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Status of the F4E Procurement of the EU ITER TF Coils

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***Abstract*—The ITER magnetic system includes 18 Toroidal Field (TF) Coils using Nb3Sn cable-in-conduit superconductor. Each TF coil, about 300-t in weight, is made by a Winding Pack (WP) composed by 7 Double Pancakes (DP) modules stacked together, impregnated and inserted in stainless steel coil case. Each DP is made by a Radial Plate (RP), a very large D-shaped stainless steel plate with grooves machined on a spiral path on both sides, in which the insulated conductor is inserted after the heat treatment. The procurement of the TF coils will be carried out by Fusion for Energy (the European Domestic Agency (DA)), responsible for 10 coils and the Japanese DA, responsible for 9 coils. The conductors will be produced by 6 different DAs, while the coil cases only by the Japanese DA. In July 2008 the Procurement Arrangement was signed between the ITER Organization (IO) and F4E defining the scope, technical and management requirements for the procurement of such coils. F4E has developed a procurement strategy aimed to minimize costs and risks, consisting of subdividing the procurement into three main procurement packages, each foreseeing an initial R&D qualification phase. One procurement package is related to the construction of 72 RP (including 2 prototypes), another to the fabrication of the 10 WP and a third to the cold test and coil-case insertion of 10 WP. So far F4E has signed 5 contracts. In 2009, we placed 2 contracts for the procurement of RP prototypes and 1 contract for the development and qualification of the welding and the Ultrasonic Test technologies for the coil case welding. In 2010 1 contract has been placed for the construction of 10 WP and 1 contract for the engineering optimization of the cold test and coil insertion.**

I. INTRODUCTION

F4E is responsible for the procurement of 10 of the 19 ITER TF coils. Each of these 300 ton, 16.5 m tall and 9.5 m wide D-shaped coils, described in more detail in the following sections, is composed by 7 double pancake modules stacked together and inserted in a stainless steel case. The procurement of such coils presents many challenges. The first challenge is related to very demanding required production rate of approximately 4 coils per year. The second challenge comes from the sharing of the production of some components among different Domestic Agencies (DA). In fact the conductor is produced by 6 different DAs (Russia, China, USA, Europe, Japan and Korea) while the coil cases only by Japan. However, the most important challenge comes from the technology utilized for such coils, the so called wind-react-and transfer (W,R&T) process, described more in detail below, presenting an unusually high level of technological risks. Finally the broad range of technologies utilized for the different components and production phases requires an unusually broad level of skills, together with a large financial and manufacturing capacity in order to handle the combination of large production rate and risks associated with the technology. This reduces strongly the number of potential suppliers capable to handle such a project, with the consequent risk of lack of competition in the call for tender.

For this reason F4E has adopted a procurement strategy aiming to reduce the technical risks by introducing intermediate R&D steps, to increase production speed by splitting the production among different suppliers and, finally, to increase competition by splitting the procurement in more coherent and smaller size work packages. Presented in this paper is a short description of the TF coil design and technology, followed by a description of our procurement strategy, both in terms of technology development and market strategy. Finaly we describe the status of the different streams of activities and the results obtained so far in our R&D with particular reference to radial plate prototypes.

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II. A DESCRIPTION OF THE ITER TF COILS

A TF coil is schematically reported in fig. 1. It is composed of 7 DP modules. Each DP is composed of a D-shaped grooved radial plate (RP) in which the conductor is embedded. The conductor is a 43.7mm diameter Cable-in-Conduit-Conductor composed of 2mm thick jacket and about 1000 between copper and Nb_3Sn strands. The conductor is first Wound, then Reacted at 650C, then Transferred, after the insulation has been applied, into the radial plate (technique named W,R & T). The conductor is locked inside the grooves by cover plates laser welded to the radial plate. Each double pancake module is insulated and impregnated separately before being assembled in the winding pack (WP). In each WP there are 2 types of radial plates: 5 regular radial plates, with 11 grooves per side and 2 side radial plate with 3 grooves on a side and 9 on the other side (see fig.2). For the radial plates a planarity of 1 mm is demanded whilst, for the position of the grooves, tolerances of few tenths of mm with respect to the inside profile are required. During welding of the cover plates only an additional 1mm distortion on planarity is allowed. After the impregnation of the winding pack, it is foreseen a cold test at liquid nitrogen temperature in order to check mainly leak tightness and electric insulation. After the cold test, the winding pack is inserted in a very thick stainless steel case (up to 140mm) that is composed of 4 parts welded together after coil insertion.

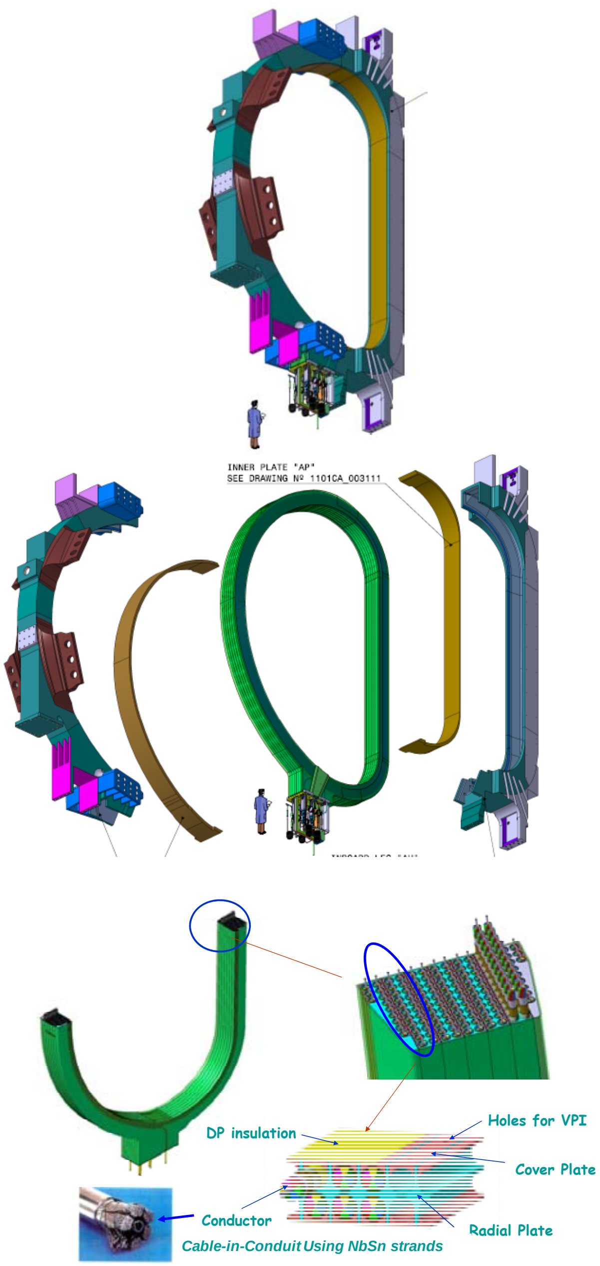

Fig.1.The main TF coil components.

III. TF COILS MAIN TECHNOLOGICAL ISSUES

The ITER TF coil, with its combination of large dimensions and tight tolerances, and the utilization of the W,R&T technology, is a very complex coil to build. So far only one superconducting coil has been manufactured utilizing the W,R &T technology: the EU TF Model Coil (TFMC) successfully completed in 2002. Because the TFMC is only about 1/3 of the TF coil size, during its manufacture some of the technological issues to be faced with the full size TF coils could not be explored. These are reported below.

A. *The radial plates manufacture*

The required production rate is of 3 RPs per month, requiring a huge production effort. From the technological point of view, one of the main difficulties is that a RP, because of its large size, cannot be manufactured from a single plate (as for the TFMC). Instead it must be manufactured in several sections butt-welded together: this represents a challenge due to the welding distortion compromising the required tolerances. In addition, the machining of the grooves requires removal of more than 2/3 of its original sections with consequent long machining time and potentially large distortions.

B. *The DPs manufacture*

Each double pancake is manufactured by using the WR&T technology, in which the conductor is first wound into a winding mould according to the nominal double pancake spiral trajectory. Then the DP is heat treated up to 650°C to form the Nb_3Sn. Finally the conductor is insulated and then inserted into the radial plate grooves (see fig.2). The radial plate is machined according to nominal dimensions and with certain tolerances.

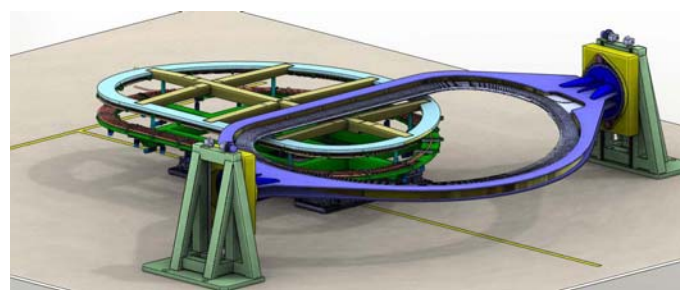

Fig.2.The operation of transfer of the DP onto the radial plate.

The matching of conductor with the RP grooves requires a very tight control of the tolerances for both the conductor trajectory and the radial plate grooves trajectory: given the machining accuracy achievable in the RP grooves (see next sections) in order to be certain to fit the conductor into the RP groves we need to achieve during winding a precision of about 65ppm (parts per million) on a conductor trajectory length of 760m. This is very difficult to achieve during conductor winding because there are many different radii along the trajectory of the DP and because it is very difficult to control the length of conductor with such an accuracy. Based also on some results gained with their R&D on winding in Japan (see [4]), they estimate an accuracy on the conductor length during winding of about 200 ppm. In addition during the heat treatment the conductor length will permanently change, modifying therefore its original as-wound trajectory. In principle this second effect can be mitigated by bending the conductor on a modified trajectory such that, after the heat treatment length change, it will coincide with the nominal required trajectory. However, many uncertainties are present because, not only will there be an inevitable scattering of results for a single conductor type (based on their R&D on heat treatment in Japan (see [4]), they report an expected uncertainty of about 100 ppm) but we will also utilize 6 different types of conductor, each with a different HT length-change behavior. It is also worth to mention that, for each type of conductor, we have only 100m of trial conductor (less than 3 full size turns) available to the TF coils supplier to learn, before starting production, how to bend precisely the conductor and to measure the length change during the heat treatment: there is a substantial risk that such trial length will not be enough to determine exactly both winding and heat treatment behavior of the conductor. Finally it is important to note that the conductor during the transfer into the radial plate cannot be deformed with a strain higher than 0.1%: therefore it must fit in the grooves with almost no additional deformation. If we sum the uncertainties estimated and reported above on winding (200ppm) and heat treatment length change (100ppm), we obtain 300ppm, that is much worse than the accuracy required to be certain to match conductor and groove trajectory (65ppm). There is therefore a non negligible risk that the conductor will not fit in the grove. As a consequence in the case that the conductor and the radial plate grooves do not match, the DP has to be rejected with consequent large financial loss (several millions euros) and delay due to the time to produce an additional conductor length and relative DP.

C. The TF coil construction

The most critical aspect associated to the final part of the TF coil manufacture is the insertion inside its case and the final closure weld. This closure weld in particular is critical for several reasons. The first is that is done on a variable thickness along the perimeter, with thicknesses ranging from 40mm up to 140mm. The second is that, just behind the weld, the winding pack placed at a distance of only 10mm with risk of damaging it during the welding. The third reason is that this weld is difficult to inspect because of the combination of large thickness and limited accessibility (accesses is available only from one side). Finally, because there is a requirement of tight tolerance, in particular on the straight leg, the deformation during the welding of the case must be minimized. This is not an easy task because of the large welding thickness. The required production rate is very demanding: 4-6 coils per year.

IV. THE OVERALL EU TF COILS PROCUREMENT STRATEGY

The combination of technical and financial risks associated to their production, combined with the very large manufacturing capacity required to satisfy the production rate, create a situation in which very few potential suppliers are interested, or capable, in taking charge of the whole production. This creates a situation of very little competition with consequent potential high bidding price. In addition the range of skills required to manufacture the different components is very broad, ranging from the radial plate, requiring large precision machining and welding of large components, to the winding pack, which requires experience in the manufacture of large magnets, and finally to the coils insertion and case welding where very large facilities with good transport links are required to handle the 300 ton coils and facilitate transportation to ITER. Because of these considerations one of the first decisions made by F4E was to split the procurement in 3 work packages:

- production of the Radial Plates for the 10 coils
- production of 10 Winding packs
- production of 10 final TF coils

Each of these work packages is more technologically coherent and manageable in terms of production and financial size than the whole TF coils production. This should give us on one side access to more competitors and, on the other side, to more specific and targeted skills for each of the 3 work packages. Within each of these work packages we have defined a procurement strategy aiming to:

- reduce technical risks by introducing intermediate R&D steps
- reduce financial risks where possible by placing first R&D contracts aiming to assess the technology before placing the contract for the whole production.

Finally the important role played by the synergy with the Japanese DA, building the other 9 coils, must be mentioned. This is achieved by sharing knowledge gained from our different R&D activities and by defining together R&D strategies in which we each explore different technologies in order to find the most efficient. In the following sections we will describe in more detail the specific strategy adopted for each of the work packages.

V. THE SPECIFIC PROCUREMENT STRATEGIES FOR THE DIFFERENT WORK PACKAGES

A. The procurement strategy for the radial plates

The first procurement package is related to the manufacture of 70 radial plates for the 10 winding packs. In fig.2 a section of a regular RP and a section of a side RP are shown. As mentioned before there is no previous experience in manufacturing such a large RP out of several sections butt-welded together. For this reason initially we decided that it would have been too risky to launch a call for tender for the series production based on a single unproven technology: the large risk perceived by the suppliers would have translated in a very high price. For this reason we are carrying out the procurement in 2 phases, a first phase with the manufacture of a full size prototype qualifying the manufacture process and a second phase related to the series production of 70 radial plates. In addition, because the regular and side radial plates have slightly different technology challenges due to the different grooves distribution, we have decided to manufacture 2 RP prototypes: 1 regular and 1 side.

Furthermore, in order to maximize the chances of success by exploring alternative routes, we have intentionally utilized different technologies to manufacture the 2 prototypes and, for the same reason, the routes chosen for the EU components are different from those selected for the Japanese prototype.

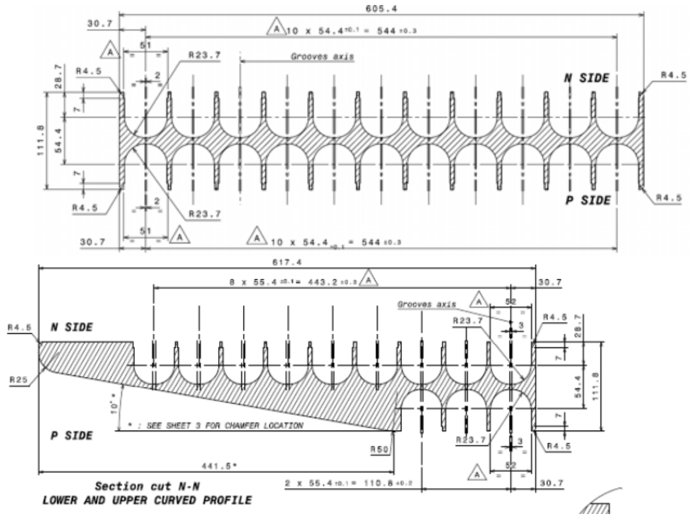

Fig. 2. Above a section of a regular radial plate and below a section of a side radial plate.

A summary of the RP F4E procurement strategy is:

1. Phase 1: Placement of 2 contracts (see table I):
   Produced a side RP with technology A and a regular RP with technology B.
   Japan producing in parallel own RP with technology C
2. Phase 2: New call for tender to produce 70 radial plates (20 side and 50 regular) with any of the technologies (or a combination of them) qualified in the 1st phase.

The EU contract for the radial plates were placed in September 2009 to CNIM (side RP) and in December 2009 to SIMIC (regular RP). In order to maximize competition, the bid for the second phase will be open also to companies which have not participated to the first phase. The 2 EU RP prototypes are at present almost complete.

TABLE I THE RADIAL PLATE TECHNOLOGIES MATRIX

	F4E SIDE RADIAL PLATE	F4E SIDE RADIAL PLATE	JADA REGULAR RADIAL PLATE
Supplier	CNIM	SIMC+METSO	TOSHIBA+IHI
Technology	A	B	C
Number of sections	7	15	10
Base Material for the sections	Forged 316 LN	HIPPED 316 LN	Hot-rolled plate 316 LN
Level of machining for each section	Fully machined to final dimensions except welded areas	Pre-machined with 8 mm over metal	Fully machined to final dimensions
Technology for butt-welding between sections.	Local Vacuum Electron Beam	Narrow Gap GTAW	Laser
Final machining after welding	Only welded areas with displaceable local	Global machining with large portal machine.	No additional machining
Cover Plates technology	Partially cold drawn and partially machined. Then bent in the curved regions.	Cold drawn and then bent in the curved regions.	Cold drawn and then bent in the curved regions.

A. The procurement strategy for the 10 winding packs

Because the winding pack construction presents an even higher level of technological risks compared to the radial plates, it makes sense to apply the same 2-phase approach utilized for the RP. On the other hand, for the winding pack R&D, the supplier is required to procure very large equipment (e.g. winding line, heat treatment oven, etc) and to develop a specific know-how; both very difficult to transfer from one company to another. This is why, whilst for the radial plates we allowed the possibility to have 2 different companies for the R&D and the production, for the winding pack we decided to place a contract to a single company for both phases.

For the winding packs we have the following phases:

1. Phase 1:R&D and qualification of processes
   a. Manufacture of several mock ups.
   b. Manufacture of a full size joint sample
   c. Manufacture of a full size side DP realized with superconducting cable.
2. Phase 2 & 3: Manufacture of 10 TF winding packs

The contract for the 10 winding pack was awarded in July 2010 to a consortium composed by Iberdrola IC, ASG Superconductors and Elytt Energy.

B. The procurement strategy for the cold test and coil insertion.

This work package represents the conclusive phase of the construction of a TF coil and includes a cold test before inserting the winding pack in the coil case.

Also for this work package we have subdivided the procurement in 2 phases:

1. Phase 1, placement of R&D contracts to:
   a. qualify both closure welding process and non destructive test (NDT) technology
   b. carry out an engineering study to analyze the processes and the facilities required.
   c. quantify the distortions induced by the final welding process
2. Phase 2:
   a. A single new contract to:
      i. procure required equipment and tolling.
      ii. cold test the 10 winding packs
      iii. Enclose the 10 WP in the case and weld.
      iv. deliver the 10 TF coils to Cadarache.

The welding process and NDT qualification contract was placed in December 2009 to CSM and ISQ and is almost complete. The engineering study contract was awarded in December 2010 to Babcock Noell GmbH. It has now been completed. The contract to assess the deformation of the TF coil awarded to NATEC ingenieros and it is ongoing.

In parallel IO is carrying out a study, together with the Rutherford Appleton Laboratory, assessing the best material and processes to use to fill the gap between the winding pack and coil case.

VI. STATUS AND ACHIEVEMENTS IN THE DIFFERENT AREAS

The status on the different work packages is reported below.

A. *Radial Plate*

The 2 radial plate prototypes are almost complete.

1) *REGULAR RADIAL PLATE PROTOTYPE*

Machining completed by SIMIC in August 2011 (see fig. 3). The results are very satisfactory. The main achieved accuracies, as measured, have been:

- Planarity (required <1mm): Measured 0.85mm (1-1.3mm soon after machining, then applied small local straightening operation to improve planarity).
- Inner /outer D-shape profile (required <1mm):Measured < 0.75mm
- Groove position with respect to inner profile (required <+/-0.3mm): < Measured +/- 0.25mm
- Length of groove trajectory: < Measured 20mm on the total length (corresponding to about 27ppm).

The cover plates should be completed by September 2011.

Fig. 3.The EU SIMIC regular radial plate prototype after machining completion.

2) *SIDE RADIAL PLATE PROTOTYPE*

The machining of this radial plate has been completed by CNIM in September 2011. Fig.4 shows the radial plate in its final state. The preliminary dimensional report on the RP after completion of welds and before starting machining is:

- Planarity (required <1mm): Measured 1.7mm (it will be corrected by straightening).
- Inner /outer D-shape profile (required <1mm) : Measured 1mm
- Groove position with respect to inner profile (required <+/-0.3mm): < Measured +/- 0.2mm

Cover plates will be completed by the end of October 2011.

To the light of the obtained results both European technologies have been successfully qualified and, for the RP series production, both can be used to manufacture a RP independently or, as we will see, in combination.

B. *The status on the winding pack procurement*

Since the signature of the contract, most of the effort has been put in designing and procuring the main tooling. The winding line is composed of an un-spooling unit, a straightening unit, a numerically controlled bending unit and a motorized winding table. The movement of these components is synchronized. At present the winding line is being assembled at sub-supplier facilities in order to calibrate it and to carry out the acceptance tests that should be completed by the end of this year. It will then be transported to and re-assembled at ASG premises.

The heat treatment oven operates with ventilated inert atmosphere and can heat treat up to 3 DPs at once. The assembly of the oven on site will start in September 2011. Almost all other tooling has been designed and is being procured. A full size DP pancake prototype, utilizing the side RP prototype, will be manufactured by ASG utilizing a fully superconducting cable produced in EU; it should be completed by the beginning of 2013.

Fig.4.The EU CNIM side radial plate prototype after final machining.

At Elytt the fabrication of helium inlet and electrical joints mock ups will start soon in order to qualify the design, the manufacturing process and the tooling. Although no R&D activity has yet been carried out on this work package in EU, it is important to report on some of the activities carried out in Japan. In particular are those related to the winding and heat treatment of 1/3 size DP. During this, although successfully carried out, the extreme difficulty in controlling the conductor trajectory during winding and heat treatment emerged. This has been taken in account by F4E in defining the strategy for the series production of the radial plates.

C. *Status of the third work package*

The contract on the case welding and NDT qualification is in its final phase: the final mockups for the qualification of the inspection method are being manufactured. Some delay was accumulated initially to find the filler metal with the right fracture toughness at 4.2K (K1C>180Pa $m^{1/2}$). Finally two fully austenitic filler materials were chosen: the Japanese JJ1 (material developed by JADA in the framework of the ITER welding process) and the more commercial 25.22.2 LMn in conjunction with a Ar+20%He+0.5%CO2 shielding gas mix. The welding technique being qualified foresees a first closure pass with Hybrid Laser (HL) technology (Laser + Gas Metal Arc Weld) and completion of the weld with Narrow Gap GMAW. GMAW is preferred to Gas Tungsten Arc Weld as it is more productive. It is possible that finally, once in production, the first pass with HL will be replaced by GMAW because of the concerns about the integrity of the winding pack during the weld. The heat input of the laser behind the weld is quite high and the protection was found ineffective even with a ceramic strip. On the other hand a metallic strip of 3mm is enough to protect the winding pack (temperature <180°C during weld) during a GMAW root pass. Regarding the NDT, a method using the combination of Phased Array, Creeping Waves and Time of Flight Diffraction (TOFD) has been developed. In the present IO specification, it is required to fulfill ASME Section V, corresponding to a defect equivalent to a hole of 6.4mm diameter, but we are verifying the minimum defect size we can detect with this NDT technology. The engineering study for the cold test and coil case insertion was completed by BNG on June 2011.

The distortion assessment contract was launched in early July 2011. A finite element model is being generated and coupled with two benchmarking mock-up will foreseen the distortion during the final weld of the TF coil structures. We expect to have the final results by mid October 2011.

The work carried out by IO on the gap filler should finish by the end of the year.

VII. Strategy for the Next procurement steps

Soon F4E will be launching the call for tender for the procurements of the radial plates and for the cold test and coil insertion.

Regarding the strategy to adopt for the RP series manufacture, F4E has decided not to focus only on the RP technology aspects but to take a more global approach, keeping in mind also the uncertainty associated to the fitting of the conductor into the RP, considered to be the highest risk in the construction. For this reason, for the series production, of the RPs we have decided to follow a 3 step approach, trying to match radial plate and DP construction. These 3 steps, regarding both radial plate and DP construction, can be summarized as follows:

- Step 1: Manufacture each radial plate in a pre-machined state where it is machined according to its nominal dimensions (including the grooves trajectory) but with 5mm over-metal are left all around the radial plate.
- Step 2: Manufacture the DP trying to match as close as possible the nominal conductor trajectory. Once the HT has been completed, measure the as-built conductor trajectory.
- Step 3: Complete the RP machining based on the as-built conductor trajectory.

With this approach, the chance of mismatch between conductor and radial plate groove is minimized. In our strategy, the pre-machined radial plate can be manufactured utilizing one of the 2 technologies (or a combination of the 2) successfully qualified in Europe. The step 3 can be achieved only by global machining of the radial plate with a portal machine. Very shortly F4E will launch the call-for-tender for the radial plate series production according to this strategy.

Regarding the cold test and coil insertion, the strategy will be to assign a single contract for both cold test and coil insertion.

A call-for-tender will be launched as soon as the Procurement Arrangement between IO and Japan for the production of 10 TF coil structures production will be signed. We hope to launch it by the end of this year.

VIII. Conclusions

Since 2009, F4E has commenced the production of the 10 TF coils for the ITER machine.

A specific procurement strategy has been adopted aiming to:

- Increase tenders competition by splitting the procurement in 3 smaller and more manageable packages.
- Reduce technological risks by utilizing a phased approach, exploring several technological routes in parallel and exploiting synergy with Japan.
- So far this strategy has proved to be successful as:
  - All contracts placed so far are within allocated budget.
  - The 2 radial plate prototypes are being successfully completed.
  - The welding and NDT technology selected for the case welding are being successfully qualified.
  - Progress to date has been, within reasonable limits, according to plan in spite the high technological uncertainty associated with the complexity of the TF coils design and technology.

We are still at the initial phase of this complex procurement and there is still a long way to go. In this sense the coming years will be crucial for its success.

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