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Magnetic Interaction Effects in ELETTRA Segmented Pure Permanent Magnet Undulators

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Abstract
The effects of finite separation and non-linear superposition between pure permanent magnet sections are considered. Measurements of finite permeability effects are compared to the results of calculations with a program, PMU3Dμ.

I. INTRODUCTION

The standard undulators for the ELETTRA synchrotron radiation facility will be 4.5 m long, and will be composed of three independent sections, for flexibility in use, greater mechanical stability and ease of construction, testing and handling [1]. A general problem of segmentation is that the correct phase relationship must be maintained between the radiation emitted in the different sections, in order to preserve the high radiation brightness. In the present case it was decided to adopt a pure-permanent magnet configuration so that phase errors could be minimized, while still permitting independent operation of the sections [1,2].

A second problem is that the fields of two adjacent sections do not superimpose exactly, due to the effects of non-unit permeability of the permanent magnet material. This is one aspect of a general problem that arises when individually measured blocks or sections are put together [3]. The situation is worse for NdFeB material compared to $SmCo_5$, since although the permeability in the direction of magnetization is similar, 1.03-1.08, that in the perpendicular direction is significantly larger: 1.15-1.18, compared to 1.02-1.08.

In this report we consider these two effects for the first two undulators that will be installed in ELETTRA, with period lengths of 5.6 cm and 12.5 cm [4]. Measurements of non-linear superposition effects are compared with the results of a computer program, PMU3Dμ, which is based on an earlier program for ideal, unit-permeability, permanent magnet undulators [5].

II. PHASE DIFFERENCE

Figure 1 shows the result of calculating the phase difference between the radiation emitted in two ideal pure permanent magnet undulators as a function of their separation, at three different gaps. The examples correspond to the first two devices that will be installed in ELETTRA [4]. It can be seen that for small separation the phase difference increases linearly with separation, and varies inversely with the period length. The variation with gap is however quite complicated since it depends on the exact form of the fringe field. The effect of the phase difference $\Delta\phi$ is to introduce an additional factor into the expression for the spectrum for one section (N periods):

$\{2 + 2\cos(2\pi N\Delta\omega/\omega_1 + \Delta\phi)\}$ for 2 sections,

$\{3 + 4\cos(2\pi N\Delta\omega/\omega_1 + \Delta\phi) + 2\cos(4\pi N\Delta\omega/\omega_1 + 2\Delta\phi)\}$,

for 3 sections. Figure 2 shows the calculated reduction in peak on-axis angular flux density (zero emittance).

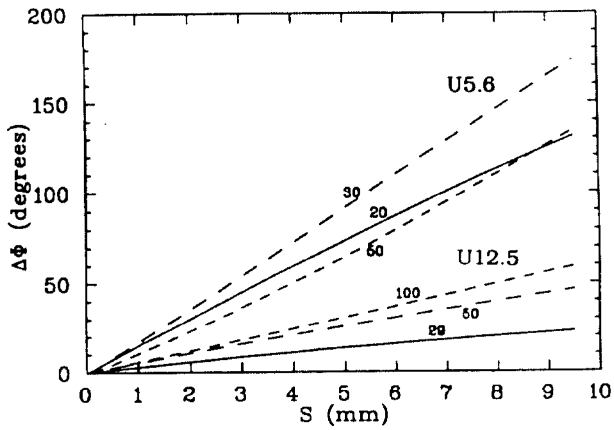

Figure 1. Phase difference as a function of separation in two undulators, with various gaps.

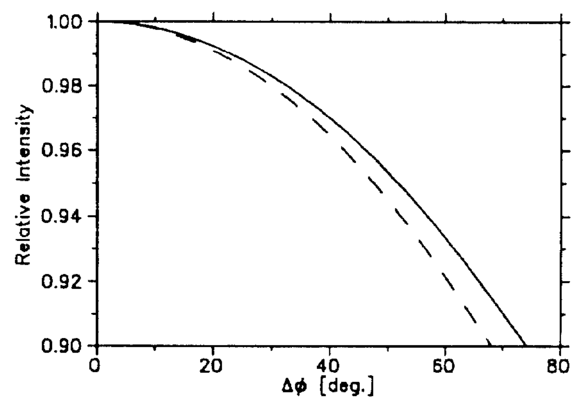

Figure 2. Relative intensity as a function of phase difference; upper curve - 2 sections, lower - 3 sections.

It can be seen that the intensity is not very sensitive to $\Delta\phi$, at least for the fundamental. However, the phase is calculated at the fundamental wavelength in each case, and is therefore 3 times larger for the third harmonic, and so on. A small separation is therefore needed in order to have negligible effect on the higher harmonics. In ELETTRA the IDs will be separated by 0.5-1 mm to give a phase difference of less than 10^o, and hence a reduction of less than 5 % for the 5th harmonic.

III. NON-SUPERPOSITION EFFECTS

A. *Calculation of Non-Unit Permeability Effects with PMU3Dμ*

To a good approximation the field inside the permanent magnet material can be expressed in the following way [6]:

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$\mathbf{B} = \mu_0 (\mu \cdot \mathbf{H} + \mathbf{B_r})$, where B_r is the remanent field and $\mu=(\mu_{\parallel}, \mu_{\perp})$ the permeability in the direction of magnetization and perpendicular to it respectively. The magnetization can therefore be written as : $\mathbf{M} = \mathbf{B_r} + \mu_0 (\chi \cdot \mathbf{H})$, where $\chi_{\parallel}=\mu_{\parallel}-1$, $\chi_{\perp}=\mu_{\perp}-1$. The equivalent current density is given by $\mathbf{J_m}$ = curl $\mathbf{M}$. The *additional* field that arises from non-unit permeability can therefore be calculated from a current density $\mathbf{J_m} = \mu_0$ curl $(\chi \cdot \mathbf{H})$. It can be seen that the additional current density contains both a volume term, due to changing H, and surface terms, arising from discontinuities in χ and H.

The program PMU3Dμ uses the fact that the additional effect is a small perturbation. It first calculates the field due to a set of ideal $\mu=1$ blocks in the standard way [5] at regularly spaced points in each block, takes the appropriate derivatives to obtain the current density, and then calculates the additional field. To be more efficient the program can divide the blocks into groups whose fields are to be superimposed. The non-linear effect within each group is not calculated since this does not appear as an additional effect when the groups are put together.

B. *Magnet Blocks*

We first consider the interaction effects between two or more individual permanent magnet blocks. In ref. [7] measurements and calculations using POISSON were shown to be in good agreement for the non-superposition effect of two blocks with perpendicular magnetization. Here we examine the more complex case of an array of 4 periods, 17 blocks, of undulator U5.6.

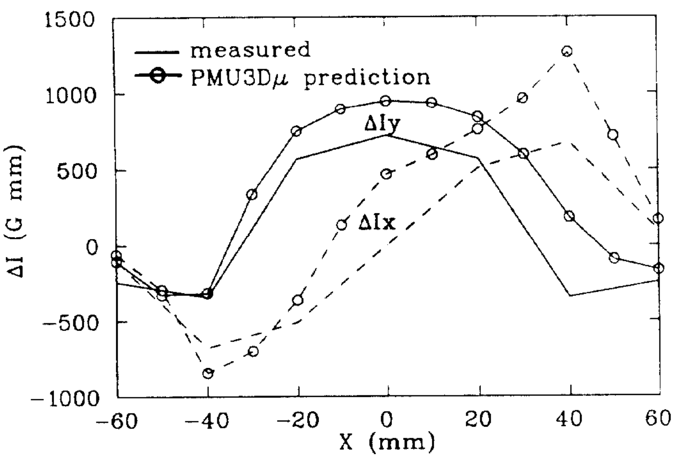

Figure 3. Measured and calculated field integrals arising from the superposition of blocks in a 4 period array.

Figure 3 shows the difference between the measured transverse variation of the field integrals and the values expected from a linear superposition of the fields of the individual blocks. The values calculated with PMU3Dμ are also shown, and it can be seen that there is good agreement, given the small magnitude of the effect. The permeability assumed in these and the following calculations are $\mu=(1.0,1.15)$. The effects are generally much less influenced by $\mu_{\parallel}$. The value of $\mu_{\perp}$ corresponds to that measured by the block manufacturer, Outokumpu Magnets.

C. *Magnet Arrays*

When individually measured linear arrays are put together above and below the electron beam there is another non-superposition effect, but only on the vertical field integral. This top/bottom effect has been measured using two 0.5 m long arrays of the undulator U5.6. Figure 4 shows the difference between the field integrals measured for the two arrays together and the sum of the integrals for the two arrays measured separately. Again there is good agreement of the vertical field integrals with the values calculated with PMU3Dμ, and the horizontal integrals are close to zero as expected.

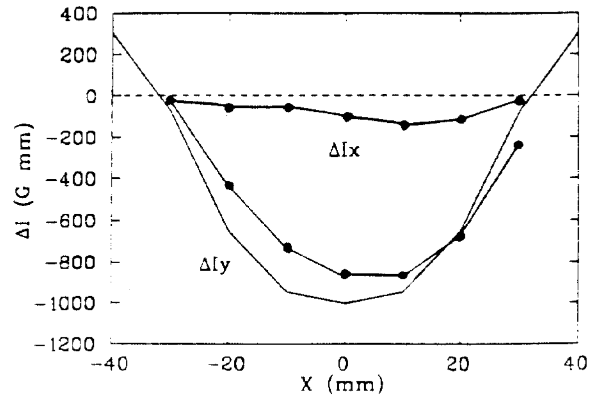

Figure 4. Measured (points) and calculated field integrals arising from the superposition of two magnet arrays.

The difference between the complete undulator, with top and bottom arrays, and the result expected from a linear superposition of the field of the individual blocks is - for the vertical field integral - twice the result shown in fig. 3 plus the top/bottom effect, as shown in fig. 5. The effect on the horizontal field integral is zero, due to cancellation of the distribution shown in fig. 3. In practise however the field integrals of a complete device are not dominated by this effect, but by sum of the errors of the many individual block measurements.

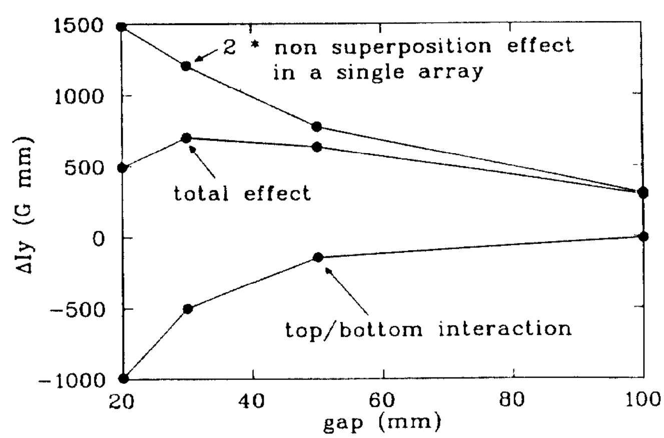

Figure 5. Calculated non-superposition effects for blocks in single and double arrays, and the top/bottom effect.

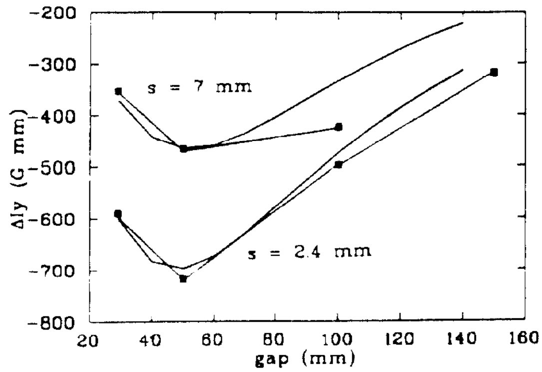

Figure 6. Measured (points) and calculated variation in field integral with gap for two sections of U12.5.

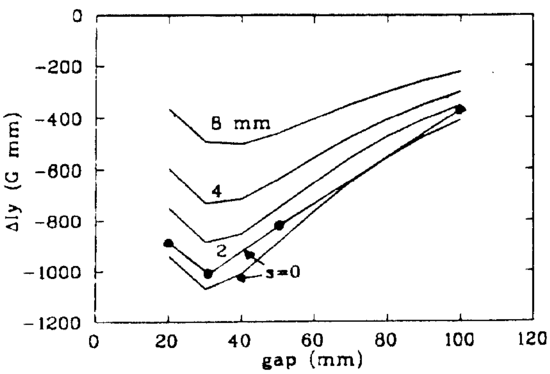

Figure 7. Measured (points) and calculated variation in field integral with gap for two sections of U5.6.

D. *Undulator Sections*

The most important effect in the present case is the non-superposition between two undulator sections, which gives rise only to a vertical field component. Figures 6 and 7 show the integral of this component at x=0 as a function gap, for various separations (s) between the sections. It can be seen that the effect decreases with increasing separation and that there is a complex variation with gap. Good agreement is again shown between measurements and calculation. Figure 8 shows the transverse variation of the field integrals, indicating a small integrated sextupole field of 0.1 T/m. The measured horizontal integral is close to zero, as expected.

Figure 9 shows the calculated longitudinal variation in the vertical field component. It can be seen that the major part of the effect of non-unit permeability occurs within the central half period.

The effect of the field integral would be to cause a variation in the storage ring closed orbit with gap. This could be corrected externally, however it also leads to a difference in the angle of radiation emission in each section. In the present case at 1.5 GeV a field integral of 1 Gm is equivalent to an angular deflection of 20 µrad. Calculations show that this results in a significant reduction in brightness at the seventh harmonic and above. For high harmonic operation therefore it will be important to correct the field integral locally. This will be done using simple air cooled correction coils that will be located on each side of the interface, each with a correction capacity of about 1 Gm.

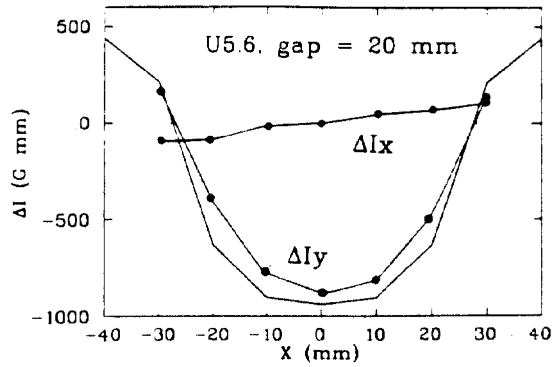

Figure 8. Measured (points) and calculated transverse variation in the field integral for two sections of U5.6.

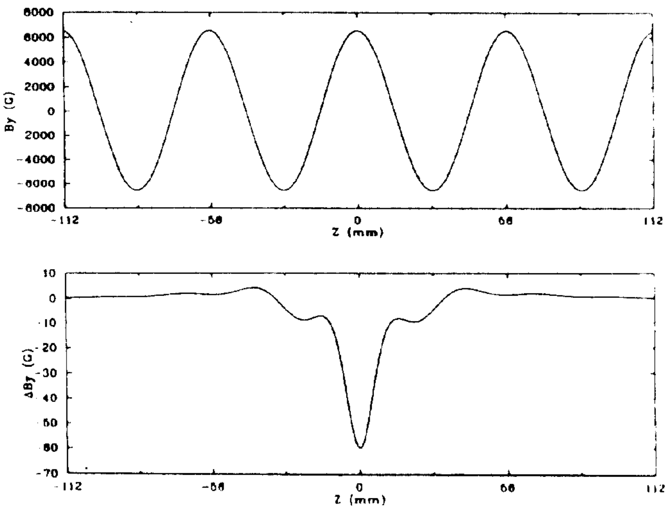

Figure 9. Calculated vertical field component for two sections of U5.6; upper-total field, lower-effect of non-unit permeability.

IV. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge J. Chavanne and P. Elleaume for fruitful discussions about non-unit permeability effects, and K. Aittoniemi of Outokumpu Magnets for carrying out the perpendicular permeability measurements.

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