CALCULATION, DESIGN AND MANUFACTURING OF A RESISTIVE QUADRUPOLE FOR THE ESS-BILBAO TRANSFER LINES

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Abstract

The first stage of the ESS-Bilbao LINAC will accelerate H^+ and H^- high current beams up to 50 MeV for different applications. After the last acceleration step in the DTL, the beam will either be transported to the experimental laboratories by the means of several transfer lines, or continue to a further acceleration step in spoke cavities. The first design of one of the quadrupoles that focus the beam along the transfer lines is presented. The quadrupoles will have an aperture of 63 mm and 20 T/m maximum gradient, featuring a short iron yoke of 100 mm. All the quadrupoles of the transfer lines are expected to be similar in order to simplify the design and manufacturing processes. The iron yoke is small and highly saturated, and an optimization of the 3D harmonics in the load-line is developed to fulfil the field quality specifications. The required current density is high (about 8.2 A/mm^2), therefore a water cooled hollow conductor is used to cool down the coils. The cooling and power supply requirements are calculated in this paper. The most important manufacturing indications are also presented.

CALCULATION PARAMETERS

The basic quadrupole design parameters and shape are proposed in [1] and they are summarized in Table 1. The reference radius for harmonic and field measurements is not defined, and therefore, two thirds of the aperture will be chosen, i.e. 21 mm. The coils will require water cooled conductors due to the high average current density estimated in the preliminary calculations (~5 A/mm^2).

Table 1: Initial Specifications of the Quadrupole

Magnitude	**Value**	**Units**
Magnet aperture	63	mm
Maximum gradient (2D)	24	T/m
Iron length	100	mm
Iron yoke width	310	mm
Iron pole width	45.51	mm
Total magnet length (between coil-ends)	208	mm

The maximum harmonic content is also not specified in [1]. Bearing in mind the location of the quadrupole (a transfer line in a LINAC), the required harmonic quality is not expected to be high, and a maximum precision of 10x10^{-4} parts of the main field should be good enough for its purpose. However, further beam dynamics calculations should be developed to cross-check that value.

The calculation of the quadrupole has been done using the program ROXIE [2] from CERN, which is specialized in the design of constant straight section magnets (cos θ and iron dominated). The model has been simulated in 2D to obtain the approximate dimensions and coil positions, and then optimized in 3D to fine tune the field quality.

CALCULATIONS

2D Calculations

The iron yoke (Fig. 1) is designed aiming to minimize the external diameter as much as possible, in order to reduce the iron weight and costs. However, this increases the saturation and non-linearity of the design. Iron holes could be used to improve linearity, although they would not be utilised in this model. Indeed, linearity concerns are not specified in [1] and they do not seem critical. In addition, the saturation barely affects the field quality because it is located far away from the pole profile. The iron yoke has a variable tangency in the hyperbolic pole to reduce the harmonic content. The optimum position of this tangency will be fixed in the 3D model.

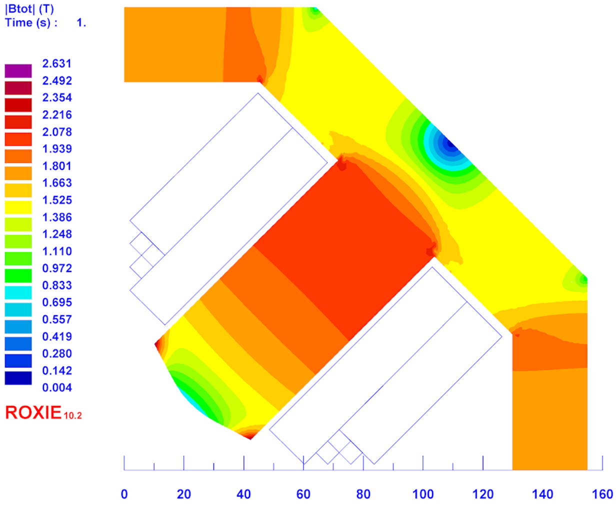

Figure 1: Quadrupole 2D cross section (X in mm).

The coil consists of 2 blocks and 3 conductor steps using a 5.5x5.5 mm^2 insulated hollow conductor (Fig. 1). The biggest block has 3 layers and 14 turns per layer (16.5x77 mm^2) and the smaller block is composed of 3 layers and 11 turns per layer (16.5x60.5 mm^2).

In order to obtain 24 T/m in the aperture, 11154 A-turn are required. This results in 143 A per conductor. The averaged current at the maximum gradient is 4.727 A/mm^2, so water cooled conductors are needed as it was previously estimated. The resultant cross section force vector on the coil is 1715 N/m @ 29.07º.

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3D Calculations

Standard racetrack coils are used for the 3D model (Fig. 2). The minimum longitudinal coil-end size is defined by the minimum bending radius of the hollow conductor, i.e. 12.5 mm (~2.5 times the conductor cross section side).

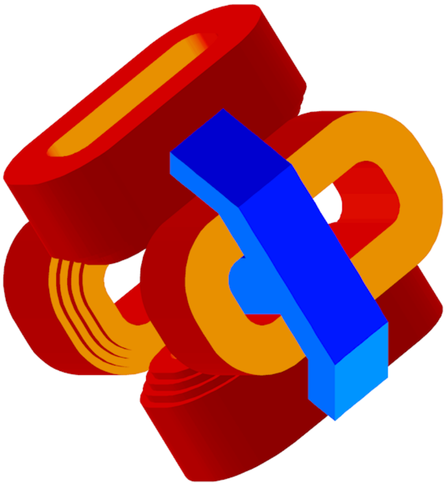

Figure 2: ROXIE 3D model with octant iron symmetry.

The design is highly saturated and the non-linearity in the load-line is about 40 %. The design presents a good linearity up to 45 % of the excitation but rapidly decreases at higher currents (Fig. 3). The high saturation of the iron not only increases the non-linearity but also the stray field around the quadrupole, which could affect neighbouring devices.

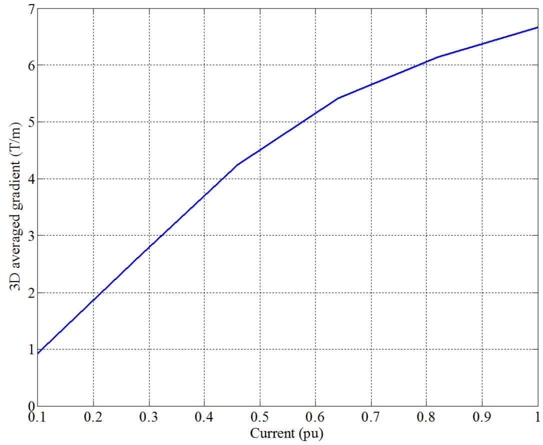

Figure 3. Quadrupole 3D load-line. 1 pu corresponds to 100 % excitation.

The maximum gradient achieved in the 3D half longitudinal section of the quadrupole is 20.1 T/m and the integrated field is 0.056 T·m (132.8 mm effective length).

The calculated harmonics at the maximum excitation for a reference radius of 21 mm are shown in Table 2. The values are units of 10^{-4} in relation to the main quadrupolar field (b2). The “allowed” harmonics in the quadrupole are shown underlined (the other values are numerical errors). The main harmonics (b6 and b10) are very small and well below ±10 units.

Table 2: Quadrupole 3D Averaged Harmonics (10^{-4} units)

b 1:	0.00000	b 2:	10000.0000	b 3:	0.00000
b 4:	-0.06805	b 5:	0.00000	b 6:	-2.71876
b 7:	0.00000	b 8:	-0.00051	b 9:	0.00000
b10:	2.10551	b11:	0.00000	b12:	0.00001
b13:	0.00000	b14:	-0.31748	b15:	0.00000
b16:	-0.00002	b17:	0.00000	b18:	-0.02480

The non-linearity of the design produces a non-linear behaviour of the harmonics in the load-line. A 3D optimization has been developed trying to balance this variation. After the optimization, the averaged b6 changes between 0 and -3 units in the full current range.

DESIGN AND MANUFACTURING

Sensitivity Analysis

In order to estimate the fabrication tolerances required for the critical parts of the quadrupole, a sensitivity analysis has been developed on the 3D model at the highest current. Three critical dimensions have been swept and simulated to determine the effect in the field quality of the quadrupole. The pole tip radius and the tangency point have been moved between ±0.2 and ±0.1 mm to simulate an error in the machining of the iron pole profile. The coil has been moved ±0.2 mm on its perpendicular planes to simulate an incorrect positioning. The modification of the main quadrupole dimensions or coil position in the indicated values changes the integrated field in a maximum of 0.6 %. The harmonic content is negligibly affected by the dimensions change.

A tolerance of ±0.05 mm is requested for the manufacturing of the iron yoke inner dimensions (pole profile and coil location side) and ±0.1 mm for the other iron areas. The coil should be positioned within ±0.1 mm tolerance limit in reference to its ideal position.

Cooling Calculations

The cooling calculations are developed for a single coil. Then, the hydraulic connection method between the coils is chosen, bearing in mind the pressure drop and the temperature increments.

The inner hole of the hollow wire should be estimated to begin the calculations. The wire manufacturers usually provide discrete values for the hole diameter of a given wire. As a first estimation, a good compromise between higher heat generation (small copper cross section) and increased cooling efficiency is a 3 mm diameter hole. This results in a copper cross section of 17.5108 mm^2 per wire and an actual copper current density of 8.17 A/mm^2.

The total wire length for a single coil is about 35.82 m. Using the typical copper resistivity for a high quality wire (100 % IACS), the total resistance results in 35.3 mΩ. The electric power required for this coil is therefore 721.19 W, which must be dissipated by the cooling water and the surrounding materials.

For a typical water velocity of 2 m/s (turbulent flow with a Reynolds number of 5976) and an input temperature of 20 ºC, the calculated temperature increment using the heat balance equation is 12.2 ºC. The pressure drop can be calculated using the Darcy–Weisbach equation and the Darcy friction factor, and it results in about 8.7 bar for a single coil.

As a result of the cooling calculations, the coils of each pole are hydraulically connected in parallel to avoid high water temperature and pressure increments. The final parameters for the magnet cooling and power supplies are shown in Table 3.

Table 3: Cooling and Power Calculations for the Full Quadrupole

Magnitude	**Value**	**Units**
Current	143	A
Actual current density	8.17	A/mm^2
Total conductor length	143.28	m
Electric resistance	0.1411	Ω
Total voltage	20.173	V
Electric power	2885	W
Water velocity	2	m/s
Total flow rate	0.0565	l/s
Temperature increment	12.2	ºC
Reynolds number	5976	
Pressure drop	8.72	bar

Iron Yoke

The calculated iron yoke mass is 33.8 kg and it should be manufactured in 4 sections (to allow space for the coil assembly). The iron pole shape is critical for the field quality of the magnet and therefore special care has to be taken in the machining. The optimized position of the tangency to the hyperbola is located 10.3 mm far from the pole tip.

All the calculations have been developed considering a solid ARMCO® iron yoke. If laminations are justified in order to make the manufacturing easier, the quadrupole integrated gradient will be lower than calculated and the field quality will also be slightly different. Being 100 mm the thickness, a solid iron yoke is preferred for this design and spark erosion wire cutting is recommended. Bolts (no welding) must be used for the assembly and attachment of any supports to the iron yoke.

Coil

The whole coil will be insulated using the same glass fibre tape as for the bare conductor, but thicker (~1 mm), to avoid short circuits to the iron yoke. The distance between the insulated conductors and the pole is 2 mm so it leaves space for the coil insulation and supports. The distance between the coil and the iron yoke is 3 mm.

Beam Pipe

The beam pipe and the ConFlat flanges must be manufactured in extremely low permeability austenitic stainless steel to reduce the magnetic field perturbations in the aperture. The pipe will have an exterior diameter of 63 mm to fit inside the magnet aperture and 1.5 mm thickness. The CF flanges will be machined by turning from blank CF63 flanges to the adequate dimension.

Assembly

The manufacturing drawings are produced bearing in mind all the previous indications. The coils are fixed to the iron poles by coil support fixtures. The four iron sections are integrated into a single unit and then tightened with supports (Fig. 4). Current lead connections, thermal interlock and wiring are set up afterwards.

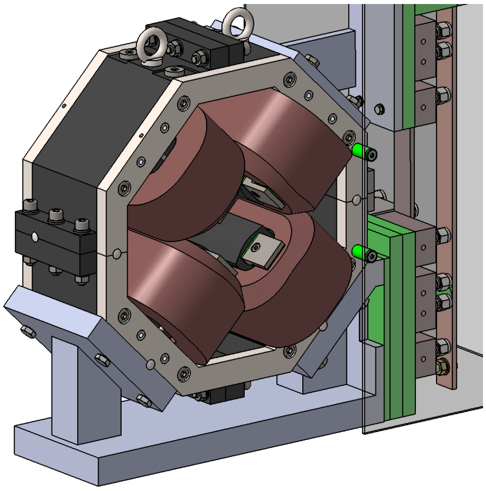

Figure 4: Assembled mechanical model in CATIA®.

CONCLUSIONS

The calculations, design and some manufacturing indications for the first quadrupole prototype for the ESS-Bilbao transfer lines have been presented in this paper. The cooling, electrical and manufacturing requirements are also analysed.

The magnetic calculations of the quadrupole perfectly fulfil the specifications within a big margin. However, the huge non-linearity in the load-line increases the power supply requirements at the nominal working point. The good point is that the iron yoke is very light.

The analytical cooling calculations are on the safe side and therefore lower pressure drops and temperature increments are expected in the manufactured device.

The device is now being manufactured by a Spanish company [3]. All the presented calculations will be cross-checked with actual empirical measurements.

REFERENCES

[1] J. Lucas, “Extraction lines of the ESS-B proton linac”, Internal report, August 2010.

[2] Stephan Russenschuck, Bernhard Auchmann, https://espace.cern.ch/roxie, 2011.

[3] ANTEC, S.A., http://www.antecsa.com/