TOLERANCE STUDIES FOR APPLE UNDULATORS IN FEL FACILITIES*

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Abstract

Errors in the undulator fields are a potential source of performance degradation especially in FELs where the undulator sections reach lengths of up to 100m. The strong transverse field variations of APPLE undulators tighten the tolerances even further. Beyond sorting methods of the magnetic blocks, the shimming of undulators is a widely accepted tool to improve the field quality of undulators and wigglers. In order to calculate realistic tolerance margins for undulator errors it is essential to take the effect of the shimming into account when the FEL performance is simulated. Furthermore, alignment tolerances have to be included. This paper presents GENESIS calculations for STARS, the planned BESSY FEL test facility, and for the 4GeV lattice of the LCLS.

INTRODUCTION

In many 3^{rd} generation light sources the magnetic properties of the transition metals and rare earth metals are studied with circularly polarized light as produced by helical insertion devices. Above 3000eV quarter wave plates can be efficiently used to transform linear polarized light from a planar undulator to circularly polarized light. For lower energies helical undulators have to be used. The APPLE II is the preferred undulator design for storage ring application worldwide since it delivers the highest magnetic field among all helical devices. Also fourth generation facilities such as the proposed Soft X-ray FEL at BESSY [1, 2] or the hard X-ray SASE-FELs currently under construction [3, 4] consider using APPLE type undulators. While the electron beam bunching could be accomplished with planar devices the circular radiation would be produced by helical undulators, in the final radiator in an cascaded HGHG-FEL or in the last modules of a SASE-FEL. Due to the complicated magnet structure APPLE undulators are sensitive to magnet block errors and careful shimming is required. Furthermore, systematic errors based on a displacement or a tilt of the magnet girders due to the strong 3D-magnetic forces or alignment errors have to be minimized. Finally, the focusing effects which depend on the state of polarization have to be compensated for. Based on the relaxed tolerances of planar devices, a crossed undulator scheme for a SASE-FELs has been proposed [5]. As above, the bunching is achieved by planar undulators. At the end planar undulators with the field direction tilted by 90° with respect to the leading undulators are installed. The light pulses from both undulators overlap behind a monochromator producing circularly polarized light. Polarization switching is achieved with a phase adapter between both undulators. The technical realization of this concept is straight forward, however, the spectral performance is significantly lower as compared to the light produced with an APPLE device: the intensity is reduced by an order of magnitude and the degree of polarization is only about 80% [6, 7]. Hence, an APPLE design would be the preferred solution for the radiation production if the required tolerances can be achieved. In this paper we concentrate on the impact of random and systematic field errors on the FEL performance.

UNCORRELATED ERRORS

Due to the split magnet arrays of APPLE type undulators the electron is exposed to the inhomogeneous field distributions of up to four magnet blocks at a time. Though the magnet material has improved a lot within the last years [8], a careful characterization and sorting of the magnet blocks is still necessary to reduce the following shimming effort to an acceptable level. APPLE undulators could also be optimized via horizontal and vertical block movement, however, this has an impact on the minimum gap and row shift dependent field integrals are introduced [9]. Usually, shimming strategies accept a limited beam wander and only a small number of shims is applied to confine the trajectories to a certain band.

In the FEL code GENESIS [10], undulator errors are simulated either as uncorrelated errors leading to unrealistically large trajectory offsets, or as correlated errors which cancel within one period. None of these models describes a real magnetic field after shimming. A program has been written, that calculates shim positions and strengths in a procedure similar to the one applied for the real undulators.

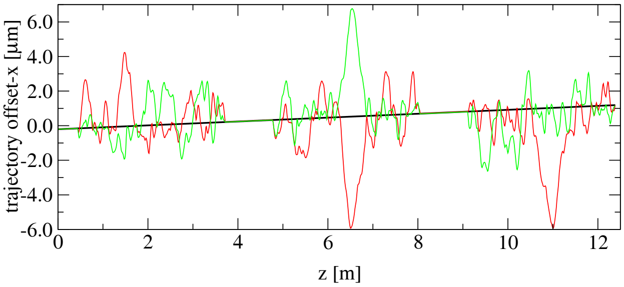

Figure 1: Two typical horizontal trajectories (red, green) calculated for uncorrelated field errors after shimming. The black line indicates the trajectory without errors. It is not zero as the S2E bunch is not perfectly aligned.

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The trajectory is approximated by an arbitrary number of straight lines. The bends of this polygon trajectory are the shim positions, and the strength is calculated such that the beam is on axis at the following shim position. The program enables a quick scanning of shimming options, dependent on the rms field error, the number of shims, the desired residual rms value of the trajectory or the maximum beam wander. The program produces GENESIS lattice files including errors and shims such that the resulting fields represent real undulator fields after sorting and shimming. So far, the program is restricted to planar undulators. Considering that the trajectory offsets are in the μm range and the field roll off takes mm, the results for the APPLE undulators are expected to be similar. Fig. 1 shows typical trajectories resulting from shimmed field errors with an rms value of $3 \cdot 10^{-3}$. The following FEL calculations are based on this new model.

In Fig. 2 a typical result of a statistical overview for the STARS final radiator is given. STARS is the planned test facility for the BESSY HGHG-FEL. The energy is $325 MeV$, the seeding wavelength is $800 nm$, and the presented results where calculated for 2 HGHG stages (5^{th} and 4^{th} harmonics) and $40 nm$ radiation wavelength. The radiator is composed of three $3.3 m$ long modules of 150 periods each. For rms field error distributions of $3 \cdot 10^{-3}$ and $7 \cdot 10^{-3}$ the residual rms trajectory offset after shimming with different numbers of shims is depicted. 16 shims per module are sufficient to reach a rms trajectory offset of $1 \mu m$ for rms field errors of $3 \cdot 10^{-3}$. For larger rms field errors, the number of required shims increases.

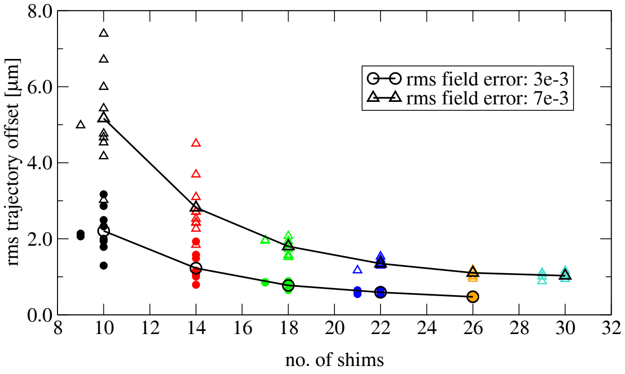

Figure 2: Statistic for different shimming scenarios for STARS: Larger field errors and fewer shims increase the uncertainty in the shimming results. The number of necessary shims increases slower than the field error.

Fig. 3 shows the pulse energies calculated after two modules of the STARS final radiator for different rms errors and different number of shims as a function of the residual rms trajectory offset. Realistic field error distributions reach rms values of $2 \cdot 10^{-3}$. Even for much larger error distributions of $7 \cdot 10^{-3}$ the rms value of the trajectory after shimming is below $2 \mu m$ for approximately one shim for every 7 periods. Maximum trajectory offsets stay below $8 \mu m$. Accordingly there is no strong reduction in the pulse energy, although there is a decline for larger trajectory offsets due to the increasing phase mismatch. But there is no clear correlation between rms field errors and pulse energy. The spread in pulse energy increases with increasing field errors. It stays below 10% for all calculations.

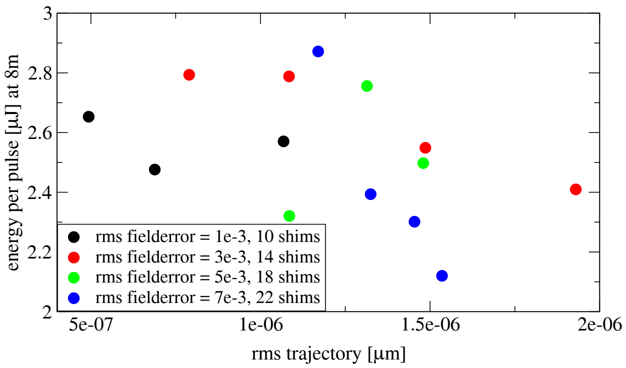

Figure 3: Pulse energy calculated for STARS for different rms field errors and different shimming scenarios. There is no correlation between rms fields errors and pulse energy, when enough shims are used.

CORRELATED ERRORS

A comprehensive overview of undulator tolerances and alignment considerations is given in [11]. As pointed out there, the mechanical tolerances for APPLE devices are tighter than for planar devices. In this paper we investigate the effects of APPLE III type devices [12], where the good field region is larger and where the row shift dependent focusing is weaker than in APPLE II devices. Transverse alignment requirements include mechanical deformations under the strong 3D forces expected for different modes of polarization as well as the geometric alignment of the whole device.

Currently a five meter long APPLE II device is under construction at BESSY for PETRA III equipped with an improved support structure and two additional servo systems. Extensive FEM-simulations have been performed to estimate the mechanical deformations [13]. The main results are summarized in Tab 1.

Table 1: Tolerances calculated for the PETRA APPLE II undulator. x: longitudinal, y: vertical, z: horizontal

Girder displacement	**x/δ** $\mu m/$ μrad	**y/ϕ** $\mu m/$ μrad	**z/θ** $\mu m/$ μrad
Parallel Translation	12	4	5
Parallel Rotation	100	17	7
Anti-parallel Rotation	20	10	0.4

Successful beam based alignment techniques for undulators reach transverse displacements in the $10 \mu m$ range. Although the expected parallel girder translations are small it is still worth to investigate their effect, as the main difference between planar and APPLE-type undulators is the strong roll-off of the horizontal field in combination with the intrinsic increase in in the vertical field.

Angular errors of the girders cause a quadratic variation of $\Delta K/K_0$. Rotations around the horizontal axis can be minimized by additional servo systems. Rotations around the vertical axis can not be compensated for.

The focusing properties of APPLE devices are not fixed as in planar undulators, but depend strongly on the row shift. The vertically focusing forces increase with increasing row shift and are maximal for full vertical polarization. The focal strength for horizontal polarization (no row shift) is a function of the gap and the period length. For the STARS final radiator considerable additional focusing in the lattice is necessary in order to control the beam size for different polarizations. In addition, transverse undulator offsets cause unacceptable beam steering. Both the focusing and the trajectory correction take place in front of each undulator module. Table 2 lists the necessary quadrupole strengths for different types of polarization for STARS.

Table 2: Focusing strength for the STARS final radiator for different polarization

Polarization	K_x^2	K_y^2	**Q1**[T/m]	**Q2**[T/m]
Horizontal	0.626	0.374	0.4	-0.8
Circular	0.068	0.932	0.7	0.7
Vertical	-0.889	1.889	2.3	3.7

For realistic estimation of FEL performances it is essential to use Start-To-End (S2E) bunches, that have been tracked through the complete accelerating structures. In order to only study the effect of the APPLE undulators, a S2E bunch has been tracked to the beginning of the final radiator without introducing errors to the preceding devices. Therefore all calculations start with an identical bunch and differ only by the representation of the final radiator.

Parallel Girder Displacement

Fig. 4 shows the power emitted by STARS for different degrees of polarization and parallel girder displacements. For circular polarization (solid line) the peak power is $\approx 30\%$ higher than for horizontal polarization (dashed line) due to the improved coupling to the radiation field. Purely vertical polarization (dash-dotted line) reaches even higher peak power because of the strong vertical focusing. The reduction in peak power due to undulator offsets (black: no offset, red: $25\mu m$, green: $50\mu m$) depends strongly on the optics and the trajectory correction applied. Largest deviations occur for vertical polarization. With less than 1.5% it is negligible for $25\mu m$ offsets. At $50\mu m$ the reduction of the peak power rises to 8%. For comparison, losses calculated for a planar undulator amount to 1% and 3.3% for $25\mu m$ and $50\mu m$ offset respectively. Offsets of $50\mu m$ lead to power reductions of 3.7% for horizontal and 1.4% for circular polarization. In view of the achievable mechanical tolerances quoted above, parallel girder displacement are of little concern. Due to the trajectory correction, maximum offsets stay below $10\mu m$ in all cases, and thus the field variation is small.

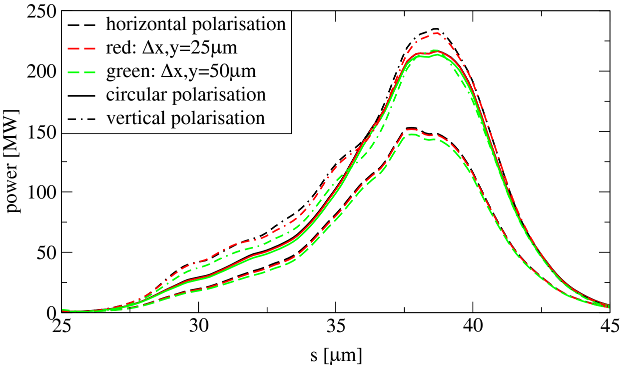

Figure 4: STARS: Temporal power for horizontal (straight line), circular (dashed) and vertical (dash-dotted) polarization and different girder offsets (black: no offset, red: $25\mu m$, green: $50\mu m$). The power reduction for $25\mu m$ is negligible.

Parallel/Anti-parallel Girder Angle

When an undulator is longitudinally tilted, a potentially straight trajectory will be closer to the magnetic poles at the beginning and the end of the undulator, thus the electron bunch experiences the quadratic increase of the vertical field. In a similar way, horizontal rotation of one girder with respect to the other will lead to a quadratic reduction of the field towards the ends of the undulator. Relatively large rotations of $200\mu rad$ correspond to K-value variations of up to $3{\cdot}10^{-3}$ at the ends of each module. These parallel and anti-parallel girder rotations where simulated for horizontal, circular and vertical polarization for the STARS radiator using a S2E bunch. The results are listed in Tab. 3 The excess of power for anti-parallel displacement, i.e. decreasing K-value, is explained by a quasi tapering function of the reduced K-value in the rear part of each undulator module where most of the power is produced. The losses below 2.5% are tolerable.

Table 3: Variation of the peak power in $\%$ for girder rotations of $200\mu rad$.

Polarization	**horizontal**	**circular**	**vertical**
parallel	-2.25	-2.00	-2.50
anti-parallel	+1.70	+1.50	+2.14

LCLS

The 4GeV lattice [14] of the LCLS has been chosen as a convenient test bed for the application of APPLE undulators in SASE-FELs. The energy is more than 10 times higher than in the STARS project, and the radiation wavelength of $\lambda_s = 1.5nm$ lies well within the range of the transition metals where the APPLE undulator is the means of choice for the production of variable polarization.

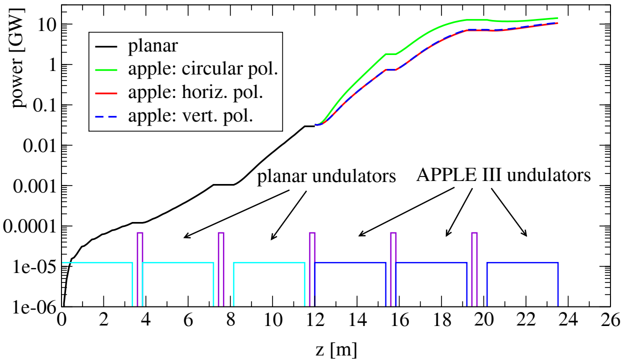

Figure 5: LCLS: Undulator configuration with three planar and three APPLE III undulators. The saturation power for circular polarization (green) is higher due to the optimal coupling.

The lattice consists of a series of undulators with 112 periods, $0.03m$ long. It has a FODO focusing structure with one quadrupole between the undulator modules, see Fig. 5. In planar mode, saturation is reached after $\approx 20m$, or six modules. The saturation power is $10GW$. In order to reach more than 99% polarization APPLE undulators need to be installed before the power reaches $100MW$ in the forth module. Again, a S2E-bunch [14] has been used. All simulations start with the S2E-bunch tracked trough the first three undulator modules in planar mode and differ by varying representations of the following three APPLE undulator modules, only. Wakefields are included in the calculations.

Uncorrelated Errors

Due to the higher energy no additional focusing or trajectory correction had to be applied in order to control the linear optics. Even with 10 shims only per module, the residual trajectories after shimming stayed below $1\mu m$ rms. The maximum power reduction detected in a couple of test runs for rms errors of $3 \cdot 10^{-3}$ was below 8%. It seems that phase shimming might improve the results.

Correlated Errors

Also for correlated errors the lattice turned out to be rather insensitive, due to the larger electron energy. Parallel girder displacements of $50\mu m$ caused trajectory offsets below $7\mu m$ rms, resulting in power reductions below 2%.

Largest effects are seen for parallel and anti-parallel girder angles, resulting in quadratic deviations in K of $3 \cdot 10^{-3}$ at the ends of the modules. The tapering effect for reduced K-values is larger than in STARS with a power increase of 5.7%, whereas power losses of 6.4% were detected for increased average K-values.

CONCLUSION

It has been shown that shimming of the undulators can restrict the residual electron trajectory below $2\mu m$ rms, where the field roll-off in APPLE undulators still is negligible. Mechanical tolerances for APPLE III undulators have been investigated for two different FEL configurations. For the low energy HGHG-FEL the focusing properties of the APPLE undulators require additional optical corrections, and trajectory compensation is mandatory. With the mechanical stiffness realizable for new devices, two additional servo systems and beam based alignment no significant impact on the output power is expected. For the high energy SASE-FEL only the girder rotations caused a variation of the output power of up to 7%, when no optic corrections are applied. This result could be improved by trajectory realignment and beam size control. The transverse field variations and the focusing properties of the APPLE III design are relaxed compared to the APPLE II design. APPLE III type undulators are well suited to be incorporated in HGHG and SASE FELs in the VUV and soft X-ray spectral range.

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