DEVELOPMENT OF $PR_2FE_{14}B$ CRYOGENIC UNDULATOR CPMU AT SOLEIL

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Abstract

Short period, high field undulators can enable short wavelength free electron lasers (FELs) at low beam energy, with decreased gain length, thus allowing much more compact and less costly FEL systems [1]. A R&D program for the construction of a 2 m long 18 mm period $Pr_2Fe_{14}B$ cryogenic undulator is under progress at SOLEIL. The use of $Pr_2Fe_{14}B$ 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. For FELs, higher magnetic field of 1.91 T at lower gap of 3 mm can be reached. $Pr_2Fe_{14}B$ was chosen instead of $Nd_2Fe_{14}B$ magnetic material, because of the absence of the Spin Reorientation Transition phenomenon [2]. 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. A cryogenic undulator U18 could be used in LUNEX5 project at SOLEIL.

INTRODUCTION

Producing hard X rays with electron beams of intermediate energy requires short period and small gap in-vacuum hybrid permanent magnet undulators [3] (U20 with Sm_2Co_{17} magnets, 20 mm period and 5.5 mm gap provides ~1 T magnetic field). 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 $Nd_2Fe_{14}B$ magnet and around 77 K for $Pr_2Fe_{14}B$ magnet [4]).

When cooling down the $Nd_2Fe_{14}B$ 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 [2] and [5]. However when cooling down $Pr_2Fe_{14}B$ permanent magnet, the remanence B_r increases down to the liquid nitrogen temperature 77 K, and it is not 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.

Unfortunately this type of magnet grade cannot be heated to high temperature without degrading the magnetic properties. Besides, keeping under control the temperature gradient and the mechanical deformation are additional technical issues. In this paper we will present the cryogenic test bench used to characterise few periods and to compare with the behaviour of a single magnet. The cryogenic undulator is derived from the conventional U20 in vacuum undulators. We describe the conventional U20 in vacuum undulator of SOLEIL and we mention the modifications added to obtain a cryogenic undulator. A dedicated Hall probe bench has been designed and assembled in the vacuum chamber of the cryogenic undulator to measure it at low temperature. Magnetic measurements have been performed with this bench at 77 K and compared to the measurement at room temperature.

CRYOGENIC TEST BENCH (CTB)

The cryogenic test bench is dedicated to the characterisation at low temperature of permanent magnets assembled together in a four period hybrid undulator [6]. The measurements will be 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. It 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.

MAGNETIC SYSTEM OF CTB

We have used Radia [7] for the simulation of the magnetic system of the CTB. It is a four period magnetic system with a period of 20 mm and a gap of 10 mm. The permanent magnets are $Nd_2Fe_{14}B$ (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).

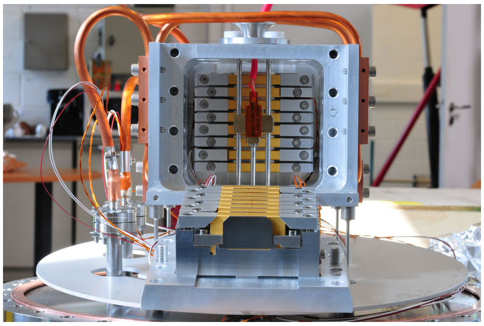

Figure 1: CTB assembly and magnetic system.

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The magnetic field of the CTB is calculated for different values of the remanence B_r and susceptibility χ 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.

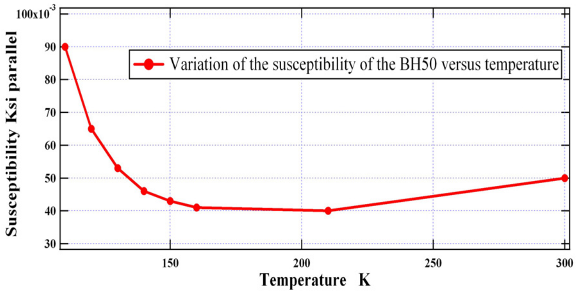

Figure 2: Variation of susceptibility versus temperature.

The value of the susceptibility at room temperature is 0.05. This value decreases to 0.04 when temperature decreases to 160 K, after it increases and reaches the room temperature value when the temperature reaches 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 down of the magnetic system of the device.

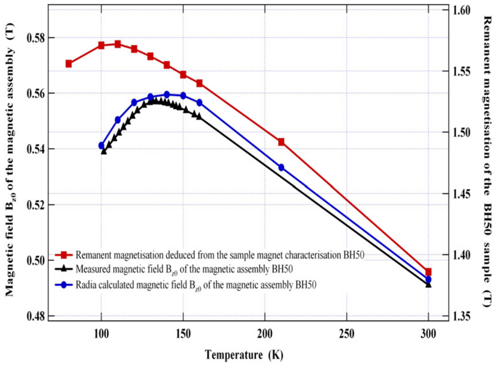

Figure 3: Variation of magnetic field of the CTB and Br of a single magnet versus temperature.

The maximum value of the remanence B_r of the magnet sample is reached at 110 K (figure 3), however 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 stops 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 assembled and measured at low temperature an 18 mm period Cryogenic Test Bench with $Pr_2Fe_{14}B$ permanent magnet. We did 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.

CONVENTIONNAL U20 IN VACUUM UNDULATOR OF SOLEIL

In-vacuum undulators are built in SOLEIL for providing high energy photons. U20s are planar hybrid in-vacuum undulators with a 20 mm period (table 1).

The carriage is composed of a metallic base and a frame; two external girders are fixed on this frame. The magnetic system is mounted on a vacuum girder connected to the external girders by rods. The carriage is equipped with two motors; one for the movement of the gap and the other for the movement of the offset in order to adjust vertically the magnetic axis of the undulator to the electron beam axis. Linear and rotated encoders are used to read the exact gap and offset. Dedicated software is developed at SOLEIL to manage all the motorisation control system and securities.

Table 1: U20 in Vacuum Undulator Main Characteristics

Undulator type	Hybrid
Magnetic material	Sm_2Co_{17}
Magnet size (mm^3)	50x30x7.5
Remanence Br (T)	1.05
Coercivity Hcj (T)	3
Pole material	Vanadium Permendur
Pole size (mm^3)	33x22x2.5
Period (mm)	20
Gap (mm)	5.5
Number of periods	98
Polarisation	Linear horizontal
Spectrum	1.4 to 30 keV

The magnetic design (figure 4) of U20 is done by Radia. The extremities have been optimised to minimise the field integral for different gaps.

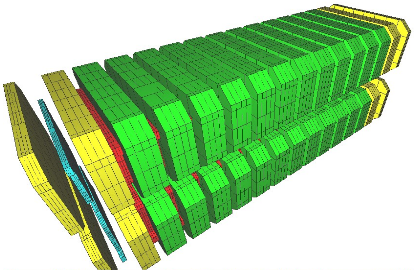

Figure 4: Radia model of U20.

Assembling, Spectral shimming and trajectory straightness correction are performed at SOLEIL by the vertical motion of the holders and poles using homemade software. Integrated multipolar terms are corrected with magic fingers located at both ends of the magnetic system using the same software.

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 2

Table 2: Cryogenic Undulator Main Parameters.

Undulator type	Hybrid
Magnetic material	$Pr_2Fe_{14}B$ (CR53)
Magnet size (mm^3)	50x30x6.5
Remanence Br (T)	1.35 at 293 K
Coercivity Hcj (T)	1.65 at 293 K
Pole material	Vanadium Permandur
Pole size (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 5 presents the calculated on axis magnetic field Bz_0 at minimum gap 5.5 mm of the $Pr_2Fe_{14}B$ cryogenic undulator at 77 K compared to Bz_0 of Sm_2Co_{17} U20 in vacuum undulator and $Nd_2Fe_{14}B$ U20 in vacuum undulator under construction at SOLEIL.

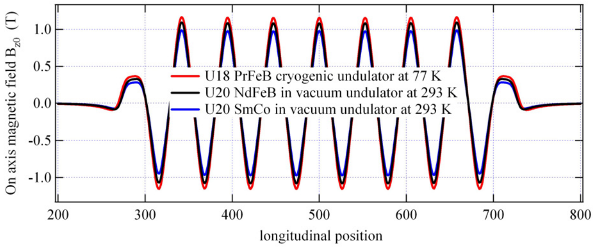

Figure 5: On axis magnetic field at minimum gap 5.5 mm of U18 cryogenic undulator at 77 K and U20 Sm_2Co_{17} and U20 $Nd_2Fe_{14}B$ at room temperature

Figure 6 presents the calculated on axis magnetic field Bz_0 at different gaps between 3 mm and 10 mm of $Pr_2Fe_{14}B$ cryogenic undulator at 77 K compared to Bz_0 of Sm_2Co_{17} U20 in vacuum undulator and $Nd_2Fe_{14}B$ U20 in vacuum undulator under construction at SOLEIL

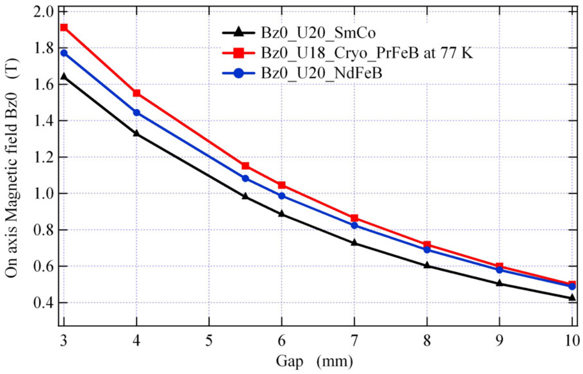

Figure 6: On axis magnetic field at different gap between 3 mm and 10 mm of U18 cryogenic undulator at 77 K and U20 Sm_2Co_{17} and U20 $Nd_2Fe_{14}B$ at room temperature.

The cryogenic undulator design is derived from the actual design of the SOLEIL U20 in-vacuum undulator. We add to the actual carriage a second motor for the movement of the gap to be able 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 (figure 7). Any deflection on the out vacuum girders could damage the phase error of the undulator.

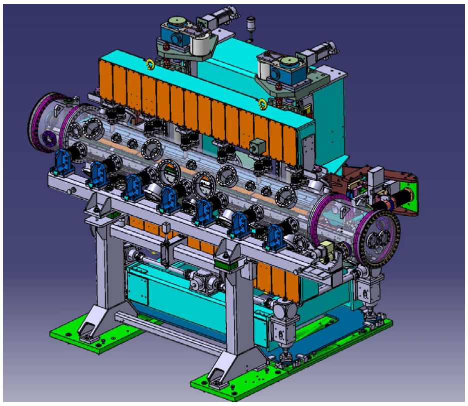

Figure 7: Cryogenic undulator.

The choice of the $Pr_2Fe_{14}B$ permanent magnet simplifies a lot the cooling system, because we need to cool down the in vacuum girder to the liquid nitrogen temperature 77 K instead of the 140 K in case of $Nd_2Fe_{14}B$. We design a hole of 12 mm diameter in the middle of the in vacuum girder where the liquid nitrogen circulates. The shape of the girder is manufactured by extruding row aluminium material. The cryogenic undulator is cooled down by a Cryotherm close loop cryogenic system. We use one circuit for both girders.

MAGNETIC MEASUREMENT BENCH AT LOW TEMPERATURE

A low temperature magnetic bench has been designed and assembled at SOLEIL. It is used to remeasure the undulator at room temperature and to do measurement at low temperature to check if any deviation on the magnetic behaviour appears. The local magnetic field is measured with a Hall probe. The low temperature magnetic measurement bench is integrated inside the undulator vacuum chamber (figure 8) and it is removed after the measurements. The Hall probe is 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.

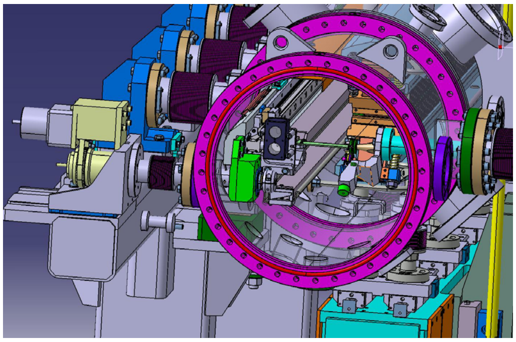

Figure 8: Low temperature magnetic measurement bench.

MAGNETIC PERFORMANCE OF U18 CRYOGENIC UNDULATOR

The magnetic system of the cryogenic undulator is assembled and shimmed at room temperature (using a conventional magnetic bench equipped with Hall probe and rotation coil) and then installed inside the vacuum chamber. The dedicated magnetic measurement bench at low temperature is mounted and aligned in the vacuum chamber. Figure 9 presents the U18 cryogenic undulator equipped with the magnetic measurements bench and connected to the Cryotherm cooling system at SOLEIL.

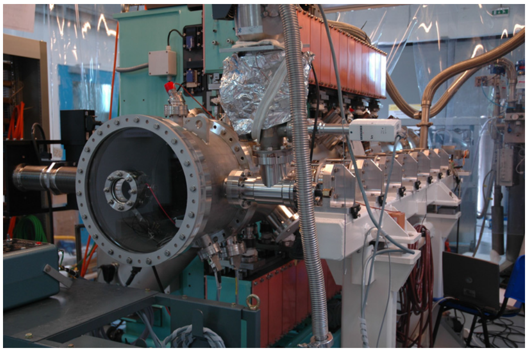

Figure 9: U18 cryogenic undulator during low temperature magnetic measurements

The magnetic system reaches a temperature of 83 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 10 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 was 2.8° RMS. When cooling down to 77 K, the phase error increased to 9° RMS, We improved this phase error by shimming the rods to reach 3.5° RMS.

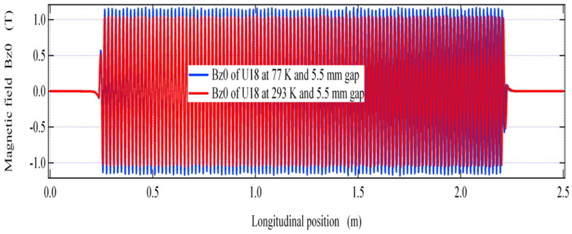

Figure 10: On axis magnetic field of U18 cryogenic undulator at minimum gap 5.5 mm at room temperature and at 77 K.

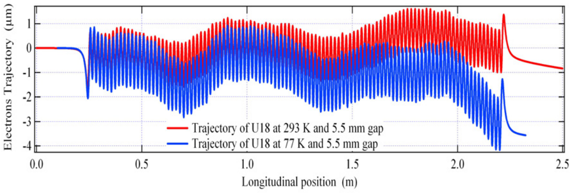

Figure 11: Electron beam trajectory in U18 cryogenic undulator at minimum gap 5.5 mm at room temperature and at 77 K.

CONCLUSION

We assembled and measured at different temperatures a cryogenic Test Bench of four periods with two different grades $Nd_2Fe_{14}B$ and $Pr_2Fe_{14}B$, compare the behaviour at low temperature. $Pr_2Fe_{14}B$ has been chosen for our U18 CPMU because of the absence of the SRT phenomenon and the simplicity of the cooling system. We assembled and shimmed the U18 CPMU at room temperature. We mounted the magnetic system in the vacuum chamber equipped with magnetic measurement bench at low temperature. We cooled down the magnetic system at the liquid nitrogen temperature 77 K. We characterised the undulator at this temperature and we adjusted the phase error to 3.5° by shimming the rods. The undulator will be installed in the storage ring in the end of August and will be commissioning with electron beam in September.

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