CHALLENGES FOR THE MAGNET SYSTEM OF LHeC

B. Holzer, G. Kirby, A. Milanese, S. Russenschuck, R. Tomas, D. Tommasini, F. Zimmermann,
CERN, Geneva, Switzerland

Abstract

The ECFA-CERN-NuPECC design study for a Large Hadron electron Collider (LHeC) considers two options to bring 60-GeV electrons into collision with the 7-TeV protons of the Large Hadron Collider (LHC), that is, using a ring accelerator on top of the LHC, or adding a recirculating energy-recovery linac tangential to the LHC. The main challenges for the normal conducting magnet system are the very compact, low field, and high precision magnets for the ring-ring option and their rapid installation in the crowded LHC tunnel. The superconducting triplet magnets require strong gradients for the protons in close vicinity of a field-free region for the electrons. The field requirements for the ring-ring option allow a number of different magnet designs using the well-proven Nb-Ti superconductor technology and making use of the cable development for the LHC. The separation distance between the electron and proton beams in Q1 requires a half-aperture quadrupole design to limit the overall synchrotron radiation power emitted by the bending of the electron beam. The requirements in terms of aperture and field gradient are more difficult to obtain for the linac-ring option and therefore we discuss maximum field gradient and minimum septum size achievable with the Nb_3Sn superconducting technology.

NORMAL CONDUCTING MAGNETS

The main magnets for the proposed LHeC accelerator, for both the linac-ring (LR) and the ring-ring (RR) configurations, were studied for the conceptual design report (CDR) [1], where cross-sections of normal-conducting, iron-dominated magnets are presented and discussed in detail. This section focuses on bending magnets; details about the quadrupoles can be found in the above cited CDR. The RR layout is based on installing a lepton machine in the LHC tunnel. For the bending magnets many concepts of the LEP [2] main dipoles still prove useful, for example, the single-turn coils acting as bus-bars. However, a couple of differences need to be pointed out. The new magnets must fit in the LHC tunnel with the LHC cryomagnets in place. This requires the most compact cross-section and magnet supports that will facilitate the installation. Moreover, the injection energy is a factor of two lower than that of LEP (10 GeV vs. 20 GeV). This corresponds to a minimum air-gap flux density of 0.0127 T, which must be achieved with a challenging cycle to cycle reproducibility of the order of $0.1 \cdot 10^{-4}$ T. The nominal air gap is 40 mm.

These challenges prompted the design and construction of several short models, both at the Budker Institute of Nuclear Physics [3] and at CERN [4]. The CERN models have a low stacking factor, with steel and plastic laminations interleaved in a 1:2 ratio. This reduces in the overall weight of the magnet and increases the flux density in the steel to about three times of that in the gap. This is beneficial especially at low excitations, where the material is brought to work in a more stable region of its magnetization curve. A similar technique was applied to the LEP magnets, where the yokes were made of steel laminations spaced with cement mortar. Three steel grades were used in the models to study the impact of coercitivity H_c: a) a rather noble (and expensive) NiFe steel, heat-treated under hydrogen, $H_c \approx 6$ A/m; b) a conventional low carbon steel with low silicon content, $H_c \approx 70$ A/m; c) a grain oriented material, $H_{c\parallel} \approx 6$ A/m and $H_{c\perp} \approx 22$ A/m. All the models showed a reproducibility within the $0.1 \cdot 10^{-4}$ T target, with an indication that the a) and c) versions perform better than the version b).

The cross-section of the proposed RR bending magnets is shown in Fig. 1. A C-type design is proposed, with the aperture of the magnet on the external of the ring, so that the emitted synchrotron radiation is not intercepted by the magnet and space is left for a vacuum antechamber. The rather unusual shape of the poles is such that the differences in magnetic reluctances across the horizontal aperture is minimized. As confirmed experimentally, this shape makes the field quality less dependent on variations of the iron characteristics. The flux density in the gap ranges from 0.0127 T at 10 GeV to 0.0763 T at 60 GeV. The total number of magnets is 3080, for a magnetic length of 5.35 m and a weight of about 1400 kg. The coil design foresees solid aluminium bars as conductor, working with a maximum current density of 0.4 A/mm^2 (current of 1300 A). The dissipated resistive power (about 50 W per meter of magnet length, which corresponds to 0.92 MW in the LHC arcs) can be extracted by the ventilation system of the LHC tunnel. This is a considerable advantage in terms of magnet manufacture, connections, and reliability because it avoids the installation of a water cooling circuit for the arc magnets.

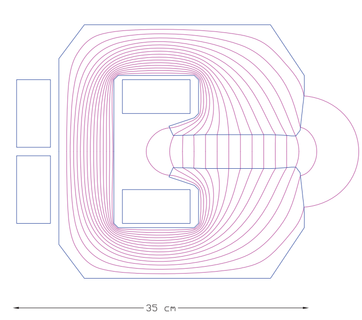

Figure 1: Bending magnets for the ring-ring option.

For the LR layout variant, the situation is straightforward for the accelerator magnets. The dipoles in the arcs are ramped from 0.046 T (10.5 GeV) to 0.264 T (60.5 GeV); the field at injection is considerably higher than in the RR case. The vertical aperture is only 25 mm and the field quality requirements are somewhat relaxed, as the arcs work de facto like transfer lines. Since these magnets are to be installed in a new tunnel, no stringent requirement on compactness or integration apply. A possible development for the LR bending and quadrupole magnets involves the use of permanent magnets, possibly in a hybrid configuration.

SUPERCONDUCTING MAGNETS FOR THE INNER TRIPLETS

The technical requirements for the RR option are easily achieved with superconducting magnets of proven technology. Although these magnets will require engineering design efforts and new tooling, there are limited challenges because the mechanical design will be very similar to the magnets built for the LHC [5], [6] and will thus also make use of the wire and cable development for the LHC. The requirements in terms of aperture and field gradient are more difficult to obtain for the linac-ring option where Nb_3Sn superconducting technology must be employed. In this paper we present the limitations for the field gradient and septum size, that is, the minimum distance between the proton and electron beams.

For both options, the interaction region requires a number of focussing magnets with apertures for the two proton beams and field-free regions to pass the electron beam after the collision point. The lattice design and the layout of the interaction region is presented in [7]. The field requirements for the RR option are a gradient of 127 T/m, a beam stay clear of 13 mm at 12 σ, and aperture radii of 21 mm for the proton beams and 30 mm for the electron beam. These allow a number of different magnet designs using the well proven Nb-Ti superconductor technology and the cables developed for the LHC. In the simulations presented here, we used the parameters (geometrical, critical surface, and superconductor magnetization) of the cables used in the LHC insertion quadrupole MQY.

For the field requirements, a superferric magnet variant as built for the KEKB facility [8] comes to its limits due to the saturation of the iron poles. Indeed, the fringe field in the aperture of the electron beam exceeds the limit tolerable for the electron beam optics, and the field quality required for proton beam stability, on the order of one unit in 10^{-4} at a reference radius of 2/3 the aperture, is difficult to achieve. Another variant that was studied is based on a superconducting block-coil magnet as proposed in [9] for a coil-test facility. The magnetic flux density in the low-field region of the magnet could, however, not be reduced below 0.3 T. Moreover, the engineering design work required for the mechanical structure of this magnet would be higher than for the proven designs shown in Fig. 2, which are based on LHC magnet technology.

The design for Q2 is shown in Fig. 2 (left). The aperture for the proton beams is 26 mm. The 127 T/m field gradient can be achieved with a comfortable safety margin to quench (exceeding 30%) using the cables of the MQY magnet of the LHC and a mechanically self-supporting coil-collar structure. The operation temperature is supposed to be 1.8 K, employing superfluid helium technology. The outer radius of the magnet coldmass does not exceed those of the triplet magnets installed in the LHC (diameter of 495 mm). The fringe field in the aperture of the electron beam is below 0.05 T. The design of Q3 follows closely that of Q2, except for the size of the septum between the proton and the electron beams that must also increase along the magnet axis.

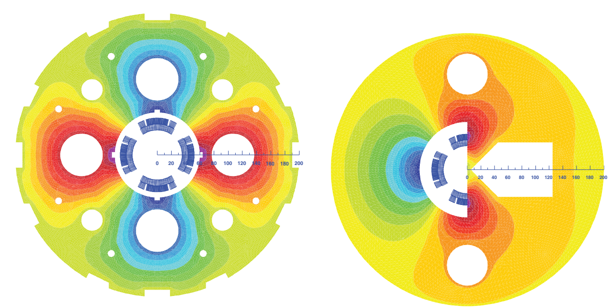

Figure 2: Cross-sections with field-lines of insertion quadrupole magnets. Left: Single aperture design for Q2 with a double layer coil using LHC cable. Right: Single half-aperture quadrupole with field-free domain [10]; design selected for Q1.

Figure 2 (right) shows a half-aperture quadrupole for Q1 in a similar design as proposed in [10]. The separation distance between the electron and proton beams in Q1 requires the half-aperture quadrupole design to limit the overall synchrotron radiation power emitted by bending of the 60 GeV electron beam.

For both designs the coil layers are individually optimized for field quality. This reduces the sensitivity to manufacturing tolerances and the effect of superconductor magnetization [11]. The mechanical design will be similar to the MQXA magnet where two kinds of interleaved yoke laminations are assembled under a hydraulic press and locked with keys in order to obtain the required prestress of the coil/collar structure. The main parameters of the magnets are given in Table 1.

The requirements in terms of aperture and field gradient are more difficult to obtain for the LR option. Consequently we present the limitations for the field gradient and septum size achievable with four-layer coils and using Nb_3Sn superconducting technology. The thickness of the coil layers is limited by the flexural rigidity of the cable, which will make the coil-end design difficult. Moreover, a thicker coil will also increase the beam separation between the proton and the electron beams. The results of the field computation are given in Table 1, column 3 and 4. Because

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of the higher iron saturation, the fringe fields in the electron beam channel are considerably higher than in the magnets for the RR option.

For the Nb_3Sn critical surface modeling we assume composite wire produced with the internal Sn process (Nb rod extrusions) [12]. The non-Cu critical current density is 2900 A/mm^2 at 12 T and 4.2 K, which is rather conservative. The filament size of 46 μm in Nb_3Sn strands give rise to higher persistent current effects in the magnet. The choice of Nb_3Sn would impose a considerable R&D and engineering design effort, which is however, not more challenging than other accelerator magnet projects employing this technology [13]. Depending on the heat-load budget the gradient could be increased by cooling the magnets to 1.8 K.

Table 1: SC = type of superconductor, g = field gradient, R = radius of the aperture, LL = working point on the load line of the superconductor, I_{nom} = operational current, B_0 = main dipole field, S_{beam} = beam separation distance, B_{fringe} = fringe field in the aperture for the electron beam, g_{fringe} = gradient field in the aperture for the electron beam.

Option		RR single	RR half	LR single	LR half
Function		Q2	Q1	Q2	Q1
SC		Nb-Ti at 1.8 K		Nb_3Sn at 4.2 K	
Coil layers		2	2	4	4
R	mm	36	35	23	46
I_{nom}	A	4600	4900	6700	4500
g	T/m	137	137	311	175
B_0	T	-	2.5	-	4.7
LL	%	73	77	83	82
S_{beam}	mm	107	65	87	63
B_{fringe}	T	0.016	0.03	0.09	0.5
g_{fringe}	T/m	0.5	0.8	9	25

Fig. 3 shows the conceptual design of the mechanical structure of these magnets. The necessary prestress in the coil-collar structure, which must be high enough to avoid unloading at full excitation, cannot be exerted with the thin stainless-steel collars alone. For the single aperture magnet as shown in Fig. 3 left, two interleaved sets of yoke laminations (a large one comprising the area of the yoke keys and a smaller, floating lamination with no structural function) provide the necessary mechanical stability of the magnet during cooldown and excitation. Preassembled yoke packs are mounted around the collars and put under a hydraulic press, so that the keys can be inserted. The sizing of these keys and the amount of prestress before the cooldown will have to be calculated using mechanical FEM programs. This also depends on the elastic modulus of the coil, which has to be measured with a short-model equipped with pressure gauges. Special care must be taken to avoid non-allowed multipole harmonics because the four-fold symmetry of the quadrupole will not entirely be maintained. The mechanical structure of the half-quadrupole magnet is

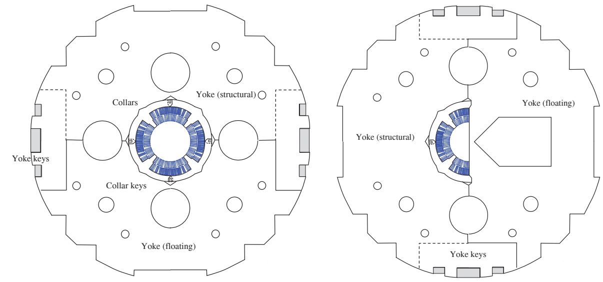

Figure 3: Sketch of the mechanical structure. Left: Single aperture magnet. Right: Half quadrupole with field-free region.

somewhat similar, however, because of the left/right asymmetry the interleaving of collars requires four different lamination types to be machined. This is a new concept that requires further magnet R&D and prototype qualifications.

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