CRYOGENIC DESIGN OF A PrFeB-BASED UNDULATOR

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Abstract

A PrFeB-based cryogenic undulator has been built at Helmholtz-Zentrum Berlin (HZB) in collaboration with the Ludwig-Maximilian-University München (LMU). LMU will operate the undulator at a laser plasma accelerator at the Max-Planck-Institut für Quantenoptik in Garching. The 20-period device has a period length of 9mm and a fixed gap of 2.5mm. The operation of a small gap device at a high emittance electron beam requires stable magnetic material. A high coercivity is achieved with PrFeB-material cooled down to 20-30K. In this paper we present the mechanic, magnetic and cryogenic design and compare predictions with measured data.

INTRODUCTION

Small period small gap in-vacuum undulators are considered as radiators in future light sources such as FELs [1-2]. The period length determines the length of the accelerator and thus the total costs of the light source. These undulators are of particular interest for table top FEL applications [3-4] where gradients of 10-100GeV/m can be realized and where the typical accelerator length amounts to only a few cm.

Electron beams of laser plasma sources still have a normalized emittance in the 1mm mrad range with a divergence of about 1mrad (rms) and a pointing stability of about 1.5mrad (rms). Small undulator gaps require magnets with a high radiation resistivity to avoid demagnetization [5-6]. The negative temperature coefficients of the remanence and the coercivity provide much better performance of cold magnets. So-called cryogenic undulators which are operated at low temperatures have been proposed by the SPRING-8 group [7-8] and have been built at several laboratories [9-11]. NdFeB-magnets show a spin-reorientation at 150K which sets a lower limit for the range of operation [12-13]. PrFeB-magnets can be used at even lower temperatures [14]. A new grade of PrFeB-material with an energy product of 520kJ/m^3 at 85K has been developed in a collaboration of HZB, Vacuumschmelze, and LMU [15-16]. This material is used in the 20 period prototype which will be discussed in this paper.

This prototype provides the possibility to study new magnetic materials and a new undulator designs. Various cooling concepts can be elaborated and tested as well and cryogenic data on materials and interfaces can be extracted. The knowledge will be used for the design of cryogenic undulators for 3rd generation storage rings and future light sources.

MAGNETIC DESIGN

Cryogenic undulators based on PrFeB-magnets have several advantages as compared to NdFeB-based devices. They can be operated at 20-30K which implies:

- The coercivity increases up to 73kOe and the remanence increases up to 1.7 T [16].
- The temperature sensitivity of B_r at low temperatures is negligible.
- Oriented Dy-material with a high saturation magnetization can be considered for the poles.
- Magnet girders made of copper have a high thermal conductivity in the range of 10-50K (large differences of various copper grades) and the thermal expansion coefficient is a factor of ten lower as compared to 150K. This minimizes the risk of girder bending due to thermal gradients.

The hybrid undulator is made from PrFeB-magnets and CoFe poles. The design of the magnetic structure was done with RADIA [17].

The magnet material is described with three tanh-functions with appropriate parameters that have been derived from measurements of the M-H curve at temperatures of 30K and 300K. The M-H-dependencies for temperatures down to 10K have been measured at HZB and the room temperature data have been determined by Vacuumschmelze as well. For the poles the vanadium permendur steel data as offered by RADIA are used.

The dimensions and the shape of the poles and magnets were optimized with RADIA in order to find a setting with maximum on-axis field excluding any risk of magnet block demagnetization at 300K in the completely assembled undulator. For the optimum layout, however, the reverse fields exceed the critical value during the assembling procedure (figure 1). The most dangerous situation occurs, when only two magnets are mounted in an adjacent position.

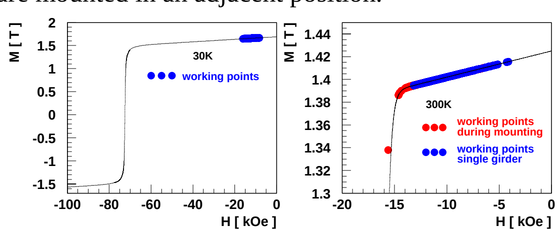

Figure 1: M-H curves of the PrFeB-material and the working points of the individual magnet segments. The working points are even more relaxed in the complete device at the gap of 2.5mm.

To avoid any damage of the magnets, the assembly of the individual magnet girders was carried out in a cold storage room at temperatures well below 0°C. After the mounting several segments in the single girder geometry are still close to the knee of the M-H curve (figure 1). The situation gets relaxed when the girders are paired with a gap of 2.5mm and at 30K the complete magnet volume is far away from the critical field-strength.

The magnetic induction of both individual girders has been measured at room temperature in a distance of 1.5mm above the pole tips. The effective on-axis field was measured to 0.377 T, while the calculation with RADIA gives a value of 0.383T. This corresponds to a deviation of 2.4 percent.

The calculated fields for the complete device at a gap of 2.5mm are: B_0=1.15T and B_{eff}=1.12T for 30K and B_0=1.03T and B_{eff}=1.01T for 300K which is 5% less as compared to earlier values [16]. The reason is a modified chamfer geometry close to the beam. Going from 300K to 30K the remanence increases by 20% whereas the on axis field increases only by 11%. This is due to the partial saturation of the pole pieces. Another pole design for the next prototype will minimize this effect.

Due to the prototype character of the undulator identical poles and magnets have been used for the periodic part and the end section. The trajectories are compensated by retracting the poles from the beam by 2mm and retracting the end magnets by 2.9mm. The resulting trajectory offset is about 9Tmm^2. The periodic poles can be adjusted in height to correct for magnet block errors which result in trajectory or phase errors. The sensitivity of the pole height adjustment of a single pole is 0.04Tmm / 0.1mm displacement.

MECHANIC DESIGN

The undulator is a fixed gap device with a gap of 2.5mm. A gap parallelism of a few µm is realized with a precision copper spacer, which is integrated in the backplane. Modifying the backplane the gap can be further reduced to 2mm yielding a field of B_0=1.42T and B_{eff}=1.37T at 30K.

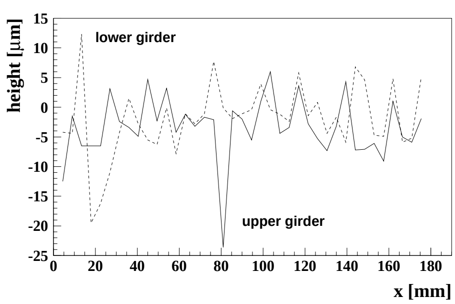

Figure 2: Pole heights of the two girders without fine tuning as measured with a 3D-coordinate measurement machine of the type PRISMO 7 (ZEISS).

The pole pieces are clamped directly onto the girder without using keepers. The neighboring magnets define the longitudinal position of the poles. The geometric precision of the magnetic structure is defined by the geometry of the girders which have been machined on a high precision milling-machine. The pole heights of the two girders are within a narrow error band without any fine tuning (figure 2). Pole height adjustment for field fine tuning is possible if required.

CRYOGENIC DESIGN

The mechanic layout of the cryogenic undulator, the cold heads and the vacuum chamber is depicted in figure 3. Copper is the preferred material for the magnet girder. In contrast to Aluminum or Titanium it has a pronounced maximum in the thermal conductivity at low temperatures which reduces the thermal gradients. However, the thermal conductivity has to be carefully balanced versus the mechanical properties such as the yield stress. To avoid differential thermal expansions all undulator parts as well as all thermal connectors are made from copper. Two two-stage GM cryo coolers of the type RDK-415D from Sumitomo Heavy Industries are used. They provide cooling capacities of 35W @ 50K at the first stage and 1.5W @ 4.2K at the second stage. The first stages can be connected to the shield of the undulator and the undulator base plate. The second stages are connected to the upper and lower undulator magnet girders. The upper magnet girder is in thermal contact to the lower girder via a massive copper backplane. All thermal connections from the cold heads to the undulator and the thermal shield are made of flexible laminated connectors manufactured out of copper strips which are press-riveted.

Temperatures are measured at an additional flange on top of the second stages, at the laminated connectors close to the girders and at the girders (figure 3). The temperatures are measured with Cernox resistors CX-1030-CU-1.4D from Lakeshore.

In a first test the undulator has been cooled down without any thermal shields. The cooling process took a bit more than three hours from room temperature to 11K at the magnet structure (figure 4). The temperature at the cold heads was 7K. In a second test a thermal shield has been adapted around the undulator. The shield was cooled with the first stages of the cryo coolers. The end temperatures in this case were identical to the temperatures without shield. The cooling process itself was faster by about 20 minutes. For the current geometry the shield is not crucial. This might be different for larger prototypes with a larger surface and a bigger cold mass.

Based on a node model (figure 3) the end temperature has been estimated to 17K. The simulations where based on RRR50 material for the laminated connectors and the girders which is a conservative guess. The lower temperature as observed in the experiment is probably due to a higher RRR value. This assumption is supported by the accelerated cooling process below 50K (figure 4) which is due to the typical maximum of the thermal conductivity of copper.

The simulations do not include the interfaces between the copper parts. The experiments demonstrate that they are not important at this temperature level. The girders are connected to the cryo cooler via four interfaces where copper pieces are bolted together using Apizoon for better thermal conductivity. The experimental data show a good thermal conductivity of all joints and in particular the good quality of the laminated connectors. In principle the number of interfaces can be reduced to two when the laminated connectors are welded onto the adapter flanges. In the future detailed material data will be extracted from the comparison of time dependent FEM simulations with time dependent measurements.

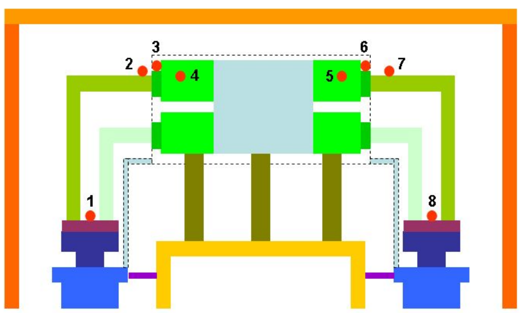

Figure 3: The nodes of the cryogenic model are plotted in individual colors. The temperature sensors are located at positions 1-8. With cooling shield installed (dotted lines) the sensors 3 and 6 have been moved to the shield.

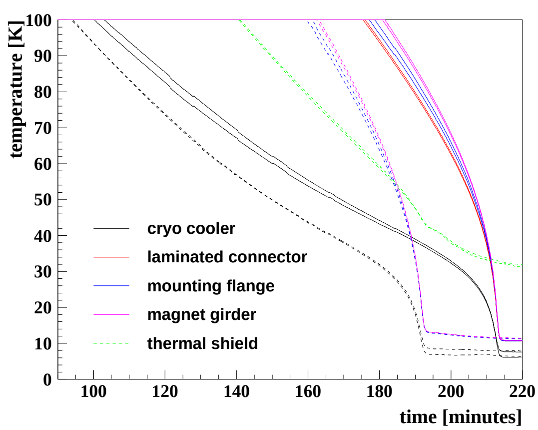

Figure 4: Temperatures as measured at the locations given in figure 3 when cooling down. Cryo cooler: sensors 1 & 8; laminated connector: sensors 2 & 7; mounting flange: sensors 3 & 6; magnet girder: sensors 4 & 5. The sensors are calibrated only for temperatures below 100K. Cooling started at time=0. Solid lines: no thermal shield; dashed lines: thermal shield installed.

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