COMPARISON OF STANDARD S-GLASS AND CERAMIC COATING AS INSULATION IN SHORT-PERIOD SUPERCONDUCTING UNDULATORS BASED ON Nb_3Sn*

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Abstract

This paper compares calculated on-axis fields for short-period superconducting undulators (SCUs) using Nb_3Sn superconductor with two different insulation thicknesses, 0.02 mm and 0.05 mm. When the insulated conductor diameter remained the same, the on-axis fields using the thinner insulation were higher by about 8 – 15% for a period range of 15 – 10 mm. When the conductor diameters with the thicker insulation were made larger than the conductors with the thinner insulation, the differences were reduced to be about 6 – 12%.

INTRODUCTION

Nb_3Sn superconductors (SCs) have much higher transition temperatures and upper critical fields than NbTi, and the conductor engineering current density reaches well over 1 kA/mm^2 at 12 T and 4.2 K. Many kinds of Nb_3Sn SC magnets have been successfully developed and are presently in use despite the fact that Nb_3Sn requires heat treatment at temperatures higher than 600 C for more than 40 hrs, which causes the wire to become brittle. Short-period, i.e., 15 to 18 mm, Nb_3Sn superconducting undulators (SCUs) are also under development at several laboratories [1–4]. Woven S-glass has been used for the wire insulation because it can survive the heat treatment. Unfortunately S-glass insulation is relatively thick compared to varnish-coated insulation for NbTi wire. This not only reduces the coil filling factor but also allows the individual conductors to shift their position more during coil winding, resulting in somewhat less field uniformity.

High-temperature superconducting YBCO tape has a transition temperature higher than 90 K, and its engineering critical current density at 4.2 K is comparable to that of NbTi. However, the tape-conductor transitions between different coil packs must be developed in order to avoid a solder joint at each transition.

Short-period SCUs must be designed with a high filling factor in the coil packs in order to achieve a high on-axis field. The high filling factor for an Nb_3Sn SCU may be further improved by using ceramic insulation because the thickness of the ceramic is expected to be less than one half the thickness of standard woven S-glass insulation [5]. This paper compares calculated on-axis fields for Nb_3Sn SCs with these two different insulation thicknesses for an undulator period range of 15 – 10 mm. The filling factor of the insulated conductors in the coil packs and insulation thicknesses remained unchanged for the period range.

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CONDUCTOR FILLING FACTORS

On-axis fields of Nb_3Sn SCUs with a period of 15 mm were calculated using three conductors and related coil parameters as listed in Table 1. Although the conductor diameter for a shorter period was reduced proportionally with period, the insulation thickness of the ceramic and S-glass remained 0.02 mm and 0.05 mm, respectively [5].

Table 1: Conductor and Coil Specifications

Bare conductor dia. (mm)	Insulation thickness (mm)	Insulated conductor dia.(mm)	Coil pack dimensions (mm × mm)
D1: 0.66	ceramic, 0.02	0.70	4.32 × 4.43
D2: 0.60	S-glass, 0.05	0.70	4.32 × 4.43
D3: 0.64	S-glass, 0.05	0.74	4.56 × 4.65

A cross-section of conductors in the coil pack is illustrated in Fig. 1. Alternating five and six turns for seven layers provides a total of 39 turns with stable conductor positions during and after the winding. The filling factor of the insulated conductors in the coil packs for D1 and D2 in Table 1 is about 0.784, which is very close to $\pi/4$. The filling factor of the bare conductors goes down further if the insulation thickness is increased.

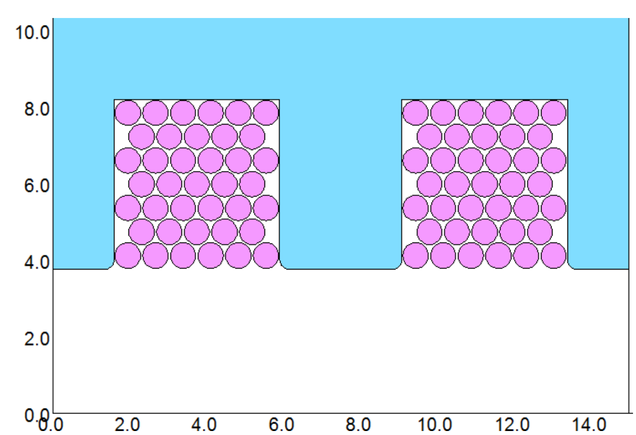

Figure 1: 39-turn conductor arrangements in coil packs for an undulator period of 15 mm. The units in the horizontal and vertical axes are in mm.

FIELD CALCULATIONS

On-axis and Conductor Maximum Fields

First, the current densities in the coil packs were set to a reference value, 1 kA/mm^2 for example, by imposing current values for the three conductors in Table 1. Then the on-axis fields for a pole gap of g = λ/2 and the maximum fields in the conductors were calculated as plotted in Fig. 2. Since the insulated conductors for D1 and D2 in Table 1 have the same coil pack dimensions, their on-axis fields are not distinguishable within calculation errors. On the other hand, the local maximum field B_m on the smaller D2 conductor is slightly higher than on the larger D1 because of its higher current density.

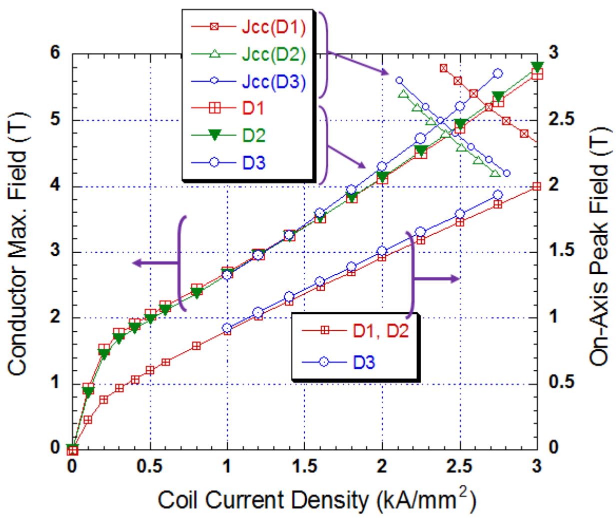

Figure 2: The on-axis peak fields B_0 (*right axis*) and the maximum fields B_m (*left axis*) were plotted for the three cases in Table 1. D1 and D2 in Table 1 have the same B_0, but the local maximum fields B_m are slightly different. The three corresponding critical current densities in the coil packs J_{CC} are scaled from critical currents at 12 T.

Critical Current Density of Nb_3Sn

Critical currents or current densities of Nb_3Sn SCs are generally specified at 12 T and 4.2 K. Since the magnetic fields in Nb_3Sn coils for typical short-period SCUs will not be much higher than 5 T, critical currents near these lower fields were estimated from the following scaling law for flux pinning [6–8]. Assuming that the conductors are free from strains, the upper critical field at 4.2 K, $B_{c2}(4.2)$, was calculated to be about 24.877 T:

$$B_{c2}(T) = B_{c2}(0)[1-t^2]\{1-0.31t^2(1-1.77\ln t)\}, \qquad (1)$$

where $B_{c2}(0)$ is the upper critical field at 0 K (about 28 T), and $t = T/T_{c0}$ is the reduced temperature with the transition temperature at zero field, T_{c0} about 18 K.

The field dependence of the critical current density $J_c(B)$ at 4.2 K with B_{c2} = 24.877 T is given by

$$J_c(B) = 2.592 \cdot J_c(12)\left(\frac{B_{c2}}{B}\right)^{1/2}\left(1-\frac{B}{B_{c2}}\right)^2, \qquad (2)$$

where $J_c(12)$ is the critical current density at 12 T and 4.2 K, and the numerical constant 2.592 was adjusted to get the correct value of J_c. At 5 T for example, the critical current is multiplied by a factor of about 3.691.

The 0.64-mm D3 conductor was assumed to have a critical current of 350 A at 12 T and 4.2 K, and the other two conductors in Table 1 were calculated according to the cross sectional ratios. The critical current densities for the three conductors were calculated as a function of magnetic field around 5 T using Eq. (2). Then, the critical current densities in the 39-turn coil packs J_{CC} were calculated. These are plotted in Fig. 2.

Figure 2 shows that, for conductor D1 with ceramic insulation, J_{CC} is about 2.7 kA/mm^2 at B_m of about 5.2 T. The corresponding on-axis peak field B_0 is about 1.85 T. Least-square-fit calculation results are listed in Table 2 for the three conductors at two undulator gaps, g = λ/2 and 8.0 mm, and coil critical current densities J_{CC} and 80% of J_{CC}. It shows that using thinner ceramic insulation increases the on-axis field by about 8% and 6%, respectively, compared with the two S-glass insulated conductors.

Table 2: Calculated Fields and Current Densities for Undulator Period λ = 15 mm

Bare cond. dia. **Insulation**	**D1: 0.66** **Ceramic**	**D2: 0.60** **S-glass**	**D3: 0.64** **S-glass**
B_m(T)	5.204	4.802	4.994
J_{CC}(kA/mm^2)	2.6887	2.4082	2.3791
$B_0(J_{CC})$, g = λ/2	1.8313	1.6797	1.7226
$B_0(J_{CC})$, g = 8.0	1.6493	1.5127	1.5513
$B_0(0.8J_{CC})$, g = λ/2	1.5405	1.4192	1.4498
$B_0(0.8J_{CC})$, g = 8.0	1.3874	1.2781	1.3056

$B_0(J_{CC})$ for the ceramic is higher by about 8% and 6% compared to the other two for the S-glass.

Tables 3, 4, and 5 list similar calculations for undulator periods of 14, 12, and 10 mm, respectively. Insulated conductor diameters and coil-pack dimensions listed in Table 1 for λ = 15 mm were reduced in proportion to the period ratio. But, the insulation thicknesses remained unchanged so that the bare conductor diameters were reduced more than the period ratios for the shorter periods, as indicated in Tables 3, 4, and 5. Though the conductor arrangement in Fig. 1 remains unchanged, the SCU scaling law is only partially applicable [9].

As the periods were reduced from 15 mm to 10 mm, the on-axis fields $B_0(J_{CC})$ with the ceramic insulation were higher by approximately 8% to 15.5% compared with those with S-glass insulated D2 in Table 1. When compared with the larger conductor size D3, the differences were from about 6% to 12%. This suggests that SCU calculation parameters may be improved to enhance the on-axis field.

Table 3: Calculated Fields and Current Densities for Undulator Period λ = 14 mm

Bare cond. dia. Insulation	0.613 mm Ceramic	0.553 mm S-glass	0.591 mm S-glass
B_m(T)	5.009	4.55	4.731
J_{CC}(kA/mm^2)	2.748	2.4188	2.4015
$B_0(J_{CC})$, $g = \lambda/2$	1.7644	1.5982	1.6436
$B_0(J_{CC})$, $g = 8.0$	1.4097	1.277	1.3148
$B_0(0.8J_{CC})$, $g = \lambda/2$	1.487	1.354	1.3866
$B_0(0.8J_{CC})$, $g = 8.0$	1.1881	1.0819	1.1079

$B_0(J_{CC})$ for the ceramic is higher by about 9.5% and 7% compared to the other two for the S-glass.

Table 4: Calculated Fields and Current Densities for Undulator Period λ = 12 mm

Bare cond. dia. Insulation	0.52 mm Ceramic	0.46 mm S-glass	0.492 mm S-glass
B_m(T)	4.5801	4.009	4.159
J_{CC}(kA/mm^2)	2.872	2.4181	2.4275
$B_0(J_{CC})$, $g = \lambda/2$	1.6199	1.4235	1.472
$B_0(J_{CC})$, $g = 8.0$	0.9596	0.8432	0.872
$B_0(0.8J_{CC})$, $g = \lambda/2$	1.3713	1.2142	1.2493
$B_0(0.8J_{CC})$, $g = 8.0$	0.8124	0.7193	0.7401

$B_0(J_{CC})$ for the ceramic is higher by about 12% and 9% compared to the other two for the S-glass.

Table 5: Calculated Fields and Current Densities for Undulator Period λ = 10 mm

Bare cond. dia. Insulation	0.427 mm Ceramic	0.368 mm S-glass	0.3933mm S-glass
B_m(T)	4.103	3.413	3.513
J_{CC}(kA/mm^2)	2.9975	2.3671	2.4129
$B_0(J_{CC})$, $g = \lambda/2$	1.458	1.2307	1.2808
$B_0(J_{CC})$, $g = 8.0$	0.5681	0.4796	0.4991
$B_0(0.8J_{CC})$, $g = \lambda/2$	1.2419	1.060	1.0964
$B_0(0.8J_{CC})$, $g = 8.0$	0.4839	0.4131	0.4272

$B_0(J_{CC})$ for the ceramic is higher by about 15.5% and 12% compared to the other two for the S-glass.

CONCLUSION

On-axis fields for short-period Nb_3Sn SCUs were compared with two different conductor insulations. Using ceramic insulation will increase the fields by about 6% to 12% for a period range from 15 mm to 10 mm.

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