# CONSTRUCTION OF A CRYOGENIC PERMANENT MAGNET UNDULATOR AT THE ESRF

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## Abstract

A cryogenic permanent magnet undulator (CPMU) has been constructed at the ESRF. The device is a full scale in-vacuum undulator with a magnetic length of 2 metres and a period of 18 mm. This prototype is still compatible with operations at room temperature; it has been mainly used to investigate the technological issues connected to operations at low temperature in detail. A considerable effort has been made to the construction of a complete measuring bench operated in-vacuum with the undulator at cryogenic temperatures at around 150 K. The bench includes a stretched wire system for field integral measurement and a local field measurement assembly suitable for the accurate characterization of the optical phase error along the undulator. The main results of the magnetic measurements are presented here; they confirm the numerical simulations performed with RADIA on the basis of NdFeB permanent magnet material models at low temperatures. The cryogenic system used to cool down the undulator is based on a reliable liquid nitrogen closed loop. The prototype was installed on the ESRF storage ring in December 2007. The first results of operations are presented here.

## INTRODUCTION

Following an initial proposal at SPRING8 [1], the concept of Cryogenic Permanent Magnet Undulators (CPMU) is presently considered as a possible future evolution of in-vacuum undulators [2][3][4]. At the ESRF, the development of CPMUs has been divided into several phases. The first phase focused on the choice of a cooling concept. At the ESRF, we have an in-depth experience of liquid nitrogen closed loops for cooling the monchromators on many of the beamlines; this technique was successfully tested on an in-vacuum undulator structure (without the magnet assembly) in November 2004. The second phase consisted of the necessary investigation into the magnetic properties of NdFeB magnet materials at low temperatures. Due to the existence of a so called Spin Reorientation Transition which occurs at 135 K, it was expected that the NdFeB material would exhibit complicated magnetic properties at cryogenic temperature. The magnetization curves of NdFeB samples were measured at different temperatures (from 80 K to room temperature) using the facilities of the neighbouring Institut Néel. From the magnetization measurements, new models for NdFeB materials have been constructed and implemented in RADIA [2]. In particular, the numerical simulations carried out at different temperatures show that the maximum field of a CPMU at a constant gap occurs at a temperature of 150 K, substantially higher than the temperature for maximum

remanence (115 K). This can be explained by the noticeable increase of the material susceptibilities (parallel and perpendicular to the easy axis) below 180 K. During 2007, as a third phase, a complete cryo-cooled undulator was constructed. This hybrid device has a period of 18 mm with a magnetic length of 2 m [2]. The NdFeB magnet material is still compatible with baking at 120 deg C and room temperature operation (Br=1.17 T, $\mu_0 Hc_J$=2200 kA/m. With this prototype, the main areas of investigation were firstly the development of dedicated magnetic measurement benches and secondly the operation of such a device on a storage ring.

## MAGNETIC MEASURMENTS BENCHES

Figure 1 shows a general view of the undulator under magnetic measurements at low temperature. The measuring system consists of a special vacuum chamber which includes a guide rail assembly equipped with a hall probe. To avoid the implementation of vacuum compatible motorizations, the hall probe carriage is magnetically coupled through the wall of the chamber to an external motorized axis.
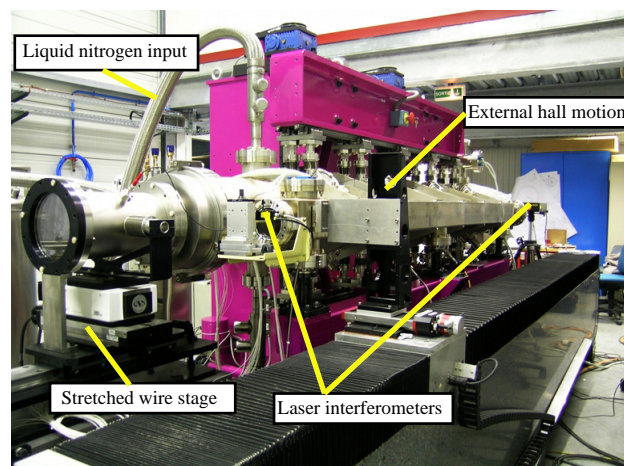


Figure 1: General view of undulator at cryogenic temperature under magnetic measurements.

The two stages of a stretched wire are mounted on either side of the vacuum chamber.

### Hall Probe Bench

The data acquisition of the three components of the magnetic field is done on the fly as for conventional benches at a typical speed of 30 mm/s over a total distance of 2.4 m. The position of the inner hall carriage is given by a laser interferometer. Due to the limited rigidity of the inner guiding system, a second laser interferometer has been used for the real time measurement of the yaw angle so that an accurate position at the hall sensor can be reconstructed from the data of the

two lasers. It has not been necessary to perform a calibration of the hall sensors at low temperature. Indeed, the internal temperature of the three hall sensors is always higher than the room temperature. Using an accurate calibration of the temperature (> 20 deg C) versus input resistance of the hall sensors one can determine the internal temperature of the sensors by knowing the input voltage and current. During the measurements the temperature drops by less than 3 deg C. This is corrected systematically in the post processing of the data.

### Stretched wire bench and gap measurements

A stretched wire bench has been used for the measurement of the first and second field integral. It has also been used to calibrate the magnetic gap versus temperature. Because of the cooling, the magnetic gap increases as the temperature is lowered. This has to be taken into account so that the magnetic measurements at different temperatures can be compared with the same gap. Figure 2 compares the calculated gap change versus temperature with reference at 300 K and the measurements performed with the stretched wire during the first campaign. From 300 K to 150 K the gap is increased by about 1 mm.
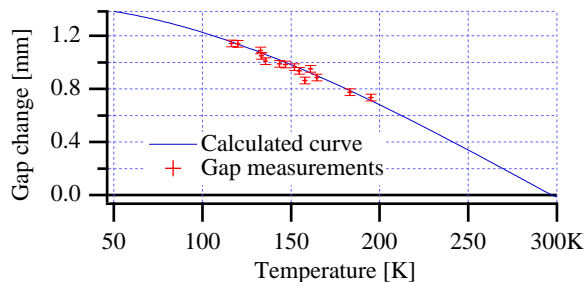
Figure 2: Change of the magnetic gap versus temperature: Blue curve: calculated, red markers :measured.

## MAGNETIC MEASUREMENTS RESULTS

### Local Field Measurements

The U18 hybrid undulator has been corrected at room temperature using conventional methods for in-vacuum undulators. The phase error has been corrected to get a r.m.s value of 4.5 degree. An important parameter is the temperature at which the undulator field reaches a maximum for a constant gap. Figure 3 presents the measured average peak field of the undulator at different temperatures. The measurements are in accordance with the numerical simulations performed with RADIA. For the NdFeB material used in the undulator, the maximum field occurs at a temperature $T_B$ between 145K and 150 K. Another interesting result is the small dependence of the peak field upon temperature around $T_B$: between 140 K and 180 K the field change is 0.5 %. Figure 3 also presents an important result regarding the change of the r.m.s. phase error $\Phi$ versus temperature. From room temperature to $T_B$, $\Phi$ increases by about 1 degree. Bellow $T_B$ there is a rapid increase of $\Phi$. The shape of this curve is a direct consequence of a residual temperature gradient

along the undulator. It is about 3K/m at 120 K in our case. A temperature gradient induces a gap tapering according to the curve in figure 2 and also a change in the performance of the NdFeB material. Above $T_B$ both effects partly compensate each other therefore limiting the impact of the gradient on $\Phi$, below $T_B$ both contributions are added and this is reflected by a rapid change of $\Phi$ versus temperature. The measured temperature gradient comes from a difficult thermal contact between the cooling pipe and the undulator at one end. Note that the effect of a constant temperature gradient can be compensated by setting an appropriate gap tapering on the undulator if this functionality is available.
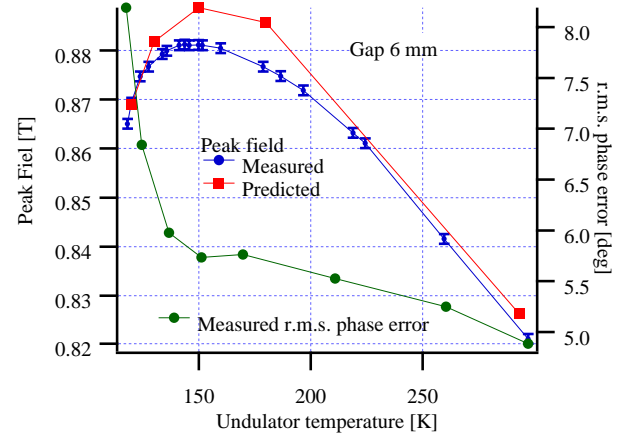
Figure 3: Peak field and r.m.s phase error of the undulator versus temperature.

### Field Integral Measurements

The field of the undulator is anti-symmetric (with first and last poles of opposite polarities). Considering the noticeable modification of the magnetic susceptibility of NdFeB material below 180 K, the systematic field integral created at each extremity is expected to change significantly. In this respect, a relevant quantity to analyse is the second field integral. Figure 4 shows the electron trajectory along the undulator axis for a magnetic gap of 6 mm at three temperatures.
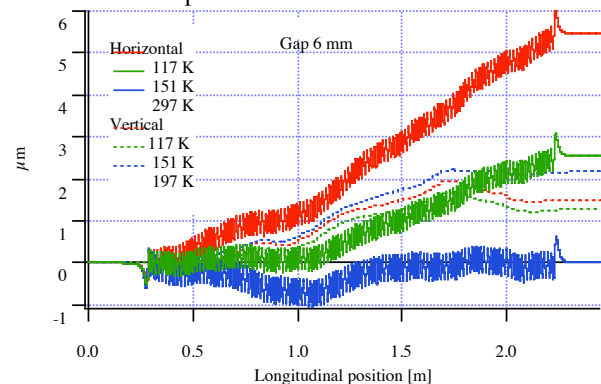
Figure 4: Electron trajectory along the undulator axis at a gap of 6 mm for three different temperatures.

The trajectory in the horizontal plane is largely dominated by a systematic extremity effect while in the vertical plane there is no significant modification. From the

measurements of the second field integral, the net field integral per extremity has been derived as a function of temperature for a gap of 6 mm. The results are consistent with numerical simulations as presented in figure 5.
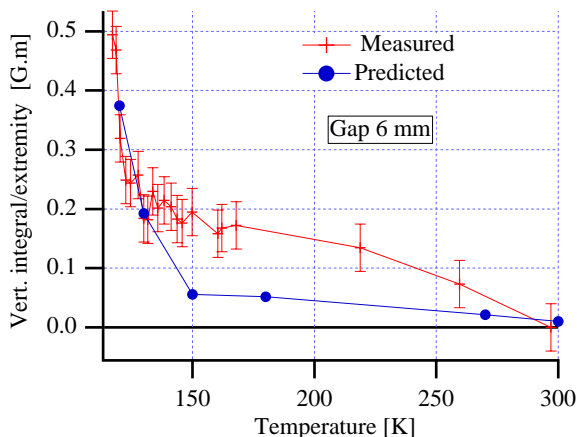


Figure 5: Vertical field integral per extremity versus temperature, red: measured, blue: predicted with RADIA.

## FIRST OPERATION RESULTS

The CPMU was installed in the ID6 straight section of the ESRF storage ring in January 2008. The primary goal was to assess the temperature of the undulator under beam and the impact on the vacuum. Without beam, the undulator reaches a steady average temperature of 143 K. The temperature increase is strongly dependent on the undulator gap and the electron beam filling pattern. In the worse case (16 bunch, 90 mA) the average temperature reaches 180 K. According to the calculation, this corresponds to a deposited power of 80 W: about twice the expected value. Regardless of the filling pattern, the heat load is dramatically reduced when the gap is closed to below 15 mm. Figure 6 illustrates the gap dependence of the average undulator temperature in the 7/8 +1 filling pattern.
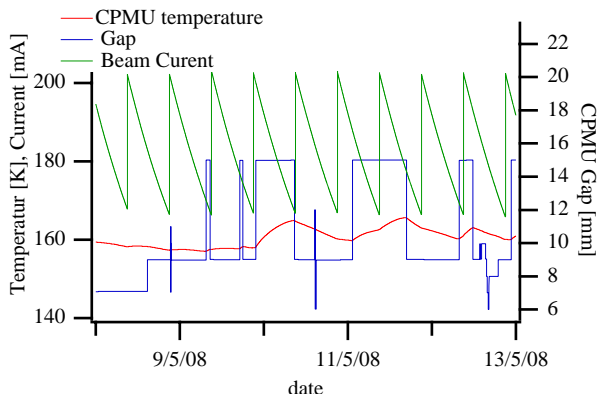


Figure 6: Typical fluctuation of the undulator temperature (red) for different gaps (blue) in the 7/8+1 filling pattern.

With the undulator gap below 10 mm, the deposited power is around 25 W for a temperature up to 155 K. The analysis of the temperature distribution along the magnetic assembly indicates that most of the deposited

power is distributed along the undulator: which is possible evidence of Higher Orbit Modes (HOM) taking place in the undulator tank. Overall, the heat budget of the complete system including the losses in the cryogenic transfer lines is about 320 W of which 150 W corresponds to the extracted power from the undulator without beam.

The undulator has been baked at 110 deg. C before installation. Some warm-up tests have been carried out with and without beam to investigate the impact on the residual pressure within the undulator. The results of these tests are presented at this conference [5].

Figure 7 shows the gap dependence of the field integral derived from Closed Orbit Distortions (CODs) and as measured with the stretched wire for the undulator at 155 K. Both measurements agree within 0.1 G.m. Nevertheless, such a variation corresponds to the limit fixed by the 10 % of beam size.
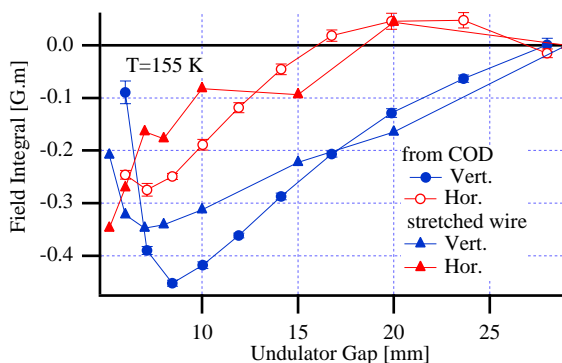


Figure 7: Field integral versus gap from COD measurements and as measured with the stretched wire.

## CONCLUSION

The construction of a cryogenically cooled undulator using liquid nitrogen seems to be technologically accessible. The extra magnetic errors coming from the cooling mostly result from residual temperature gradients along the undulator . This global contribution can be further reduced by the improvement of heat transfer between the cooling pipes and both extremities of the undulator. The operation of this first prototype reveals a significant extra heat load from the beam raising the temperature up to 180 K. A new device with high remanence NdFeB material and low residual phase error ($\Phi < 2.5$ deg) is planned.

## REFERENCES

[1] T. Hara et Al. Phys. Rev. Spec. Top. Accelerators and beam, Vol. 7 2004.

[2] C.Kitegi et Al., EPAC'06, June 2006,p. 3559

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