MAGNETS FOR THE CANDLE BOOSTER SYNCHROTRON, DESIGN AND PROTOTYPING

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Abstract

CANDLE booster synchrotron magnetic lattice contains 48 dipoles of H-shape. Detailed magnetic and mechanical design of those magnets is performed within the framework of the project. In this report, the design considerations of the dipole magnet, including the magnetic field simulation is presented. The results of the numerical simulation are compared with the magnetic field measurements of the first prototype dipole magnet.

INTRODUCTION

Third generation synchrotron radiation source CANDLE booster synchrotron will accelerate electrons from 100 MeV to 3 GeV for the injection into storage ring. 48 H-type parallel ends dipole magnets will provide required curvature of the beam orbit within the given energy range. Magnets will be 1.8 meters long and will be curved following beam trajectory in an attempt to keep sizes as minimal as possible [1]. Table 1 presents the main parameters of the magnet.

SIMULATIONS AND DESIGN

The parameters defining design are listed in the Table1. With the distance between booster and storage ring minimally being 2.8 m, stray fields from booster magnets may influence the storage ring beam. H-type shape closed yoke magnets are a good choice to minimize those stray fields. To allow access to the pole area and to mount the coils, the magnet yoke is divided at the horizontal median plane.

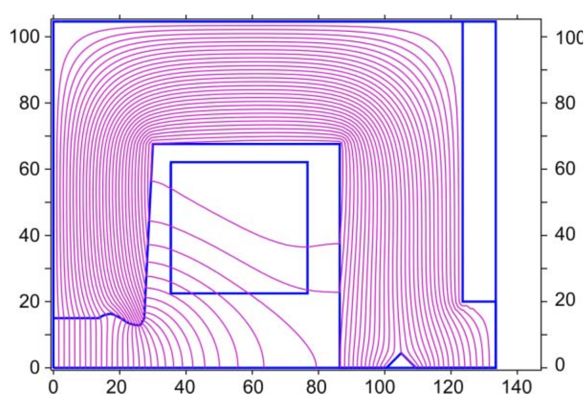

Figure 1: The plot of field-lines of the CANDLE booster dipole magnet.

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Magnet Pole Design

Earlier versions of POISSON/SUPERFISH group of electromagnetic simulation codes contain pole design software utility MIRT [2], which now is considered as obsolete [3]. We employed the approach of the N. Marks et al [4] relaying on the some basic principles and a great deal of trial and error to determine magnet geometry in both transverse and longitudinal planes to meet the required field parameters.

Table 1: Dipole magnet main parameters

Number of magnets	48
Magnet Length	1.8 m
Magnet Type	H-frame, curved
Injected Beam Energy	100 MeV
Beam Maximum Energy	3 GeV
Bend Angle	0.1309 radians
Inter-Pole Gap	30 mm
Maximum Field	0.723 Tesla
Good Field Region Width	30 mm
Field Uniformity in Good Field Region	$\Delta B/B \leq 5\times10^{-3}$
Curvature Radius	13.75 m
Lamination Width	0.5 mm
Lamination Weight	0.066 kg
Number of Laminations per Core	~ 6980
Stacking Factor	0.98
Assembled Core weight	560 kg
Chamfer Depth	27 mm, (45°)
Material	Russian 2213 steel
Number of Turns per Pole	6
Amperes- Turns	8684
Current max. /min.	1447A / 50 A
Ramping Repetition Rate	2 Hz
Conductor Size (width×height, hole diameter)	20.5×14 mm^2, ∅=10 mm
Conductor Area	203.1 mm^2
Resistivity	0.0178 mΩ×mm^2/m
Current Density (max.)	7.4 A/mm^2
Conductor Length per Magnet	48.3 m
Coils Weight	2 × 48 kg
Magnet Resistance	4.23 mΩ
Magnet Inductance	0.99 mH
Voltage Drop per Magnet (max.)	16 V
Power per magnet (max.)	9.5 kW

One can derive from the contemporary methods of convenient magnets design the following procedure for the design of the magnetic pole shape:

- The central part of the pole surface can coincide with the equipotential surface for the magnetic material infinite permeability ($\mu = \infty$).
- Finite pole minimum width can be calculated to be equal to good field region plus pole overhang, which can be defined by the formula $\nu = (-0.14 \ln(e) - 0.25)h$, where $e = \Delta B / B$ is the required field quality and h is the magnet half gap [5]. For $e = 5 \times 10^{-3}$ and $h = 15mm$, one gets $\nu = 0.492h = 7.4mm.$ and $w = 54.8mm$ for the shimmed pole total width. We applied $13.8mm$ wide positive-negative shims at the pole corners.
- One should terminate pole corners with the either of three ways: strait cut, tapering or Rogowski roll of [6]. We choose strongly tapered pole sides.

Field Quality Control

The magnetic field is calculated using the POISSON code [2]. Only quarter of the magnet was considered in the simulation due to the 90 degrees symmetry of the problem. The yoke sizes are adequate to avoid saturation and to provide flux return path. The pole gap is 30 mm at the centre and provides enough room for the beam vacuum chamber. Positive-negative shape shimming used provides necessary good field region with some redundancy over entire range of the excitation. Figure 1 shows field homogeneity in the middle plane of the magnet for the either of lowest (corresponding to injection energy E=100 MeV) and highest (corresponding to extraction energy E= 3GeV) excitations.

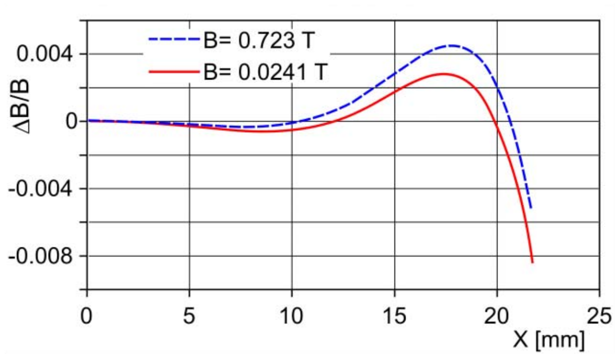

Figure 2: Field homogeneity on the middle plane in the transverse direction. Coordinates origin is positioned at the centre of the magnet.

The results of a harmonic analysis show the existence of a good quality field within the required good field region. Due to the magnet symmetry, quadrupole error fields are eliminated. The third and higher order terms in the field harmonic content at 11 mm normalization radius are at a level 0.1% of the dipole component or smaller (vacuum chamber inner vertical diameter is equal to 22 mm). The results of field harmonic analysis are given in Fig. 2. The shimming shape proves to be effective in suppressing higher order multipoles.

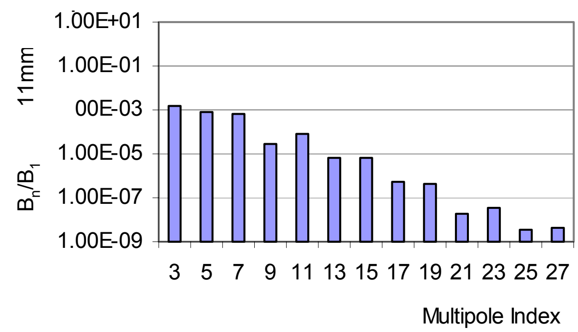

Figure 3: Booster dipole magnet field random error multipole content. Normalization radius is 11mm, which corresponds to the inner vertical size of the vacuum chamber.

End-Fields

The problem that stands for magnet designers is to find an appropriate shape of the magnet ends eliminate the difference between the value of field integral along the z –line and the value of BL, where B is magnet nominal field and L is the magnet's magnetic length while avoiding sharp corners at magnet ends that cause

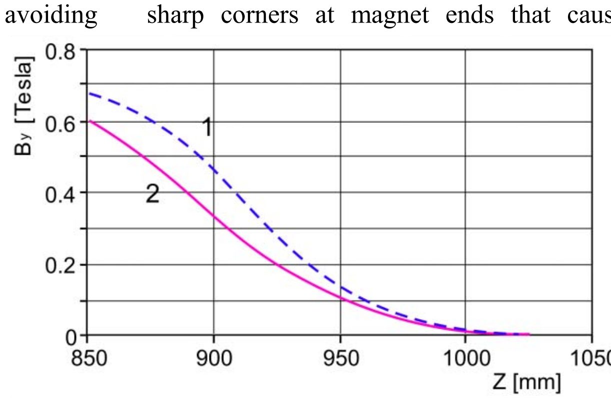

Figure 4: CANDLE Booster dipole magnet vertical end field distribution at centerline. 1-dotted line represents the field before the chamfer and 2 –solid line represents the field after chamfering. Coordinates origin coincides with magnet center.

saturation is the second reason forcing to shape magnet ends. Though POISSON is 2-dimensional code [2] it gives possibility to evaluate magnet end-fields distribution for the development of an appropriate chamfering procedure. This method is most fruitful for dipole end field numerical estimations. Geometry model includes some non-physical abstractions to provide return path for the flux [4]. The aim of the simulations is to find chamfer that makes integral vertical field along the magnet centreline equal to B×L. For engineering simplicity we decided to limit ourselves by straight cut at the ends under 45 degree instead of more appropriate Rogowski tapering which excludes saturations at sharp corners [7]. The required chamfer depth turned out to be 27 mm. Figure 3 illustrates the reduction of the field due to chamfering.

Magnet Steel

Russian 2212 magnetic steel has been chosen [8]. Magnetic parameters of this steel are close to those of AISI 1010 steel, which is the most popular material of choice for the accelerator magnet fabrication. Measured magnetic properties used in the field simulation with the POISSON code is shown in the Figure 4.

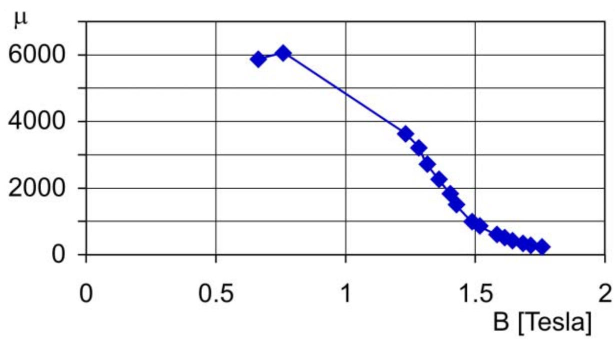

Figure 5: Measured relative permeability μ of the Russian 2212 magnetic steel versus flux density that used for magnetic simulations of the dipole with POISSON code.

FABRICATION

Despite the fact that curved magnet construction entangled with assembly complications it allows to minimize sizes and hence weight of the magnet. Though dipole magnet is the largest among the CANDLE booster magnets it is light enough (560 kg without coils) to be hang on the inner wall of the CANDLE ring.

Magnet Core

Parallel ends core of 1.8 m length is assembled from about 7000 laminations with the thickness equal to 0.5 mm (Fig.5). Lamination are stacked and glued other steel frame excluding welding that could cause mechanical and

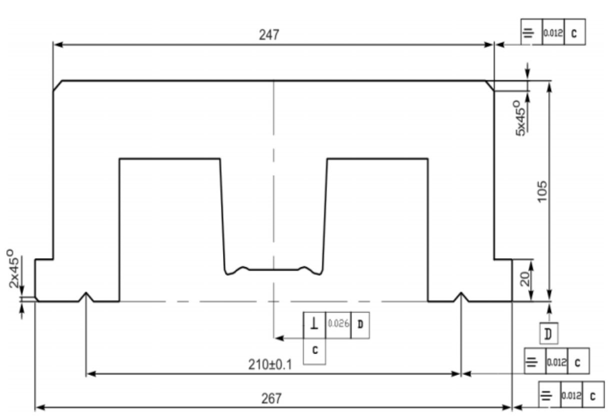

Figure 5: BDM Lamination Cross Sectional View.

d magnetic distortions due to local heating in the welding process. The core is assembled from two halves allowing installation of the coils and vacuum chamber.

Coil System

Coil main parameters are shown in the Table 3. Low number of the turns (6 per pole) results rather low magnet inductance. Magnet coil can be treated as Solenoid of arbitrary cross section. Force on the one half of the magnet coil caused by other half can be calculated approximately applying formula $\frac{F}{S} = B^2/2\mu_0$ [5]. For the CANDLE Booster Dipole Magnet coil winding cross section area is $S \approx 0.24m^2$, field induction is $B = 0.723T$, and $\frac{F}{S} \approx 2\times10^5 N/m^2$, hence $F \approx 5\times10^4 N$.

Prototype magnet is already fabricated and mechanical measurements were performed. Magnetic field mapping is anticipated to verify magnet design and to develop a chamfer of an appropriate shape.

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