Wrocław University of Technology

Update of the cryogenic risk analysis following the 19 September 2008 incident

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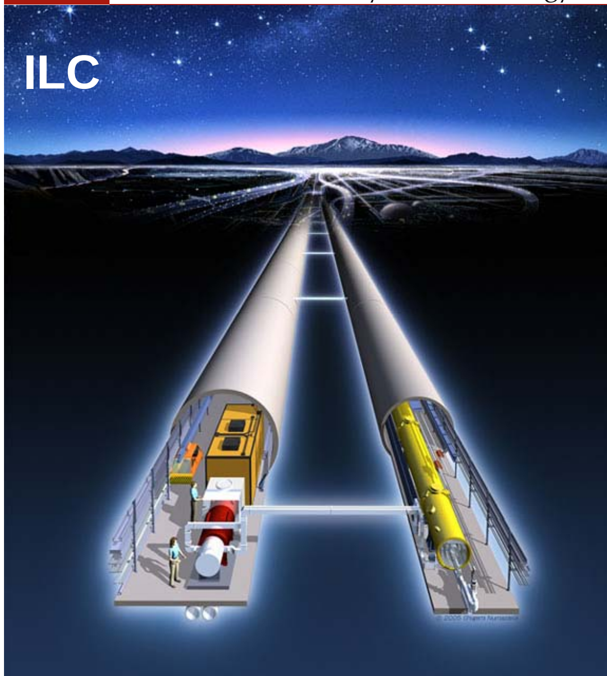
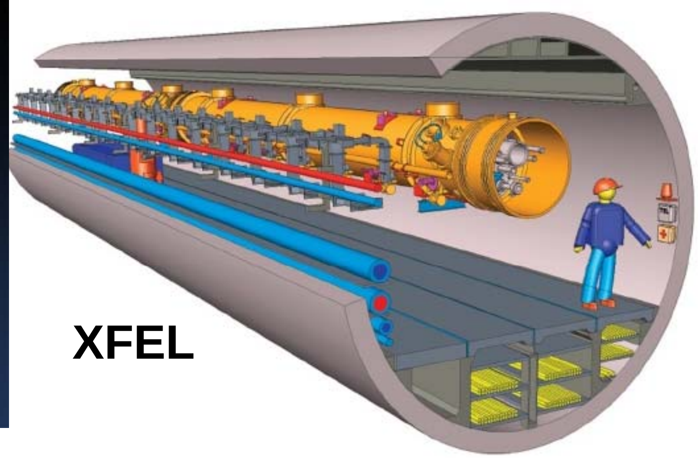
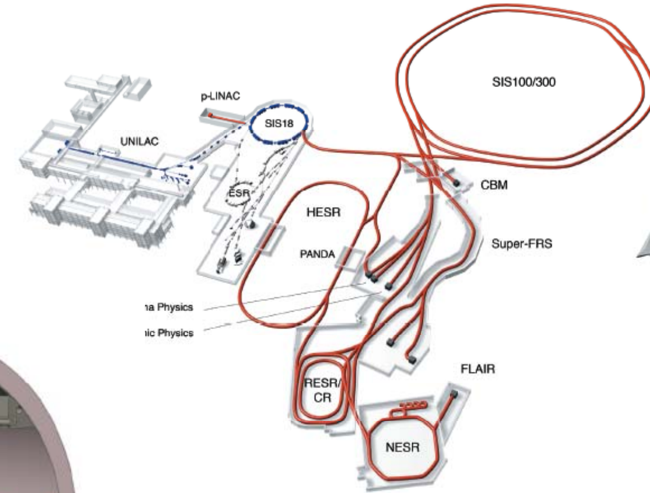
CERN, TE Seminar 12.11.2009

Cryogenics in „Big Science”

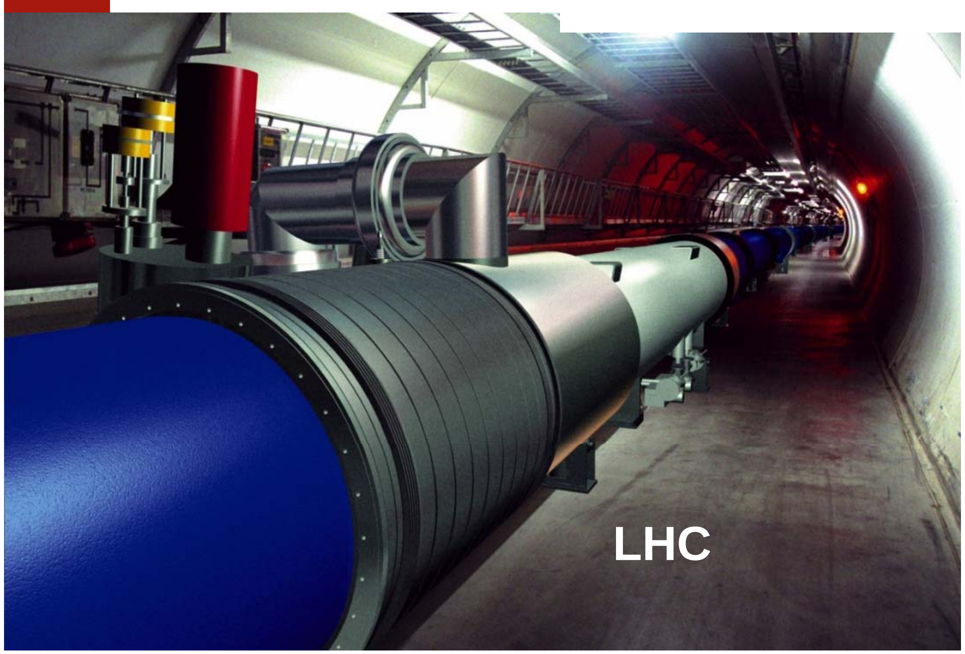




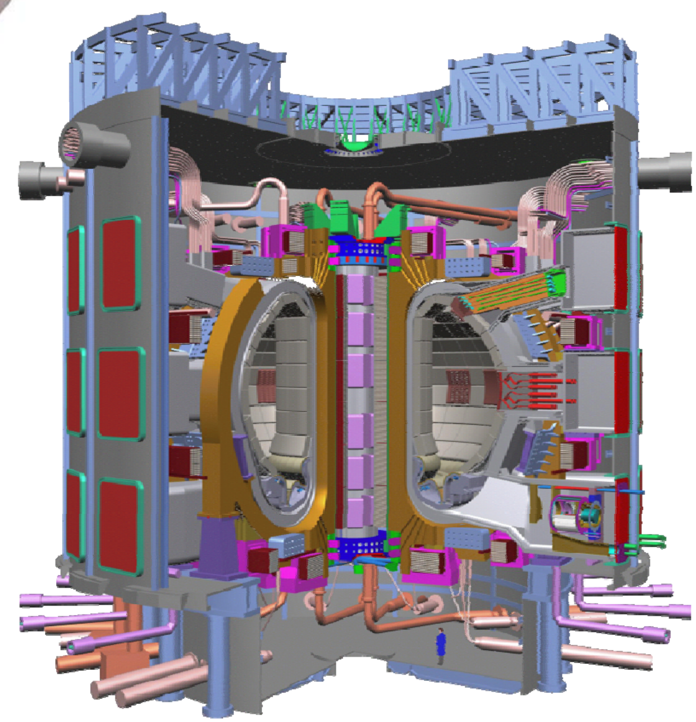
XFEL



FAIR



ITER



Cryogenics in „Big Science” projects

Installation, location	Type	Cooling power	Helium inventory
LHC, CERN, Geneva	pp collider	144 kW	120 ton
FAIR, GSI, Darmstadt	ions accelerator	42 kW @ 4.4	11 ton
XFEL, DESY, Hamburg	free electron laser	12 kW	5 ton
W7-X, Max Planck Greifswald	fusion stellarator	5 kW	2 ton
ITER, ITER IO, Cadarache	fusion tokamak	60 kW @ 4.5 K 950 kW @ 80 K	20 ton
ILC, no decision	e+ e- lin. collider	211 @ 4.5 K	100 ton

Properties of cryogenic liquids

Cryo g-en	M [g]	T_N [K]	ρ_1 [kg/m^3]	ρ_2 [kg/m^3]	ρ_3 [kg/m^3]	T_C [K]	P_C [MPa]	ΔH_V [kJ/kg]	V_2 / V_1 ----	V_3 / V_1 ----
He	**4,003**	**4,2**	**124,9**	**16,91**	**0,178**	**5,2**	**0,229**	**20,3**	**7,4**	**701**
H_2	2,01	20,3	70,81	1,34	0,089	33,04	1,29	446,0	52,8	**788**
Ne	20,18	27,17	1207	9,58	0,90	44,5	2,73	85,8	126,0	**1341**
N_2	28,01	77,3	808	4,62	1,25	126,2	3,39	199,0	175,0	**646**
O_2	32,00	90,2	1140	4,47	1,43	154,6	5,04	213,0	255,0	**797**
CH_4	32,00	111,6	423	1,82	0,717	190,5	4,60	510,0	232,0	**590**

LHC Project Note 177

1999-01-12

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Preliminary risk analysis of the LHC cryogenic system

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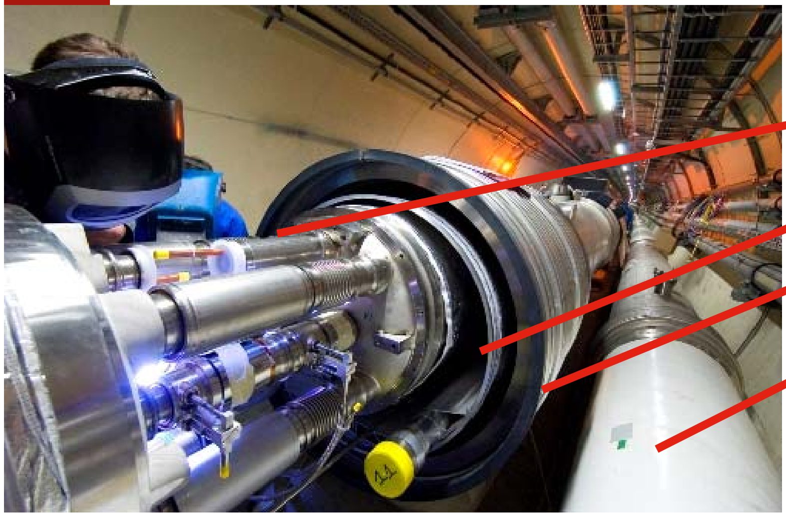
** LHC-ACR Group

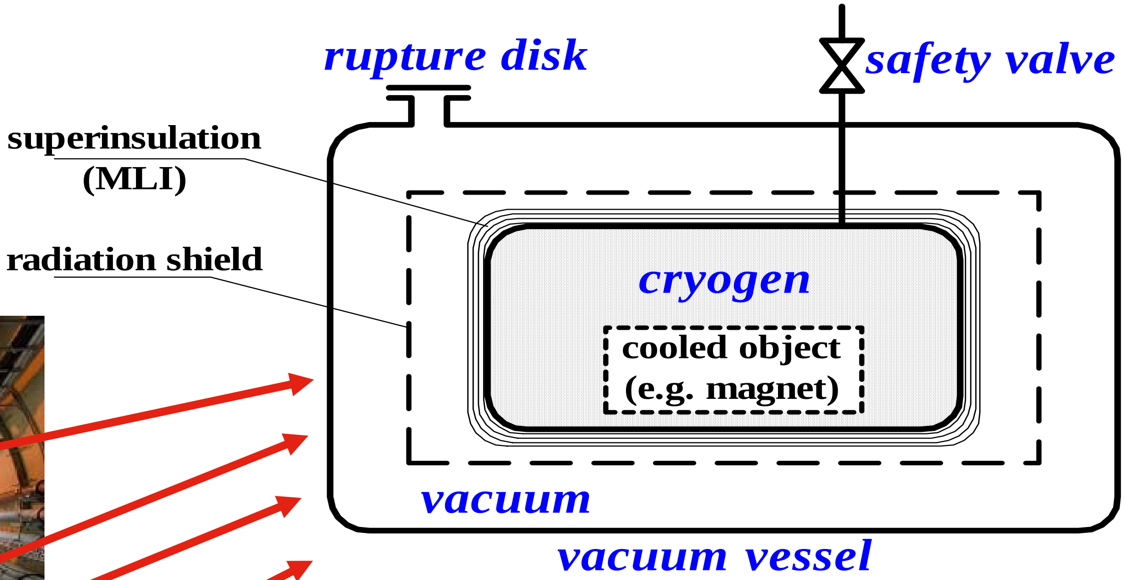
Summary

The objective of the study is to identify all risks to personnel, equipment or environment resulting from cryogenic failures that may accidentally occur within the cryogenic system of Large Hadron Collider in any phase of the machine operation, and that could not be eliminated by design. We then formulate recommendations concerning lines of preventive and corrective defence, as well as further, more detailed studies.

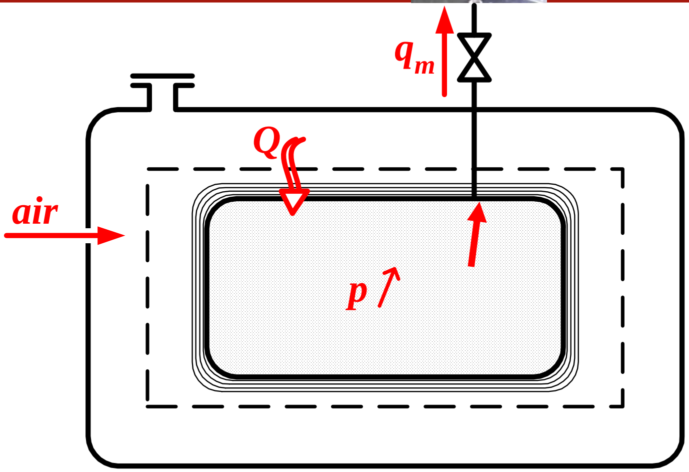
Cryogenic node - simplest element of the cryogenic system - basis for the risk analysis

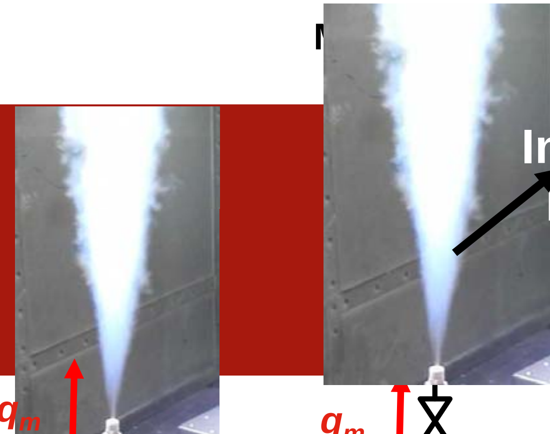
Each component of the machine like pipe, vessel, heat exchanger, and cryostat can been treated as separate helium enclosure, characterized by the amount and thermodynamic parameters of helium.

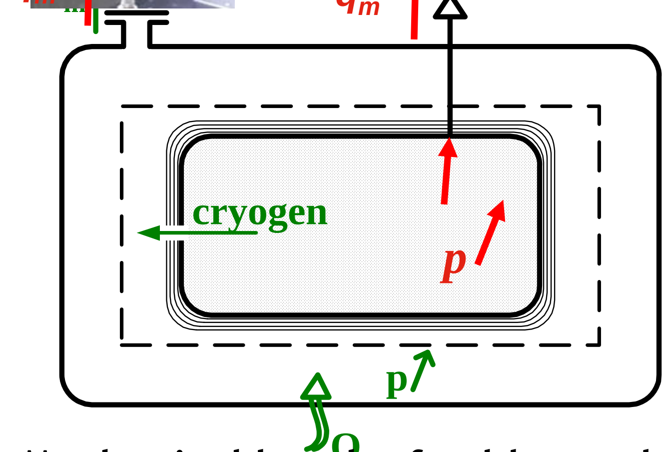




Possible failures of cryogenic node followed by the cryogen discharge



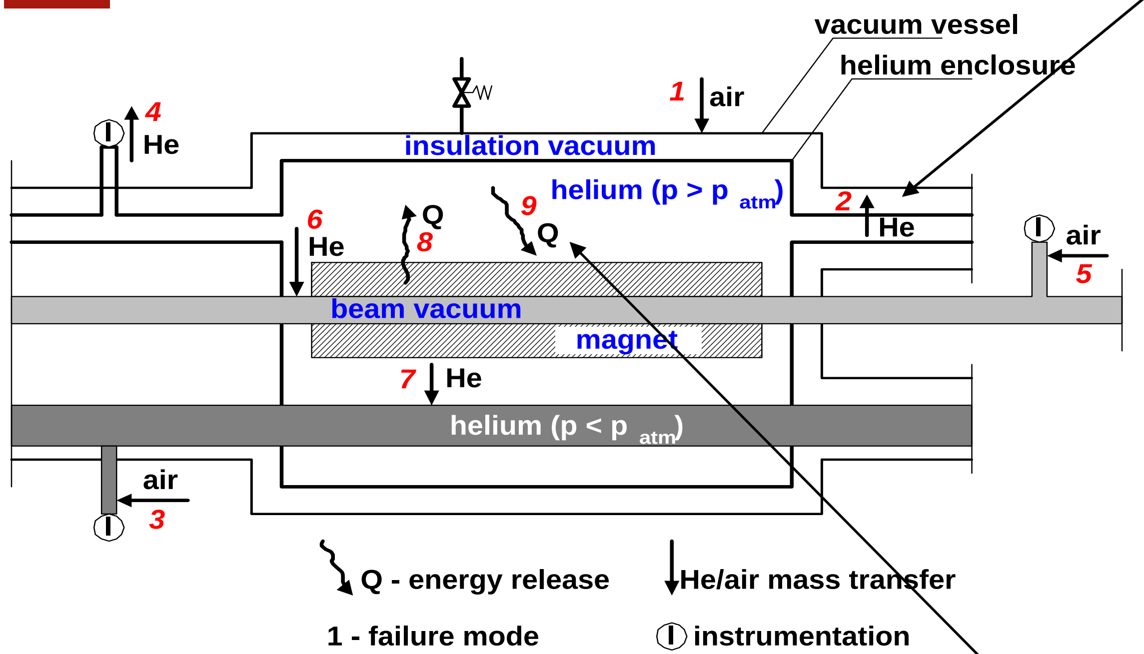




- Mechanical break of warm vacuum vessel
- Fast degradation of vacuum insulation with air
- Intensive heat flow to the cryogen
- *Magnet quench (optionally)*
- Pressure increase of the cryogen
- Opening of the safety valve
- Cryogen discharge through the safety valve

- Mechanical break of cold vessel
- Fast degradation of vacuum insulation with cryogen
- Intensive heat flow to the cryogen
- *Magnet quench (optionally)*
- Pressure increase of the cryogen and in the vacuum space
- Opening of the rupture disk and/or safety valve
- Cryogen discharges through the rupture disk and/or safety valve

Possible failure modes of the LHC cryogenic system



1 Air flow to insulation vacuum

2 Helium flow to the insulation vacuum

3 Air flow to the sub-atmospheric helium

4 Helium flow to environment

5 Air flow to beam vacuum

6 Helium flow to beam vacuum

7 Pressurised helium flow to sub-atmospheric helium

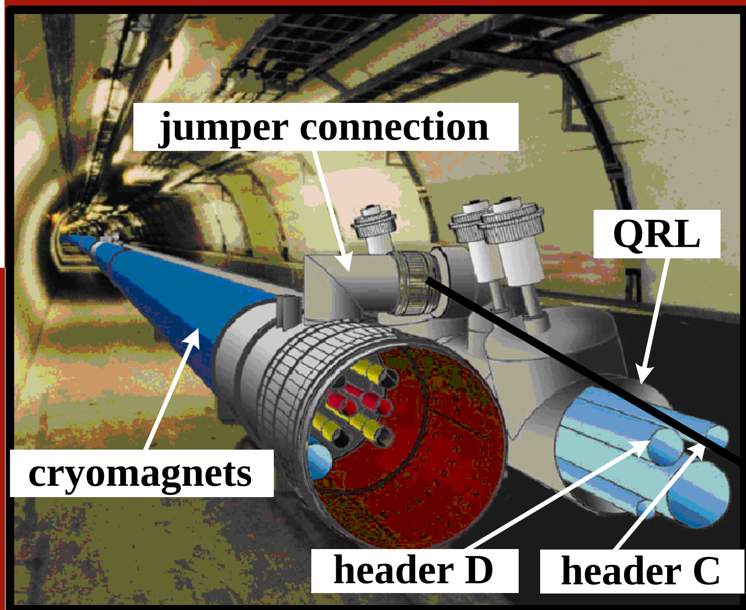
8 Energy release to cold mass helium due to magnet quench

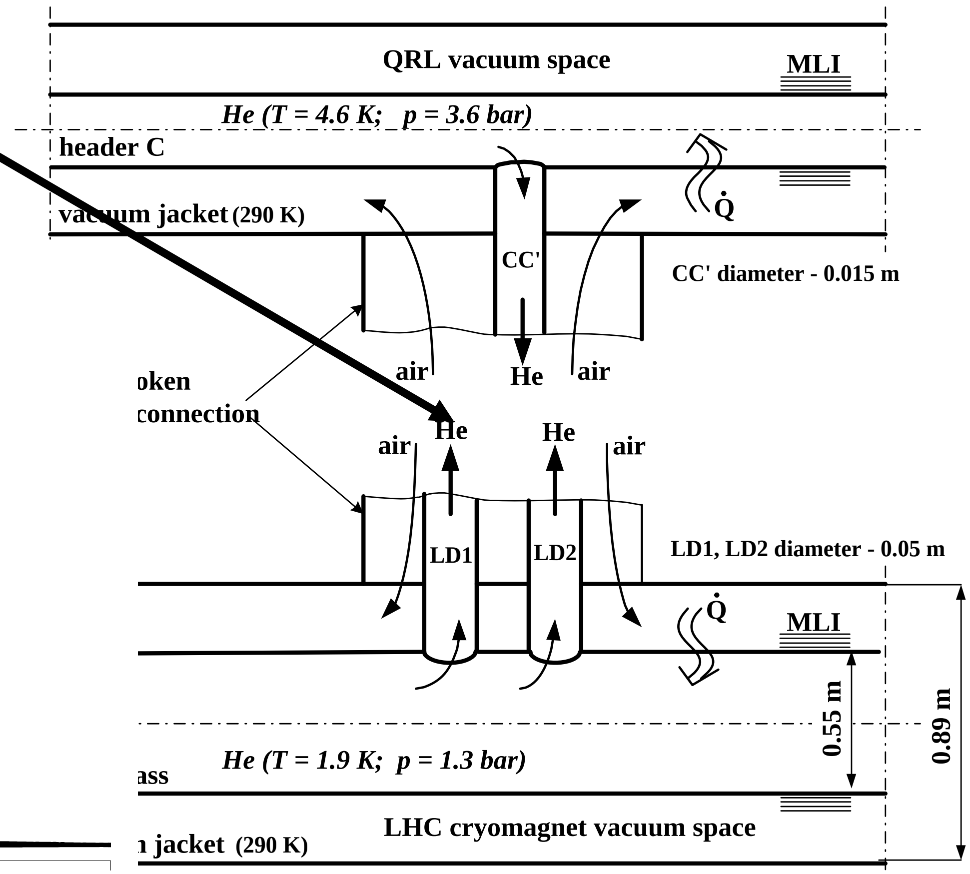
9 Energy release to cold mass helium due to electrical arc

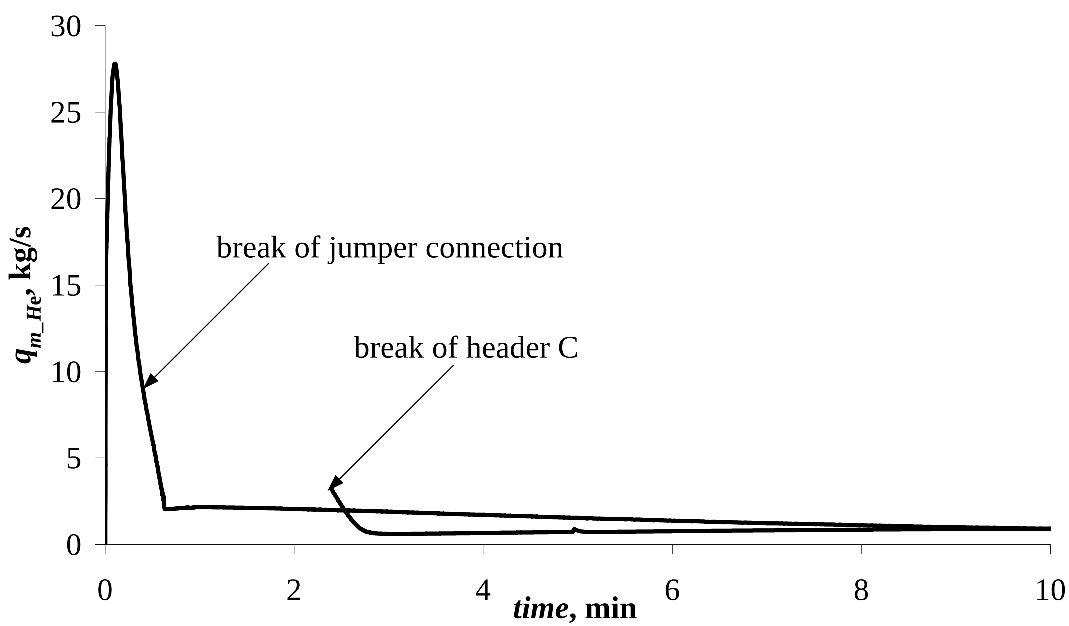
LHC Project Note 177

Failure	Maximum amount of helium relieved to the tunnel [kg]/ approximate flow rate [kg/s]	Recommendations
R1.2 LHC cryomagnets: He flow to cryostat insulation vacuum	475 / below 2 → **(resulting from 5 cm^2 hole)**	Further analysis necessary
R1.4 LHC cryomagnets: He flow to air	475 / He flow of a leak order	Consequences of the failure fully covered by R1.2 and R2.4
R1.6 LHC cryomagnets He flow to beam vacuum	475 / to be calculated	Further analysis necessary
R1.9 LHC cryomagnets energy release – electrical arc	475 kg / flow rate similar to R1.2	Not directly related to cryogenics, consequences covered by R1.2
R2.2 He flow to QRL insulation vacuum, assumption of header C break	3300 kg / lower than 2	Second, after R2.4 worst case scenario, further modelling of helium expulsion to the tunnel as well as helium propagation in the tunnel is necessary
R2.4 He flow to air, assumption of jumper connection break	4250 / about 20. About 600 kg are discharged in the first 60 s. After this time the mass flow-rate reduces by an order of magnitude.	Worst case scenario, further modelling of helium expulsion to the tunnel as well as helium propagation in the tunnel is necessary

Risk analysis - worst case scenario analysed - full break of jumper connection







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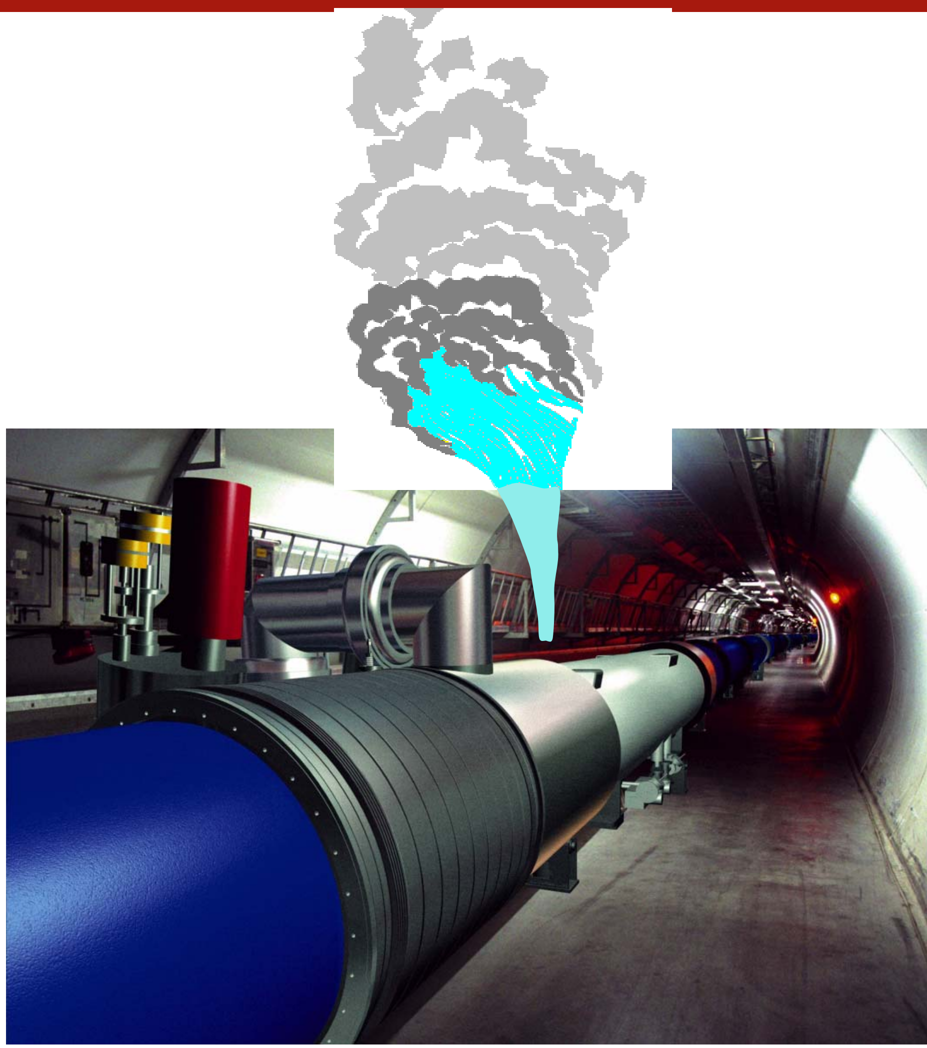
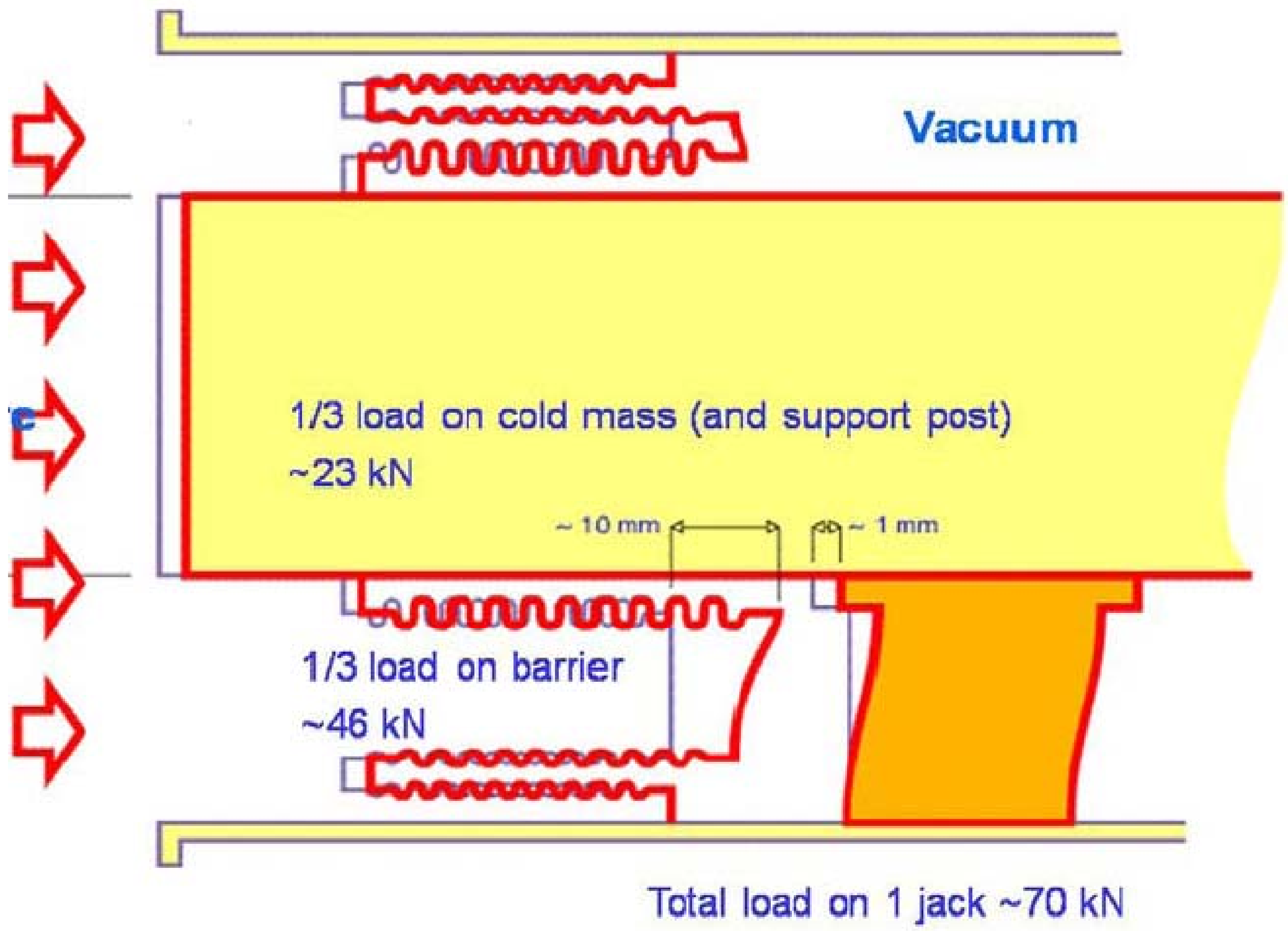
Can the helium discharge be avoided? Geneva, 19 September 2008:



„Investigations at CERN following a large helium leak into sector 3-4 of the Large Hadron Collider (LHC) tunnel have indicated that the most likely cause of the incident was a faulty electrical connection between two of the accelerator's magnets. Before a full understanding of the incident can be established, however, the sector has to be brought to room temperature and the magnets involved opened up for inspection. This will take three to four weeks. Full details of this investigation will be made available once it is complete".

Not foreseen in PRA: pressurization of the vacuum space



Damage caused by the pressurization of the vacuum space

Figure 14: Damage to interconnection QQBI.27R3 by excess compression

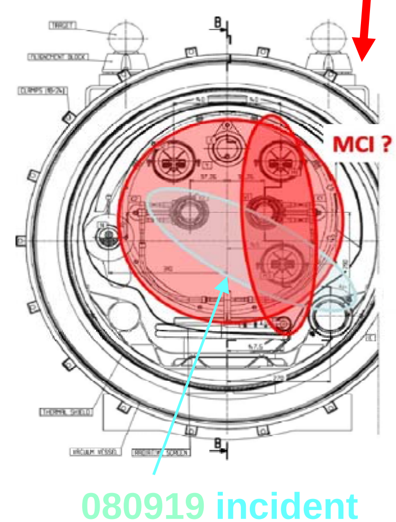
Preliminary Risk Analysis update

- Redefinition of Maximum Credible Incident with respect to He flow to cryostat insulation vacuum – **full cut of interconnecting pipes**
- Development of mathematical model
- Modeling of the 19. Sept. 08 incident
- Modeling of the MCI (Maximum Credible Event)
  - original SV scheme
  - temporary SV scheme
  - final SV scheme
- Analysis of the pressure rise in the LHC tunnel following the helium significant discharge
- Conclusions

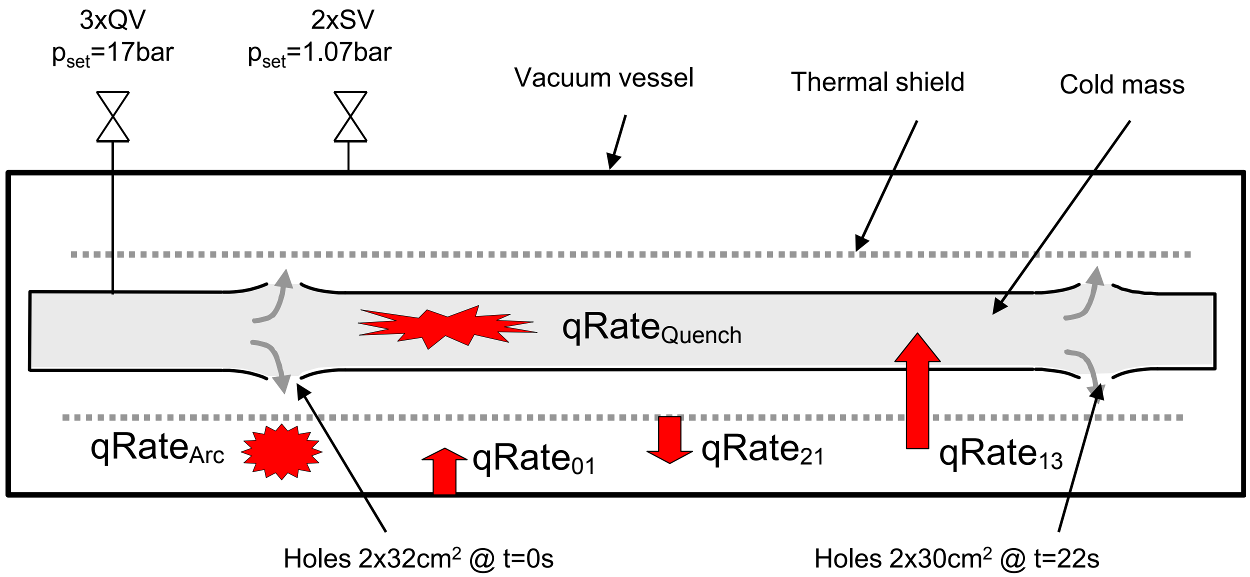
Preliminary Risk Analysis update: STEP 1: Redefinition of Maximum Credible Incident with respect to He flow to cryostat insulation vacuum - full cut of interconnecting pipes

Interconnection pipe	**PRA (LHC PN 177) cm^2**	**19. Sept. 08 , cm^2**	**MCI, cm^2**
Bus-bar piping	5	2 x 32	6 x 32
Line E	0	2 x 50	2 x 50
Line C via Line C’	0	1.8	2 x 1.8

A limiting factor which has to be taken into account is the available free cross-section for longitudinal flow in the magnet cold-mass lamination, limited to about 60 cm2. Therefore, even in the case when breaches appearing in the interconnection are larger than 2 x 60 cm2, the magnet laminations will limit the total effective opening to 120 cm2.



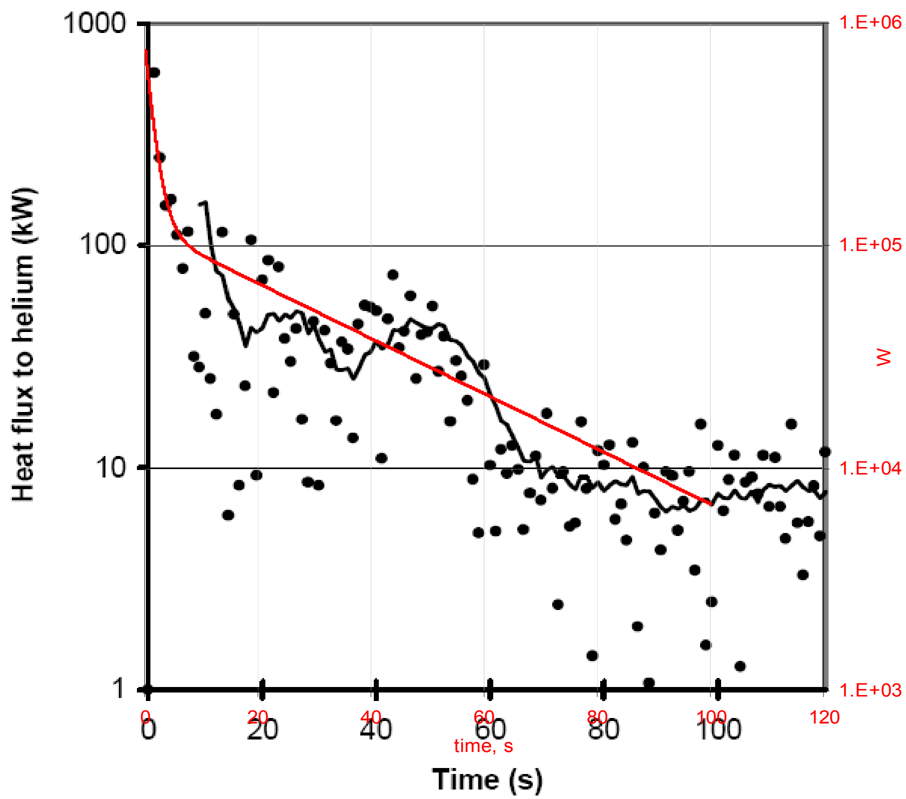
Preliminary Risk Analysis update: STEP 2 - Development of mathematical model



Thermodynamic model input:

$qRate_{Quecnch}$ – heat transfer to Cold Mass helium from quenched magnets
$qRate_{Arc}$ – heat transfer to helium from electrical arc
$qRate_{01}$ – heat transfer to Vacuum helium form Vacuum Vessel
$qRate_{21}$ – heat transfer to Vacuum helium form Aluminum Shield
$qRate_{13}$ – heat transfer to Cold Mass helium from Vacuum helium

Magnet quench heat transfer to cold mass helium - data from String experiments

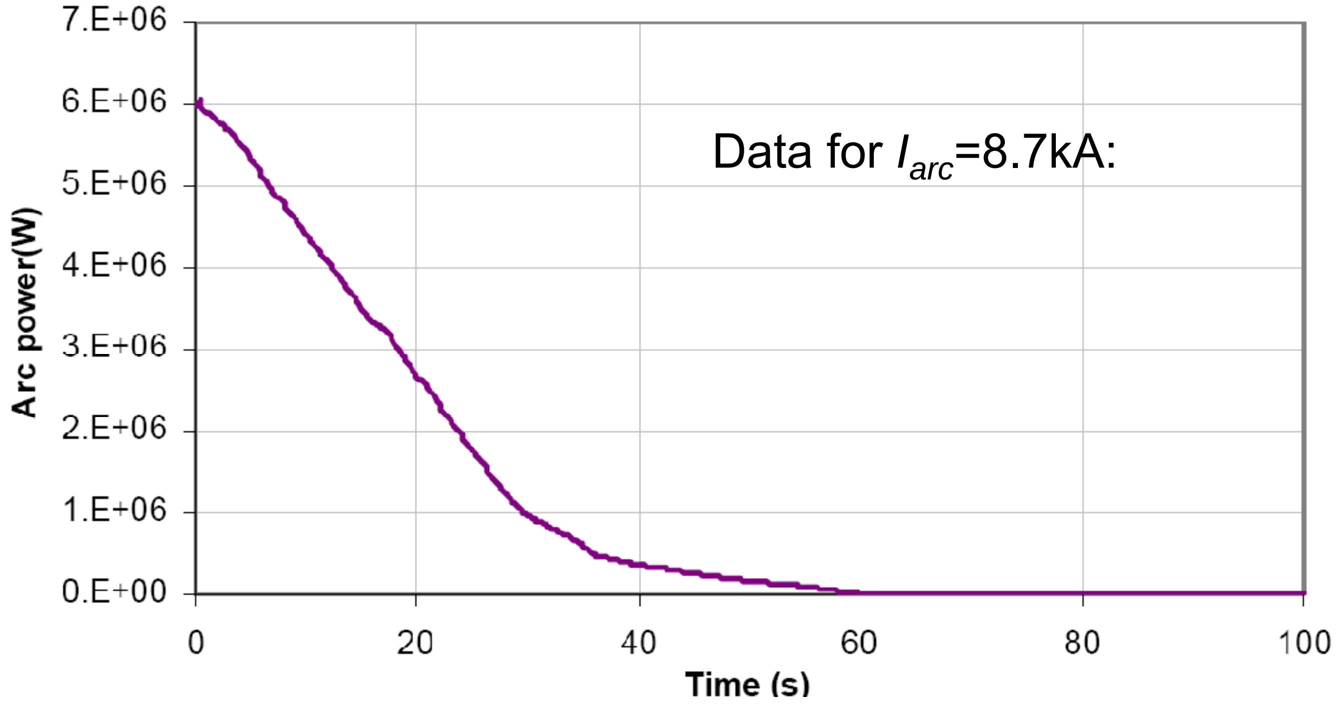


Data have been scaled according to the equation

$$E_{mag} = \frac{1}{2} L \cdot I^2$$

M. Chorowski, P. Lebrun, L. Serio, R. van Weelderen - *Thermohydraulics of Quenches and Helium Recovery in the LHC Magnet Strings* - LHC Project Report 154

Electrical arc heat transfer to helium - data from 19. Sept. 08 incident



Conservative scaling with the current:

$$Q_{ele\_arc}(I_{arc}) = \left(\frac{I_{arc}}{8.7kA}\right)^2 Q_{ele\_arc}(8.7kA)$$

A Perin - "*LHC Project Report 1168 - Annex F: Estimation of the mass flow of helium out of the cold masses and of the pressure evolution in the cryostat of sub-sector 23-25* „

Gas helium heat transfer - convection heat transfer

Heat transfer from Vacuum Vessel to Vacuum helium – Q_{Rate01}

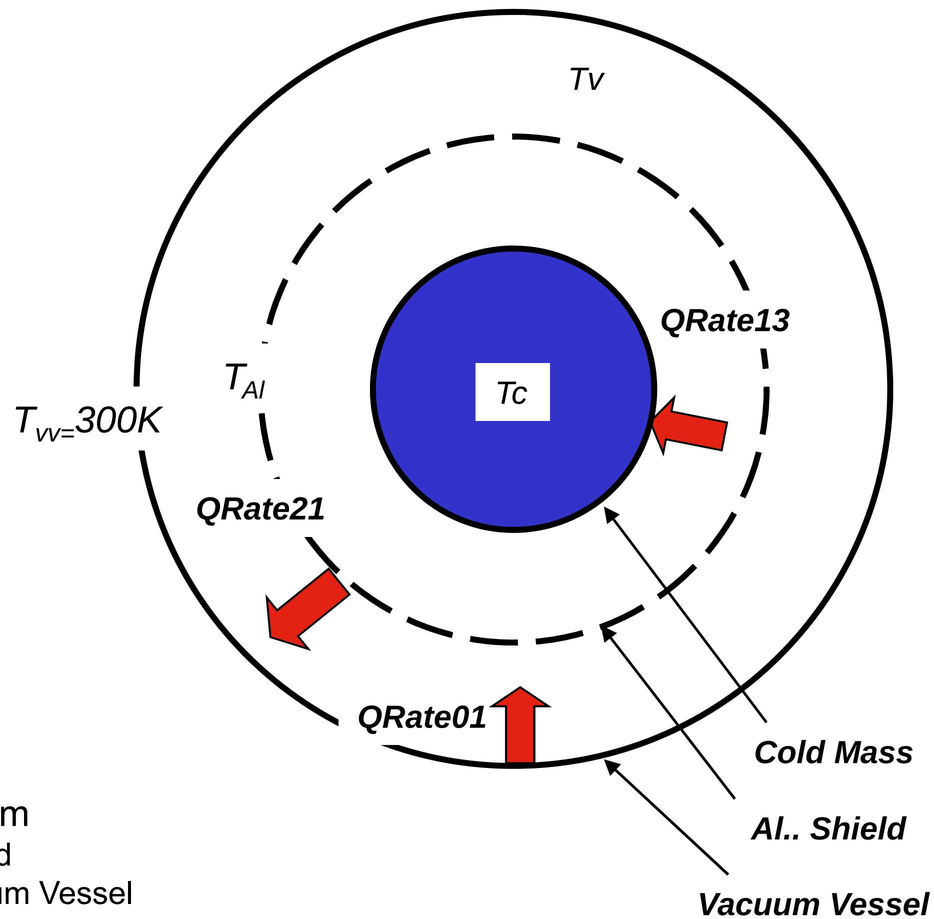
$$Q_{Rate01} = A_{vv} \cdot h_{01} \cdot (T_{vv} - T_v)$$

Heat transfer from Aluminum Shield to Vacuum helium – Q_{Rate21}

$$Q_{Rate21} = 2 \cdot A_{Al} \cdot h_{01} \cdot (T_{Al} - T_v)$$

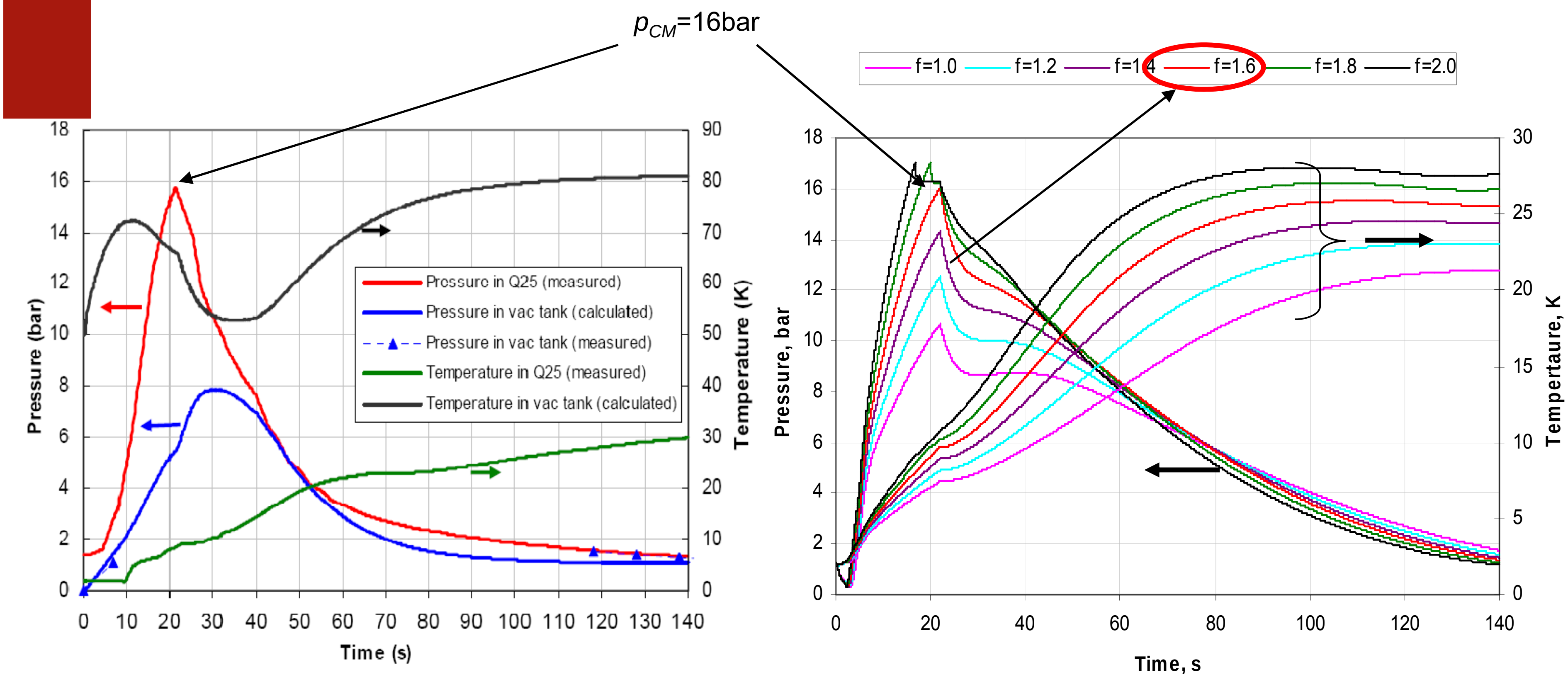
Heat transfer from Vacuum helium to Cold Mass helium – Q_{Rate13}

$$Q_{Rate13} = A_{Al} \cdot h_{13} \cdot (T_v - T_c)$$



T_c, T_v – helium temperature in Cold Mass, Vacuum
T_{Al}, T_{vv} –temperature of Vacuum Vessel, Aluminum Shield
A_c, A_{Al}, A_{vv} – area of Cold Mass, Aluminum Shield, Vacuum Vessel

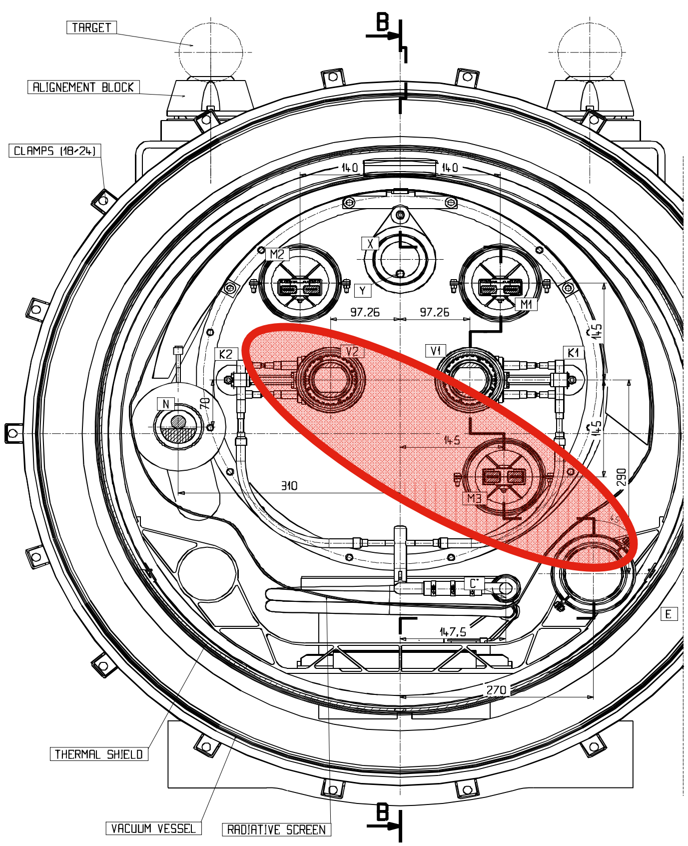
Model tuning - the only parameter to tune the model was the natural convection heat transfer coefficient



Measured and calculated data for 080919 LHC failure

Evolution of the helium temperature and pressure in Cold Mass

Modelling of 19. Sept. 08 incident



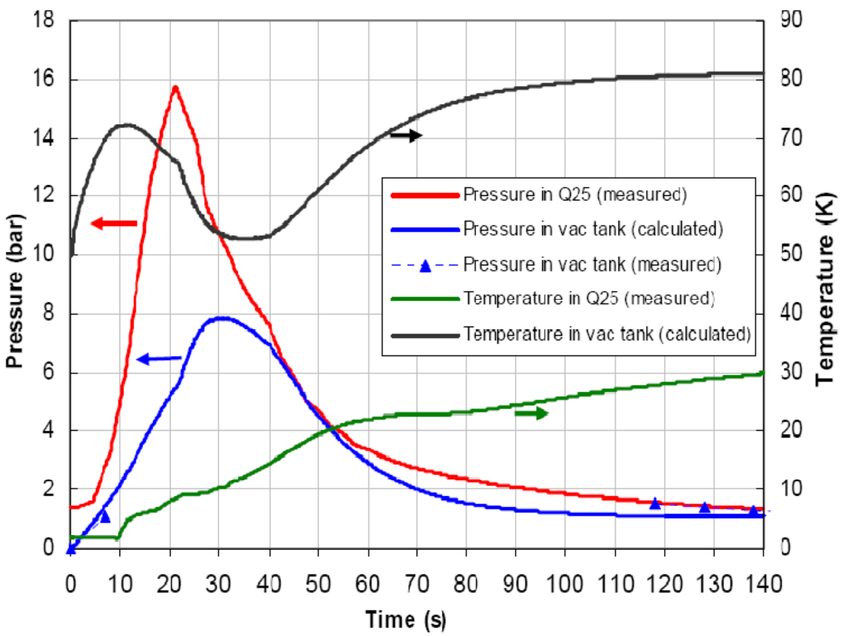
Sequence of events

19. Sept. 08 Incident

Time	Event
t=0	M3 pipe break, hole area: 2x32 cm^2 caused by Electrical arc at I=8.7kA
t=5s	Quench of 4 magnets for I=8.7kA
t=22s	pipe break, hole area: 2x30 cm^2

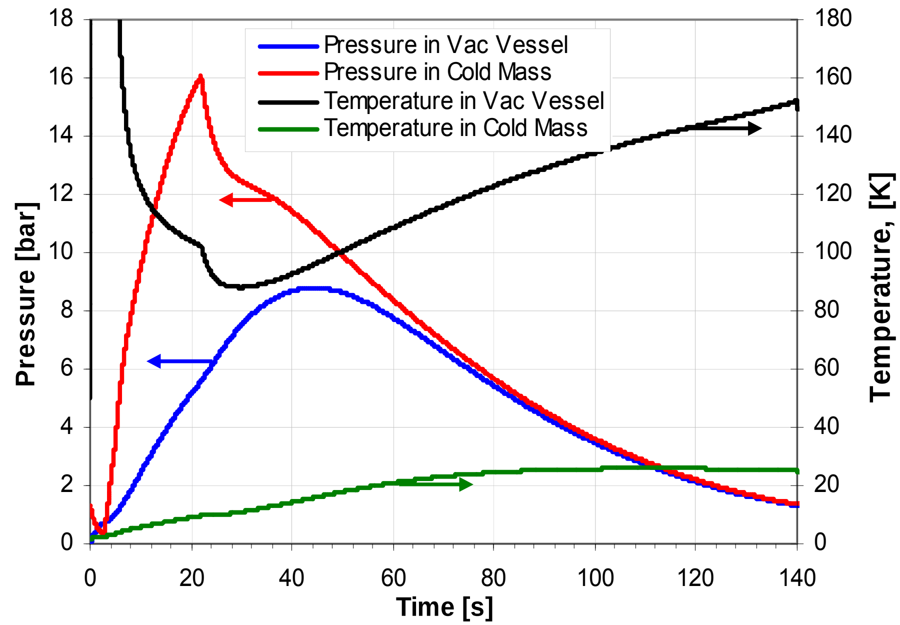
Model validation: 19. Sept. 08 incident modeling results vs. measured data

CERN data



Measured and calculated data for the 19. Sept. 08 incident (*LHC Project Report 1168*)

WUT calculations

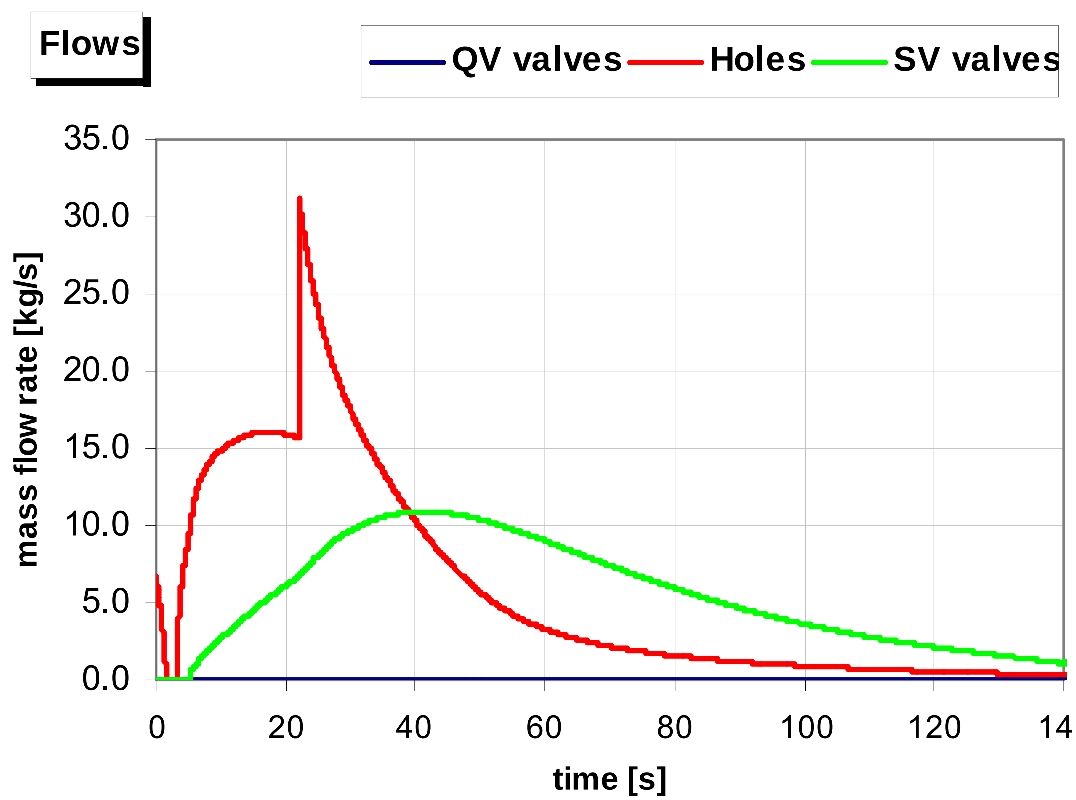


Modeling results

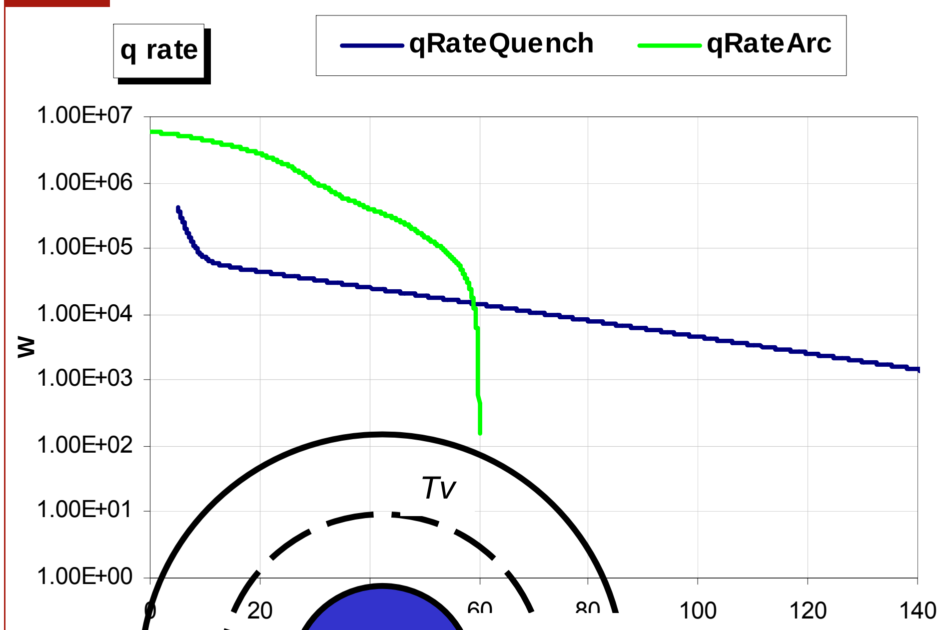
19. Sept. 08 incident - He mass flows through the holes and SV: modeling results

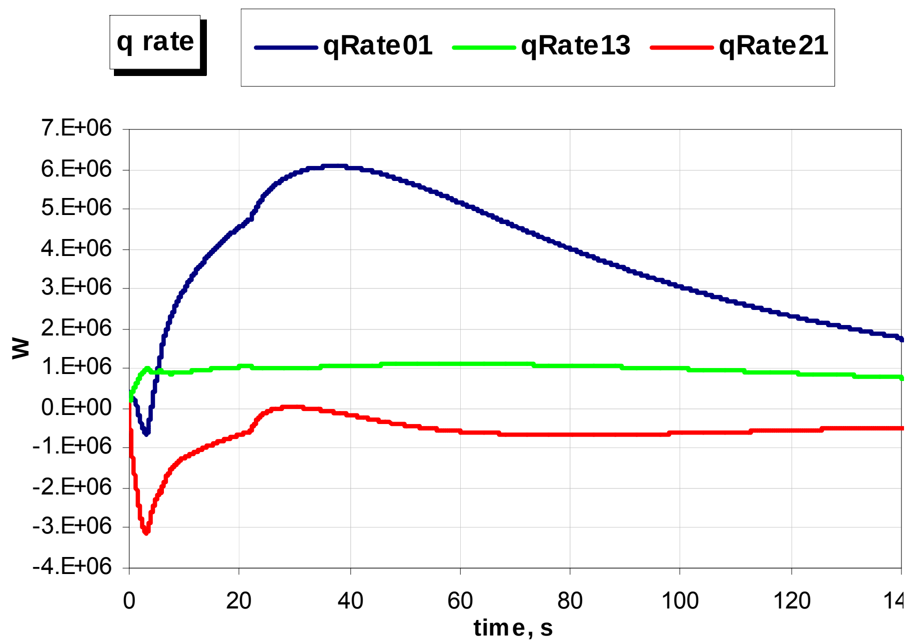
19. Sept.08 incident

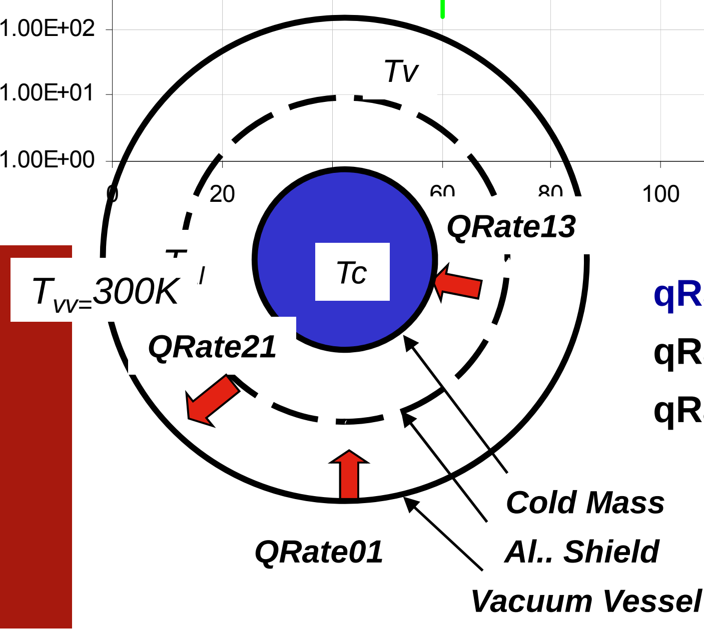
Time	Event
t=0	M3 pipe break, hole area: 2x32 cm^2 Electrical arc at I=8.7kA
t=5s	Quench of 4 magnets for I=8.7kA
t=22s	pipe break, hole area: 2x30 cm^2



19. Sept. 08 incident - heat transfer modeling results





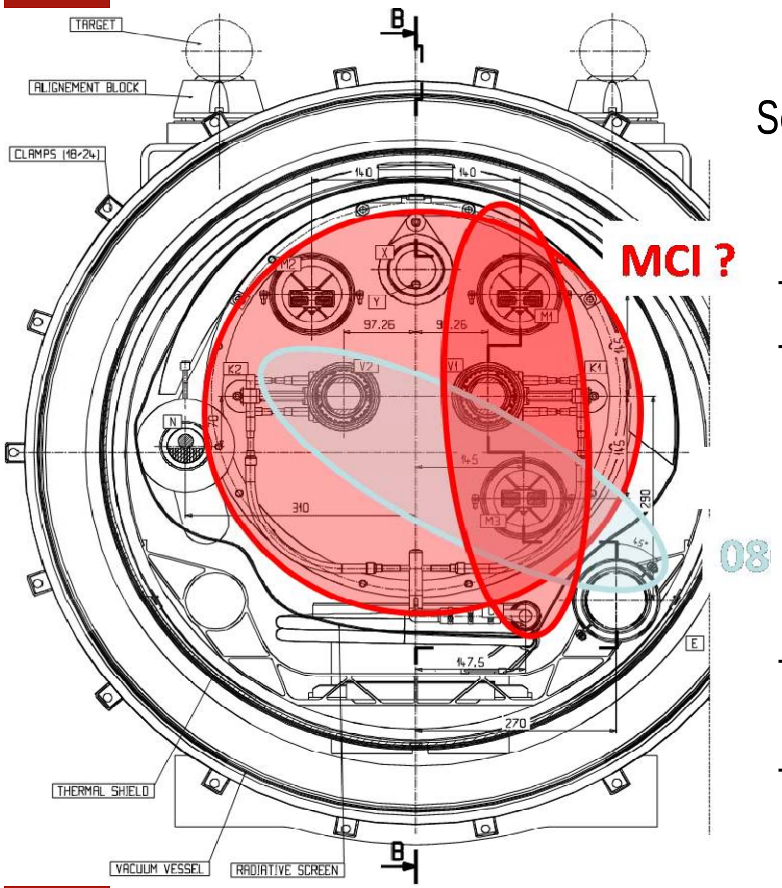


$qRate_{01}$ – heat transfer to Vacuum helium form Vacuum Vessel

$qRate_{21}$ – heat transfer to Vacuum helium form Aluminum Shield

$qRate_{13}$ – heat transfer to Cold Mass helium from Vacuum helium

Maximum Credible Incident analysis



Sequence of events – comparison with 19. Sept. inc.

19 Sept. 08 incident

Time	Event
t=0	M3 pipe break, hole area: 2x32 cm^2 caused by Electrical arc at I=8.7kA
t=5s	Quench of 4 magnets for I=8.7kA
t=22s	pipe break, hole area: 2x30 cm^2

MCI

Time	Event
t=0	Pipe break with total area of the holes: 6x32 cm^2 = 192 cm^2 but Cold Mass free flow area is 60cm^2 and Quench of all (16) magnets at I=13.1kA caused by Electrical arc at I=13.1kA

Vacuum vessel safety valves (SV) schemes

Prior to 19.Sept. 08 incident SV scheme

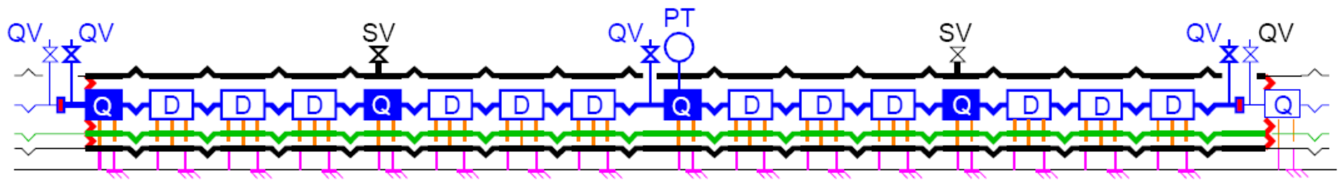
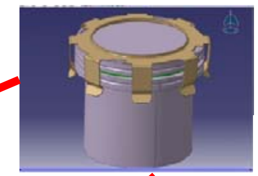


Figure L2: Present SV scheme: 2 DN90 SV. Discharge cross section: 127 cm²



Final SV scheme

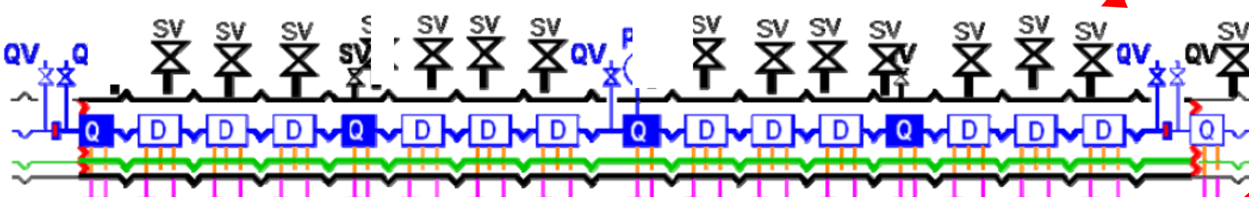


Figure L3: Final SV scheme: 1 added DN200 SV on each dipole, PRS. Discharge cross section: 4190 cm²

Temporary SV scheme

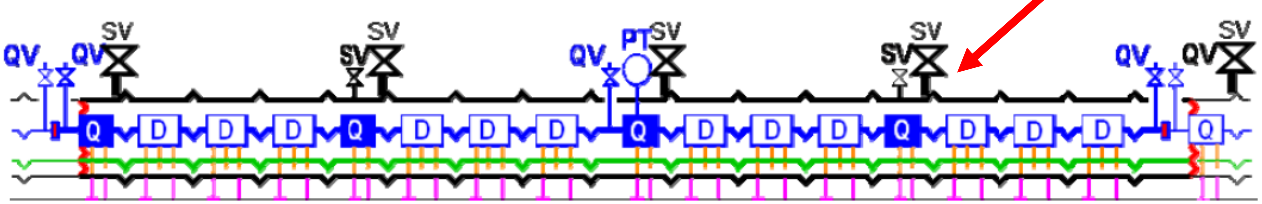
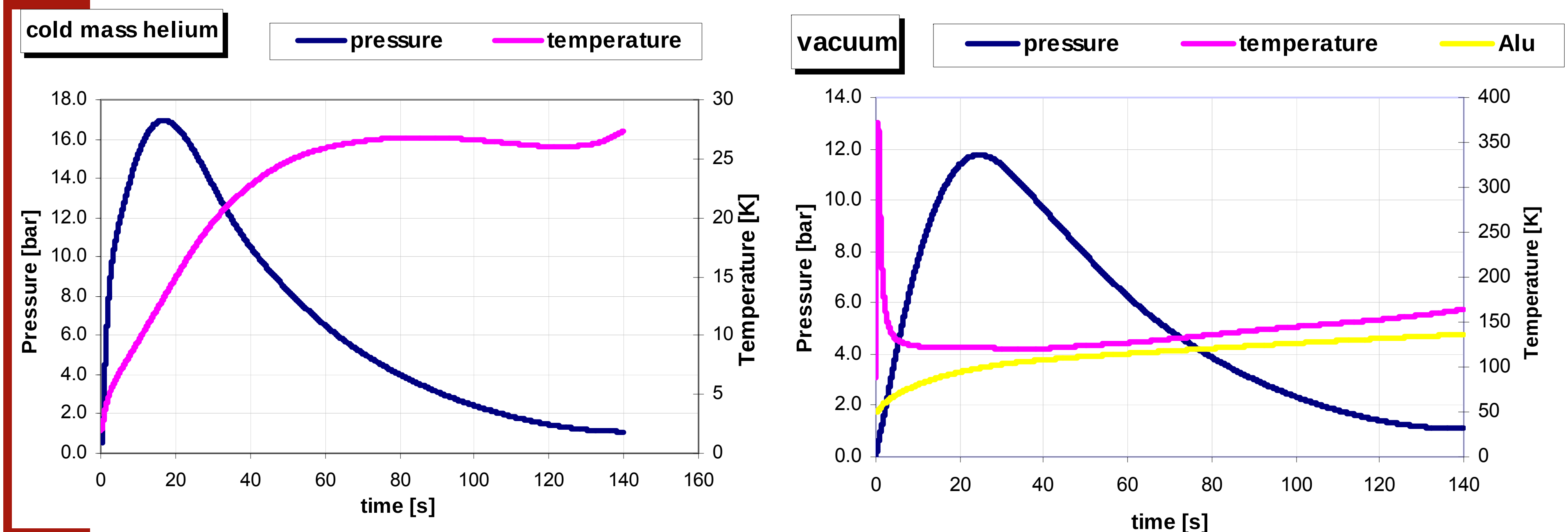


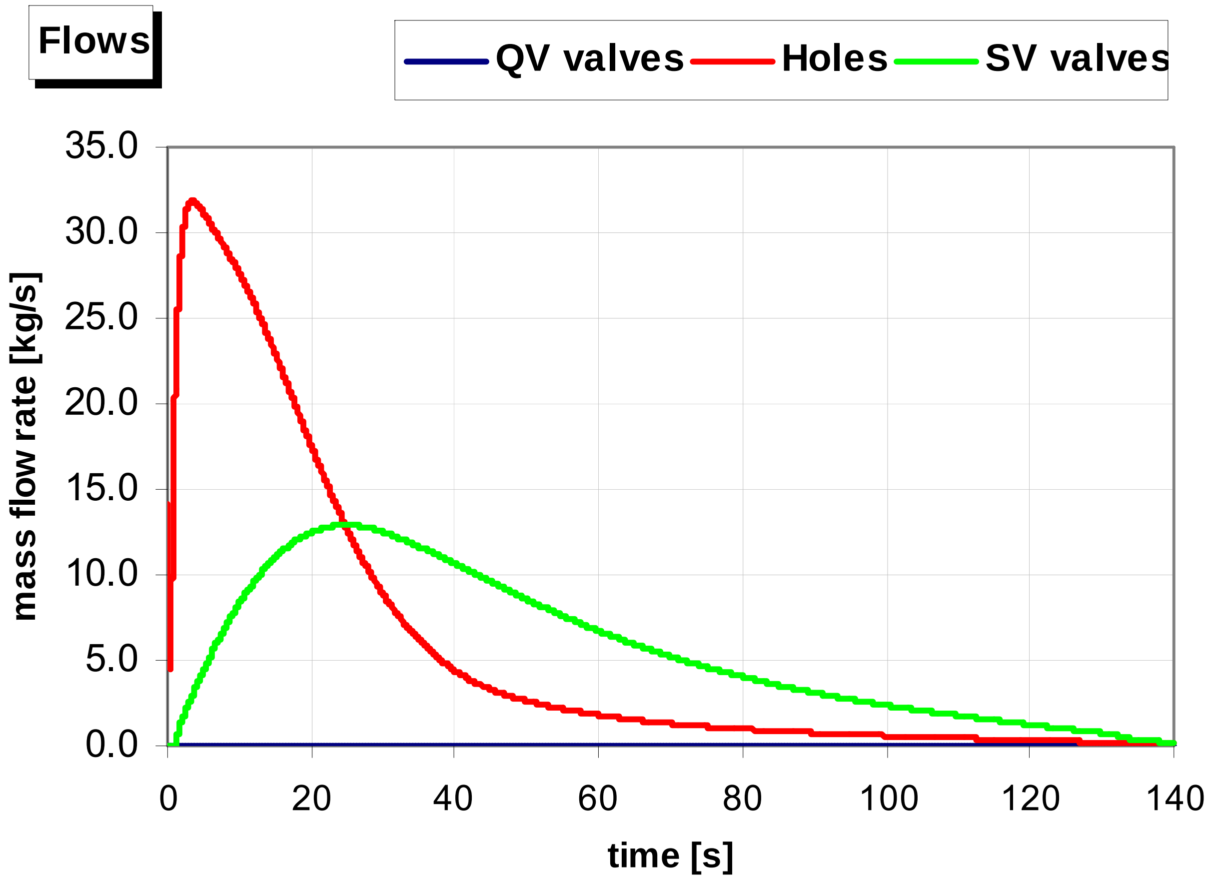
Figure L4: Temporary SV scheme for cold sectors, using PRS: 2 DN90 SV, 13 DN100 SV, 4 DN63 SV. Discharge cross section: 1270 cm²

Modeling results for MCI with SV scheme prior to 19. Sept. 08 incident



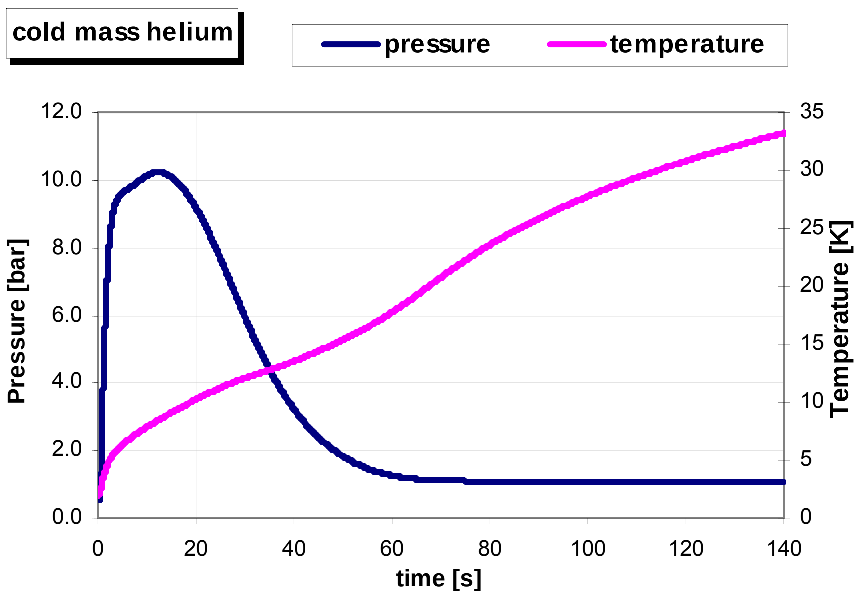
Evolution of helium pressure and temperature in Cold Mass (left) and Vacuum Vessel (right) + evolution Al. Shield temperature (right)

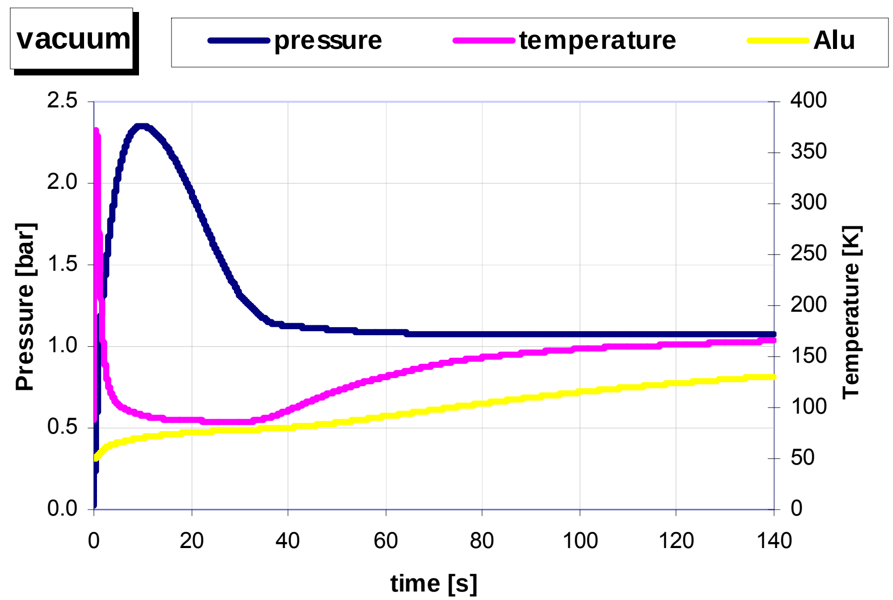
Modeling results for MCI with SV scheme prior to 19. Sept. 08 incident



Helium mass flow thought holes, SV and QV valves

Modeling results for MCI with temporary SV scheme





Evolution of helium pressure and temperature in Cold Mass (left) and Vacuum Vessel (right) + evolution Al. Shield temperature (right)

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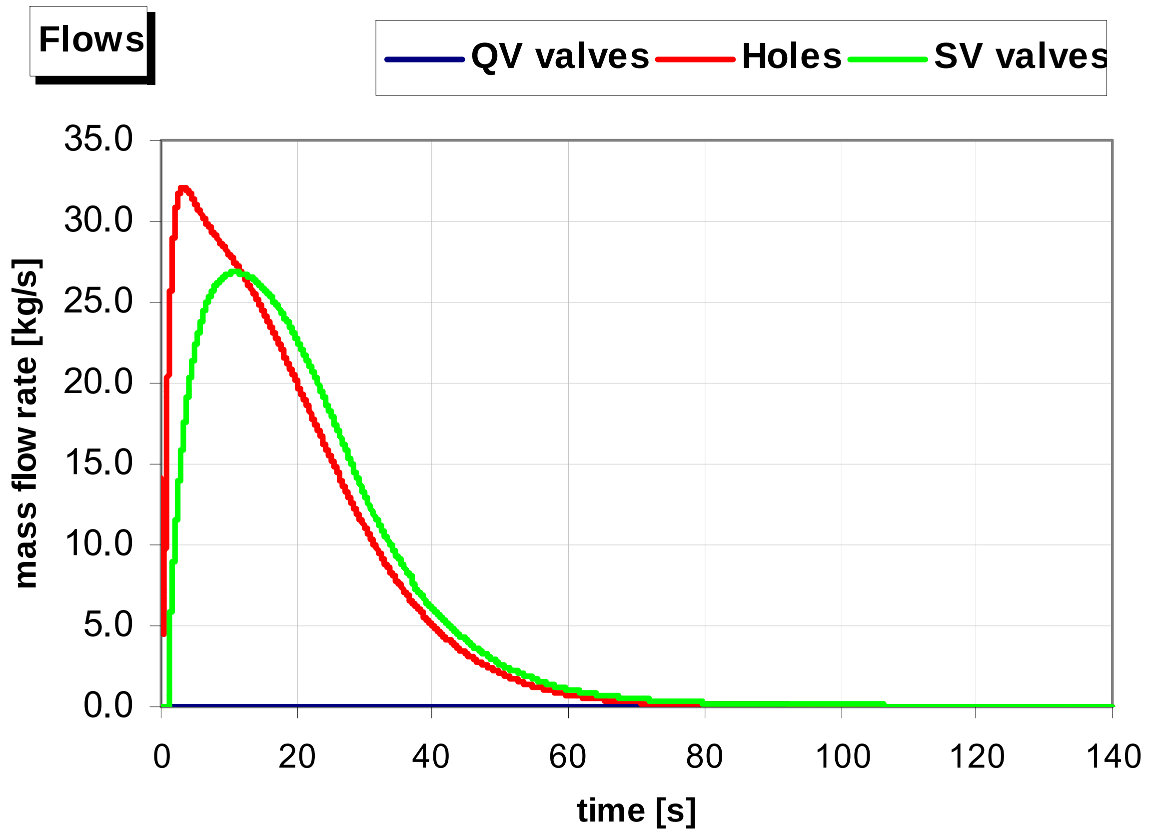
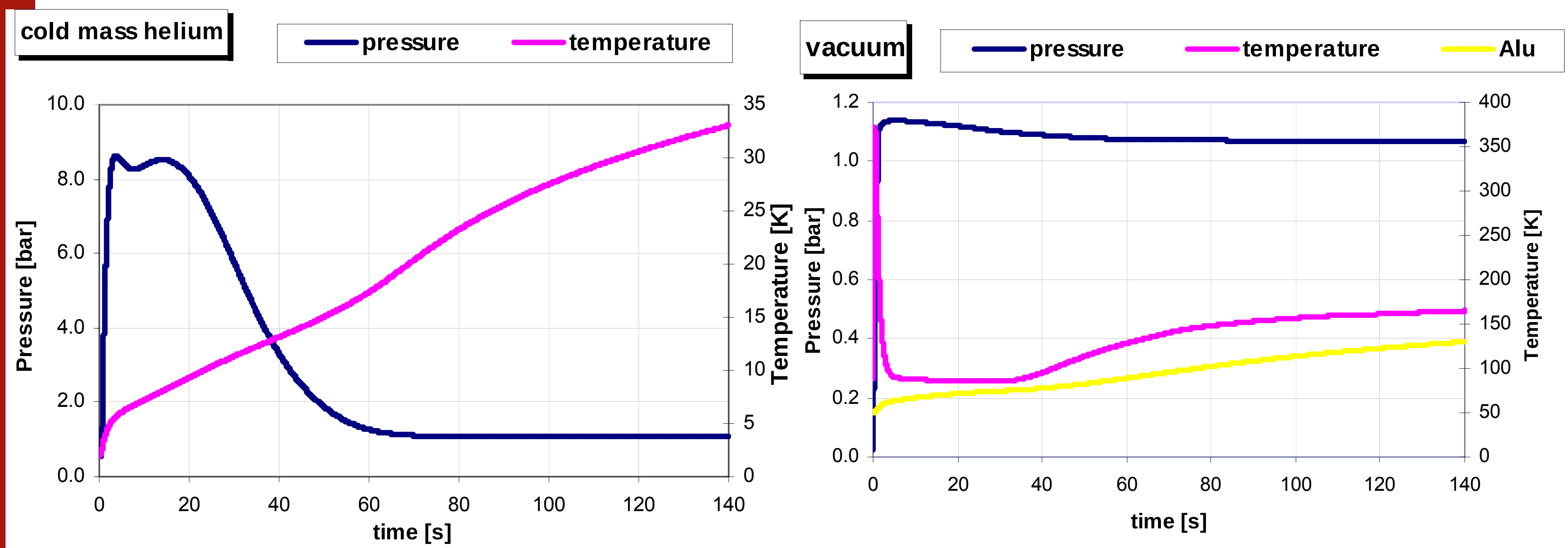
Modeling results for MCI with temporary SV scheme



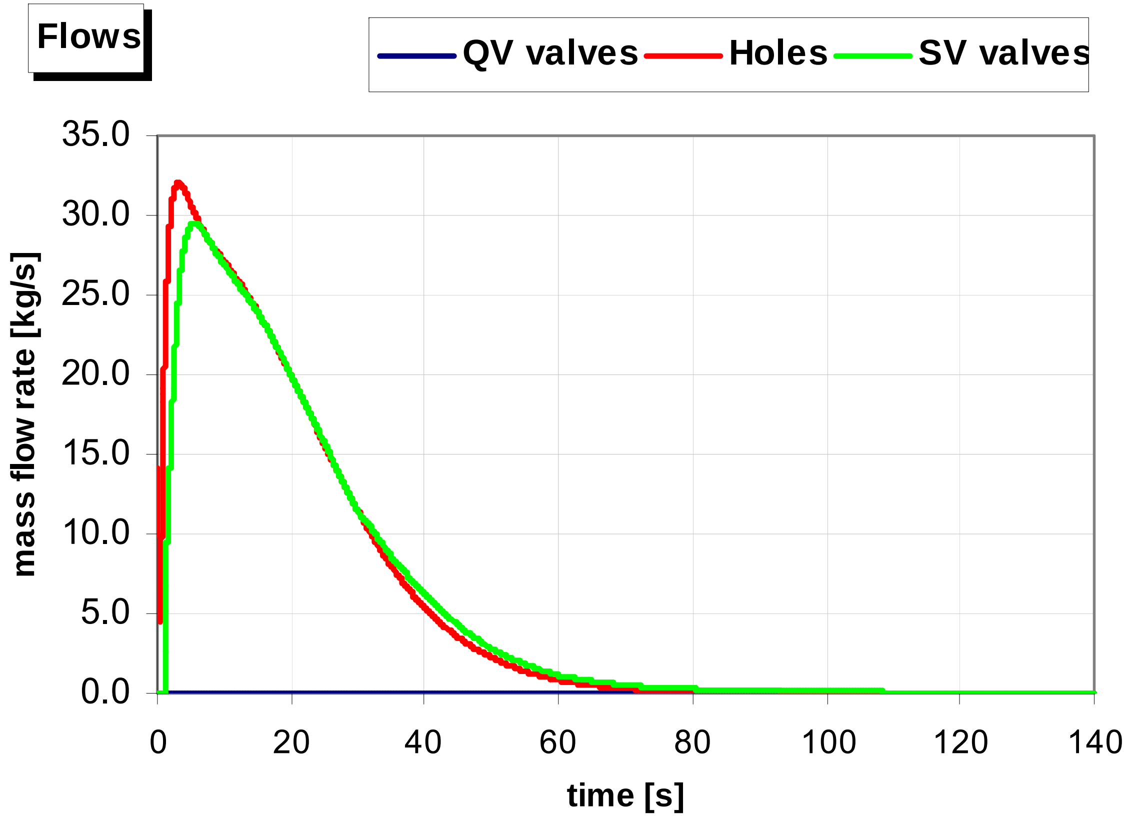
Helium mass flow thought holes, SV and QV valves

Modeling results for MCI with final SV scheme



Evolution of helium pressure and temperature in Cold Mass (left) and Vacuum Vessel (right) + evolution Al. Shield temperature (right)

Modeling results for MCI with final SV scheme

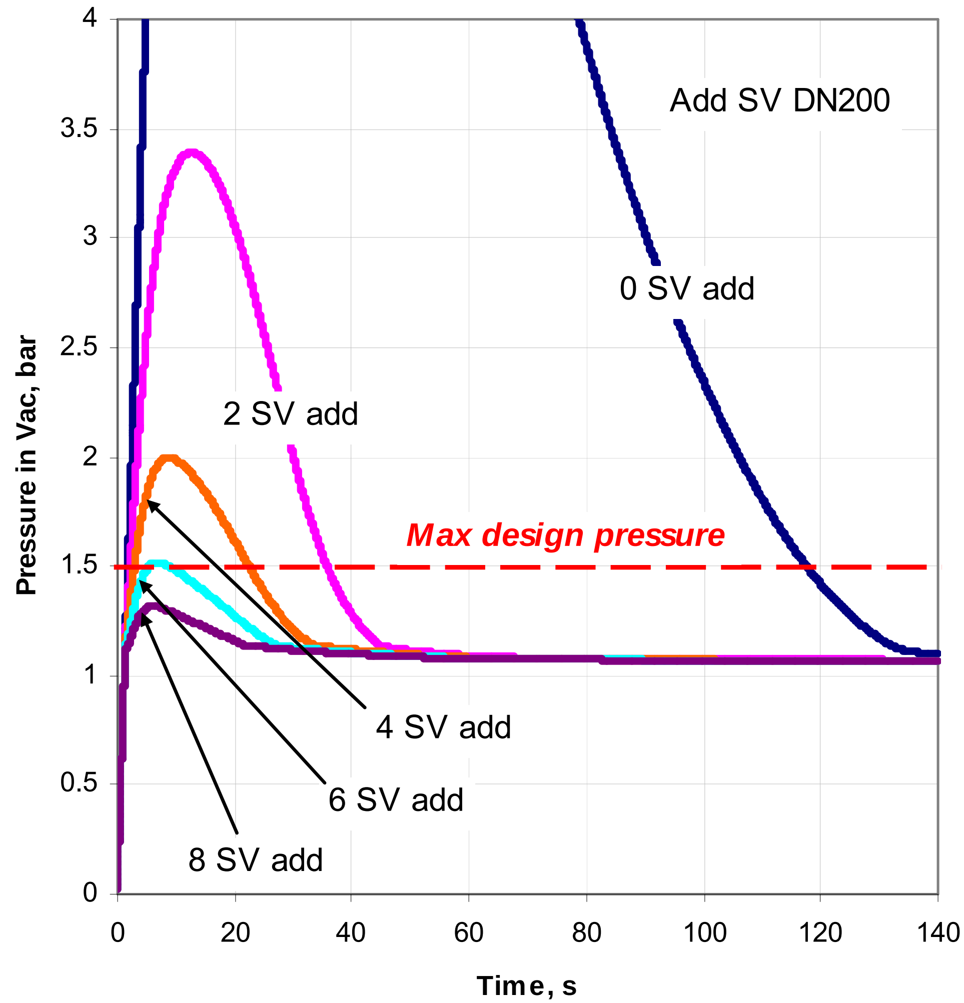


Helium mass flow thought holes, SV and QV valves

Sensitivity analysis of the number of additional SV DN200 on the pressure in vacuum space (MCI case)

He pressure evolution in Vacuum Vessel for different number of additional SV for MCI.
Additional SV: DN=200mm.

To avoid overpressurization of the vacuum space at least 8 valves should be added.



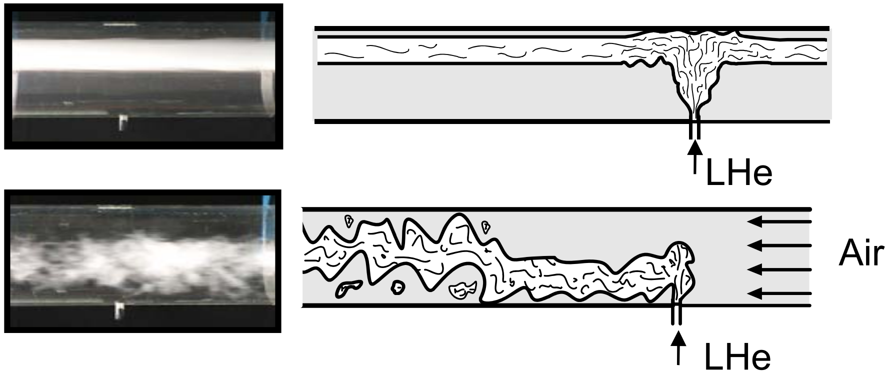
Helium propagation, tunnel pressurization and ODH

During the incident the amount of about 6 ton of helium has been released into the LHC tunnel in the way that can be classified as a physical phenomenon with a high rate volume production.

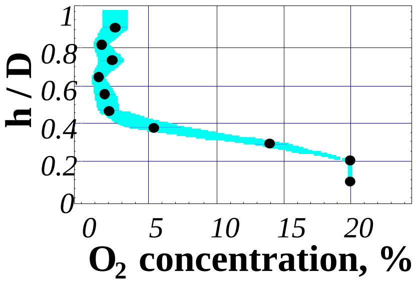
The observed oxygen concentration decrease was in good agreement with a small scale modelling of the helium discharge to the LHC tunnel mock-up

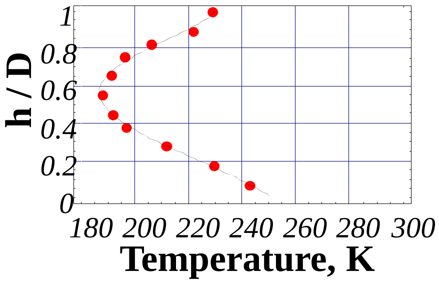
Test set-up
build and operated at WUT

Visualisation results



Measurement results





As well as with a full scale modelling of the helium discharge to the LHC tunnel mock-up

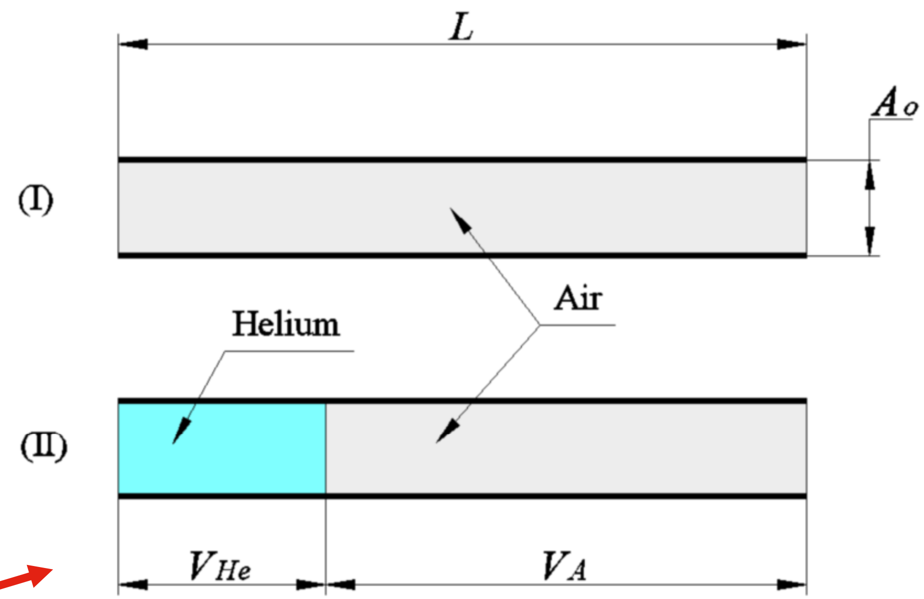
Cold helium propagation in the LHC tunnel

Large scale experiment at CERN

Model of helium injection to the tunnel sector - static approach to the tunnel presurization

(I) tunnel of volume V_o = *33000 m*^{3} filled only with air of pressure p_o.

(II) tunnel after injecting some amount of helium under assumption that both gases do not mix together.



L – tunnel length
Ao – tunnel cross-section area
VHe – volume occupied by helium
VA – volume occupied by air after injection.

Static approach - governing equations in the case of adiabatic air compression

$$\begin{cases} V_A + V_{He} = V_o \\ pV_{He} = mR_{He}T \\ p_o V_o^{\gamma_{Air}} = pV_A^{\gamma_{Air}} \end{cases}$$

- for isothermal air compression

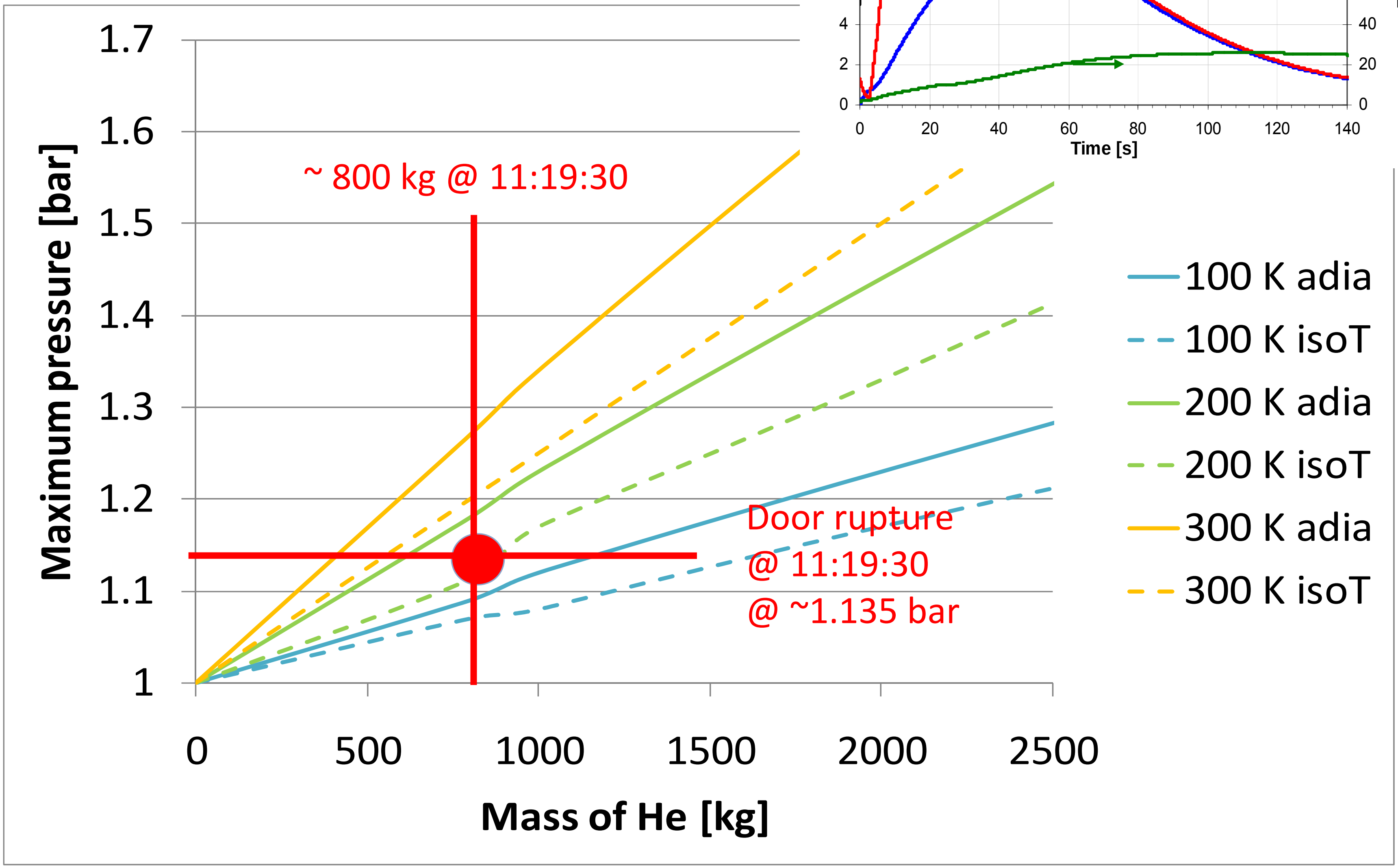
$$\gamma_{Air} = 1$$

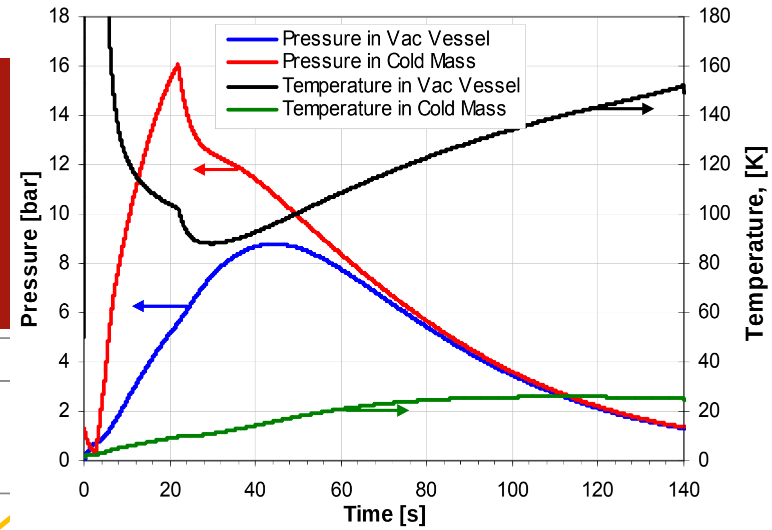
V_{He} – volume occupied by helium
V_A – volume occupied by air after injection
m – mass of the injected helium
R_{He} – helium specific gas constant
g_{Air} – specific heat ratio of air

Calculation assumptions:

- There is a clear interface between air and helium.
- The tunnel is tight so there is no escape of air or helium from it.
- During helium injection air remaining in the tunnel is compressed. This process can be considered as adiabatic or isothermal, depending on how fast or slow is the compression.
- During a whole process the pressure *p* in is uniform along the tunnel.
- The initial temperature of air in the tunnel is *To* = 300 K, and the initial pressure is atmospheric i.e. *po* = 1·105 Pa.
- The temperature of injected helium remains constant and is equal *T*

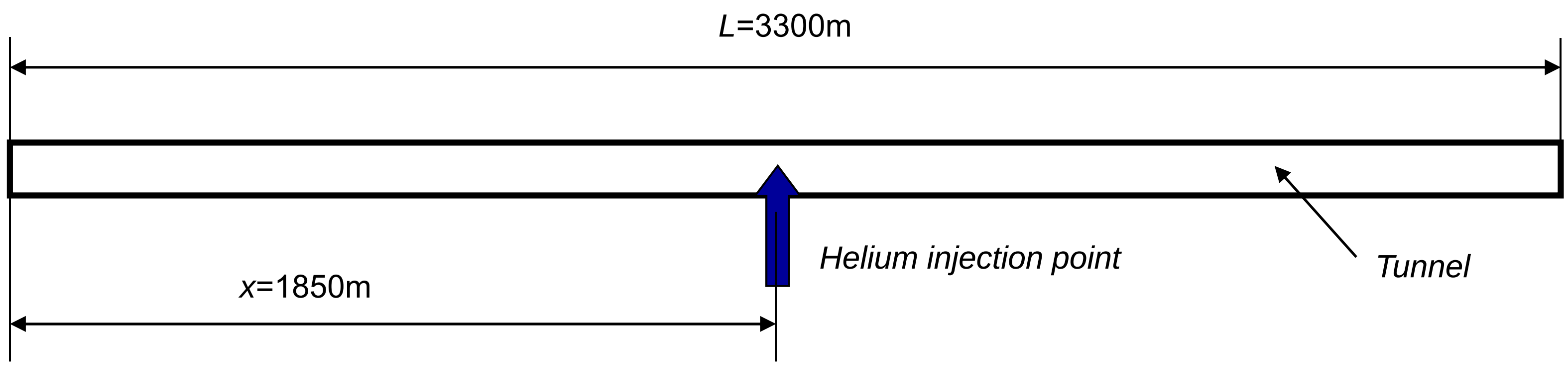
Tunnel pressurization





Helium injection to the tunnel sector - verification of blasting effect

Model scheme



Governing equations:

$$\frac{\partial \rho}{\partial t} = -\rho \frac{\partial v}{\partial x} - v \frac{\partial \rho}{\partial x} + W$$

$$\rho \frac{\partial v}{\partial t} = -\rho v \frac{\partial v}{\partial x} - \frac{\partial p}{\partial x} + \frac{4}{3} \eta \frac{\partial^2 v}{\partial x^2}$$

$$p \rho^{-\gamma} = const$$

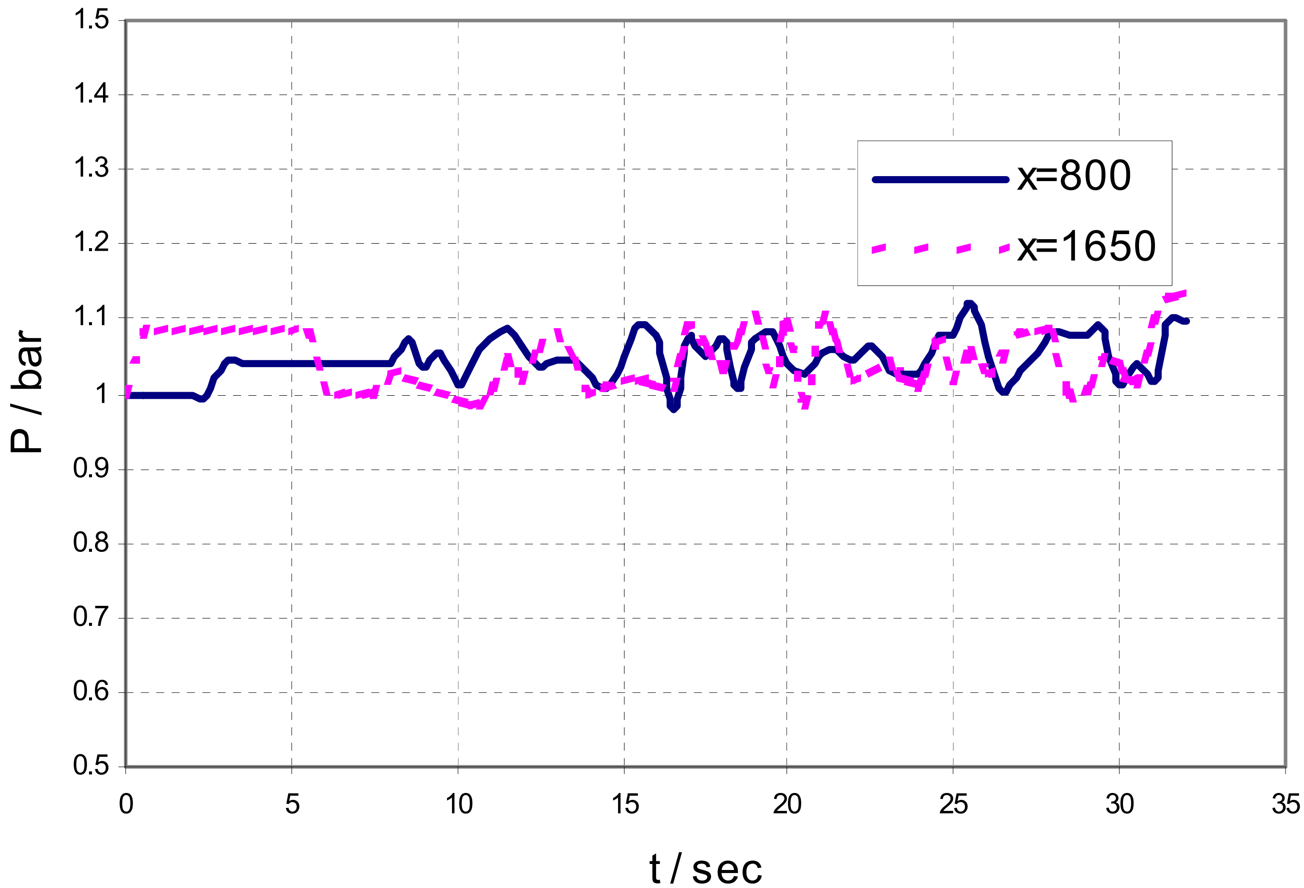
Boundary conditions:

$$v(0,t) = v(L,t) = 0$$

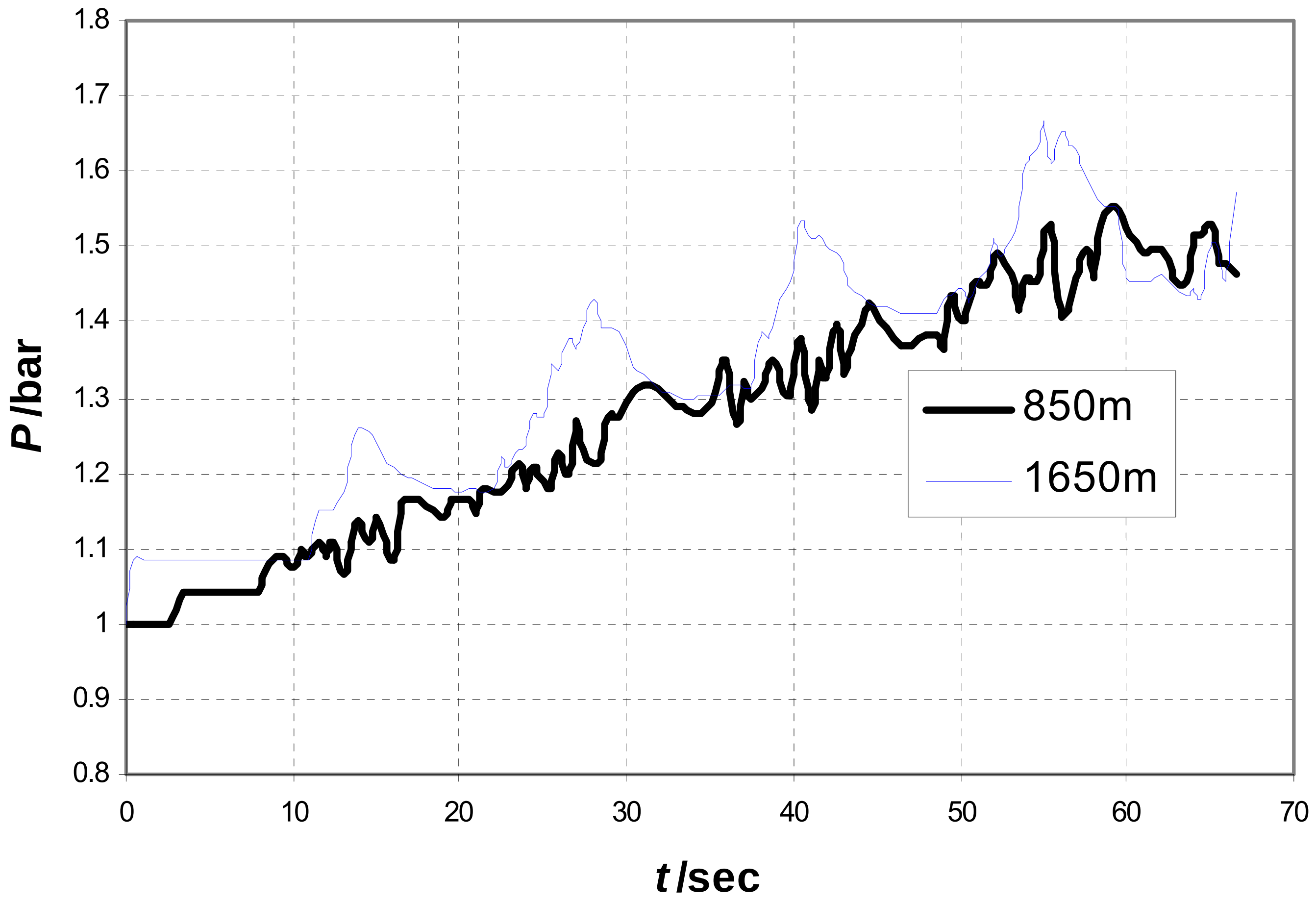
$$\frac{\delta \rho(0,t)}{\delta x} = \frac{\delta \rho(L,t)}{\delta x} = 0$$

Wrocław University of Technology

Pressure history in two points of the LHC tunnel for mass rate production density equal 2.02 $kg*m^{-3}*s^{-1}$ and injection time 60 s



Pressure history in two points of the LHC tunnel for mass rate production density equal 20.2 kg*m-3*s-1 and injection time 60 s



Conclusions

- Preliminary risk analysis of the LHC cryogenic system has been updated, taking into account the experience resulting from the 19. Sept. 08 incident.
- A new Maximum Credible Incident has been formulated.
- Mathematical modeling based on a thermodynamic approach has shown that the implemented safety relief system protecting the vacuum vessels against over pressurization is characterized by a reasonable safety margin.
- Temporary SV configuration is justified for low energy runs, especially in standard subsectors.
- The tunnel pressurization resulting from significant helium discharge is a static process and no blasting effect can be expected.
- To avoid the tunnel pressurization over, self-opening doors should be installed.

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Personal cool down to 110 K!