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FEASIBILITY STUDY OF FAST POLARIZATION SWITCHING SUPERCONDUCTING UNDULATOR

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Abstract

Polarization switching in an undulator relies on modulating the undulator magnetic field. This, however, inevitably incurs losses in superconductors, which need to be mitigated for safe operation of the device. In this study, feasibility of fast polarization switching has been investigated through fabricating and testing several short prototype magnets wound with different superconductors and new design concepts. The losses at different frequencies and field amplitudes are measured and details are presented. It has been found that by design optimization the losses can be reduced by about 40% at 2 Hz.

INTRODUCTION

Introduction of superconducting wire to undulators has increased their performance significantly and has introduced new opportunities for building various types of undulators. The Superconducting Arbitrary Polarization Emitter (SCAPE) is a new 4-magnet concept for a universal undulator, that offers linear, elliptical, or circular polarization states in one device [1, 2]. In investigation of the magnetic properties of materials, polarization switching capability i.e., horizontal linear polarization to vertical linear polarization or circular left to circular right, is a powerful tool. One way of achieving polarization switching is the complete reversal of current; however, this is accompanied by huge losses making it impractical. In order to avoid complete current reversal while switching between different polarization states, a SCAPE device composed of two modules in series—one for each polarization state—has been envisioned (see Fig. 1) [3]. This dual-SCAPE will enable fast polarization switching via fast current modulations by a rather small amount (~2.5-3.5% of the operating current). The corresponding modulation in x-ray energy is, nevertheless, large enough such that the desired polarization (left and right circular or horizontal and vertical linear) can be selected by a monochromator. Even this small current modulation might generate enough losses to exceed the available cooling capacity and it is important to characterize them.

AC LOSS MEASUREMENTS

In order to characterize the losses, an experimental setup is designed as shown in Fig. 2. Simulations indicated that only one cryocooler is enough to characterize the prototype magnets. A 2-stage Sumitomo cryocooler was used in the test stand. The thermal shield is connected, not shown in the figure, to the 1st stage that runs at about 55 K. The room temperature connections are thermally sunk to the shield or 1st stage before connecting to the second stage. The shield also acts as the radiation barrier. Magnets connected to the 2nd stage runs at about 3.2 K in the static case.

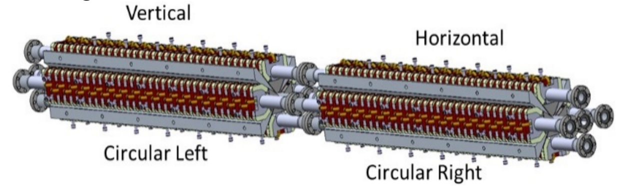

Figure 1: Dual SCAPE concept. Flux from each device can be selected by a monochromotor with the energy shifts by the current bumps.

AC losses are typically measured by two methods—electrical and thermal. The designed test setup allows measurements of both. The cold head can be calibrated by the heat deposited through the heater and AC losses generated during the field modulations can be found using this calibration. In addition, the measured voltage multiplied by the measured current can be integrated over a cycle to find the losses.

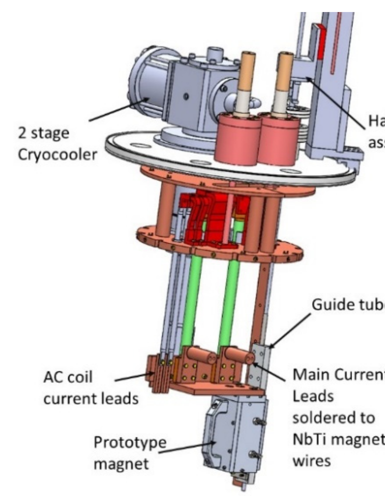

Figure 2: AC loss measurement setup.

A Hall probe is assembled to the system to measure the field. It stands off from the pole face of the magnet by a copper guide tube, as shown in Fig. 2. This guide tube is connected to the 2nd stage copper block with four low thermal conductivity peak washers. NbTi main and AC coil current leads are soldered to copper terminals at the end of the HTS current leads. Then these are routed to room temperature current terminals via copper chromium rods. The prototype magnets are attached to the bottom of the 2nd stage Cu block. The magnet is equipped with voltage taps and two heaters located at the bottom for calibration.

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Prototype Magnets

The prototype magnet design is matured by the thermal models; a picture of the magnet is provided in Fig. 3. The winding former is fabricated in one piece with poles inserted. The impregnation mold is designed to be an integral part of the prototype magnet as it helps to heat flux. Each prototype consists of 7 winding grooves and 8 poles. It was continuously wound layer-by-layer and the transition from one groove to another is accomplished by a 180° turn around the turnaround pins. Each winding groove has 105 turns with dimensions of 7.69 mm wide and 8 mm deep (shown in Fig. 4). The base layer in a groove has 10 turns and subsequent one has 9 turns. This pattern alternates until 105 turns are completed. The former material is oxygen-free copper and the pole material is 1018 low carbon steel. The superconductor wire is round NbTi wire purchased from Supercon Inc. It is 0.7 mm in bare diameter and 0.754 mm with the formvar insulation. The period length is 30 mm and the pole width is 7.31 mm. Each magnet has 3.5 periods.

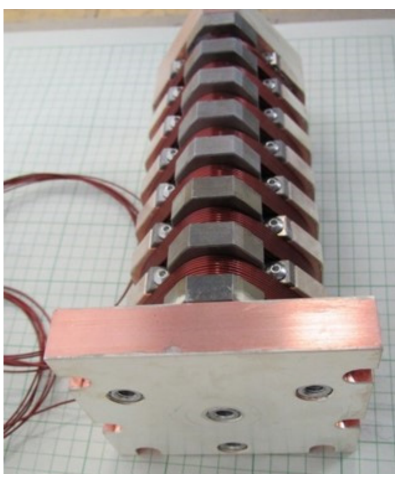

Figure 3: Prototype SCAPE magnet showing NbTi wires wound layer-by-layer. Ferromagnetic pole pieces and oxygen-free copper former are also visible.

Right after winding the prototype magnets, they are epoxy impregnated and cured using the manufacturer's suggested curing cycle.

Two coil pack winding to reduce AC losses

Several loss mechanisms contribute when a superconductor experiences a time varying magnetic fields. Two dominant ones are hysteresis and interfilament coupling losses. Interfilament coupling losses are mainly altered through matrix stabilizer resistance and the wire twist pitch. Increasing the stabilizer resistance and reducing the twist pitch reduce this loss component. The hysteresis loss component is proportional to the wire filament diameter. All these parameters are controlled by the wire manufacturers. It is also possible to reduce these losses by reducing the volume of the superconductor that experiences the field modulation. The 2D simulation shows that this could be achieved by separating the single-coil pack into two—DC and AC coil packs (Fig. 4). A cross-section sketch of a single-pack-wound coil is shown in Fig. 4 (bottom left) with 105 NbTi turns. In the bottom right sketch, the coil is separated into DC and AC windings; the DC pack is wound with a 0.7-mm standard wire (95 turns) and the AC coil pack is wound with a very fine-filamented AC optimized wire [4]. The AC wire diameter is 0.8 mm, totaling 0.843 mm with the formvar insulation. Due to the difference in wire diameters, this AC wire can be wound only eight turns as shown in Fig. 4 (bottom right, blue color). The filament diameter of the AC-optimized wire is about 3 µm, whereas the standard wire's filament diameter is about 60 µm. This AC-optimized wire also has a CuMn jacket around each filament and all around the wire. Both features—small filament diameter and CuMn—help reduce both hysteresis and interfilament coupling losses.

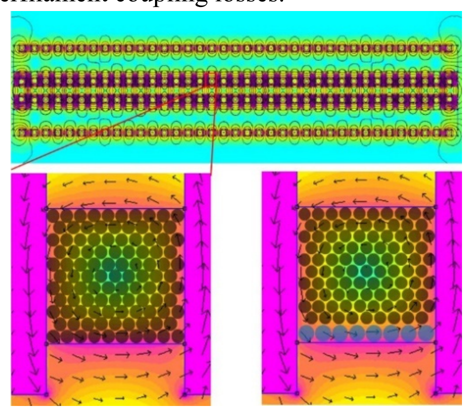

Figure 4: Top is the 2D field simulation model. Below are a single-coil pack (left) and a two-coil pack (right)—one for the AC field modulation (blue) and the other for the DC field.

RESULTS AND DISCUSSIONS

In the double undulator scheme, each module provides a fixed polarization state, and a small current bump in each of the modules is used to shift undulator energy by an amount comparable to the monochromator bandwidth. Then the monochromator becomes the polarization selector. The required current modulation is about 7 A at around the operating current of 500 A when the undulator is wound in a single-coil pack. However, the situation changes when a two-coil pack winding is pursued. In order to achieve a similar DC field as compared to the single-coil pack, the operating current for the DC coil must be increased to 600 A. In addition, the AC coil, which has only 8 turns, needs to alternate about 0-40 A in order to achieve the same level of modulation.

The 2D simulation model is shown in Fig. 4 with the field arrow and simulation results are provided in Fig. 5 at an arbitrarily chosen peak position. Dashed lines are the modulated field values, and the solid lines are the static undulator field values. Current in the magnet wound with a single-coil pack is modulated between 500 and 506A, whereas the DC coil current is kept stationary in the magnet wound with two coil packs. Then, the AC field superimposed on this DC field component is applied

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($I_{dc}+I_0 sin(wt)$). The amount of field modulation is about 10 mT in both cases.

Table 1: 3.5 Period Magnets Parameters and AC Losses

Coil type	AC [A]	DC [A]	Frequency [Hz]	Loss [mW]
Single	7	500	2	27
Single	7	500	1	11
Two coil	40	600	2	16
Two coil	40	600	1	7

Table 1 summarizes the AC losses generated by the field modulation, which is about 10 mT at different frequencies for both magnet types. The losses are calculated from the temperature rise at the cold head and compared with the integrated voltage and current over a cycle. They agree closely. The losses in a single-coil wound magnet is at least 40% higher at 2 Hz as compared with the magnet wound with two-coil packs. This difference is slightly reduced to about 35% at 1 Hz. Winding the magnets with two-coil packs substantially reduces the AC losses without sacrificing on-axis undulator field value. Per period loss amounts are 8 mW and 4.6 mW for single- and two-coil wound magnets, respectively at 2 Hz. These numbers can be extrapolated to an envisioned full-scale SCAPE undulator magnet length (about 1.8 m long). In total, each SCAPE undulator requires double 4-magnet geometry totaling to 8 magnets in one cryostat. The losses for single- and two-coil-pack wound magnets would be about 7.7 W and 4.4 W, respectively, for two 1.8-m-long SCAPE modules. The envisioned cryostat has 5 cryocoolers with room for potential extra ones. Each cryocooler has a cooling capacity of about 2 W, bringing the total cooling capacity to about 10 W. Both of these numbers are within the cooling capacity. However, two-coil packs have a higher excess cooling capacity. This allows modulation at higher frequencies. Measurements show that the losses are linearly dependent on the frequency with $Q = 0.0158f - 0.0049$ for a 3.5-period single coil pack magnet, where Q is the AC loss and f is the frequency. The maximum calculated frequency (within the 10 W cooling capacity) the magnets can be operated at is 2.6 Hz if the magnets are wound with a single coil pack. The losses are also linearly dependent on the frequency in the 3.5-period two-coil-pack-wound magnet with $Q = 0.0038f + 0.0055$. In this case, the losses can be tolerated up to a switching frequency of 8 Hz. In these calculation, heat loads from other sources are ignored. The switching frequency can be further increased by reducing the length of the magnet or using different types of superconductors such as Nb3Sn [5] or 2G-HTS [6].

Ideally, users want the flux to be on and off at about 10 Hz switching frequencies. This requires a trapezoidal field profile instead of sinusoidal. However, generating a trapezoidal field profile is not possible with a single winding as the field considerably lags and does not grow and decay fast enough to allow such a wave form. Such a field profile can be generated by two-coil packs since the AC coil pack has it is own power supply and it has relatively low inductance – only 8 turns per groove compared to 105 turns in full coil pack. With this winding scheme the user required field profile can be generated at the expense of higher losses. Increased loss can be offset by reducing the overall length of the SCAPE magnets.

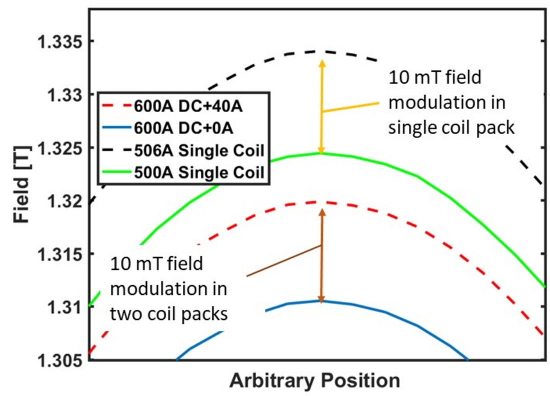

Figure 5: Field modulation for both magnets wound with singe and two coil packs. The modulation is about 10 mT.

CONCLUSION

AC losses in a fast switching SCAPE-type undulator has been investigated. It has been found that separating AC and DC coils by winding the magnet in two-coil packs inside the undulator winding groove reduces the AC losses significantly, thus allowing higher switching frequencies. In addition, the desired field profile can be tuned by adjusting the current profile in the two-coil-pack winding scheme as it has a lower number of turns and is powered by a dedicated AC power supply. Using a combination of the double undulator scheme with the two-coil-pack coil winding idea, it is feasible to build a field-modulated SCAPE module with manageable loss values.

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