Experience on Series Production of the Superconducting Magnet Package for the Linear Accelerator of the European XFEL

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***Abstract*—The procurement of 103 superconducting magnet packages is part of the Spanish in-kind contribution to the European X-FEL. Each package consists of a main superferric quadrupole and two steerers, vertical and horizontal, fed by conduction-cooled current leads and enclosed in a stainless steel vessel. The operation temperature is 2 K, as they are embedded in a superfluid helium bath. The magnetic and mechanical designs are published elsewhere. The magnets are being produced in the Spanish company ANTEC, while the vessels are fabricated by another Spanish company, Trinos Vacuum-Projects, which is also responsible for the integration, under the supervision of CIEMAT. The helium vessel manufacturer needs to accomplish the requirements given by the European Pressure Equipment Directive, namely PED 97/23/EC. This paper describes the series fabrication techniques, the production follow-up, the quality assurance and the magnet testing at the manufacturer site. Cold tests are realized at DESY premises. The main problems found during the fabrication of the first half of the series are also reported: a) the reproducibility of the quadrupole coil dimensions; b) the accuracy of the beam position monitor housing after final welding of the vessel; and c) the minimization of the magnetization effects on the transfer function of the magnets.**

***Index Terms*—Accelerator magnets, superconducting magnets, magnetization.**

I. Introduction

SUPERCONDUCTING magnet packages for the European XFEL[1] will be housed in 103 cryomodules (84 in the main LINAC, 12 between the two bunch compressors, 4 between injector and BC1, and 3 pre-series modules, XM-3 to XM-1). The magnet package consists of a superconducting quadrupole used for focusing and two horizontal and vertical deflecting superconducting dipoles used for beam steering, enclosed in a stainless steel vessel, which is leak tight for vacuum operation (thermal insulation vacuum all around except the beam pipe, where ultra-high vacuum is present).

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During the research and development phase, five prototypes have been built from 2006 to 2010. In the last one, some design changes have been done to optimize production in industry and reduce costs [2]. XFEL has given final acceptance on the prototype in January 2011. CIEMAT has allocated the contract for the series production in August 2011. The whole production of the Superconducting magnets packages has been assigned to Trinos Vacuum-Projects, S.L (Valencia, Spain) with duration of 31 months.

II. Technical Requirements

The complete list of parameters of the XFEL superconducting magnet packages has been published elsewhere [2]. The required integrated quadrupole strength is 5.2 T, while the integrated dipole field is about 9 mT·m. The overall length of the helium vessel from flange to flange is 300 mm. The nominal current is very low (only 50 A) to afford the efficient use of conduction-cooled copper current leads. Therefore, it means that the cross section of the superconducting wire will be small, at the same time the number of turns will be high, resulting in a relatively large quadrupole self-inductance (0.9 H).

The magnet is contained in a vessel filled with helium at 2 K. Since all the magnet and cavity vessels are interconnected, the magnet vessel has been produced according to the Pressure Equipment Directive, reference PED/97/23/EC, appendix III, module B + F, category IV.

CIEMAT is fully responsible for the conceptual and engineering designs.

III. Magnet Fabrication Techniques

The superferric quadrupoles and the dipole coils have been fabricated in ANTEC, a Spanish company specialized in magnet fabrication and subcontracted by Trinos Vacuum-Projects. The winding techniques are described elsewhere [3].

The main manufacturing challenge has been the reproducibility of the quadrupole coil dimensions. Correct coil dimensions ensure that when the quadrupole is assembled, the coils are well supported by wedges. So during the energizing of the magnets, no free movements of the coils are allowed and premature quenches will not be triggered.

One should be especially careful with the following features during the quadrupole winding process:

1) To keep a constant winding tension, even when wrapping

the wire around the corners of these racetrack coils.

2) To be careful with the stacking of the layer jumps (21 per coil). As the most important dimensions are those of the coil straight section, the layer jumps are done at the coil ends.

3) The coils are wet impregnated with Araldite AW106 epoxy resin and HV953U hardener. Each coil takes about three hours to be wound, so several mixings are necessary for each coil to apply a low viscous resin. If not, the central part of the coil cross section will get too thick, because the excess of resin in between the inner layers is evacuated thanks to the winding tension of the outer layers. It is worth to mention that the winding duration is now half of that at the beginning.

4) The mould must be closed applying enough pressure to get right coil dimensions, but without spoiling the wire insulation. This problem has been finally solved by adding stoppers which limit the pressure. Besides, these stoppers help to guarantee the parallelism between both sides of the coil straight section.

5) Once the coil has been demoulded, the resin burrs must be carefully cut away without damaging the wire insulation. If some burrs are left, the contact of the coil with the iron or the wedges may be incorrect, resulting in a poor quench performance.

The most important dimension to be checked is the cross section width of the quadrupole coils. The deviations detected at the beginning of the production have been improved as shown in Fig. 1.

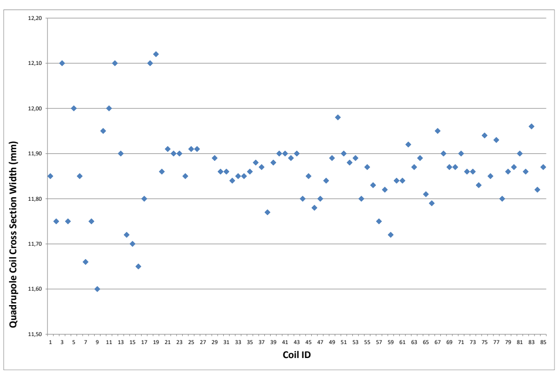

Fig.1. Quadrupole coils cross section width data.

In the same way, special care has been taken for the fabrication of the iron yoke as it determines the good quality of the magnetic field in a superferric magnet with low saturation. Besides, the iron lamination package must not be twisted and a special tool has been developed for that (Fig. 2).

The iron yoke of the magnet prototype was done with 2.5 mm thick laminations. Since the twisting of the stacking was difficult to control due to the high number of laminations, it was decided to use 4 mm thick laminations for the series. When the same torque (12.5 Nm) was used to press the package, one could notice that the filling factor was not high enough. The variation of the iron stack length with the torque was analyzed, concluding that a torque of 40 Nm was necessary to get the same filling factor of the prototype. As this torque was beyond the Young modulus of the threaded rods of the prototype, the material choice was changed, from 8.8 quality steel to 12.9, fitted with A4 class 80 nuts. The significant torque increase can be explained not only because of the intrinsic higher stiffness of the thicker laminations, also due to the different fabrication process: 2.5 mm thick laminations are cold rolled while 4 mm thick ones are hot rolled.

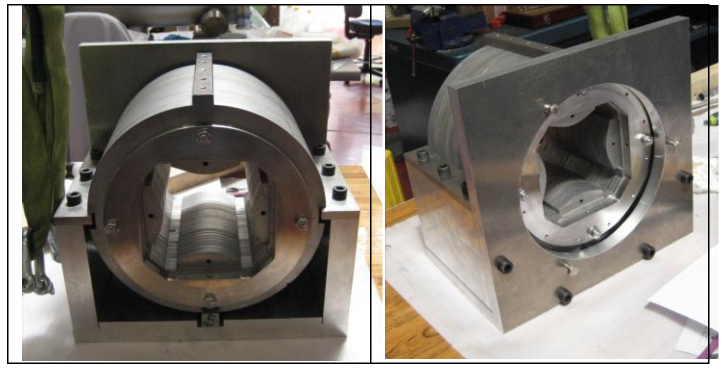

Fig.2. Two different views of the iron yoke stacking tool.

The magnetization effects on the prototype magnet were very high, especially for the dipoles [2]. The wire used in the dipole coils had very thin filaments (3.5 micron) but distorted. For the series, a wire with 6 micron filaments has been used. Even so, magnetization effects are still significant. A custom wire could be an option to minimize the magnetization, but it is not possible as there are just few superconducting wire suppliers in the market.

One should notice that the iron yoke is also contributing to the magnetization effects, which are basically proportional to the coercive force of the iron, that is, the grain size and the friction between magnetic domains. The coercive force of 2.5 mm thick laminations is higher than for 4 mm thick ones, because the grains are smaller. It means that the dipole field is not strong enough to change the orientation of the magnetic domains and, therefore, the dipole transfer function is not split. One magnet was fabricated with 2.5 mm thick laminations, and the magnetization effects on the dipole transfer function were reduced by 30%. As expected, quadrupole transfer function was hardly modified. Further investigations are ongoing.

IV. VESSEL FABRICATION TECHNIQUES

Once the magnetic part is finished, it is shipped to the company which is in charge of the vessel manufacturing and final integration, Trinos Vacuum-Projects.

The main challenge has been to limit the deformations due to the welds. The vessel is not only a pressure container, it is also the responsible to properly align and center the quadrupole and the dipole coils. Furthermore, the beam position monitor (BPM) shall be attached to one of the endplates, correctly placed respect to the coils as well. Due to the PED requirements, the welding preparation has been changed from the one used in the prototype to guarantee full penetration welding. The deformations become bigger because the heating is more intense. The decision was to drill the holes for the BPM alignment with a smaller diameter, and finish them after the welding. A small twist angle between both endplates was detected, which is measured on a granite table before the final machining of the pin holes.


Fig.3. Custom tool for positioning during welding.

Custom tools have been used to guarantee the right positioning of the elements (nozzles, supports, connection box…) welded to the main body of the vessel (see Fig.3).

Some problems have been found during the production of the curved pipes which host the current leads. These pipes were produced by welding several short individual parts. Due to the lack of thickness uniformity of the elbows, some of these pipes were rejected in the radiography tests. It seemed that the weld penetration was not complete, while the problem was that both sides of the weld had different thickness. Therefore, it was decided to fabricate just a single piece bended tube (see Fig. 4) which is more efficient and less expensive for a series. The fabrication procedure of the elbow has been supervised and qualified by the notified body TÜV-NÖRD.


Fig.4. Detail of the bended tube.

The pipe samples have been checked dimensionally and visually for validation of the procedure and bending tool. For the visual inspection, several cuts have been done and the thickness in the more critical areas has been checked. The external surface has been also checked as it must be free of cracks.

V. QUALITY ASSURANCE

The main goal of the quality assurance system of this project is to guarantee the achievement of the technical specifications. Both warm and cold magnetic tests are made once the packages are delivered at XFEL facilities [4]. Individual magnetic measurements on dipole and quadrupole coils before assembly were discarded because the mechanical reference is provided by the vessel. Besides, these tests would be made in addition to the final ones on the complete magnet, yielding a significant cost incompatible with the available budget. Therefore, the companies need to find alternative methods to guarantee the magnet performance without magnetic measurements. In any case, the risk exists: if a magnet package fails at the magnetic tests, the vessel and the dipole coils would be spoilt.

Both companies have created and followed a Quality Management System according to ISO 10005.

The main dimensions that were initially planned to be checked during the magnet production are listed as follows:

1) The wire diameter, both for the dipole and quadrupole coils.

2) The thickness and height of the coil straight section, at three different points along the coil.

3) The angle of the wedges which are placed in between two coils.

4) The profile of the iron poles directly determines the field quality in a non-saturated superferric magnet. In contrast, the field quality dependence on the coil positioning is weak. The four pole profiles are checked for every magnet, at three different heights, to assure that the laminations are not twisted nor had a conic shape. The reference system is defined by the key slots which are used afterwards to align the vessel endplates. The tolerance shape is +/- 0.02 mm. Some small deviations have been detected, in the range of +/-0.03mm limits, but the yokes have been accepted because they were local defects. In the case of larger deviations, a custom analysis could be possible using numerical computation.

5) In the case of the dipoles, the most important dimension is the span angle of the central post. Besides, the thickness of all the fiberglass spacers has been checked to guarantee that the wires cannot roll over neighbor ones during the winding.

Some other controls have been added during the series fabrication. For instance, the longitudinal centering of the quadrupole coils with the iron yoke is being checked, because some of the first magnets performed a dipole harmonic higher than expected, although within tolerances.

Similarly, the positioning of the dipole coils after being glued onto the beam pipe is being checked in a 3-D coordinate measuring machine. This control was included when two of the magnets performed an error in the angular positioning of the dipole respect the quadrupole, slightly out of specifications.

On the other hand, some electrical tests have been done to certify the electromagnetic behavior of the magnets. The DC resistance and inductance measurements on the individual coils are a first indication for the number of turns and for the dimensional conformity. They shall be made with an accuracy of +/- 0.2% at a known temperature. The measurements on the first magnets have served to find the average values and the spread.

In the case of the dipoles, the inter-turn insulation can be checked by a simple method: a capacitor is discharged across the coil, recording the dumping curve. This method is not sensitive enough for the quadrupole coils, due to their high number of turns. The inter-turn insulation of the quadrupole coils is checked by measuring the loss factor, that is, the ratio of resistance and admittance, at different frequencies. In the case that one turn is short-circuited, the variation of the loss factor value is around one order of magnitude.

The ground insulation of the assembled magnets is checked by applying a voltage of 500 V during one minute. The coil polarity is checked with a magnetic field sensor while powering the coils with a low current.

Regarding the vessels, the notified body TÜV-NÖRD is the responsible to certify the production according PED 97/23/EC. The company Trinos Vacuum-Projects, as responsible for the vessel fabrication, is certified according to the standard ISO 3432-4. A weld plan has been developed in order to achieve the welding requirements on the technical specifications. The necessary welding procedure qualification reports (WPQR) to qualify the welding procedure specifications (WPS) have been done according to the standards ISO 15607, ISO 15609 and ISO 15614-1. TÜV-NÖRD has checked and approved the vessel design during the prototyping phase. During the industrialization phase, TÜV-NÖRD has to witness the leak and pressure tests of each vessel.

First of all, there are a number of non-destructive tests on the materials and welds which must be followed: radiography, visual inspection, ultrasound tests. Careful visual inspection of the sealing surfaces is compulsory. They must be scratches free. At the beginning, this control was done only by standard leak tests. However, a leak was detected when the magnet was already at the clean room for integration into the cryomodule. It was caused by a very small blowhole, which has not been noticed during the previous leak tests.

There are also some dimensional measurements on the individual parts of the vessel and the final assembly. Since the holes for the BPM dowel pins are so important, their position is checked with a FARO arm and also with a customized go/no go tool. A custom tool is also used to check the dimensions of the sealing surfaces on the beam pipe, which becomes elliptical due to the welding.

Leak and pressure tests have been performed for every magnet vessel. The same set-up has been used for both tests to reduce the duration, because the inspector needs to be present. Up to five magnets can be tested in one day. The set-up consists of a big vacuum chamber where the vessel is introduced. The magnet vessel is connected to the atmosphere through a pipe, while the vacuum chamber is pumped down to a vacuum level in the order of 1E-6 mbar. It is the same configuration that can be found in the accelerator cryomodule. The connection box is closed with an aluminum gasket and a blind flange. The vacuum chamber around the magnet vessel also serves as personal protection in case of magnet vessel failure during the pressure test.

For the pressure test, nitrogen gas at 5.8 bar is introduced into the magnet vessel through the mentioned pipe. A 0.6 class manometer checks that the pressure keeps constant during 30 minutes. After this time, the variation of the pressure on the vacuum side is also checked with a gauge, as a fine control. At the beginning, helium gas was used, but some rests remained in between the iron laminations which were difficult to evacuate and cheated the leak detector when a leak test was directly performed on the magnet vessel itself (vacuum inside).

Afterwards, the helium gas is introduced at atmospheric pressure into the magnet vessel and the leak detector is connected to the vacuum chamber to look-up for any leak. The results recorded by a calibrated leak detector are sent to CIEMAT.

For each complete magnet package, a thorough set of documentation is compiled and stored at XFEL database system. It includes the following reports:

1) The material certificates for raw materials.

2) The dimensional control reports for magnet and vessel of each magnet package.

3) The non-destructive tests reports, as visual inspections, and welding radiography test report.

4) Pressure and leak tests reports.

5) The traceability report in which the serial numbers of all incorporated semi-finished products and manufacturing groups are stated in the form of a part list, including position information. All parts have been clearly identified with a serial number for traceability, and they have non removable stamps. If stamps are not visible on the finished vessel, the tracking documentation allows identification of those parts.

6) The conformity certificate to assure that every magnet package has been produced according to specification, and that all requirements have been checked and complied.

XFEL stores all production data in EDMS system for document management [4]. All documents created by the manufacturers, such the specifications, inspection sheets, conformity certificates or dimensional controls sheets are recorded in EDMS. A closely collaboration has been developed between the EDMS team for the superconducting magnets and the producers of the documents.

VI. Conclusion

Trinos Vacuum Project has been awarded with the contract to supply 103 superconducting magnet packages for the main linac of the European XFEL, under CIEMAT supervision and with Antec as a subcontractor. About 45 packages have been already delivered, without any rejection.

The fabrication techniques are based on the prototyping developed by CIEMAT in collaboration with the industry. Some problems found during the production are reported. The pressure vessel is produced according to the PED requirements.

The quality control is described in detail. It aims to guarantee the achievement of the technical specifications before the magnetic measurements on the final assembly, because the magnet package cannot be disassembled without spoiling the vessel and the dipole coils.

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