

## DEVELOPMENT OF $\text{Pr}_2\text{Fe}_{14}\text{B}$ CRYOGENIC UNDULATOR CPMU AT SOLEIL

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### Abstract

A R&D programme for the construction of a 2 m long 18 mm period CPMU is under progress at SOLEIL. The cryogenic undulator will provide photons in the region of 1.4 to 30 keV. It is installed in the end of august on the long straight section (SDL13) of the storage ring, and could be used later on to produce photons for the NANOSCOPIUM beamline. The use of  $\text{Pr}_2\text{Fe}_{14}\text{B}$  which features a 1.35 T remanence ( $B_r$ ) at room temperature enables to increase the peak magnetic field at 5.5 mm minimum gap, from 1.04 T at room temperature to 1.15 T at a cryogenic temperature of 77 K.  $\text{Pr}_2\text{Fe}_{14}\text{B}$  was chosen instead of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  magnetic material, because it is more resistant against the appearance of the Spin Reorientation Transition. Different corrections were performed first at room temperature to adjust the phase error, the electron trajectory and to reduce the multipolar components. The mounting inside the vacuum chamber enables the fitting of a dedicated magnetic measurement bench to check the magnetic performance of the undulator at low temperature.

### INTRODUCTION

SOLEIL is a 2.75 GeV energy storage ring, on which hard X rays production is achieved by short period small gap in vacuum hybrid undulators [1]. In order to shift further the radiation toward higher energies, the peak magnetic field of the undulators can be further increased while operating at cryogenic temperature (around 140 K for  $\text{Nd}_2\text{Fe}_{14}\text{B}$  magnet and around 77 K for  $\text{Pr}_2\text{Fe}_{14}\text{B}$  magnet [2]).

When cooling down the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  permanent magnets, the remanence  $B_r$  increases down to a certain temperature at which the process is limited by the appearance of the Spin Reorientation Transition (SRT) phenomenon [3] and [4]. However when cooling down  $\text{Pr}_2\text{Fe}_{14}\text{B}$  permanent magnet, the remanence  $B_r$  increases down to the liquid nitrogen temperature 77 K, without being affected by the SRT phenomenon. In both cases, the coercivity is also increased at cryogenic temperature, the resistance to radiation is significantly improved, and is not affected by the SRT.

$\text{Pr}_2\text{Fe}_{14}\text{B}$  magnet grade with high remanence cannot be heated to high temperature for baking without degrading the magnetic properties. One should also pay attention to the temperature gradient and the mechanical deformation issues.

### CRYOGENIC TEST BENCH (CTB)

A cryogenic test bench dedicated to the characterisation at low temperature of permanent magnets assembled together in a four period hybrid undulator [5] has been built. The measurements have been compared with the results of the single magnet characterisation. The bench is constituted of a vacuum chamber with several flanges for pumping and vacuum instrumentation. The magnets are mounted with poles on modules which are fixed on aluminium girders maintained with a frame. The bench is cooled down by liquid nitrogen which circulates in a copper tube fixed on it. The magnetic field is measured by a Hall probe. A stepper motor moves the Hall probe from outside the vacuum chamber. A bellow transmits the movement inside the chamber.

The simulation of the magnetic system of the CTB has been performed with RADIA [6]. It is a four period magnetic system with a period of 20 mm and a gap of 10 mm. The permanent magnets are  $\text{Nd}_2\text{Fe}_{14}\text{B}$  (BH50 grade from HITACHI) with a remanence of 1.41 T and the poles are vanadium Permendur with a saturation induction of 2.35 T (figure 1).

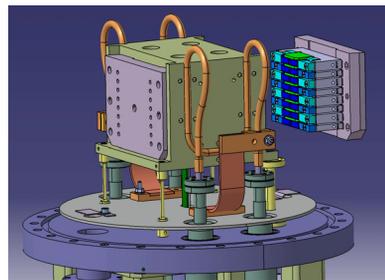


Figure 1: CTB assembly and magnetic system.

The magnetic field of the CTB is calculated for different values of the remanence  $B_r$  and susceptibility  $\chi$  versus temperature, deduced from the characterisation of the magnet sample with the magnetometer. The variation of the susceptibility versus temperature is presented in figure 2.

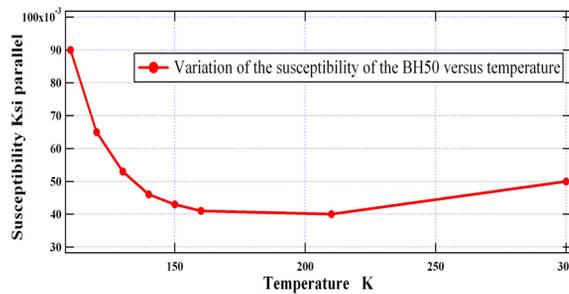
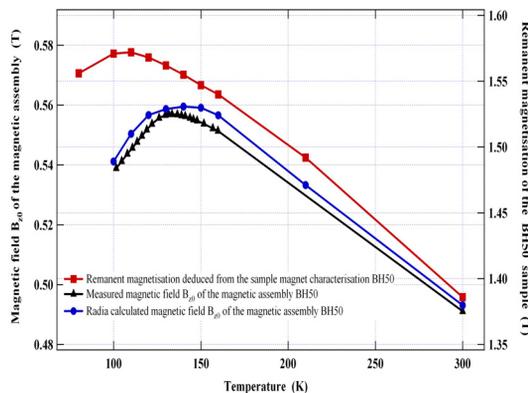


Figure 2: Variation of susceptibility versus temperature

The value of the susceptibility at room temperature is 0.05. This value decreases to 0.04 when the temperature is reduced to 160 K, after it increases to reach the room temperature value for a temperature of 140 K. When the temperature decreases below 140 K, the susceptibility value continues to increase and reaches 0.09 at the temperature of 100 K.

The results of the simulation and magnetic measurements of the CTB are presented in figure 3. The measured magnetic field of the CTB grows by 11.5 % due to the cooling of the magnetic system of the device.

Figure 3: Variation of magnetic field of the CTB and  $B_r$  of a single magnet versus temperature.

The maximum value of the remanence  $B_r$  of the magnet sample is reached at 110 K (figure 3), whereas the maximum of the magnetic field of the CTB is reached at 140 K. This shift is due to the increase of the susceptibility of the permanent magnet below 140 K and the appearance of the SRT at lower temperature, which prevents the increase of the magnetic field. The homogeneity of the magnetic field between 130 K and 160 K is 0.09%, it limits the constraints of the cryogenic undulator cooling system.

We have assembled and measured at low temperature an 18 mm period Cryogenic Test Bench with  $\text{Pr}_2\text{Fe}_{14}\text{B}$  permanent magnet. We do not see any appearance of the SRT. The measured magnetic field grows by 13 % due to the cooling down of the magnetic system close to the liquid nitrogen temperature 77 K.

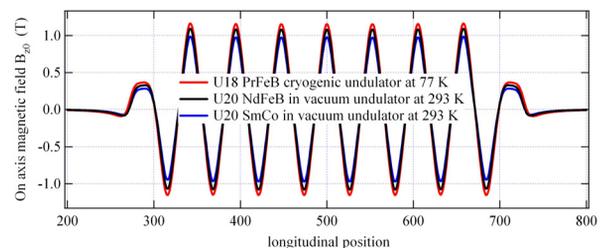
## DESIGN OF U18 CRYOGENIC UNDULATOR

The design of the cryogenic undulator is done by RADIA software. The main parameters of U18 cryogenic undulator are given by Table 1

Table 1: Cryogenic Undulator Main Parameters

|                               |  |
|-------------------------------|--|
| Undulator type                | Hybrid                                     |
| Magnetic material             | $\text{Pr}_2\text{Fe}_{14}\text{B}$ (CR53) |
| Magnet size ( $\text{mm}^3$ ) | 50x30x6.5                                  |
| Remanence $B_r$ (T)           | 1.35 at 293 K                              |
| Coercivity $H_{cj}$ (T)       | 1.65 at 293 K                              |
| Pole material                 | Vanadium Permendur                         |
| Pole size ( $\text{mm}^3$ )   | 33x22x2.5                                  |
| Period (mm)                   | 18   |
| Gap (mm)                      | 5.5  |
| Number of periods             | 107  |
| Polarisation                  | Linear horizontal                          |
| Spectrum                      | 1.4 to 30 keV                              |

Figure 4 presents the calculated on axis magnetic field  $B_z$  at minimum gap 5.5 mm of the  $\text{Pr}_2\text{Fe}_{14}\text{B}$  cryogenic undulator at 77 K compared to  $B_z$  of  $\text{Sm}_2\text{Co}_{17}$  U20 in vacuum undulator and  $\text{Nd}_2\text{Fe}_{14}\text{B}$  U20 in vacuum undulator under construction at SOLEIL.

Figure 4: On axis magnetic field at minimum gap 5.5 mm of U18 cryogenic undulator at 77 K and U20  $\text{Sm}_2\text{Co}_{17}$  and U20  $\text{Nd}_2\text{Fe}_{14}\text{B}$  at room temperature

The cryogenic undulator design is derived from the present one of the SOLEIL U20 in-vacuum undulators. We add to the actual carriage a second motor for the movement of the gap is added to the carriage in order to correct systematic taper on the gap, and we have equipped the out vacuum girders with copper plates to avoid temperature gradient and then deflection of the girders. Any deflection on the out vacuum girders could damage the phase error of the undulator.

The choice of the  $\text{Pr}_2\text{Fe}_{14}\text{B}$  permanent magnet simplifies a lot the cooling system, because it is necessary to cool down the in vacuum girder to the liquid nitrogen temperature 77 K instead of the 140 K if we use  $\text{Nd}_2\text{Fe}_{14}\text{B}$ .

## MAGNETIC PERFORMANCE OF U18 CRYOGENIC UNDULATOR

The magnetic system of the cryogenic undulator is assembled and shimmed at room temperature and then

installed inside the vacuum chamber. The dedicated magnetic measurement bench at low temperature is mounted and aligned in the vacuum chamber. It comports a Hall probe fixed on a chariot which is moved by a stepper motor on a rail. The rail is mechanically independent from the undulator vacuum chamber and fixed from outside the vacuum chamber by seven rods. The deformation of the rail is measured with an optical system. The longitudinal position of the Hall probe is measured with an optical rule.

Figure 5 presents the U18 cryogenic undulator equipped with the magnetic measurements bench and connected to the Cryotherm cooling system at SOLEIL.

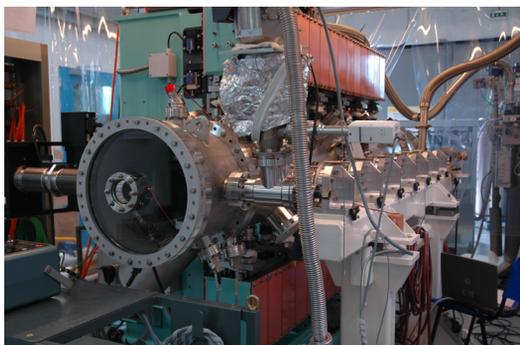


Figure 5: U18 cryogenic undulator during low temperature magnetic measurements

The cryogenic undulator is cooled down to the nitrogen liquid temperature of 77 K using a close loop Cryotherm system. The magnetic system reaches a temperature of 82 K. The thermal gradient a long the undulator is less than 1 K/m.

The cryogenic undulator is measured at low temperature and compared to the performance at room temperature. Figure 6 presents the measured on axis magnetic field of 107 periods at 5.5 mm at room temperature and at 77 K. The magnetic field at 77 K is 10% higher than the one at room temperature.

The phase error of U18 cryogenic undulator at minimum gap 5.5 mm at room temperature is 2.8° RMS. When cooling down to 77 K, the phase error increases to 9° RMS, and has been reduced down to 3.5° RMS by shimming the rods.

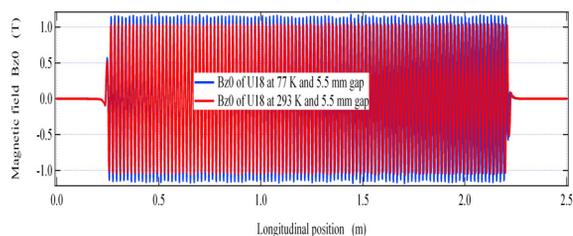


Figure 6: On axis magnetic field of U18 cryogenic undulator at minimum gap 5.5 mm at room temperature and at 77 K.

Figure 7 presents the spectrum of the cryogenic undulator calculated with SRW at minimum gap of 5.5 mm at room temperature and at cryogenic one at a distance of 17 m trough a slit of 0.1 x 0.1 mm<sup>2</sup>. We gain 20% on the 7<sup>th</sup> harmonic of the spectrum at cryogenic temperature of 77 K compared the one at room temperature.

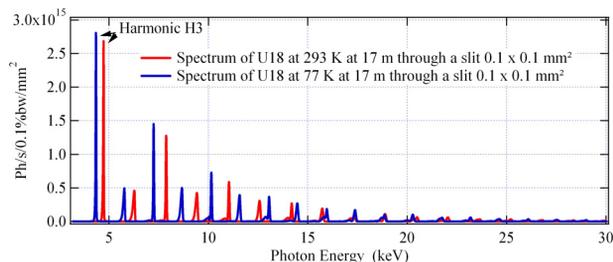


Figure 7: Spectrum of U18 cryogenic undulator at minimum gap 5.5 mm at room temperature and at 77 K.

### CONCLUSION

The behaviour of two different cryogenic Test Bench of four periods with two different grades Nd<sub>2</sub>Fe<sub>14</sub>B and Pr<sub>2</sub>Fe<sub>14</sub>B have been compared at low temperature. Pr<sub>2</sub>Fe<sub>14</sub>B has been chosen for our U18 CPMU because of the absence of the SRT phenomenon and the simplicity of the cooling system. A full 2 m U18 CPMU has been assembled and corrected at room temperature. It has been cooled down at 77 K and measured, leading to a phase error of 3.5° RMS after shimming the rods.. The undulator has been installed in the storage ring in the end of August and will be commissioning with electron beam in September.

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