APPLICATIONS OF TEXTURED DYSPROSIUM CONCENTRATORS IN ULTRA-SHORT PERIOD INSERTION DEVICES

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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. Dysprosium (Dy) is a rare earth metal with unique ferromagnetic properties below 90 K, including saturation inductance above 3.4 Tesla. However, due to the high magnetic anisotropy of Dy, such a high level of magnetization can only be realized when the external field lies in the basal plane. This requirement is partially satisfied in the textured dysprosium presently under development at RadiaBeam and BNL. Textured Dy development status is discussed, as well as potential applications as field concentrators in the insertion devices, with particular emphasis on the next generation of cryogenically cooled short period hybrid undulators.

INTRODUCTION

A spectacular success 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 additional developments from the FEL community [2], such as controlling pulse length at the attosecond time scale, achieving higher repetition rates [3], and developing compact and, ultimately, table-top systems [4]. A common 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 permanent magnet undulator (PMU) technology [5], 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 [6]. 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.

At present, the most reliable short period insertion devices developed on a practical scale are In-Vacuum Undulators (IVUs) based on permanent magnet technology [7]. IVUs were initially introduced for light source applications in the early 1980's and quickly became the standard in the synchrotron radiation community. State-of-the-art IVUs utilize permanent magnets such as neodymium-iron-boron ($Nd_2Fe_{14}B$) and samarium-cobalt (Sm_2Co_{17}) with remanent fields on the order of 1.0-1.2 T.

A well-known important concept to increase field in the gap of insertion devices is to use hybrid geometry [8], 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.

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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 [9], 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 <10$\underline{1}$0> and easy <11$\underline{2}$0> directions. This is why a polycrystalline Dy sample, which is comprised of randomly oriented crystallites, would be a very hard ferromagnetic, with an apparent saturation in moderate magnetizing fields, < 10 kOe, well below of the absolute value. To realize the advantage of Dy over a well-established V-P material, one needs an oriented Dy pole so that the magnetizing field is directed along the easy axis or, at least, in the basal plane. A straightforward solution would be cutting the pole from a single crystal. However, small size of the available crystals and the expensive equipment involved in the process make this rout impractical.

Secondary re-crystallization (Fig. 1) is widely used to induce texture in rolled foils of fcc metals, such as Ni, Al, Fe-Si alloys. In early 70x Westinghouse research group suggested that secondary re-crystallization process to manufacture large-scale Dy foils [10]. 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

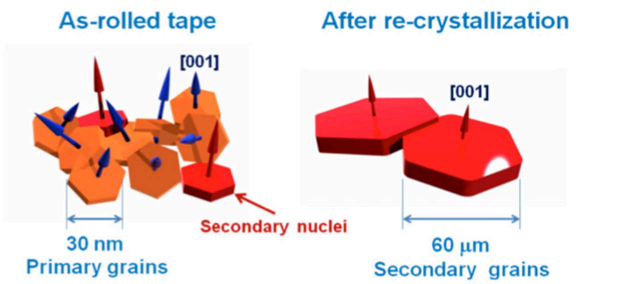

Figure 1: A simplified illustration of secondary re-crystallization process.

abnormal grain growth mechanism. At the end of this processing step, the tape has only very large (> 10 µm), well-oriented secondary grains remain.

In 2008, 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 [11], far exceeding the texture quality reported by Westinghouse. The optical micrograph shown in Fig. 2(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.

A prototype laminated textured Dy pole has been composed from 25 µm annealed foil, such as shown in Fig. 2(b). Fig. 2(c) shows initial results of magnetization

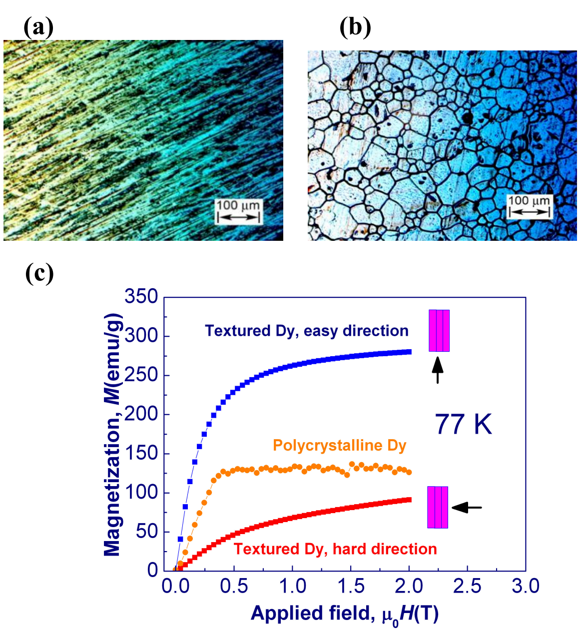

Figure 2: Optical surface micrograph of as-rolled 60 µm Dy foil (panel a); the effect of 10 min of annealing at 1050 °C on a bright-field micrograph (panel b). A corresponding magnetization curve measurements results at 77K (panel c), show the prototype textured Dy laminated pole saturation just under 3T.

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 improvement in the saturation field can dramatically improve performance of cryo-cooled short period undulators, if textured Dy poles replace V-P as field concentrators. The examples below include textured Dy applications in ultra-short period cryogenically cooled permanent magnet IVU and high temperature superconducting undulators.

IN-VACUUM HIGH PERFORMANCE HYBRID UNDULATOR CONFIGURATIONS

First we analyze feasibility of using re-crystallized Dy foils as poles of a cryo-cooled hybrid undulator. As an example we use geometry derived from the U-20 undulator designed for NSLS-II X-ray ring. A three different hybrid geometry design configurations has been used (Fig. 3a), and magnetic simulations using code RADIA demonstrate that a ferromagnetic material with B_s > 3 T (such as in texture Dy) does provides a significant advantage over vanadium permendur as the pole material (Fig. 3b).

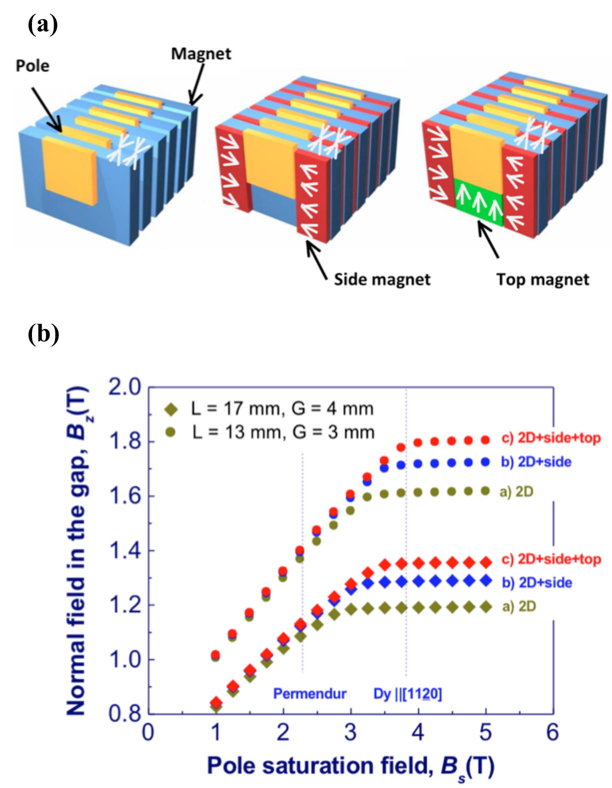

Figure 3: Schematic layout of the hybrid magnet array geometries for 2D, 2D+side magnets, and 2D+side+top configurations (panel a); RADIA simulations for the corresponding gap field as a function of the saturation

inductance (panel b), showing clear advantage of textured Dy over vanadium permendur.

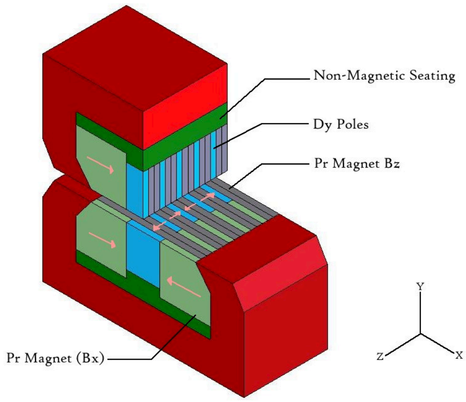

Figure 4: The Pr-Dy undulator assembly with conceptual keeper structure.

Fig. 3 assumes utilization of textured Dy with NdFeB, a widely used permanent magnet material due to its large energy product and ability to fine tune the magnetic properties for a given application by controlling dopant composition and impurity concentration in the lattice. In cryogenic applications, however, such magnets have a limitation associated with the spin-axis reorientation, which in NdFeB magnets starts at about 135 K and results in a deviation angle as large as 30° at lower temperatures [12]. As a consequence, the remanent field in NdFeB magnets is peaked at 135 K and degrades with further cooling. To mitigate this deficiency, and to take a full advantage of textured Dy properties below 90 K, an experimental permanent magnet configuration is considered to replace 80% neodymium in the NdFeB with praseodymium (Pr) [13]. The resulting $Nd_{0.2}Pr_{0.8}Fe_{14}B$ permanent magnet material does not show signs of spin-axis reorientation even at temperatures below 30 K, and at these low temperatures it shows improvement in remanent field and a large gain in coercivity with an energy product exceeding 1000 MGOe [13]. As such, PrFeB is an ideal material for ultra-high performance cryo-cooled undulator applications, in combinations with texture Dy (Fig. 4).

Even more challenging, but promising approach involves replacing permanent magnets with high temperature superconducting (HTS) coils. It is important to note, that the same low-temperature environment necessary for texture Dy to be below Curie temperature and exhibit its strong ferromagnetic properties is also required for the HTS tapes to stay superconducting. As a consequence the two technologies can be combined, such as an example shown in Fig. 5, where we adapted the stacked HTS tape undulator design [14] developed at Lawrence Berkeley National Lab (LBNL), and included textured Dy field concentrators in place of the air gaps. Maxwell-3D magnetostatic simulations indicate that introducing of textured Dy concentrators enable a significant increase in the on-axis gap field without exceeding the critical current in the HTS tape.

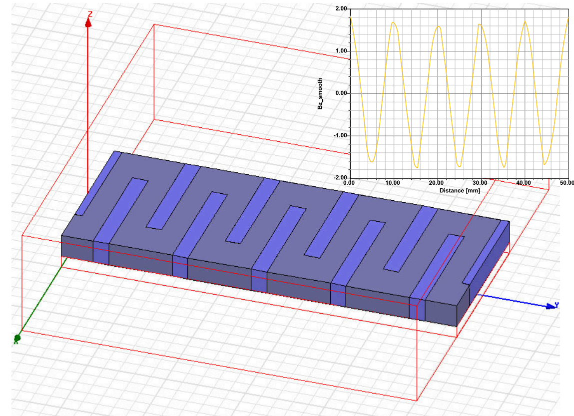

Figure 5: On-axis magnetic field of a stacked HTS tape undulator using current density of ~100 KA/cm^2, undulator period of 1 cm and gap of 3.3 mm. Textured Dy field concentrators increase the on-axis field to ~ 1.6 T.

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 (77 K). A number of examples has been considered where in combinations with permanent magnet materials or HTS tapes texture Dy allows to achieve sub-cm period undulators with ~ 1.5 T on-axis field. Such device could enable the near future 4th generation hard X-ray light sources driven by the room size ~ 1 GeV accelerators.

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