HiLumi HL-LHC PROJECT

ICEC/ICMC
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Cryogenic architecture and heat loads for the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN

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ICEC29/ICMC24

Geneva, 23/07/2024

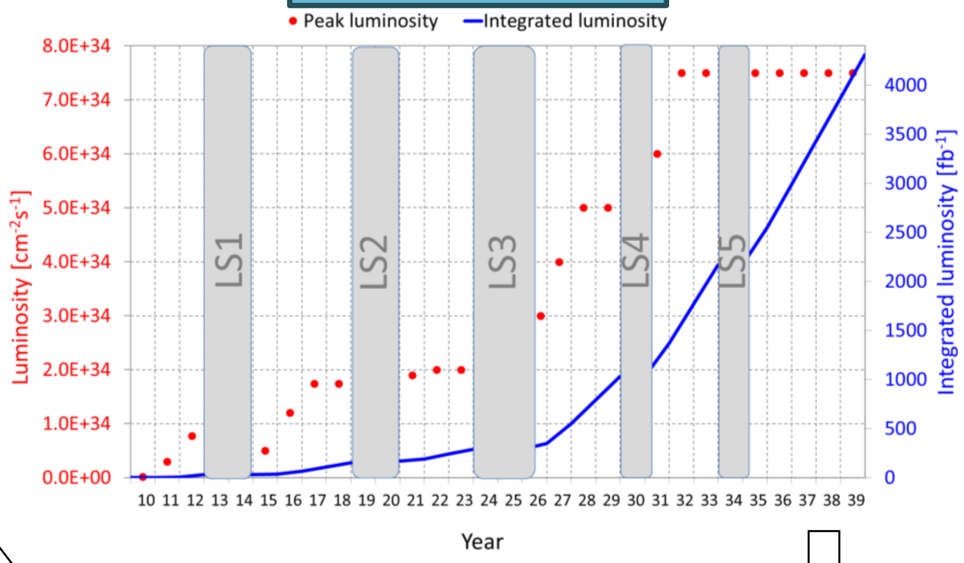
Outline

1. Global scope overview and HL-LHC cryogenic architecture
2. Methodology for heat load definition
3. Heat Load Summary
   - Machine components
   - Cryogenic distribution
4. Required helium refrigerators cooling capacity
5. Conclusions and way forward

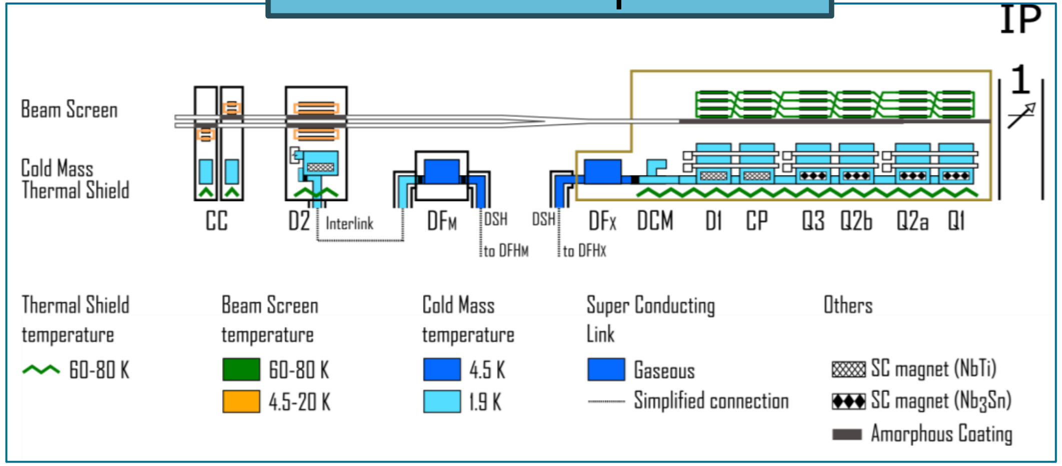
Global scope overview

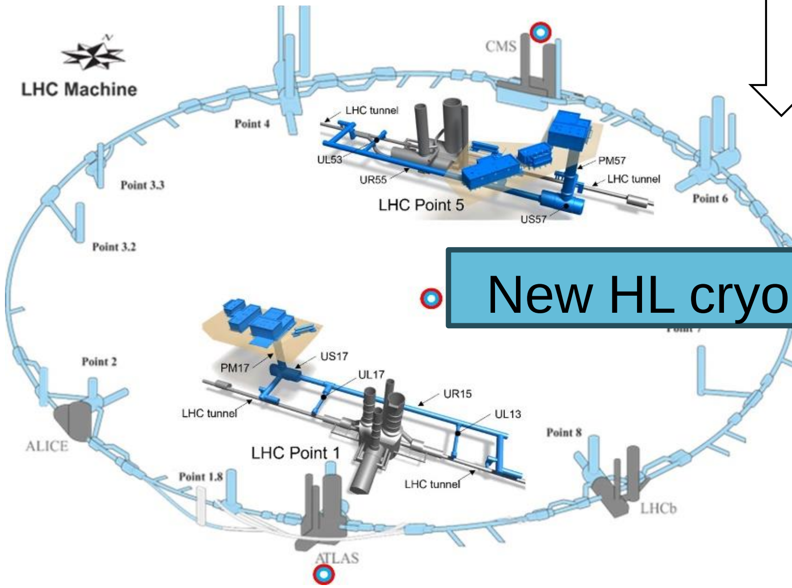
- **HL-LHC goal** : producing in that period 10 times more data as compared to the nominal LHC operation period.
- Requires an upgrade of the final focusing components both for **machine lifetime** and **performance** by increasing the peak luminosity by a minimum of five times wrt LHC nominal.
- **New superconducting elements** having increased cryogenic demand requires the installation of new Refrigerator and Infrastructure in IP1 and IP5.

Performance



Machine components





New HL cryoplants

HL-LHC P1/P5 Cryogenic architecture

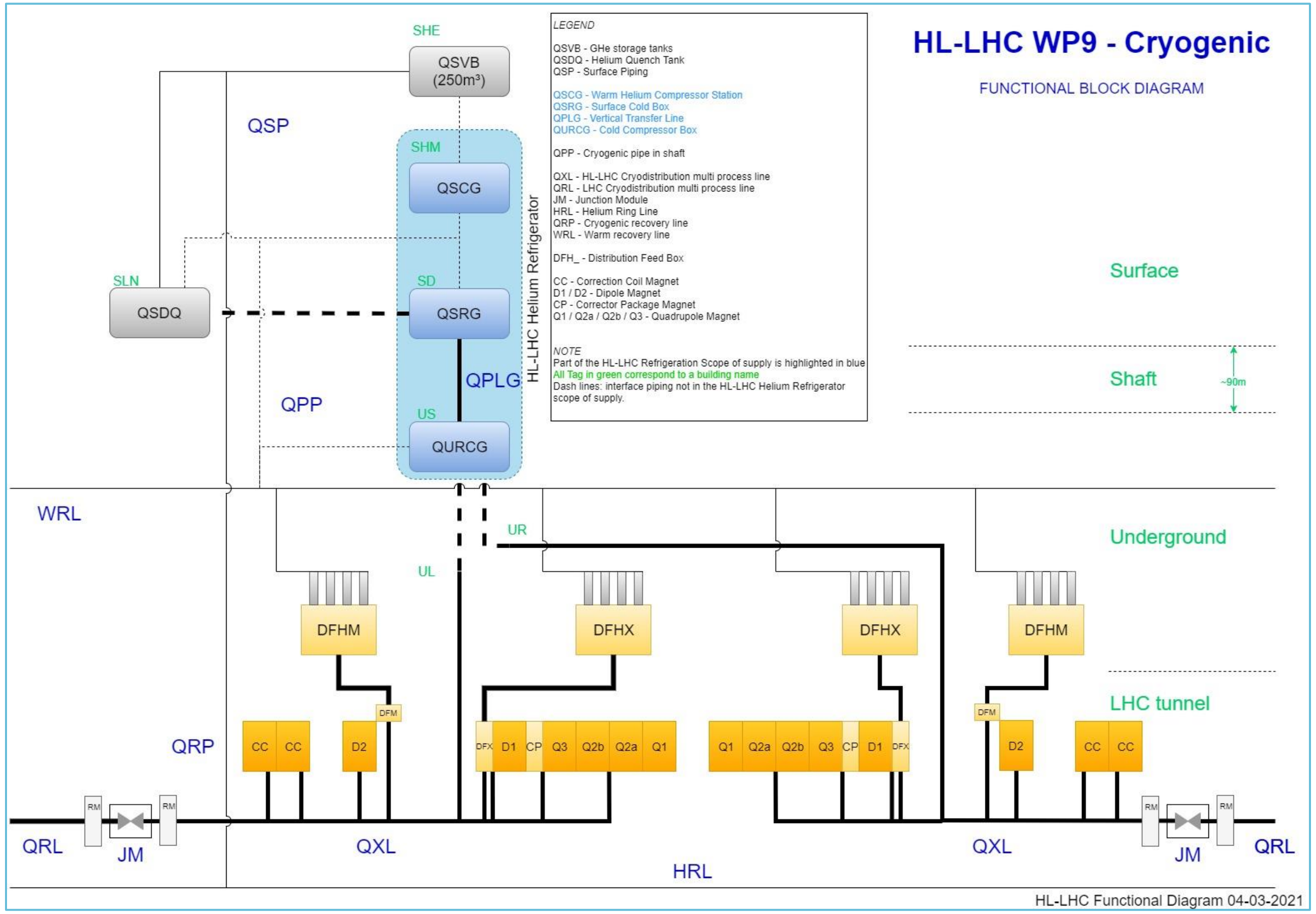
QSCG : Compressor station → gaseous helium **20 bara**

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

QPLG : Vertical transfer line (~100 m height)

QURCG : Cold compressor → cooling capacity at **1.8 K**

Machine Components at tunnel level



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

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

Heat loads at machine component level + Heat loads from the distribution system → Refrigerator capacity

Heat load classification and mechanisms

Static

- Depends on cryostat design and insulation vacuum
- Constant at nominal conditions

Dynamic Heat Load

Resistive

- Resistive heating occurs in splices of the superconducting cables and in current leads.

Beam Induced

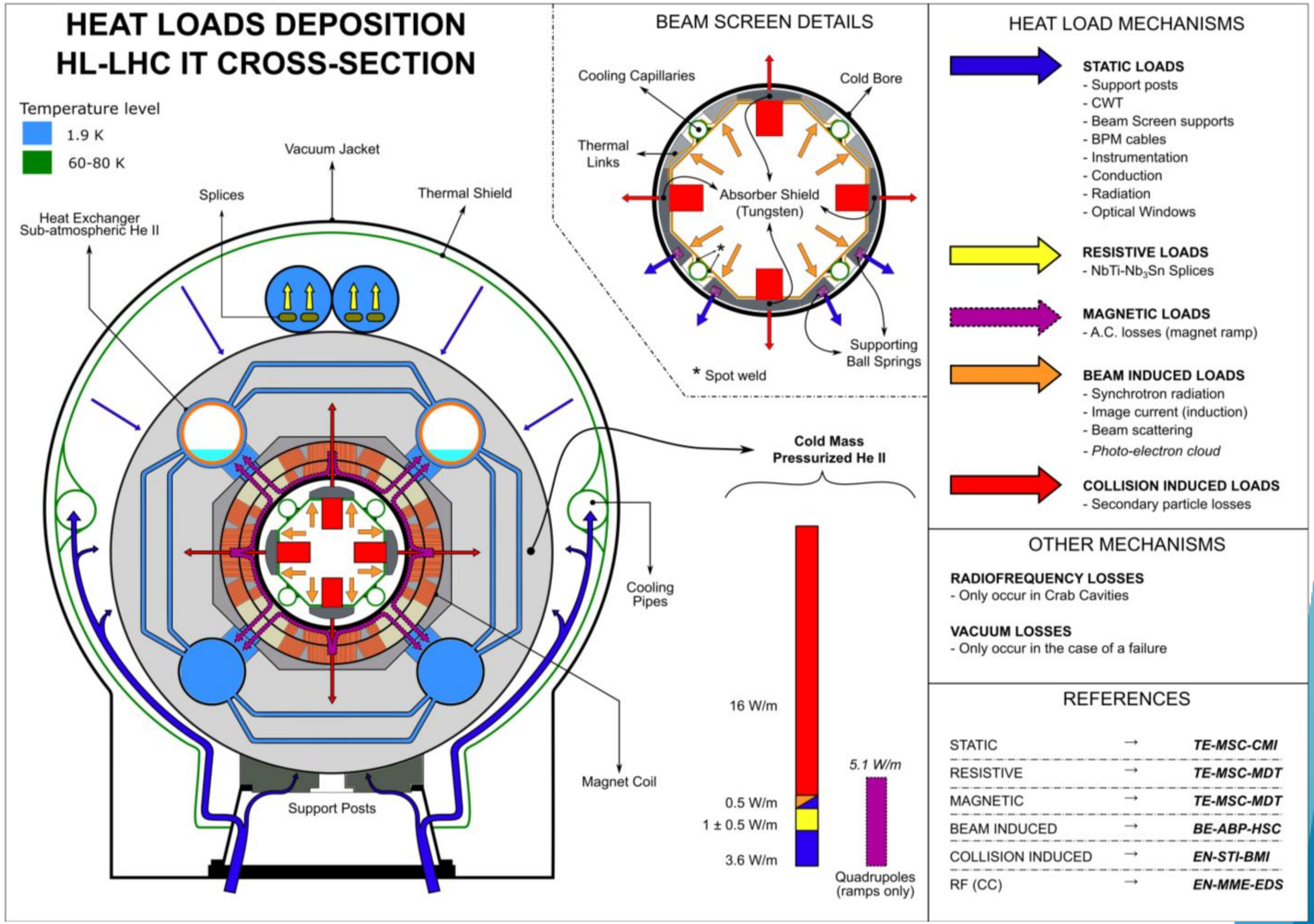
- Image current depend on beam characteristics
- Electron cloud considering Carbon coating

Collision Induced

- Secondary particle losses
- Mainly depend on luminosity and beam energy

Magnetic Induced

- Dissipation of Eddy currents due to change of magnetic field
- Occurs at ramp up and ramps down



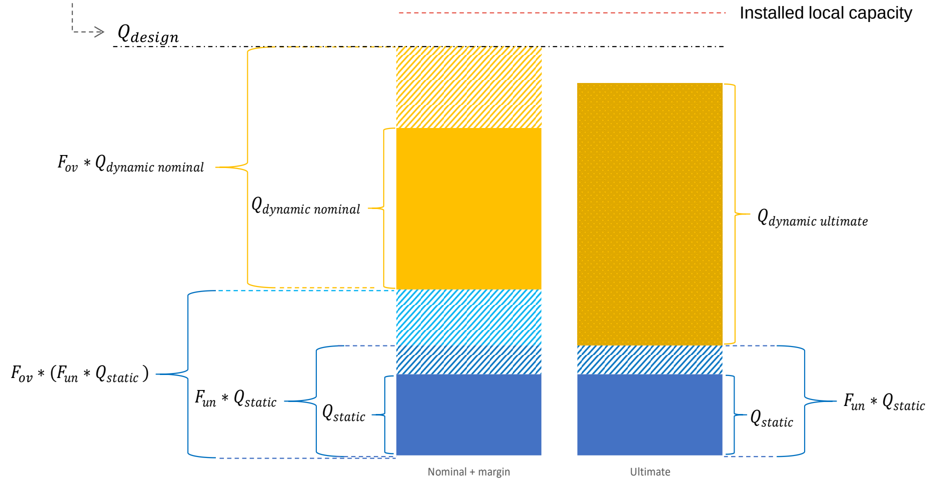
Methodology at Machine component level

- **Design cooling capacity** Q_{design} is calculated for each temperature level and machine component considering an uncertainty factor F_{un} applied only on the static heat loads and an overcapacity factor **Fov at 1.5** applied only on the Nominal conditions (7 TeV and 5L0).

- **Estimation of the static heat load** consider the characteristic of each individual components and design maturity.

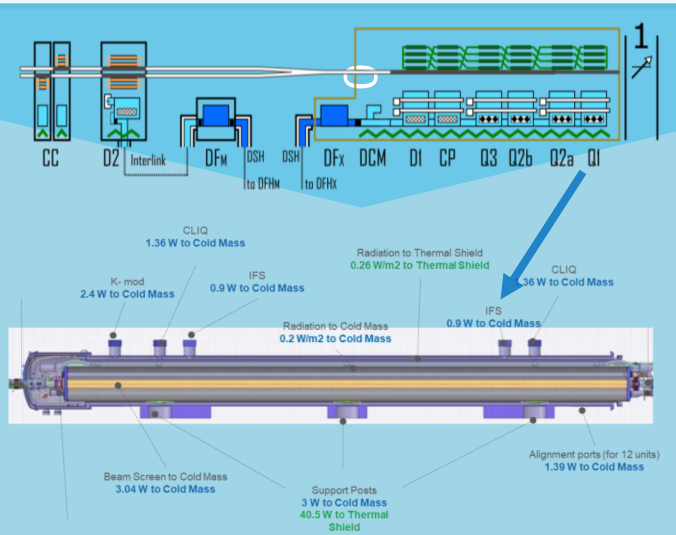
- The **installed local capacity** is the maximum heat load which can be extracted from any cooling circuit limited by the systems design. It should be at least as high as the design capacity.

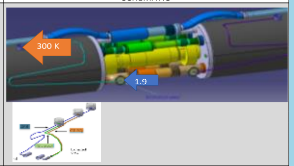
$$Q_{design} = Max[\ F_{ov} * (F_{un} * Q_{static} + Q_{dynamic\ nominal})\ ;\ F_{un} * Q_{static} + Q_{dynamic\ ultimate}\ ]$$



Q_{static} heat load

Approach for each Temperature level





K-mod

Type	K-mod
Function	Used for modulating of the quadrupole gradients.
Number of items	2 (4 feeders, 2 per K-mod)
CONTACT	
Name(s)	J. Liberadzka / T. Koettig
Department	Be-BI-ML
Latest Reference	HL-LHC K-mod current feeders Cryolab thermal performance test
EDMS	2279955
Version	3
Date	05/12/2019

PROPERTIES

Property	Value	Unit
Conducter cross section	10	mm^2
Number of wires	2	-
Length of conductor	2	m
Temperatures		
Operating temperature	1.9	K
Warm	300	K
Intercept	-	K
No intercept implemented		
Powering		
Current	25	A

SCHEMATIC

HEAT LOAD components

Data	Value	Unit	Items
Conduction to 1.9 K	1.2	W	4
Resistive load at 1.9 K	0.1	W	4

LAYOUT

edms 2279202

MAGNET	K-mod/ Cliq	Drawing Nr.
Q1A	K-mod	LHCQQXF_DQ0077
Q1A	CLIQ	LHCQQXF_DQ0044
Q1B	CLIQ	LHCQQXF_DQ0044
Q2A	CLIQ	LHCQQXF_DQ0044
Q2B	CLIQ	LHCQQXF_DQ0044
Q3A	K-mod	LHCQQXF_DQ0077
Q3A	CLIQ	LHCQQXF_DQ0044
Q3B	CLIQ	LHCQQXF_DQ0044

Heat Load Data per Unit

Heat load 1.9 K	Value	Unit	Data type	Comment
Static	1.2	W	Measurement	Per K-mod
Resistive	0.1	W	Measurement	Per K-mod
Total	1.3	W	Measurement	Per K-mod

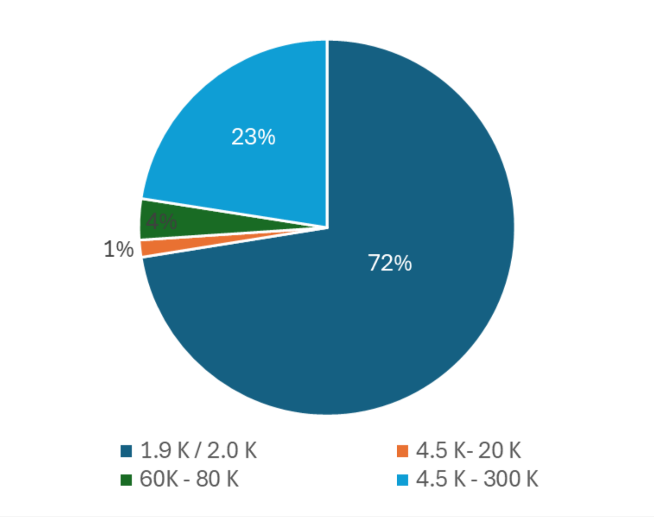
Heat Load	Applicable
Static	yes
Resistive	yes
Magnetic	-
Beam Induced	-
Collision Induced	-

Machine Component Heat Load Summary

Temperature level	Component	Static x F_{un}	Nominal	Ultimate	Design
1.9 K /2.0 K [W]	Inner Triplet	224	892	1358	1358
	D2	30	56	74	84
	CC module	23	45	45	68
4.5 K to 20 K [W]	D2	34	86	87	129
	CC module	11	16	16	24
60 K to 80 K [W]	Inner Triplet	697	1677	2134	2515
	D2	186	186	186	279
	CC module	255	264	264	396
4.5 K to 300 K [g/s]	IT Cold Powering	3.0	4.8	5.0	7.0
	MS Cold Powering	3.1	3.0	3.0	4.5

- Machine component led by the heat load at 1.9 K on the Inner Triplet.
- More specifically, heat load on the IT is led by the Collision heat Induced heat load.

Equivalent 4.5 K eq. repartition



Heat load distribution at 1.9 K level

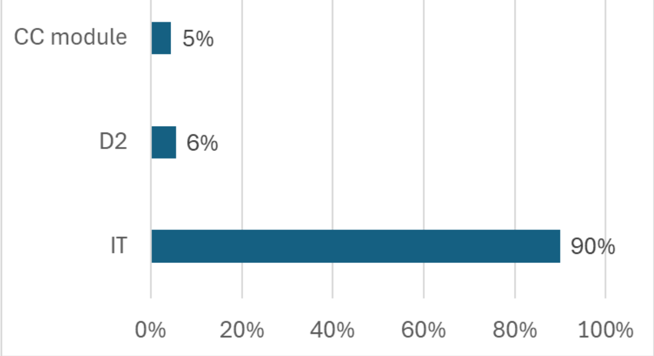
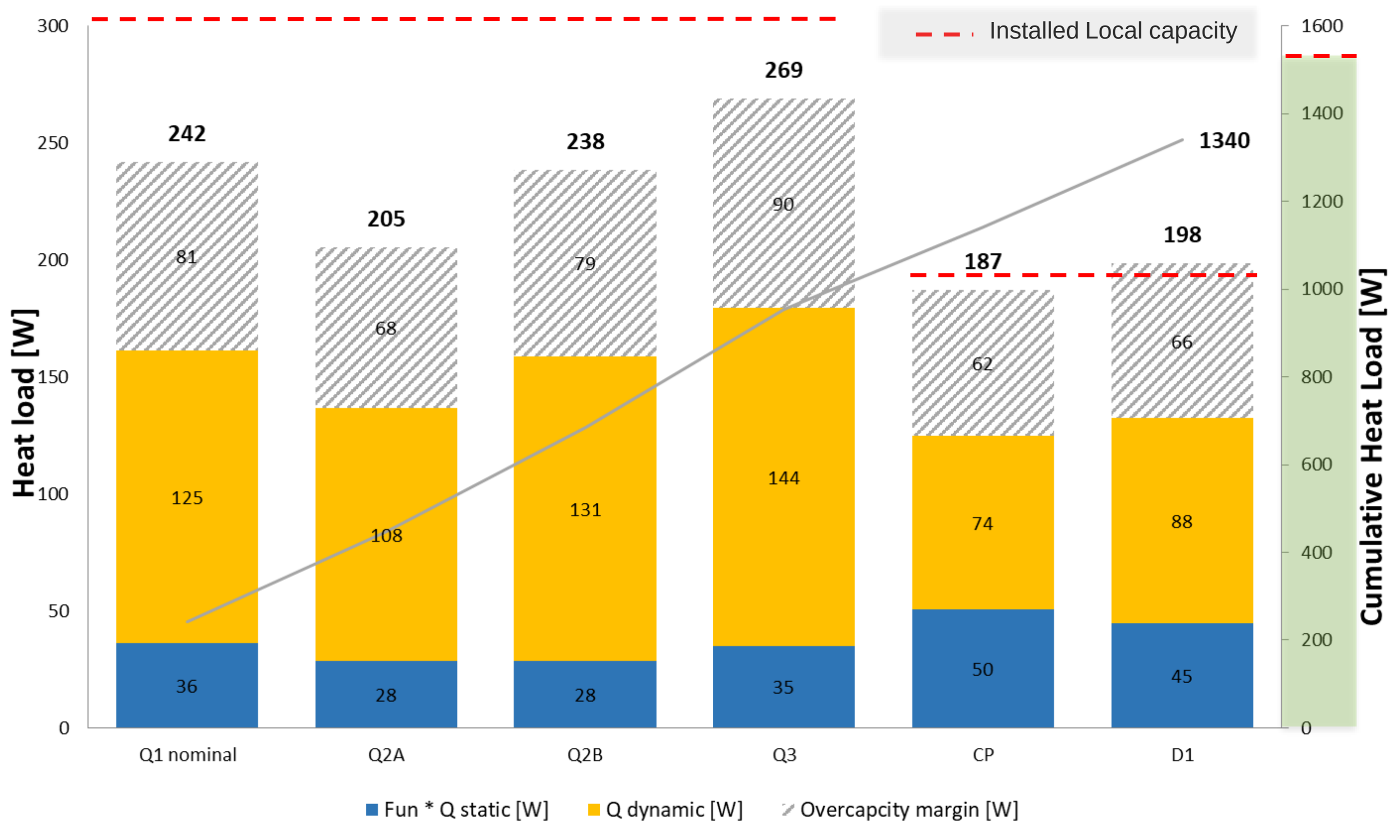
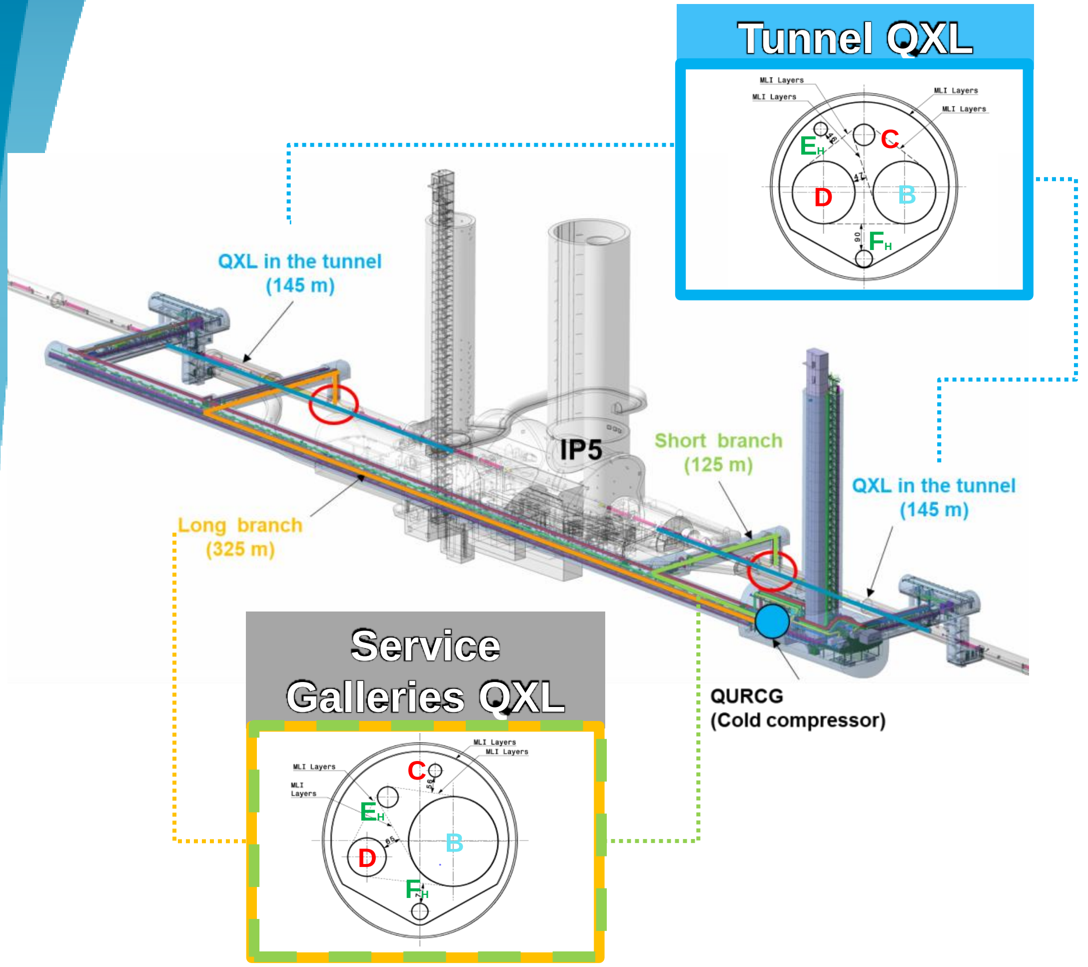


Illustration of heat loads for one IT @ 1.9 K



- **Dynamic** heat loads account for **~ 75%**
- **Installed local cooling** capacity is determined by the gas velocity in the magnet heat exchangers in the Inner triplet depending on **cold mass temperature.**

Design heat loads on the Cryogenic distribution system

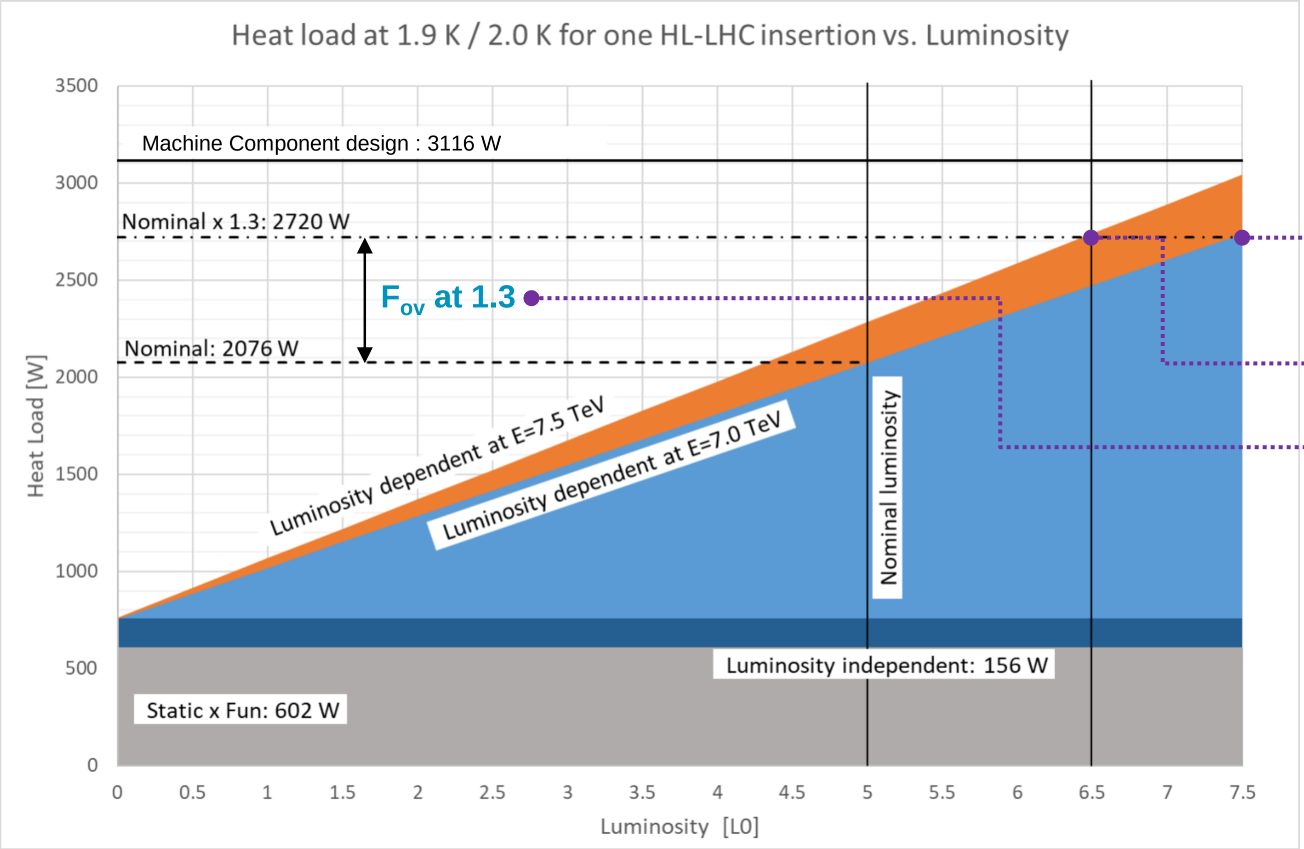


- The cryogenic distribution system includes :
  - **Five process pipes** in a single vacuum envelope, thermally shielded by an actively cooled thermal shield.
  - **Service modules** including valves and sub-cooling heat exchangers to connect the insertion elements.
  - **Return modules**, located close to the interaction point (IP), including valves, heaters, and a phase separator.
  - **Junction modules**, located at the junction to the LHC distribution (QRL), including valves, heaters and a phase separator.

QXL	P nominal	T nominal	Specified Heat load	Design HL for Refrigerator Design
Line B	~15 mbar	~4 K	0.2 W /m	374 W
Line C	~4 bar	~5 K	0.1 W /m	187 W
Line D	~1.3 bar	~20 K	0.3 W /m	560 W
Line E_H	~21 bar	~60 K	0.05 W/m	95 W
Line F_H	~20 bar	~80K	3 W/m	5600 W

Towards Refrigerator design : consideration on 1.9/2.0 K level

- **Heat load to 1.9K / 2.0 K level** at the component level represents more than **70% of the charge** coming mostly from dynamic load.
- **Dynamic heat loads** are well controlled based on a **return of experience** from LHC machine and **model benchmark**.



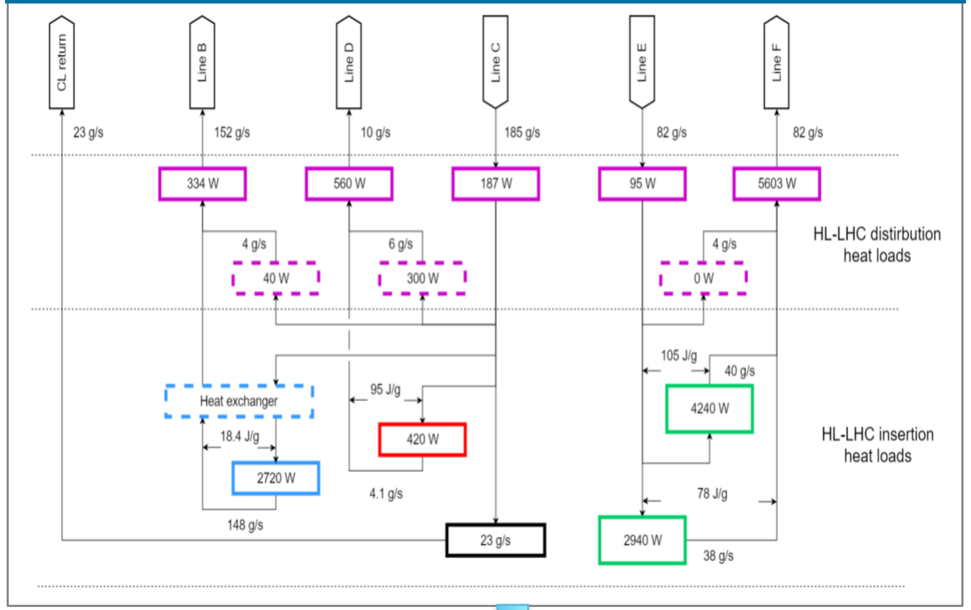
- To avoid non-necessary overdesign for the refrigerator and allow for more energy efficient turn-down operation, the design capacity was chosen at **2720 W @1.9/2.0 K (F_{ov} at 1.3)** for the refrigerator allowing :
  - To cover the heat loads at ultimate luminosity of 7.5 L0 at 7 TeV.
  - To cover the heat loads at maximum beam energy of 7.5 TeV and a luminosity of 6.5xL0.
  - To guarantee an overall overcapacity factor of 1.3 for the nominal luminosity at 7 TeV.
- At the machine component level, all cryogenic elements were designed for at least 3116 W.
- At maximum, the cold compressor are designed to **3210 W** to absorb excess heat deposited on the cold mass when collision occur.

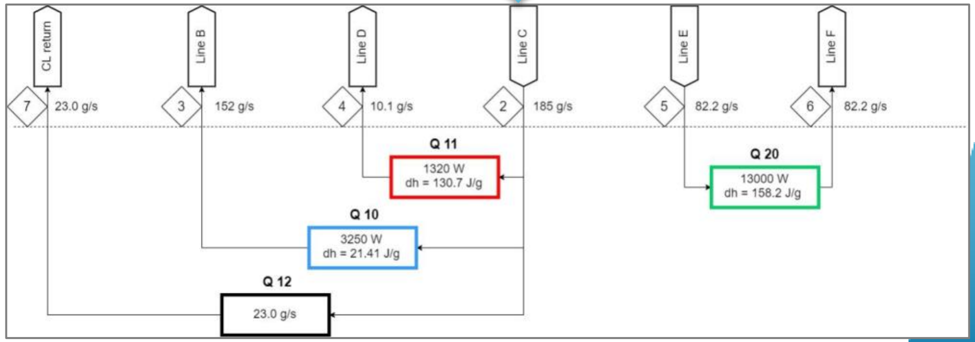
Refrigerator cooling capacity

- Summarizing all the previous data, each P1 and P5 Refrigerators shall be designed for **14 kW at 4.5 K eq.**

- Three operating cases were considered for the Refrigerator design :
  - The **Maximum Capacity mode**, corresponding to the moment when collision occurs. This mode last one hour during each fill with a supplementary charge being compensated by buffered liquid helium in the Refrigerator;
  - The **Design Capacity mode**, covering a steady state operating mode when the design heat load is extracted at the HL-LHC machine component level.
  - The **Turndown mode**, characterized by minimum helium cooling before beam injection and after beam dump.

Heat load distribution for Design Case





Operating mode	C→B	Isothermal 4.5K	C→D	C→300 K	E→F
Maximum Capacity	3760 W	-	1320 W	23 g/s	13000 W
Design Capacity	**3250 W**	**700 W**	**1320 W**	**23 g/s**	**13000 W**
Turndown	1100 W	-	700W	10 g/s	6000 W

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Conclusion

- The **HL-LHC heat loads** were assessed taking into account beam parameters, luminosity, and beam energy as well as the maturity of design of the machine components considering overcapacity contingencies.
- The **installed cryogenic capacity** was found adequate for each machine component, with sufficient local margins.
- The Refrigerator capacity was defined for an equivalent capacity of **14 kW@4.5 K, including 3.25 kW@1.9 K**, based on the machine components and cryogenic distribution heat loads with a limited overcapacity.
- The contracts of the two new cryogenic plants and associated cryogenic distribution lines required for the HL-LHC upgrade are currently **under manufacturing phase** → The next phases to come will be the installation, commissioning and tests, and handover to operation.
- In the same while, the machine components are currently tested at CERN with **thermal measurements as per expectation**.

Installation of gaseous storage tank

PFHE test at Linde premises

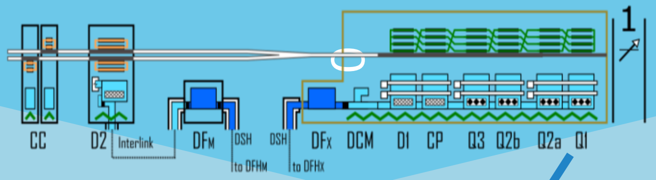
Vacuum vessel in stock at KrioSystem

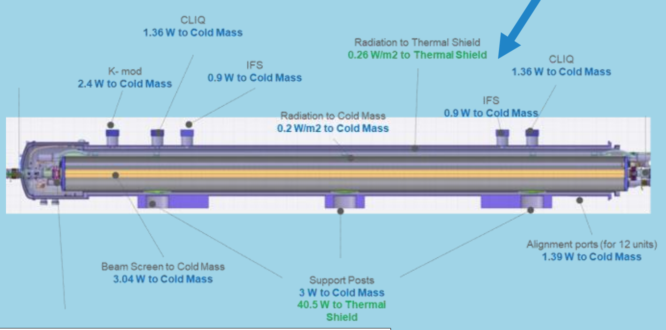
Thanks for your time and questions

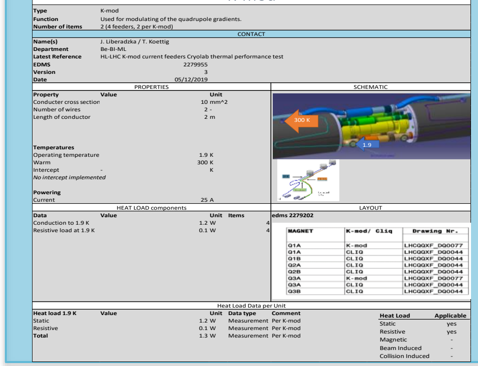
Static heat loads on Inner Triplet

Q_{static} heat load

Approach for each Temperature level






K-mod

- Documentation
  - Edms
  - Indico
- Review
- Communication

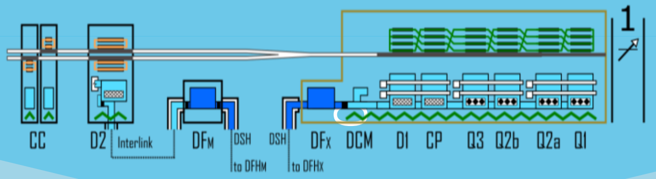
Cold Mass - 1.9 K Static		Q1	Q2a	Q2b	Q3	CP	D1	DCM	Grand total	
	Uncertainty factor	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	F_{un} * Q_{static}
Support posts	1.25	3.00	3.00	3.00	3.00	2.00	2.00	-	16.00	20.00
Vacuum barrier	1.50	-	-	-	-	-	-	5.00	5.00	7.50
Radiation Thermal Shield to	1.25	4.23	4.02	4.02	4.16	2.47	3.03		21.93	27.41
Radiation beam screen to cold	1.25	3.04	2.94	2.94	3.04	1.22	2.21		15.39	19.24
CWT / Interconnect	1.50	4.89	4.14	4.14	4.14	4.14	4.35		25.80	38.70
IFS type 1	2.00	1.76	0.88	0.88	1.76	0.88	-		6.16	12.32
IFS type 2	2.00	-	0.16	0.16	-	0.16	0.16		0.64	1.28
K-MOD	1.25	2.60	-	-	2.60	-	-		5.20	6.50
CLIQ	1.25	3.32	1.66	1.66	3.32	-	-		9.96	12.45
Phase Separator	1.50	1.28	1.28	1.28	1.28	1.28	1.28		7.68	11.52
Alignment ports	1.50	1.39	1.39	1.39	1.39	-	-		5.56	8.34
Lambda Plate	1.50	-	-	-	-	-	-	11.60	11.60	17.40
XB Pumping line	1.25	1.57	1.57	1.57	1.57	1.57	1.57	-	9.45	11.81
Local powering current leads	1.50	-	-	-	-	20.00	-		20.00	30.00
Total	-	27.08	21.04	21.04	26.26	33.72	14.60	16.60	160.37	224.47

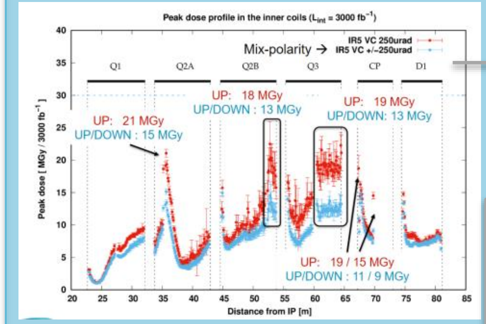
Thermal Shield 60-80 K		Q1	Q2a	Q2b	Q3	CP	D1	DCM	Grand total	
	Uncertainty factor	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	Q_{static}	F_{un} * Q_{static}
Support posts	1.25	39.60	39.60	39.60	39.60	26.40	26.40	-	211.20	264.00
Vacuum barrier	1.50							30.00	30.00	45.00
Radiation to Thermal Shield	1.25	34.74	31.37	31.37	32.51	19.29	23.60	10.00	182.88	228.60
Current leads (conduction)	1.50	-	-	-	-	106.00	-	-	106.00	159.00
Total	-	74.34	70.97	70.97	72.11	151.69	50.00	40.00	530.08	696.60

- Uncertainty factor (F_{un}) was tailored made for each users according to the uncertainty /room to growth left for each component taking into account recommendation from heat load review panel.
- This table does **not** include the overcapacity factor (F_{ov}) that is still to be included in design heat load

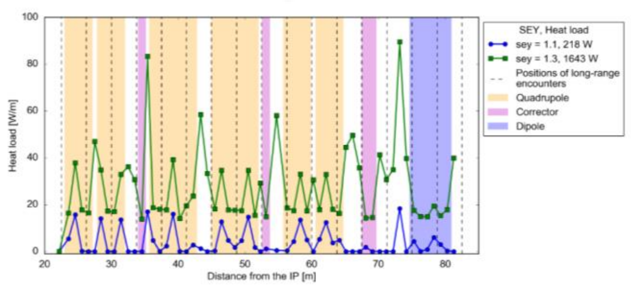
Dynamic heat loads on Inner Triplet

$Q_{dynamic}$ heat load





- WP10 : Collision induced
  - FLUKA Simulation
- WP2 : Beam induced
  - PyEcloud simulation for electron cloud
  - Analytical for impedance

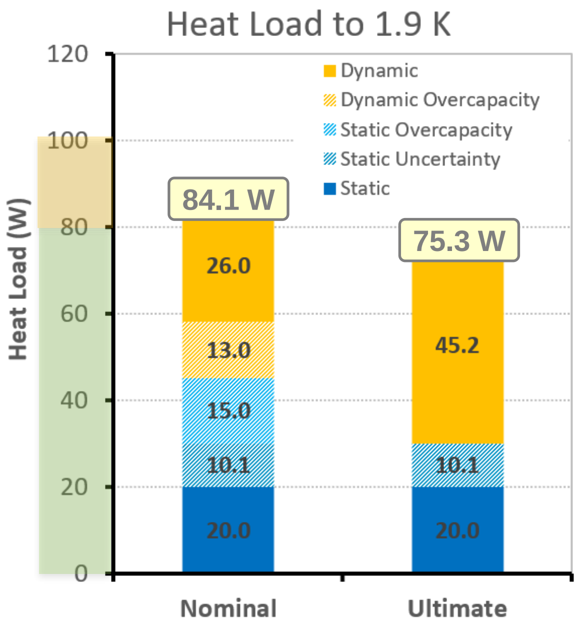


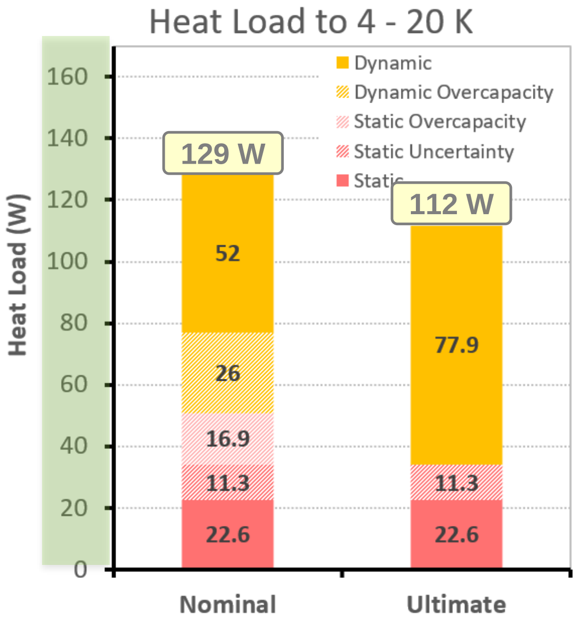
Cold Mass 1.9 K Dynamic	Overcapacity factor	Q1 $Q_{dynamic}$	Q2a $Q_{dynamic}$	Q2b $Q_{dynamic}$	Q3 $Q_{dynamic}$	CP $Q_{dynamic}$	D1 $Q_{dynamic}$	DCM $Q_{dynamic}$	Grand total $Q_{dynamic}$	Grand total F_{ov} * $Q_{dynamic}$
Resistive	1.50	7.11	3.72	3.72	6.85	6.06	0.44	0.95	28.84	43.26
Beam Induced	1.50	0.38	0.29	0.37	0.40	0.13	0.19	-	1.75	2.63
Collision Induced	1.50	116.89	104.22	126.22	136.89	68.22	84.22	-	636.67	955.00
Total	-	**124.38**	**108.23**	**130.31**	**144.14**	**74.41**	**84.85**	**0.95**	**667.26**	**1000.89**

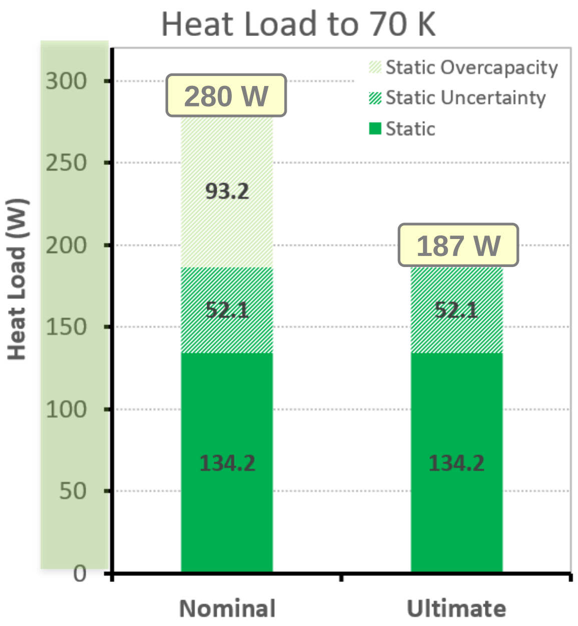
Beam Screen 60-80 K	Overcapacity factor	Q1 $Q_{dynamic}$	Q2a $Q_{dynamic}$	Q2b $Q_{dynamic}$	Q3 $Q_{dynamic}$	CP $Q_{dynamic}$	D1 $Q_{dynamic}$	DCM $Q_{dynamic}$	Grand total $Q_{dynamic}$	Grand total F_{ov} * $Q_{dynamic}$
Beam Induced	1.50	75.70	58.12	73.82	80.12	25.22	37.22	-	350.20	525.30
Collision Induced	1.50	193.00	85.67	105.00	97.67	73.67	75.00	-	630.00	945.00
Total	-	**268.70**	**143.79**	**178.82**	**177.79**	**98.89**	**112.22**	**0.00**	**980.20**	**1470.30**

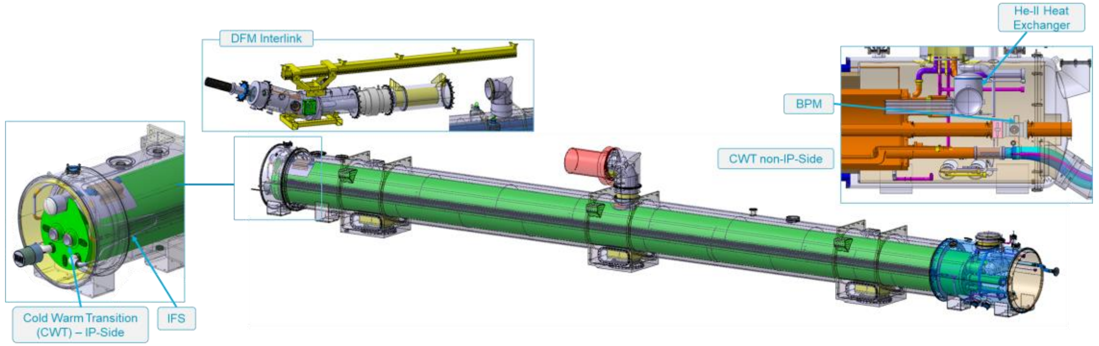
Heat Loads on D2

The following graphs summarise the heat loads on the cryogenic circuits of the D2, including the uncertainty and overcapacity margins which have been applied:

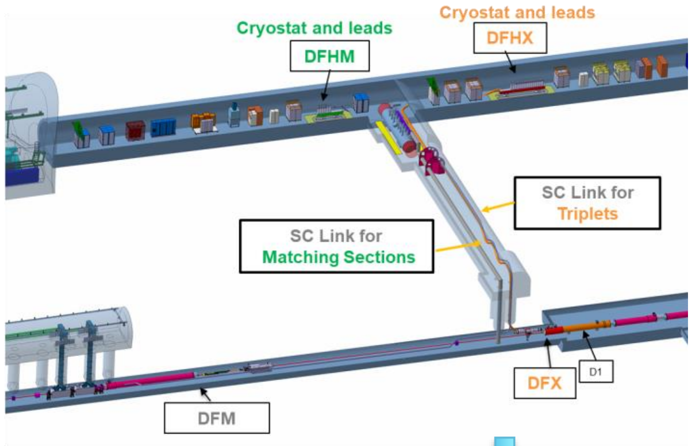






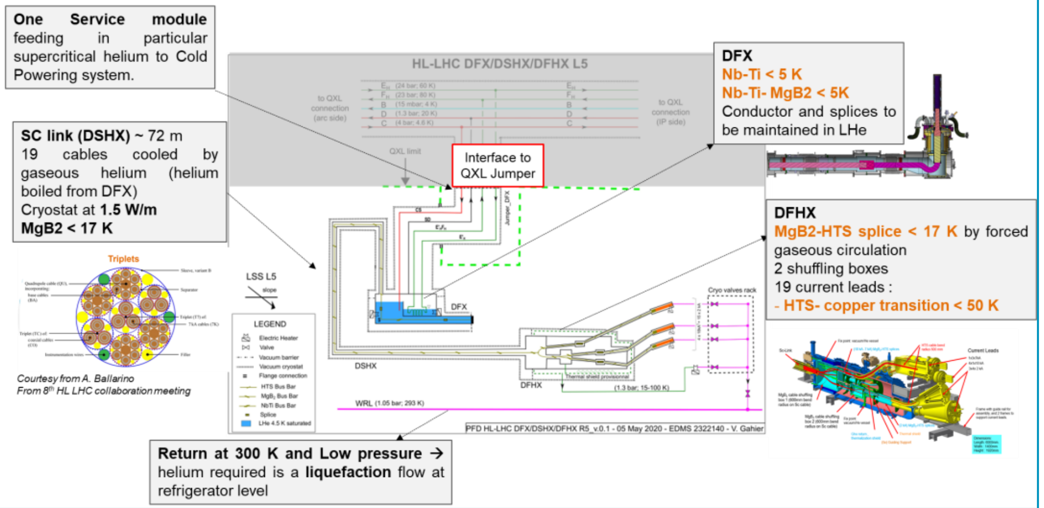


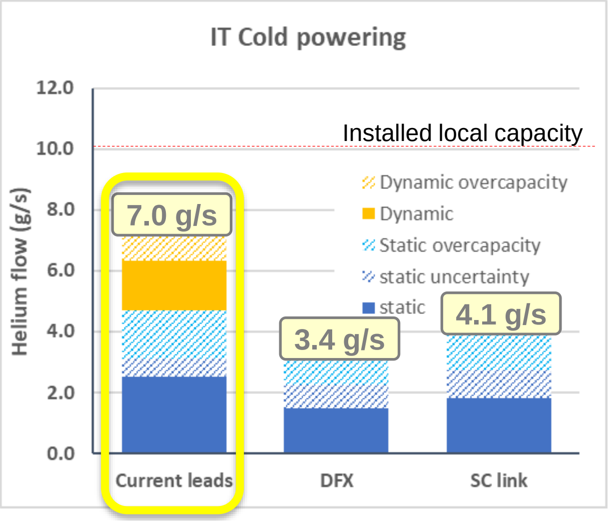
Heat loads on Cold powering systems

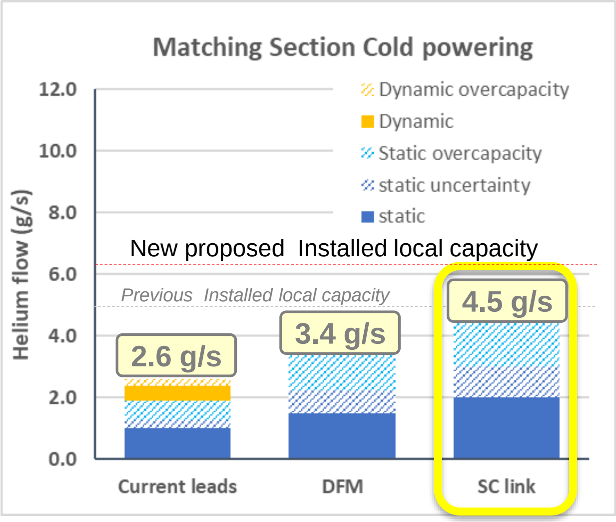


Courtesy from A. Ballarino
From Internal review of DFH detailed design

One cooling circuit from 4.5K to 300 K







- Cold Powering for **IT** is designed for **current lead requirement,**
- Cold Powering for **MS** is designed for **SC link requirement,**
- Refrigerator to be designed for **23.0 g/s.**

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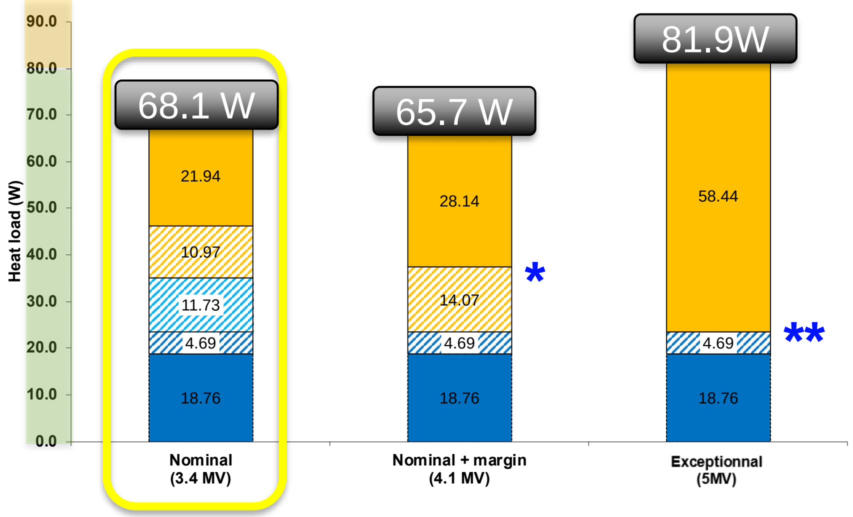
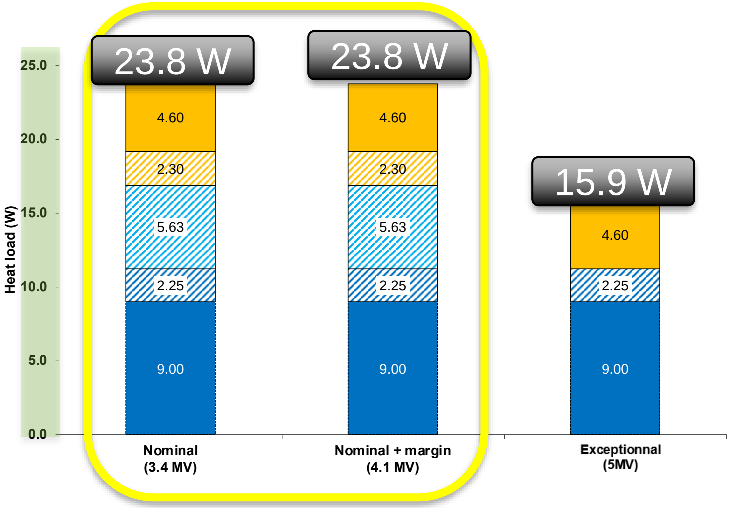
Heat load on Crab Cavities

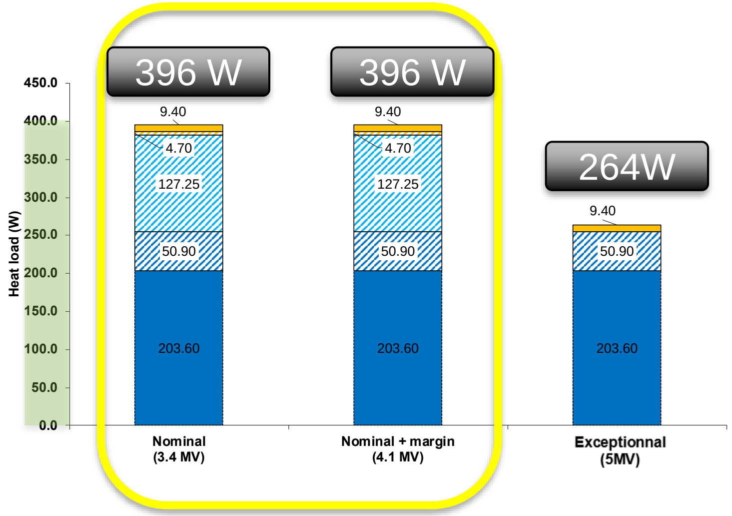
2 K Design Heat Load



4.5 - 20 K Design Heat Load



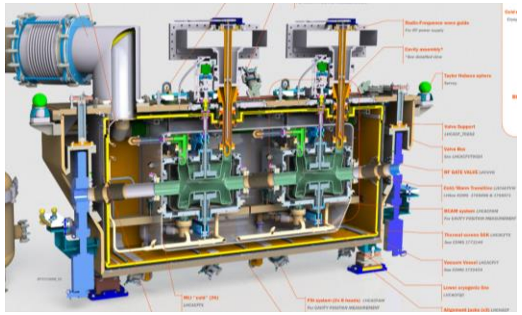
80 K Design Heat Load



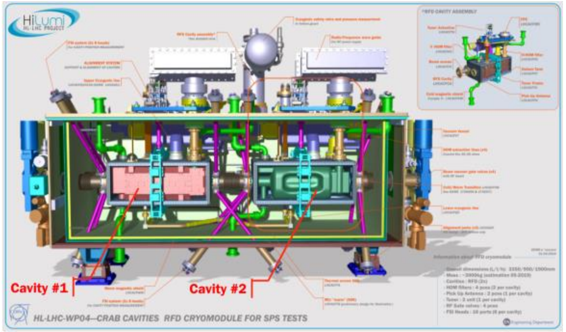
**** Static overcapacity not applied to the 4.1 MV case as already included on RF side for nominal 3.4 MV case***

***** No overcapacity applied to ultimate case***

DQW prototype (length = 3 m)



RFD prototype (length = 3.36 m)



Considerations:

- 3.4 MV – nominal operation
- 4.1 MV – design operation
- 5 MV – exceptional operation