DEVELOPMENT OF DY POLES FOR HIGH TEMPERATURE SUPERCONDUCTING UNDULATOR APPLICATIONS*

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Abstract

A High Temperature Superconducting Dysprosium Pole Undulator (HTS-DPU) is proposed to achieve an ultra-high peak field in a very short period undulator structure. This design utilizes the unique ferromagnetic properties of dysprosium (Dy) at liquid nitrogen temperature. The fabrication of textured Dy via economic and highly reproducible process is studied experimentally with the goal to achieve better than 10:1 magnetic anisotropy and a field saturation level on the order of 3 T, at a practical cost. In addition, utilizing the latest capabilities of the 2G HTS wire is investigated. The practical implementation of HTS-DPU will enable the development of short period insertion devices with superior performance.

INTRODUCTION

Synchrotron radiation light sources deliver essential research capabilities to chemistry, material science, crystallography, pharmaceutics and other applied disciplines. Of particular interest to many important applications of synchrotron radiation, such as protein crystallography [1], is the generation of high spectral brightness hard X-rays (10^{19}-10^{21} photons/sec-mm^2-mrad^2 per 0.1% bandwidth at 10-30 KeV). Given the typical 3 GeV operating energy of a medium size electron storage ring, the goal of achieving high brilliance emission at hard X-ray wavelengths translates into a strong need for shorter-period, higher peak-field insertion devices, beyond the limits of presently mature technologies [2].

RadiaBeam Technologies is developing in a collaboration with Brookhaven National Laboratory (BNL) a High Temperature Superconducting (HTS) Dysprosium Pole Undulator (HTS-DPU) to achieve an ultra-high peak field in a very short period undulator structure. This design utilizes the unique ferromagnetic properties of dysprosium (Dy) at liquid nitrogen temperature. The practical implementation of HTS-DPU will enable the development of short period insertion devices with superior performance in the context of delivering higher brightness and improved spectral and spatial resolution X-ray fluxes to the most demanding applications of synchrotron radiation.

At present, the most reliable short period (~ 2 cm) insertion devices developed on a practical scale are In-Vacuum Undulators (IVUs) based on permanent magnet technology [3]. IVUs were initially introduced for light source applications in the early 80's [4,5], and quickly became the standard in the synchrotron radiation community. The IVU field strength is defined by a dimensional undulator parameter $K=eB_0/k_u m_e c$, defined by the field strength B_0, and undulator wave number k_u. The strong undulator emission harmonic lines are instrumental in reaching the hard X-ray photon wavelengths, which requires large K values (K >1.5). Yet with a typical field of ~ 1 Tesla, large K requirements limits the undulator period. In practical terms, this limitation prohibits efficient magnetic design for undulator periods much shorter than 2 cm. On the other hand, scaling an undulator design towards shorter periods while maintaining high K value demands higher peak field values at the poles. State-of-the-art IVUs utilize permanent magnet materials such as neodymium ferrite ($Nd_2Fe_{14}B$) and samarium-cobalt (Sm_2Co_{17}) with remnant field on the order of 1.0-1.1 T. An incremental improvement in peak fields can be achieved in a hybrid configuration IVU, which combines permanent magnets with high saturation ferromagnetic pole pieces [2]. Yet these improvements are limited, and there is a quest to develop more efficient short period insertion devices for moderate energy light sources.

One promising new approach is a Cryogenic Permanent Magnet Undulator (CPMU) [6,7,8], which is similar to IVU but cryo-cooled to around 150 K. Another important direction of research towards shorter period devices is the development of superconducting undulators (SCU) capable of higher fields in compact geometries [9,10,11]. Most of the SCU experience comes from utilizing NbTi wire (although an experimental investigation is under way to develop an SCU based on the Nb3Sn [12], which has higher critical current). An obvious disadvantage of the SCUs is the low operating temperature (<10 K), which drives up considerably the cost and complexity of these devices.

HTS-DPU CONCEPT

High temperature superconducting technology has the potential to significantly reduce these problems, but has been given limited attention due to lower critical current values in the HTS wires at 77 K, compared to the conventional superconducting wires at 4.2 K. However, recent progress in HTS wires based on epitaxial Y-Ba-Cu-O layers (so called second-generation or 2G wire) resulted in availability of practical HTS conductors with high critical current density and, unlike with the first generation (Bi-Sr-Ca-Cu-O) of HTS wires, a very good retention of the critical current in the magnetic field. Hence, combining HTS wire with high saturation ferromagnetic material presents an interesting opportunity to develop a short period, high efficiency undulator operating at liquid nitrogen temperature.

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The rare-earth metal dysprosium has one of the largest magnetic moments in the lanthanide series. In the ferromagnetic ordered state, the spontaneous magnetic moment of the Dy ion reaches 10 μ_B, where μ_B is the Bohr magneton. Such a high magnetic moment explains the record high saturation inductance B_s of Dy metal, $B_s = 3.8$ T at 4.2K. This is the highest saturation inductance value for any known material; for example, for pure γ iron and Vanadium Permendur alloy (50% Fe 48% Co 2%V), the saturation values are $B_s = 2.1$ T and $B_s = 2.4$ T, respectively. Dy orders ferromagnetically at 90 K [13], thus imposing no additional requirements for the refrigeration, if utilized as the pole material for HTS undulator. In addition, the strong anisotropic properties of dysprosium allow one to minimize the undulator period, while maintaining the minimum gap size. The combination of 2G HTS wire with a textured Dy pole is the key for the HTS-DPU concept described herein.

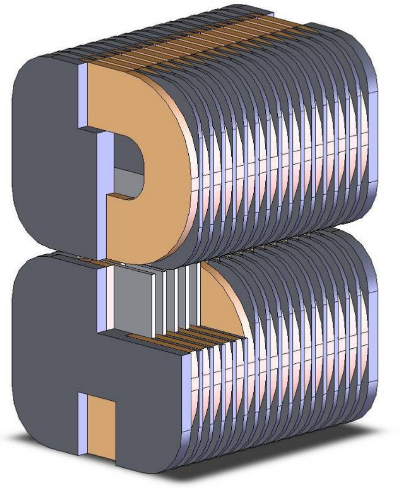

Figure 1: CAD rendering showing section view of the HTS-DPU prototype.

The basic approach towards the HTS-DPU undulator geometry adopts the approach described in [9], which is successfully used in several other SC electromagnet undulator designs [14, 15]. With this approach, the HTS coils are wound around the low carbon steel core and Dy pole pieces act as concentrators to enhance the on-axis undulator field. Since the length of the HTS-DPU is expected to be significantly smaller than a conventional IVU, the gap was reduced to 3.3 mm, which is permissible by light source standards for short length insertion devices.

Table 1: HTS-DPU parameters

Undulator gap	Undulator period	HTS current density	Peak field on-axis
3.3 mm	12 mm	50 kA/cm^2	1.5 T

The basic geometry of the HTS-DPU is shown in Figure 1. 3-D finite element magnetic simulation with code Maxwell has been used for initial design optimization, and the results are listed in *Table 1*. A peak on-axis field achieved exceeds 1.5 T, which allows to develop a 12 mm period undulator with very high harmonic content ($K \sim 1.7$).

TEXTURED DY POLES DEVELOPMENT

In the HTS-DPU concept, one of the key innovations is using the rolling-recrystallization approach towards Dy pole fabrication, which enables a very high saturation field at the pole tips. Dysprosium metal has a hexagonal close packed (hcp) structure, identical to that of cobalt. This type of structure usually imposes strong anisotropy on the magnetic properties of the material. Dysprosium is magnetically very "hard" (difficult to saturate) when the external magnetic field is directed perpendicular to the basal (0001) plane [16]. Saturation is much easier when the magnetic field is parallel to the basal plane. There are two magnetically important directions in the basal (0001) plane: the easy direction <11-20> and the moderately hard direction <10-10> [13].

A polycrystalline Dy sample, which is comprised of randomly oriented crystallites, would be a very hard ferromagnetic material with an apparent saturation of about π/4 of absolute saturation, i.e. 20% less than the theoretical maximum; hence, Dy applications so far have been limited to concentrators for very high-field magnets. To achieve > 3 T induction for HTS-DPU with reasonable fields, one needs a single crystalline sample with external magnetic field directed parallel to the <11-20> direction. Dy single crystals are traditionally grown by the Bridgman method and are too small (less than 1 cm) and expensive for the pole application.

A different approach to the Dy anisotropy problem was explored in the early 1970s by Westinghouse Labs in Pittsburg, PA [17]. The Westinghouse group employed the rolling and recrystallization method to induce (0001)<10-10> texture in Dy foils. It has been demonstrated that reasonably sharp texture can be induced by the simple and inexpensive sequence of cold rolling and annealing of polycrystalline Dy foils. The saturation inductance of the textured foils approached those of a single crystal magnetized along the (0001)<10-10> direction. Still, the saturation was reached at a field strength approximately 4 times higher than that of a crystal, indicating imperfect (0001). The rolling-recrystallization method employed by the group had been also used to texture metals with face-centered cubic (fcc) structure, such as Al, Cu, and Ni [18]. The important implication of the work is that it is possible to apply the technology developed for the fcc metals to induce rolling-assisted texture in a hcp metal, such as Dy.

INITIAL RESULTS

This approach was recently tested at RadiaBeam. Dy foils were manufactured by progressive cold rolling of Dy ingots. Two thicknesses (25 and 60 microns) were used in the experiments. The as-rolled foils were characterized by optical microscopy and 2-Theta diffraction to determine phase composition of the foil. X-ray diffraction data was analyzed using the Williamson-Hall method to determine initial grain size in the as-rolled foils and RMS strain. The foils were subjected to re-crystallization without any pre-treatment.

In Fig. 2 surface optical micrographs are compared of as-rolled 60 µm Dy tape and the same tape after 10 min annealing at 1050 °C. The as-rolled sample had minor surface oxidation with no visible grains. After 10 min of annealing, a well defined grain structure appeared. The sample had a clean, metallic surface with occasional oxide platelets.

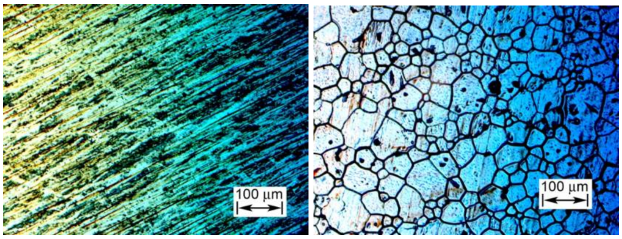

Figure 2: Optical micrographs of surface of 60 µm Dy foil as-rolled (left), and formation of large secondary grains after 10 min of annealing (right).

As expected, the recrystallization effect resulted in formation of magnetically anisotropic structure. The tapes were characterized by DC magnetometry. The samples were measured using an Oxford Instrument SQUID magnetometer equipped with a 6 T superconducting magnet. The foil sample was placed in a gel capsule, with the magnetic field always parallel to the foil plane, and Fig. 3 shows the results of the initial magnetization measurement. As-rolled foil could be saturated at 7000 Oe, which is consistent with poorly textured Dy. The saturation became easier as the foil texture improves. Also, it was observed that in a 25 µm foil a formed texture quality is generally better than that in a 60 µm foil.

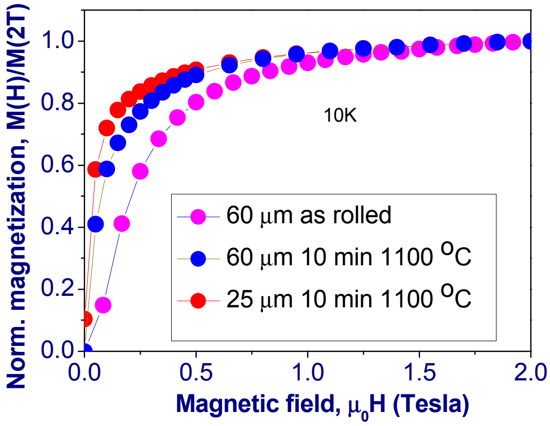

Figure 3: Normalized magnetization curves of as-rolled and recrystallized foils.

The prototype pole was assembled from 20 each 25 µm thick recrystallized foils. The re-crystallized Dy foils turned out to be quite pliable, conforming into a dense structure even under moderate pressure. The pole dimensions were 5×5×0.5 mm and the average density of 85% of the theoretical density of bulk Dy. The pole demonstrated a factor of 5 magnetic anisotropy and initial permeability of 5. These composite values are significantly lower than the individual foil data (which demonstrated magnetic anisotropy as high as ~15) because of the inferior quality of the rolled foil batch, and less than composite density. The magnetic field saturation in the pole was measured at 2.9 T. Further development to improve the composite pole quality is underway.

CONCLUSON

A significant progress has been made in developing a textured Dy poles for ultra-short period insertion devices applications. A sample pole was fabricated, and initial measurements demonstrated strong anisotropic behavior, and a saturation field close to 3 T. The next steps are to further improve the quality of textured Dy and fabricate a sample section of HTS-DPU. Further progress can lead to commercially viable, ultra-short period, high field undulator operating at liquid nitrogen temperature.

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