PRASEODYMIUM IRON-BORON UNDULATOR WITH TEXTURED DYSPROSIUM POLES FOR COMPACT X-RAY FEL APPLICATIONS

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Abstract

The next generation light sources require development of the insertion devices with shorter periods and higher peak field values, well beyond the presently available designs limited by magnetic properties of conventional materials. Radiabeam Technologies is developing a novel ultra-high field short period undulator using two unconventional materials: praseodymium permanent magnets (PrFeB) and textured dysprosium (Tx Dy) ferromagnetic field concentrators. Both materials exhibit extraordinary magnetic properties at cryogenic temperatures, such as very large energy product and record high induction saturation, respectively. The proposed device combines PrFeB and Tx Dy in 3-D hybrid undulator geometry with sub-cm period and up to 3 Tesla pole tip field. Practical realization of these features will significantly surpass state-of-the-art and offer an ideal solution for the next generation of compact X-ray light sources. Textured Dy development status, along with initial simulations, and proof of concept prototype cryogenic measurements will be presented.

INTRODUCTION

A successful commissioning of the Linac Coherent Light Source (LCLS) X-ray Free Electron Laser (FEL) [1] has opened up a new frontier to the light source community, providing researchers with ultra-fast X-ray pulses and an energy density that has exceeded 3rd generation light sources by many orders of magnitude. While this is an exciting beginning of FEL-based X–ray science, the full realization of FEL technological potential requires developing more compact and, ultimately, table-top systems [2]. One limiting factor for all these projected developments is in the need of shorter periods and higher peak fields insertion devices. Indeed, the state-of-the-art in-vacuum permanent magnet undulator technology [3], while extremely successful in its application to LCLS, could not be directly extended into sub-cm period range while maintaining undulator parameter K above unity [4]. In order to foster the success and utility of emerging FEL-based light sources, it is imperative to explore innovative approaches towards developing high quality, high field and short period-to-gap ratio devices.

A well-known important concept to increase field in the gap of insertion devices is to use hybrid geometry [5], where high saturation field concentrators are utilized to increase the pole tip field beyond the remanent field of the permanent magnets. In the hybrid geometry a limiting factor is the actual ferromagnetic saturation level of the pole material. To date the most promising pole material considered for undulator applications is a vanadium-permendur (V-P) alloy whose saturation induction exceeds 2.3 T. The objective of the effort presented in this paper is to further increase achievable pole tip field level by utilizing textured dysprosium concentrators.

TEXTURED DYSPROSIUM DEVELOPMENT

Dysprosium metal has the highest saturation inductance of all known materials, reaching 3.8 T at 4.2 K. Relatively high Curie temperature, 90 K, makes Dy suitable for magnetic applications below 77 K. Dysprosium has a hexagonal close packed (hcp) structure [6], which imposes strong anisotropy on the magnetic properties of the material: dysprosium has very hard direction along [0001] (normal to the basal plane), followed by the moderately hard direction $\langle 10\bar{1}0\rangle$ and easy $\langle 11\bar{2}0\rangle$ directions. Polycrystalline Dy, comprised of randomly oriented crystallites, would therefore be very hard ferromagnetically, with an apparent saturation in moderate magnetizing fields, < 10 kOe. To realize the advantage of Dy over V-P material, one needs to orient the Dy pole so that the magnetizing field is directed along the easy axis or, at least, in the basal plane. Cutting the pole from a single crystal is impractical due to the small size of the available crystals and the expensive equipment involved in the process make this route impractical.

Secondary re-crystallization is widely used to induce texture in rolled foils of fcc metals, such as Ni, Al, Fe-Si alloys. In early 70s Westinghouse research group suggested that secondary re-crystallization process to manufacture large-scale Dy foils [7]. A cold-rolled Dy tape is polycrystallite, comprised of small (<100 nm) primary Dy grains. Some grains have favorable orientation, with [001] direction parallel to the tape normal and the fast-growth ab-plane parallel to the tape face. The better oriented grains gain a small energetic advantage over other grains, which becomes amplified as the grains start to grow during the subsequent annealing. During the annealing the secondary grains expand rapidly, consuming misoriented primary grains through so-called abnormal grain growth mechanism. At the end of this processing step, the tape has only very large (> 10 μm), well-oriented secondary grains remain.

RadiaBeam adapted the Westinghouse method, with some proprietary improvements, and obtained high quality samples of Dy foil with better than 10 degrees out of plane texture [8], far exceeding the texture quality

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reported by Westinghouse. The optical micrograph shown in Fig. 1(a-b) of the Dy secondary recrystallization process demonstrates a large abnormal-oriented grain growth that peaks after about 10 minutes of annealing. This synthesis method can be easily scaled-up to produce large quantities of the textured foil.

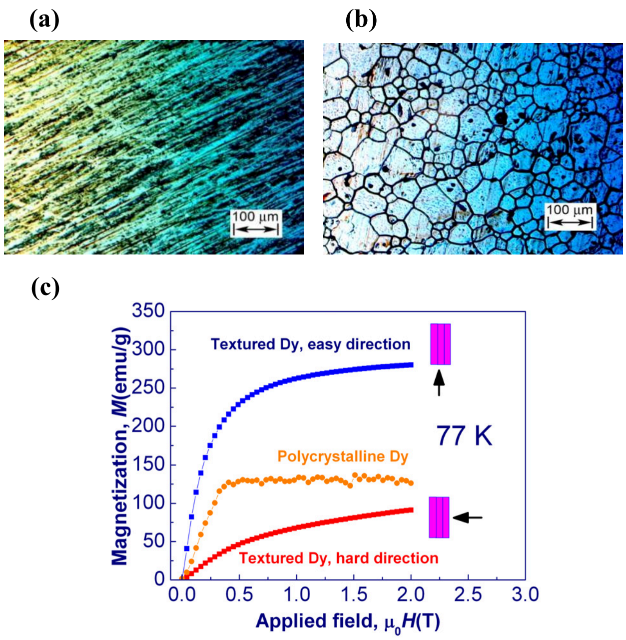

Figure 1: (a) Optical surface micrograph of as-rolled 60 µm Dy foil; (b) The effect of 10 min of annealing at 1050°C on a bright-field micrograph; (c) Magnetization curve measurements results at 77K show the prototype textured Dy laminated pole saturation just under 3T.

A prototype laminated textured Dy pole has been composed from 25 µm annealed foil, such as shown in Fig. 1(b). Fig. 1(c) shows initial results of magnetization of textured Dy pole. The magnetization curve demonstrates close to a 3 T saturation induction, 20% above the vanadium permendur saturation level. Simply increasing the density of the textured Dy composite sample and improving the quality control of cold rolling procedure is expected to yield further improvement of about 10-15%. Such improvements in the saturation field can dramatically improve the performance of cryogenic short period undulators, if textured Dy poles replace V-P as field concentrators..

PROTOTYPE PrFeB HYBRID UNDULATOR

A short prototype for the purpose of providing a direct comparison at cryogenic temperatures between Tx Dy poles, and V-P poles was manufactured. This prototype utilized the UCLA-HZB [9] geometry and PrFeB magnets with V-P poles except for an opposing pair of Dy poles, as shown in Figure 3. PrFeB magnets were chosen since at cryogenic temperatures it does not show signs of spin-axis reorientation down to temperatures below 30 K, exhibits increased remnant fields at lower temperatures, robust radiation resistance and an energy product exceeding 1100 MG-Oe, even at 85 °K. [9]. As such, PrFeB is an ideal material to combine with TxDy for ultra-high performance cryogenic undulator applications.

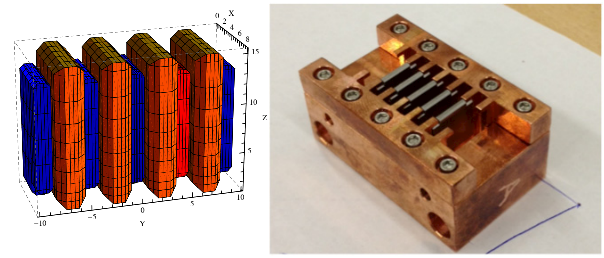

Figure 2: ¼ model where blue pieces are V-P poles, orange are PrFeB magnets and red the pole that will be either V-P, or TxDy (left); ½ of the fabricated holder (right).

Initial simulations of this undulator design using the code Radia [10] had shown that the peak field in the UCLA-HZB undulator using Tx Dy poles would be ~90% of the identical undulator design using V-permendur. Initially, the shortfall was ascribed to the insufficient strength of the PrFeB lattice, whose design was optimized for V-P and not Tx Dy and thus did not take advantage of the TxDy's higher magnetization saturation. Further, the measurement of the magnetization curve of the Tx Dy material was believed to be yielding an artificially low initial permeability due to the grain size in the foil samples being larger/comparable to the foil thickness and the lateral size of the specimen. This means that the mean field model cannot be reliably used, and typically the measured mu would be lower than in a bulk sample where grains are smaller than the sample. Therefore, to test our predictions, a prototype 2-period undulator section was manufactured such that direct comparison between the simulations and measurements were possible by interchanging a single pair of V-P poles with poles made from Tx Dy, shown in Figure 2.

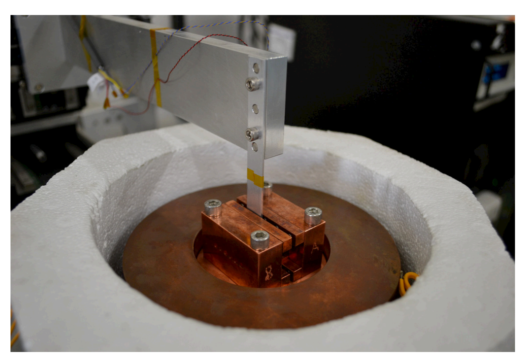

Figure 3: The proof of principle magnetic field test setup.

To take full advantage of Pr magnets (as well as Tx Dy poles) it would have been desirable to conduct the measurements at ~ 30°K; however, due to budgetary constraints, a test stand operating at 77°K (liquid N2) was developed, see Figure 3, with a small area cryogenically

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compatible Hall probe for the proof of principle measurements and temperature monitoring with a RTD.

The first measurement of the cooled test undulator was made using only Vanadium permendur poles as a test of the accuracy of Radia in general. The agreement between the measured and simulated peak fields was very good (at approximately 1%). This level of accuracy is standard for magnetostatic problems in Radia when using well-known materials. Next, the V-P poles (the red pole in Figure 2) were replaced with the Tx-Dy laminated poles in in each jaw, a measurement of the on-axis field was performed at 77°K with Tx Dy poles (laminated in the z-direction). The measured peak field was 11% higher than simulation. The simulation curve shows the predicted short fall of the Tx Dy poles due to the magnetization curves that are material measurement limited.

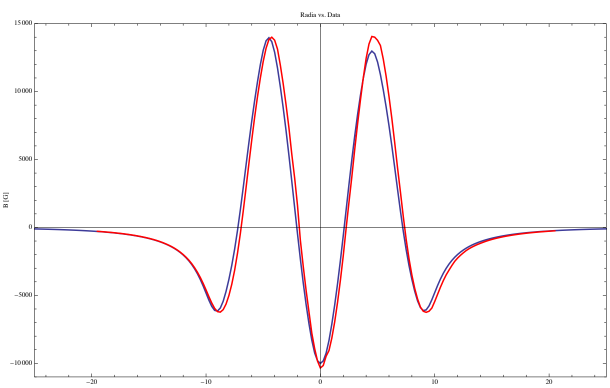

Figure 4: Comparison of simulation (blue curve) to measurement (red curve) for the test undulator containing a pair of Tx Dy poles.

This measurement of a PrFeB undulator with Tx Dy poles indicated on-axis peak field of ~1.45 T in a 9 mm period undulator structure (K~ 1.2). This is an encouraging result given that there is a significant room for further optimization of both material properties and the undulator design. Tx Dy sample poles demonstrated even better ferromagnetic properties than anticipated from the initial magnetization curve.

Finally, an initial thermal vs. field characterization plot shows the increased flux concentration of TxDy within the undulator gap as the temperature decreases. The probe does not remain as well aligned during these measurements as we would have liked, most likely a result of the thermal contraction of the assembly during N2 bathing. However, there is good correlation between these measurements and the field plots shown in (Figure 5). Further, an interesting conclusion from this data is that although the TxDy does seem to be moving into saturation, it is most likely that we would continue to see gap field increases as the magnets are cooled even further than this initial test at 77K would allow. The increased flux at lower temperatures is a highly valued property of the PrFeB magnets.

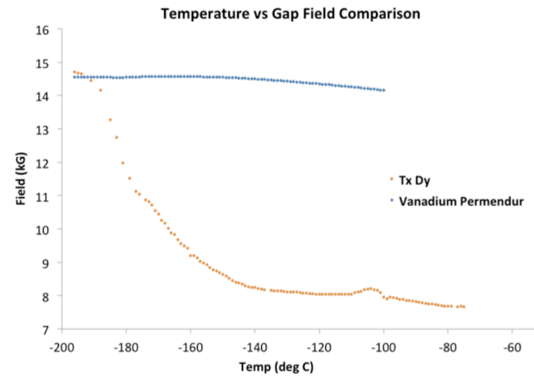

Figure 5: Temperature vs. gap field plot of the Tx Dy.

CONCLUSION

The initial development of textured Dy tape material indicates feasibility of highly anisotropic ferromagnetic field concentrator with saturation above 3 T for insertion device applications at the cryogenic temperatures.

Simulations and measurement with V-P poles indicates that, Tx Dy magnetization curves are not sufficiently accurate for simulation purposes. Fortunately, the Tx Dy sample poles demonstrated even better ferromagnetic properties than anticipated from the initial magnetization curve

Future work, if granted, will revolve around designing an undulator that is optimized for TxDy's high saturation inductance by reducing the period to 7mm from the 9mm design utilized in this presented work and cooling the device further to increase the peak undulator field to 1.5T or higher.

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