Multilayer thermal insulation for superconducting particle accelerators

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Abstract

Superconducting particle accelerators are an indispensable tool for high energy physics and basic sciences research. These accelerators use superconducting magnet and superconducting cavities for particle beam manipulation, needing cryogenic temperatures down to 2 K. Thermal insulation in the form of multilayer insulation is a key technology for reducing thermal load on these superconducting devices. This technical note is a compilation of data taken on the usage of multilayer insulation from several accelerator labs in order to aid cryogenic thermal design of superconducting particle accelerators.

1. Introduction

Superconducting accelerators that use superconducting magnets (niobium titanium and niobium tin) and superconducting radiofrequency cavities (pure niobium, niobium tin coated on pure niobium) are becoming increasingly popular due to their high wall-plug to particle beam energy conversion efficiency [1,2]. These accelerators need base temperatures in the range of 2 – 4 K for keeping the magnets and cavities at superconducting temperatures. Staged cooling from room temperature (~300 K) to the base temperature is usually provided in order to keep the base cryogenic load to as small as practical. The cooling is generally provided at ~80 K and then at ~5 K. All of these thermal stages need to see heat load as small as practical so as to minimize the cryogenic plant compressor input power.

2. Thermal insulation

Thermal insulation in superconducting accelerators is provided mainly in three forms (1) the use of low thermal conductivity structural components that reduce conduction heat leak (2) the use of high vacuum around the cryogenic components that reduce convection heat leak and (3) thermal shield and multilayer insulation that keep the incident thermal radiation heat load to a small value.

Multilayer insulation comprises intertwined layers of shiny metallic reflective sheets interposed with low thermal conductivity fabric or paper, as schematically shown in Figure 1. By providing several radiation reflective sheets in series, the radiation load reaching to the last layer adjacent to the cold surface is greatly reduced [3]. Multilayer insulation is shown to be the most effective at temperatures near and above 80 K. They tend to become transparent to thermal radiation originating from ~80 K temperatures and incident on surface operating at 20 K and below. However, the use of multilayer insulation helps to mitigate drastic effects arising from accidental scenarios such as sudden loss of insulating vacuum that can cause rapid air condensation and heat load on cryogenic surfaces. A detailed investigation of this benefit is given in papers by Lehmann and Zahn [4], Dhuley, Dalesandro, Bosque and Van Sciver [5-11], and Heidt and Grohmann [12-13].

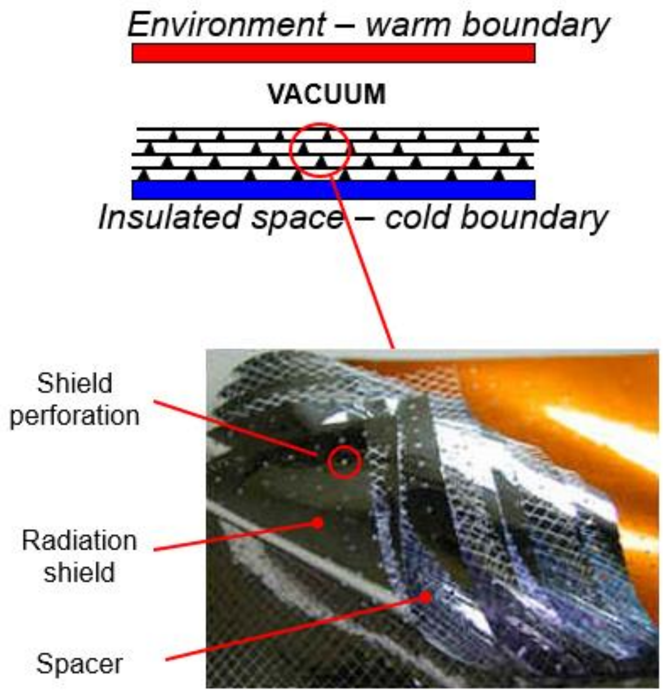

Figure 1: Multilayer insulation construction

3. Use of multilayer insulation in accelerator systems

The efficient use of multilayer insulation depends on proper selection of a number of performance determining parameters. These include (1) material used to make the shiny reflective sheets and the intertwined low conductivity spacer, (2) number of layer of multilayer insulation, (3) layer packing density (4) operating temperature, (5) vacuum level around the multilayer insulation, (6) type and pressure of residual gases, (7) multilayer insulation installation procedure around edges and corners, etc. Although analytical frameworks are available for calculating heat leak through multilayer insulation [14, 15], optimization of these numerous parameters is time and resource intensive, often requiring first-hand experimental validation. Hence, empirical data from prior experience can be immensely helpful for designing multilayer insulation systems. In the following, tables 1, 2, and 3 present case examples of multilayer insulation installation at several superconducting particle accelerators [16]. Multilayer insulation parameters such as the number of layers, layer packing density, and thermal intercept material are summarized based on the temperature level.

Table 1: Multilayer insulation for warm temperature intercept stages (HTS)

Project/component	**HTS details**			
	Temperature	**Material**	**No. of MLI layers**	**MLI layer density**
SSC dipole cryostat	80 K	Al 6061	64 (2x 32 layer blankets)	3.6 layers/mm
LHC dipole cryostat	80 K	Al 1100	30	Details NA

Tesla/ILC/XFEL CMs	40 - 80 K	Al	30	Details NA
LCLS-II CM	40 - 80 K	Al	30	Details NA
CEBAF C20 CM	50 K	Cu	45 - 60	Details NA
SNS CM	50 K	Cu	60 (4x 15 layer blankets)	Details NA
PXIE SSR1 CM*	45 - 80 K	Al 6000 series	30 (2x 15 layer blankets)	Details NA
XFEL AMTF CTL**	80 K	Al	30	Details NA
LCLS-II CTL***	55 K	Cu	>45	Details NA

Table 2: Multilayer insulation for cold temperature intercept stage (LTS)

Project/component	**LTS details**			
	Temperature	**Material**	**No. of MLI layers**	**MLI layer density**
SSC dipole cryostat	20 K	Al 6061	10	Details NA
LHC dipole cryostat	LTS not used			
Tesla/ILC/XFEL CMs	5 - 8 K	Al	5 - 10	Details NA
LCLS-II CM	LTS not used			
CEBAF C20 CM	LTS not used			
SNS CM	LTS not used			
PXIE SSR1 CM*	LTS not used			
XFEL AMTF CTL**	LTS not used			
LCLS-II CTL***	LTS not used			

Table 3: Multilayer insulation for components at base temperature

Project/component	**Cold mass/cold process lines**		
	Temperature	**No. of MLI layers**	**MLI layer density**
SSC dipole cryostat	4.2 - 20 K	Details NA	Details NA
LHC dipole cryostat	1.8 - 10 K	Details NA	Details NA
Tesla/ILC/XFEL CMs	5 - 8 K	5 - 10	Details NA
LCLS-II CM	5 - 8 K	5 - 10	Details NA
CEBAF C20 CM	2 K	15 - 30	Details NA
SNS CM	2 K	24 (2x 12 layer blankets on He vessel); 15 layers on piping	Details NA

PXIE SSR1 CM	2 K	Details NA	
XFEL AMTF CTL	4.5 - 40 K	10	Details NA
LCLS-II CTL	2 - 55 K	>15	Details NA

Note: All data sourced from [16] except those for PXIE SSR1 CM, XFEL AMTF CTL, and LCLS-II CTL.

4. Summary

This technical note presented a brief compilation of multilayer usage on several superconducting particle accelerators systems. It is generally concluded that 40-60 insulation layers at a dentary of 3.5 layers/mm are sufficient for use near 80 K. For temperatures 40 K and below, about 10-15 insulation layers are adequate. In this lower temperature range, multilayer insulation primarily mitigates the catastrophic effects of sudden loss of insulating vacuum rather than reducing radiation heat load. It is anticipated that cryogenic engineers and designers will benefit from this data aggregation for the design of future accelerator systems.

5. References

[1] LHC Design Report, 2004. DOI: 10.5170/CERN-2004-003-V-1

[2] XFEL: The European X-Ray Free-Electron Laser. Technical design report, 2006. DOI: 10.3204/DESY_06-097

[3] R. F. Barron, “Cryogenic Systems”, Oxford University Press; 2nd edition, 1985.

[4] W. Lehmann and G. Zahn, “Safety Aspects for the LHe Cryostats and LHe Transport Containers,” Proc. of the ICEC 7, London, IPC Science and Technology Press, pp. 569-579, 1978

[5] R. C. Dhuley and S. W. Van Sciver, “Epoxy encapsulation of a Cernox™ SD thermometer for measuring the temperature of surfaces in liquid helium”, Cryogenics 77, 49-52, 2016. https://doi.org/10.1016/j.cryogenics.2016.05.001

[6] R. C. Dhuley and S. W. Van Sciver, “Propagation of nitrogen gas in a liquid helium cooled vacuum tube following sudden vacuum loss- Part I: Experimental investigations and analytical modeling”, International Journal of Heat and Mass Transfer 96, 573-581, 2016. https://doi.org/10.1016/j.ijheatmasstransfer.2016.01.077

[7] R. C. Dhuley and S. W. Van Sciver, “Propagation of nitrogen gas in a liquid helium cooled vacuum tube following sudden vacuum loss- Part II: Analysis of propagation speed”, International Journal of Heat and Mass Transfer 98, 728-737, 2016. https://doi.org/10.1016/j.ijheatmasstransfer.2016.03.077

[8] Ram C. Dhuley and Steven W. Van Sciver, “Sudden vacuum loss in long liquid helium cooled tubes", IEEE Transactions on Applied Superconductivity 25(3), 9000305, 2015. https://doi.org/10.1109/TASC.2014.2367156

[9] R. C. Dhuley and S. W. Van Sciver, “Heat transfer in a liquid helium cooled vacuum tube following sudden vacuum loss”, IOP Conference Series: Material Science and Engineering 101, 012006, 2015. https://doi.org/10.1088/1757-899X/101/1/012006

[10] Ernesto S. Bosque, Ram C. Dhuley, and Steven W. Van Sciver, “Transient heat transfer in Helium II due to sudden vacuum break”, AIP Conference Proceedings 1573, 260-267, 2014. https://doi.org/10.1063/1.4860710

[11] Andrew A. Dalesandro, Ram C. Dhuley, Jay C. Theilacker, and Steven W. Van Sciver, “Results from sudden catastrophic loss of vacuum on scaled superconducting radio frequency cryomodule”, AIP Conference Proceedings 1573, 1822-1829, 2014. https://doi.org/10.1063/1.4860929

[12] C. Heidt, S. Grohmann, and M. Süßer, “Modeling the pressure increase in liquid helium cryostats after failure of the insulating vacuum”, AIP Conference Proceedings 1573 (1), 1574-1580, 2014. https://doi.org/10.1063/1.4860894

[13] C. Heidt, H. Schön, M. Stamm, and S. Grohmann, “Commissioning of the cryogenic safety test facility PICARD”, IOP Conference Series: Materials Science and Engineering 101 (1), 012161, 2015. https://doi.org/10.1088/1757-899X/101/1/012161

[14] J. Polinski, M. Chorowski, A. Choudhury, and T. S. Datta, “Synthesis of the multilayer cryogenic insulation modelling and measurements”, AIP Conference Proceedings 985, 1367 2008. https://doi.org/10.1063/1.2908496

[15] R G Ross Jr., “Quantifying MLI Thermal Conduction in Cryogenic Applications from Experimental Data”, IOP Conference Series: Material Science and Engineering 101, 012017, 2015. https://doi.org/10.1088/1757-899X/101/1/012017

[16] J.G. Weisend II, “Cryostat Design: Case Studies, Principles and Engineering”, Springer Cham; 1st edition, 2016. https://doi.org/10.1007/978-3-319-31150-0