Heat load review
Summary table / refrigeration requirement

V. Gahier on behalf of WP9

EDMS 2560557
https://indico.cern.ch/event/1023016/

CERN, 27/04/2021

Outline

1. Introduction : HL- LHC Cryogenic upgrade

2. HL-LHC Cryogenic architecture
   - P1/P5 Cryogenic architecture
   - Refrigerator Scope of supply
   - From Users needs to Refrigerator supply

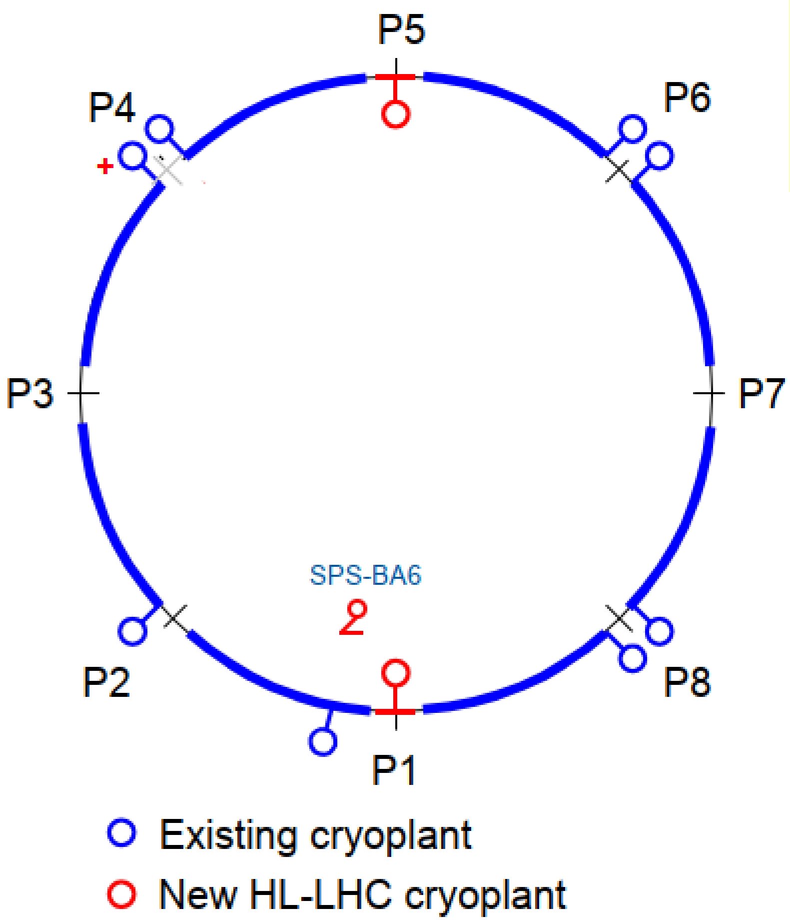
3. Distribution system
   - QXL (cryogenic distribution line) heat loads – Example of IP5
   - Service Module Heat loads

4. Cooling capacity at 60/80 K
   - Users requirements
   - Cooling capacity for User

5. Cooling capacity from Supercritical helium
   - Users requirements
   - Cooling capacity for User

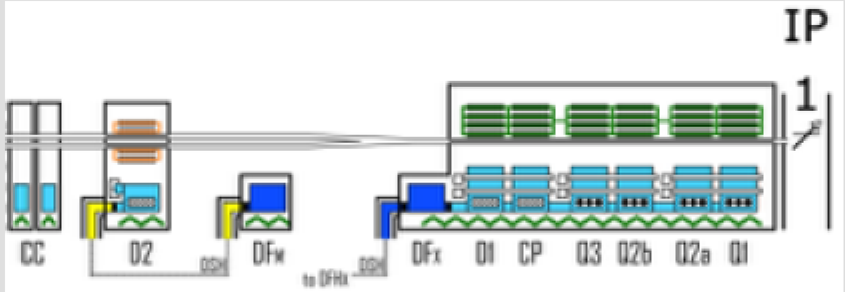
6. Refrigerator design capacity and conclusions

1. HL- LHC Cryogenic upgrade



- P1-P5: 2 new cryoplants (~15 kW @ 4.5 K incl. ~3 kW @ 1.8 K) and 2 x 750m cryo-distribution for high-luminosity insertions
- P4: upgrade (+2 kW @ 4.5 K) of an existing LHC 18 kW @ 4.5K cryoplant
- *SPS-BA6: SRF test facility with beam primarily for Crab-Cavities*

P1/P5: Provide adequate cooling for this



Other test facilities related activities not reported here

Outline

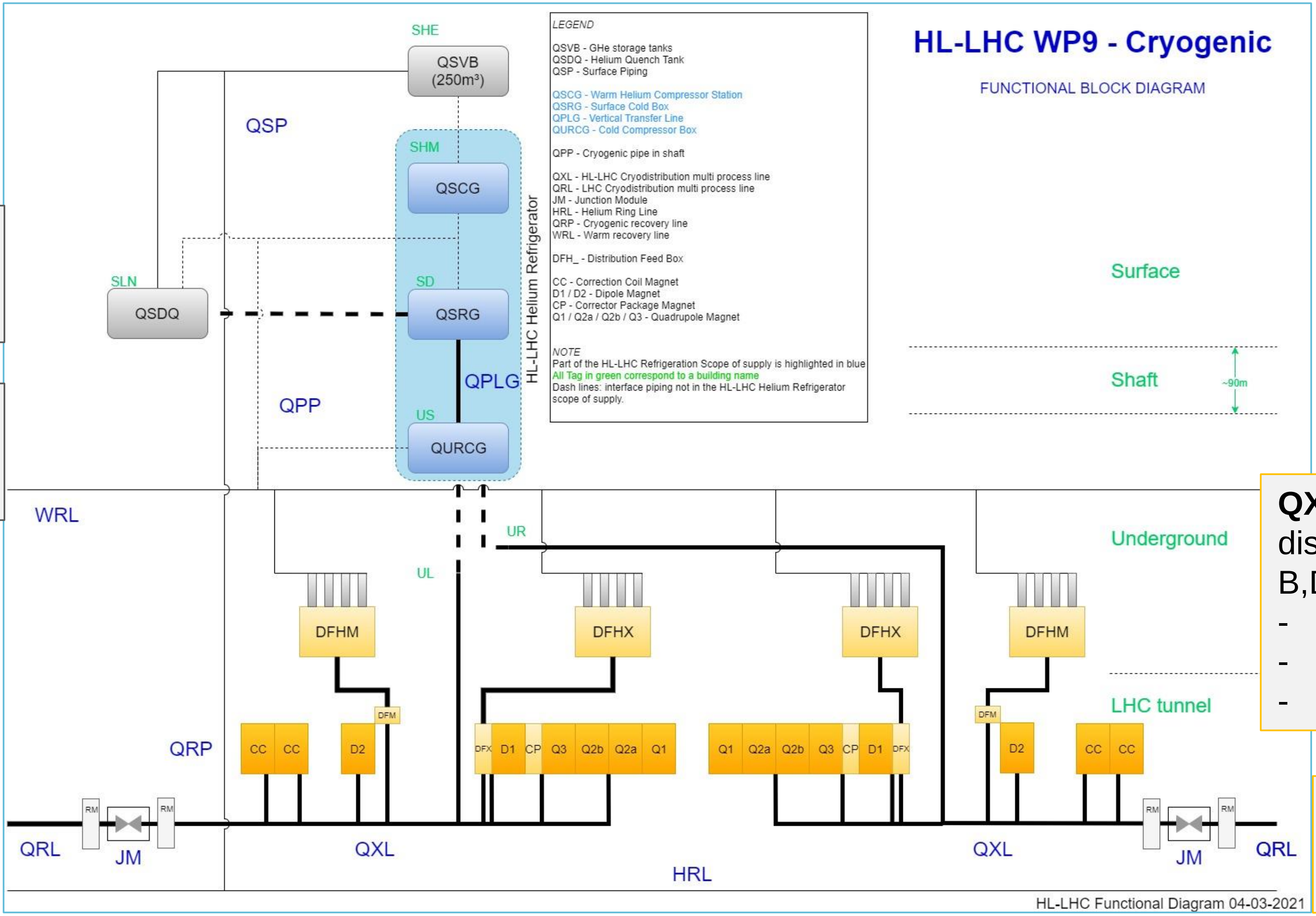
HiLumi HL-LHC PROJECT

2. P1/P5 Cryogenic architecture

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

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

Users at tunnel level



Block Flow Diagram from E. Monneret

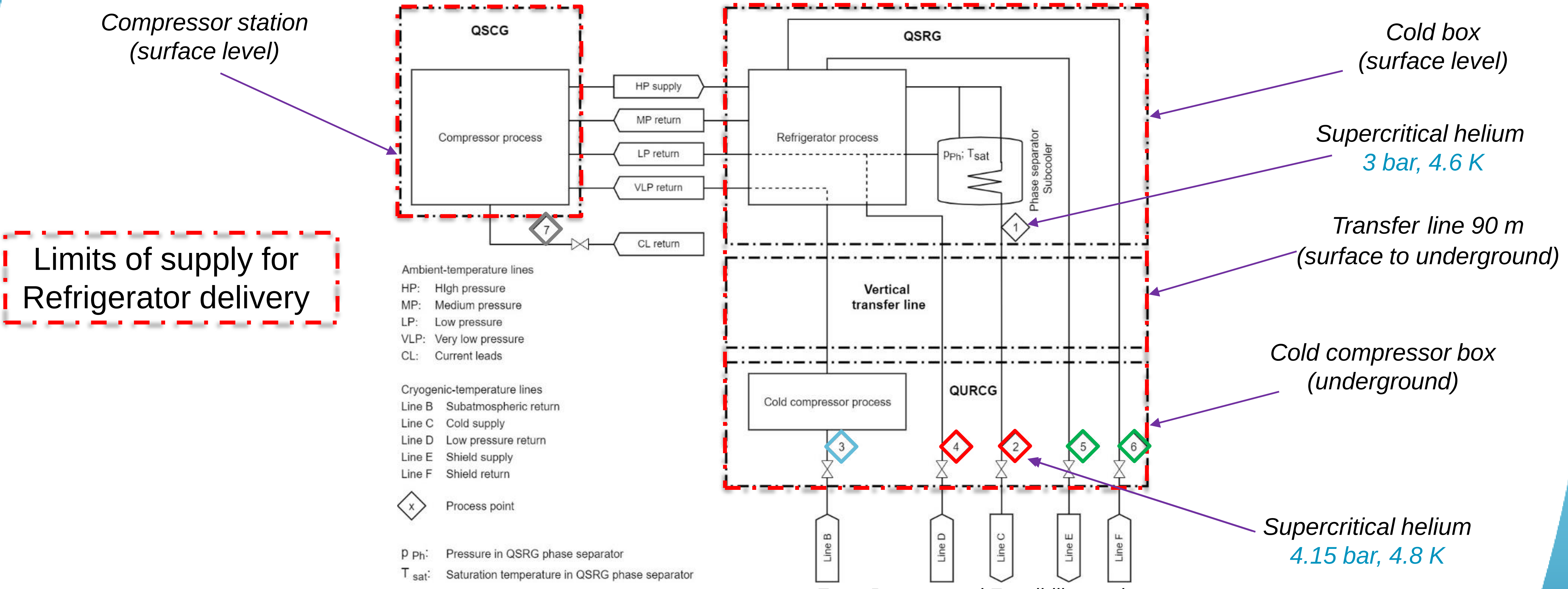
Refrigerator providing cooling capacity through distribution system for one point (ie P1 or P5) to the users located on the right and left of IP

QPLG : Vertical transfer line (~100 m height)

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 at extremities for transient handling.

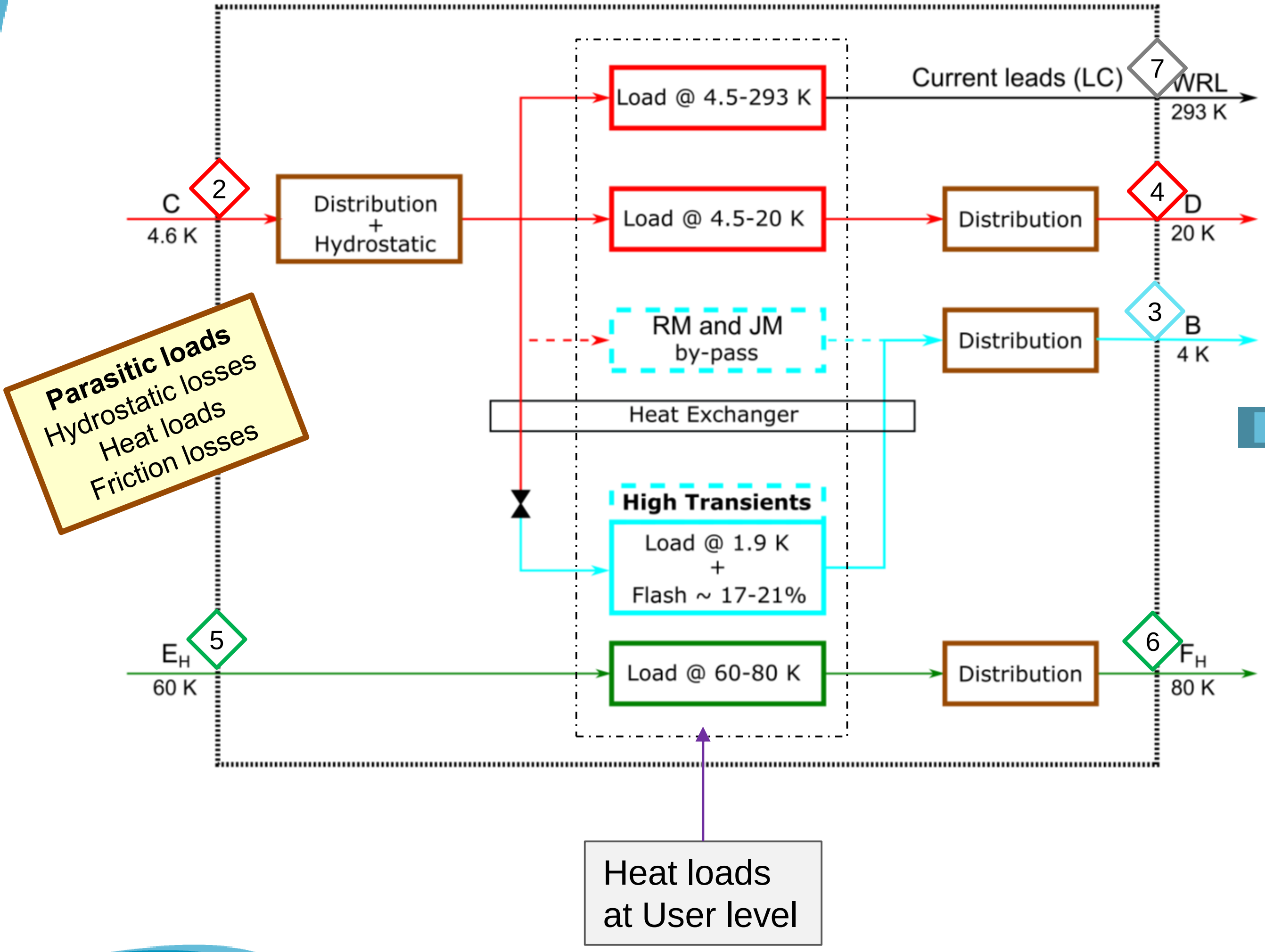
2. P1/P5 Cryogenic architecture : Refrigerator Scope of supply

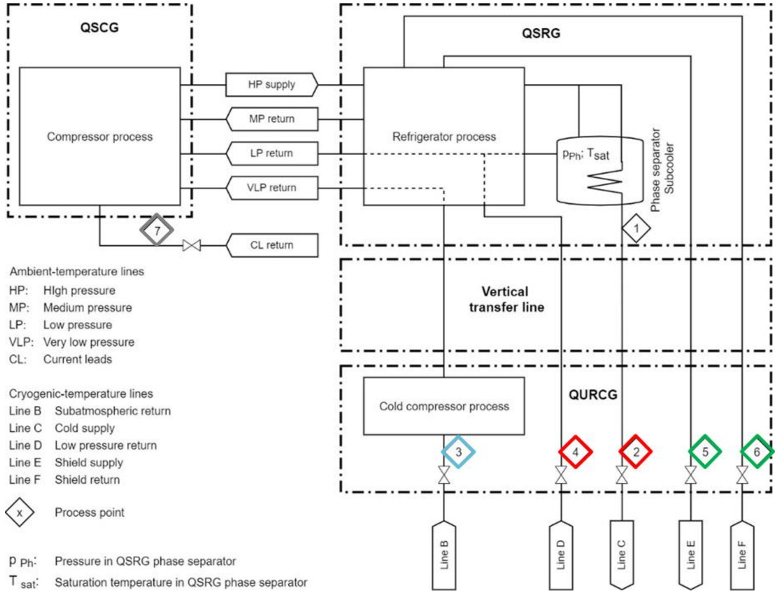


From Process and Feasibility study

In order to **define the Refrigerator**, the helium **mass flow rate, pressure and temperature** shall be known at the different process points in order to fulfill the heat loaf at user level. This shall take into account the distribution system (QXL and valving system)

2. P1/P5 Cryogenic architecture :
From Users needs to Refrigerator Supply (1/2)

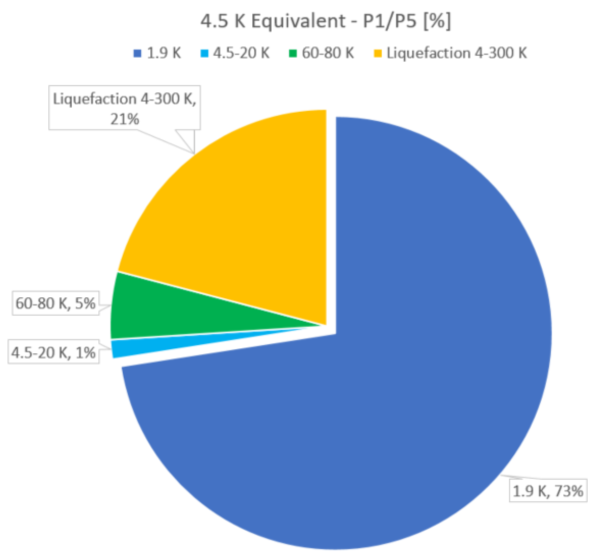




- Heat loads at user level are defined from previous talks.
- Parasitic loads from distribution (QXL and service module) shall be taken into account for proper evaluation of Refrigerator supply

2. P1/P5 Cryogenic architecture : From Users needs to Refrigerator Supply (2/2)

- The sum of installed local capacity (at users level) is higher than the refrigeration global capacity (at the refrigerator level).
- For magnets (IT+D1 and D2), the maximum of {Nominal considering overcapacity or Ultimate} has been considered for the Refrigerator design.
- For Cold Powering or Crab Cavities, **reduced performance** of some components have been considered with the overcapacity factor **at 1.5 on the Nominal case** to cover in particular :
  - Degraded SC link cryostat performance
  - Degraded crab cavity quality
- For **60/80K level and 4.5-20 K**, the sum of installed local capacities can be considered since they account for less than 10% of the refrigerator capacity.

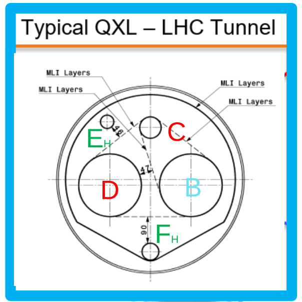


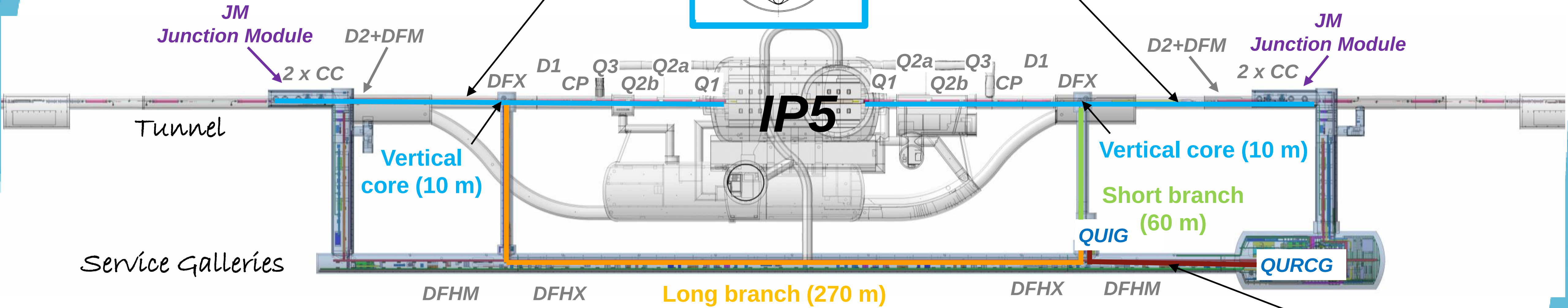
Outline

1. Introduction : HL- LHC Cryogenic upgrade
2. HL-LHC Cryogenic architecture
   - P1/P5 Cryogenic architecture
   - Refrigerator Scope of supply
   - From Users needs to Refrigerator supply
3. Distribution system
   - QXL (cryogenic distribution line) heat loads – Example of IP5
   - Service Module Heat loads
4. Cooling capacity at 60/80 K
   - Users requirements
   - Cooling capacity for User
5. Cooling capacity from Supercritical helium
   - Users requirements
   - Cooling capacity for User
6. Refrigerator design capacity and conclusions

3. Distribution system
QXL (cryogenic distribution line) heat loads – Example of IP5

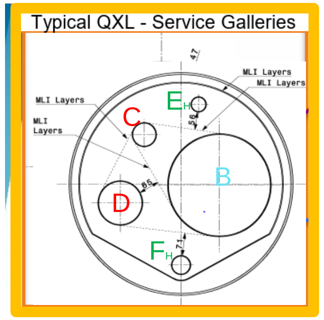
Total QXL Length : 750 m





QXL	Raw Heat losses
Line B	0.2 W /m
Line C	0.1 W /m
Line D	0.1 W /m
Line E	0.05 W/m
Line F	3 W/m

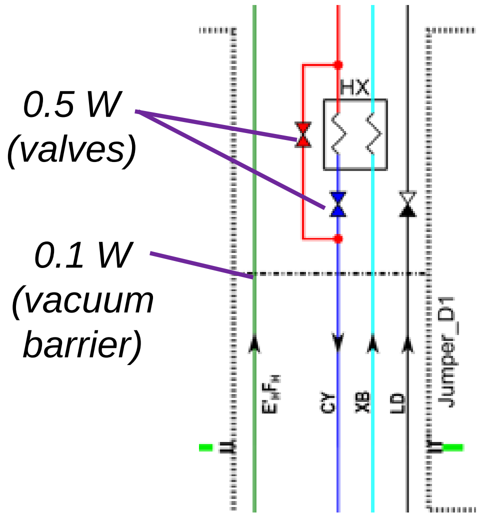
- → Heat loads for HL-LHC (QXL) extrapolated from LHC (QRL) measured at 0.2 W/m for B/C/D considering reduced engineering effort.
- → Uncertainty factor of 1.5 will be considered on those values.



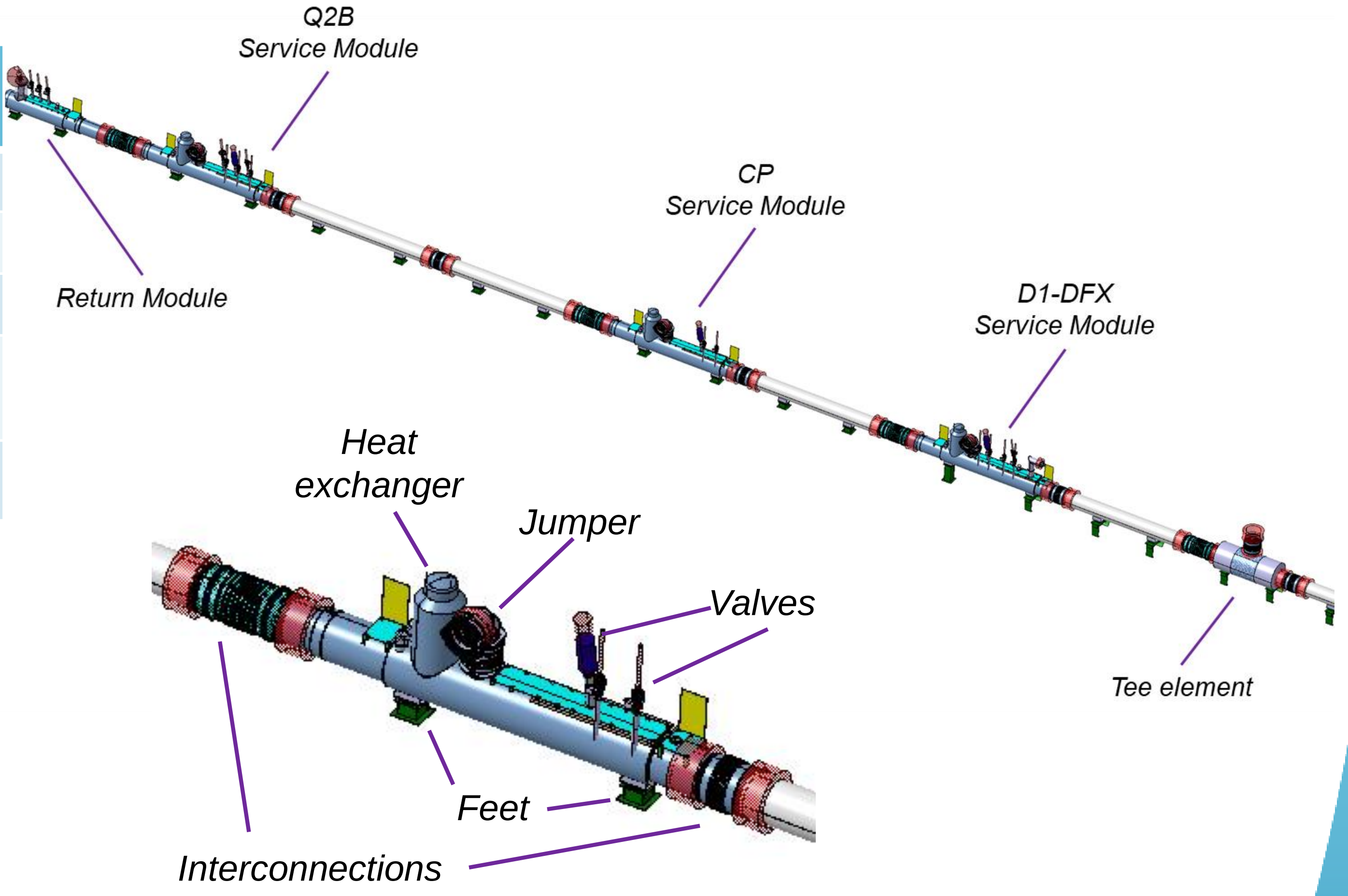
HiLumi HL-LHC PROJECT

3. Distribution system
Service Module Heat loads at 1.9 K

Generic service module	Raw Heat loads line C→ User
Control valves	1 W
Vacuum barrier	0.1 W
Instrumentation	0.5 W
Radiation / support (QXL not included, jumper included)	0.3 W/m
TOTAL	**3 W / service module**



Extract of PFD for IT (service module + jumper for D1)



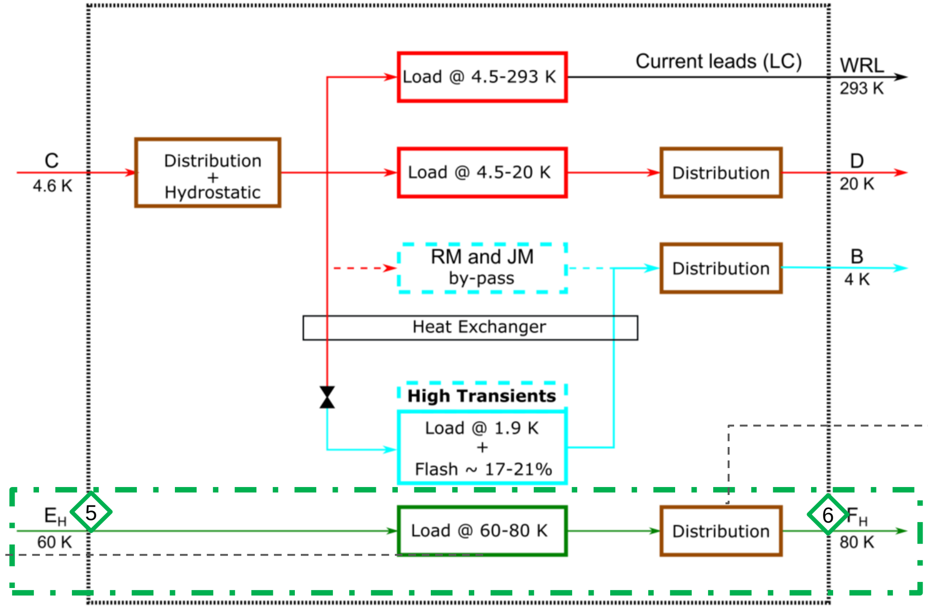
Service module is thermally shielded with an active cooled thermal shield
Measured heat load on LHC heat exchanger was negligible and hence not considered here.

All drawings are courtesy from Michele Sisti – Integration meeting October 2020

Outline

1. Introduction : HL- LHC Cryogenic upgrade
2. HL-LHC Cryogenic architecture
   - P1/P5 Cryogenic architecture
   - Refrigerator Scope of supply
   - From Users needs to Refrigerator supply
3. Distribution system
   - QXL (cryogenic distribution line) heat loads – Example of IP5
   - Service Module Heat loads
4. Cooling capacity at 60/80 K
   - Users requirements
   - Cooling capacity for User
5. Cooling capacity from Supercritical helium
   - Users requirements
   - Cooling capacity for User
6. Refrigerator design capacity and conclusions

4. Cooling capacity at 60/80 K



Total Parasitic (Distribution)

Cooling rqt at 60-80 K	Total
Cooling capacity at Refrigerator design	3435 W

2290 W (raw) x 1.5 (F_{un}) = 3435 W

User Requirement for one LSS (from previous talks)

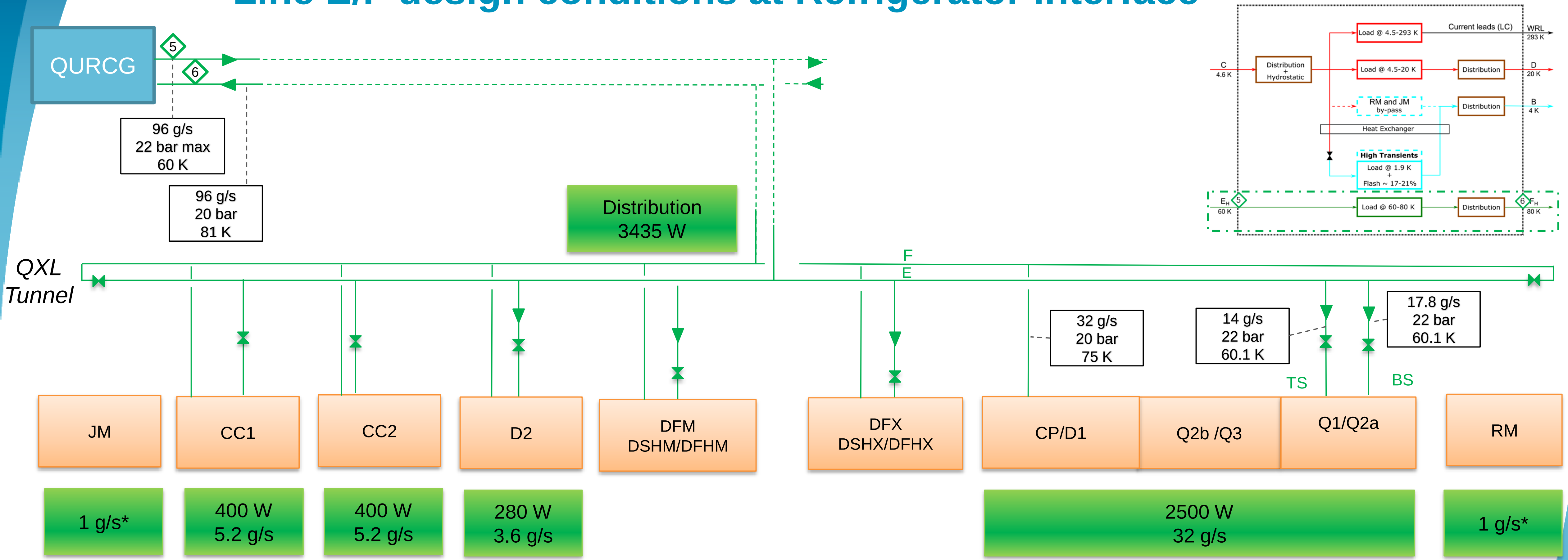
Cooling rqt at 60-80 K	CC 1	CC 2	D2	IT + D1	Total for one LSS
Cooling capacity for Refrigerator design	400 W	400 W	280 W	2500 W	3580 W

← From previous talks

** Installed local capacity considered when available*

HiLumi HL-LHC PROJECT

4. Cooling capacity at 60/80 K
Line E/F design conditions at Refrigerator Interface



15 K temperature difference considered on Beam Screen /Thermal Shield

Cooling capacity for Refrigerator design at 60-80 K : 10600 W

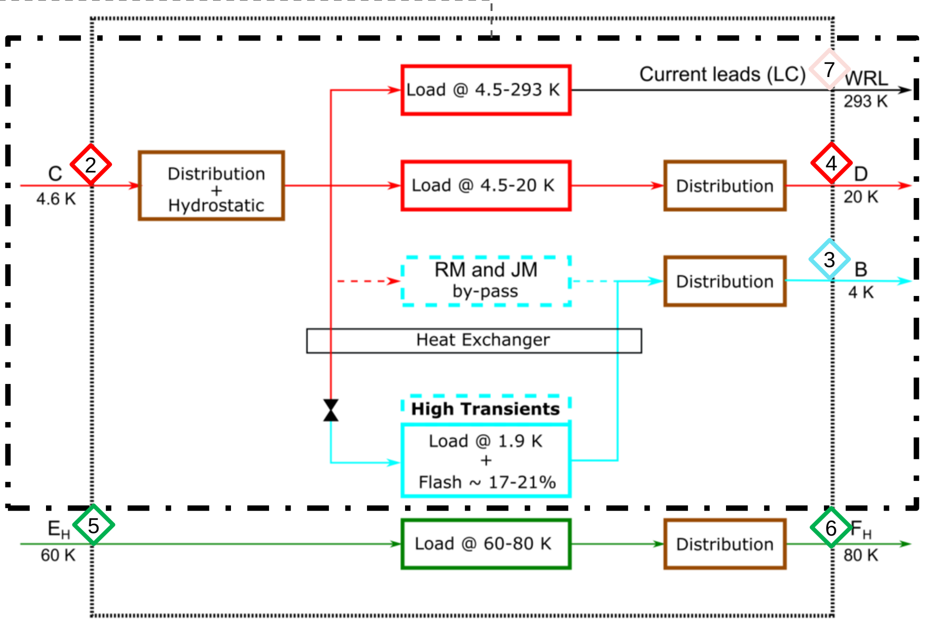
- 2 x 3580 W = 7060 W at user level (for two LSS)
- 2290 W x 1.5 = 3435 W for parasitic heat loads

HiLumi HL-LHC PROJECT

Outline

1. Introduction : HL- LHC Cryogenic upgrade
2. HL-LHC Cryogenic architecture
   - P1/P5 Cryogenic architecture
   - Refrigerator Scope of supply
   - From Users needs to Refrigerator supply
3. Distribution system
   - QXL (cryogenic distribution line) heat loads – Example of IP5
   - Service Module Heat loads
4. Cooling capacity at 60/80 K
   - Users requirements
   - Cooling capacity for User
5. Cooling capacity from Supercritical helium
   - Users requirements
   - Cooling capacity for User
6. Refrigerator design capacity and conclusions

5. Cooling capacity from supercritical helium



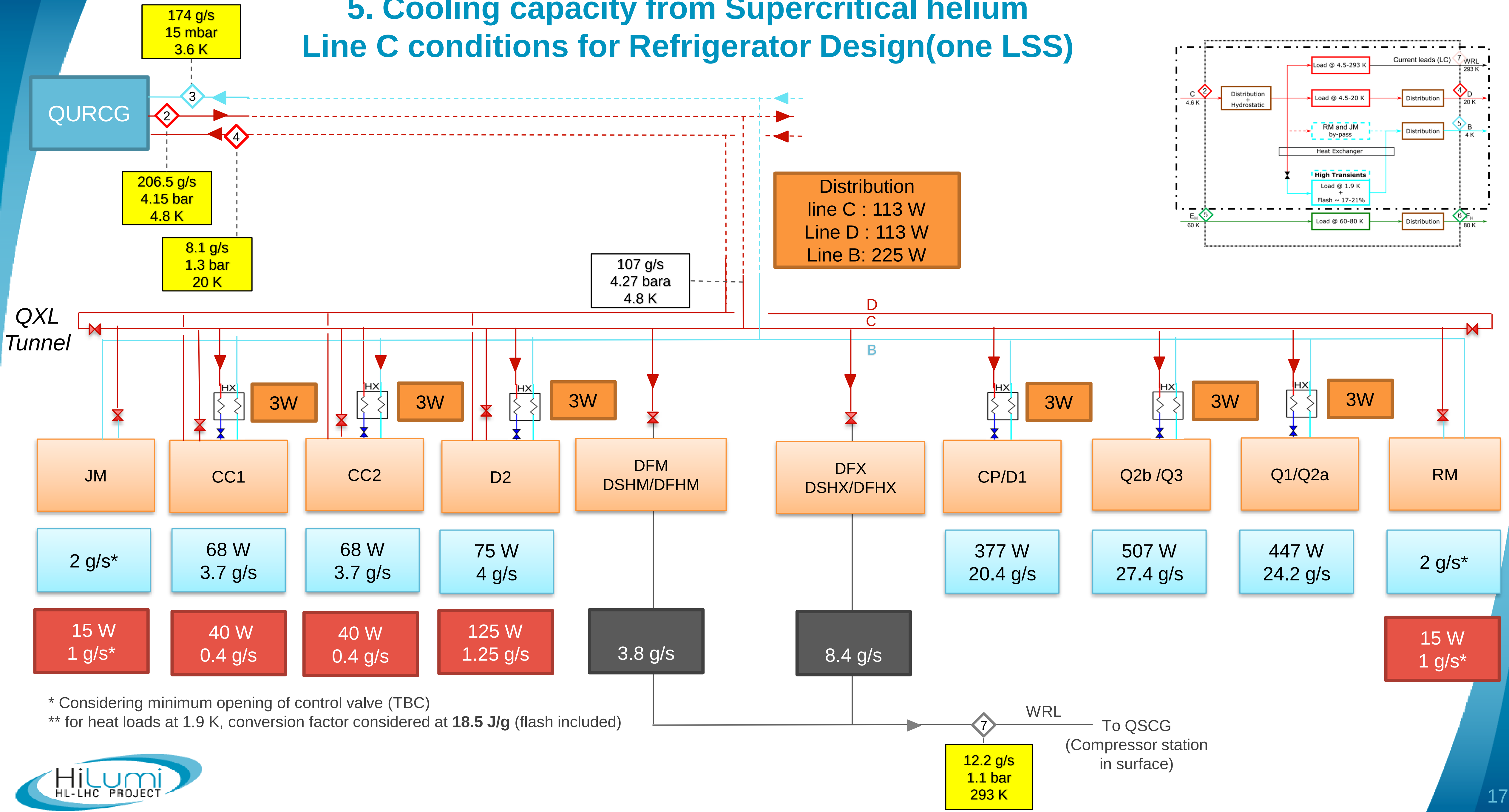
Total Parasitic (Distribution)

Cooling capacity for Refrigerator design	Raw	Raw x F_{un}
Line C supply	75 W	113 W
Line D return	75 W	113 W
Line B return	150 W	225 W

User Requirement for one LSS (from previous talks)

Cooling capacity for Refrigerator design	CC 1	CC 2	D2	IT Cold Pow.	IT Cold Pow.	IT + D1	Total for one LSS
1.9 K	68 W	68 W	74 W	-	-	1330 W	1540 W
4.5 – 20 K	40 W	40 W	125 W	-	-	-	205 W
4.5 – 293 K	-	-	-	8.4 g/s	3.8 g/s	-	12.2 g/s

5. Cooling capacity from Supercritical helium
Line C conditions for Refrigerator Design(one LSS)

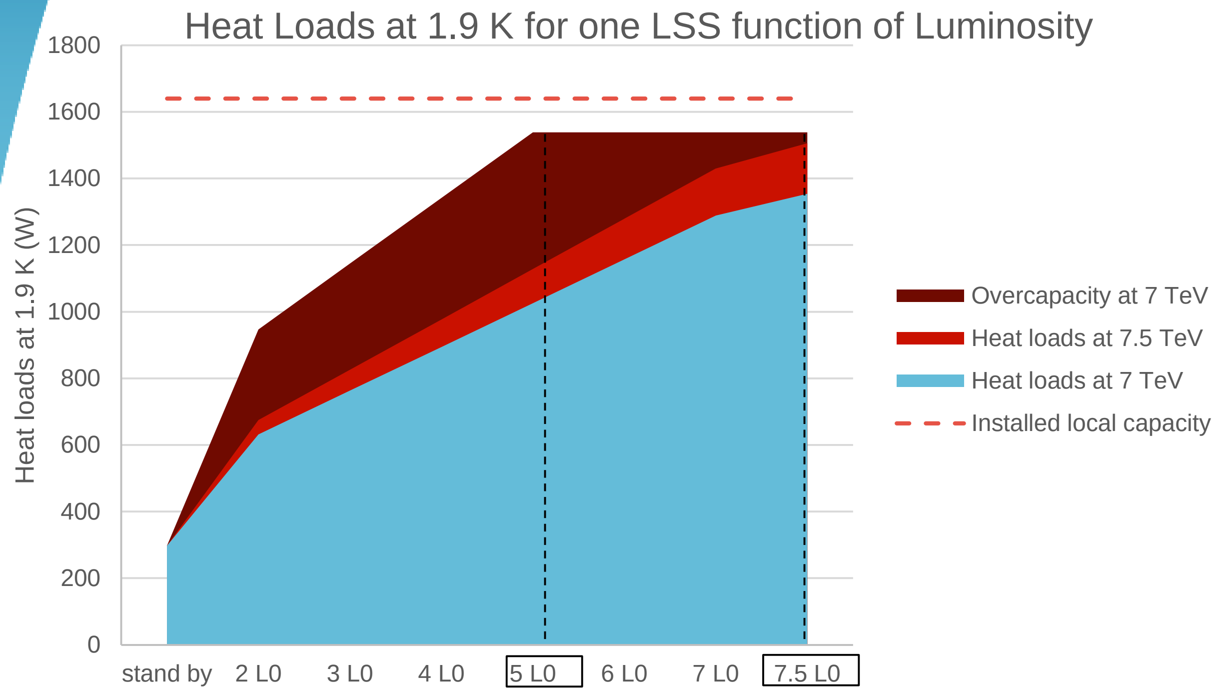


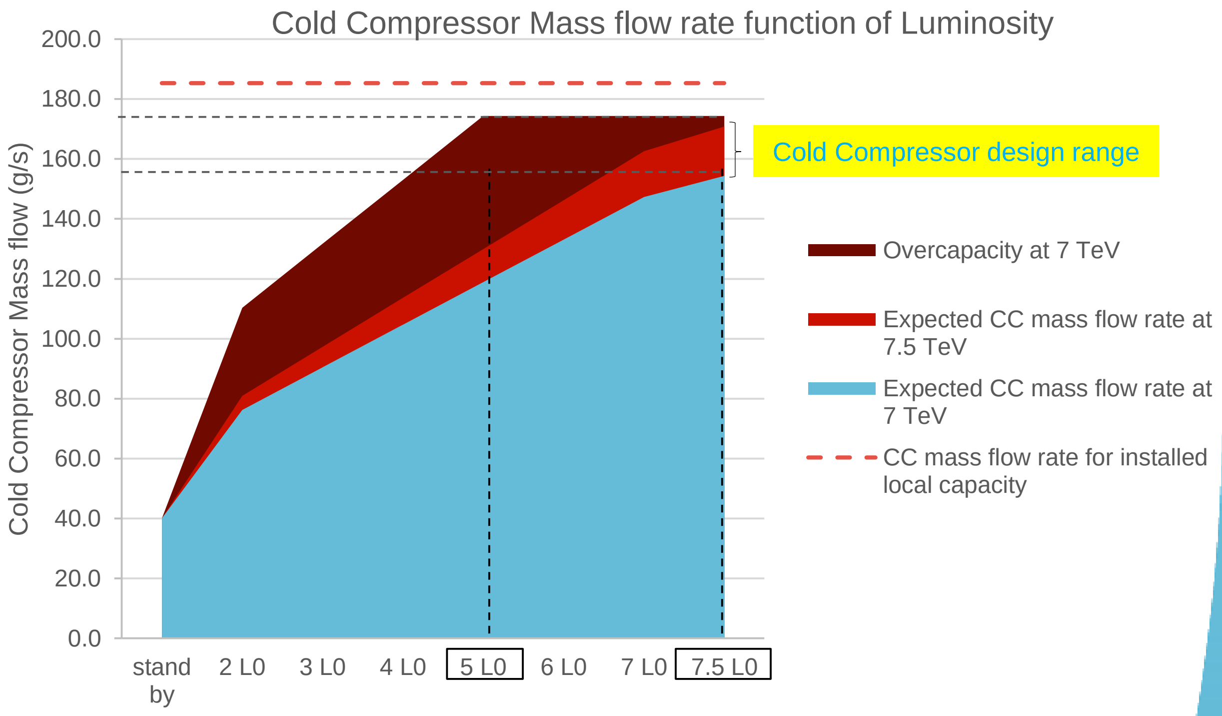
* Considering minimum opening of control valve (TBC)

** for heat loads at 1.9 K, conversion factor considered at **18.5 J/g** (flash included)

HiLumi HL-LHC PROJECT

5. Cooling capacity from Supercritical helium
Specific example of Loads at 1.9 K





- In order to avoid non-necessary overdesign leading to difficulty in operability and design of cold compressor, the installed local capacity **is not taken** into account for Cold Compressor and Refrigerator design.
- Cold compressor design flow rate range between 154 g/s and 174 g/s. Transient from collisions heat induced loads to be considered in Cold compressor design as well (not covered in this review).

	Luminosity [L0 = 10^{34} Hz/cm²]	Energy [TeV]	CC mass flow (g/s)
Sum of Installed local capacities	-	-	185
Nominal * Fov	5 L0	7.5	**174**
Ultimate L – Ultimate E	7.5 L0	7.5	**171**
Ultimate L	7.5 L0	7	**154**
Run 3 equivalent	2 L0	7	76

Outline

1. Introduction : HL- LHC Cryogenic upgrade

2. HL-LHC Cryogenic architecture
   - P1/P5 Cryogenic architecture
   - Refrigerator Scope of supply
   - From Users needs to Refrigerator supply

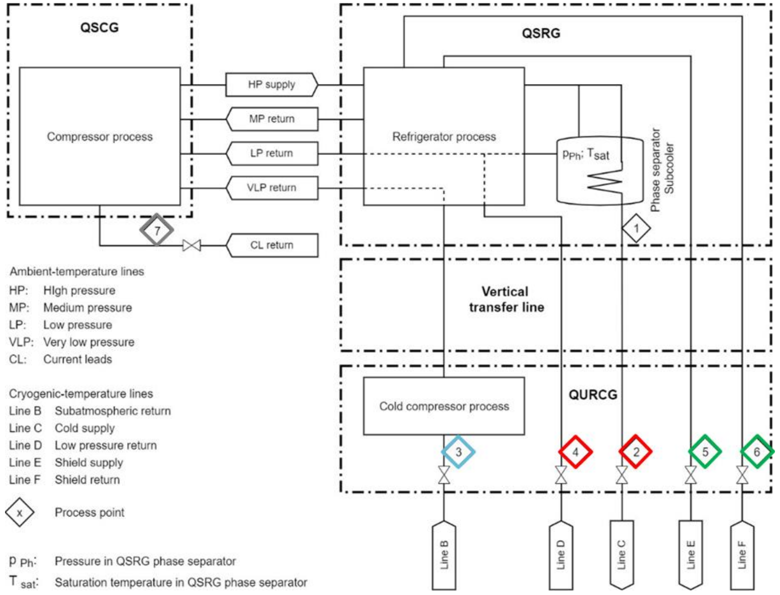
3. Distribution system
   - QXL (cryogenic distribution line) heat loads – Example of IP5
   - Service Module Heat loads

4. Cooling capacity at 60/80 K
   - Users requirements
   - Cooling capacity for User

5. Cooling capacity from Supercritical helium
   - Users requirements
   - Cooling capacity for User

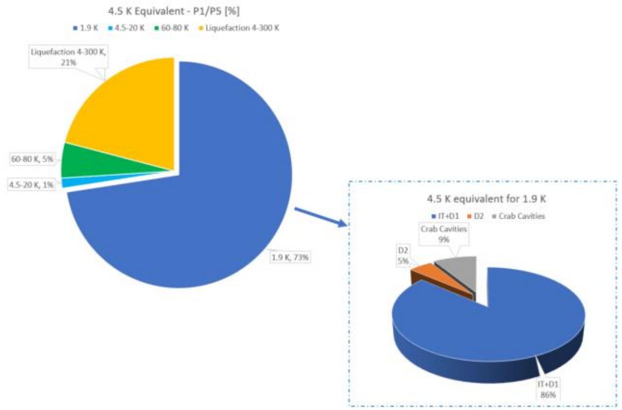
6. Refrigerator design capacity and conclusions

6. Refrigerator summary



At refrigerator level	Unit	Line E → F Thermal shield + Beam screen	Line C→ D Beam Screen 4.5-20 K	Line C→ B 1.9 K loads	Line C→ WRL Liquefaction
Temperature level	**K**	**60-80**	**4.5-20**	**1.9**	**4.5-293**
Total design heat loads	**(W)**	**10600**	**425**	**3305**	**-**
User design heat loads	(W)	7160	330	3080	-
Parasitic heat loads	(W)	3435	115	225	-
RM/JM flow	(g/s)	4	4	8	-
T in	(K)	60	4.76	4.76	4.76
T out	(K)	81	20	3.6	293
P in	(bar)	22	4.15	4.15	4.15
P out	(bar)	20	1.3	0.015	1.1
Total design flow	**(g/s)**	**96**	**8.1**	**173**	**24.4**
Equivalent @ 4.5 K	**kW**	**0.74**	**0.21**	**10.58**	**3.05**

➢ One refrigerator shall be designed for **14.6 kW** equivalent at 4.5 K.



6. Conclusion

- Users heat loads requirements needs now to be frozen.

- Refrigerator is mostly defined by the load at 1.9 K for the IT+D1. Detailed evaluation has been performed for IT static heat loads taking into account the maturity of design.

- Margin considered for the refrigerator seems reasonable to us :
  - Ultimate luminosity and energy case is covered;
  - Nominal case with overcapacity factor of 150% is covered;
  - Potential performances degradation of material is considered.

⇨ Based on the outcome of the review →Final tuning of the required capacity for the refrigerator will be decided for Refrigerator IT.

Thanks for your time and questions

Thanks for your time and questions

Cool down and Quench Case

Assumptions

Momentum flow across magnets in LHC = momentum flow across magnets in HL-LHC

Equivalent diameter for LHC magnets = equivalent diameter for HL-LHC magnets = 50 mm

IT max mass flow (HL-LHC) is ascribable to a standard cell max mass flow (LHC baseline) → **100 g/s**

SUMMARY TABLE			
Branch	**Normal cool down [g/s]**	**Fast* cool down [g/s]**	**Special cool down [g/s]**
LSS.L+R	120	120	120
LSS.L	60	120	120
Inner Triplet	36**	72**	**100**§
SAMs	24	48	20†

* **Fast** => total mass flow for **one side**
** **IT** magnet length ~ 60% of **LSS**
§ **IT** mass flow in special case ~ 85% of **LSS**
† prevision of 5 g/s per each SAM in special case

Due to the required cooling power, **the cooldown case will not be a designing case for the Refrigerator** and will be covered by the equipment in place.

Quench (at ~40 MJ) will not be designing either the Refrigerator.

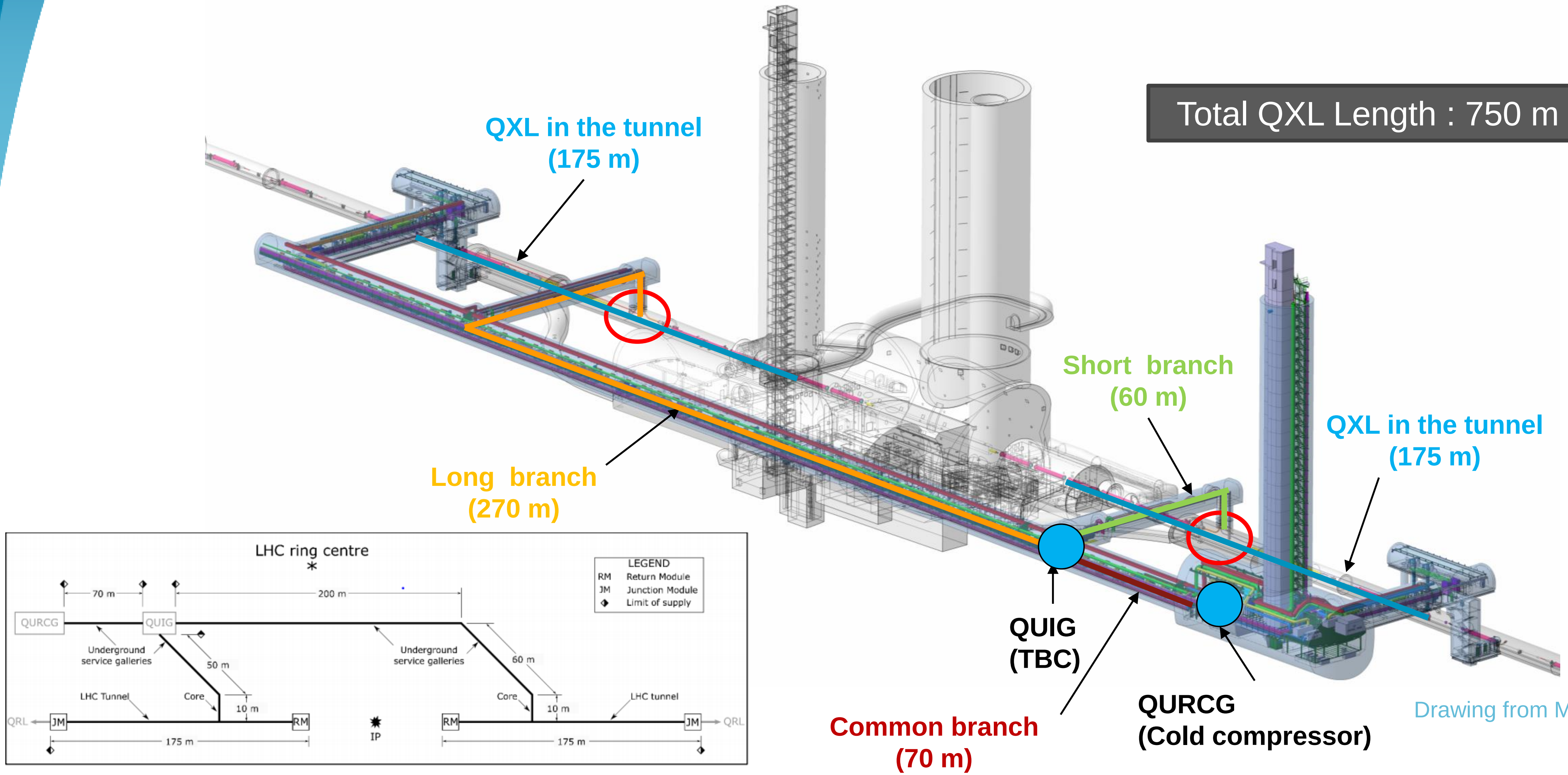
	HL-LHC (LSS.R5 + L5)	LHC (generic sector)
Cool down mode	Normal / Fast	Normal / Fast
Mass to be cooled [tons]	350 / 175	4600
Supply headers [-]	C	C, E, F
Return headers [-]	D	D
Max ΔT supply – return [K]	150	150
Max ΔT per magnet [K]	50	75
Cooling power [kW]	~ 90	600 / 1200
He mass flow [g/s]	120	770 / 1540
Cooling time [days]	~ 6 / 11	7 / 14

Considerable mass flow change w.r.t. what was considered in LHC

Due to the mass to cooldown for HL-LHC : cooldown is forecast in 7-10 days to 80 K, 2-3 weeks to 1.9 K.

3. Distribution system
QXL (cryogenic distribution line)– Example of IP5

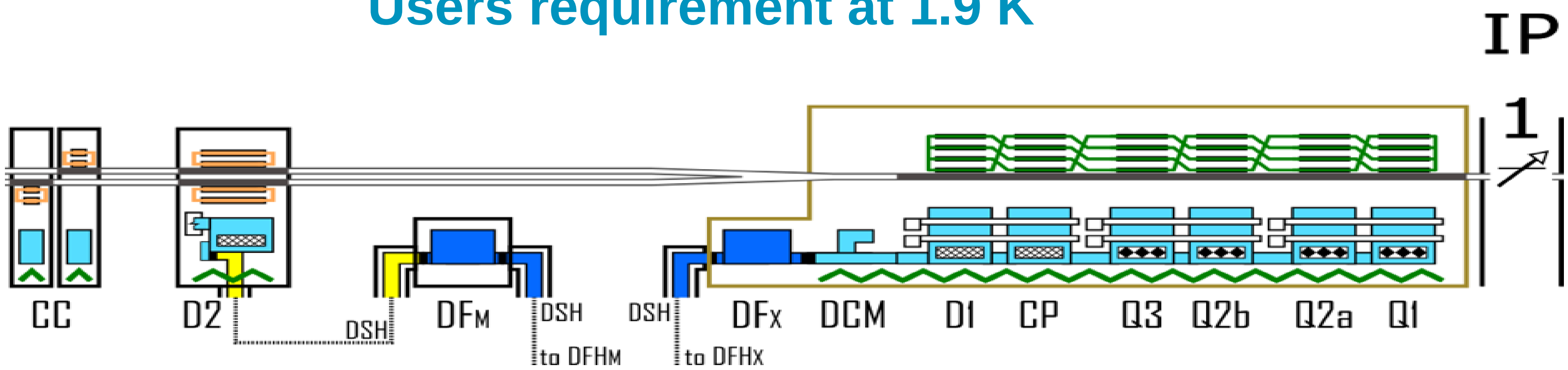
Total QXL Length : 750 m



Drawing from M. Sisti

Extract from Market Survey for QXL
EDMS 2381328

5. Cooling capacity from Supercritical helium
Users requirement at 1.9 K



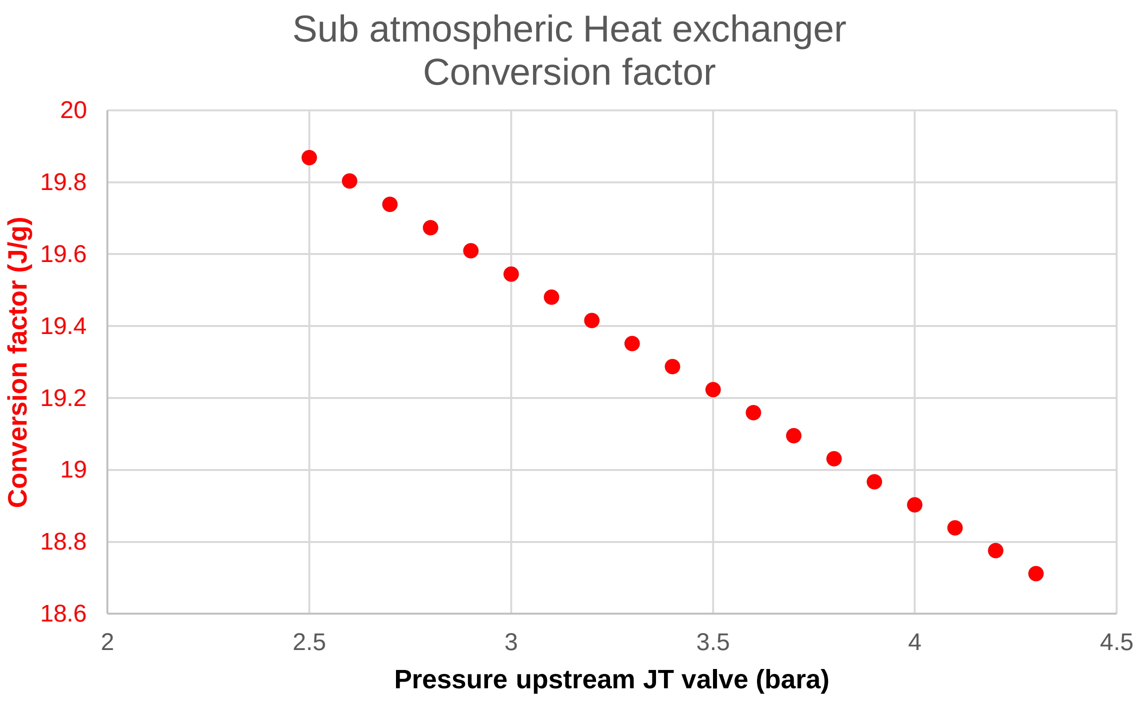
Cooling rqt at 1.9 K	CC 1	CC 2	D2	IT + D1	Total for one LSS
Installed local capacity	80 W	80 W	80 W	1400 W	1640 W
Design static (with uncertainty margin)	24 W	24 W	29 W	220 W	297 W
Nominal (5 L0, 7 TeV) with overcapacity **(static design + nominal dynamic + overcapacity)**	**68 W***	**68 W***	**75 W**	**1330 W**	**1540 W**
Ultimate (7.5 L0, 7.5 TeV) (static design + ultimate dynamic)	45 W**	45 W**	60 W	1330 W	1480 W

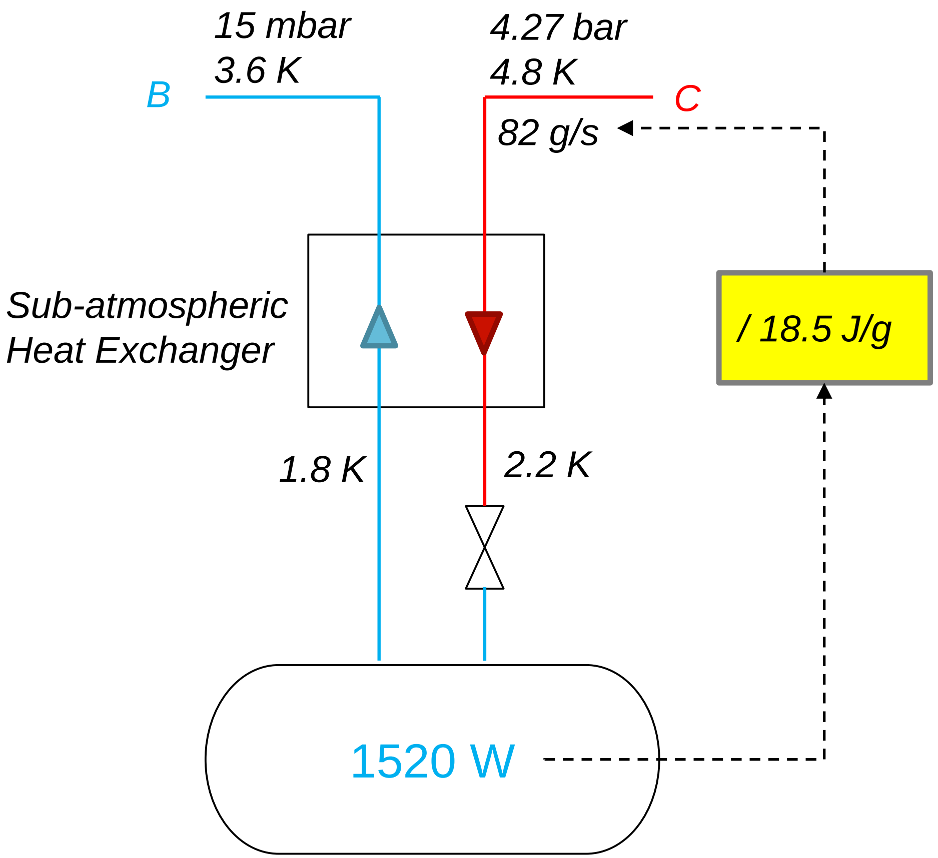
** Considering an average cavity quality*

*** 82 W for Exceptional case, expected 45W at 3.4 MV cavity voltage*

→ Nominal case with overcapacity considered for Refrigerator Design

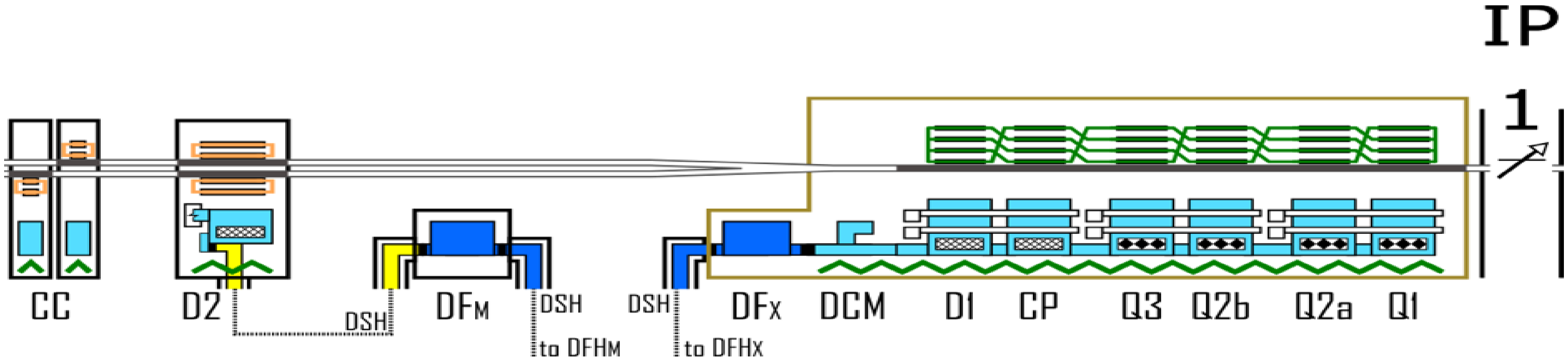
5. Conversion factor for Sub-atmospheric heat exchanger





- Conversion factor increase with line C pressure decrease due to the vapor content after flash
- Conversion factor taken conservatively at 18.5 J/g

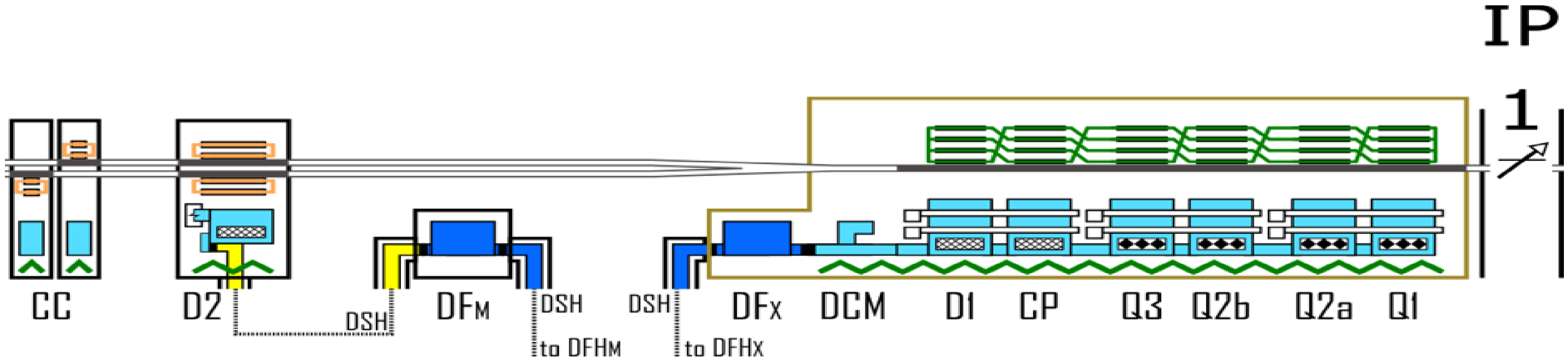
5. Cooling capacity from Supercritical helium
User requirement 4.5K - 293 K



Cooling rqt at 4.5 K-293 K	DFM	DFX
Installed local capacity	5 g/s	10 g/s
Nominal with overcapacity **(static design + nominal dynamic + overcapacity)**	**3.8 g/s**	**8.4 g/s**
Design Static	2.5 g/s	3.1 g/s

- Refer to Cold Powering Heat Loads talk.
- For Refrigerator Design, Nominal with Overcapacity will be considered

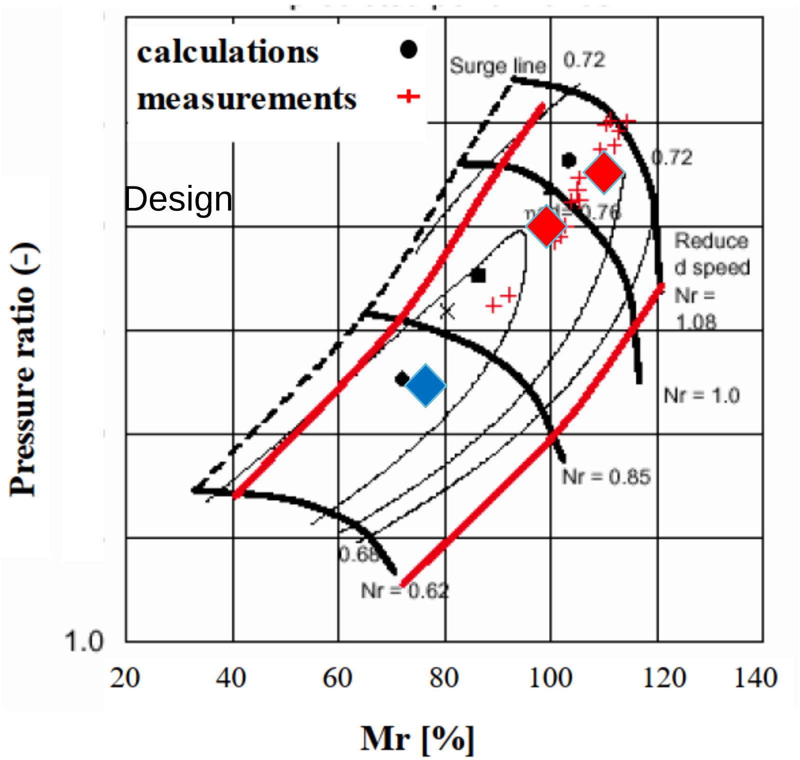
5. Cooling capacity from Supercritical helium
User requirement at 4.5K - 20 K (beam screen)



Cooling rqt at 4.5 K-20 K	CC1	CC2	D2
Installed local capacity	**40 W**	**40 W**	**125 W**
Nominal (5 L0, 7 TeV) with overcapacity (static design + nominal dynamic + overcapacity)	24 W	24 W	123 W
Ultimate (7.5 L0, 7.5 TeV) (static design + ultimate dynamic)	16 W	16 W	123 W
Static Design (with uncertainty margin)	11 W	11 W	34 W

→ Installed local capacity considered for Refrigerator Design

5. Definition of design steady mode for cold compressor

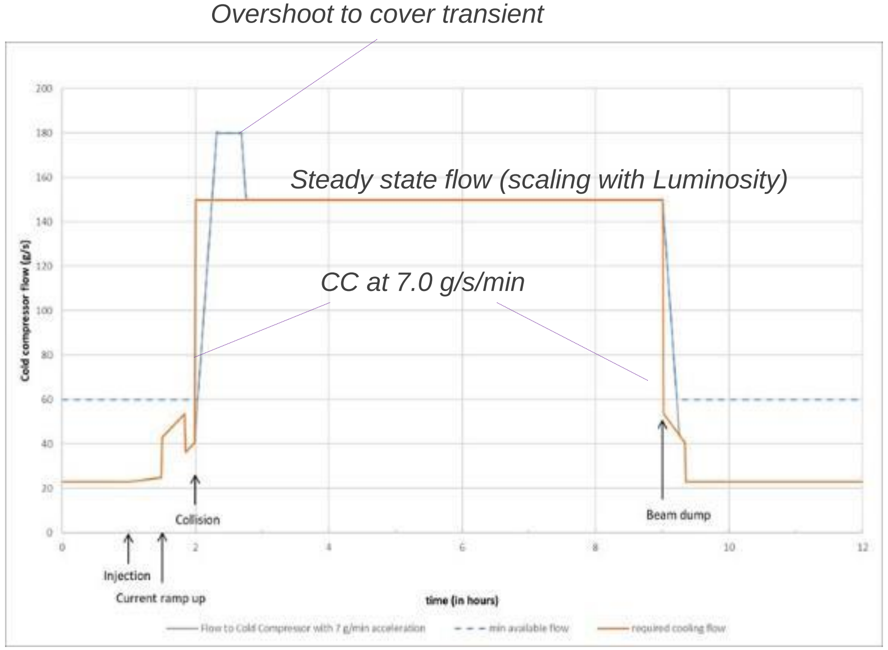


◆ Specified operating points

◆ LHC design point

- Design steady state is defined the maximum of :
  - Heat loads at Ultimate Conditions (7.5 L0; 7.5 TeV)
  - Heat loads at Nominal Conditions (7.5 L0; 7.5 TeV) with Overcapacity margin
  - Design steady state was taken at 150 g/s for the process and feasibility study of Industrial – with an overshoot of +**30** g/s → 180 g/s
- Natural turndown is at 30%. It is important to not overdesign the cold compressors otherwise heating for flow generation or recycling will be required to run the compressors.
- Furthermore Wheel diameter / flow design may be challenging. LHC was designed for 130 g/s at 15 mbar.

5. Impact of collision pulsed loads : Consequences on Cold Compressor box



Cold compressor flow for a Typical fill

- Collision induced heat loads are instantaneous and scale with Luminosity. In order to handle those high transients, it is considered a pre-load of 40 % in the cold mass. As a back up plan, pre-loading in RM/JM is considered.
- Cold compressors (CC) is a serie of centrifugal machines with a maximum acceleration/decceleration considered at 7.0 g/s/min.
- Natural turndown is considered to 30% of maximum compressor capacity.
- To cover this dynamic effect and subsequent overshoot, the cold compressor has a maximum capacity of **+30 g/s** compared with the design steady mode.