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# CRYOGENIC PERMANENT MAGNET UNDULATOR FOR AN FEL APPLICATION*

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*Abstract*

Cryogenic Permanent Magnet Undulator (CMPU) is capable of achieving high brightness radiation at short wavelengths, by taking advantage of the permanent magnet's enhanced performance at low temperature. A CPMU of period 18 mm (U18) that has been built at Synchrotron SOLEIL is used for the COXINEL project to demonstrate Free Electron Laser (FEL) at 200 nm using a laser plasma acceleration source. Another undulator of period 15 mm (U15) is currently being built to replace U18 undulator for FEL demonstration at 40 nm. A new method is also introduced, using SRWE code, to compute the spectra of the large energy spread beam (few percent) taking into account the variation of the Twiss parameters for each energy slice. The construction of U18 undulator and the magnetic measurements needed for optimization, as well as the mechanical design of U15, are presented.

## INTRODUCTION

Third generation synchrotron radiation has been used widely in different applications, due to the intense brightness produced ranging from infrared to x-rays. This intensity is generated by the use of a low emittance beam and an insertion device most commonly known as undulator. An undulator consists of periodic arrangements of dipole magnets generating a periodic sinusoidal magnetic field, and is capable of producing an intense and concentrated radiation in narrow energy bands as relativistic electrons are traversing it. The emitted radiation wavelength observed is expressed as $\lambda_R = (\lambda_u/2\gamma^2)[1 + K^2/2]$, where $\lambda_u$ is the magnetic period, $K = 93.4\lambda_u[m]B[T]$ the deflection parameter, and $B$ the peak field. Fourth generation sources, such as Free Electron Laser (FEL) based experiments, exceed the performance of previous sources by one or more orders of magnitude in important parameters such as brightness, coherence, and shortness of pulse duration. The future FEL based projects relies on the compactness of the machine. Hence, compact undulators are needed for such developments.

Permanent magnet undulators are able to function at room temperature and attain a fair magnetic field depending on the magnet material. Most pure permanent magnet undulators use the Halbach geometric design [1], and by replacing poles with the vertically magnetized magnets making it a hybrid type [2] and enhances its magnetic peak field. In order to achieve a more compact undulator with sufficient field, one has to decrease the size of magnets which will reduce the peak field. So the idea was proposed at SPring-8 [3] to cool down the undulator to cryogenic temperature and enhancing the performance of the permanent magnets. The Cryogenic Permanent Magnet Undulator (CPMU) design is easily adapted to the in-vacuum undulator, achieving a high peak field with a shorter period length making it suitable for compact FEL based applications.

## MAGNETIC AND MECHANICAL DESIGN

The prototypes design has been done using RADIA [4] as shown in Fig. 1. The magnets used are $Pr_2Fe_{14}B$ [5] and Vanadium Permendur poles, and their characteristics are presented in Table 1 for both CPMUs, period 18 mm (U18) and period 15 mm (U15).

Figure 2 shows the field computed for the two cryogenic undulators at both room and cryo temperature. The field is increased by ~12 % from room temperature to cryo temperature. The mimnimum gaps reached by U15 and U18 are 3 mm and 5 mm respectively.

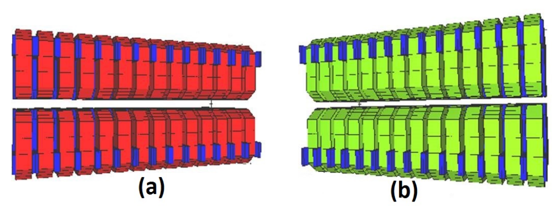


Figure 1: (a) prototype design of the undulator U18 and (b) of U15 with 7 periods, using RADIA code with IGOR Pro as front end.

Table 1: U18 prototype characteristics.

| Parameters | Value | Unit |
|---|---|---|
| Magnet dimension (U18) | 50 x 30 x 6.5 | $mm^3$ |
| Magnet dimension (U15) | 50 x 30 x 5.5 | $mm^3$ |
| Pole dimension (U18) | 33 x 26 x 2.5 | $mm^3$ |
| Pole dimension (U15) | 33 x 26 x 2 | $mm^3$ |
| $B_r$ @ RT | 1.32 | T |
| $B_r$ @ CT | 1.57 | 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 system components are fixed on two in-vacuum girders connected to the

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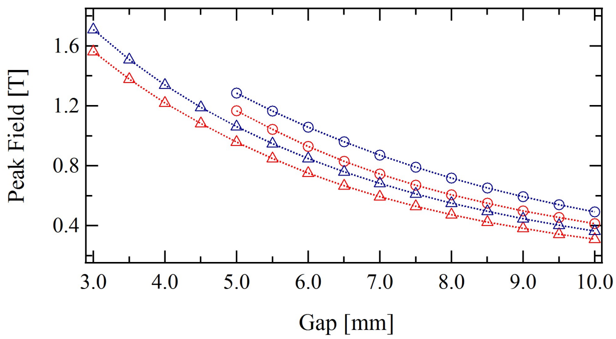


Figure 2: Peak field computed by RADIA versus magnetic gap. (blue) at cryogenic temperature, (red) room temperature, (○) U18, (△) U15.

external ones by 24 rods in U18 (Fig. 3-a) case and 36 rods in U15(Fig. 3-b). The in-vacuum girders are separated by a gap to let the electron beam pass through 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.

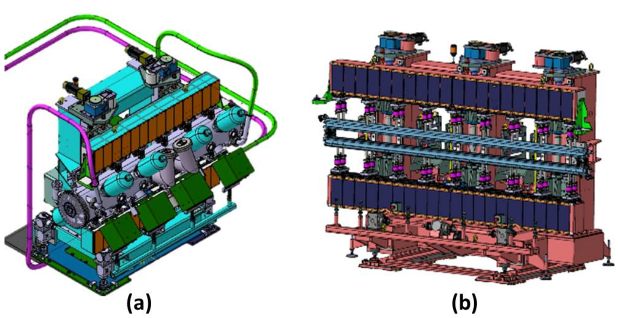


Figure 3: Mechanical design, (a) U18, (b) U15.

## MAGNETIC MEASUREMENTS AND OPTIMIZATION

The brightness of the radiation emitted as the electrons traverse the undulator should be as intense as possible. Also the beam dynamics should not be disturbed especially in the case of a 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 CPMU are performed at room temperature with a standard magnetic bench allowing Hall probe and flip coil measurements [6]. An optimization software called ID-Builder developed at SOLEIL [7] 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 multipole shim magnets also known as magic fingers (small magnets installed at the extremities of the undulator to correct the field integrals). For U18 the phase error RMS was 12.5° after assembly and has been corrected (using shims) to reach 2.5°.

Figure 4 shows the optimization of the field integrals, which are proportional to the angle and trajectory of the electrons as they propagate through the undulator, using multipole trim magnets also known as magic fingers.

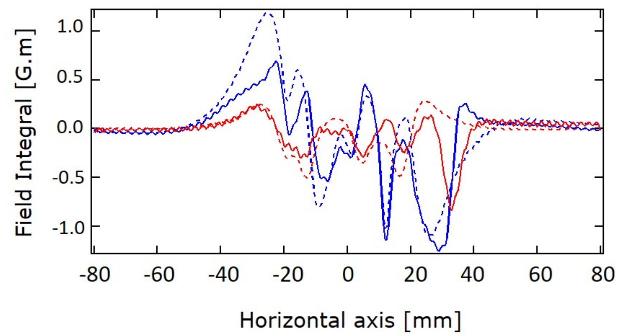


Figure 4: Field integrals across the transverse planes before and after applying the magic fingers. (blue) horizontal axis, (red) vertical axis, (dashed) before magic fingers, (line) after magic fingers.

## SPECTRAL FLUX

The undulator radiation calculation is not completely straightforward in the case of COXINEL [8, 9] due to high energy spread leading to chromatic effects. One now takes into account the transmission of the line as in electron beam energy, charge, and their Twiss parameters inside the undulator. Thus a new approach has been done on simulating the spectrum radiation using SRWE code [10], in the case of 5% rms energy spread, by taking slices of the beam energy, get the spectrum of each slice and add them up.

Figure 5 shows the variation of the Twiss parameters versus electron energy, and Fig. 6 presents the result of the spectra computed using these values compared to an average case. The method has been also used for the broad energy case (~30% energy spread rms), where it showed a very different spectrum compared to the average case.

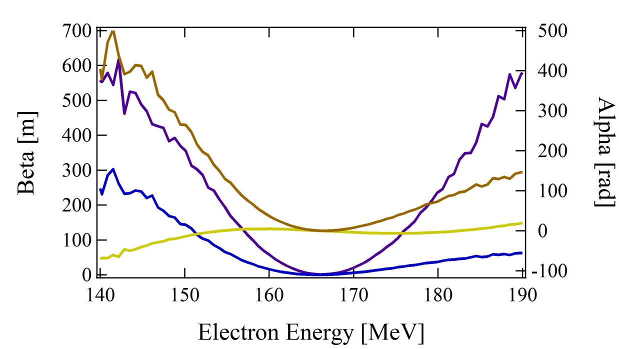


Figure 5: Twiss parameters for each energy slice. (Purple) horizontal beta, (Blue) vertical beta, (Yellow) horizontal alpha, (Brown) vertical alpha.

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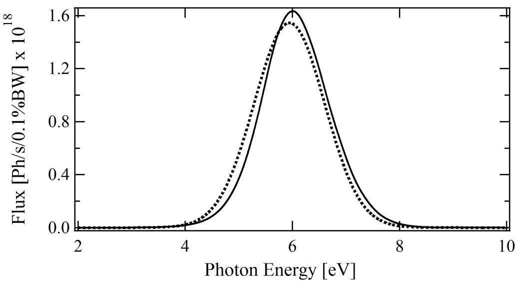


Figure 6: Spectral flux of the first harmonic. Gap = 5.5 mm, Peak field = 0.98 T. (...) average case taking into account an average value of the Twiss parameters and emittance, (—) slicing method taking into account the variation of the Twiss parameters and emittance for each energy slice.

## INSTALLATION AND COMMISSION

U18 has been installed at COXINEL as shown in Fig. 7, it is operating at room temperature due to infrastructure reasons. A Coupled Charged Device (CCD) camera is installed 3 m after the undulator exit, and the transverse beam shape has been measured and showed good agreement with the simulated one, after 8 m of controlled transport line.

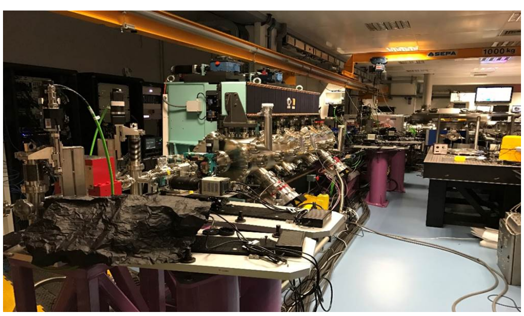

Figure 7: U18 undulator installed at LOA operating at room temperature. A CCD camera is installed downstream the undulator 3 m away.

## CONCLUSION

A CPMU of period 18 mm has been successfully installed at COXINEL and synchrotron radiation were detected using a CCD camera installed 3 m away from the undulator. Another CPMU of period 15 mm is still under progress and its mechanical design allows for a minimum gap of 3 mm. An original method using SRWE has been developed to compute the spectrum for a broad energy spread case.

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