Synchrotron Radiation News

ISSN: 0894-0886 (Print) 1931-7344 (Online) Journal homepage: https://www.tandfonline.com/loi/gsrn20

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Introduction

In-vacuum undulators (IVU) [1–7] are used extensively at light source facilities, in particular at medium-energy storage rings, where these devices are the main sources of high-brightness hard X-rays. The relatively small vertical magnetic gaps that are used in these planar undulators make them rather sensitive to misalignments of magnet arrays with respect to the electron orbit in the vertical plane. Based on commissioning results of undulator-based hard X-ray beamlines at the National Synchrotron Light Source II (NSLS-II)—a Department of Energy Office of Science User Facility at Brookhaven National Laboratory—IVU misalignment was found to be the most frequent cause of spectral "underperformance." It is possible, nevertheless, to restore the performance using a spectrum-based IVU alignment procedure described in this article.

In IVUs, thanks to the absence of a solid vacuum chamber, magnet arrays can be placed close to each other, requiring only a gap of a few millimeters for the electron beam motion. The small magnetic gaps allow the usage of smaller magnetic periods, while reaching high enough deflecting parameter values (K ~ 2) that ensure perfect spectral tunability of an undulator. The use of small magnetic periods allows the increase of the number of periods in an undulator of a definitive length, resulting in an increase of undulator radiation (UR) flux and brightness. IVUs are particularly important for medium (~3 GeV) electron energy synchrotron radiation sources, where only this type of undulator allows reaching the hard X-ray spectral range—a highly desired spectral range for user experiments—with its UR harmonics.

Due to the use of small magnetic gaps, the IVU spectra, especially at high UR harmonics, are very sensitive to the quality of permanent magnets (in particular, their magnetization errors), geometrical accuracy of poles and entire magnetic assemblies, and quality of shimming. After shimming and magnetic measurements, but before the start of its use, an IVU undergoes a multistep process that may affect the quality of its magnetic field "seen" by the electrons, including transport, installation, mechanical survey and alignment, baking, etc. All of these steps may result in misalignments of IVU magnet arrays with respect to the electron beam and to each other. Such misalignments may reach hundreds of microns in the vertical position and tens (or even hundreds) of micro-radians in a vertical angle. For large-gap out-of-vacuum undulators, these misalignment values may not pose significant problems; however, they affect spectral performance of small-gap IVUs in low-emittance storage rings considerably.

During initial commissioning with the electron beam, an IVU typically goes through some alignment procedures with respect to the beam. This alignment has the goal of minimizing negative impacts of the IVU on electron beam dynamics. In general, such IVU alignment does not guarantee the highest possible quality of emitted UR spectra, since an imperfect undulator alignment may have considerably more significant effects on the spectra than on the electron beam dynamics. The analysis of such effects and the evaluation of strategies for their elimination in installed IVUs are the main subjects of this article.

The procedure described in this article can be directly applied to standard room-temperature IVUs and to the emerging cryogenically cooled in-vacuum permanent magnet undulators, which offer higher magnetic and spectral performance [8–10]. The magnet array misalignment effects may need to be taken into account for the development of superconducting undulators [11, 12], especially if these devices will be designed with smaller magnetic gaps.

Characterization of spectral performances by comparing measurements to simulations, which we used in our work, was done earlier for many room-temperature [3, 6, 7] and even some cryo-cooled [10] undulators. The undulator gap tapering technique that we applied is well-studied [13]. The spontaneous UR spectrum-based alignment of undulator segments with respect to electron beam is used at X-ray free electron lasers [14]. We hope that our analysis and results are useful for currently operating and possible future (ultra-)low-emittance light sources.

It is important to distinguish the problem of undulator magnet array misalignment with respect to electron beam (which we address) from misalignment of X-ray optical elements with respect to the UR axis. Even though the optics misalignment and off-axis UR collection is known to affect spectral flux and UR harmonic shapes [15], it is easy to fix; e.g., by determining the UR axis position from intensity distributions of monochromatic UR and aligning optical elements as necessary with respect to it.

Simulating impacts of undulator magnet array misalignment

Figure 1 shows the schematic of a general misalignment with respect to an average electron trajectory passing through a planar undulator. Two non-parallel bold bars represent undulator magnet arrays that have some vertical gap "taper" characterized by the gap difference between the undulator exit and entrance, $\Delta g = g_2 - g_1$, or by the tapering angle $\Delta g / L_u$, where L_u is the undulator length. Besides the gap taper, an undulator may have some vertical tilt characterized by the angle θ between its median plane and the electron trajectory, and some vertical offset/"elevation" Δh of its magnetic center from the electron trajectory.

The magnetic field "seen" by an electron passing along the average trajectory in a misaligned undulator is approximately:

$$B(z) \approx B_0(z)\exp\left(-\frac{c\Delta g z}{\lambda_u L_u}\right)\cosh\left[\frac{2\pi a}{\lambda_u}(\Delta h + \theta z)\right], \qquad (1)$$

where $B_0(z)$ is the on-axis magnetic field of a perfectly aligned undulator as a function of longitudinal position z (z = 0 at the magnetic center), λ_u is the undulator period, a and c are constants specific to the undulator magnet system type and design. These constants can be determined from magnetic modeling or from magnetic measurements of a real undulator. For the 1.5-m-long, 21-mm-period IVU of the Submicron Resolution X-ray spectroscopy (SRX) beamline at NSLS-II, these constants were found to be: $a \approx 1.134$, $c \approx 4.134$. Equation (1) can be obtained from the well-known Halbach formula for the peak undulator field [16] at an assumption of a small gap taper ($\Delta g \ll g_{1,2}$, $\Delta g \ll L_u$) and small natural focusing effects produced by the misaligned undulator.

To avoid losses in UR brightness and flux, the total field $B(z)$ has to be perfectly periodic over the undulator length. Without magnetic errors, $B_0(z)$ in Equation (1) is a periodic sine-like function in the undulator central part, vanishing to zero at its extremities. The non-zero Δg and θ lead to non-periodic perturbation/modulation of the field "seen" by electrons in the undulator. Such modulation may reduce the spectral flux of UR harmonics. Note that if $\theta = 0$, $\Delta g = 0$, yet $\Delta h \neq 0$, no magnetic field modulation takes place. However, if $\theta \neq 0$ (i.e., if the undulator has a tilt with respect to the average electron orbit), some $\Delta h \neq 0$ (i.e., non-zero vertical offset of the undulator magnetic center from the average trajectory) may significantly "amplify" the field modulation compared to the $\Delta h = 0$ case.

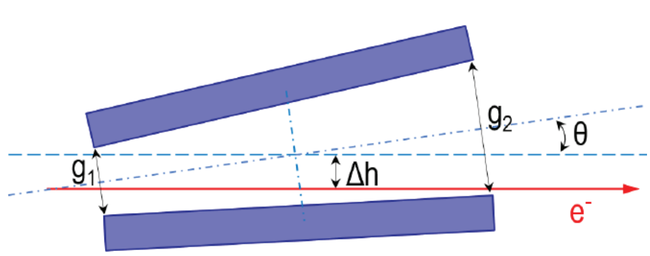

Figure 1: A general misalignment case of a planar undulator with respect to electron trajectory and parameters used for characterizing this misalignment.

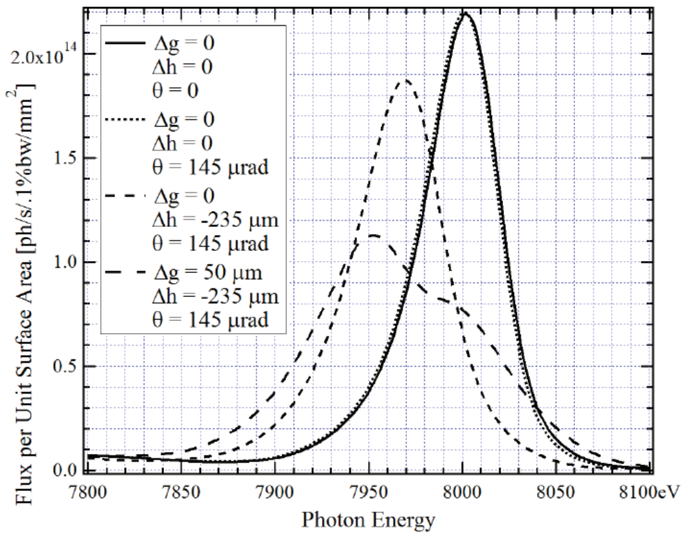

Figure 2: Calculated on-axis spectral flux per unit surface at 33 m observation distance at fifth harmonic of perfectly aligned IVU21 of SRX beamline (solid line) and for three misalignment cases (dotted/dashed lines).

Figure 2 shows on-axis UR spectra calculated with the SRW code [17, 18] for the IVU of the SRX beamline using its measured magnetic field at ~6.8 mm gap, which was modified according to Equation (1) to simulate the impact of different misalignment cases. These cases were chosen in an attempt to reproduce an imperfect UR spectrum measured during early commissioning of the beamline (see Figure 4). The calculations were done for NSLS-II's operation mode with the gap of only one (out of three) damping wigglers "closed," which resulted in a horizontal emittance of $\varepsilon_x \approx 1.45$ nm and relative RMS electron energy spread of $\sigma_E/E \approx 0.72 \times 10^{-3}$. Figure 2 shows a nearly realistic IVU misalignment case combining $\Delta g = 50$ µm, $\Delta h = -235$ µm, θ = 145 µrad, which results in a reduction of on-axis peak spectral flux by a factor of ~2 at 5th UR harmonic, and an increase of the harmonic width by a similar factor. A very similar effect, in terms of the measured harmonic width and shape, as compared to simulations for a perfectly aligned undulator, was observed at the SRX beamline (see Figure 4). The simulation results (Figure 2) show that if $\Delta g = \Delta h = 0$, the IVU tilt alone, even as large as θ = 145 µrad, does not have almost any impact on the spectral performance. This suggests that in the absence of a significant gap taper ($\Delta g \approx 0$), spectral performance of a tilted undulator can possibly be restored by simply changing its elevation with respect to the electron orbit.

Spectrum-based alignment of IVU at the SRX beamline of NSLS-II

Figure 3 shows the optical schematic of the initial part of the SRX beamline that was used for the measurements of the undulator spectra. The radiation from the IVU, installed in a short straight section of

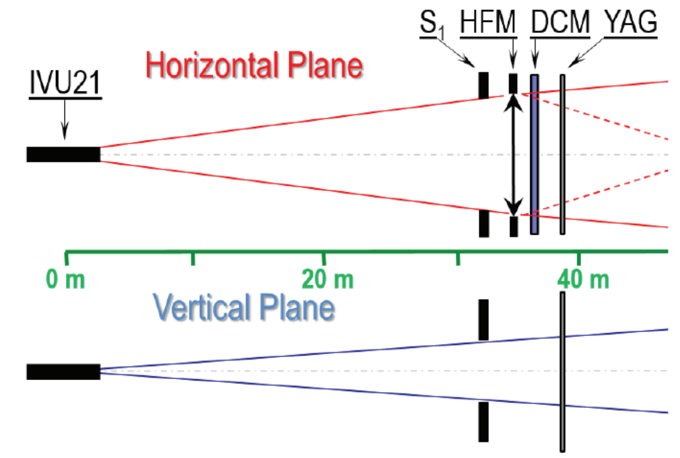

Figure 3: Optical schematic of the SRX beamline (initial part) used in UR spectral flux measurements.

NSLS-II, passes through a front-end mask (not shown in Figure 3), slits (S_1), and a bendable horizontal focusing mirror (HFM) that was kept flat during the measurements. This radiation is then monochromatized by a horizontally deflecting dual-crystal monochromator (DCM) and is registered by an X-ray camera consisting of a YAG screen, which converts X-rays to visible light, followed by a re-imaging lens and a CCD camera.

Figure 4 shows the measurement results of the on-axis spectral flux per unit surface area and within a finite aperture at 5th UR harmonic at ~6.8 mm IVU gap obtained using the X-ray camera at different photon energies (defined by varying DCM crystal angles). The lowest blue rectangular marker curves correspond to the initial IVU spectrum before any alignment.

First, the spectral performance was tested at different electron orbit "bumps" combining vertical offsets in position and angle at the IVU location. These tests demonstrated a substantial increase of the peak spectral flux (per unit surface area and within a finite aperture) and a reduction of the harmonic width (see red triangular markers "after e⁻ orbit corr." in Figure 4). After this, the impact of changing the IVU gap taper was tested (without any electron orbit bump), benefiting from the available four independently motorized gap motion axes in this undulator. These tests also resulted in an increase of the IVU spectral performance (see green triangular markers "after IVU taper corr."). Finally, the two "corrections" were combined, and this resulted in maximal increase of the UR harmonic peak and decrease of its width, as illustrated by black diamond markers in Figure 4. All of the experimental spectra shown in Figure 4 (left and right) are normalized by the peak value of this optimal spectrum.

The IVU gap taper and the optimal positional offset in the electron orbit bump that were found experimentally seem to be close to simulated values; i.e., $\Delta g \approx 50$ µm and $\Delta h \approx -250$ µm. At these optimal values, the changes in the electron orbit vertical angle at the undulator's location were found to have no effect on the spectral flux, which agrees with the simulations. Such large vertical electron orbit offsets could not be maintained during user operation, due to the associated closed orbit distortion over the entire storage ring and the existing SRX beamline alignment. Therefore, as a subsequent step, it was decided to attempt to reproduce the result in terms of the spectral flux by changing the IVU elevation with respect to the tunnel floor for the standard electron

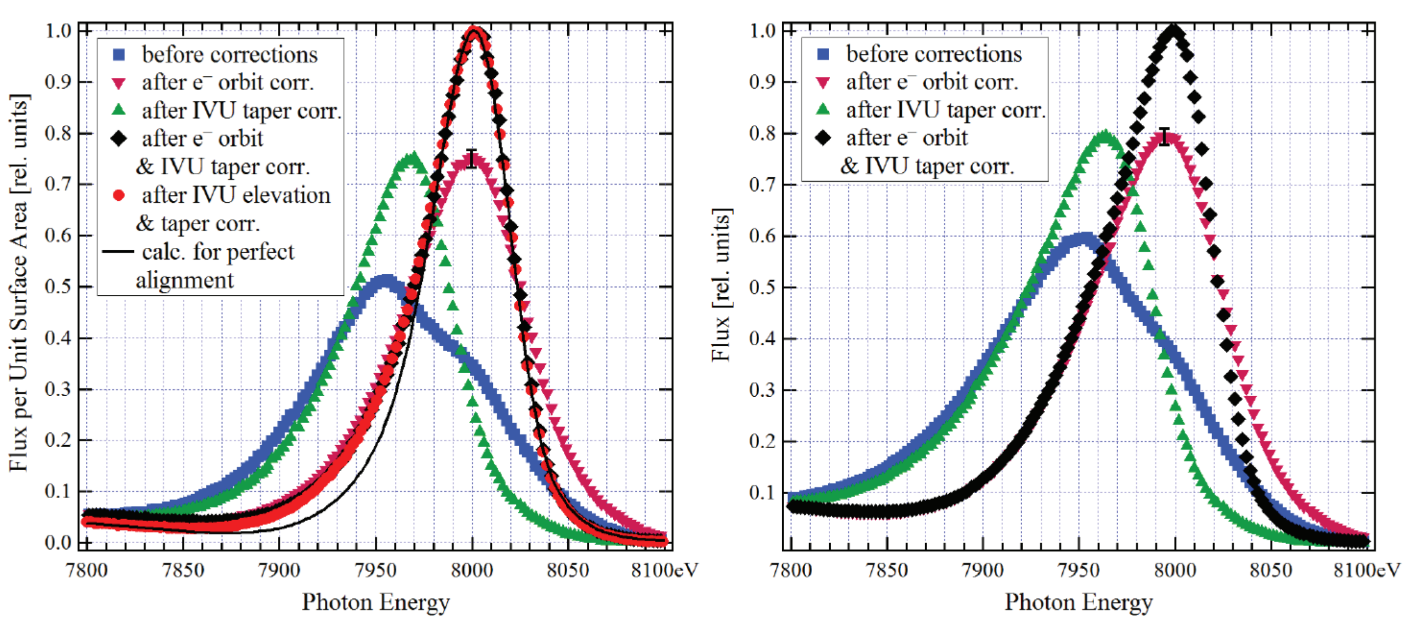

Figure 4: SRX IVU radiation spectra at fifth harmonic before and after applying electron orbit, undulator taper, and elevation corrections: on-axis spectral flux per unit surface area (left), and spectral flux within ~40 × 40 µrad² aperture that is typically used for experiments at SRX (right).

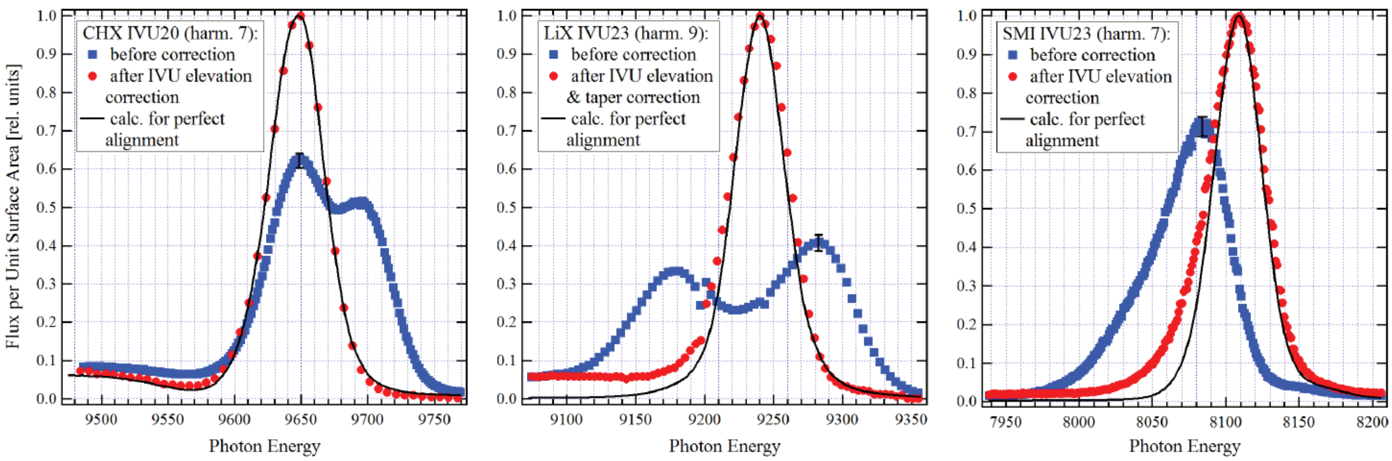

Figure 5: On-axis UR spectral flux per unit surface area measured before and after the spectrum-based alignment of IVU at three NSLS-II beamlines other than SRX: 3-m-long IVU20 at CHX (left), and 2.8-m-long IVU23 at LiX (middle) and SMI (right) beamlines. Solid lines in the graphs depict the corresponding calculated spectra at the assumption of perfect IVU alignment. All measurements and calculations were done at $\varepsilon_x \approx 0.9$ nm and $\sigma_E/E \approx 0.89 \times 10^{-3}$, corresponding to the normal NSLS-II operation with the gaps of all three damping wigglers when closed.

orbit. These new tests were carried out, and the same level of the IVU spectral performance, as in the previous optimization, was reached. The resulting spectrum is plotted with red dots in the left graph in Figure 4, after the normalization by its peak value. This spectrum is practically indistinguishable from the spectrum found previously using the electron orbit and taper corrections.

In addition to all of the experimental spectra, the left graph in Figure 4 also includes the spectrum calculated for a perfectly aligned undulator (continuous black curve), normalized by its peak value. The full width at half maximum of this curve is only ~10% smaller than that of the optimal experimental curves. This can possibly be explained by detector effects, some remaining small IVU misalignment, differences between assumed and actual electron beam parameters, and differences between ambient fields in the magnetic measurement lab and in the tunnel.

The obtained gain in the on-axis peak spectral flux per unit surface area or per unit solid angle (the entity which is sometimes used for characterizing peak spectral brightness [6, 7]) due to the spectrum-based IVU alignment is ~2 (see left graph in Figure 4). It is important to note that the gain in the flux integrated within ~40 × 40 μrad^2 angular aperture, which is typically used for user experiments at the SRX beamline, is also significant (~1.67, see right graph in Figure 4).

More IVU spectrum-based alignment results from NSLS-II beamlines

After the successful application of the spectrum-based IVU alignment at the SRX beamline, it was decided to "assess" spectral performances of all NSLS-II hard X-ray beamlines using IVUs. This assessment consisted of a comparison of the on-axis monochromatic UR spectral flux per unit surface area measured at each beamline (at one or several harmonics), with calculations made for their corresponding undulators (based on magnetic measurements data), taking into account nominal electron beam parameters in the straight sections, where the undulators are located. Quite surprisingly, nearly every second assessed beamline appeared to have some "signatures" of IVU misalignment in their spectra. For each of these identified cases, the spectrum-based IVU alignment was performed (in a few cases, this was preceded by mechanical realignment of the IVU in the tunnel). The spectrum-based alignments were done during dedicated low-current (~10 mA) shifts to minimize risks of damaging impedance-reducing liner foils located on magnet arrays, due to some manipulation error or control system malfunction. During these alignments, no electron beam steering was made; only the available motorized, remotely controlled undulator motion "axes" were used. The UR spectra were measured using standard equipment of the beamlines (X-ray cameras or slits and photodiodes).

Figure 5 shows the results of the spectrum-based IVU alignment for three beamlines: Coherent Hard X-ray (CHX), Life Science X-ray Scattering (LiX), and Soft Matter Interfaces (SMI). The experimental data (blue rectangles and red dots) in Figure 5 are normalized by spectral peaks obtained after alignment, and the calculated curves (black solid lines) by their corresponding spectral peaks (following the conventions used in Figure 4). The obtained gains in peak spectral flux per unit surface area are within factors of 1.4–2.5.

It should be noted that the CHX IVU does not have a possibility of remote control of the gap taper, so only the elevation of the entire IVU with respect to the experimental floor was modified (by ~300 µm). Despite this, the spectral performance of this IVU was restored almost completely (see overlapping red dots and the solid curve in the left graph in Figure 5). This means that the original misalignment consisted of a tilt and offset of this IVU "as a whole" with respect to the electron beam. A similar type of initial misalignment took place in the case of the SMI IVU, which was considerably "cured" by introducing a –400 µm change in the elevation (right graph in Figure 5). However, in the case of the LiX beamline (middle graph in Figure 5), the initial misalignment included not only some vertical tilt and offset, but also a considerable (~70 μm) gap taper.

After the alignment, the UR spectra became more sensitive to changes of the electron beam energy spread values, which allowed for using some of these IVUs for high-accuracy electron beam energy spread diagnostics at NSLS-II's electron beam studies [19].

Conclusion

An important cause of spectral "underperformance" of small-gap IVUs at NSLS-II was found to be a misalignment of IVU magnet arrays with respect to the electron beam. This was determined thanks to modeling of possible magnetic field imperfections and high-accuracy spectral calculations of undulator radiation generated in such modulated non-periodic magnetic fields. We showed that negative impacts of IVU misalignment on UR spectra can be effectively compensated for by the IVU taper and elevation adjustment, using the qualities of measured UR spectra (peak intensities, and in particular spectral harmonic widths) as criteria. Such spectrum-based IVU alignment is currently routinely performed at NSLS-II beamlines (the spectral performance of about half of all installed IVUs was improved using this procedure by the time of this writing). Such alignment could be used in future ultra-low-emittance storage-ring-based synchrotron light sources.

Acknowledgments

We would like to thank A. Blednykh, M. Musardo, T. Shaftan, L. Berman, W.-K. Lee, P. Zschack, E. Johnson, Q. Shen, and R. Laasch (NSLS-II) for assistance and support.

Funding

The work was supported in part by U.S. DOE contracts DE-SC0012704 and DE-SC0011237. ■

References

1. P. M. Stefan et al., *Proceedings of the 1991 IEEE Particle Accelerator Conference*, 1096–1098 (1991).
2. T. Tanabe et al., *Review of Scientific Instruments* **69**(1), 18–24 (1998).
3. P. M. Stefan et al., *Journal of Synchrotron Radiation* **5**, 417–419 (1998).
4. T. Hara et al., *Journal of Synchrotron Radiation* **5**, 403–405 (1998).
5. J. Chavanne et al., *Proceedings of the 2003 IEEE Particle Accelerator Conference*, 253–255 (2003).
6. J. M. Ablett et al., *Journal of Synchrotron Radiation* **11**, 129–131 (2004).
7. J. M. Ablett et al., *Nuclear Instruments and Methods in Physics Research A* **582**, 37–39 (2007).
8. T. Hara et al., *Phys. Rev. Special Topics–Accelerators and Beams* **7**, 050702 (2004).
9. J. Chavanne et al., *Proceedings of the 2008 European Particle Accelerator Conference*, 2243–2245 (2008).
10. C. Benabderrahmane et al., *Phys. Rev. Accel. Beams* **20**, 033201 (2017).
11. A. Bernhard et al., *Proceedings of the 2009 IEEE Particle Accelerator Conference*, 2465–2467 (2009).
12. Y. Ivanyushenkov et al., *Phys. Rev. Special Topics–Accelerators and Beams* **18**, 040703 (2015).
13. B. I. Boyanov et al., *Nuclear Instruments and Methods in Physics Research A* **339**, 596–603 (1994).
14. T. Tanaka et al., *Phys. Rev. Special Topics–Accelerators and Beams* **15**, 110701 (2012).
15. R. Walker, *Nuclear Instruments and Methods in Physics Research A* **267**(2–3), 537–546 (1988).
16. K. Halbach, *Nuclear Instruments and Methods in Physics Research* **187**, 109–117 (1981).
17. O. Chubar and P. Elleaume, *Proceedings of the 1998 European Particle Accelerator Conference*, 1177–1179 (1998).
18. O. Chubar et al., *Proceedings of SPIE* **10388**, 1038811 (2017).
19. A. Blednykh et al., *Proceedings of the 2017 International Particle Accelerator Conference*, 3224–3226 (2017).

Erratum

In Issue 30.2 (2017), the affiliations of the authors of the meeting report "SWC-TPS Workshop of Synchrotron-Based X-ray Spectroscopies on Energy Materials" were inadvertently reversed. The correct authors' affiliations are: Jun Zhong (Soochow University, Suzhou, Jiangsu, China), Di-Jing Huang (National Synchrotron Radiation Research Center, Hsinchu, Taiwan), Xuhui Sun (Soochow University, Suzhou, Jiangsu, China), and Tsun-Kong Sham (Soochow University, Suzhou, Jiangsu, China). *Synchrotron Radiation News* regrets this error.