Small-gap insertion-device development at the National Synchrotron Light Source – performance of the new X13 mini-gap undulator

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The National Synchrotron Light Source (NSLS) 2.8 GeV electron storage ring continues to set high standards in insertion-device research and development. The Chasman–Green NSLS lattice design provides for dispersion-free long straight sections in addition to a very small vertical β function. As the electron beam size is proportional to the square root of this function, a program to exploit this feature was undertaken more than a decade ago by implementing short-period small-gap insertion devices in the NSLS storage ring. The possibility of utilizing existing moderate-energy synchrotron radiation electron storage rings to produce high-brightness photon beams into the harder X-ray region have been realised using in-vacuum undulators. In this article the operation of a 1.25 cm-period mini-gap undulator, operating down to a gap of 3.3 mm within the NSLS X13 straight section, is reported. It is the brightest source of hard X-rays in the energy range ~3.7–16 keV at the NSLS, and replaces an in-vacuum undulator which had a more limited tunability.

Keywords: undulators; small gap; mini-gap; short period; in-vacuum; brightness.

1. Introduction

For many years the NSLS has continued to improve machine performance and stability (Safranek *et al.*, 1993). By decreasing both the emittance coupling and vertical dispersion, brighter X-ray beams are being delivered to the experimental end-stations. Installation of compact in-vacuum small-gap insertion devices at the center of the NSLS straight sections have been realised owing to the small size of the electron beam in the vertical dimension [14.1 μm full width at half-maximum (FWHM)]. For more than a decade the NSLS has been dedicated to the research and development of these small-gap undulators.

Several programs had originally motivated the conception of small-gap devices at the NSLS. Firstly, it was realised that protein crystallography would benefit greatly from these small-gap undulators because weakly diffracting macromolecular assemblies require the high brightness of an undulator source to increase the resolution. The ability to tune this high-brightness radiation to the absorption edges of anomalous scatterers would provide the opportunity to carry out multiwavelength anomalous diffraction (MAD) studies at the bromine and selenium *K* edges. It was also realised that X-ray microdiffraction would benefit greatly from the implementation of these small-gap undulators (owing to the high brightness and small source size at the center of the NSLS straight-sections), and the energy ranges accessible from such a device would be optimal for such studies (see §3).

In order to study the physics and operation of small-gap devices, the first prototype magnet array was installed in the NSLS X13 straight section during 1993 (Rakowsky *et al.*, 2001; Stefan, Krinsky *et al.*, 1998; Stefan *et al.*, 1995, 1996). This 16 mm-period prototype small-gap undulator (PSGU), conceived at the NSLS and built at the Rocketdyne Division of Rockwell International (now Boeing), was operated in air with a variable-gap vacuum chamber, allowing independent control of the magnetic gap and physical aperture. With the gap of this 36-pole undulator closed down to 6 mm, and with the NSLS storage ring operating at 2.584 GeV, a 2.5 keV fundamental energy could be reached. The successful commissioning of the PSGU confirmed that small-gap devices could be located within the NSLS vacuum, and could ultimately work down to gaps as small as 3 mm without affecting the electron beam lifetime (Stefan *et al.*, 1995, 1996), provided that the device is not more than 35 cm long. During 1997 the NSLS, in collaboration with SPring-8, designed and built an in-vacuum undulator (IVUN), which replaced the PSGU. The 11 mm-period (62-pole) IVUN (Rakowsky *et al.*, 2001; Stefan, Krinsky *et al.*, 1998; Stefan, Tanabe *et al.*, 1998; Stefan, 1998; Tanabe *et al.*, 1998) could effectively operate down to gaps of 3.3 mm and, with the NSLS electron beam energy now increased from 2.584 to 2.8 GeV, a fundamental energy of 5.4 keV was obtainable. During 2001 the IVUN device was replaced by an in-vacuum mini-gap undulator (MGU) (Rakowsky *et al.*, 2001; Lynch *et al.*, 2002) which, owing to the higher on-axis magnetic field, provided for a greater tunability over IVUN.

The NSLS-designed-and-constructed MGU has a magnetic period of 1.25 cm and is comprised of 54 poles of permanent NdFeB magnets with vanadium permendur poles. It resides at the center of the X13 straight, where the vertical β function is minimized, producing a vertical electron source size of only 14.1 μm FWHM (705 μm FWHM in the horizontal). Operating down to a gap of 3.3 mm, it delivers a magnetic field of 0.92 T with a deflection parameter, *K*, of about 1.07. High-brightness X-ray photon beams are delivered in the first, second and third harmonics, tunable within the energy ranges 3.7–5.5 keV, 7–10 keV and 11.2–16 keV, respectively.

The motivation for the advancement of in-vacuum small-gap devices is twofold (Stefan, Krinsky *et al.* 1998):

(*a*) By reducing the magnetic period λ_u, the harmonics of the radiation are correspondingly shifted to shorter X-ray wavelengths, and thus short-period small-gap insertion devices can effectively extend a medium energy machine into the harder X-ray region. This can be realised through the following equation, where the on-axis fundamental wavelength is given by

$$\lambda_1 \simeq \left(\lambda_u/2\gamma^2\right)\left[1+\left(K^2/2\right)\right], \tag{1}$$

where γ is the relativistic factor (~5480 at the NSLS) and *K* is the deflection parameter which is proportional to the product of the magnetic period and peak on-axis field B_u,

$$K \simeq 0.934\, B_u\,[\mathrm{T}]\ \lambda_u\,[\mathrm{cm}]. \tag{2}$$

For example, with the MGU operating at a *K* value of ~1.07 and at a gap opening of 3.3 mm ($B_u \simeq 0.92$ T), the third harmonic is around 11.3 keV.

(*b*) The reduction of the magnetic gap *G* allows for a proportionate reduction in the magnetic period λ_u for a given peak on-axis magnetic field B_u,

$$B_u \propto \exp(-\pi G/\lambda_u). \tag{3}$$

This shorter period enables relatively compact devices to be built while maintaining high-brightness X-ray photon beams. At the NSLS this feature is exploited by combining a five-pole elliptically polarized wiggler (EPW) (Gluskin *et al.*, 1995) and the MGU within the same straight section. In addition, a second MGU has been installed between the RF cavities in the X29 straight section. One disadvan-

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Table 1
X13 mini-gap undulator parameters.

Magnetic period	1.25 cm
Number of poles	54
Deflection parameter	1.07†
Peak on-axis field	0.92 T†

† At a gap of 3.3 mm.

Table 2
MGU magnetic design structure.

Pole width	22 mm
Pole length	2.54 mm
Pole height	17 mm
Magnetic gap	3.3–10 mm
Overall undulator length	350 mm
Period	12.5 mm

tage of a shorter magnetic period, however, is that the tunability is diminished due to the lower value of the deflection parameter. Ultimately, in the design of a small-gap undulator, there is a trade-off between tunability, the achievable range of photon energies and brightness.

2. MGU spectral measurements

In order to determine the performance of the MGU, a single-crystal spectrometer was used to record the spectral output of the undulator. Located within the white-beam X13B experimental hutch, the spectrometer was housed within a steel tank, and comprised of a silicon (111) crystal and ionization chamber, which were mounted on a Huber $\theta/2\theta$ two-circle diffractometer. A copper water-cooled block with an indium–gallium thermal contact provided cooling for the crystal, and the tank was connected to the X13B beryllium window exit port *via* a flight tube. A set of Huber entrance slits were positioned upstream of the crystal (25.1 m from the center of the MGU), within the tank and on a motorized x–y micro-stepping stage, to carefully define the photon beam dimensions and accurately record the on-axis undulator brightness [0.45 mm opening in the vertical ($\sim$18 μrad), 2 mm opening in the horizontal ($\sim$80 μrad)]. The spectrometer arrangement and flight path were purged with either helium or nitrogen gas depending upon the energy range being measured: the lower-energy first harmonic was recorded using a helium environment so that the measurement was insensitive to the higher-order harmonics, and the second and third MGU harmonics were determined using a nitrogen gas atmosphere. The spectrometer housing was allowed to purge for 1 h and the silicon crystal was permitted to thermally stabilize before data collection was initiated. Energy calibration of the spectrometer was performed by measuring the position of the absorption edges of several EXAFS-standard thin foils, and the voltage applied to the ion chamber was $\sim$700 V. The measurements of the MGU harmonics were performed by rotating the Si(111) crystal and ionization chambers together to record the Bragg diffracted beam. Through knowledge of the ionization potential of the gas and length of the ion chamber, the number of diffracted photons could be determined by measuring the current produced by the ionization process.

To transform the photon-beam intensity into on-axis brightness, several corrections were applied to the data: the electron beam source size, angular acceptance of the Huber slits, gas absorption, beryllium window absorption and window impurities (three Be windows, 250 μm thickness each) were considered. X-ray absorption cross sections were obtained from the data tables within the *XOP* computer package (Dejus & Sanchez del Rio, 1996; Sanchez del Rio *et al.*, 1998) and beryllium impurity data were taken from the contamination tables provided by the manufacturer (Brush-Wellmann ultrahigh-purity IF-1 grade). In addition, absorption within the silicon crystal and the Darwin widths were computed at varying X-ray energies. To calculate the on-axis brightness values for comparison with the MGU spectral measurements, the *XUS* undulator code was utilized (Dejus & Sanchez del Rio, 1996; Sanchez del Rio & Dejus, 1998). Magnet measurements were performed on the undulator (Hall probe, pulsed wire *etc.*), and the magnets were shimmed to minimize trajectory errors, integrated multipoles and optical phase errors. The MGU parameters are shown in Tables 1 and 2, and the NSLS electron source characteristics (at the center of the straight sections) are displayed in Table 3.

Table 3
Electron beam parameters for the 2.8 GeV NSLS straight sections.

Source size and divergence are r.m.s. values.

Horizontal source size	300 μm
Vertical source size	6 μm
Horizontal divergence	260 μrad
Vertical divergence	35 μrad
Horizontal emittance	78 nm rad
Horizontal β function	1.60 m
Vertical emittance	0.133 nm rad
Vertical β function	0.35 m

3. Discussion

Fig. 1 shows a comparison between the calculated and measured values of the on-axis MGU brightness at a magnetic gap opening of 3.3 mm. At this gap opening, the deflection parameter K was determined to be 1.07, corresponding to a peak on-axis magnetic field of 0.92 T. As can be clearly seen, the calculated and measured values agree well and confirm the quality of the magnetic design. At this gap setting the fundamental energy of the MGU was recorded at $\sim$3.7 keV with a corresponding brightness of $\sim 4 \times 10^{17}$ photons s^{-1} mm^{-2} mrad^{-2} (0.1% bandwidth)$^{-1}$ (300 mA)$^{-1}$. The on-axis brightness measurement at the first harmonic (at $\sim$3.7 keV) is approxi-

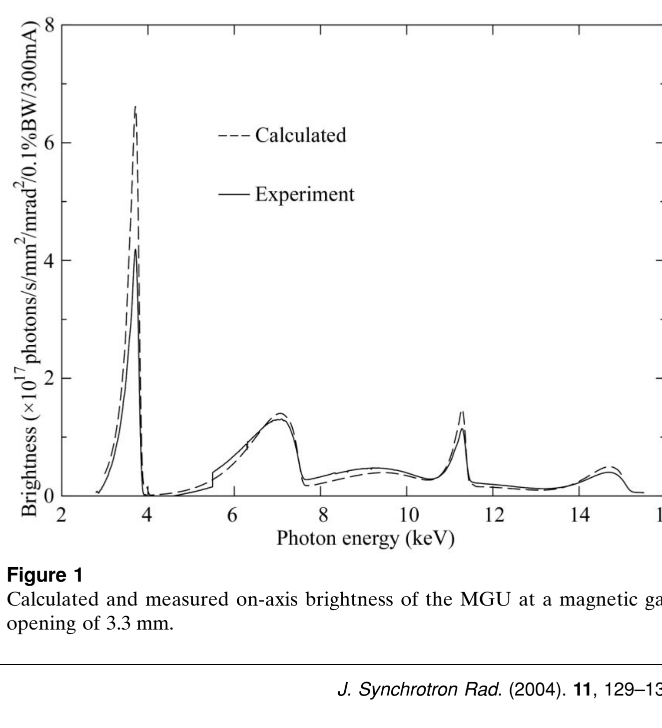

Figure 1
Calculated and measured on-axis brightness of the MGU at a magnetic gap opening of 3.3 mm.

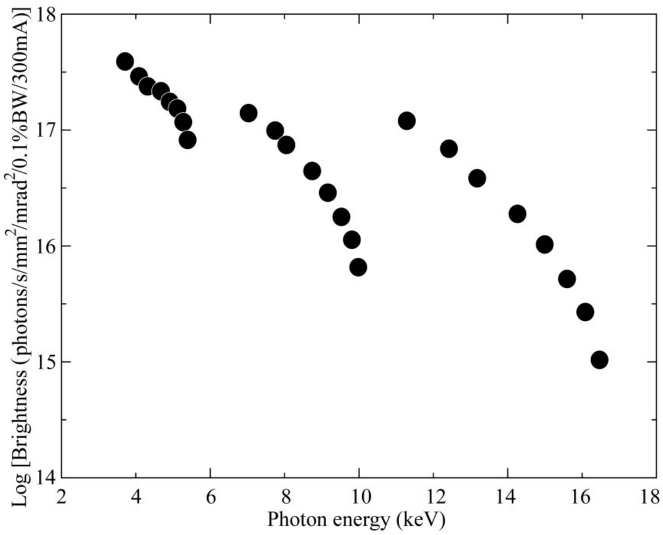

Figure 2
Peak on-axis brightness measurements recorded at magnetic gap openings of 3.3, 3.7, 4.0, 4.5, 5.0, 5.5, 6.0 and 6.5 mm. The three curves represent the first, second and third undulator harmonics.

mately 60% of the expected value. This is probably due to an underestimation of the absorption effects, particularly the heavy-metal contamination (corrections applied using the manufacturer's supplied data), within the X13B beryllium windows. The strong second harmonic is due to the relatively large emittance of the NSLS storage ring (see Table 2), which also broadens the odd harmonics in comparison with third-generation-light-source undulator line-widths. By opening the magnetic gap, the undulator harmonics are shifted to higher X-ray energies, which allows the energy range of interest to be selected. This is emphasized in Fig. 2, which shows the peak on-axis brightness measured at the first, second and third harmonics, at gap openings of 3.3, 3.7, 4.0, 4.5, 5.0, 5.5, 6.0 and 6.5 mm. It is clear from these plots that the MGU continues to deliver high-brightness X-ray photon beams in the energy range $\sim$3.7–16 keV. However, there are 'holes' in the MGU energy spectrum which cannot be reached. This will be addressed in the future by replacing the permanent magnets by a superconducting array. In this situation the higher obtainable magnetic fields will allow for the overlap of the first and third harmonics, thus providing a continuous spectrum of harder X-ray energies.

An X-ray microfocusing program has recently been implemented at X13B. The high brightness of the MGU, the extremely small source size in the vertical direction, and the tunability of the device make it an important component of an X-ray microfocusing system. Using elliptical mirrors in the Kirkpatrick–Baez configuration, a system designed primarily for high-pressure X-ray spectroscopy has recently been constructed (Ablett *et al.*, 2002). It is now intended to design and build a hard X-ray microdiffraction instrument at the X13B beamline. By combining submicrometer spatial resolution, energy tunability, good reciprocal space access and a wide variety of X-ray microfocusing optics, the new instrument will extend research frontiers in materials characterization and design. As can be seen from Fig. 2, the energy range covered by the MGU is optimal for such an instrument.

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