MODELING THE MAGNETIC FIELD OF THE LCLS-I UNDULATOR FOR THZ@PITZ*

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Abstract
An accelerator-based THz source for pump-probe experiments at the European XFEL is under development at the Photo Injector Test Facility at DESY in Zeuthen (PITZ). For the proof-of-principle experiments an LCLS-I undulator is planned to be installed downstream of the PITZ accelerator. The fields of the undulator module 26 have been re-measured at DESY in Hamburg and the results are consistent with earlier SLAC measurements. A model for 3D field reconstruction based on the undulator magnetic measurements has been developed. It includes also a horizontal gradient of the vertical field. Tracking of the 17 MeV/c beam has revealed that the transverse gradient will lead to a significant off-axis trajectory in the horizontal plane. This offset has to be corrected with a steering coil, the design of which is also presented. The performance of the THz generation with the correction coil is discussed as well.

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The axial magnetic field profile was measured using a Hall probe scan along the \( z \)-axis with a step of 0.5 mm.

The measurements are in good agreement with previous measurements at SLAC. The 2\(^{nd} \) field integral is in good agreement with similar measurements at SLAC before transportation of the undulator to DESY.

Fourier transformation to the measured field profile

\[
B_y(x = 0, y = 0, z) = \sum_{n=1}^{N_h \cdot N_U} \{a_n \cos(k_{zn}z) + b_n \sin(k_{zn}z)\}
\]

\[
k_{zn} = \frac{2\pi n}{N_U \lambda_U}
\]

\[
a_n = \frac{2}{L} \int_{-L/2}^{L/2} B_y(x = 0, y = 0, z) \cos(k_{zn}z) \, dz,
\]

\[
a_0 = \frac{1}{L} \int_{-L/2}^{L/2} B_y(x = 0, y = 0, z) \, dz \to 0,
\]

\[
b_n = \frac{2}{L} \int_{-L/2}^{L/2} B_y(x = 0, y = 0, z) \sin(k_{zn}z) \, dz.
\]

\[
L = N_U \lambda_U\quad \text{effective undulator field length}
\]
According to the original design the magnets are slightly canted with a 4.5-mrad opening angle. This results in a horizontal gradient of the undulator.

Modeling the horizontal gradient of the vertical magnetic field

\[
\frac{B_y(x, y, z)}{B_0} \propto \cosh[k_x(x_0 + x)] \approx \cosh[k_x x_0] + \sinh[k_x x_0] \cdot k_x x \sim 1 + \tanh[k_x x_0] \cdot k_x x
\]

\[
\tanh[k_x x_0] \cdot k_x = \alpha
\]

\[
\chi(x, y, z) = -\frac{\cosh[k_x(x_0 + x)]}{\cosh[k_x x_0]} \cdot \sum_{n=1}^{N_h \cdot N_U} \left\{ a_n \cos(k_{zn} z) + b_n \sin(k_{zn} z) \right\} \cdot \frac{\sinh(k_{yn} y)}{k_{yn}}
\]

\[
k_{yn} = k_{zn}^2 - k_x^2
\]
BEAM DYNAMICS IN UNDULATOR

3D magnetic field map including the horizontal gradient based on measurements

\[
B_x(x, y, z) = \frac{\sinh[k_x(x_0 + x)]}{\cosh[k_x x_0]} \cdot \sum_{n=1}^{N_h \cdot N_U} \left\{ a_n \cos(k_z n z) + b_n \sin(k_z n z) \right\} \cdot \frac{k_x}{k_{yn}} \cdot \sinh(k_{yn} y)
\]

\[
B_y(x, y, z) = \frac{\cosh[k_x(x_0 + x)]}{\cosh[k_x x_0]} \cdot \sum_{n=1}^{N_h \cdot N_U} \left\{ a_n \cos(k_z n z) + b_n \sin(k_z n z) \right\} \cdot \cosh(k_{yn} y)
\]

\[
B_z(x, y, z) = \frac{\cosh[k_x(x_0 + x)]}{\cosh[k_x x_0]} \cdot \sum_{n=1}^{N_h \cdot N_U} \left\{ -a_n \sin(k_z n z) + b_n \cos(k_z n z) \right\} \cdot \frac{k_z n}{k_{yn}} \cdot \sinh(k_{yn} y)
\]
CORRECTION COIL IN UNDULATOR
To compensate the impact of the horizontal undulator field gradient

Coil design using CST EM Studio

Permanent magnet, $\mu=1$

Vacoflux, $\mu=1000$

Simulated field profiles

Reference particle trajectories in the undulator with horizontal gradient

$\mathbf{B}_y(\mathbf{mT}) \approx 0.279 \, \text{mT}$
**THZ SASE FEL SIMULATIONS**

ASTRA for the beam dynamics and WARP for THz SASE FEL

**Electron bunch:**
- $<P_z>=17$ MeV/c
- $Q_b=4$ nC
- Temporal flattop $\sim 22$ ps FWHM

**THZ SASE FEL**
- $<\lambda_{rad}>=100$ µm

**Case studies:**
- simulation with a 3D field map with horizontal gradient and without/with compensation coil

**Reference case:**
- simulation with a 3D field map without a horizontal gradient

**Reference particle horizontal trajectories**

**Beam rms sizes along the undulator**

**Simulated THz energy of the SASE FEL pulse along the undulator**

The output THz pulse energy $\sim 0.6$ mJ is recovered

Transverse distribution of THz power density at the output of the undulator $z=3.43$ m

Trajectories in the undulator with horizontal gradient

vacuum chamber border
CONCLUSIONS

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- The LCLS-I undulator L143-112000-26 is planned to be installed downstream of the PITZ accelerator for the proof-of-principle experiments on the accelerator-based THz source for pump-probe experiments at the European XFEL.
- The undulator field re-measured at DESY is in good agreement with previous measurements at SLAC.
- A model was implemented for 3D field reconstruction based on magnetic measurements, including the horizontal field gradient.
- Tracking the beam with the modeled field revealed a significant horizontal offset of the beam, which cannot be compensated by the initial beam angle.
- A correction coil was developed to compensate for this effect.
- Beam dynamics simulations showed the possibility of almost complete compensation of the undulator field horizontal gradient effect with the correction coil for both the beam trajectory and envelope, as well as for the radiation performance of the THz SASE FEL.