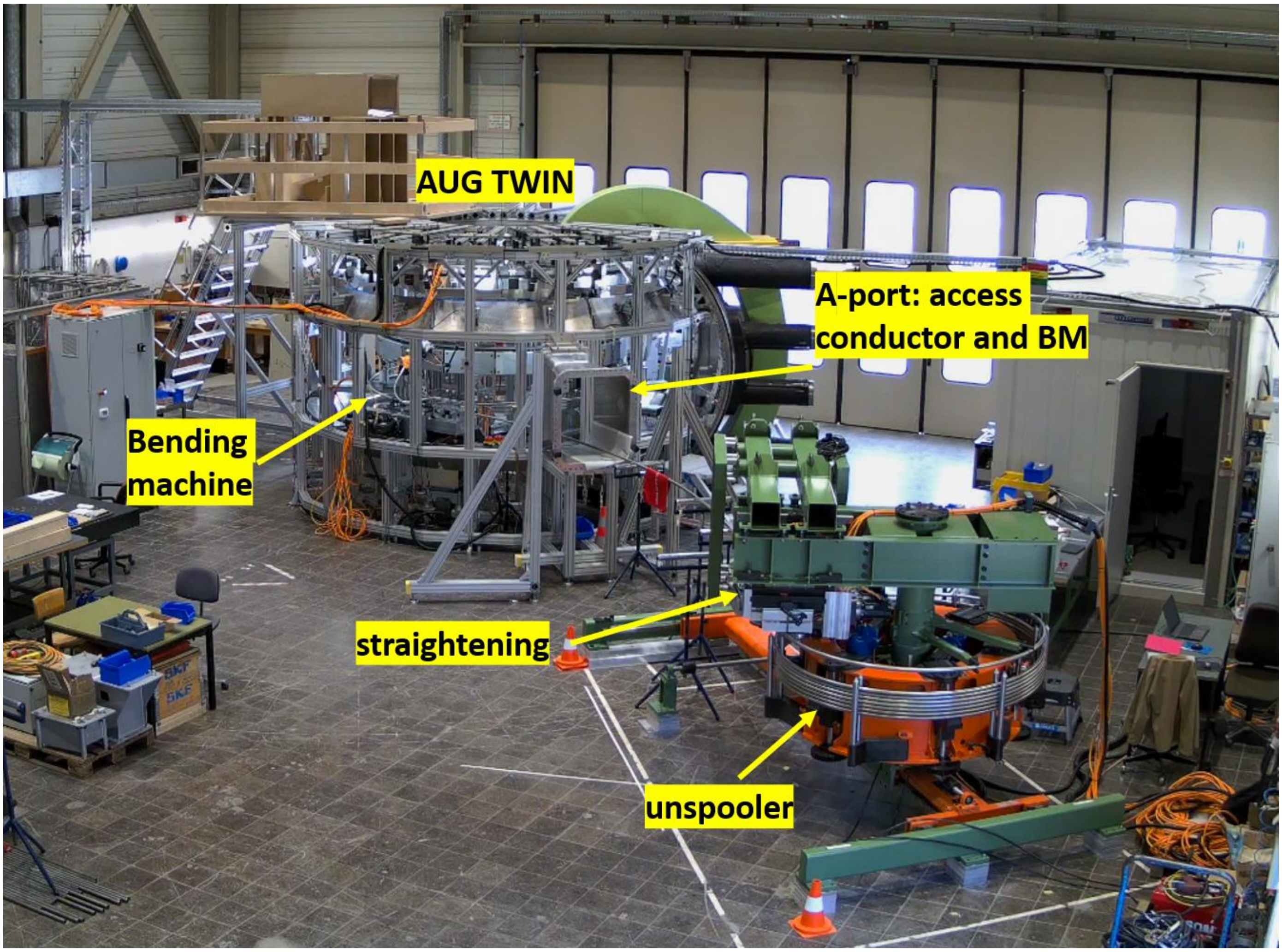

Fig. 4 Overview of the winding line and of the AUG mechanical twin installed in the hall. The main components are indicated.

For risk mitigation, a mechanical twin of the ASDEX Upgrade vessel was constructed, enabling the testing of mechanical components, winding procedures and providing a platform for training. The constrained space inside the vessel posed challenges during the bending and integration processes, which were simulated and practiced extensively on the mechanical twin. Using a prototype of the vacuum vessel from AUG, which has always been used as a test dummy for new components, a frame structure was built all around it to replicate the maneuvering spaces inside the vessel. The frame structure is made of lightweight, modular, and relatively inexpensive aluminum profile items. With the assistance of the laser tracker, the attachment points of the in-vessel components were positioned with an accuracy of less than a millimeter.

The Fig. 4 shows the hall where the mechanical twin of AUG has been assembled with the components required for bending. In the mechanical twin, the assembly of the new divertor and the coil bending procedures have been specifically addressed, as reported in the next paragraphs.

3. HARDWARE

3.1 Winding line

The winding line in the AUG torus hall is positioned in the only sector (sector 3) that allows a decent margin of maneuver for the components with the overhead crane. A massive disassembly of a bulky diagnostics was done to clear space. Nonetheless, the available space constrained the size of the conductor spool to a diameter smaller than 2 meters. A second access to the vessel, allowing entry for personnel and components, is provided at sector 9.

The winding line comprises a so-called unspooler tool, in which the conductor spool is inserted. The unspooler enables the unwinding of the conductor from the top through its axial rotation and maintains the bending plane. On top of the unspooler is positioned a straightening machine which counter-bends the conductor with a defined radius. Once again, due to space limitations and geometric constraints, the conductor's access to the vacuum vessel can only occur if it is counter-bent respect to the coil's radii. The conductor exiting the unspooler feeds into a second bending machine with three rolls positioned inside the vessel.

To ensure precise bending, the relative position between the bending machine and the unspooler must remain constant. But as explained in the following sections, the bending machine will undergo radial and tangential shifts, therefore the unspooler has likewise to accommodate these movements by means of a supporting frame.

The winding line is controlled by an automatic system, with the bending machine inside the vacuum vessel acting as the master and the unspooler outside as the slave. The master's motion is determined by a DXF file containing the coil geometry. The relationship between the bending machine's roll stroke and the coil's radius is established using a calibration curve derived from practical tests. Basically, for many roll-strokes the outgoing radius of the bent conductor is measured, defining in this way the bending characteristic of the conductor on which the spring-back effect is also considered. Indeed, due to the elastic return of the conductor, it will be necessary to overbend the conductor.

Another important component of the winding line is the measuring carriage whose function is to accurately measure the length of the conductor fed into the bending machine inside the vessel. This is made of two encoders wheels in contact with the conductor by means of springs. The measuring carriage unit is free to move in the vertical direction to allow accompanying the incoming conductor in each phase of the bending procedure. On top of that, a printer head is installed to mark references lines useful to align the turns during the phase of the coil assembly or to make length measurements.

3.2 Bending machine

The design of the bending machine has been made as compact as possible to pass the vacuum port, while also being as rigid as possible to ensure the necessary accuracy for the conductor bending.

A compact design with roll screws, brushless motor and speed reducer has been chosen. In order to minimize the number of variables and moving components within the vessel, the bending machine will handle all the movements necessary for the bending procedure. Therefore, the bending machine has three rollers for bending, which can translate in a direction perpendicular to the incoming conductor line, in order to create coils with different bending radii.

The main body of the bending machine accesses the vacuum vessel through a midplane port, commonly referred to as the A-port, which provides the maximum dimension (400 mm x 800 mm) possible to enter the vessel. The main body of the bending machine has been custom-designed to fit through this port. The insertion of the bending machine is facilitated by a supporting guiding structure, which allows its insertion with a tolerance of about 10 mm on each side from the inner walls of the port.

Inside the vessel, the assembly of the bending machine is completed (brushless motor and speed reducer) in Sector 3, where there is more maneuvering space thanks to the access port.

The final weight of the bending machine is about 1.3 tons, versus the 800 kg weight of the main body alone. Inside the vessel, the bending machine is maneuvered from Sector 3 to the Sector 1-16 with the aid of a crane capable of lifting 2.5 tons, which is in turn mounted on two steel toroidal guides. This positioning involves a toroidal motion and a rotation around the horizontal axis of the bending machine of approximately 40 degrees, allowing the bending machine to overcome insurmountable obstacles placed on the low field side, such as the ICRH system's antenna with its limiter and faraday screen.

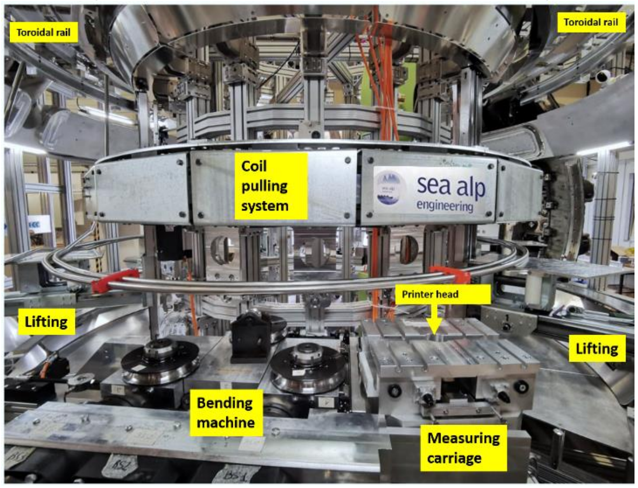

Fig. 5 Inside the AUG twin: the main component inside the dummy vacuum vessel are highlighted.

The bending machine, positioned across multiple sectors of the vessel, ultimately finds its own placement on a steel support previously positioned and fixed in the lower divertor of AUG. The coupling between the steel support and the bending machine is achieved through a linear guide that enables the bending machine to tangentially translate during the creation of the turn-to-turn transition phase.

The bending machine is placed in the vacuum vessel with a tolerance of ±0.2mm, calling for a continuous support from the metrology team to uphold the stringent assembly tolerances necessary for achieving the specified bending precision.

The 4 turns coil are realized with a winding from the inside towards the outside, the turn-to-turn transition is done with a so-called smooth transition, on which a straight conductor is followed by a tight radius of curvature. This is achieved with a synchronized movement of the bending machine in the direction of the incoming line and unspooler (Sea Alp patented solution). Furthermore, since the coils are not in a horizontal plane but have a 5-degree inclination, just like the outer upper divertor where the coils are embedded, a hydraulic press is necessary to plastically impart this vertical shift. The so-called vertical joggles tool is shown in Fig. 6.

3.3 Ancillary Systems

Generally, the bending of toroidal coils is assisted by a turntable. However, in this case, to achieve a lighter structure, it is replaced by the so-called lifting system. This has the dual function of supporting the coils on their bending plane, enabling eccentric radial movements, as well as lifting the coil to its mounting position within the casing. It is made of lightweight aluminum elements attached to the central column of the vessel where the heat shield is usually positioned: in 6 positions of these supports, vertical support structures are secured, which, with the assistance of drivers, speed reducers and linear guides, enable the lifting of the radial supports.

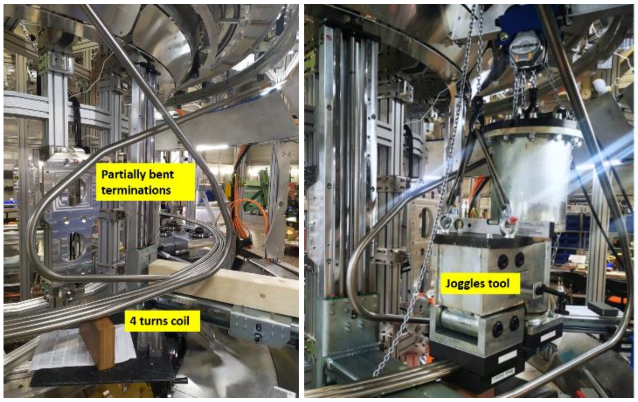

Fig. 6 Inside the AUG twin: the main component inside the dummy vacuum vessel are highlighted.

The radial extension of the arm and the vertical stroke of the lifting are heavily constrained at the bottom by the ELM coils connected to the lower passive stabilizing loop, and on the top by the coil casings itself. The lifting system allows the insertion of the coil through the oblique port (G-port), allowing the tilting of the coils plane in two directions, moving the coil eccentrically and lifting it.

In addition, a coil pulling system is also connected to the lightweight aluminum structures, which consists of a rotating rack that guides the coil termination during the turn winding process. In this case as well, the rotation is assisted by electric motors.

For the various types of bends in the termination bending, three portable bending machines have been developed. Each of them has been calibrated and tested according to the specific curves that need to be achieved to verify the amount by which the conductor must be overbent. The manual bending is assisted by template prepared ad hoc to verify the bending accuracy. In the Fig. 7, the phase in which one of these manual tools is used to make the final bends of the coil to insert the termination into the G-port is shown.

4. Winding Experience in the AUG mechanical twin

During the conductor production phasea portion of the material was rejected as it did not meet the electrical requirements. In particular, during the extrusion process of the electrical insulator onto the conductor, air bubbles were observed, significantly reducing the electrical properties of the conductor. Nevertheless, the production of this batch was carried out to completion, leading to the creation of what is referred to as a "bad TIC." This conductor was purchased as production scrap, but it exhibits the same mechanical properties as the TIC conductor. The "bad TIC", with a length of about 110 meters, was sufficient for conducting initial bending tests for plant acceptance, calibration, and the creation of the first two dummy coils. The dummy coils are made with a reduced number of turns, only 2, in order to preserve valuable conductor material while still going through all phases of the bending process. The only difference lies in the turn jumps, which, though always of the correct count, were distributed along the turns in order to bend all the coil radii. For the first dummy the standard calibration procedure, where the radius of the outgoing bending is measured in the laboratory for each roller stroke, was implemented.

Fig. 7 Positioning of one of the hand tools developed to realized one of the final bends required to insert the termination in the G-port.

Due to geometrical constrains, the first bent coil is the innermost: the initial phase of the procedure involves creating the straight length of the conductor that corresponds to one termination of the coil. In this phase, in a comfortable position, the conductor feedthrough is prepared along with the copper threading. As mentioned before, the initial bending of the terminations takes place even before entering the vessel, precisely to ease the access. Subsequently, the conductor is bent vertically while the conductor is still disengaged from the bending machine. Finally, the conductor is engaged, and a quarter of coil's turn is realized to move the conductor away from the bending machine, allowing for the execution of the next two bends.

Then, the two winding of the dummy coil were realized always checking the correctness of the bend radius with templates. Once again, for the second termination, a second straight conductor was made by the straightening machine and a procedure similar to insertion was repeated: first the end was realized, then a bending is made to access the vessel and the next two were finished inside the vacuum vessel. At this point, the vertical joggle tool is used, before to complete the coils with other four manual bends.

The outcome of the first dummy coil was not optimal, due mainly to the following problems:

1. The conductor has an intrinsic twist of about 4 degrees per meter, which is evident in the phase where the conductor is engaged only in the straightening machine. Once the conductor is engaged also in the bending machine within the vessel, the twist oscillates around its null position. Initially, in the first termination, we attempted to compensate it, but the correction effort, by predicting the twist per meter, led us down the wrong path, and in fact the termination was wrongly placed. In the second outgoing termination, the twist was ignored, and the

result was within the expected tolerances. The solution for the conductor twist is then to simply disregard it.

2. The standard calibration is not appropriate for the TIC conductor. In fact, due to internal stresses, likely induced during manufacturing, cutting the conductor leads to plastic deformation. The solution to this issue is to suspend a test piece containing various bending radii inside the vessel, tension free, and then to scan is using a laser scanner.

3. A wrong setup in control system end up in an overlength of circa 100 mm. As a solution to this issue several programmed stops have been implemented to verify that the conductor's advancement lengths are correct.

The first dummy coil has been nevertheless inserted in the G-port overbending the wrongly shaped termination. Much has been learned from the first dummy coil, but the result shown significant deviations from the nominal configuration (Fig. 8). On the bright side, it has been learnt that the elasticity of the conductor helps a lot in avoiding collision in the insertion at the A-port and correcting the coil radii in the coil assembly phase.

After a new calibration with the new method, the outermost coil was bent again using the remaining “bad TIC”. This time, the realization time was significantly reduced, and the result was within the tolerances. Per definition, the tolerances in the termination region are relaxed, since the magnetic field is anyway perturbed in its axial symmetry, and millimeter variations from the nominal position will not introduce significant deviations.

Since no showstoppers have been seen during the 2 turns coil bending, the outermost 2 turns coil was dismissed to enable the insertion of a new 4 turns coil realized with a proper TIC conductor. A new calibration was mandatory, also because the production batch was different from the “bad TIC”.

Again, the installation of the new coil was quite fast in comparison with the first one, since all the difficulties were already addressed. At the end of the bending process, the coil is measured using a laser scanner, and the results were satisfactory (Fig. 8). Before completing the insertion of the coil terminations into the G-port, a Helium leak test was carried out, to verify that the orbital welding seams were not cracked by the bending process: no leaks were observed as previously confirmed during the qualification of the conductor.

Finally, the coil was lifted in its resting position, and the feedthrough was completed allowing the electrical and water connection of the coils.

5. CONCLUSION AND OUTLOOK

In 2024, AUG will return to operation with a new upper divertor, which will include, among others, two divertor coils (see Fig. 9). The winding line, procedures, components and jigs have all been refined and validated in the mechanical twin of AUG. In verifying all the steps outlined in the procedures, a total of 3 coils were bent: 2 with only 2 turns (one of which has been discarded) and one complete with 4 turns.

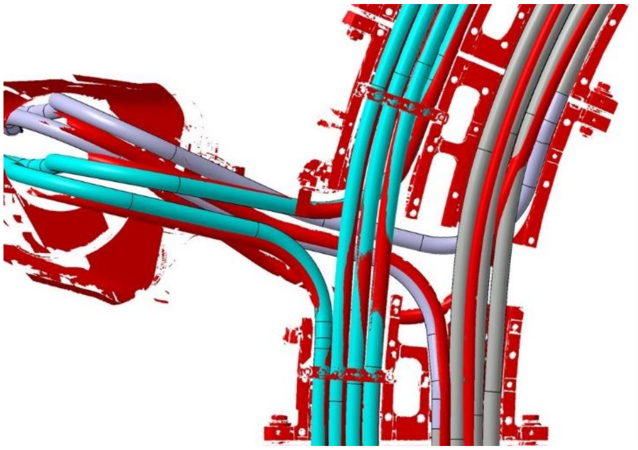

Fig. 8 Comparison between the CAD model and the scanned geometry (red one) in the G-port region, where the tollerances are relaxed. The deviation from the nominal position is well within the tollerances.

In summer 2023, both coils were electrically tested: the 4-turns coil was tested at full current (52 kAt per 3 s) for more than 1200 cycles reaching the maximum increase of temperature of 60°K, while the 2-turns coil underwent testing with approximately 20 shots, experiencing an overheating about 3 times greater than the nominal value. Both coils withstood the tests, showing no degradation of the electrical insulation. Therefore, as no showstoppers have been identified, the AUG Hall and torus are in preparation to repeat the bending procedures within the tokamak.

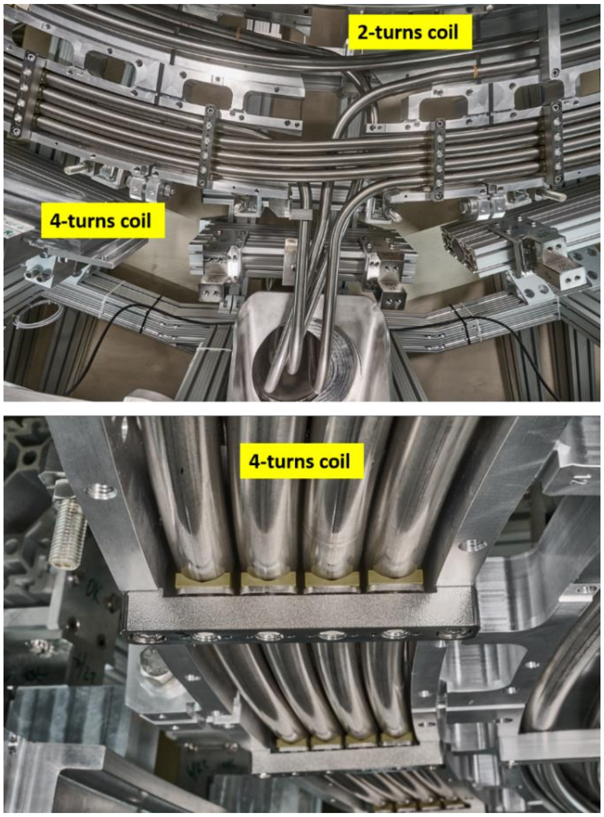

Fig. 9 In-vessel coils bended in the AUG mechanical twin.

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