DAΦNE TECHNICAL NOTE

INFN - LNF, Accelerator Division

Frascati, December 2, 1994

Note: **MM-4**

MEASUREMENTS ON TESLA QUADRUPOLE PROTOTYPE FOR THE DAΦNE ACCUMULATOR AND MAIN RINGS

B. Bolli, F. Iungo, M. Modena, M. Preger, C. Sanelli,
F. Sgamma, M. Troiani, S. Vescovi

1. INTRODUCTION

The first prototype of the Accumulator quadrupole, built by TESLA Engineering, Water Lane, Storrington (U.K.) has been delivered to LNF on June 21, 1994. It was immediately realized that the mechanical reference holes had been wrongly placed on the magnet joke. We decided to proceed anyway to measure magnetic, electric and thermal properties of the magnet, leaving the check on alignment tolerance on a corrected version of the prototype. We recall in Table 1 the main parameters of the quadrupole magnet.

Table 1 - Prototype quadrupole parameters

Nominal Gradient (Tesla/m)	8.06
Maximum Gradient (Tesla/m)	12.07
Magnet Bore Diameter (mm)	100
Pole shape	Hyperbolic + Straight line
Good field region (mm)	30
Field quality (ΔB/B)	$\leq 5\times10^{-4}$
Magnetic length (mm)	300
Turns per pole	32
Conductor Size (mm^2)	8x8
Coolant hole diameter (mm)	5
Current density (A/mm^2)	5.9
Nominal current (A)	261.1
Maximum current density (A/mm^2)	10.73
Maximum current (A)	473
Magnet Resistance (@20°C, mΩ)	43
Magnet Inductance (mH)	10.8
Nominal Voltage (V)	11.2
Maximum Voltage (V)	20.4
Nominal Power (kW)	2.9
Maximum Power (kW)	9.65

2. ELECTRICAL MEASUREMENTS

The resistance of the quadrupole has been measured by means of a micro-ohm-meter, finding 43.3 mΩ at 22.5 °C, corresponding to 42.9 mΩ at 20 °C; in addition, we used the Volt-Ampere method, measuring the voltage across the magnet at the nominal and maximum currents. We measured:

- 11.45 V @ 261 A, corresponding to 43.9 mΩ; this value was obtained at a room temperature of 22.5 °C and water inlet temperature of 22.2 °C; this corresponds to an average temperature increase $\Delta T \approx 3$ °C.

- 20.95 V @ 473 A, corresponding to 44.3 mΩ; the average temperature increase is $\Delta T \approx 6$ °C.

These values are in good agreement with Tesla's design value (46 mΩ) and measurement (42 mΩ) @ 20°C.

The resistance and the inductance of the quadrupole have been measured at different frequencies by means of a LCR meter HP4284A. The results are shown in figure 1. The corresponding dc values can be estimated from these data. They are consistent with the design and measured data.

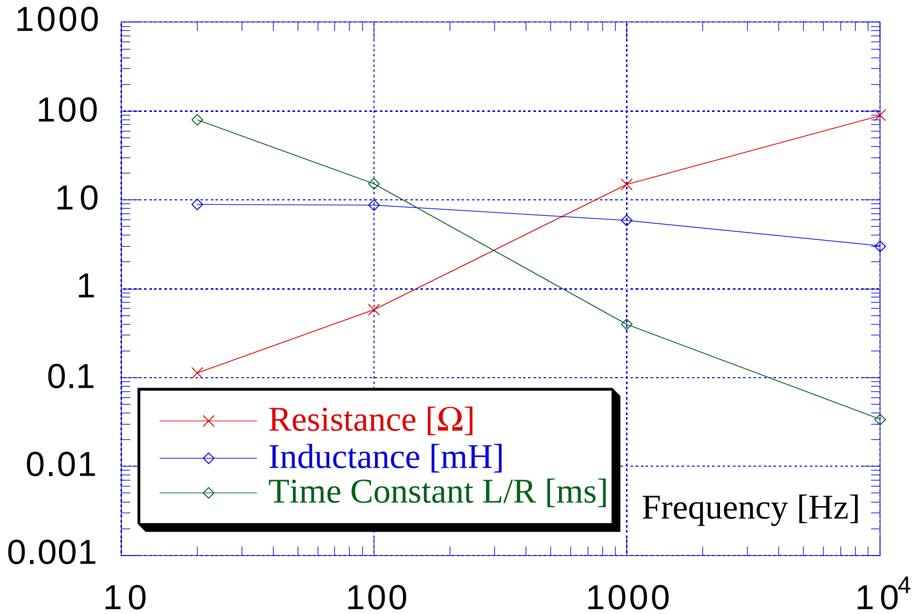

Figure 1 - Resistance, inductance and time constant versus frequency

3. HYDRAULIC AND THERMAL MEASUREMENTS

The hydraulic and thermal measurements have been performed at both the nominal and maximum specified currents. Table 2 shows the results.

Table 2 - Hydraulic and thermal characteristics

Excitation current (A)	261	473
Water flow (l/s)	0.07	0.147
Water inlet temperature (°C)	22.2	22.2
Water outlet temperature (°C)	27.3	34.0

The time needed to arrive at thermal stabilization is 10 minutes and 15 minutes at 261 A and 473 A respectively.

The pressure drop has not been measured due to the lack of a suitable pressure gauge on the quadrupole hydraulic circuit.

3. MAGNETIC MEASUREMENTS

The gradient of the quadrupole has been measured as a function of the current by means of a Hall probe mounted on the Micro Controle coordinatometer of the magnetic measurement laboratory[1]. The result is shown in Figure 2. The behavior is linear up to 300 A, corresponding to ≈9.4 T/m. The "nominal" working point has been set to 262.28 A (260 A on the power supply reference), and the measured gradient is 8.118 T/m, in very good agreement with the calculated value set in the Specification[2]. The "maximum" gradient is 12.075 T/m at a current of 402.78 A (400 A on the power supply reference). The current given by the tridimensional code to obtain the same gradient was ≈15% higher than the measured value.

A rough estimate of the field quality at the magnet center has been performed with this system, which looked immediately cumbersome, due both to the alignment problems related to the mistake in the reference holes and to the accuracy of the measurement system, hardly sufficient to assess the required tolerance of 5×10^{-4}, corresponding to ≈1 Gauss at the nominal good field radius of 30 mm. However, the result of the measurement showed that there were no large deviations from the ideal quadrupole field. The system has already been improved with a new mechanical table and completely re-checked to match the requirements of the magnetic measurements on the dipoles.

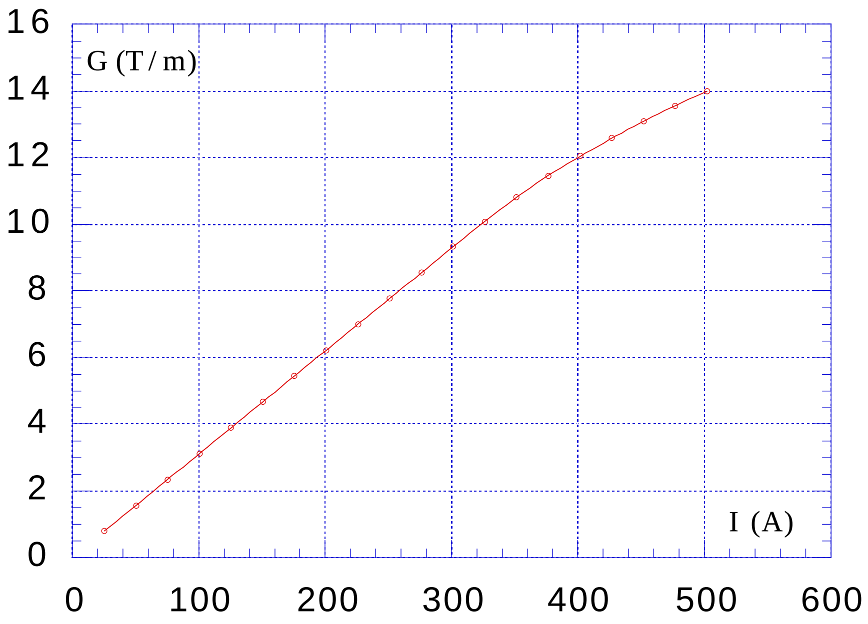

Figure 2 - Quadrupole gradient as a function of excitation current

With the Hall probe system the magnetic field as a function of the longitudinal position has also been measured to compare the magnetic length with the calculated one.

Figure 3 shows the result at the nominal gradient at different horizontal positions on the horizontal symmetry plane, obtained by subtracting from any measured field value the corresponding one measured on the magnet axis to correct for the slight misalignements due to the above described reasons (the field measured on axis never exceeded 7 G, corresponding to less than 0.1 mm).

Figure 4 shows the same measurement at the maximum gradient.

The magnetic length, defined as the field integral divided by the field at the magnet center, does not depend on the distance from the axis within 0.2% and is 301.8 mm at the nominal working point and 299.1 mm at the maximum one.

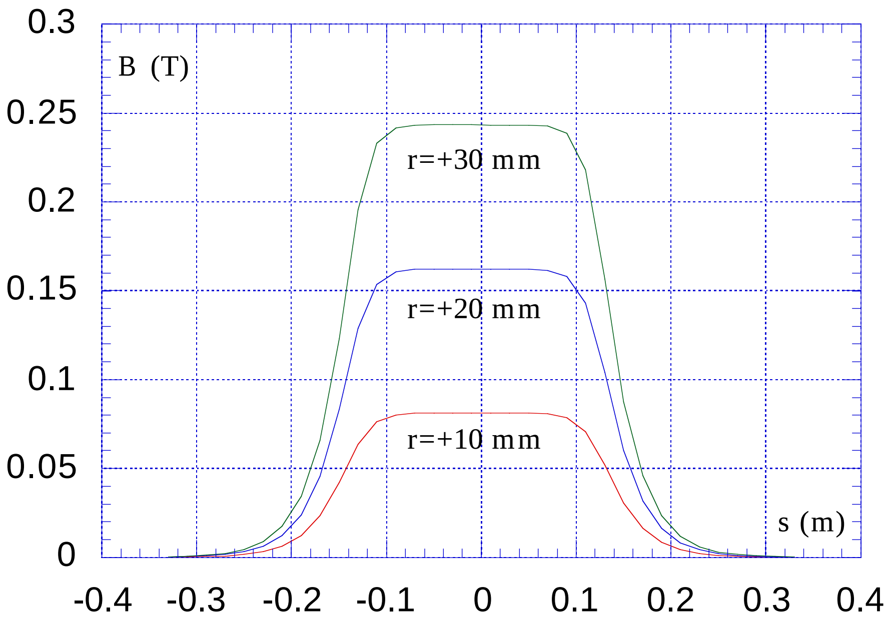

Figure 3 - Quadrupole magnetic field along the longitudinal coordinate at different horizontal positions before chamfer (8 T/m)

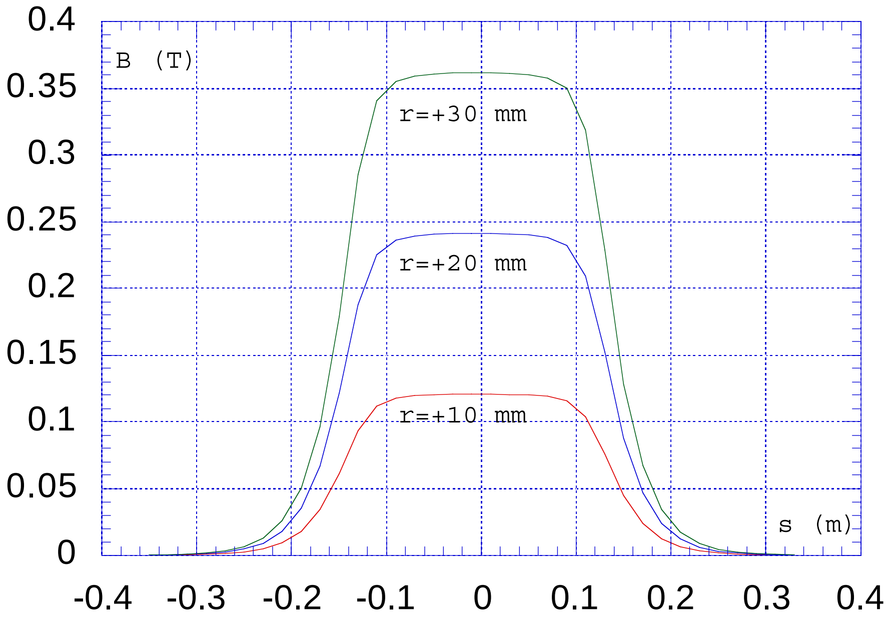

Figure 4 - Quadrupole magnetic field along the longitudinal coordinate at different horizontal positions before chamfer (12 T/m)

A first investigation with the Danfysik rotating coil system showed high order multipole contributions coming from 6-pole (2.3×10^{-4} @ 30 mm), 8-pole (0.8×10^{-4}) and 12-pole (12.9×10^{-4}). All other terms, including 20-pole, were negligible. Figure 5 shows the radial and azimuthal components of the field error, together with their vector sum over a full coil revolution.

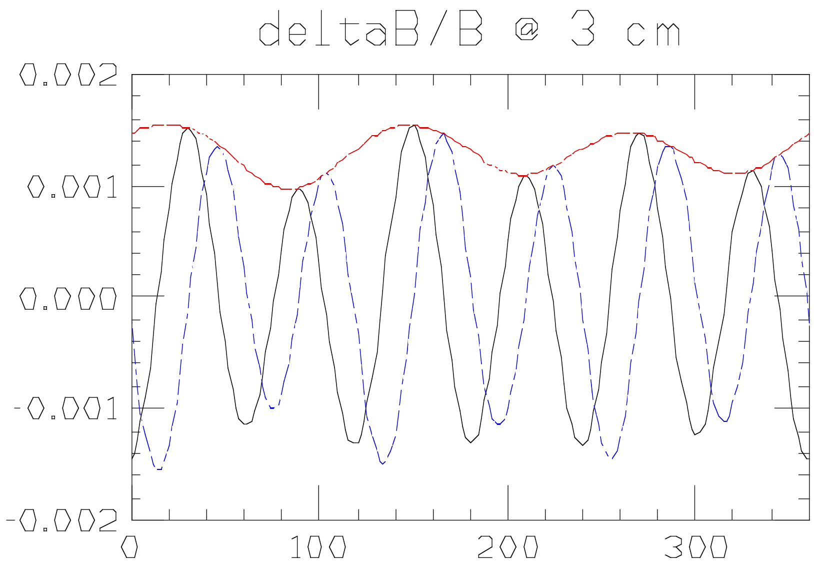

Figure 5 - Quadrupole field error at 30 mm from the center before chamfer (8 T/m)

Since the main contribution came from the 12-pole, at an amount quite similar to the one expected from the fringing field contribution only[3], we proceeded to chamfer the removable pole tips, making a straight cut at 45 degrees of increasing depth.

Figure 6 shows the behavior of 6-pole, 8-pole, 12-pole and 20-pole as a function of the chamfer (defined as the straight edges of the triangle cut away from the pole end cap cross-section) at the nominal working point, while Figure 7 is the same at the maximum gradient. The 12-pole drops linearly with the chamfer, while the other terms keep remarkably constant. The result of the chamfering procedure was that a 10 mm chamfer was the right one to bring the 12-pole contribution below 10^{-4}, the main contribution to the overall error now coming from the 6-pole term.

Figure 8 shows the error field components at 30 mm from the axis, measured with the rotating coil @ 8 T/m, while Figure 9 is the corresponding one @ 12 T/m.

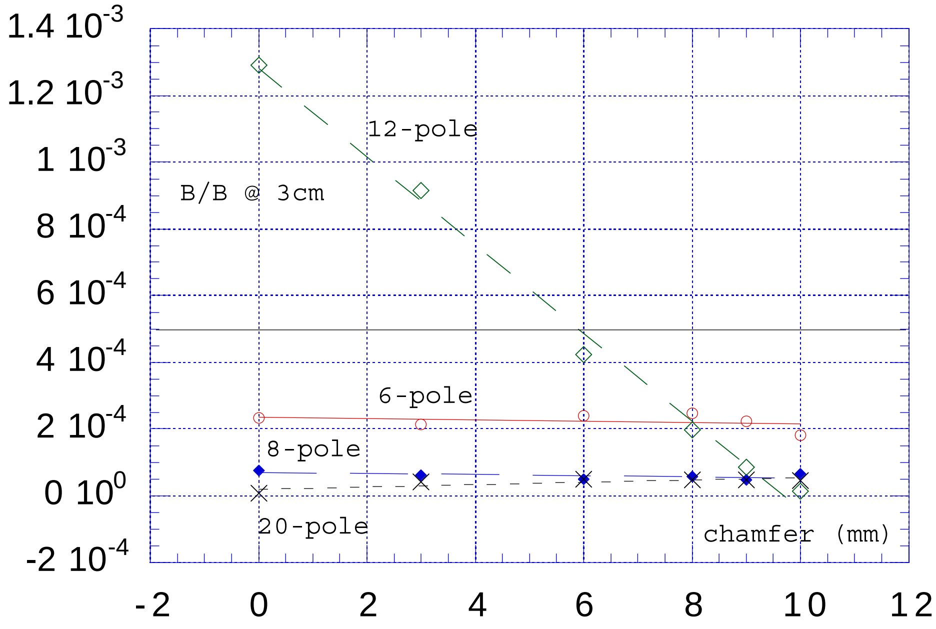

Figure 6 - Multipole contributions to the quadrupole field error as a function of the chamfer (@ 8 T/m)

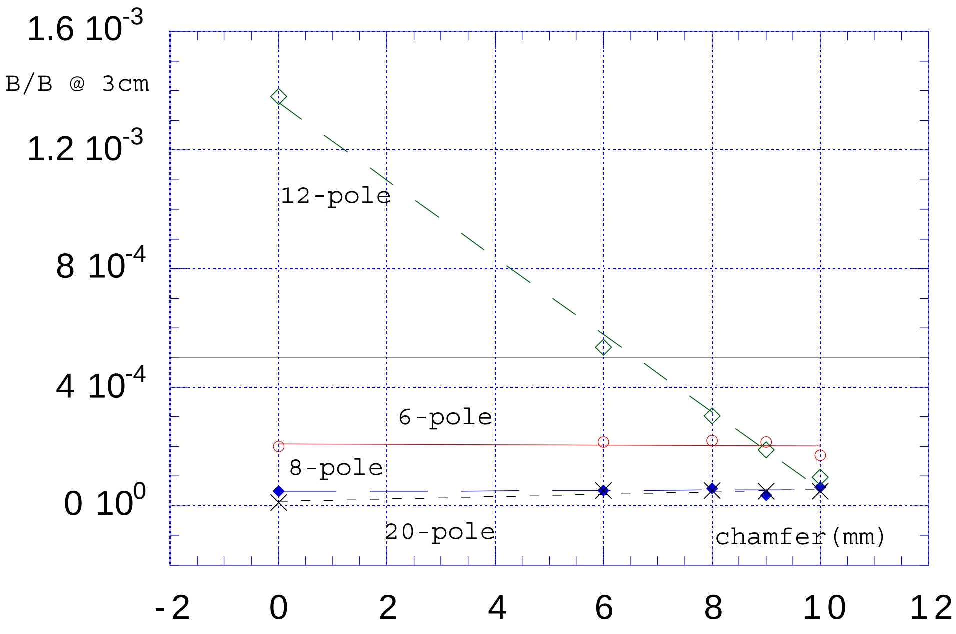

Figure 7 - Multipole contributions to the quadrupole field error as a function of the chamfer (@ 12 T/m)

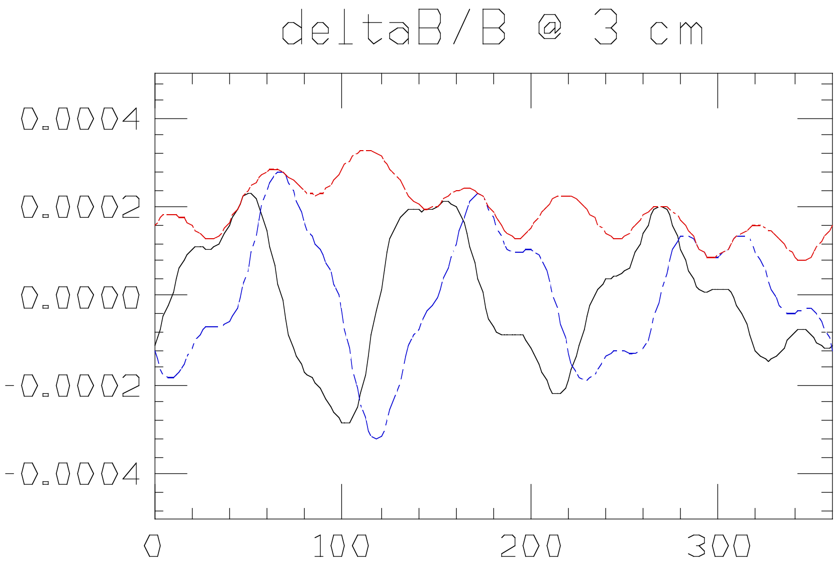

Figure 7 - Quadrupole field error at 30 mm from the center after chamfer (@8 T/m)

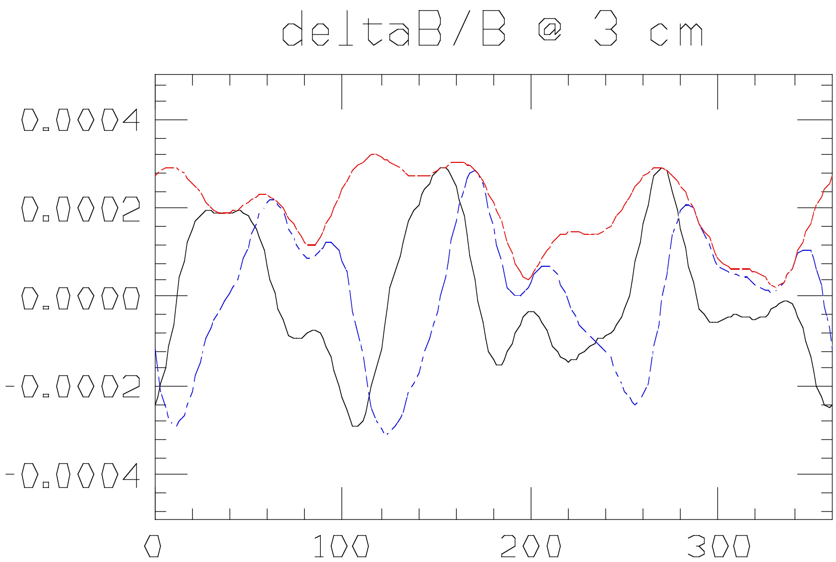

Figure 9 - Quadrupole field error at 30 mm from the center after chamfer (@12 T/m)

Of course, it was necessary at this point to measure the magnetic length again. Figures 10 and 11 show the results of the measurement on both the nominal and maximum working points. The measured magnetic length was now 295.9 mm at 8 T/m and 293.6 mm at 12 T/m.

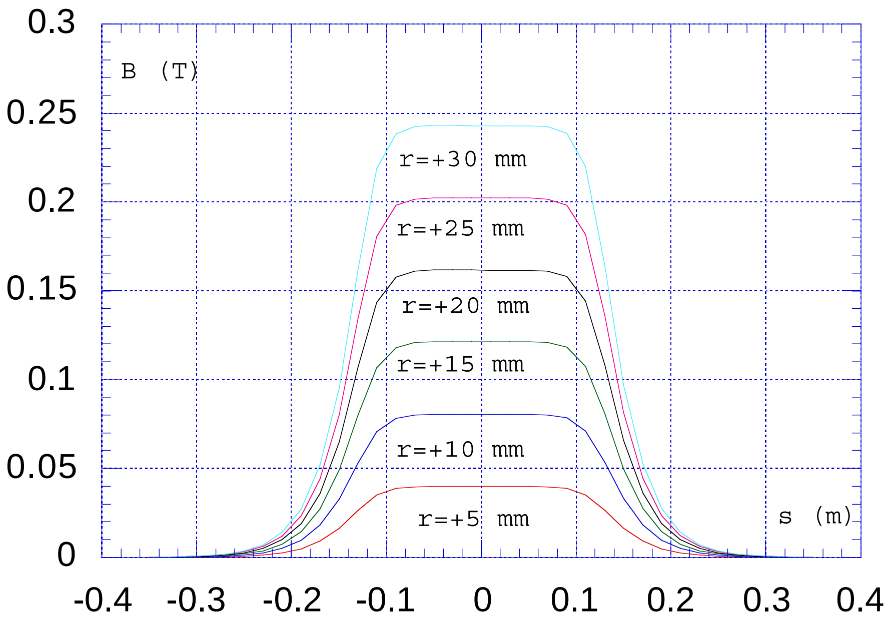

Figure 10 - Quadrupole magnetic field along the longitudinal coordinate at different horizontal positions after chamfer (@ 8 T/m)

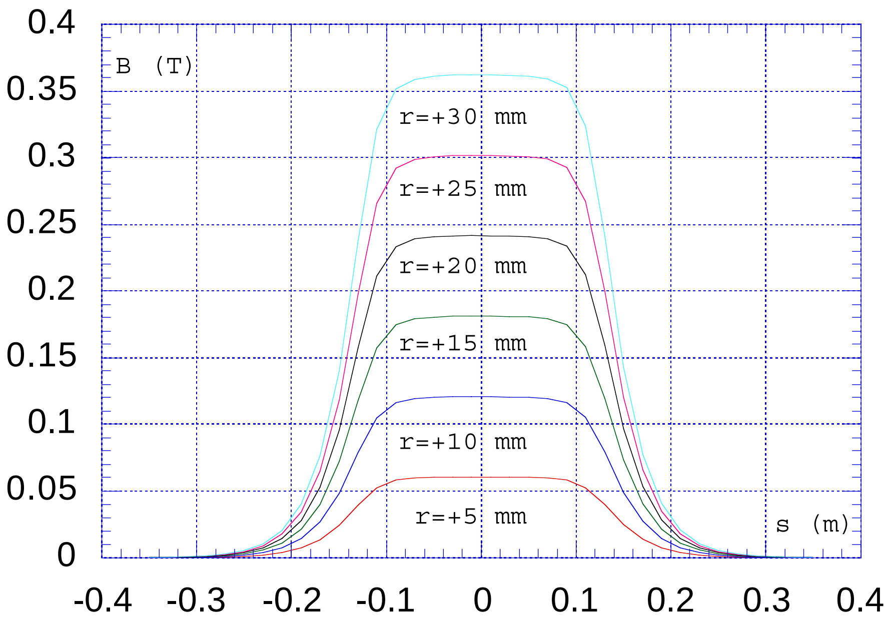

Figure 11 - Quadrupole magnetic field along the longitudinal coordinate at different horizontal positions after chamfer (@ 12 T/m)

As a last check, the quadrupole was measured with the rotating coil, opened, the upper part taken away with a crane, closed and measured again. The sextupole term practically disappeared, demonstrating that the magnet was not closed properly before shipping. The overall error field at 30 mm from the axis was now measured to be within 1.2×10^{-4}, well below the specification. Figure 12 shows the final result of the rotating coil measurement.

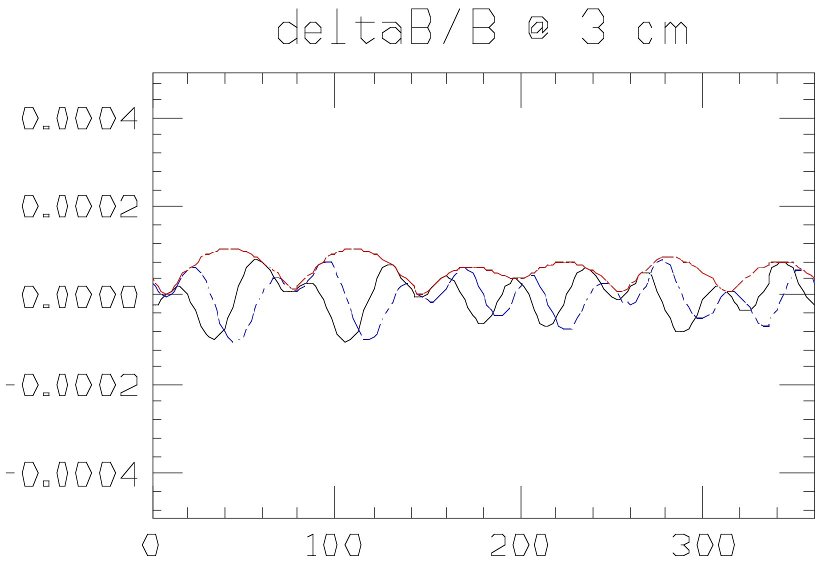

Figure 12 - Quadrupole field error at 30 mm from the center after opening and closing the magnet (@ 8 T/m).

4. CONCLUSIONS

The electrical, hydraulic and magnetic measurements performed on the quadrupole magnet have demonstrated that the prototype fully satisfies the Specification. In particular, the integrated gradient quality is ≈5 times better than the requirement for the DAΦNE Accumulator. This result makes us confident that this magnet is suitable for use in the collider Main Rings.

Unfortunately, the mistake on the reference holes did not allow us to check the distance of the magnetic center with respect to the mechanical one. For this reason the prototype itself has been rejected and the vendor asked to deliver a second magnet to LNF for testing.

REFERENCES

[1] F. Iungo, M. Modena, Q. Qiao, C. Sanelli, "DAΦNE magnetic measurements systems", DAΦNE Technical Note MM-1 (4/11/1993).

[2] "Specifications for Electron-Positron Accumulator - DAΦNE Project" - Specification No. AR-00.15-SP01-4-B.

[3] W.V. Hassenzahl, "An algorithm for eliminating the duodecapole component in quadrupole magnets".