DFX safety aspects in the LHC tunnel

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Contents

- Safety at CERN
- Pressure vessels
- System description
- Cryogenic safety
  - Preliminary risk assessment and sizing of safety
- Summary

Safety at CERN

- Include safety assessments early in the design phase

- Managing safety covers multiple aspects:
    - Safety of personnel
    - Safety of equipment
    - Protection to the environment

- Risk assessment to cover safety hazards of various nature:
    - Electrical safety (electrocution, burns, arcing, fires, etc.)
    - Cryogenic safety (overpressure, ODH, burns, etc.);
    - Lifting and handling of equipment
    - …

  → CERN has relevant Safety Codes

- Design the equipment to include measures to achieve safe operation for personnel. This is a must: *“no physics is worth a human life” (F.Bordry New Year’s speech 2019).*
    - Design of protection devices (e.g. overpressure safety device, IPx protection covers, etc.)
    - Make provisions for safety inspections and maintenance (e.g. burst disks accessible to inspections and replacement)
    - Consider the environment in which the equipment is installed (e.g. define no-stay zones, install protective barriers, deflectors)

- Design the equipment to be safe for operation (asset value)

- Safety training of personnel to operate and maintain the equipment (e.g. tunnel access procedures and limitations, work procedures, specific tools, proper Personnel Protection Equipment, evacuation training, etc.)

Safety at CERN, codes

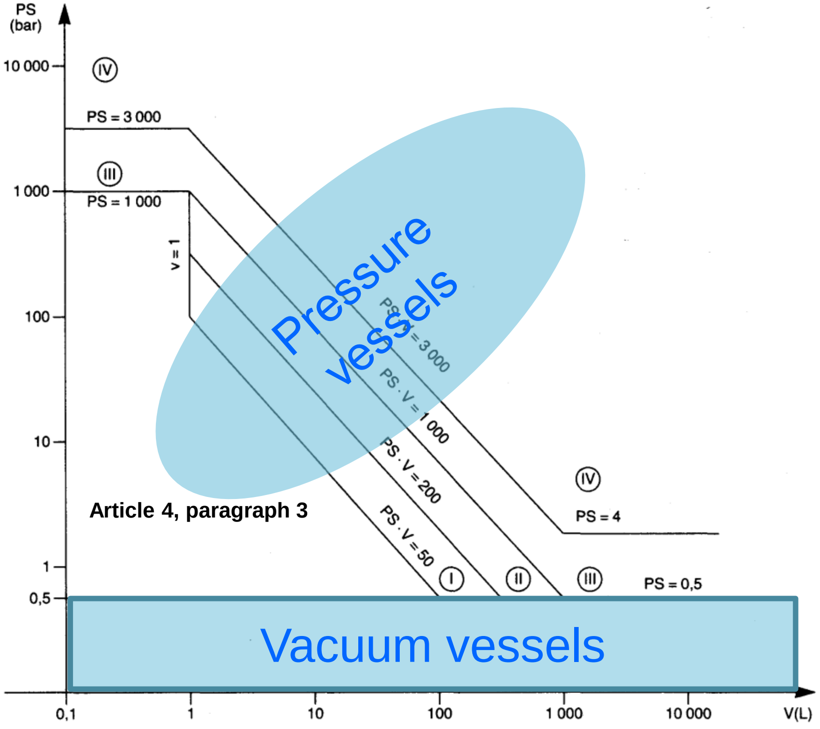
(https://hse.cern/content/safety-rules)

- Electrical Safety Code C1 (EDMS 335725)
- GENERAL SAFETY INSTRUCTION GSI-M-4 – Cryogenic Equipment (EDMS 1327191)
  - “Cryogenic equipment liable to have major safety implications” because of “high-level hazard for people, the environment or other installations in the event of failure”
  - Safety Guideline SG-M-4-0-1
- Requested compliance with European Directives:
  - Pressure Equipment Directive 2014/68/EU where relevant

→ Electrical safety is not covered, the scope of this presentation covers conceptual design of safety against overpressure only.

Pressure vessel codes regulations

- Pressure European Directive 2014/68/EC (PED) is a legal obligation in the EU since 2002 and CERN's Safety Unit (HSE) requests to comply with it:
  - Applies to internal pressure **≥ 0.5 bar gauge**
  - Vessels must be designed, fabricated and tested according to the requirements defined
  - Establishes the conformity assessment procedure depending on the vessel category, which depends on the stored energy, expressed as Pressure x Volume in bar.l
- → CE marking and notified body required from and above cat II

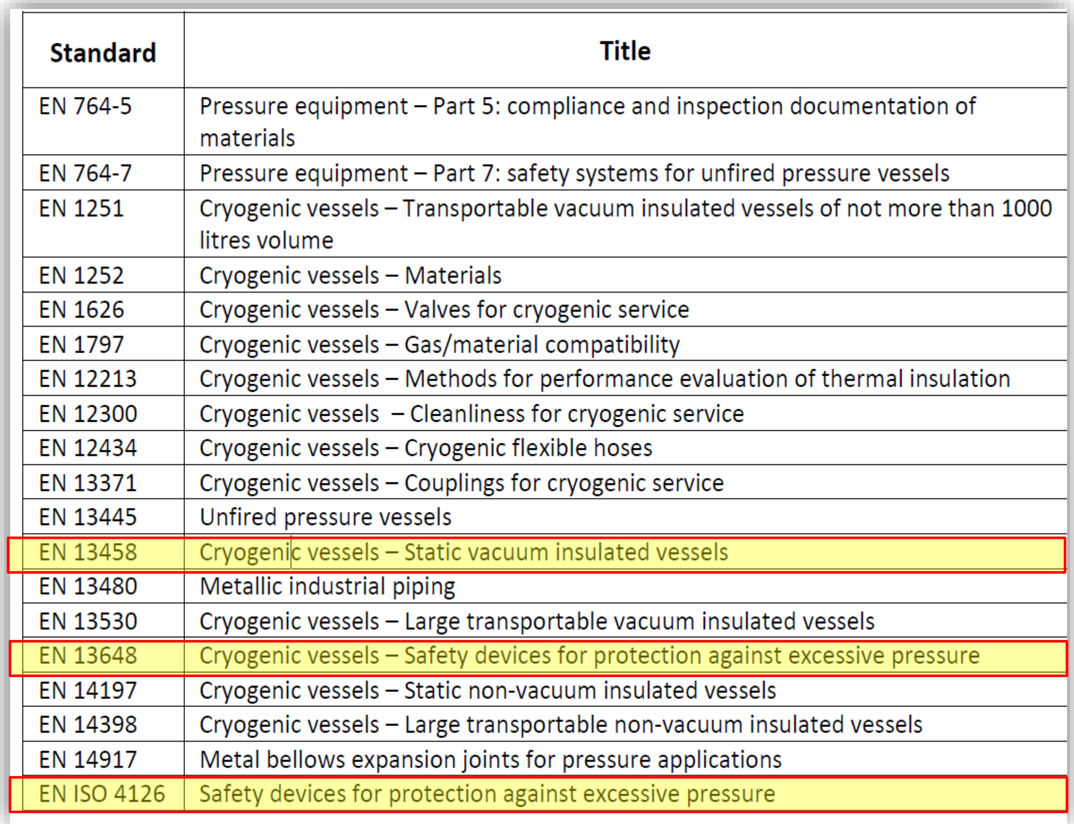


For vessels with non-dangerous gases, Group 2, (cryogenic liquids are treated as gas)

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, including safety devices:



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

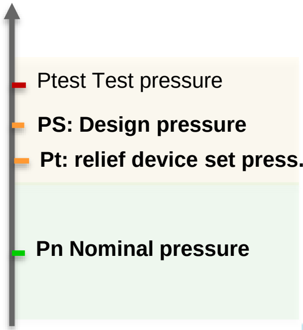
→ Now being replaced by ISO 21013-3

Very useful guidelines and design rules !

The overpressure safety design process

- Identify all circuit/enclosed volume(s) for the cryostat to be protected *(as a minimum vacuum and helium vessels)*

- Build the scale of pressures. As a minimum:
  - Nominal operating pressure (Pn), related to the operation of the device
  - Design Pressure (PS), related to mechanical limits or to operational scenarios (e.g. magnet quench)
  - Set pressure (Pt) of the relief device < PS
  - Test pressure (Ptest) depending on the norms



Ptest Test pressure

PS: Design pressure

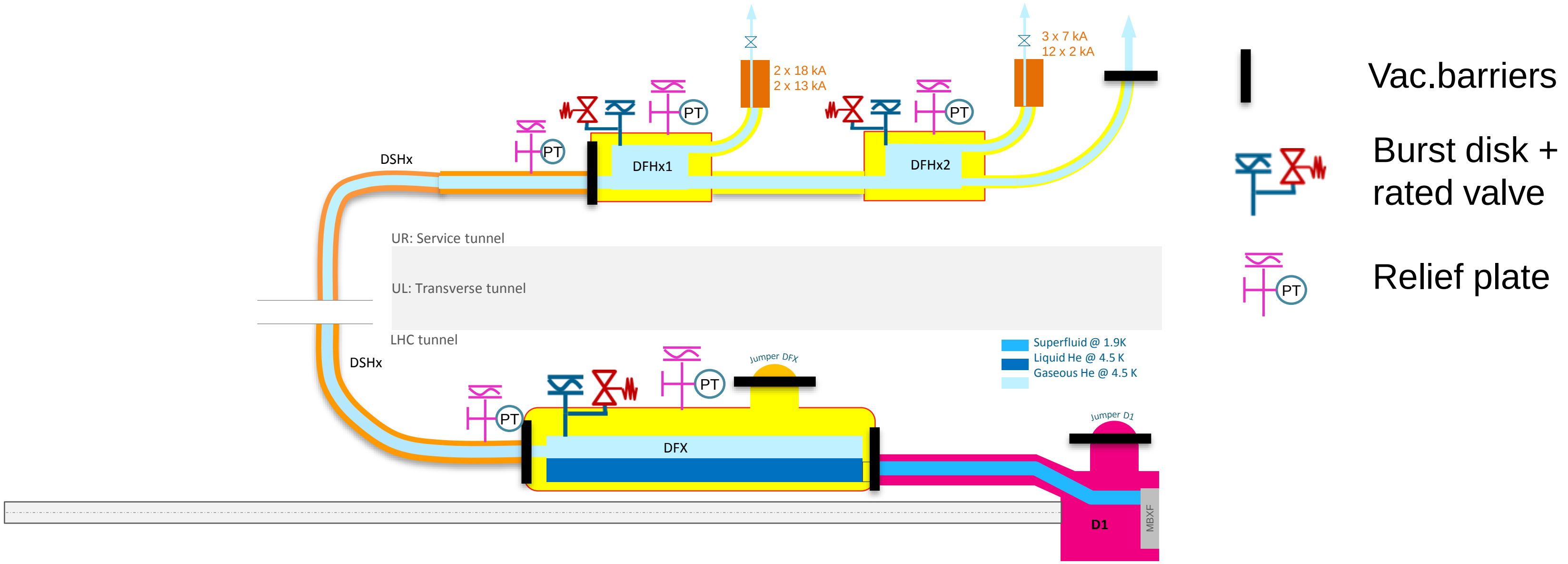
Pt: relief device set press.

Pn Nominal pressure

- Make risk hazard analysis & mitigation measure:
  - Risk matrix: risks, likelihood vs. severity
  - Identify mitigation measures (e.g. protections of exposed bellows)
  - Identify the credible worst-case scenario

- Design the safety relief system according to the worst-case
  - The safety relief system must be designed to keep pressure rise within the limits of the Design Pressure (PS)
  - Sizing of devices according to EN 13648 and ISO4126

Cold powering system

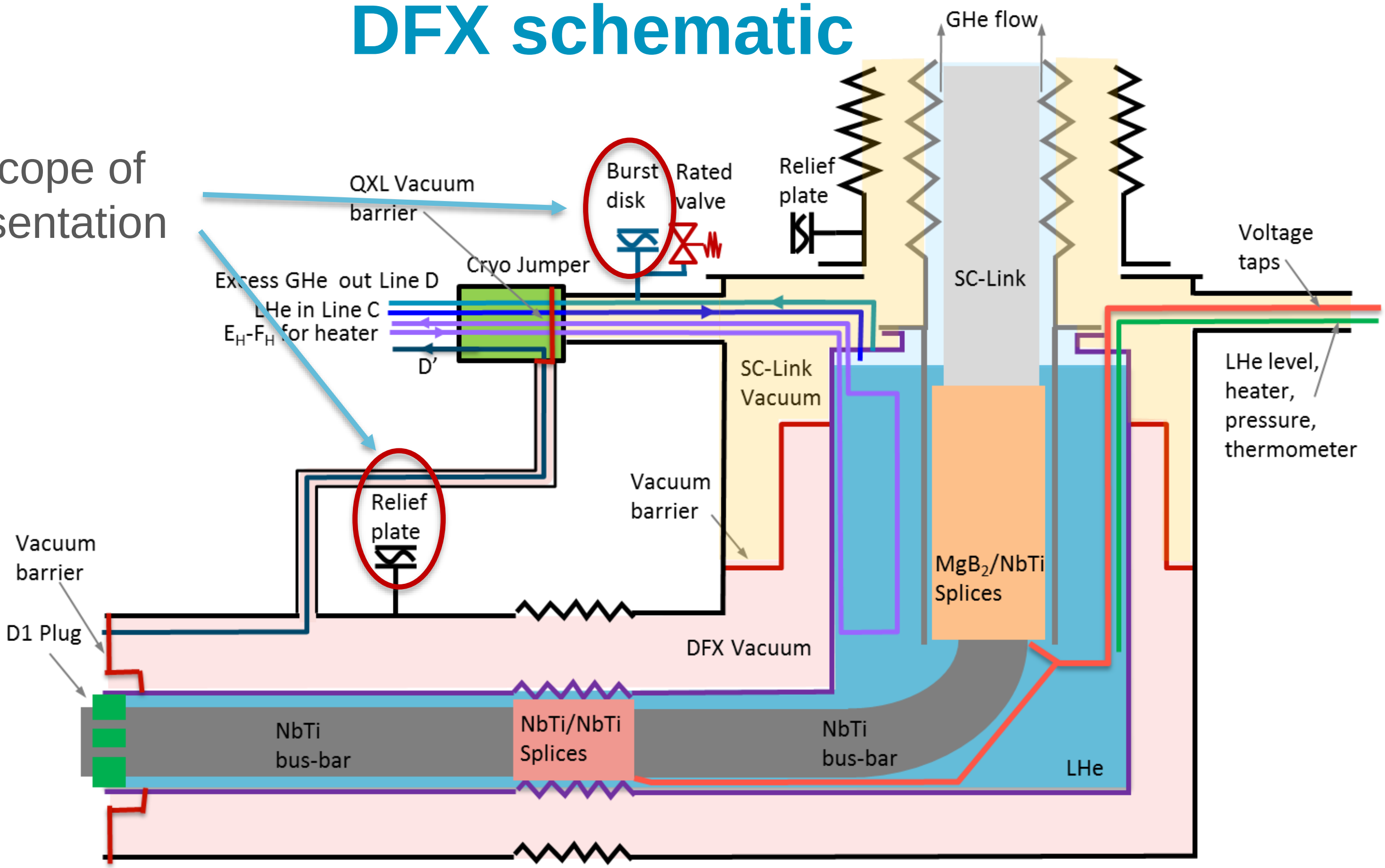


Item	Helium volume [l]	Insulation vac. volume [l]
DFX	800	1300
DSHX	600	1360
DFHX1+DFH2	~250	~3000

- DF mounted burst disks protect helium circuits of DSH too
- Relief plates protect insulation vacuum

DFX schematic

Within scope of this presentation



Data from SOTON

Volumes and surface areas		Units
DFX Horizontal Section, liquid	568	Litres
DFX Vertical Section, liquid	212	Litres
DFX Total Liquid Volume	**780**	Litres
DFX Vapour Helium Volume (at nominal conditions)	21	Litres
DFX Vacuum Volume (between Plug and DFX vacuum barriers)	1292	Litres
DFX Vacuum Volume (SC link side to vacuum barrier)	70	Litres
DFX Cold Surface Area (Plug side to vacuum barrier)	7.6	m^2
DFX Cold Surface Area (SC Link side to vacuum barrier)	1.2	m^2

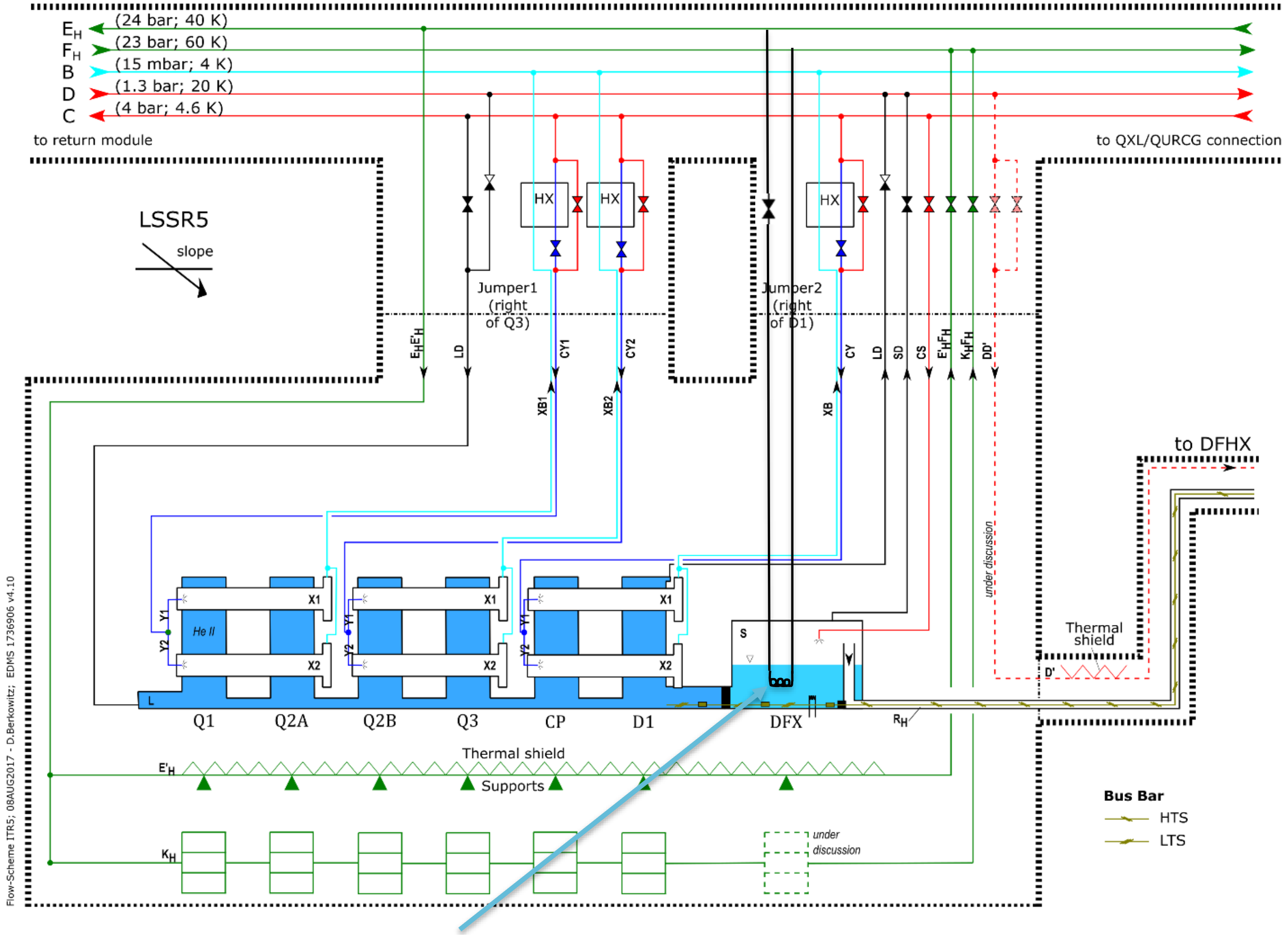
First considerations

Quantity	Value	Units	Comment
UR gallery volume	6000	m3	
DFH He volume	250	l	
DFH vac.volume	3000	l	
DSH He volume	600	l	
DSH vac.volume	1360	l	
DFX He volume	800	l	
DFX vac.volume	1300	l	
Total He volume	**1650**	**l**	
Total vac. volume	**5660**	**l**	
He vapour density (T=4.5 K, p=1.3 bar)	22	kg/m3	Saturated vapour density
He liquid density (T=4.5 K, p=1.3 bar)	118	kg/m3	Saturated liquid density
He vapour mass	**18.70**	**kg**	
He liquid mass	**94.40**	**kg**	
He volume at RT	553.64	m3	
O2 with perfect mix	**19.06**	**%**	**<19.5% ODH limit (assuming complete venting at RT of He inventory to UR gallery)**

- In case of complete venting of helium inventory to the UR gallery (very conservative assumption) could cause ODH ($O_2 < 19.5\%$ for perfect mix, locally could be <18%, CERN ODH limit)
- Reducing helium inventory is an important mitigation measure
- Design of the DFX safety devices has to limit the overpressure within the design pressure but also limit mass-flow along the DSH/DFH to the UR tunnel (dynamic modelling needed) → cold powering to be considered as a system

Cryogenic scheme

(EDMS1736906)



Note: Cryogenic boiler circuit not yet included (recently added)

Helium envelopes
(DFX specification, EDMS1905633)

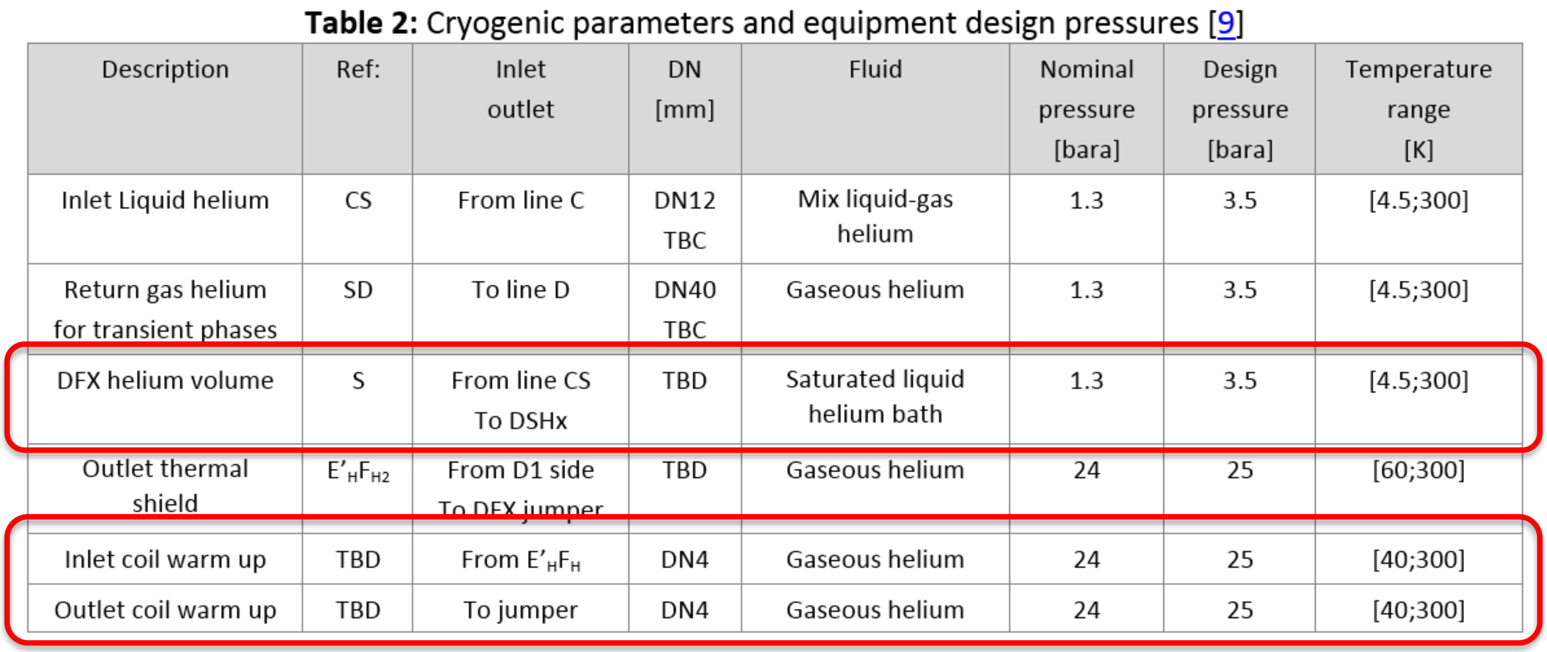
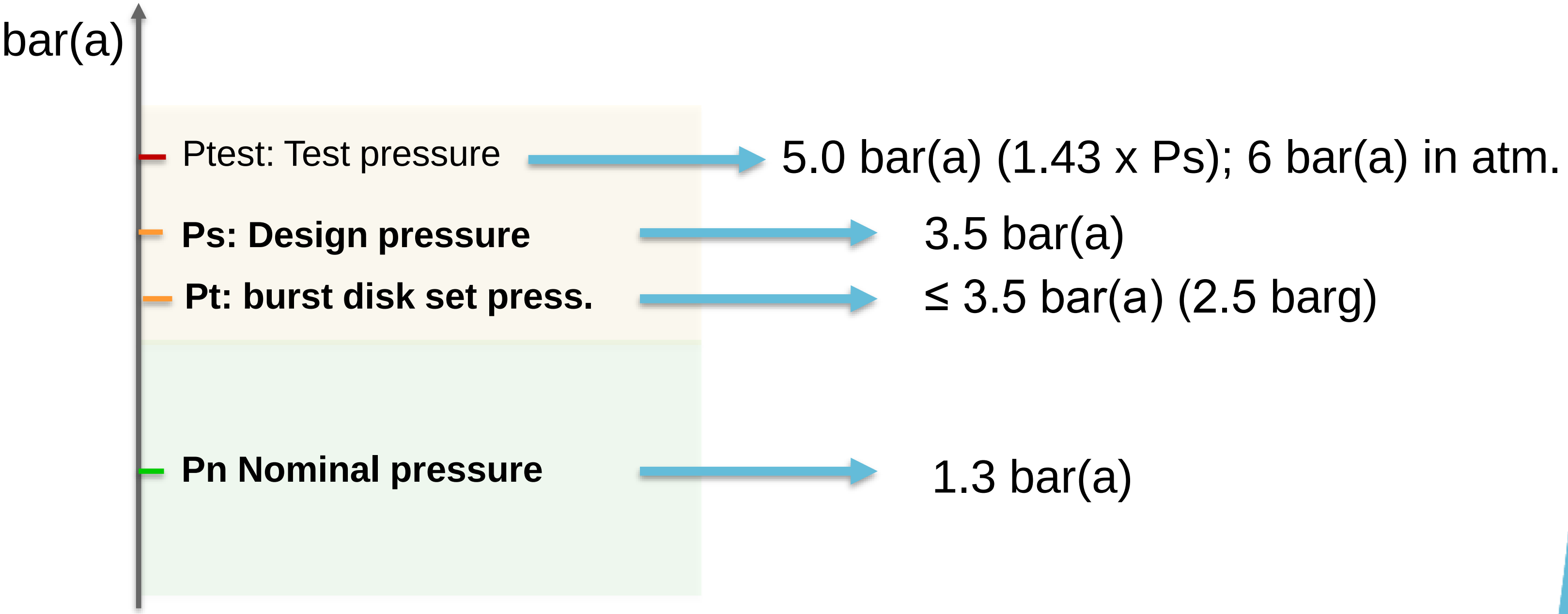


Table 2: Cryogenic parameters and equipment design pressures [9]

Description	Ref:	Inlet outlet	DN [mm]	Fluid	Nominal pressure [bara]	Design pressure [bara]	Temperature range [K]
Inlet Liquid helium	CS	From line C	DN12 TBC	Mix liquid-gas helium	1.3	3.5	[4.5;300]
Return gas helium for transient phases	SD	To line D	DN40 TBC	Gaseous helium	1.3	3.5	[4.5;300]
DFX helium volume	S	From line CS To DSHx	TBD	Saturated liquid helium bath	1.3	3.5	[4.5;300]
Outlet thermal shield	E'_HF_{H2}	From D1 side To DFX jumper	TBD	Gaseous helium	24	25	[60;300]
Inlet coil warm up	TBD	From E'_HF_H	DN4	Gaseous helium	24	25	[40;300]
Outlet coil warm up	TBD	To jumper	DN4	Gaseous helium	24	25	[40;300]

Scale of pressures, helium vessel



bar(a)

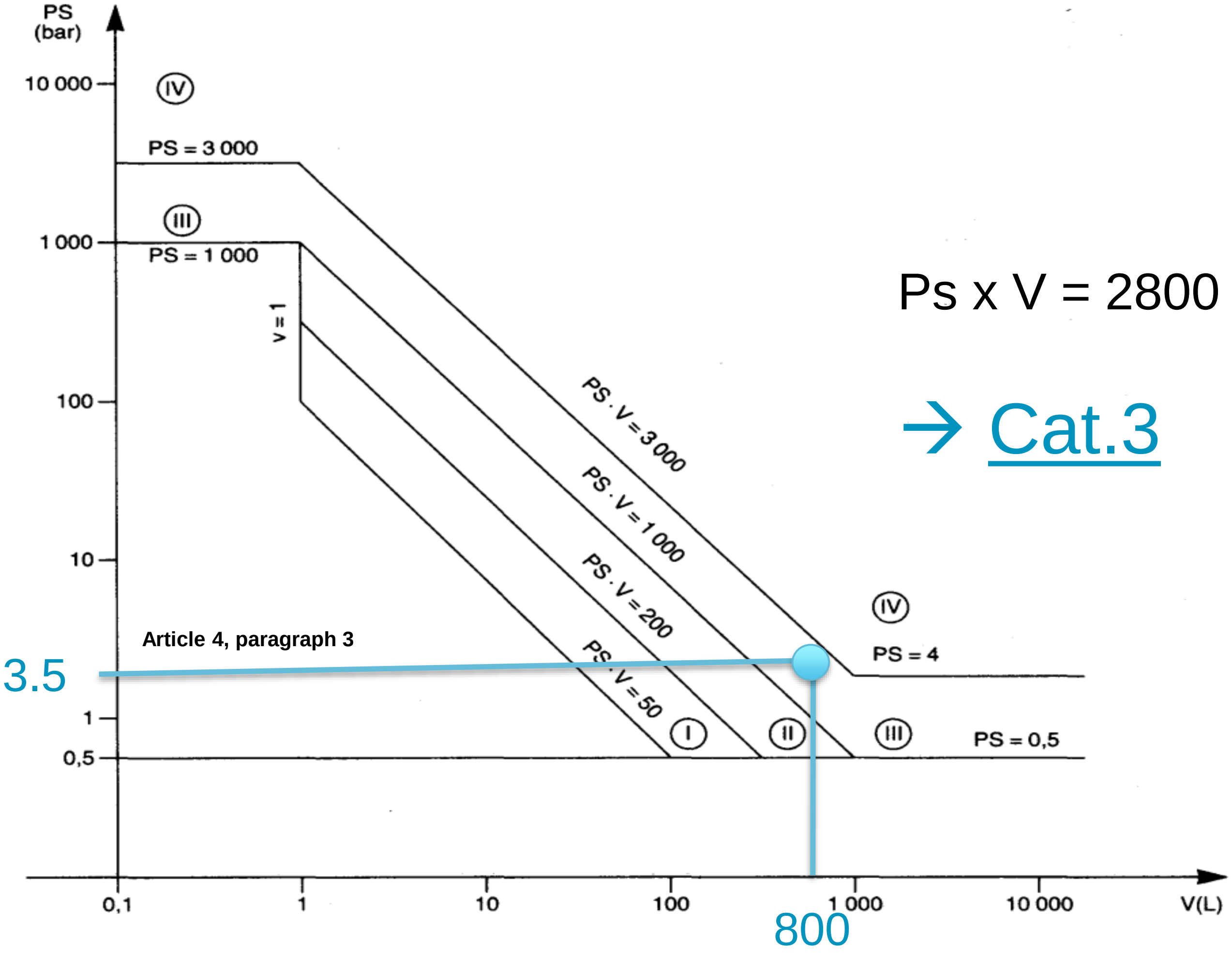
Ptest: Test pressure → 5.0 bar(a) (1.43 x Ps); 6 bar(a) in atm.

Ps: Design pressure → 3.5 bar(a)

Pt: burst disk set press. → ≤ 3.5 bar(a) (2.5 barg)

Pn Nominal pressure → 1.3 bar(a)

PED category



Ps x V = 2800 bar.L

→ Cat.3

Risk assessment matrix

RISK MATRIX, Overpressure hazard for the DFX

	Source of overpressure	Possible cause	Consequence	LIKELIHOOD	IMPACT	Mitigation measures
A	Loss of insulation vacuum to air	External bellows failure, relief plate accidental removal	sudden air inrush and cryocondensation on cold surfaces	Possible	Major	Adequate design, manfacture & QC of bellows; protection of bellows against accidental damage; limited mechanical work in cyogenic operation.
B	Helium spill to insulation vacuum	internal bellows failure	helium spill through orifice (size?) to vacuum vessel.	Possible	Major	Adequate design, manfacture & QC of bellows; consider protection sleeves to limit spill mass flow;
C	Helium spill to insulation vacuum	dielectric failure, development of excessive resistance in splice	arc bursting helium envelope, helium pressurized at burst disk pressure, spill helium inventory to vacuum vessel.	Rare	Catastrophic	Adequate electrical insulation design, installation, and QC; online Vtap measurements acrooss all splices to monitor degradation;
D	Pressure build-up from triplets at quench	Lambda plug failure	sudden mass flow through damaged plug to DFX, providing pressure rise	Possible	Moderate	Adequate design, manfacture and QC testing of plugs;
E	Expansion of cryopumped air leaks	elastomeric ring leaks	Pressure increase at warm-up	Possible	Moderate	Leak checks of all sealed elements;
F	Pressure surge	fluid velocity change caused by e.g. starting/stopping pumps, opening/closing valves	pressure increase with limited mass flow change	Frequent	Moderate	Add rated valve to open at lower pressure than burst disk set pressure
G	Pressure build-up from EH-FH boiler line	failure of a junction (st.steel/Cu)	Pressure increase due to HP helium venting to helium reservoir	Rare	Moderate	Adequate design, manfacture and QC testing of boilers;
H	...					

🟥 **High Risk**

🟧 **Medium Risk**

🟩 **Low Risk:**

Remarks:

- causes of excessive pressure are considered to be unrelated (single jeopardy theory) unless cause/effect exists

Preliminary retained pressure hazards

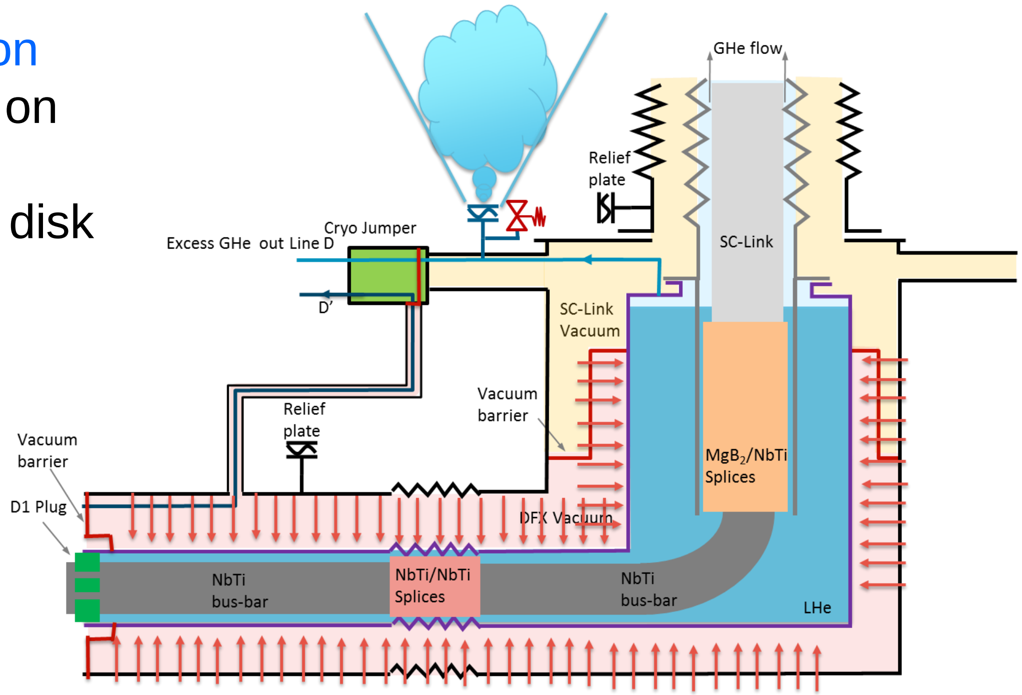
- A) Accidental air venting of insulation vacuum with sudden condensation on cold surfaces, helium boil-off and pressure build-up → sizing of burst disk

- C) Accidental release of cryogenic fluid from helium vessel to insulation vessel due to arc bursting helium envelope, helium pressurized at burst disk pressure, spill of helium inventory to vacuum vessel → sizing of vacuum vessel relief plate

- D) Accidental release of pressurized cryogenic fluid from triplets through damaged lambda plug(s) → check sizing of burst disk

Hazard A

A) Accidental air venting of insulation vacuum with sudden condensation on cold surfaces, helium boil-off and pressure build-up → sizing of burst disk



Preliminary sizing:

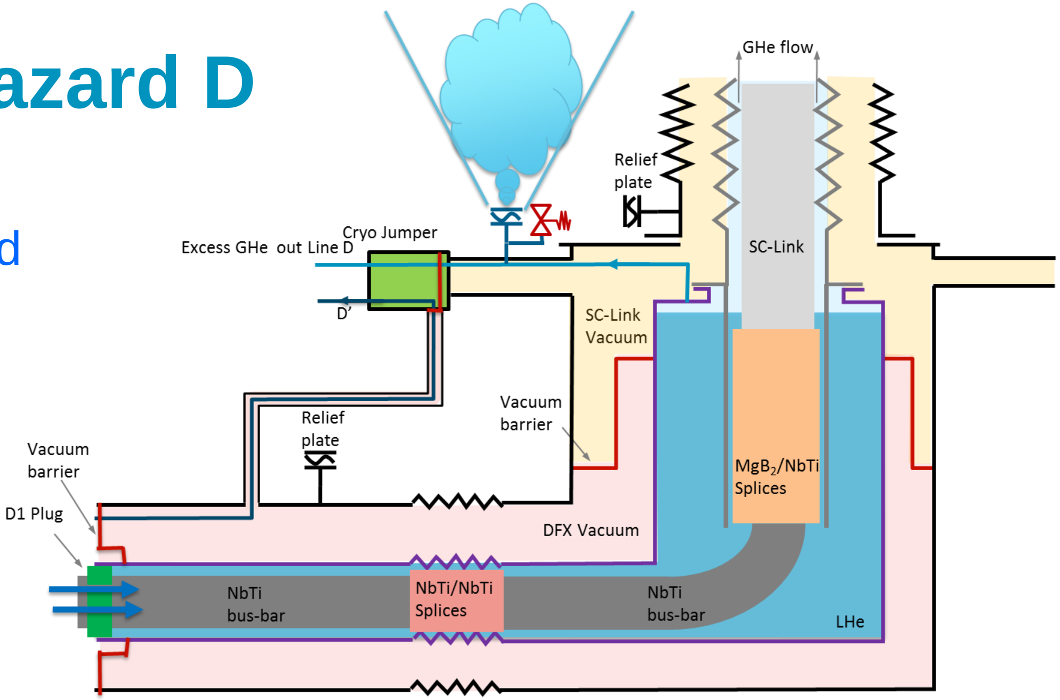
- Heat power density (10 effective MLI layers): 6.2 kW/m2
- Heat flux: 54 kW
- Bust disk rupture pressure Pt: 3.5 bara (2.5 barg)
- Safety device sizing (EN13648-3; EN4126-6 Annex C): supercritical He at ~6.2 K:
  - → Qm = 2.8 kg/s
  - → DN > 35 mm → DN50

Example of DN50-mm bust disk

Thanks to Y.Leclercq for his calculation spreadsheet!

Hazard D

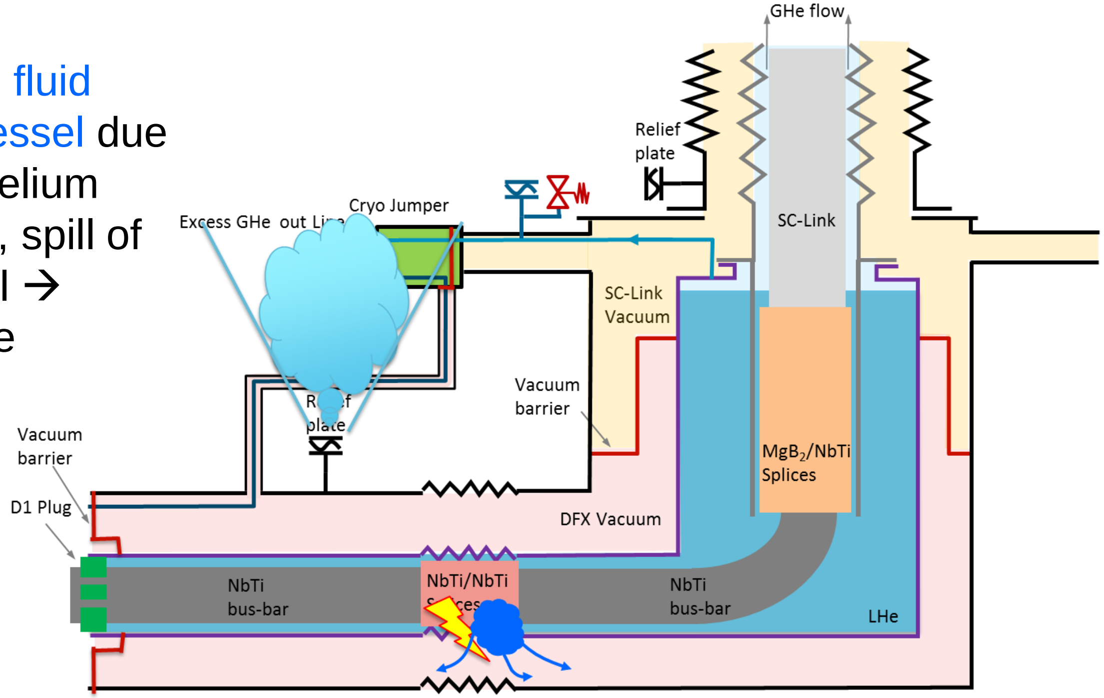
D) Accidental release of pressurized cryogenic fluid from triplets through damaged lambda plug(s) → check sizing of burst disk



- Assume: 2 x 18 kA plugs fail: DN46 equivalent orifice
- P_{quench} = 16 bara; Pt = 3.5 bara
- supercritical He at ~6.2 K:
  → Qm = 1.9 kg/s < 2.8 kg/s (previous case)

Hazard C

C) Accidental release of cryogenic fluid from helium vessel to insulation vessel due to arc bursting helium envelope, helium pressurized at burst disk pressure, spill of helium inventory to vacuum vessel → sizing of vacuum vessel relief plate

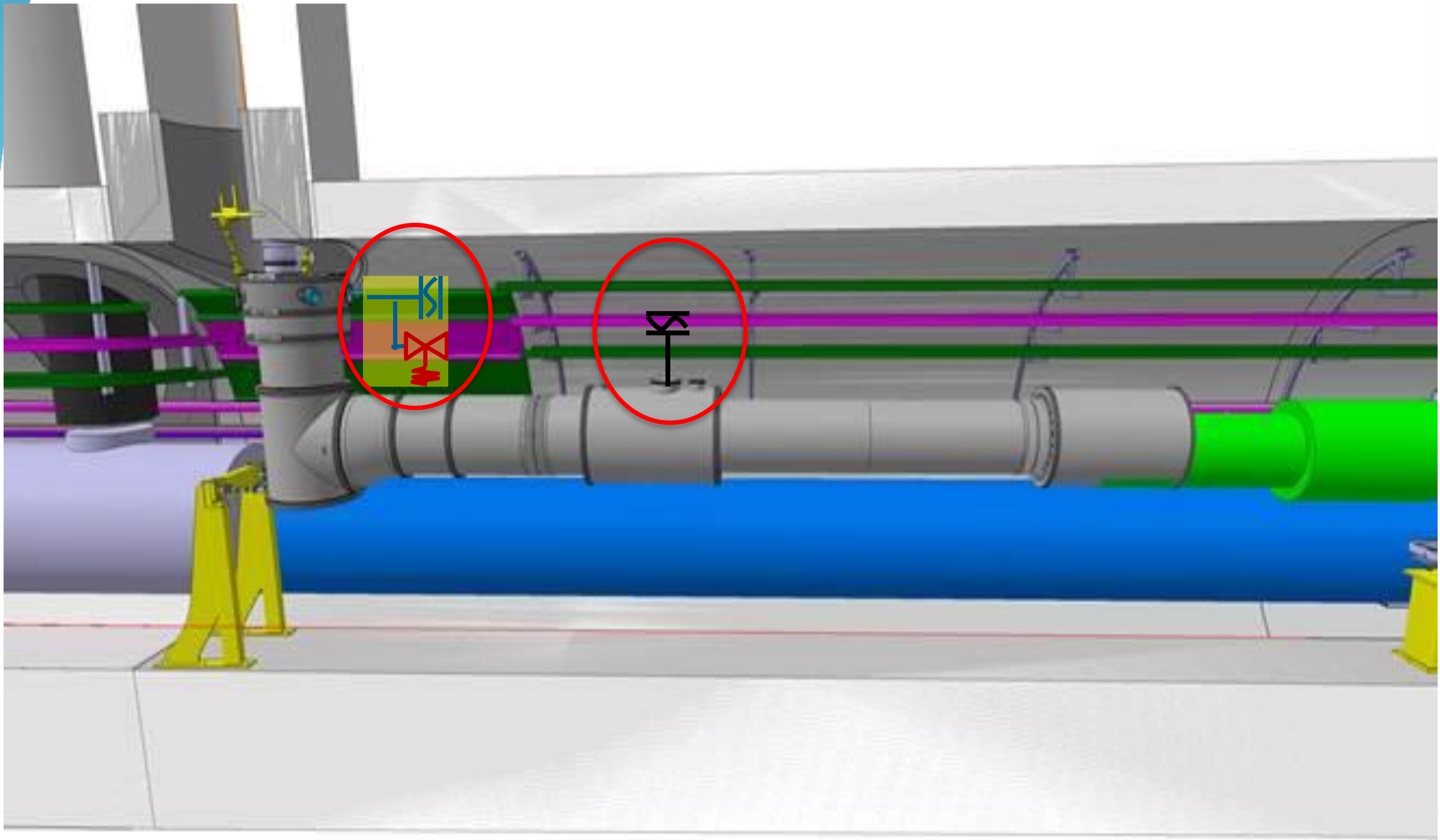


Preliminary sizing:

- Assume orifice: DN50
- Pt=3.5 bara; Pb=0 bara; T_{rel}= ~5 K
  → Qm_{vessel} = 11.2 kg/s to the vac.vessel
- Relief plate to limit ΔP to 0.5 barg (opens at 1.5 bara)
- Assuming continuity of mass relief (conservative): $Qm_{vessel} = Qm_{relief}$
  → ~DN100

Example of DN200-mm relief plates,
(also exists in DN90,100, 160, 230)

Possible locations of safety device



Summary

- Scope of this presentation was limited to pressure equipment, overpressure and cryogenic safety for the DFX

- Electrical safety not covered, will be covered at a later stage when the design of the DFX will be more mature (e.g. bus-bars isolation, splices, electrical instrumentation,etc.)

- DFX is a pressure equipement under PED, falling under cat.3, it should be CE marked, pressure tested, and it should be designed and manufacturing according to the adequate conformity assessment module

- A preliminary risk matrix for overpressure hazards has been presented and estimated worst case scenarios identified

- First preliminary sizing of overpressure protection devices for the DFX helium vessel and vacuum vessel provides an indication of acceptable dimensions and possible locations for the safety devices

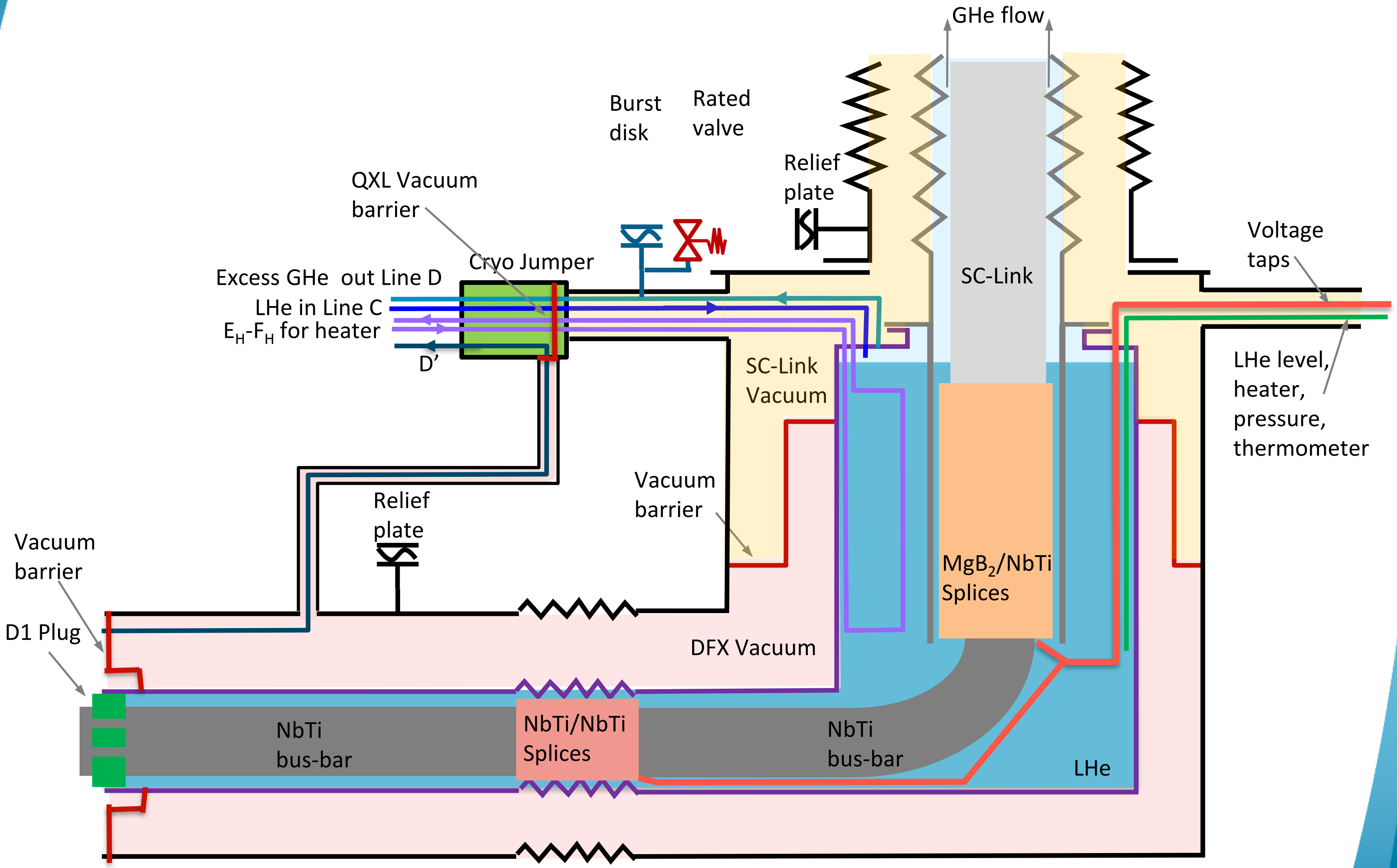
- Further development of the overpressure risk matrix needs to be done as the DFX design evolves, and especially including the effects of the connection to the DSH

- The identification of realistic failure scenarios (e.g. orifice size of arc-punctured helium envelopes) and mitigation measures by design will have to be included if conservative assumptions translate into unacceptable requirements (e.g. too large safety devices)

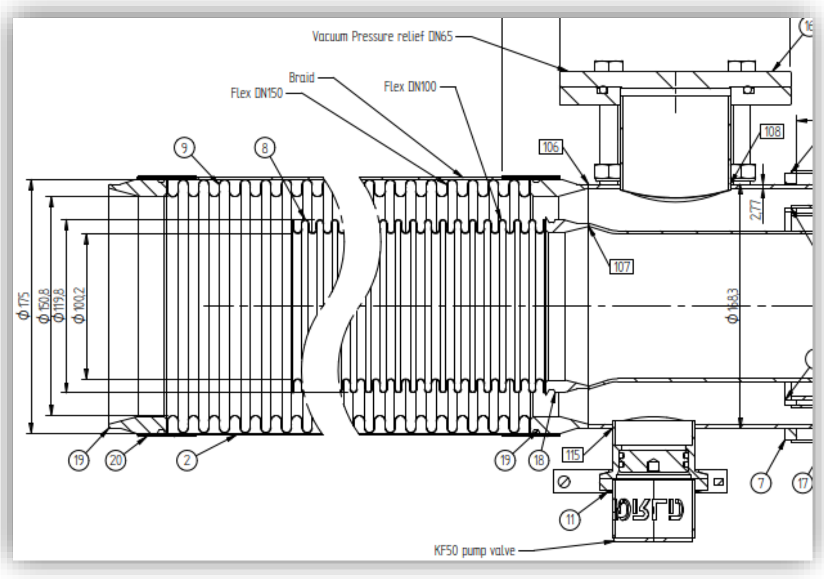
Thank you !

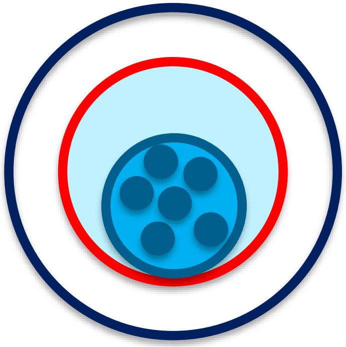
Q/A

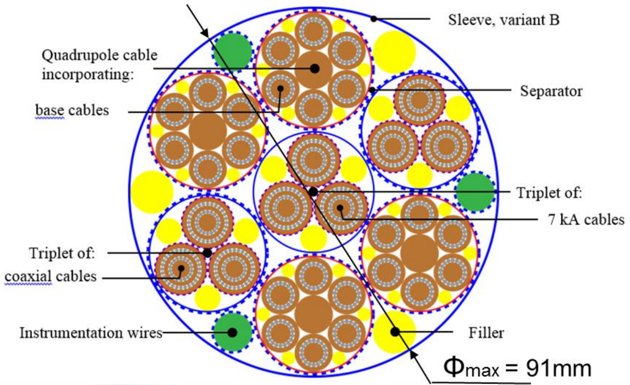
Spare slides

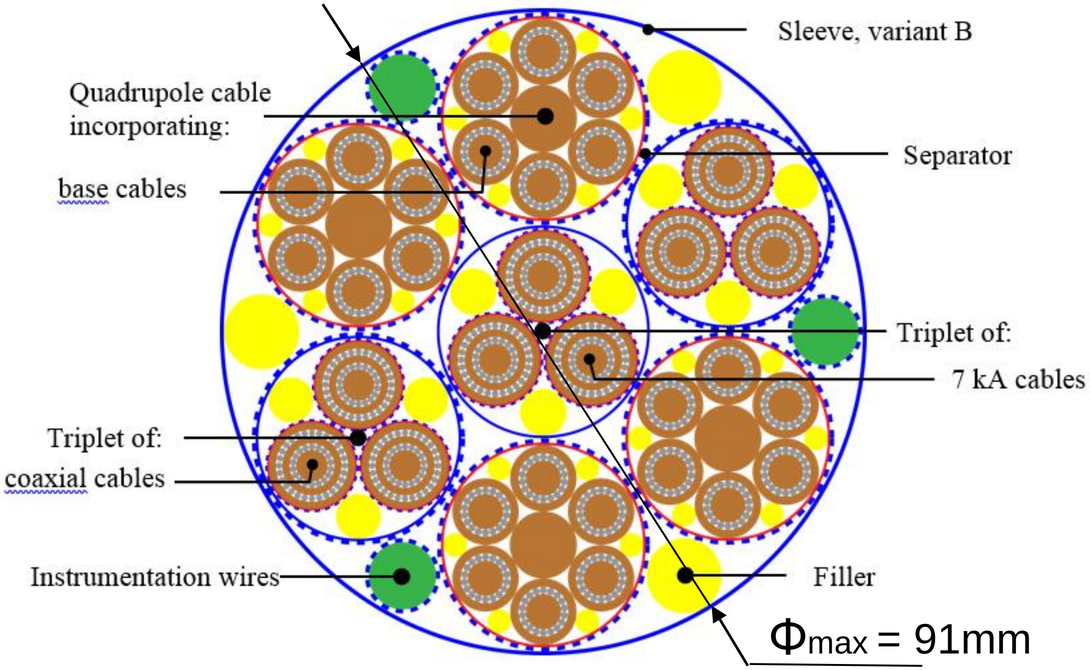

GHe flow
Burst disk
Rated valve
Relief plate
QXL Vacuum barrier
Cryo Jumper
Excess GHe out Line D
LHe in Line C
E_H-F_H for heater
D'
SC-Link
Voltage taps
SC-Link Vacuum
LHe level, heater, pressure, thermometer
Vacuum barrier
Relief plate
Vacuum barrier
D1 Plug
MgB_2/NbTi Splices
DFX Vacuum
NbTi bus-bar
NbTi/NbTi Splices
NbTi bus-bar
LHe

DSH cross section








Sleeve, variant B
Quadrupole cable incorporating:
base cables
Separator
Triplet of:
7 kA cables
Triplet of:
coaxial cables
Instrumentation wires
Filler
Φ_{max} = 91mm