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The Bending Magnets For The Proton Transfer Line of CNGS

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The project "CERN neutrinos to Gran Sasso (CNGS)", a collaboration between CERN and the INFN (Gran Sasso Laboratory) in Italy, will study neutrino oscillations in a long base-line experiment. High-energy protons will be extracted from the CERN SPS accelerator, transported through a 727 m long transfer line and focused onto a graphite target to produce a beam of pions and kaons and subsequently neutrinos. The transfer line requires a total of 78 dipole magnets. They were produced in the framework of an in-kind contribution of Germany via DESY to the CNGS project. The normal conducting dipoles, built from laminated steel cores and copper coils, have a core length of 6.3 m, a 37 mm gap height and a nominal field range of 1.38 T – 1.91 T at a maximum current of 4950 A. The magnet design was a collaboration between CERN and BINP. The half-core production was subcontracted to EFREMOV Institute; the coil fabrication, magnet assembly and the field measurements were concluded at BINP in June 2004. The main design issues and results of the acceptance tests, including mechanical, electrical and magnetic field measurements, are discussed.

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***Abstract*— The project "CERN neutrinos to Gran Sasso (CNGS)", a collaboration between CERN and the INFN (Gran Sasso Laboratory) in Italy, will study neutrino oscillations in a long base-line experiment. High-energy protons will be extracted from the CERN SPS accelerator, transported through a 727 m long transfer line and focused onto a graphite target to produce a beam of pions and kaons and subsequently neutrinos. The transfer line requires a total of 78 dipole magnets. They were produced in the framework of an in-kind contribution of Germany via DESY to the CNGS project. The normal conducting dipoles, built from laminated steel cores and copper coils, have a core length of 6.3 m, a 37 mm gap height and a nominal field range of 1.38 T – 1.91 T at a maximum current of 4950 A. The magnet design was a collaboration between CERN and BINP. The half-core production was subcontracted to EFREMOV Institute; the coil fabrication, magnet assembly and the field measurements were concluded at BINP in June 2004. The main design issues and results of the acceptance tests, including mechanical, electrical and magnetic field measurements, are discussed.**

***Index Terms*—Normal Conducting Magnet, Dipole, Transfer Line, CNGS.**

I. INTRODUCTION

The CERN Neutrino to Gran Sasso (CNGS) facility will provide a neutrino beam directed towards the INFN Gran Sasso Laboratory in central Italy. Neutrinos are generated from the decay of mesons, produced by a primary proton beam coming from the Super Proton Synchrotron (SPS) and impinging on a graphite target. Neutrinos ν_μ will then proceed over 730 km towards Grand Sasso, where ν_τ appearance can be studied. The SPS extraction system foreseen for the LHC allows fast extracted pulses to be sent to the TI8 transfer line. With some modifications, this system can also provide protons for the CNGS target. The total length of the proton beam line, from the SPS to the CNGS target, is 840 m. The beam branches off the TI8 line into TT41 after 110 m, switched by 8 MBS magnets recuperated from another facility at CERN. It is then bent by a 580 m long arc providing 33º horizontal deflection and a final slope of 5.6% to aim into the direction of Gran Sasso, followed by a 90 m long focusing section to obtain the desired beam size on target [1], [2].

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II. MBG DESIGN ASPECTS

A total of 73 MBG dipole magnets are being installed in TT41; five spare magnets plus five additional spare coils had to be built as well. For budget and man-power reasons it was desirable to profit as much as possible from existing know-how, technologies and installations from the MBI magnet production [3], proceeding until summer 2001 at the Budker Institute of Nuclear Physics and sub-contractors thereby fixing parameters like the core length of 6.3 m, the magnetic properties of Russian 21848st steel (see below), a maximum steel sheet thickness of 1 mm, the fabrication tolerances of the stamping tools at NIIEFA, St. Petersburg, etc. The MBG gap height was scaled to 37 mm [1], [2]. It was decided to specify the magnets for proton energies of 400 - 450 GeV, although the operation down to 350 GeV should be kept as option. For the required deflection of 8 mrad at 6.3 m core length, this corresponds to a flux density in the gap of 1.482 T $\leq$ B $\leq$ 1.906 T, B_{nom} = 1.694 T for the nominal 400 GeV. However, the most demanding criteria was the requested integral field quality in the good-field region (x = ±37 mm; y = ±17 mm) following beam optics calculations [4]. A $\Delta B/B_0 < \pm 2 \times 10^{-4}$ over the full range of operation from 1.48 T to 1.91 T and tight limits on the sextupole content, expressed in terms of $\Delta B/B_0 < -1 \times 10^{-4}$ at x = ±17 mm (no positive sextupole allowed), have been specified. The design of the MBG magnets had to be compatible with the existing power supplies; they have been recuperated from the LEP accelerator and will be switched in operation between the MBI dipole [3] line of TI8 and the MBG line of TT41, since a filling of the LHC and providing protons for the CNGS target at the same time is not foreseen [1]. The current is therefore limited at 5.4 kA, the available voltage of two converters in series amounts to 3.6 kV. Additional limits are set by the tunnel layout and the magnet installation scenario. The overall width of the MBG had to be less than 720 mm and the total weight not exceeding 11 tons [4]. Altogether, the above mentioned constraints did not allow for much flexibility in the design. At a flux density B = 1.91 T in the gap, some regions in the pole and in the return yoke are fully saturated, leading to a considerable distortion of the flux distribution. A precise knowledge of all the input parameters incl. fabrication tolerances and steel magnetic properties (see below) was of

TABLE I
DESIGN CONSTRAINTS DUE TO EXISTING COMPONENTS/INSTALLATIONS/TOOLS

Item	Parameter	Value
Power converter	Max. current	**5.4 kA**
	Max. voltage	**3.6 kV**
Tunnel	Overall magnet width	**< 720 mm**
	Total magnet weight	**≤ 11 tons**
Production	Steel quality	**21848st; 1 mm**
	Core length	**6.3 m**
	Stamping precision	**~0.02 mm**

major importance for preparing the magnetic model and designing the final shape of the pole.

III. THE COIL DESIGN

Following the design of the MBI magnets [3] no external busbars will be used for the bending dipoles in TT41. Each MBG coil thus consists of two overlapping half-coils impregnated together in one mould, with enough precautions to withstand the max. 3.6 kV between adjacent conductors. Only a double layer half-coil could fulfill the requirements of the specific connection scheme and the required ampere-turns for the limited maximum width of the magnet. A 3D model of such a coil is shown in Fig.1, a quarter of the cross section as used in OPERA2D™ can bee seen in Fig.2. One additional water outlet per half-coil is placed in the central winding at one coil end, the cooling water is fed into all electrical connectors. Otherwise an efficient cooling of the inner windings can not be guaranteed and thermal stress might occur in the coil insulation between cold and hot conductor parts. Table II is summarizing the parameters of this 13 winding coil built from hollow copper conductor bars of 30 mm x 24 mm, and 10 mm cooling hole diameter for a current density of 3.82 – 4.73 A/mm2.

TABLE II
COIL PROPERTIES

Excitation		400 GeV – 450 GeV [a]
Conductor H x W	(mm x mm)	30 x 24
Cooling hole	(mm)	10
No. of turns		13
Resistance (hot)	(mΩ)	4.72 – 4.88
Inductance	(mH)	5.7
Operating current	(A)	4050 - 4950
Current rms	(A)	2450 - 3060
Dissipated power	(kW)	31 - 48
Cooling (per half coil)		
Pressure drop	(bar)	4
Water flow	(l/min)	4 x 13
Temperature rise	(K)	< 10 - 15
Weight	(Kg)	1150

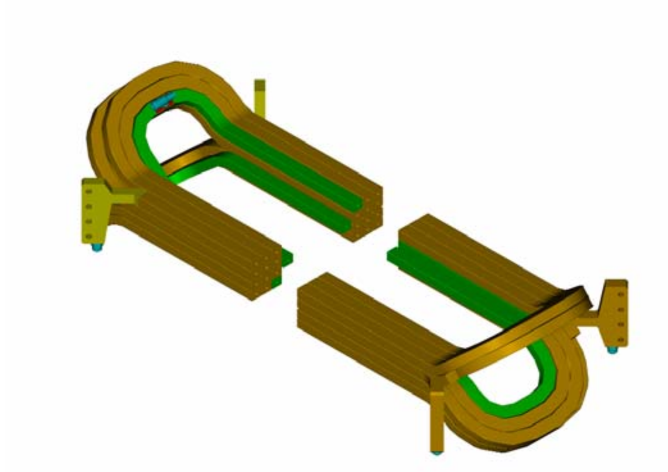

Fig. 1. The MBG coil is composed of two double layer pancakes of 7 ½ turns each.

IV. THE MAGNETIC MODELING

For long magnets, where the iron length is large compared to the aperture height and width, the influence of the end-fields is, in a first approach, negligible and the integral field quality can be approximated from integrating the 2D fields over the length of the core. All two-dimensional models have been realized in the OPERA™ finite elements program and the Russian MERMAID™ code. A model based on the coil of Fig. 1 is shown in Fig. 2. It has a characteristic wide pole and a reduced total width of the magnet. The inner turn of the coil is placed inside the gap thereby acting strongly on the field off-axis. The usual pole shims [3] are no longer needed. In region 2 we have placed an air hole at x = 40 mm plus a smaller central hole at x = 0. They have been introduced to provide field homogeneity at higher flux density. Such holes cause higher saturation losses, but they allow for optimizing the design for a full range of operation.

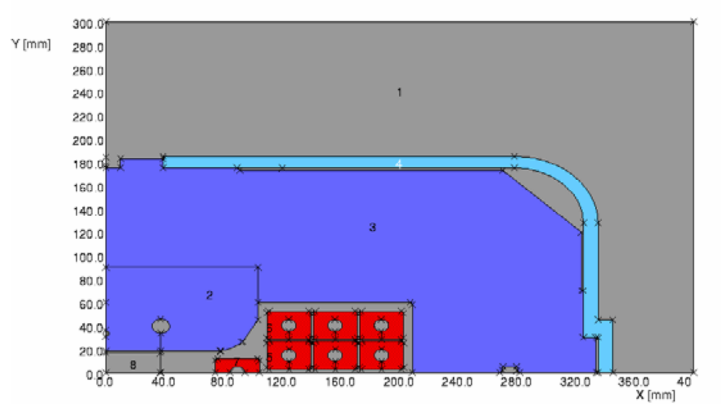

Fig. 2. The MBG cross-section

The field homogeneity requirement $\Delta B/B_0 < \pm 2\cdot 10^{-4}$ is respected for the entire section inside the vacuum chamber (x = ±37 mm; y = ±17 mm). To make-up for variations in series production specifically shaped end-shim geometries for correction of dipole and sextupole content have been developed after 3D calculations in MERMAID™.

TABLE III
FABRICATION TOLERANCES

Parameter	Tolerances	critical
Hole diameter	± 1 mm	no
Hole position	± 0.5 mm for x,y	no
Pole geometry	± 0.02 mm	yes
Inner conductor placement	± 0.5 mm for x	no
Stacking factor	0.97 – 0.99	no
Steel	B_{spec} + 2 % avg.	no

The stability of the optimized magnetic model against fabrication tolerances has been studied in OPERA2D™ as well. The result is given in Table III.

The MBG magnet is 6.3 m long and relatively narrow (692 mm x 440 mm). The mechanical design was made for minimum sag, yielding a minimum loss of aperture for an optimized position on two support plates. Calculations [5] predicted a sag of the magnets, supported at 1405 mm from the two core ends, between 0.2 and 0.3 mm, being closer to 0.2 mm as measured during production. The half cores are compressed to achieve a 98.3+/-0.2% stacking factor after stacking laminations between massive end plates (60 mm thick) and welded onto 10 mm thick precision machined angular plates. The tension channel formed by this all welded construction gives excellent stiffness to the slim structure. Holes in the angular plates allow for accessing the reference faces on the laminations used for positioning the alignment targets and for geometry measurements. Each endplate is housing a series of 1 mm shims, compressed by a 45° chamfered end shim of specific shape to adjust for the nominal magnetic length and multipoles.

V. MAGNETIC MEASUREMENTS

A. *Pre-series magnet evaluation*

The magnetic model results have been checked in detail against three MBG pre-series magnets assembled for that purpose without vacuum chamber. The measurements were carried out by a dedicated Hall probe array sledge (19 probes), driven by a stepping motor and guided along the pole faces. Three different positions of the sledge in vertical direction provided for off-axis measurements at ± 5 mm as well. The same measurements have been applied in series production after each re-sharpening of the stamping dies. Magnets measured by Hall probes have been disassembled afterwards and, after re-assembly with vacuum chamber, measured by series measurement technique as well.

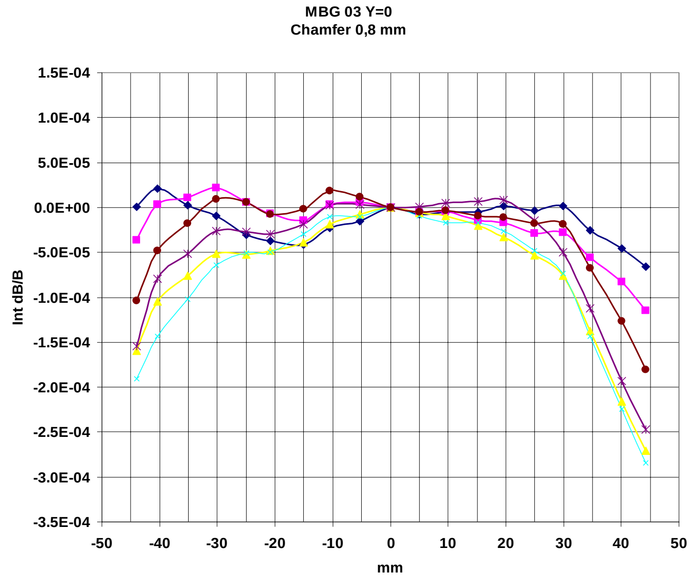

Fig. 3. Pre-series MBG03 measured with optimized end chamfer – Integral field quality at different flux density levels between 1.3 T – 1.91 T

B. *Series Magnetic measurement*

The magnetic field of dipole magnets contains, in addition to the dipolar content, higher order multipoles. As final quality control of the production, three main contributions to the field, the dipole, quadrupole and sextupole components were evaluated. Asymmetry of the pole in transverse direction generates a gradient while a sextupole is governed by the chosen pole shape, production accuracy, steel saturation and edge effects. An integral method to approximate these components using fixed strip coils on a stiff support (see Fig. 4) was developed. It fulfills the following basic requirements:

- The measurements are carried out in the vacuum chamber without contamination of the walls;
- The system provides effective measurements with a mean throughput of, at least, one dipole per day;
- The relative measurement accuracy of the dipole component integral for all dipole magnets relative to a reference magnet is better than $5{\cdot}10^{-5}$;
- Quadrupole and sextupole contents measurement accuracy is $\pm 3{\cdot}10^{-5}$ relative to the dipole component.

The fixed strip coils system consists of a reference coil placed in the reference magnet and three measuring coils in the magnet to be measured. The timing of the measurement has been adapted to the characteristics of the transfer line cycles. Two identical coils are placed in two different magnets powered in series. This method provides high relative field integral accuracy. This is also valid for two side coils located in the same magnet in different transverse sections whilst the system proves to be rather insensitive to the accuracy of the coil positioning.

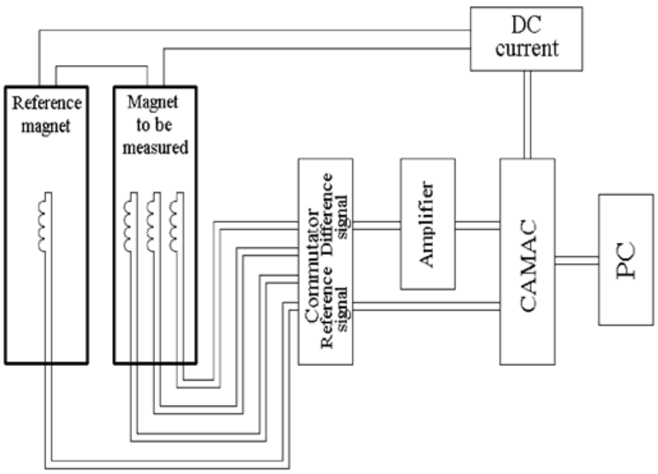

Fig.4. Functional scheme of the strip coils measuring system

Each coil is glued on a glass- fibre reinforced substrate of 15 mm width and 1 mm thickness. The substrate is fixed on the backing strip of 55 mm width of the same material. Due to the given coil length the end-fields of the magnet are included in the measurement. Two adjacent measuring coils are placed at 29 mm distance between the centers.

The strip coil is equipped with non-magnetic stainless steel brackets placed on the lower part of the vacuum chamber at 450 mm spacing and fixing the measurement position. The strip coils are pulled on both sides by ~300 N for reducing the sag of the strip. The signals of all coils were calibrated against Hall probes and NMR and made equal to an accuracy $\pm 1 \cdot 10^{-5}$. This uniformity was regularly checked and no changes were observed.

VI. MBG SERIES PRODUCTION

1100 tons of 1 mm thick low-carbon steel have been ordered from the Russian producer ESTA/VIZ Ekaterinburg according to CERN specification [6]. The permeability of all steel rolls has been measured [7] and the rolls were grouped in five categories accordingly – the laminations were then mixed in equally distributed ratio in the half-core stacking. The series steel turned out to be superior in permeability than the pre-series recuperated form MBI production making an adjustment of the magnetic length of the pre-series reference magnet necessary. The organic insulation coating of the steel has lowered the surface hardness when compared to steel with oxide layers produced by "blue steaming" [3], increasing the intervals between the stamping die re-sharpening. The full quantity of laminations for 78 MBG magnets has been produced by only one stamping tooling. The laminations have been stacked to obtain 98.5% - 98.8% stacking factor at the given length of the half-cores.

The MBG coils were soldered, wound and impregnated in well established processes [8] at BINP. Hollow copper (high purity; OF) bars of 8.95 m length have been produced by Austria Buntmetall.

All quality control measures and specific tests were developed during MBI magnet production and later on adapted to MBG magnets. All series magnets were individually shimmed in view of integral magnetic length and "sextupole" content. The MBG integral magnetic length at different excitation level of the entire production relative to the reference magnet is shown in Fig. 5:

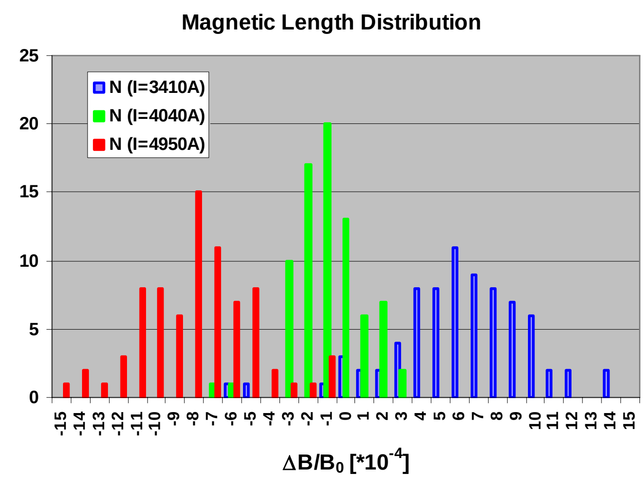

Fig.5. Magnetic length distribution of all MBG magnets against reference magnetic length at different field levels.

VII. CONCLUSION

The CNGS project has been approved just in time for continuing a well established collaboration between CERN and BINP in the design and production of normal conducting magnets, leading to maximum cost savings. Some difficulties experienced in the MBI magnet production [9] could be overcome by modified material specifications and controls. There is some margin in the design of the MBG in terms of thermal robustness and integral field quality to satisfy the needs of operation in a transfer line at varying working points. Intrinsic weak points of the design like high voltage between the overlapping half-coils and the additional water outlet in the coil heads have been addressed with specific precautions and tests. The transfer line is now installed and commissioning will start early 2006.

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