LARP IR Cryogenics: Quench Pressure Calculations

Roger Rabehl
January 9, 2007

Introduction

Quench pressure calculations are required in order to design the magnet cold mass for the pressures it must withstand during operation. The calculations presented here for a LARP quadrupole include both the initial pressure spike following a quench and the pressure in the magnet cold mass during heat transfer to the bulk helium.

Initial Pressure Spike

The initial pressure spike is calculated using the two-volume model [1]. The first volume of helium is that in close contact with the magnet coils, the second volume is the bulk helium contained in the cold mass structure. Immediately following a quench, the rapid expansion of the helium in close contact with the coils causes an isentropic compression of the bulk helium. Energy balances, as given by Equations 1-2, are written for both helium volumes. A mass balance, as given by Equation 3, is written for the system with the assumption of constant system volume.

Coil He energy balance: $$M\,x\left(u\left(T_{x,2},P_2\right)-u\left(T_1,P_1\right)\right)=Q-W \qquad (1)$$

Bulk He energy balance: $$W=M\left(1-x\right)\left(u\left(s_1,P_2\right)-u\left(T_1,P_1\right)\right) \qquad (2)$$

System mass balance (constant volume): $$\frac{M\,x}{\rho\left(T_1,P_1\right)}+\frac{M\left(1-x\right)}{\rho\left(T_1,P_1\right)}=\frac{M\,x}{\rho\left(T_{x,2},P_2\right)}+\frac{M\left(1-x\right)}{\rho\left(s_1,P_2\right)} \qquad (3)$$

Two parameters are required in order to solve these equations: the fraction x of the total helium in close contact with the coils, and the temperature of this helium $T_{x,2}$ immediately after its initial expansion.

The estimated maximum coil temperature underneath the quench protection heaters of a LARP Nb_3Sn quadrupole is 127-180 K for heater coverages of 25-50% [2]. If a 150 K temperature is assumed, and a ΔT of 110 K is assumed as per the CERN calculations [1], the final temperature of the expanded helium in close contact with the coils is 40 K.

The CERN calculations use 2% as the fraction of helium in close contact with the coils [1]. This value is based on micrographs of NbTi coil cross-sections. Micrographs of potted Nb_3Sn coils show complete impregnation [3]. The volume of helium in contact with the coils is therefore assumed to be equal to the volume of the Kapton and ceramic insulating wraps. Based on a 6 m long cold mass with the cross-section given in [2] with the addition of two end domes, the estimated fraction of helium in close contact with the coils is 0.15%.

Figure 1 shows the calculated quench pressure spikes as a function of expanded helium temperature and fraction of helium x in contact with the coils. The results agree with those in [1]. For a Nb_3Sn magnet with x=0.15% and a 40 K expanded helium temperature, the calculated pressure spike is only 4.7 bar.

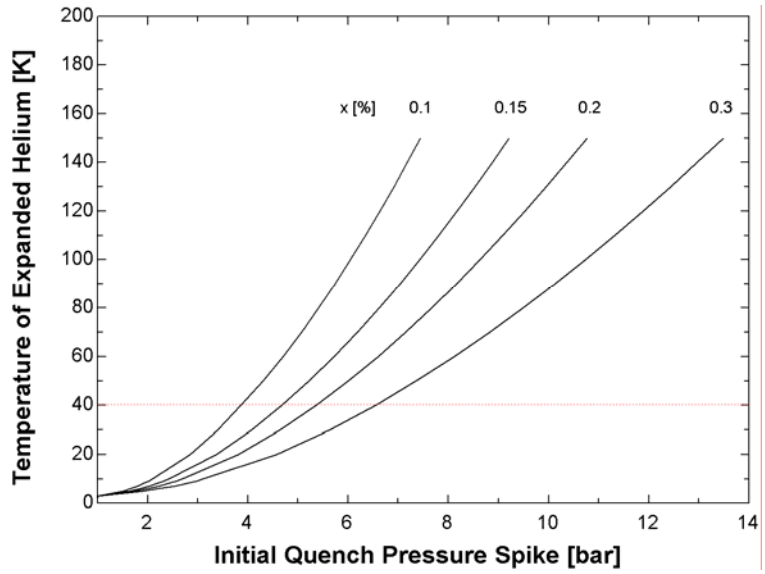


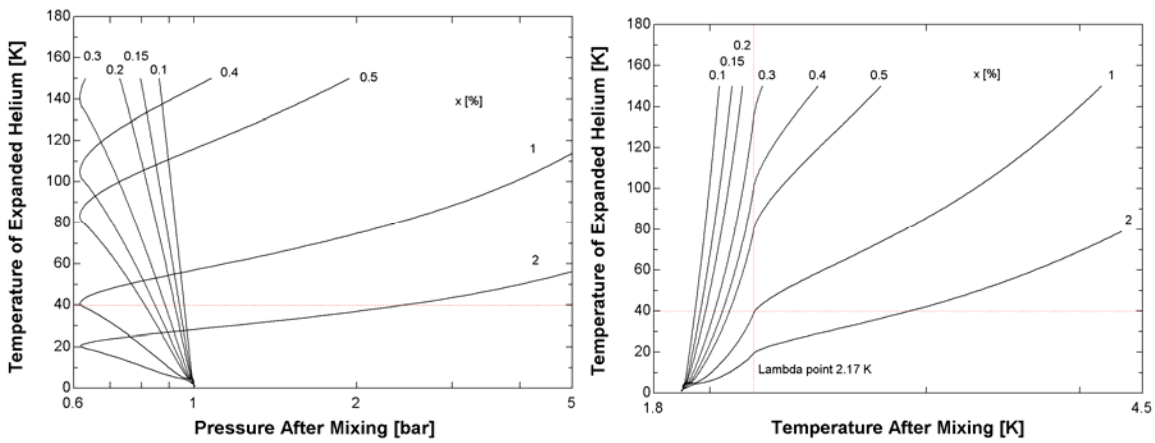
Figure 1 Final temperature of expanded helium vs. initial quench pressure spike for a range of helium fraction x in contact with the magnet coils.

Mixing

Following the initial pressure spike, the two helium volumes (the expanded helium near the coils, and the bulk helium) will mix. This results in a rise in temperature of the now-single volume, and a drop in the pressure. As the two helium volumes are mixing, heat is being transferred from the magnet coils to the cold mass structure. The warmed cold mass in turn heats the helium, causing the pressure to rise. This pressure is eventually vented when the setpoint of the quench relief valves is reached.

If this mixing was complete, without the addition of any more heat to the helium, the pressure would become subatmospheric. For a given helium fraction x, this mixed pressure is minimized when the initial heat input results in the mixed volume reaching the lambda point. This is illustrated in Figure 2.

There is good agreement with the CERN data, however. With 2% of the helium in close contact with the coils, the after-mixing temperature is calculated to be 3 K, as shown by Figure 2b. This agrees with Figure 14 in [1], where the measured temperature is 3 K a few seconds after the quench.



(a) (b)

Figure 2 (a) Pressure and (b) temperature after mixing as a function of the initial temperature of the expanded helium.

Similar to the method in [1], the process of heat transfer from the cold mass to the bulk helium can be modeled using the lumped approach where the magnet cold mass is treated as an isothermal mass and the cold mass helium is treated as an isothermal fluid. The heat transfer coefficient can be approximated by extrapolating from the data presented in [1]. The LHC prototype string had 850 l of LHe and a stored energy of 15.3 MJ [1]. The total cold mass is 10^5 kg [4]. Collars are austenitic stainless steel, and yokes are low carbon mild steel, with the collars accounting for approximately 25% of the cold mass cross-section. Treating the cold masses as lumped, the temperature following a quench would reach approximately 25 K. A simple model can be written to estimate the heat transfer coefficient hA from the cold mass to the helium. With a value of hA=3000 W/K, after 60 s the helium remaining in the cold mass has a temperature of a little over 8 K after an initial temperature of 3 K. This is in good agreement with Figure 14 in [1].

This value of hA can then be corrected for the LARP quadrupole, correcting for LHe-cold mass interface surface area. It is estimated that one LARP 6-m quadrupole has approximately one-quarter the LHe-cold mass interface surface area as the LHC test string. This then yields a value of hA=750 W/K for the LARP quadrupole. The estimated LHe volume for a single LARP quadrupole is 275 liters.

The maximum stored energy of a TQC magnet is 224 kJ/m [5], so a 6 m cold mass will have a stored energy of 1.34 MJ. For the LARP magnet, the ratio of the mass to the stored energy is less than that of the LHC test string. The cold mass will thus reach a higher temperature, 32 K, but the LARP quadrupole has a relatively large quantity of helium.

Figures 3 (a)-(b) show the calculated cold mass pressure and the cold mass and helium temperatures for a closed system (i.e., no venting of mass through a relief valve).

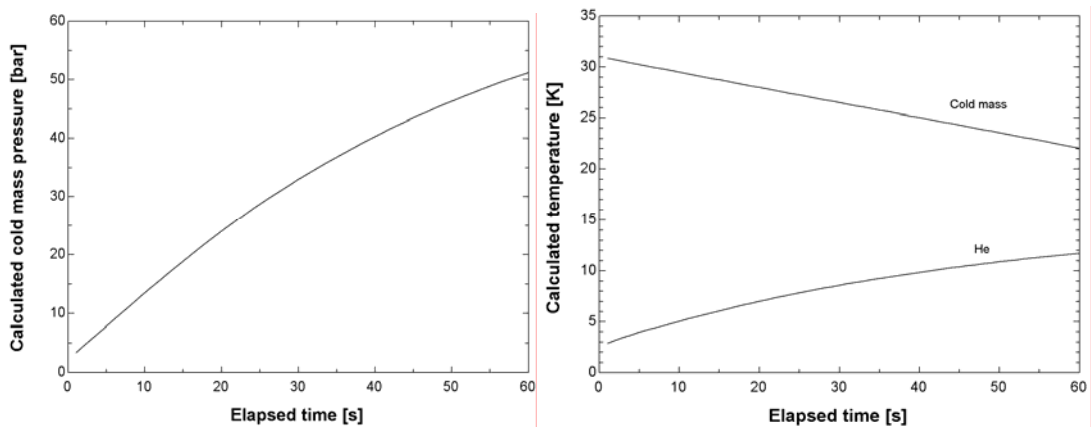


Figure 3 Closed system (a) pressure and (b) cold mass and helium temperatures during heat transfer from the cold mass to the bulk helium.

Conclusions

The sequence of events can be summarized as follows. The initial pressure spike reaches approximately 5 bar. As the stored energy diffuses as heat through the cold mass, the mixed helium volume remains as subcooled liquid at approximately 1.97 K/0.94 bar. The heat transfer rate between the 32 K cold mass and the 1.97 K subcooled liquid is high, quickly raising the pressure beyond the critical pressure of 0.2275 MPa at a temperature of 2.86 K. Only 10% of the magnet stored energy is required to do this. The cold mass temperature is reduced by 1 K, to 31 K. Heat transfer between the cold mass and the supercritical helium is then greatly reduced to 750 W/K, and the cold mass pressure rises at a rate of approximately 1 bar/s until the quench valve setpoint is reached.

The accuracy of this document's calculation of the initial pressure spike for a Nb_3Sn coil is considered marginal, at best. One critical parameter for this calculation, the fraction of helium in close contact with the coil, does not seem applicable for a potted Nb_3Sn coil. Spaces between the cable strands are filled with epoxy rather than helium. A helium layer surrounding the coil with a thickness equal to the insulation thickness was assumed instead. Another important parameter is the temperature of this expanded helium. A ΔT of 110 K between the quenched coil and the surrounding helium is used, which for lack of better information is the same as that for the LHC test string. Prototype magnet tests are required to better understand these parameters for the LARP quadrupoles.

References

[1] M. Chorowski, et al., "Thermohydraulics of Quenches and Helium Recovery in the LHC Magnet Strings," LHC Project Report 154 (1997).

[2] A. Zlobin, et al., "Conceptual Design Study of Nb3Sn Low-beta Quadrupoles for 2nd Generation LHC IRs," Applied Superconductivity Conference 2002 (Houston, TX).

[3] R. Bossert, "TQ Collar Design – Details and Plans," U.S. Department of Energy Review of the Fermilab High-Field Magnet Program, November 1-4, 2005.

[4] J. Casas-Cubillos, et al., "Operation, Testing and Long Term Behaviour of the LHC Test String Cryogenic System," LHC Project Report 210.

[5] R. Rabehl, "Verification of VMTF Relief Sizing for LARP High-Field Magnet Testing," Fermilab Technical Division Note TD-06-042, August 2006.