Measured performance of hybrid small-gap in-vacuum undulator 08ID-1 at the CLS intermediate energy storage ring

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Abstract. The recent development of undulator in-vacuum technology has allowed intermediate energy storage rings, such as the Canadian Light Source (CLS), to build high brilliance protein crystallography beamlines. The Canadian Macromolecular Crystallography Facility (CMCF) beamline 08ID-1 is the first small period (20 mm) hybrid small-gap in-vacuum undulator (SGU) to be employed at the CLS as a source of high harmonic, high brightness radiation (6.5 – 18 keV). The SGU was assembled and shimmed at the CLS Magnetic Mapping Facility. It is installed in the upstream part of straight section 8 of the CLS ring and chicaned inboard by 0.75 mrad. The downstream half of this section is reserved for future development. To achieve a maximum undulator field ($B_0$) in conjunction with low sensitivity to radiation damage, a hybrid layout for the undulator is used with Sm$_2$Co$_{17}$ permanent magnets sandwiched between Vanadium Permendur ferromagnetic poles. To date, operations in the 6.5 – 18 keV energy range have been achieved using the 3rd to 9th harmonics, with gap sizes of 5.9 – 8.6 mm. Gaps smaller than 5.9 mm are not being used since in the 5.0 – 5.9 mm range the rms phase errors are larger than 2.5° and lower harmonics at larger gaps are being used instead. The goal of the present study is to measure the output spectrum for various gap sizes and compare these with theoretical expectations calculated from the magnetic characteristics of the undulator measured at the CLS Magnetic Mapping Facility. The 08ID-1 beamline now has several years of successful operation as a highly competitive, high brilliance beamline.

1. Introduction
The Canadian Light Source (CLS) is a 2.9 GeV national synchrotron radiation facility located on the University of Saskatchewan campus in Saskatoon. The CLS is funded by the Canadian government, provincial, industrial and academic sources. The initial project consisted of construction of the storage ring along with seven beamlines. This first phase included the development, construction and installation of a small period, hybrid, small-gap, in-vacuum undulator (SGU) to produce high energy, high brightness x-rays otherwise not available at an intermediate energy facility. The 08ID-1 beamline that is illuminated by this first SGU installed in the CLS ring, together with the 08B1-1 beamline constitute the Canadian Macromolecular Crystallography Facility [1].
Here we report on the measured performance of the SGU. The SGU has been routinely operated at gaps of 5.9 – 8.6 mm at the 08ID-1 macromolecular crystallography beamline at the CLS for 7 years. The success of this device has led to the development of similar devices for use at other beamlines.

![Image of SGU device](image_url)

**Figure 1.** 08ID-1 small-gap in-vacuum undulator in the CLS Magnetic Mapping Facility (left) and final installation in the vacuum chamber with water cooled flexible taper (right).

2. **Design and Construction**

   The design is based on the SPring-8-type SGU [2] in use at numerous facilities [3]. The specifics of the design were optimized with the CLS lattice and operational goals in mind. The magnetic assembly, including shimming, was performed at the CLS in the on-site magnet mapping facility, while the mechanics and vacuum chamber were outsourced. Final assembly, bake-out, alignment and instrumentation was performed by CLS staff. The device as seen in the CLS magnet mapping facility and final installation in the vacuum chamber is shown in figure 1 and is chicaned inboard by 0.75 mrad in the upstream part of straight section 8 of the CLS ring. The downstream half of section 8 is reserved for a future insertion device.

2.1. **Mechanics**

   The device is driven by a single motor drive with a resolution of ~2 µm in the range of 5 – 35 mm. The gap is measured with two absolute rotary encoders attached to the out of vacuum drive shafts.

2.2. **Magnetics**

   The SGU is of the hybrid type, with a 20 mm period constructed of 159 poles (157 full sized poles). The total magnet assembly length is 1583 mm with 79 periods. The peak magnetic field and k values at gaps of 5.0 mm and 5.5 are respectively, $B = 1.172$ T, $k = 1.90$ and $B = 0.923$ T, $k = 1.72$. The magnet blocks were constructed using Sm$_2$Co$_{17}$ to protect against possible radiation damage and to achieve higher bake-out temperatures, while Vanadium Permendur material with equal amounts of Co and Fe and about 2% V was used to construct poles to compensate for the lower remanence ($B_r$) compared to the more common NdFeB.

   To achieve the desired UHV performance, the magnet blocks are coated with Ni and the poles are first coated with Cu and then with Ag. These coatings also have the added benefit of reducing friction between components, making the shimming process easier. An assembled pole is shown in figure 2. Both vertical and horizontal correction coils are installed in vacuum. The first harmonic energy at minimum gap (5 mm) is 1.49 keV with an 8.4% contribution from higher order harmonics.
2.3. Measurements
Measurements were done in half mm steps from gaps of 5 mm to 9 mm, 2.5 mm steps up to a 20 mm gap and then in 5 mm steps to the maximum gap of 35 mm before leaving the CLS magnet mapping facility. A flip coil with 3 mm diameter and 19 turns was used to measure the first field integrals (and integrated multi-poles) with the vertical correction coil powered and set to eliminate the vertical first integral, which also gave very low values for the vertical second field integral. The horizontal correction coils could not be used in the magnet mapping facility and they were therefore optimized using stored beam. The RMS phase angle error (figure 3), the photon energy and the second field integrals were determined from Hall probe scans. There was difficulty in reducing the phase angle error at small gaps and the design specification of RMS phase angle error less than 2.5 degrees is only met at gaps greater than 5.9 mm. The peak magnetic field values from these measurements were used to create an idealized model to be used at gaps other than those at which the measurements were taken.

3. Measured Performance

3.1. Methods
Flux measurements were performed at two SGU gaps (5.9 and 6.7 mm) using a calibrated intensity monitor immediately downstream of the double crystal monochromator (DCM) by incrementing the DCM energy by 1 eV increments across the entire energy range of the beamline. The machine functions at the center of the SGU when the measurements were taken were, \( \delta = 0.0011, \ v_x = 22.70 \ \text{nm}, \ v_y = 0.1017 \ \text{nm}, \ \beta_x = 9.34 \ \text{m}, \ \beta_y = 3.174 \ \text{m}, \ \alpha_x = 0.136 \ \text{m}, \ \alpha_y = 0.487 \ \text{m}. \) Simulated theoretical expectations were computed for the same SGU gaps using the idealized magnetic model, as described in section 2.3 and the Synchrotron Radiation Workshop Software (SRW) [4] using machine functions at the center of the SGU of \( \delta = 0.0011, \ v_x = 20 \ \text{nm}, \ v_y = 0.2 \ \text{nm}, \ \beta_x = 8.665 \ \text{m}, \ \beta_y = 4.955 \ \text{m}, \ \alpha_x = 0.147 \ \text{m}, \ \alpha_y = 0.271 \ \text{m}. \) The simulation results were shifted upwards in energy by 250 eV to facilitate comparison with the measured spectra. Figures 4 and 5 show the measured and theoretical spectra of the SGU for gaps of 5.9 (\( B = 0.8298 \ \text{T} \)) and 6.7 mm (\( B = 0.7173 \ \text{T} \)), respectively. Both measured and simulated results used horizontal and vertical angular acceptances of 0.19 mrad and 0.095 mrad, respectively.

3.2. Results and Discussion
In both cases (5.9 and 6.7 mm gaps) the measured and shifted theoretical spectra are in close agreement in terms of the overall shape of the spectra. The measured fluxes are lower and this is most likely due to using an idealized model when calculating the theoretical spectra. This would also explain the need to shift the theoretical spectra to make a comparison. Future studies directly comparing the measured flux at a gap for which detailed magnetic measurements are available are planned and will determine if this is in fact the case.
Table 1. SGU harmonics used for energy ranges

| Energy range (keV) | SGU harmonic used |
|--------------------|-------------------|
| 6.5 – 8.5          | 3rd               |
| 8.5 – 9.5          | 4th               |
| 9.5 – 11.5         | 5th               |
| 11.5 – 14.5        | 6th               |
| 14.5 – 18          | 8th               |

For beamline operations the maximum available flux is desirable. To that end it is worth noting that the output at 12.6 keV of the 7th harmonic at a 5.9 mm gap is lower than the output of the 6th harmonic at a 6.7 mm gap and that the output near 14.5 keV is higher on the 8th harmonic at 5.9 mm gap than the 7th harmonic at 6.7 mm gap (see figures 4 and 5). This observation holds true for all gaps and for beamline operations only the 3rd, 4th, 5th, 6th and 8th harmonics are used as shown in table 1.

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