QUENCH PROPERTIES OF TWO PROTOTYPE SUPERCONDUCTING UNDULATORS FOR THE ADVANCED PHOTON SOURCE*

C. L. Doose#, M. Kasa, S. H. Kim, ANL, Argonne, IL 60439, U.S.A.

Abstract

The quench properties of two 42-pole prototype superconducting undulators (SCUs) (one having a steel core the other with an aluminium core) have been tested. Since the SCUs have relatively low stored energy, the quench protection has relied on an over-voltage protection feature of the power supply, and the inherent quench back from the core. Concerns about conductor damage (during a quench) due to heating and high induced voltages were raised. The maximum conductor temperatures and voltages have been deduced from voltage and current measurements during a quench. The deduced maximum hot-spot temperature of the conductor was less than 150 K and the maximum voltage across each SCU coil was less than 300 V.

INTRODUCTION

Short-period superconducting undulators (SCUs) are presently being developed for the Advanced Photon Source. Two prototype SCUs have been built, one all steel and the other with an aluminum (Al) core. The Al core provides better thermal conductivity while the steel core gives higher on-axis field strength. Questions about the differences in quench characteristics were raised due to the different core materials. The properties of the SCUs have been studied to determine the inductance as a function of current, the current decay time constant, and voltages across the SCU coils during a quench.

Estimates of the induced and IR voltages were based on the measured voltages across the two SC coils during a quench and the current decay rate.

Using the measured current decay data, calculations of the hot-spot temperatures of the (SC) coils were done. A conservative formula was used assuming only a shunt resistor across the SC coils without considering the quench back from the cores [2].

The primary goals of these tests were to determine:

1. The maximum hot-spot temperature of the quenched conductor T_m.
2. The maximum IR and induced voltages across the coils during a quench.

SCU EXPERIMENTAL TEST SETUP

The prototype SCU assemblies consisted of two 16-mm-period 42-pole cores with 41 continuously wound race track SC coil packs per core. The 41 individual coil packs were wound in alternating directions in order to produce the on-axis undulator field. For identification, the complete sets of 41 coils on each core assembly were designated "*A*" and "*B*". The gap between the cores was 9.5 mm. Figure 1 shows the cold mass with the two 42-pole Al-core assemblies. For these tests the SCUs were immersed in LHe in a vertical cryostat. Voltage taps were connected across each coil *A* and *B*, and the current was measured using a Danfysik 860 current transducer. Figure 2 is a simple schematic of the two coils, power supply, current transducer, and voltage taps.

Heaters were installed on each core to provide the ability to quench either coil. During a quench event the current and voltage waveforms of each coil were recorded using a National Instruments NI-4462 24-bit digital signal analyzer (DSA) PXI module. The sampling rate of the DSA was typically set to 100 kS/s.

The power supply (PS) used for these tests was an Agilent model 6680A, with maximum 5-V and 895-A output. An over-voltage protect (OVP) feature of the PS was used and the voltage limit was typically set to 2 volts. During a quench when the PS terminal voltage reached 2 volts, the PS shut down and effectively shunted the SCU coils with a resistor and diodes. The power supply absorbed a portion of the stored SC coil energy and limited the back EMF across the coils to ±2 volts.

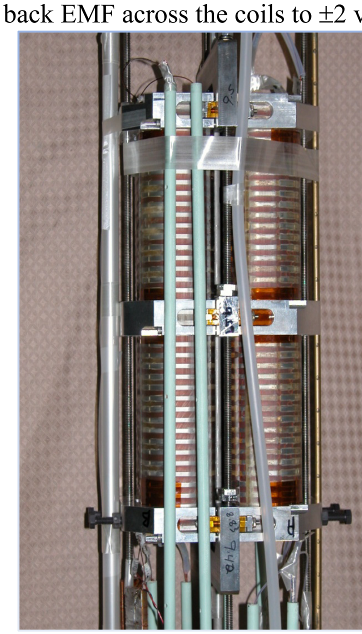

Figure 1: Cold mass assembly consisting of two identical 42-pole cores, *A* and *B*, with 41 coil packs of 39 turns each.

The higher the OVP setting, the longer time it takes for the PS to shut down, which will increase the maximum conductor temperature during a quench. Typically the OVP was set to 2 V, which was less than 0.5 V above the nominal PS terminal voltage at 700 A.

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#doose@aps.anl.gov

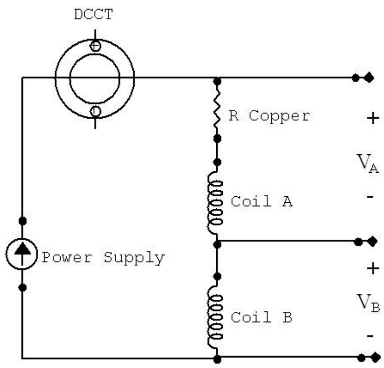

Figure 2: Simplified schematic depicting voltage taps, current transducer (DCCT), power supply, coils *A* and *B*, and the Cu resistance during a quench.

MEASUREMENTS

Inductance and Stored Energy

The inductance of each coil *A* and *B* was determined by ramping the current at 5 A/s and recording the induced voltages and the instantaneous current. The inductance can then be calculated by dividing the induced voltage by the ramp rate. Figure 3 is a plot of the inductance of one core as a function of current.

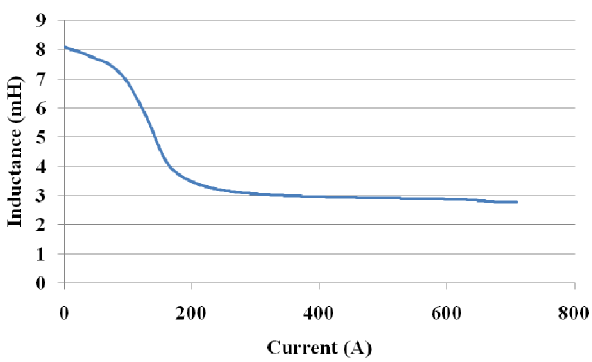

Figure 3: Measured inductance of the Al core coil *A* as a function of current. Each coil had effectively the same inductance response so the total inductance of both coils was twice the coil *A* value. It can be seen that the steel poles were fully saturated near 200 A.

The initial total stored energy E_0 of both cores can be determined by:

$$E_0 = \frac{1}{2} L I_0^{\,2}, \tag{1}$$

where L is the total inductance of coils *A* and *B* and I_0 is the initial coil current. L was 5.6 mH for the Al core SCU, so the stored energy at 785 A was 1725 J.

Current and Voltage Waveforms

Figure 4 shows the measured current and voltages during a quench at 785 A for the Al core SCU. Positive voltage across coil *A* was an indication that the positive $I{\cdot}R_{Cu}$ drop was larger than the absolute value of the negative induced voltage $L_A di/dt$. This indicates that coil *A* quenched before coil *B* since V_A was positive. The initial time constant of the current decay was 9.6 ms.

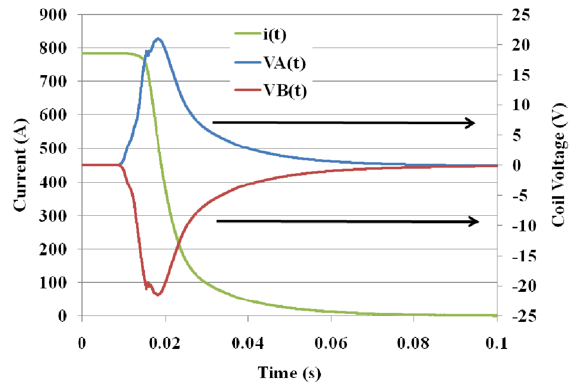

Figure 4: Current and voltage waveforms during a quench at 785 A. Coil *A* quenched first and thus is the positive blue curve. The voltages were almost mirror images of each other, due to the fact that the absolute value of the PS terminal voltage was no greater than 2 V.

The voltages across coil *A* and *B* can be described by Eqs. (1) and (2):

$$V_A(t) = i(t) R_A(t) + \frac{di(t)}{dt} L_A(t), \tag{2}$$

$$V_B(t) = i(t) R_B(t) + \frac{di(t)}{dt} L_B(t), \tag{3}$$

where L_A, L_B, and R_A, R_B are the inductances and resistances of coils *A* and *B*, respectively. In this case L_A and L_B have the same inductance characteristics, so the difference between R_A and R_B can be calculated by Eq. (4):

$$R_A(t) - R_B(t) = \frac{V_A(t) - V_B(t)}{i(t)}. \tag{4}$$

The difference in power and energy absorbed by the increased resistance in coil *A*, as shown in Fig. 5, were calculated using Eqs. (5) and (6):

$$\Delta P(t) = (R_A(t) - R_B(t)) i^2(t), \tag{5}$$

$$\Delta E = \int_{t=0}^{0.06} \Delta P(t) dt. \tag{6}$$

It can be seen in Fig. 5 that coil *A* absorbed approximately 220 J more energy than coil *B* since it was the first coil to quench, but the absolute value of energy absorbed by each coil is not known at this time.

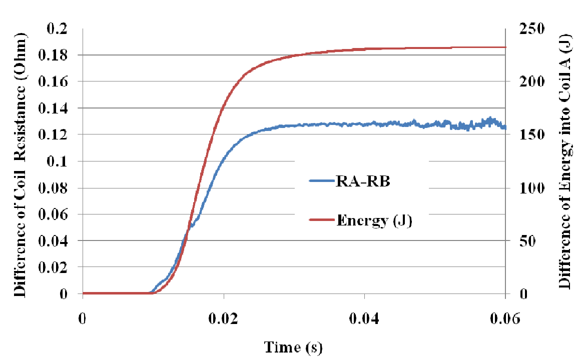

Figure 5: Plot of the difference in resistance of coils *A* and *B*, and the difference in energy transferred to coil *A* calculated using Eqs. (4), (5), and (6).

CALCULATIONS

Calculated Induced Voltages

Using the measured current decay and the inductance as a function of current, the induced voltages were numerically calculated for both the Al and steel core SCUs. Ignoring the effects of quench back due to the cores, the induced voltage across coil *A* can be easily calculated by Eq. (7):

$$V_A(t,i) = \frac{di(t)}{dt} L_A(i). \qquad (7)$$

From Fig. 6 it can be seen that the absolute value of the maximum induced voltage across either coil is less than 260 V. Using Eqs. (2) and (3), the calculated IR voltages are less than 280 V for either coil. The 25-µm-thick Formvar insulation had a breakdown voltage of 2 kV, well above the maximum IR or induced voltages.

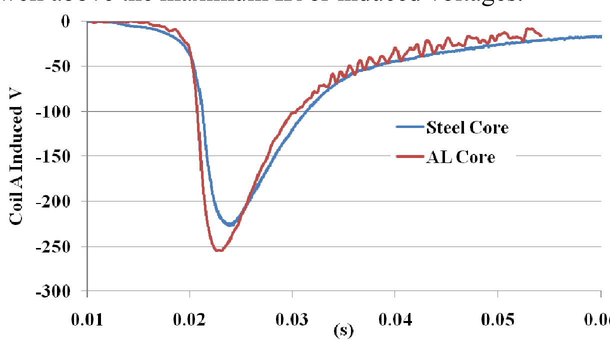

Figure 6: Calculated induced voltages of coil *A* for both the steel and Al core SCUs based on the measured di/dt and the inductance as a function of current.

Hot-Spot Temperatures

The maximum hot-spot temperatures T_m for the Al and steel core SCU coils using an external shunt resistance were calculated using Eq. (10) [2]:

$$F(T_m) = \frac{r-1}{r} j_0^2 \left(\frac{\tau_d}{2} + t_{so} \right) = \int_{T_0}^{T_M} \frac{C(T)}{\rho(T)} dT. \qquad (10)$$

$F(T_m)$ is a function related to the specific heat per unit volume *C* and resistivity ρ of the conductor. T_m is the maximum coil hot-spot temperature, *r* is the copper-to-SC ratio (0.9 for the 0.7-mm Supercon conductor), j_0 is the current density prior to the quench, τ_d is the initial current decay time constant, and t_{so} is the time from the onset of the quench to when the PS shuts off.

The values of *$F(T_m)$* were calculated using the parameters listed in Table 1 and the *$F(T_m)$* curves for Cu with a RRR of 100 [3]. The calculated T_m values were 145 K and 95 K for the steel and Al cores, respectively. Coil hot-spot temperatures below 300 K are considered safe [3]. Although the E_0 was higher for the Al case in Table 1, it appears the T_m was less than the steel case because of the shorter t_{so}.

Table 1: Parameters used for Calculations

Parameter	Steel Core	Al Core
*I_0	685 A	785 A
#J_0	1780 A/mm^2	2040 A/mm^2
*L (both coils)	6.8 mH	5.6 mH
*E_0	1595 J	1725 J
r (Cu/SC ratio)	0.9	0.9
RRR	100	100
*τ_d	5.80 ms	9.60 ms
*t_{so}	12.0 ms	3.75 ms
#$F(T_m)$	9.96×10^{16}A^2 m^{-4}	7.51×10^{16}A^2 m^{-4}
#T_m	145 K	95 K
#*Ldi/dt max (per coil)*	-220 V	-250 V

* denotes measured values

\# denotes calculated results

CONCLUSION

The two prototype SCUs have similar quench characteristics even though one core is Al and the other steel. It appears since most of the flux is concentrated in the steel poles, the inductances are similar. The low inductance and stored energy of the 42-pole SCUs keep the calculated maximum hot-spot temperature less than 150 K and the coil voltages below 300 V for both cores. These values appear to be safe to prevent conductor damage and voltage breakdown of the conductor insulation. These results were calculated conservatively without considering the effects of quench back, which should lower both the maximum conductor temperature and voltages considerably. Detailed studies of the quench back for the 42-pole SCUs have not been done at this time. Further study will be done to quantify the amount of energy absorbed by the coil and cores of future longer SCUs. The t_{so} and thus the T_m can be minimized by setting the OVP just above the nominal PS voltage so the PS shuts down as quickly as possible after a quench.

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