FIRST OPERATIONAL EXPERIENCE WITH A CRYOGENIC PERMANENT MAGNET UNDULATOR AT THE ESRF

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Abstract

A cryogenically cooled in-vacuum undulator was installed in the ID6 test beamline of the ESRF in January 2008. This 2 metre long hybrid undulator has a period of 18 mm. The magnetic assembly is based on NdFeB permanent magnets cooled at a temperature close to 150 K. A liquid nitrogen closed loop is used for the cooling of the undulator. This cooling system is well adapted to achieve a uniform temperature along the magnetic assembly. A large part of the study was focused on the heat budget of the undulator under beam in the different filling modes delivered at the ESRF. The impact of the undulator on the ultra high vacuum of the ring was investigated with several warming/cooling cycles. This paper presents the main outcomes from this first experience.

INTRODUCTION

A Cryogenic Permanent Magnet Undulator (CPMU) is an in-vacuum undulator which makes use of the enhanced magnetic properties of NdFeB material at low temperature [1]. It therefore allows the extension of high brilliance undulator radiation to higher photon energy than is usually achieved with conventional in-vacuum undulators. The maximum performance can be reached using NdFeB grades having the highest remanence (B_r > 1.4 T) at room temperature but also the lowest coercivity (Hc_j <1000 kA/m). Such coercivity is insufficient to operate an in-vacuum undulator safely at room temperature due to the possible demagnetization of permanent magnets under electron beam exposure with small gaps. This weak point is eliminated when the magnet material is cooled at cryogenic temperature. Typically, the coercivity is increased by a factor of 2.5 when the NdFeB material is cooled from 293 K to 150 K. The temperature of 150 K corresponds to an optimum in the dependence of the undulator field on the temperature [2]. It is related to a specific magnetic property of the NdFeB material called Spin Reorientation Transition (SRT). Below 150 K the undulator peak field decreases. This unusual magnetic behaviour has required some studies on NdFeB samples at low temperature [2],[4]. An accurate magnetic model of NdFeB material at low temperature requires a non linear representation. A linear model can still be used but requires knowledge of the material magnetic permeability versus temperature [5] in order to correctly predict the field performances of a CPMU .

At the ESRF, all in-vacuum undulators are baked at 120 deg C after their installation in the ring in order to limit the Bremstrahlung sent to the beamline .This baking of the undulators is not compatible with the use of low coercivity NdFeB material. Consequently, the use of high remanence NdFeB material for the CPMU requires the suppression of the baking phase; this aspect is discussed further in this paper. In order to retain the baking option, the first CPMU was based on high coercivity NdFeB (Hcj=2400 kA/m) and therefore with reduced field performances (Br=1.16 T). The undulator is a hybrid structure with a period of 18 mm and a total magnetic length of 2 m. The primary target of this prototype was to develop the required magnetic measuring systems and cryogenic cooling method as well as to obtain some experience in the operation of such a device in a storage ring. The two first topics have already been discussed [2],[3]. This paper focuses mainly on the operation of this first prototype installed in the ID6 straight section in January 2008 (Fig. 1). The undulator is connected to a liquid nitrogen cryo-pump system located in the technical gallery with a cryogenic line totalling 50 m in length.

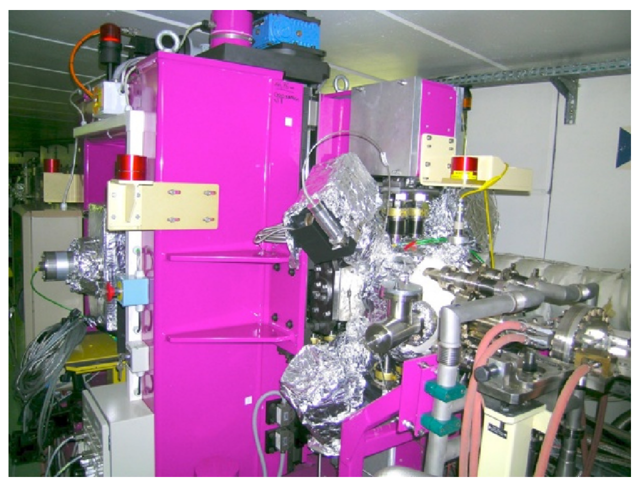

Figure 1: First CPMU prototype installed in the ESRF ID6 straight section.

HEAT BUDGET WITH BEAM

Average Temperature

The undulator was cooled to a temperature of 138 K before the accelerator re-start in January 2008. Due to the high thermal constant of the undulator (12.5 hours) it was not possible to use machine dedicated time for the thermal study. Instead, the device was monitored during use by the ID6 beamline. The temperature measurements of the undulator rely on 20 thermocouples distributed along the magnetic assembly. The power extracted from the cryogenic loop is derived from the measurement of the differential pressure and temperature of liquid nitrogen between the input and output of the cryogenic pump.

Figure 2 shows the average temperature of the undulator (green) and power extracted from the cryogenic loop (blue) in 7/8 filling mode with 200mA (Fig. 2 a) or in 16 bunch mode with 90 mA (Fig. 2 b) versus time. It reveals a strong dependence of the power on the undulator gap. The maximum extracted power and temperature are reached for a fully opened gap. This effect is observed in all beam filling patterns. The origin of this effect is still not clearly established but it is suspected that it originates from Higher Orbit Modes (HOM) of the radio frequency resonating in the undulator tank. Table 1 presents the measured average temperature of the undulator and power extracted from the cryogenic loop for different filling mode and gap settings. The last column of Table 1 corresponds to the net power due to the electron beam. The highest power of 106 W is observed in the hybrid filling pattern (24x8+1 bunch, 200 mA).

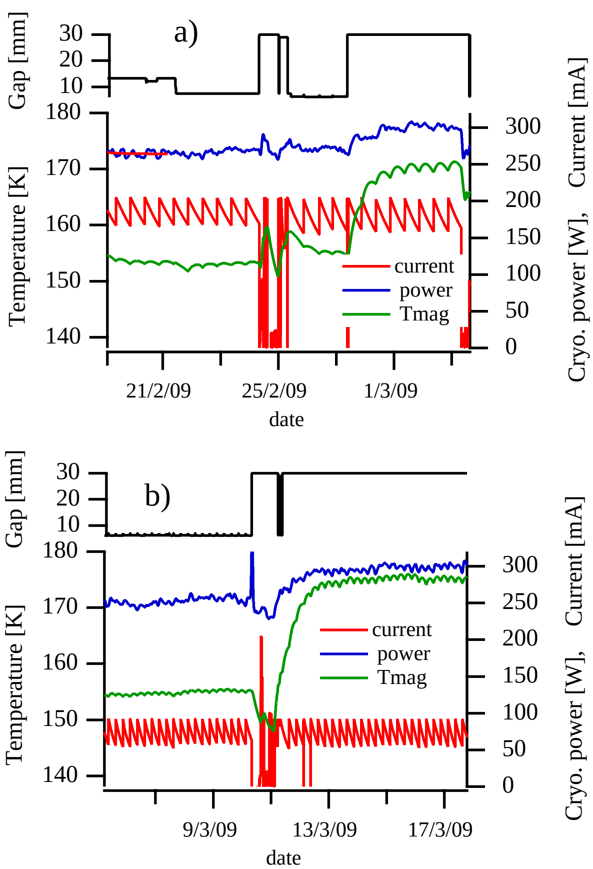

Figure 2: Average temperature of the CPMU (Green) and power extracted from the cryogenic loop (blue) versus time in 7/8 filling pattern, 200mA (a) and 16 bunch mode, 90mA (b). The beam current is shown in red and the undulator gap in black.

The measured power of 209 W without beam corresponds to the conduction and radiation losses in the undulator vessel (~ 150 W) plus the losses in the cryogenic line (~60 W). The average temperature of the undulator with beam varies from 151 K to 177 K. According to the magnetic measurements this corresponds to a change in peak field lower than 0.4 % [2],[3].

Table 1: Measured average temperature of the magnetic assembly and extracted cryogenic power for different beam filling modes and gap settings.

Filling mode	Gap [mm]	Tmag [K]	Cryo. Power[W]	Beam power [W]
16 Bunch	30	174	296	87
16 Bunch	6.2	154	252	43
7/8	6	151	241	32
7/8	30	168	280	71
hybrid	15	177	315	106
No beam		138	209	0

From the data in Table 1, one can fit a linear dependence of the undulator temperature T_{mag} with the beam power P_{beam}:

$$T_{mag}[K] = T_0 + a P_{beam}[W] \qquad (1)$$

with T_0=138.5 ± 1.5 K and a=0.38 ± 0.02 K/W.

Temperature Gradient

The variation of the temperature along the 2 m long undulator was carefully investigated. As one important outcome from the magnetic measurement phase, any temperature gradient has an influence on the r.m.s. phase error of the device. According to a dedicated analysis [3], a residual gradient lower than 2 K/m is required for keeping the r.m.s. phase error below 2.5 deg. A constant gradient affects the field in a very similar way as a small mechanical gap tapering. The measured gradient after the installation reached 7K/m in the hybrid mode. This large gradient was due to a poor thermal connexion between the cooling pipe and the copper blocks at the entrance of the undulator (Fig. 3). The temperature gradient was later reduced to below 2 K/m after the installation in-situ of a flexible thermal connection in August 2008.

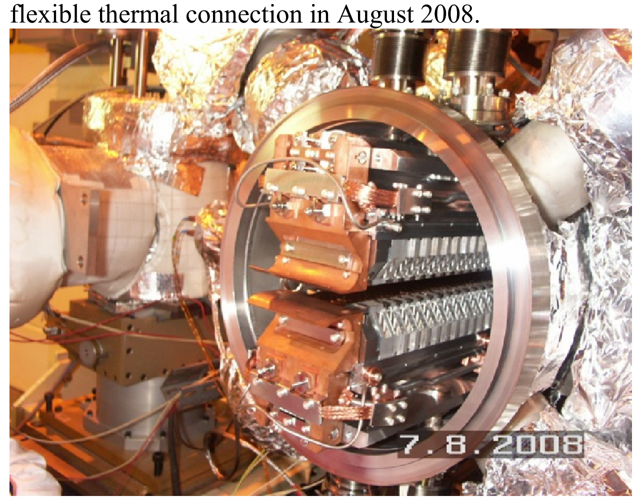

Figure 3: CPMU opened at the entrance for the installation of a flexible thermal connection (August 2008).

IMPACT ON BEAM VACUUM

As far as the vacuum is concerned, the preparation of the CPMU was similar to that done for a conventional room temperature in-vacuum undulator. Following final assembly, the CPMU was baked at a temperature of 120 deg C. After the installation, the cooling of the undulator from 300 K to 150 K had a visible impact on the vacuum. The residual pressure was reduced by one order of magnitude from a 10^{-9} mbar range to 10^{-10} mbar range without beam (Fig. 4). The rapid decrease of the pressure from the start of the cooling is due to the low temperature (82 K) of the cooling tubes inside the vacuum vessel.

Under beam loading, the device showed similar vacuum conditioning to that of in-vacuum undulators installed since 1999 [6].

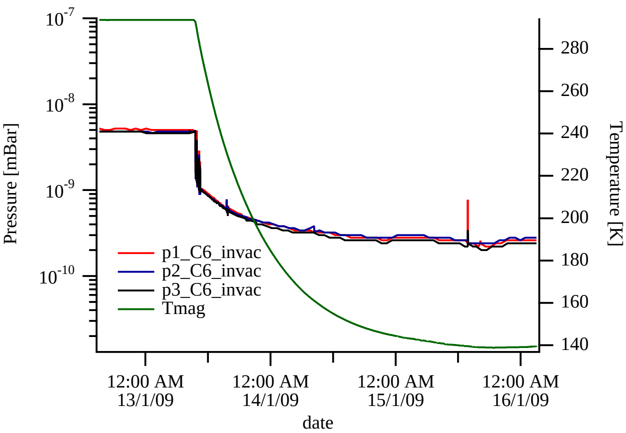

Figure 4: Evolution of the residual pressure seen from the three penning gauges installed on the CPMU during a cooling phase. The average temperature of the undulator (Tmag) is shown in green.

Figure 5 shows the normalized pressure (mbar/mA) versus integrated current for three different in-vacuum undulators installed in the ESRF ring. It compares the vacuum conditioning of the three undulators. All three devices are hybrid magnetic structures with a length of 2m. The first case is the CPMU prototype (pink curve) which was baked according to the usual procedure. The second device also baked (blue curve) has a period of 20 mm (IVU20) and uses the same magnet material as the CPMU but is operated at room temperature. The third device (green) was installed in May 2008. The magnetic assembly of period 22 mm (IVU22) is based on Sm_2Co_{17} permanent magnet material. This undulator was used as a test device for the future installation of a CPMU based on high remanence / low coercivity NdFeB material. It was not baked before installation as opposed to all other in-vacuum undulators. The sharp peak seen on the green curve of Fig. 5 corresponds to frequent sublimation of titanium in the titanium sublimation pumps. The ID15 beamline was able to take the X-ray beam from the undulator a few days after the re-start. The beam lifetime was back to 47 hours after an integrated dose of 11 A hours. The vacuum conditioning of the three in-vacuum undulators shown in Fig. 5 suggests that the installation of a non baked CPMU should lie in the range covered by the three curves. In particular, due to the low temperature a non baked CPMU should be better conditioned than the worse case tested with the IVU22.

Because of the large thermal constant, the cryogenic loop can be stopped for a few hours and switched on again without significant impact on the undulator temperature.

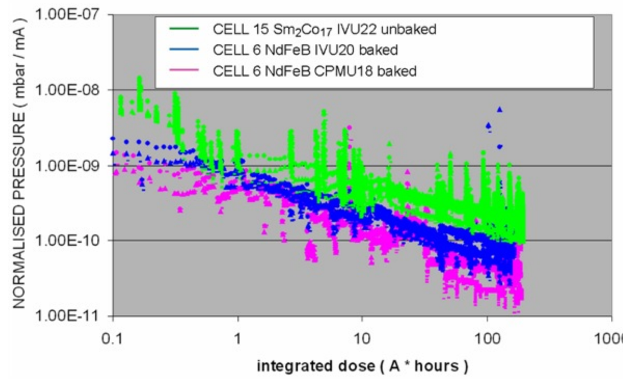

Figure 5: Dynamic pressure in mbar/mA versus integrated current for three different in-vacuum undulators: Cell 6 CPMU (pink), cell 9 IVU20 (blue) and cell 15 IVU22 (green).

CONCLUSION

The operation of a cryogenic undulator in the ESRF storage ring is compatible with the requirements set by the storage ring operation . The temperature of the undulator under beam evolves between 151 K and 177 K depending on the gap and the electron beam filling pattern. The resulting influence on the peak field of the undulator remains very limited. Further studies including X-ray spectral output will be carried out on this device. A new CPMU is presently under construction. It has been designed with high remanence NdFeB and benefits from a number of improvements which were identified from the first prototype.

ACKNOWLEDGMENTS

The authors would like to acknowledge the permanent support from the vacuum group : R. Kersevan, M. Hahn, D. Cognie, M. Garrec and I. Parat.

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