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Abstract

The Ring-Ring option of a Large Hadron electron Collider (LHeC) requires 3080 bending magnets, 5.35-meter-long each providing a magnetic field ranging from 0.0127 T at 10 GeV to 0.0763 T at 60 GeV. Main issues in the design of these magnets are the very low injection field, constituting a challenge in achieving a satisfactory field reproducibility from cycle to cycle, and the required compactness to fit in the existing LHC tunnel. This paper describes and discusses a design meeting these requirements, together with its experimental validation by the manufacture and measurement of a 400-mm-long magnet model.

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***Abstract*—The Ring-Ring option of a Large Hadron electron Collider (LHeC) requires 3080 bending magnets, 5.35-meter-long each providing a magnetic field ranging from 0.0127 T at 10 GeV to 0.0763 T at 60 GeV. Main issues in the design of these magnets are the very low injection field, constituting a challenge in achieving a satisfactory field reproducibility from cycle to cycle, and the required compactness to fit in the existing LHC tunnel. This paper describes and discusses a design meeting these requirements, together with its experimental validation by the manufacture and measurement of a 400-mm-long magnet model.**

***Index Terms*—Magnetic field reproducibility, LHeC.**

I. Introduction

THE Large Hadron electron Collider (LHeC) is a proposed hadron-lepton (electrons and positrons) collider that is being considered to complement and extend the physics research of the LHC. It should run at the same time as hadron collisions take place in the LHC experiments. Two options are being considered to accelerate the leptons to an energy of 60 GeV: the so-called Linac-Ring option and the Ring-Ring one. The first consists in a full energy accelerator injecting the 60 GeV leptons directly against the hadrons in the LHC. The Ring-Ring option on the other hand consists in a pre-accelerator injecting 10 GeV leptons in a new synchrotron installed in the LHC tunnel. This new ring would perform the acceleration from 10 GeV to 60 GeV and thereafter collide the leptons against the hadrons in the LHC. Its lattice [1] is based on an asymmetric FODO cell of half the LHC FODO cell length to account for LHC service modules and the DFBs (Fig.1).

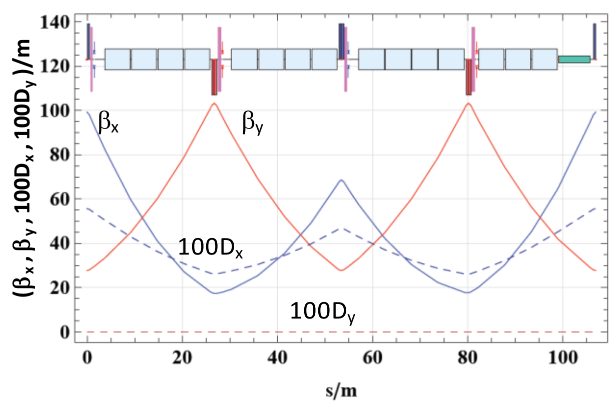

Fig. 1. LHeC arc cell optic: one arc cell consists of two FODO cells symmetric in the placement of the quadrupoles and asymmetric for the dipoles

The main requirements for the arc dipoles are summarized in Table 1: the low injection energy, corresponding to a magnetic field intensity in the main dipoles of only 127 Gauss, represents a major concern to provide a magnetic field reproducibility and quality in the range of few parts in 10^4 over the full range of the acceleration from 10 GeV to 60 GeV. Furthermore, these magnets shall be compact to fit in the present LHC tunnel and shall be compatible with the synchrotron radiation power emitted by the particle beam.

TABLE I Main Requirements for the Ring-Ring Arc Dipoles

Description	Value	Units
Beam energy (injection - collision)	10 - 60	GeV
Number of magnets in the arcs	3080	
Magnetic length	5.35	m
Magnetic field induction @ 10 GeV	127	Gauss
Magnetic field induction @ 60 GeV	763	Gauss
Minimum horizontal physical half aperture	± 30	mm
Minimum vertical physical half aperture	± 20	mm
Horizontal good field region	± 10	mm
Vertical good field region	± 6	mm
Magnetic field homogeneity in good field region	$\pm 2 \cdot 10^{-4}$	
Magnetic field reproducibility at injection	± 0.1	Gauss

II. Magnet Design

The proposed design consists of compact C-Type dipoles, with the C-aperture on the external side of the ring to possibly allow the use of a vacuum pre-chamber and in any case to avoid that the synchrotron radiation hits the magnet. The unusual pole shape allows minimizing the difference of flux line length over the horizontal aperture (Fig.2), making magnetic field quality less dependent on the iron characteristics than in a C-type dipole of a conventional shape.

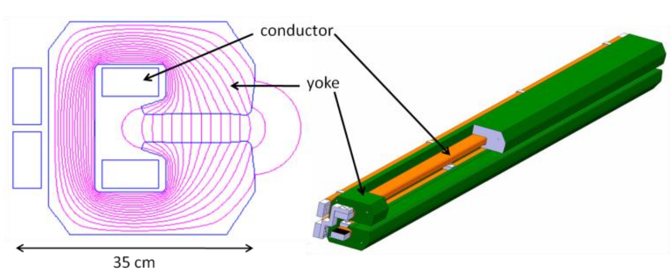

Fig. 2. Field lines and artistic view of a LHeC arc dipole

Because of the very low magnetic induction, the yoke is composed of ferromagnetic laminations interleaved with plastic spacers, with a thickness ratio between plastic and iron of 2:1.

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This solution allows to increase the working magnetic induction in the iron, thus being less sensitive to differences in quality of the iron itself and in particular to the coercive force.

In principle the horizontal magnetic field distribution should be computed in 3D to take into account the fact that the steel laminations are interleaved with a non magnetic material. This issue is presently being considered in a larger frame with the aim of establishing the best tools and procedures for designing magnets with interleaved laminations in the 10^{-4} range of accuracy.

Concerning the design of these model magnets, based on past experience it was decided to perform the first optimization of the pole profile with 2D computation (Poisson) taking into account the magnetic field induction increase in the iron due to the interleaved laminations.

The relevant horizontal field distribution, shown in Fig. 3, meets the requirements in the good field region. It is important to remind that at injection one unit of the vertical scale corresponds to only 0.0127 Gauss. It is not clear at this stage how much the material properties of steel and the modelization itself could affect any further possible attempt in improving field quality.

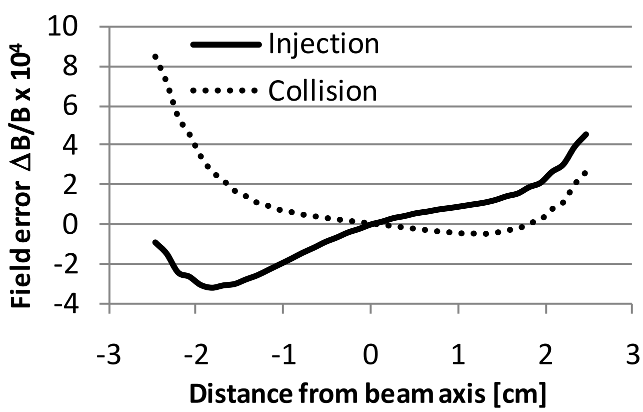

Fig. 3. Computed (2D) magnetic field error in the horizontal (transversal) axis. The outside of the magnet C-shape is towards the right (positive coordinates).

The coils are made by solid single bars of conductor, connected in series, thus constituting a 2-turns magnet excitation. Each bar, once insulated, is individually slit inside the magnet. The connections between bars can be bolted and/or braized at the magnet extremities.

The conductor, carrying 1340 A at fully energy, can be in aluminum or in copper depending on economical reasons coming from a correct balance between investment and operation costs, and possibly on weight issues. In either cases the conductor size is sufficiently large to reduce the dissipated power (about 300 W per magnet in case of copper conductors) within levels which could in principle be dealt with by the ventilation in the LHC tunnel: this would be a considerable advantage in terms of simplicity of magnet manufacture, connections and reliability.

III. Models Manufacture

To explore the whole potential of the proposed design, in particular in terms of magnetic field reproducibility at beam injection, three different 400 mm long model madels have been built using three different steels:

- a Supra 36 NiFe steel (1.0 mm thick laminations, with a measured coercive field, after heat treatment for 4 hours at 1050°C under hydrogen, H_c<6 A/m) which will acts as a benchmark (Model 1);
- a conventional low carbon steel with low silicon content (1.0 mm thick laminations,0.5% Si, H_c<70 A/m) (Model 2);
- and a 35M6 grain oriented steel (0.35 mm thick laminations, 3.1% Si, with H_c<7 A/m in the direction of the grain orientation and H_c<25 A/m perpendicular to the grain orientation) (Model 3).

The yoke design is based on steel laminations interleaved by plastic spacers (Fig. 4). In all cases 2-mm-thick phenolic sheets have been used as spacers, stacked and glued with an epoxy resin together with the steel sheets according to a sequence of 1 mm of steel followed by 2 mm of plastic. The model made with the thinner grain oriented sheets is composed by a sequence of three steel laminations followed by 2 mm thick plastic spacer to keep a similar magnetic field distribution as in the stacks with non oriented steel.

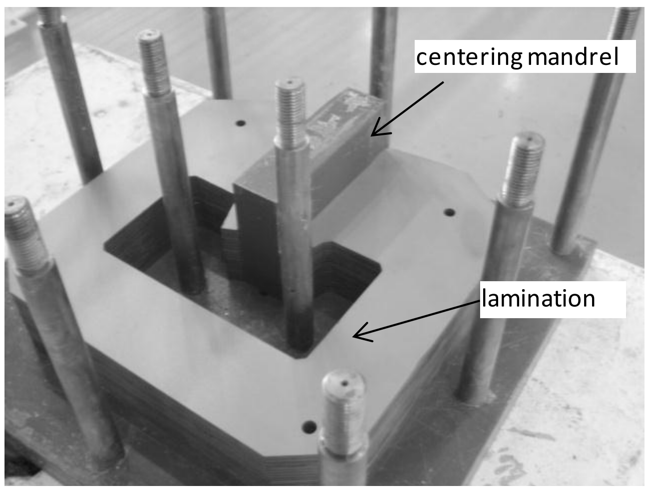

Fig. 4. Stacking steel and plastic laminations

The coils are made with single copper bars insulated with a shrinkable sleeve. The assembled magnet is shown in Fig. 5.

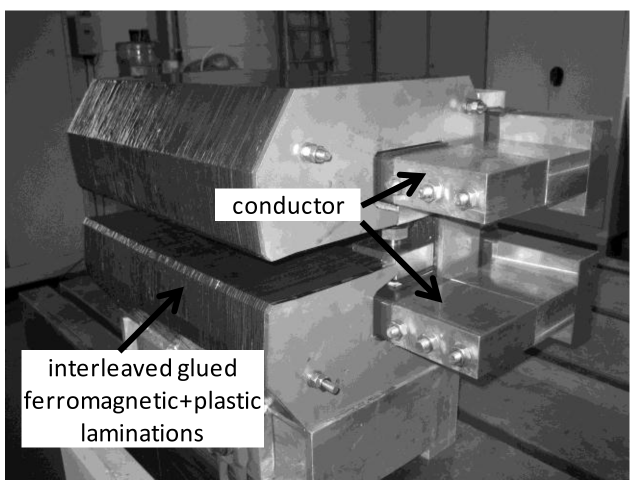

Fig. 5. The 400 mm long model

IV. Test Results and Analysis

The main purpose of the tests was the measurement of the magnetic field reproducibility at currents corresponding to the ones needed for the LHeC injection. A cycle from 10 GeV to 60 GeV, requiring a dipole field of 127 Gauss and 763 Gauss respectively, corresponds to currents from 210 A to 1340 A.

Unfortunately the available power converter could provide a sufficiently good stability only over a smaller range, between 260 A and 1300 A, with measured stabilities of 4×10^{-5} at 260 A and 2×10^{-5} at 1300 A. Each of the models was submitted to 5 conditioning cycles and thereafter to 8 cycles at a ramp rate of 400 A/s. The reproducibility of the magnetic field was measured with an integral coil coupled with a digital integrator, providing the results summarized in Table II.

TABLE II Reproducibility of Magnetic Field over 8 Cycles

Model	Low field	High fields
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5\cdot10^{-5}$	$4\cdot10^{-5}$
Model 2 (Low carbon steel)	$6\cdot10^{-5}$	$6\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4\cdot10^{-5}$	$6\cdot10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3\cdot10^{-5}$	$3\cdot10^{-5}$
Model 2 (Low carbon steel)	$4\cdot10^{-5}$	$5\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2\cdot10^{-5}$	$4\cdot10^{-5}$

Though there is an indication that Model 1 and 3, as expected, perform better than Model 2, it is difficult to state a conclusion based on these numbers, which are close to measurement errors and in any case all very satisfactory. In practice these results show that within this range of field levels the value of the coercive field does not seem to play a major role in the reproducibility of the magnetic field from cycle to cycle and that all three models meet the LHeC specifications.

For sake of knowledge, though not being relevant for machine operation, we measured the remanent field, which is of 1.4 Gauss, 14 Gauss and 3.5 Gauss for Model 1, 2 and 3 respectively well in agreement to what expected.

We also measured the excitation curves of the three models (Fig. 6), showing the better performance of the grain oriented steel, even compared to the low carbon steel model.

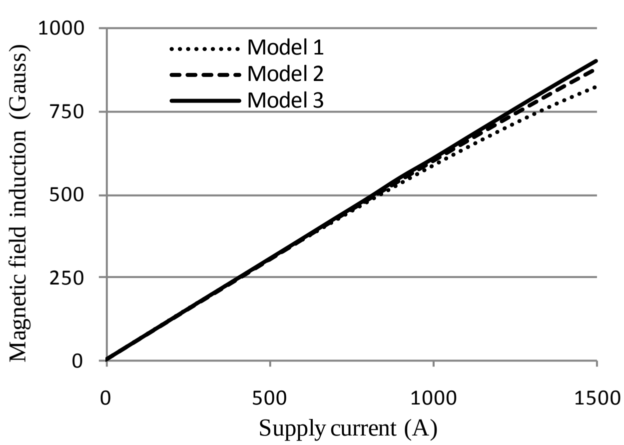

Fig. 6. Central magnetic field induction as a function of the supply current

Finally, we measured the magnetic field homogeneity in the horizontal plane. The measurements were carried out with a 20-cm-long coil, with 5 mm transversal steps from the beam axis, at the magnetic injection energy. The results shown in Fig. 7 refer to Model 3.

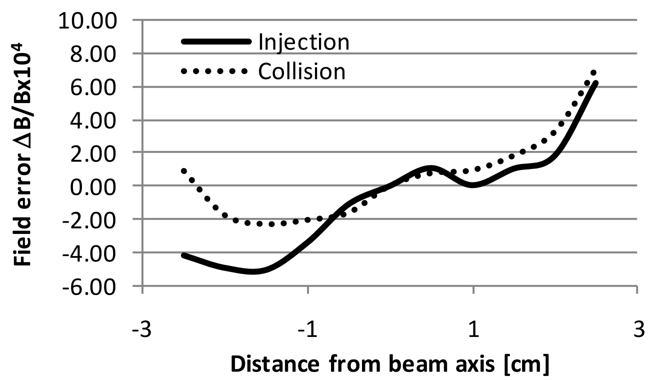

Fig. 7. Measured central magnetic field as a function of the supply current. The outside of the magnet C-shape is towards the right (positive coordinates).

The behaviour of these curves at a magnetic field induction of 127 Gauss and 763 Gauss, corresponding to injection and to collision, is very similar to the computed ones shown in Fig. 3. Such good match goes beyond what could be reasonably expected, in particular when considering the specific construction with interleaved laminations and the low working field induction, confirming the validity of the choice of designing the pole profile in 2D. There is however a remarkable average anti-clockwise rotation of the curves, corresponding to a slight imperfection in the pole parallelism of about 4 micro-meter per centimeter, which on the assembled magnet could not be intercepted because within measurement errors. On possible series magnet similar errors could be easily compensated by acting on the stamping tool and eventually with additional shimming.

V. Conclusion

The manufacture and test of three short dipole models for the LHeC could prove that a compact, light and economical solution meeting the tight requirements of the project in terms of field quality and reproducibility at very low magnetic field induction does exist. Though all three models would meet the requirements, the use of grain oriented steel interleaved with plastic spacers appears the most interesting compromise between performance and costs.

Acknowledgment

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References

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