

PROGRESS OF $Pr_2Fe_{14}B$ BASED HYBRID CRYOGENIC UNDULATORS AT SOLEIL*

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Abstract

Cryogenic Permanent Magnet Undulators (CPMUs) take advantage of the enhanced field performance of permanent magnets when cooled down to low temperature, enabling shorter period with sufficient magnetic field to achieve high brightness radiation in the X-ray domain. Several CPMUs have been manufactured at SOLEIL. The first CPMU of period 18 mm (U18), optimized with a phase error of 3.2° at temperature of 77 K, has been installed and operated for the past 5 years at SOLEIL for the NANOSCOPIUM beamline. We report a photon beam based alignment enabling for a better adjustment of the vertical position offset of the undulator, and a correction of the taper to enhance the radiation flux. A second U18 cryo-ready undulator, assembled with a new mechanical and magnetic sorting of module shimming, has attained a phase error of 2.3° at room temperature without any further adjustments after the assembly. Currently, two more CPMUs are being built: a 2 m long U18 undulator for SOLEIL ANATOMIX beamline, and a 3 m long 15 mm period undulator (U15) reaching a magnetic gap of 3 mm.

INTRODUCTION

Third generation synchrotron radiation has been used widely in different applications, due to the intense brightness produced using a low emittance beam and an insertion device most commonly known as undulator. An undulator consists of periodic arrangements of dipole magnets that generate periodic sinusoidal magnetic field, and is capable of producing a very intense and concentrated radiation in narrow energy bands. In the particle's frame, the magnetic period is shrunk by the factor γ due to Lorentz contraction, and for the outside observer the wavelength is further shrunk by factor 2γ due to the relativistic Doppler effect. In total, the emitted wavelength observed at the experiment is expressed as $\lambda_R = \frac{\lambda_u}{2\gamma^2} [1 + K^2/2]$, where λ_u is the magnetic period, $K = 93.4\lambda_u[m]B[T]$ the deflection parameter, γ the Lorentz factor, and B the peak field.

Permanent Magnet Undulators (PMUs) are able to function at room temperature and attain a fair magnetic field depending on the magnet material. Most Pure Permanent Magnet Undulators (PPMUs) use the Halbach geometric design [1]. Also introducing poles between the magnets of a PMU makes it a hybrid type [2] and enhances its magnetic peak field. In order to achieve higher brightness, one ought

to shorten the period, to achieve larger number of periods for a given length. However if the magnet sizes are to be reduced the peak field drops resulting in a deflection parameter K less than one; i.e the electric field emitted has a sinusoidal shape, hence only one peak is observed corresponding to the resonance wavelength. The CPMU design is easily adapted to the in-vacuum undulator and the magnet performance is enhanced, as in remanence field and coercivity, achieving a higher magnetic field with a shorter period length.

The progress of $Pr_2Fe_{14}B$ based cryogenic undulators at SOLEIL alongside magnetic measurements and optimization are presented. Applications using spectral measurement on one of the CPMUs installed on SOLEIL NANOSCOPIUM beam line are reported. Another CPMU is used after transporting a beam generated by laser plasma acceleration in the COXINEL project [3–5].

DESIGN

At cryogenic temperature (CT), $Nd_2Fe_{14}B$ experiences the so-called Spin Re-orientation Transition (SRT) phenomenon, which exhibits a negative dependence of remanent field against temperatures below 130 K. SRT is the change in the preferred direction of the magnetization with respect to the easy axis of magnetization. So another grade of magnet has been introduced, the Praseodymium Iron Boron ($Pr_2Fe_{14}B$), that does not undergo the SRT effect as shown in Fig. 1. These magnets can be cooled down to 30 K, and attain a high coercivity (7300 KA/m) and high field remanence (1.7 T). The coercivity of all grades maintain increasing with lower temperature.

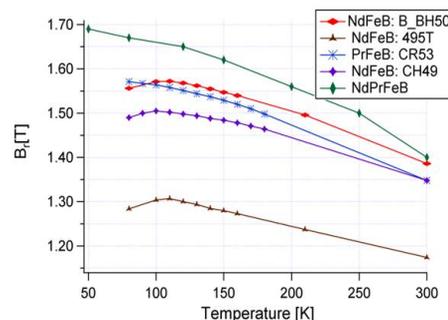


Figure 1: Magnet grades remanent field versus temperature [6, 7].

The design calculations have been done using RADIA [8] as shown in Fig. 2. The field at room temperature (RT) is 1.035 T and increased by almost 14 % to 1.155 T at CT.

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As for U15, the peak field is increased from 1.57 T at RT to 1.75 T at CT. Table 1 compares the different undulator characteristics to show the improvement of the cryogenic undulators.

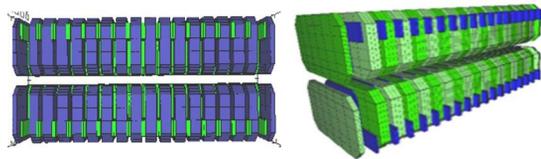


Figure 2: Prototype design of the undulator U18 (left) and U15 (right) with 7 periods, using RADIA code with IGOR Pro as front end.

Table 1: Undulator characteristics. N is the number of periods, T the temperature, and B the peak field.

	Magnets	N	Gap	T	B
U20	$Nd_2Fe_{14}B$	96	5.5 mm	293 K	1.06 T
U20	$SmCo_5$	96	5.5 mm	293 K	0.96 T
U18	$Pr_2Fe_{14}B$	107	5.5 mm	77 K	1.153 T
U15	$Pr_2Fe_{14}B$	200	3 mm	77 K	1.735 T

The mechanical design consists of a carriage with a metallic base where the frame is welded, two out-vacuum (external) girders fixed on the frame that can move vertically thanks to two series of sliders. The magnetic systems components are fixed on two in-vacuum girders connected to the external ones by 24 rods in U18 case and 36 rods in U15. The in-vacuum girders are separated by a gap where the electron beam crosses the undulator. The gap variation is enabled by two steps motors Berger Lahr VRDM3910, and a third one to move vertically the undulator in order to align the magnetic axis in the vertical direction with the electron beam axis.

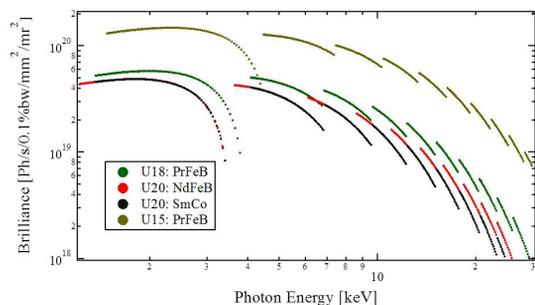


Figure 3: Brilliance in logarithmic scale, with beam energy 2.75 GeV, energy spread rms 0.01 %, beam current of 0.5 A, horizontal emittance of 3.9 nm, vertical emittance of 0.039 nm, $\beta_x = 5.577$ m, $\beta_z = 8.034$ m, $\alpha_x = -1.296$ rad, $\alpha_z = -1.477$ rad.

The spectral performance of the undulators presented in Table 1 are compared. Figure 3 shows the brilliance calculated with SRW software [9] using electron beam character-

istics for SOLEIL long straight section beam line and are presented the caption. Larger brilliance is achieved with the CPMUs (U18 and U15) than with the other undulators due to the additional number of periods. Also the photons emitted from the CPMUs have higher energies, due to the smaller periods which is proportional to the photon wavelength.

MAGNETIC MEASUREMENTS AND OPTIMIZATION

The electron beam should emit the most intense radiation when it crosses the undulator without disturbing the beam dynamics in the storage ring. The figures of merit during the assembly and corrections are the field integrals, the trajectory straightness and the phase error. They have to be minimized to reduce the impact of the magnetic errors on the undulator performance in terms of photon spectrum and beam dynamics. The assembly and the magnetic corrections of the cryogenic undulator are performed at room temperature with a standard magnetic bench allowing Hall probe and flip coil measurements. An optimization software called ID-Builder developed at SOLEIL [10] has been used at all steps of the undulator construction: magnets sorting, period assembly, shimming (vertical displacement of magnets and poles to correct the field integrals and the phase error), and magic fingers (small magnets installed at the extremities of the undulator to correct the field integrals). For U18n^o1 the phase error RMS was 12° after assembly and has been corrected (using shims) to reach 2.8°. As for U18n^o2,3 a new technique has been applied by shimming the poles to attain an altitude difference not larger than 15 μ m between them and the magnets. This technique enabled to reach a low phase error without magnet or pole shimming after assembly.

The undulator U18n^o1 is cooled down using a cryocooler system, and it takes approximately 6 hours to reach 77 K. Although the undulator is not baked to avoid demagnetization of the magnets due to the low coercivity, the undulator vacuum pressure drops quite rapidly reaching 10^{-9} mbar thanks to the cold mass which acts as a cryo-pump. After the cooling down, the RMS phase error is increased to 9.1° because of mechanical contractions. The rods are contracted vertically by 1 mm, leading to an in-vacuum girder deformation and then phase error degradation. Mechanical shims have been used to modify the vertical position of the 24 rods in order to correct the RMS phase error and bring it down to 3.2°.

MEASURED UNDULATOR SPECTRUM

The U18n^o1 cryogenic undulator is in use by the NANOSCOPIUM long beamline [11]. In Fig. 4, the photon flux measured on this beamline on the harmonics H9, H11 and H13 of the spectrum is compared to the one calculated from the magnetic measurements. A very good agreement has been found in terms of bandwidth confirming that the magnetic measurements carried out at cryogenic temperature had high precision.

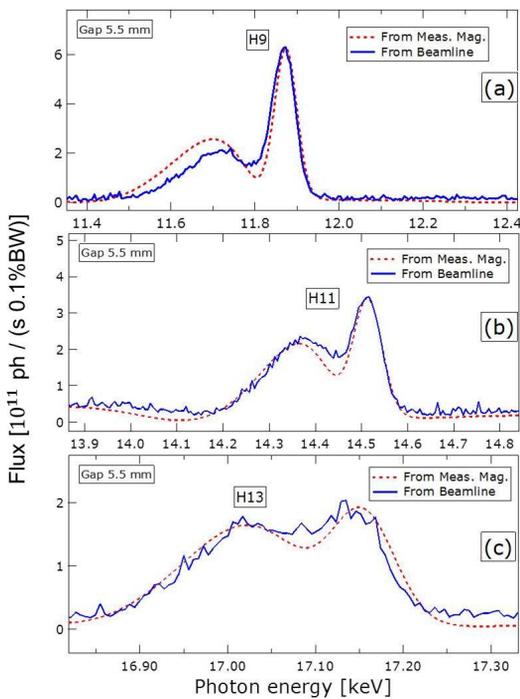


Figure 4: Normalized spectra measured on the beamline (non absolute) and calculated from magnetic measurements at 5.5 mm gap through a 0.05 mm x 0.05 mm aperture at a distance of 20.3 m from the undulator. Electron beam parameters same as of Fig. 3 caption, but with $\beta_x = 8.906 m$, $\beta_z = 7.216 m$, $\alpha_x = -1.296 rad$, $\alpha_z = -1.477 rad$. (a): 9th harmonic, (b): 11th, and (c): 13th harmonic.

Photon Beam Based Alignment

An offset optimization, as in moving the girders up or down without changing the gap, has been done while monitoring the spectrum of the undulator radiation on the NANOSCOPIUM long section beamline with a window aperture (0.2 mm x 0.8 mm) placed 77 m away from the undulator, and a photodiode placed at a distance of 83 m. The adjustment has been done by observing the 11th harmonic, since higher harmonics are very sensitive to any change in the undulator characteristics. The offset was varied, as in moving the girders up or down, while keeping the magnetic gap constant (5.5 mm). Figure 5 shows the spectra of the 11th as the offset is varied from -0.1 mm up to 0.4 mm. The difference between the resonant energy is due to the variation of the peak field, i.e. as the offset is increased the field increases as well causing a lower resonant energy. The best alignment is found when the highest intensity with the lowest band width are observed, thus U18 offset had been adjusted by 100 μm .

Taper Optimization

Undulator tapering refers to variation of the deflection parameter (either changing the peak field or period length) along the undulator axis. So another experiment is done to find the zero taper operation mode of the undulator. One way to modify the field is to slightly vary the gap at the exit

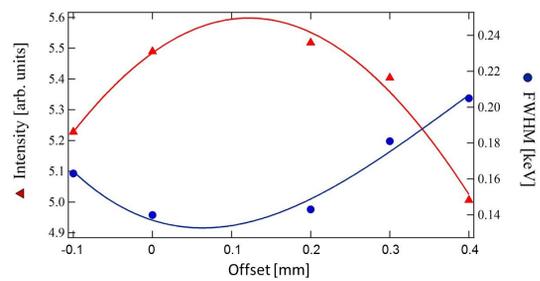


Figure 5: Intensity and Full Width Half Maximum (FWHM) of the 11th harmonic as a function of the offset that varied from -0.1 mm up to 0.4 mm.

of the undulator, either by closing or opening the girders at the extremity. Figure 6 shows the change of intensity of the 11th harmonic as the taper value is changed. The highest intensity with the lowest bandwidth is at -10 μm ; i.e. the girders at the exit of the undulator are closed by 10 μm . This optimization with a precision of $\sim 5 \mu rad$ corresponding to the angle of the internal girders enabled to increase the flux by $\sim 0.6\%$.

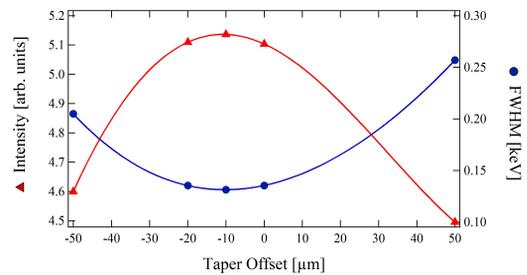


Figure 6: Intensity and Full Width Half Maximum (FWHM) of the 11th harmonic as a function of the taper offset.

CONCLUSION

A first full scale PrFeB based cryogenic undulator has been installed on a machine at SOLEIL and commissioned the past 5 years. Photon beam alignment has been done with U18n^o1 on the NANOSCOPIUM beamline, as well as taper optimization to improve the emitted radiation. The results of the spectrum show that the undulator has good field quality with a low RMS phase error (3.2 $^\circ$). U18n^o2 has been successively installed and in use for COXINEL project. U18n^o3 is planned to be installed at the end of year 2017. U15 is capable of achieving a brilliance almost one order of magnitude more due to the additional number of periods, and its construction is under progress.

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