RISK ASSESSMENT

Failure Modes of the HL-LHC Cold Powering System (WP 6a) Leading to Helium release

ABSTRACT:

In this note, the components of the HL-LHC cold powering system are briefly described.

Cryogenic failure modes leading to Helium release are identified and described, including the location of the final release to the working environment.

Mitigation measures and safety devices, together with calculation, will be presented in companion notes, referenced here.

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HISTORY OF CHANGES

REV. NO.	DATE	PAGES	DESCRIPTIONS OF THE CHANGES
0.1	20.12.2019	All	First draft
0.2	14.01.2020	All	Corrections on version 0.1 by N. Grada

Contents

1. Introduction

The underground service areas of HL-LHC, in the UW, UR and UA galleries, shall remain accessible to technical personnel even during operation of the accelerator with beam.

For this purpose, technical systems in these galleries must reply to minimal safety requirements to

- avoid incidents and accidents (for example, equipment must be built in accordance with safety standards),
- be able to react to accidental situations, for example by evacuating personnel

In this note, cryogenic release scenarios following failure modes of components of the cold powering system are identified and described. Mitigation measures and detailed calculations are presented in a series of companion documents, here referenced.

2. Description of the Cold Powering System

For the HL-LHC upgrade, novel superconducting lines, the so-called Superconducting (s.c.) Links, are being developed to supply current to the magnets in the LHC tunnel from the UR Gallery, over a distance of approx. 100 m.

On each side of the HL-LHC interaction points P1 and P5, two magnet power connections will be installed:

- From power converters over a warm-cold transition ("current leads") into the feedbox DFHx, the s.c. link DSHx to the feedbox in the tunnel DFX, for supplying the inner triplet Q1 – Q3 and Dipole D1 with power.
- From a power converter over a warm-cold transition ("current leads") to a feedbox DFHm, the s.c. link DSHm to the feedbox in the tunnel DFM, for supplying dipole D2 with electrical power.

The powering system for D2 is smaller than the one for Q1-Q3 and D1.

A link will carry all together up to about 150 kA in LHC P1 and P5.

The Cold Powering System consists of [1], (Figure 1):

- Current leads. The leads transfer the current from room temperature to 4.2 K. They are made from high-temperature superconducting (HTS) cables connected to the power converters via room temperature conventional cables. Thye are cooled by helium gas.
- A dedicated cryostat (DFHx and DFHm), in which the cold terminations of the HTS leads are spliced to the MgB_2 cables in the link, cooled by gaseous helium.
- A link, made of MgB_2 housed in a semi-flexible cryostat, cooled by gaseous helium (DSHx and DSHm);
- A cryostat (DFX or DFM) where each cable of the link is spliced to a Nb-Ti bus-bar feeding a magnet circuit. This cryostat supplies, by evaporation, the cold helium gas required for the preceding elements of the Cold Powering System.
- For the Q1-Q3 quadrupoles and the D1 dipole, after a lambda plate, a splice of NbTi busbars to Nb_3Sn busbars

- Cryogenic instrumentation required for control, monitoring and interlock functions as well as electrical instrumentation needed for protection of superconducting components and current leads.

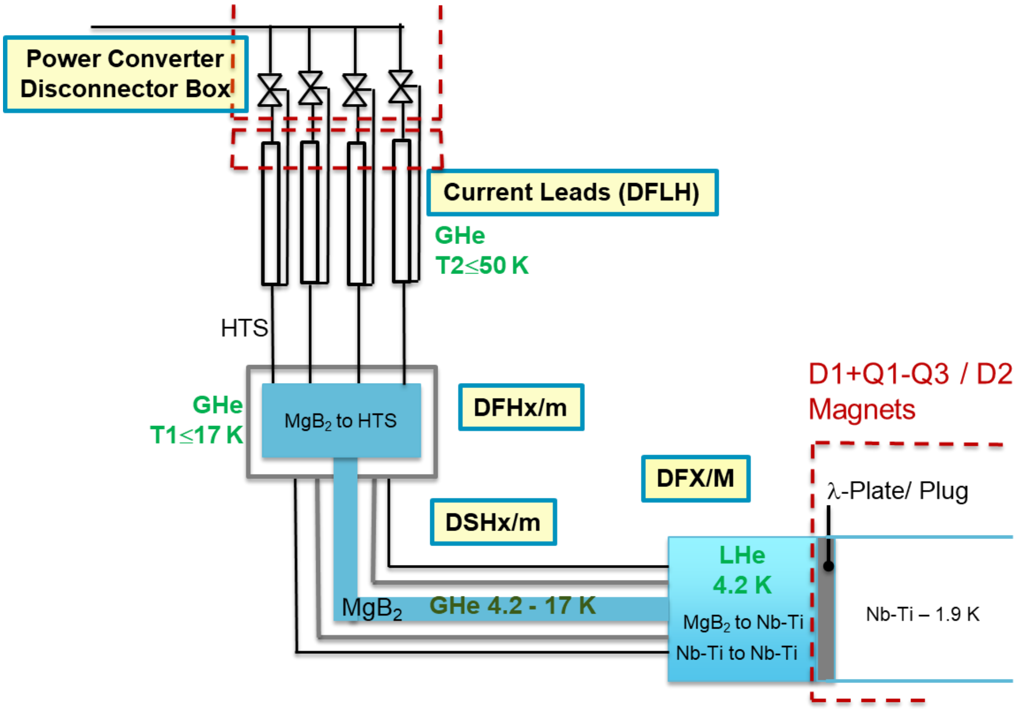


Figure 2-1 : Schematic lay-out of Cold Powering. From A. Ballarino, Int. Review of HL-LHC Magnet Circuits, 9-10 September 2019, CERN, https://indico.cern.ch/event/835702/ (modified)

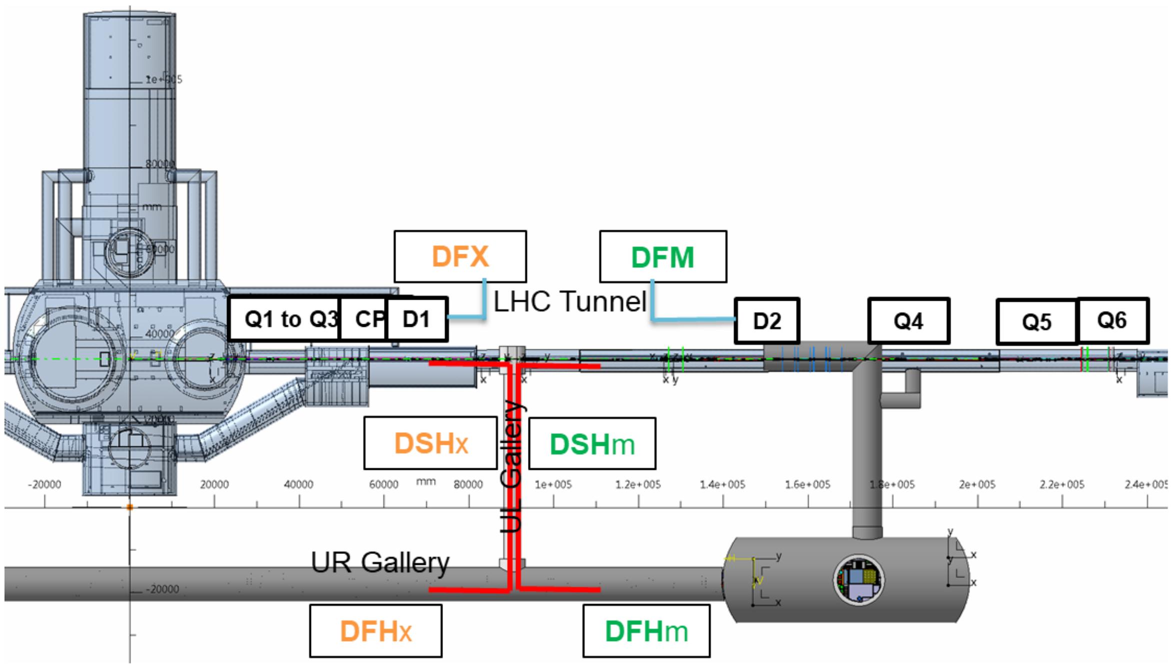
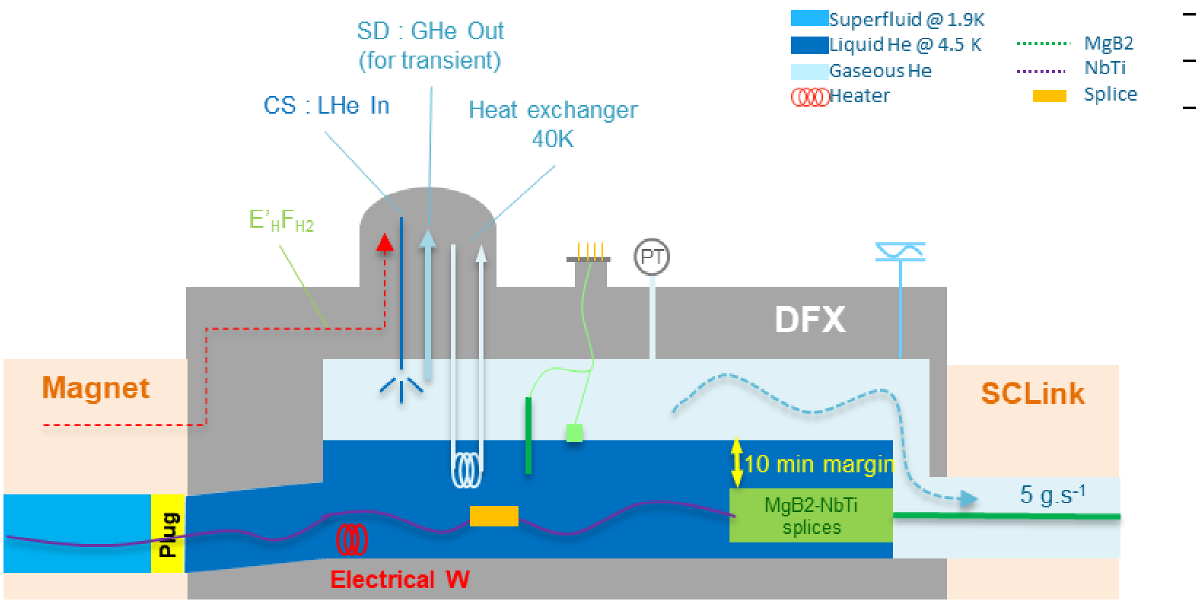


Figure 2-2:Layout of cold powering in the HL-LHC and LHC underground areas. From A. Ballarino, Int. Review of HL-LHC Magnet Circuits, 9-10 September 2019, CERN, https://indico.cern.ch/event/835702/ (modified)

2.1 DFX

- Main functions: two-phase Helium bath (lHe + gHe at about 4.5K). In the DFX cryostat, each cable of the link is connected to the Nb-Ti bus-bar feeding a magnet circuit.
- The gaseous helium for cooling DSHx and DFHx is supplied in form of vapour generated in the DFX cryostat.
- A plug separates the DFX cryostat from the cryostat of the Inner Triplet cold mass, filled with superfluid helium at 1.9K. The plug has feedthroughs for the Nb Nb–Ti busbars, carrying the current to the IT magnets Q1-Q3 and D1.
- Functional Specification EDMS 1905633
- Technical Specification EDMS 2169136
- Technical data:

Volume	Xx L
Helium inventory	16 kg
Helium temperature (liquid)	4.2 K
Helium temperature (gas)	4.5 K
Operating pressure	1.3 bar (a)
Design pressure	3.5 bar (a)



– Figure 2-3 : Functional design drawing of DFX. From Y. Leclercq, "DFX Functional Specification"; https://indico.cern.ch/event/821876/. In the present design, the s.c. link is connected vertically to the DFX, see **Error! Reference source not found.**.

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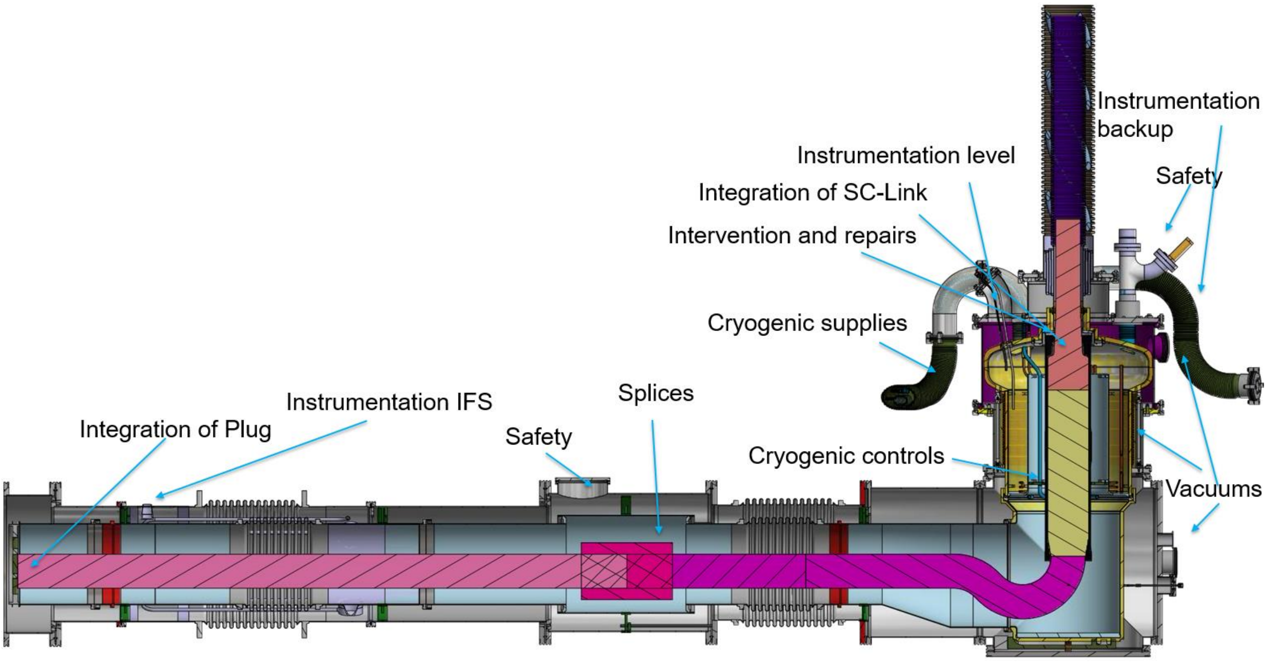


Figure 2-4 : Technical design drawing of DFX with main components. From Y. Yang, "DFX detailed design" https://indico.cern.ch/event/821876/

2.2 DFM

- Main functions: two-phase Helium bath (lHe + gHe at about 4.5K). In the DFM cryostat, each cable of the link is connected to the Nb-Ti bus-bar feeding a magnet circuit.
- The gaseous helium for cooling DSHm and DFHm is supplied from DFM in form of vapour generated in the DFM cryostat.
- A plug separates the DFM cryostat from the cryostat of the D2 cold mass, filled with superfluid helium at 1.9K. The plug has feedthroughs for the Nb Nb–Ti busbars, carrying the current to the D1 magnet.
- DFM Functional Specification EDMS 2052614
- Technical data:

Volume	Xx L
Helium inventory	Xx kg
Helium temperature (liquid)	4.2 K
Helium temperature (gas)	4.5 K
Operating pressure	1.3 bar (a)
Design pressure	2.5 bar(a)

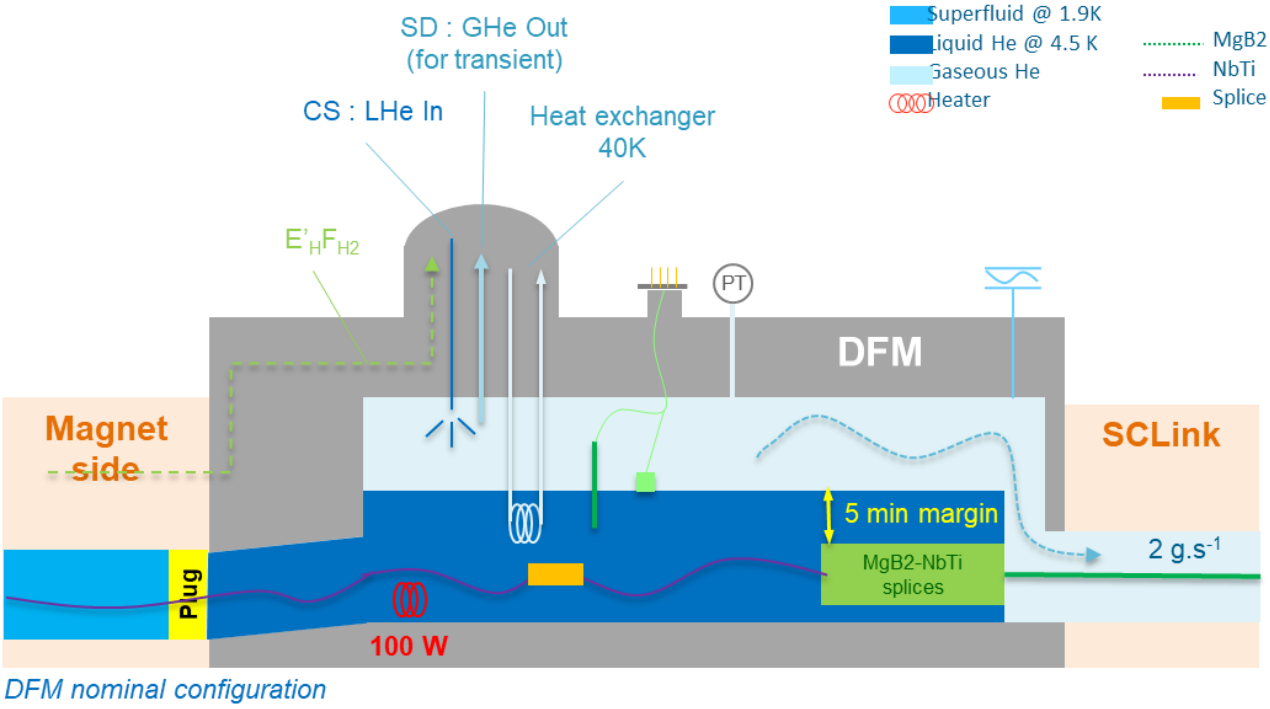


Figure 2-5 : Functional design drawing of DFM. From Y. Leclercq, "DFM Functional Specification", https://indico.cern.ch/event/821879/

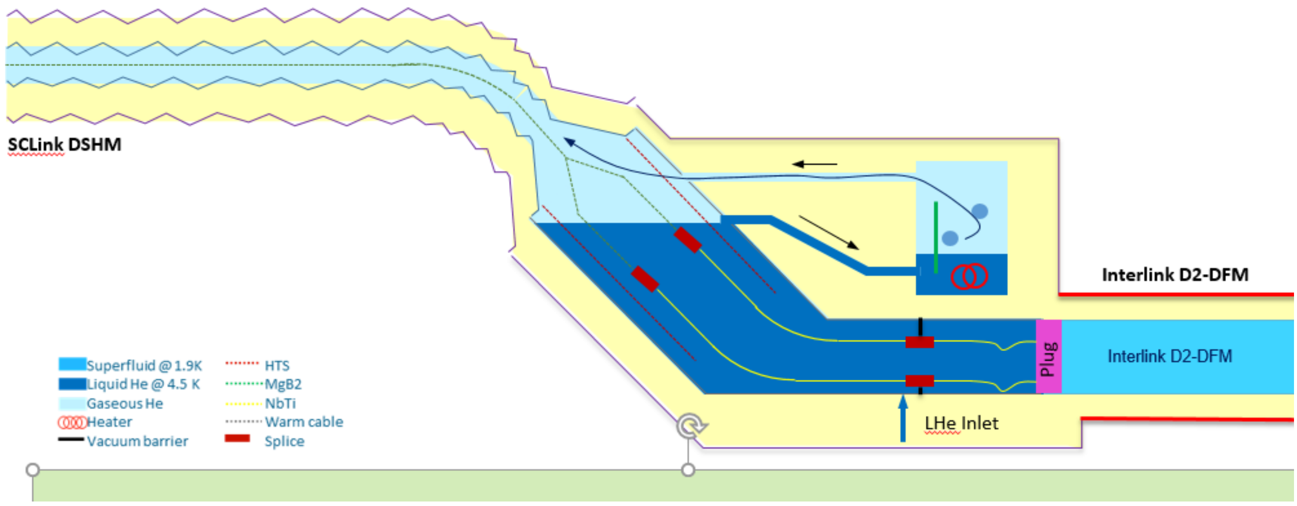


Figure 2-6 : Conceptual Design drawing of DFM. From Y. Leclercq, "CDR_DFM Conceptual Design" https://indico.cern.ch/event/821879/

2.3 DSHx

- A semi-flexible, vacuum-isolated cryostat for cooling of the s.c. links with helium gas.
- DSHx contains Helium vapour cooled s.c. cables leading current via the DFX to D1 and Q1-Q3. The gas cools the s.c. cables in the link and warms from 4.2 K to about 17 K while absorbing the static heat load of t he cryostat.
- Technical data:

Total current	120 kA
External diameter	176 mm
Cable diameter	90 mm
Length	60 m
Volume	Xx L
Operating pressure	1.3 bar (a)
Design pressure	3.5 bar (a)?
Helium temperature	(5 – 17) K
Helium inventory	16 kg

- Cryostat: Criotec P, diameter of the flexible part 176 mm; Other data, drawing

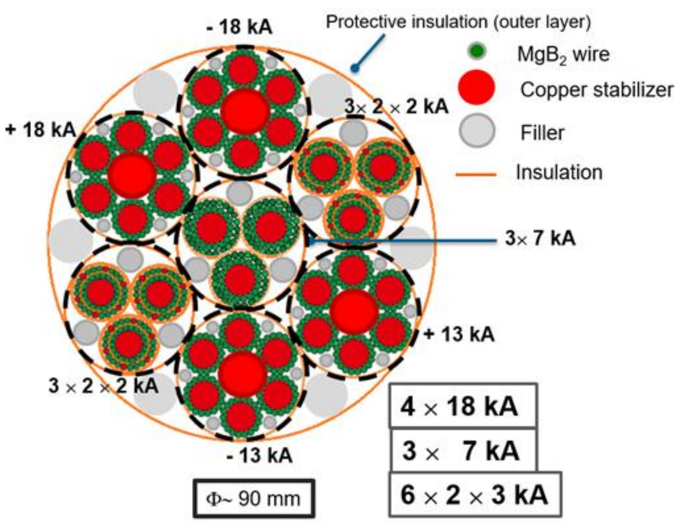


Figure 2-7 : Lay-out of MgB_2 cables in the s.c. link for the triplet (Q1-Q3, D1). From A. Ballarino, Int. Review of HL-LHC Magnet Circuits, 9-10 September 2019, CERN, https://indico.cern.ch/event/835702/

2.4 DSHm

- A semi-flexible, vacuum-isolated cryostat for cooling of the s.c. links with helium gas.
- DSHm contains Helium vapour cooled s.c. cables leading current via the DFM to D2. The gas cools the s.c. cables in the link and warms from 4.2 K to about 17 K while absorbing the static heat load of the cryostat.

- Technical data:

Total current	60 kA
External diameter	
Cable diameter	60 mm
Length	100 m
Volume	Xx L
Operating pressure	1.3 bar (a)
Design pressure	2.5 bar (a) ?
Helium temperature	(5 – 17) K
Helium inventory	Xx kg

- Cryostat: ??, diameter of the flexible part xx mm; Other data, drawing ?

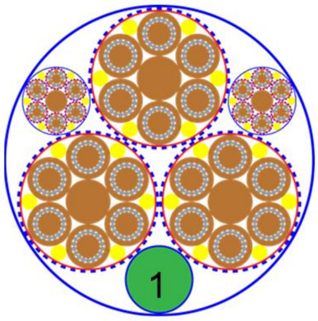


Figure 2-8 : Lay-out of MgB_2 cables in the s.c. link for the matching section (D2). From A. Ballarino, Int. Review of HL-LHC Magnet Circuits, 9-10 September 2019, CERN, https://indico.cern.ch/event/835702/

2.5 DFHx

- Main functions: Connection of current leads to MgB_2 cables delivering current via the DSHx and the DFX to D1 and Q1-Q3; cooling of the current leads at about 30K.

- Technical data:

Volume	Xx L
Operating pressure	1.3 bar (a)
Design pressure	3.5 bar (a)
Helium Temperature (gas)	(17 – 30) K
Helium inventory	6 kg

- Current leads: The leads assure the transition from room temperature by High Temperature Superconducting (HTS) materials to the 17 K gaseous helium cooled s.c. link. The leads are connected to the disconnection box via water-cooled conventional cables. The leads are electrically connected to the cables in the SC link via a dedicated cryostat, the DFHm. They are cooled at the level of the DFHm by the mixture of the helium flow of the shield and of the cold mass.

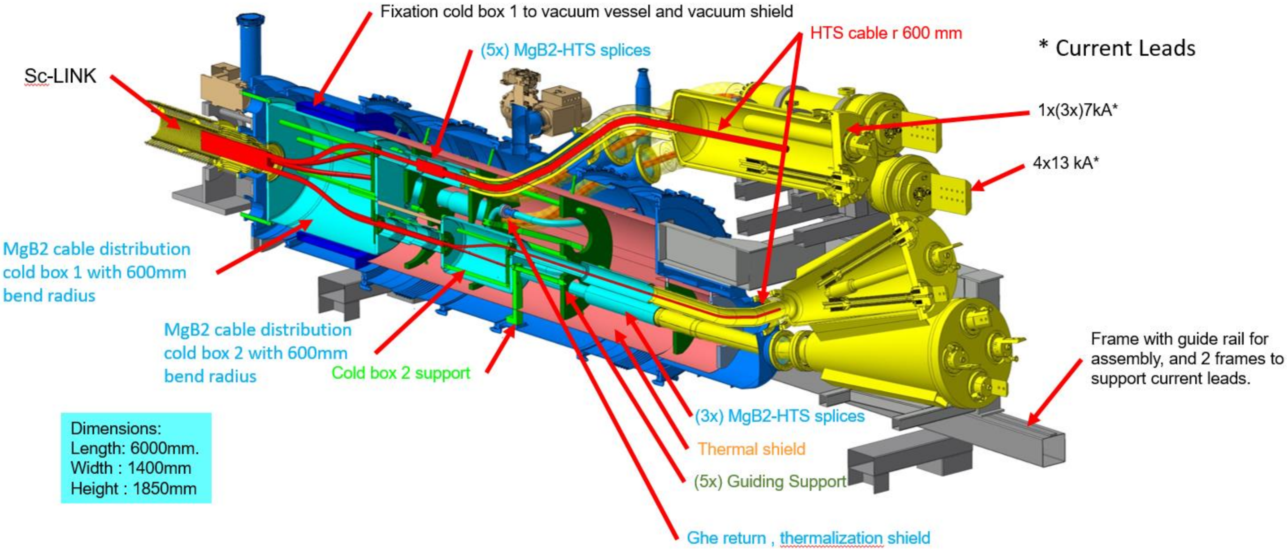


Figure 2-9 : Conceptual design drawing for DFHx

2.6 DFHm

- Main functions: Connection of current leads to MgB_2 cables delivering current via the DSHm and the DFM to D2; cooling of the current leads at about 30K.

- Technical data

Volume	Xx L
Operating pressure	1.3 bar (a)
Design pressure	3.5 bar (a)
Helium Temperature (gas)	(17 – 30) K
Helium inventory	xx kg

- Current leads: The leads assure the transition from room temperature by High Temperature Superconducting (HTS) materials to the 17 K gaseous helium cooled s.c. link. The leads are connected to the disconnection box via water-cooled conventional cables. The leads are electrically connected to the cables in the SC link via a dedicated cryostat, the DFHm. They are cooled at the level of the DFHm by the mixture of the helium flow of the shield and of the cold mass.

2.7 Other components (belonging to WP 6b)

2.7.1 Power Converter

- Main functions: SC circuits of LHC require more than ± 1.5 MA of current from the Power Converters to the magnets. The main power converter for the Inner Triplet circuit will have a rating of 18 kA. The room temperature path between Power Converters and current leads is done via conventional copper cables.
- Location: The Power Converters are located in the UR gallery, an underground, radiation free and easy access area in a gallery running parallel to the LHC tunnel. Access to this area may be granted, under certain conditions, also during the HL-LHC run.

- The risk assessment for Power converters is reported elsewhere.

2.7.2 Disconnector Box

- Main functions: The disconnector box is an electrical interface between the power converter and the current leads. When required, it permits a clean electrical separation between these two pieces of equipment. A connection to earth of the Power converter and of the current leads and the following magnet powering circuit can be realised in the disconnector box.
- The risk assessment for the Disconnector box is reported elsewhere.

3. Helium Release from Cold Powering System

HL-LHC technical services (mainly related to cryogenics and electrical powering) are installed in galleries physically separated from LHC (UW, UR and UA) and with separate access points from LHC. One objective of this lay-out is to have the underground service areas accessible to technical personnel even during operation of the accelerator with beam.

As a consequence, no dangerous accidental situations originating from HL-LHC operation may occur in or propagate to the HL-LHC technical service areas. For cryogenic safety this means that the mass of Helium releases to the UW, UR and UA galleries must not cause an oxygen deficiency hazard (ODH).

3.1 Qualitative description of Helium Release

The total mass of Helium in one branch of the cold powering system (approx 80 kg) would take a volume of 450 m^3 at standard temperature and pressure (STP; 293 K and 10^5 Pa). This is less than 10% of the volume of the UR gallery and would not lower the O_2 concentration below 18%. Furthermore, gaseous Helium with $T > 40$ K is less dense than air and rises to the ceiling by buoyancy.

Results from dedicated Helium release experiments and numerical studies show that the local effect of a Helium release is the creation of a turbulent mixing zone between air and helium, with low temperatures and oxygen concentrations for a short time. The size and persistence time of this turbulent zone depend on the Helium mass flow, the total amount of Helium released and the lay-out of the area in which the release is directed. Presently, no model for assessing the volume of the impacted zone and the duration is available. Rough estimates can be drawn from the above mentioned experiments.

3.2 Safety Principles and Layout

If an accidental helium release should occur from the cold powering system, the following principles shall apply:

- Calibrated burst disks protect the cryogenic volumes from exceeding the design pressure P_S. At the time of writing, P_S = 3.5 bar(a).

- Small pressure rises in the Helium envelope of all cryostats, leading to releases with small mass flow (a few g/s until a few 10 g/s) and small overall mass can be released by purge valves mounted in parallel to the burst disks.
- Large pressure rises will lead to the opening of burst disks, rapidly evacuating the excess pressure. When burst disks open on the DFX or DFM in the LHC tunnel, then a two-phase mixture of GHe / LHe or superfluid helium will be released.
- Burst disks shall be calibrated in a way that they open preferably in the LHC tunnel (i.e. on the DFX or DFM).
- The purge valves mounted in parallel to the burst disks are calibrated to open below the burst disk's set pressure, so that small pressure rises do not cause the pending of the burst disks.

4. Failure Modes leading to Helium Release

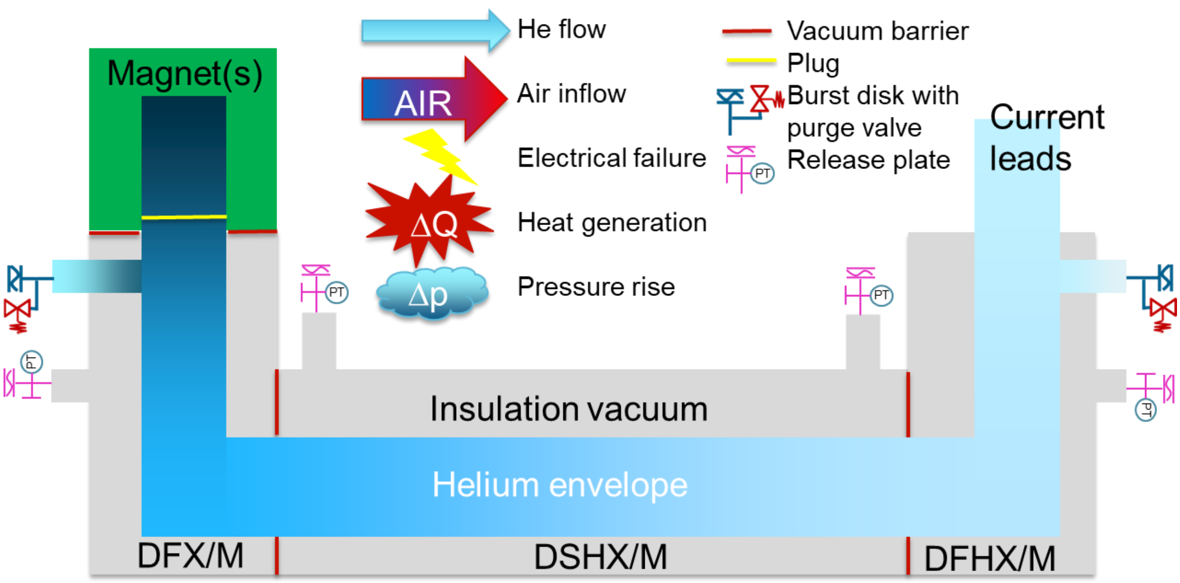
Different failure modes of the cold powering components were identified and analysed. Here, the failure modes are qualitatively described. The detailed analysis and the dimensioning of safety devices is found in a series of affiliate documents to which references are given.

Each failure mode is characterised by

1. The location and the nature of the failure
2. The path to where helium migrates under influence of temperature and pressure
3. The location where helium is finally released to the working environment.

The dynamics of the release (helium mass flow, thermodynamic state and pressure) and the resulting dimension of the safety devices are found in the affiliate documents.

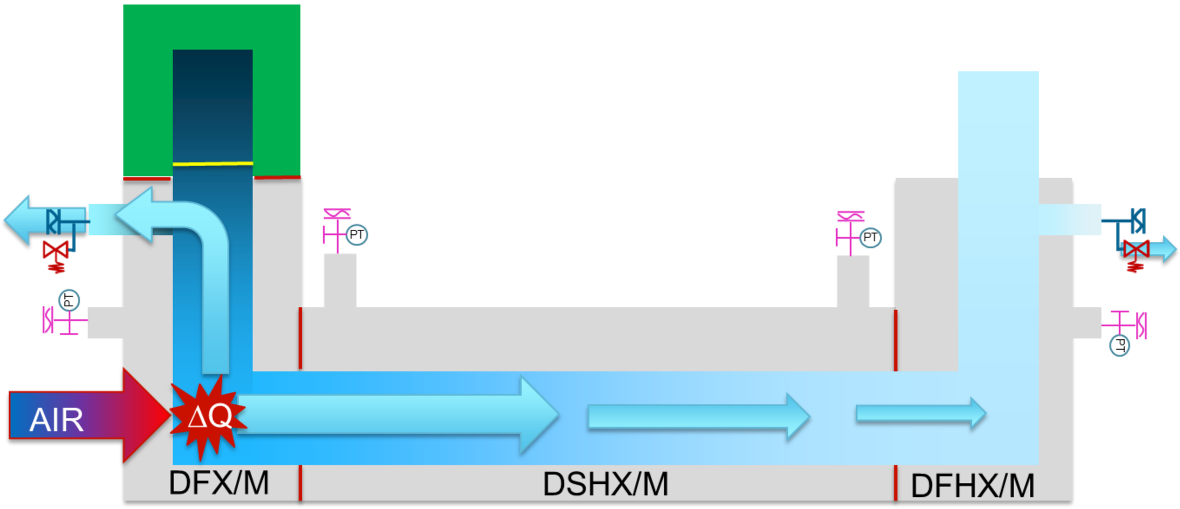
The schematic illustrations of the failure modes use symbols as explained in the following figure:



4.0 Symbols in Failure Mode Schematics

4.1 Failure Modes of the DFX

4.1.1 Insulation vacuum failure of DFX



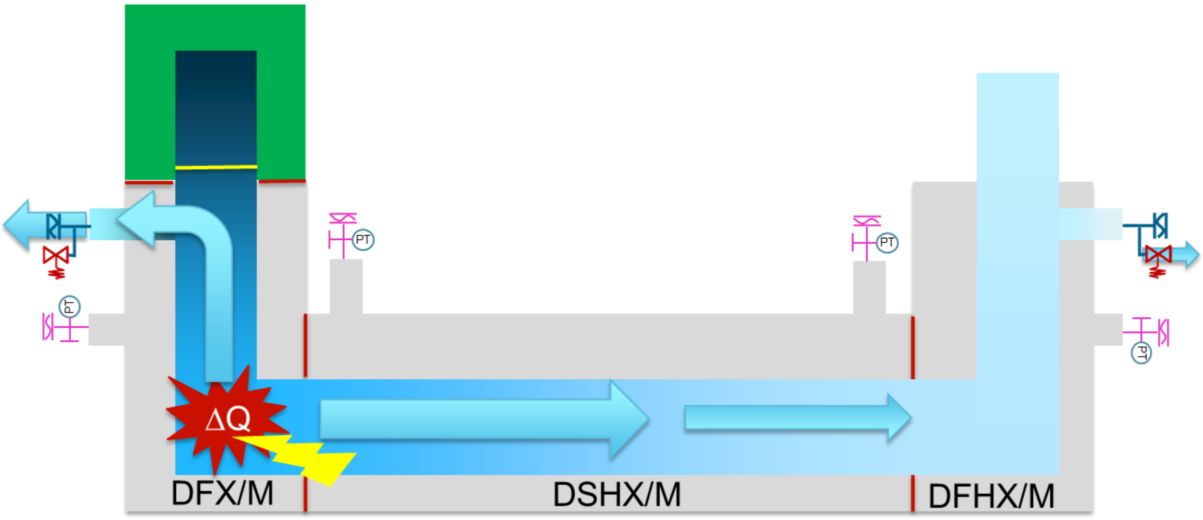
4.1.1. Insulation vacuum failure on DFX/M

Failure: During an opening in the outer shell of the insulation vacuum of DFX, room temperature air penetrates the vacuum space containing multilayer insulation and condenstaes on the outer wall of the helium envelope. The desublimation heat is transferred to LHe, GHe, which leads to an increase of temperature and pressure (T,p).

He propagation: The pressurised LHe and GHe will propagate to the DSHx and eventually to the DFHx. The pressure drop and time delay in the long DSH must be evaluated.

Pressure relief: The LHe/GHe pressure will be released by the burst disk on the DFX into the LHC tunnel. A gaseous Helium overpressure release by the DFHx purge valve to the UR gallery is possible, but the release of a large quantity by the DFHx burst disk shall be avoided.

4.1.2 Electrical short circuit or quench in DFX



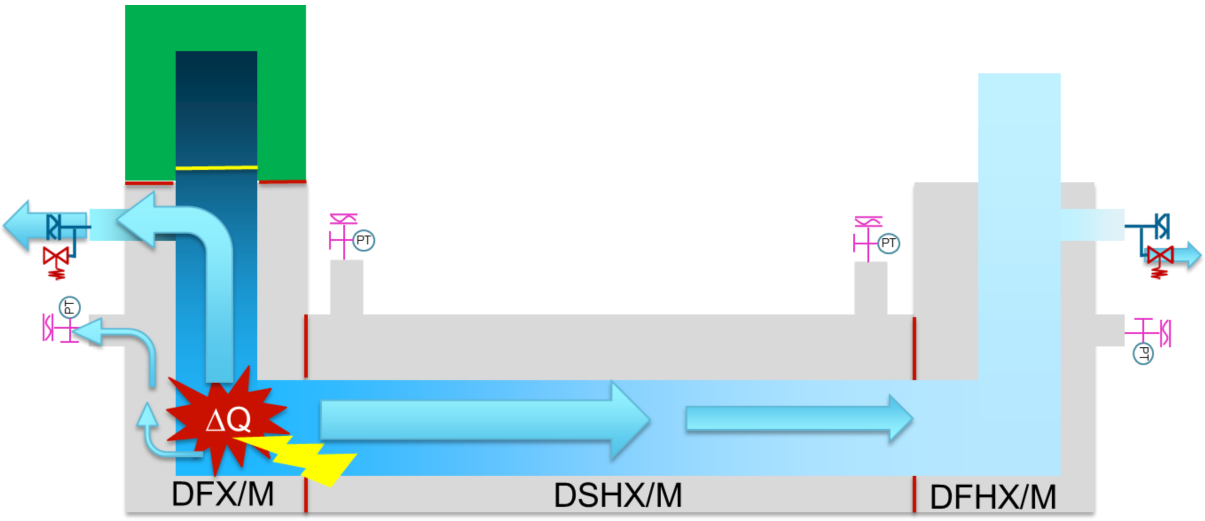
4.1.2 Electrical short circuit or quench in DFX/M

Failure: An electrical short circuit develops between electrical cables or bus-bars in the DFX. Alternatively, the leads quench and ohmic heating sets in. The electrical energy deposited leads to resistive heating of the cables and then of the LHe or GHe

He propagation: As in 4.1.1

Pressure relief: As in 4.1.1

4.1.3 Electrical arc in DFX



4.1.3 Electrical arc in DFX/M

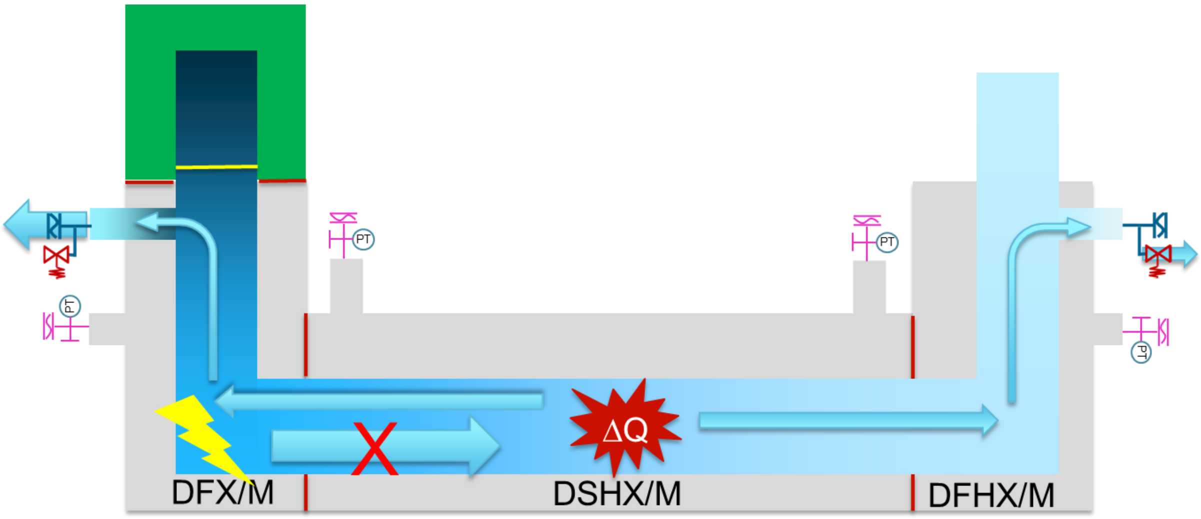
Failure: An excess electrical resistance in an s.c. splice leads to a voltage high enough to create an electrical arc in helium between the splice and the inside of the helium envelope. If the electrical energy stored in the circuits is high enough, the helium envelope is damaged.

He propagation: (p,T) of LHe/ GHe will rise, the two phases will propagate within the helium envelope to the DSHx and the DFHx. If the helium envelope is compromised, LHe/ GHe will enter the insulation vacuum of the DFX.

Pressure relief: For helium in the helium envelope, as in 4.1.1.

For helium in the insulation vacuum, by the pressure relief plate on the DFX insulation vacuum.

4.1.4 Heater failure in the DFX



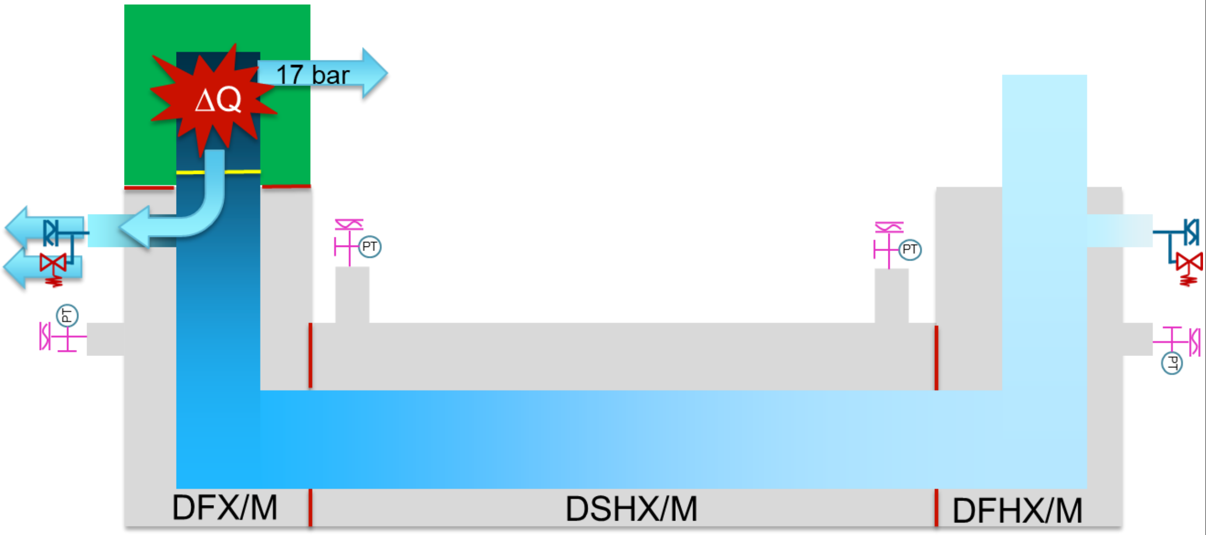
4.1.4. Heater Failure in DFX/M

Failure: the electrical heater used for evaporating LHe and supplying GHe in the SC link (DSHx) fails. This would lead to a lack of cooling in the DSHx and a quench of the SC link. Resistive heating would lead to pressure rise of the remaining GHe (T > 20 K) in DSHx. See failure Mode 4.3.1.

He propagation: As in 4.3.1.

Pressure relief: As in 4.3.1.

4.1.5 Quench in Q1-Q3, D1 and ruptured separation plug to DFX



3.1.5 Quench in Magnet and ruptured separation plug to DFX/M

Failure: A quench in the Q1-Q3 or D1 magnets leads to a pressure rise of LHe in their cold masses. At the same time the plug between D1 and the DFX is damaged and leaking.

He propagation: LHe / GHe will pass the leaky plug and enter the DFX helium envelope before the internal pressure in the Q1-Q3, D1 reaches 17 bar and the quench valves open to the recovery line.

Pressure relief: The pressure relief devices (purge valve, burst disk) on the DFX He envelope are designed large enough to cope with this accident and not to let He leaking from Q1-Q3, D1 propagate further into the DSHx. It depends on the size of the leak in the plug, if a pressure release by the DFX purge valve alone is sufficient before the opening of the quench valves, or if the DFX burst disk will open as well.

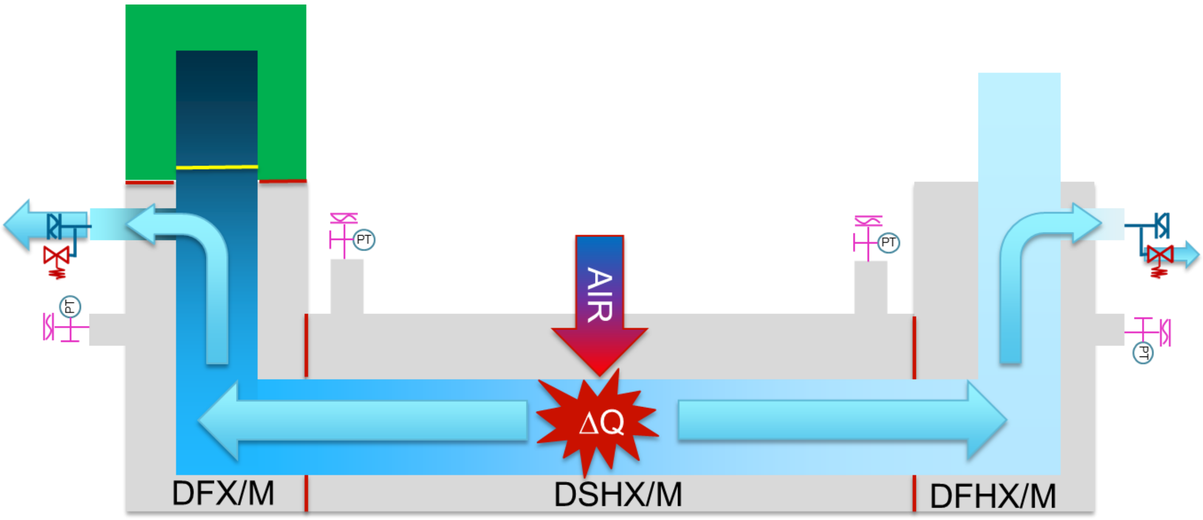
4.2 Failure Modes of the DFM

The failure modes of the DFM are similar to those of the DFX. One obtains their description by the following replacements in those of section 4.1:

- DFX with DFM,
- DSHx with DSHm,
- DFHx with DFHm
- Q1-Q3, D1 with D2.

4.3 Failure Modes of the DSHx

4.3.1 Insulation Vacuum Failure in DSHx



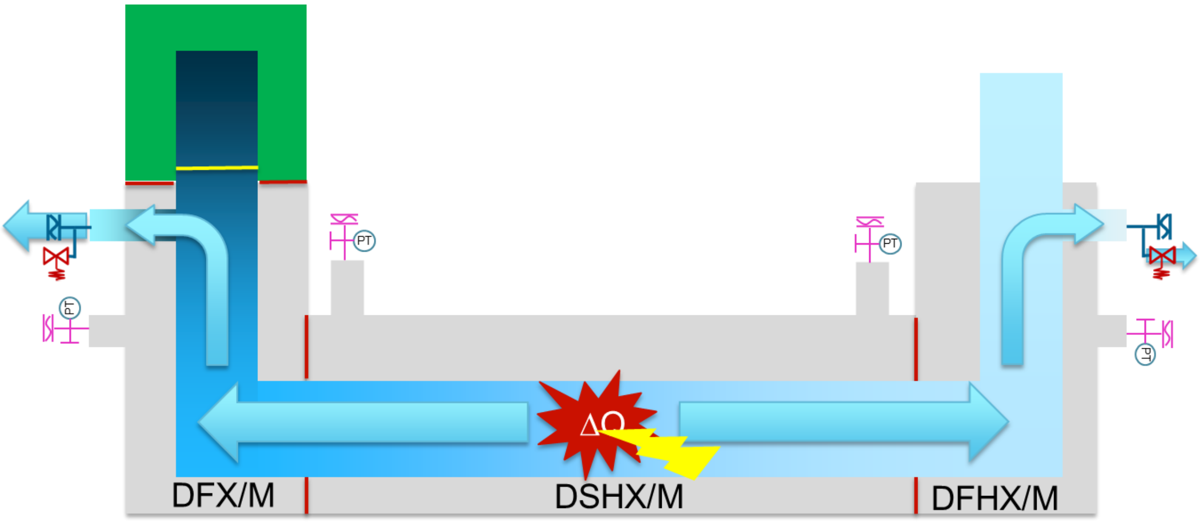
4.3.1. Insulation vacuum failure on DSH

Failure: The insulation vacuum of the DSHx is accidentally compromised, for example by external mechanical force. Room temperature air penetrates the vacuum space containing multilayer insulation and condensates on the outer wall of the helium envelope. The desublimation heat is transferred to GHe, which leads to an increase of temperature and pressure (T,p).

He propagation: The overpressure in the DSHx He envelope propagates to the helium envelopes of DFX and DFHx

Pressure relief: The He overpressure is evacuated by the safety devices of the DFX and DFHx He envelopes. Their opening pressures are calibrated such that most of the the pressurised He is evacuated by the DFX burst disk into the LHC tunnel. On DFHx, the purge valve may open and release a small quantity of Helium to the UR.

4.3.2 Electrical Short circuit in DSHx



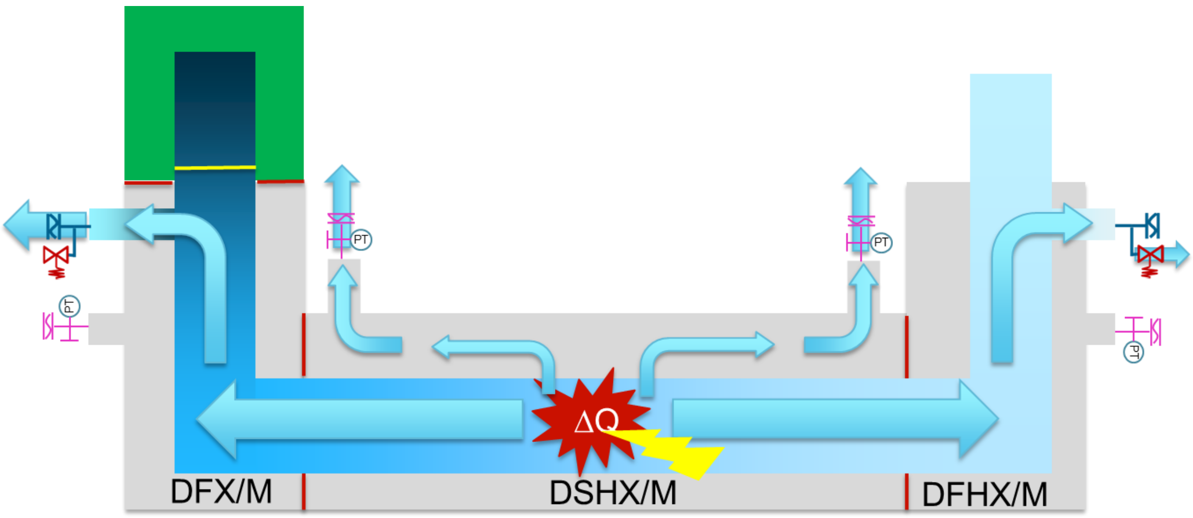
4.3.2. Electrical Short circuit in DSH

Failure: An electrical short circuit develops between electrical cables or splices in the DSHx. Alternatively, the leads quench and ohmic heating sets in. The electrical energy deposited leads to resistive heating of the cables and then of the GHe, leading to an increase of temperature and pressure (T,p).

He propagation: as in 4.3.1

Pressure relief: as in 4.3.1

4.3.3 Electrical arc in DSHx



4.3.3. Electrical Arc in DSH

Failure: An excess electrical resistance in an s.c. lead leads to a voltage high enough to create an electrical arc in helium between the lead and another lead or the inside of the helium envelope of the DSHx. If the electrical energy stored in the circuits is high enough, the helium envelope is damaged.

He propagation: The arc leads to an increase of temperature and pressure (T,p) in the He envelope, propagating to the DFX and the DFHx. If the He envelope is pierced by the arc, He will also enter the DSHx insulation vacuum.

Pressure relief: For He overpressure in the DSHx He envelope, as in 4.3.1.

If the He envelope is pierced by the arc, He will also evacuated by the safety device on the DSHx insulation vacuum

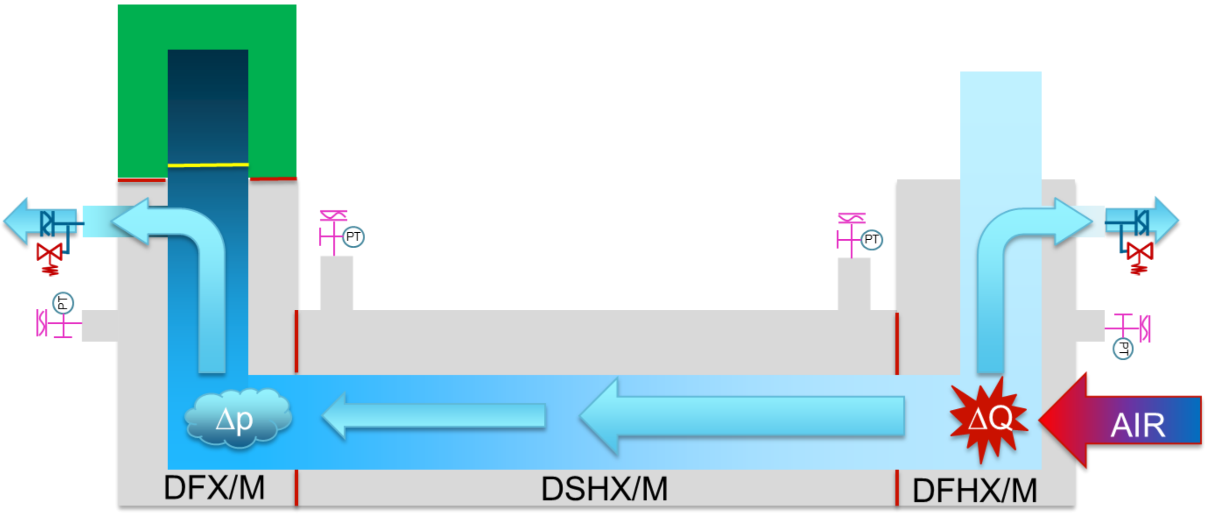
4.4 Failure Modes of the DSHm

The failure modes of the DSHm are similar to those of the DSHx. One obtains their description by the following replacements in those of section 4.3:

- DSHx with DSHm,
- DFX with DFM,
- DFHx with DFHm.

4.5 Failure Modes of the DFHx

4.5.1 Insulation Vacuum Failure in DFHx



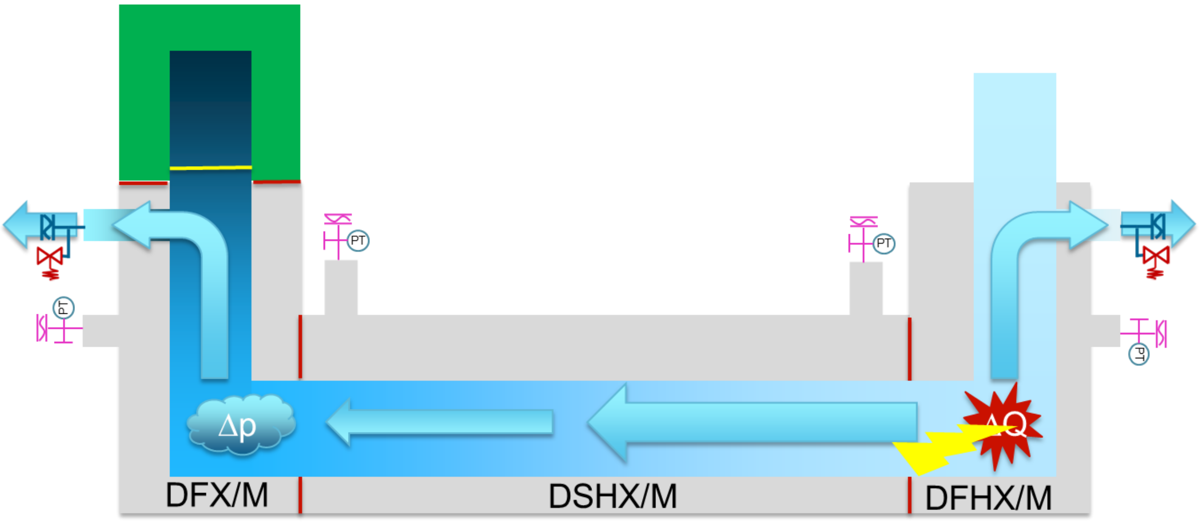
4.5.1. Insulation vacuum failure on DFHX/M

Failure: During an opening in the outer shell of the insulation vacuum of DFHx, room temperature air penetrates the vacuum space containing multilayer insulation and condensates on the outer wall of the helium envelope. The desublimation heat is transferred to GHe, which leads to an increase of temperature and pressure (T,p).

He propagation: The pressurised GHe will propagate to the DSHx and eventually to the DFX. The pressure drop and time delay in the long DSHx must be evaluated.

Pressure relief: The pressure head of the long DSHx is probably too high to force the release by the burst disk of the DFX He envelope alone. Consequently, the DFHx burst disk will open and gaseous Helium released to the UR gallery. Nevertheless, Helium will propagate to the DFX and generate enough pressure there to opening the DFX burst disk releasing the remainder of the cold powering helium inventory to the L HC tunnel.

4.5.2 Electrical Short circuit in DFHx



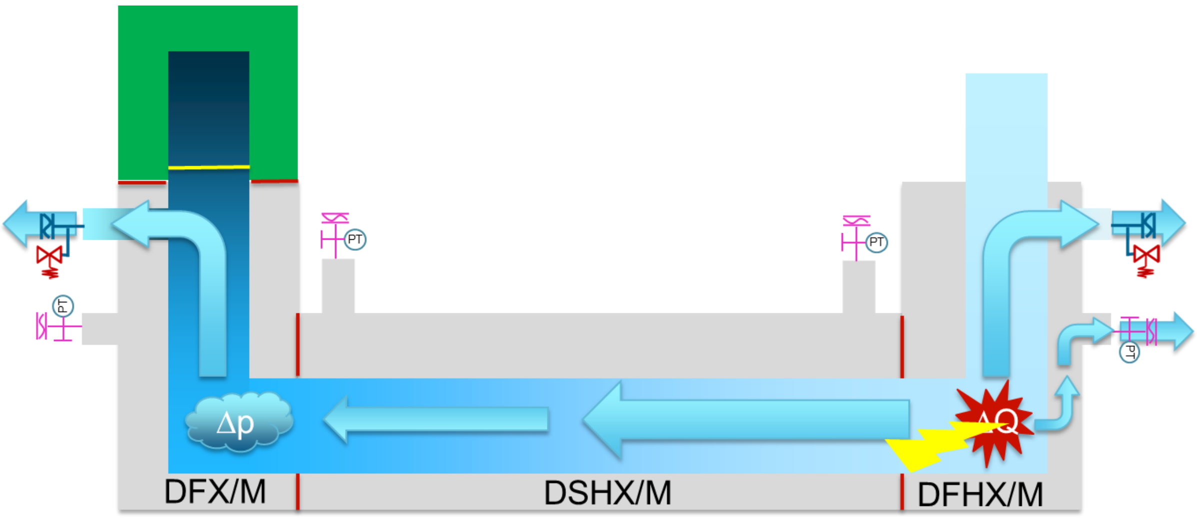
4.5.2. Electrical Short Circuit in DFHX/M

Failure: An electrical short circuit develops between electrical cables or splices in the DFHx. Alternatively, the leads quench and ohmic heating sets in. The electrical energy deposited leads to resistive heating of the cables and then of the GHe, leading to an increase of temperature and pressure (T,p).

He propagation: as in 4.5.1

Pressure relief: as in 4.5.1

4.5.3 Electrical arc in DFHx



4.5.3. Electrical Arc in DFHX/M

Failure: An excess electrical resistance in an s.c. splice or current lead leads to a voltage high enough to create an electrical arc in helium between the splice and the inside of the helium envelope of DFHx.

If the electrical energy stored in the circuits is high enough, the helium envelope is damaged.

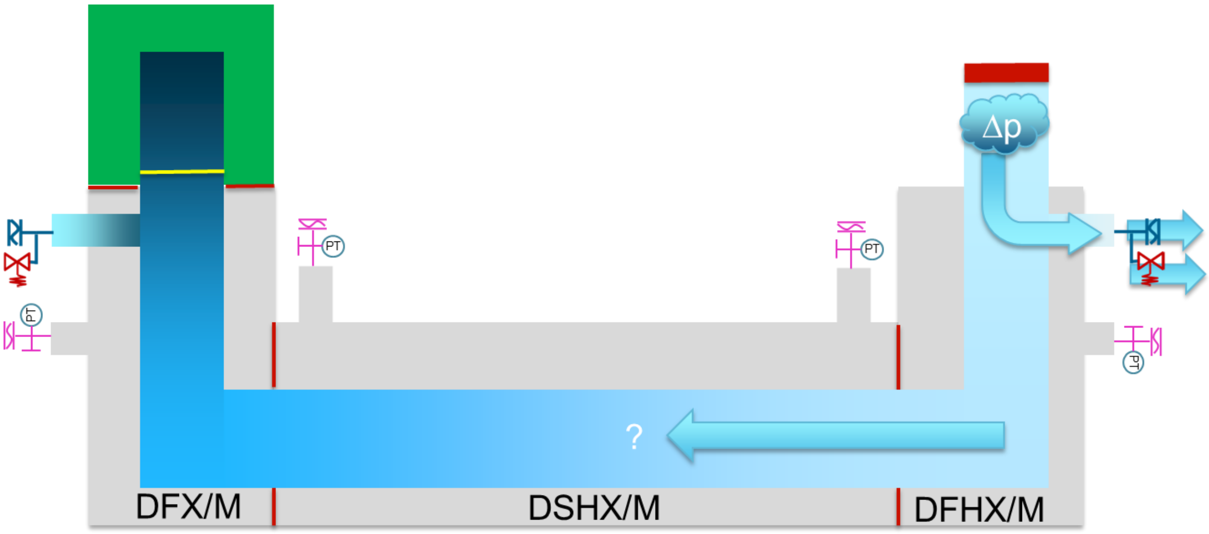
He propagation: The arc leads to an increase of temperature and pressure (T,p) in the He envelope of the DFHx, propagating to the DSHx and the DFX.

If the He envelope is pierced by the arc, He will enter the DFHx insulation vacuum.

Pressure relief: Overpressure in the He envelope of DFHx, DSH and DFX as in 4.5.1.

If the He envelope is pierced, additional gaseous He will be released by the relief plate on the DFHx insulation vacuum.

4.5.4 Obstruction of the DFHx He recovery Line



4.5.4. Obstruction of the He recovery Line

Failure: The recovery line from the DFHx current leads to the He buffer may become obstructed, for example in case of contamination by condensable gases. He pressure would build up, as a continuous supply of He comes from the DFX via the DSHx.

He propagation: GHe pressure builds up in the DFHx, A potential propagation of GhE pressure along the DSH to the DFX does not appear to be likely but must be investigated in detail.

Pressure relief: The pressure build-up in the DFHx would open the DFHx purge valve, and if the flow requires it, the DFHx burst disk. It cannot be predicted at this stage if any of the purge /safety devices on the DFX would react.

4.6 Failure Modes of the DFHm

The failure modes of the DFHm are similar to those of the DFHx. Obne obtains their description by the following replacements in those of section 3.1:

- DFHx with DFHm,
- DSHx with DSHm,
- DFX with DFM.

5. Summary and Conclusion

The following table summarises the identified failure modes and points to the sections where these are described in detail.

	DFX	DSHx	DFHx	DFM	DSHm	DFHm
Insulation vacuum failure	4.1.1	4.3.1	4.5.1	4.2.1	4.4.1	4.6.1
Short circuit or lead quench	4.1.2	4.3.2	4.5.2	4.2.2	4.4.2	4.6.2
Electrical arc	4.1.3	4.3.3	4.5.3	4.2.3	4.4.3	4.6.3
Heater failure	4.1.4			4.2.4		
Magnet quench	4.1.5			4.2.5		
Recovery obstruction			4.5.4			4.6.4

The table on pages 24-27 summarises the failure modes which have been described in text and graphics above.

	Case Nr.	Failure Mode	Helium pressure propagates to	Safety Devices activated	Calculation Note
4.1 DFX	4.1.1	Insulation vacuum failure in DFX	DFX helium envelope DSHx helium envelope DFHx helium envelope	DFX helium envelope *DFHx helium envelope**	See DFX internal review
	4.1.2	Short circuit in DFX, Resistive heating	As 4.1.1.	As 4.1.1	
	4.1.3	Electrical Arc in DFX Helium flow to DFX insulation vacuum	DFX helium envelope DSHx helium envelope DFHx helium envelope DFX insulation vacuum	DFX helium envelope *DFHx helium envelope** DFX insulation vacuum	-
	4.1.4	Heater failure in DFX, Lack of Helium gas for DSH cooling, quench	As 4.1.1.	As 4.1.1	QPS takes over
	4.1.5	Quench Q1-Q3, D1 and Plug damaged for $p < 17$ bar	DFX helium envelope	DFX helium envelope, to prevent further propagation by DSHx to UR	Model of breakage of PEEK; dp/dt in the magnets; He flow to DFX
4.2 DFM	4.2.1	Insulation vacuum failure in DFM	DFM helium envelope DSHm helium envelope DFHm helium envelope	DFM helium envelope *DFHm helium envelope**	See DFM internal review
	4.2.2	Short circuit in DFM	As 4.2.1	As 4.2.1	Cases : - Resistive heating (arc, stored energy, QPS , WP7)
	4.2.3	Electrical Arc in DFM Helium flow to DFM insulation vacuum	DFM helium envelope DSHm helium envelope DFHm helium envelope DFM insulation vacuum	DFM helium envelope *DFHm helium envelope** DFM insulation vacuum	Cases : - Leak into insulation vacuum - Resistive heating (arc, stored energy, QPS , WP7)

	Case Nr.	Failure Mode	Helium pressure propagates to	Safety Devices activated	Calculation Note
	4.2.4	Heater failure in DFM Lack of Helium gas for DSHm cooling, quench	As 4.4.1	As 4.4.1	QPS takes over
	4.2.5	Quench D2 and Plug damaged for $p < 17$ bar	DFM helium envelope	DFM helium envelope, to prevent further propagation by DSHm to UR	Model of breakage of PEEK; dp/dt in the magnets; He flow to DFM
4.3 DSHx	4.3.1	Insulation vacuum failure in DSHx Pressure increase in DSHx helium envelope	DSHx helium envelope DFX helium envelope DFHx helium envelope	DFX helium envelope *DFHx helium envelope**	Staged opening of burst disks Estimation of d2p/dtdx , test in DEMO
	4.3.2	Short circuit in DSHx Pressure increase in DSHx helium envelope	As 4.3.1	As 4.3.1	As 4.3.1
	4.3.3	Electrical arc in DSHx Pressure increase in DSHx helium envelope Helium flow to DSHx insulation vacuum	DSHx helium envelope DFX helium envelope DFHx helium envelope DSHx insulation vacuum	DFX helium envelope *DFHx helium envelope** DSHx insulation vacuum	Arc depends on delta-U and stored energy, QPS intervenes
4.4 DSHm	4.4.1	Insulation vacuum failure in DSHm Pressure increase in DSHm helium envelope	DSHm helium envelope DFM helium envelope DFHm helium envelope	DFM helium envelope *DFHm helium envelope**	Staged opening of burst disks Estimation of d2p/dtdx , test in DEMO
	4.4.2.	Short circuit in DSHm Pressure increase in DSHm helium envelope	As 4.4.1	As 4.4.1	As 4.4.1
	4.4.3	Electrical arc in DSHm Pressure increase in DSHm helium envelope Helium flow to DSHm insulation vacuum	DSHm helium envelope DFM helium envelope DFHm helium envelope DSHm insulation vacuum	DFM helium envelope *DFHm helium envelope** DSHm insulation vacuum	Arc depends on delta-U and stored energy, QPS intervenes

	Case Nr.	Failure Mode	Helium pressure propagates to	Safety Devices activated	Calculation Note
4.5 DFHx	4.5.1	Insulation vacuum failure in DFHx Helium pressure increase in DFHx helium envelope	DFHx helium envelope DSHx helium envelope DFX helium envelope	DFHx helium envelope DFX helium envelope	Awaiting design of the DFHx
	4.5.2	Short circuit in DFHx Helium pressure increase in DFHx helium envelope	As 4.5.1	As 4.5.1	As 4.5.1
	4.5.3	Electrical arc in DFHx Helium pressure increase in DFHx helium envelope Helium flow to DFHx insulation vacuum	DFHx helium envelope DSHx helium envelope DFX helium envelope DFHx insulation vacuum	DFHx helium envelope DFX helium envelope DFHx insulation vacuum	Awaiting design of the DFHx
	4.5.4	Obstruction of the Helium recovery line Back pressure from cold box in DFHx helium envelope	As 4.5.1	As 4.5.1	As 4.5.1
4.6 DFHm	4.6.1	Insulation vacuum failure in DFHm Helium pressure increase in DFHm helium envelope	DFHm helium envelope DSHm helium envelope DFM helium envelope	DFHm helium envelope DFM helium envelope	Awaiting design of the DFHm
	4.6.2	Short circuit or arc in DFHm Helium pressure increase in DFHm helium envelope	As 4.6.1	As 4.6.1	As 4.6.1
	4.6.3	Electrical arc in DFHm Helium pressure increase in DFHm helium envelope Helium flow to DFHm insulation vacuum	DFHm helium envelope DSHm helium envelope DFM helium envelope DFHm insulation vacuum	DFHm helium envelope DFM helium envelope DFHm insulation vacuum	Awaiting design of the DFHx
	4.6.4	Obstruction of the Helium recovery line Back pressure from cold box in DFHm helium envelope	As 4.6.1	As 4.6.1	As 4.6.1

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