Thermal Model of a Quench in Superconducting Undulators

Y Shiroyanagi, Q Hasse, Y Ivanyushenkov, and M Kasa
Advanced Photon Source, Argonne National Laboratory, Argonne IL, 60439 USA

yshiroyanagi@aps.anl.gov

Abstract. Currently there are two 1.1 m long planar superconducting undulators (SCUs) in operation in the Advanced Photon Source storage ring. Their NbTi magnets are cooled with liquid Helium (LHe) penetrating through a channel in the magnet coil formers. In this scheme, the latent heat of LHe provides an effective energy buffer that allows the magnet to return to normal operation within minutes. An FEA-based dynamic thermal model of the SCU is being developed to analyze the behavior of the SCU cryogenic systems during a quench. In this paper, preliminary results of these FEA-based calculations and a comparison with the current operation of SCUs are presented.

1. Motivation
There are currently two 1.1 m long planar superconducting undulators in operation in the storage ring [1]. A steady state (equilibrium) thermal model for a planar SCU was developed in 2015 [2]. The model has been benchmarked with the current SCU cryogenic system and used for a new HSCU [3] cryostat design. In the current planar SCU system, the magnet is cooled by the LHe in the channel and it can absorb the heat during a quench. A simple dynamic thermal model of this system is useful for future SCU cryostat development. A quench and its recovery were modeled with a simplified boundary condition. The preliminary results of the FEA model and a comparison with the operational data are discussed in this paper.

2. A planar SCU magnetic structure and an observed quench
The planar SCU magnetic structure is shown in figure 1. The top left picture in figure 1 shows the 1018 steel pole side of the magnet and the picture right shows the backside of magnet with the wire turns around. G-10 insulations are between the windings. Each magnet consists of copper racetrack coils periodically nested in the 1018 steel core with 18 mm period. 53 turns of a 0.6 mm diameter NbTi conductor was wound at the 4.25 mm deep ×5.25 mm wide groove. Two 1.1 m fully epoxy impregnated magnets are paired and the beam chamber is placed between pole surfaces as shown in the picture at the bottom. Temperature sensors are located at copper block at the pole extensions. A Helium channel is located at the center of the core.
An observed quench event at the operational current of 450 A is shown in figures 2 and 3. During a quench, the current decays with a range of time, 0.01 - 0.02 s, as shown in figure 2. Figure 3 shows the temperature of the magnet during and after the quench. The maximum temperature of the magnet (upstream feet section) is ~16 K. A temperature recovery time to the operational state (~ 4.2 K) takes a few minutes, which is much slower than actual quench and a current decay. A Helium pressure recovery takes a few hours (not shown). Ideally, the FEA model of a quench will be a multi-physics simulation that involves both electromagnetic and thermal models. Cooling by Helium needs to be included for the temperature recovery calculation [4]. However, the time range of temperature recovery is $10^5$ times larger than a quench. Therefore, it is possible to deal with the electromagnetic and thermal model separately or as a weakly coupled model. Most of the past FEA model was built with such an approach [5], [6], [7], [8]. This FEA model also deals with the thermal model separately using the simplest boundary conditions. Therefore, the primary heat source is Joule heat released during the quench.
Figure 2. Quench of the planar SCU at 450 A.

Figure 3. Measured temperature of core (magnet) in the planar SCU.
Figure 4. Temperature disturbance is imposed at the small section of the wire at $t = 0$ s.

3. FEA model and calculation
The FEA model geometry does not include an individual conductor nor individual insulation of the wire. It also does not include the detailed geometry of the turnaround section of the wire. The conductor is modeled as a bus bar with a cross-section of 4.25 mm deep $\times$ 5.25 mm wide, and a temperature disturbance is imposed at a small portion of the conductor. Although NbTi is used as a conductor for an actual SCU, copper property is used for this model. Since thermal conductivity of copper is much higher than NbTi, this is a good enough approximation. The solver used for this thermal model is ANSYS 17.1 transient thermal and command snippet. The analysis consists of two steps. The initial temperature is set to 4.2 K for the entire geometry. $T_c = 8$ K is set to mimic the critical temperature of NbTi wire. Then a quench is imposed by raising $T = 9$ K at the short section of the wire as shown in figure 4. When the temperature of the conductor is above $T_c$, Joule heat is applied in that section of conductor within 0.01 s. This determination is based on the analysis of the measurement in figure 2. In the first step, current is set at 450 A for 0.01 s, then abruptly drop to zero. The second step involves only a temperature recovery, so there is no heat generation. Joule heat generated at the first step continue to dissipate through the magnet.

These three cases are discussed below. It is reasonable to model one racetrack as the smallest unit first. CASE 1 simulates one racetrack geometry and the Helium channel is at 4.2 K. CASE1 results are shown in figure 5 and 6. CASE 2 simulates a full planar SCU geometry (a pair of 1.1 m core) and the Helium channel is at 4.2 K. CASE 2 results are shown in figure 8 and 9. CASE 3 simulates the same planar SCU geometry and there is no Helium in the channel. The Helium channel temperature is therefore free. CASE 3 results are shown in figure 10 and 11.

3.1. One racetrack with LHe (CASE 1)
The initial temperature of the coil is set to 4.2 K. The temperature disturbance imposed along the wire denoted as x direction is shown in figure 4. The same temperature disturbance at 9 K is shown at the bottom of figure 5. The Helium channel that is shown as a center hole is set to 4.2 K. The constant current 450 A is applied for 0.01 s on the conductor. Figures 5 and 6 show the temperature distribution of the cross-sectional view of the coil. The first contour is set to 8 K. Longitudinal quench velocity is calculated from the distance that the quench front (8 K surface) travelled divided by time: in this particular case $\sim 13$ m/s, as seen in figure 6.
Figure 5. I = 450 A, time = 0 s, temperature disturbance is at the bottom center part of a conductor.

Figure 6. I = 450 A, at time = 0.01 s. 8 K front moves to the half of the conductor. Longitudinal velocity based on the distance and 0.01 s is v = 0.13 m/0.01 s = 13 m/s.

Figure 7. Hot spot temperature in the first 5 ms.

Figure 7 shows the hot spot temperature where a quench is initiated for the one racetrack geometry. The initial 9 K rose to ~ 60 K within 1 ms. The hot spot temperature does not change when LHe channel temperature is not fixed, which corresponds to no LHe. However, this temperature is sensitive to RRR of copper wire and current density.

3.2. A pair of 1.1 m magnets with LHe (CASE 2)
A planer SCU geometry is used. The initial temperature of the entire geometry is set to 4.2 K. The constant current 450 A is applied for 0.01 s on the conductor in the first step. LHe channel temperature is fixed at 4.2 K. A hot spot temperature is ~50 K within 0.01 s after the temperature disturbance is initiated. This temperature is very close to the one racetrack case, as shown in figure 8. Figure 9 shows 60 s after the quench. Since LHe channel is at 4.2 K, a quench is recovering fast enough, and the majority of the coil is at ~ 4.2 K. The pole at its closest to the hot spot is at ~ 9 K. For convenience, the first
contour is set to 8 K. When the quench is in progress, this represents a quench front. Obviously, this is just a temperature boundary after the current become zero.

**Figure 8.** 1.1m core, 4.2K in the channel I = 450 A for 0.01s, 0.01 s after quench.

3.3. *A pair of 1.1m magnets without LHe (CASE 3)*

A planar SCU geometry is used. The constant current 450 A is applied for 0.01 s on the conductor in the first step. The Helium channel temperature is at free, which represents no Helium in the channel. Figure 10 shows 0.01 s after the quench is initiated, a longitudinal quench velocity is at v = ~10 - 20 m/s, which is very similar to the one race track case. Figure 11 shows temperatures at 60 s after the quench is initiated. Since there is no Helium, temperature has not recovered and still rising. As time goes on, maximum temperature is ~120 K and feet becomes warmer than ~30 K at the closest location at the quench. This is a lot warmer than the measured temperature in figure 2.

**Figure 10.** 1.1m core, no LHe in the channel I = 450 A for 0.01 s, time = 0.01 s, Maximum temperature is 53 K.

**Figure 11.** A quench recovery of 1.1 m core without Helium. I = 450A for 0.01 s. 60 s after a quench. Since no cooling is provided, temperature keeps rising.
4. Discussion

Figure 12. The function $U(\theta)$ based on copper wire with RRR = 150 and 0.6 mm diameter.

Using the adiabatic model [8], a quench velocity is calculated by

$$v = \frac{j_0 \cdot L_0 \frac{\partial \theta}{\partial \theta}}{\gamma C \frac{\partial \theta}{\partial \theta}}$$

(1)

$j_0$: current density of the copper wire; $\gamma$: density; $C$: average heat capacity of the winding; $\theta_0$, $\theta_0$ temperature across the quench front; $L_0 = 2.45 \times 10^{-8}$ WΩK$^{-2}$: Lorentz number. By taking $\gamma C = 3.83 \times 10^4$ Jm$^{-1}$K$^{-1}$, $\theta_0 = 9$ K, $\theta_0 = 7$ K, $v = \approx$ 15 m/s along the wire. Temperature rise in the adiabatic model are given by

$$\int_{\theta_0}^{\theta_m} \frac{\gamma C(\theta)}{\rho(\theta)} d\theta = U(\theta_m) = j_0^2 Td = \int_{0}^{t} f(T)^2 dT$$

(2)

Figure 12 shows function $U(\theta)$ based on copper property. By analyzing the measured current decay data in figure 2, a function $\int_{0}^{t} f(T)^2 dT = 3.68 \times 10^{16} A^2 s m^{-4}$ = $U(\theta_m)$, so the hot spot temperature based on RRR = 150 copper is 47.4 K. The time constant $Td = 0.015$ s. On the other hand, ANSYS calculated propagation velocity is $\approx$ 10 - 20 m/s and the hot spot temperature in the one racetrack is $\approx$ 50 - 60 K. Now when it includes the full SCU magnets, the velocity along the conductor length is still $\approx$ 10 - 20 m/s. Since each racetrack is isolated by steel, quench propagation in the conductor is limited by the poor thermal conductivity of steel. Before increasing the temperature of the adjacent segment of the coil, temperature at the steel increases. Quench finishes within first 0.01 s. Three cases show very similar temperature distribution within the first 0.01 s. The rest is a recovery to the operational temperature. Apparently keeping the Helium channel at 4.2 K is an over simplification. The feet section of the magnet remain cold after 60 s after the quench. Maximum temperature at the sensor location is $\approx$ 9 K, as shown in figure 9. Without Helium, the core becomes much warmer. The maximum temperature at the sensor location is $\approx$ 30 K, as shown in figure 11. Helium cooling plays the role of an energy buffer during the temperature recovery after the quench. Therefore, the real temperature
distribution will be between “4.2 K” and “free” boundary conditions. To get more physical picture, instead of using fixed temperature, Helium boiling and cryocooler load map needs to be incorporated. Due to a decreasing field, eddy current increases in the steel core. Induced voltage at the steel pole can be estimated from an area of the steel pole 0.00019mm$^2$ and the rate 1T/0.01s to be 0.019V. By assuming 1018 steel resistivity of $1.50 \times 10^{-8}$ Ωm at 4.2K, estimated eddy current is $\sim$50 A, which produce $\sim$kJ at each pole. These are still negligible compared with total stored energy $\sim$3 kJ (Inductance of each core is 0.016 H, the maximum field of is $\sim$1 T at 450 A [9]). Further calculation include a quench back and a protection circuit needs a separate non-ANSYS model [10], [11].

5. Discussion
An ANSYS based dynamic thermal model successfully calculates temperatures with full 1.1 m magnet geometry with the simplest boundary condition. Next step will be electromagnetic model including quench back effect, which would be a separate model.

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References
[1] Ivanyushenkov, Y., et. al. “Development and operating experience of a short-period superconducting undulator at the Advanced Photon Source,” Phys. Rev. Accel. Beams 19, 110702 (2016).
[2] Shiroyanagi, Y., et. al. “Thermal analysis of superconducting undulator cryomodules,” IOP Conf. Series: Materials Science and Engineering 101 (2015) 01214.
[3] Fuerst, J., et. al, “A second-generation superconducting undulator cryostat for the APS,” C4OrB, This conference.
[4] Paudel D., Quench Simulation of Superconducting Magnets with Commercial Multi-Physics Software, Thesis, chapter 4 pp 32-52. 2015
[5] Murakami T., et. al. Two-dimensional quench simulation of composite CuNb/Nb3Sn conductors, Cryogenics 40 (2000) 393-401.
[6] Wake, M., et. al. “Complete Quench Simulation of Large Solenoid Magnet,” IEEE Trans. Appl.Supercon., 22, No.3, June 2012, 4704504.
[7] Yamada, R., et. al, “2-D/3-D Quench Simulation Using ANSYS for Epoxy Impregnated Nb$_3$Sn High Field Magnets,” IEEE Trans.Appl.Supercon., 13, No.2, June 2003.
[8] Wilson, M., Superconducting Magnet, chapter 9 pp 200–217. 1982.
[9] Ivanyushenkov, Y., et. al. “Development and operating experience of a 1.1-m-long superconducting undulator at the Advanced Photon Source,” Phys. Rev. Accel. Beams 20 100701 (2017).
[10] C.L.Doose et al, “Quench Properties of Two Prototype Superconducting Undulators for the Advanced Photon Source,” Proceedings of PAC (2011) 1121.
[11] Green, M.,”The Role of Quench Back in Quench Protection of A Superconducting Solenid,” Cryogenics 24 (1984) 657