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Flow and Thermo-mechanical Analysis of the LHC Sector Helium Relief System

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Abstract

A simultaneous resistive transition of a LHC magnet sector, which may occasionally occur, will cause rapid helium outflow from magnet cryostats to a special relief system composed of long pipes, buffer volumes and accessories. The paper presents some safety and operational aspects of this system. The results show helium dynamic property distributions along the pipes as well as FEM calculations of thermo-structural stresses in the pipe walls.

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A simultaneous resistive transition of a LHC magnet sector, which may occasionally occur, will cause rapid helium outflow from magnet cryostats to a special relief system composed of long pipes, buffer volumes and accessories. The paper presents some safety and operational aspects of this system. The results show helium dynamic property distributions along the pipes as well as FEM calculations of thermo-structural stresses in the pipe walls.

INTRODUCTION

The Large Hadron Collider, presently under construction at CERN, will make an extensive use of superconducting magnets located in the underground tunnel of about 26.7 km length and divided into eight sectors. The amount of helium stored in the magnet cold masses located in the sector will be of about 6400 kg. A simultaneous resistive transition of the sector magnets has been defined as an event that may occasionally occur during a life-time of the machine and is called a sector quench. In case of such an event the helium would be vented from the cold masses to cold recovery header D in the cryogenic distribution line (QRL). The capacity of header D will not allow gathering all the helium blown from the sector cold masses. The excess helium would have to be relieved via the pressure valve (PV) and quench line (QL) to two buffer volumes, each composed of four 250 m^3 tanks and located on the surface at both extremities of the sector. To fulfill safety requirements, there is also a possibility to discharge the helium from header D via the safety valve (SV) or two bursting disks (BD) and further through the vent line (VL), which directly opens to the environment. A set of SV and two BD constitute the connection between header D and the VL. The PV, SV and BD are located at the QRL extremities (return module, RM and cryogenic interconnection box, QUI) as shown in Figure 1. Header D, lines QL and VL as well as the accessories compose the helium relief system (see Figure 1).

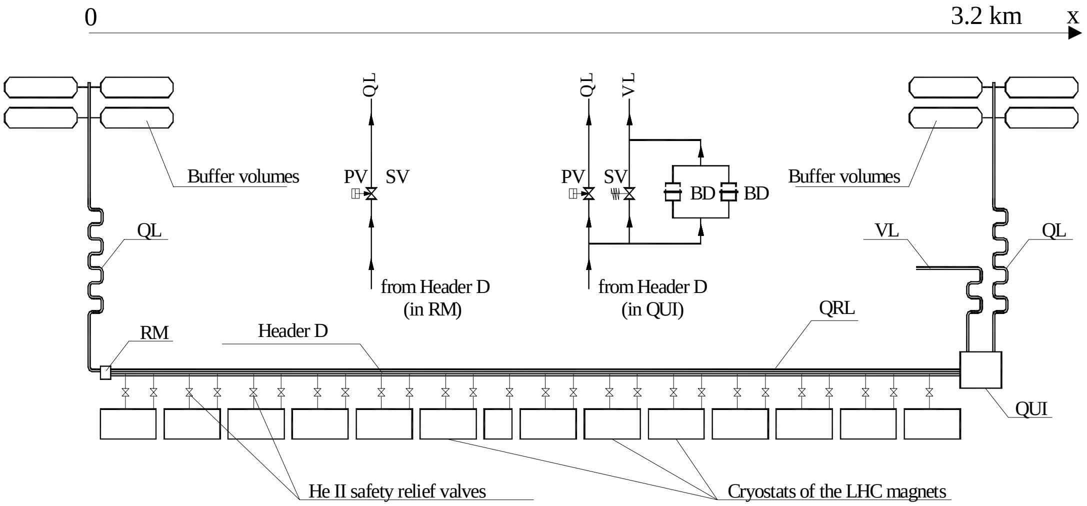

Figure 1 Simplified scheme of helium relief system

The set pressures of PV, SV and BD are equal to 6 bar, 9 bar and 14 bar respectively. If the pressure inside header D exceeds 6 bar, the PV will open and the helium will be evacuated to the buffer volumes. If the pressure still increases and reaches the level of 9 bar, then the SV will open. In case the pressure inside header D exceeds the value of 14 bar, one BD will rupture. If the BD ruptures, most of the helium will be lost and vented into environment.

The main issue of the analysis is to study safety, operational and mechanical aspects of the helium relief system. The QL and VL are not thermally insulated and their nominal stand-by temperature is equal to 300 K. Therefore after cold helium rapid inflow into the lines, their walls will be exposed to impact of thermal and pressure loads.

HELIUM FLOW FROM COLD MASS TO HEADER D AFTER A SECTOR QUENCH

The helium flow into QL (or VL) will be triggered by the pressure growth in header D. After a sector quench a part of the magnetic energy will be dissipated in the cold mass helium and will cause the increase of its temperature and pressure. Based on experimental data gathered from String 1 [1] and String 2 [2] the heat flux to the helium in the cold mass after a sector quench was estimated (Figure 2a). The heat flux will reach the highest value during the first second and it will rapidly go down to 3.7 MW. It will then decrease to about 1 MW during a period of 20 s, and afterwards it will constantly and gradually reduce with a much slower rate.

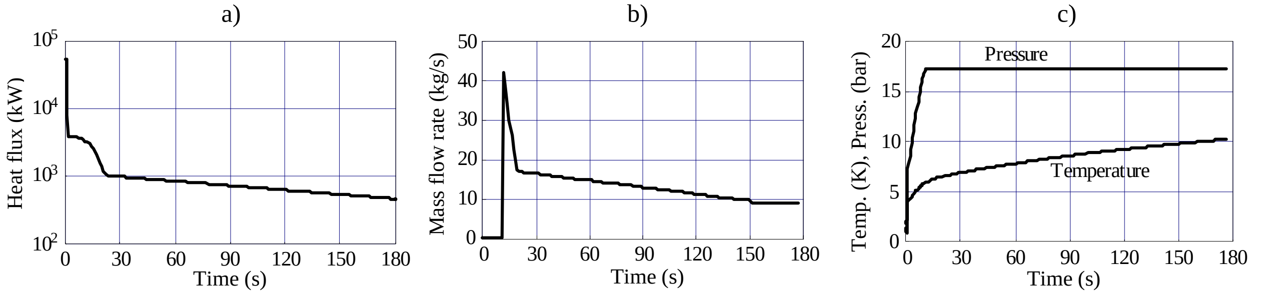

Figure 2 Evolutions of: a) heat flux to the cold mass helium, b) helium mass flow out of the cold mass and c) helium temperature and pressure in the magnet cryostats after a sector quench

The helium internal energy U of the helium in the magnets can be calculated from the equation hereafter:

$$U_2(T_2, p_2) = U_1(T_1, p_1) + \int_{t1}^{t2} P(t)dt - h(T_1, p_1) \cdot \Delta m \ , \tag{1}$$

where P refers to power dissipated in the helium, h is specific enthalpy of helium and Δm denotes the mass of helium that flows out from the magnet cryostats to header D. Equation (1) together with the helium equation of state [3] enables to calculate the helium mass flow rate $q_m = \Delta m/\Delta t$ from the cold mass to header D (Figure 2b) as well as the helium temperature and pressure evolutions (Figure 2c). After 10.5 s following a sector quench, the helium pressure in cold mass will reach the value of 17 bar and HeII safety relief valves will open and will allow helium to flow into header D. The helium mass flow rate will then increase rapidly to 42 kg/s. During the following 9 s the flow rate will sharply decrease to the value of 18 kg/s, and afterwards it will further go down, but much more smoothly and gradually. Based on the calculated helium outflow from cold mass, the helium temperature and pressure evolutions in header D

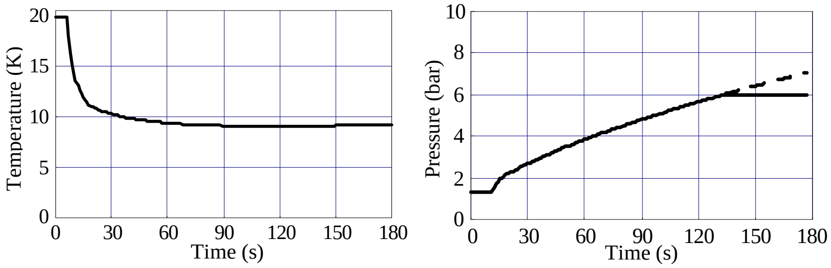

Figure 3 Evolutions of helium temperature and pressure in header D after a sector quench

were calculated taking into account the thermal capacity of header D (Figure 3). The calculation revealed that the lowest value of temperature will be of about 9 K and it will be reached after 85 s following a sector quench. At the same time the pressure in header D will exceed 6 bar and PV will open.

HELIUM OUTFLOW FROM HEADER D

To estimate the values of helium flow rate from header D to QL a complex numerical flow model has been elaborated. The model describes unsteady turbulent compressible and thermal helium flow from header D through QL (about 400 m long) to the buffer volumes. The initial helium temperature and pressure inside header D were equal to 9 K and 6 bar respectively. The initial helium temperature and pressure inside QL and the buffer volumes were equal 300 K and 1.3 bar respectively. The selected model results are shown in Figures 4 and 5 which gives the helium properties along header D and QL for the chosen time periods.

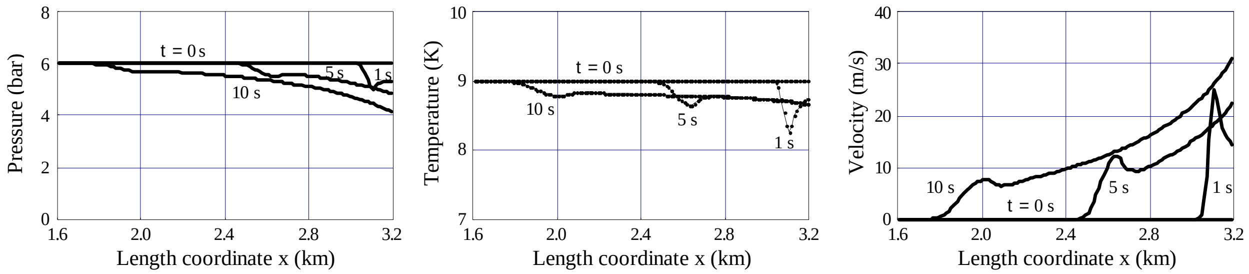

Figure 4 Helium properties along header D after PV opening

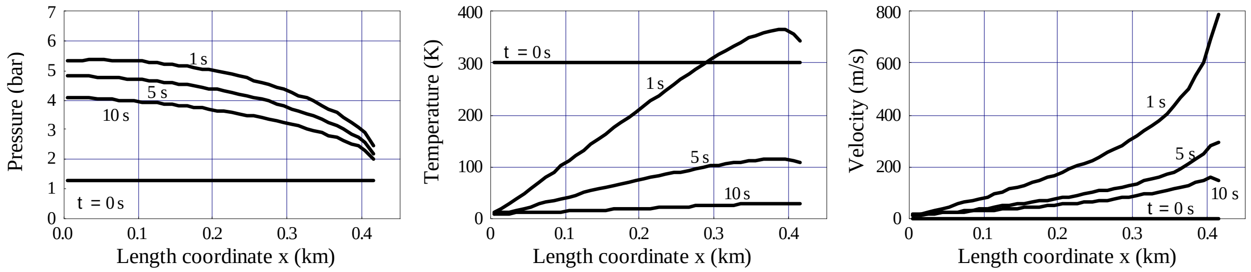

Figure 5 Helium properties along QL after PV opening

When the helium flow starts, the pressure inside header D will suddenly decrease by almost 1 bar in the vicinity of the header extremities (Figure 4). It should be emphasized that due to continuous helium flow from cold mass, the pressure in the middle region of header D will slightly increase, and will reach the maximum value of about 2.5 bar above the initial pressure of 6 bar. The local decrease of helium temperature due to the helium expansion will not exceed 1 K.

The evolution of the overall helium mass outflow from header D at the inlet of QL is shown in Figure 6. After the PV opening the flow will rapidly increase to almost 20 kg/s and then drop for a few seconds to about 16 kg/s. This drop is caused by the helium thermal expansion, and when the QL pipe wall is cold enough the flow rate will increase again and reach asymptotically 24 kg/s.

The comparison of Figures 2b and 6 reveals that at about 90 s after a sector quench (5 s after the PV opening) the helium mass inflow to header D starts to be lower by 10% than the potential helium outflow rate. The temperature inside header D results to be stable (see Figure 3), and after the PV opening the mean pressure in header D will be at the level of 6 bar (see the solid line in the graph of Figure 3 giving the pressure evolution in header D). If due to unexpected reasons both PV valves do not open, the pressure in header D would further increase, and it would reach the SV set pressure (9 bar) at about 230 s after a sector quench (value obtained by extrapolating the dashed line of Figure 3).

Table 1 gives the masses of helium that can be kept within the main components of the helium recovery system on the assumption that temperature and pressure reach the maximal values.

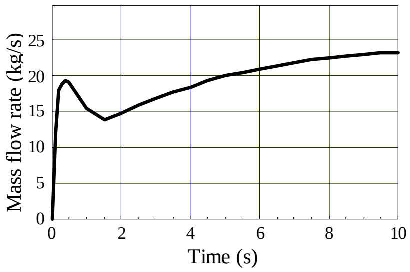

Figure 6 Helium mass outflow from header D into QL after PV opening

Table 1 Helium masses that can be kept by the main components of helium recovery system after a sector quench

	Volume m^3	Pressure Bar	Temp. K	Density kg/m^3	Helium mass Kg
Cold masses	43	17	30	26.1	1130
Header D	66	9	13	36.4	2415
QL	8	9	300	1.44	12
Buffer vol.	2000	9	300	1.44	2875
				Total mass:	6432

THERMO-MECHANICAL STRESSES IN PIPE WALL MATERIAL

The results of helium flow model reveal that the worst condition with respect to thermo-mechanical strength of the QL pipe wall will occur at the inlet region of the line just after beginning of the helium flow (see Figure 5). The temperature of the helium blown into the QL will rapidly reach the value of about 10 K, and the pressure will remain slightly below 6 bar. To analyze the thermo-mechanical strength of QL and VL the dynamic FEM calculations of thermo-structural stresses in the walls of the pipes were carried out. In the pipe strength model we assumed forced convection on the inner pipe wall surface, with a convective heat transfer coefficient of about 2400 W/m^2K [4], and natural convection on the outer surface, with bulk temperature of 300 K and film heat transfer coefficient of 15 W/m^2K [5]. The results of the thermo-mechanical strength analysis are shown in Figure 7.

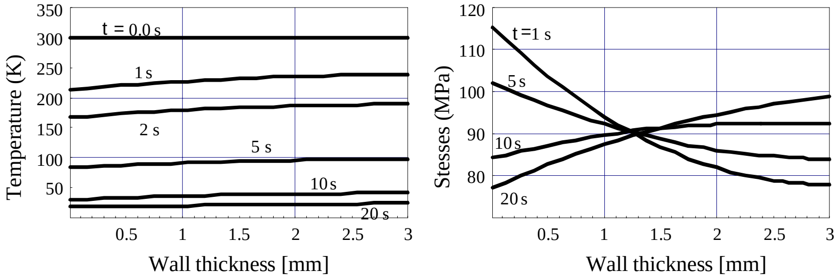

Figure 7 Temperature and stress distributions along the QL wall thickness after the start of the inflow of cold helium to the pipe

CONCLUSIONS

The LHC sector helium relief system is designed to recover a simultaneous resistive transition of a magnet sector (sector quench) without releasing helium in the atmosphere. The cold buffer constituted by header D can retain up to 46 % of the helium discharged from the magnets.

The stresses in QL and VL pipe wall material have been calculated and they will not exceed 120 MPa. This value is twice lower than the yield strength of the applied material (240 MPa).

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