WP9
Heat load review,
Inner Triplet and D1 Heat loads

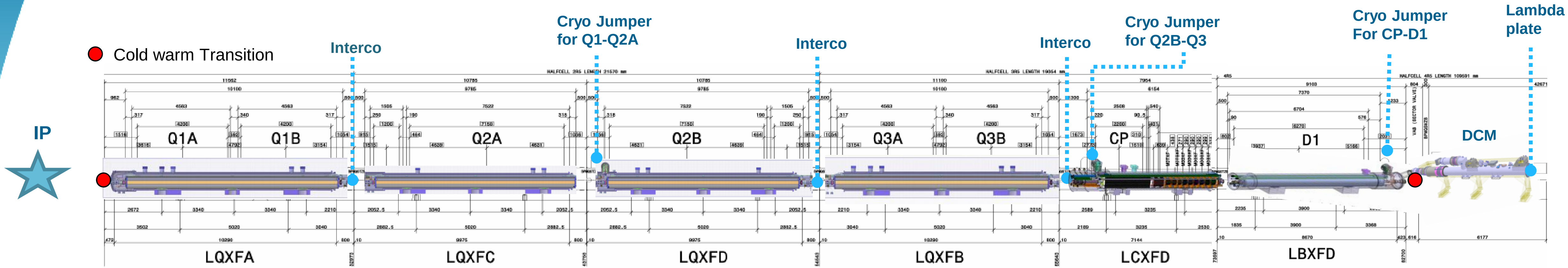
P. Zijm, V. Gahier and M. Sisti on behalf of WP9 and
H. Prin, D. Ramos, L. Williams, Y. Leclercq on behalf of WP3.

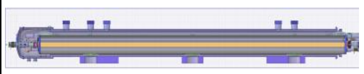
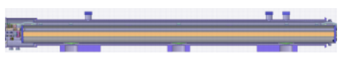
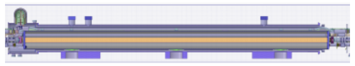
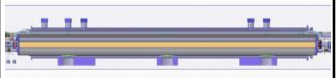
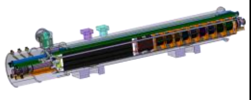
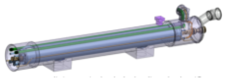
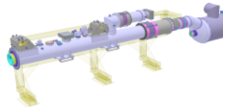
https://indico.cern.ch/event/1019569/
EDMS 2560550
CERN, 27/04/2021

Content

- Inner Triplet Mechanical configuration
- Inner Triplet cooling scheme
- Heat loads Mechanisms
- Static Heat loads
- Dynamic Heat loads
- Design Heat loads
- Evolution
- KPI Benchmark
- Conclusions

Inner Triplet Mechanical configuration

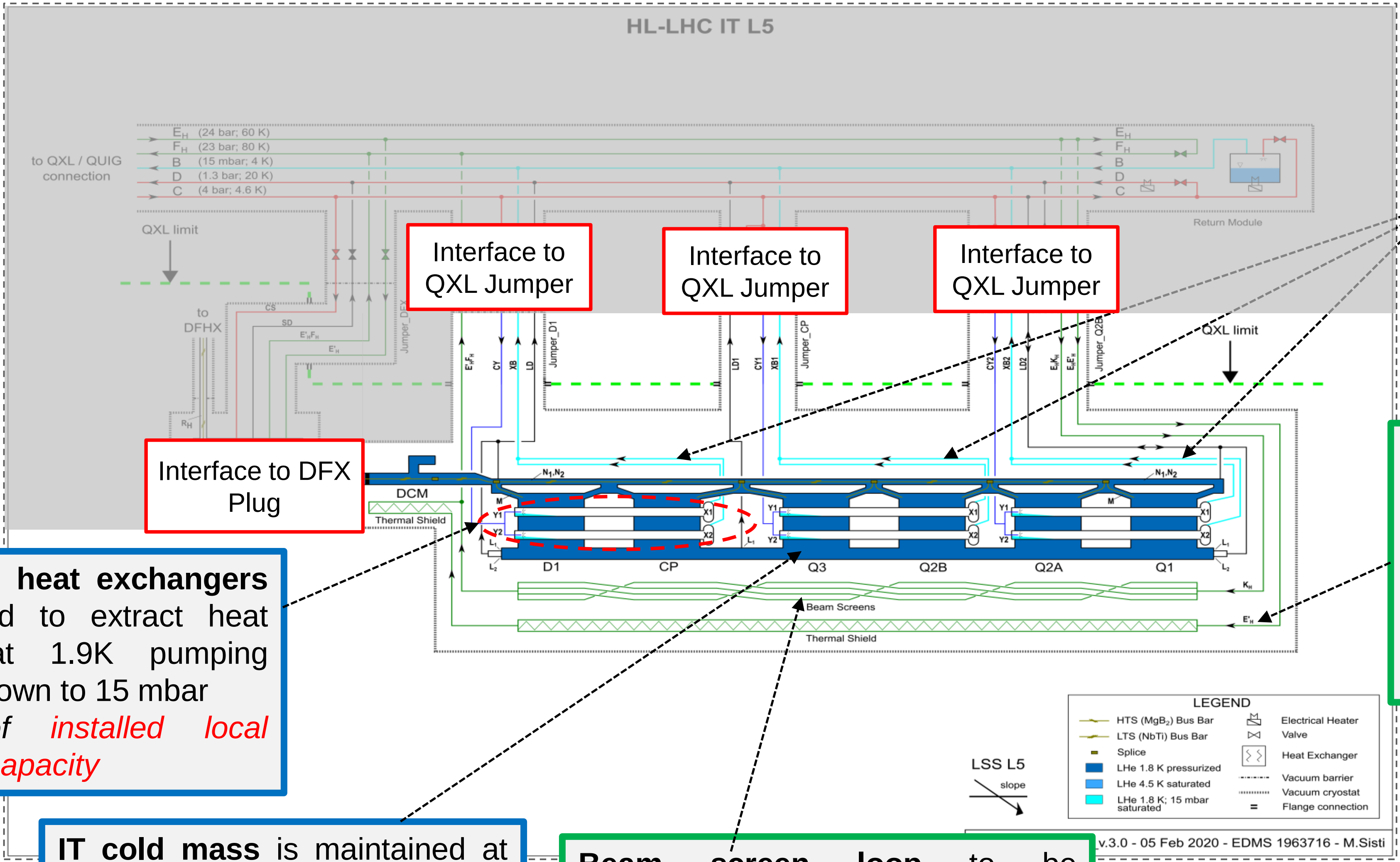


		Q1	Q2A	Q2B	Q3	CP	D1	DCM
								
		Aperture: 150 mm NbSn3 Coated SEY @ 1.1	Aperture: 150 mm NbSn3 Coated SEY @ 1.1*	Aperture: 150 mm NbSn3 Coated SEY @ 1.1	Aperture: 150 mm NbSn3 Coated SEY @ 1.1	NbTi Coated SEY @ 1.1	NbTi Coated SEY @ 1.1	NbTi splices in He II bath
Cryostat length		11.56 m	10.78 m	10.78 m	11.10 m	7.95 m	9.1 m	6.17 m
Heat loads on the cold mass at 1.9 K	Static	++	+	+	++	++	+	+ (plug to SC link)
	Resistive	+/2	+/4	+/4	+/2	+/2	+/4	+/4
	Beam induced	Reduced by coating	Reduced by coating	Reduced by coating	Reduced by coating	Reduced by coating	Reduced by coating	None
	Collision induced	+++++++++	++++++++	++++++++++	+++++++++++	+++++	++++++	Negligible

+ = 20 W (approximately)

* Plug in module not coated; SEY 1.3 (RF Fingers)

Inner Triplet + D1 cooling scheme



3 coolings loops
→ one for each magnet pair
Linked to the cryo-distribution through 3 service modules

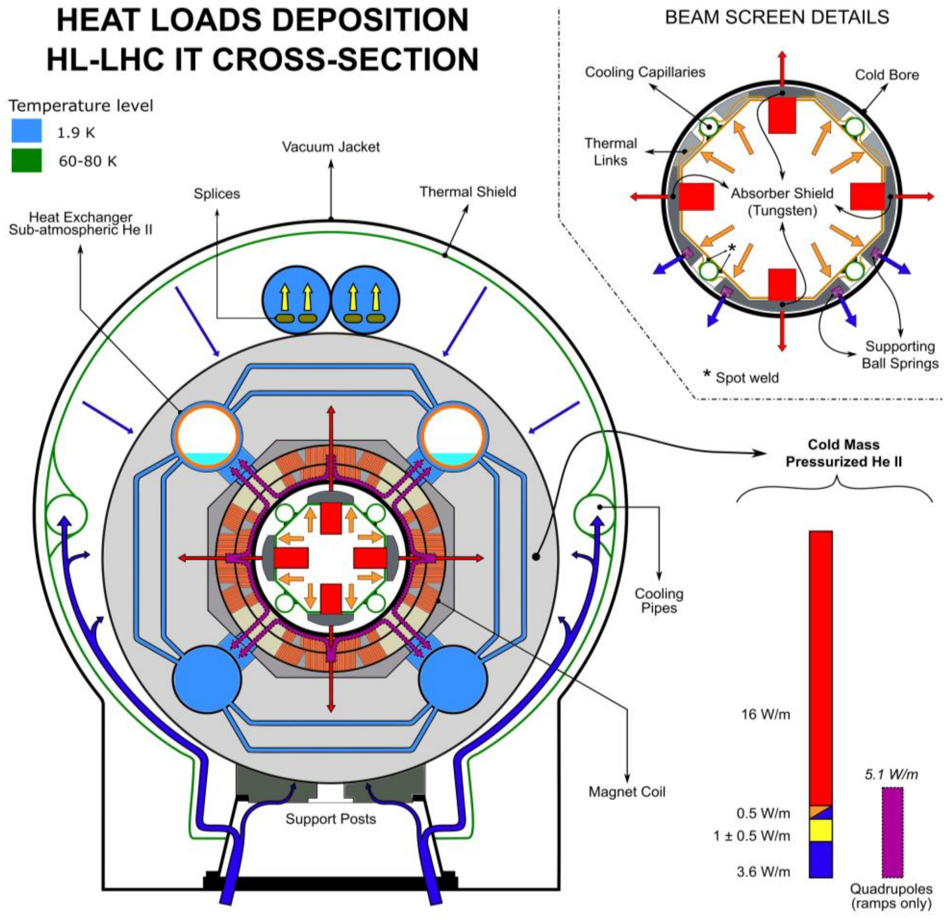
Thermal shield loop at **60-80 K** to limit the heat loads at 1.9 K
Reduction of the heat loads to 1.9K of 90%.

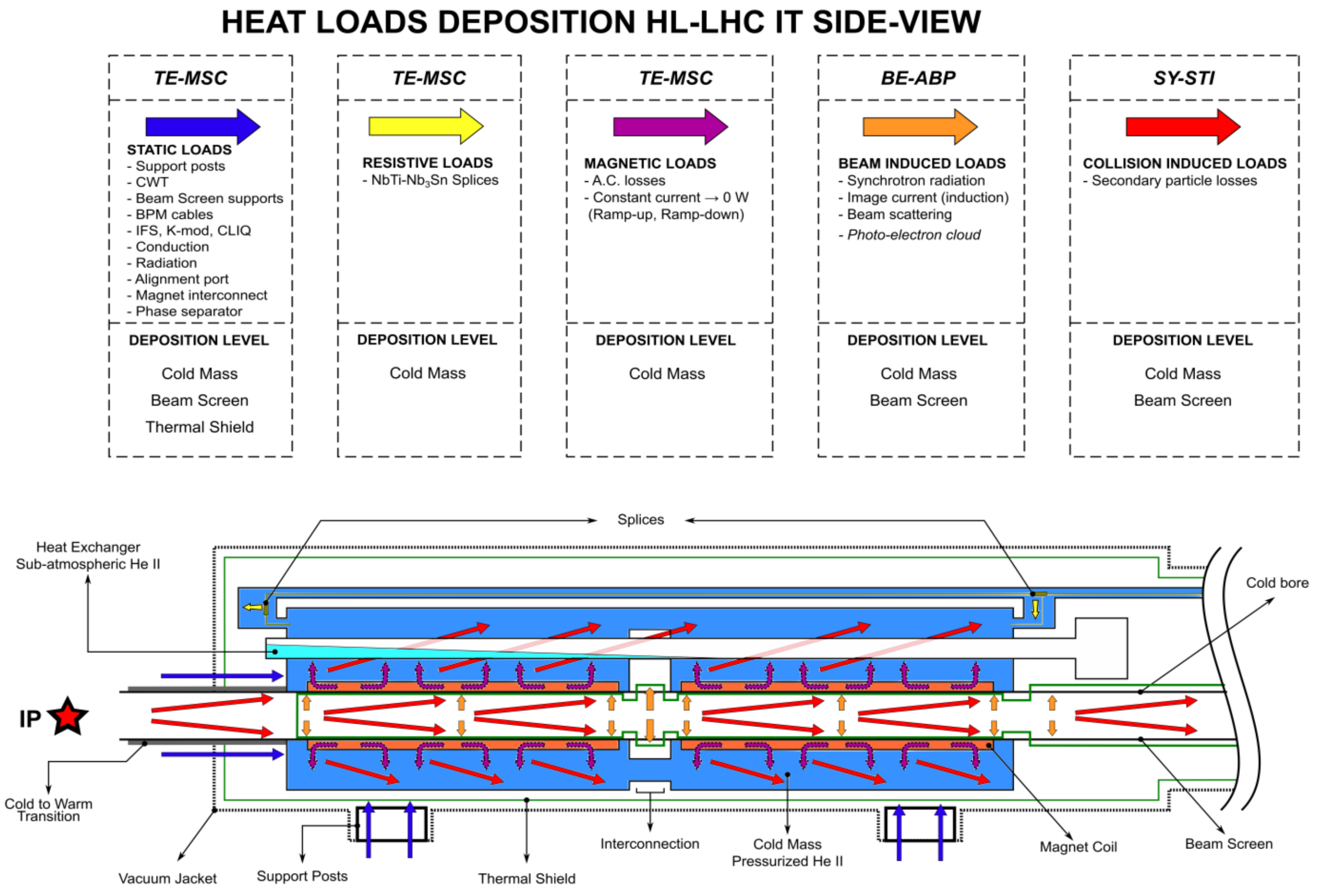
Bayonet heat exchangers are used to extract heat loads at 1.9K pumping helium down to 15 mbar
Limit of installed local cooling capacity

IT cold mass is maintained at **1.9 K** in a **common** He-II bath at 1.3 bar allowing to balance cooling loop capacity.

Beam screen loop to be maintained above **60 K and below 80 K** to avoid cryo pumping and vacuum degassing at cold bore.

Heat loads Mechanisms on a Quadrupole Magnet





Example of Q1 – Static heat loads Identification

XB pumping line
1.57 W to Cold Mass

CLIQ
1.36 W to Cold Mass

Cold Warm Transition
4.89 W to Cold Mass
1.85 W to 60-80 K

K- mod
2.6 W to Cold Mass

IFS
0.9 W to Cold Mass

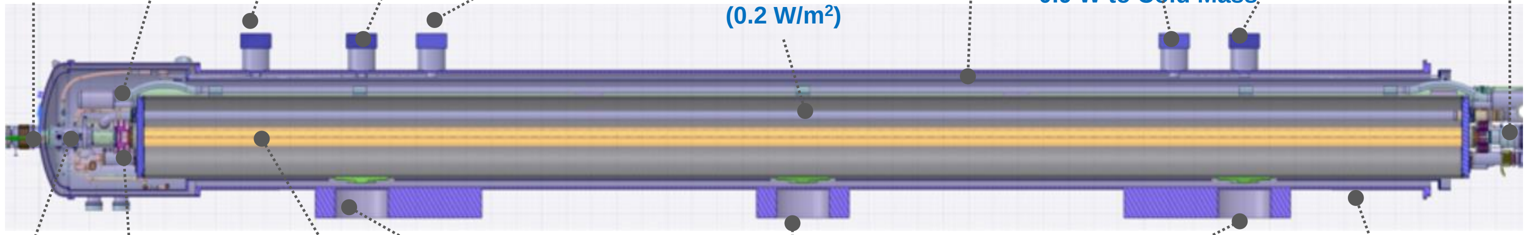
Radiation to Thermal Shield
35 W to Thermal Shield
(1.3 W/m^2)

CLIQ
1.36 W to Cold Mass

Radiation to Cold Mass
4.23 W to Cold Mass
(0.2 W/m^2)

IFS
0.9 W to Cold Mass

Magnet Interconnect
0.1 W to Cold Mass



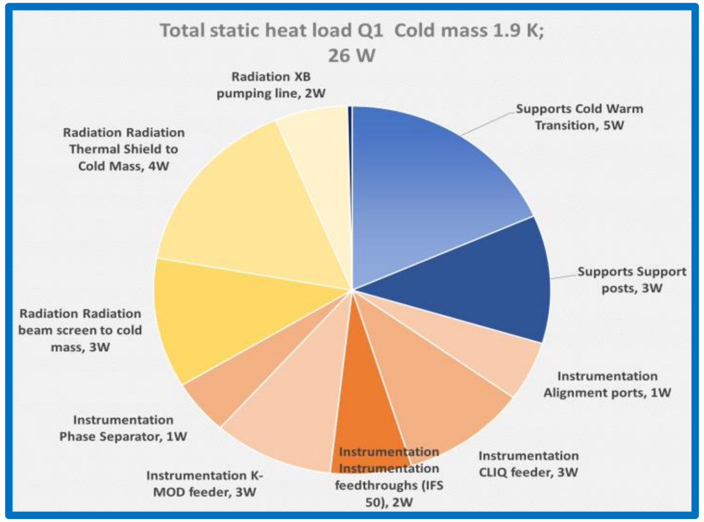
BPM
2.8 W to 60-80 K

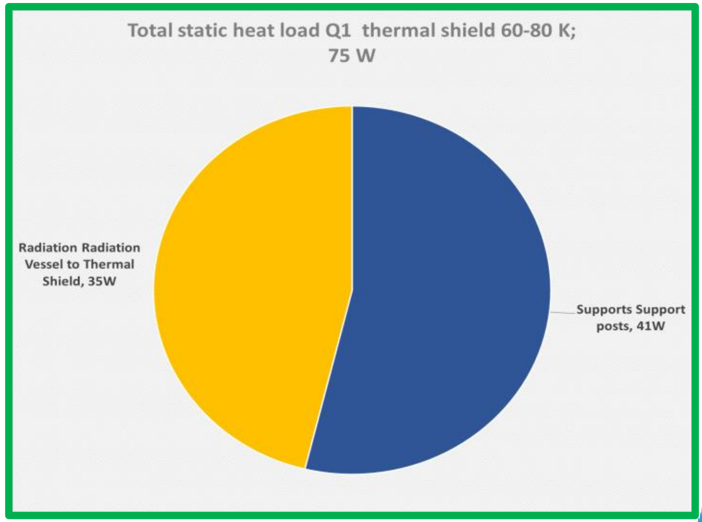
Beam Screen to Cold Mass
3.04 W to Cold Mass

Support Posts
3 W to Cold Mass
40.5 W to Thermal Shield

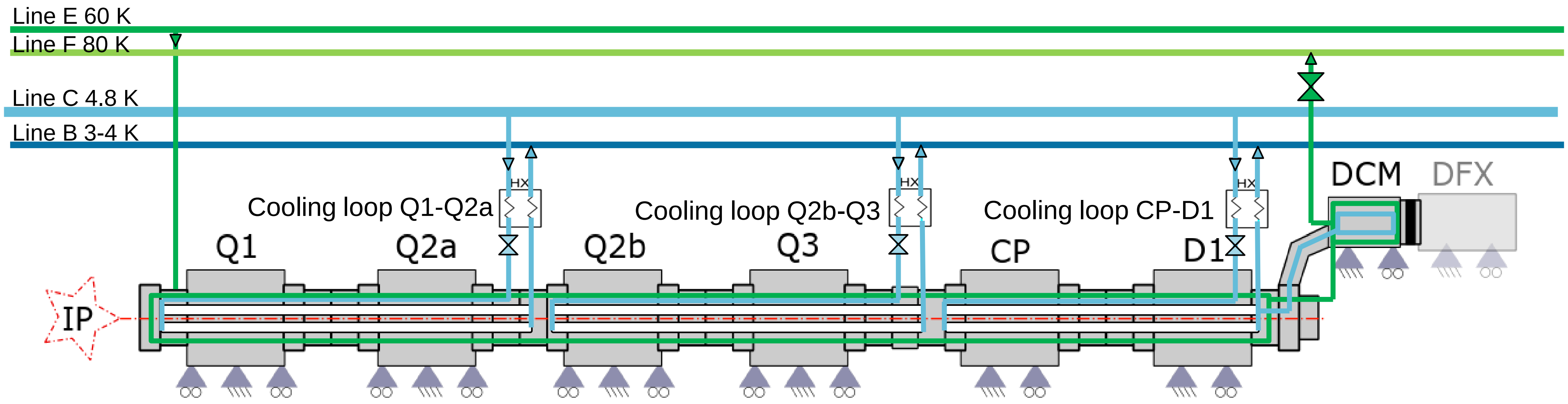
Alignment ports (for 12 units)
1.39 W to Cold Mass

Phase Separator (slope dependent)
1.28 W to Cold Mass





Static heat loads – Sources identification



Cooling loop Q1-Q2a		Cooling loop Q2b-Q3		Cooling loop CP-D1		
Q1	**Q2a**	**Q2b**	**Q3**	**CP**	**D1**	**DCM**
• Support posts • CWT long • K-mod • CLIQ • IFS 402 • Phase Separator* • Alignment ports • Thermal Shield • Beam Screen • Interconnect • XB pumping line	• Support posts • CLIQ • IFS 280/402 • Phase Separator* • Alignment ports • Thermal Shield • Beam Screen • Interconnect • XB pumping line	• Support posts • CLIQ • IFS 402/280 • Phase Separator* • Alignment ports • Thermal Shield • Beam Screen • Interconnect • XB pumping line	• Support posts • K-mod • CLIQ • IFS 402 • Phase Separator* • Alignment ports • Thermal Shield • Beam Screen • Interconnect • XB pumping line	• Support posts • IFS 402/280 • Phase Separator* • Thermal Shield • Beam Screen • Current leads • Interconnect • Beam pumping line** • XB pumping line	• Support posts • IFS 280 • CWT long • Phase Separator* • Thermal Shield • Beam Screen • Interconnect • XB pumping line	• Vacuum barrier • Thermal Shield • Lambda plate • IFS 280

Q1/Q2a/Q2b/Q3/CP/D1/DCM						
• CWT/BPM • Radiation • Support posts	• BPM • Radiation • Support posts	• BPM • Radiation • Support posts	• BPM • Radiation • Support posts	• BPM • Radiation • Support posts • Current leads	• CWT/BPM • Radiation • Support posts	• Radiation • Support

**Phase separator location is slope dependent (2 per magnet pair)*
*** Negligible*

Static heat loads – Systematic ID card created for each element
Example for K-mod

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)	L. Williams / T. Koettig
Department	BE-BI-ML / TE-CRG
Latest Reference	HL-LHC K-mod current feeders Cryolab thermal performance test
EDMS	2279955
Version	3
Date	28-Sep-20

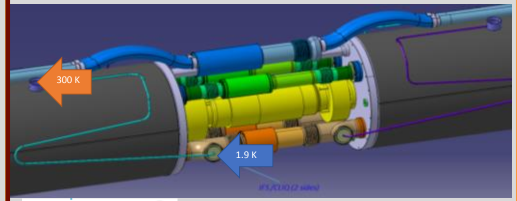
PROPERTIES

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	-

Contact person/department describing the references for data

Summary of data (temperature, material, dimensions)

Schematic and layout

Summary of heat loads

All available in EDMS : https://edms.cern.ch/document/2560668/0.0

Static heat loads – Systematic ID card created for each element
Example for Magnet interconnect

- Hilumi magnet interconnect temperature is at 60-80 K.
- ➢ **Particularity for Hilumi**

- **5 magnet interconnect result in ~21 W heat load to 1.9 K**

Magnet Interconnect short;

Type	HL LHC short magnet interconnect
Function	Connection between magnets
Number of items	4

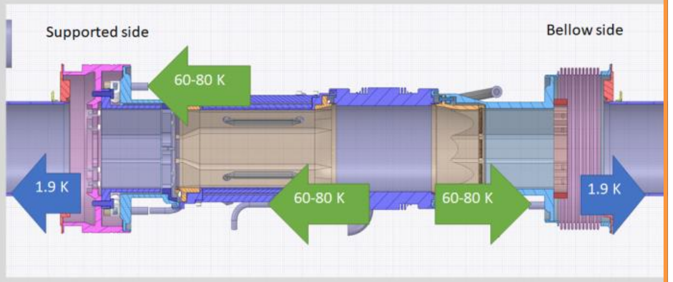
CONTACT

Name(s)	C. Garion
Department	TE-VSC
Latest Reference	-
EDMS	-
Version	-
Date	-

PROPERTIES

Property	Value	Unit	Comment
Temperatures			
Operating Temperature	-	K	
Temperature Intercept	60-80	K	Beam Screen
Temperature Cold	1.9	K	Cold bore

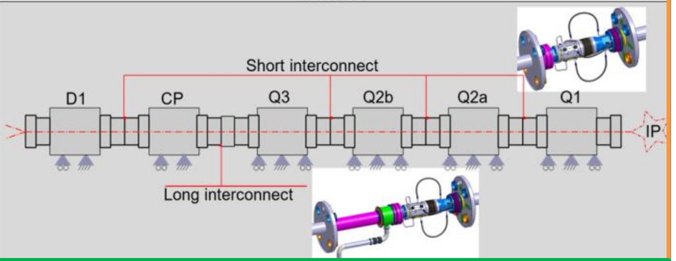
SCHEMATIC



HEAT LOAD components

1.9 K	Value	Unit	Comment
Supported side Conduction	4.1	W	
Bellow side conduction	0.1	W	

LAYOUT



Heat Load Data

Heat load 1.9 K	Value	Unit	Data type	Comment
Static	4.2	W	ANSYS FEA	Per interconnect

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

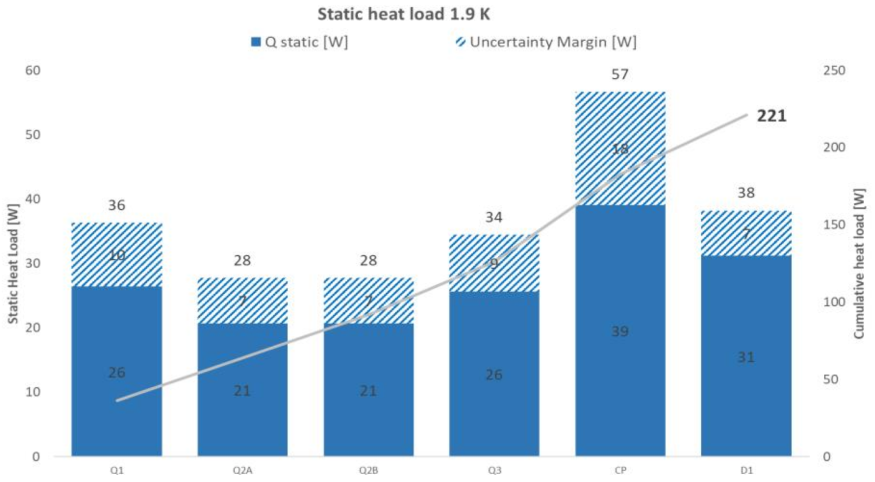
All available in EDMS : https://edms.cern.ch/document/2560668/0.0

Static heat loads on 1.9 K in Watt – Summary for one IT+D1

Cold Mass	Uncertainty factor	Q1		Q2a		Q2b		Q3		CP		D1		DCM		Grand total	
		Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}
Support posts	1.25	3.00	3.75	3.00	3.75	3.00	3.75	3.00	3.75	2.00	2.50	2.00	2.50	-	-	16.00	20.00
Vacuum barrier	1.50	-	-	-	-	-	-	-	-	-	-	-	-	5.00	7.50	5.00	7.50
Radiation Thermal Shield to Cold Mass	1.25	4.23	5.29	4.02	5.03	4.02	5.03	4.16	5.20	2.47	3.09	3.03	3.79			21.93	27.41
Radiation beam screen to cold mass	1.25	3.04	3.80	2.94	3.68	2.94	3.68	3.04	3.80	1.22	1.53	2.21	2.76			15.39	19.24
CWT / Interconnect	1.50	4.89	7.34	4.14	6.21	4.14	6.21	4.14	6.21	4.14	6.21	4.35	6.53			25.80	38.70
IFS type 1	2.00	1.76	3.52	0.88	1.76	0.88	1.76	1.76	3.52	0.88	1.76	-	-			6.16	12.32
IFS type 2	2.00	-	-	0.16	0.32	0.16	0.32	-	-	-	-	0.16	0.32			0.48	0.96
K-MOD	1.25	2.60	3.25	-	-	-	-	2.60	3.25	-	-	-	-			5.20	6.50
CLIQ	1.25	2.72	3.40	1.36	1.70	1.36	1.70	2.72	3.40	-	-	-	-			8.16	10.20
Phase Separator	1.00	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28			7.68	7.68
Alignment ports	1.50	1.39	2.09	1.39	2.09	1.39	2.09	1.39	2.09	-	-	-	-			5.56	8.34
Lambda Plate	1.00	-	-	-	-	-	-	-	-	-	-	-	-	11.60	11.60	11.60	11.60
XB Pumping line	1.25	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97	-	-	9.45	11.81
Local powering current leads	1.50	-	-	-	-	-	-	-	-	25.56	38.34	-	-			25.56	38.34
Total	-	**26.48**	**35.68**	**20.74**	**27.77**	**20.74**	**27.77**	**25.66**	**34.46**	**39.12**	**56.67**	**14.60**	**19.14**	**16.60**	**19.10**	**163.97**	**220.60**
Uncertainty factor	-	1.35		1.34		1.34		1.34		1.45		1.31		1.15		1.35	

- Uncertainty factor (F_{un}) is tailored made for each users according to the uncertainty /room to growth left for each component (refer to Methodology talk for choice of coefficient)
  - This table does **not** include the overcapacity factor (F_{ov}) that is still to be included in design heat load

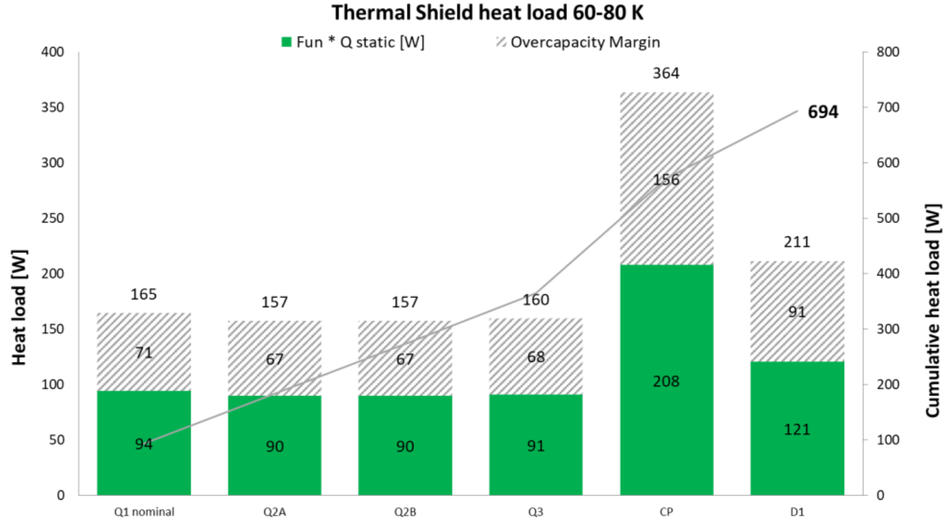
- **Uncertainty factor (F_{un}) decreased with the evolution to detailed design**



Static heat loads on Thermal shield (60-80 K) in Watt – Summary for one IT+D1

Thermal Shield 60-80 K	Uncertainty factor	Q1		Q2a		Q2b		Q3		CP		D1		DCM		Grand total	
		Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}	Q_{static}	F_{un} * Q_{static}
Support posts	1.25	40.50	50.63	40.50	50.63	40.50	50.63	40.50	50.63	27.00	33.75	27.00	33.75	-	-	216.00	270.00
Vacuum barrier	1.50													30.00	45.00	30.00	45.00
Radiation to Thermal Shield	1.25	34.74	43.43	31.37	39.21	31.37	39.21	32.51	40.64	19.29	24.11	23.60	29.50	10.00	12.50	182.88	228.60
Current leads (conduction)	1.50	-	-	-	-	-	-	-	-	100.00	150.00	-	-	-	-	100.00	150.00
Total	-	75.24	94.05	71.87	89.84	71.87	89.84	73.01	91.26	146.29	207.86	50.60	63.25	40.00	57.50	528.88	693.60
Uncertainty factor	-	1.25		1.25		1.25		1.25		1.42		1.25		1.44		1.31	

- Values correspond to heat applied
- Uncertainty factor (F_{un}) is tailor made for each users according to the uncertainty /room to growth left for each component (refer to Methodology talk for choice of coefficient)
- This table does **not** include the overcapacity factor (F_{ov}) that is still to be included in design heat load
- **Uncertainty factor decreased with the evolution to detailed design**



Dynamic heat loads on 1.9 K & 60-80 K
Summary for one IT+D1

Refer to Beam induced heat loads by G. Iadarola (WP2) and
Collisions induced Heat loads by M. Sabate Gilarte (WP10) for more details
Collision induced values from vertical crossing (global worst case)

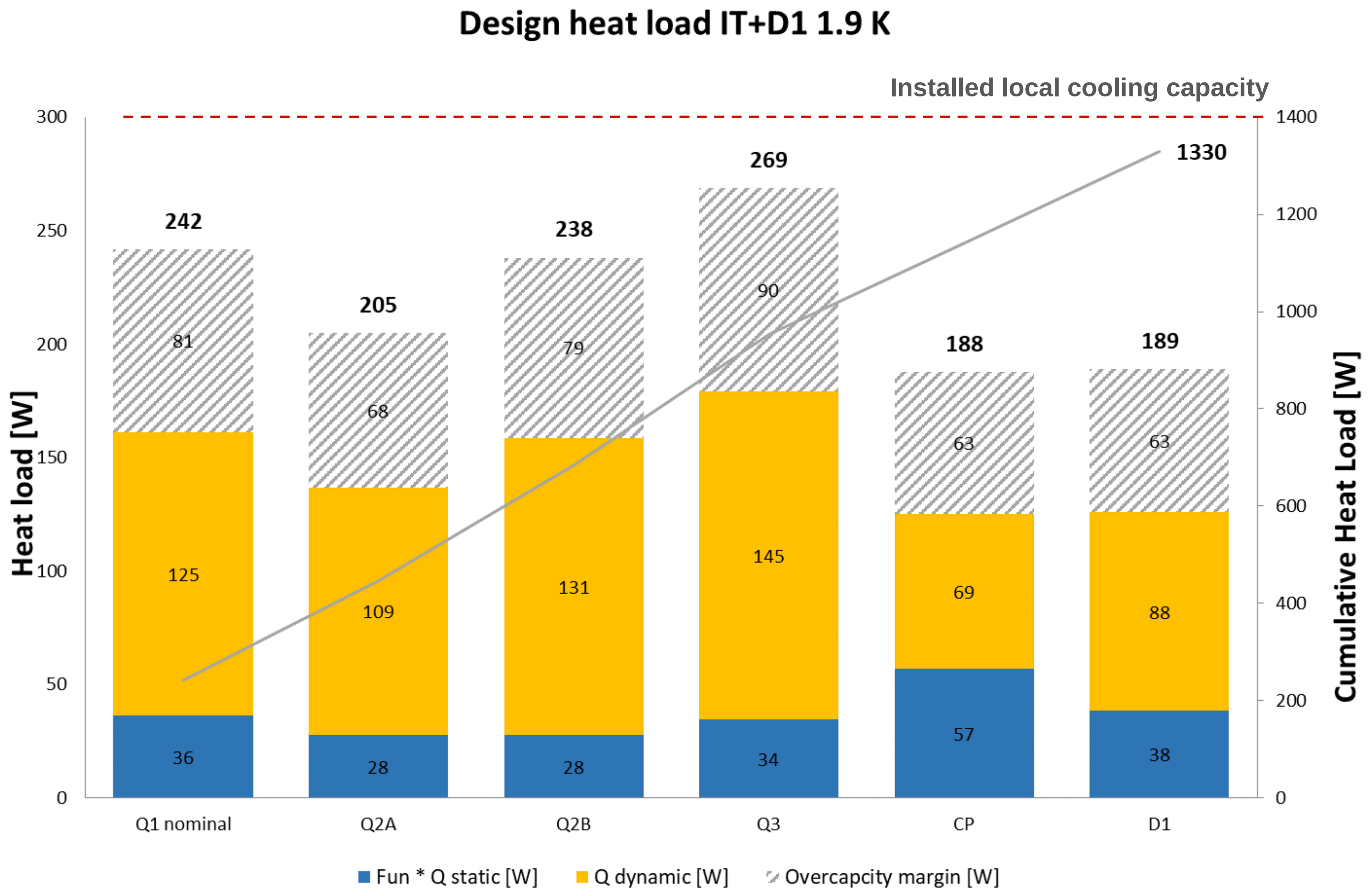
- **Overcapacity on Nominal (5Lo / 7 TeV) dynamic heat loads is taken at 1.5;**
- **Ultimate conditions (7.5 Lo/ 7.5 TeV) are not designing;**
- **Beam induced heat loads at 1.9 K conservative estimate; no additional margin**

Cold Mass		Q1	Q2a	Q2b	Q3	CP	D1	DCM	Grand total	
	Overcapacity factor	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$F_{ov} * Q_{dynamic}$
Resistive	1.50	7.00	4.00	4.00	7.00	0.00	1.00	2.30	25.30	37.95
Beam Induced	1.00	1.00	0.50	0.75	0.75	0.32	0.20	-	3.51	3.51
Collision Induced	1.50	116.89	104.22	126.22	136.89	68.22	84.22	-	636.67	955.00
Total	-	**124.89**	**108.72**	**130.97**	**144.64**	**68.54**	**85.42**	**2.30**	**665.48**	**996.46**

Beam Screen 60-80 K		Q1	Q2a	Q2b	Q3	CP	D1	DCM	Grand total	
	Overcapacity factor	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$Q_{dynamic}$	$F_{ov} * Q_{dynamic}$
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**

HiLumi HL-LHC PROJECT

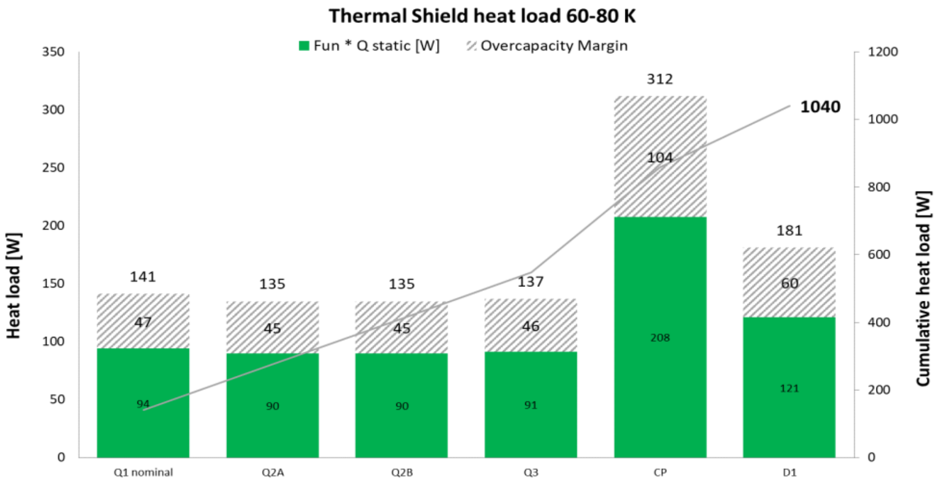
Design heat loads for one IT + D1 @ 1.9 K



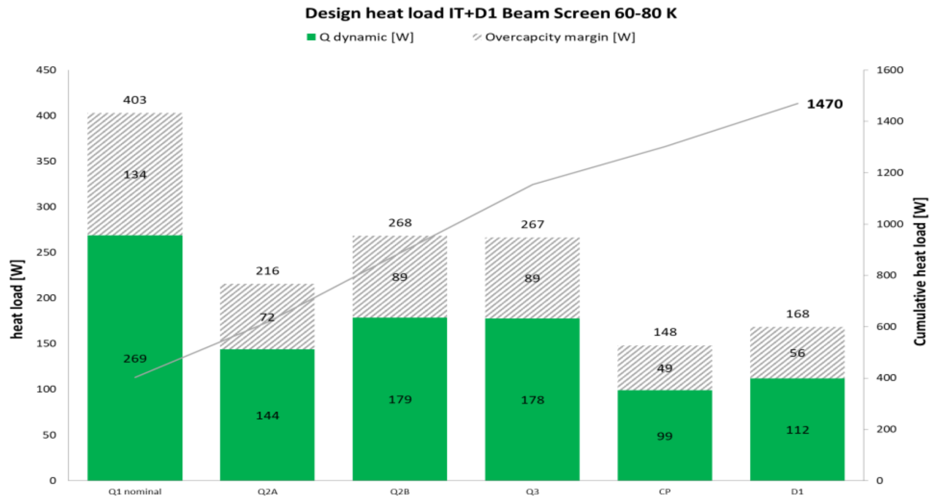
- ***Local cooling capacity for one IT+ D1 is 1330 W at 1.9 K***
- ***Dynamic heat loads account for ~ 75%***
- **Installed local cooling capacity (fixed limit of capacity)**
  - Bayonet heat exchangers in Inner triplet + D1 designed for **1400 W in total**

Design dynamic heat loads for one IT + D1 @ 60-80K

Thermal Shield heat load at 60-80 K



Beam screen heat load at 60-80 K



- ***Thermal shield design heat loads for one IT+D1 is at ~1000 W***
- ***Beam screen data provided by WP2 (beam induced) / WP10 (collisions)***
- ***Beam screen design heat loads for one IT is taken at ~1500 W***
- ***Total design for 60-80 K ~2500 W***

Hilumi KPI benchmark (for information)

		LHC arc*	LHC IT
Cold mass 1.9 K	Static	0.17 W/m	1.25 W/m
	Dynamic	0.45 -0.6 W/m	7.4 W/m
	Installed	0.9 W/m	10 W/m***
Beam screen 4.5 -20 K	Static	0.14 W/m	0.13 W/m
	Dynamic	1.7 W/m**	2.4 W/m
	Installed	2.4W/m/aperture	-
Thermal Shield 50-75 K	Static	4.5 W/m	-

* Static are without contingencies from Design report
** Nominal case is indicated
*** For 500W bayonet exchanger initially installed- was changed to 300 W

		HL-LHC IT + D1
Cold mass 1.9 K	F_{un} x Q_{static}	3.6 W/m
	Q_{design}	21.2 W/m
	Installed*	22.8 W/m
Beam screen 60-80 K	Q_{design}	21.2 W/m
Thermal Shield 60-80 K	F_{un} x Q_{static}	11.2 W/m
	Q_{design}	16.8 W/m

* Considering installed local capacity at 1400 W for HL-LHC

- Static heat loads were highly optimized for LHC due to the overall length to be considered;
- Contribution on 1.9 K is consequently higher on HL-LHC due to the Luminosity

Evolution of heat loads 2016 – 2020 – 2021 for one IT+D1

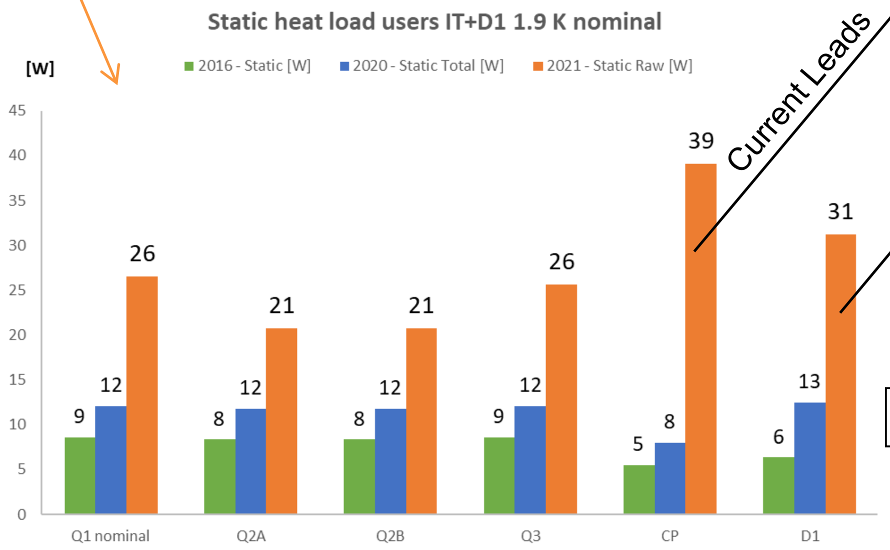
- **Evolution of heat loads due to maturing design as well as addition of new components**
  - Static heat loads increased significantly
  - Dynamic heat loads relatively stable

Main additions to static heat loads
60-80 K Magnet interconnect
60-80 K Thermal shield radiation
Local powering current leads
DCM module
XB pumping line

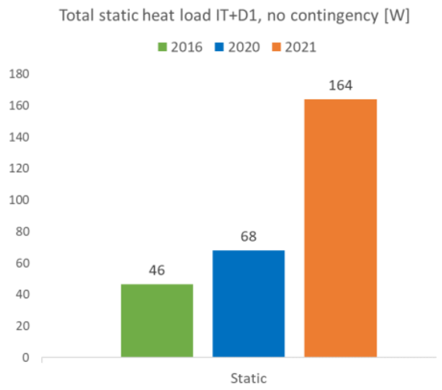
~4 W per magnet due to Interco at 60-80 K. (21 W total)

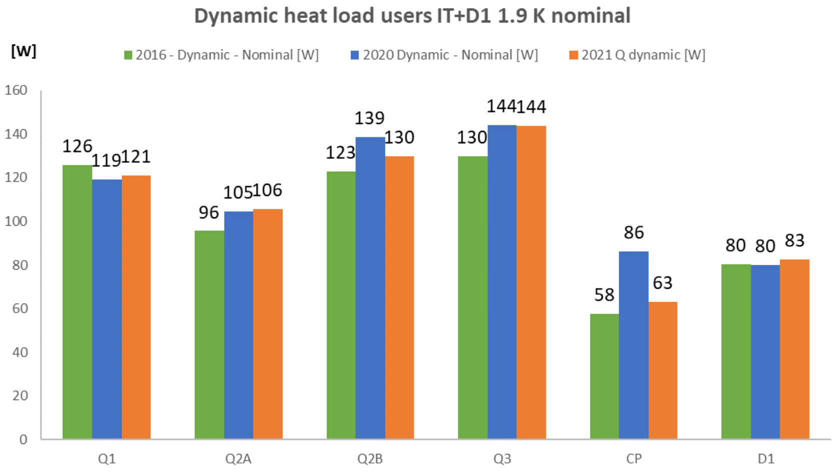
Increase due to change of design of the local powering 26 W : Current leads

Addition of cold diode module 17 W : DCM



Total





Conclusions

- Detailed evaluation of heat loads
  - ID cards to validate configuration and heat loads
- Revised baseline
  - latest configuration and estimates.
- Review of the heat loads
  - Confirmation nothing puts future performance at risk.
- The total design heat load at 1.9 K is very close to the limit of the installed local cooling capacity.

All parties involved shall be aware of the situation

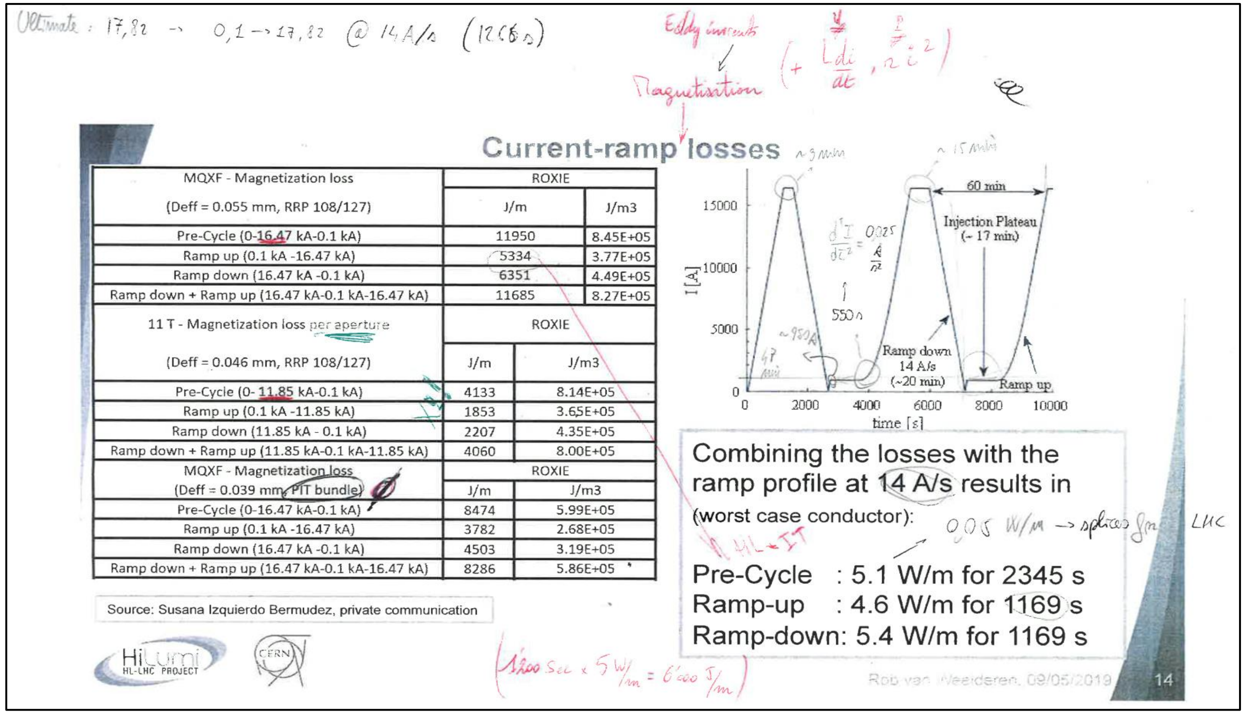
→ It is time to freeze the configuration and commit on these figures considering fabrication and installation phases

Thanks for your time and attention

Thanks for your time and answers

Magnetization heat loads (explanation of a fill)

- Heat load due to magnet ramping. Occurs before collision is started and therefore does not impact refrigerator capacity requirement.



Current-ramp losses

MQXF - Magnetization loss (Deff = 0.055 mm, RRP 108/127)	ROXIE J/m	ROXIE J/m3
Pre-Cycle (0-16.47 kA-0.1 kA)	11950	8.45E+05
Ramp up (0.1 kA -16.47 kA)	5334	3.77E+05
Ramp down (16.47 kA -0.1 kA)	6351	4.49E+05
Ramp down + Ramp up (16.47 kA-0.1 kA-16.47 kA)	11685	8.27E+05
11 T - Magnetization loss per aperture (Deff = 0.046 mm, RRP 108/127)	**ROXIE J/m**	**ROXIE J/m3**
Pre-Cycle (0- 11.85 kA-0.1 kA)	4133	8.14E+05
Ramp up (0.1 kA -11.85 kA)	1853	3.65E+05
Ramp down (11.85 kA - 0.1 kA)	2207	4.35E+05
Ramp down + Ramp up (11.85 kA-0.1 kA-11.85 kA)	4060	8.00E+05
MQXF - Magnetization loss (Deff = 0.039 mm, PIT bundle)	**ROXIE J/m**	**ROXIE J/m3**
Pre-Cycle (0-16.47 kA-0.1 kA)	8474	5.99E+05
Ramp up (0.1 kA -16.47 kA)	3782	2.68E+05
Ramp down (16.47 kA -0.1 kA)	4503	3.19E+05
Ramp down + Ramp up (16.47 kA-0.1 kA-16.47 kA)	8286	5.86E+05

Source: Susana Izquierdo Bermudez, private communication

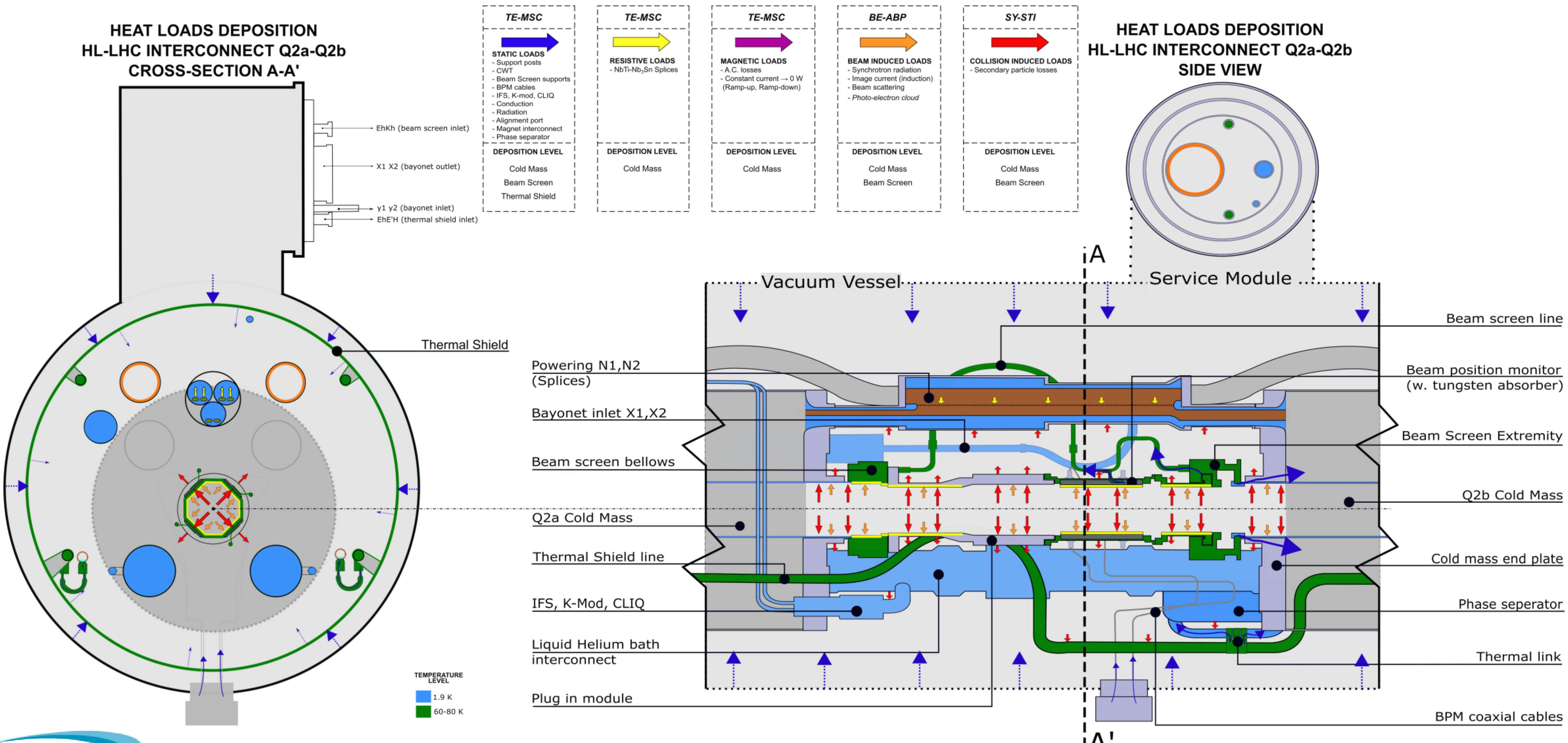
Combining the losses with the ramp profile at 14 A/s results in (worst case conductor):

Pre-Cycle : 5.1 W/m for 2345 s
Ramp-up : 4.6 W/m for 1169 s
Ramp-down: 5.4 W/m for 1169 s

Rob van Weelderen, 09/05/2019 14

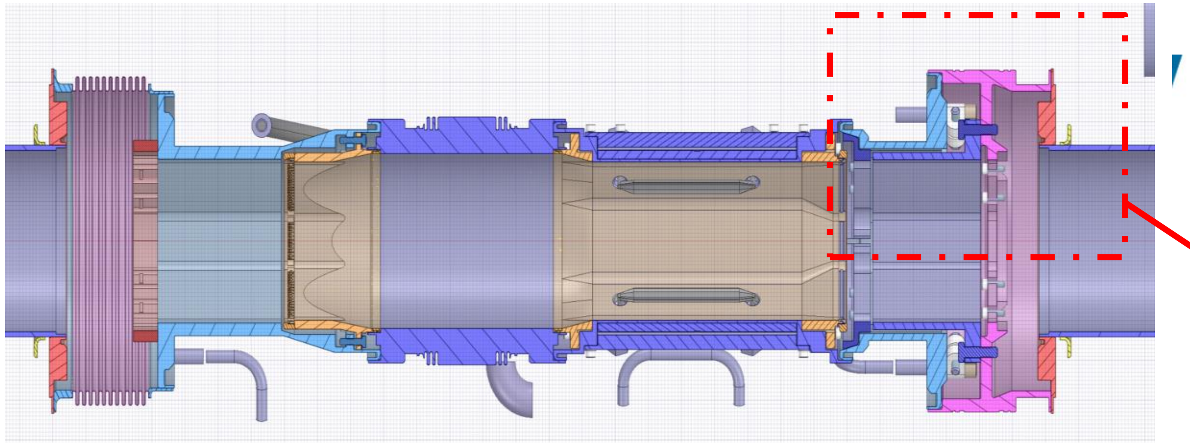
THESE HEAT LOADS ARE ONLY PRESENT EITHER DURING RUMP-UP OR RAMP-DOWN OF THE "Q" MAGNETS (DIPOLES ARE NEGLIGIBLE)

Heat load mechanism in the warm Hilumi interconnect



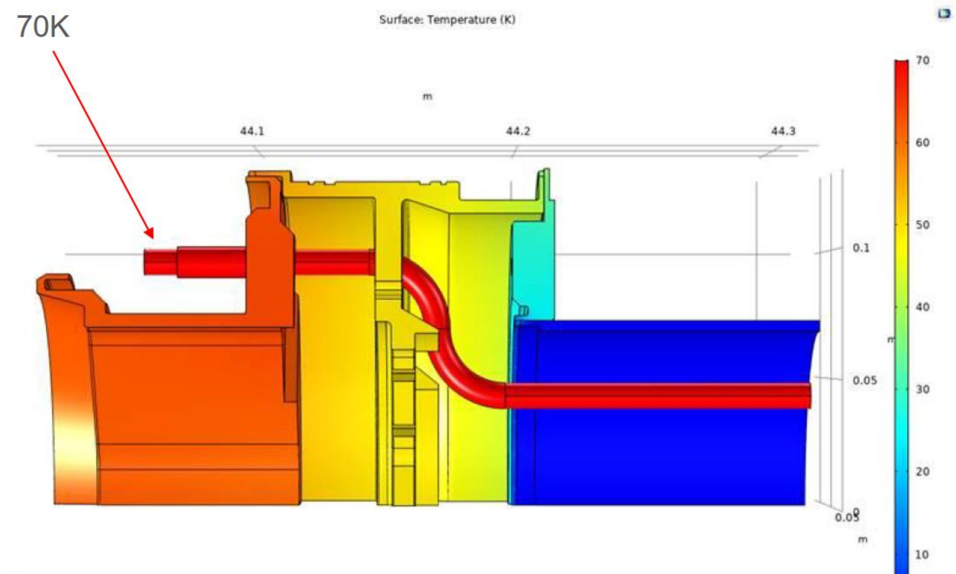
Particularity of the Hilumi interconnect

Interconnect between triplet magnets



Courtesy C. Garion

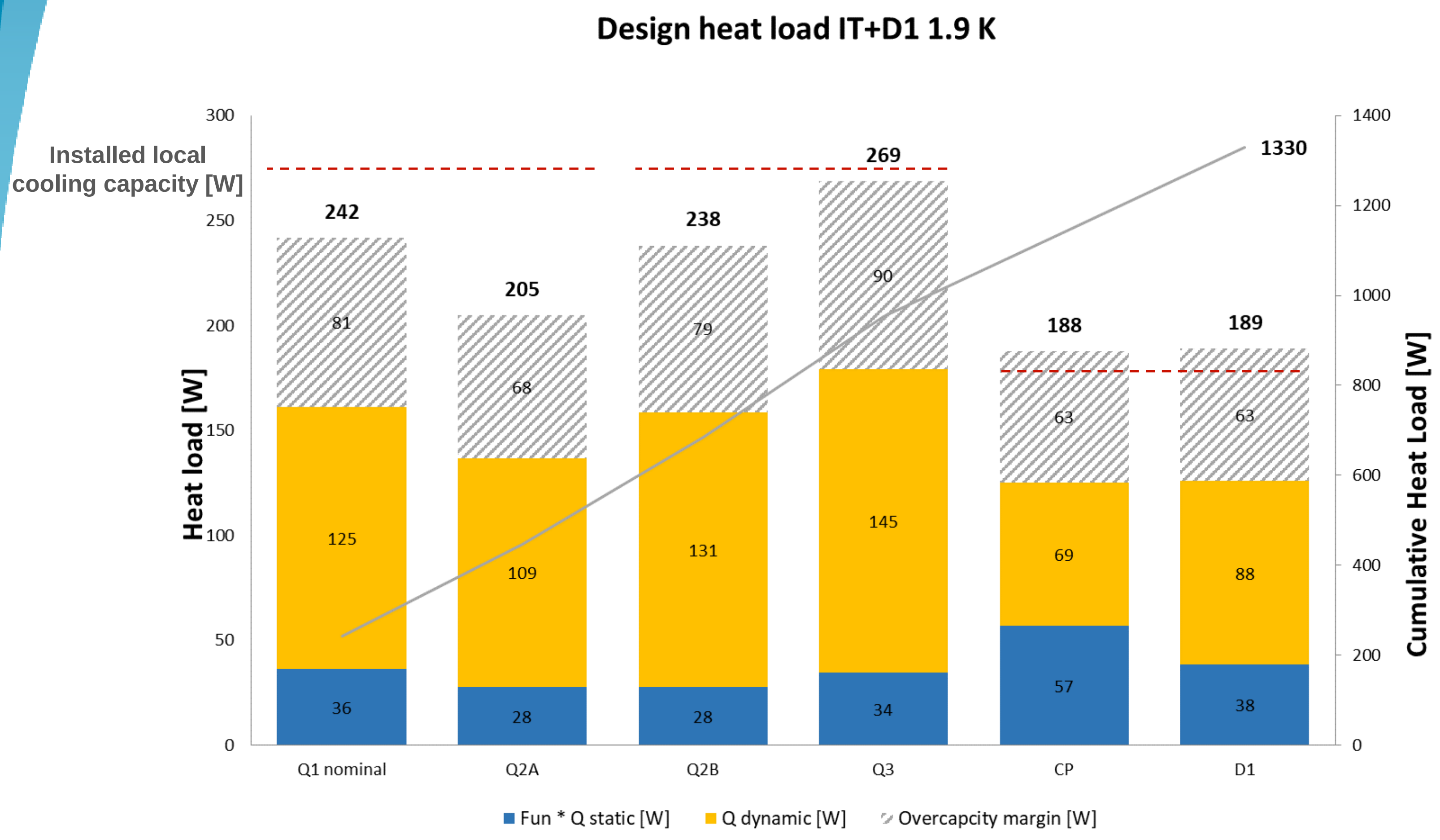
Heat load on the 1.9K cold bore



Temperature profile in the triplet interconnection (fixed point)

- Hilumi magnet interconnect temperature is at 60-80 K.
- Particularity for Hilumi
- **5 magnet interconnect result in ~21 W heat load to 1.9 K**

Installed local cooling capacity



Heat Load Constrains

Bayonet limit (Dash line)

~550 W (for Q1 to Q3 with Ø68mm) and **~350 W** (for CP-D1 with Ø54mm) → due to flow constrains ($\dot{v} \leq 7\ m/s$) at each bayonet HX (Line X). (For $\dot{q} \approx 23.3\ W/g;\ \rho \approx 455\ g/m^3$)