DAΦNE TECHNICAL NOTE

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MAGNETIC MEASUREMENTS ON THE DAΦNE WIGGLERS AFTER THE SECOND MODIFICATION

S. Bettoni, B. Bolli, S. Ceravolo, F. Iungo, M. Preger, P. Raimondi, C. Sanelli, F. Sardone

1. Introduction

In the original design of the DAΦNE wigglers [1], in spite of the large width of the poles (14 cm), the roll-off of the field and the amplitude of the beam oscillation inside the magnet (≈2.5 cm peak-to-peak) were the source of non negligible contributions to the non-linearities of the lattice. Measurements of the tune shift versus beam displacement in the wiggler section indicated an octupole component (in MAD units) $K_3^{MAD} \approx 8x10^2 m^{-3}$. A first modification has been performed in 2004 [2][3], by compensating the field roll-off with properly shaped iron plates glued on the poles. The octupole term was reduced to $\approx 3x10^2 m^{-3}$, but the length of the magnetic circuit was increased by 22 mm, with a corresponding reduction by 4% of the maximum field.

In the original structure with all the poles aligned and the beam orbit oscillating around the wiggler axis, due to the alternating sign of the field in the wiggler poles and the condition of vanishing first field integral to avoid closed orbit distortion, the even terms of the polynomial expansion around the beam orbit tend to cancel, whereas the odd ones add coherently, increasing with the distance between the magnet axis and the beam trajectory. The idea of shifting the poles in such a way that the axis of each pole is centered with respect to the beam trajectory has therefore been proposed [4][5] to substantially reduce the contributions to the field non linearities. This solution, although presenting a significant impact on the mechanical realization, avoids the use of additional iron plates and therefore the maximum field at a given current can be larger than in the previous configuration. Moreover, the gap in the wiggler has been reduced from the original 40 mm to 37 mm, with an additional benefit on the obtainable field, thus allowing substantial savings of the power bill of the laboratory. By short-circuiting one of the five windings in the terminal poles coils and slightly modifying the position of the field clamps (as described in [2] to compensate the sextupole introduced to obtain a better chromatic compensation) it has been also proposed to power in series the coils of all the poles, including the terminal ones. This allows to get rid of 8 power supplies, reducing the occurrence of failures and making the wiggler cycling procedure easier.

2. Measurements on the spare wiggler

The spare wiggler built in 2004 to test the first modification has been modified a first time by shifting the main poles by ±7.3 mm with respect to the wiggler axis, as indicated by the minimization of the octupole term from magnetic field calculations [5], and by machining the "C" shaped supports of the magnet (see Fig. 6) in order to reduce the gap from 40 to 37 mm. Field measurements on the horizontal mid-plane in steps of 8.35 mm from -1.35 m to + 1.35 m in the longitudinal direction (s) and in steps of 10 mm from -7 cm to + 7 cm in the transverse one (x) have been performed at the excitation current of 550 A, as in the normal operation of DAΦNE for the Siddharta experiment, and also at 500 A and 450 A in view of a possible reduction of power cost for the next KLOE run. The field maps have been obtained with the double Hall probe configuration already discussed in [2]. Table 1 shows the current in the terminal poles required to cancel the first field integral.

Table 1 – First field integral cancellation with terminal poles on the wiggler axis and main poles shifted by 7.3 mm

	Terminal poles current (A)	$\int B_y\,ds$ (Gm)
450	360	-1.53
500	395	-0.17
550	432	1.14

A second set of measurements has then been performed with the terminal poles shifted by the same amount. Since the current in the terminal poles was approximately lower by 20% than the current in the main ones, the first winding near the magnet gap in the terminal coil was short-circuited and all coils powered at the same current, still with two independent power supplies. The measurements showed a rather large first field integral, and therefore the current in the terminal coils was set to cancel it. In this configuration the field maps have been measured at 400 A, 450 A and 500 A. Table 2 shows the results.

Table 2 – First field integral cancellation all poles shifted by 7.3 mm and first winding in the terminal coils short-circuited

Main poles current (A)	Terminal poles current (A)	$\int B_y\,ds$ (Gm)
400	378.6	-0.80
450	411.0	1.96
550	486.7	0.90

Magnetic field simulations have therefore been performed to check if short-circuiting different windings in the terminal coils would yield different results, as shown in Table 3. The simulation clearly indicates that the third coil is the best one to cancel the first field integral.

Table 3 – Simulated first field integral obtained by short-circuiting different windings in the terminal coils. Winding 1 is near the wiggler gap

Winding	$\int B_y\,ds$ (Gm)
1	-108
2	-40
3	19
4	58
5	86

3. Measurements with the third winding in the terminal coils short-circuited

Tracking the particle motion through the simulated magnetic field of the wiggler showed that the best linearity of the exit angle versus the shift of the initial position is obtained when all the poles are shifted by 8.0 mm instead of 7.3 mm, as indicated by the minimization of the octupole term [6]. Meanwhile the shutdown for the roll-in of KLOE started, and the first two wigglers (EL201 and PS201) were modified by shifting all the poles by 8.0 mm and short-circuiting the third winding in the terminal coils. The measurements in these two wigglers, however, indicated a first field integral larger than the simulated one (40.5 Gm and 62.0 Gm respectively). Assuming a constant difference between measurement and simulation, it was clear that the best winding to be short-circuited is the second one. Moreover, since a slightly negative integral is expected, it is possible to obtain an almost perfect compensation of the field by changing the position of the field clamps, as described in [2]. The two wigglers were modified accordingly, as all the other ones. All measurements have been performed at a current of 450A in all the poles.

Before starting the systematic measurements on all the wigglers, since the two Hall probes have not be recalibrated after the first modification in 2004, a check has been performed by measuring the difference between them on the same point in the magnet, and also by changing the sign of the field and taking the difference on the same probe. Figure 1 shows the result of the first check. The situation is clearly worse than in 2004: in the positive field poles the difference is of the order of 10 G, in the negative field ones it reaches 35 G.

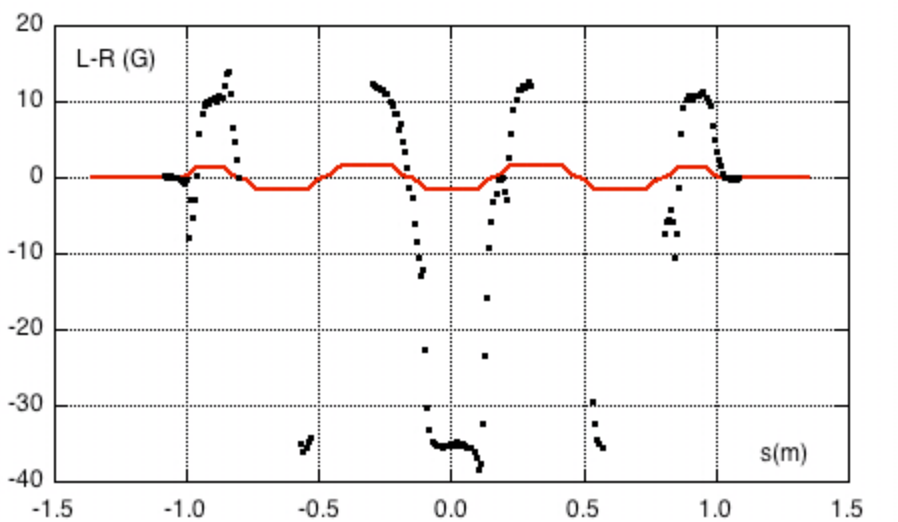

Fig. 1 – Difference between the left and right Hall probes measured on the same point in the wiggler (black dots). The field is indicated for reference in red.

Fig. 2 and Fig. 3 show the difference between the measurement performed with the field in the right direction and in the opposite one (multiplied by -1) for the left probe and the right one respectively. While in the case of the left probe the difference in the zones where the field is flat is less than 5 G, in the case of the right one the difference is much larger, of the order of 20 G, and always positive, indicating a lower amplification of the right probe in presence of a negative field. If we assume that both probes measure correctly where the field is positive and that the right one has a lower amplification where the field is negative, the effect on the field integral would a positive overestimate of ≈7 Gm. The measurements of the field integral performed on wiggler EL201 with the two field polarities yields a difference of +13 Gm. We conclude that the measurements performed on all the wigglers in their final configuration can be affected by a positive overestimate of the order of 10 Gm.

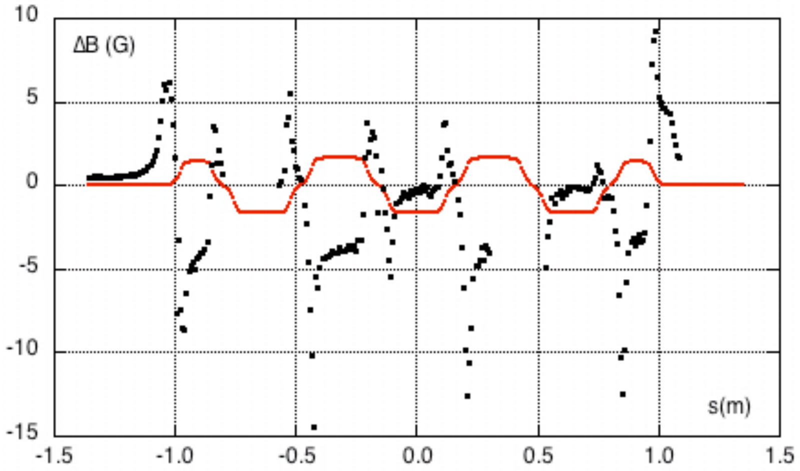

Fig. 2 – Difference between the measurements with the field in the right direction and the opposite one for the left probe (black dots). The field is indicated for reference in red.

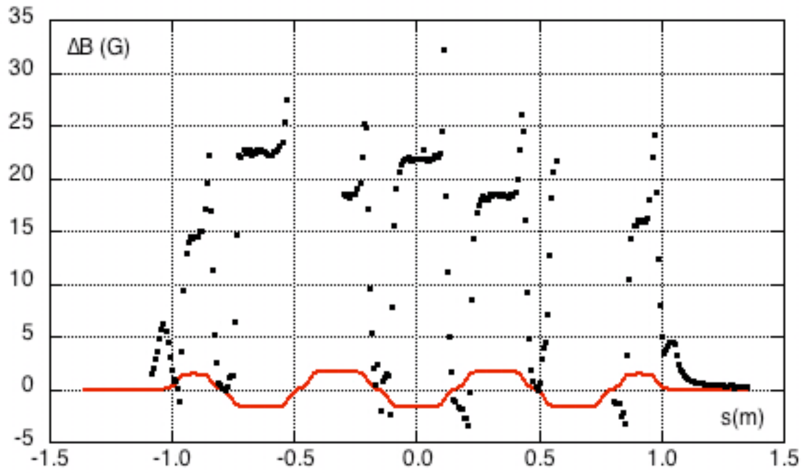

Fig. 3 – Difference between the measurements with the field in the right direction and the opposite one for the right probe (black dots). The field is indicated for reference in red.

4. Final configuration. Cancellation of the first field integral

The 8 wigglers of the DAΦNE Main Rings have been measured in their final configuration with all poles shifted by 8.0 mm with respect to the mechanical axis of the wiggler, the second winding in the terminal poles coils short-circuited, all poles in series with a current of 450A. The wiggler axis will be aligned in the machine with a displacement of 12.88 mm in the horizontal direction towards the outside of the rings, and all the analyses described in the following are done in this configuration. Fig. 4 shows the beam trajectory in the wiggler: the line at the center of each pole is the position of its mechanical axis. It can be observed that the beam is approximately half outside and half inside in the horizontal direction with respect to each pole axis.

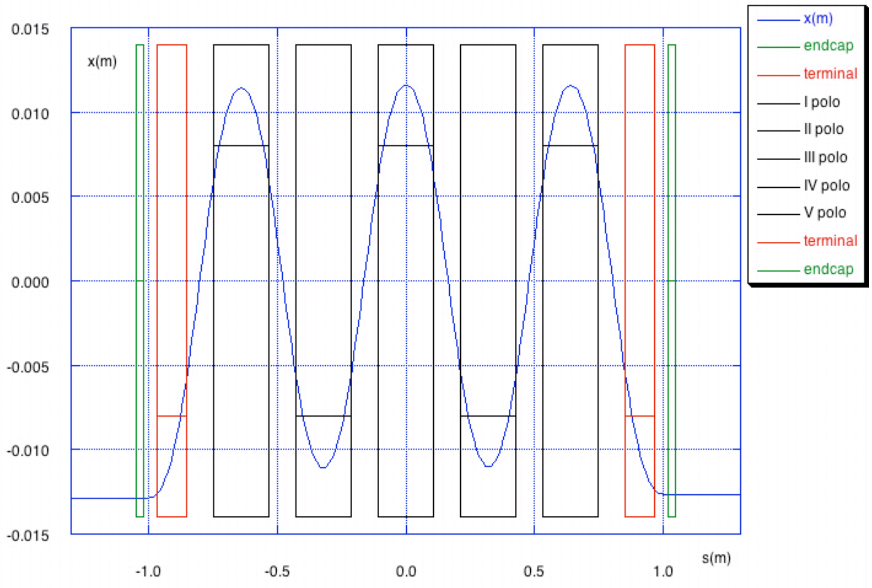

Fig. 4 – Beam trajectory inside the wiggler. The line inside each pole shows the position of its axis. The width of the poles is truncated at ±14 mm. The real width is ±70 mm.

In the previous configuration one of the two terminal poles has been modified by shaping the iron plates glued on the pole face with a profile yielding an additional sextupole term to help in the overall chromaticity correction of the ring [2]. The asymmetry introduced by this modification was compensated in the field integral (which should be equal in the two halves of the wiggler to avoid a horizontal displacement of the beam even with an overall vanishing field integral) by increasing the gap between the field clamps (endcaps) from the original 37 mm to 111 mm. For this reason half of the endcaps had 8 holes for joining them to the main yoke of the magnet. In the case of the first wiggler (PL101), two scans on the wiggler axis have been performed, one with the gap in the endcaps at 37 mm, the second at 111 mm. By linearly interpolating the two first integrals, the gap in the endcap necessary to make the first integral vanish has been found to be 66 mm. Four holes have been drilled in the corresponding position finding -7.4 Gm for the first field integral.

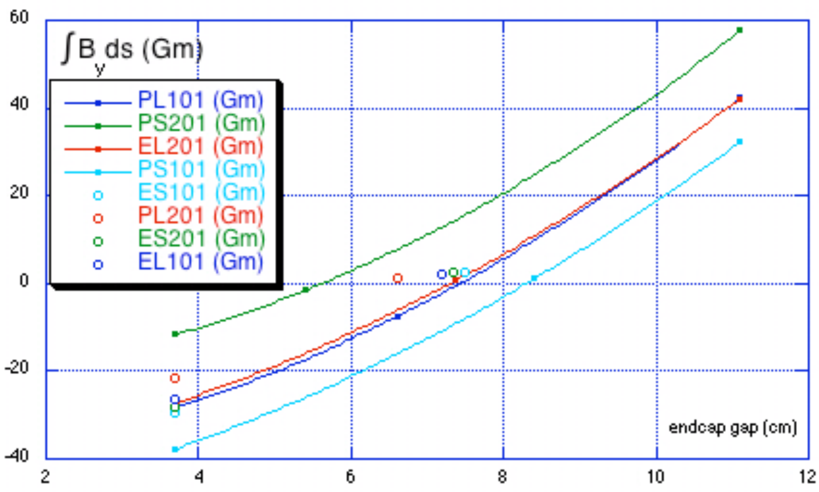

Fig. 5 – Interpolation of the gap in the endcaps to cancel the first field integral.

The measured points have been fitted by a second order polynomial, as shown in Fig. 5, and these coefficients have been used to better predict the gap in the endcaps for the following wigglers. The first four wigglers in the legend in Fig. 5 have therefore been measured by two scans on the wiggler mechanical axis with both original gaps (37 mm and 111 mm) followed by a complete map with the optimized endcap gap on the horizontal symmetry plane of the magnet to obtain the largest possible set of coefficients to be used in the following interpolations. They are shown with the interpolating parabolic curve in Fig. 5. The last four were equipped with endcaps having only the original four holes, and for them the final endcap gap has been calculated from the coefficients of the first four. They are shown as empty circles in Fig. 5. Table 4 gives the endcaps and the residual field integrals for the eight wigglers.

Table 4 – Final gap in the endcaps and field integrals in the wigglers

WIGGLER	Endcap gap (mm)	$\int B_y\, ds$ (Gm)
PL101	66	-7.4
PS101	84	1.2
PS201	54	-1.4
PL201	66	1.3
EL101	72	1.9
ES101	75	2.5
ES201	73	2.5
EL201	74	0.9

The worst case (PL101) corresponds to a deflection of 0.43 mrad, which can be compensated by a current of 0.6 A in the two horizontal correctors near the wiggler.

5. Final configuration. High order terms

The main criterion adopted to choose the best configuration for the wiggler has been the linearity of the exit angle of a particle tracked through the simulated and measured wiggler field as a function of horizontal shift of the beam trajectory at the entrance of the wiggler. The results are described in [5, 6]. Here we present a different kind of analysis, based on the measured maps of the vertical field component on the horizontal symmetry plane of the magnet.

Each map consists of 4875 positions (325 in the longitudinal direction in steps of 8.35 mm [2] and 15 in the transverse one in steps of 10 mm) of the double Hall probe support, shown in Fig. 6. The reason for adopting this configuration is that the positions under the aluminum "C" shaped supports of the iron yoke (white in Fig. 6) cannot be reached by a single straight probe support. Therefore there are 91 longitudinal positions that the left probe cannot reach, the same by the right one, and 153 can be reached by both probes. The field value is given by a single probe where the other one cannot arrive, by the average where both measurements are available.

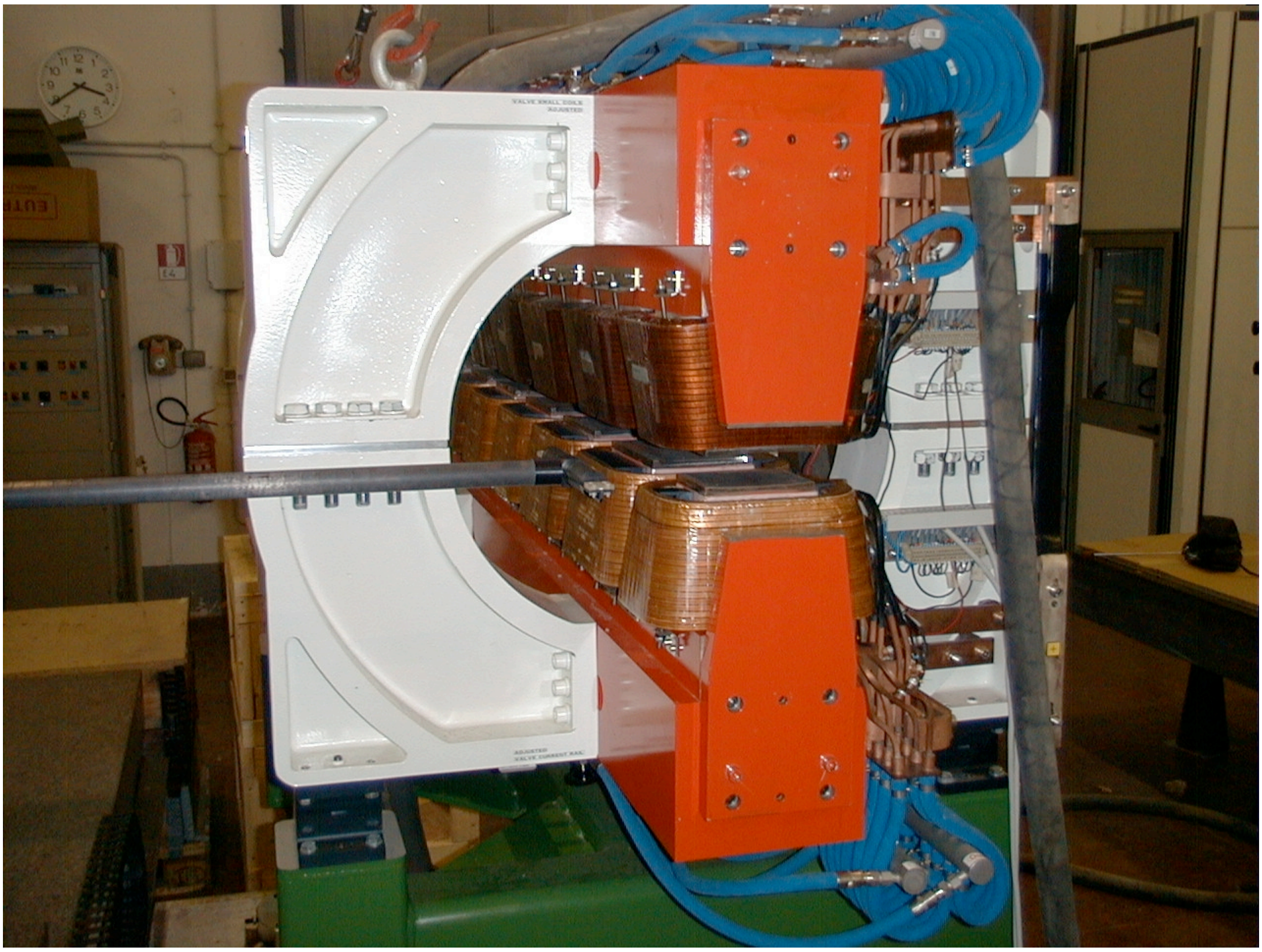

Fig. 6 – The wiggler with the double Hall probe measuring device.

The beam trajectory is estimated from the second integral of the field measured on the wiggler axis and subtracting the offset of the wiggler axis with respect to the axis of the ring straight section (12.88 mm). At each longitudinal position in the map 15 field points are taken along a straight line perpendicular to the beam trajectory by means of a parabolic interpolation between the measurements taken at the three nearest longitudinal positions. A fourth order polynomial fit is then performed on these points taking into account only those within ±40 mm from the point of the beam trajectory. The fit is therefore:

$$B_y(s) = b_o(s) + b_1(s)x + b_2(s)x^2 + b_3(s)x^3 + b_4(s)x^4$$

where the coefficients b_i are related to the corresponding MAD coefficients by:

$$k_n^{MAD} = \frac{n!b_n}{B\rho}$$

with Bρ = 1.7 Tm for DAΦNE at 0.51 GeV. Figures 7, 8, 9, 10, 11 show the behaviour of each coefficient for the wiggler PL201. The figures contain the positions of the endcaps, terminals and main poles for reference. The compensation of the octupole term is clearly shown in Fig. 10, where the contributions inside the poles are almost cancelled by those between the poles.

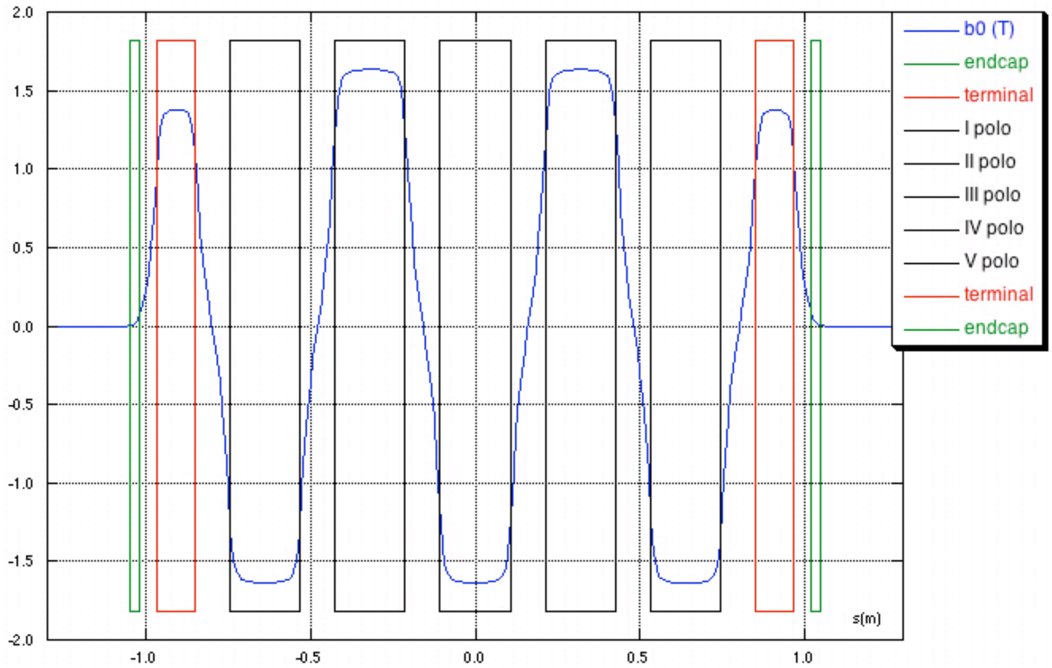

Fig. 7 – Zero order term of the transverse expansion of the field around the beam trajectory.

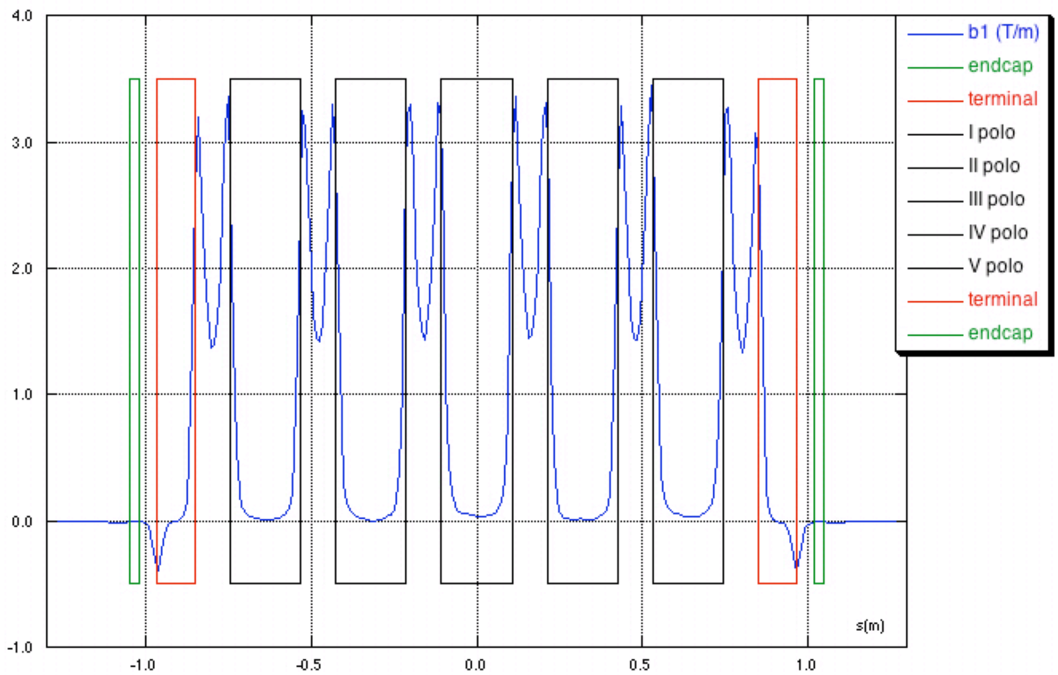

Fig. 8 – First order term of the transverse expansion of the field around the beam trajectory.

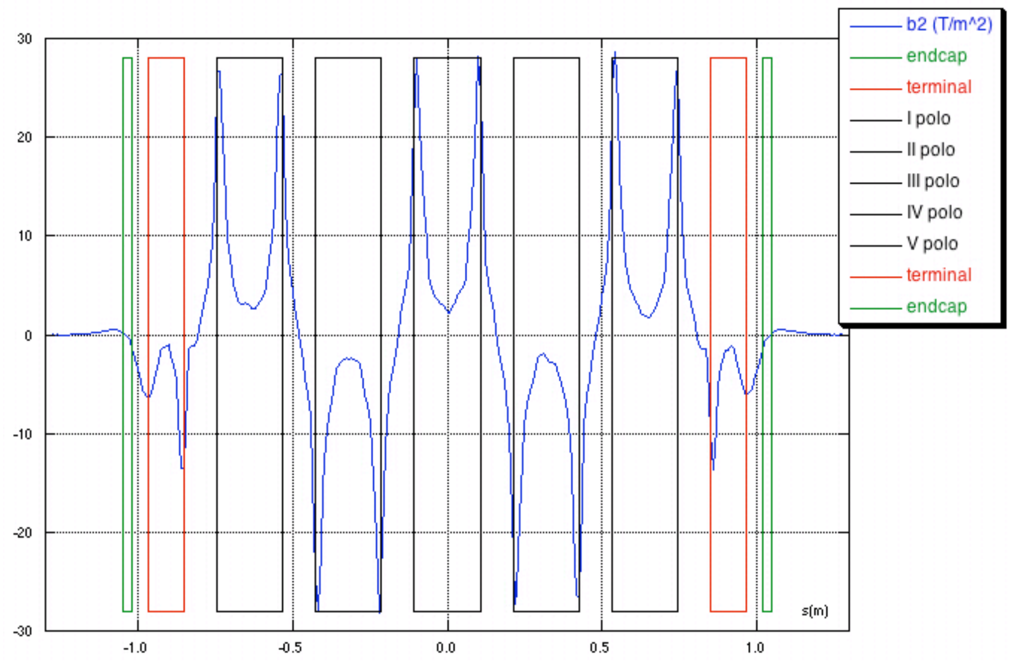

Fig. 9 – Second order term of the transverse expansion of the field around the beam trajectory.

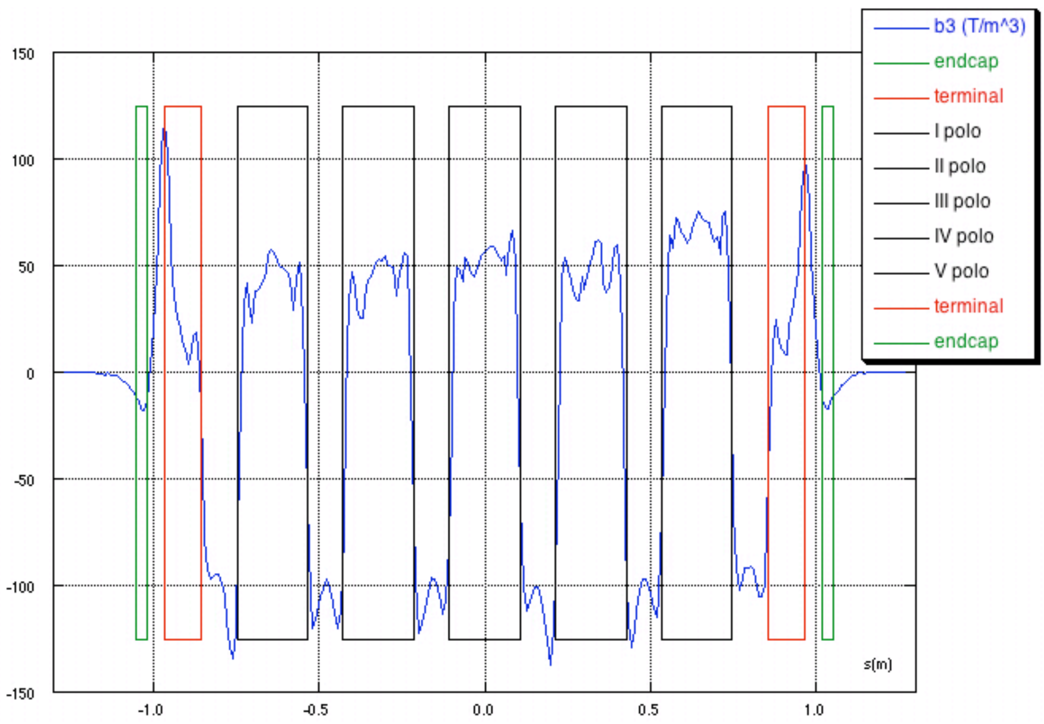

Fig. 10 – Third order term of the transverse expansion of the field around the beam trajectory.

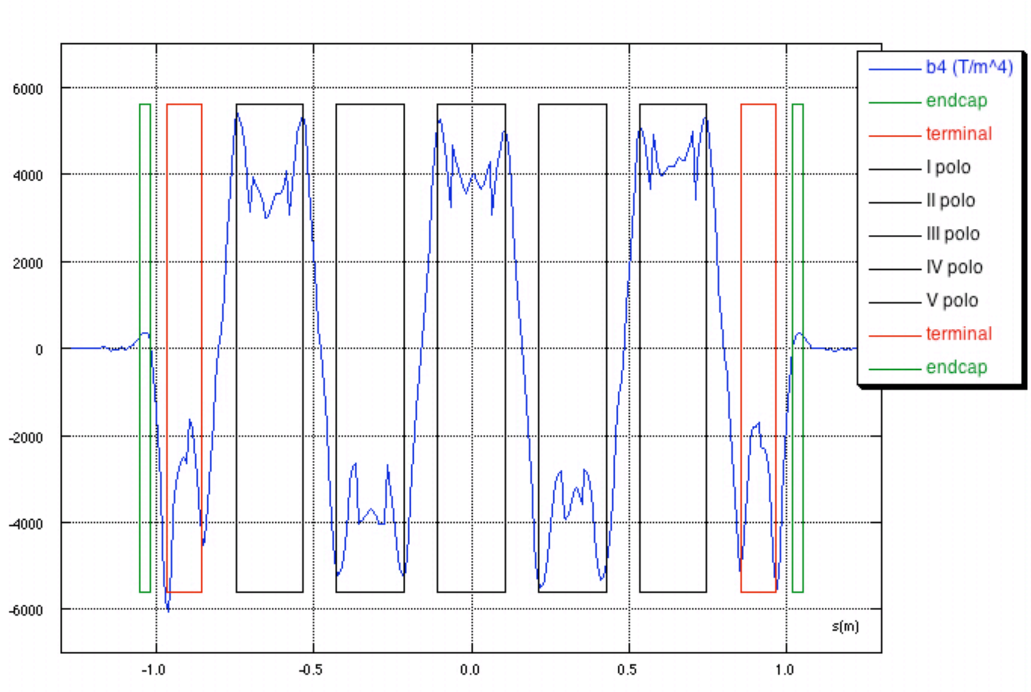

Fig. 11 – Fourth order term of the transverse expansion of the field around the beam trajectory.

Fig. 12 shows the average distance (absolute value) between the measured points and the fourth order polynomial fit, typically less than 2 G. Table 5 indicates the integrated values of the coefficients (in MAD units).

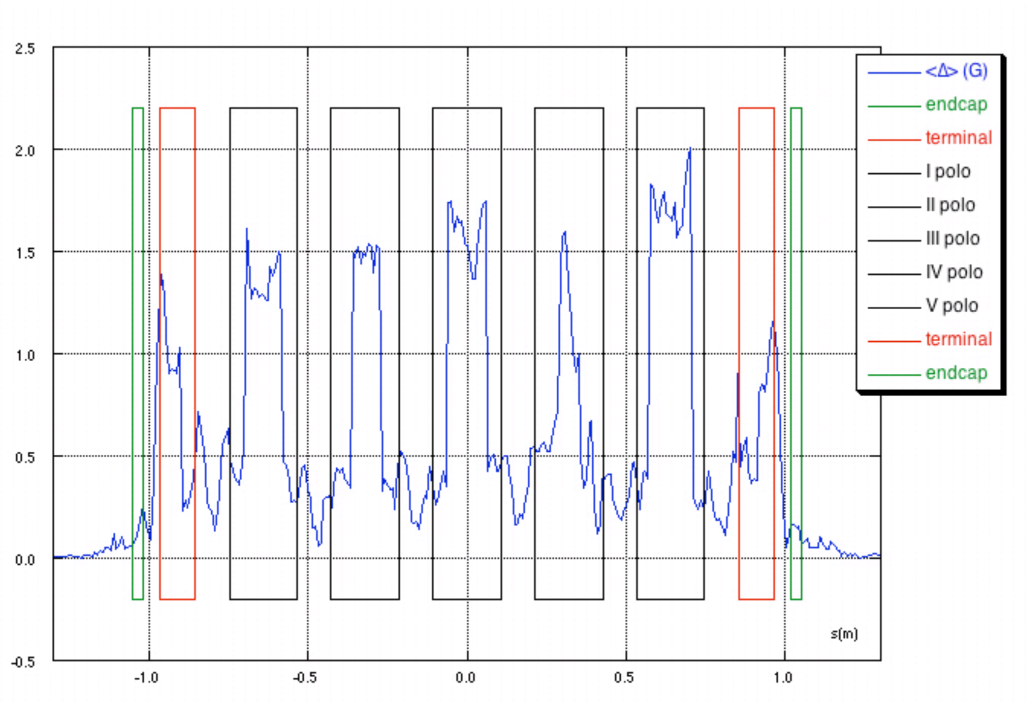

Fig. 12 – Average deviation of the measured points from the fourth order polynomial fit.

Table 5 – Integrated MAD coefficients from first to fourth order

Wiggler	K_1 (m^{-1})	K_2 (m^{-2})	K_3 (m^{-3})	K_4 (m^{-4})
PL101	1.12	1.30	-87.5	280
PS101	1.11	1.46	-73.9	221
PS201	1.10	1.40	-73.7	-889
PL201	1.11	1.37	-48.0	389
EL101	1.09	1.52	-80.9	-311
ES101	1.11	1.27	-84.6	1066
ES201	1.11	1.24	-107.4	1074
EL201	1.09	1.29	-85.43	457

The average value of the octupole term is –80 m^{-3}, about 4 times smaller than in the configuration with the glued iron plates. The average sextupole term is 1.35 m^{-2}, and is horizontally defocusing. The effect of the decapole term becomes competitive with the sextupole at distances larger than 1 cm from the beam trajectory.

6. Conclusions

The eight wigglers of the DAΦNE Main Rings have been modified during the 2010 shutdown for the roll-in of KLOE, by shifting the poles with respect to the wiggler axis in order to minimize the effect of high order terms in the field. Measurements on a prototype and on all the magnets have confirmed the results of magnetic simulations. The elimination of the glued iron plates of the preceding configuration allows to run the wiggler at 450A instead of the previous 550A at approximately the same field, with significant reduction of the power consumption. The terminal poles will be powered in series with the main ones, reducing the occurrence of failures and making the cycling procedure of the wiggler easier.

REFERENCES

[1] C. Sanelli, H. Hsieh: "Design of the 1.8 Tesla Wiggler for the DAΦNE Main Rings" Proceedings of the 3rd EPAC Conference, Berlin 24-28 March 1992, vol. 2, p. 1391-1393.

[2] A. Battisti, S. Bertolucci, B . Bolli, S. Ceravolo, M. Incurvati, F. Iungo, M. Paris, M. Preger, P. Raimondi, C. Sanelli, F. Sardone, F. Sgamma, M.Troiani: "The modified wiggler of the DAΦNE Main Rings" DAΦNE Technical Note MM-34, 7/1/2004.

[3] S. Guiducci, S. Bertolucci, M. Incurvati, M. Preger, P. Raimondi, C. Sanelli, F. Sgamma: "The modified DAΦNE wigglers" Proceedings of EPAC 2004, Lucerne, Switzerland, p.1678.

[4] S. Bettoni, "Reduction of the integrated odd multipoles in periodic magnets", Phys. Rev. ST-AB, 10, 042401 (2007).

[5] S. Bettoni, S. Guiducci, M. Preger, P. Raimondi, C. Sanelli "Reduction of non-linearities in the DAΦNE Main Rings wigglers" Proceedings of PAC 2007, Albuquerque, USA, p.1463.

[6] S. Bettoni, B. Bolli, S. Ceravolo, S. Guiducci, F. Iungo, M. Preger, P. Raimondi, C. Sanelli, F. M. Sardone: "Multipoles minimization in the DAΦNE wigglers" Proceedings of IPAC 2010, Kyoto, Japan.