STATUS OF PRASEODYMIUM UNDULATOR WITH TEXTURED DYSPROSIUM POLES FOR COMPACT X-RAY FEL APPLICATIONS*

F. H. O'Shea, R. Agustsson, Y.-C. Chen, T. Grandsaert, A. Murokh and K. Woods
RadiaBeam Technologies, Santa Monica, CA 90404, USA
V. Solovyav, BNL, Upton, NY 11973, USA
J.-H. Park and R. Stillwell, NHMFL, Tallahassee, FL 32310, USA

Abstract

The demand for high-brightness hard x-ray fluxes from next generation light sources has spurred the development of insertion devices with shorter periods and higher fields than is feasible with conventional materials and designs. RadiaBeam Technologies is currently developing a novel high peak field, ultrashort period undulator with praseodymium-iron-boron (PrFeB) permanent magnets and textured dysprosium (Tx Dy) ferromagnetic field concentrators. This device will offer an unparalleled solution for compact x-ray light sources, as well as for demanding applications at conventional synchrotron radiation sources. A 1.4T on-axis field has already been achieved in a 9mm period undulator (K∼1.2), demonstrating the feasibility of using Tx Dy poles in a hybrid undulator configuration with PrFeB magnets. Facets of the undulator design, optimization of the Tx Dy production and characterization process, and magnetic measurements of Tx Dy will be presented.

INTRODUCTION

Research into in-vacuum cryogenic permanent magnet undulators (IV-CPMUs) has increased a great deal since the introduction of the concept nearly a decade ago [1]. This research has been spurred on by the promise of higher peak magnetic fields which leads to larger flux in synchrotron light sources, especially at higher harmonics, and shorter gain lengths in free-electron lasers using shorter period undulators. The benefits of the latter being well demonstrated at SACLA, which produced sub-$\mathring{a}$ngstrom x-rays in a device less than one kilometer long [2]. The principal benefits of this technology, when compared to superconducting technology, are the relaxed heat load tolerance due to the ability to pump a great deal more heat at higher temperatures and the well developed fabrication strategies for permanent magnet undulators. Most research has focused on development of materials compatible with the vacuum requirements [3] and radiation conditions of 3^{rd} and 4^{th} generation light sources and improving fabrication strategies to deal with the more complex thermal designs [4, 5, 6].

One of the developments of the research into apposite magnetic materials for CPMUs is materials that do not contain a significant fraction of neodymium, that shows a spin axis reorientation at approximately 135K [7], but have higher remanent fields than samarium-cobalt magnets. One such candidate is praseodymium based magnets, of which several varies of magnet have been developed [1, 3, 8, 9]. An undulator made of one such material has been measured at 17K [5, 9] and operationally demonstrated at sub-50K temperatures [10].

The operation of CPMUs at low temperatures offers the opportunity to develop new pole materials that take advantage of the existing cryogenic conditions to create higher peak field undulators. To this end we have been investigating the use of rare-earth materials such as dysprosium and gadolinium to replace the cobalt iron (CoFe) typically used in high field hybrid undulators. CoFe is the pole material of choice for high field undulators because of its large saturation magnetization (2.35 T), very large initial permeability ($\mu_i \sim 10^4$) and small non-linear knee region which is the transition between the two regions.

In single crystal form, dysprosium demonstrates much higher magnetic moment (>3 T [11]) at low applied field and cryogenic temperatures than CoFe (see Fig. 1). However, single crystals of these materials are difficult and expensive to produce at the dimensions and scale required for undulator fabrication and polycrystalline versions of the materials are not useful for undulator applications because of low initial permeability.

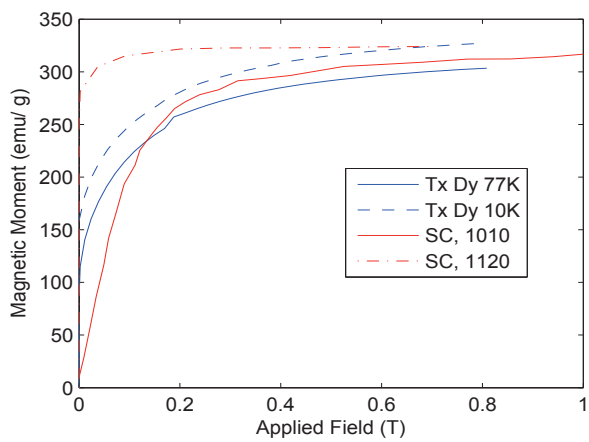

Figure 1: Comparison between single crystal magnetic moment at 77K (red) and the performance of Tx Dy (blue) at two different temperatures.

A compromise between the single crystal and polycrystalline forms can be reached through a processing technique that generates so-called texture in the material. This technique takes advantage of a favorable energy difference

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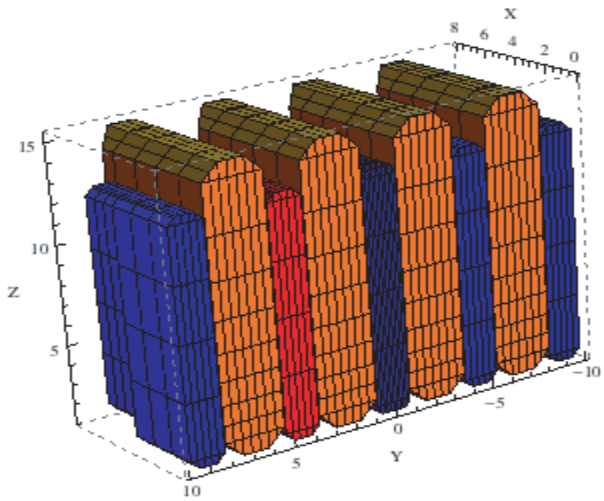

Figure 2: One half of the upper half of the experimental 2-period undulator of the inital experiment, cut away to show detail. The orange objects are PrFeB magnets and the blue objects are CoFe poles. The red object is a pole that is first CoFe for a calibration measurement and is then replaced with Tx Dy.

between crystallographic orientations during a rolling and annealing cycle [12]. Briefly, the polycrystalline material is rolled out and then annealed near the melting point. For dysprosium, which has an *hcp* structure, grains within the foil that are oriented with the hardest axis within the plane of the foil are taken over by grains that have the hardest axis pointed normal to the plane of the foil in a process known as secondary re-crystallization. This process dramatically increases the permeability within the plane of the foil [11]. The foils can then be annealed together in stacks to produce a macroscopic piece for further machining.

Tx Dy, therefore, has two easy axes and one very hard axis. Because planar undulator design does not require large magnetic field gradients in the direction of electron oscillation, the hard axis of the material can be chosen along that direction. The material development process then becomes focused on developing the highest possible permeability and saturation magnetization within the plane of the foils.

TX DY MATERIAL TESTING

As a preliminary test of the material, a 2 period test undulator was built based on an existing PrFeB undulator design [4, 5, 10, 14]. The model was a 2-period device consisting of four magnets and five poles as shown in Fig. 2. In the first experiment all of the poles are made of CoFe to make a comparison to Radia [13] simulations using a well known material. Once agreement between Radia and the measurement results had been achieved the red pole in Fig. 2 (and its compliment across the undulator gap) was replaced with a Tx Dy pole with the laminations in the x-direction.

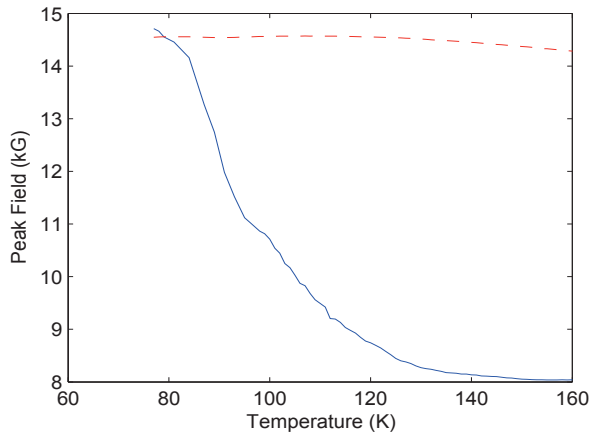

Figure 3: Comparison of the on-axis fields of the 2-period undulator as a function of temperature between the Tx Dy poles and CoFe poles. It can be seen that the Tx Dy poles perform better than the CoFe poles near 77K.

With the Tx Dy poles in place the temperature of the undulator is decreased via a liquid nitrogen bath and the field between the Tx Dy poles is compared to the field between the pair of CoFe poles on the other side of the undulator. The results of this measurement are shown in Fig. 3. Because dysprosium is antiferromagnetic at temperatures above 85K (and paramagnetic above 180K), the poles do not increase the flux in the undulator gap until the dysprosium becomes ferromagnetic. When the poles are cold enough the Tx Dy outperforms the CoFe by ∼3%. The gradual slope of the field in the Tx Dy poles is due to the nonuniform cooling of the poles; some parts of the poles were colder than the probe used to measure the undulator temperature.

A vibrating sample magnetometer (VSM) measurement of the Tx Dy material was performed at 77K. This sample was cut from the poles used in the previous experiment. The demagnetization factor, N, for the measured sample was calculated using Radia. To confirm the material properties, the VSM experiment is simulated by modifying the measured demagnetization curve to correct for the demagnetizing factor such that $H = H_{applied} - NM_{measured}$. When these magnetization curves are used in a Radia simulation of the experiment, the agreement between the simulated magnetization and the measured magnetization is quite good (see Fig. 4). When this material is used to simulate the initial experiment, the Radia simulations show a 3% increase in the peak field at the Tx Dy poles over the CoFe at 77K, replicating the experiment (see Fig. 3).

UNDULATOR DESIGN

The goal of the design process is to produce a 7 mm period, K∼1 undulator, implying an on axis field of 1.5 T. The starting point for the Tx Dy pole undulator design is CPMU9 [4] previously demonstrated at Helmholtz-

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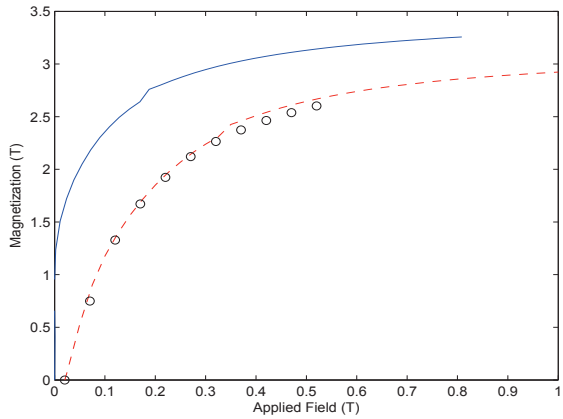

Figure 4: Easy axis magnetization curve of the textured dysprosium poles from phase I. The measurement was performed at 77 K. The dashed red curve shows the raw data while the solid blue curve shows the curve after correction for instrument offset and the demagnetizing factor of the sample. The black circles are the results of a Radia simulation replicating the conditions of the VSM measurement.

Zentrum Berlin [5] and UCLA [10]. In this undulator, the Tx Dy does not show an improvement over CoFe at any temperature because CPMU9 was optimized for CoFe poles. In order to see the benefit of the Tx Dy, the field applied to the pole tips must be increased by approximately 50%. Using 2D undulator designs this would require either higher energy magnets or larger magnets and thus longer periods, which is contra to the goal of this project.

Another way to increase the magnet volume per period is to make the poles thinner, but this provides only a small increase in gap field as most of the higher flux is channeled into higher harmonics of the field. 3D designs using side and backing poles would increase the complexity of the engineering design, potentially beyond the value of the $\sim$10% increase in peak field. However, backing poles alone would not significantly change the engineering design. Currently, the mechanical design restrains the poles via small fingers that hold the poles in place with the ”shoulders” that can be seen in Fig. 2. Backing magnets could be placed above the poles and, by decreasing the height of the poles, used to force larger flux through the Tx Dy poles.

An increase in the complexity of the design is necessary to take advantage of the higher saturation magnetization in the Tx Dy. While the 2-period prototype did show an increase in the field using Tx Dy poles, this is a result of the pole position at the ends of the undulator. These poles are exposed to higher applied fields because of the divergentless condition on the magnetic field of the device. As such, the poles at other positions in the undulator see smaller field and the CoFe outperforms Tx Dy because of its very large initial permeability and smaller non-linear knee region.

There are two other ways in which the magnetic field amplitude can be increased. The first is by cooling the undulator further. The previous tests were done at 77K because of the simplicity of direct cooling with liquid nitrogen. The Tx Dy shows improved performance at lower temperatures as magnetization between 0.1 and 0.2 T applied field increases by about 10% from 77K to 10K. Operating at lower temperatures has also been suggested to increase the conductivity of the copper used to make the undulator mechanical structure [14]. Further, both initial permeability and saturation magnetization can be increased by reducing the foil thickness from 100 μm, as used in the 2-period prototype, to 25 μm [11].

The previously tested CPMU9 was limited to a minimum 9 mm period length because of the risk of demagnetization of the magnets during assembly near room temperature [14]. Because rare-earth poles are not ferromagnetic near room temperature, these materials should allow shorter period designs as the magnets are only exposed to ferromagnetic field concentrators well into the region of high coercivity at low temperature.

SUMMARY

We have successfully characterized the textured dysprosium material used in the initial experiment performed at RadiaBeam Technologies such that the results of that experiment can be replicated in Radia. Based on these results we have found that the Tx Dy pole undulator design must take advantage of at least one of the following changes to achieve maximum performance: operation at sub-LN_2 temperature, processing to thinner laminations and backing magnets. These changes are predicted to lead to a significant improvement in peak field over CoFe poles. In addition, the relaxed assembly requirements allowed by the Tx Dy should allow shorter period undulators when compared to CoFe.

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