DEVELOPMENT OF A CRYOGENIC PERMANENT MAGNET IN-VACUUM UNDULATOR AT THE ESRF

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Abstract

Lowering the temperature of NdFeB materials increases their field remanence and intrinsic coercivity. This property is potentially interesting for the construction of a cryogenic permanent in-vacuum undulator (CPMU). Around 150K, the coercivity is so increased that the NdFeB material is comparable to the Sm2Co17 material as far as resistance to radiation damage is concerned. The improvement in field remanence is less remarkable (8% at 150K) and is dominated by a reversible Spin Reorientation Transition (SRT) occurring around 135K. Below this temperature, the remanence decreases. The magnetization curves of NdFeB material measured at different cryogenic temperatures are presented. Non-linear models have been constructed and used in the RADIA code in order to compute the field performance of a hybrid NdFeB in-vacuum undulator. A prototype CPMU is currently under construction at the ESRF. It has a period of 18mm and a magnetic length of 2m. The field integral and local field measurements of the device at cryogenic temperature require new systems operated in vacuum. A stretched wire bench and a hall probe bench are under construction: their main characteristics will be presented.

INTRODUCTION

Over the past ten years, the field performance of permanent magnet undulators has been dramatically improved by mean of gap reduction. With in-vacuum undulator technology, the minimum gap achievable corresponds to the vertical aperture needed for the electron beam, which is typically 6mm. For such small gap values, the probability of loosing electrons in the magnetic array is not negligible. This can result in partial local demagnetisation of the magnet blocks and consequently a degradation of the undulator field quality. Further improvement in magnetic field can only be based on the optimisation of magnetic structure and performance of the permanent magnet material. As far as magnetic structure is concerned, considering the relatively small ratio gap/period for in-vacuum undulators, the hybrid technology performs better than the pure permanent magnet technology [1]. The question connected to the choice of the permanent magnet material is more complex. At room temperature the Sm2Co17 material is preferred to NdFeB, because of its higher resistance to radiation damage, but the remanent induction is limited to 1.05T. Recently, NdFeB based in-vacuum undulators operated at cryogenic temperatures (150 K) have been proposed at SPRING 8 [2][3]. The major impact of cooling on the NdFeB material properties is a large increase of the intrinsic coercivity. With such high coercivity, NdFeB magnets are expected to be very resistive to radiation damage [4]. This allows the selection of NdFeB grades with remanence higher than 1.25T at room temperature. In addition, cooling improves the remanence down to a limited temperature where a reversible Spin Reorientation Transition (SRT) takes place. Below this temperature the remanence decreases. The temperature of the SRT depends on the exact composition of the NdFeB alloy. This phenomenon was reported and analysed in 1984 [5]. At temperatures close to the SRT, NdFeB materials reveal non linear magnetic properties, which need to be characterized in detail in order to build consistent material models.

MAGNETIZATION MEASUREMENTS

A number of small NdFeB samples of cubic shape (size 4 mm) have been cut from magnet blocks intended to be used for the construction of a CPMU prototype (NEOREM 595t [6]). One face of the cubes was precisely perpendicular to the easy axis. The hysteresis loops were measured at the Louis Neel Laboratory [7] using a superconducting magnetometer with magnetic field capacity of ± 10T. This system allows a precise control of the temperature at the sample from 1.8K to 300K with a stability of 0.01K. The magnetization measurement is made according to the so-called flux extraction method. The cubic shape was selected so that measurements perpendicular to the easy axis could be made. Figure 1 shows the magnetization parallel to the easy axis versus intrinsic field for different temperatures. The effect of the SRT is clearly visible at 80K.

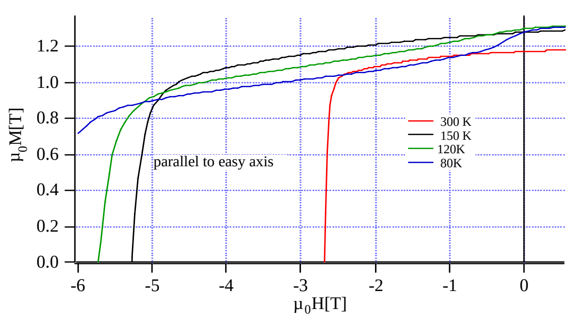

Figure 1: Recoil curves for NdFeB material at different temperatures.

The temperature dependence of the remanence and coercivity are presented in Figure 2. The optimum remanence is found at a temperature close to 110K. This temperature is lower than the values generally reported:

the explanation comes from the significant Dysprosium content included in the studied NdFeB material. At 130K the coercivity is higher than 55kOe: about twice the coercivity at room temperature. The measurements of the magnetization perpendicular to the easy axis are shown in Figure 3. The observed non linearity taking place below 150K is also connected to the SRT. The measurements presented in Figures 1 and 3 suggest that the magnetic simulation of the NdFeB cryogenic undulator type cannot be correctly done using conventional linear anisotropic models. In both directions parallel and perpendicular to the easy axis the material model needs to be non linear.

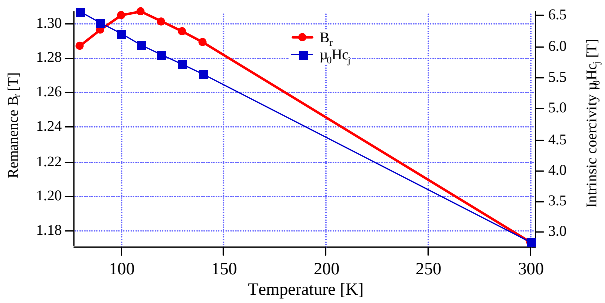

Figure 2: Measured intrinsic coercivity and remanence for NdFeB material versus temperature.

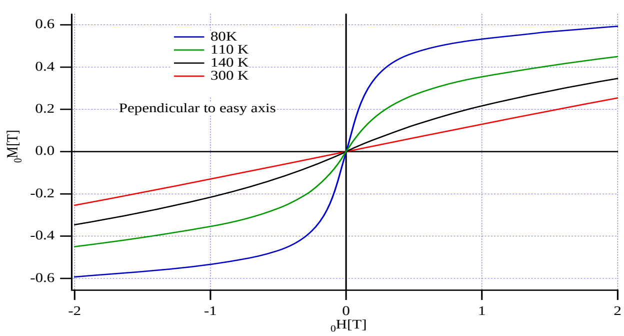

Figure 3: Measured magnetization perpendicular to the easy axis for different temperatures.

3D RADIA MODEL

Geometry

The 3D magnetostatic software RADIA [8] was used for the calculation of the magnetic field of a hybrid in-vacuum undulator of period 18mm. The geometrical characteristics of the magnet blocks and poles are presented in Table 1. The geometry of the undulator as used in RADIA is drawn in Figure 4. The model includes the standard end field termination adopted at the ESRF. The termination is optimised for minimizing the field integral versus gap.

Table 1: Size of magnet blocks and poles for the U18 hybrid in-vacuum undulator.

	Magnet	Pole
Width (x)	50 mm	32 mm
Height (z)	30 mm	24 mm
Thickness (s)	6.2 mm	2.8 mm

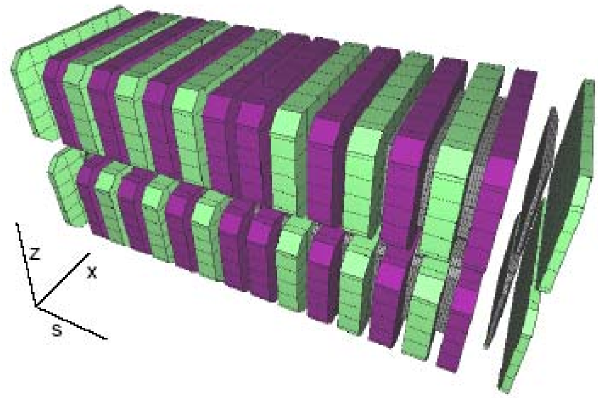

Figure 4: Hybrid undulator with end field termination adopted at the ESRF modelled in RADIA.

Material models

One important feature of RADIA is the possibility to describe non linear anisotropic materials [9] under the form:

$$M(H)=\sum_{i=1}^{3} M_{si}\,Tanh\left(\frac{\chi_i}{M_{si}}(H+H_{ci})\right) \quad (1)$$

The above expression is used for both directions, parallel and perpendicular to the easy axis. For the direction perpendicular to the easy axis, the coercive fields Hc_i are set to zero. The coefficients Ms_i, χ_i and Hc_i have been determined using non linear fits of the measured magnetization curves at different temperatures. The fits were limited to -1500kA/m to 1000kA/m for the magnetic field H in order to get a good accuracy on the magnetization in a range including the possible working points in the magnet blocks of the undulator. The pole material used is low carbon steel with a saturation magnetization of 2.1T. We assumed that the pole material has constant properties at all temperatures.

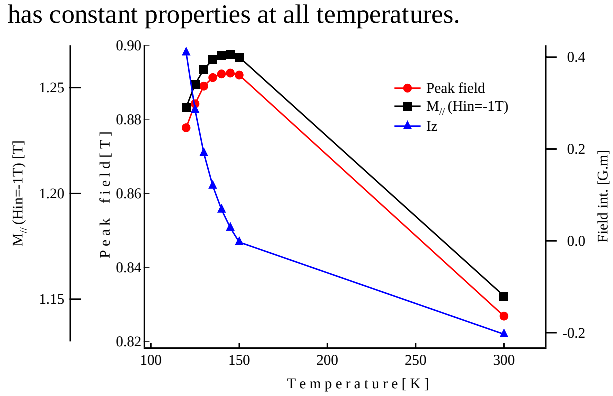

Figure 5: U18 peak field and on-axis vertical field integral versus temperature (blue) for a gap of 6 mm.

Figure 5 shows the calculated effective peak field and the on-axis vertical field integral of the U18 versus temperature for a gap of 6mm. The working points obtained from the RADIA model were roughly located around -800kA/m at all temperatures. The parallel magnetization versus temperature obtained for a field close to the working points of magnets is also plotted. Because of non linearity taking place in the second quadrant of the hystereris loops, the highest magnetization around the working points is not obtained at the temperature that maximises the remanent field. The maximum field is found for a temperature of 145K. This value is 35K above the temperature corresponding to the optimum remanence. The field integral corresponds to the systematic contribution originating from the end field termination.

STATUS OF ESRF CPMU

Undulator

A 2m long hybrid CPMU is under construction at the ESRF. The device of period 18mm is currently undergoing magnetic measurements at room temperature. The technology is very similar to that of conventional ESRF hybrid in-vacuum undulators. The cooling system is based on a liquid nitrogen closed loop. In order to obtain the desired temperature around 150K at the magnet, the aluminium supporting girder will be connected to cooling pipes through longitudinally distributed spacers acting as thermal resistors. One critical aspect is the mechanical deformation induced by temperature gradients along the magnetic assembly. In December 2004, the principle of this cooling technique was tested without magnetic assembly on a support equipped with stainless steel girders (Figure 6).

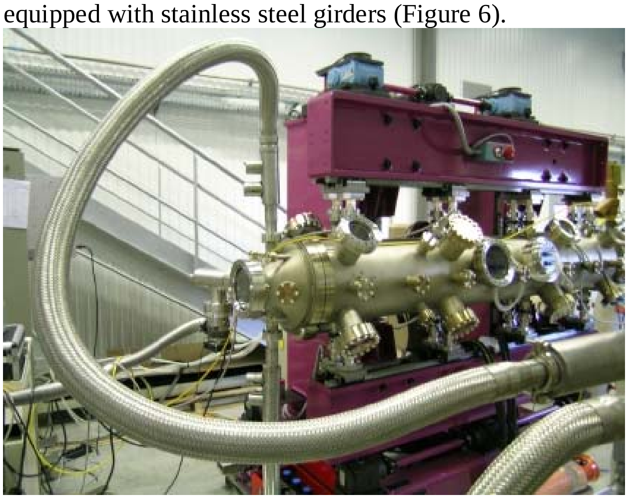

Figure 6: ESRF in-vacuum structure under cryogenic tests.

The modification of the gap between room temperature and 100 K was measured along the girders. The gap fluctuations around a net offset of 1 mm were smaller than 15 µm over a central part of 1.5m in length. At both extremities, the deviations peaked at 80µm due to the very poor thermal exchanges with the cooling pipes (limited clamping). The use of aluminium girders together with adapted mechanical connection of the cooling pipes is expected to limit the residual deformations below 15µm. A typical heat budget of 150W was observed, roughly equally shared between radiative and conduction contributions.

Magnetic measurement benches

The magnetic measurements of cryogenic in-vacuum undulators require dedicated measuring benches operated under vacuum conditions (10^{-6}mbar). A critical point is the evolution of the optical phase error versus temperature. A complete measuring assembly is being constructed at the ESRF. It is shown in Figure 7. The bench includes a dedicated vacuum chamber, which forms the central part. It is mounted between the two motorized stages of a stretched wire. The wire can be moved in a horizontal (vertical) range of ± 25mm (± 5mm). The wire is made of Beryllium copper or Titanium Aluminium. External motors connected to the wire with bellows provide all motions. The vacuum chamber includes a 2.4m long rigid guide rail equipped with a small hall probe carriage. A magnetic coupling with an external linear stage provides the motion of the hall probe carriage. The position of the hall probe will be surveyed with a laser interferometer. The hall probe measurements will be done according to the “on the fly” method with a typical measuring speed higher than 20mm/s. The assembly of the stretched wire has been completed; the bench is expected to be in operation for October 2006.

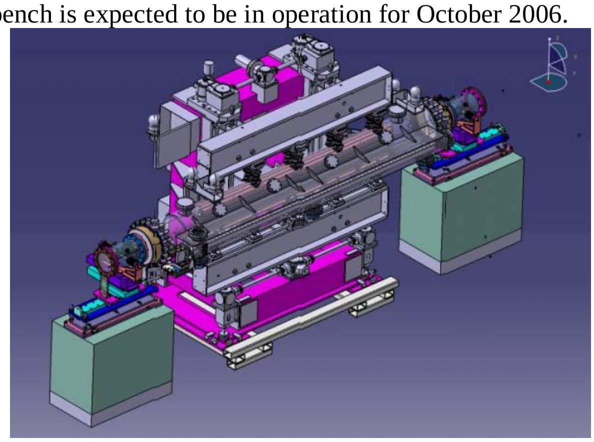

Figure 7: Schematic view of the measuring bench with its vacuum chamber.

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