SPL Short Cryomodule Design

Supporting System and Pressure Relief Devices

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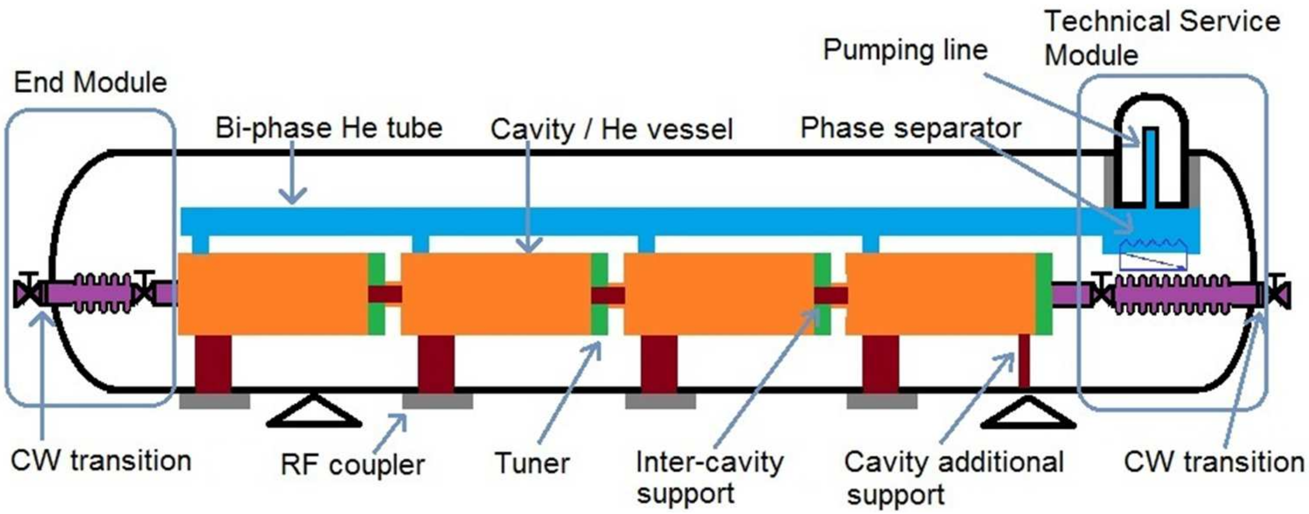
ESS Accelerator Division 2012 Retreat, 29/11/2012

Summary

1. Overview of cavity supporting system
2. Status of supporting system mock-up
3. Pressure relief devices: introduction
4. Bursting discs for LHe 2K volume
5. Vacuum vessel relief plate
6. Lower protection levels (for process and vacuum volumes)

1. Overview of cavity supporting system

Supporting concept: *Power coupler double tube as support*



- The power coupler double tube acts as vertical support and longitudinal positioner
- The design is simplified
- Better thermal performance - less heat conduction paths from room temperature

1. Overview of cavity supporting system

Alignment tolerances

TOLERANCES BUDGET FOR SPL CRYOMODULE			
Step	**Description**	**Position tolerance of every cavity (3σ)**	**Cumulative tolerances**
1_0	Cavities delivery to CERN	**±0.4 mm**	**±0.4 mm**
6_1	Assembling tuner outside clean room.	±0.1mm (?)	±1.6mm (?)
1	Alignment string of He vessels under assembly girder	± 0.1 mm	± 0.1 mm
2	Load transfer to vac.vessel	± 0.3 mm	± 0.4 mm
3	Re-alignment via vessel flange screws adjustment	± 0.2 mm	± 0.2 mm
4	Mechanical mounting of top lid	± 0.3 mm	± 0.5 mm
5	Pump down	± 0.1 mm	± 0.6 mm
6	Transport & Handling	± 0.1 mm (?)	± 0.7 mm (?)
7	Cryostat @ cold (nominal operating T)	± 0.1 mm (?)	± 0.8 mm (?)
8	RF power on	< ± 0.1 mm	< ± 0.9 mm (?)
9	CD/WU cycles	± 0.1 mm (?)	< ± 1.0 mm (?)

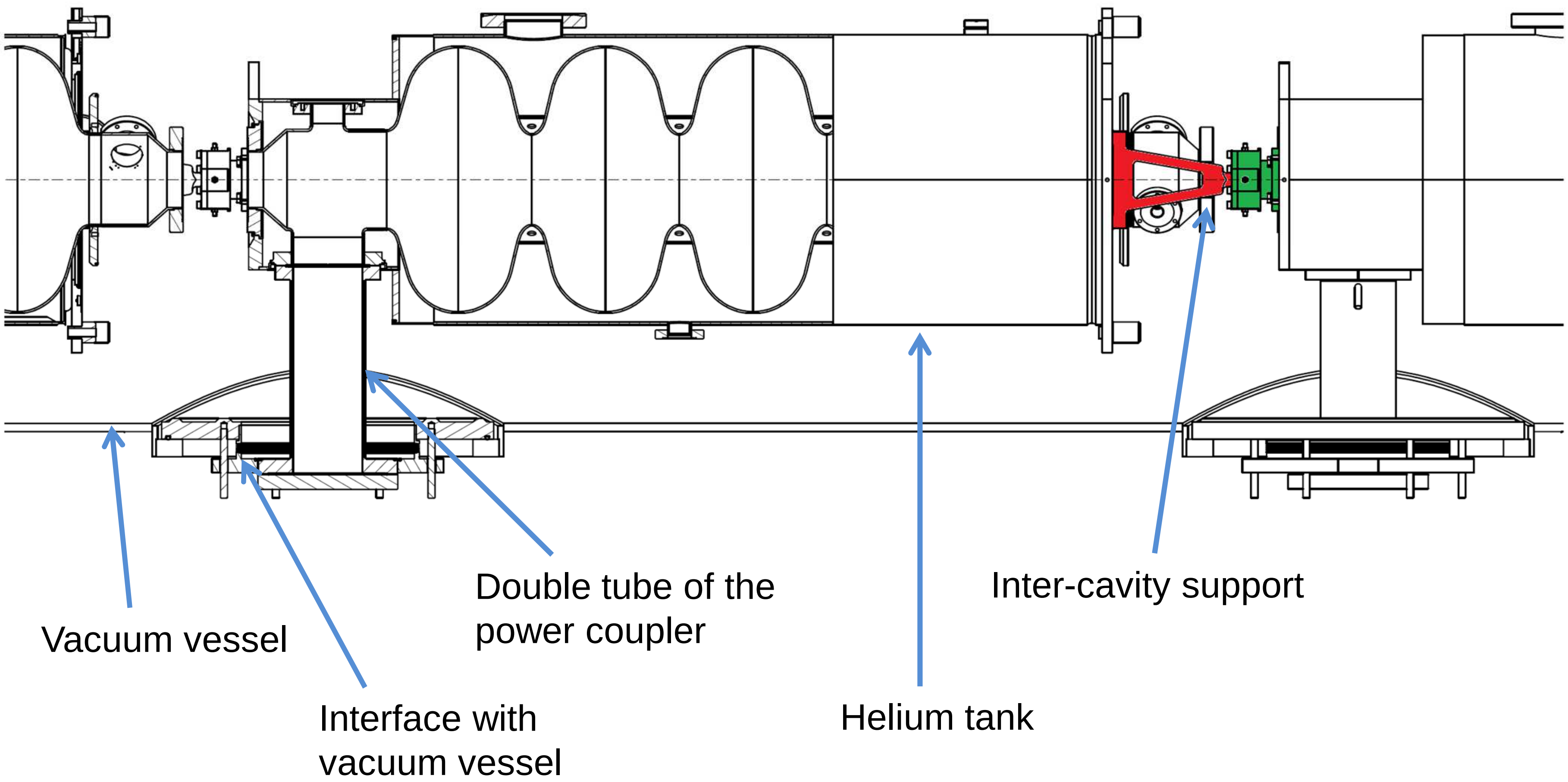
Cryomodule tolerances, V. Parma

	Sum of tolerances (mm)	
	Arithmetic	Quadratic
Cavity / He tank	1.6	0.55
Cryomodule	1	0.42
Total	2.6	0.69

1.2 mm is an acceptable value for the cavities misalignment (3σ)*

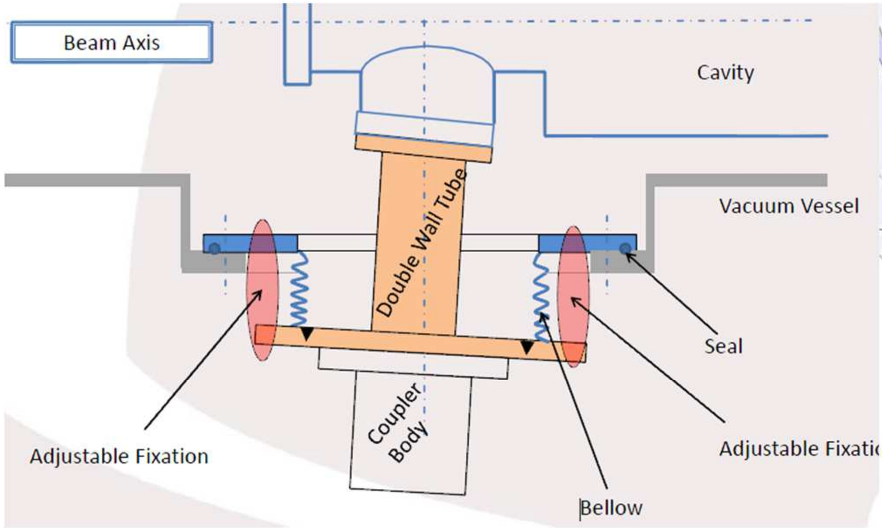
**Summary of the 4th SPL SCM Working Group meeting held on 26/06/2012;* R.Bonomi

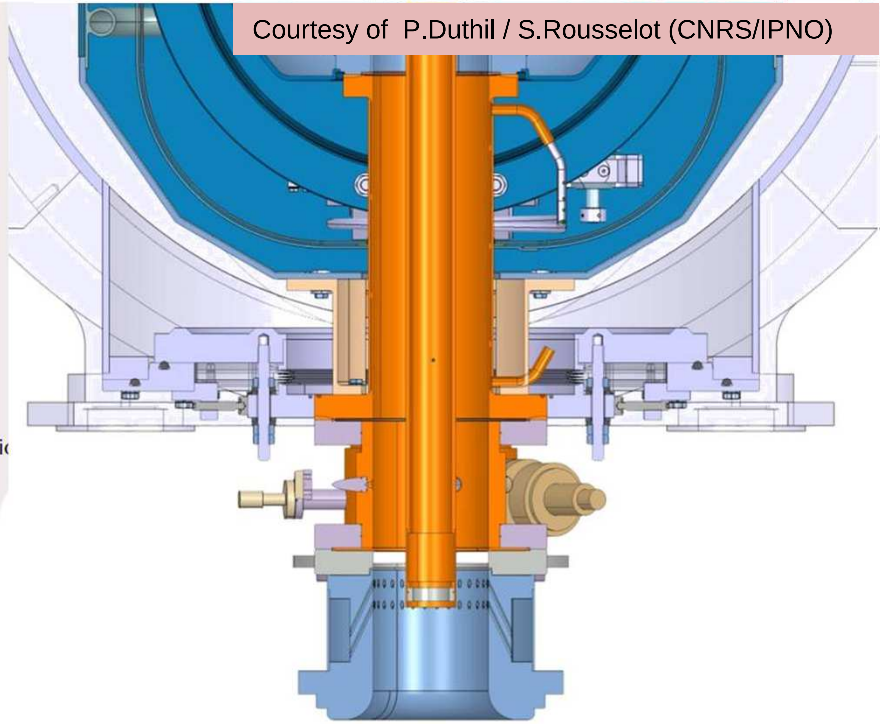
1. Overview of cavity supporting system

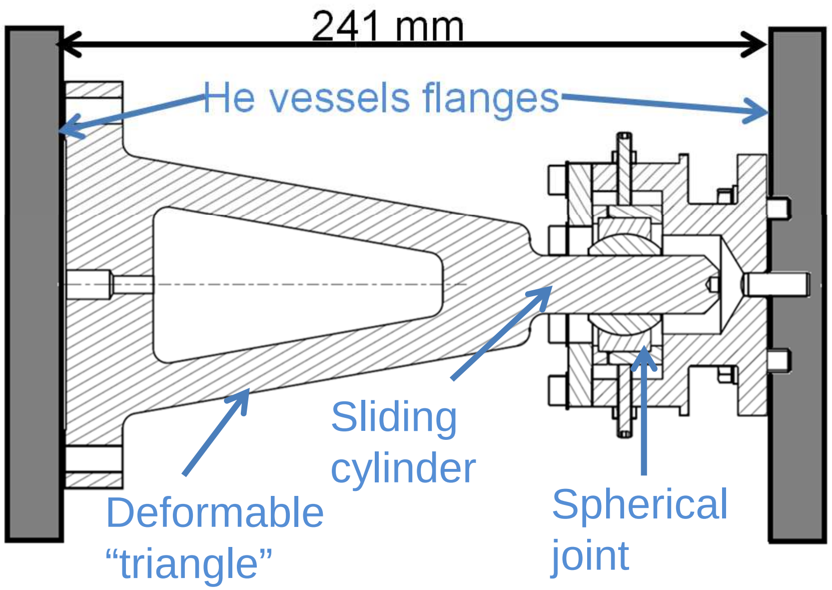


1. Overview of cavity supporting system

Vacuum vessel / double tube interface and inter-cavity support



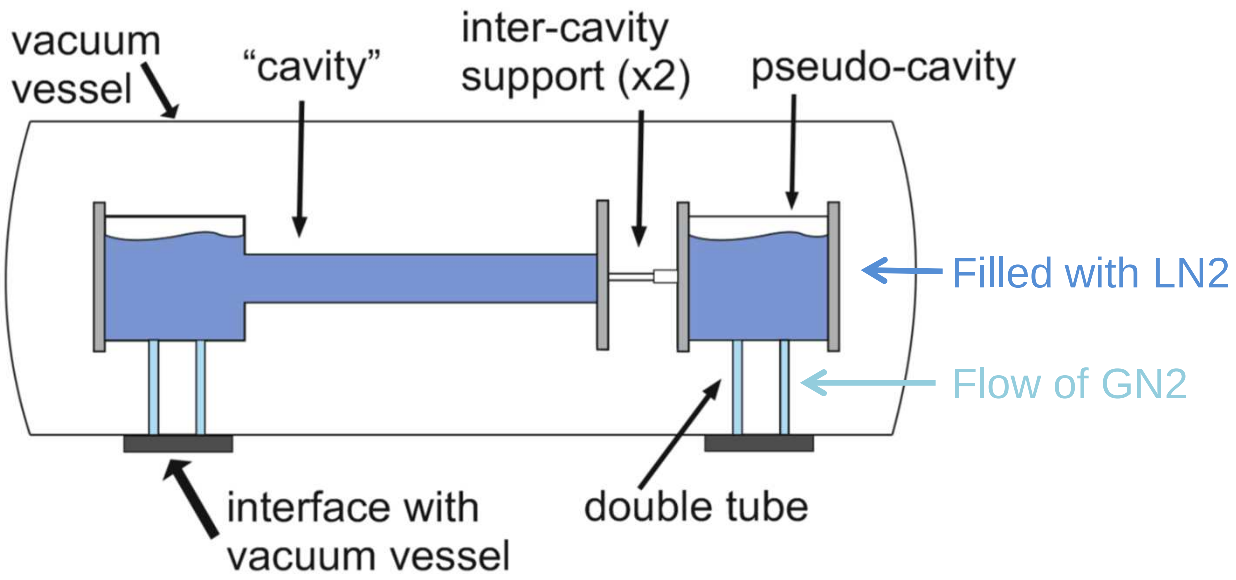




For more information on the design of these components and calculation notes concerning the supporting system, check the SPL workspace (references)..

2. Status of supporting system mock-up

Introduction

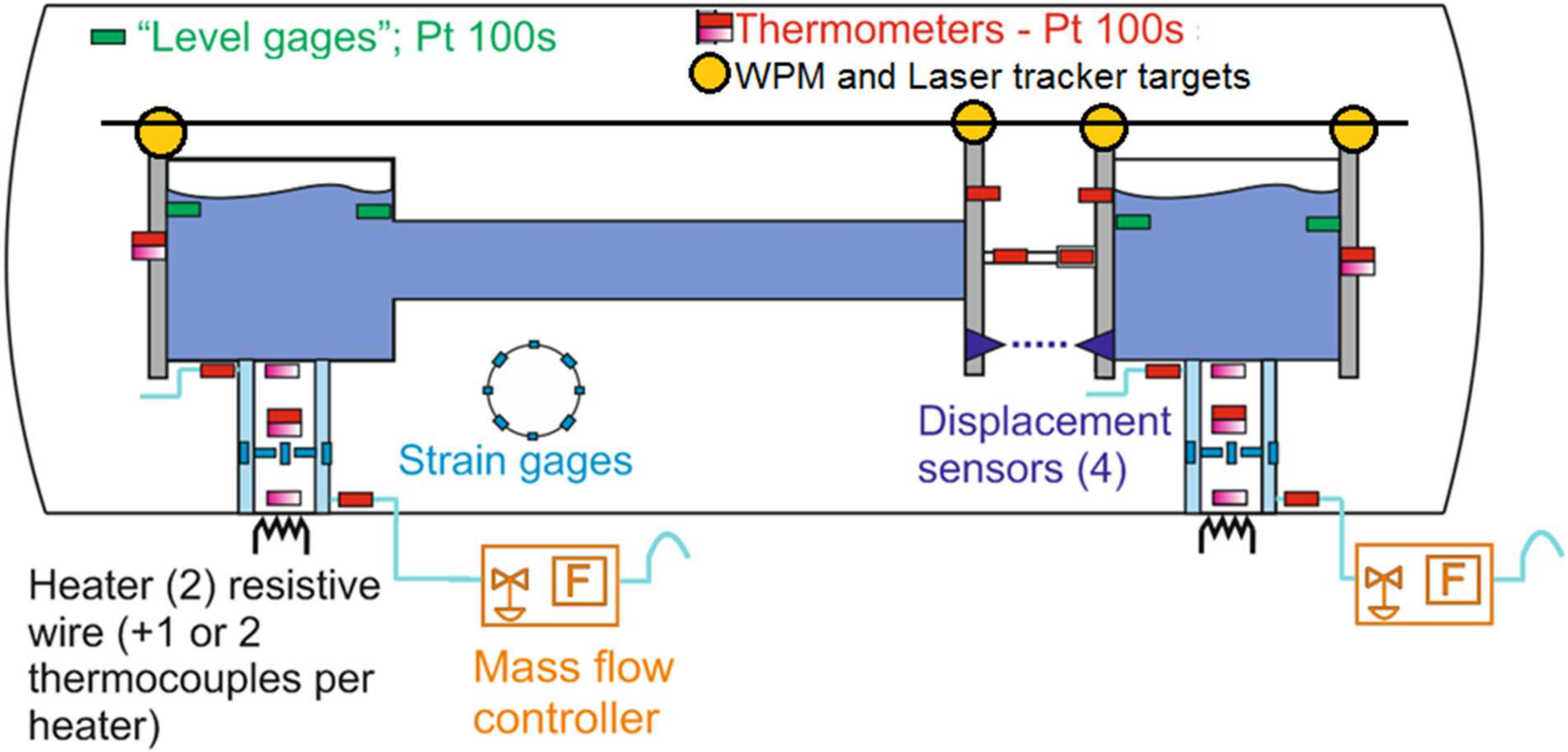


- Validate the supporting and alignment concept
- Test critical components of unknown behaviour, the interface with vacuum vessel and the inter-cavity support, during assembly and cool-down
- Validate thermal calculations – namely the thermal model of actively cooled double
- Learn about alignment survey methods and other measurements relevant for the SPL short cryomodule

Mock-up developed by J-B. Deschamps, A. Vande Craen, R. Bonomi and P. Azevedo , in collaboration with different CERN groups . For more information, check the SLHiPP2 meeting presentation *Mock-ups of the SPL cavity supporting system*

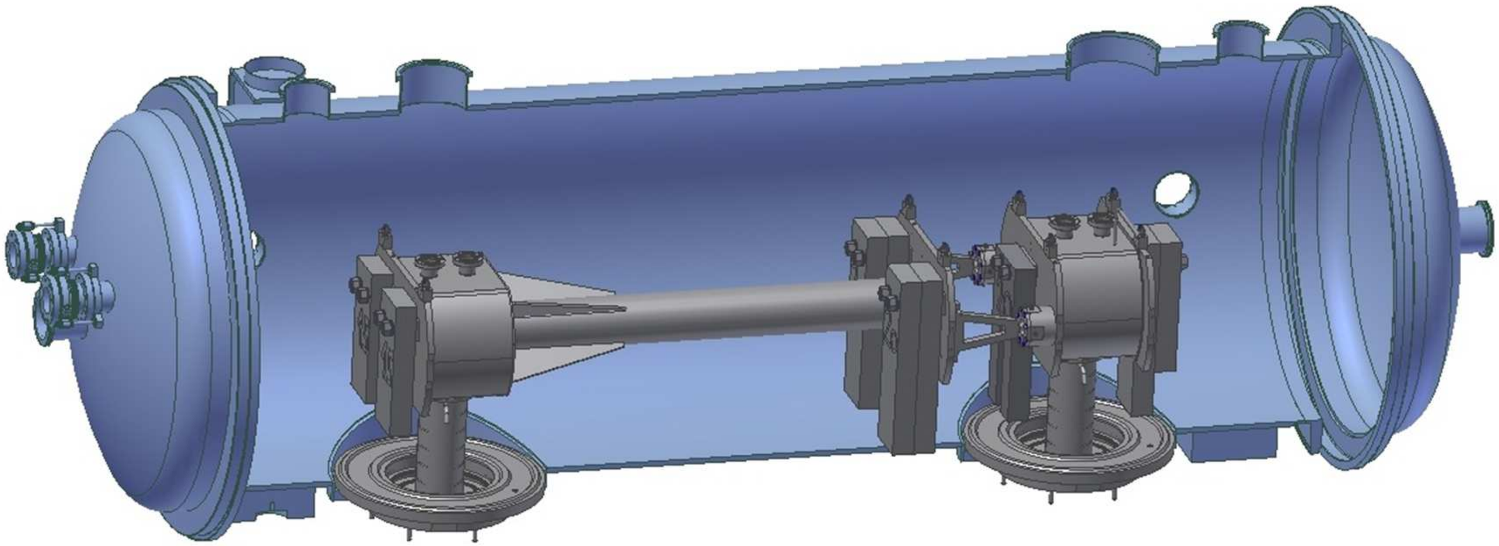
2. Status of supporting system mock-up

Instrumentation Scheme:



Optical wire positioning monitor (stretched wire) will be installed in a second phase

2. Status of supporting system mock-up

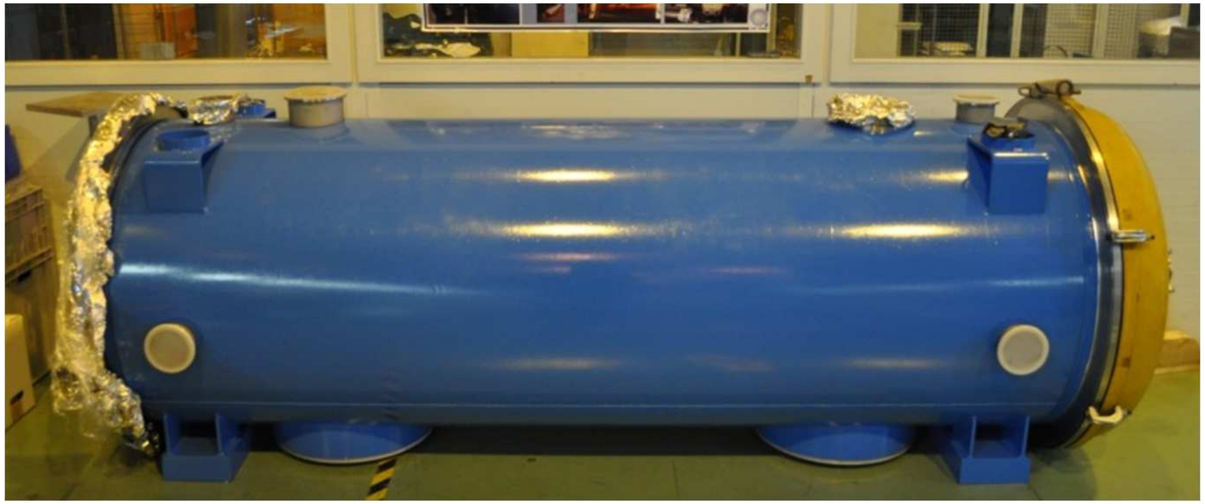


- Design is finished – all components, cryogenic equipment and sensors have been defined / ordered
- Vacuum vessel has been manufactured
- Interfaces with vacuum vessel welded to double tubes (EBW)
- Cold mass (LN2 tanks) ready in a couple of weeks
- Assembly and instrumentation process defined
- Assembly and first alignment measurements: December 2012 / January 2013
- Cool down and first cold tests: first months of 2013

2. Status of supporting system mock-up

Courtesy of E. Rigutto

Courtesy of E. Rigutto



3. Pressure relief devices: Introduction

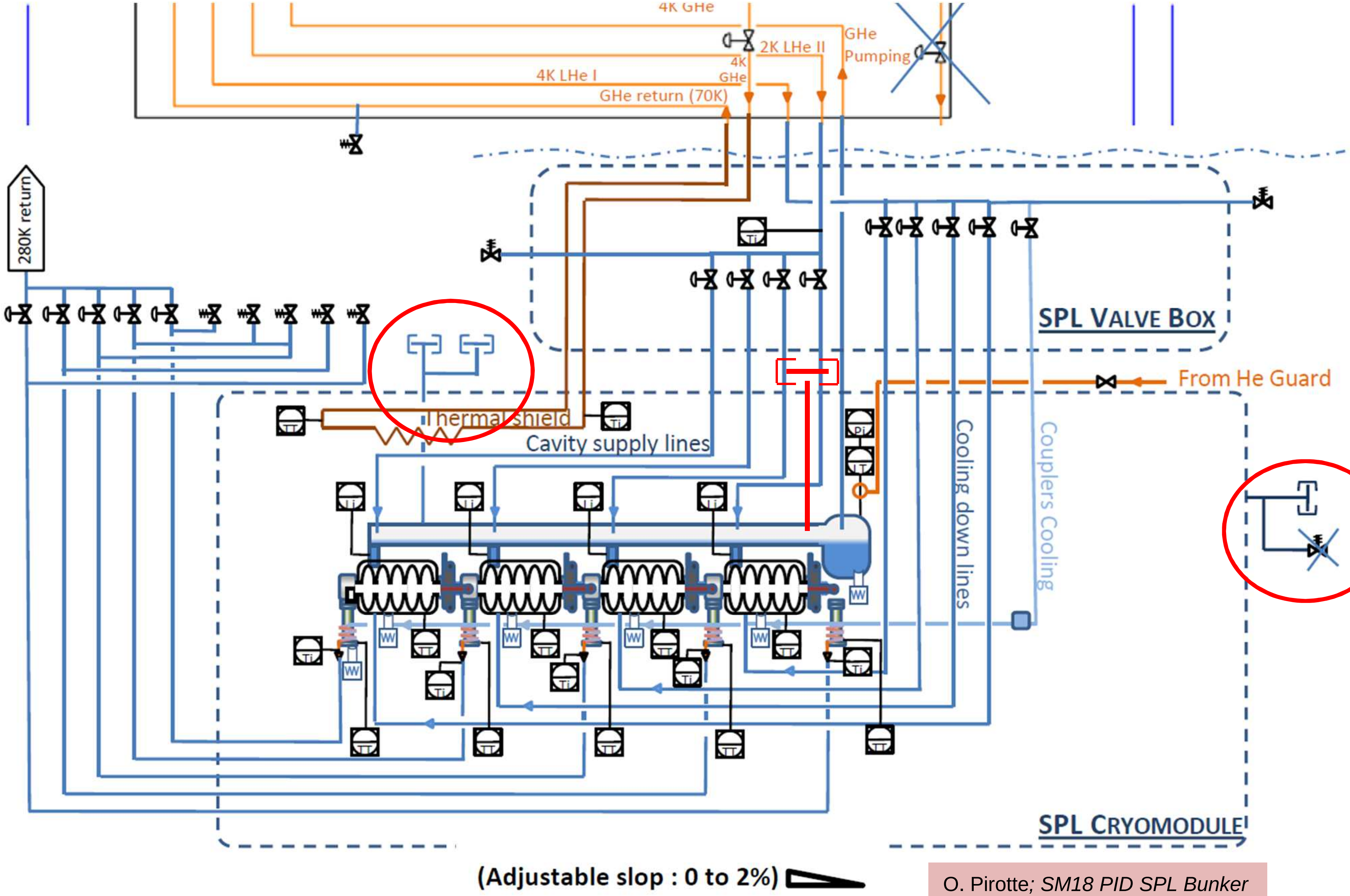
Pressure / Temperature table:

Line	Description	Pipe Size (ID min value) [mm]	Normal operating pressure [MPa]	Normal operating temperature [T]	Cool-down / warm-up pressure [MPa]	Cool-down / warm-up temperature [K]	T range [K]	Maximum operating pressure [MPa]	Maximum pressure in case of MCI [MPa]	Design pressure [MPa]	Test pressure [MPa]	Comment
Z	cavity/beam vacuum	N.A.	I.P. 10^{-9} mbar (tbc)	2	N.A.	N.A.	2-293	N.A.	0.2 @ 2K	0.15 @ 293K	N.A.	design pressure limited by cavity plastic deformation
L	Cavity-helium vessel enclosure	cavity OD + 10	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.15 @ 293K; 0.2 @ 2K (tbc)	0.2 @ 2K	0.15 @ 293K	N.A.	design pressure limited by cavity plastic deformation
X	Bi-phase pipe	**100**	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.15 @ 293K 0.2 @ 2K (tbc)	0.2 @ 2K	0.15 @ 293K	N.A.	"
Y	Cavity top connection	80	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.15 @ 293K 0.2 @ 2K (tbc)	0.2 @ 2K	0.15 @ 293K	N.A.	"
XB	Pumping line	80	0.0031	2	0.13 @ 293K 0.2 @ 2K	293-2	2-293	0.15 @ 293K 0.2 @ 2K (tbc)	0.2 @ 2K	0.15 @ 293K	N.A.	"
E	Thermal shield supply	15	1.8	~50	2	293-50	50-293	2	N.A.	2	2.5	Heat intercept
E'	Thermal shield return	15	1.8	~50	2	293-50	50-293	2	N.A.	2	2.5	Return only
W	Cryostat vacuum vessel	TBD	I.P. 10^{-6}mbar	293	vacuum	293	237-293	O.P. 0.1	I.P. 0.15 @237K	O.P. 0.1 @ 293K; I.P. 0.15 @237K	N.A.	
C/C1	Cavity filling	6	0.1	4.5	0.1	293-4.5	4.5-293	0.15 @4.5K	N.A.	0.15 @ 293K	N.A.	Liquid supply
C2	Coupler cooling	6	0.1	4.5-293	0.1	293-4.5	4.5-293	0.15 @ 4.5K	N.A.	0.15 @ 293 K	N.A.	Gaseous supply
C3	Cavity top supply	10	0.1	2	0.1	293-4.5	2-293	0.15 @ 4.5K	N.A.	0.15 @ 293 K	N.A.	Liquid supply

V. Parma; *SPL Pressure / Temperature Table*

3. Pressure relief devices: Introduction

Cryogenic Scheme:



O. Pirotte; *SM18 PID SPL Bunker*

3. Pressure relief devices: Introduction

<u>Risks overview:</u>

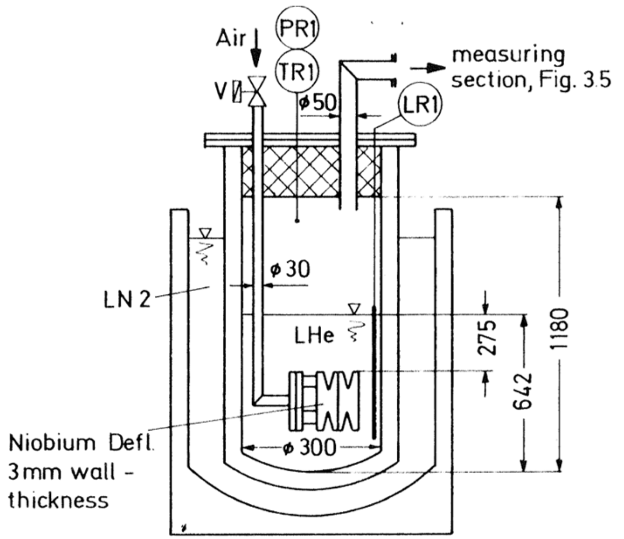
<table>
<tr><th>Hazard</th><th colspan="2">Cause / Component</th><th>Consequences</th><th>Probability / Frequence</th><th>Control measures related to pressure relief</th></tr>
<tr><td rowspan="2">Leak to vacuum vessel</td><td>Thermal cycles
Mechanical loads
Corrosion</td><td>Welds
Bellows
Pipe
Flanges</td><td>Pressure increase in vacuum vessel
Loss of insulating vacuum (heat load)</td><td>Low</td><td>Vacuum vessel relief plate; P_s = 0.5 barg (design pressure)</td></tr>
<tr><td colspan="2">Temporary (small) leak of air into vacuum volume</td><td>Vaporization of condensed air</td><td>High</td><td>Vacuum vessel relief valve; P_s < 0.5 barg</td></tr>
<tr><td rowspan="5">Pressure increase</td><td colspan="2">Loss of insulating vacuum</td><td rowspan="4">Pressure increase in 2K circuit</td><td rowspan="4">Low</td><td rowspan="4">2K circuit bursting discs; P_s = 0.5 barg (design pressure)</td></tr>
<tr><td colspan="2">Loss of beam vacuum</td></tr>
<tr><td colspan="2">Overpressure in cryogenic supply</td></tr>
<tr><td colspan="2">Return pipe blocked</td></tr>
<tr><td colspan="2">Power failure</td><td>Static heat loads not compensated</td><td>High</td><td>2K circuit relief valve; P_s < 0.5 barg</td></tr>
</table>

4. Bursting discs for LHe 2K volume

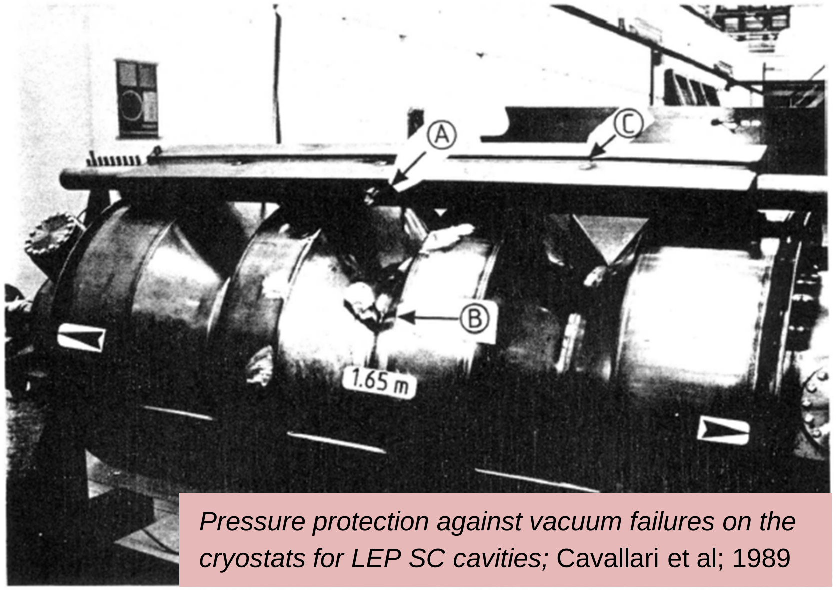
Heat input due to loss of beam vacuum: different tests, different results

- **LHe bath cooled Nb deflector**: 3 mm thick; 30 mm opening; **w = 18 kW/m2**
- **LEP cavity**: 25 mm opening; 120 g/s; **w = 10 kW/m2**

  80 mm opening; 1200 g/s, **w = 40 kW/m2**
- **XFEL cryomodule**: beam pipe opening; **w = 23 kW/m2** (+/- 50 % uncertainty); **w = 14.2 kW/m2** (+/- 10 % uncertainty) – different heat load estimation methods
- **Work in progress:** these values are the result of tests carried out with different equipment and in different conditions. A proper understanding of the geometrical and physical parameters is required before estimations can be made for the SPL cryomodule (cavity geometry, venting diameter, relief devices set pressure, peak pressure)



Safety aspects for LHe cryostats and LHe transport containers; Lehmann, Zahn; (1978)

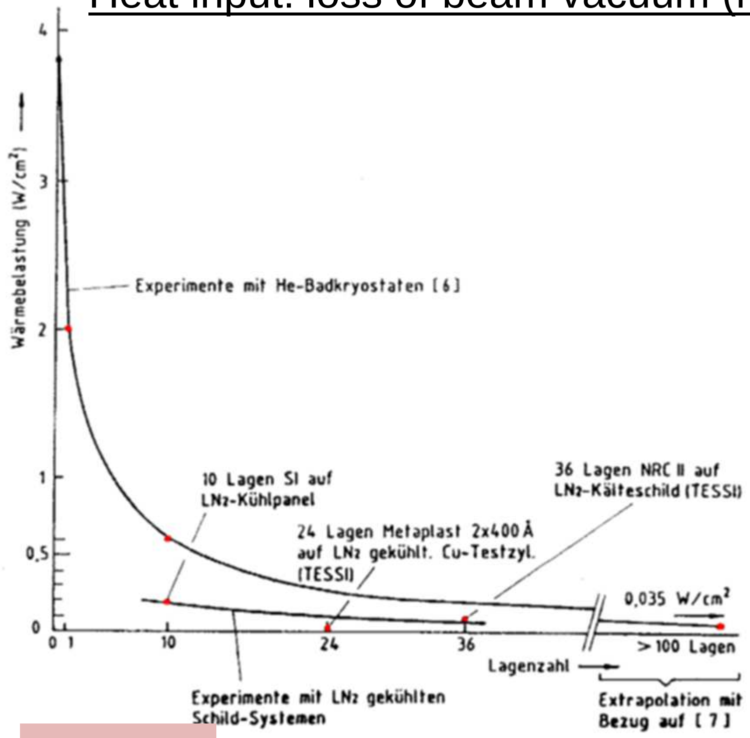


Pressure protection against vacuum failures on the cryostats for LEP SC cavities; Cavallari et al; 1989

Experimental tests of fault conditions during the cryogenic operation of a XFEL prototype cryomodule; *Boeckmann et al;*

4. Bursting discs for LHe 2K volume

Heat input: loss of beam vacuum (no insulation) → **Estimate**



W. Lehmann

For the moment, the safety experts at CERN recommend 38 kW / m^2

LIV						
Air ingress into vacuum space						
	Q [W/m^2]					
Vessels	Helium (1)	Nitrogen (2)	Argon	Oxygen	Krypton	Hydrogen (3)
Vacuum insulated (no MLI)	38000	5000	5000	5000	5000	30000
Vacuum insulated (with MLI)						
10 layers	6000	2000	2000	2000	2000	4737
36 layers	2000	1000	1000	1000	1000	1579
Vacuum insulated (no shield) (4)						
10 layers	23368	----	----	----	----	22105
36 layers	7789	----	----	----	----	7368

Table by C. Parente (DGS-SEE-XP) based on multiple sources; from calculation sheet developed by A. Henriques (DGS-SEE-XP)

Heat input determines mass flow:

$$Q_m = 3{,}6\left(\frac{v_g - v_l}{v_g}\right)\frac{W}{L}$$

for $0.4 \cdot P_{crit} < P_{relief} < P_{crit}$

EN 13648-3

For an overpressure of 10% (P_{relief} = 1.55 bara):

W/S **(kW/m2)**	***W*** **(kW)**	Q_m **(kg/s)**
38	266	**12**
20	140	6.3

4. Bursting discs for LHe 2K volume

Heat input: loss of insulating vacuum (with MLI) ⟶ **Estimate**

For comparison purposes, an estimation of the heat input and relief mass flow in the event of loss of insulation vacuum (not the dimensioning scenario) was carried out:

LIV						
Air ingress into vacuum space						
	$Q\ [W/m^2]$					
Vessels	Helium (1)	Nitrogen (2)	Argon	Oxygen	Krypton	Hydrogen (3)
Vacuum insulated (no MLI)	38000	5000	5000	5000	5000	30000
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For an overpressure of 10% (P_{relief} = 1.55 bara):

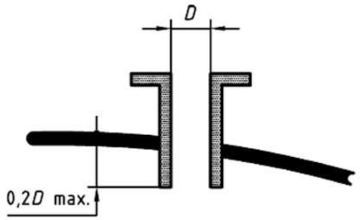
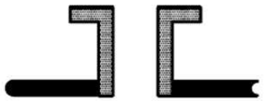
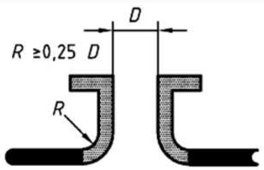
W/S **(kW/m2)**	***W*** **(kW)**	Q_m **(kg/s)**
6	48	**2.2**

4. Bursting discs for LHe 2K volume

<u>Relieving temperature and bursting disc(s) discharge coefficient</u>

- The saturation temperature at the relieving pressure is 4.7 K. A value of 5 K was taken as relieving temperature, based on U. Wagner's* initial estimates (conservative)
- A discharge coefficient (*α)* of 0.73 was taken – depending on final design, this value may be conservative

Table C.1 — Discharge coefficients *α*

Number	Branch/nozzle type		Discharge coefficient, α
1		In the case of an internally protruding branch/nozzle	0,68
2		In the case of a flush branch/nozzle or a block flange whose inlets are not of hydrodynamic configuration	0,73
3		In the case of a branch/nozzle or a block flange of hydrodynamic configuration, e.g. with rounded or chamfered inlets	0,80

EN ISO 4126-6

*U. Wagner; *Cryogenic scheme, pipes and valves dimensions; SPL Conceptual Design Review; 04/11/2011*

4. Bursting discs for LHe 2K volume

Results: Sizing of bursting discs

w/S **(kw/m2)**	**No. Burst. Discs**	***D_{min}*** **(mm)**
20	1	93
	2	65
38	1	127
	2	90

$$A_o = 3{,}469 \frac{Q_m}{C.K_b.\alpha\sqrt{\frac{V_o}{P_o}}}$$

EN ISO 4126-6

- *Formula units are not always consistent with the units presented*
- K_b *is a correction factor for subcritical flow (function of the isentropic expansion coefficient* k *and pressure ratio)*
- *C is a function of k*

Heat input value should be clarified before final design decisions

Also affecting the design of the cryomodule: “The liquid container shall be protected against overpressure by a minimum of two relief devices in parallel, preferably of different types”*

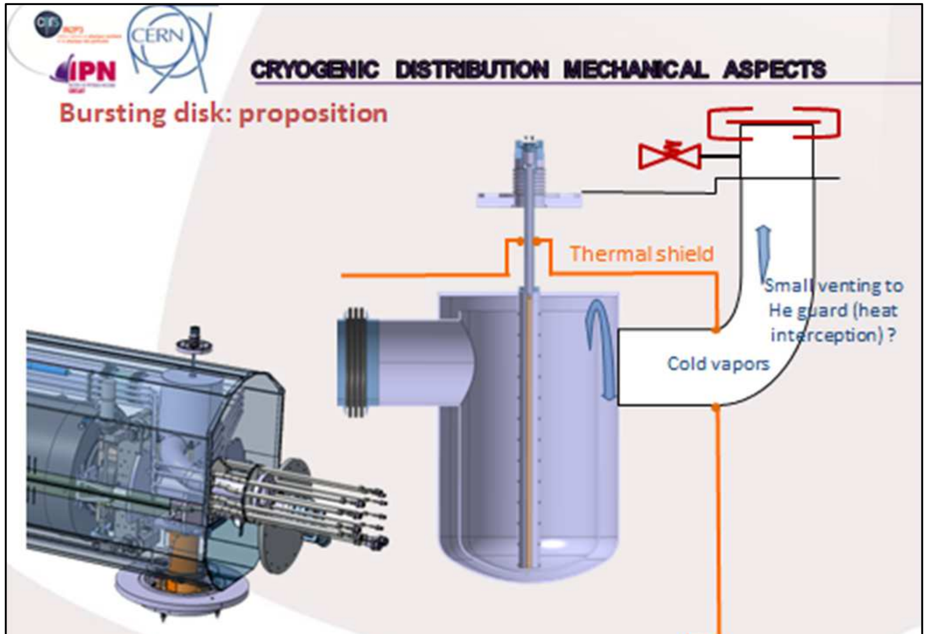
**Safety instruction IS 47: The use of cryogenics fluids ; CERN EDMS doc. 335812,* by the Safety Comission

4. Bursting discs for LHe 2K volume

Pressure drop limits and cryomodule design

w/S (kw/m²)	No. Burst. Discs*	*ΔP* (mbar)**	$\Delta P/P_s$ (%)
20	1	16	3
	2	3	1
38	1	59	12
	2	10	2

** For 2 bursting discs, these are considered to be placed on opposite ends of the bi-phase pipe.*
*** Pressure drop along the bi-phase pipe: no local pressure drops considered*



Courtesy of P. Duthil, S. Rousselot et al, CNRS / IPNO

- The pressure drop along the bi-phase pipe is significant - it should be limited to 3% of P_s (EN 13648-3) – 15 mbar
- Local pressure drops have to be determined: since the dynamic/ velocity pressure of the discharged mass flow is 119 mbar, for an heat input of 20 kW/m², we are limited to very small local pressure drop coefficients
- An additional problem is the fact that only part of the bi-phase pipe will constitute a “free relief path” for a zero slope configuration (common LHe bath as opposed to the “roman fountain” solution for a positive slope)

5. Vacuum vessel relief plate

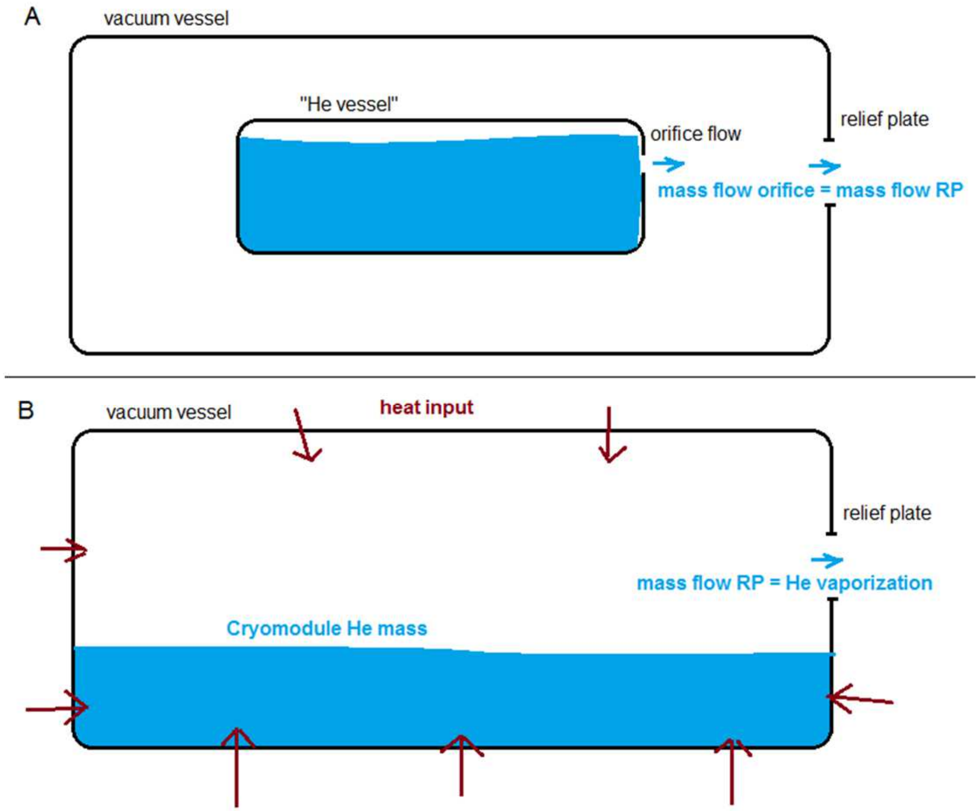
Methodology – there is no "standard" method; 2 different methods were used:

A) An orifice in the 2K LHe circuit causes a discharge of LHe into the vacuum vessel (incompressible fluid). This mass flow, which depends on the orifice diameter, is the mass flow discharged by the relief plate, at subcritical flow and higher T_{relief}.

- Highly dependent upon orifice hole and T_{relief}
- Turns a highly transient phenomenon (LHe release into the vacuum) into a steady state process

B) Complete rupture of the 2K LHe enclosure: the vacuum vessel becomes a non-insulated cryostat. The heat load to the helium volume causes a discharge through the relief plate

- The He density in the vacuum vessel is lower than the saturated vapour density at the relief pressure – mass flow calculation is not trivial



For both cases, the process volume relief devices (same set pressure) are ignored – conservative assumption

5. Vacuum vessel relief plate

Method A

1st Step - incompressible flow through an orifice, into vacuum:

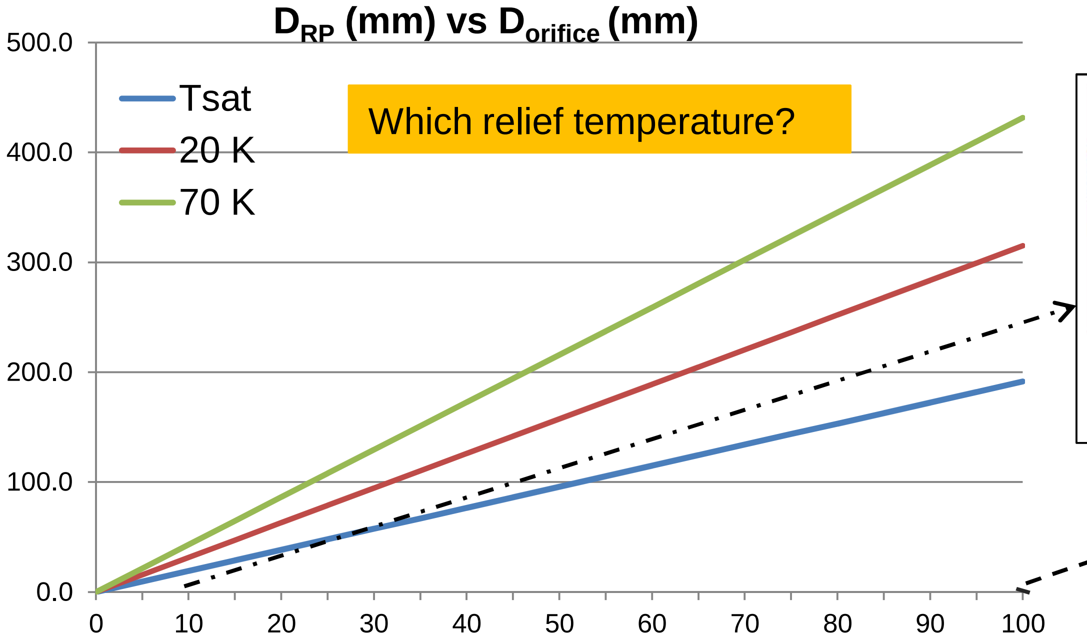
$$Q_m = K_d \times A \times \sqrt{2 \times \rho \times P_P}$$

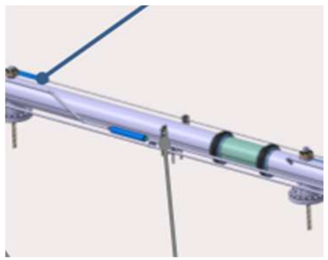
- A *is the area of the orifice*
- K_d *is the orifice coefficient of discharge;* K_d*=0.62 (HSE recommendation)*
- P *is the pressure in the process volume;* P*=1.5 bar (design pressure)*

2nd Step - compressible and subcritical flow through vacuum vessel relief plate:

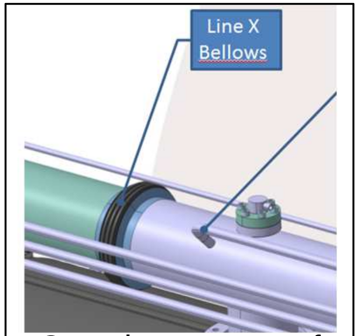
$$Q_m = K_{d,RP} \times Y \times A_{RP} \times \sqrt{2 \times \rho \times (P_V - P_b)}$$

- $K_{d,RP}$ *is the coefficient of discharge of the relief plate;* K_d*=0.73 was taken*
- Y *is the expansion factor for the He vapour*
- A_{RP} *is the area of the relief plate orifice*
- P_V *is the relief pressure (1.5 bara)*
- P_b *is the back pressure (atmosphere)*





Complete rupture of C3 line bellows



Complete rupture of bi-phase pipe bellows

For the moment we can assume a 10 mm diameter as “reasonable”. This value corresponds to the complete rupture of the line C3, and to a “reasonable size for an hypothetical orifice in the bi-phase pipe bellows

5. Vacuum vessel relief plate

Method B

Due to large vacuum vessel volume, helium density is lower than density of saturated vapour at relief pressure. Two hypothesis:

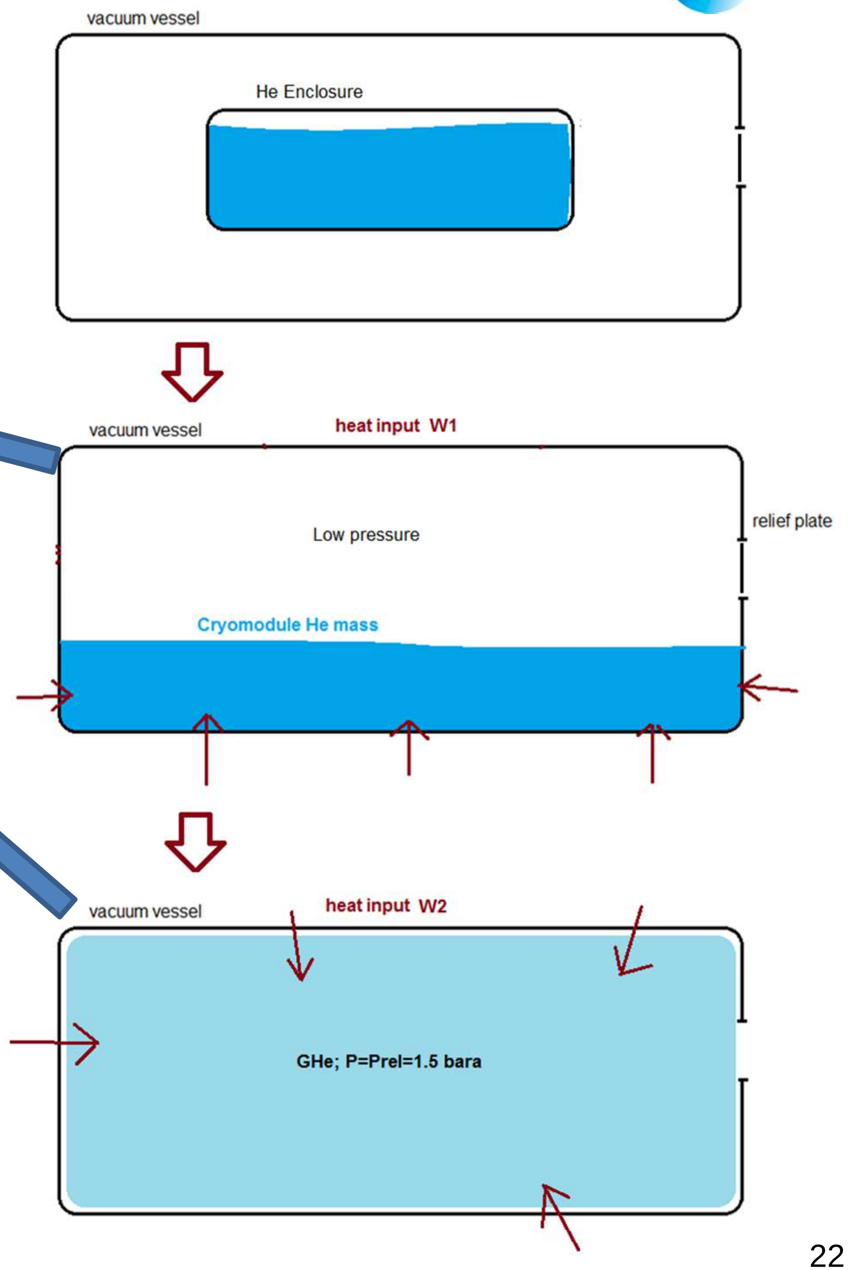
1) Vaporization of LHe mass correspondent to cryomodule volume (identical to the 2K LHe relief flow presented before)

2) Transient heat conduction to the Ghe mass filling the vacuum vessel; mass flow correspondent to density decrease due to temperature increase

Calculation by R. Bonomi

		1)	2)
W (kW)		184	59
Q_m (kg/s)		8.2	0.2
D_{RP} (mm)	"Tsat"	103	21
	20 K	169	26
	70 K	232	36

Which relief temperature?



6. Lower protection level

LHe 2 K circuit

- Event: power failure
- Heat input: static heat loads – 70 W heat load to LHe bath*

*R. Bonomi, *SPL Short Cryomodule Heat loads;* 3rd SPL SCM WG Meeting, 22/5/2012

P_s (barg)	0.3
P_{rel} (bara)	1.33
K_d	0.5
K_{dr}	0.45
w (W)	69.7
Q_m (g/s)	3.0
T_{rel}* (K)	5
D_{min} (mm)	**3.0**
$\Delta P/P_s$ (%)	0

*T_{sat} = 4.5 K

$$Q_m = p_o\, C\, A\, K_{dr}\, K_b \sqrt{\frac{M}{Z T_o}} = 0{,}2883\; C A\, K_{dr}\, K_b \sqrt{\frac{p_o}{v}}$$

- *Formula units are not always consistent with the units presented*
- K_b *is a correction factor for subcritical flow (function of the isentropic expansion coefficient* k *and pressure ratio)*
- C *is a function of* k
- K_d *(K_{dr}=0.9 K_d) is the coefficient of discharge*

EN ISO 4126-1

- The mass flow and discharge area calculation follows the method used for the rupture discs (loss of beam vacuum)
- Diameter is highly dependent on the coefficient of discharge (depends on the valve, and is usually lower for low set pressures)

6. Lower protection level

Vacuum vessel

- Event: temporary leak of air / air freezes immediately / leak is not detected / pressure rises during warm-up
- Heat input calculation – appropriate method?
- Relief plate (0.5 barg) behaviour at relief valve set pressure (0.3 barg, for instance)?
- Possibility of using a specific relief plate design which can deal with both higher and lower protection levels (different relief pressures and discharge flows) – is being studied

References

- SPL Workspace: https://espace.cern.ch/spl-cryomodule
- V. Parma; "Cryomodule tolerances"
- R.Bonomi; "Summary of the 4th SPL SCM Working Group meeting held on 26/06/2012"
- P. Azevedo et al; "Mock-ups of the SPL cavity supporting system"; SLHiPP2 meeting; 03/05/2012
- EN ISO 4126: Safety devices for protection against excessive pressure (parts 1,6, and 7)
- EN 13648: Cryogenic vessels – Safety devices for protection against excessive pressure (part 3)
- EN 13458: Cryogenic vessels – Static vacuum-insulated vessels (part 2)
- U. Wagner; "Cryogenic scheme, pipes and valves dimensions"; SPL Conceptual Design Review; 04/11/2011
- R. van Weelderen; "Open Cryogenic Action Items"; 4th SPL Short Cryomodule WG; 26/06/2012, updated 04/07/2012
- R. Bonomi*; "*SPL Short Cryomodule Heat loads"*;* 3rd SPL SCM WG Meeting, 22/5/2012
- O. Pirotte; "SM18 PID SPL Bunker"
- V. Parma; "SPL Pressure / Temperature Table"
- A. Henriques; "Safety Accessory Calculation Tool for Cryogenic Vessels"
- Lehmann and Zahn; "Safety aspects for LHe cryostats and LHe transport containers" (1978)
- Cavallari et al; "Pressure protection against vacuum failures on the cryostats for LEP SC cavities" (1989)
- Boeckmann et al; "Experimental tests of fault conditions during the cryogenic operation of a XFEL prototype cryomodule"
- CERN Safety Comission; "Safety instruction IS 47: The use of cryogenics fluids"; CERN EDMS doc. 335812

Thank you for your attention

Spare slides

Heat loads table - TOTAL

Static heat loads
(1) RF off, cool off
(2) RF off, cool on
Dynamic heat loads
(3) RF on, cool on
(4) RF on, cool off

Subassembly	Type	Source	Desti-nation	2 K				4.5 K				50 K
Double-walled tube	cd rad RF	DWT	bath	13 $^{(1)}$ x 5 = 65	0.1 $^{(2)}$ x 5 = 0.5	0.5 $^{(3)}$ x 4 + 0.1 x 1 = 2.1	22 $^{(4)}$ x 4 + 13 x 1 = 101	-				-
	cv	DWT	gas	-				- $^{(1)}$	60 $^{(2)}$ x 5 = 300	60 $^{(3)}$ x 5 = 300	- $^{(4)}$	-
Cold-warm transition	cd	WF	TS	-				-				23.0 x 2 = 46.0
	cd	TS	CM	0.8 x 2 = 1.6	0.8 x 2 = 1.6	0.8 x 2 = 1.6	0.8 x 2 = 1.6	-				-
	rad	WF + wall	CM	1.0 x 2 = 2.0	1.0 x 2 = 2.0	1.0 x 2 = 2.0	1.0 x 2 = 2.0	-				-
	rad	WF	TS	-				-				0.2 x 2 = 0.4
	rad	VV	TS	-				-				45
	rad	TS	CM	1.6	1.6	1.6	1.6	-				-
Cavity	RF	cavity	CM	- $^{(1)}$	- $^{(2)}$	20.0 $^{(3)}$ x 4 = 80.0	20.0 $^{(4)}$ x 4 = 80.0	-				-
TOT for SCM (W)				**68.7** $^{(1)}$	**5.7** $^{(2)}$	**87.3** $^{(3)}$	**186.2** $^{(4)}$	**-**	**300** $^{(2)}$	**300** $^{(3)}$	**-**	**91.4**

(R.Bonomi)

Expansion factor

$$(4) \qquad Y = \sqrt{r^{2/k}\left(\frac{k}{k-1}\right)\left(\frac{1-r^{(k-1)/k}}{1-r}\right)}$$

where:

Y = Expansion factor, dimensionless

r = P_2/P_1

k = specific heat ratio (c_p/c_v), dimensionless

Critical / subcritical flow

Critical flow occurs when:

$$\frac{p_b}{p_o} \le \left(\frac{2}{k+1}\right)^{(k/(k-1))}$$

and subcritical flow occurs when:

$$\frac{p_b}{p_o} > \left(\frac{2}{k+1}\right)^{(k/(k-1))}$$

EN 16648-3 – Pressure drop

5 Rule for the safety devices installation

The pipe between outer jacket and safety device should not be longer than 0,6 m otherwise, heat transfer to the released flow shall be taken into account. This heat transfer reduces the product density and consequently reduces the effective discharge rate of the relief system (see calculation methods in the bibliography).

The maximum pressure drop of the pipework to the pressure relieving valve at the maximum flow capacity of the safety valve shall be 2% (of the set pressure of the pressure relief valve) less than the specified minimum blowdown of that pressure relief valve.

Where the blowdown is not known, the pressure drop shall be no greater than 3% of the safety valve set pressure at the rated flow.

Helium volume inside SPL cryomodule

Volume of 2K circuit (l)				
4	cavities	64	l	
1	phase separator	5	l	
1	x line	47.1	l	l=6000; d=100
4	Y lines	2.5	l	l=100; d=100
	total	318.3	l	

Heat input table by C. Parente

LIV						
Air ingress into vacuum space						
	Q [W/m^2]					
Vessels	Helium (1)	Nitrogen (2)	Argon	Oxygen	Krypton	Hydrogen (3)
Vacuum insulated (no MLI)	38000	5000	5000	5000	5000	30000
Vacuum insulated (with MLI)						
10 layers	6000	2000	2000	2000	2000	4737
36 layers	2000	1000	1000	1000	1000	1579
Vacuum insulated (no shield) (4)						
10 layers	23368	----	----	----	----	22105
36 layers	7789	----	----	----	----	7368

Notes:

(1) Source Lehmann, vessels shielded with LN2 bath

(2) Source Lebrun and Lehmann. Extrapolation made for Ar, O2 and Kr (Tsat liquid approximately the same, conservative as delta T is slightly smaller)

(3) Extrapolation made based on the ratio of delta T (wrto helium case); same heat transfer mechanisms

(4) Considered only applicable to helium and hydrogen vessels; extrapolation made using ratio of delta T; same heat transfer mechanisms - not a likely case

From *A. Henriques; "Safety Accessory Calculation Tool for Cryogenic Vessels"*

Local pressure drop coefficients

Examples of Minor loss coefficients for different components common in air duct distribution systems:
(http://www.engineeringtoolbox.com/minor-loss-air-ducts-fittings-d_208.html)
:

Component or Fitting	**Minor Loss Coefficient - ξ -**
90º bend, sharp	1.3
90º bend, with vanes	0.7
90º bend, rounded radius/diameter duct <1	0.5
90º bend, rounded radius/diameter duct >1	0.25
45º bend, sharp	0.5
45º bend, rounded radius/diameter duct <1	0.2
45º bend, rounded radius/diameter duct >1	0.05
T, flow to branch (applied to velocity in branch)	0.3