HL-LHC WP9 Cryogenics Safety studies

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HL-LHC P1/P5 Cryogenic architecture

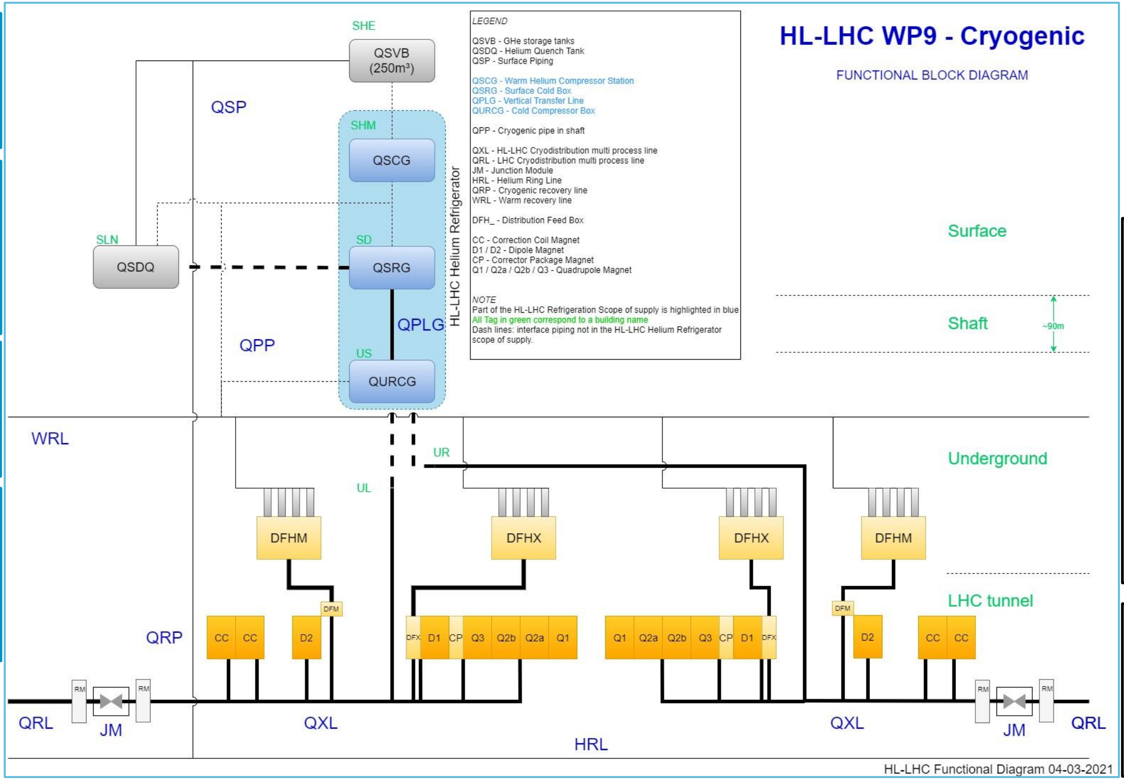
QSCG : Compressor station providing gaseous helium **20 B**

QSRG : 4.5K refrigerator providing supercritical helium at **3 bara and 4.6 K**

QPLG : Vertical transfer line (~100 m height)

QURCG : Cold compressor box providing cooling capacity at **1.8 K**

Users at tunnel level



QXL : Distribution line distributing C,E and returning B,D,F

- 70 m for the common branch
- 270 m for the long branch
- 60 m for the short branch

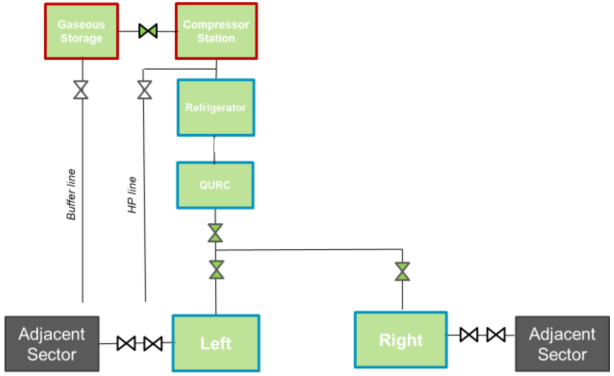
RM/JM : Return module and junction module at extremities for transient handling and back-up

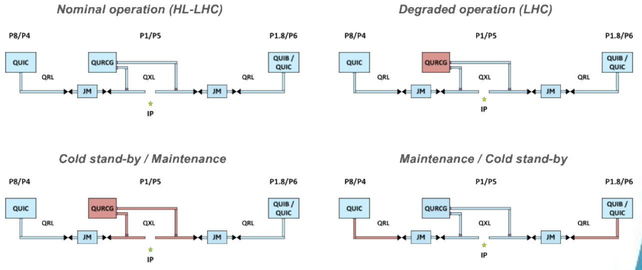
Operating modes and dependency with adjacent sector

- All **operating modes** (similar as for LHC) will be possible:
  - Pressure tests,
  - Lock-out,
  - Cool-down or warm-up,
  - Stable operation at 80K, 20K, 4.5K, 3K, 1.9K, IT@20K-LSS/ARC@nominal,
  - Maintenance / Technical stop,
  - Intervention at magnets level.

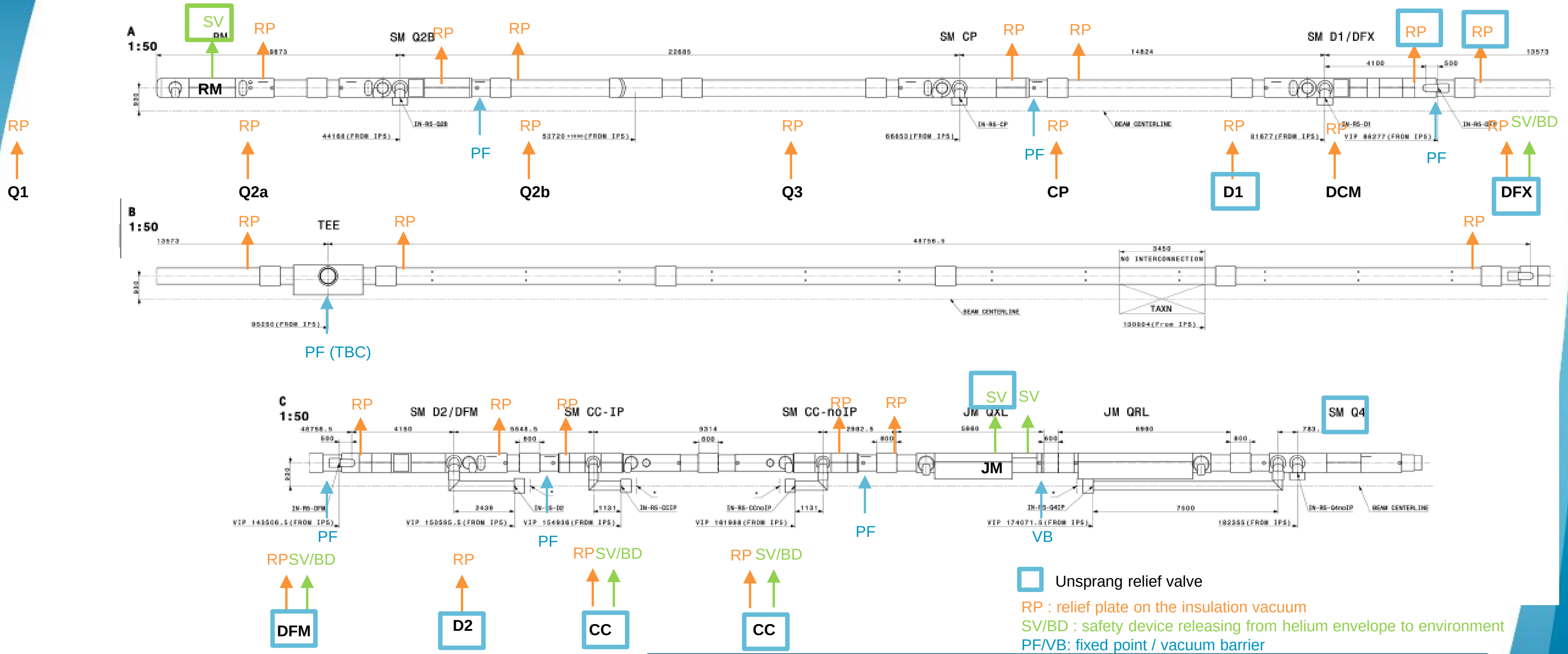
- "Only" one refrigerator at P1/P5 does not allow to operate the 2 LSS in a different mode → HL-LHC **LSS independent** from LHC operation thanks to **sectorization**.

- HiLumi magnets/users can be cooled by :
  - New HL Refrigerators → **nominal HL performances**
  - Adjacent sectors – **up to twice the LHC nominal luminosity** → Degraded operation
- Flexibility during the maintenance period of the HL-LHC cryoplant thanks to the Junction Module functionalities.
- Possible to cooldown one LSS per point independently.



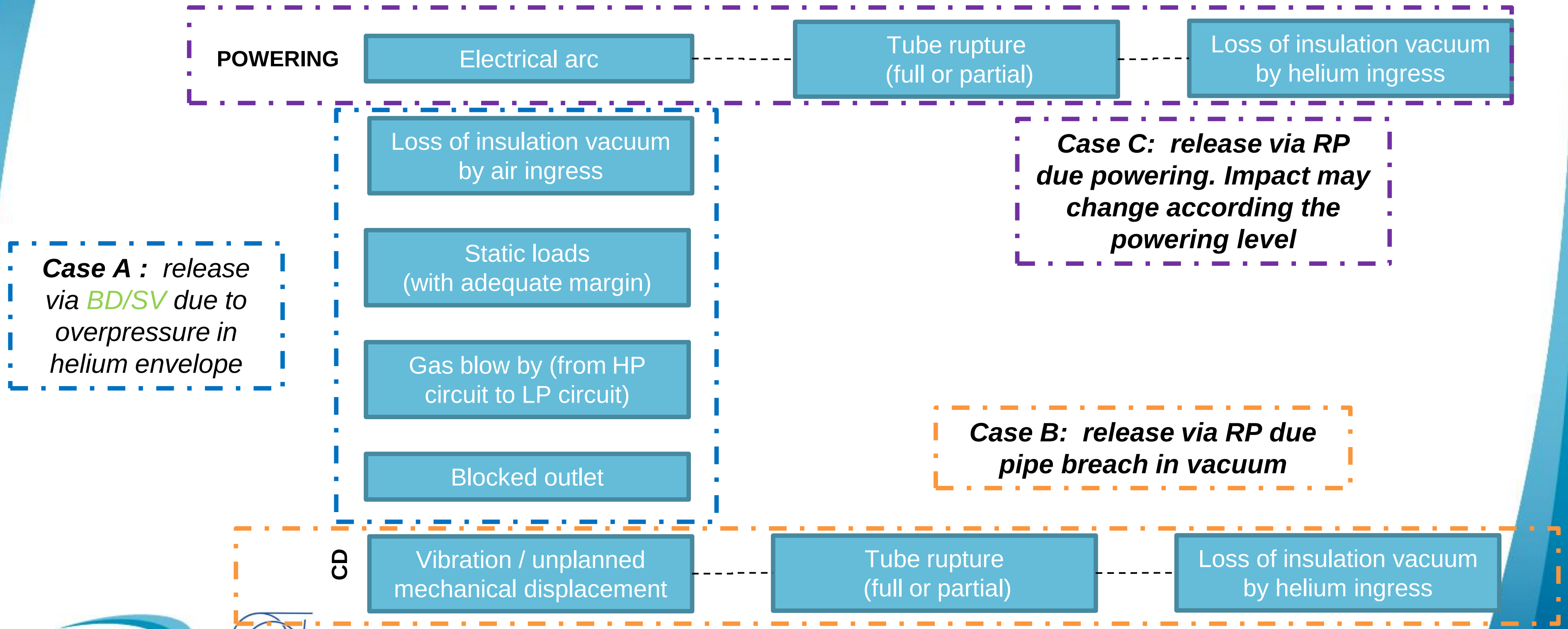


Protecting devices releasing helium to environment- Preliminary Layout



- **Position of safety devices is preliminary and approximate.**
- **Magnet DCM RP TBC**
- **Foreseen : SV DN100 for QXL / SV DN 200 for the IT.**
- **QXL tunnel design is still in preliminary phase.**

Failure modes and cases considered for helium release in the tunnel



Different accesses cases with potential helium release to tunnel environment

Case	A	B		C	
Volume to be protected	Helium	Insulation vacuum	Insulation vacuum	Insulation vacuum	Insulation vacuum
Operating cases	Nominal conditions	First Cooldown	Other Cooldown / *Nominal conditions*	Powering > 1.1 kA *(powering level TBC)*	Powering < 1.1 kA *(powering level TBC)*
Access	**Access**	**NO ACCESS**	**Access**	**NO ACCESS**	**Access**
Failure modes	LIV 2 x Static HL	Any line full rupture	Line partial rupture	Electrical arc leading to line full rupture + Quench	Limited electrical arc (partial rupture)
System	DFX DFM CCs RM QXL JM QXL	QXL line C IT CM interco *D2* *CC* *DFM* *DFX*	All	IT line M or N D2 DFX DFM *CC?*	IT D2 DFX DFM *CC?*
Goal	*Sizing of the protecting device*	*Sizing of the protecting device*	Define the release location and stagging	*Sizing of the protecting device*	Define the release location and stagging

CASE A - helium circuit overpressure – Preliminary flow and inventory

	Liquid inventory [kg]	SV design case	SV SP [barg]	SV flow [g/s]	BD design case	BD SP [barg]	BD flow [g/s]	Reference
DFX	~60	2x Static load	1.8	10 g/s	LIV	2.2	550 g/s	EDMS 2365987
DFM	~50	2x Static load	1.8	10 g/s	LIV	2.2	500 g/s	Private communication
CC	~20	2.5 x Static load	0.75	5 g/s	Beam vacuum loss	1.1	3510 g/s	EDMS 1900654
JM line C QXL	<0.05	LIV	20	<10 g/s	NA	NA	NA	TBA
RM QXL	*~15 (TBC)*	LIV	4	270 g/s *(TBC)*	NA	NA	NA	TBA

Addition of Relief device for the operational case of RM considered.

It is understood that below 1 kg/s, the release in the tunnel does not lead to a helium jam (refer to Note 2010-057)

CASE B – Helium pipe breach to Insulation vacuum– Preliminary flow and inventory

1st cooldown : NO ACCESS *Full tube rupture*		
	Liquid inventory [kg]	flow [kg/s]
QXL line C (long branch)	243	*2.2 - 4.6*
IT cold mass interconnect	418	TBC
DFX	~60	TBC
DFM	~50	TBC
CC	*~20*	TBC
D2	*~70*	TBC

Dynamic simulation to be run for evaluation

Other : ACCESS *Partial tube rupture – 1 kg/s*			
Pressure [bara]	Temperature [K]	Area [mm2]	Diameter [mm]
4	4.8	*124*	*12.6*
20	65	*255*	*18*
1.3	1.9	*336*	*20.7*
1.8	10	*1078*	*37.1*
1.8	4.55	*280*	*18.9*
15	*25*	*206*	*16.2*

Similar to LHC

Above 280 mm2 defined in Access and powering LHC doc

Above 500 mm2

Local pressure in the vacuum enclosure still be checked with the longitudinal vacuum impedance
It is understood that below 1 kg/s, the release in the tunnel does not lead to a helium jam (refer to Note 2010-057)

CASE C – MCI or any other case due to powering energy- – Preliminary flow and inventory

Powering >1.1 kA - NO ACCESS *Full tube rupture + Quench*		
	Liquid inventory [kg]	**flow [kg/s]**
IT line M or N	418	*~10 (TBC)*
DFX	~60	2.4
DFM	~50	0.3
D2	*~70*	TBC
CC?	*~20*	TBC

Work in progress

Powering <x kA - ACCESS *Partial tube rupture – 1 kg/s*		
	Liquid inventory [kg]	**Diameter of hole [mm]**
IT line M or N	418	*20.7*
DFX	~60	*18.9*
DFM	~50	*18.9*
D2	*~70*	*20.7*
CC?	*~20*	TBC

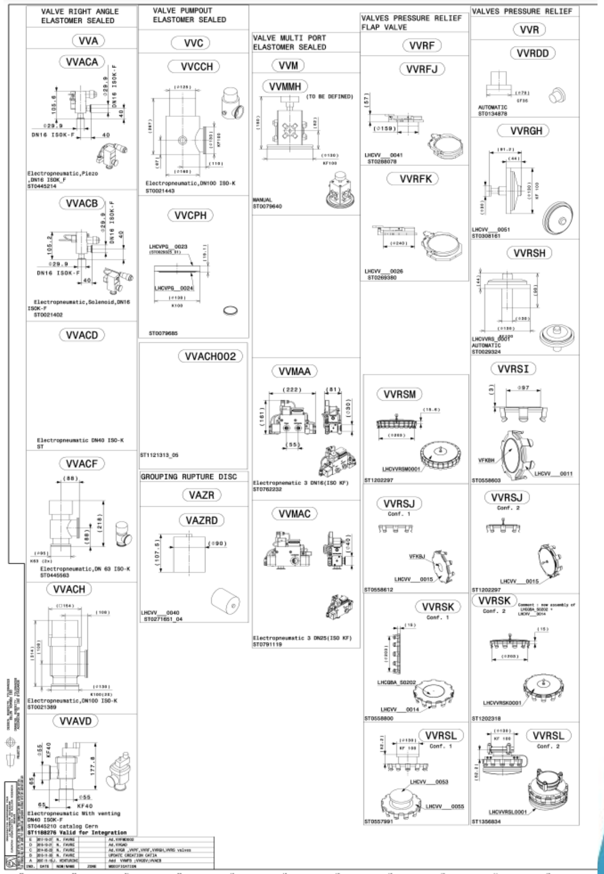
Local pressure in the vacuum enclosure still be checked with the longitudinal vacuum impedance
It is understood that below 1 kg/s, the release in the tunnel does not lead to a helium jam (refer to Note 2010-057)

Way forward

- Sizing to be completed
- Impedance in the vacuum enveloppe to be calculated when design is further progressed for the QXL.

Vacuum safety valves

Unsprung valve	VVRGH		Gravity loaded valve, DN100/90
	VVRFJ		Flap valve, DN160
	VVRFK		Flap valve, DN200
			Special joint for flap valve DN200
Spring relief valve	VVRSH		Spring release valve, SV90
	VVRSI		Spring release valve, DN100
			Spring
			Blank flange K100
	VVRSJ		Spring release valve, DN160
			Spring
			Blank flange K160
	VVRSK		Spring release valve, DN200
			Spring
			Retention plate
			Special blank flange DN200 (supplied by WP3)



Volumes to be protected and protecting devices

SYSTEMS

- QXL
  M. Sisti
- D2 – WP3
  D. Ramos - *A. Lees*
- IT/D1/DCM – WP3
  D. Ramos - *R. Van Der Weelderen and P. Tavares*
- Cold Pow – WP6a
  Y. Leclercq –*V. Gahier*
- Crab Cavities – WP4
  T. Capelli / L. Dassa -
  L. Delprat / K. Brodzinski

VOLUME TO BE PROTECTED

Case B, C

- Vacuum
  - Beam
  - Insulation

Covered by VSC

Case A

- Helium
  - Beam screen: *60-80 K ~18 bar* **or** *4.5-20 K ~1.5 bar*
  - Thermal shield: *60-80 K ~18 bar*
  - Cold mass: *1.9 K ~1.3 bar*
  - Magnet HX: *1.8 K ~0.018 bar*
  - Liquid helium: *4.6 K ~1.5 bar*

PROTECTING DEVICES

SV spring loaded
- → *opens at 69 mbar to 134 mbar*
- → *DN65 to DN90*

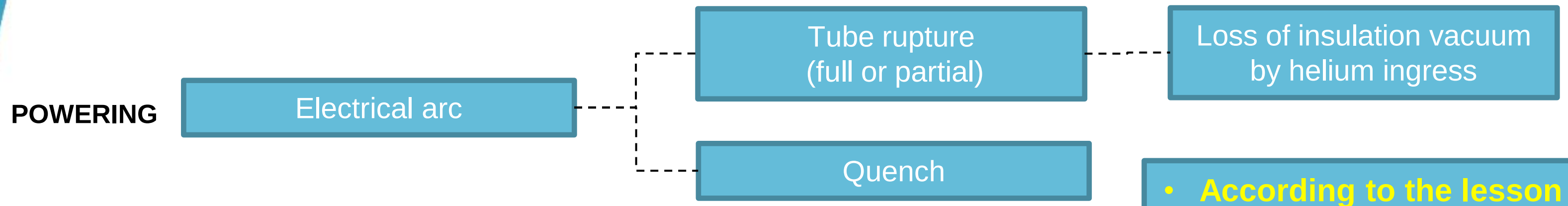
Relief plate with spring
- → *opens ranging 30-165 mbar*
- → *DN65 to DN230*

Relief plate w/o spring
- → *opens lower than 10 mbar*
- → *DN65 to DN230*

Safety valve
- → *Generally for operating cases*
- → *Closes after event*

Burst Disc
- → *Generally for MCI*
- → *Requires intervention for replacement*

Failure modes – MCI or any other case due to powering energy- CASE C



c. MCI or any case due to powering energy

- To be assessed in case of electrical energy (arc)
- Energy and typical topology lead to at least 1DN200/cryostat or 2DN160 (tbc)
- Position and size of relief plates considering Ins. Vac. longitudinal impedance
- **IT+D1+DCM, D2, DFX-DFM, Q4(SAM), DSL**
- Any other ?!? **CC?**
- Sizing done or being done, depending on maturity of design
- LHe inventory, peak flow, location to be compared with references for definition of access rules, a priori with "no access" when powering >1kA

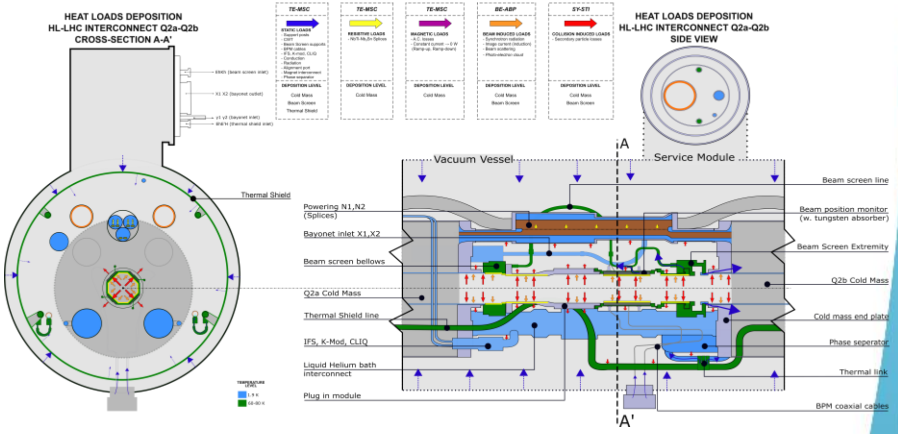
- **According to the lesson learnt of 19th of Sept. 2008 incident, the MCI should consider full rupture of the pipe at the magnet interconnection.**
- **Quench and electrical arc failure modes are linked with powering and consequences are linked with the powering level.**
- **One failure mode can provoke other failure modes in cascade (refer to 19th of Sept. 2008 LHC incident)**

Inner triplet process data and inventory (1/2)

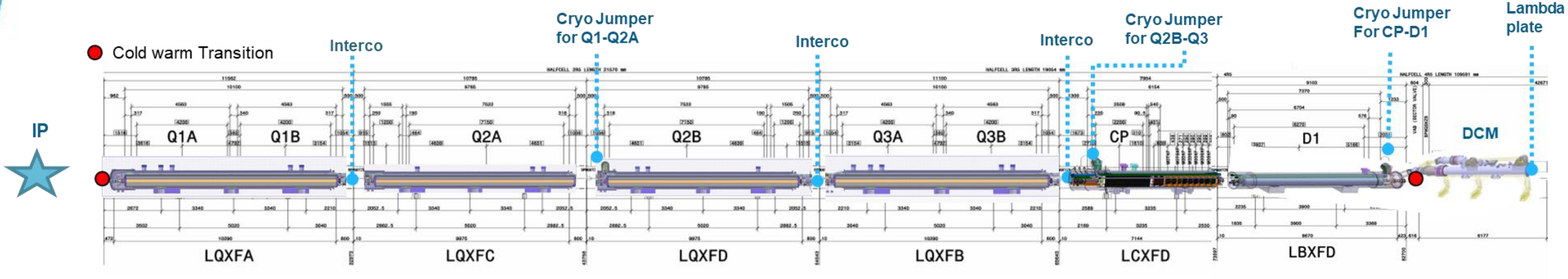
Line	ID [mm]	Area** [cm2]	P [bara]	T [K]
N1 / N2	50	19.6	1.3 – 17*	1.9 – 22.2*
LD	40	12.6	1.3 – 17*	1.9 – 22.2*
Cold mass interco	100	78.5	1.3 – 17*	1.9 – 22.2*
CY1 / CY2	14	1.5	0.05	
TS	34.2	9.2	10-22	60-80
BS	25.5		10-22	60-80
XB1 / XB2	100	78.5	0.020	1.85

*Conditions indicated for a 39.1 MJ quench

** Area indicated is the cross section for corresponding ID



Inner triplet inventory given in helium litre (2/2)



		DCM	D1	CP	Q3	Q2A	Q2B	Q1	Line N	Total
Length [m]		6.17	9.1	7.95	11.1	10.78	10.78	11.56	56	
Inventory [kg]	1.9 K cold mass	16.3	31.0	72.4	68.0	68.0	68.0	68.0	27.6	418.2

The total liquid inventory at 1.9 K is much higher (43.5 l/m) than the previous considerations at 25 l/m.

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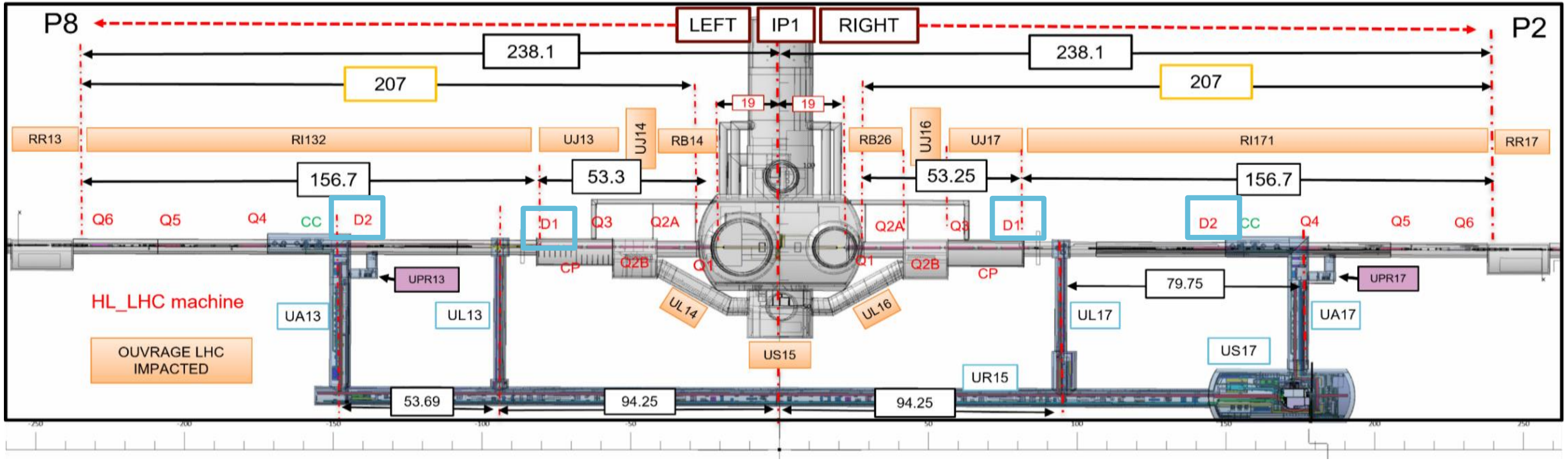
Configuration in case of access

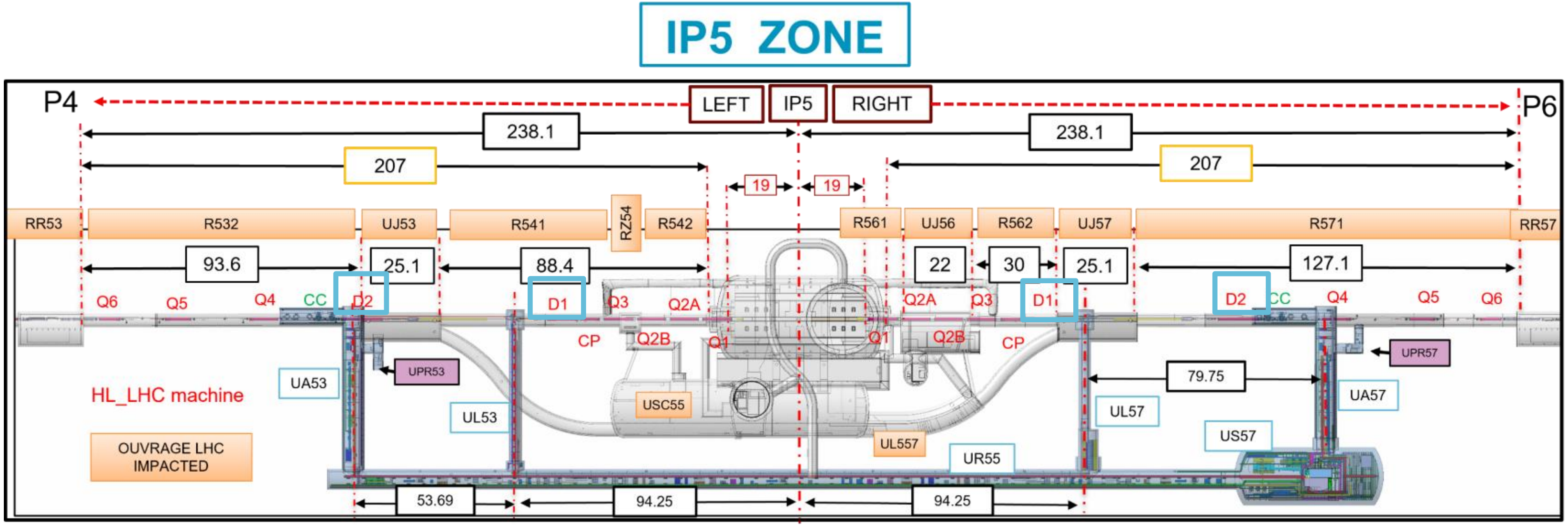
IP1 ZONE



Many relief plates to be expected:

- Q1 to DFX and QXL "T" below ULx3-x7 cores
- D2/DFM to Q4

Configuration in case of access



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- Q1 to DFX and QXL "T" below ULx3-x7 cores
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Reminder of all LHC failure modes

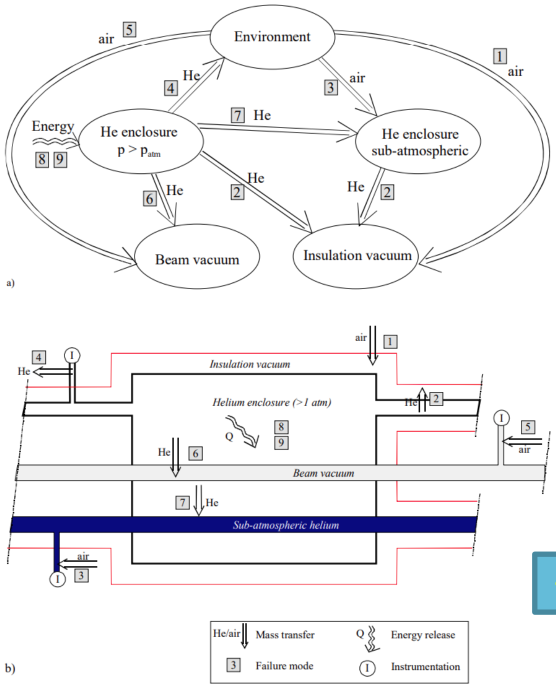


Table 1: Cryogenic failure modes

No.	Cryogenic failure
1	Air flow to insulation vacuum
2[(1)]	Helium flow to insulation vacuum
3	Air flow to sub-atmospheric helium
4[(1)]	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 a sector quench
9	Energy release to cold mass helium due to electrical arc
10	Oil flow to environment (in case of helium compressors only)

[(1)] in case of nitrogen tanks on surface the failure mode deals with "nitrogen flow" instead of "helium flow"

- **Extract of Preliminary risk analysis of the LHC cryogenic Project Note 177.**

Failure modes leading to helium circuit overpressure - CASE A

POWERING

- *Quench → helium release to line D via quench valve*
- Loss of insulation vacuum (LIV) by air ingress
- Static loads (with adequate margin)
- Gas blow by (from HP circuit to LP circuit)
- Blocked outlet

A. Helium circuits, overpressure

- To be assessed for usual cases (heat loads, extra mass-flow, loss of insulation vacuum, any extra energy dissipated in helium)
- For LHC tunnel, QRL or QXL header D as cold collector when possible
- Stagging of devices possible: SV for ~2xheat_loads, SV-RD for max case
- **QXL: RM** (Return Module), **JM** (Junction Module) for local close(able) volumes
- **DFX-DFM, CC**
- Any other ?!?
- Sizing done or being done, depending on maturity of design
- LHe inventory, peak flow, location to be compared with references for definition of access rules

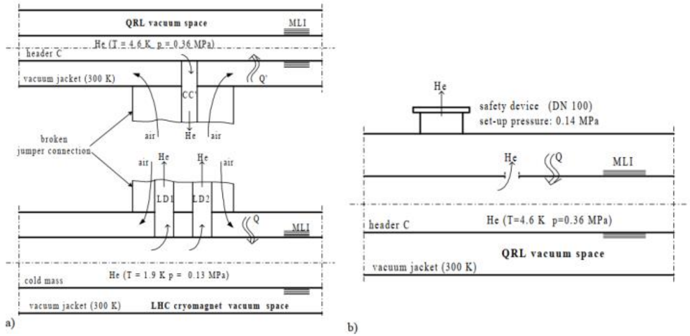
Basics towards helium safety for HL tunnel 11

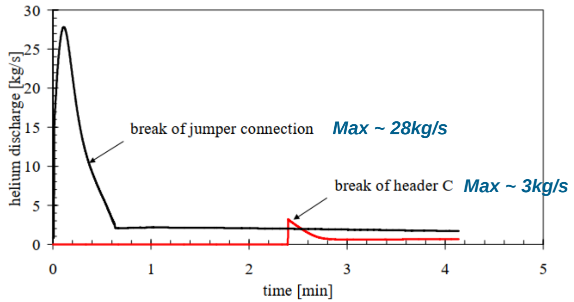
- **Helium is released to the atmosphere when it is not possible to collect it in the line D (low pressure equipment such as CC, Cold powering system, RM module)**
- **When the helium release is limited, as an example: protection of double valves system at JM**

LHC model benchmark

	Cold mass	Header C	QRL vacuum jacket
Pressure [bar]	1.3	*3.6*	*10-9*
Temperature [K]	1.9	4.6	NA
Helium sub-sectorization [m]	214	3300	NA
Vacuum sub-sectorization [m]	214	428	428
Helium Mass per sub-sector [kg]	*475*	3300	NA
Volume per sub-sector [m3]	*3.21*	26	88.04
Diameter	*0.58*	0.1	0.61
Area of heat transfer [m2]	*389.93*	134.46	820.2

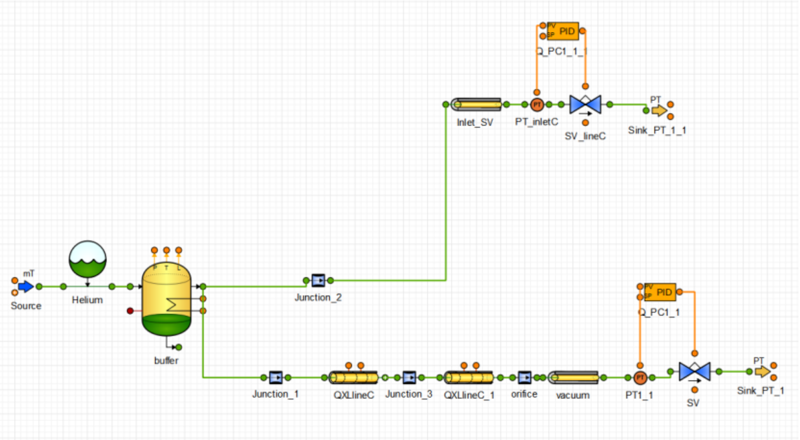
- Two cases were considered as sizing for LHC for helium discharge in the tunnel (prior the sept 2009 incident)
  - Jumper connection rupture – air to insulation vacuum – not considered for HL-LHC
  - QRL line C rupture to insulation vacuum
- Those cases were modelled in Ecosim for benchmark.

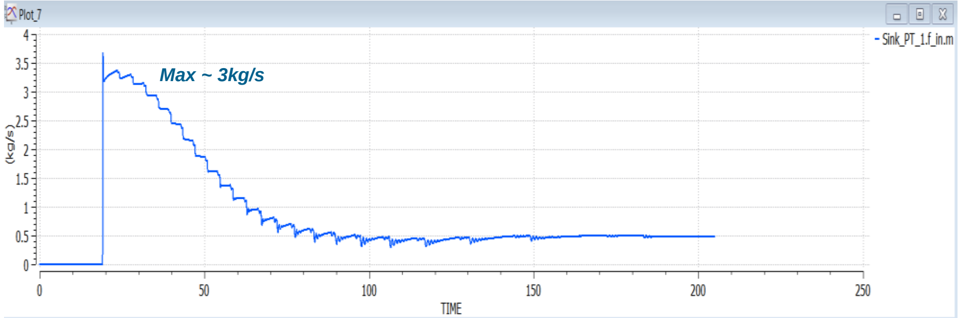




Extract from PN 381 – helium discharge and dispersion in the LHC accelerator tunnel in case of cryogenic failure

QRL line rupture





	Header C
Heat load [W]	*40200*
Heat Load [W/cm2]	0.03
SV on vacuum [m2]	3 x 0.005
SV set pressure [bara]	1.3
Vacuum initial temperature [K]	75
Orifice diameter [mm]	100

- 3 SVs of DN100 were considered.
- Heat load as per PN381.
- Vacuum initial temperature considered to the shield temperature.
- Max helium flow rate discharged to the atmosphere is similar to the value found in PN381 though the opening occurs after ~20 s whereas it occurs after 2 min 40 in PN381.

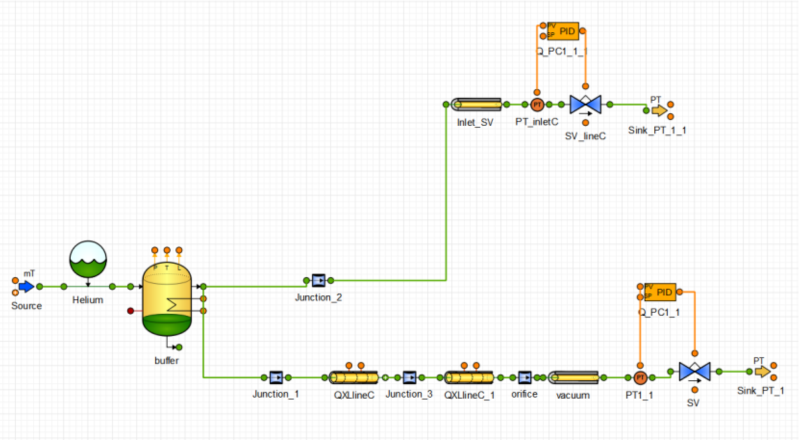
HL-LHC model – case B

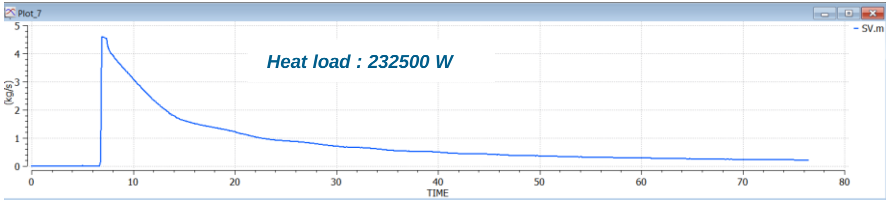
	Cold mass IT	Header C Long branch	QXL vacuum jacket
Pressure [bar]	1.3	*4*	*10-9*
Temperature [K]	1.9	4.8	NA
Helium sub-sectorization [m]	60	530	NA
Vacuum sub-sectorization [m]	60	155	155
Helium Mass per sub-sector [kg]	*418*	275	NA
Volume per sub-sector [m3]		2.3	30.7
Diameter	*0.58*	0.065	0.6
Area of heat transfer [m2]	*113*	1.13 – 17.55	292

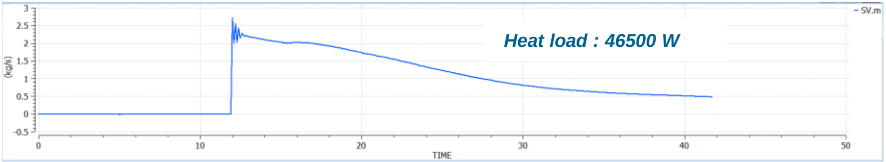
- Cases considered :
  1. Line C for QXL – vacuum sectorization limited between fixed point
     - Partial – 189 mm2
     - Full
  2. Cold Mass IT
     - Partial
     - Full at interconnect

- For helium leak to insulation vacuum, the heat load considered is the convective transfer from the vacuum space at the shield temperature to the cold mass.
- Heat coefficient is considered to 17 W/m2/K.
- Heat load is calculated to ~ 0.15 W/cm2 versus 0.03 W/cm2.

QXL line C full rupture – case 1



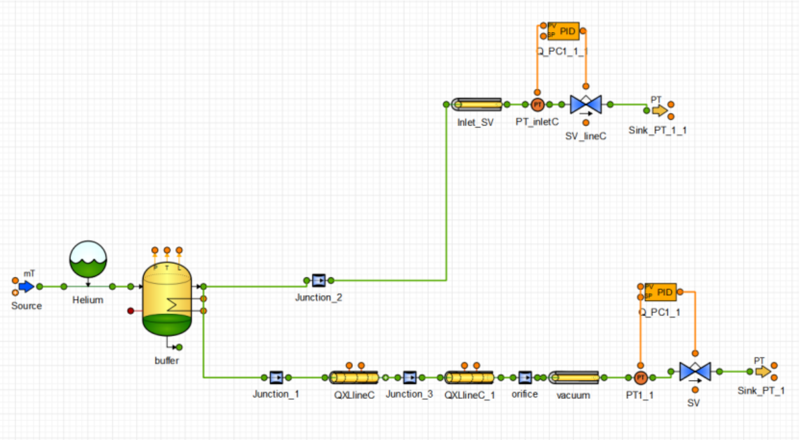


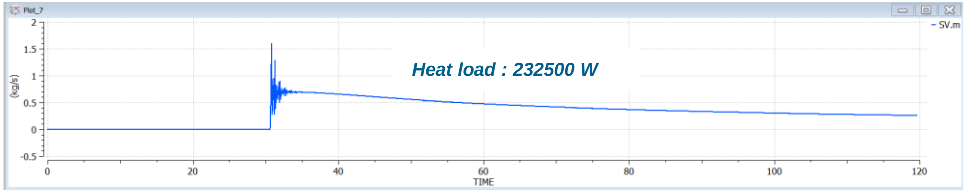


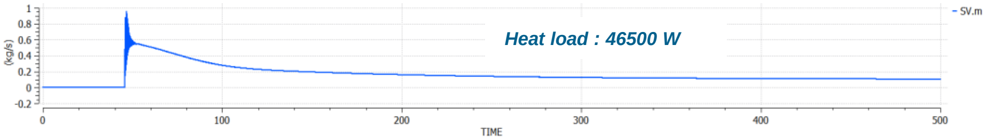
- 3 SVs of DN100 (assumed at 5000 mm2 each) were considered.
- Vacuum initial temperature considered to the shield temperature at 90 K
- Peak flow in the vacuum is 4.6 kg/s.

	Header C 0.03 W/cm2	Header C 0.15 W/cm2
Heat load [W]	*46500*	*232500*
Heat Load [W/cm2]	0.03	0.15
SV on vacuum [m2]	0.02	0.02
SV set pressure [bara]	1.3	1.3
Vacuum initial temperature [K]	90	90
Orifice diameter [mm]	65	65
Peak flow [kg/s]	2.2	4.6

QXL line C partial rupture – case 1







- 3 SVs of DN100 (assumed at 5000 mm2 each) were considered.
- Vacuum initial temperature considered to the shield temperature at 90 K
- Peak flow in the vacuum is 4.6 kg/s.

	Header C 0.03 W/cm2	Header C 0.15 W/cm2
Heat load [W]	*46500*	*232500*
Heat Load [W/cm2]	0.03	0.15
SV on vacuum [m2]	0.02	0.02
SV set pressure [bara]	1.3	1.3
Vacuum initial temperature [K]	90	90
Orifice diameter [mm]	12.6	12.6
Peak flow [kg/s]	0.5	0.7

Pressure drop evolution versus the discharge length

- Hypotheses:
  - DN200 SV: kv = 900 m3/h
  - Vacuum enclosure: free section = 0.35 m2, hydraulic diameter = 135 mm
  - Mass flow = 1 kg/s