ACTIVE SHIMMING OF THE DYNAMIC MULTIPOLES OF THE BESSY UE112 APPLE UNDULATOR

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Abstract

APPLE undulators produce strong dynamic multipoles in the elliptical and inclined mode which can significantly reduce the electron beam lifetime and dynamic aperture. A large horizontal dynamic aperture is essential for the top up operation planned at BESSY. The dynamic multipoles generated in the elliptical mode have already been compensated efficiently with L-shaped iron shims. For the inclined mode no passive compensation scheme is available. In case of the strong BESSY UE112 APPLE device flat current wires have been glued onto the undulator chamber, which permit the generation of arbitrary real multipoles for compensation purposes. The dynamic aperture has been recovered in the inclined mode and further improvements in the elliptical mode are possible

INTRODUCTION

The dynamic multipole strength scales with the square of the period length, the square of the peak field and the inverse of the square of the electron energy. Most of the BESSY APPLE undulators have been shimmed for the dynamic multipoles in the elliptical mode using L-shaped shims [1,2]. The 4.2m long BESSY APPLE undulator UE112 has a period length of 112mm and a peak field of 1T. Therefore, the effects on the electron beam are one order of magnitude larger (3Tmm) as compared to the other BESSY devices and the compensation is essential for top up operation [3]. A passive compensation with L-shims reduces the effects in the elliptical mode significantly. In the inclined mode an active compensation is required. Two strategies have been considered: i) rotating permanent magnets at either end of the device; ii) a combination of individually powered flat wires above and below the vacuum chamber. This latter method has been proposed by I. Blomquist [4]. The permanent magnets have the advantage that the minimum gap does not have to be increased. On the other hand, the shape of field integrals is frozen and only the strength can be adapted. Besides the potential for an efficient dynamic multipole compensation in the inclined mode the flat wires provide further options: i) compensation of the residual field integrals in the elliptical mode which can not be removed with L-shims; ii) generation of high order multipoles for the study of beam dynamic effects in a storage ring; iii) simple adjustment of the compensation currents for varying electron beam energy. Therefore, the flat wire option was chosen and implemented at BESSY.

FIELD INTEGRAL EXPANSION

In complex notation the transverse field integral distribution produced by a wire at the horizontal and vertical position of z_0 and y_0, respectively, can be expressed as:

$$\begin{aligned}
&\bar{B}(\bar{x}) = -id\,\frac{\bar{x}_0-\bar{x}}{\left|\bar{x}_0-\bar{x}\right|^2}\\
&\bar{B} = B_z - iB_y\\
&\bar{x}_{(0)} = z_{(0)} - iy_{(0)}\\
&d = \frac{\mu_0}{2\pi} IL
\end{aligned} \qquad (1)$$

where I is the current in the longitudinal direction and L is the length of the wire. For $|\bar{x}|<|\bar{x}_0|$ the complex function $\bar{B}$ is analytic and, hence, it can be expanded into a converging power series around $\bar{x}=0$. The real and imaginary part of $\bar{B}$ can be represented as a converging power series as well which is equivalent to the decomposition into regular and skew multipoles:

$$B_z = -\sum_{m=0}^{\infty} z^m \cdot d\cdot y_0 \cdot \sum_{i=istart}^{m+1} c_{ij}\cdot \frac{z_0^{2(\lceil m/2\rceil + i - m - 1) - \mathrm{mod}(m,2)}}{r_0^{2i}}$$

$$istart = \lceil m/2 \rceil + 1$$

$$j = \mathrm{mod}(m/2) + 1 + 2(i - istart)$$

$$c_{ij} = \binom{i-1}{j-1}\cdot(-1)^{i+j-2}\cdot 2^{j-1}$$

$$r_0^2 = z_0^2 + y_0^2$$

$$\begin{aligned}
&B_y = \sum_{m=0}^{\infty} z^m \cdot d\cdot \sum_{i=istart}^{m+1} c_{ij}\cdot \frac{z_0^{2(\lceil m/2\rceil + i - m - 1) - \mathrm{mod}(m,2)+1}}{r_0^{2i}} -\\
&h(m)\cdot \sum_{i=istart-\mathrm{mod}(m,2)}^{m} c_{ij_1}\cdot \frac{z_0^{2(\lceil (m-1)/2\rceil + i - m) - \mathrm{mod}((m-1),2)}}{r_0^{2i}}\\
&j_1 = 2 + 2(i - istart) + \mathrm{mod}(m,2)\\
&h(0) = 0\\
&h(m) = 1 \forall m \neq 0
\end{aligned} \qquad (2)$$

Using these equations the multipoles of any arbitrary spatial distribution of wires carrying individual currents can be evaluated. The radius of convergence r_0 of the complete wire system is given by the smallest radius of convergence of the individual wires (figure 1).

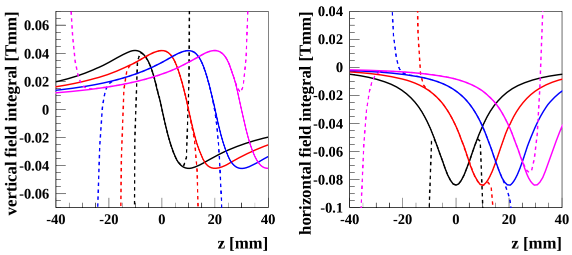

Figure 1: Accuracy of field integral description (y = 0) with multipoles for wire positions of z_0 = 0, 10, 20, 30mm and y_0 =10mm. Thick lines: exact field integrals according to eq.1, thin lines: approximation according to eq.2 with m =20.

The dynamic multipoles can be derived either from tracking simulations or from analytical expressions [5]. Using the response functions of the individual wires the current settings are evaluated from a matrix inversion. Theoretically, the dynamic multipoles can be suppressed by two orders of magnitude (figure 2). In reality several iterations are required for this accuracy since the geometry of the wires is not perfect and, furthermore, the remaining effects of the L-shims have to be cancelled as well. With a vertical offset with respect to the midplane of 10mm the maximum current needed is 10A (figure 3).

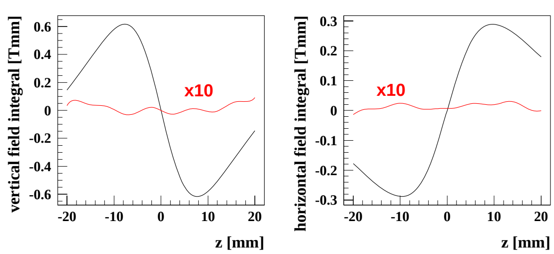

Figure 2: Dynamic multipoles in the inclined mode without (black) and with (red) currents strips. The residuals are enhanced by a factor of ten.

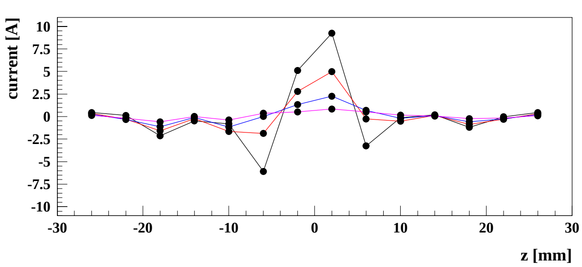

Figure 3: Current settings of the power supplies for gaps of 20mm (black), 24mm (red), 30mm (blue) and 40mm (magenta).

MECHANICAL LAYOUT

The flat wires are made from round copper wires which have been rolled to a cross section of 0.3mm x 3mm. 7 wires are laminated with 0.05mm capton foils on both sides. The wire centres have a distance of 4mm. 14 wires have been glued onto the upper surface and 14 wires onto the lower surface of the vacuum chamber. The 14 wires on each surface are composed of three sets with 7 wires, 4 wires and 3 wires, respectively (figure 4).

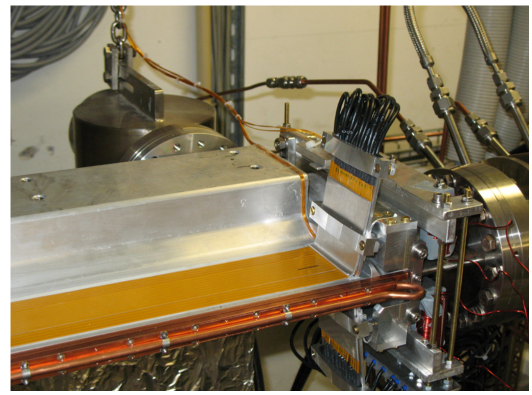

Figure 4: Mechanical layout of the current strips.

Due to symmetry considerations two diagonally arranged wires need the same current and can be powered with one power supply (figure 5), limiting the total number of power supplies to 14.

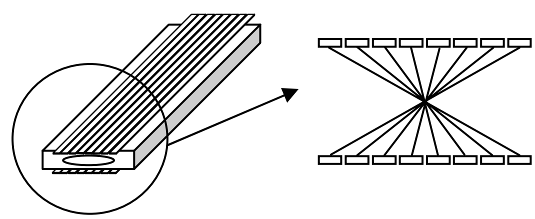

Figure 5: Wiring of the current strips. For clarity only 16 out of 28 wires are plotted.

The wire thickness of only 0.3mm, the lamination of 2x0.05mm and the double-faced scotch tape of 0.2mm enhances the minimum gap by only 1.2mm.

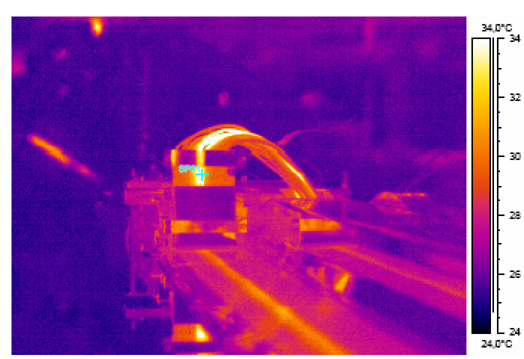

Figure 6: The system has been tested via powering one current strip with 16A. The maximum current will be only 10A. The total temperature variation at the chamber is 3°C. The ambient temperature is 23°C.

The small wire cross section requires a careful cooling design. The wires must have a good thermal contact to the Al-chamber and the camber itself is water cooled from the side (figure 4). The quality of the thermal contact has been checked with an infrared camera which shows a smooth heat distribution without any hot spots (figure 6).

MESUREMENTS

Tune Shift

The field gradients of the undulator produce strong horizontal and vertical tune shifts which depend on the horizontal coordinate. With an appropriate current setting the horizontal tune shifts can be compensated (figure 7) whereas the vertical tune shift is still large. Generally, both tunes can not be compensated simultaneously due to the specific behaviour of the dynamic multipoles which differ from the real multipoles of the wires with respect to origin and shape. However, the effects in the vertical plane are usually smaller due to the smaller betatron function and part of it can be compensated with the ring quadrupoles.

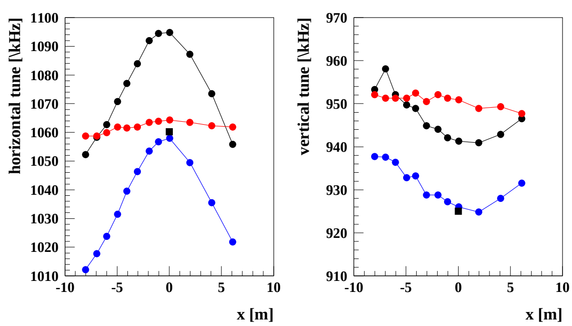

Figure 7: Horizontal (left) and vertical (right) tune shift at gap = 24mm and row phase = 28mm, inclined mode, versus transverse displacement of the electron beam. Black: no currents, no tune forward; blue: no currents, with tune feed forward; red: with currents, no tune feed forward.

Injection Efficiency

During injection the electrons experience transverse excursion between 10-20mm in the high beta sections. The real and dynamic multipoles have to be minimized within this region to provide a good injection efficiency. The current settings used in the measurements of figure 7 recover the full injection efficiency in the inclined mode around 45° tilt angle of polarization (figure 8).

The current settings at ±56mm can further be improved to avoid the drop in injection efficiency. The enlargement of the horizontal dynamic aperture using the flat wires is demonstrated also in another type of experiment where the electron beam is excited to large betatron oscillations and the beam losses are monitored [6].

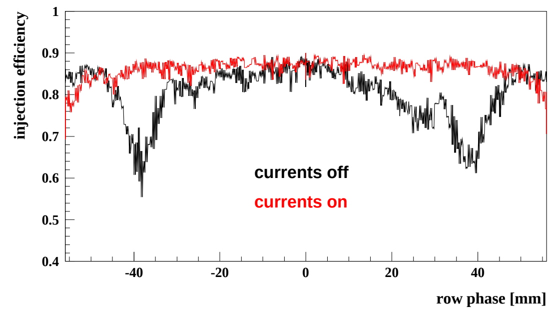

Figure 8: Injection efficiency with UE112 at gap = 24mm and row phases between -56mm and 56mm. Black: currents switched off, red: currents switched on.

Coupling

In the inclined mode an APPLE undulator couples the horizontal and vertical plane. This coupling is efficiently suppressed with the flat wires as demonstrated with source size measurements versus magnet row phase (figure 9).

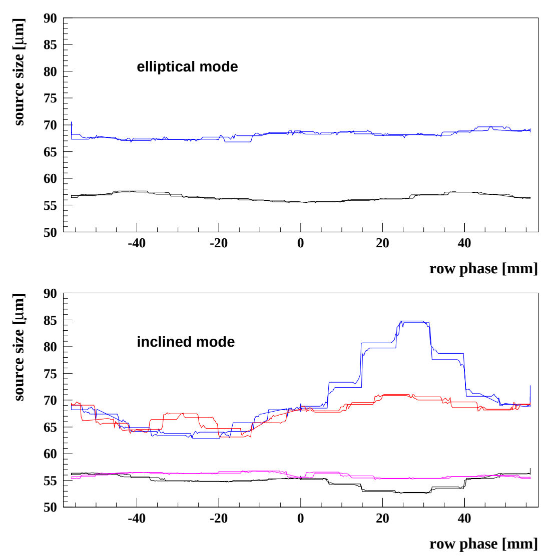

Figure 9: Source size variation with row phase of the UE112 at gap = 24mm in the elliptical mode (top) and the inclined mode (bottom). Black, blue: currents switched off; red, magenta: currents switched on.

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