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2013 J. Phys.: Conf. Ser. 425 032020

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11th International Conference on Synchrotron Radiation Instrumentation (SRI 2012) IOP Publishing
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Operation experience of the UE44 fixed gap APPLE II at SLS

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Abstract. All soft x-ray beamlines at the Swiss Light Source (SLS) are served with variable polarization from APPLE II [1] type and electromagnetic undulators. Three APPLE II type undulators are used: a twin and a single standard APPLE II (UE56 and UE54) and a fixed gap APPLE II (UE44) which follows the adjustable-phase undulator approach by R. Carr [2], [3]. The demand to rotate the linear polarization vector from 0 - 180 ° required all four magnet arrays to be shiftable. This opened the possibility to also vary the energy by a suitable shift of the magnet arrays with a simplified support structure lacking in any gap drive system [4], [5]. The current photon beam quality in linear and circular mode and the pros and cons of the operation of the UE44 will be discussed, namely the underestimated influence of gradients in the complex field distribution. As a consequence the spectra are degraded, but can be recovered by use of distributed coils or by a simple change in the operation mode.

1. Introduction

The photon source of the ADRESS beamline [6] is the undulator UE44, an APPLE II with 75 periods of 44 mm, a total length of 3.4 m and NdFeB magnets with a remanence of $B_r = 1.24\,\mathrm{T}$, delivering a flux density of $B_z = 0.85\,\mathrm{T}$ and $B_x = 0.61\,\mathrm{T}$ ($K_{z0} = 3.5$ and $K_{x0} = 2.5$) at the fixed gap of 11.4 mm. The phase error is about 4°. A preliminary account of this device is reported in Refs. [4], [5]. Briefly, UE44 is based on the APPLE II design where all four magnet arrays can be shifted, which gives full control of the polarization (circular and $0 - 180°$ linear) [7]. Furthermore, the energy can be varied by shifting the magnet arrays [2], [3]. UE44 was the first APPLE II undulator to practically realize this fixed-gap concept. A twin undulator based on this concept followed at the Photon Factory [8].

Figure 1. Shift modi of a fixed gap APPLE II: phase shift ϕ with pairwise shifts of diagonal magnet arrays (left) and energy shift ρ with shift top versus bottom (right).

The relative shift of the diagonal arrays ϕ changes polarization like in the standard APPLE II. The common shift of the two upper versus two lower arrays ρ, in the first approximation, transforms the on-axis transverse components of the field into longitudinal and thereby tunes the energy, replacing the conventional change of the gap. In general, the ϕ- and ρ-shifts show significant coupling. For the circular mode, the values of ϕ and ρ can be found analytically [5]:

$$\phi = 2\arctan R_h \frac{K_{z0}}{K_{x0}}, \qquad \rho = 2\arccos\sqrt{2\left(\frac{E_{max}}{E}-1\right)\frac{1}{K_{z0}^2\cos^2\frac{\phi}{2}+K_{x0}^2\sin^2\frac{\phi}{2}}} \tag{1}$$

As the gap remains constant, the phase shift for the circular mode is constant for all energies. $K_{z0} = 0.934 \cdot B_{z0} \cdot \lambda_U$ is the peak value of the vertical field at $\phi = 0$, K_{x0} the corresponding peak value at $\phi = \pi/2$ for the horizontal field. $E_{\max}$ is the maximum photon energy for the first harmonic (1254 eV for UE44) when the K - value trends toward zero. R_h controls the degree of polarization: $R_h = 1(0.4)$ for 100% (80%) circular polarization for the first and third harmonic according to the figure of merit flux times degree of polarization squared [9], but can be adapted to the demands of the experiment, more flux or higher degree of polarization. For the linear mode, there is no analytic solution. To determine the ϕ- and ρ-shifts for given E and polarization angle α, the following equations have to be solved numerically.

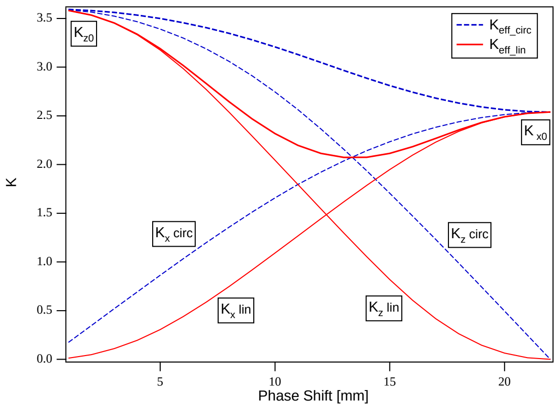

Figure 2. K-values of UE44 versus the ϕ polarization shift for $\rho = 0$ in the circular (cos-function) and linear mode (cos^2-function). At $\phi = 2\arctan(K_{z0}/K_{x0})$ fully circular light coincides with a maximum photon energy (minimum $K_{\text{eff}} = \sqrt{K_z^2 + K_x^2}$) in linear mode, which can be used to verify experimentally the correct phase for circular light.

$$E = \frac{E_{max}}{1+0.5(K_{z0}^2\cos^2\frac{\phi}{2}\cos^2\frac{\phi+\rho}{2}+K_{x0}^2\sin^2\frac{\phi}{2}\sin^2\frac{\phi+\rho}{2})} \tag{2}$$

$$\rho = 2*\arctan\left(\frac{K_{z0}}{K_{x0}}\cot\frac{\phi}{2}\cot\alpha\right)-\phi \tag{3}$$

2. Operational experience

The operation of the UE44 fixed gap undulator is more challenging in comparison to the other APPLE II type undulators at SLS. The UE44 is more than twice as long and is operated at a significant smaller gap (11.4 mm compared to 16 mm), but most important is the specific characteristic of the fixed gap operation. The UE44 is operated so far with earth field coils providing a vertical and horizontal dipole correction. While the vertical correction was set already in the magnetic laboratory, the horizontal correction was not obvious. Apart from the classical configuration with zero energy shift, the spectrum was observed to be too wide with oscillations in the red shift tail. A large but constant horizontal field correction of 156 A·turns (2200 G·cm) can restore the spectrum, as shown in figure 3 for the LH mode.

Simulations are carried out using 3D field maps produced with RADIA [10] as input files for SpontLight [11], a code can track electrons through fields under consideration of all three field components. In fixed gap operation there are on-axis longitudinal fields but they do not result in a focusing as do the vertical off-axis longitudinal fields because of a different phase with respect to the transverse field components. A vertical misalignment results in a vertical focusing, which can be compensated with the horizontal dipole field of the earth field coil, but at $\rho = 0$ the coil is decreasing the field quality. Away from the peak field positions there is a gradient of the vertical field versus vertical position with a large gradient of 100 T/m. But as the vertical beam size is so small, the electrons see a different field with a ΔB/B of 0.1% only, which is a factor of 10 too small to be responsible for the widening of the spectra.

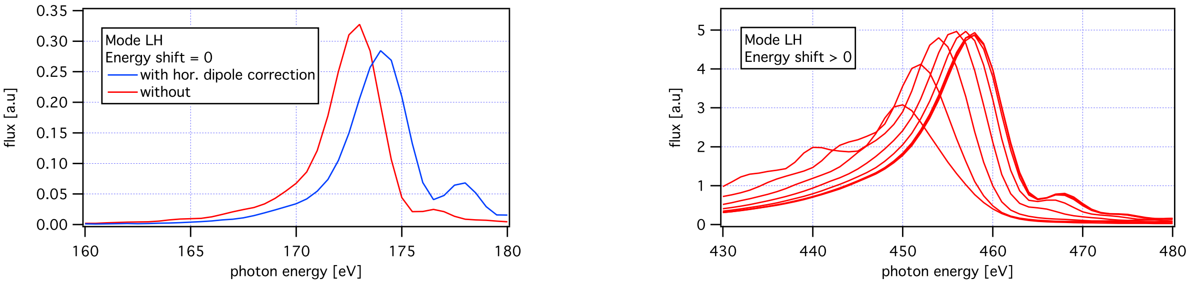

Figure 3. Linear mode: Measured flux into 0.12 × 0.12 mrad^2 at energy shift $\rho = 0$ (left) and with energy shift of 15 mm (right) shown for increasing strength of the distributed horizontal field correction.

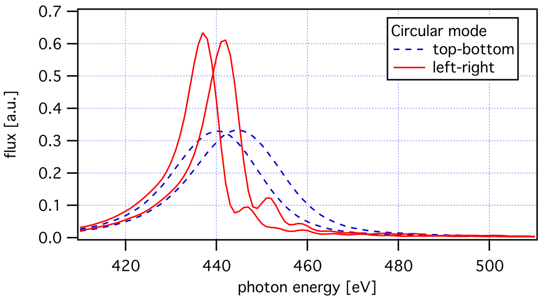

Figure 4. C+/C- for the energy shift in top-bottom and left-right mode. In the top-bottom mode the circular spectra show a smeared out blue edge due to gradients in the vertical field in horizontal direction and non-negligible beam size. In left-right mode, the intensity is doubled and the spectra are recovered.

More harmful gradients can be found in the circular mode: First we observed that the spectra for circular left and circular right had their maxima at different energies. This could be explained with a horizontal misalignment in the the presence of a gradient of the the vertical field (again 100T/m). So the effective field was different for circular left and right. Once corrected, the spectra had equal energies but the blue edge was found to be smeared out. A widening of the blue edge of the spectral line is a clear hint to an energy effect, because all angle effects like emittance and finite aperture result in a red shift. Indeed, the rather large width of the electron beam ($\sigma_x = 111\,\mu$m) combined with the field gradient, leads to exactly the widening of the blue edge.

A solution was found in the functional principle of the fixed gap undulator: The energy shift which has been implemented with a shift of top versus bottom magnet arrays can also be realized with a shift of left versus right magnet arrays. In this setup the magnetic field has gradients in the vertical direction (see figure 5) and because the vertical beam size with $6\mu m$ only is significantly smaller than the horizontal the influence is much smaller. As expected, the change of the setting mode results in a significant improvement of the spectra (see figure 4).

3. Conclusion

Operation of a fixed gap APPLE II at a storage ring is challenging. Field gradients in conjunction with the size of the beam are getting important. The UE44 works well with adapted operation modes and the use of a dipole correction coil. Systematic studies including adjustments of the undulator are elaborate, because the fixed small gap has to enclose the vacuum chamber tightly. The integration of the vacuum chamber in the undulator would allow an in-situ remote controlled

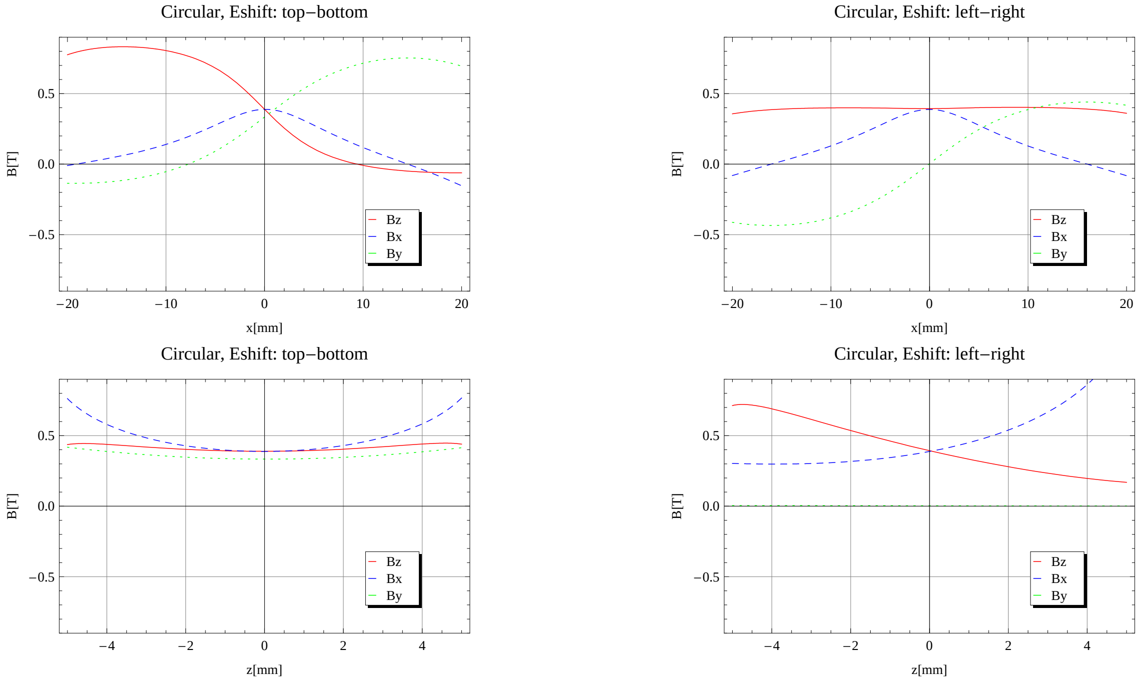

Figure 5. Field distribution for the circular mode in top-bottom (left) and left-right (right) energy shift setup. The gradient of the vertical field inl x-direction (horizontal) broadens the spectrum. The gradient in z-direction (vertical) is harmless because of the small vertical beam size.

alignment. Linac based FEL with small emittances should not be affected by the field gradients and fixed gap undulators including APPLE II may be considered as cost effective options. However, the highest flexibility APPLE II operation is based on 4 shiftable axes combined with a gap drive. This allows the fixed gap operation at different gaps and allows a linear relation between the polarization angle and the energy shift in inclined mode, as described in [5].

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