THERMAL MODEL OF A QUENCH IN SUPERCONDUCTING UNDULATORS

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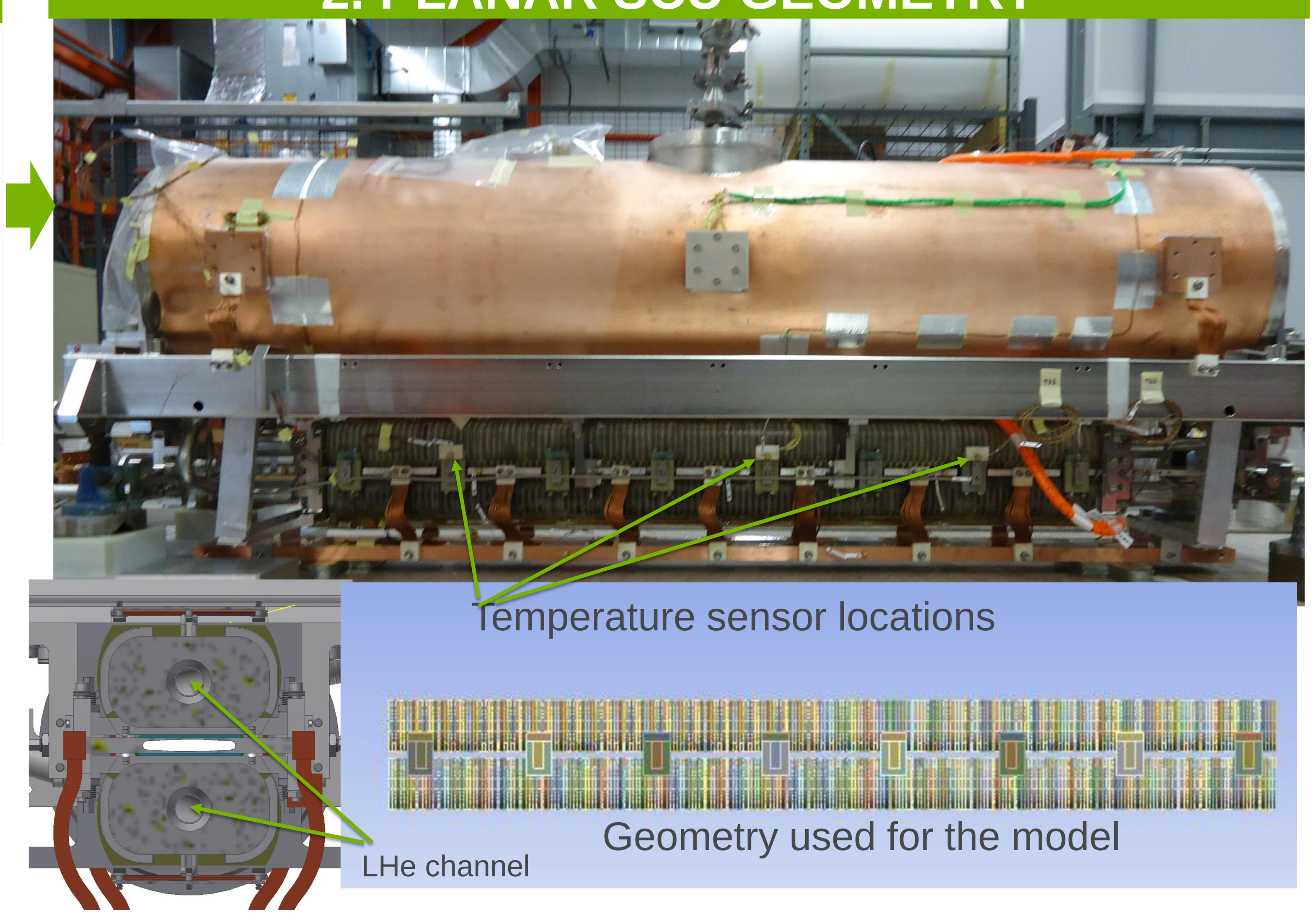
ABSTRACT

There are currently two 1.1 m long planar superconducting undulators (SCUs) in operation in the Advanced Photon Source storage ring. Their NbTi magnets are cooled with 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. BACKGROUND

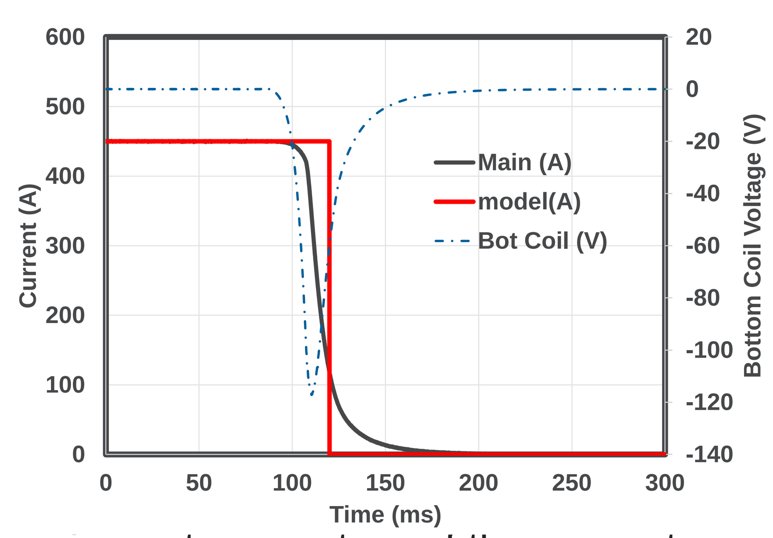
A steady state (equilibrium) thermal model for a planar SCU was previously developed [2]. The model has been benchmarked with the current SCU cryogenic system and used for a new HSCU cryostat design [3]. In the current planar SCU system, the magnet is cooled by the LHe in the channel, and it can absorb the heat during a quench. A simple dynamic thermal model of this system is useful for future SCU cryostat development.

2. PLANAR SCU GEOMETRY

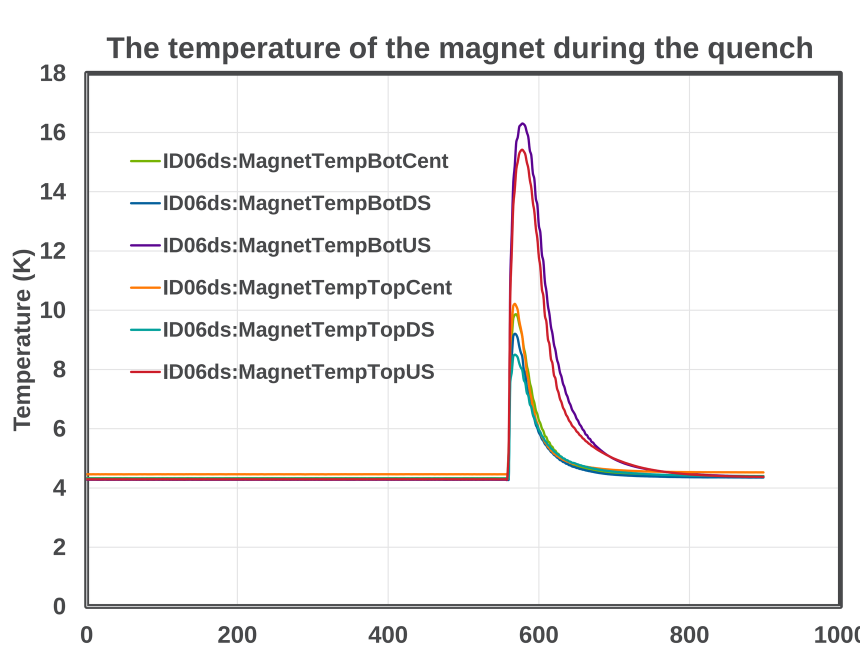


3. OBSERVED QUENCH

- During a quench the current decays with a range of time, 0.01 - 0.02 s.



- The maximum temperature of the magnet (upstream feet section) is ~16 K. A temperature recovery time to the operational state (~4.2K) takes a few minutes, which is much slower than actual quench and a current decay.



- A Helium pressure recovery take a few hours (not shown).
- Based on the observation, the FEA model is built to calculate temperature during the quench and recovery after the quench

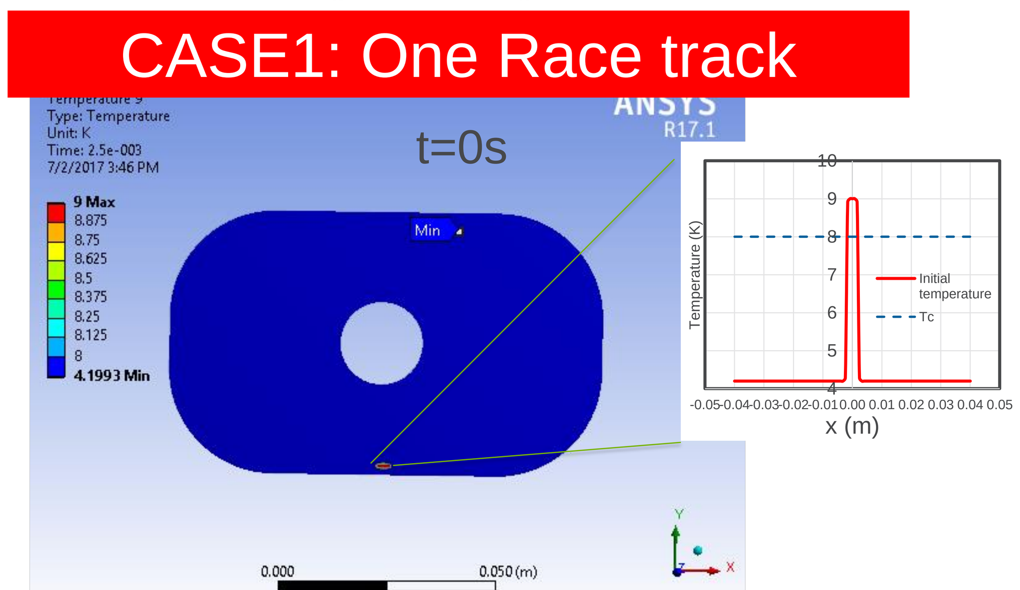
4. FEA MODEL

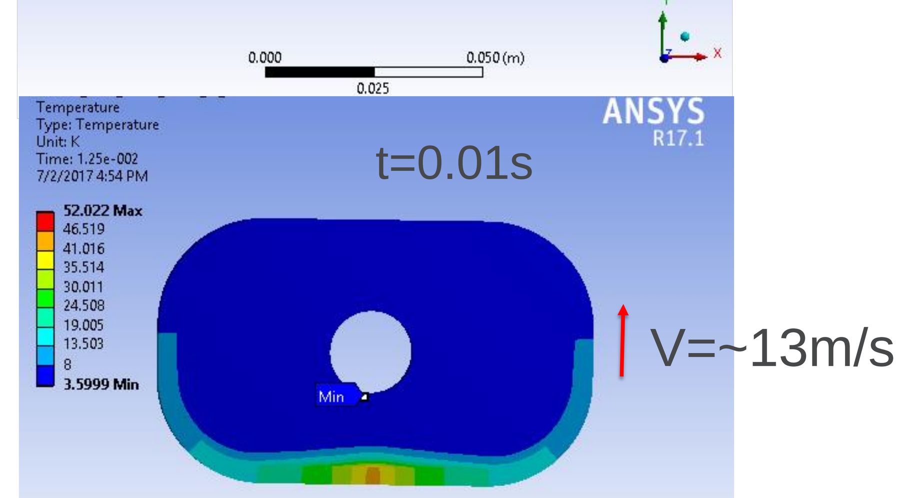
The time range of temperature recovery is 10^5 times larger than a quench. It is therefore possible to deal with the electromagnetic and thermal models separately. Most of the past FEA model was built using such an approach. This FEA model also deals with the thermal model separately using the simplest boundary conditions. So the primary heat source is Joule heat released during the quench.

BOUNDARY CONDITION

- 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.
- The 1st step: current is set at 450 A for 0.01s, then abruptly dropped to zero. Joule heat is applied in that section of conductor where the temperature is above Tc.
- The 2nd step: I=0, so there is no heat generation during this period. Joule heat generated at the 1st step continues to dissipate through the magnet.

CASE1: One Race track

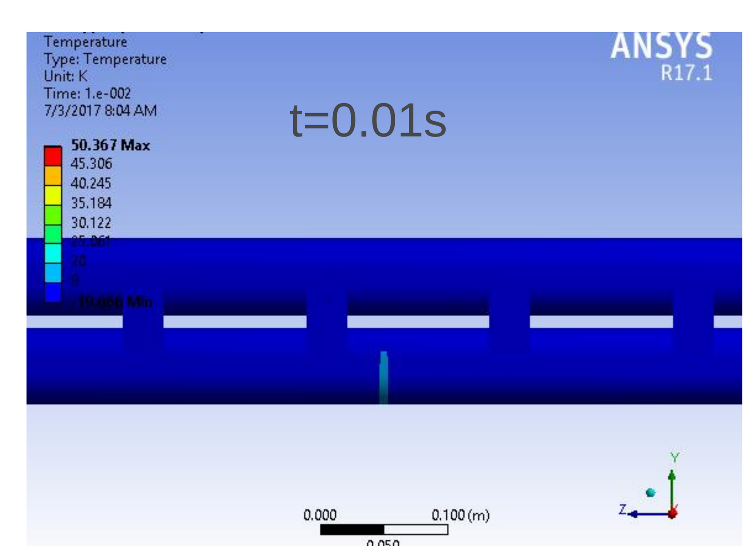


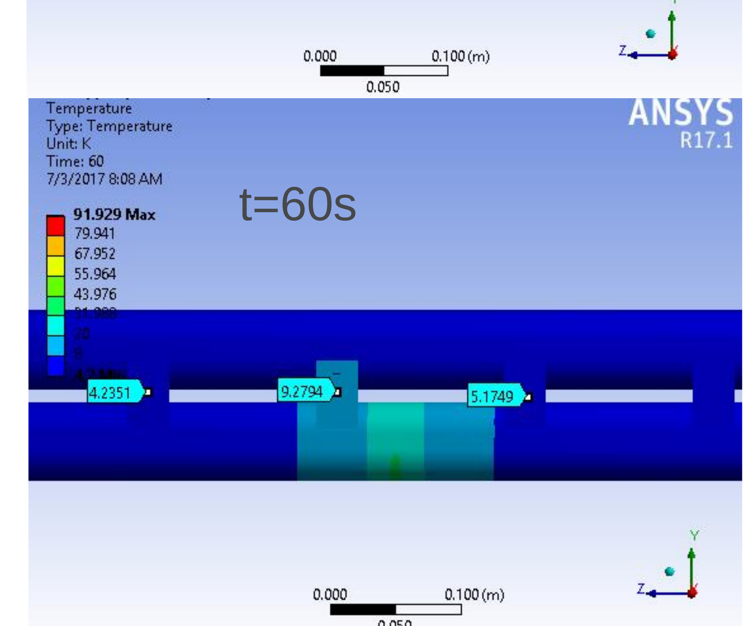


4.FEA MODEL

CASE2: A planar SCU, 4.2K

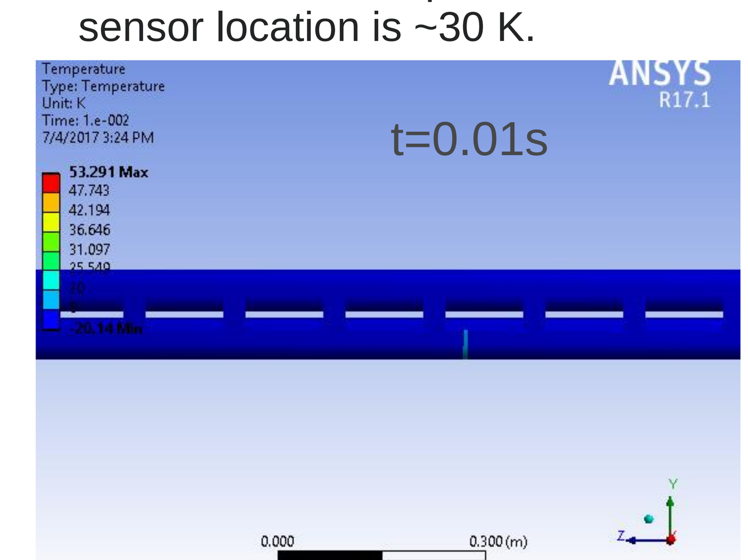
- LHe channel is at 4.2K.
- Apparently keeping the He channel at 4.2 K is an over simplification. The feet section of the magnet remain cold after 60 s after the quench. Maximum temperature at the sensor location is ~9 K.

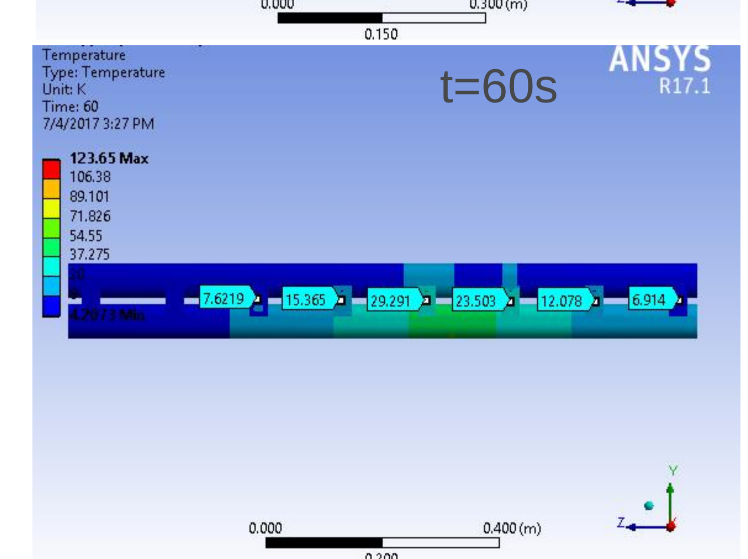




CASE3: A planar SCU, no LHe

- LHe channel temperature is free. No LHe in the channel.
- Quench behaviour is the same as CASE2. The same hot spot temperature ~50K.
- The temperature recovery does not happen since no cooling is provided. The maximum temperature at the sensor location is ~30 K.





5.DISCUSSION

- Using the adiabatic model [4], a quench velocity is calculated by

$$v = \frac{j0}{\gamma C}\frac{L0\theta_s}{\theta_s - \theta_0}$$

J0: current density of the copper wire,

γ: density,

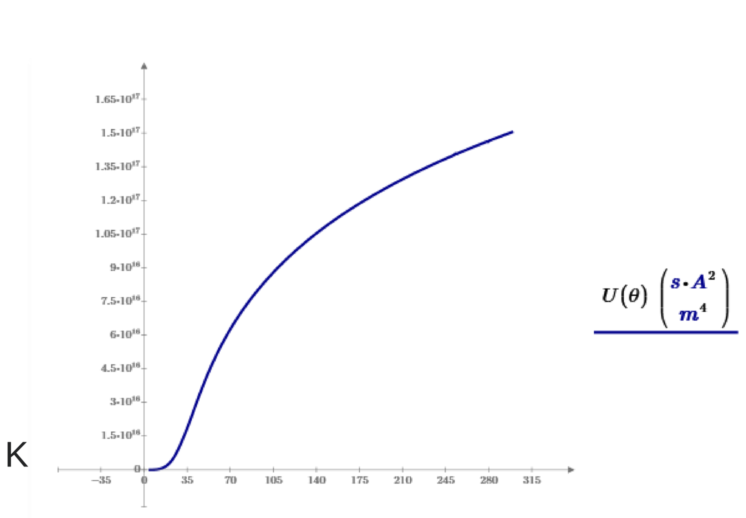
C: average heat capacity of the winding,

θs, θ0 temperature across the quench front,

L0 = 2.45×10^{-8} WΩK^{-2}: Lorentz number.

By taking γC = 3.83×10^4 $Jm^{-3}K^{-1}$, θs = 9 K, θ_0=7 K

v =~ 15 m/s along the wire.



Temperature rise in the adiabatic model are given by

$$\int_{\theta 0}^{\theta m} \frac{\gamma C(\theta)}{(\theta)} d\theta = U(\theta m) = j0^2 Td = \int_0^t J(T)^2 dT$$

- By analyzing the measured current decay data, a function $\int_0^t J(T)^2 dT = 3.68 \times 10^{16} A^2 s m^{-4}$= U (θm), so the hot spot temperature based on RRR=150 copper is 47.4 K. The time constant Td = 0.015 s.

- ANSYS calculated propagation velocity is ~10 - 20 m/s and the hot spot temperature in the one race track ~50-60 K for all three cases. The velocity perpendicular to the conductor is too slow to proceed across the next coil section. This is because the model considers Joule heating only. Each race track is then isolated by steel, which has poor thermal conductivity. Due to the changing field, there is an eddy current throughout the steel core, which will contribute to the propagation through the steel.

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) Y. Shiroyanagi 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) Wilson M, *Superconducting Magnet,* chapter 9 pp 200–217. 1982.

6.SUMMARY

- An ANSYS based dynamic thermal model successfully calculates temperatures with full 1.1 m magnet geometry with the simplest boundary condition.
- Three cases shows very similar temperature distribution within the first 0.01s. Hot spot temperature is ~50K -60K. The rest is a recovery to the operational temperature.
- Helium cooling plays the role of an energy buffer during the temperature recovery after the quench. So the real temperature distribution will be between "4.2 K" and "free" boundary conditions.
- Eddy current needs to be incorporated into the command snippet. The quench back voltage needs to be calculated to compare with the measured voltage.
- Helium cooling can be implemented using Helium thermal conductivity and cryocooler load maps to provide proper cooling power.

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