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STATUS OF THE ELENA MAGNET SYSTEM

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Abstract

ELENA, the Extra Low ENergy Antiproton ring, will be a CERN facility with the purpose to deliver antiprotons at lowest energies aiming to enhance the study of antimatter. It will be a hexagonal shaped ring with a circumference of about 30 m decelerating antiprotons from energies of 5.3 MeV to 100 keV. Due to the extra-low beam rigidity the design of the magnet system is especially challenging because even small fields, for example arising from residual magnetization and hysteresis, will have a major impact both on the beam trajectory and beam dynamics. In this paper the design approach for such an extra-low beam rigidity magnet system is presented. The main challenges are outlined and solutions for the design of the magnet system are discussed.

INTRODUCTION

The ELENA ring will decelerate antiprotons delivered by CERN's Antiproton Decelerator (AD) with energies of 5.3 MeV to 100 keV. The ring will be of hexagonal shape with a circumference of about 30 m as illustrated in Figure 1. A detailed design report on ELENA can be found in [1].

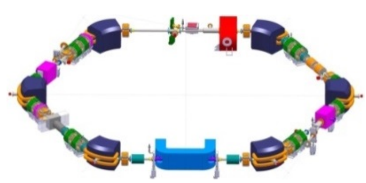

Figure 1: ELENA ring.

The ring magnet system consists of six C-shaped bending magnets, 12 quadrupoles, two skew quadrupoles, four sextupoles, eight two-plane correctors, and two compensation solenoids. The same magnet types will be used also in the injection transfer line from AD to ELENA; in addition two 40 degree H-type dipole magnets will have to be procured for this transfer line.

For each of these six new magnet families, one spare magnet will be foreseen. As within every family the magnets share identical electrical, mechanical, and magnetic characteristics, they will have the same design. The key magnet parameters are summarized in Table 1. For each magnet type the requested field quality (FQ) in units of the main field is given within the requested good-field-region (GFR). One unit stands for a fraction of 10^{-4} of field multi-pole components other than the main field component.

To allow stable operation of the ELENA ring and to increase the reproducibility of the magnetic field of the ELENA magnets, diluted laminated yokes consisting out of electrical steel and non-magnetic filler material were investigated. Diluting yokes by a factor of 1 (magnetic material) to *d* (non-magnetic material) results in a 1+*d* larger field in the magnetic material compared to the one seen in the magnet aperture. By using this approach, the average relative permeability in the magnetic yoke material can be maximised, the remanent field can be minimised and operation in the highly non-linear area at very low field can be avoided. This results in a better predictability of the magnetic field and in a minimization of changes in the field quality over the dynamic range.

Table 1: Key Parameters of ELENA Magnet System

Magnet	**Nr.**	**Aperture** [mm]	**Strength**	**Magnetic length** [mm]	**FQ** [Unit]	**GFR** [mm]
Dipole	8	76	0.37 T-0.05 T	970	±2	66 x 48
Quadrupole	16	Ø124	1.45 T/m	250	±5	Ø54
Skew Quadrupole	3	Ø124	0.9 T/m	150	±100	Ø46
Sextupole	5	Ø89	40 T/m^2	150	±20	Ø40
H+V Corrector	14	Ø124	25 Gm	310	±100	Ø44
Solenoid	3	Ø89	350 Gm	-	-	-
TL Dipole	3	65	0.67 T	350	±10	68 x 48

RING DIPOLE

A total of six C-shaped laminated bending magnets with bending angles of 60°, bending radii of 0.927 m, and edge angles of 17° for beam focusing will be installed in the ELENA ring, as shown in Figure 2, left. The ramp down will be performed in around 10 s. A C-shaped design was selected to allow for pumping ports in the vacuum chamber inserted in the apertures of the magnets [2].

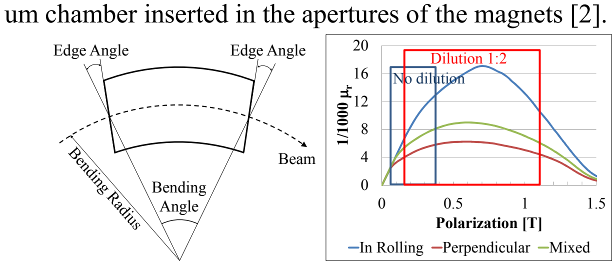

Figure 2: Sketch of ELENA dipole and operation range.

To meet firstly the stringent field quality request and, secondly, to minimize the remanent field effects, special care in the selection of the yoke's magnetic material composition was taken. In detail, the following actions were carried out: (1) a dilution with a ratio of 1:2 was selected to shift the operation range in the iron by a factor 1+2, as shown in Figure 2, right; (2) a study on available magnetic materials was performed [3] and with the aim to minimize the coercive force and maximise the permeability, the non-grain oriented Fe-Si steel M270-50 A HP was selected; and (3) a detailed optimization of the cross-section and the fringe fields with FEM programs was performed.

The dilution can be roughly optimized by searching for the maximum relative permeability. For an undiluted yoke, the polarization in the electrical steel will be $J_{\min} = B_{\min} - \mu_0 H = 0.05\text{ T}$ and $J_{\max} = 0.36\text{ T}$. The maximum polarization can be expressed in terms of the minimum polarization and the dynamic factor as $J_{\max} = \frac{0.36\text{ T}}{0.05\text{ T}} \cdot J_{\min} = 7.2 \cdot J_{\min}$. Therefore, we can write for the

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calculation of the mean value of the permeability over the working range:

$$\bar{\mu}_r = \frac{1}{J_{\max} - J_{\min}} \int_{J_{\min}}^{J_{\max}} \mu_r(J)\, \mathrm{d}J$$

Searching for the maximum of the relative mean permeability one finds $J_{\min} \approx 0.15$ T. Therefore, the value of the field in the yoke has to be increased by a factor of $\frac{0.15\,\mathrm{T}}{0.05\,\mathrm{T}} = 3$, which yields a dilution factor 1:2.

The cross-section design was optimized in such a way that a small and constant positive sextupole of 1 unit is present in the cross-section design to partially compensate for the sextupole drop-off coming from the fringe fields. To simulate the dilution with a 2D FEM code, two approaches were pursued (1) the current was increased by a factor of 1+2 and (2) the *B*-*H*-curve was diluted replacing the measured magnetic flux density B by

$$B^* = (1-p)\mu_0 H + pB,$$

with $p = 1/3$ being the packing factor. Both simulation methods give similar results for the cross-section but they vary for 3D simulations. The cross-section and an artistic view of the magnet are shown in Figure 3.

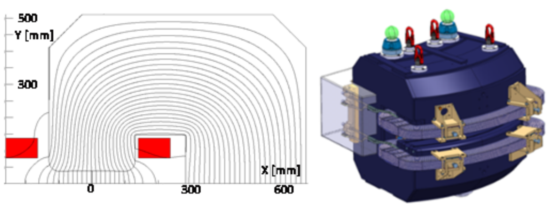

Figure 3: Field lines & artistic view of an ELENA dipole.

To verify the simulation results and to decide on the final design, a full-scale straight dipole magnet was constructed and measured [3]. The yoke's prototype is made of 0.5 mm thick M270-50-A HP electrical steel mixed with 1 mm thick 304 L stainless steel sheets. The end shims are made out of 30 mm thick and 100 mm high solid ARMCO pure iron sheets placed in a cut-out of the yoke. For mechanical reinforcement a 25 mm thick 304 L stainless steel end-plate was foreseen. The prototype magnet is shown in Figure 4.

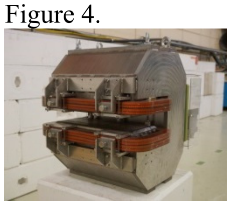

Figure 4: Prototype dipole.

An intense measurement campaign was pursued to permit an accurate comparison between the behaviour of the prototype and simulation results [4]. First, the field repeatability was measured by using a NMR probe placed in the centre of the magnet gap operated in DC mode. The measurements show that the field repeatability is better than 0.1 units after two cycles.

Second, the magnetic length was measured and compared to different simulations. The 3D simulation using a diluted *B*-*H*-curve with a packing factor of 33%, as described above, resulted in a precise prediction of the magnetic length. To minimise the variation of the magnetic length a detailed analysis showed that a solid iron end plate with a thickness of around 40 mm reduces the variation of the magnetic length between injection and extraction to almost zero. Due to the fringe fields and the dilution, the magnet ends start to saturate; this effect is counter-acted by the pure iron end-plate which has a decreasing reluctance while the field is increased. Therefore, at a thickness of the end-plate of around 40 mm the simulation predicts no change in the magnetic length between injection and ejection, see Figure 5, left. Third, in the prototype the eddy current effects were measured to be in the size of a few units (2 units at 0.1 T/s). Measurements confirmed that the eddy-currents are mainly concentrated on the two magnet ends. For the solid iron end-plate, a skin depth in the order of 20 mm is calculated [2] for a frequency of 0.1 Hz and $\mu_r = 1000$. Therefore, eddy current effects will be more pronounced, and will be verified by adding a solid ARMCO end-plate to the prototype magnet. To minimize eddy current effects the end plates could be also split into four parts, because the mechanical deformation of the end plate is still small (below 0.3 µm for one end-plate and below 5 µm for the split design).

The laminations used for manufacturing of the prototype magnet were laser-cut, which comes with larger tolerances than allowed for the series production made by stamped laminations. Nevertheless, the multi-pole measurements showed good results. Correction is easily possible by using the fivefold divisible end shims to meet the specification (±2 units), because the multi-poles are almost constant over the dynamic range; except for the quadrupole b_2 (Figure 5, right). This is not considered as a problem, if taken into account for determining the quadrupole settings. By using the prototype, the key points of the design were evaluated and confirmed. The production of the eight dipole magnets is launched.

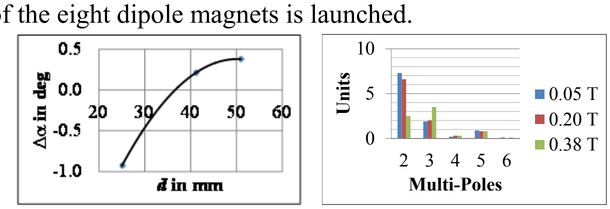

Figure 5: Bending angle Δα between injection and extraction for different end-plate thickness d (left) and multi-poles (rotating coil, reference radius 30 mm, right).

H/V CORRECTOR

Fourteen two-plane correctors with an integrated strength of 25 Gm and a magnetic length of 310 mm are required for the ELENA ring and transfer line. A standard, non-diluted, window-frame design was initially proposed. Such a magnet was intensively measured [5] to clarify if the strict requirements for a low-energy ring can be met. The key findings of this measurement campaign are (1) that the hysteresis effects account for 5% of the magnetic field after one cycle but they fall down to 5‰ after the second cycle, after the third cycle they fall to 1‰ and at the fourth to 0.5‰, this means that after pre-cycling the magnet one time the field is repeatable within 5‰; (2) that at low field remanent effects are quite pro-

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nounced (up to 5% of that of the main field); (3) that multi-poles are becoming worse with low field; and (4) that applying a demagnetization cycle before the measurements cycle results only in a difference of the absolute field value of 2-3‰.

The measurement campaign showed that the design has to be adapted to the optimum working point, if a standard window-frame magnet is used in such a low-energy ring. This can be done by using dilution, and if possible, by foreseeing a pre-cycle each time the magnetic cycle has to be changed. Operation will nevertheless be complicated because magnetic cycles of correctors are often changed. In addition, due to the strong remanent effects at low field, the prediction of the relationship between the excitation current and magnetic field is complicated and an active field of research. An iterative and time-consuming process to find the correct settings of this magnet in operation might be required.

To improve, and possibly ease, the operation of this low-energy ring, coil-dominated corrector magnets without iron-core [6] were studied and a simplified layered cos-theta design was proposed, as shown in Figure 6. This design allows easy winding and very short ends, which enable the integration of the magnet into the 250 mm available space in the ELENA ring. Here, the main advantage of coil-dominated, iron-free magnets lies in the linear relation between excitation current and magnetic field in the magnetic gap; as a consequence also the field quality is constant over the full working range. On the other hand, large coil sizes are required to generate the required magnetic fields.

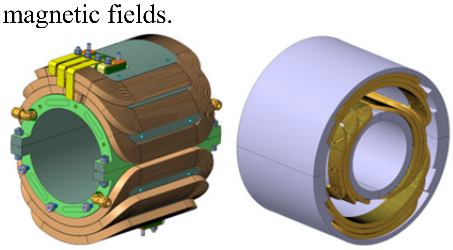

Figure 6: Corrector magnet's inner shell and two shell concept for horizontal and vertical plane.

The mandrel on which the conductor is placed will be made out of copper and will be cooled by using demineralized water. A current density of 2.5 A/mm^2 was chosen to limit the total dissipated power to 150 W and 360 W for the inner and outer shell. This power dissipation results in a thermal gradient between the coil and the cooled mandrel of 5 K and 15 K for the inner and outer shell. The forces on the coils are below 10 N; therefore, gluing of the coils to the mandrel is foreseen. The field quality was optimized to below 10 units, which gives enough margins for mechanical errors of the cable position, which will directly influence the field distribution and quality. To verify the simulations and study the manufacturing of such a magnet, a prototype is under construction.

QUADRUPOLE

Sixteen quadrupole magnets and three skew quadrupole magnets are required for the ELENA ring and the transfer line [7]; skew and normal quadrupoles will use the same lamination design. The cross-section and an artistic view of the quadrupole magnet are shown in Figure 7. To study remanent field effects four quadrupole magnet prototype magnets with two electrical steels are currently under construction: (1) a non-grain oriented (NGO) M250-35 A HP and (2) a grain-oriented electrical steel (GO) M140-35 S electrical steel (thickness 0.35 mm) stacked either alone or alternating stacked with 2 mm thick stainless steel (dilution ratio 1 : 5.71). The magnet prototype showing the smallest remanent field effects and the least variation of the field quality over the dynamic range will be selected. The same design principle will be applied for the sextupole magnets.

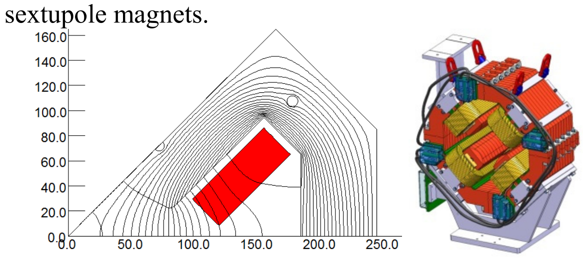

Figure 7: Field lines & view of an ELENA quadrupole.

CONCLUSION

The magnets for ELENA, an extra-low energy antiproton ring, were optimized in such a way that remanent field effects are minimized allowing for a flexible and reliable operation. A dipole prototype magnet showed the proof-of-principle of the chosen diluted design and quadrupole prototype magnets are under construction to select the optimal material mix of the magnet yoke. To cope with the extra-low field in the corrector magnets and to totally avoid remanent field effects, coil-dominated and iron-free corrector magnets were designed.

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