DEMONSTRATION OF A TRANSVERSE GRADIENT UNDULATOR IN AN X-RAY FREE-ELECTRON LASER

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Abstract

Modern synchrotron light sources employ various types of undulators to generate highly coherent and well collimated X-rays. A large and homogeneous magnetic field around the beam axis is typically the preferred configuration, since it simplifies both alignment and operation. Nevertheless, a nonhomogeneous field, such as that of a transverse gradient undulator (TGU), offers attractive possibilities for advanced operating modes, for example enabling large bandwidth operation in a free electron laser. In this contribution, we present the first beam-based characterization of such a TGU for various magnetic field gradients and X-ray polarization settings, and we compare the experimental results with corresponding simulation data. The measurements were carried out at Athos, the soft x-ray beamline of SwissFEL. This line employs Apple X undulators, whose independent radial and shift motion of all four magnetic arrays makes them uniquely capable of generating the required transverse gradients.

INTRODUCTION

Modern light sources, like free-electron lasers (FEL), employ undulator modules for generating coherent and well-collimated X-rays. The fundamental undulator equation describes the resonance condition, which is used to calculate the photon wavelength (λ) based on the undulator period length (λ_u) and the Lorentz factor (γ) of the electron beam, incorporating the K-value:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right). \tag{1}$$

Typically, a transversally homogeneous magnetic field around the beam axis is preferred inside the undulator modules, due to its simplicity in alignment and operation. However, certain non-homogeneous magnetic fields, such as those produced by transverse gradient undulators (TGU), offer significant advantages for advanced operating modes.

A TGU is characterized by a gradient in the undulator field strength, known as the K-value, along a specified transverse direction, orthogonal to the electron beam's propagation. Such a design implies that electrons traversing the undulator experience varying K-values depending on their transverse path offset from the central electron trajectory. This contrasts with conventional undulators that aim for a constant magnetic field region to ensure stable photon generation, even if the electron beam trajectory deviates slightly from the magnetic axis.

While TGUs require much more precise alignment compared to their no-gradient counterparts, they offer attractive possibilities for advanced operating modes. These include: (1) Electron Energy Spread Compensation: They can be utilized to compensate for large energy spreads in FEL oscillators [1] and plasma wakefield accelerators [2]. (3) Large Bandwidth Operation: TGUs can enable large bandwidth operation in free-electron lasers (FELs) [3].

The Athos soft X-ray beamline at SwissFEL [4], at PSI in Switzerland, employs 16 APPLE-X undulator modules [5]. They offer full polarization control for the full K-range (0.9 to 3.8) with the exception of reduced K-values around linear polarizations of $\pm 45°$. The undulator modules have four magnetic arrays, each of these are equipped with their own motor for radial and longitudinal movements, which define the undulator strength and polarization, respectively. Additionally, the independent radial movement makes these modules very suitable to create transverse K-gradients of arbitrary strength.

Each of the 12 ton APPLE-X modules is installed on top of a 5-axis remote positioning system, based on motorized camshafts. This is to move the modules to their correct transverse positions, evaluated from dedicated photon-beam-based alignment procedures. Furthermore, the Athos undulator line employs a feedback system to stabilize the electron trajectory passing through it. It uses beam position monitors between each two undulator modules to determine its actual position and sends corrections to the neighbouring corrector dipoles.

MODELLING AND SIMULATIONS

In an APPLE-X undulator module a K-gradient can be achieved by opening two neighbouring arrays radially more ($r + \delta r$) in relation to the remaining two arrays (r). Thus the effective K-value ($\hat{K}$) can be calculated as:

$$\hat{K} = \frac{1}{2}K\left(r\right) + \frac{1}{2}K\left(r + \delta r\right)\ . \tag{2}$$

The TGU model for APPLE undulator devices was described in detail in [6]. From this, we can derive a functional model to describe the K-gradient, also described as α, as:

$$\frac{d\hat{K}}{dx} = \frac{1}{2\sqrt{2}}\left[\frac{dK}{dr}\left(r + \partial r\right) - \frac{dK}{dr}\left(r\right)\right] \tag{3}$$

Calculations were done with the RADIA code for circular and linear polarizations. This revealed a very good agreement between the model and simulations in the circular polarization case (see Fig. 1) with differences well below 1%. However, a significant mismatch for the linear case can be observed. For this reason we adapted the model for linear

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polarizations empirically by adding a simple scaling factor of $\sqrt{2}$ as a stop-gap measure:

$$\frac{d\hat{K}}{dx} = \frac{1}{2}\left[\frac{dK}{dr}(r+\partial r) - \frac{dK}{dr}(r)\right]. \tag{4}$$

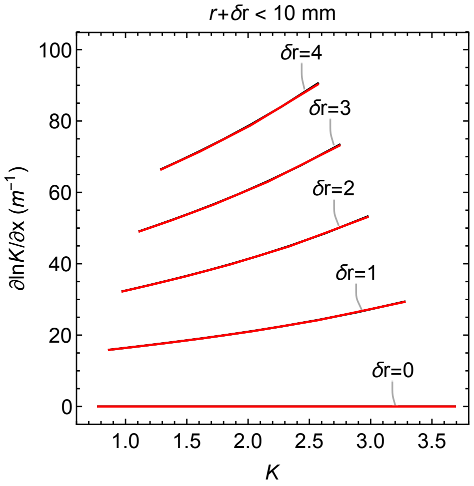

Figure 1: K-gradient comparison for model (red) vs. simulated data via RADIA (black) for circular polarization. It is difficult to see differences by eye, indicating a very good agreement.

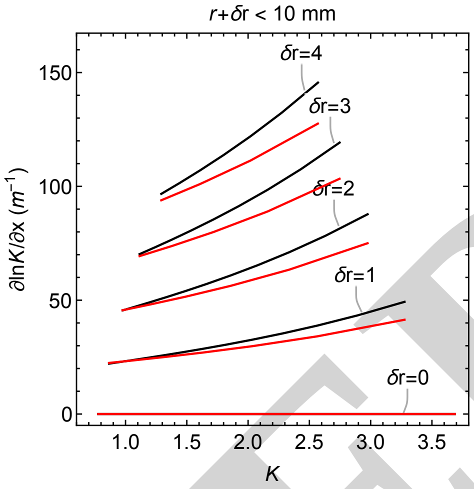

Figure 2: K-gradient comparison for model (red) vs. simulated data via RADIA (black) for circular polarization. There are significant differences between them, which needs further study.

With this adjustment we still see some differences though (see Fig. 2). Especially towards higher $\hat{K}$-values and for the highest K-gradients the differences are increasing. The RADIA calculations show K-gradients up to 13% stronger compared to the adapted model. In this case a better understanding of the mismatch is still needed and will be part of our future studies.

MEASUREMENTS

After implementing the model in a prototype controls application for SwissFEL to set K-gradients in the undulator line, studies were executed to determine the quality of the gradients and to verify it against the model. For time limitations we chose to work with 9 undulator modules only, which were specifically re-aligned to ensure a good overlap of their magnetic axes with the electron trajectory. These modules were then set-up to lase at 400 eV. To scan the gradient in the transverse direction all undulator modules in use were shifted as a group via their individual remote-positioning systems in the same direction, simply by adding offsets to their transverse positions. Meanwhile, the electron beam was kept fixed at its initial trajectory with the help of the feedback system. The K-gradient is characterized by measuring the photon energy of the produced radiation for different transverse positions. For detecting the average photon energy of the resulting spectrum a large bandwidth spectrometer was employed.

For circular and linear horizontal polarizations several gradients were set, their transverse position scanned and the photon spectra measured. Figure 3 shows the results in circular polarization, while Fig. 4 shows them for linear horizontal polarization.

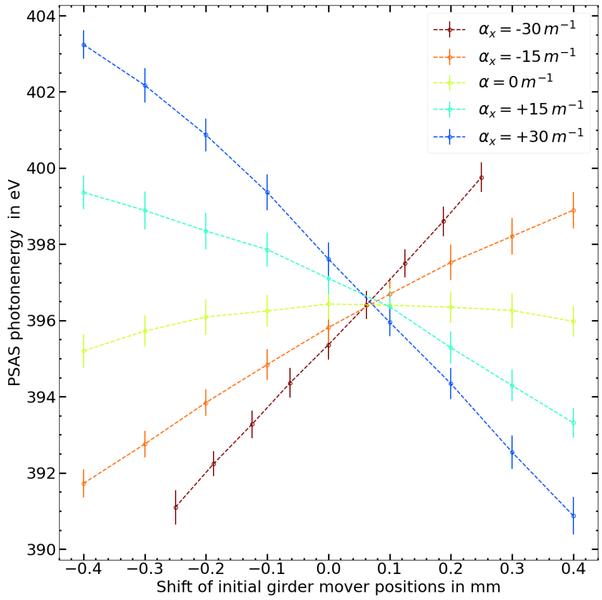

Figure 3: Photon energies vs. transverse positions for measured points in circular polarization at 400 eV.

The measured photon energies measured at all transverse positions can be converted into K-values with the knowledge of the electron beam energy (3.34 GeV) via the Planck-Einstein relation and the undulator resonance condition (see Eq. 1). Figure 5 plots the fitted vs. calculated K-gradients, showing an overall good agreement.

For the circular polarization case one can see a the measured gradients being in average of 10% stronger than the model predicts, which is about twice the combined estimated measurement and fitting errors for this polarization measurement series. However, for the linear polarization case one can observe a stronger measured K-gradients compared to the model predictions with an average of 30%, but with esti-

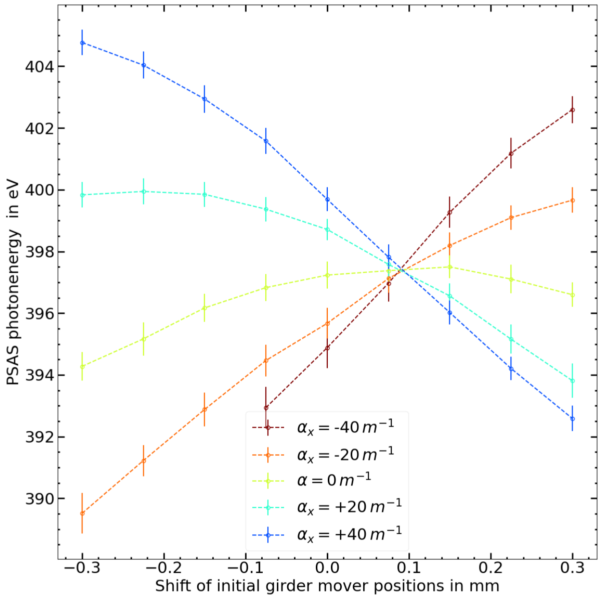

Figure 4: Photon energies vs. transverse positions for measured points in linear horizontal polarization at 400 eV.

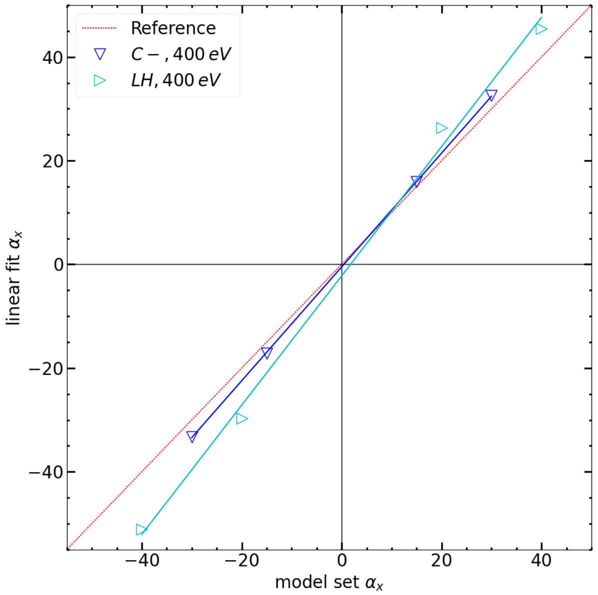

Figure 5: Correlation of model vs. fitted measured gradient values at 400 eV in circular and linear horizontal polarization.

mated measurement and fitting errors of around 10%, due to more non-linearities of K gradients at linear polarizations. The results suggests, that the fitted K-gradients on the measured photon energies are in fact consistently stronger than our model and the RADIA simulations, the reasons of which are currently under investigation. However, it also confirms the consistently stronger K-gradients in linear polarizations found in the RADIA simulations compared to our model. More research is needed to fully comprehend the various differences.

CONCLUSION

In this paper we showed our current model to calculate transverse K-gradients in an APPLE-X undulator module and compared the predictions of this model to K-gradients derived from calculated magnetic field maps in RADIA for various gradient conditions. Furthermore, the TGU was demonstrated with lasing in the Athos beamline for two polarizations and verified by comparing the fitted K-gradients from the measurement data with the ones derived from the model. Overall a good qualitative agreement can be observed among models, simulations and measurements. But the K-gradients derived from the measurements and the simulations are stronger for linear horizontal polarization than the model predicts. Further studies are needed to understand the differences. With the TGU feature successfully implemented and demonstrated, several applications employing this capability are currently studied at SwissFEL.

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