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Magnetic Measurements of the Prototype QTG001 Quadrupole Magnet (CNGS)

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Summary

The QTG resistive quadrupole magnets will be part of the “CERN Neutrino to Gran Sasso” (CNGS) transfer line TT41. This technical note describes the magnetic measurements at CERN of the prototype magnet manufactured by BINP (Budker Institute for Nuclear Physics, Novosibirsk).

1. INTRODUCTION

The CERN Neutrino to Gran Sasso (CNGS) project, presently under construction, is a collaboration between CERN and the Gran Sasso Laboratory in Italy to study neutrino oscillations in a 730 Km long base line experiment.

High energy protons will be extracted from the SPS accelerator, transported through a 727 m long transfer line (TT41) and focused onto a graphite target to produce a beam of neutrinos.

The TT41 line will be equipped with conventional magnets including 23 QTG type quadrupoles. They are built by BINP (Budker Institute for Nuclear Physics, Novosibirsk) according to the CERN technical specification [reference 1]. All the magnets of the series will be measured by BINP and the first one, QTG001, is measured at CERN according to the CERN technical specification [reference 2]. The aim of this note is to compare measurements between the two institutes (BINP and CERN) and to check that the performances are in accordance with the conceptual design [reference 3].

2. PRINCIPLES AND PRECISIONS

2.1 Principle

The field is measured by a mole which is displaced in a stainless steel (316 L grade) tube (diam. 43/44.5 mm, 5 m long) at four longitudinal positions. This special tube is inserted inside the 45 mm aperture of the QTG quadrupole. It is supported by the lower poles and fixed at one end to avoid its rotation during the measurements. From the four mole position, two mole positions are inside the magnet symmetrically around the centre of the yoke and 0.40 m outside for the two other positions. The mole is pushed by one shaft for the three first positions; it is guided by a 2.35 m long rail, with two displacements (X_1 , X_2) of approximately the length of the coils of the mole. For the fourth position of the mole an extension shaft (approx. twice the length of the coils) is added starting from the coordinate X_1 of the rail. The gradient integral and the integral gradient harmonics are obtained from the sum of the four positions corrected for the gap in between the mole positions.

Due to the slight dissymmetry observed between the connection side and the non connection side, measurement of the field at a fifth position (i.e. the mole in the central part of the magnet) has been undertaken; it gives more accuracy for the calculation of the equivalent length of the QTG quadrupole.

An overview of the fundamentals, the mole and its associated equipment is given in a dedicated note [reference 4].

2.2 Coordinates and alignment

Contrarily to the note given in reference 4, it is the mole axis which is taken as the reference.

Due to the play between the stainless steel tube and the poles, the incertitude of the position with respect to the poles is ± 0.25 mm.

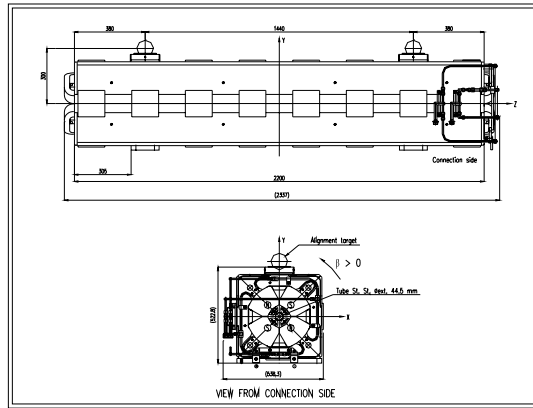


Figure 1 – Quadrupole QTG

2.3 Excitation current

The magnet is powered by a 1000 A rectifier type R21. The ripple is around 1‰ of the current.

The current is detected with a 5000 A DCCT (Hazemeyer), the signal of which (500 A/V) is measured with a 16 bit ADC module (INCAA) type VD 20.57.25.

The relative accuracy of the reading of the current is

$$|\varepsilon_1| \leq 1 \times 10^{-3} \text{ for } 250 \text{ A} \leq I \leq 550 \text{ A}$$

The reproducibility is 10 times better.

Before the magnetic measurement campaign, the magnet has been demagnetized and then magnetized five times at 530 A with the polarity indicated in figure 1. After demagnetization all the measurements are done with the positive polarity without polarity reversal. The current is ramped at speeds of ± 100 A/S, the value of the current is obtained after a positive ramp without overshoot. After each measurement the current is pulsed to the maximum current of 530 A before coming back to 0 A; thus, the same hysteresis loop is always reproduced for the steel of the yoke.

The measured current differs of less than 1‰ from the theoretical current, and all the measurements are normalized to the theoretical current.

2.4 The mole

The mole used is named “Taupe_38 mm_N°1”. Four coils of its five coil positions are used. The first one gives the absolute signal, while the bucked combination of the four coils give the compensated signal in such a way that the main component (quadrupolar) as well as the dipolar component are suppressed.

The main parameters of the mole are:

Effective length $L = 0.7499$ m

Number of turns $N = 400$

Surfaces	$S_0= 1.67292 \text{ m}^2$ $S_2= 1.67106 \text{ m}^2$	$S_1= 1.66901 \text{ m}^2$ $S_3= 1.67253 \text{ m}^2$
Baricenters	$d_0= 15.307 \text{ mm}$ $d_2= -0.015 \text{ mm}$	$d_1= 7.677 \text{ mm}$ $d_3= -7.619 \text{ mm}$

The following parameters may be deduced (for $0 \leq j \leq 3$), with respect to the four coils:

$$W_j = \frac{S_j}{NL} ;$$

$$\text{Left radius} \quad R_{lj} = d_j - \frac{W_j}{2} ; \text{Right radius} \quad R_{rj} = d_j + \frac{W_j}{2}$$

From these radii the sensitivity coefficients may be calculated:

$$\text{Relative accuracy of the length : } |\varepsilon_L| \leq 1.4 \times 10^{-4}$$

$$\text{Relative accuracy of the surfaces : } |\varepsilon_S| \leq 2 \times 10^{-4}$$

$$\text{Relative accuracy of baricenter } d_0 : |\varepsilon_d| \leq 3 \times 10^{-4}$$

2.5 The integrators

Two digital integrators (AT680-2030) are used.

For the absolute signal, the input impedance is balanced to ground with $2 \times 10 \text{ M}\Omega$ resistances, compatible with the input impedance of the integrators used for the calibration of the mole; the gain is $G_a = 1$.

For the compensated signal, the input impedance is left floating, the gain is $G_c = 100$. Each measurement is resumed three times over clockwise and anticlockwise rotations; thus the offsets, which are regularly checked and readjusted, are theoretically cancelled.

For $I \geq 250 \text{ A}$, the relative accuracy of the main component is:

$$|\varepsilon_a| \leq 1 \times 10^{-3}$$

For $I \geq 250 \text{ A}$, the relative accuracy of the harmonics is:

$$|\varepsilon_c| \leq 5 \times 10^{-3}, \text{ due to the gain of } 100, \text{ this corresponds to an error of } 0.5 \text{ units}$$

(1 unit = 10^{-4} x main field component)

2.6 Harmonic contents

The multipole coefficients (a_n and b_n) are referred to the main field $B_2^{r_o}$ at the reference radius (r_o):

$$B_y + i B_x = \sum_{n=1}^{\infty} (z/r_o)^{n-1} (B_n + iA_n)$$

For the analysis n is limited to 15:

$$B_y + i B_x = B_2^{r_o} \times 10^{-4} \sum_{n=1}^{15} (z/r_o)^{n-1} (b_n + ia_n)$$

$$r_o = 17 \text{ mm}$$

$$b_n = 10^4 B_n / B_2^{r_o} \text{ [unit]}$$

$$a_n = 10^4 A_n / B_2^{r_o} \text{ [unit]}$$

2.7 Magnetic centre

The coordinates D_x and D_y are those of the magnetic axis with respect to the rotation axis of the mole, after averaging over the four longitudinal positions.

The absolute values given in Table 1 cannot be taken into account with respect to the alignment target which was not installed at that time, but the maximum error expected is ± 0.5 mm.

2.8 Magnetic length and central gradient

The MathCad analysis programme computes automatically an equivalent length (l_m) by summing the integral of the main field at the fourth position and corrected by the gap created by different displacements of the mole which do not correspond exactly to the multiple of the mole length.

$$l_m = \frac{\sum_{i=0}^3 (B_2^{(r)})_i \times L + gap \times (B_2^{(r)})_2}{(B_2^{(r)})_2}$$

where $gap = shaft3 + X_1 - 3L$

length of the extension shaft: shaft 3 = 1.4911 m

displacement for the 4th Position: $X_1 = 0.75115$ m

effective length of the mole: $L = 0.7499$ m

For more precision, this equivalent length is corrected by the measured value $(B_2^{(r)})_c$ of the field at the central position, therefore:

$$L_m = \frac{l_m \times (B_2^{(r)})_2}{(B_2^{(r)})_c}$$

The gradient at the centre is given by:

$$\text{Grdc} = \frac{(B_2^{(r_o)})_c}{r_o}$$

The error of the magnetic length is ± 1 mm, the relative error of the gradient is :

$$|\varepsilon_G| \leq 2 \times 10^{-3}$$

2.9 Roll angle

The magnet has been aligned with a telescope by adjusting horizontally the median plane between the upper and lower quadrants of the quadrupole, seen from the non connection side.

The roll angle β_m is that of the magnet with respect to the rotation axis of the mole after averaging over the four longitudinal positions (see figure 1 for the convention of sign).

The absolute values given in table 1 cannot be taken into account, because the offset angle of the mole was not calibrated at that time, but the maximum error expected is ± 1 mrad.

3. MAGNETIC MEASUREMENTS

The magnetization curve $(B_2^{(r_o)})_c = B_2^{(r_o)}(I)$ is given in figure 2. The saturation effect is only sensitive above 450 A and leads to a 2.65 % field drop at 530 A, as expected from ref. 3.

Aperture		
Current (A)	Grdc(T/m)	ABS(Re[B2 (T)])
0.000	0.071	0.0012
100.000	7.840	0.1333
157.600	12.349	0.2099
220.000	17.203	0.2924
267.300	20.878	0.3549
339.200	26.427	0.4493
360.800	28.086	0.4775
381.600	29.697	0.5048
431.700	33.491	0.5693
490.000	37.701	0.6409
530.000	40.106	0.6818

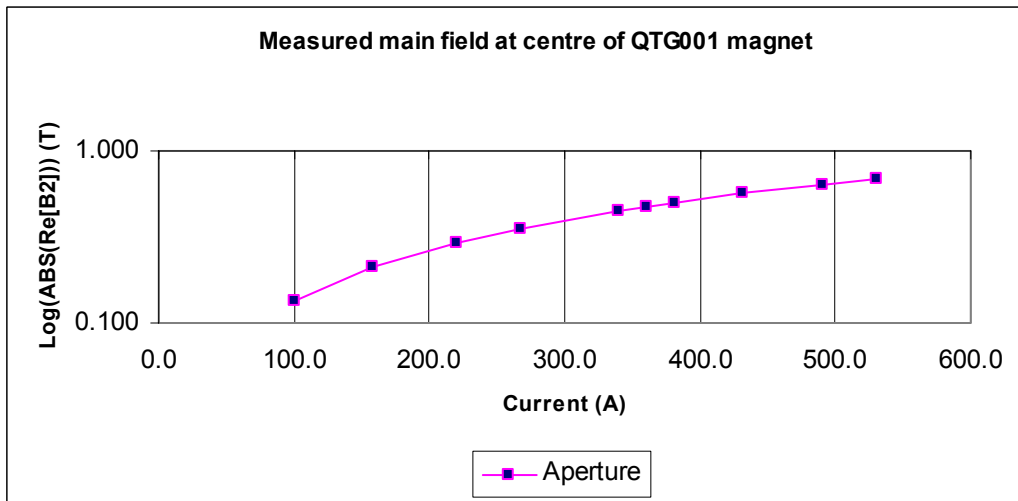
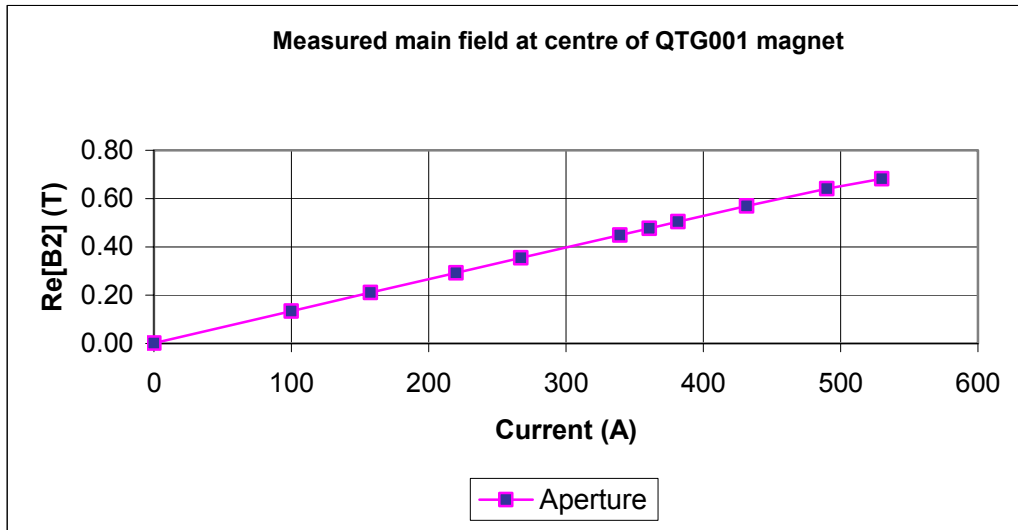


Figure 2 - Magnetization curve

3.1 Result table

The table 1 gives the measurement results with the integral harmonics (normal and skew) expressed in normalized units up to order $n = 15$.

The natural harmonics 6, 10 and 14 are small (lower than 0.6 units even at maximum current) which proves the good design of the magnet. On the other hand several units are measured for the subharmonics, which denote mechanical errors in the assembly of the quadrants.

Magnetic Measurements of QTG001 magnet (28th August 2003) - 5 coils mole

n	Aperture											
	157.6 A		267.3 A		339.2 A		431.7 A		490 A		530 A	
	Re	Im	Re	Im	Re	Im	Re	Im	Re	Im	Re	Im
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	10000.00	0.00	10000.00	0.00	10000.00	0.00	10000.00	0.00	10000.00	0.00	10000.00	0.00
3	2.47	0.86	2.91	0.79	2.93	0.84	2.71	1.23	1.68	1.94	0.43	2.74
4	2.86	0.46	2.74	0.48	2.63	0.48	2.45	0.47	2.32	0.47	2.21	0.47
5	0.80	-0.23	0.83	-0.21	0.84	-0.21	0.81	-0.22	0.74	-0.25	0.64	-0.29
6	-0.33	0.21	-0.37	0.21	-0.37	0.21	-0.43	0.21	-0.52	0.21	-0.61	0.21
7	0.02	-0.03	0.00	-0.02	0.00	-0.02	0.01	-0.03	0.04	-0.05	0.08	-0.07
8	-0.09	-0.06	-0.08	-0.06	-0.08	-0.06	-0.08	-0.05	-0.07	-0.05	-0.07	-0.05
9	-0.06	0.01	-0.06	0.02	-0.06	0.02	-0.06	0.02	-0.06	0.02	-0.05	0.02
10	-0.11	-0.02	-0.11	-0.02	-0.11	-0.02	-0.12	-0.02	-0.13	-0.02	-0.13	-0.02
11	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.01
12	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
14	0.09	0.00	0.09	0.00	0.08	0.00	0.08	0.00	0.08	0.00	0.08	0.00
15	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dx [m] =	2.60E-04		2.64E-04		2.59E-04		2.63E-04		2.64E-04		2.72E-04	
Dy [m] =	4.05E-04		4.05E-04		4.11E-04		4.13E-04		4.15E-04		4.19E-04	
Lm [m] =	2.2108		2.2105		2.2090		2.2075		2.2042		2.2014	
Bm [rad] =	3.08E-04		1.45E-04		1.58E-04		3.60E-05		-1.60E-05		-9.10E-05	
sign =	1		1		1		1		1		1	
Grdc [T/m] =	12.349		20.878		26.427		33.491		37.701		40.106	

Dx(Magnetic center in x direction), Dy (Magnetic center in y direction), Lm (Magnetic length), Bm (Magnetic field direction), sign (Quadrupole sign), Grdc (Field gradient at the centre)

X1=0.75115 m X2=0.75108 m (distance between first and second position of the motor, and between second and third positions, respectively)

4. CONCLUSION

The magnetic measurements confirm the magnetic measurements already undertaken by BINP (Novosibirsk) and the characteristics expected in the design report.

The subharmonics measured ($n = 3,4$ and 5) confirm some mechanical errors measured after the assembly of this prototype. Action will be taken to obtain still better homogeneity curves for the rest of the series.

5. REFERENCES

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