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FIRST AND SECOND ORDER CLOSED ORBIT EFFECTS IN SHORT DIPOLES

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ABSTRACT

In small colliders and damping rings, such as DAΦNE [1] and its Accumulator [2,3], the bending dipoles are typically designed with a large gap to length ratio, thus enhancing fringing field effects. The trajectory of the beam inside the dipoles may be significantly different from the predictions of the rectangular approximation, as well as the overall length of the synchronous orbit. Second order terms in the transverse field expansion in the fringing region may also contribute to the chromaticity of the ring. The measurements and simulations on the DAΦNE Accumulator dipoles are presented and discussed.

1. Magnetic measurements

The 8 dipoles of the DAΦNE Accumulator [4] have a nominal magnetic length of 864 mm with a nominal bending radius of 1.10008 m. The magnets are built as an "H" type iron core with a vertically focusing gradient. The gap at the magnet center is 42 mm high. The prototype magnet has been realized with removable end caps in order to leave a possibility of tuning the magnetic length as a function of the results of magnetic measurements.

The vertical field component on the symmetry plane has been measured by means of a Hall Probe system driven by a computer controlled positioning system with an accuracy of ±5 μm. The field has been measured along the nominal trajectory of the beam, namely a 45° arc with the nominal bending radius and two 0.35 m long straight lines tangent to the arc. The distance between the measured points on the arc has been set as the bending radius times 0.5°, while on the two straights it is kept fixed at 10 mm. The field was measured also along 6 other lines parallel to the first one at distances of ±10, ±20 and ±30 mm. With such a mesh of measured points, each "longitudinal" position along the nominal trajectory corresponds to 7 "transverse" field measurements. These 7 values can be fitted with a polynomial and figures 1 and 2 show the behaviour of the zero (b0) and first (b1) order terms of the transverse expansion in the first half of the dipole (the second one is symmetric).

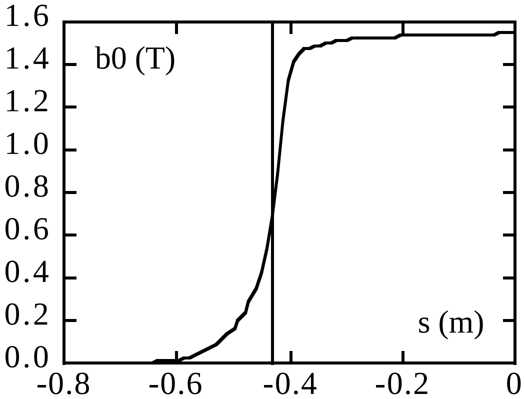

Figure 1: *Zero order term of the transverse expansion*

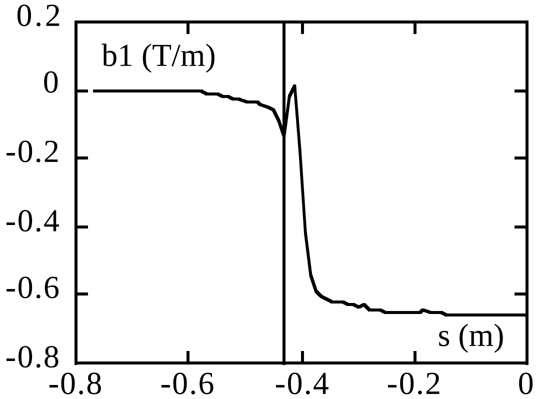

Figure 2: *First order term of the transverse expansion*

The first figure, showing the behaviour of the field on the nominal trajectory, indicates clearly that the fringing region is dominant, since a flat top central region can hardly be defined. The vertical straight line represents the position of the dipole edge in the rectangular approximation. The second one illustrates the gradient as a function of the longitudinal position along the dipole and the fringing region.

One can observe that the integrated gradient is smaller than its value at the magnet center times the nominal length of the dipole by a significant amount. The measured gradient can be easily integrated to give a good estimate of the effective field index to be used in building a reliable model for the lattice [5]. The second unexpected feature is the small positive peak near the dipole edge: it is due to the fact that the length of the yoke is slightly shorter than the nominal length of the dipole, while the angle between the end faces is the nominal one. There is therefore a small angle between the physical end face and the line connecting the 7 transverse measured points at the corresponding azimuth in the dipole. This angle is in the opposite direction with respect to a rectangular dipole, and therefore yields a focusing effect in the horizontal plane.

2. Orbit calculations

The mesh of measured field points can also be used to calculate the trajectory of a particle in the bending magnet, by integrating the equations of motion driven by the Lorentz force. The initial position and angle of the particle are taken on the ideal trajectory before the dipole well outside the fringing field region, namely on a straight line pointing to the center of the end face in the rectangular model. The distance between the position of the particle and the nominal trajectory (an arc plus two straight lines) is calculated as a function of the position along the nominal trajectory. Since there is field well before the

position of the nominal edge of the dipole in the rectangular approximation (see figure 1), the particle is bent towards the inside and follows a path which depends on its energy.
There is an energy of the particle at which its trajectory at the output of the dipole is bent by the nominal bending angle (I shall call this energy the "synchronous" one). However, at this energy, the distance between the output trajectory and the nominal one vanishes only if the dipole field is symmetric in the longitudinal direction with respect to its center.
The full line labelled by "0" in figure 3 shows the result of the calculation performed with the field mesh measured on the prototype dipole with the original thickness of the end caps: the deviation from the nominal trajectory reaches in this case 2.3 mm.

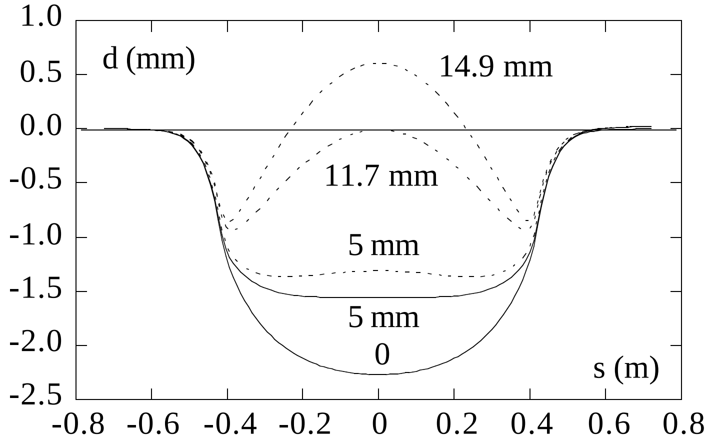

Figure 3. *Distance between calculated and nominal trajectory in the dipole. The labels indicate the depth of the cut performed on the removable end caps. Full lines correspond to real measurements, dotted ones to simulations.*

Since the deviation of the trajectory is towards the inside of the dipole, its length is shorter than the nominal one. The difference in the original configuration was 1.5 mm per magnet. The ring circumference came out to be 12 mm shorter than in the ideal lattice.
It is possible to reduce both the shortening of the orbit and the deviation of the trajectory from the nominal one by decreasing the physical length of the yoke. This can be done by reducing the thickness of the removable end caps. The dotted lines in figure 3 show the expected effect, obtained by an interpolation on the measured points, on the particle trajectory for different cuts performed on the end caps: cutting away 11.7 mm of iron from each side, the trajectory is coincident with the nominal one at the magnet center, while a 14.7 mm cut yields an orbit length equal to the nominal one.
However, such large reduction of steel length corresponds to larger center field values required to keep the synchronous energy constant. Since the magnet is operated already in the saturation region (≈1.55 T), it was decided to reach a reasonable compromise by cutting away 5 mm from each end cap. The resulting trajectory is shown by the full line

labelled "5 mm" in figure 3: the discrepancy with the simulated result is due to the different saturation conditions between the simulation and the real magnet. The distance between the particle trajectory and the nominal one is reduced to 1.6 mm and the overall reduction of the synchronous orbit length drops from 12 to 8.8 mm.

3. Second order effects

The dotted lines labelled "no shim" in figures 4 and 5 show the behaviour of the second (b2) and fourth (b4) order terms of the transverse expansion in the first half of the dipole (the magnet center is on the right and the third order contribution is negligible).

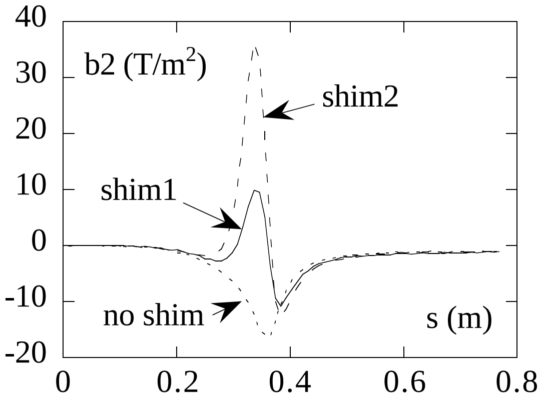

Figure 4: *Second order term of the transverse expansion*

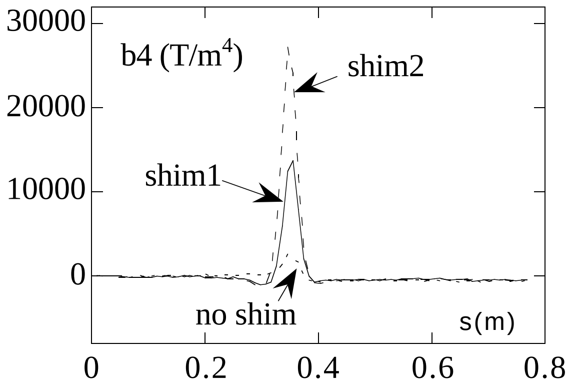

Figure 5: *Fourth order term of the transverse expansion*

It can be noticed from Figure 4 that there is a rather strong integrated second derivative. Its contribution to the chromaticity of the ring has been estimated by considering a dummy sextupole at each dipole end face with an intensity given by the integrated second order term of the transverse expansion. These contributions are listed in Table 1: by comparing the first column, where the chromaticity is calculated only with the mass term in the quadrupoles, with the second one, where the sextupole effect in the fringing field is taken into account, one can see that the two contributions are of the same order.

Table 1: *Contributions to the ring chromaticity versus shim configuration*

	quads only	no shim	shim1	shim2
$\int$ b2 ds (T/m)		-4.3	-2.0	+0.4
Horizontal chromaticity	-4.4	-7.7	-5.3	-3.9
Vertical Chromaticity	-4.2	-0.4	-2.3	-4.3

It was therefore decided to correct, at least partially, the sextupole effect in the dipole fringing field by adding shims on the end caps, following the example of the SLAC damping rings, where the chromaticity in both planes is corrected by properly shaping the dipole end faces.

We have adopted a similar approach: looking at the end caps in the direction of the incoming beam, the pole width is 170 mm. For each end cap two 40 mm wide iron shims have been machined with the same shape of the pole and placed one on the right and the other on the left side of the end cap, leaving a free space of ±45 mm around the end cap center. The thickness of the shims is 5 mm. This configuration of the dipole is called "shim1" and the result of the corresponding transverse field expansion is shown as a full line in figures 4 and 5.

As shown in figure 4, the behaviour of the second order term with "shim1", always negative without it, exhibits an oscillating behaviour. However, the negative part is still larger than the positive one and the overall integrated second order contribution, as shown in the third column, is reduced by more than 50%, but not cancelled.

We have then increased the thickness of the shims to 10 mm and repeated the field measurement, calling "shim2" this end cap configuration. In this case the negative and positive peaks cancel out almost perfectly in the integration (see figure 4 again) and the chromaticity in both planes is almost the same as that estimated by taking into account only the contribution from the quadrupoles. The shims, however, introduce a rather large fourth order term contribution: the effect is clearly evident in figure 5.

In order to decide on the final thickness of the shims, tracking simulations have been performed to estimate the dynamic aperture without and with the shim configurations by adding non linear thin lenses at the dipole end faces. Figure 1 shows the result of these tracking studies in the original configuration without the shims: the external "dot-dash" line represents the dynamic aperture in the "ideal" lattice where the chromaticity is excited by the mass term of the quadrupoles and corrected to zero in both planes by two families of lumped sextupoles placed in the dispersive region in the bending arcs of the ring [6]. The dashed line is calculated by taking into account also the contribution of the sextupole term in the dipole fringing field and correcting to zero the chromaticity with larger currents in the lumped sextupoles. As expected, the aperture drops by a significant amount. The full line comes from a simulation where, in addition to the above mentioned contributions, also the fourth order term is taken into account by means of decapole lenses at the end faces of the dipoles. Since this contributions is small without the shims, there is no much difference between these two last apertures. For sake of comparison, the dashed rectangle represents the physical aperture.

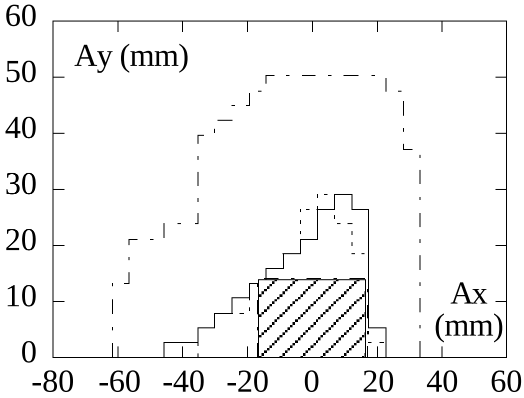

Figure 6: *Dynamic aperture without shims*

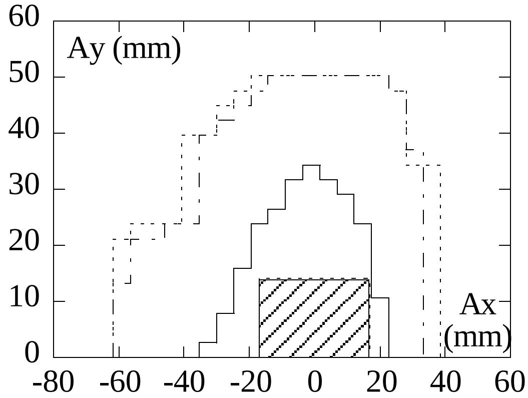

Figure 7: *Dynamic aperture with "shim2"*

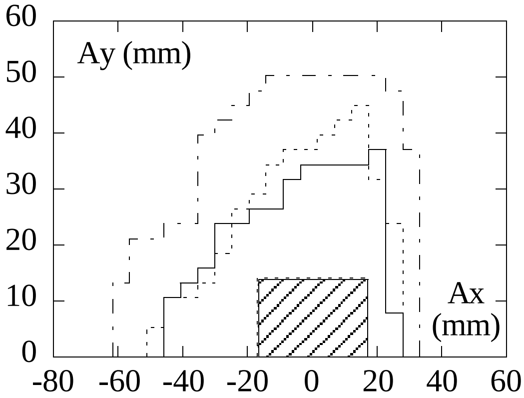

Figure 8: *Dynamic aperture with "shim1"*

Figure 7 shows the same apertures in the "shim2" configuration: in this case there is almost no difference between the "ideal" aperture and that calculated without the decapole lenses, since the sextupole contribution in the fringing is almost cancelled, and the lumped sextupole intensity is almost the same as in the "ideal" case. However, the decapole contribution shrinks the aperture significantly.

The final choice has been therefore the "shim1" configuration, shown in figure 8, where the final aperture with all contributions included is reasonably larger than the physical aperture.

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