MAGNETIC DESIGN CONSIDERATIONS FOR IN-VACUUM UNDULATORS AT ESRF

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Abstract

The two main permanent magnet technologies (hybrid and pure permanent magnets) are compared for in-vacuum undulator design. The small ratio gap/period favours the hybrid technology despite of the difficult passive field termination design. The choice of the permanent magnet material is an issue. Based on non linear permanent magnet models, simulations using RADIA are presented. The material intrinsic coercivity H_{cj} is determined for both NdFeB and Sm_2Co_{17} material to avoid any irreversible demagnetisation during the required baking (≤140 deg. C) of the undulator. The resulting commercially available material are compared. The status of ESRF in-vacuum undulators is presented. Four devices have been completed and the main magnetic measurement results are summarized. In particular, the spectrum shimming performances are discussed. The construction of additional devices has started.

1 INTRODUCTION

There is a high interest for in-vacuum undulators in third generation X-ray facilities recently commissioned or being constructed. The development of in-vacuum undulators is presently a central activity in the insertion device group at ESRF. It is mainly focused on the improvement of photon fluxes at high energy (50 keV to 100 keV) and concerns the replacement of a number of existing wigglers. The required baking of the magnetic structure of in-vacuum undulators brings specific boundary conditions to the magnetic design. The permanent magnet material has to withstand temperatures of 140 degrees C. without any significant irreversible losses. This can be investigated with non linear permanent magnet models. Suitable permanent magnet materials can be identified and used in the optimisation of the magnetic design.

2 PERMANENT MAGNET MATERIAL

Permanent magnet blocks for Insertion Devices are produced using different powder metallurgical methods. Among them, the so called transverse die pressing process is the most adapted to the manufacture of permanent magnets for undulators. In the following, we only investigate NdFeB and Sm_2Co_{17} permanent magnet materials produced according to this method. The main magnetic parameters for permanent magnet materials are the remanent induction B_r and the intrinsic coercivity H_{cJ}. As always presented in data sheets, only the minimum values for B_r and H_{cj} have been taken into account.

2.1 NdFeB material

Figure 1 shows the noticeable dependence of $\mu_0 H_{cJ}$ upon B_r at room temperature for NdFeB materials. The values have been collected from data sheets of six suppliers. This relation may be expressed using a linear fit under the form:

$$\mu_0 H_{CJ}[T] = a_0 + a_1 B_r[T] \qquad (1)$$

with a_0= 9.08 T and a_1=-5.77.

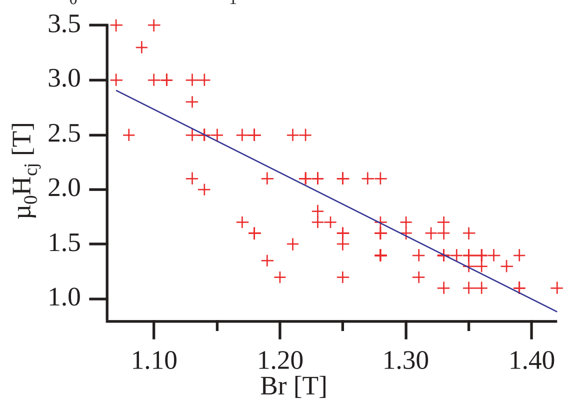

Figure1: Intrinsic coercivity H_{cj} as a function of remanence Br for commercially available NdFeB material. Red markers: data, blue line: linear fit

The equation (1) will be used to identify NdFeB materials compatible with baking requirements for in-vacuum undulators.

2.2 Sm_2Co_{17} material

The Sm_2Co_{17} materials do not show such a clear relation. Nevertheless, the data reveals two distinct families characterised with low and high coercivities. The high coercivity grades are the only suitable for in-vacuum undulators with the following average (minimum) properties at room temperature: Br=1.03 T and $\mu_o H_{cJ}$=2 T.

3 3D NON LINEAR MODELS

A non linear model of NdFeB and Sm2Co17 permanent magnet materials has been used in RADIA [1]. It requires the description of the magnetisation curve in the first and second quadrant. The details of this model have already been presented [2]. In all cases, the values for B_r and H_{cJ} in modelled magnetisation curves are defined according to sections 2.1 and 2.2 above. The temperature coefficients for B_r and H_{cJ} are used to derive material representations at various temperatures. It is therefore possible to analyse the magnetic behaviour of permanent magnet structures as a function of temperature. In particular, the effect of the baking on the magnetic performance of an undulator can be investigated.

Figure 2 shows the magnetic structure of a pure permanent magnet (p.p.m.) and a hybrid undulator as used in RADIA. Both undulators have the same period of 22 mm. The segmentation applied to the magnet blocks is not uniform in both vertical (z) and longitudinal (s) directions. The high segmentation in critical area of the magnet blocks is required for the determination of reliable values of the magnetic field and magnetisation inside the permanent magnets. The sizes of magnet blocks are 41 mm (x), 11 mm (z) and 5.5 mm (s) for the p.p.m. structure. The hybrid structure has larger magnet blocks (50 mm, 30mm, 8 mm) and narrow iron poles (32 mm, 24 mm, 3 mm). The pole material was a low carbon steel with a saturation magnetisation of 2.1 T. It is also assumed that the pole material has constant properties at all temperatures.

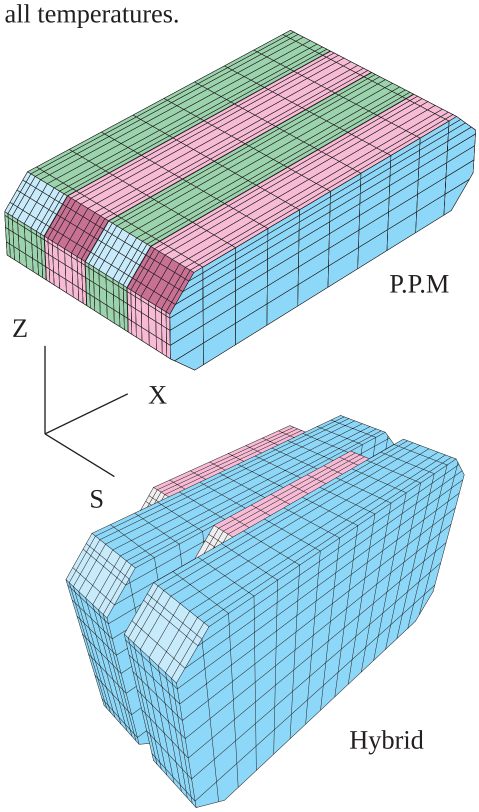

Figure 2: pure permanent magnet and hybrid structure modelled in RADIA.

For both structures, the irreversible losses on the on-axis magnetic field have been determined at different (baking) temperatures. The p.p.m. and hybrid structures have very similar losses. In addition, the calculated losses are relatively independent of the period. Figure 3 shows the irreversible losses for the two designs as a function of the baking temperature using NdFeB and Sm_2Co_{17} permanent magnet materials. The NdFeB material was defined with a remanent induction of 1.1 T and a coercivity of 2175 KA/m ($\mu_0 H_{cj}$=2.73 T) according to equation 1 at room temperature. The effect of the magnetic gap set during the baking is clearly visible. Indeed, small magnetic gaps reduce the demagnetising field in the permanent magnets and can be of practical use for the baking. The Sm_2Co_{17} material was defined with room temperature remanence and coercivity as derived in section 2.2. The related losses are negligible at a baking temperature up to 160 deg C regardless of the magnetic gap.

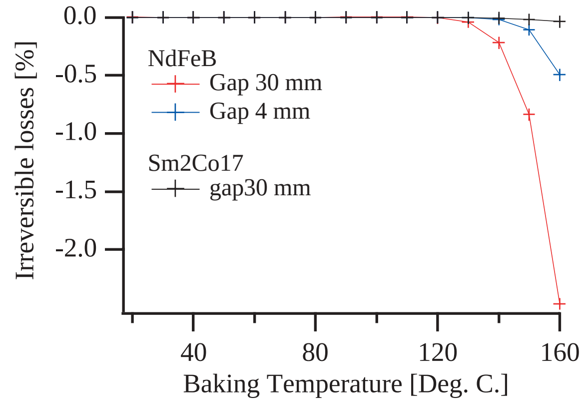

Figure 3: Calculated irreversible losses on the magnetic field of both p.p.m. and hybrid undulator as a function of baking temperature.

As far as baking is concerned, suitable commercially available NdFeB materials can be used. This requires high coercivity grades ($\mu_0 H_{cj}$> 2.8 T, Br< 1.1 T) to ensure negligible partial demagnetisation. Using higher remanence and therefore lower coercivity would result in unacceptable irreversible demagnetisation.

The question of radiation damage in the permanent magnet material is also another important aspect because in-vacuum undulators may operate at very small gaps (5 mm). There are presently no possibilities of carrying out numerical simulations on this subject. Nevertheless, various experiments [3], [4], [5], [6] clearly indicate the higher resistance to radiation damage of the Sm_2Co_{17} material as compared to all grades of NdFeB materials.

4 HYBRID VERSUS P.P.M DESIGN

In this section, we compare the performances of the p.p.m. and hybrid structures for in-vacuum undulators operating at a low magnetic gap (6mm). Undulators of periods 18 mm to 26 mm are examined. In all cases, the transverse horizontal size of the magnet blocks and poles are the same as for the period 22 mm analysed in the previous section. Only their vertical and longitudinal sizes are rescaled proportionally to the period (the period 22 mm being the reference). The peak field ratio between the hybrid (B_{hyb}) and the p.p.m. design (B_{ppm}) is presented in figure 4 for a magnetic gap of 6 mm. It clearly reveals a possible advantage of the hybrid structure. This result is independent of the magnetic material used for the permanent magnets. The calculated peak field is understood as the first harmonic in the magnetic field (effective field). Note that the ratio presented on figure 4 may be traduced in terms of gap difference. With respect to the hybrid design, the gap of a p.p.m undulator of the same period needs to be reduced by about 1.2 mm to produce the same peak field. The investigation into hybrid designs for in-vacuum undulators is therefore unavoidable. There are nevertheless dedicated efforts to carry out on the field terminations and the structure of the magnetic assembly to allow easy field tuning. The advantage of the hybrid design relies on magnet blocks with vertical sizes significantly higher than in the p.p.m. structure. Knowing that a suitable opened gap has to be taken into account (>=30 mm),this has direct implications on the size of the mechanical parts to be placed in ultra high vacuum including the vacuum chamber itself.

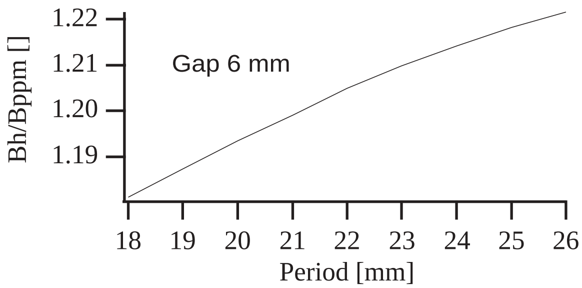

Figure 4: Ratio between peak field for hybrid and p.p.m design as function of the undulator period (gap 6 mm).

5 STATUS OF ESRF IN-VACUUM UNDULATORS

The construction of new in-vacuum undulators with a nominal length of 2 metres started in year 2000 at ESRF [7]. Four devices are presently in operation while a fifth segment (U18) will be installed in summer 2002 (Table 1). All devices are based on the Sm_2Co_{17} permanent magnet material.

Device	Period [mm]	Length [m]	technology
U23	23	1.6	hybrid
U23	23	2	p.p.m.
U17	17	2	p.p.m.
U21	21	2	p.p.m.
U18	18	2	p.p.m.

Table 1: Main parameters for the 5 ESRF in-vacuum undulators.

The four undulators recently completed are based on the p.p.m. design. The operation at gap 6 mm has limited impact on the beam lifetime (lower than 10 %). The measured closed orbit distortions versus gap are small enough to avoid any active corrections. The multipole shimming is anticipated during the assembly of the magnetic structure. It is based on the online sorting of short modules initially measured with a dedicated fast stretched wire bench. The final correction is provided by arrays of small SmCo magnet blocks (magic fingers) placed at either ends of the undulators. Spectrum shimming has been applied on both p.p.m. U23 and U21 giving residual r.m.s. optical phase errors of 1.8 deg and 2.3 deg respectively at the minimum gap of 6 mm. Figure 5 shows the computed photon fluxes versus energy in a finite square aperture (1mm x 1mm) at 30 m from the source (U23 with a gap of 6 mm). The red curve is the spectrum computed with the actual magnetic field (including residual errors) and the blue curve corresponds to the output from an ideal device (error free). In both cases the calculations assume standard ESRF electron beam (I = 200 mA), emittance 4 nm (40 pm) horizontally (vertically) and a high beta straight such as ID22. The differences between both spectral fluxes are essentially visible on the high harmonics. In particular the losses observed on the harmonic 15 (E = 95 keV) are lower than 30%. Such a result has a direct beneficial impact for beamlines operating at high photon energy (50 keV to 100 keV). This is the object of a new series of three in-vacuum undulators presently being constructed. The characteristics of these new devices are presented in Table 2. Note that ,as a possible new standard, the last device (U22) is based on the hybrid design.

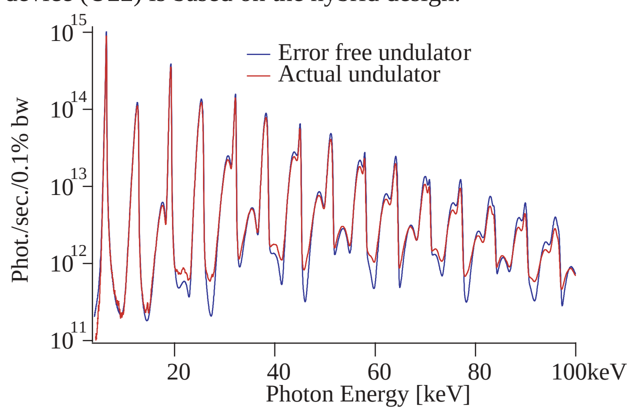

Figure 5: Spectral fluxes computed from measured magnetic field (red) and an error free undulator (blue).

Device	Period [mm]	Length [m]	technology
U23	23	2	p.p.m.
U23	23	2	p.p.m.
U22	22	2	hybrid.

Table 2: Main parameters for the next in-vacuum undulators

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