10th Int. Particle Accelerator Conf. IPAC2019, Melbourne, Australia JACoW Publishing
ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS020

ESS MAGNETS AT ELETTRA SINCROTRONE TRIESTE

D. Castronovo†, D. Caiazza, A. Fabris, R. Fabris, A. Gubertini and G. Loda,
Elettra Sincrotrone Trieste, Trieste, Italy

Abstract

Elettra Sincrotrone Trieste Research Center (Elettra) is one the Italian Institutions, together with Istituto Nazionale di Fisica Nucleare (INFN) and Consiglio Nazionale delle Ricerche (CNR), committed to the realization of the Italian in-kind contributions for the European Spallation Source [1]. One of these consists in the supply of several conventional iron dominated electro-magnets to be installed in the superconducting part of the linac and in the transfer lines, which are 139 quadrupoles, 2 dipoles and 72 correctors. This document reports all related magnetic design and optimisations carried out to meet the required specifications and supplies.

OVERVIEW

Regarding the ESS related activities at Elettra-Sincrotrone Trieste [2], for the contribution of the magnets Elettra has carried out the following main activities: collaboration in defining the specifications required by ESS; collaboration with the power converter (PC) contribution for the definition of nominal currents and powers [3]; design and optimization of magnetic models; definition of mechanical models; the R&D and the production of the documentation packages the Critical Design Review (CDR) of the magnets Q5, Q6, Q7, C5 and C6; the definition of the Preliminary Design Review (PDR) of magnets D1, Q8 and C8; compilation of the technical specifications for the tenders issued by INFN in the framework of the trilateral agreemnts between ESS, Elettra and INFN; control of the execution of the contracts with Danfysik for the realization of the magnets Q5, Q6, Q7, C5 and C6 and with Sigmaphi for the realization of the magnets D1, Q8 and C8; the development of a bench for the magnetic measurement of the magnets Q5, Q6, Q7, C5, and C6.

Q5, Q6, Q7, C5 AND C6 MAGNETS

The first magnet activities concerned the definition of magnet Q5, Q6 and Q7. Originally, these magnets were required to work in the pulsed mode to significantly reduce the electrical power and therefore the required energy consumption. The main requirements were:

- Repetition rate of 14 Hz.
- Magnetic field flat top length >3 ms (beam length).
- Peak voltage <0.85 kV (to avoid medium voltage techniques and rules).
- RMS current density <1.1 A/mm^2 (to allow a coil air cooling system).

In addition to these main requirements, each family was characterized by the performance specifications listed in Table 1. Taking into consideration all the required parameters, and, in particular, the maximum peak voltage and the repetition rate, the first and most important parameter to be defined was the maximum current.

Table 1: Requirements of Q5, Q6 and Q7

Parameters	Q5	Q6	Q7
Bore diameter [mm] ≥	67	112	112
Overall length [mm] ≤	250	350	400
Nom magnetic length [mm] ≥	150	250	250
Nom integrated gradient [T] =	1.8	2.2	2.7
Max integrated gradient [T] >	1.9	2.3	2.9
God Field Region radius [mm] ≥	22	35	35
B_n/B_2 (n = 3÷10) [%] < ±	0.1	0.1	0.1

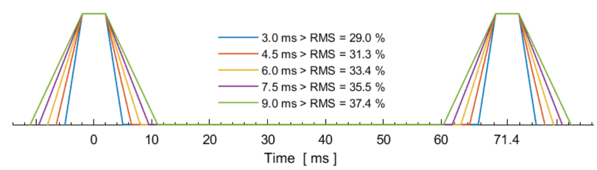

Figure 1: Trapezoidal pulse shapes.

After evaluating different forms of trapezoidal pulse, as shown in Fig. 1, taking into consideration a pulse with an RMS value of approximately 33.4%, the maximum current was chosen equal to 400 A, see Fig. 2, equivalent to 138 A RMS as shown in Fig. 2. Consequently, in order to maintain the current density RMS < 1.1 A/mm^2, it was decided to use a conductor with a cross section of 20 mm x 6.3 mm = 125.5 mm^2.

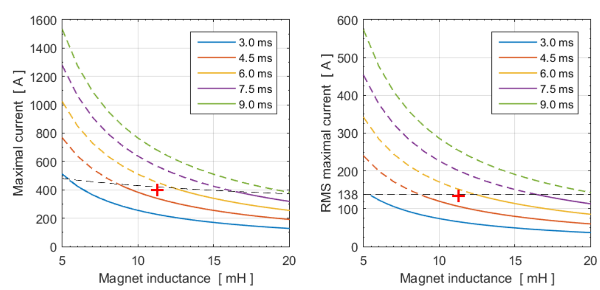

Figure 2: Magnet maximal current chart.

Fixed the same value of the maximum current for the three quadrupole types, defined the number of turns to ensure the required performances, the magnetic design was driven by the objective of minimizing the width of the poles in order to minimize the amount of iron and therefore the inductance (<12 mH). For Q6 and Q7, since the quadrupoles having the same 2D geometry, the solution was to draw polar expansions (and coils) of conical geometry. In order to minimize the transition times, the iron had to be made of laminated Fe-Si steel sheets of 0.5 mm thickness glued together. As already done in other

† davide.castronovo@elettra.eu

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS020

projects [4], also in this case the pole profile shimming was defined by geometric formulas with only four parameters. The used formulas has been the following:

$$y = \frac{R^2}{2x} - K_y \left(\frac{x - x_s}{x_t - x_s} \right)^N \quad (1)$$

Where:

$$K_y = \frac{R^2}{2x_t} - y_t \quad (2)$$

$$x_s = x_t + N \frac{K_y}{\tan\alpha + \frac{R^2}{2x_t}} \quad (3)$$

Figure 3 reports the pole profile parameters plot.

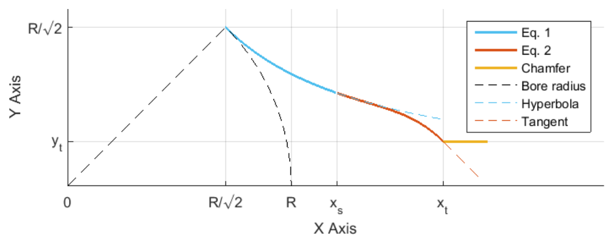

Figure 3: Pole profile equation and plot.

The optimization of the profiles was done using the Esteco MODEfrontier [5] optimization code, which, in turn, coordinated the VF Opera [6] Modeller, Tosca, Elektra and post-processor modules together with the special post-processing data via Matlab [7]. The MODEfrontier workflow is illustrated in Fig. 4.

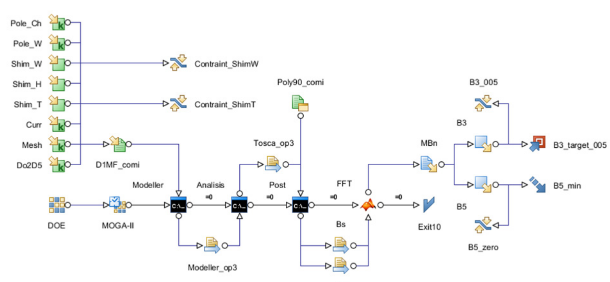

Figure 4: MODEfrontier workflow.

Since the operation in pulsed mode of the quadrupoles turned out to introduce various issues caused by the eddy currents in the vacuum chamber adopted by the project, after the initial approval of the pulsed design, all the quadrupoles Q5, Q6 and Q7 have been modified to work in DC mode. Thanks to the fact that the pulsed mode design had as well taken into account the possibility of using water-cooled coils in DC mode, this step was made possible by changing only the design of the coils. Even if the initial idea was to have the value of the maximum current in DC mode equal to the RMS value, i.e. 138 A, in order to reduce the turns and therefore the pressure drop of the cooling water, the value of the maximum current was increased to 200 A. Table 2 reports the parameters of the quadrupoles thus obtained. The use of laminated Fe-Si steel sheets of 0.5 mm was no longer necessary.

Unlike quadrupoles, since the first CDR, the correctors C5 and C6 were designed to work in DC mode with a current density such as to allow air-cooling. Table 3 reports the parameters of the magnets C5 and C6. These two correctors are both window style with a pole shape to minimize the sextupole component (< 4 %).

Table 2: Parameters of Q5, Q6 and Q7

Parameters	**Q5**	**Q6**	**Q7**
Bore diameter [mm]	68	112	112
Coil overall length [mm]	250	340	400
Magnetic length [mm]	201	278	338
Max int gradient [T]	2.2	2.5	3.0
B_n/B_2 (n = 3÷10) [%] <	0.04	0.02	0.01
Required current [A]	148	173	179
Inductance [mH]	8.2	36.5	45
Cooling system	Demineralized-H_2O		
Cond cross section [mm]	8.2 x 7.2 - Ø 3.8		
Required power [kW]	0.6	2.7	3.1

Table 3: Parameters of C5 and C6

Parameters	**C5**	**C6**
Full aperture [mm]	68	112
Coil overall length [mm]	68	98
Magnetic length [mm]	146	221
Max integrated field [Gm]	16.7	31.5
Integrated field quality [%]	4.2	2.7
Inductance [mH]	2.4	9.4
Required current	12.5	13.2
Required power [kW]	8	22

Since the correctors will be mounted between two quadrupole, the effect of corrector installation near them was simulated and the results showed a modification of the integral field compatible with the required specifications. Figure 5 shows the field longitudinal distribution in the two cases.

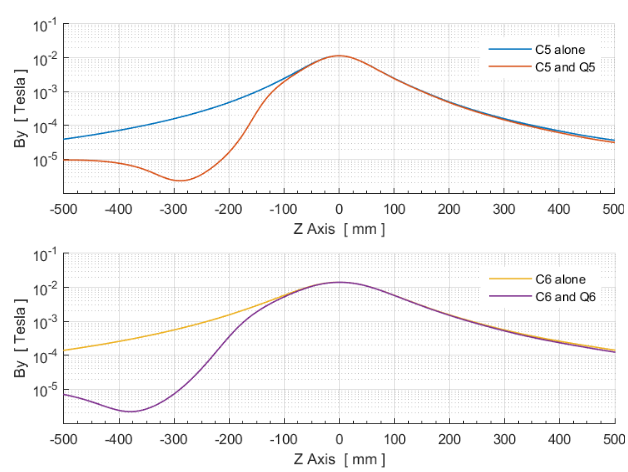

Figure 5: C5 and C6 B_y field distribution.

10th Int. Particle Accelerator Conf. IPAC2019, Melbourne, Australia JACoW Publishing
ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS020

After the CDR, the realization of Q5, Q6, Q7, C5 and C6 was assigned following an international tender to Danfysik. Some of the final Danfysik step models are visible in Fig. 6. The production of these magnets will be completed by summer 2019. Completed magnets are delivered to Elettra where they are measured and characterized. Figure 7 shows one of the Q6 on the measuring bench developed at Elettra, which employs rotating coils made in collaboration with CERN.

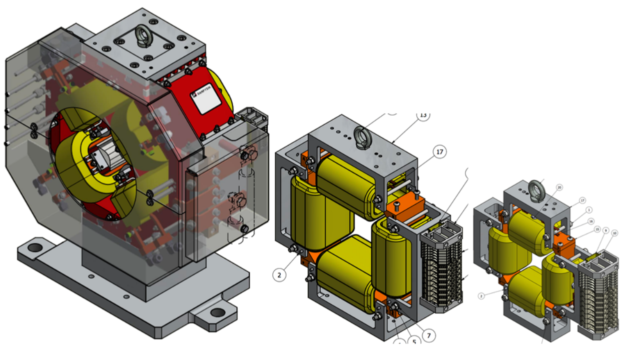

Figure 6: Q5, C6 and C5 step models.

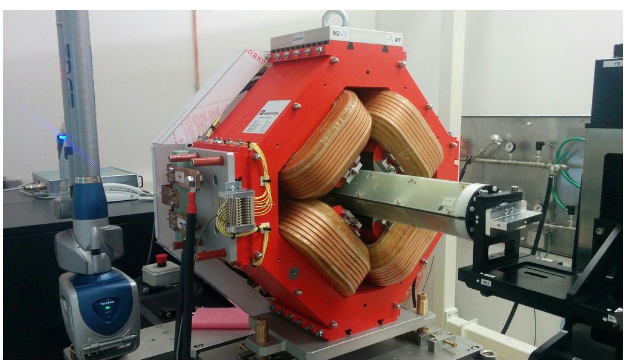

Figure 7: Q6 on magnetic measurement bench.

D1, Q8, AND C8 MAGNETS

For the realization of the magnets D1, Q8 and C8, Elettra has developed the magnetic models and the relative basic mechanical models. These were part of the technical documentation package for the preliminary design reviews (PDR).

Table 4: Parameters of D1, Q8 and C8

Parameters	D1	Q8	C8
Gap / Aperture [mm]	116	126	130
Yoke length [mm]	1800	755	300
Coil overall length [mm]	1969	940	348
Magnetic length [mm]	1800	809	466
Max field / int.grad. [T]	0.43	7.8	0.02
Current max PC [A]	400	400	17.3
Inductance [mH]	103	93	62
Required power [kW]	13.6	2.7	0.18

In the case of D1 and C8 the maximum current of 400 A has been defined with the purpose to use two PCs, identical to those used for Q5, Q6, and Q7, in parallel configuration. After these PDRs, the realization of these magnets was assigned with an international tender to Sigmaphi. After some magnetic modifications and mechanical finalization, the models have been defined with the parameters listed in Table 4. The Q8 and C8 step models are shown in Fig. 8, while the D1 step model is illustrated in Fig. 9. These magnets will be completed, tested and shipped to ESS by the end of 2019.

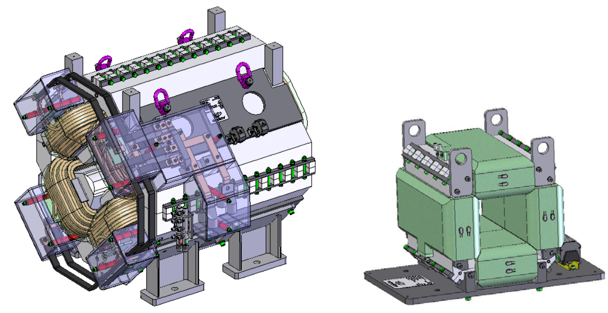

Figure 8: Q8 and C8 step models.

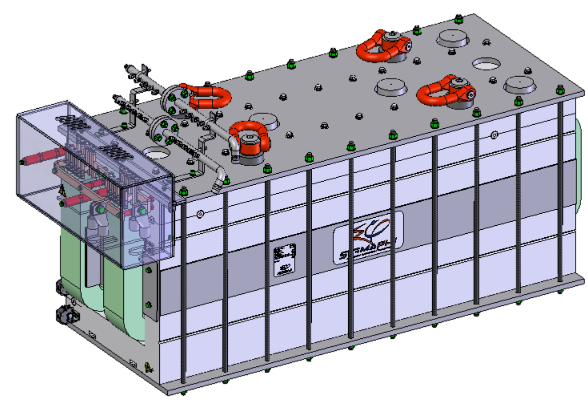

Figure 9: D1 step model.

CONCLUSIONS

The ESS magnets project at Elettra was an excellent opportunity to collaborate to one of the major Europan research infrastructures in construction and, at the same time, apply and develop what was and will be one of Elettra's know-how, namely in design and magnetic measurements. The excellent results obtained give us confidence in our new and upcoming project, which is Elettra 2.0 [4, 8].

REFERENCES

[1] ESS, http://europeanspallationsource.se

[2] A. Fabris *et al.*, “ESS related activities at Elettra Sincrotrone Trieste”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper MOPTS043, this conference.

[3] R. Visintini, M. Cautero, T. N. Gucin, and C. A. Martins, “Power converters for the ESS warm magnets: procurement status”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper TUPMP012, this conference.

[4] D. Castronovo, E. Karantzoulis, “Magnets for Elettra 2.0”, presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper THPTS021, this conference.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS020

[5] Esteco, https://www.esteco.com

[6] Opera, https://operafea.com

[7] Mathworks, https://www.mathworks.com

[8] E. Karantzoulis, A. Carniel, S. Krecic, "Elettra, present and future", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper TUPGW031, this conference.