# ANALYSIS AND CORRECTION OF IN-VACUUM UNDULATOR MISALIGNMENT EFFECTS IN A STORAGE RING SYNCHROTRON RADIATION SOURCE*

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*Abstract*

In-vacuum undulators (IVU) are currently extensively used at light source facilities, in particular in medium-energy storage rings, for the production of high-brightness and high-flux hard X-rays. The relatively small (~5 mm or less) vertical magnetic gaps used in these planar undulators make them rather sensitive to the accuracy of the alignment of magnet arrays with respect to the electron orbit in the vertical plane. Based on commissioning results of hard X-ray beamlines at NSLS-II, misalignment of IVU with respect to the electron beam was found to be frequent among the reasons for spectral "underperformance". We present results of analyses of different IVU misalignment effects on the magnetic field "seen" by the electron beam and on the emitted undulator radiation spectra. An example of applying spectrum-based IVU alignment, which resulted in a ~2-fold increase in spectral flux at one of the NSLS-II beamlines, is presented.

## INTRODUCTION

Achieving maximal-possible spectral performance is an obvious goal of the optimization, design, construction and commissioning of undulators at light source facilities. A considerable improvement of spectral performance of undulator sources was made thanks to the invention of permanent-magnet and hybrid IVU [1-3]. These Insertion Devices (ID) allowed for reducing the minimum magnetic gaps down to very small values (less than 5 mm). This enabled using small magnetic periods (around 20 mm and less) and yet creating high enough magnetic fields for reaching deflection parameter values K ~ 2 and so providing high-intensity Undulator Radiation (UR) spectra in the X-ray spectral range in medium- and high-energy storage rings. Due to the use of small magnetic gaps and relatively high spectral harmonic numbers (up to 15-25 in medium-energy rings), the spectra of these undulators are, however, very sensitive to the quality of their magnetic fields, which depends on the quality of permanent magnets, shimming, and on undulator alignment with respect to the electron beam.

After shimming and final magnetic measurements but before the start of use as a radiation source at a beamline, an IVU undergoes a number of operations that may potentially affect the quality of its magnetic field "seen" by the electron beam. This includes transport, installation, mechanical alignment, vacuum baking, etc. All these operations may result in imperfect alignment of IVU magnet girders with respect to the electron beam trajectory, as well as in mutual misalignment of the girders with respect to each other, that may take place after the final magnetic measurements and hence would not have been seen before installation. This misalignment may reach hundreds of microns in vertical position and tens (or hundreds) of micro-radians in vertical angle. Whereas for large-gap out-of-vacuum undulators such misalignment might not pose significant problems, it may considerably impact the spectral performance of small-gap IVUs in low-emittance storage rings.

During the initial commissioning with electron beam, an IVU typically undergoes some alignment procedures with respect to the beam. However, this alignment usually has a goal of minimizing negative effects of the IVU on electron beam dynamics (closed-orbit distortion, dynamic aperture, lifetime, etc.). This does not guarantee the highest-possible quality of the emitted UR spectra, since an imperfect undulator alignment may have considerably more severe effects on the resulting spectra than on the electron beam. Analysis of such effects and a search for the best strategies for their compensation are the main subjects of this paper.

## SIMULATED IMPACTS OF UNDULATOR MISALIGNMENT

A schematics of a general misalignment case of a planar undulator (or wiggler) with respect to average electron trajectory passing through it is illustrated in Fig. 1. Two slightly non-parallel bold bars represent the undulator magnet arrays that have some vertical gap taper between them. This taper can be characterized by the gap variation between the undulator exit and entrance, $\Delta g = g_2 - g_1$, or by tapering angle $\Delta g / L_u$, where $L_u$ is the undulator length. Besides the gap taper, the undulator has some vertical tilt angle $\theta$ between its median plane and the electron trajectory, and some vertical offset / "elevation" $\Delta h$ of its magnetic center from the electron trajectory.

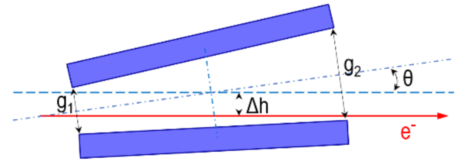


Figure 1: A general misalignment case of a planar undulator with respect to average electron trajectory and parameters used for characterizing this misalignment.

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The magnetic field "seen" by an electron passing along the average trajectory in such a misaligned undulator can be approximately represented as:

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

where $B_0(z)$ is the magnetic field of a perfectly aligned undulator as a function of longitudinal position z (z=0 at the magnetic center of the undulator), $\lambda_u$ is the undulator period, $a$ and $c$ are constants specific to the undulator magnet system type and design. The latter constants can be determined from magnetic modeling of such undulators, assuming the absence of any misalignment or magnetization errors, or from magnetic measurements on a real device. E.g. for 1.5 m long 21 mm period IVU of 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 [4] 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 (so that the vertical projection of the electron trajectory in it can be approximated by a straight line).

For a magnetic error free undulator, $B_0(z)$ is a periodic sine-like function in the undulator central part, and it vanishes to zero at its extremities. In the presence of magnetic errors (e.g. due to geometrical or magnetization errors and/or imperfect shimming) $B_0(z)$ is not periodic even in the central part of undulator. As illustrated by Eq. (1), the non-zero $\Delta g$ and $\theta$ also lead to non-periodic perturbation / modulation of the magnetic field as "seen" by electrons in the central part of undulator, and this may result in the reduction of spectral flux at UR harmonics. If $\theta = 0$, $\Delta g = 0$, yet $\Delta h \neq 0$, no magnetic field modulation takes place (though the field magnitude changes). However, if $\theta \neq 0$ (i.e. if the undulator has some tilt with respect to the average electron orbit), $\Delta h \neq 0$ (i.e. non-zero vertical offset of the undulator magnetic center from the average trajectory) may "amplify" the modulation of the magnetic field "seen" by electrons.

On-axis UR spectra calculated with the SRW code [5] for the IVU of the SRX beamline using its measured magnetic field at ~6.8 mm gap modified according to Eq. (1) to simulate impacts of different misalignment cases, are shown in Fig. 2. The misalignment cases were chosen in attempt to reproduce an imperfect UR spectrum measured during early commissioning of the beamline (see next section). The calculations were done for the NSLS-II operation mode with the gap of one (out of three) damping wigglers closed, which results in the horizontal emittance $\varepsilon_x \approx 1.45$ nm and relative RMS electron energy spread $\sigma_E/E \approx 0.72\text{x}10^{-3}$. As one can see from Fig. 2, a quite realistic IVU misalignment case combining $\Delta g = 50$ µm, $\Delta h = -235$ µm, $\theta = 145$ µrad results in a reduction of the on-axis peak spectral flux by factor of ~2 at 5th UR harmonic, and an increase of the harmonic width by ~same factor. A very similar effect, in terms of the measured harmonic width and shape (as compared to simulations for perfectly aligned undulator) was observed at the SRX beamline. The simulation results in Fig. 2 also show that if $\Delta g = \Delta h = 0$, the IVU tilt angle $\theta = 145$ µrad alone does not have ~any impact on the spectral performance. Based on these simulations, a strategy for improving the spectral performance, consisting of a correction of an IVU gap taper and steering its position with respect to the electron beam, was chosen.

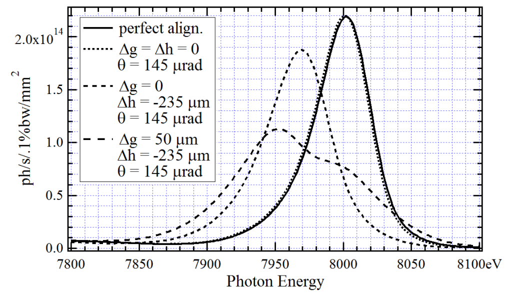


Figure 2: Calculated on-axis spectral flux per unit surface at ~33 m observation distance at 5th harmonic of perfectly aligned IVU of SRX beamline (solid line) and for different cases of misalignment (dotted / dashed lines).

## SPECTRUM BASED ALIGNMENT OF IVU AT SRX BEAMLINE OF NSLS-II

The optical scheme of the initial part of the SRX beamline that was used for the measurements of undulator spectra is shown in Fig. 3. The radiation emitted by the 21 mm period 1.5 m long IVU, installed in a canted configuration 1.25 m downstream from the center of a short straight section of NSLS-II, passes through the front-end mask, slits ($S_1$), bendable variable focal length Horizontal Focusing Mirror (HFM). This radiation is then monochromatized by a horizontally-deflecting Dual Crystal Monochromator (DCM) and is registered by an X-ray position-sensitive detector including a YAG screen converting X-rays to visible light, re-imaging lens and a CCD camera. Other optical elements of the SRX beamline were not used in the measurements described in this paper.

The results of the initial measurements of the on-axis spectral flux per unit surface and within a finite aperture at 5th UR harmonic at ~6.8 mm IVU gap are shown by lowest dashed curves in Fig. 4 (note similarity of these curves to one of calculated curves in Fig. 2).

It was decided to start spectrum based alignment from a test of the IVU spectral performance at different electron orbit "bumps" combining vertical offsets in position and angle at the SRX source location. These first 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 Fig. 4.

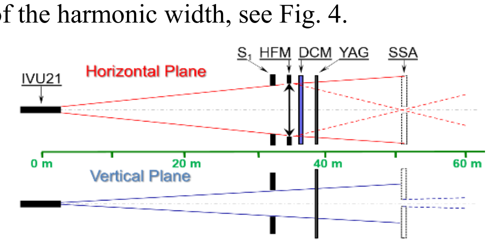


Figure 3: Optical scheme of the SRX beamline initial part.

After this, the impact of varying of the IVU gap taper was tested (without an 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. Finally, the two "corrections" were combined, and this resulted in a further increase of the UR harmonic peak and decrease of its width, as illustrated in Fig. 4. The optimal variations of the IVU gap taper and the positional offset in the electron orbit bump that were found experimentally appeared to be quite close to the values predicted by simulations, 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 location of the undulator was found to have ~no effect on the spectral flux (which is also in line with the simulations).

However, the obtained large value for the optimal vertical electron orbit offset could not be maintained for user operation (both from the point of view of the corresponding closed orbit distortion and the existing beamline alignment), therefore, as a subsequent step, it was decided to attempt to reproduce the same result in terms of the spectral flux by changing the IVU elevation instead of implementing the electron orbit bump. Such new tests were carried out after a new "advanced" version of the IVU control system was implemented, and the same level of the IVU spectral performance as in the previous optimization was reached. The resulting spectrum is plotted in Fig. 5, together with the spectrum obtained during the previous optimization. Besides these spectra, the spectrum calculated for perfectly-aligned undulator is also included in Fig. 5, with all spectral curves being normalized by their corresponding maximum values.

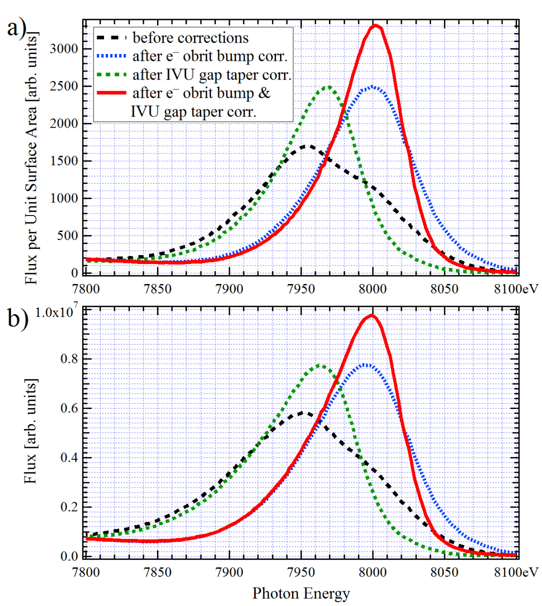


Figure 4: UR measured at 5th harmonic of IVU at the SRX beamline before and after applying electron orbit "bump" and undulator gap taper corrections: a) on-axis spectral flux per unit surface area; b) spectral flux within ~40 x 40 µrad$^2$ aperture (used for experiments at SRX).

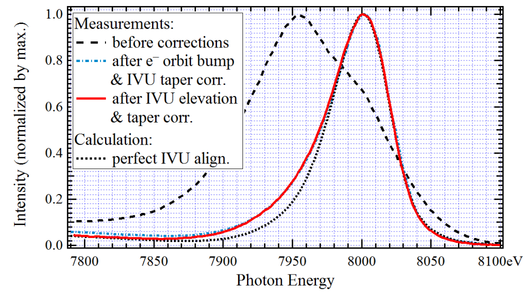


Figure 5: On-axis UR spectral flux per unit surface area at 5th harmonic of SRX IVU, measured before and after spectrum based alignment by two different methods, compared to calculation made for perfectly aligned IVU.

The results of the two experimental optimizations are almost indistinguishable from each other, and are quite close to the calculated curve: their FWHM values are larger by only ~10%. This can possibly be explained by a detector effect, some still remaining small IVU misalignment, difference between assumed and actual electron beam parameters and/or other small effects (e.g. difference between ambient fields in the magnetic measurement lab and in the storage ring tunnel).

## CONCLUSION

An important cause of spectral "underperformance" of small-gap IVUs at NSLS-II and possibly at other low-emittance storage ring sources 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 non-periodic fields. The negative effects of IVU misalignment on UR spectra can be effectively compensated or minimized by the IVU taper and elevation adjustment, using the quality of the measured spectra (peak intensity, harmonic width) as a criterion. Such spectrum-based alignment of IVUs is currently routinely performed at NSLS-II; the performance of about half of all installed IVUs was improved using this procedure by the time of this writing. The spectrally-aligned IVUs are often used for high-accuracy electron beam energy spread diagnostics at NSLS-II [6], besides their every-day applications in user experiments.

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