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JT-60SA toroidal field coils procured by ENEA: A final review

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ABSTRACT

Within the Broader Approach Program between Europe and Japan for the early realization of fusion with the construction of the JT-60SA tokamak, ENEA, the Italian Agency for New Technologies, Energy and Sustainable Economic Development, was in charge, among others, to supply ten superconducting Toroidal Field (TF) coils for the JT-60SA magnet system. The related procurement started in 2011 and was concluded in 2018 with the delivery of the tenth coil to the Cold Test Facility in France. The construction of each TF coil module consisted of two main phases: manufacturing of the superconducting winding pack and integration in the corresponding casing structure. With all the foreseen modules already completed, this paper provides a critical review of the contract for the manufacturing of the coils highlighting the main difficulties occurred in the different manufacturing steps and evaluating the performances obtained from the measurements taken at the acceptance tests.

1. Introduction

In September 2011, ENEA, the Italian Agency for New Technologies, Energy and Sustainable Economic Development, started, with a contract to ASG Superconductors in Genoa, the procurement for the construction of nine superconducting Toroidal Field (TF) modules of the JT-60SA magnet system. The procurement, that represents one of the several in-kind contribution of Italy to the Broader Approach program, was successively increased to account also for an additional module for spare purposes. Each module consists of a winding pack (WP) made of 6 double pancakes (DP) in NbTi [1]. The WP are inserted in a steel casing [2] that provides the necessary structural containment to the WP. Each WP weights about 6 Mg, and the completed module about 16 Mg. The operating current is 25.7 kA at 4.5 K. In operation, 4 g/s of supercritical helium will flow inside each cable in conduit conductor having a rectangular cross section (22 x 26 mm jacket external dimensions and about 32% internal void fraction) with an inlet pressure of 0.6 MPa in order to ensure the proper heat removal and conductor stability. Fig. 1 shows the first coil manufactured at the end of the acceptance tests. The coil is about 7 m high, 4.5 m wide and weighs about 16 tons (see Fig. 1).

ENEA procurement covers only half of the whole TF magnet system, the remaining being procured by ENEA's French counterpart CEA [3]. Both ENEA and CEA have been coordinated in Europe by Fusion for Energy that acted also as interface with Japan authorities. Assembly in Japan of the 18 TF coils of JT-60SA started in 2016 and was completed in mid-2018, two spare coils remain available in case of future needs [4]. Before shipment to Japan, all the 20 TF modules have been successfully tested in cryogenic conditions at full current in the CEA cold test facility in Saclay [5].

In the following sections, the two main phases of the manufacturing activity are reviewed with particular emphasis to the time required for the completion of each single step, then a review of the main electrical and geometrical tests carried out at the end of the WP and Toroidal Field Coil (TFC) integration phases is reported.

2. Review of manufacturing process

The first two years of the procurement were devoted to the engineering activity related to the design, construction and set-up of the manufacturing tooling, to the issuing of the manufacturing drawings and to the qualification of the main critical processes. The following two years were reserved to the WP manufacturing and the remaining two years and half were spent in the TFC integration phase.

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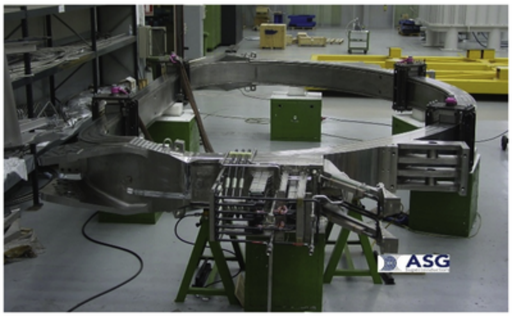

Fig. 1. Picture of TFC-01 at the end of the factory acceptance tests. The terminations and inner joints are shown in the foreground.

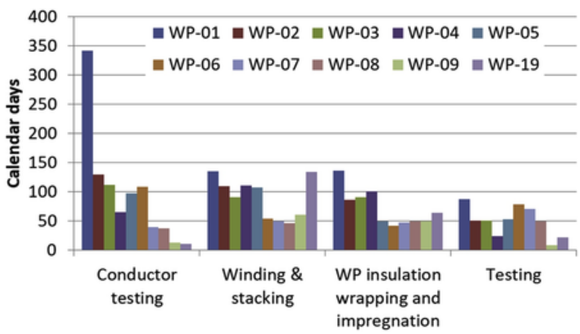

Fig. 2. Time for completion of the steps in WP manufacturing.

Table 1
Summary of average and best timing performances in WP manufacturing [calendar days].

Calendar Days	Conductor testing	Winding & stacking	WP insulation wrapping and impregnation	Testing	Total
Ave.	95.4	89.7	71.4	49.5	**306**
Min	11	46	42	8	**132**

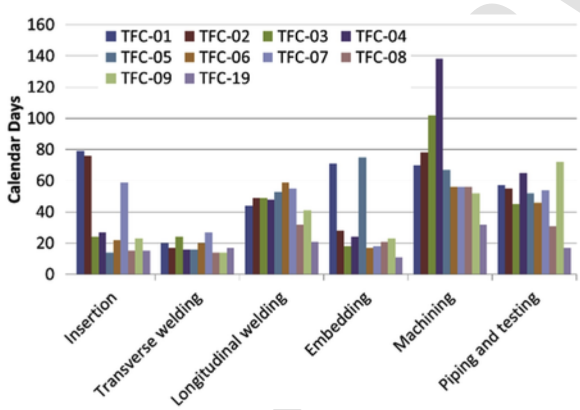

Fig. 3. Time for completion of the steps in TFC integration.

Table 2
Summary of average and best timing performances in TFC integration excluding the time needed for the repair of TFC-02 [calendar days].

Calendar days	TFC integration steps						Total
	i)	*ii)*	*iii)*	*iv)*	*v)*	*vi)*	
Ave.	35	19	45	31	71	49	**250**
Min	14	14	21	11	32	17	**113**

2.1. WP manufacturing

Fig. 2 shows the calendar days needed to complete the four steps in which the WP manufacturing activity can be grouped [6].

The first step, "conductor testing", refers to the time between the arrival at the manufacturer's premises of the conductor for the first DP and its insertion in the winding line. This time is in principle due only to the time needed for leak and flow testing of the conductor, actually it considers the waiting for the availability of the winding line. In the first WP this time was rather large as the qualification activity of winding process was not yet completed when the first conductor arrived. In the last two WPs, instead, it consisted only of the testing time thanks to an overall acceleration of the manufacturing processes and better synchronization between conductor delivery and its need in the winding process. The second step shown in the figure is the winding and the subsequent stacking of the six DPs of a WP. In the plot, it is apparent that from WP-06 the time was halved thanks to the doubling of the stations and tooling for DP insulation wrapping. In the last WP, intended for spare purposes, instead, the time was again larger because its completion was not in the critical path at that time. The third step regards the WP insulation wrapping and impregnation. In this case the time was significantly reduced starting from WP-05 due to doubling of the tooling for WP vacuum pressure impregnation (VPI). The last step concerns the final testing from the completion of VPI process.

Table 1 summarizes the timing shown in Fig. 2 by reporting the average values and the best performances. On average, about ten calendar months were needed for a WP from the delivery of the conductor up to the completion of the acceptance tests. Summing the best performances obtained in each step, it would have been possible, instead, to complete a WP in only 132 days.

The acceleration in the manufacturing process, highlighted in Fig. 2, might also be apparent when comparing the dates of completion declared at the beginning of the contractual activities with those actually achieved [7]. Although initially the WPs were delayed with respect to the original prevision, the last WP was completed few months in advance.

2.2. TFC integration

TFC integration has been divided in the following six steps of manufacturing [7,8]: *i)* insertion of the WP in the relevant casing structure; *ii)* transverse welding of the casing; *iii)* longitudinal welding of the covers; *iv)* embedding impregnation to fill the gap between the WP and the casing; *v)* machining of some casing interface areas; *vi)* assembly of the piping for He flow in the TFC and execution of the final acceptance tests. Fig. 3 shows the timing, in calendar days, for each of the mentioned steps. It is worth noting that, during the machining phase of TFC-02, an accidental fall in a handling operation caused an out of plane deformation of 10 mm. Although the repairing activity was carried out after the very end of the supply, large delays were introduced in the machining of the subsequent modules. Note in particular that the time for the machining of TFC-02 shown in Fig. 3 does not take into account the time needed for the repair of the non-conformity.

As for the WP manufacturing, also for the TFC integration phase, the following Table 2 summarizes the average and best timing achieved in the six steps of the activity mentioned before. It should be noted that the starting of the operation was represented by the arrival of the relevant casing structure, and that the time spent in the repair of TFC-02 was omitted because irrelevant for the evaluation of the timing of the standard manufacturing steps.

The about eight months, necessary, on average, to complete a TF coil from the delivery of its casing up to the completion of the acceptance tests at room temperature, should be compared with the six

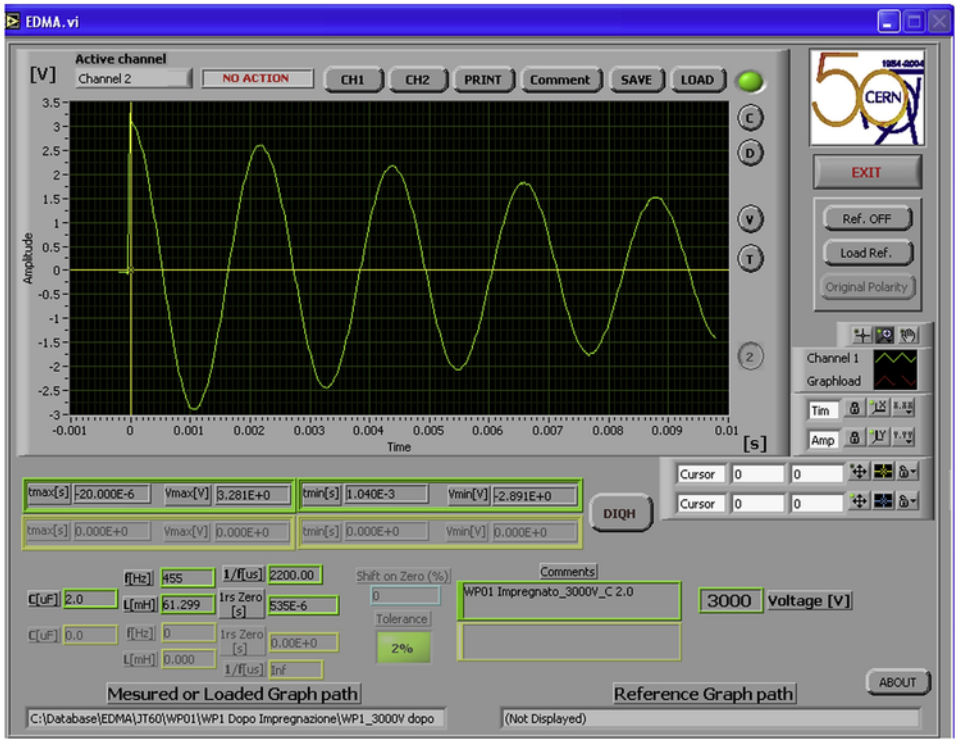

Fig. 4. Example of a surge test result on a WP after VPI.

Table 3
Summary of electrical properties of the ten WPs produced after the VPI.

WP-ID	f [Hz]	L [mH]	C [nF]	R [mOhm]
1	455	61.3	160.7	128.1
2	455	61.3	206.2	127.5
3	454	61.6	185.7	127.5
4	455	61.3	206.9	127.7
5	459	60.2	209.6	128.9
6	460	59.9	209.0	128.5
7	460	60.0	204.2	128.4
8	460	59.8	212.5	128.9
9	460	60.0	199.6	129.0
19	451	62.2	199.6	129.9
average	456.9	60.8	199.4	128.4

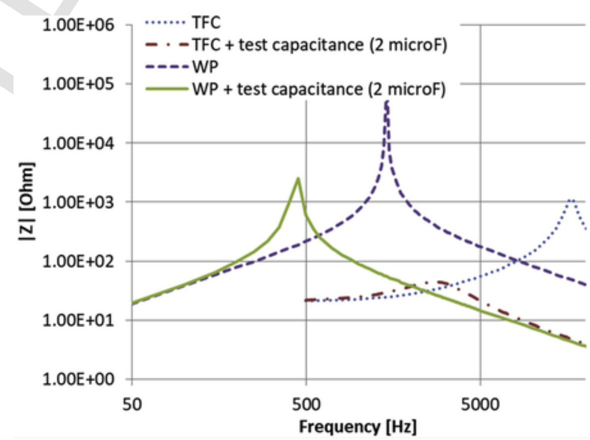

Fig. 5. Impedance spectrum calculations obtained from reference electrical parameters of the modules.

Table 4
Summary of electrical properties of the ten TFCs produced measured after *vi*) step.

TFC-ID	f [Hz]	C [nF]	R [mOhm]
1	1786	65	128.9
2	1767	65	127.5
3	1779	70	128.1
4	1795	63	128.6
5	1812	65	128.9
6	1773	60	128.5
7	1767	57	128.4
8	1773	64	128.9
9	1761	65	129.0
19	1767	65	129.9
Average	1778	63.9	128.7

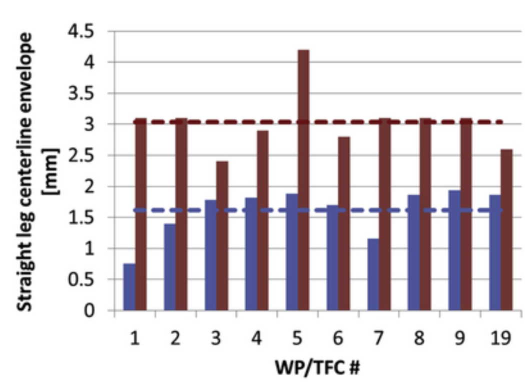

Fig. 6. Straight leg centerline envelopes at the end of WP (blue bars) and TFC (red bars) manufacturing (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

months estimated at the beginning of the contractual activity for this operation. Nonetheless, it is worth highlighting that the best performance, of less than 4 months, was indeed achieved for the integration of the first spare coil.

3. Review of technical performances

In the course of the manufacturing activity, a large number of tests were conducted to monitor the electrical and geometrical properties of the coils. In the following sub-sections some of the most significant are reviewed (the interested reader may find further information in Ref. [7]).

3.1. Electrical properties

Among the electrical tests performed during manufacturing, the so-called "surge test" is one of the most relevant because it is able to highlight turn to turn insulation weaknesses [9]. It consists in applying an impulsive voltage (3 kV) at the terminals by means of a capacitive discharge. The test capacitance together with the coil constitutes a RLC circuit in which the voltage, and hence the current, oscillates at a specific frequency. The oscillation is damped by the resistance of the coil. In the standard practice, the waveform of the oscillation of the first coil is used as reference for comparison with the subsequent coils to detect possible weaknesses in the insulation. Nonetheless, from the analysis of the waveform it is also possible to measure indirectly the self-inductance and the resistance of the coil. This measurement was performed during DP manufacturing, at the end of the stacking operation, before and after VPI and in the different steps of the integration activity. Although the measurements in each step were quite homogenous among the different coils, the differences from one step to the other were significant. To comprehend this differences, the same approach described in [10] was used. In particular, using for the inductance, resistance and capacitance of the coil the values computable theoretically, a good agreement with the experimental measurements has always been found.

Fig. 4 shows an example of the surge test result on a WP after the VPI. The natural frequency of the oscillation is easily computed and it is equal to about 450 Hz which is in line with the 414 Hz obtained from the model described in [10].

The following Table 3 shows the summary of frequency, inductance, capacitance and resistance measured in the ten WPs produced after the VPI.

While the frequency and inductance values in Table 3 are obtained from the surge tests, the capacitance is measured directly by the dissipation factor test and the resistance is measured by a standard four wires measurement. The large scattering in the measurements of the capacitance is due to the different measurements conditions used. Indeed, starting from second, the WPs were wrapped by a thin aluminum foil during the test.

Table 4 summarizes the electrical properties of the modules after the integration phase. Inductance values are not reported because, as it is clearly shown in [10], the casing around the WP acts as the secondary of a transformer in which the WP is the primary winding. Therefore at high frequency the influence of the casing cannot be neglected whilst at low frequency, as in the case of the fast discharge in the tokamak, the dynamic is dominated by the self-inductance of the WP. The natural frequency measured of 1778 Hz is in line with the 1888 Hz computed theoretically. The casing affects also the capacitance of the coil since it acts as a capacitance in series with the capacitance of the WP. The values reported in Table 4 are well in agreement with those computable theoretically.

In order to judge the consistency of the measurements shown so far, Fig. 5 presents the impedance spectrum of the four equivalent circuits analyzed.

The green solid curve refers to the WP during the surge test with a test capacitance of 2 μF in parallel to the coil: the corresponding natural frequency is 414 Hz. The purple dashed curve refers to the WP alone: the corresponding natural frequency is 1.4 kHz. The red dot-dashed curve pertains to the TFC during the surge test with the test capacitance in parallel: the corresponding natural frequency is 1.89 kHz. The blue dotted curve is associated to the TFC alone: the corresponding computed natural frequency is 16.25 kHz. The measurement, by means of a Impedance analyzer, confirmed the well agreement of the model with the measurements of the TFC alone, whilst the results of the surge tests confirm the result computed with the test capacitance in parallel.

3.2. Geometrical properties

Among the several geometrical measurements carried out during the manufacturing, one of the most relevant is the measurement of the centerline of the straight leg. This is associated to the position of the mean line of current and then to the magnetic field in the inboard side of the tokamak. In the technical specification, it was prescribed that the centerline should have been contained in a cylinder of 2 mm diameter to limit the ripple in the magnetic field. This specification was achieved at the end of WP manufacturing but was lost at the end of the integration phase due to the large deformation induced by the welding.

Fig. 6 shows the results of the measurements carried out at the end of the WP manufacturing (blue bars) and at the end of the TFC integration (red bars). In the figure, the average value of the cylinder diameter that envelopes the centerline (1.6 mm for WP and 3 mm for TFC) is also plotted. Note that the deformation induced by the welding of the covers led to a roundness of the coils with an increase of about 8 mm in the width. Half of this increment was taken by the straight leg and half by the curved one. The 4 mm displacement on the straight leg was however partially compensated by a corresponding change of curvature. At the end of the WP manufacturing the curvature was, indeed, directed towards the outboard of the coil, instead, at the end of the integration, the curvature pointed internally. This mechanism explains why the difference between blue and red bars is less than 4 mm. It is worth noting that although the requirement on the centerline was not met in the TFC fabrication, the tolerance foreseen in the final assembly in the tokamak whose larger and hence the error was compensated by a careful assembly activity in Japan [4].

4. Concluding remarks

The procurement by ENEA of ten TF coils of JT-60SA within the Broader Approach program has started in September 2011 and was completed in about 6.5 years. Manufacturing processes were characterized by improvements that led to apparent accelerations in the fabrication schedule although several difficulties caused initial delays both in the WP manufacturing and in the TFC integration. Although the manufacturing covered a so large time period, nonetheless the performances in terms of electrical and geometrical parameters were always acceptable and of limited variation. As a final remark, it is worth noting that all the coils passed the cryogenic acceptance tests at full current and the subsequent high voltage DC and AC tests [5].

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