Pressure relief protection in cryostats: CERN's experience on LHC and HIE Isolde

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Outline

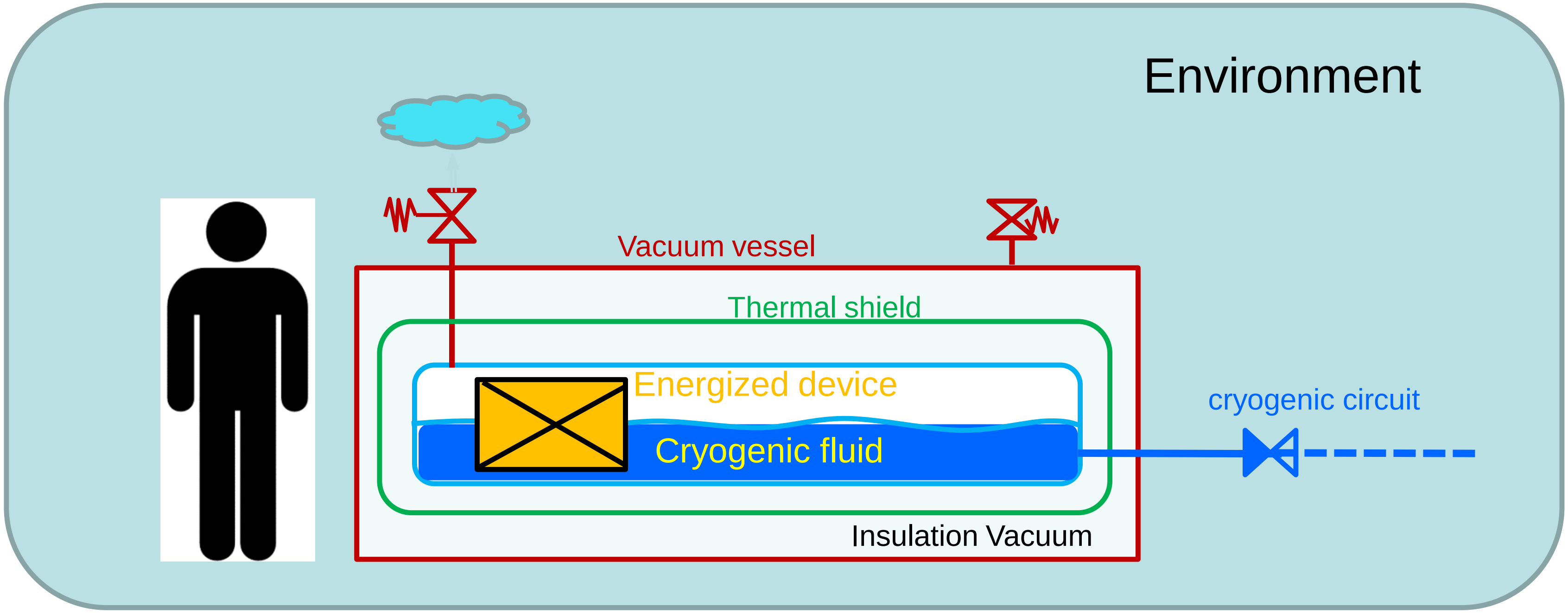
- General considerations

- Pressure safety in cryostat design

- Experience at CERN:
  - HIE Isolde cryo-modules
  - The LHC magnet cryostats

- Summary

Cryostat, an element in a system



- The cryostat cannot be dissociated from the cryogenic circuit and the environment in which it will operate:
  - Sources of pressure hazard may come from the cryoplant (e.g. HP from compressors)
  - Safety hazard from relief of cryogens to the environment (safety of personnel and surrounding equipment)

- The cryostat design must include the cryogenics system and the overall safety of the facility

- The cryostat pressure safety design aims at understanding the pressure hazards and making the correct choice of the pressure relief devices to protect from overpressure of the cryostat envelopes

Pressure hazards

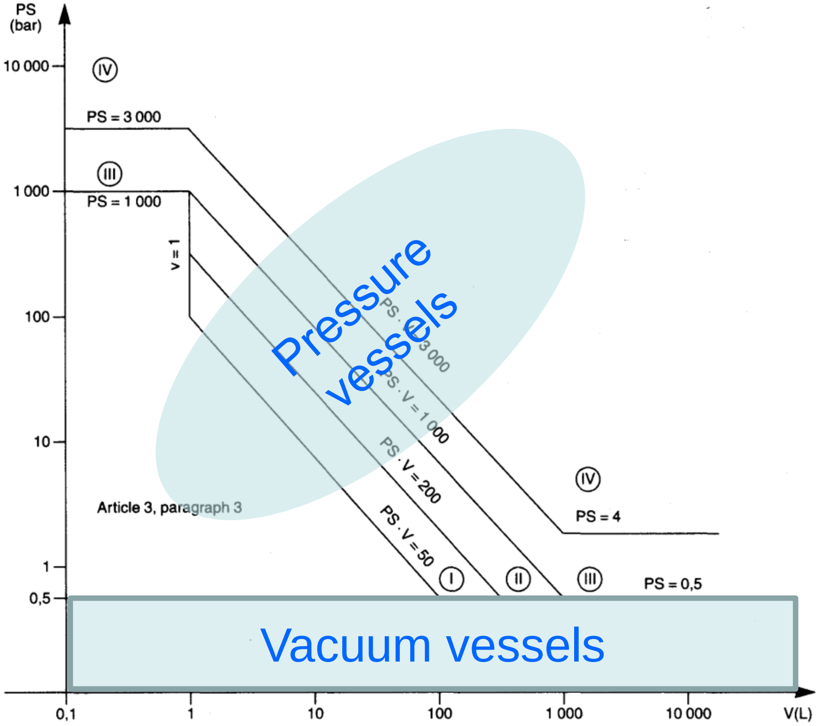
- Cryostats include inventory of cryogenic fluids, sometimes large stored energy (e.g. energized magnets) and large cold surfaces
  - Potentially unstable energy storage which will tend to find a more stable state of equilibrium…
  - …through a thermodynamic transformation which can be <u>sudden</u> and <u>uncontrolled</u> with dangerous increase of pressure

- Potential pressure hazards:
  - Compressors connected to cryo lines
  - Connection to higher pressure source (e.g. HP bottles)
  - Heating of "trapped" volumes (typically in a circuit between valves) during warm-ups
  - Helium leak to insulation vacuum, with consequent increased conduction/convection heat loads to cryogenic liquid vessels
  - Cryo-condensed air leaks on cold surfaces and consequent pressure increase and increased conduct/convection heat loads during warm-ups
  - Heating/vaporization of cryogens from sudden release of stored energy in SC device (e.g. quench or arcing in a SC magnet circuit)
  - Accidental air venting of insulation vacuum with sudden condensation on cold surfaces
  - Accidental release of cryogenic fluid to higher T surfaces (thermal shield and vacuum vessel), and consequent pressure increase and increased of conduction/convection heat loads to cold surfaces

Often the most critical

Pressure vessel codes regulations

- Pressure European Directive 97/23/EC (PED) is obligatory throughout the EU since 2002
  - Applies to internal pressure **≥ 0.5 barg**
  - Vessels must be designed, fabricated and tested according to the essential requirements of Annex 1 (Design, safety accessories, materials, manufacturing, testing, etc.)
  - Establishes the conformity assessment procedure depending on the vessel category, which depends on the stored energy, expressed as Pressure x Volume in bar.L

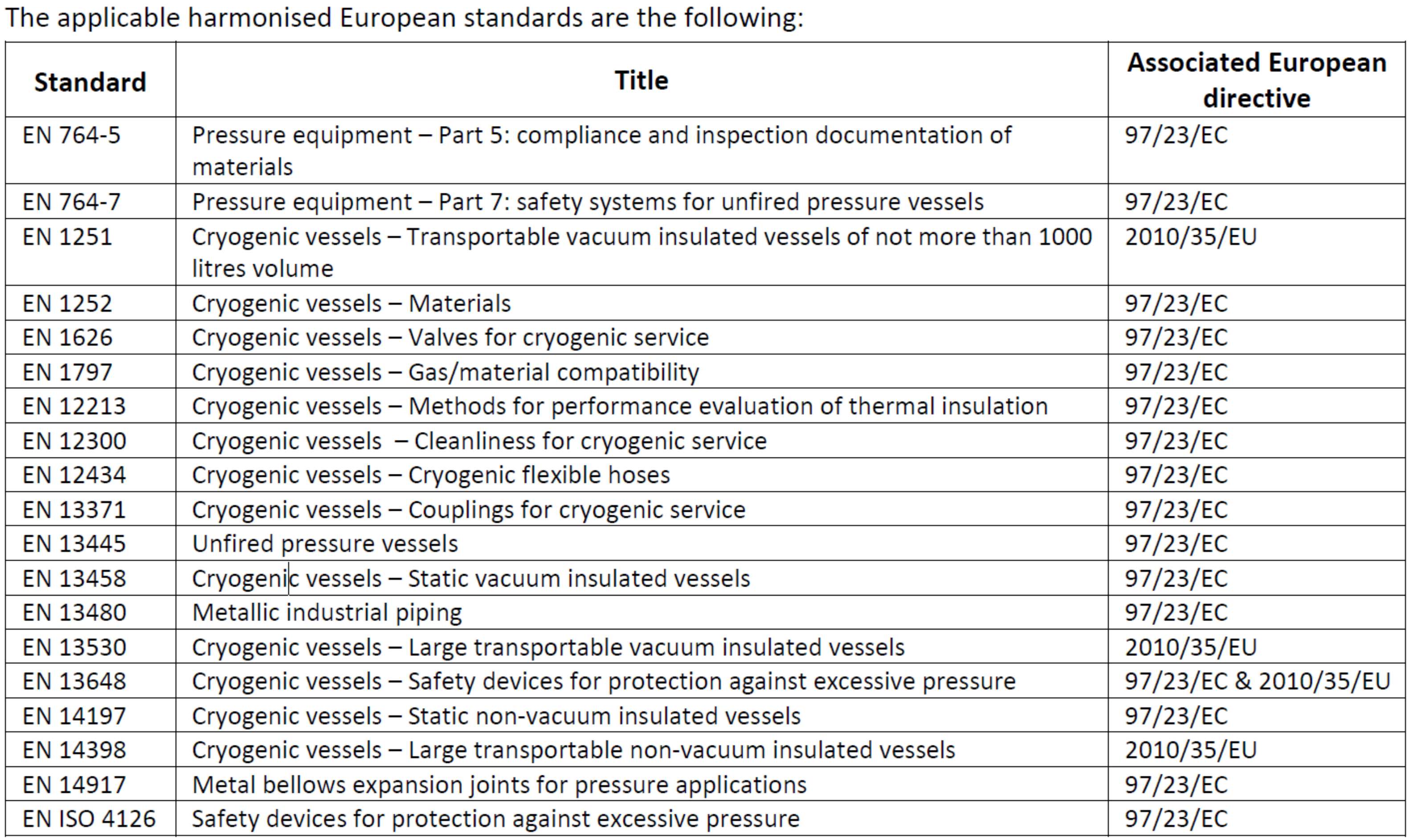


For vessels with non-dangeroureous gases (cryogenic liquids are treated as gas)

Category	Conf. assessment module	Comment
SEP	None	The equipment must be designed and manufactured in accordance with sound engineering practice. No CE marking and no involvement of notified body.
I	A	CE marking with no notified body involvement, self-certifying.
II	A1	The notified body will perform unexpected visits and monitor final assessment.
III	B1+F	The notified body is required to approve the design, examine and test the vessel.
IV	G	Even further involvement of the notified body.

Harmonised codes and standards

- Harmonised standards give presumption of conformity with the PED, within their scope. Useful codes for cryostat design and fabrication:



The applicable harmonised European standards are the following:

Standard	Title	Associated European directive
EN 764-5	Pressure equipment – Part 5: compliance and inspection documentation of materials	97/23/EC
EN 764-7	Pressure equipment – Part 7: safety systems for unfired pressure vessels	97/23/EC
EN 1251	Cryogenic vessels – Transportable vacuum insulated vessels of not more than 1000 litres volume	2010/35/EU
EN 1252	Cryogenic vessels – Materials	97/23/EC
EN 1626	Cryogenic vessels – Valves for cryogenic service	97/23/EC
EN 1797	Cryogenic vessels – Gas/material compatibility	97/23/EC
EN 12213	Cryogenic vessels – Methods for performance evaluation of thermal insulation	97/23/EC
EN 12300	Cryogenic vessels – Cleanliness for cryogenic service	97/23/EC
EN 12434	Cryogenic vessels – Cryogenic flexible hoses	97/23/EC
EN 13371	Cryogenic vessels – Couplings for cryogenic service	97/23/EC
EN 13445	Unfired pressure vessels	97/23/EC
EN 13458	Cryogenic vessels – Static vacuum insulated vessels	97/23/EC
EN 13480	Metallic industrial piping	97/23/EC
EN 13530	Cryogenic vessels – Large transportable vacuum insulated vessels	2010/35/EU
EN 13648	Cryogenic vessels – Safety devices for protection against excessive pressure	97/23/EC & 2010/35/EU
EN 14197	Cryogenic vessels – Static non-vacuum insulated vessels	97/23/EC
EN 14398	Cryogenic vessels – Large transportable non-vacuum insulated vessels	2010/35/EU
EN 14917	Metal bellows expansion joints for pressure applications	97/23/EC
EN ISO 4126	Safety devices for protection against excessive pressure	97/23/EC

- Other codes such as the French CODAP or the American ASME Boiler and Pressure Vessel Code can be used, but proof of conformity is at the charge of the manufacturer

The cryogenic pressure safety design process

- Identification of the circuit/enclosed volume(s). Related to the cryogenic circuits

- Identification of the scale of pressures. As a minimum:
  - Nominal operating pressure (units: bara), related to the operation of the device
  - Maximum Allowable Working Pressure or Design Pressure (MAWP or Ps, units: barg), related to mechanical limits (e.g. cavity plastic limits) or to operational scenarios (e.g. CD/WU transients, magnet quench)
  - Set pressure, PT of the relief device (units: barg) < MAWP
  - Test pressure, Ptest (units: barg). = Ps x 1.43 (or 1.25) as defined according to the code(s)

- Risk hazard analysis & mitigation measure:
  - Make a thorough risk analysis and identify risk hazards and consequences
  - Identify mitigation measures (e.g. protections of exposed bellows and flanged connections)
  - Evaluate severity of consequences and appreciate probability of the event
  - Identify the worst case scenario or Maximum Credible Incident (MCI)

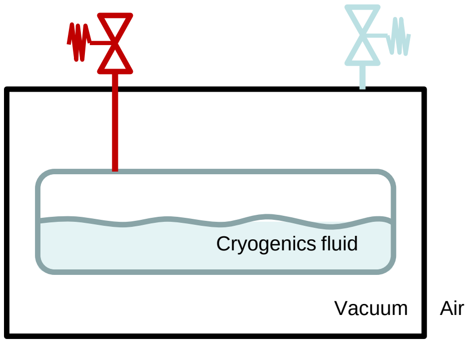
- Design the safety relief system according to the MCI
  - The safety relief system must be designed to keep pressure rise within the limits of the Maximum Allowable Working Pressure (MAWP)

Pressure Safety Relief Devices

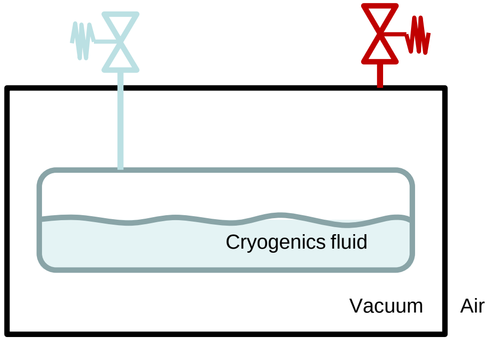
Design steps:

- Estimate the heat exchange and its conversion to mass flow rates to be discharged
- Check the sizing of piping (generally designed for normal operation) to the relief device and increase if necessary
- Choose the type of safety device (burst disks, valves, plates) and size the safety device (DN and set pressure). Make use of safety device manufacturers formulas and charts
- Size recovery piping downstream of safety device and check venting needs in the buildings where the release occurs (personnel protection, ODH)

- Cryogenic fluid vessel(s)
  - Typical ΔPmax < PS
  - PS depends on the device (~few bar for SC cavities, up to ~ 20 bar for magnets)
  - Define DN of valve and set pressure, P_T

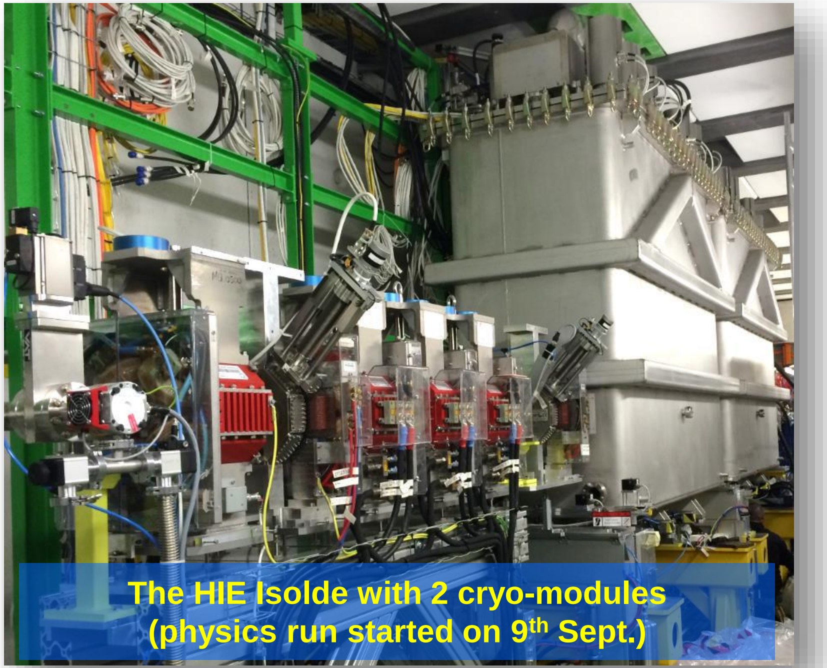


- Vacuum vessel
  - Typical ΔPmax < PS (0.5 bar relative to atm. for vac.vessels)
  - Define DN of valve and set pressure, P_T



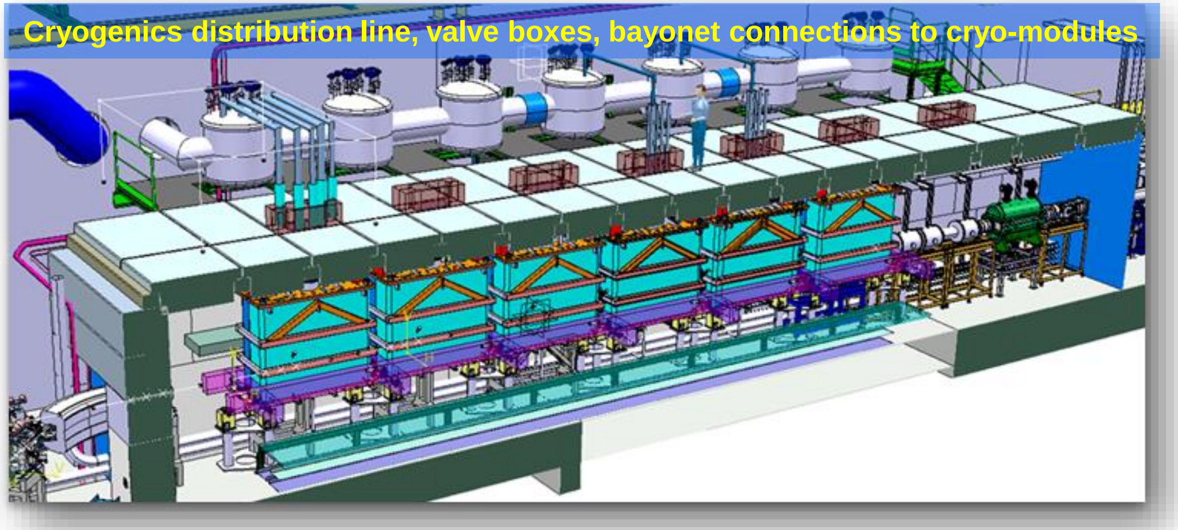
- Sizing of devices according to EN 13648-3 and ISO4126

HIE Isolde cryo-modules

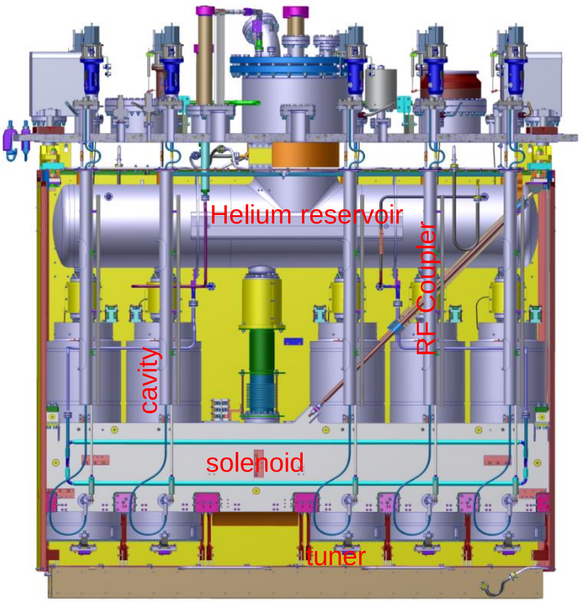


The HIE Isolde with 2 cryo-modules
(physics run started on 9th Sept.)

5 Nb sputtered Cu SRF cavities, 1 SC solenoid, 4.5 K LHe
(no MLI for cleanliness compatibility)



Cryogenics distribution line, valve boxes, bayonet connections to cryo-modules



Safety design : applied standards

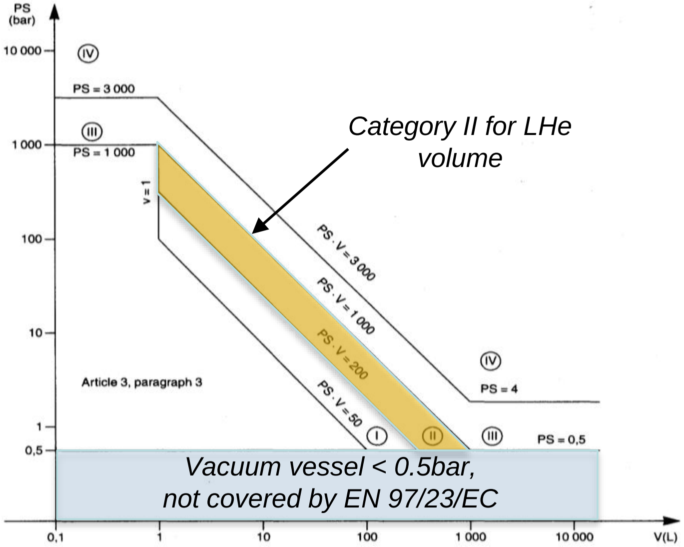
Cryomodule element:

- Pressure vessel
- Contains cryogenic fluids
- Static insulated vessel

Standards applied for design, manufacturing and assembly

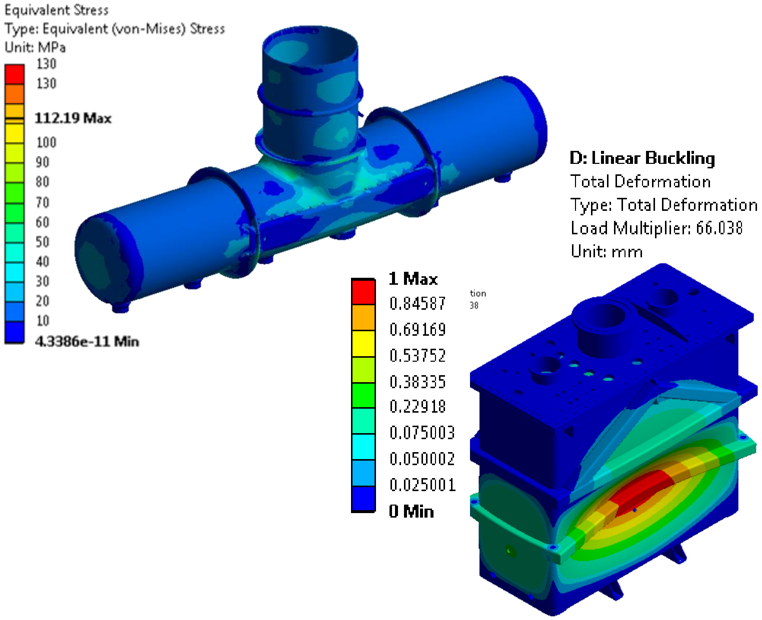
- **EN 97/23/EC directive : Category II**
- CERN GSI-M3 applies:
  - special equipment (cavities in copper, thermal shield copper tube)
- Mechanical design with EN13445-3 DBA method
- Safety devices EN ISO 4126 and EN13648
- Materials:
  - IS47 internal CERN rules
  - Raw material EN rules
- EN rules for welds
  - Material properties, procedures, qualifications, acceptance, inspections
- Vacuum leak tests
  - Procedure EN 13185Personnel qualification EN ISO 9712 NDT level2

Characterisation following EN 97/23/EC



Category II for LHe volume

Vacuum vessel < 0.5bar, not covered by EN 97/23/EC



Results from pressure vessel designs following EN 13445-3 DBA method

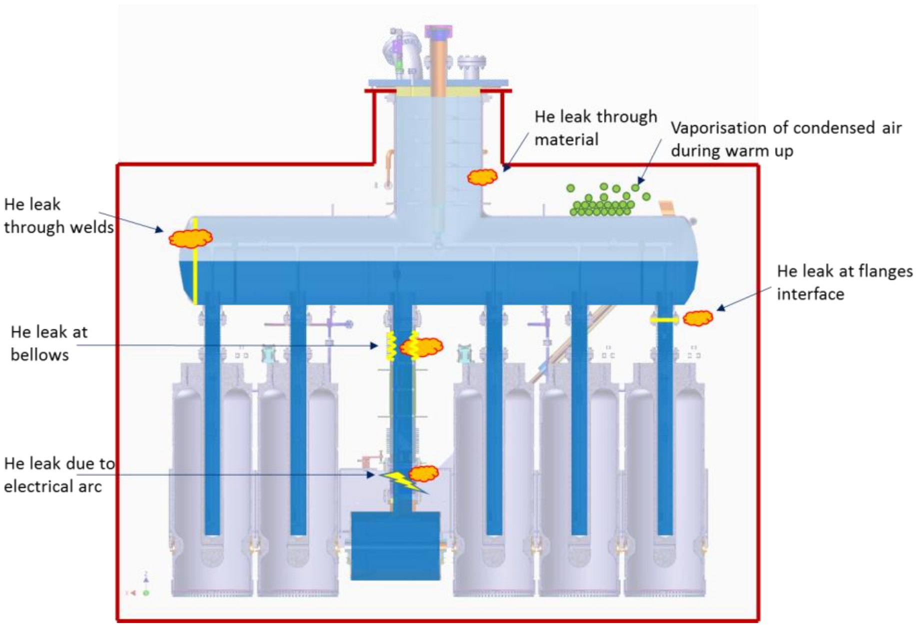
Risk assessment : Pressurised cryogenic fluids

Case #1: Over pressure in the vacuum vessel

- Helium leak from the helium circuits
- Vaporisation of condensed air during warm up

Case #2: Over pressure in the He volume

- Quench (pressure increase below PS)
- Over pressure from cryogenic lines
- Heat load to the circuit



He leak through material

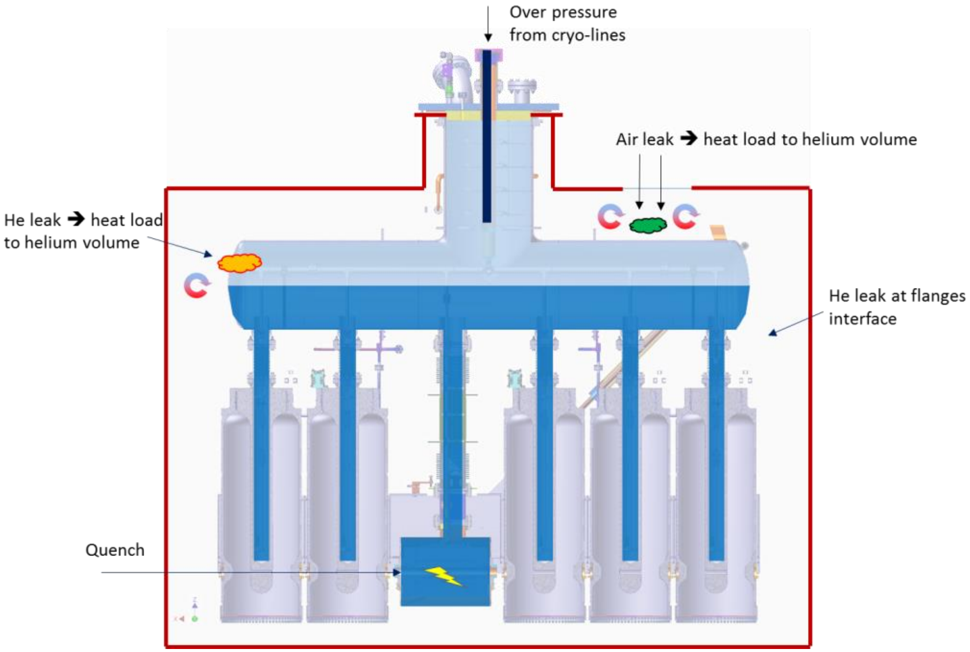
Vaporisation of condensed air during warm up

He leak through welds

He leak at flanges interface

He leak at bellows

He leak due to electrical arc



Over pressure from cryo-lines

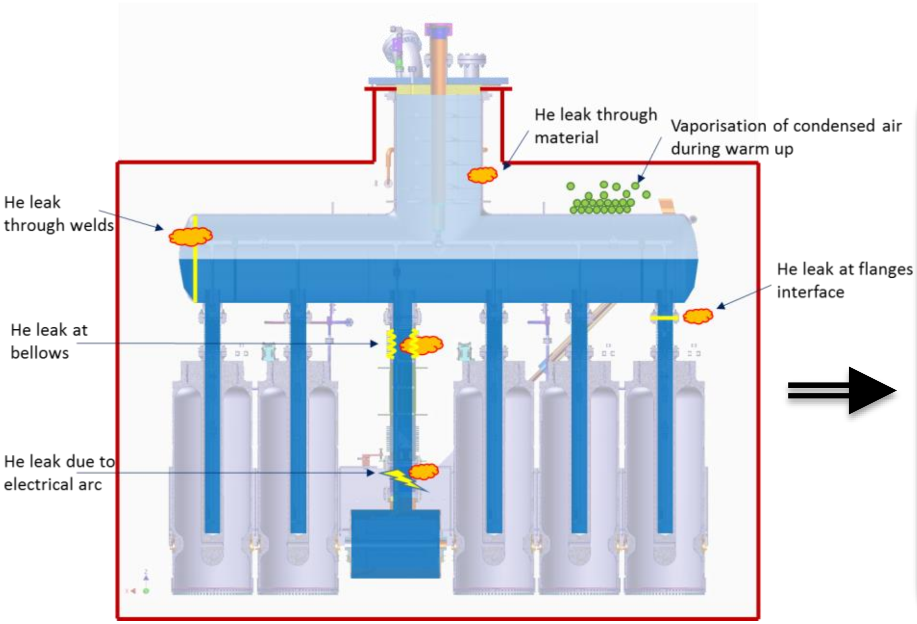
Air leak ➔ heat load to helium volume

He leak ➔ heat load to helium volume

He leak at flanges interface

Quench

Risk assessment : Case #1:
Over pressure in vacuum vessel



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tests,

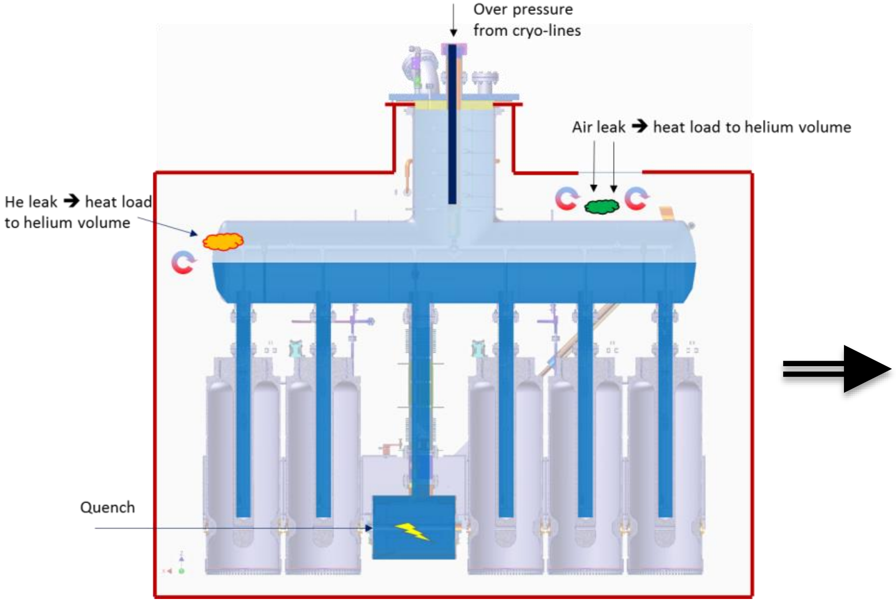
➔ worst case scenario:

During mechanical adjustment at cold, excessive torsion is applied to the bellows leading to the complete rupture of ONE bellows leading to a 5 kg/s helium leak to the vacuum vessel

Control Measure

Safety relief device on the vacuum vessel and the helium volumes

Risk assessment : Case #2
Over pressure in the helium circuits

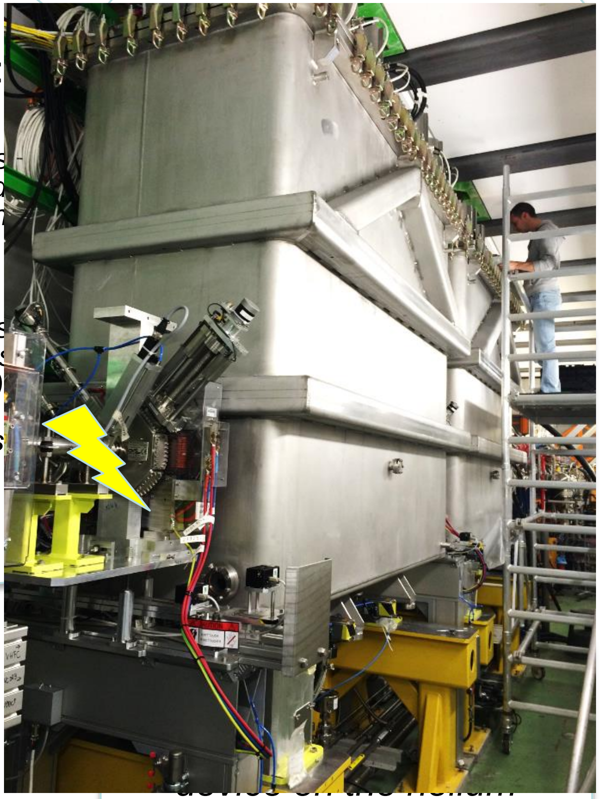


Mitigation actions:

Design: *reliable connections (CF flanges double seals), standar welding design, transien simulations*

Manufacturing: *strict application of standard (radiographic inspection certification, leak tests)*

Assembly: *“stress-less assembly, leak tests, pressure test*



device on the helium volumes

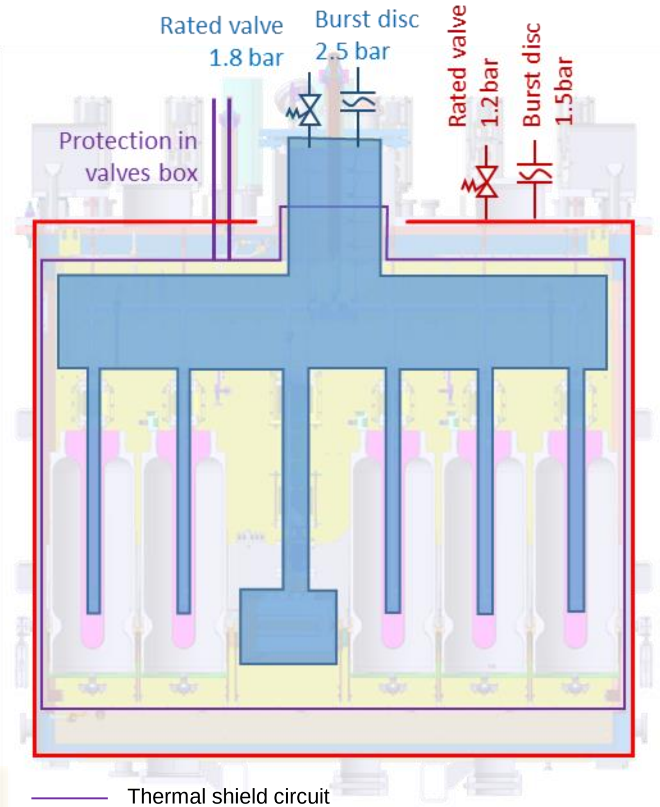
➔ worst case scenario:

A vacuum break of the beam line leads to an rapid air leak to the vacuum vessel condensing on the cold surfaces (no MLI) and transferring 76 kW heat load to the helium circuit in nominal operation leading to a 5 kg/s released mass flow to remain under PS

Safety devices sizing : EN 13648-3 and EN ISO 4126

Layout

- Over-pressure safety relief device :
  - 1 burst disc on helium volume
  - 1 burst disc on vacuum vessel
- For operation:
  - 1 additional rated valve on each volume
- All cryogenic valves in the valve box equipped with relief devices



Thermal shield circuit
Vacuum vessel
Helium volume: 250l

Relief pressure devices of the thermal shield circuit are located in the jumper box

Scales of pressures

Helium volume
[bara]
4.6 : Test pressure
3.5 : PS: bursting pressure
2.8 : Rated valve opening pressure
2.5 : Maximum transient pressure
1.3 : Nominal pressure
<1.10^{-3} : Purge pressure

Vacuum volume
[bara]
1.5 : PS: bursting pressure
1.2 : Rated valve opening pressure
1.10^{-8} mbar : Nominal pressure

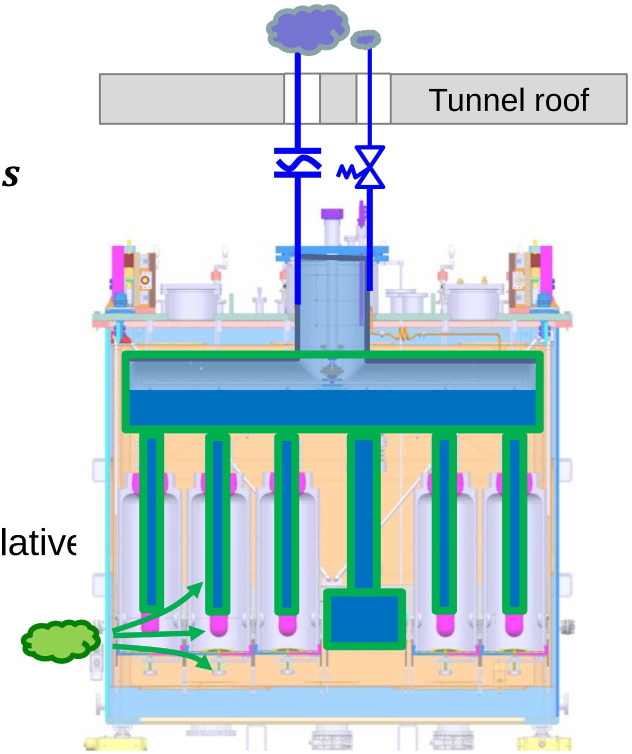
Thermal shield circuit
[bara]
24 : Test pressure
17 : PS: safety valve opening pressure
16 : Maximum transient pressure
13 : Nominal pressure
<1.10^{-3} : Purge pressure

Safety devices sizing : EN 13648-3 and EN ISO 4126

Helium volume safety relief device

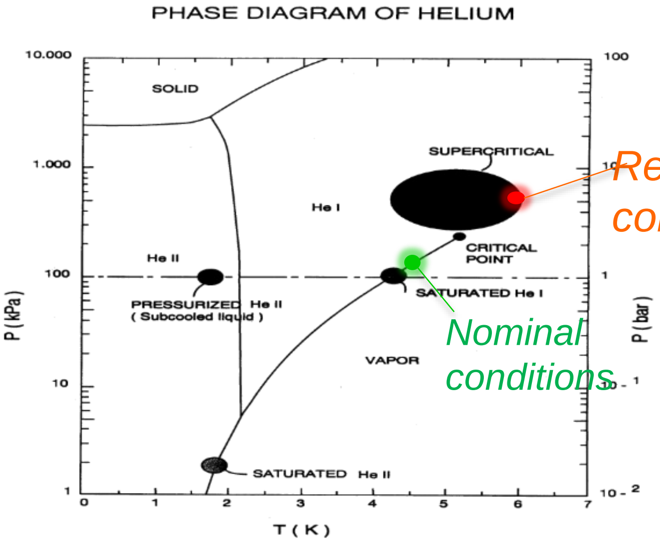
- Heat load to the Helium volume: $\boldsymbol{P_{He} = 76\ \mathrm{kW}}$
  - Power introduced by a choked air flow through the beam tube: 0.16kg/s at 300K
- Mass flow to be relieved by the safety device at 3.5 bara : $\boldsymbol{Q_m = 5kg/s}$
  - P>Pc ➔ $Q_m = \frac{W}{L'} = \frac{76\ kW}{19.4\ kJ/kg} = 3.9\ kg/s$ (See EN13648-3.4 for L' calculation)
  - +25% margin in case of area obstruction during release
- Release temperature of the supercritical helium: $\boldsymbol{T_{He} = 6.2\mathrm{K}}$
  - where $\frac{\sqrt{v}}{v\left[\frac{\partial h}{\partial v}\right]_{P0}}$ is maximum:

v specific volume of supercritical helium at relieving pressure p0.
h enthalpy of helium at relieving conditions



- **➔ Relief area > Ø46mm**
  - Choked flow of supercritical helium at 6.2K with 2.5 bar relative pressure
- **➔ burst disk DN50**

DN50 bust disk



Relief conditions

Nominal conditions

0. Nominal conditions: *saturated liquid 1.3 bara*

1. Vacuum break through beam port

2. Air in-flow to the VV

3. Heat transfer to cold surfaces (no MLI!)

4. P increase to 3.5 bara & device opening

Safety devices sizing : EN 13648-3 and EN ISO 4126

Vacuum vessel safety relief device

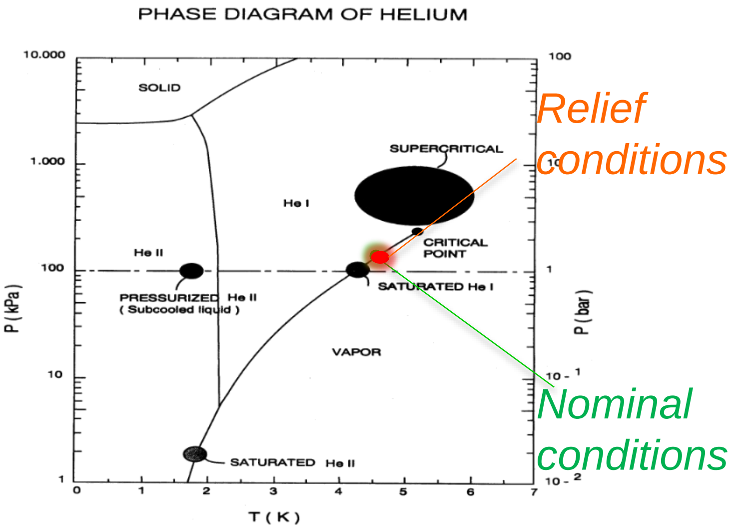
- Mass flow to the vacuum vessel through the broken bellows : $Q_m = 4.7 kg/s$
  - Helium flow through orifice in nominal conditions: P=1.3 bara

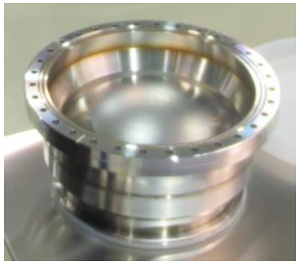
- Mass flow to release through the device = Mass flow entering the vacuum vessel

- Relief temperature at the relief device: 12K (estimated warm up along path: most critical parameter for sizing)

- ➔ **Relief area > Ø112mm**
  - Choked flow of GHe at 12K with 0.5 bar relative pressure to atmosphere

- ➔ **burst disk DN180**





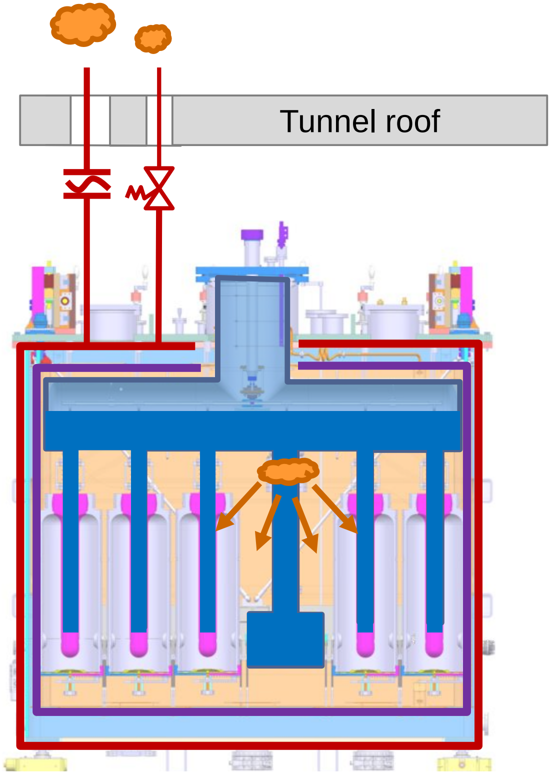
DN180 bust disk

0. Nominal conditions: ***P=1.10^{-8}mbar***

1. Bellows rupture: ***4.7 kg/s mass flow***

2. Pressure increase

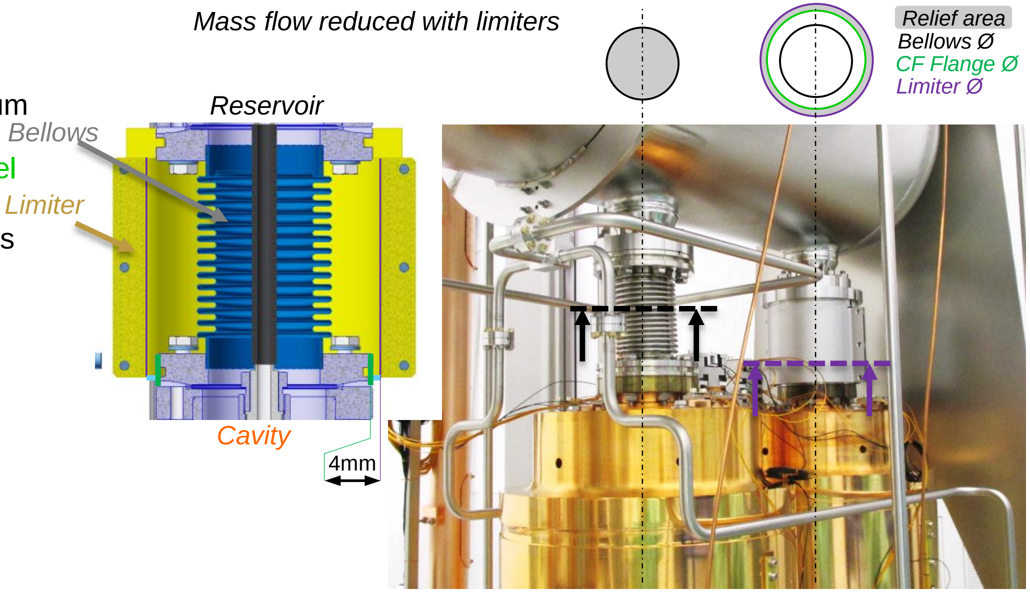
3. Relief devices opening: ***at P=1.5 bara***



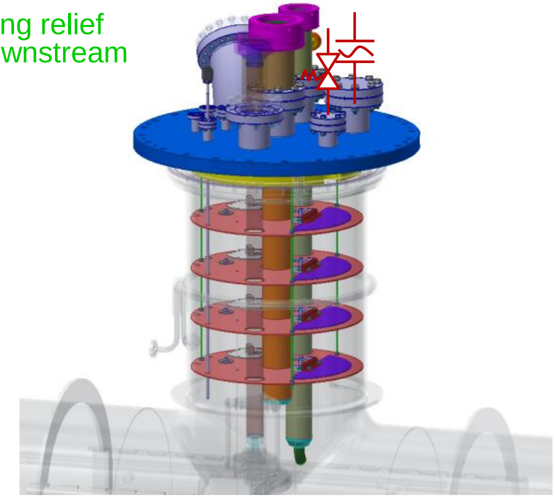
Risk mitigation by design, a few examples

Optimisation of the fluid release

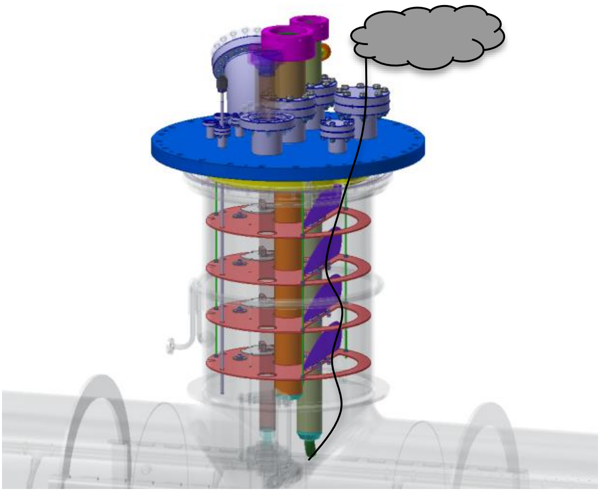
- Vacuum vessel relief devices
  - Protection on bellows to limit effective flow area to vacuum vessel
    - ➔ reduction of mass flow rate to the vacuum vessel
  - Reduction of path to the burst disc to limit warm up of gas before exhaust
    - ➔ reduction of relief area



- Helium volume relief devices:
  - Opening flaps in neck baffles:
    - ➔ Minimise path to relief device
  - Location of burst disc directly on the reservoir
    - ➔ minimise fluid temperature for reducing relief area and diameters of exhaust pipes downstream
  - Increase design pressure PS
    - ➔ reduce relief area



Nominal configuration



Release configuration

Incident on 12 August 2015

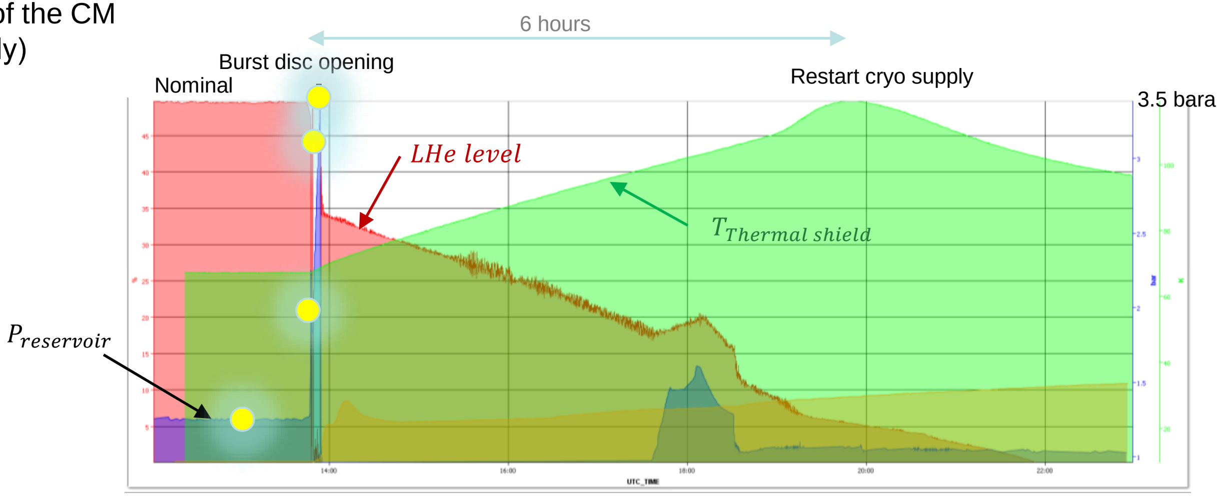
Event chronology:

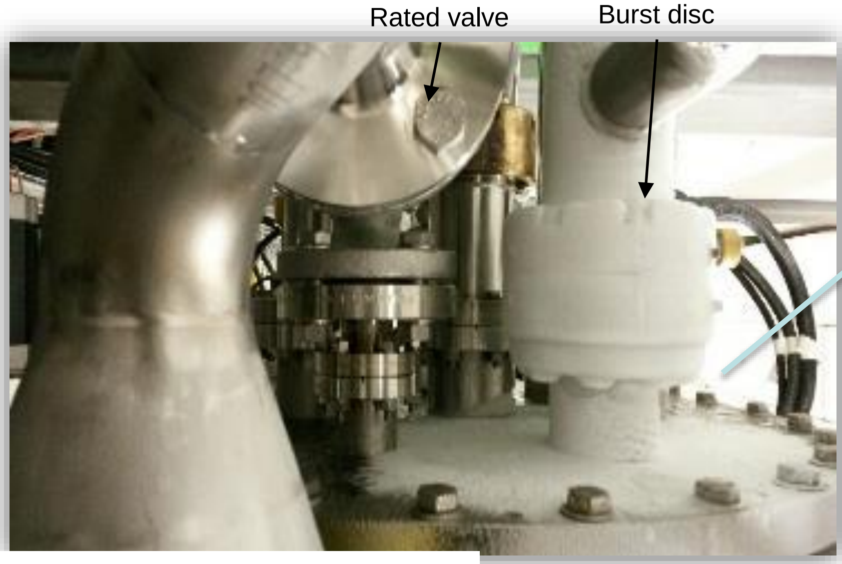
- 1.3 Pressure rise on the compressor side
- ➔ pressure increase in the helium volume of the CM
- 3.1 ➔ Rated valve doesn't open (or only partially)
- 3.5 [bara] ➔ Burst disc open
- 32 l of 150l vaporised

Post event:

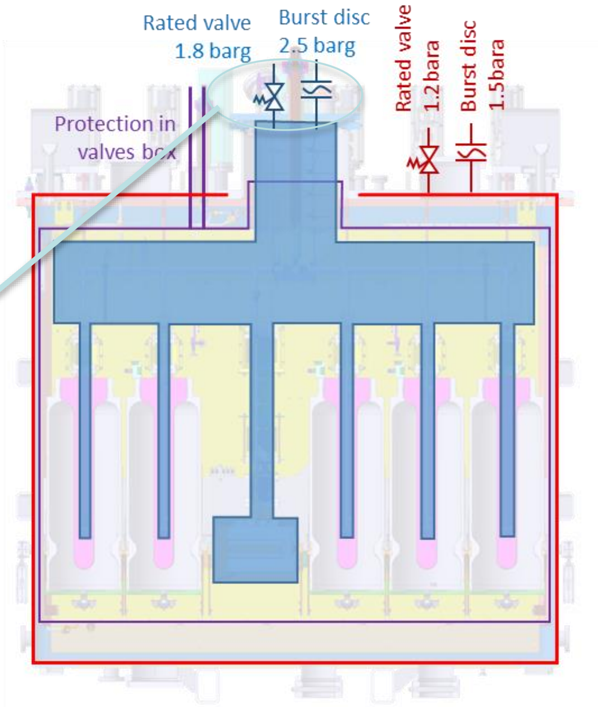
- Quick replacement of burst disc
- Alignment kept within 0.1mm
- Internal instrumentation: OK
- ➔ Equipment has not suffered any damage

Internal pressures and temperatures 12 August 2015

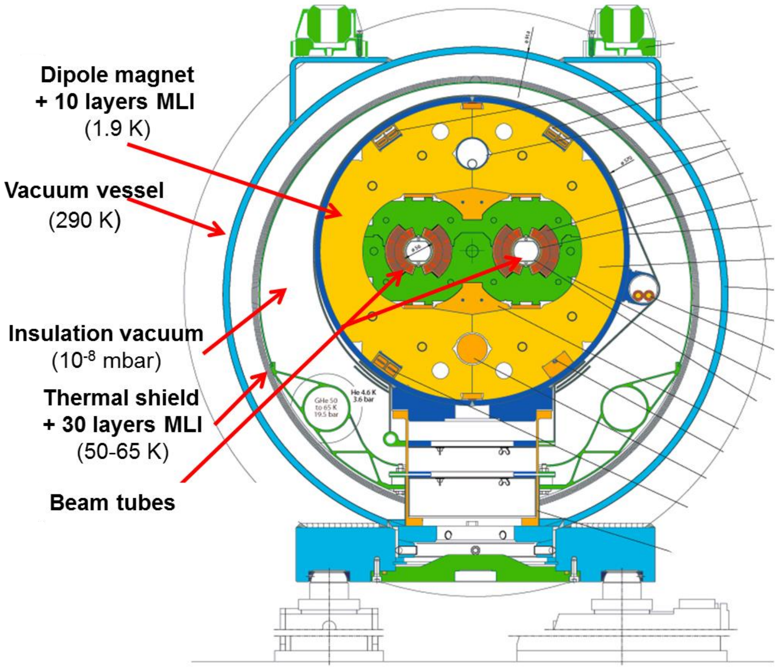


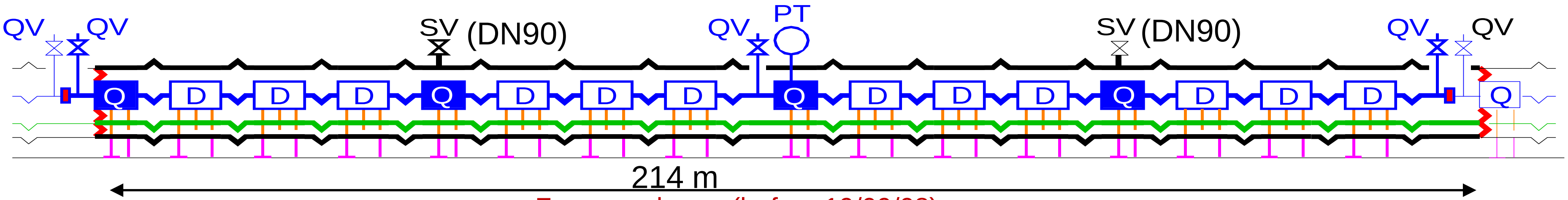


After burst disc opening 12 August 2015



The LHC magnet cryostats





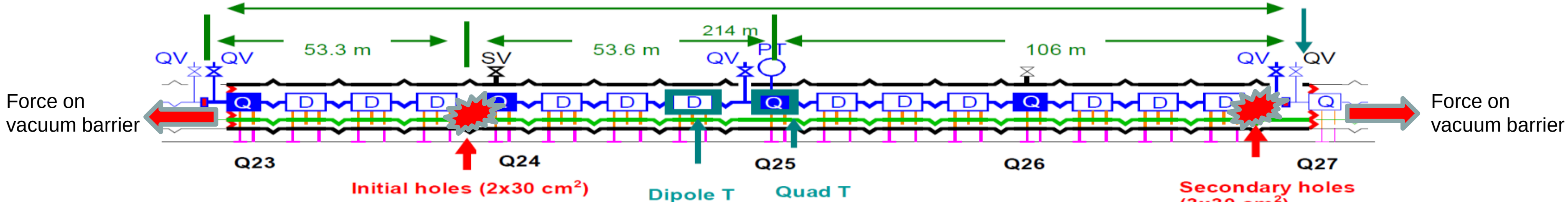
Former scheme (before 19/09/08)

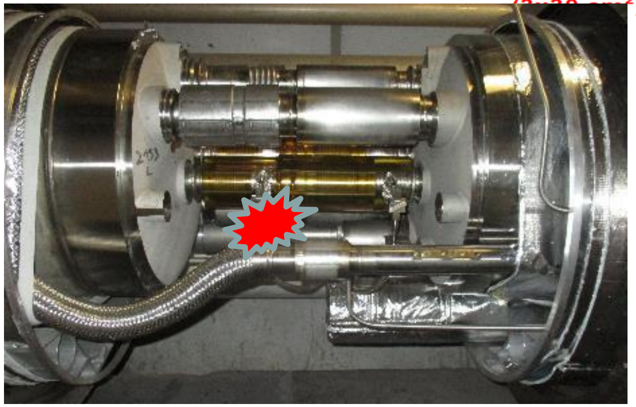
- x 8 continuous arc cryostats, ~2.7 km each
- Insulation vacuum sub-sectorisation barriers every 214m (→ ~80 m^3 /vac.sub.sector)
- ~ 25 l/m liquid helium (→ ~ 5 m^3 /vac.sector)
- Volume ratios: $V_{liquid} / V_{ins.vac.} = \sim 6\%$; $V_{gas} / V_{ins.vac.} = \sim 40$
- 3 DN40 quench valves (QV) per vac.sector, open at Ps=20 bar exhaust in a DN150 line
- Before 19/09/08 event: 2 DN90 safety relief devices (SV) on cryostat vessel, then 1 DN100 added on each dipole vessel

🟦	Cold-mass
■	Vacuum vessel
🟩	Line E
|	Cold support post
|	Warm Jack
⌵	Compensator/Bellows
⚡	Vacuum barrier

The LHC: the 19th September 2008 incident

Ph. Lebrun et al. "Report of the task force on the incident of 19th September 2008 at the LHC", LHC Report 1168



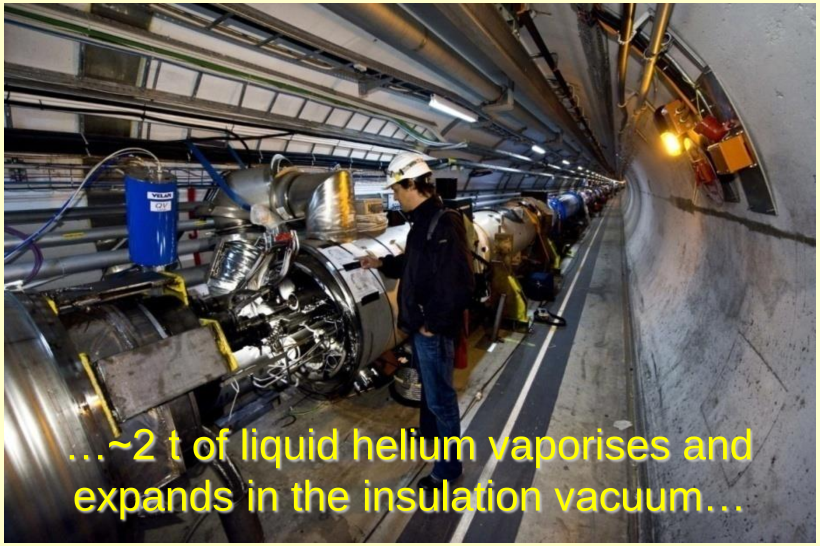


Sequence of events:

- Electrical fault produced an arc (~4 MW) in an interconnection between magnets (to)
- 1st breach of the helium enclosure (and beam vacuum pipes) (to)
- Magnet quenches, pressure rise in helium enclosure (~to+5s to ~to+20s)
- Liquid helium expelled to the insulation vacuum, expands and vaporises
- Additional heat to helium from the electrical arc and degraded insulation of the cryostat
- Pressure increase in vacuum vessel up to ~ 8 bara, safety relief devices insufficient for the mass flow, longitudinal force developed on vac.barrier (~to+30s)
- Longitudinal forces up to ~600 kN, ground failure at some external jacks anchoring
- Longitudinal displacement of magnets creating secondary arcs and breaches in the interconnections with a cascading effect
- 4 vacuum sub-sectors concerned by magnet damage (~50 magnets replaced), beam vacuum contamination on good fraction of the 2.7 km arc

Direct and collateral damage


…punctured He envelope and beam lines

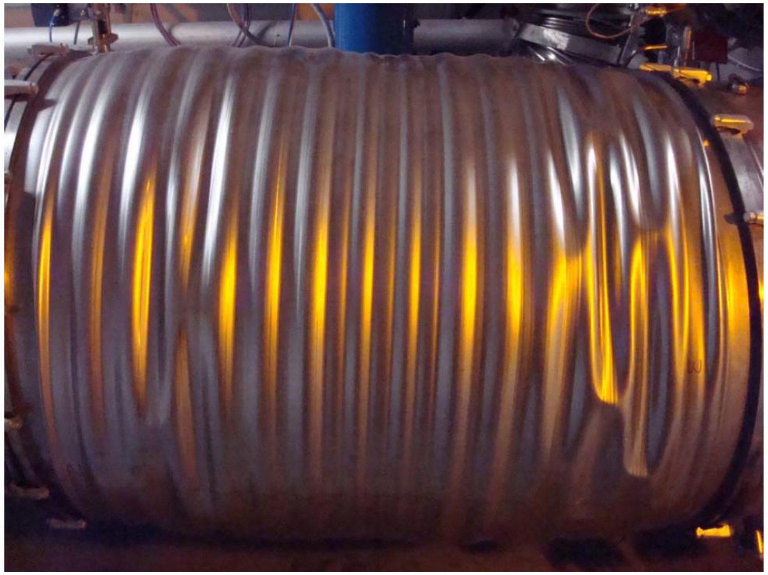

…~2 t of liquid helium vaporises and expands in the insulation vacuum…


…exerting ~50 t longitudinal forces on SSS with vacuum barriers…

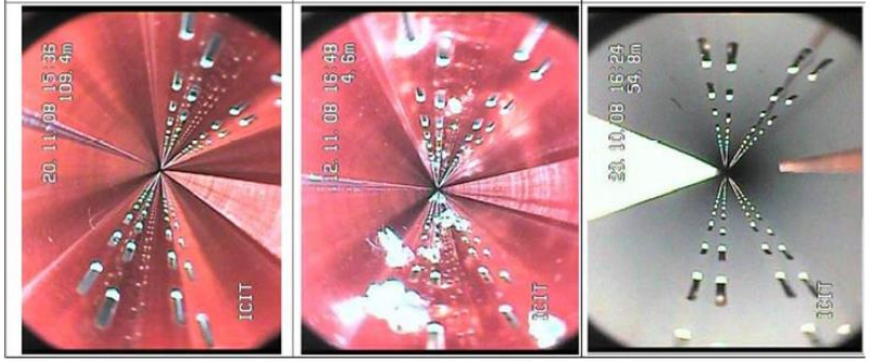

…supports uprooted floor breaks

Collateral damage

Damage to interconnection QBQI.27R3 by excess extension



Picture of the sleeve in interconnection QBQI.27R3 after the incident (internal pressure calculated up to 8 bara)



Beam Screen (BS) : The red color is characteristic of a clean copper surface

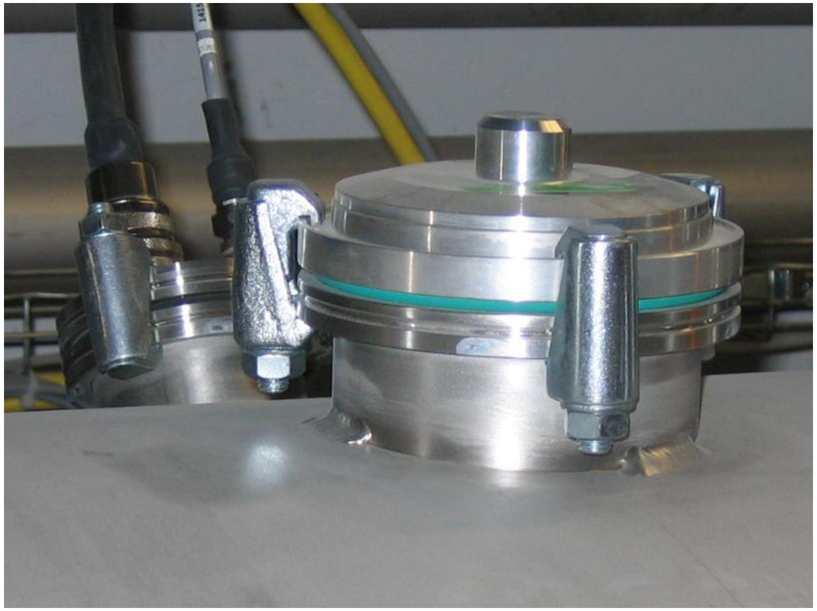
BS with some contamination by super-isolation (MLI multi layer insulation)

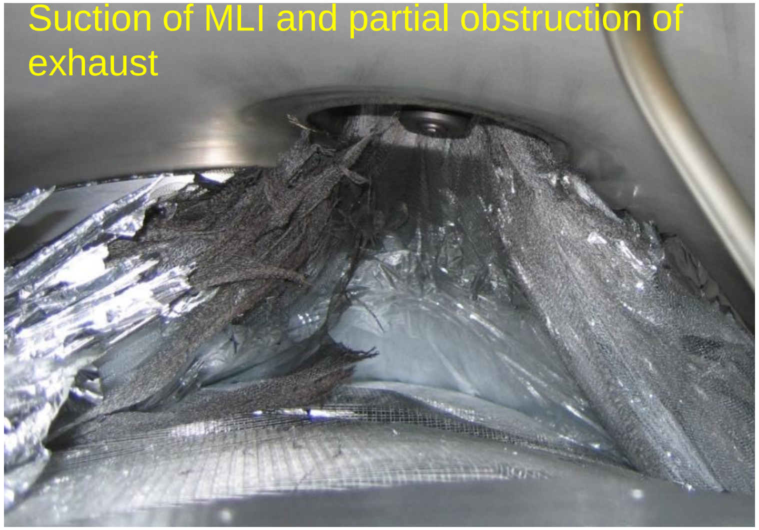
BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.

Contamination of the vacuum beam pipes

Damage to “jumper” connections of cryogenic distribution line

DN90 safety relief devices

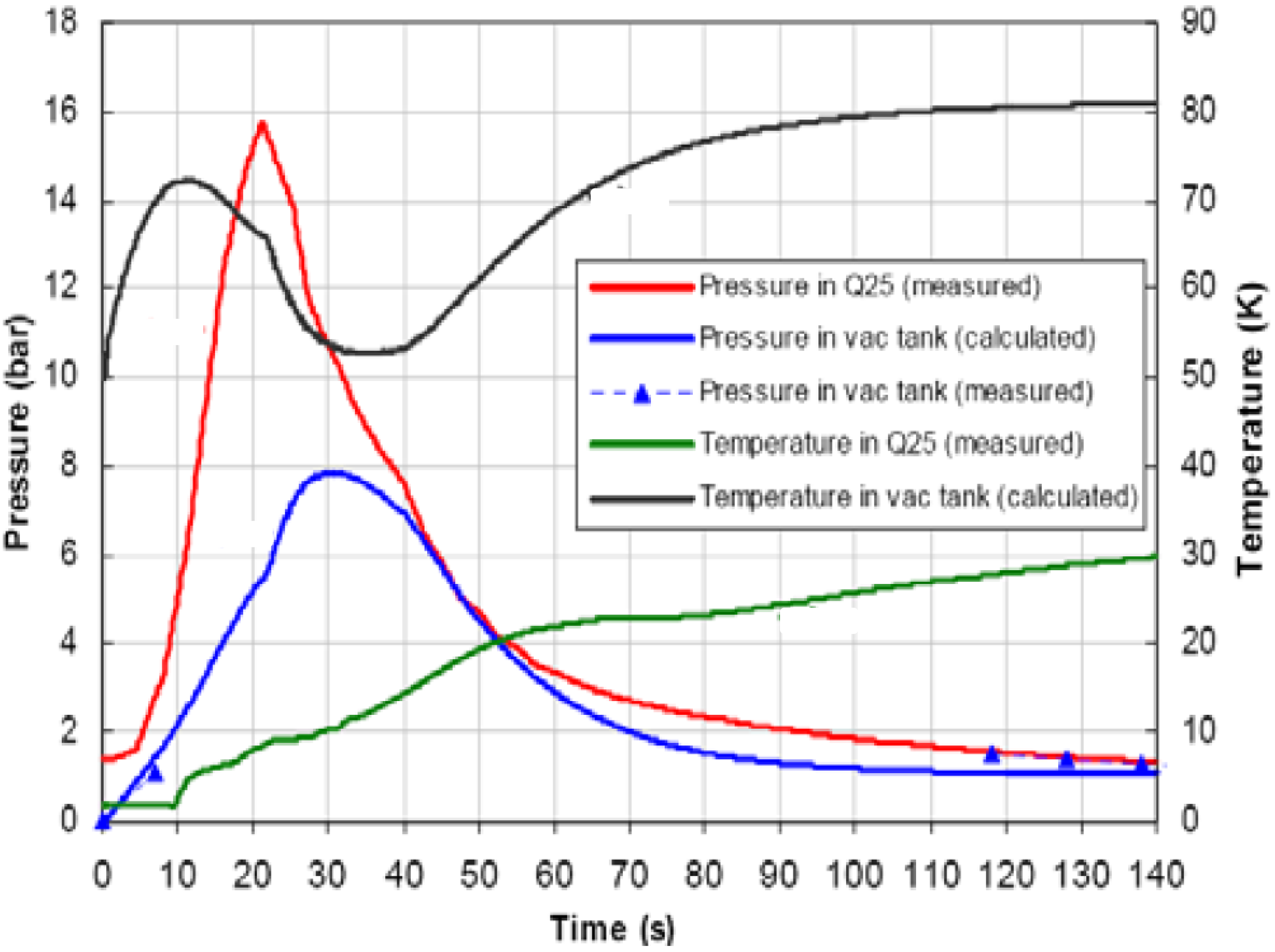




Suction of MLI and partial obstruction of exhaust

MLI residues

Pressures and temperatures



Pressures and temperatures as measured in Q25 and calculated in the cryostats

Original risk analysis

Critical event 1

- Full break of “jumper” connection
- Release of 4’250 kg of helium to the tunnel
- Peak flow of 20 kg/s
- Discarded because highly improbable

Critical event 2:

- Full break of liquid helium header C (DN15) in the cryogenic distribution line
- Release of 3’300 kg of helium to the tunnel
- Peak flow of 2 kg/s
- Retained as Maximum Credible Incident (MCI) design condition for relief devices

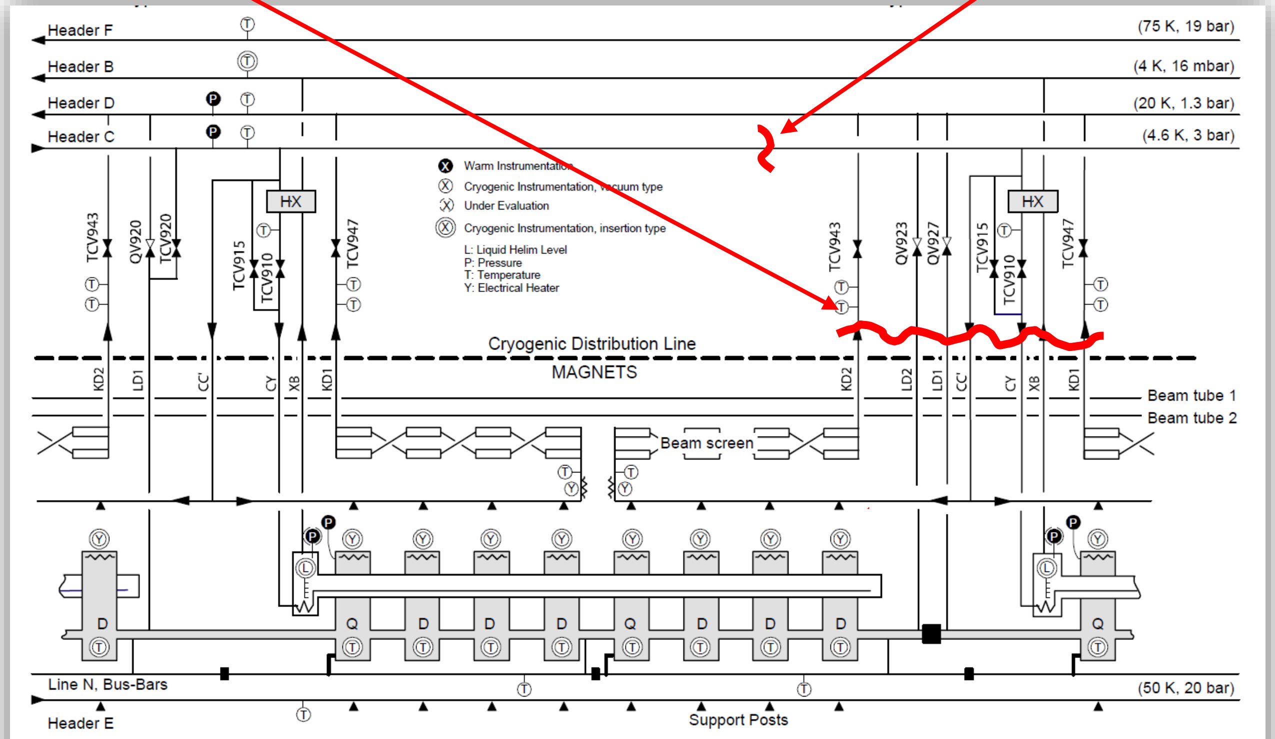


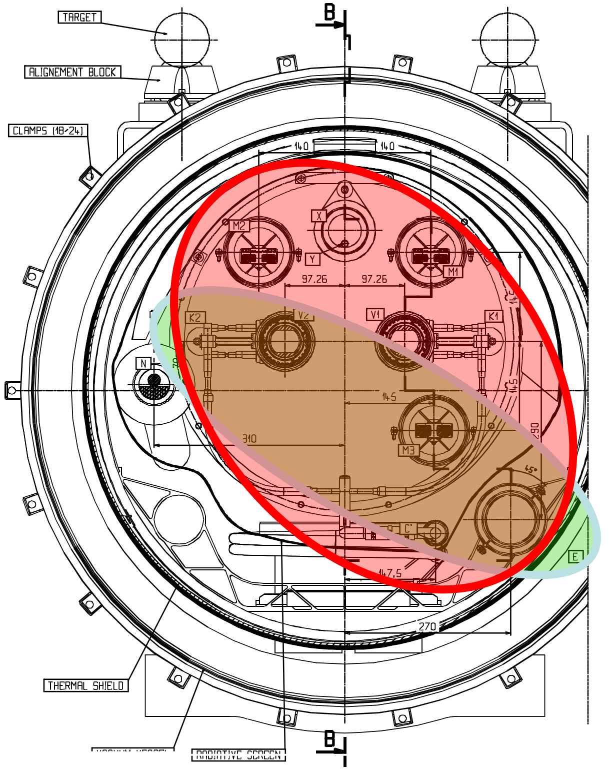
Figure 11.5: Cryogenic flow-scheme and instrumentation of a LHC lattice cell

→ Neither of these events resembles the incident of 19th of September 2008 !

M.Chorowski et al. ”Preliminary risk analysis of the LHC cryogenic system”, LHC Project Note 177, 1999-01-12

Newly defined MCI

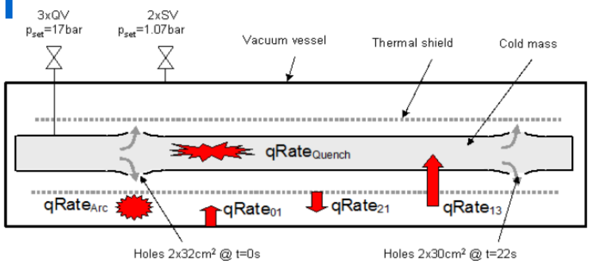
M.Chorowski et al. "Upgrade on risk analysis following the 080919 incident in the LHC sector 3-4", CERN/ATS/Note?2010/033 (TECH), 2010-07-01



MCI **Sect.3-4 incident**

Available cross-section for different failure scenarios [cm²]

Interconnection pipe	Preliminary Risk Analysis [2]	19th Sept. 08 Incident	Maximum Credible Incident
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



Mathematical model tuned to the sec.3-4 incident data

New MCI with former SV conf.

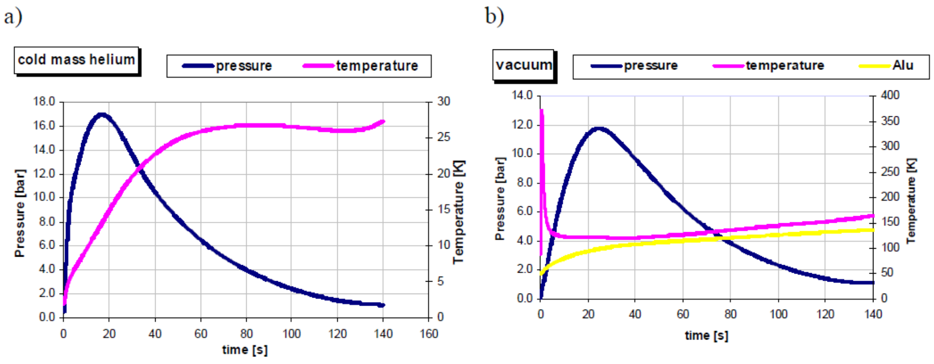


Figure 16. Modelling results with original SV configuration scheme.
a) b)

Peak mass flow rate: 32 kg/s, Max Pcm: 17 bar, Max Pvv: 12 bar

New MCI with new SV conf.

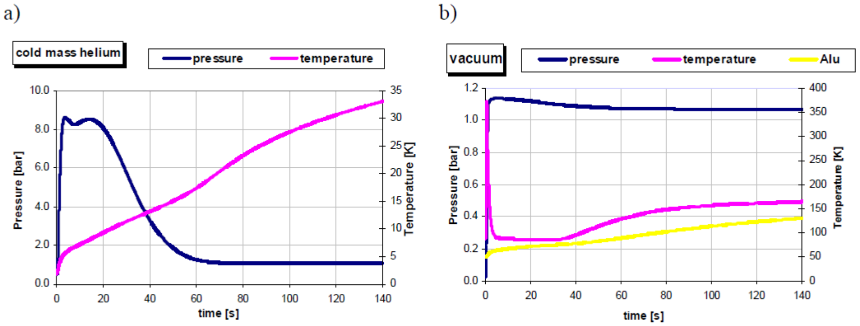


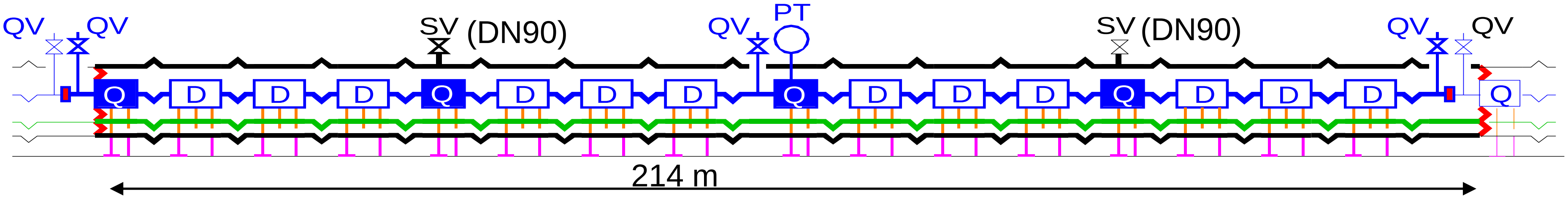
Figure 20. MCI modeling results with final SV configuration scheme, a) – cold mass helium parameters, b) – vacuum space helium parameters and temperature of the aluminium thermal screen

Peak mass flow rate: 30 kg/s, Max Pcm: 9 bar, Max Pvv: 1.2 bar

Former and new vacuum vessel relief devices (SV)

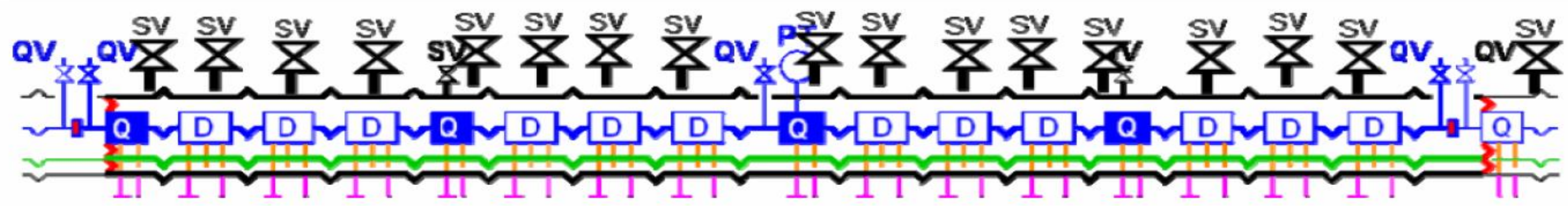
Original configuration (prior to 19 th Sept.2008 incident):

- 2 DN90 safety relief devices (SV) on cryostat vessel



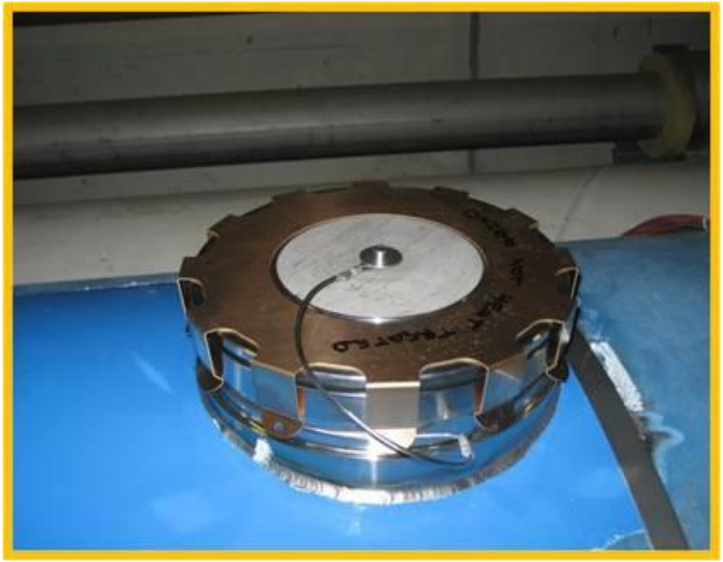
Final configuration (to cope with new MCI)

- Additional DN200 safety relief devices (SV), 1 on each on dipole cryostat vessel



P.Cruikshank et al.''New protection scheme and pressure relief-valve staging of the LHC insulation vacuum enclosure following the 19th September 2018 incident'', CERN/ATS/Note/2010-057 TECH

New LHC safety relief devices (BD)



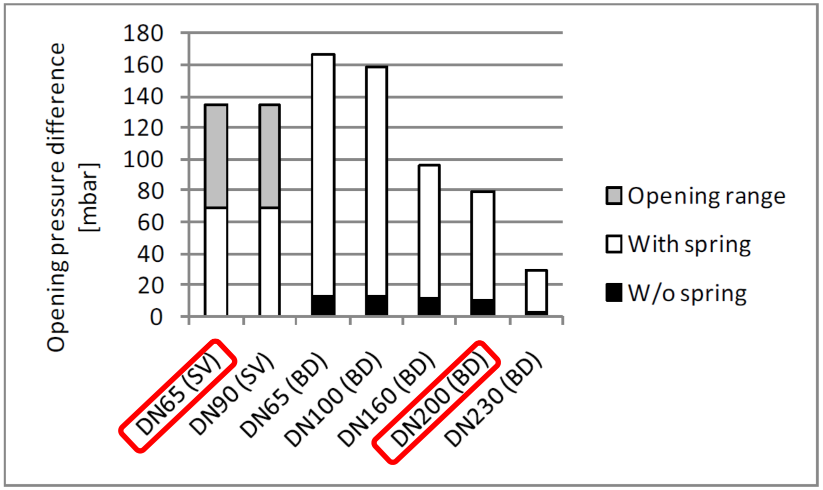
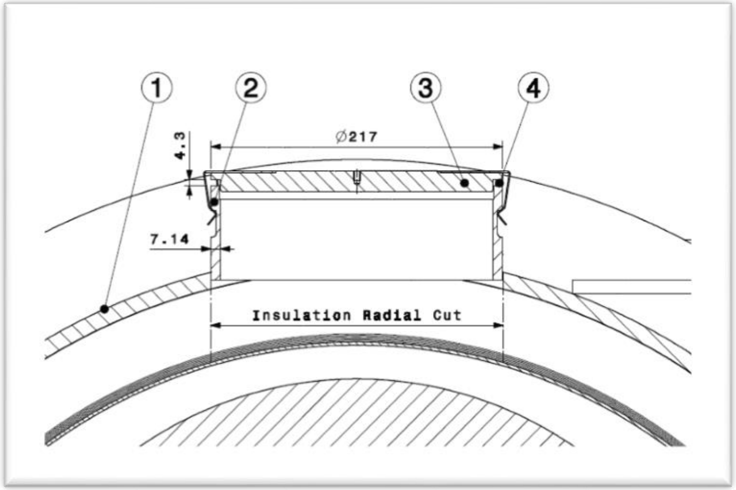


Figure 3 Opening pressure of safety relief devices



1 flap valve per sub-sector (opens first, can take up to 1 kg/s, re-closes)

Summary

- Cryostats are elements in complex systems, where the definition of pressure protection requires collegial work with systems specialists, in particular cryogenics and safety specialists

- Still the main responsibility for safety remains with the cryostat engineer in charge

- Pressure vessel codes and standards are well established and provide very useful guidelines for design purposes (e.g. calculating mass flows once heat fluxes are known) but there are no dedicated standards for LHe cryostats.

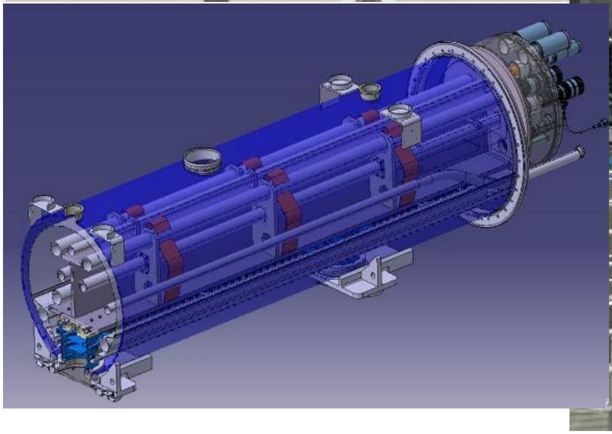
- Pressure safety design aspects must be included at the earliest convenient stage of the design (e.g. suitable choice of Ps, risk mitigation measures by design)

- Risk analysis and identification of the worst case scenarios is the most complex part in safety design. Failure modes can be difficult to model and, in some cases, simplifications lead to over-conservative scenarios making the choice of pressure relief devices unpractical (size, housing, etc.) requiring an iterative refinement process.

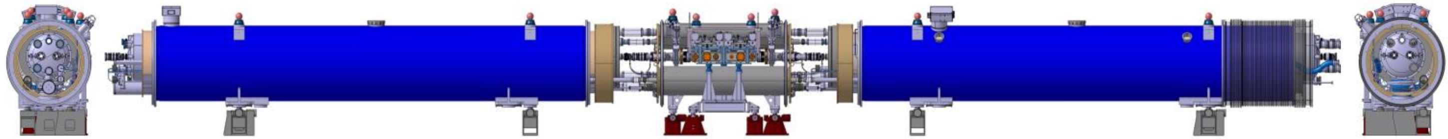
- Sizing of the safety devices is as adequate as the failure assumptions made are and is based on calculations (full-scale experimental validation is not systematic). As a consequence, safety calls for conservative and reliable approaches based on simplified models.



Thank you for your attention!





Spare slides

Risk assessment : sources of risks

Pressurised cryogenic fluids

P from cryoplant/Expansion of cryo fluids	Mitigation actions

• CD/WU transients:
  • 250l of supercritical He at 2.5 bara
  • 10l of Ghe at 16 bara, 50-300K
• Nominal:
  • 150l of LHe at 1.3 bara
  • 10l of Ghe at 13 bara, 50K
	• Pressure control
	• Safe relief

Stored energy

Applied to cryomodule	Mitigation actions
• Quench • 19 kJ stored in the superconducting solenoid • Pressurised volumes	• Safe dissipation directly in 150l LHe bath at 4.5K • ➔ keep the increase of pressure below design pressure