DAΦNE TECHNICAL NOTE

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MEASUREMENTS ON THE WIGGLER MAGNET FOR THE DAΦNE MAIN RINGS

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ABSTRACT

This paper describes the electrical, mechanical and magnetic measurements made on the prototype 1.8 Tesla wiggler magnet for the DAΦNE Main Rings, built by the Danish Company DANFYSIK, in order to verify the accuracy of the magnetic calculations, the end pole design and the multipole content of the integrated magnetic field.

1. INTRODUCTION

DAΦNE, an electron-positron colliding beam facility at the Φ energy (1.02 GeV c.m.), is currently under construction at INFN's Frascati National Laboratory. The accelerator complex consists of two storage rings, an intermediate accumulator ring for injection, an electron/positron linac and transfer lines.

Four wiggler magnets are needed in each storage ring to improve radiation damping. The magnet is of the iron core electromagnetic type, with a maximum magnetic field on axis of 1.8 T, and a 40 mm gap. In order to match ring lattice requirements, the structure is composed of 5 full poles and two half poles at the magnet end. The wiggler half period, namely the distance between two successive full pole centers is 320 mm.

In order to verify the validity of the magnetic design, accomplished by means of 2-D and 3-D codes, a full size prototype has been built by DANFYSIK. A complete set of electrical, mechanical and magnetic measurements has been carried out and the results, which put in evidence a few inconveniences to be corrected for the series production, are described in the following.

2. ELECTRICAL MEASUREMENTS

A first set of electrical measurements has been performed connecting all the coils of the full poles and half poles in series. The results agree with the design values with the following deviations :

- 1.8 T magnetic field has been reached on the mid plane of the central pole at a current of 702 A, while the value obtained from the 3-D simulation is 675 A.

- The resistance of the electric circuit is a little higher than the design value, so that some small changes have been made on the characteristics of the power supplies for the final configuration.

Table I lists the main parameters of the wiggler prototype.

The resistance and the inductance of the two electrical circuits, full poles and the half poles respectively, have been measured at different frequencies by means of a LCR meter HP4284A. The results are shown in Figs. 1 and 2. Figure 3 shows the variation of the time constant L/R as a function of frequency. The corresponding d.c. values can be estimated from these data. They are in good agreement with the design values.

TABLE I
Parameter list for the wiggler prototype

Nominal Field (Tesla)	1.8
Magnetic Period Length (mm)	640
Number of periods	3
Magnet Gap (at pole center, mm)	40
Turns per Pole	80
Conductor Size (mm^2)	7*7
Coolant Hole Diameter (mm)	4
Nominal Current Density (A/mm^2)	18.69
Nominal Current (A)	702
Ten "Full Pole" Resistance (mΩ) (series connected and @ 60 °C)	406
Four "Half Pole" Resistance (mΩ) (series connected and @ 60°C)	131
Ten "Full Pole" Inductance (mH)	94
Four "Half Pole" Inductance (mH)	22
Ten "Full Pole" Voltage (V)	285
Four "Half Pole" Voltage (V)	92
Ten "Full Pole" Power (kW)	200
Four "Half Pole" Power (kW)	64.5

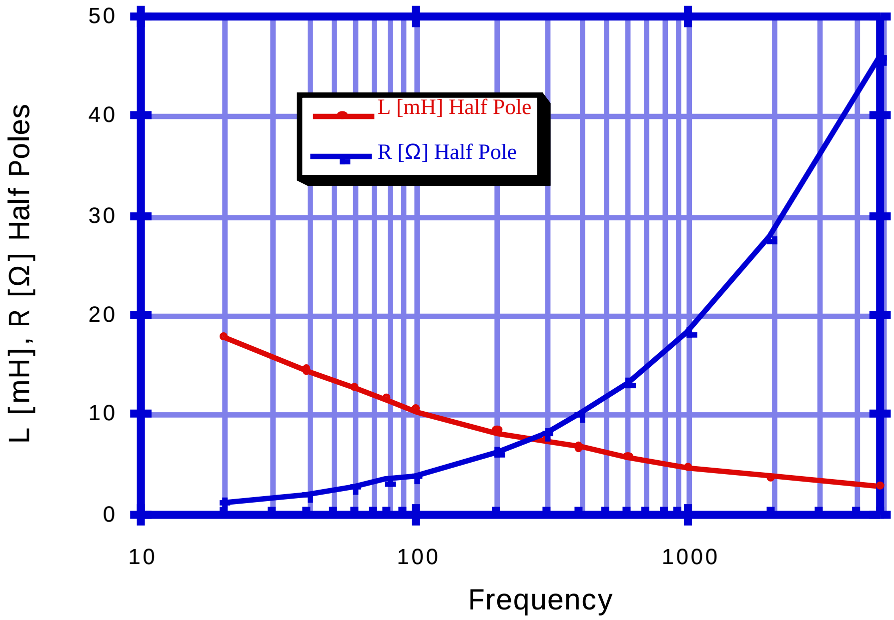

Fig. 1 - Half Poles circuit, Inductance and resistance versus frequency

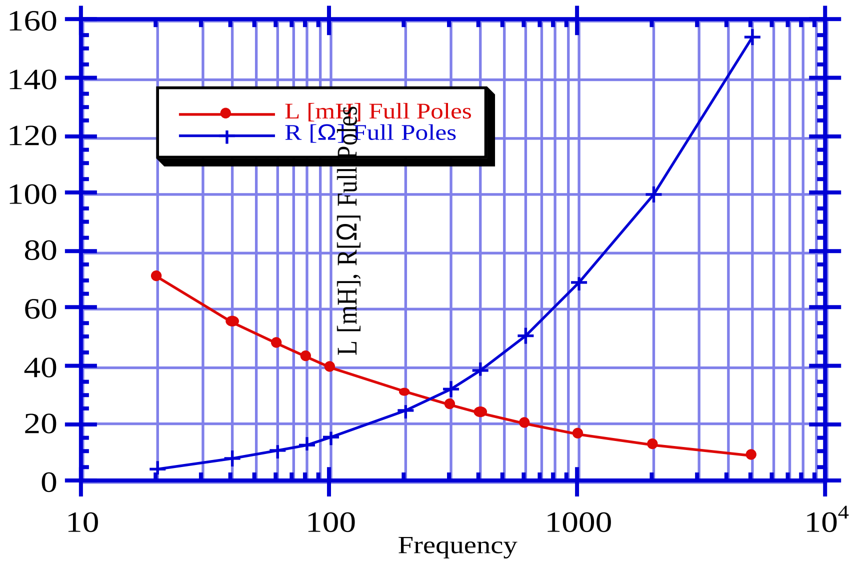

Fig. 2 - Full Poles circuit, Inductance and resistance versus frequency

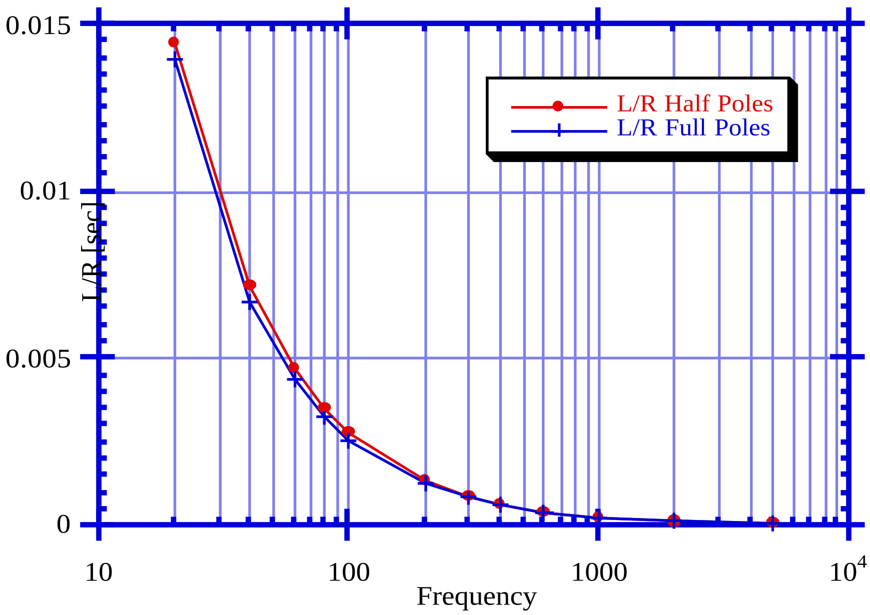

Fig. 3 - Time constant L/R for the Half Poles and Full Poles circuits versus frequency

3. HYDRAULIC AND THERMAL MEASUREMENTS

Each coil of the magnet, full pole and half pole, has five hydraulic circuits in parallel, and all coil circuits are hydraulically in parallel.

The hydraulic and thermal measurements have confirmed the design values. Table II lists the main parameters.

TABLE II
Cooling system parameters

Full pole coil total water flow (lt./min.)	10
Half pole coil total water flow (lt./min.)	11.5
Cooling water pressure drop (bar)	4.5
Cooling water inlet temperature (°C)	20
Cooling water temperature rise (°C)	19

All hydraulic circuits are connected to the same manifolds, and in order to equilibrate the difference in hydraulic impedance among the full pole circuits and the half pole circuits, the hole of the hoses of the half pole circuits have been narrowed from 3 to 1.5 mm diameter. This reduction has given some problems in water flow, so that we have decided to change the manifolds in such a way that no occlusion can arise in the final version of the device.

4. MECHANICAL MEASUREMENTS

The mechanical measurements have evidenced the following problems and suggested the relative correction actions:

- The initial three jacks support scheme gave an asymmetrical deformation between the two ends of the magnet. The final support will therefore have four jacks and in addition, due to the particular support structure, will keep the horizontal plane of symmetry unchanged. This is the preferred solution from the alignment point of view.

- The gap between the poles, without magnetic field, varies between 40.12 mm and 40.17 mm (the measurement was performed using Johnson blocks).

- The two reference planes on the extreme sides of the top yoke look not well finished and their position cannot be used as a fiducial: their distances from the pole surfaces are different by 0.2 mm and their inclinations are different both with respect to the pole surfaces and between themselves (they have an opposite inclination, larger than 0.16 mm/m, along the magnet longitudinal axis and towards the pole surfaces: they are pitched outwards). Better machining of these reference planes will be required for the series production.

- The attractive force produced by the magnetic field reduces the gap by 0.35 mm (with a standard deviation of 0.05 mm), as predicted by the 3-D simulation, and corresponds to about 34 tons. The vertical parts of the four lateral C supports, directly supported by the four jacks, don't move (negligible compression): the yoke movements are due to the combination of bending and rotation of the C supports.

5. PRELIMINARY MAGNETIC TESTS

Before starting with the detailed investigations of the wiggler magnetic field, the following preliminary tests have been carried out :

- The two available Hall Probes, a Bruker B-H15B Teslameter and Group 3 DTM-141 Digital Teslameter, have been calibrated against a NMR, Metrolab PT2025. Figure 4 shows the comparison between the three devices, The relative error in the full range 0-1.8 T of the Bruker Hall Probe, that used for the field mapping, varies from -1 to 4 Gauss. The error of the Group 3 teslameter is a little larger than the Bruker, probably because of the necessity of recalibrating the probe when the meter scale is changed.

- Load curves of the central pole and end poles, connected in series, shown in Fig. 5.

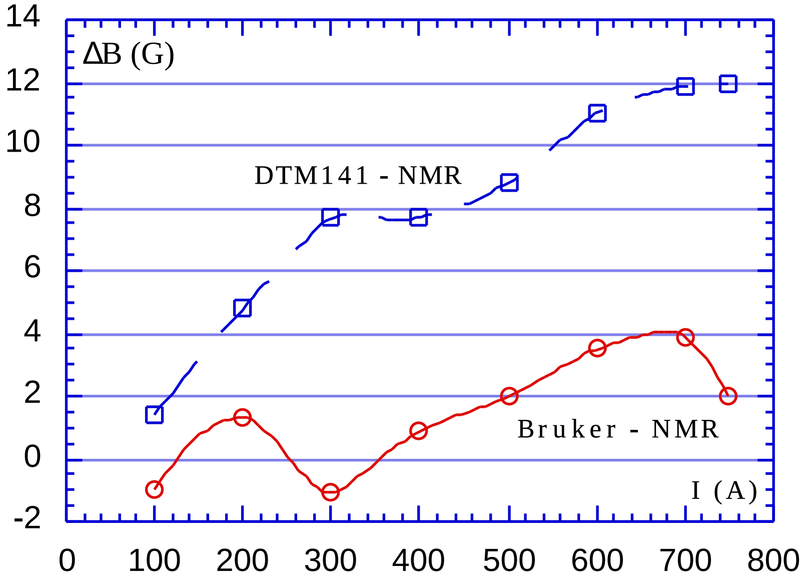

Fig. 4 - Bruker-Group 3 DTM141 Hall probes comparison with NMR

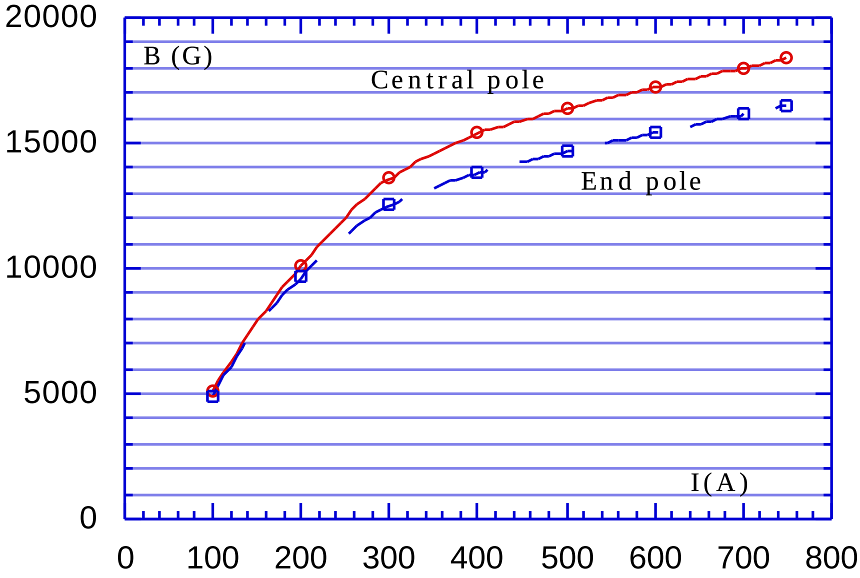

Fig. 5 - Central and end pole excitation curves

- The residual magnetic field has been measured and it is ≈23 G maximum.
- The fringing field all around the magnet has also been measured: at a distance of 0.5 m it is less than 10 G.

6. TEST OF POWER SUPPLIES

At this point of the measurements, the coils of the end poles have been powered by means of two independent power supplies. Figure 6 shows schematically the test situation. Note that in Fig. 6 the connections of the full poles coils are the same as in the final configuration.

- Measure of the induced voltage. As can be seen from Fig. 6 the end pole is magnetically coupled to the nearby full pole. This means that in the case of fault of one of the two power supplies a voltage will be induced on the other proportional the mutual inductance. This induced voltage has been measured and is ≈ 5.6 V, which for one time constant and 700 A, gives a mutual inductance of 2.4 mH. This induced voltage can be easily born by the other power supply.

Many problems arose from the "small" power supply, but nevertheless we have been able to complete the prototype wiggler mapping. This power supply has been shipped back to the builder to be repaired and modified.

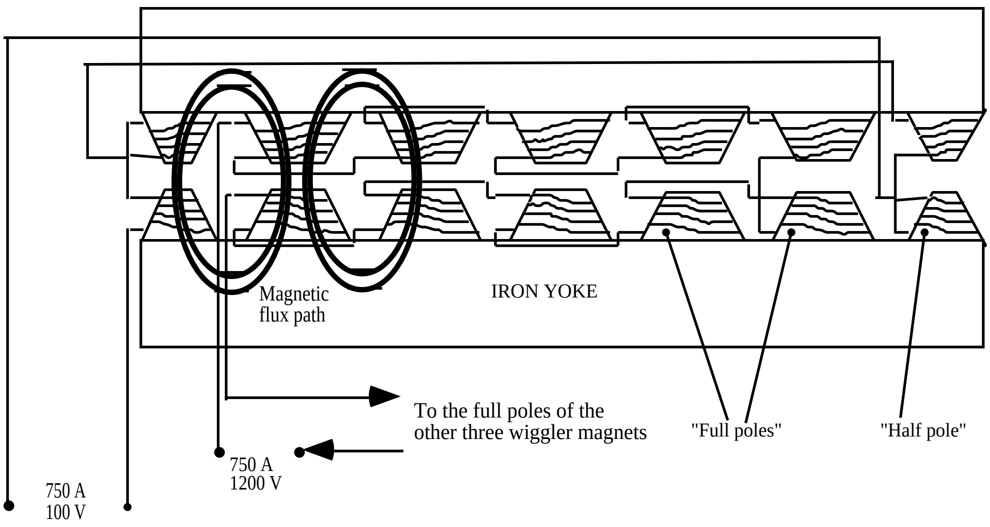

Fig. 6 - Wiggler magnet layout and connections

7. ROTATING COIL SYSTEM

A first set of magnetic measurements has been made by a continuously rotating coil. This system was developed to measure the Adone superconducting wiggler in 1988. The coil length is 3m, the width 15.6 mm, the number of turns 494. The measurements have been performed at 1 Hz revolution frequency.

The aim of this kind of measurement is to find rapidly the end pole current for which the integral of the magnetic field vanishes. In addition, by looking at the higher harmonics of the voltage signal from the coil, one can give a first rough estimate of the integrated multipoles.

The voltage induced in the coil was observed by means of an oscilloscope and a spectrum analyzer. Changing the current in the end poles at fixed full poles excitation, one should find a minimum in the peak induced voltage, and ideally this minimum should be zero when the field integral on axis vanishes. Unfortunately our observed minimum voltage was rather large, corresponding to ≈45 G.m. The most reasonable explanation for this effect is a "twist" of the coil. We have estimated that ~1 degree twist over 3 m coil length could give the observed result.

The minimum voltage signal, with 1.8 T under the central pole (corresponding to 712 A in the coils of the central pole), was obtained with a current of 573 A in the coils of the end poles. Fig. 7 shows the end pole current delivering the minimum coil signal as a function of the full pole current, together with the field under the center pole and the value of the minimum coil signal.

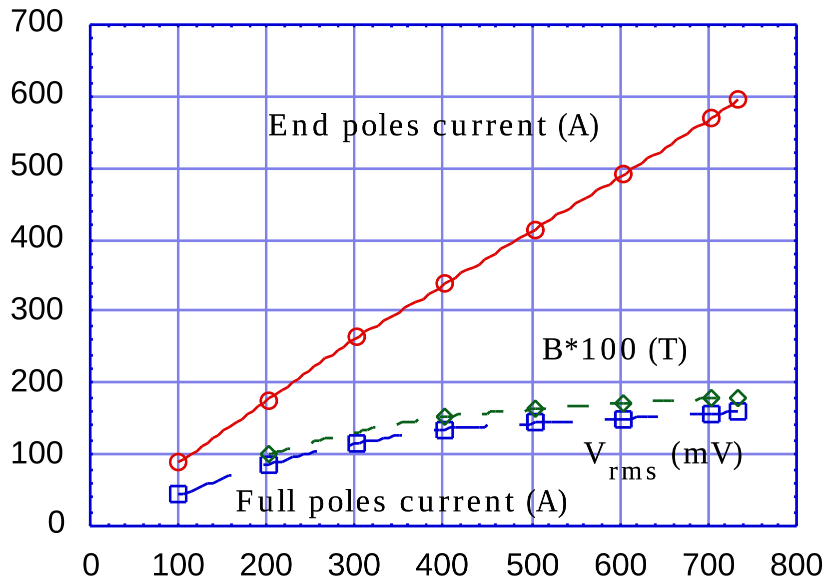

Fig. 7 - Measurements with rotating coil

The voltage signal has been analyzed also by a FFT and the higher order terms, the most important being an integrated sextupole at 3 Hz, have been recorded. The observed amplitude was (6±1) mV, corresponding to an integrated sextupole:

$$\int \frac{\partial^2 B}{\partial x^2}\, ds = (5.8 \pm 1.2)\ T/m$$

8. HALL PROBE SYSTEM

Also this system was developed to measure the Adone super conducting wiggler in 1988. It is basically a Hall probe device mounted on pneumatically suspended carriage in a reference guiding box. A bronze ribbon moves the carriage and an encoder reads the probe longitudinal position during field mapping. The probe can be moved by ±30 mm horizontally and ±5 mm vertically on the carriage in 5 mm steps to measure the magnetic field outside the wiggler axis. The probe displacement can only be performed after completely extracting the carriage from the box. The resolution of the encoder on the longitudinal position is 0.1 mm. The Hall probe and acquisition system is the above mentioned Bruker B-H15 B Teslameter.

The main difficulties faced in using this system were:

- Errors on longitudinal Hall probe positioning larger than 0.1 mm: these errors have been corrected via software by means of a correction loop.

- "Locked" field readings: sometimes, varying the Hall probe longitudinal position and therefore the magnetic field value, the Bruker system didn't show any change in the measured field. This problem has been solved via a software-hardware correction: at any Hall probe reading, the program checks if the result is equal to the last one and, if there is no field variation, resets the Bruker Teslameter, and starts the measurement again.

- Unreasonable longitudinal position: occasionally the encoder electronics sends an unreasonable value for the longitudinal position of the Hall probe. We have checked that it is not a transmission error because the wrong reading does not change if one repeats it a second time. Probably there is a problem on the encoder electronics, which has not jet been solved.

With this system we performed the following field longitudinal scans:

- on the horizontal symmetry plane;
- on an horizontal plane shifted vertically by +5 mm;
- on an horizontal plane shifted vertically by -5 mm;
- with the Hall probe rotated by 180°;
- on both longitudinal directions ("in" and "out").

Due to mechanical constrains, it is impossible to rotate the Hall probe by 90° to measure the horizontal field components.

The field integral on axis has been compensated at 1.2 T, 1.5 T and 1.8 T. The current value of the end coils that makes the integral vanish (at 1.8 T under the central pole, with 713 A from the main power supply) has been found to be 562 A, very near to the value obtained by means of the rotating coil system.

The average time for a single longitudinal scan is ≈ 30 minutes. 53 scans, 140 points each (corresponding to 20 mm steps) have been recorded.

9. FIELD MEASUREMENTS WITH THE HALL PROBE

Fig. 8 shows a typical longitudinal scan with compensated field at the nominal maximum field of 1.8 T.

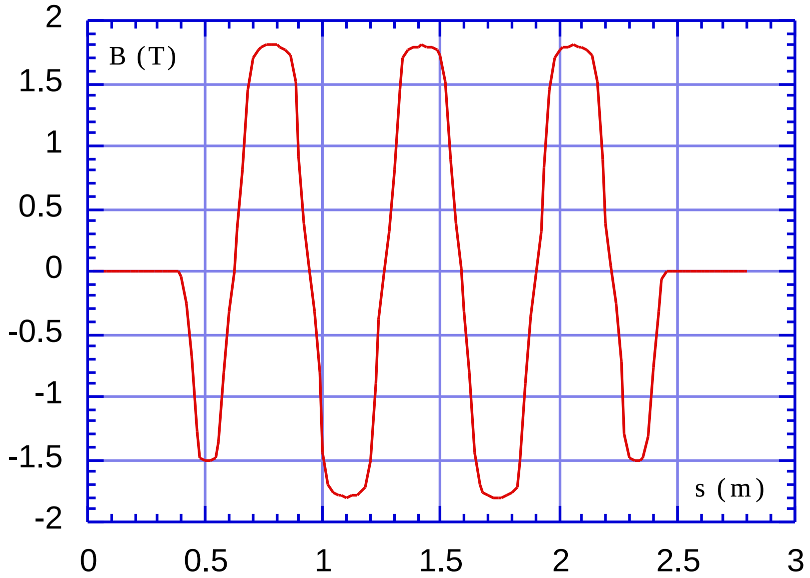

Fig. 8 - Vertical field component on the wiggler axis

By summing up the measured field values times the 20 mm step between successive measurements we get the field integral and find the end pole current for perfect compensation. Care has been taken in setting the initial position of the probe in such a way that the 70th point (there are 140 points interleaved by 20 mm) falls exactly in the center of the wiggler. Taking several scans in the same conditions, we have found a repeatability in the field integral of ≈±1 Gm, which we assume as a standard error for the following considerations. We have also checked that the field integral is not sensitive to small shifts of the initial position and to the integration method, by comparing the result with that obtained from a fine interpolation of the measured points, the difference being less than 0.1 Gm.

Figure 9 shows the compensation curves, namely the field integral as a function of the compensation current, at maximum fields near 1.8 T (with 712.8 A in the full poles), 1.5 T (382.6 A) and 1.2 T (251.8 A). Comparing with Fig. 7, one can see that the compensation with the rotating coil method was accurate within ≈10A in the end pole current.

The field integral @ 1.8 T has been measured as a function of the horizontal displacement with respect to the wiggler axis. Figure 10 shows the measured points, interleaved by 10 mm, up to 20 mm on the power connections side and up to 30 mm on the other. It was not possible to measure at 30 mm on both sides because of a mechanical constraint due to the air feed tube necessary to suspend the Hall probe carriage. The experimental points are fitted with a second order polinomial, and the fit value for the integrated sextupole term is -2.2 T/m, more than two times smaller than the result obtained from the rotating coil.

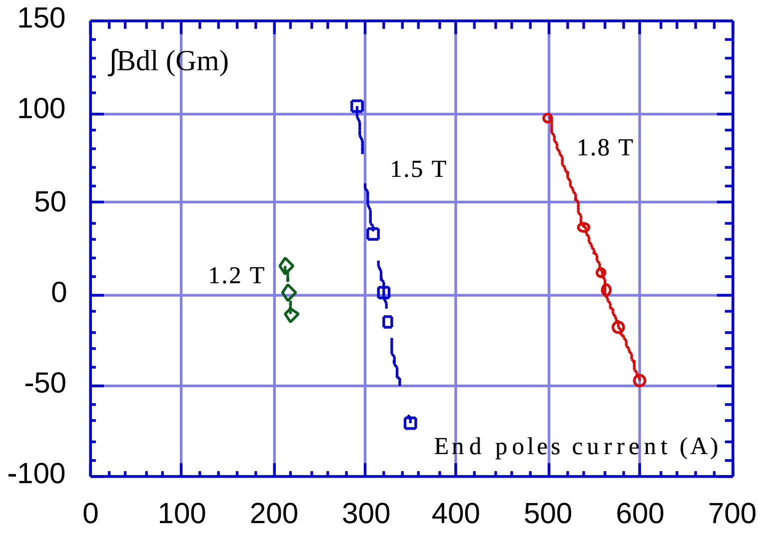

Fig. 9 - Compensation curves @ 1.2, 1.5, 1.8 T

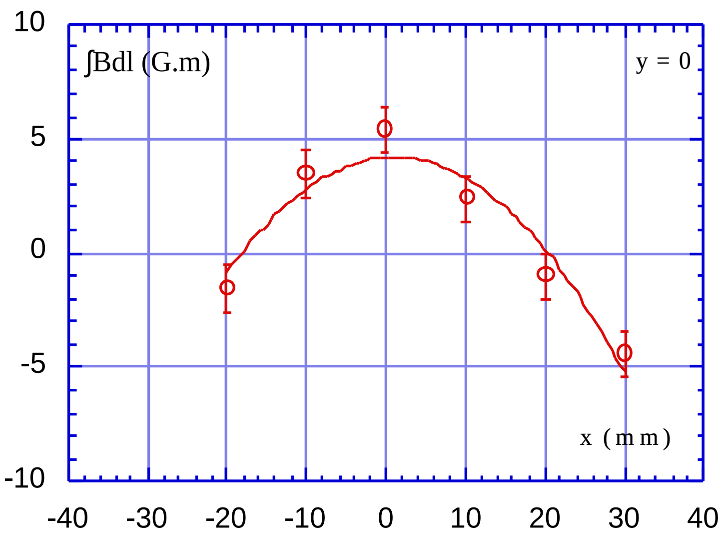

Fig. 10 - Field integral as a function of horizontal position on the wiggler symmetry plane

Figure 10 clearly shows that the experimental error on the field integral is such that the error on the sextupole term is quite large. In order to have an independent estimate we can use the second order fit of the points measured at the center of the single poles, where the measurement is almost independent of the longitudinal position of the probe, multiply each sextupole term by the magnetic length of the pole (defined as the pole field integral divided by the maximum field), and sum up the seven contributions. The result is -1.9 T/m, in good agreement with the above mentioned value. Table III shows the fitted sextupole term and the magnetic length for each pole. Figure 11 shows the behaviour of the vertical field at the center of the end poles (1,7) as a function of the horizontal position, Figure 12 is the same for the positive poles (2,4,6) and Figure 13 for the negative ones (3,5). It can be seen from those figures that the wiggler field is not symmetric with respect to its center, and that the asymmetry between symmetric poles is of the order of 50 G.

TABLE III

Sextupole term and magnetic length of the wiggler poles

Pole number	$\partial^2 B/\partial x^2$ (T/m^2)	L_m (m)
1	+ 11.0	0.142
2	-20.4	0.237
3	+20.4	0.237
4	-20.6	0.237
5	+20.6	0.237
6	-20.2	0.237
7	+9.4	0.142

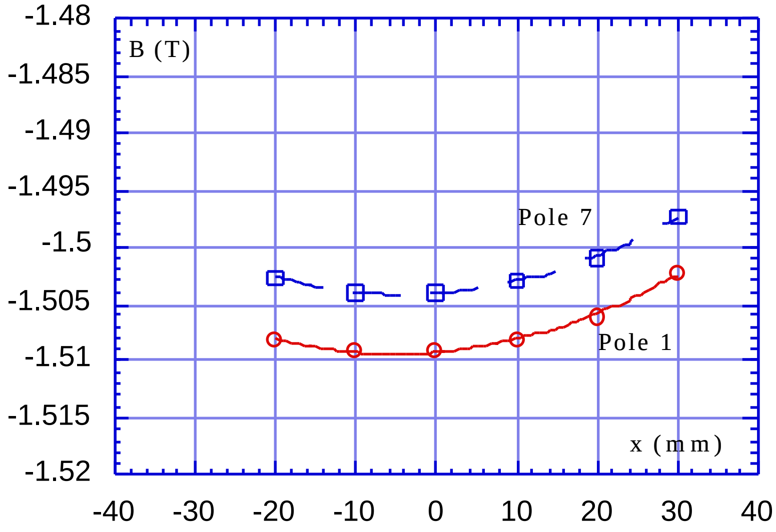

Fig. 11 - Vertical field in the center of end poles

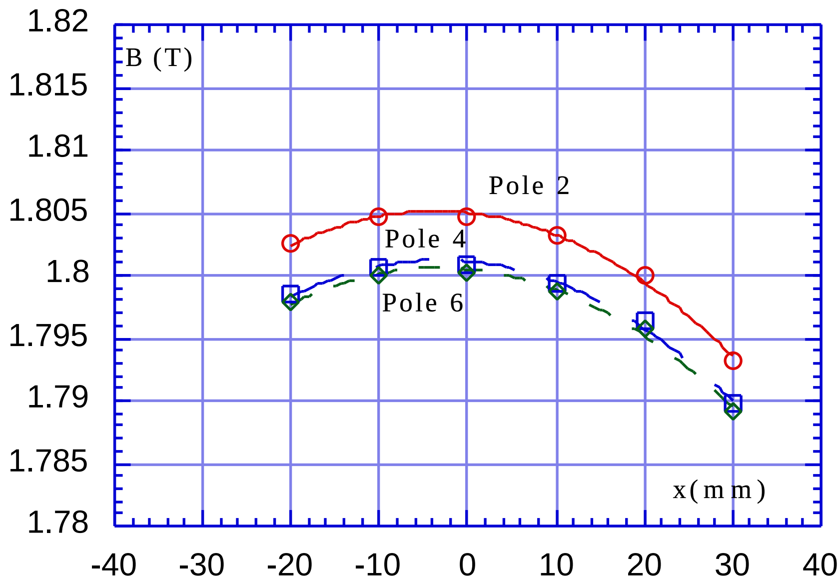

Fig. 12 - Vertical field in the center of positive poles

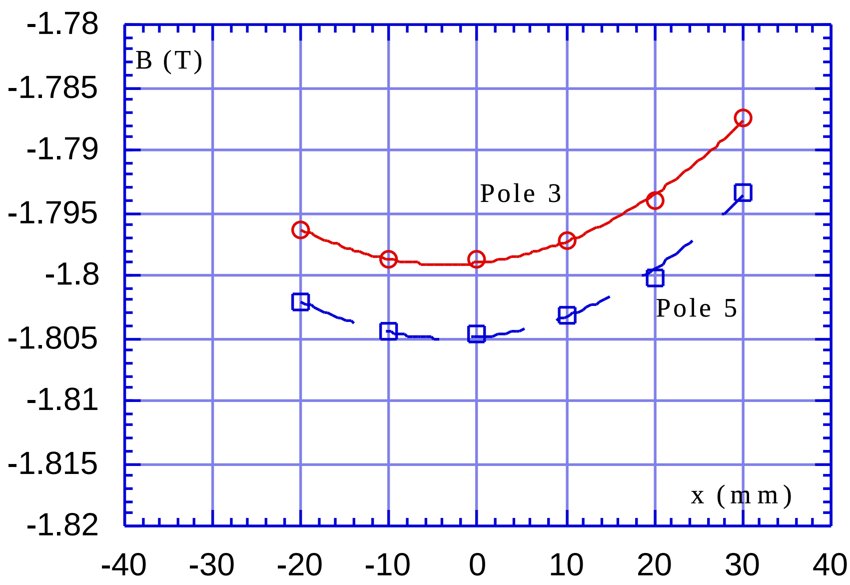

Fig. 13 - Vertical field in the center of negative poles

The slope of the field integral in Fig. 10 is such that the sextupole component has the same sign of the end pole field (see Fig. 9). Since we want the particle trajectory inside the wiggler to be towards the outside of the ring, the end poles must have the opposite field with respect to the bending magnets in the DAΦNE achromats. The measured sextupole term is therefore of the D type, and corresponds to a thin lens, with a sextupole constant of ≈1.3 m^{-2}. This value can be compared with the achromat sextupoles used for the chromaticity correction, which have sextupole constants in the order of 10 m^{-2}. The fit of the field integrals and of the field at the center of the poles also shows that the quadrupole term of the wiggler field is negligible, of the order of 10^{-3} m^{-1}, to be compared to typical value of ≈1 m^{-1} of the normal quadrupoles in the DAΦNE lattice.

Similar vertical field maps have been performed at two different vertical positions, namely 5 mm above and 5 mm below the horizontal midplane of the wiggler, which is the maximum range of the vertical displacement of the Hall probe. Figure 14 shows the behaviour of the vertical field component in the center of the wiggler central pole as a function of the vertical position.

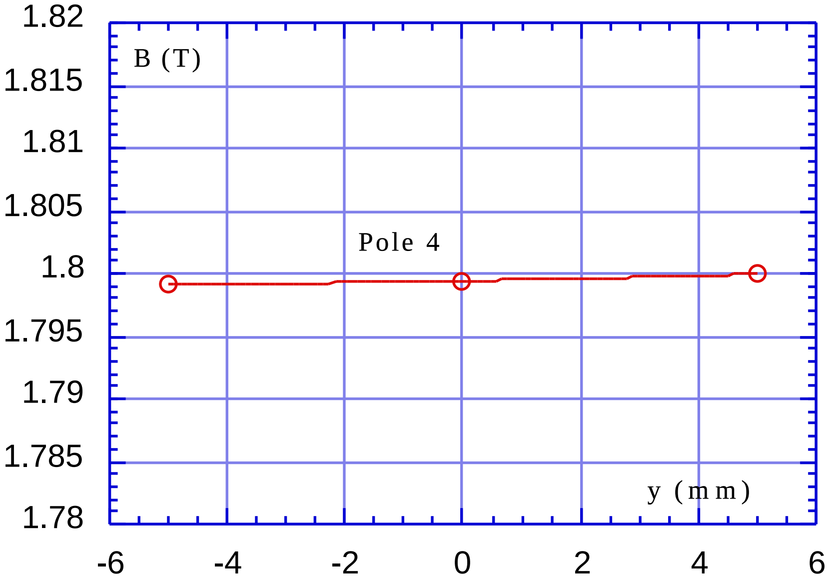

Fig. 14 - Vertical field in the center pole as a function of vertical position

It can be seen that, also because of the small measurable vertical range (the gap is ±20 mm) the field variation is very small. However, the behaviour of the integrated field as a function of the horizontal position is quite different from the result obtained on the midplane. Figure 15 gives this behaviour for the measurement performed 5 mm above the wiggler midplane.

From the best fit of the points of Fig. 15 with a second order polynomial, we can estimate an integrated sextupole term of -3.4 T/m. Taking the field at the pole center, as described before, and multiplying by the magnetic length of the pole, we find instead -1.6 T/m. This difference shows how the estimate of the sextupole term depends on the field integral uncertainty. The same measurement 5 mm below the median plane gives -1.9 T/m from the field integrals in good agreement with -1.6 T/m with the other method. Figure 16 shows the behaviour of the field integral in this case.

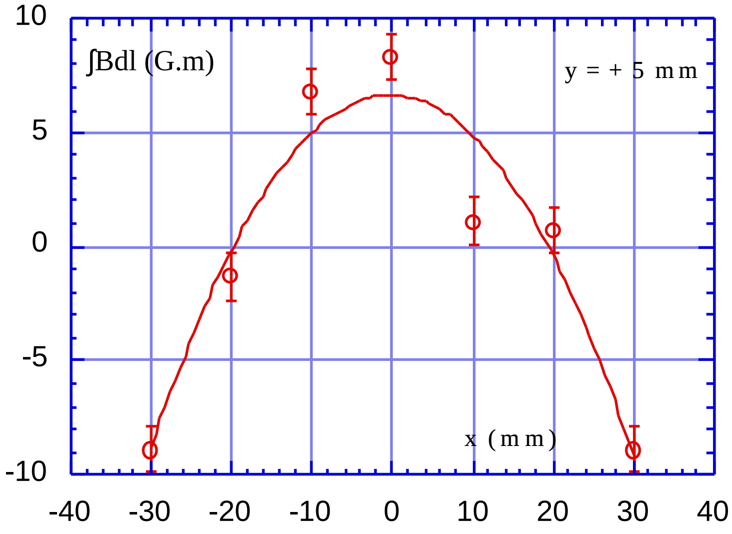

Fig. 15 - Integrated field as a function of horizontal positionat a vertical distance of 5 mm above the wiggler midplane

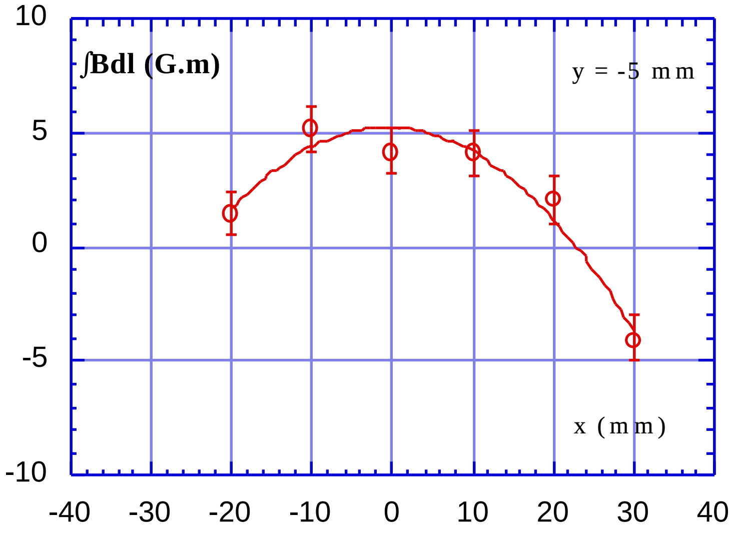

Fig. 16 - Integrated field as a function of horizontal positionat a vertical distance of 5 mm below the wiggler midplane

10. COMPARISON WITH MAGNETIC DESIGN

In order to check the reliability of the 3-dimensional code used in designing the magnets of the DAΦNE project, we have compared the measured field of the wiggler with the prediction of MAGNUS[1] in a section of the wiggler starting from the midpoint of the last full pole, going through the end pole and the field clamp, and ending up in the fringing field region. Figure 17 shows the calculated field (line) and superimposed experimental points (dots): the agreement is quite satisfactory.

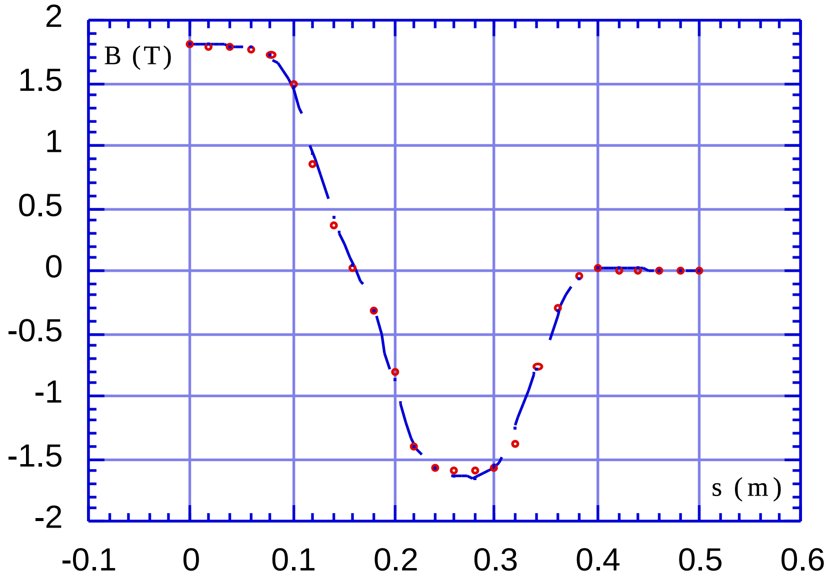

Fig. 17 - Comparison between measured and calculated field

11 - CONCLUSIONS

A complete set of mechanical, electrical, hydraulic and magnetic tests has been performed of the prototype wiggler magnet delivered by DANFYSIK to LNF on January 1994. Figure 18 shows a picture of the wiggler magnet prototype on the field clamp side. These tests have suggested a number of modifications to be developed on the final version of the magnet and the power supplies. Using both a rotating coil system and a Hall probe driven by an accurate positioning system, the field integral on the wiggler axis has been carefully compensated for three different operating points.

Although some asymmetries in the field and a non-negligible sextupole term have been revealed by the measurements, we feel confident that the magnetic quality of the wiggler is sufficient for our purposes, and therefore we can authorize the series production without changing the shape of the poles.

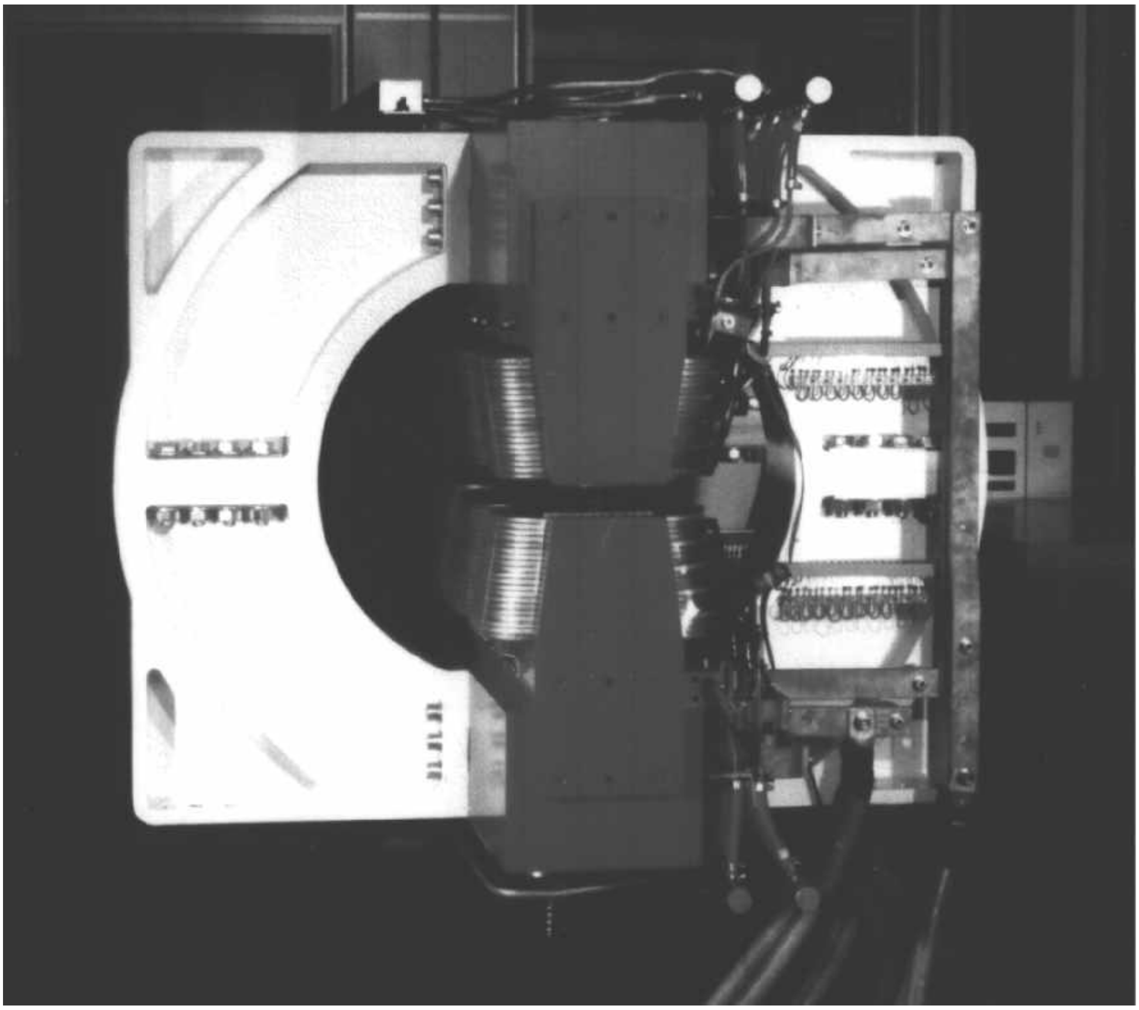

Fig. 18 - Wiggler Magnet prototype

REFERENCE

[1] The MAGNUS Package - Ferrari Associates, Inc.- P.O. Box 1866, Orange Park, FL 32067 USA.