European Organization for Nuclear Research

EDMS No. 399 883

Design Report of the MDG Corrector Magnets

B.Langenbeck

Abstract

This report presents a design of the MDG correctors. The magnets are part of the "CERN Neutrino to Gran Sasso" (CNGS) beam transfer line TT41. The correctors are C-magnets with a flux density of 0.2 T and a good field region of 45 mm in diameter for $|\Delta B/B| \leq 0.3\%$. The 490 mm long yokes will be built from glued low carbon steel laminations. The two coils are wound from enamelled copper wire and cooled by natural convection and radiation. The design is optimized for a nominal beam energy of 400 GeV, but allows operation of up to 450 GeV.

Geneva, Switzerland, August 2003

Contents

1 Introduction

The design of the MDG corrector magnets for beam line TT41 (CNGS project) shall guarantee the following requirements:

Bending angle up to 450 GeV	80	μrad
Yoke length	490	mm
Gap height	45	mm
Good field region, radius	$\leq$ 22.5	mm
for $\lvert\Delta B/B\rvert$	$\leq$0.3	%
Excitation current	$\leq$3.5	A
Voltage drop	$\leq$40	V

Current and voltage refer to power supplies in house which shall be re-used. A magnet of C-type is foreseen, the coils shall be wound around the yoke's back leg. The distances between coil and center of the aperture shall be 80 mm to respect the diameter of the clamp chains of the vacuum chamber flanges. The magnet is optimized for 400 GeV protons (I_{nom} = 3 A), but can be also operated at 450 GeV.

The yoke shall be manufactured from glued laminations of thickness 1 mm. Fig.1 shows the cross-section of the magnet. Bores for screws will be drilled along the back leg which will clamp the upper and lower yoke halves. The coils shall be wound from copper wire 2.8 mm (bare) diameter.

Heat removal from the coils was estimated for 3.5 A (450 GeV), assuming as a worst case that heat transfer would take place by natural convection and radiation, but only through the free lying surfaces of the coils, i.e. surfaces not adjecent to the yoke or other coil parts. The result of a calculation is 24 mW/cm^2. Coil surface temperature will be approximately 19^{0}C higher than room temperature as estimated using formulas given in: G. Schnell, Magnete, Verlag Karl Thiemig, 1973. Heat removal by direct transfer to the yoke mass was not taken into account.

The geometry has been tested with OPERA-2d software to verify field homogeneity. Fig.2 and Fig.3 display the result for a pole width of 84 mm.

The effective magnetic length as given in the data tables below has been estimated using formula $l_{eff} = l_{yoke} + \alpha \cdot gap$ with the frequently assumed value of $\alpha = 1.3$. Compensation of errors of the integrated field distrubution shall be done by defining proper chamfers and/or shims at the pole ends during measurements on the first magnet.

The following tables show constructional and operational data of the magnets in detail.

2 Short Summary

Number of magnets	17	
Bending angle	80.000	μrad
Gap height	45.000	mm
Gap width	84.000	mm
Good field region, radius	$\leq$22.500	mm
for $\lvert\Delta B/B\rvert$	$\leq$0.300	%
Effective magnetic length	548.500	mm
Construction length of yoke	490.000	mm
Construction length of coils	711.000	mm
Yoke weight per magnet	210.800	kg
Conductor weight per magnet	198.260	kg
Number of coils	2	
Number of turns per coil	1190	
Heat flow through coil surface	$\leq$24.000	mW/cm^2
for (450 GeV)	3.500	A
Coil surface temperature rise	$\leq$19.000	^{0}C

3 Operational Data

Nominal current	3.000	A
Resistivity	10.650	Ω
Inductivity	17.840	H
Voltage	31.940	V
Dissipated power (dc)	95.800	W
Stored energy	80.300	J

4 Yoke Data

Magnetic rigidity of protons	1337.400	Tm
Flux density × magnetic length	0.1070	Tm
Yoke length	490.000	mm
Magnetic length	548.500	mm
Flux density	0.200	T
Bending radius	6.858	km
Gap height	45.000	mm
Gap and pole width	84.000	mm
Effective field width	215.000	mm
Total yoke width	302.000	mm
Yoke height	310.000	mm
Shim width	10.000	mm
Shim height	1.240	mm
Good field region, radius	≤22.500	mm
for $\lvert\Delta B/B\rvert$	≤0.300	%
Sagitta	5.500	μm
Construction: straight yoke		
Magnet width including coils	412.000	mm
Magnet length including coils	711.000	mm
Magnet height	310.000	mm
Coil window width	143.000	mm
Coil window height	220.000	mm
Thickness of sheets	1.000	mm
Number of sheets per magnet	970	
Filling factor	0.990	
Weight per sheet	217.300	g
Weight of yoke (net weight)	210.800	kg
Ampere-turn losses	≤0.300	%
Stored energy	80.300	J
Distance coil - aperture center	85.000	mm
Flux density in poles	≤0.430	T
Rel. permeability, poles	6400	
Flux density, return path	≤0.840	T
Rel. permeability, return path	5700	
Flux density, back leg	≤0.620	T
Rel. permeability, back leg	6400	

5 Coil Data

Number of coils per magnet	2	
Number of turns per coil	1190	
Columns	34	
Layers	35	
Current	3.000	A
Coil width	296.000	mm
Coil length	711.000	mm
Coil cross-section width	100.000	mm
Coil height	103.000	mm
Conductor diameter	2.800	mm
Conductor insulation, from heat-resistant Polyimid enamel	$\leq$0.040	mm
Ground insulation, from glass fibre cloth and tape	$\leq$1.000	mm
Copper cross-section	6.157	mm^2
Current density	0.487	A/mm^2
Mean coil circumference	1.510	m
Resistivity (30^0C)	10.650	Ω
Free lying surface per coil	0.290	m^2
Volume per coil	15.550	ℓ
Dissipated power per magnet	95.800	W
Copper filling factor	71.100	%
Copper weight per magnet	198.260	kg

6 Coil Data for Operation at 3.5 A

Supposed room temperature:	20.000	^{0}C
Supposed heat conduction number	1.000	$W/m/^0C$
Convection heat-transfer number	7.170	$W/m^2/^0C$
Radiation heat-transfer number	5.790	$W/m^2/^0C$
Mean temperature of coil	55.000	^{0}C
Resistivity	11.400	Ω
Dissipated power per magnet, dc	139.700	W
Heat transfer/free surface	24.000	mW/cm^2
Surface temperature rise	19.000	^{0}C

7 Contour of the Yoke Sheet

The contour of the yoke sheet is given in a coordinate system with origin in the center of the aperture of the magnet (see Fig.1).

N^o	x/mm	y/mm	N^o	x/mm	y/mm
1.	0.00	22.50	2.	32.00	22.50
3.	32.00	21.26	4.	42.00	21.26
5.	42.00	155.00	6.	-230.00	155.00
7.	-230.00	110.00	8.	-260.00	110.00
9.	-260.00	0.00	10.	-185.00	0.00
11.	-185.00	110.00	12.	-42.00	110.00
13.	-42.00	21.26	14.	-32.00	21.26
15.	-32.00	22.50	16.	0.00	22.50

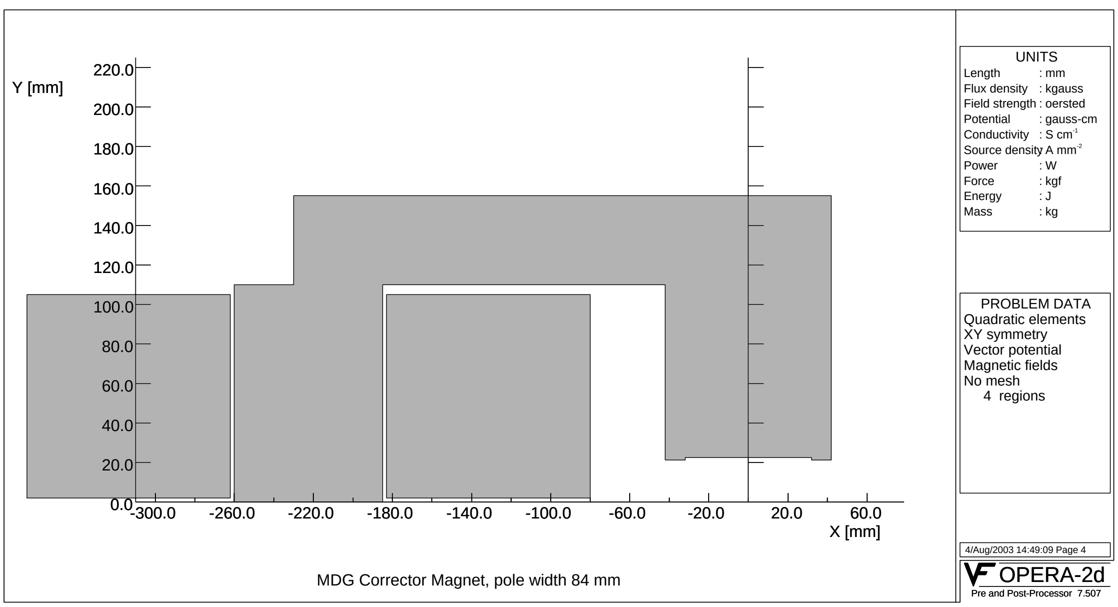

Figure 1: Cross-section of MDG Corrector Magnet

8 Field Homogeneity

Fig.2 shows the field homogeneity along a circle of radius 22.5 mm around the apertur's center. Shims in the pole peripherie (10 mm wide, 1.24 mm high) have been optimized to keep inhomogeneity along this line and within the inscribed disk well below 0.3%. Multipole analysis has been done for the same radius too, using subroutines of the OPERA-2d programs. See table in page 7.

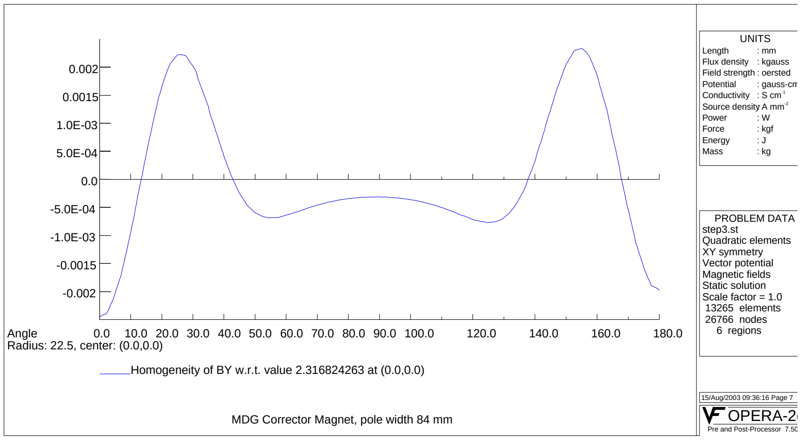

Figure 2: Field Homogeneity of MDG Corrector Magnet

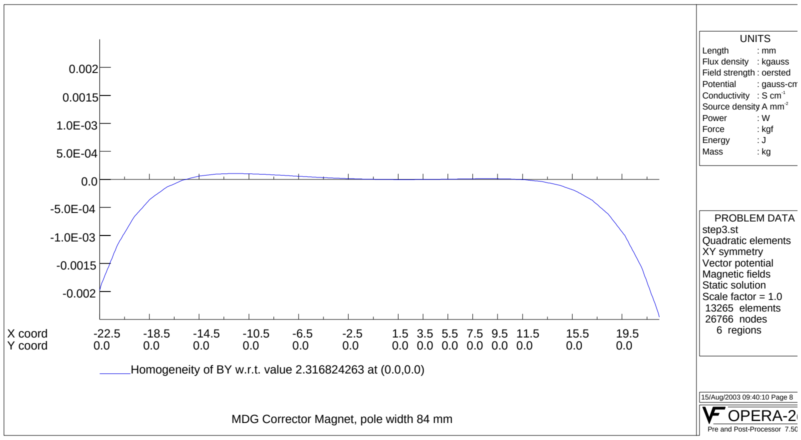

Figure 3: Field Homogeneity in Midplane

Harmonic analysis of field component along line.
Harmonic analysis of (X*BX+Y*BY)/SQRT(X*X+Y*Y)/2.31759
(normalized radial field component)

Along line (22.5 ,0.0) to (-22.5 ,0.0)
with curvature = -0.04444444 = -1/22.5

Fourier coefficients,
half period analysed, odd terms only

Order	Sine term	Cosine term	Amplitude	Phase
0	0.0	2.10829E-08	2.10829E-08	0.0
1	1.000000883	-4.2166E-08	1.000000883	-89.9999999
2	-7.5333E-05	4.21658E-08	7.53331E-05	89.96792765
3	3.62320E-04	-4.2166E-08	3.62320E-04	-90.0066654
4	-1.0528E-04	4.21658E-08	1.05278E-04	89.97704951
5	-5.5521E-04	-4.2166E-08	5.55213E-04	90.00434883
6	-5.2902E-05	4.21658E-08	5.29018E-05	89.95432942
7	-0.00121122	-4.2166E-08	0.001211215	90.00199212
8	-1.2632E-05	4.21658E-08	1.26322E-05	89.80874609
9	-7.6853E-04	-4.2166E-08	7.68530E-04	90.00314106
10	-1.3959E-06	4.21658E-08	1.39657E-06	88.26983362
11	-1.7895E-04	-4.2166E-08	1.78947E-04	90.01349827
12	5.28763E-07	4.21658E-08	5.30442E-07	-85.4406426
13	3.46499E-05	-4.2166E-08	3.46500E-05	-90.0697211
14	5.56789E-07	4.21658E-08	5.58384E-07	-85.6692423
15	3.14473E-05	-4.2166E-08	3.14473E-05	-90.0768219
16	1.19136E-07	4.21658E-08	1.26378E-07	-70.5096595
17	2.43062E-09	-4.2166E-08	4.22358E-08	-176.700870
18	-1.1304E-07	4.21658E-08	1.20645E-07	69.54312401
19	-9.7747E-06	-4.2166E-08	9.77482E-06	90.24715588
20	-8.4568E-08	4.21658E-08	9.44967E-08	63.49892448
21	-7.0803E-06	-4.2166E-08	7.08043E-06	90.34121050

Harmonics with amplitudes lower than 10^{-5}, which do not become smaller and smaller with increasing harmonic number, are noise. They are caused by discretisation and computer rounding errors of the mathematical model used to simulate the magnet.

9 Opera-2d Command-Input File

SET SYMM=XY SOLN=AT ELEM=QUAD FREQ=1 FIEL=MAGN
UNIT LENG=MM FLUX=KGAU FIEL=OERS POTE=GCM COND=SCM DENS=AMM2,
POWE=WATT FORC=KGF ENER=JOUL MASS=KG
RECO -300 -75 0 225
/ Region 1 Background
DRAW SHAP=BACK MATE=0 N=0 SYMM=0 PHAS=0 SIGM=0 PERM=1 DENS=0,
VELO=0 MIRR=NO ROT=1 DX=0 DY=0 NX=1 NY=1 TMIR=0 TROT=0,
XCEN=0 YCEN=0 ANGL=0
CART XP=-500 YP=0
CART XP=-365 CURV=0 N=5 BIAS=0.5 F=DV V=0 DV=0
CART XP=-262 N=5
cart xp=-260 n=1
cart xp=-185 n=8
cart xp=-183 n=1
cart xp=-100 n=9
cart xp=-80 n=9
cart xp=-50 n=16
cart xp=0 n=25
cart xp=50
cart xp=100
cart xp=500
n=20 CART XP=500 yp=300 N=10 F=V
CART XP=-500 N=20
FINI N=10
QUIT
/ Region 2 Yoke + Pole
DRAW SHAP=POLY MATE=3 N=0 SYMM=0 PHAS=0 SIGM=0 PERM=1E4 DENS=0,
VELO=0 MIRR=NO ROT=1 DX=0 DY=0 NX=1 NY=1 TMIR=0 TROT=0,
XCEN=0 YCEN=0 ANGL=0
CART XP=-42 YP=21.26
CART XP=-32 CURV=0 N=5 BIAS=0.5 F=NO V=0 DV=0

```
cart yp=22.5 n=1
cart xp=0 n=20
CART XP=32 N=20
CART YP=21.26 N=1
CART XP=42 N=5
CART YP=50 N=15
CART yp=155 N=11
CART xp=-230 N=28
CART yp=110 N=5
CART xp=-260 N=3
cart yp=0 n=5
cart xp=-185 n=8 f=dv
cart yp=110 n=11 f=no
cart xp=-42 n=14
cart yp=50 n=6
fini N=15
/yes
QUIT
/ Region 3 Coil cross-section rhs
DRAW SHAP=POLY MATE=1 N=1 SYMM=1 PHAS=0 SIGM=6.06E5 PERM=1 DENS=0.393,
VELO=0 MIRR=NO ROT=1 DX=0 DY=0 NX=1 NY=1 TMIR=0 TROT=0,
XCEN=0 YCEN=0 ANGL=0
CART XP=-182 YP=2
CART XP=-100 CURV=0 N=9 BIAS=0.5 F=no V=0 DV=0
CART xp=-80 N=9
CART yp=50 N=25
cart yp=105 n=6
cart xp=-182 n=10
FINI N=10
QUIT
/ Region 4 Coil cross-section lhs
DRAW SHAP=POLY MATE=1 N=2 SYMM=1 PHAS=0 SIGM=6.06E5 PERM=1 DENS=-0.393,
VELO=0 MIRR=NO ROT=1 DX=0 DY=0 NX=1 NY=1 TMIR=0 TROT=0,
XCEN=0 YCEN=0 ANGL=0
```

```
CART XP=-262 YP=2
CART yp=105 CURV=0 N=5 BIAS=0.5 F=no V=0 DV=0
CART xp=-364
CART yp=2
FINI
QUIT
/ Region 5 Gap region lhs
draw shap=poly mate=0 n=0 symm=0 phas=0 sigm=0 perm=1 dens=0,
velo=0 mirr=no rot=1 dx=0 dy=0 nx=1 ny=1 tmir=0 trot=0,
xcen=0 ycen=0 angl=0
cart xp=-80 yp=0
cart yp=2 curv=0 n=2 bias=0.5 f=no v=0 dv=0
cart yp=50 n=38
cart xp=-42 n=27
cart yp=21.26 n=23
cart xp=-32 n=8
cart yp=22.5 n=2
cart xp=0 n=30
cart yp=0 n=19
cart xp=-50 n=38 f=dv
fini xp=-80 n=23
quit
yes
/ Region 6 Gap region rhs
draw
cart xp=0 yp=22.5
cart xp=32 n=26 f=no
cart yp=21.26 n=2
cart xp=42 n=8
cart yp=50 n=21
cart xp=100 n=30
cart yp=0 n=38
cart xp=50 f=dv
cart xp=0 n=38
fini n=18 f=no
quit
```