MANUFACTURING OF MEBT COMBINED QUADRUPOLE & STEERER MAGNETS FOR THE LINEAR IFMIF PROTOTYPE ACCELERATOR LIPAC*

J. Castellanos†, B. Brañas, J. Mollá, C. Oliver, I. Podadera & F. Toral, CIEMAT, Madrid, Spain
R. Iturbe & B. López, Antec SA, Portugalete, Spain
O. Nomen, IREC, Barcelona, Spain

Abstract

The Medium Energy Beam Transport line MEBT [1, 2] is currently being installed on the LIPAC accelerator [3] and has among its components, five quadrupole and steerer magnets which were recently manufactured and tested.

Given the compactness of the MEBT line, each magnet combines, in a common yoke, a strong quadrupole field with a minor horizontal and vertical steering. In this way, each yoke integrates four water-cooled coils (quadrupole coils) and eight air-cooled coils (steerer coils) made of copper wires.

The magnetic design of the five combined magnets was done by CIEMAT [4] and the manufacturing and testing (excluding magnetic measurements) were carried out by the Spanish company Antec SA. With respect to the engineering design, it was mainly done by Antec SA but reviewed and agreed with CIEMAT.

This paper focuses on the technical aspects considered during the manufacturing and assembly of the MEBT magnets. Some details about the factory acceptance tests that were carried out before the magnetic measurements are also described.

INTRODUCTION

The Medium Energy Beam Transport line [1, 2] of the LIPAc accelerator [3] is placed between the RFQ system and the SRF Linac. Figure 1 shows the MEBT line where its five magnets are indicated as MMA01 to MMA05.

One important characteristic of the MEBT magnets is that, due to the short length available, it was decided to use combined magnets, according to the scheme represented in Fig. 2. Basically, each of the four poles of a magnet includes one quadrupole and two steerer coils which are centered on the iron pole. Steerers are located under the quadrupole coils in order to use the available space close to the pole tip [4].

The MEBT magnets should fulfill some strict magnetic quality requirements in order to have the desired control of the beam [4], and their performance should not be affected by ionizing radiations with an integrated dose up to 10^5 Gy. The fundamental MEBT magnets parameters are showed in Table 1.

All the considerations stated above, that is: 1) the compact design, 2) the strict magnetic requirements and 3) the ionizing radiations have a strong impact in the manufacturing techniques that should be followed during the construction and assembly of the magnets. For instance, the compact design complicates the positioning of the coils and the routing of their terminals as well as the design of the electrical and hydraulic connections; the strict magnetic requirements lead to specific manufacturing techniques for the machining of the pole tips and finally, the consideration of ionizing radiations requires a careful selection of the materials and the manufacturing methods, especially those related to the insulation of the conductors and the coils.

This paper summarizes the manufacturing techniques that were followed during the construction of the MEBT magnets in order to fulfill the requirements previously described. In addition, some details of the factory acceptance tests are also presented.

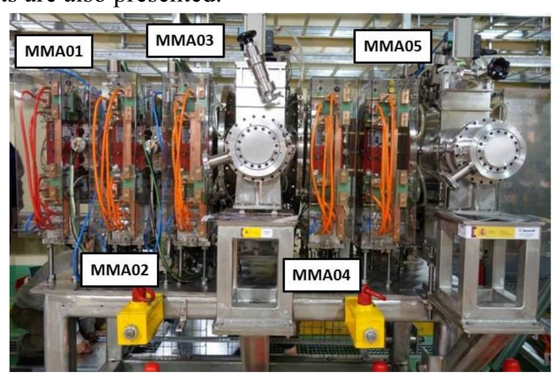

Figure 1: The MEBT line with the magnets installed. The five magnets are indicated as MMA01 to MMA05.

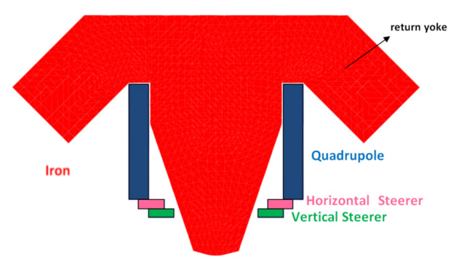

Figure 2: Schematic section of one of the four poles of a MEBT combined magnet. The quadrupole coils and the horizontal and vertical steerer coils are indicated.

Table 1: Main Magnet Parameters. Extract from [4]

Yoke length, height & width, mm	108–500–500
Total mass (including support), kg	220
Water flow, l/min & pressure drop, bar	3 // 5
Design gradient, T/m	25
Aperture diameter, mm	56
Integrated magnetic field (at 75% of aperture), T·m	0.0683
Steerer integrated field, G·m	25

* Work included in BA Agreement activities supported by the Spanish Ministry of Economy and Competitiveness.
† jesus.castellanos@ciemat.es

MANUFACTURING

The main operations that were conducted during the manufacturing of the MEBT magnets were: a) machining of the magnetic yokes, b) insulation of the copper conductors, coils winding and coils impregnation, c) fabrication of the magnet supports and of the auxiliary components such as electrical, hydraulic and electrohydraulic connections and d) assembly of the magnets. The rest of this section will summarize some relevant aspects considered during the main operations of manufacturing.

Magnetic Yokes

The magnetic yokes are made of ARMCO® pure iron grade 4. Each magnetic yoke is formed by four solid yoke quadrants as it is showed in Fig. 3. The base support is made of an aluminium alloy.

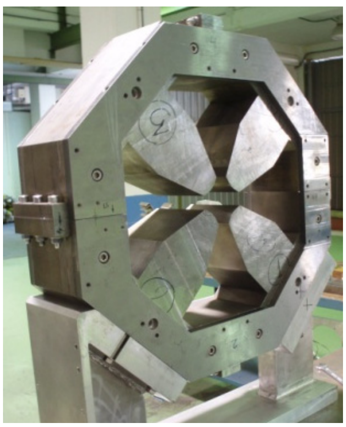

Figure 3: Magnetic yoke quadrants assembled and mounted in the magnet base support.

The manufacturing process of the yokes can be divided into two main stages: 1) CNC machining (milling and drilling) for the front and rear faces of the yokes and the surfaces not requiring very tight tolerances and 2) Wire Electrical Discharge Machining (WEDM) for the surfaces where the magnetic field quality requirements impose very tight machining tolerances: the hyperbolic pole tips and some area close to them. A couple of WEDM passes were conducted in these areas in order to obtain a shape tolerance for the profile of the surfaces better than ±20 µm. In addition, the four pole tips were wire-cut at the same time (with the four quadrants assembled), in order to minimize mechanical asymmetry in the yoke profile.

For each magnet, the top face of the upper yoke and the lower face of the lower yoke have eight machined reference surfaces (four per face), and each of them has an interface hole for a laser tracker holder, which allowed the fiducialization of the magnets, i.e., the transfer of the magnetic/mechanic centerline position to these external fiducials.

Quadrupole and Steerer Coils

Each quadrupole coil has *N*= 44 turns (4x11) of a high-conductivity oxygen-free copper conductor with a round hole for water cooling. The conductor cross section is a rectangle of 7.5x5 mm with the inner round hole of diameter 3 mm. The conductor insulation was made of 0.3 mm thick fiberglass tape, impregnated with H class polyesterimidic resin, according to the standard EN 60317-0-4.

On the other hand, each steerer coil has *N*= 18 turns (2x9) of electrolytic tough pitch copper conductor enamelled according to EN 60317-29. The mean cross sections of the bare and enamelled conductors are 5x2 and 5.14x2.13 mm respectively.

After winding, each whole coil was wrapped with fiber glass tape and place in a specifically designed aluminium mould to perform a vacuum impregnation process. The resin used during impregnation was ARALDITE F® with a specific proportion of components and fillers.

The vacuum impregnation technique was chosen in order to obtain high quality coils from the electrical point of view and also to fulfill the strict requirements about the shape of the coils due to the compact design imposed by the MEBT line.

Finally, it is also worth mentioning that during the design phase of the magnets, some CERN radiation damage databases [5, 6] were consulted in order to check the performance of the materials used for the electrical insulation of the conductors and the coils. It was determined that these materials should not be significantly affected by the total radiation dose of LIPAc (~10^5 Gy for the MEBT magnets).

Figure 4 a) and b) show, respectively, a set of quadrupole and steerer coils after vacuum impregnation, ready to be installed in the magnet yoke.

As shown in Fig. 4, the coils have long terminations since no joints are allowed within the coils, including their leads, until they reach the corresponding electro-hydraulic connection (for quadrupole coils) or the connection block (for steerer coils) which are placed inside a protection cover in the lateral of each magnet.

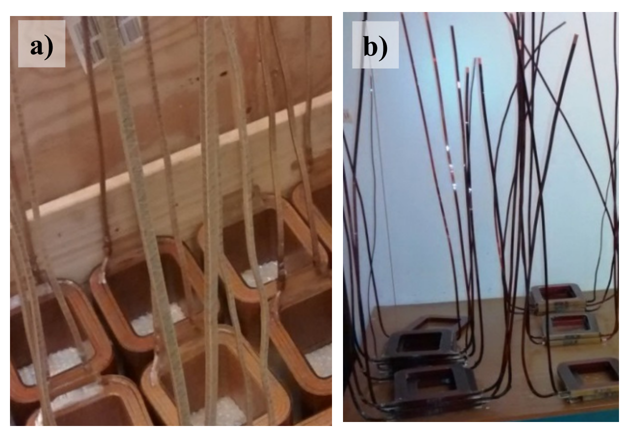

Figure 4: a) Quadrupole coils and b) Steerer coils after vacuum impregnation ready to be installed on the magnet yoke (showed in Figure 3).

Assembly

Figure 5 shows a picture of a MEBT magnet. It is observed that the electrical and hydraulic connections as well as the cables for instrumentation (there are some thermal switches to protect the quadrupoles coils from accidental

ISBN 978-3-95450-169-4

overheating, as recommended in [7]) are placed at the right side of the magnet which is the only space available to perform the connections.

The magnets can be easily separated into two halves for the installation of the beam pipes. This consideration affects the design of the routing of the coil terminations and the position of the electrohydraulic connections since any brazing joint can be undone during this task.

Some recommendations stated in [7] were also followed, taking advantage of the experience of other institutions. For instance, low conductivity water hoses (in orange in Fig. 5) made of a polyester elastomer, with synthetic fiber reinforcement and polyurethane cover was selected and also the brazed joints in the electro-hydraulic connections were carefully done and tested. In addition, ceramic terminals for instrumentation were employed to minimize degradation from radiation and thermocouples type T (recommended in the presence of magnetic fields) were used to monitor the temperature of steerer coils.

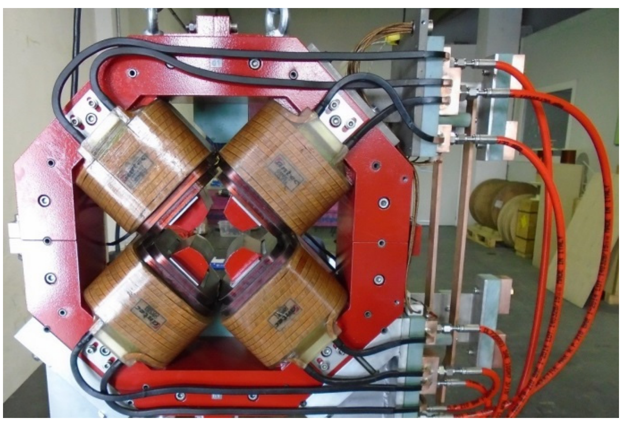

Figure 5: Front view of a MEBT magnet for the LIPAc accelerator.

FACTORY ACCEPTANCE TESTS

A considerable number of factory acceptance tests (FATs) were conducted at Antec SA workshops. The main aim of these tests is to check the performance of the magnets and their components from the mechanical, electrical, and hydraulic point of views. The most relevant tests are listed below.

With respect to the conductors, their insulation was checked with a Megger before winding of the coils.

After winding but before impregnation of the coils, multiple electrical tests were performed to check possible errors. Particularly, a short circuit test, using an impulse winding tester was done in each coil to check the inter-turn insulation. In addition, the resistance and inductance were measured with a RLC bridge.

Finished impregnated coils were also checked. First, visual inspection and dimensional control of each coil were done to check the uniformity and homogeneity of the impregnation as well as the general dimensions of the coils. Electrical short circuit tests and measurements of the resistance and inductance were again conducted to confirm small variations with respect to the results obtained in the coils before impregnation. The ground insulation was also checked. In addition, each quadrupole coil was subject to the nominal pressure drop (~5 bar) and the water flow inside each coil was measured in order to check the absence of flow restrictions in the conductors. Finally, some quadrupole coils were subject to thermal cycling in order to check if the electrical insulation can resist multiple temperature variations without degradation or cracking.

Regarding the magnetic yoke, a Coordinate Measuring Machine, CMM, was employed to measure the profile of the pole and to carry out the mechanical fiducialization of each magnet. It was found that the great majority of the measurements carried out on the hyperbolic pole tips were under the tolerance limit allowed (±20μm).

Finally, the full magnets were checked. Among other tests, the performance of each magnet were checked at the maximum DC current for the quadrupole circuit (178 A) by using a power supply, a hydraulic test bench and some thermocouples as temperature transmitters.

After the completion of FATs, the magnets were sent to ALBA-CELLS laboratory for magnetic characterization [8]. For a couple of magnets, normal sextupolar and octupolar terms (b_3 and b_4) were found to be a little bit higher than the acceptable limits initially imposed (±10 units).

Then, in one magnet, the quadrant positions were slightly corrected to improve yoke symmetry and magnetic measurements were again conducted. The new results revealed that b_4 term was strongly reduced to ~1 unit. In contrast, b_3 term was kept in the same range (higher than 10 units only for low currents) which could be attributed to some asymmetry on the magnetic properties of the yoke. The slightly higher b3 & b4 terms were implemented in the beam dynamics code. It was confirmed they had no significant influence on the beam dynamics.

CONCLUSIONS

MEBT magnets were successfully manufactured and commissioned. Tests showed they are compliant with the stringent design technical specifications.

ACKNOWLEDGEMENT

Work included in BA Agreement activities supported by the Spanish Ministry of Economy and Competitiveness.

REFERENCES

[1] I. Podadera *et al.*, “Manufacturing, assembly and test of the LIPAc Medium Energy Beam Transport Line (MEBT)”, presented at LINAC’16, September 2016, this conference.

[2] I. Podadera *et al.*, in *Proc. of IPAC’11*, pp. 2628-2630.

[3] P. Cara *et al.*, in *Proc. of IPAC’16*, pp. 985-988.

[4] C. Oliver *et al.*, in *Proc. of IPAC’11*, pp. 2424-2426.

[5] G. Lipták *et al.*, Rep. CERN 85-02, Mar. 1985, pp. 36 & 40.

[6] M. Tavlet *et al.*, Rep. CERN 98-01, May 1998, pp. 35.

[7] C.M. Spencer, “Improving the Reliability of Particle Accelerator Magnets: Learning from our Failures”, *IEEE Trans. Appl.Supercond.*, vol. 24, no 3, 2014.

[8] J. Marcos *et al.*, in *Proc. of IPAC’16*, pp. 1151-1153.