Commissioning results of the U14 cryogenic undulator at SLS

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Abstract. After 10 years of operation the wiggler-source Materials Science beamline at the Swiss Light Source was the first beamline to undergo a significant upgrade. The replacement of the W61 wiggler by the cryogenic undulator U14 makes the SLS the first wiggler free third generation light source. With the help of the cryogenic technology [1], the period length could be reduced from 19 mm to 14 mm. With a minimum gap of 3.8 mm and the x-ray energy range could be extended to nearly 40 keV. The undulator has been built in cooperation with SPring-8 and Hitachi. PSI designed the liquid-nitrogen-based cryogenic system and made the magnetic measurements under cryogenic conditions before installation. To be cost efficient, the undulator shares the cryogenic refrigeration system with the monochromator. Operational aspects like stability or temporal response to gap changes will be discussed as well as the spectral performance.

1. Introduction

In the last decade short period undulators have been installed in medium-energy synchrotron radiation facilities to produce high-energy photons. For a given undulator length, the higher number of periods increases the brightness of the radiation. In the SLS there are four hard x-ray beam-lines equipped with 19 mm period in-vacuum undulators. Shorter periods require stronger and more stable magnets, which were not available of the initial SLS design phase. To go beyond the limit of this technology it was proposed to cool in-vacuum undulators down to cryogenic temperature [1]. NbFeB magnets have a negative temperature coefficient with regards to both, the remanence and the coercivity. The increase in the magnetic strength at lower temperature is not monotonic for NbFeB and reaches a phase transition around 130 K. Below this temperature, the magnetic moment starts to precess around the main axis with a net decrease of the magnetic field. The total gain in the magnetic filed strength is not very high, but crucially the coercivity increases by a factor of 2-3. This allows one to use high-strength magnets, which would otherwise not be stable enough at room temperature, but they can be safely operated at cryogenic temperatures.

2. U14 design

The U14 is an in-vacuum undulator with a hybrid magnetic structure, made out of NbFeB (S45SH Hitachi Metal Ltd) magnets and permendur poles. The period length is 14 mm and the total number of periods including ends is 120. The gap is operated between 3.8 and 20 mm.

2. 1. Mechanical design

The design of the frame and the gap drive system is a reinforced version of the U19 series. A C-shape welded frame holds the outer I-beams, which transfer the required stiffness to the magnetic structure. The gap drive system has two motors (upstream and downstream), but currently the spindels are mechanically coupled to one motor only. The inner I-beam is held to the outer I-beam by columns, which are integrated in the vacuum vessel by mean of a system of bellows. The large thermal contraction between the room temperature during assembly and the cryogenic temperatures of operation requires special care in the design of the mechanical tolerances. ANSYS simulations show a maximum deformation of the inner I-beam of about 20 μm. The large mechanical contractions do not allow out-of-vacuum (i.e. room temperature) measurements of the gap. To overcome this problem, an optical measurement device was installed, based on a transmitter/receiver both at room temperature and two optical windows through which the laser beam can cross the gap.

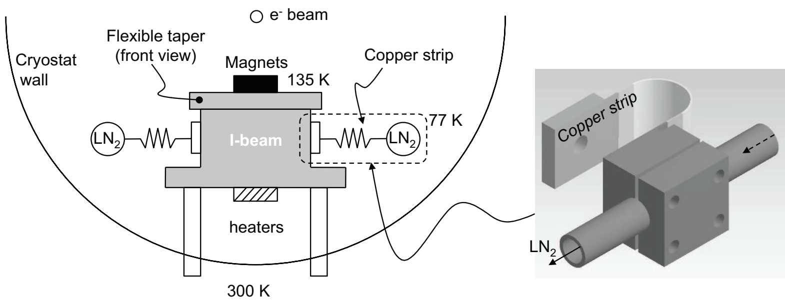

Figure 1 The cooling system schematically represented, on the right the detail of the copper foil and the liquid nitrogen pipes.

2. 2. Cooling system

The cryogenic system was designed at PSI, implemented by Hitachi at SPring-8 site and tested as well at the SLS Magnetic Measurement Lab. Figure 1 shows a schematic description of the cooling circuit. The refrigeration power is shared with the monochromator and comes from a commercial available vibration-free closed-loop circuit using sub-cooled liquid nitrogen, which includes a phase-separator station, LN_2 closed loop refrigerator and LN_2 transfer lines. The cold liquid nitrogen enters the cryostat at about 77 K and it is connected to the middle of the undulator by stainless steel tubes with bellows, which replaced the copper tubes in the original design. The tubes are routed around the I-beam to exchange heat by mean of 32 copper strips which act as thermal resistors. The target value for the magnet temperature is 135 K and this is achieved with external power generated in stainless steel heater. The reference temperature for the magnets is measured at the upper surface of the I-beam just below the magnet keepers. This signal is used to feedback the power in the heaters to stabilize the magnet temperature at the desired value. Stabilizing the temperature of the magnet at the phase transition has the added advantage of maximizing the magnet strength and reducing the sensitivity to temperature variation.

2. 3. Magnetics

The NbFeB grade magnetic material chosen has a remanence at room temperature of Br > 1.3 T and a coercivity of Hcj > 1600 kA/m, while at cryogenic temperatures around 135 K these properties improve substantially, the Br > 1.5 T and a Hcj > 4000 kA/m. The magnet stability at room temperature is enough to allow the assembly of the magnetic array but would not guarantee safe operation at low gaps in the synchrotron, where the radiation would deposit enough energy to partially induce demagnetization. At cryogenic temperatures, the coercivity is large enough to allow the operation as low as 3.8 mm gap, while the strength is high enough to reduce the period length to 14 mm.

3. Magnetic Measurements

The U14 has been measured and optimized at room temperature at SPring-8. During the first cool down, the magnetic field of the undulator was measured at the operating conditions inside the vacuum chamber with the SAFALI system [1][3]. The phase error was corrected in situ with local gap changes made adjusting the columns height [4]. In the following the description of the PSI in-vacuum measuring system is reported together with measurements results.

3. 1. Magnetic measurement equipment

To check and optimize the U14 after shipment, PSI developed its own in-vacuum measuring bench. The working principle is identical to SAFALI: a compact rail is inserted into the vacuum chamber and is supported by UHV-compatible two-axis linear stages. The Hall sensor module is mounted on a carriage fit to the rail and two pinholes with a diameter of 2 mm are attached to the Hall sensor module. Two laser beams are introduced through the viewport to irradiate the pinholes and create two optical spots. During the movement along the undulator axis, the transverse position of the Hall sensor fluctuates due to a mechanical error and deflection of the rail. Such a positional error is detected by the position sensitive detectors (PSDs) as a fluctuation of the optical spot positions, and then corrected by translating the two-axis linear stages supporting the rail.

3. 2. Magnetic measurement results and optimization

The first step of the measurement procedure was the commissioning of the new measurement system. Special care was taken to synchronize the fast ADC with the laser interferometer used to measure the position of the Hall probe along the undulator axis. To achieve this goal we ensured that both the ADC and interferometer card were integrated into the same VME technology. This lends the advantage to use the internal bus to transfer data. Finally, the magnetic field was directly measured at longitudinally equally spaced positions with an interval of 100 ± 2 μm. The K-value versus the gap was measured and the data fit (see Fig. 2a) with the following empirical formula,

$$K = K_0 \exp\left(-a\frac{g}{\lambda_U} + b\frac{g^2}{\lambda_U^2}\right) \tag{1}$$

where g is the gap and λ_U is the period. The fitting parameters values are $K_0 = 5.9$, $a = 5.55$ and $b = 2.31$. The phase error was measured and optimized using the differential screws for adjusting the local gap. The results are presented in Figure 2b. Starting with a value of about 6° RMS phase error after 10 steps of adjustments, the phase could be reduced below the target value of 2.5°. An erroneous adjustment (see step number 8 in Fig. 2b) can bring the phase back to unacceptable values. After the successful optimization at 4 mm gap, the phase was measured as a function of the gap. Figure 2c shows the RMS phase error as a function of the gap. The measurement was repeated after a thermal cycle to estimate its impact on the field quality. The reproducibility of the bench concerning the phase measurement is about ±0.5°. This is the main reason why it is involved to appreciate any correlation in Fig.2c.

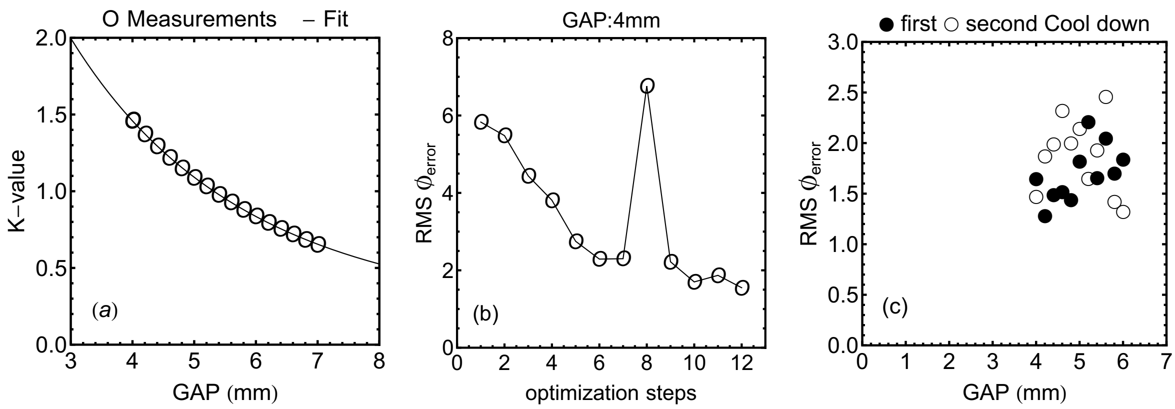

Figure 2 The main experimental results of the cold magnetic measurements on the U14. On the left the K-value versus gap, the markers are the measurements results and the solid line is the fit for hybrid undulator; at the centre the RMS phase error before and during the optimization; on the right the phase versus gap after the optimization.

4. U14 spectra characterization at the beamline

The undulator was installed in the SLS and commissioned. In the SLS tunnel the undulator has been aligned with a five axes mover to the nominal beam axis. With the help of a radiation detector , the alignment was further improved by minimizing the particle losses.

The main characterization activities involved the calibration of the gap versus photon energy for each harmonics up to 40 keV. At this early stage it was not possible to perform energy scans, so the research for the peak harmonic has been carried out with gap scans for a given photon energy. With the help of the compute code Synchrotron Radiation Workshop (SRW) (see Fig.3a) and the magnetic measurements of the K-value versus gap it was possible to minimize the number of measurements to obtain the full characterization of the undulator spectrum. In Fig.3b the experimental data are also presented and they show a very good agreement with the values obtained by theory.

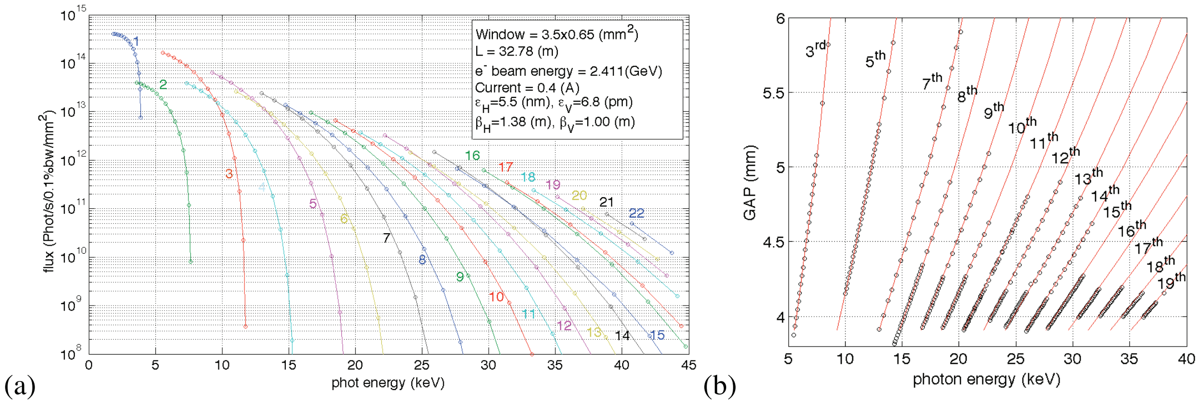

Figure 3 On the left, Brilliance calculations made with SRW taking into account the emittance and electron beam optics; on the right (b) the predicted gap versus energy (solid line) and the measured values (symbols) for different harmonics.

Conclusions

The cryogenic system works reliably both during the cool down phase and regular operation, for which temperature stability and temperature homogeneity along the magnet array are better than 0.1 K. The magnetic measurement accuracy and reproducibility were within the requirements (RMS phase error ±0.5°) but more flexibility in the optical system is mandatory to simplify and speed up the procedure. The in-situ optimization was very effective and a RMS phase error lower than 2.5° was achieved in the full operational gap range. The magnetic measurement results and the SRW calculation gave reliable inputs for the calibration of the beamline. The total monochromatic flux measured at the beamline is about the 85% of the calculated value with SRW at low photon energies, dropping to approximately 65% above 30 keV. The orbit perturbation generated while closing the GAP down to 3.8 mm are compensated with look up feed forward tables. The effect was nevertheless very small. The tune and dynamic acceptances of the SLS machine are basically not affected by the operation of U14.

References

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