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Transient behaviour and helium discharge in cryogenic distribution line (QRL) headers following breakdown of insulation vacuum

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Summary

An accidental breakdown of the insulating vacuum in the cryogenic distribution line (QRL) will cause a high heat flux to the helium stored in the headers[1]. Helium will warm up, expand and finally will have to be discharged through the safety valves. The purpose of this analysis is to simulate the behaviour of the helium during this transient. Then the number, location and flow coefficients k_v of the safety valves protecting the headers are determined.

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1. Initial conditions in QRL headers preceding the breakdown of the insulating vacuum

The worst case initial conditions corresponding to the highest helium density in the headers are given in Table 1.

The insulating vacuum breakdown scenarios

The headers that compose cryogenic distribution line QRL will be vacuum-insulated and covered with multi-layer insulation. The insulating vacuum will be segmented with vacuum barriers. The distance between the adjacent vacuum barriers will be of the length of four full-cells, i.e. about 428 m.
The following defects are considered as a potential cause of breakdown of the insulating vacuum.

1. Venting to helium: leaking header B, C, D, E or F (minor leakage).
   In case of a leaking header, the insulating vacuum will fill with helium at the pressure of 1 bar. According to reference[2] a surface heat flux to the headers will be the range of 0.02 - 0.25 W/cm^2. A value of 0.038 W/cm^2 has been calculated using the QRL line thermal model developed by G. Riddone[3].

2. Venting to air: damage to the vacuum jacket (e.g. accidental break of a vacuum gauge).
   In case of damage to the vacuum jacket, the insulating vacuum will be filled with air which will start to condense on the surface of headers B, C, D, E and F. The condensation will proceed as long as the header temperature remains below 77 K. The surface heat flux to the headers will be of the order of 0.5 W/cm^2 (ref.[2]). For the calculation of helium vessel safety valves, the even higher value of 0.6 W/cm^2 is recommended in industrial practice (ref.[4]).

Table 1. Worst case helium conditions in QRL headers preceding the insulating vacuum breakdown.

	Inner diam./wall th. [mm/mm]	Design pressure [bar]	Initial temperature [K]	Initial pressure [bar]	Additional helium (two-phase)	Initial mass of helium in the header [kg]
B	267/2.9	6	4.0	0.016	675 l LHe at 1.8 K (100 kg)	136 (36 +100)
C	100/2.0	20	4.6	6	-	3694
D	150/2.0	20	9.5	3.4	-	1160
E	80/2.0	25	30	20	-	521
F	80/2.0	25	30	19	-	521

- The additional helium in header B will flow from the bayonet heat exchanger threading its way along magnet strings. An amount of liquid helium filling one heat exchanger is about 25 l. For a total number of 27 heat exchangers in a sector we get about 100 kg of helium.
- Initial conditions in header C are for a normal operation mode with a possibility of the pressure control system malfunctioning (6 bar instead of 3 bar)[4].
- The initial conditions in header D are as after a limited quench[5].
- The initial conditions in headers E and F result from the parameters of the existing Linde plants[4]. For further analysis we will assume the same behaviour of header F and E.

Table 2 gives the surface and linear heat flux to QRL headers in case of venting of the insulating vacuum to helium and air.

As seen from Table 2, the worst case scenario corresponds to venting the insulating vacuum to atmospheric air. In this case the heat flux to the header is limited only by the efficiency of air condensation on the header surface.

Table 2. Heat fluxes to QRL headers in case of venting of the insulating vacuum.

Header	Venting to helium		Venting to air	
	[W/cm^2]	[W/m]	[W/cm^2]	[W/m]
B	0.038	320	0.50	4190
C	0.038	120	0.50	1570
D	0.038	180	0.50	2350
F + shield*	0.038	3220	0.50	8500

*copper, diameter 0.55 m, wall thickness 2 mm, thermally coupled with header F

2. Thermohydraulic transients in headers C, D, E and F following the venting of the insulation vacuum to air

The thermohydraulic transients in the headers are calculated for the following (conservative) assumptions:

1. The insulating vacuum is vented to air over a length of 500 m. The estimated amount of air which will condense over the surfaces of headers B, C and D is about 20 kg/s for a heat transfer efficiency 0.5 W/cm^2 - see Table 2. A flow of 20 kg/s will require a hole in the vacuum jacket with a hydraulic diameter of about 8 cm.

2. Heat is transferred to the headers at a flux of 0.5 W/cm^2 as long as the header temperature remains below 77 K. For higher temperatures a residual heat flux of 0.03 W/cm^2 is assumed - see Figure1.

3. Transient behaviour and helium discharge from the headers is calculated for the following configurations of the safety valves and air-vented zone (see Figure 2):

- One safety valve. The safety valve is located at one end of the sector (in the cryoplant interconnection box QUI), the vented zone of the length of 500 m lies next to the return box (2900 m to 3400 m from the QUI) - referred later as *case 1*.
- Two safety valves. The valve is located at each end of the sector (both in the QUI and in the return box). The central part of the QRL is air vented over a length of 500 m, i.e. between 1450 and 1950 m from the QUI) - referred later as *case 2*.

4. The safety valves are set at 20 bar (absolute pressure).

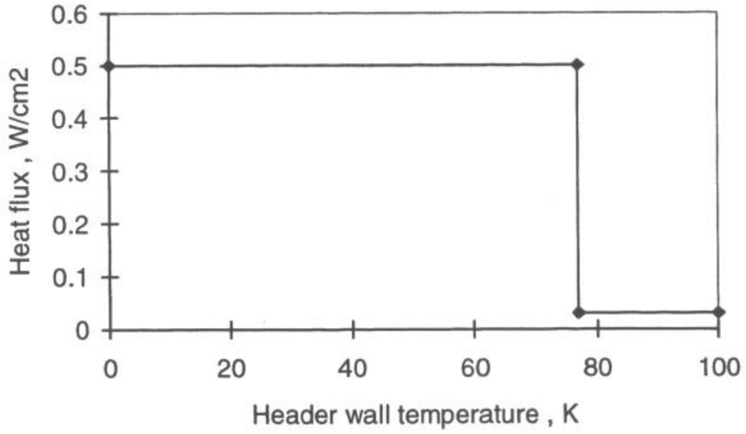

Figure 1. Worst case surface heat flux to the headers after venting of the insulating vacuum to air, used as input to simulations.

The numerical simulations have been performed with the computer code GANDALF[6,7]. GANDALF is the numerical implementation of a 1-D model for the simulation of quench initiation and quench propagation in so-called "cable-in-conduit-conductors" (CICCs). Due to a very similar geometry of CICCs cables (e.g. length up to 1500 m and hydraulic diameter of the helium passage of the order of several cm for the ITER coils) and QRL headers (length 3400 m, hydraulic diameter 8 - 26 cm), the code can be used for the present analysis.

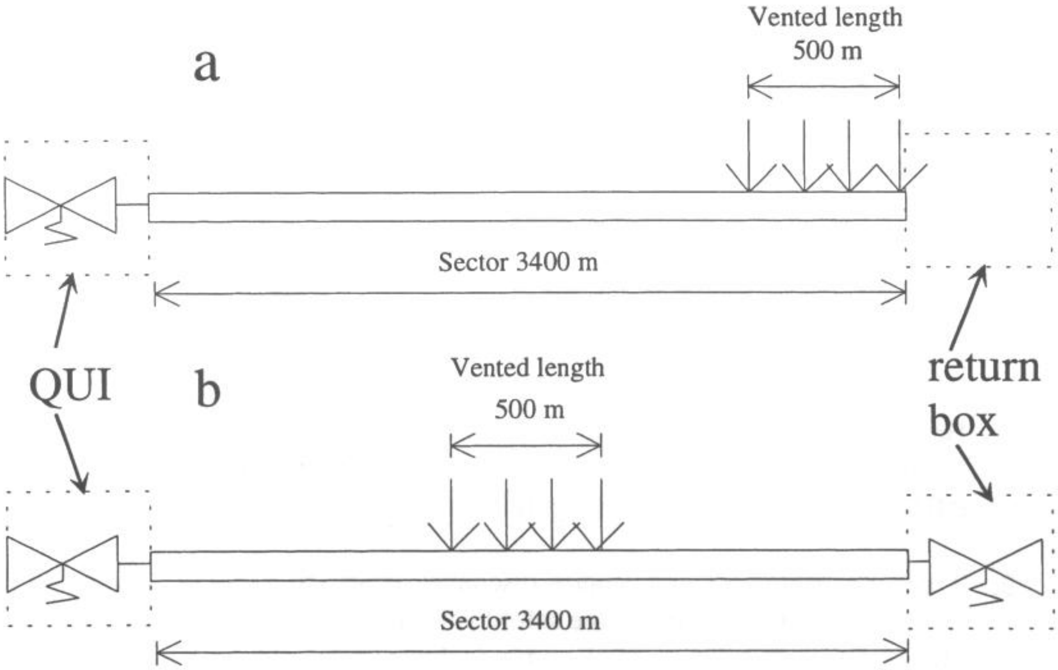

Figure 2. Two cases of the safety valves and air vented zone configuration, a - one safety valve, the insulating vacuum vented at the end of a sector (*case 1*), b - two valves, the insulating vacuum vented in the centre of a sector (*case 2*).

2.1. Header B

The volume of header B is 190 m^3 per sector. The density of the helium in the header is 0.72 kg/m^3. Even in case of the fast warm up to 300 K, the pressure will reach 4.5 bar, thus remaining below the design value (6 bar), and no helium discharge will be necessary. The safety valve of header B should be sized on the basis of the maximum assumed leak from header C.

2.2. Header C

Case 1. One safety valve located in the QUI, the insulating vacuum vented close to the return box.

The location of the safety valve and the heated zone are shown on Fig. 2a. Surface heat flux to the header is shown in Fig. 1.

Figures 3 and 4 show the development of the header and the helium temperature in the middle of the heated zone (3150 m from the safety valve). The header temperature reaches 77 K in about 20 seconds, then stays roughly constant for about 250 seconds, and starts to increase again with a moderate speed of about 0.05 K/s, reaching about 95 K after 600 s.

The helium temperature within the heated zone increases in a quasi linear way and reaches about 26 K after 600 s. The average temperature difference between the header wall and the helium is of the order of 75 K.

The temperature profiles of helium and wall of header C along the sector are shown in Figures 5 and 6. The temperature increase both of the header wall and of the helium is significant only in the vicinity of the heated zone.

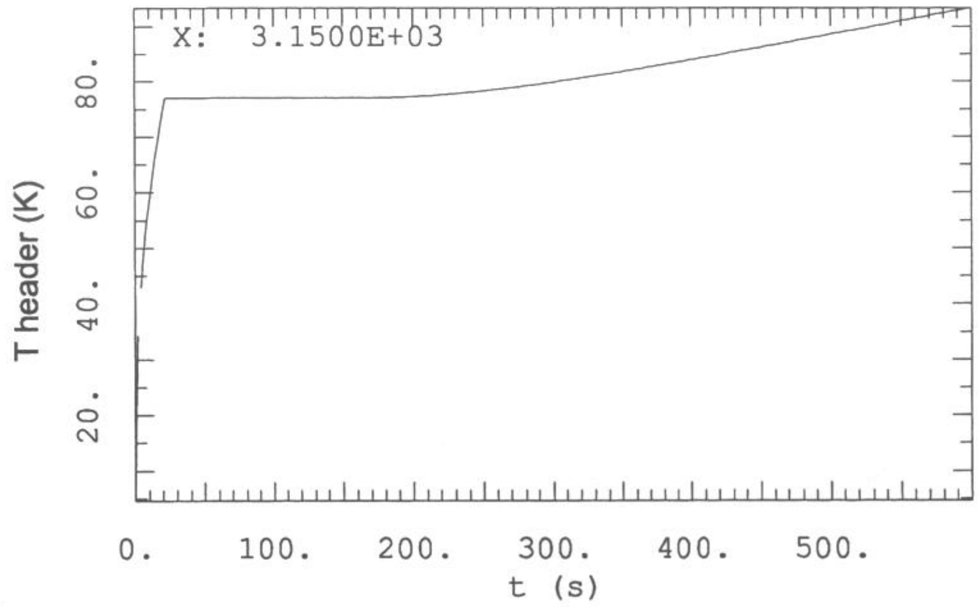

Figure 3. Development of header C temperature in the middle of the heated zone (calculated).

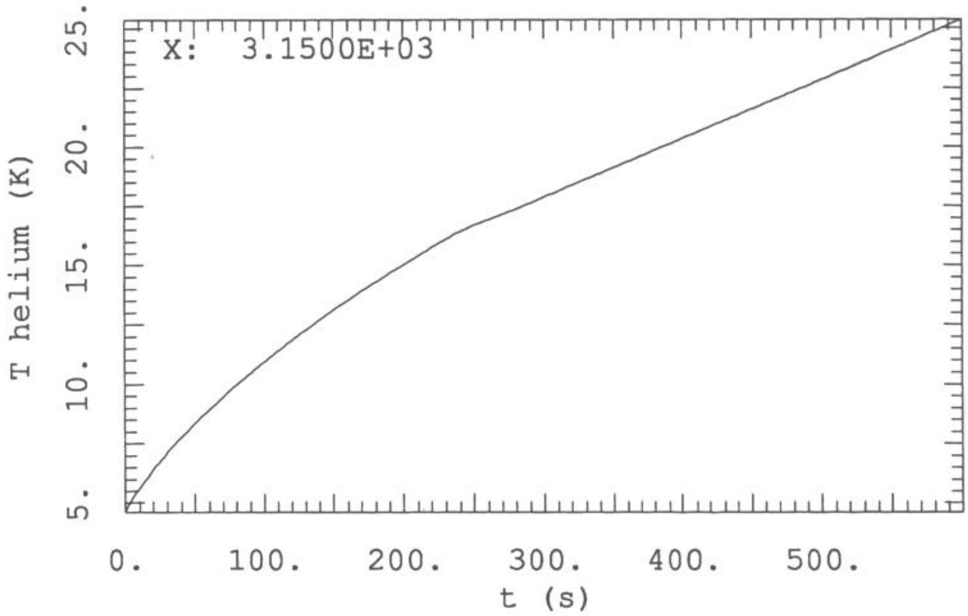

Figure 4. Development of helium temperature in header C in the middle of the heated zone (calculated).

The large temperature difference between the header and the helium is caused by the relatively low heat transfer coefficient between them, reaching a maximal value of about 45 W/(m^2K) a few seconds after breakdown of the insulating vacuum - see Fig. 7. The surface heat flux from the header to the helium is then of about 0.1 W/cm^2 , almost an order of magnitude below the values given in Table 2.

The amount of heat transferred to the helium in header C is then limited by the heat transfer efficiency between the header wall and the helium, and not by the air condensation rate at the outer surface of the header.

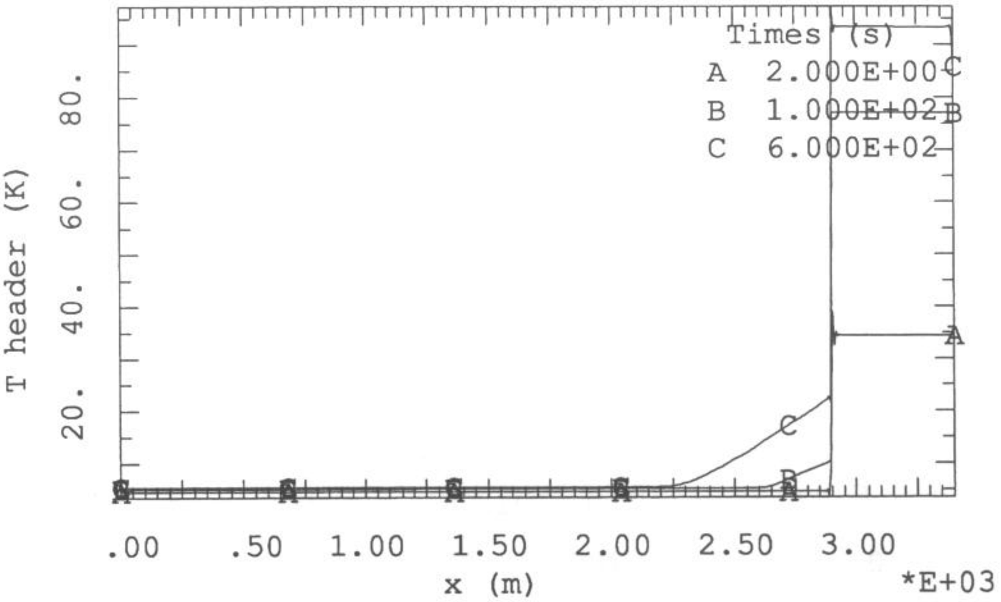

Figure 5. Temperature profiles of header C wall in 2, 100 and 600 s after breakdown of the insulating vacuum (calculated).

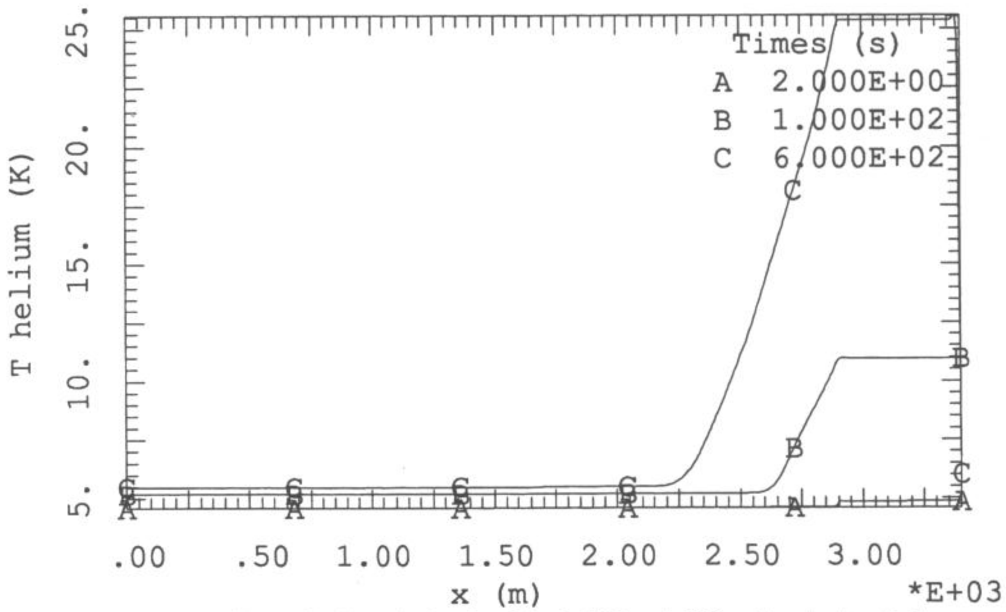

Figure 6. Temperature profiles of helium in header C in 2, 100 and 600 s after the insulating vacuum breakdown (calculated).

The helium velocity in the header and corresponding Reynolds number are given in the Appendix.

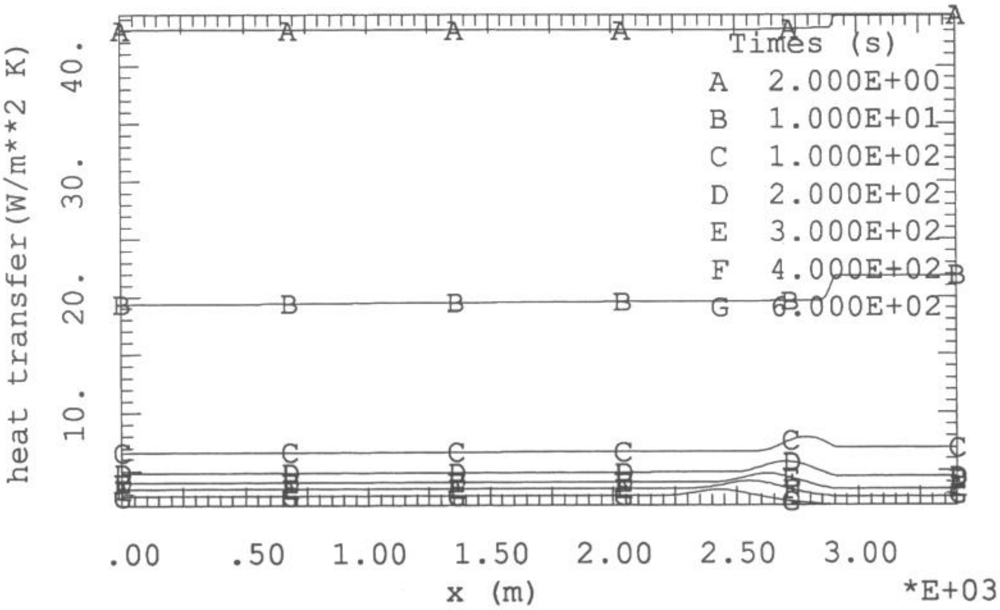

Figure 7. Heat transfer coefficient between header C wall and the helium (calculated).

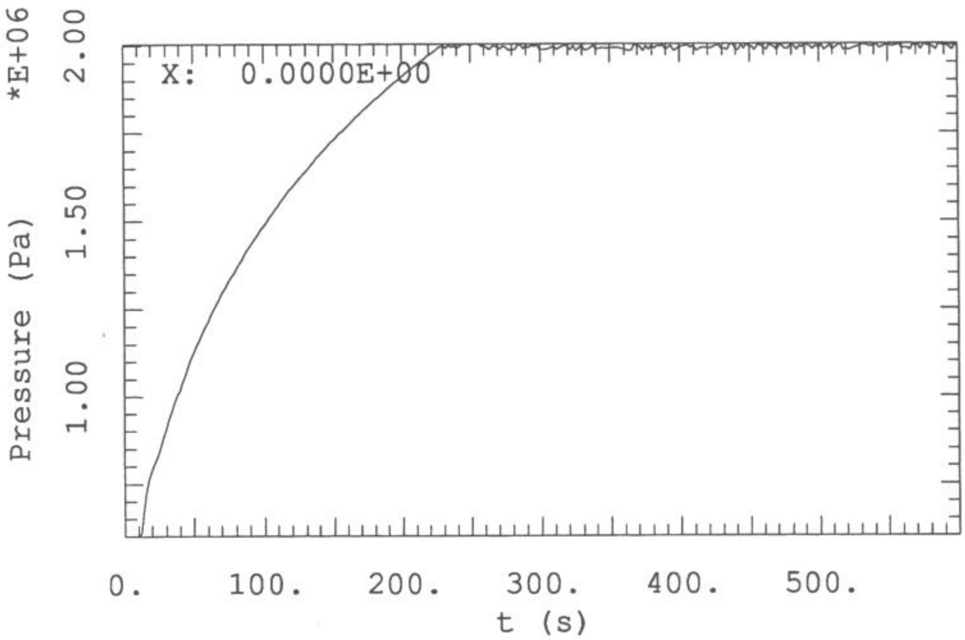

Figure 8. Pressure development of the helium in header C close to the safety valve, (calculated).

Figures 8 - 10 show the development of the helium pressure at the ends of the header and the pressure profile along the header; the pressure oscillations are less than 1 bar and remain within 5% of the valve setting pressure.

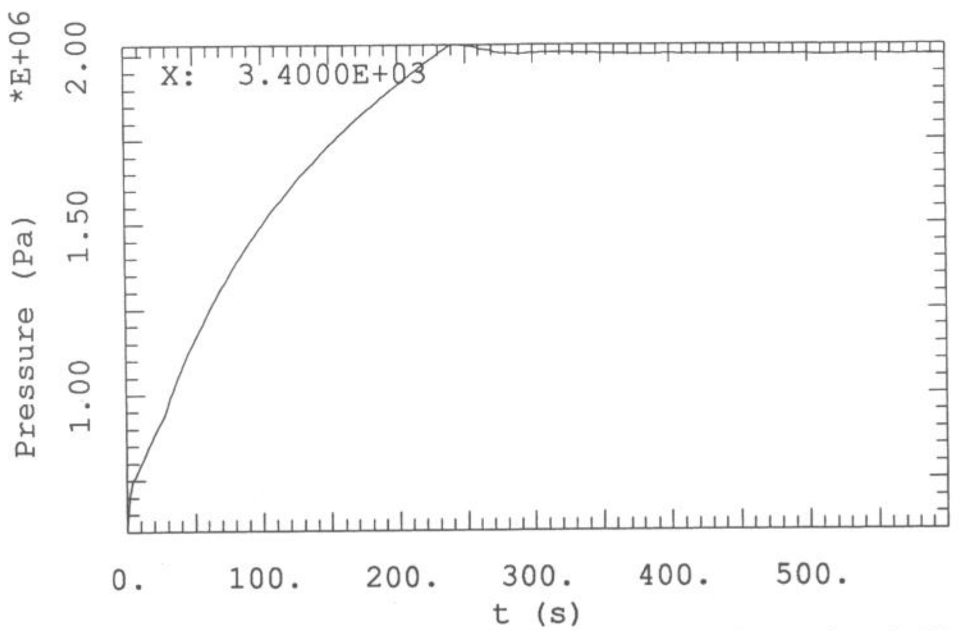

Figure 9. Pressure development of the helium in header C close to the return box, at the end of the heated zone (calculated).

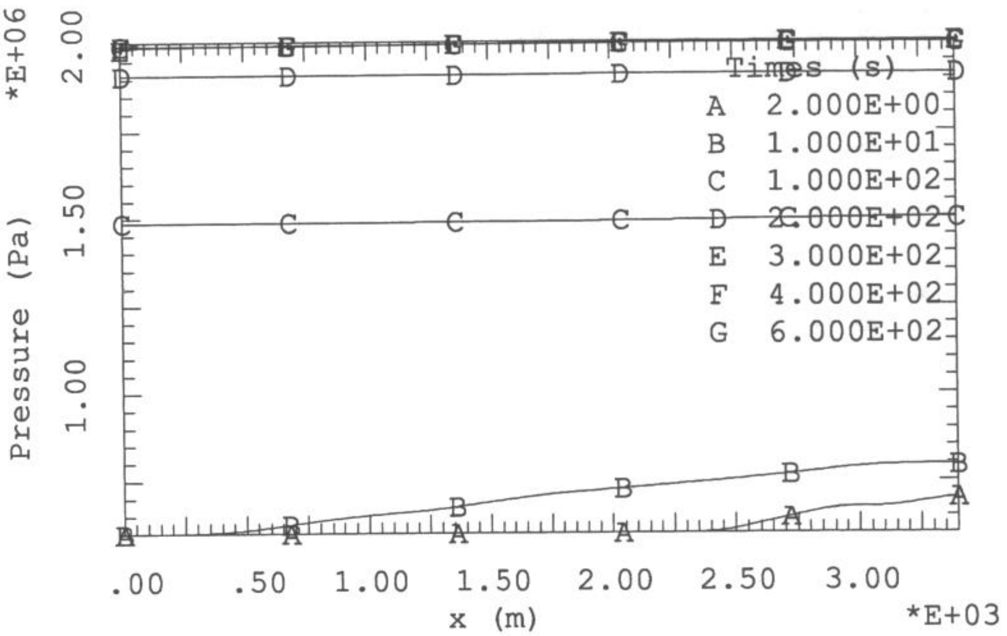

Figure 10. Pressure profile of the helium in header C (calculated).

The mass flow of the helium discharged from the header is shown in Fig. 11. The flow oscillations preceding the helium pressure rise up to 20 bar are caused by the pressure wave propagating with the speed of sound.

The valve opens when the pressure reaches 20 bar and the mass flow rises sharply up to 1.5 kg/s, decreasing afterwards to about 1 kg/s.

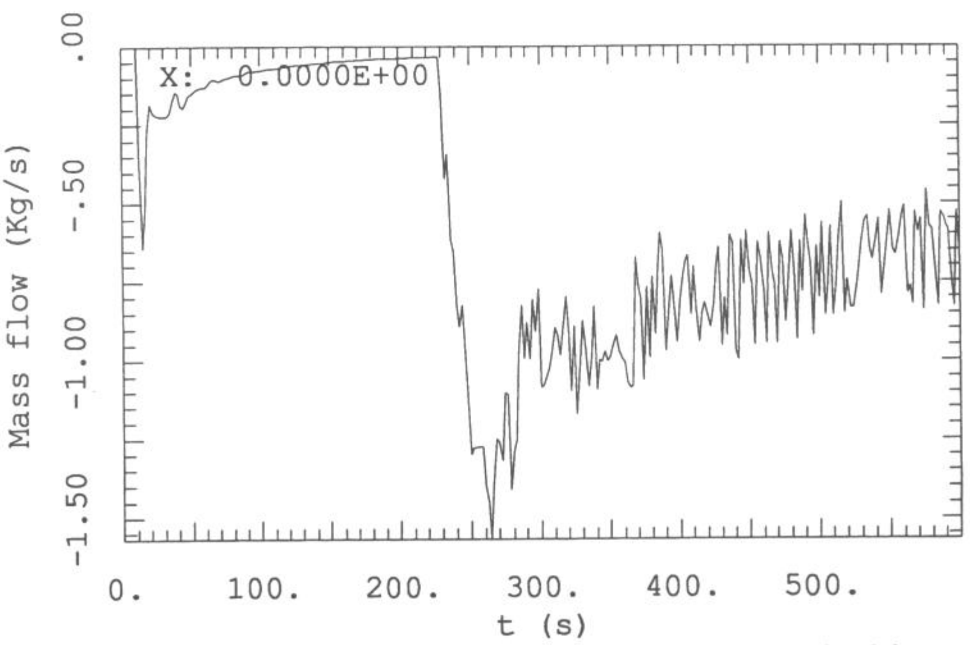

Figure 11. Helium mass flow discharge from header C after the insulating vacuum breakdown (calculated).

Case 2. Two safety valves located in QUI and RETURN BOX, the insulating vacuum vented at the centre of the sector (Fig. 2b).

The position of the safety valves and the heated zone are shown in Fig.2b. The surface heat flux to the header is shown in Fig.1.

Figures 12 and 13 show the development of the header and the helium temperatures in the middle of the heated zone (1700 m from the QUI). Similar to the previously analysed *case 1,* a relatively high temperature difference (of about 60 K) exists between the header and the helium (compare Figures 3, 4 and 12, 13).
The development of the helium pressure close to the safety valve is shown in Fig. 14, while Fig. 15 gives the pressure profile along the header at different times. The helium flow through one of the safety valves is shown in Fig. 16.
The pressure oscillations are of the order of 0.5 bar ie 2.5 % of the valve setting pressure. Pressure variations along the header are noticeable only during a few seconds after the insulating vacuum breakdown - see Fig. 15. The helium pressure development and profile are similar in *case 1* and *case 2* - compare Fig. 8, 9, 10 and 14, 15.
The maximal helium mass flow discharged through one valve is of about 1 kg/s, the total mass flow is similar to *case 1* (compare Fig. 11 and 16).

On the basis of the simulation results it can be stated that the addition of the second valve does not change either pressure evolution or helium discharge in a critical way. The second safety valve is then not a must and may be added if the redundancy is required.

In the following we will analyse transient behaviour and helium discharge from other headers only for the more conservative *case 1*, i.e. header equipped with one safety valve only and vented at the opposite end (Fig. 2 a).

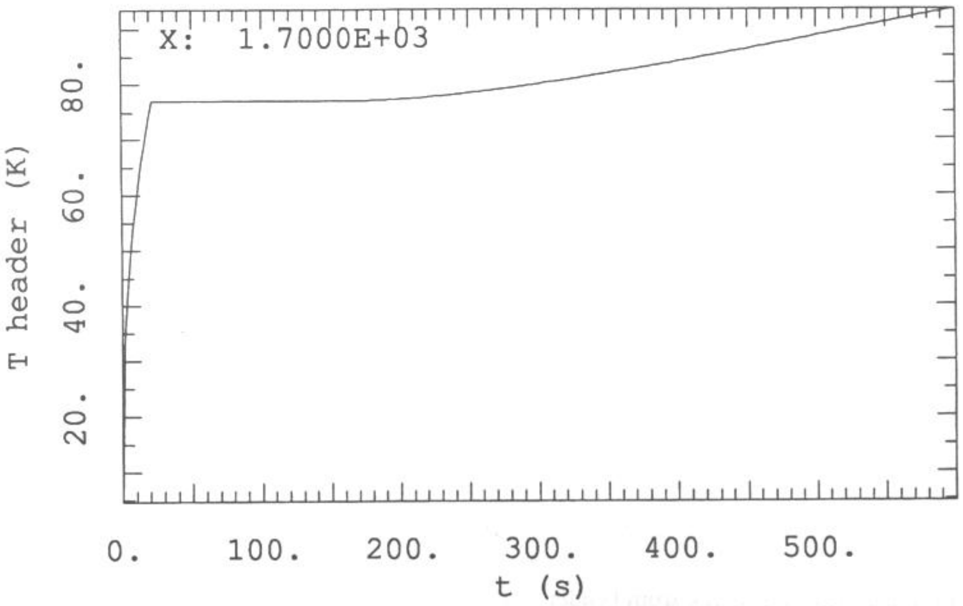

Figure 12. Development of header C temperature in the middle of the heated zone, two safety valves (calculated).

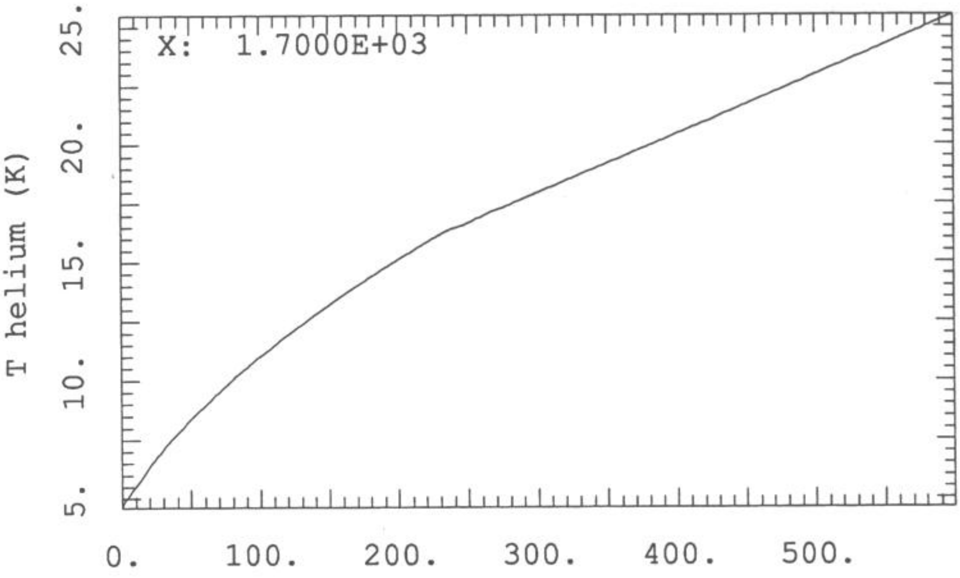

Figure 13. Development of the helium temperature in header C in the middle of the heated zone, two safety valves (calculated).

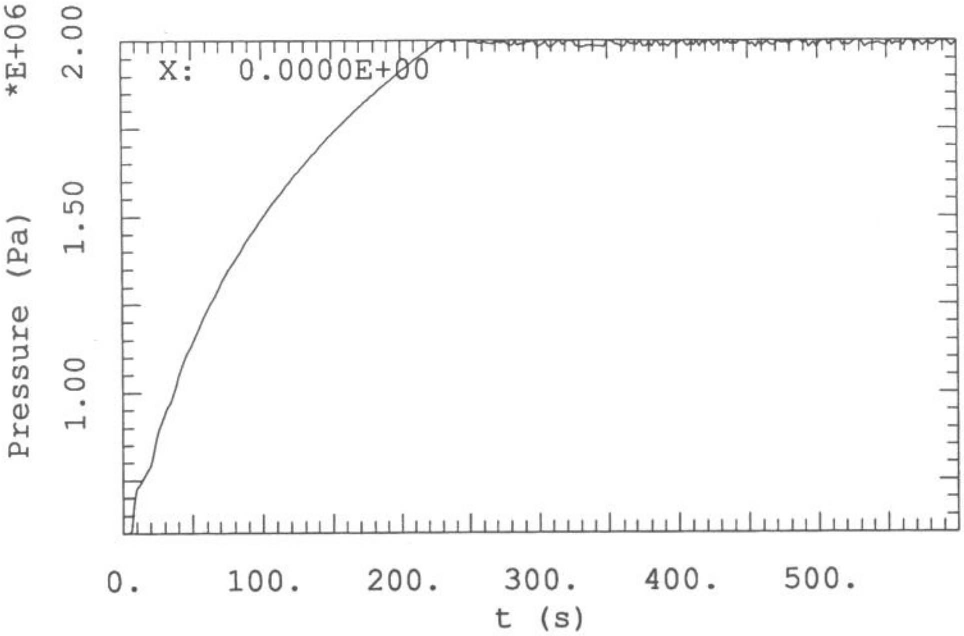

Figure 14. Development of the pressure in header C close to the safety valve, two safety valves (calculated).

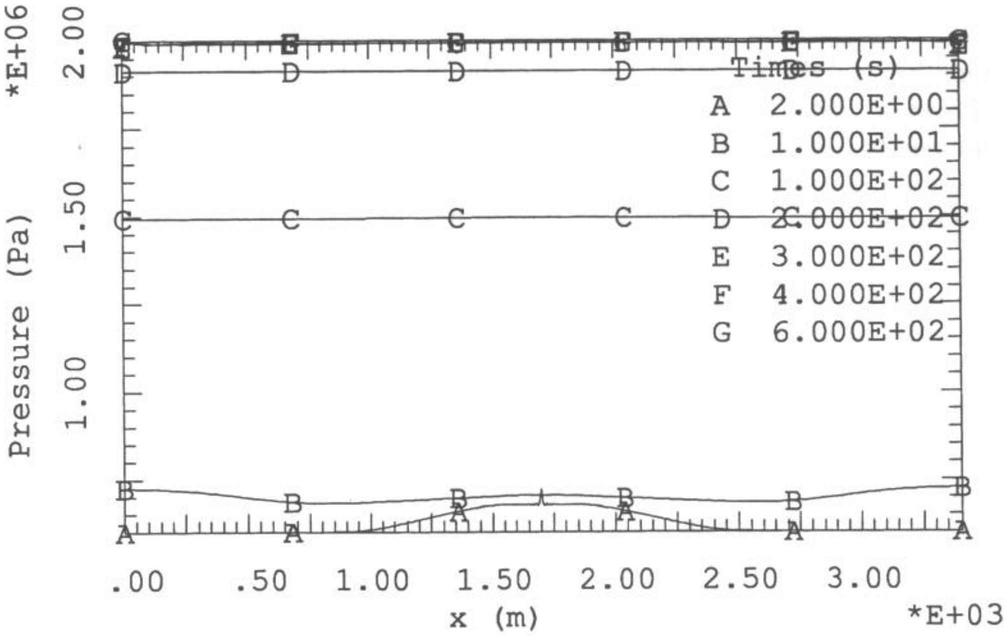

Figure 15. Helium pressure profile in header C, two safety valves (calculated).

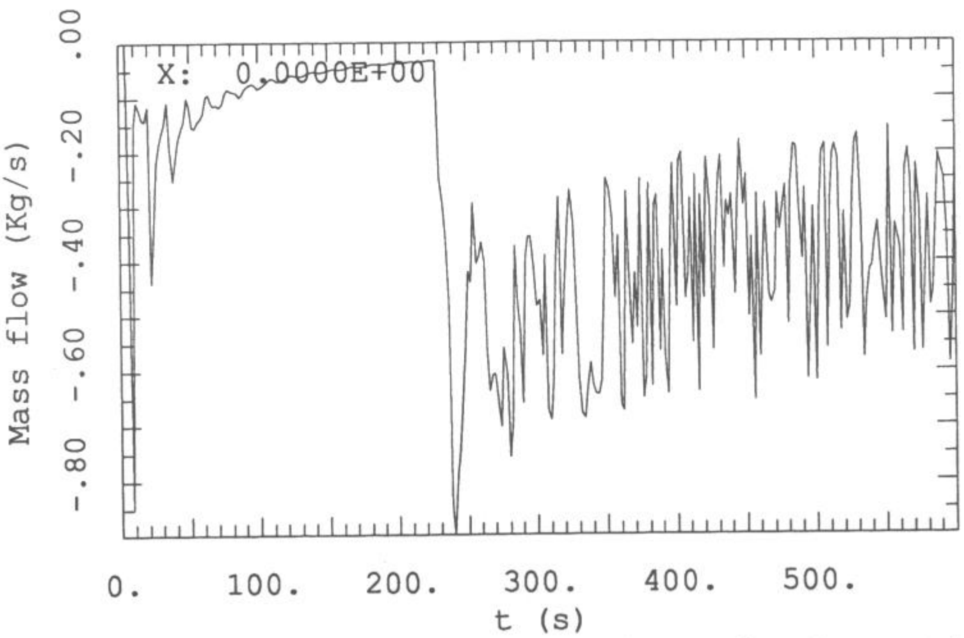

Figure 16. Development of helium mass flow through one safety valve, two safety valves mounted (calculated).

2.3 Header F

Header F is thermally coupled to the thermal shield. In a worst case scenario it may be as cold as 30 K. The calculations are made for the input surface heat flux shown in Fig. 1, resulting in a linear heat flux of 8500 W/m when the header temperature is below 77 K. Having in mind that the initial temperature of the header, even in a worst case scenario, is much above 4.2 K (for which a value 0.5 W/cm^2 was measured, ref.^{2}), the input heat flux to header F is estimated in a very conservative way.

Fig. 17 shows the helium pressure in header F close to the safety valve. Pressure oscillations are much below 0.1 bar and are negligible from a practical point of view. The pressure profile along the header is shown in Fig. 18.

The helium temperature development close to the safety valve is shown in Fig. 19. Like for header C the temperature away from the heated zone stays close to the initial value. The helium flow from the header through the safety valve is shown in Fig. 20. The maximum flow is about 0.3 kg/s and the average flow is about 0.15 kg/s.

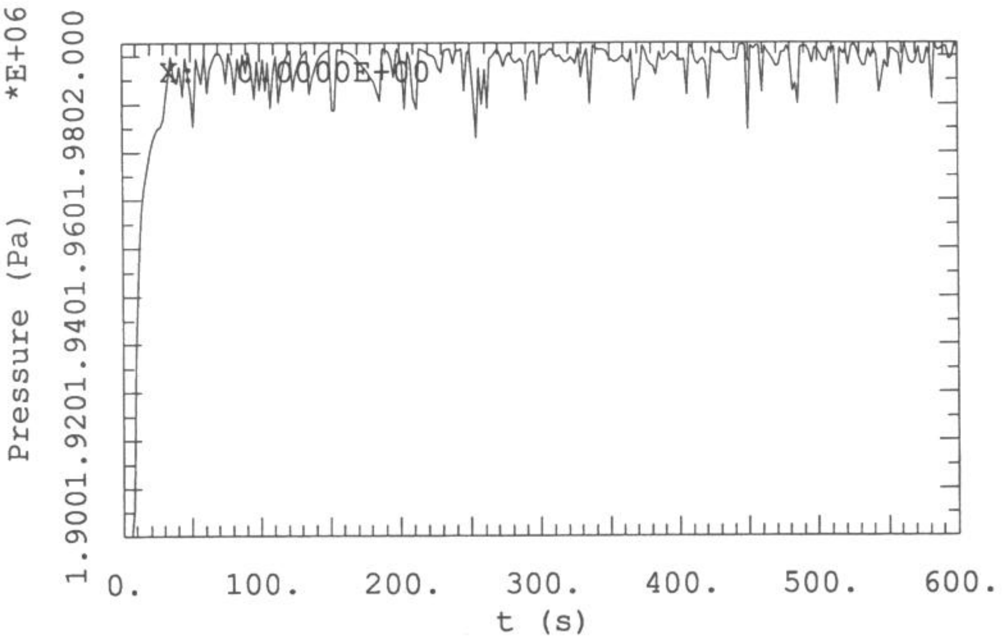

Fig. 17. Pressure development in header F close to the safety valve after breakdown of the insulating vacuum (calculated).

2.4 Header E

The helium development in header E will be similar to that in header F.

2.5 Header D

Header D is a cold buffer, used for temporary recovery of the helium discharged from the cold mass after a magnet quench. It should also recover helium discharged from other headers through the safety valves. The helium pressure development in header D equipped with one safety valve and vented at the opposite side (see Fig. 2 a) is shown in Fig. 21. The pressure will rise up to about 5 bar in 600 s and the safety valve will remain closed.

Fig. 22 shows the pressure profile along header D at 2, 100 and 600 s after breakdown of the insulating vacuum.

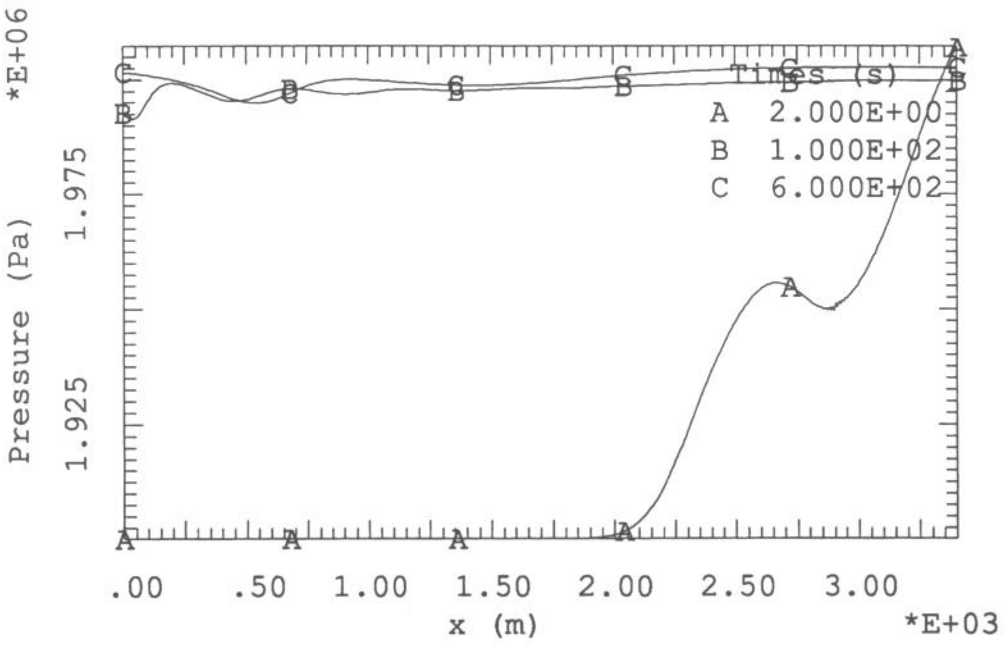

Fig. 18. Helium pressure profile along header F at 2, 100, 600 s after breakdown of the insulating vacuum (calculated).

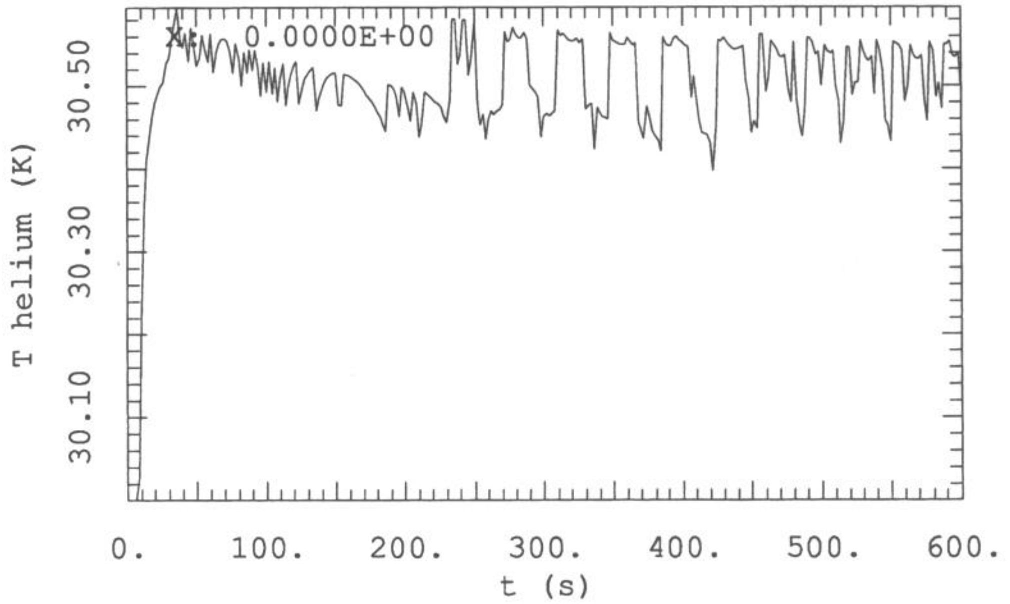

Fig. 19. Development of the helium temperature in header F close to the safety valve after breakdown of the insulating vacuum (calculated).

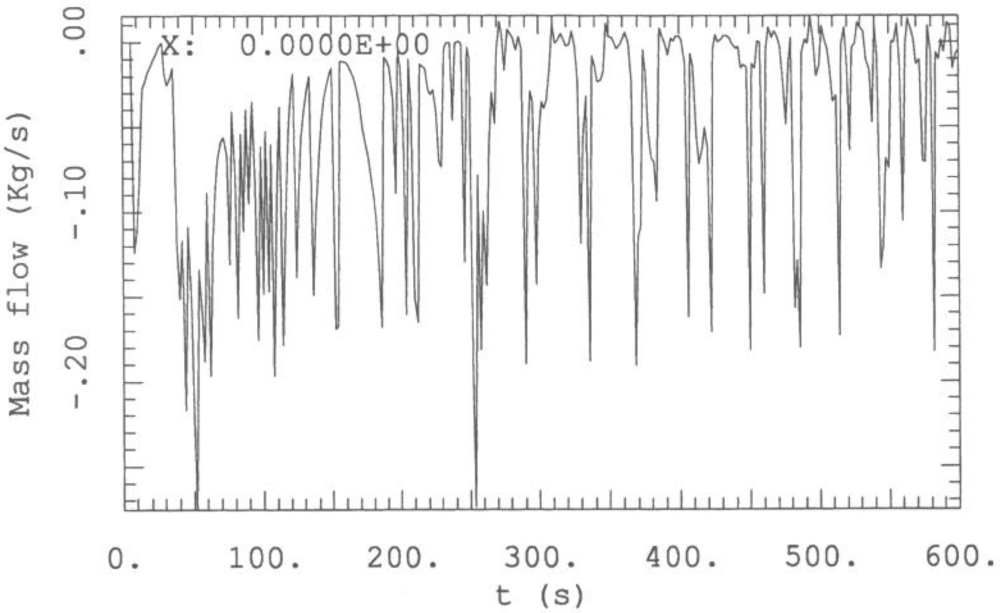

Fig. 20. Helium flow from header F through the safety valve after breakdown of the insulating vacuum (calculated).

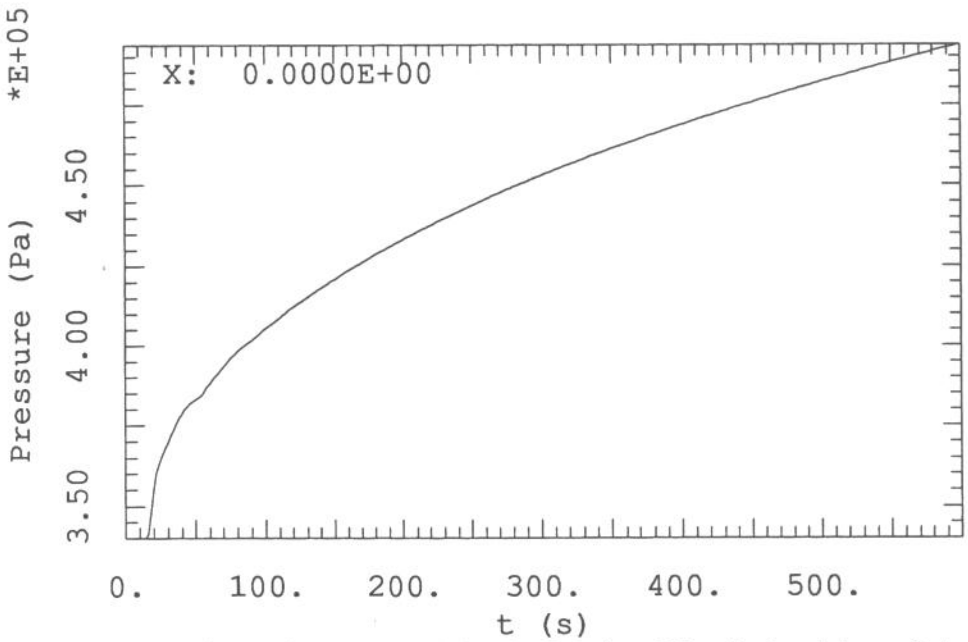

Figure 21. Development of the helium pressure in header D during 600 s after breakdown of the insulating vacuum (calculated).

The distribution of the helium flow along header D at 2, 100 and 600 s after the vacuum venting is shown in Fig. 23. The header capacity outside the heated zone is sufficient to accommodate the helium expelled from the zone. The velocity of pressure rise in the header is of about 1 mbar/s. In these conditions the header will accommodate the helium expelled from headers C, E, and F with a total flow of about 2 kg/s. For comparison, the instantaneous helium discharge from a cold mass after a limited quench is of about 16 kg/s.

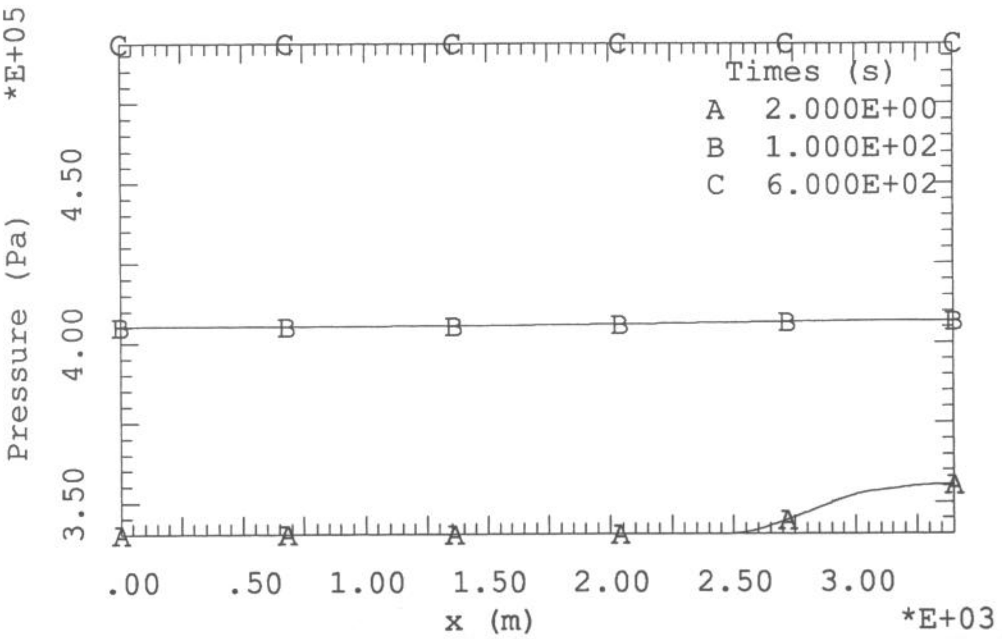

Figure 22. Helium pressure profile along header D at 2, 100, 600 s after breakdown of the insulating vacuum (calculated).

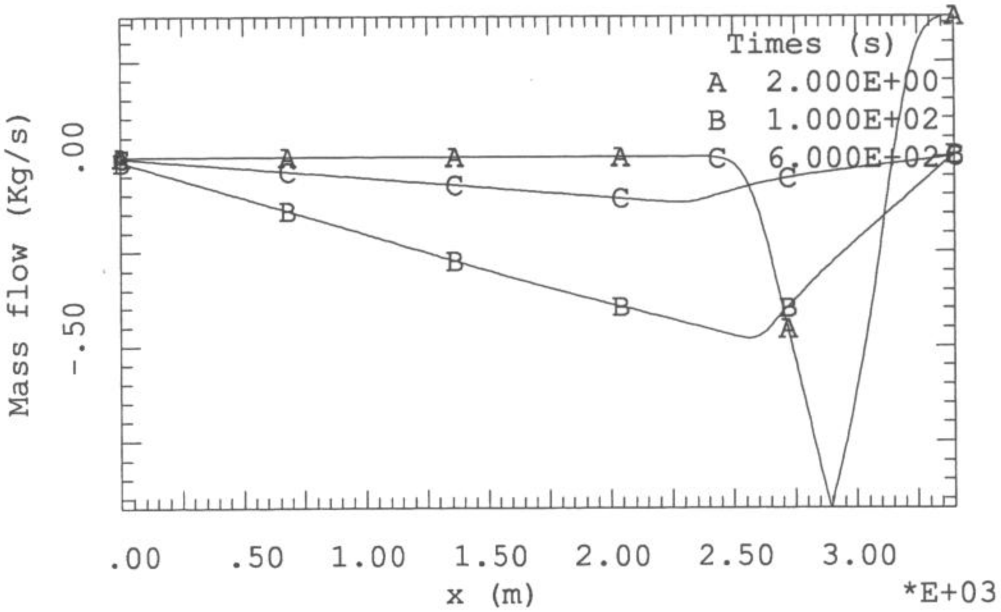

Figure 23. Distribution of helium flow along header D at 2, 100 and 600 s after breakdown of the insulating vacuum (calculated).

Sizing of QRL safety valves.

If header D is to be a sink for the helium expelled from headers C, E and F, its safety valve should be set at a lower pressure than the valves mounted on other headers. In the estimation of the required flow coefficient k_v of the safety valves, a pressure drop of 2 bar across the valve has been assumed. It means that the setting pressure of the safety valves mounted on header D should be e.g. 18 bar and for other valves 20 bar.

It follows from the above analysis that it is sufficient to protect headers B, C, E and F with a single safety valve. To cope with a sector quench header D must be protected with two valves.

The safety valves flow coefficients k_v are calculated for helium flow, temperature and pressure given in Table 3. The discharge temperature is taken as the highest helium temperature in the header (true if the safety valve is located close to the vented zone). The flow coefficients are calculated with a 50 % margin.

Table 3. Flow coefficients kv of the safety valves protecting QRL headers.

	Dia./wall th. [mm/mm]	Helium discharge [kg/s]	Setting pressure [bar]	Discharge temperature [K]	Delta p [bar]	kv/DN [-]/[mm]	Remarks
B	267/2.9	0.5	6	300	5	15/25	Assumed leak from header C, discharge to atmosphere
C	100/2.0	1.5	20	25	2	36/40	See Fig. 5, 6, 8, 11
D	150/2.0	20	18	10	10	162/100	See ref.[2]
F	80/2.0	0.2	20	60	2	15/25	Analogous to header F

3. Conclusions and recommendations

1. The heat flux to the helium in the headers after venting to air of the insulating vacuum is limited by heat transfer between the header wall and the helium and not by the air condensation rate on the header outer surface. The resulting heat fluxes are an order of magnitude lower than estimated for air condensation on the header surface and given in ref.[2].
2. Header B should be equipped with one safety valve only, final sizing of the valve depends on the assumed maximum helium leak from header C to header B. The valve should discharge the helium to the environment.
3. Headers C, E and F should be equipped with one safety valve each. The helium discharged from headers C, E and F can flow to header D.
4. Header D should be equipped with two safety valves, sized to cope with a sector quench.
5. In case when header D acts as a helium sink for headers C, E and F the safety valves mounted on header D should be set to a lower value, e.g. to 18 bar instead of 20 bar. The valves mounted on headers C, E and F must be insensitive to the counter-pressure in header D.
6. It is recommended to design and run a dedicated experiment to confirm the helium transients in the headers predicted by the simulations. An existing cryo-line, should be suitably instrumented and vented to air. Mass and energy balances should be measured and compared with the simulations performed with GANDALF[7]. In case of discrepancies the above conclusions should be revised.

Acknowledgements

The author would like to thank Germana Riddone, Wolfgang Erdt, Ralf Trant and Udo Wagner for helpful discussions, Philippe Lebrun for his suggestions and thorough proofreading and Luca Bottura for the introduction to GANDALF and help in simulations.

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Appendix - Reynolds number and helium flow velocity in header C after breakdown of the insulating vacuum

The results shown in Figures A1 to A5 are calculated for the *Case 1* shown schematically in Figure 2a (one safety valve located in the QUI, the insulating vacuum vented at the opposite end of the sector).

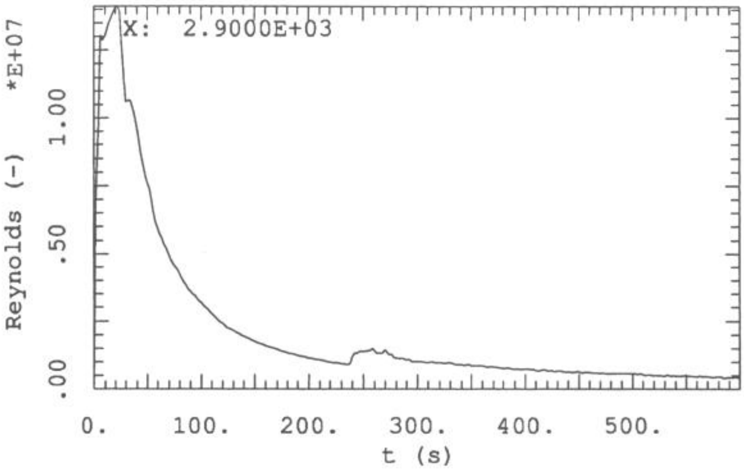

Figure A1. Reynolds number at the beginning of the heated zone of header C after the insulating vacuum breakdown (calculated).

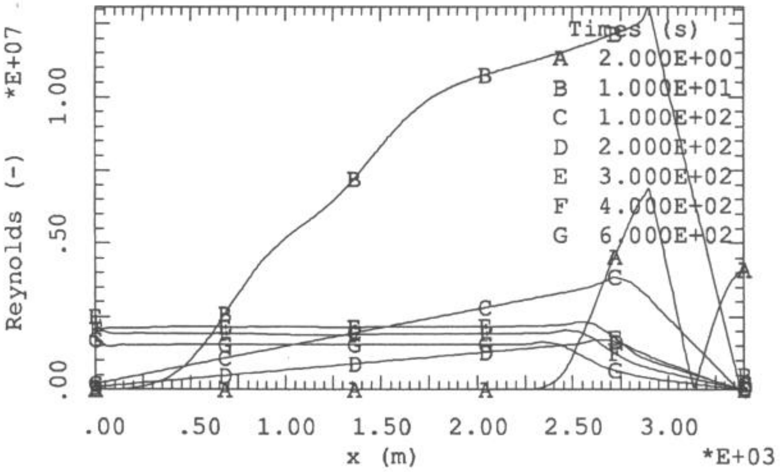

Figure A2. Reynolds number profile along header C after breakdown of the insulating vacuum (calculated).

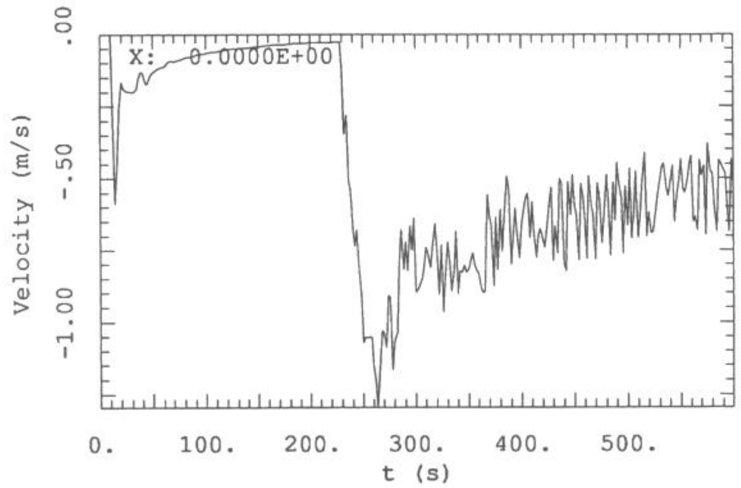

Figure A3. Development of the helium velocity in header C close to the safety valve after breakdown of the insulating vacuum (calculated).

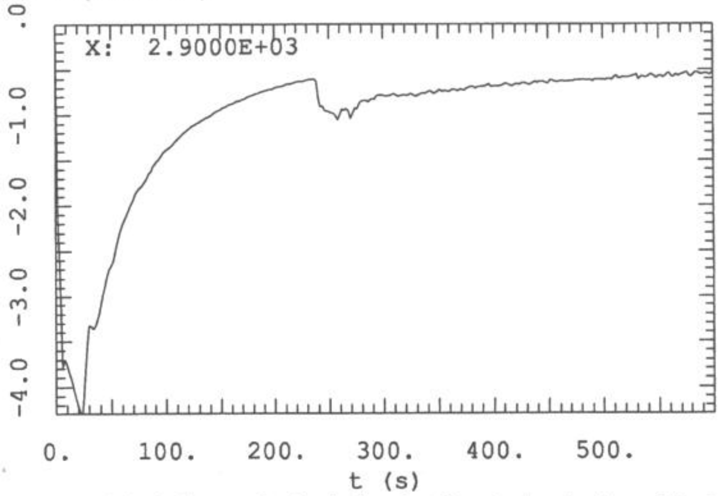

Figure A4. Development of the helium velocity in header C at the beginning of the heating zone after breakdown of the insulating vacuum (calculated).

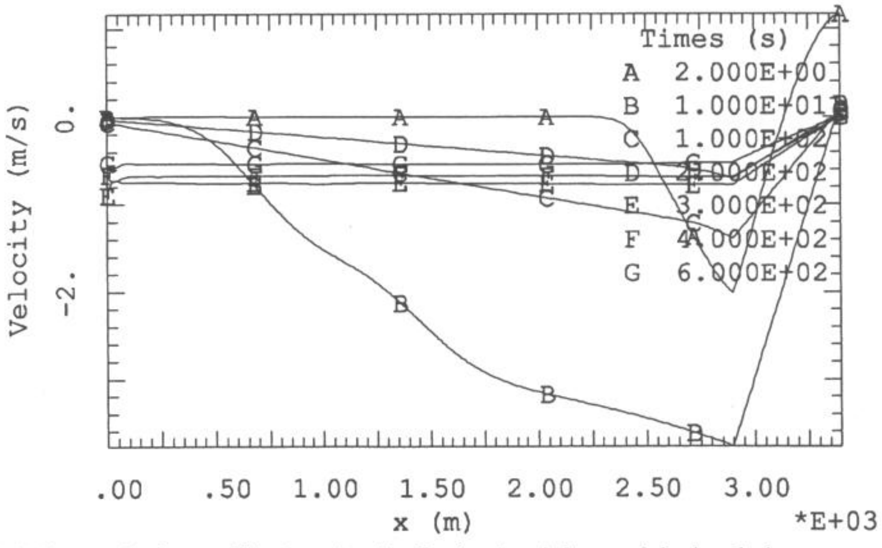

Figure A5. Helium velocity profile along header C after breakdown of the insulating vacuum (calculated).