Performance of Small-Gap Undulators at the SLS Intermediate Energy Storage Ring

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Abstract. The Swiss Light Source (SLS) at the Paul Scherrer Institut (PSI) became the first medium energy synchrotron user facility to rely on the high harmonic operation of small gap, short period undulators to extend high brightness radiation into a regime (3-18 keV) otherwise only accessible using lower brightness wigglers or operation at higher electron beam energy. Today several facilities with beam energy 2-3 GeV follow a similar route. A PSI/SPring-8 collaboration was formed to install and operate the first in-vacuum undulator shortly after commissioning of the SLS storage ring (2.4 GeV) in 2001. The goal of the joint project was to prove that high harmonic operation of small period undulators at small gaps is a valid concept to operate the PX-I beamline at 1 Å under user operation conditions. The performance of the PX-I beamline proved to be excellent and launched the installation of meanwhile 4 new in-vacuum undulators. Having routinely operated such devices for 5 years, our experience confirms that (1) the concept of operating short period undulators (19-24 mm) on higher harmonics (11./13.) is valid, (2) reliable small gap (5-6 mm) undulator operation is feasible in the presence of top-up injection, and (3) during gap scans the photon beam can be stabilized to sub-μrad precision using non-intercepting photon beam monitors.

Keywords: short period undulator, high harmonic operation, x-ray beam stability.

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INTRODUCTION

In an undulator, radiation from different periods interfere coherently, producing on axis ($\theta=\psi=0$) sharp harmonics at wavelengths $\lambda_n = \lambda_u / 2n\gamma^2(1 + K^2/2)$ of the fundamental ($n=1$), where B_0 and λ_u are the undulator peak magnetic field and period, γ the relativistic electron energy, and $K=0.934 \cdot B_0[T] \cdot \lambda_u[cm]$ the deflection parameter in practical units. Instead of increasing the beam energy, a short undulator periodicity enables (1) the emission of high energy x-rays, and (2) the increase of brightness due to a larger number of periods N per unit length. Besides generating and controlling low emittance electron beams, short period undulator technology is crucial to lower construction and operation costs of synchrotron light source and SASE-FEL facilities.

Small-gap operation is needed to obtain a sufficient strong magnetic field on-axis. This again puts stringent requirements on the engineering design as well as the magnetic and operational performance. In the past 15 years short period undulators have been developed using both permanent magnet (PM) [1] and superconducting (SC) [2] technology. A breakthrough in the in-vacuum design pioneered by KEK/SPring-8 [3] allows operation of PM magnet arrays (high coercivity NdFeB material) inside vacuum, eliminating the physical limitations of vacuum chambers and allowing a much smaller gap. Because of potential radiation damage, $\text{Sm}_2\text{Co}_{17}$ magnets have also been used [4]. According to a recent proposal [5] 30%-50% higher magnetic fields can be achieved compared to the performance discussed in this paper, if the PM arrays are operated close to liquid nitrogen temperatures.

Here we report on the performance of in-vacuum undulators operated at room temperature. In a PSI/SPring-8 collaboration, the U24 undulator (period: 24 mm) has been the first device routinely operated at minimum gaps of 6-7 mm in top-up mode at the PX-I beamline for 3.5 years. This success launched the construction of 4 new U19 in-vacuum undulators with shorter period (19 mm) to increase the brilliance beyond 10 keV. The undulators have been manufactured by 2 companies (NEOMAX: 3 devices and DANFYSIK: 1 device). They are operated at the beamlines PX-I and PX-II (protein crystallography), μXAS /FEMTO (microfocus, time-resolved x-ray absorption) and cSAXS (coherent small angle x-ray scattering). The devices have a length of 2 m and are installed in low-beta straight sections ($\beta_y \simeq 1$ m).

FIGURE 1. U24 in-vacuum undulator: (a) The undulator is installed on a mover-system for in-situ alignment. Large area scintillator detectors mounted above and below midplane at the downstream taper section are used to monitor electron losses at small gaps. Window frame steering coils are mounted at the up- and downstream end for FF correction of the electron beam during gap change. (b) New design (proposed by Kitamura) of a watercooled, flexible taper transition to minimize the impedance and resistive wall heating when the electron beam enters the small gap region. For the same reason, the magnet arrays are also watercooled and covered with a Cu/Ni sheet of thickness 60/50 μm .

DESIGN AND CONSTRUCTION

Nominally the same design ('SPRING-8 type') is used for all undulators. The new U19 undulators have been conceptually designed and specified by the PSI based on the operational performance of the U24 device (see Figure 2 and 3). The manufacturer has been responsible for mechanics, magnetics (including shimming) and vacuum, and the PSI for all assemblies which are crucial for regular operation: motorization and control, mover-alignment, taper sections, vacuum pumps, final bake-out, beam position monitors, ID- interlock, loss monitors and feedforward (FF) correction coils.

Mechanics. The drive system is designed to enable scanning operation with 1 μm gap resolution in the range 4-40 mm. If needed, the standard 1-motor drive could be switched to a 2-motor drive to control the gap parallelism below 5 μm . The gap is measured with 2 incremental linear encoders attached to the out-vacuum beams. In-situ alignment with stored beam is used to precisely center the undulator prior to small gap operation (see Figure 1a).

Magnetics. The U24 (U19) devices are of the hybrid type, with 57 (96) periods and effective field $B_{eff}=0.84\text{ T}$ (0.86-0.94 T, depending on the magnetic material used) at minimum gap of 6 (5) mm. To study possible long term radiation damage (see Figure 3a), the U19 undulators have been built using 3 different magnet materials (NdFeB: NEOMAX-32EH, NEOMAX-27VH and $\text{Sm}_2\text{Co}_{17}$). To guarantee UHV performance, the NdFeB ($\text{Sm}_2\text{Co}_{17}$) magnets are coated with TiN (Ni). The vacuum performance typically is $2 \cdot 10^{-10}$ mbar (no beam) and $(2-4) \cdot 10^{-9}$ mbar (with beam, multibunch, 330 mA).

To manufacture high-performance magnet arrays, optimization must proceed in several steps: (1) single magnet block characterization and sorting, (2) 1/2-period module characterization and sorting, (3) undulator field correction by in-situ sorting (1/2-period module exchange and swapping) [6], and (4) multiple trim magnet ('magic finger') correction. The end field terminations consist of specific modules which keep the field integral variation versus undulator gap small.

Measurements. For in-situ undulator field correction a flip-coil or stretched wire system is used for first and second field integral optimization, and Hall-probes for trajectory and phase shimming. To check the magnetic performance after delivery, magnetic measurements are repeated at PSI. Because Hall-probe measurements are difficult, the pulsed wire technique is used instead to confirm the on-axis trajectory straightness after the final assembly of a device.

FIGURE 2. U24 undulator: First field integrals (flip-coil measurement) and on-axis trajectories (Hall-probe measurement) for the gap range 6-40 mm after in-situ magnetic field correction described in reference [6].

FIGURE 3. U24 undulator at PX-I beamline: (a) The measured spectrum of the 7th harmonic compared to the theoretical spectrum. To calculate the theoretical spectrum, the energy spread and the emittance of the electron beam has been included. No evidence of possible degradation of the magnet material (NEOMAX-32EH) has been found after 3.5 years of operation. (b) Sub- μm stability of the X-ray beam can be achieved during gap variation when in addition to (global) FOFB corrections the following corrections are successively applied [7]: (i) FF (ID feedforward tables using local (analogue) BPM- and XBPM-readings) and (ii) slow FB (1 Hz) using XBPM readings. The residual x-ray beam variation is of the order of $1 \mu\text{m}$ measured in 8.6 m distance from the center of the undulator.

PERFORMANCE

Operational. For U24 (U19) user operation the relevant gap range is 6.5(5.5)-12 mm. All U19 in-vacuum undulators show a similar magnetic performance as shown for the U24 undulator in Figure 2. The first field integral distributions both for the vertical and horizontal field are within ± 25 (50) G-cm for the range $x = \pm 10$ (20) mm horizontally. Variations within these limits ensure that any residual higher integrated multipoles are negligible. The on axis trajectory straightness is $\pm 1.5 \mu\text{m}$ (horizontal and vertical). The measured phase error is 2.2° rms (at 5 mm gap), corresponding to a flux degradation of 20% for harmonic 21. Consistent with the magnetic measurement data, without any corrections local orbit changes $< 25 \mu\text{m}$ have been observed in both planes during undulator commissioning for the gap range 5-40 mm using local analogue (Bergoz) BPMs. These systematic changes can easily be corrected by applying feedforward (FF) correction. For global correction the fast orbit feedback (FOFB) system is used, designed to decouple IDs in different straights.

For beamline operation the x-ray stability beam is relevant. The residual walk of the x-ray beam (caused by

FIGURE 4. Illustration of the ID feedforward correction (IDFF): the local analogue "BPM-1/2" and the slow correctors $\Phi_{12/21}$ are not included in the FOFB loop, whereas the fast correctors $\Phi_{11/22}$ as well as the XBPMs are integrated in the FOFB.

FIGURE 5. U19 undulator: Measured flux spectrum at the PX-I beamline. The undulator is designed to operate up to harmonic 11/13, to reach 18 keV at 2.4 GeV.

systematic kicks at the entry and exit of the ID when the gap is changed) can be corrected locally to sub- μ rad pointing stability in two steps as described in Figure 3b. Non-interceptive 4-blade tungsten x-ray beam monitors (XBPMs) [8] installed 8-10 m from the source are used. For the XBPM-calibration we find a linear dependence when the electron beam is parallel displaced inside the ID by local bumps. For the operating range 5-12 mm there is no background due to up- and downstream dipole radiation. Because the first harmonic energy is well matched to the spectral response of the tungsten blades, the bending magnet background is electronically (and geometrically) suppressed. Also the calibration over this range does not change drastically, because the change in shape of the detected beam caused by the convolution of energy and angular distribution is small.

Spectral. Using the field shimming methods mentioned, despite the small magnetic gap short period undulators can be built that produce nearly the theoretical brightness at high harmonics. Undulators with small phase errors ($< 2.5^\circ$) cause a minor reduction in flux and brightness. It is rather the emittance and the energy spread of the electron beam which cause a reduction in intensity with increasing harmonic number.

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