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DEVELOPMENT OF ADVANCED MAGNET STRUCTURES FOR CRYOGENIC IN VACUUM PERMANENT MAGNET UNDULATORS

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Abstract

Short period undulators and in particular in-vacuum cryogenic permanent magnet undulators are the upcoming technique for FEL radiators, because they permit a significant reduction of linac and undulator length. For achieving high photon energies with low electron energies (short period lengths, e.g. below 10mm) permanent magnet structures are superior, due to their high surface current density of 16 kA/cm as compared to electromagnetic or even superconducting devices. The geometrical tolerances scale with the period length. This requires new fabrication techniques and structure designs, particularly for sub-cm period lengths. Solutions for these demands will be presented and results from a first prototype using various new technologies such as compound poles will be discussed and compared with common approaches.

INTRODUCTION

Upcoming technologies for the production of high energy photons in 3rd generation storage rings and next generation synchrotron light sources are based on short period undulators (SPUs). They generate high energy photons from low energy electrons and thus reduce costs in accelerator development, which is one of the main cost drivers in light sources like USRs, FELs and ERLs. There are several techniques to realize SPUs either in permanent magnet or superconducting technology. The performance of permanent magnet structures rises with cooling [1]. The potential of these so-called cryogenic permanent magnet undulators (CPMUs), particularly with short periods, is discussed in [2]. The development of superconducting undulators can hardly be predicted because the material development is rapidly developing. In contrast, the material limits of CPMUs are well known. On the other hand, CPMUs are based on a mature technology and they will be the working horses for the next years in many facilities. In this paper we concentrate on permanent magnet based SPUs.

The requirements for the mechanical tolerances increase with shorter period lengths and PM-SPUs demand new and sophisticated manufacturing, joining, and assembling methods to take full advantage of the new magnetic materials available such as PrFeB - GBD.

Choice of Undulator Design

The first pure permanent magnet undulator design was proposed by Halbach in 1981 [3]. The magnetic flux density B can further be enhanced utilizing soft iron poles as proposed by Halbach in 1983 [4]. In these so-called hybrid structures the pole pieces are made of material with high permeability (e.g. CoFe with a saturation magnetization of 2.35 T) and they are magnetized by permanent magnets which are oriented longitudinally and located in the space between the poles.

Cutting edge PM-SPUs are realized as hybrid undulators. The magnetic performance is further improved when cooling the magnets.

It is worthwhile to cool the structure below 50 K. The intention isn't, as could easily be suspected, the gain in coercivity, 20 kOe, for the range from 135 K to 10 K. The gain in coercivity doesn't increase the stability against radiation damages [5] [6]. But the thermic stability benefits from the significant higher thermal conductivity of Cu (girders) between 50 K and 10 K and thus may help to avoid temperature gradients and the resulting negative effects. Increased demands on mechanical tolerances, in presence of strong magnetic forces and less available space, necessitate new solutions for fastening and precise positioning.

MAGNET MATERIAL

Today permanent magnetic material with the highest energy product $(BH)_{max}$ is $Nd_2Fe_{17}B$ therefore it is used in the most permanent magnetic undulators (PMUs). A drawback is the spin reorientation effect in this material at 135 K which complicates the cooling technology. This effect can be avoided with a different material which does not show a spin reorientation. We used a special grade of $(Pr,Nd)_2Fe_{14}B$ from Vacuumschmelze [7] with the following, specifications: a remanence of $B_r > 1.38$ T for room temperature (293 K) and expected 1.62 T at 77 K and a coercivity of $H_{cj} > 1640$ kA/m @ 293 K and expected 5340 kA/m @ 77 K. At room temperature the material is rather unstable. To permit a safe assembly the material is treated with the so-called Grain Boundary Diffusion Process (GBD) which enhances the coercivity without sacrificing the remanence. In the GBD process Dy diffuses along the grain borders without penetrating into the grains [8]. The magnets were manufactured by Vacuumschmelze Hanau (VAC) and they are commercially available, now. For the soft magnetic poles is $Co_{49}Fe_{49}V_2$ with a saturation magnetization of about 2.35 T used. This material is also distributed by Vacuumschmelze with the trade name Vacoflux 50.

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ADVANCED POLE DESIGN

The transverse good field region for single pass light sources is only defined by the transverse extension of the electron beam and alignment tolerances. This fact permits the use of transversal narrow and shaped poles which enhances the field (Figure 5) [9].

Pushing the on axis field, especially for these short period lengths, the straight pole hybrid magnet structure consisting of conventional pure CoFe poles and permanent magnets is inferior to a design with compound poles [10] as concluded from calculations. These poles, for our 9 mm period length device, consist of four pieces. A trapezoidal CoFe part for flux concentrating, two triangular and one rectangular part made from $(\mathrm{Pr,Nd})_2\mathrm{Fe}_{14}\mathrm{B}$. The geometrical dimensions of the whole compound pole are $14\ \mathrm{mm} * 14\ \mathrm{mm} * 2.44\ \mathrm{mm}$ and the transverse gap extension of the CoFe is 4 mm. The easy axes of side magnets are pointing to the poles. Because of their mutual opposite and/or 90 degree easy axis orientation, the pole parts must be joined in the final magnetization state. To avoid a complicated handling with the tiny individual components, the use of expensive jigs and too achieve the desired mechanically tolerances, greater pieces where joined in a less tightly tolerated jig and in further steps the poles were cut and grinded (Figure 1).

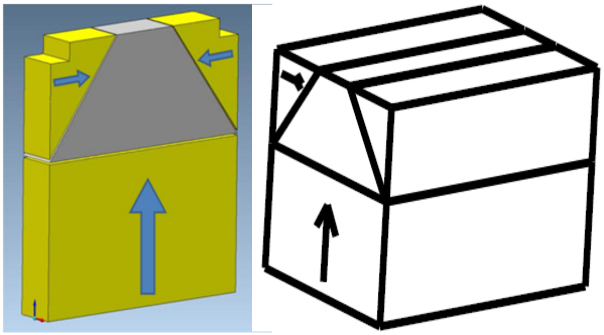

Figure 1: Single compound pole and pole block orientation of easy axes.

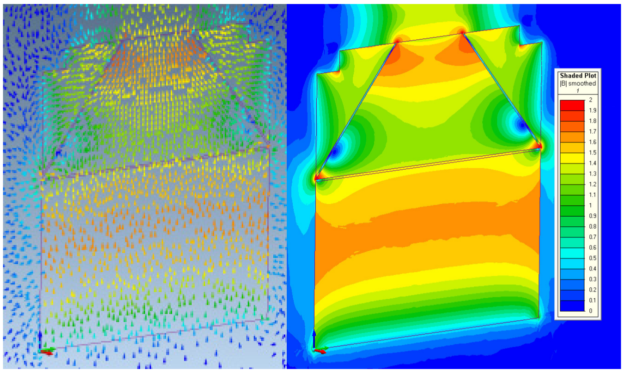

Figure 2: Arrow flux plot and shaded field plot of the compound pole simulated with Magnet from Infolytica [11].

MAGNET STRUCTURE

Based on the compound poles a hybrid undulator prototype with a period length $\lambda_0 = 9$ mm, a gap of 2.5 mm and 11 periods was built. Similar to the first prototype [12] [13] the fixed gap structure consists of two copper (Cu-ETP) girders and a backing plate from the same material which precisely defines the gap. The heat conductivity for Cu-ETP is specified with 394 W/(mK) at 293 K and 1298 W/(mK) at 20 K. The girders have been gold plated for improved thermal management. As in the first prototype the number of parts has been reduced to a minimum. The longitudinal position of magnets and compound poles are defined by high precision milled slots in the girders. Due the magnetic forces the magnets are pushed into the slots at the chosen gap of 2.5 mm. Only the poles which are attracted by their counterparts need to be clamped from the top. For safety reasons and by virtue of changing the directions of magnetic forces for smaller gaps the magnets are, together with the poles, clamped, too. As before the pole clamps are utilized for pole height adjustment and field optimization.

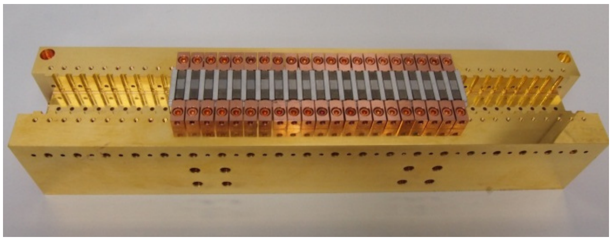

Figure 3: Single girder with magnets and poles.

RESULTS

The device has been measured with a first prototype of a new in-vacuum Hall probe bench which is described in [14].

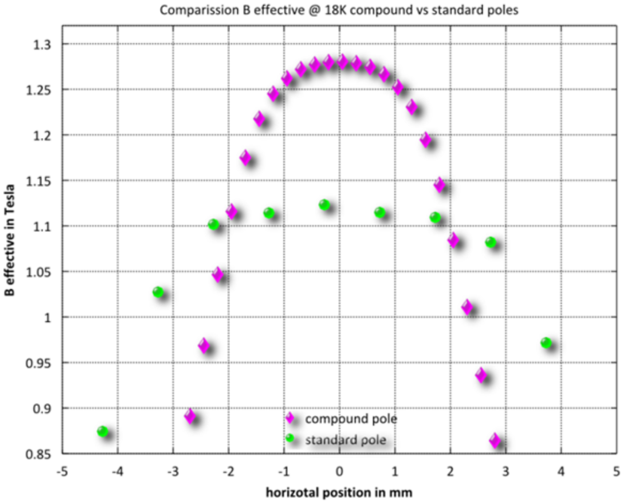

Figure 4: Comparison of results from field measurements.

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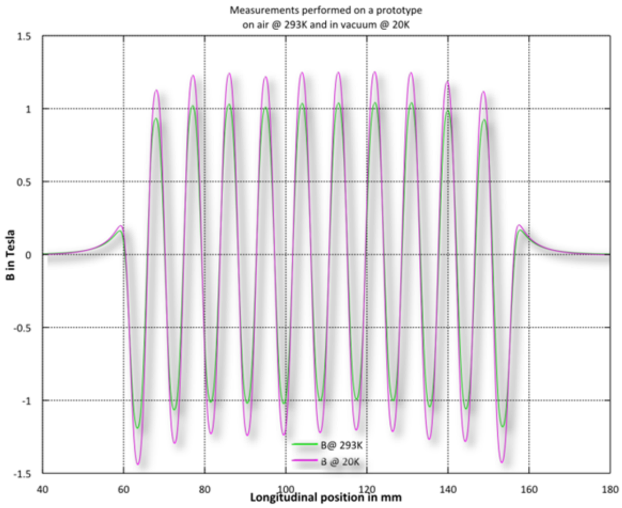

Figure 5: Field scan longitudinal @ 293 K and 20 K.

Figure 4 shows the significant increase of the effective field B_{eff} over the transversal gap position Z in mm. The green points shows the field from the first 9 mm 20 period PrFeB prototype undulator built at HZB in 2010 [12] [13] and measured with a 0.5m prototype in-vacuum Hall probe bench. This structure is magnetically identical except for the pole design. Booth structures have been measured at 20 K and at a gap height of 2.5 mm. The gain for B_{eff} is in a magnitude of 15 percent. The gain in magnetic field by decreasing the temperature from 293 K to 20 K for a longitudinal Hall probe scan is shown in Figure 5.

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