Tuning the Cryogenic system to HiLumi Luminosity, or vice-versa, or a mix of „knobs“ for it...

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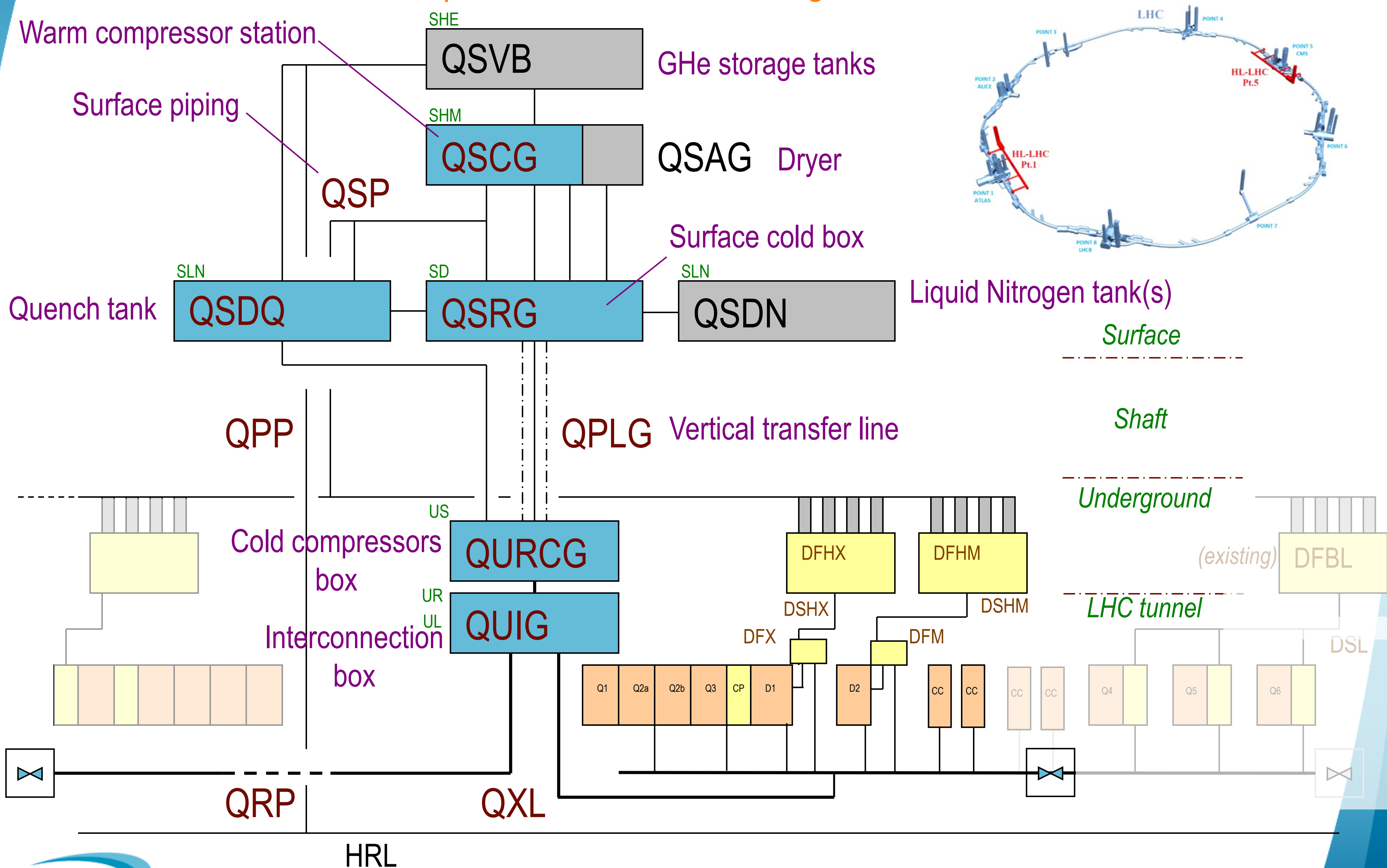
On behalf of the Cryo team for HiLumi
HL-LHC / Work Package 9 / Heat Load Working Group

CERN

P1/P5 Cryogenic architecture

15 kW equivalent at 4.5 K, including 3 kW at 1.8 K



Major concerns and present studies

- Revision of heat loads at user interface and conversion into refrigeration capacity requirements

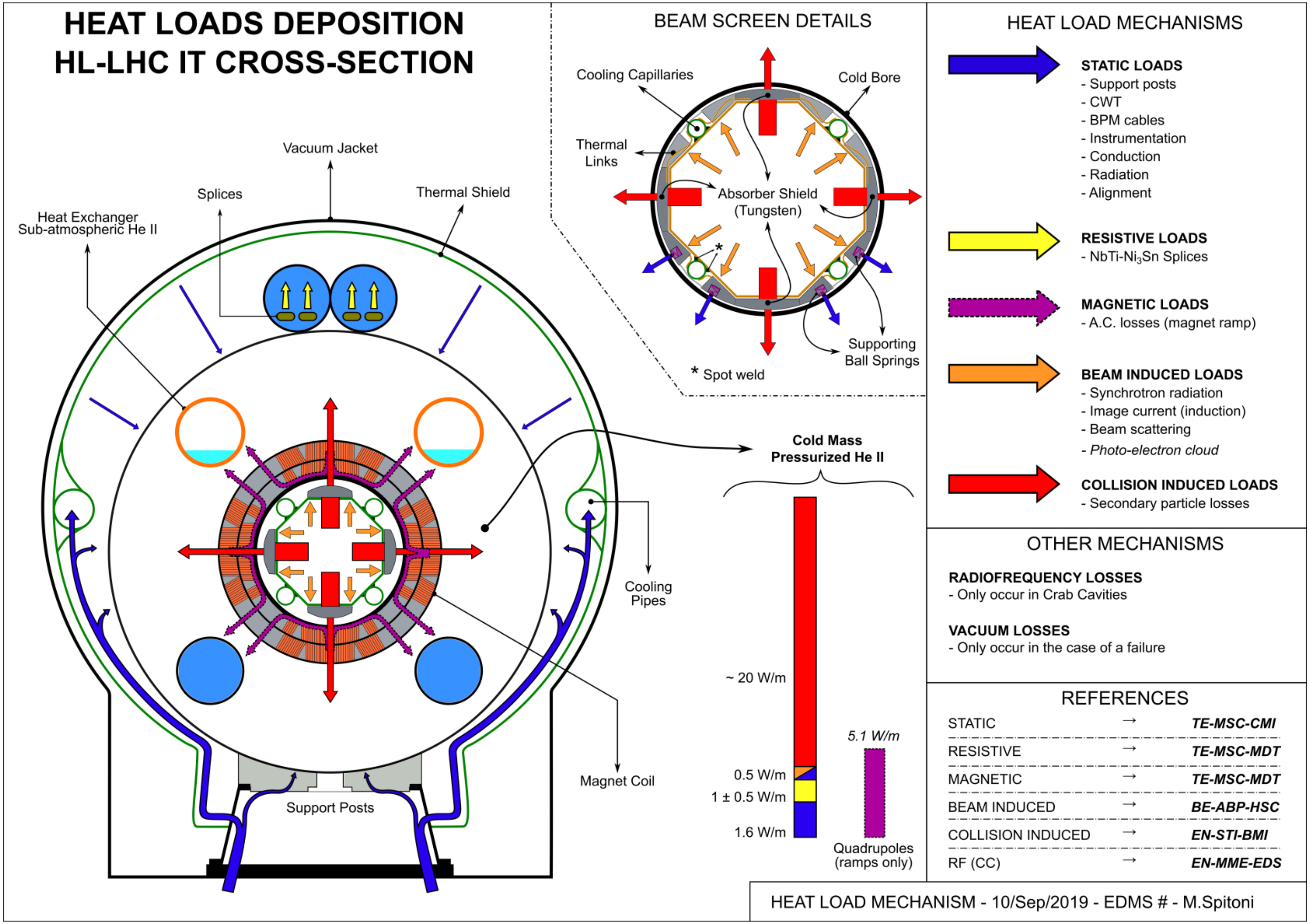
(Baseline few years old with few changes identified, not that bad but, real need for a complete and comprehensive update, including BS temperature level, sc link requirements, impact of Matching Section Optimisation, management of transients)

- Management of dynamic heat loads

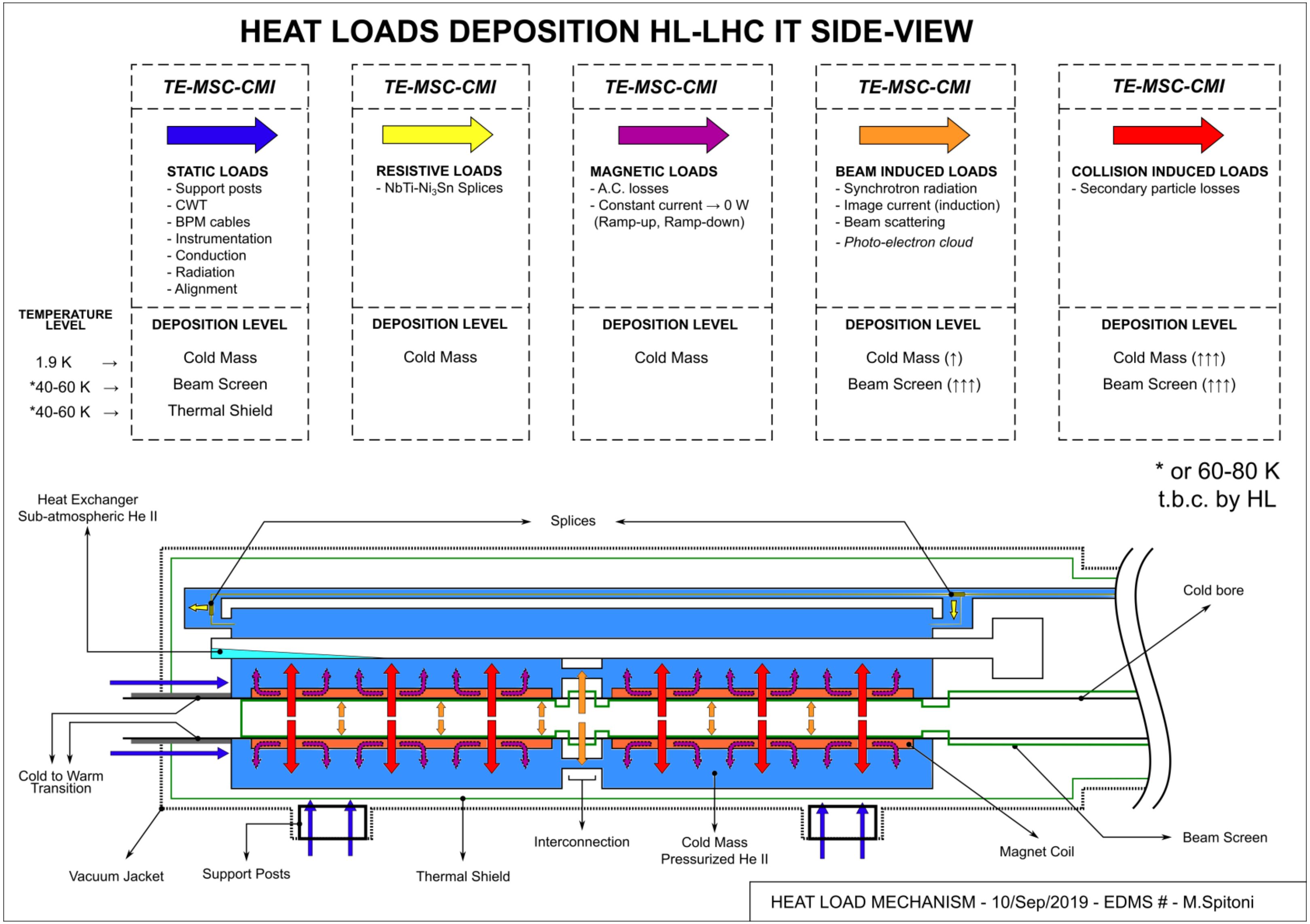
  The real specificity of HiLumi for Cryogenics!

  - Maximum possible done with QXL Cryoline, but 10x shorter than QRL (smaller volumes) and so far not enlarged in machine tunnel, a moderate possibility in service galleries but not much gain expected
  - Active control required, with reliable instrumentation and pre-loading heaters in 100 kGy environment

Heat loads mechanisms - Cross Section



Heat loads mechanisms – Side View



Heat load mechanisms - summary

Static → **occurs at any time** with the same magnitude

Magnetic → occurs only during current **ramp-up** and **ramp-down**

Specific load → 5.1 W/m   Magnetic length at cold → 31.1 m

Resistive → goes with the square of current intensity in **splices**

Splices resistance → 1 nΩ   Total number of splices → 78   CP local powering

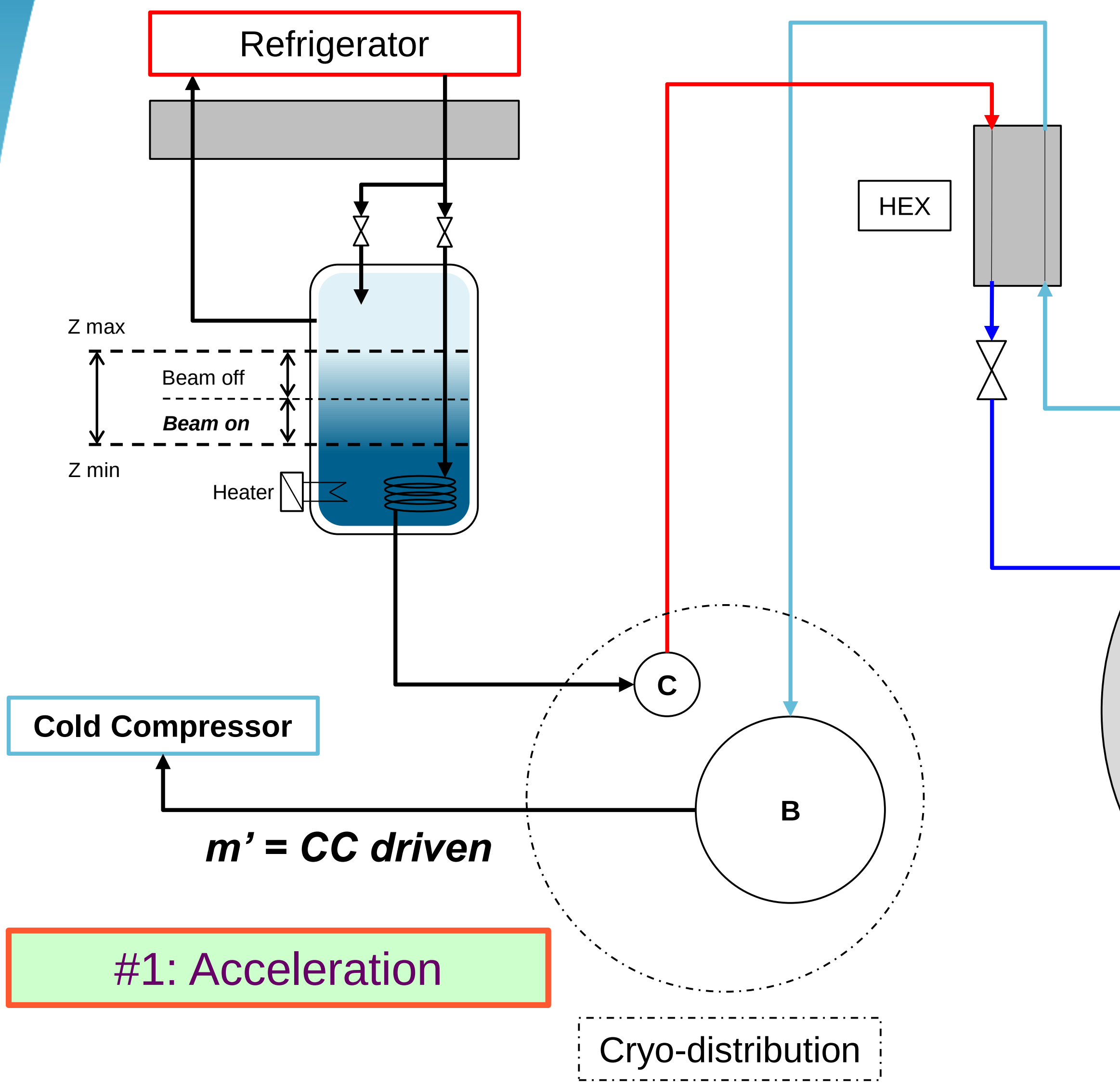
Beam induced → occurs as long as the **beam is circulating**

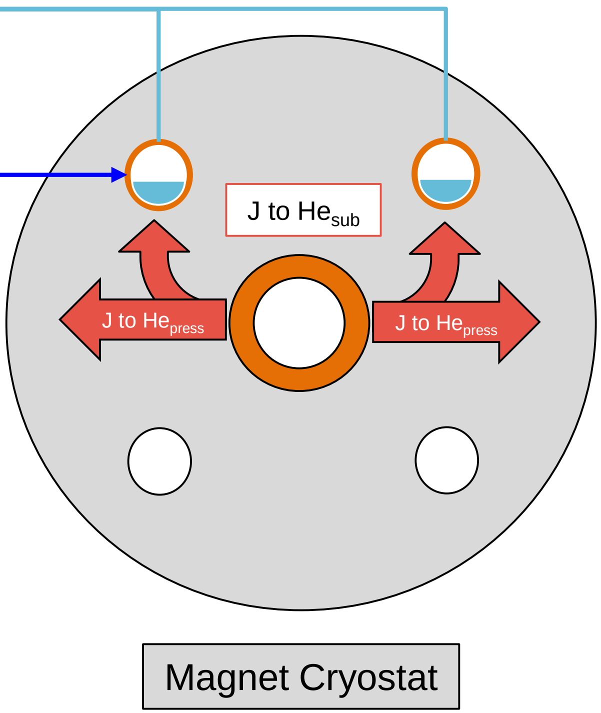
Assumed linear with injection → 17 min   Beam dump assumed instantaneous

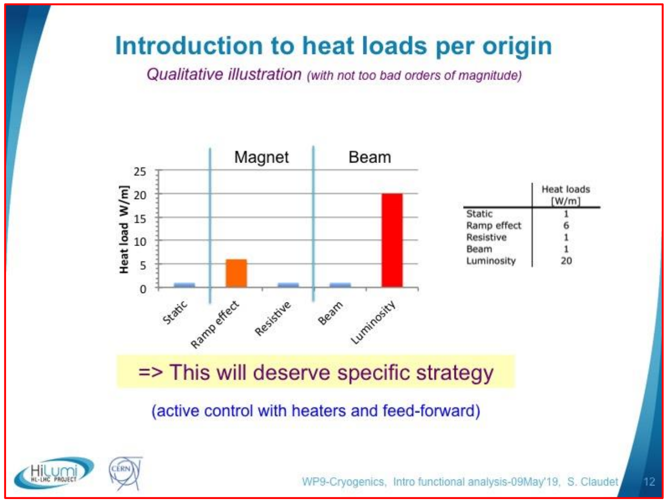
Collision induced → suddenly occurs when an experiment takes place

Required time to regime → 5 min   Collision time could be higher

Schematic model







Strategies for pre-loading

The action should be OK for both *Cold Compressor* and *Bayonet* operations

#2: Pre-load + active controls

OK for Cold Compressor

OK for Bayonet

Type of action	*Remarks*	*YES/NO*
Cold Compressor (CC)	Unstable with foreseen phase separator	**NO**
Valve box (QUI)	Not yet foreseen a phase separator for this	**NO**
Return Module (RM)	Stable, foreseen But, no help for magnets Buffer volume? Temperature in magnets?	YES
Heater as foreseen	Radiation dose	**NO**
Heater (shielded)	Requires 20 cm of steel, not foreseen yet	**NO**
Heater (shielded by CM)	Feasibility to be discussed (MSC)	YES
Gaseous He (serpentine)	Feasibility to be discussed (MSC + CRYO)	YES

To substitute electrical heaters with He serpentine is an interesting possibility → under study

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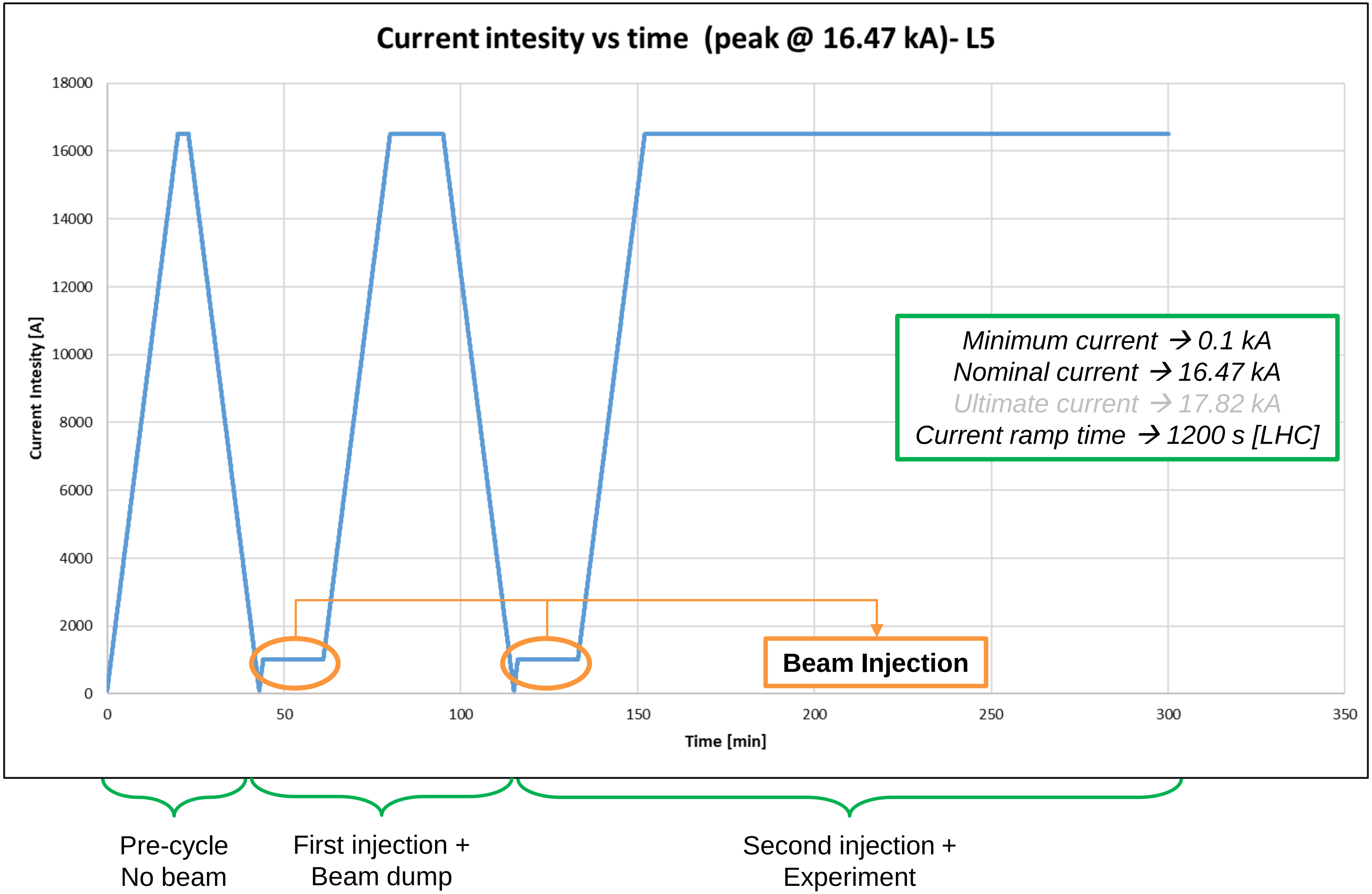
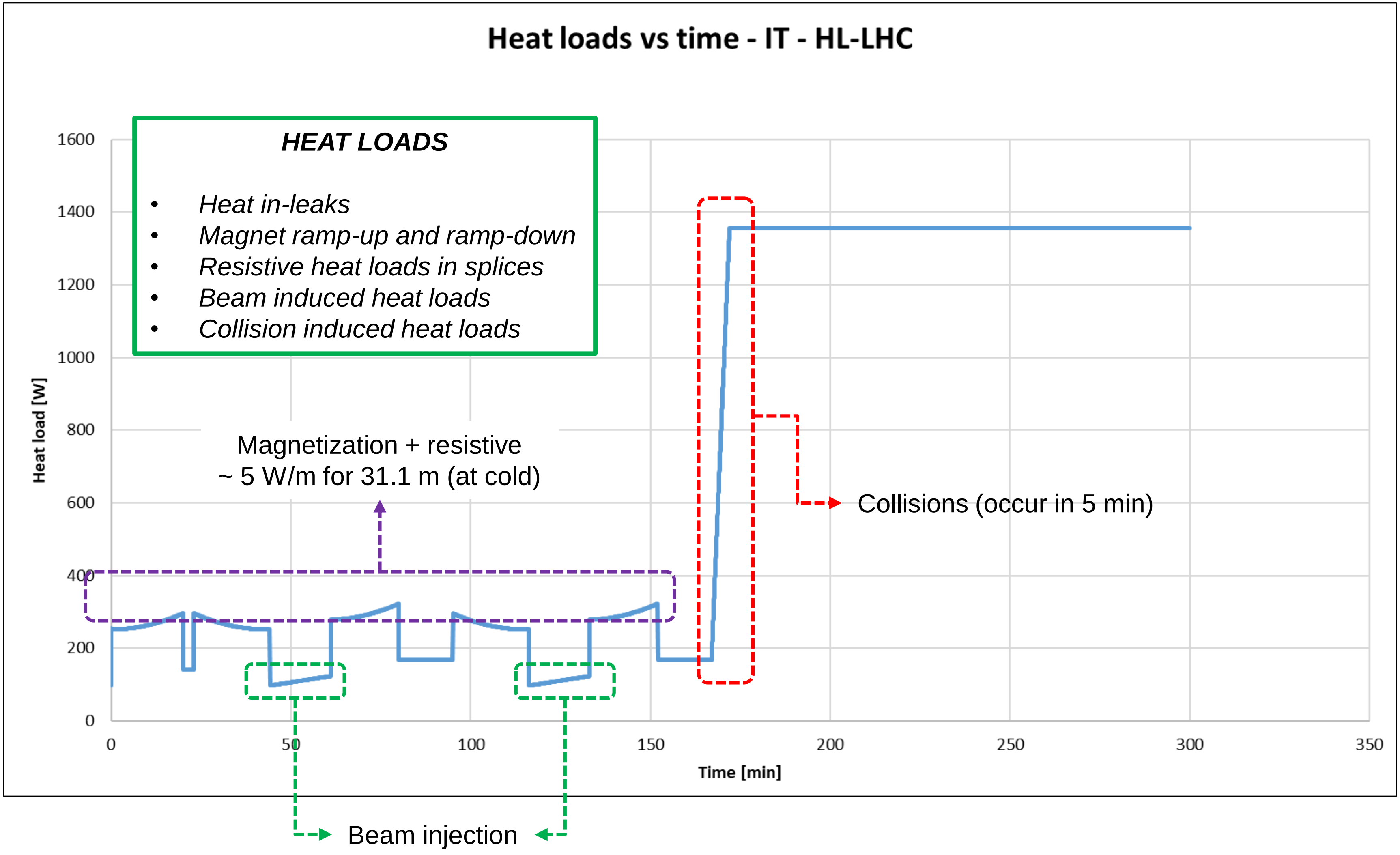
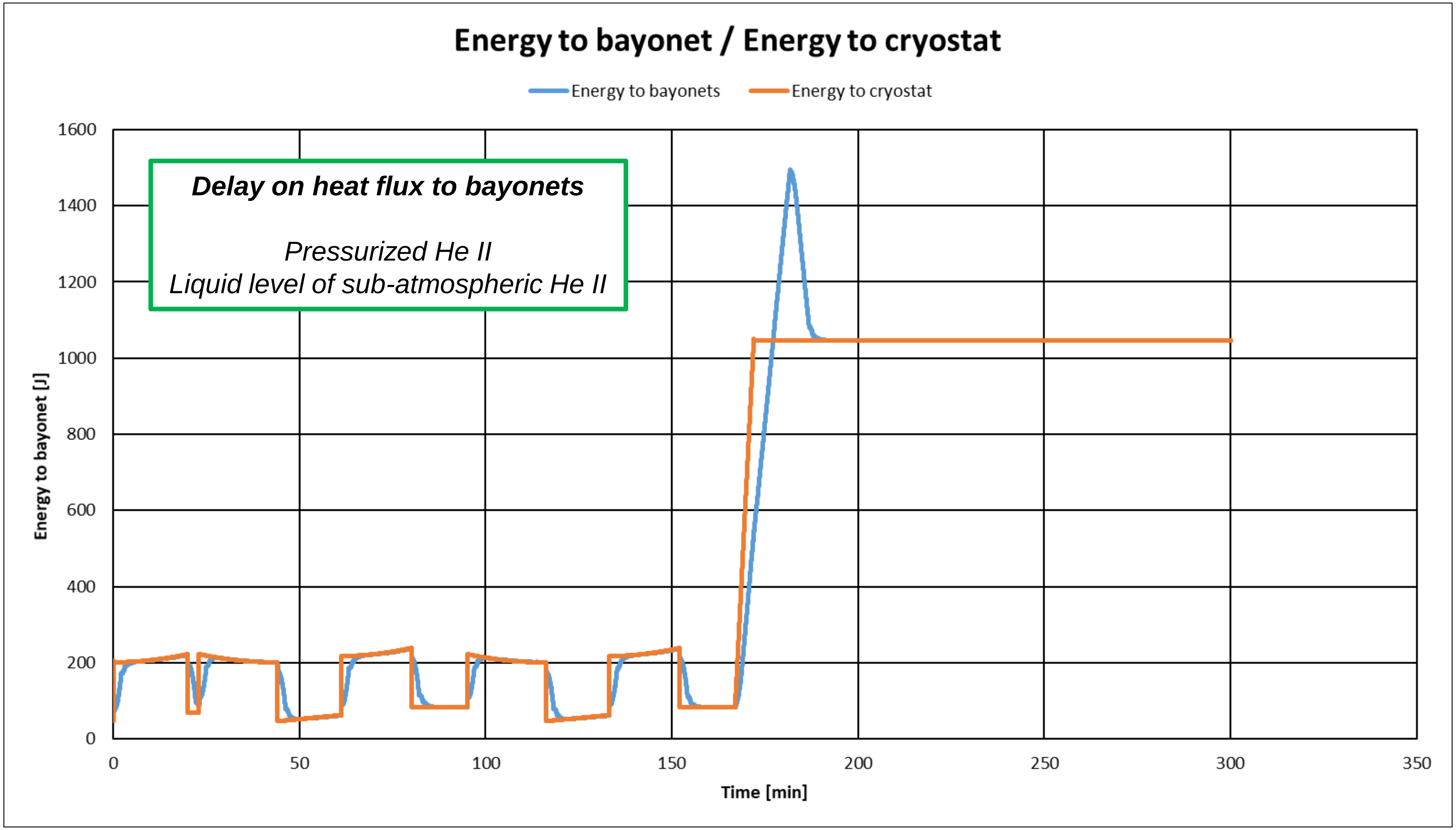
Current ramp – Considered profile



Total heat loads – Nominal vs Design

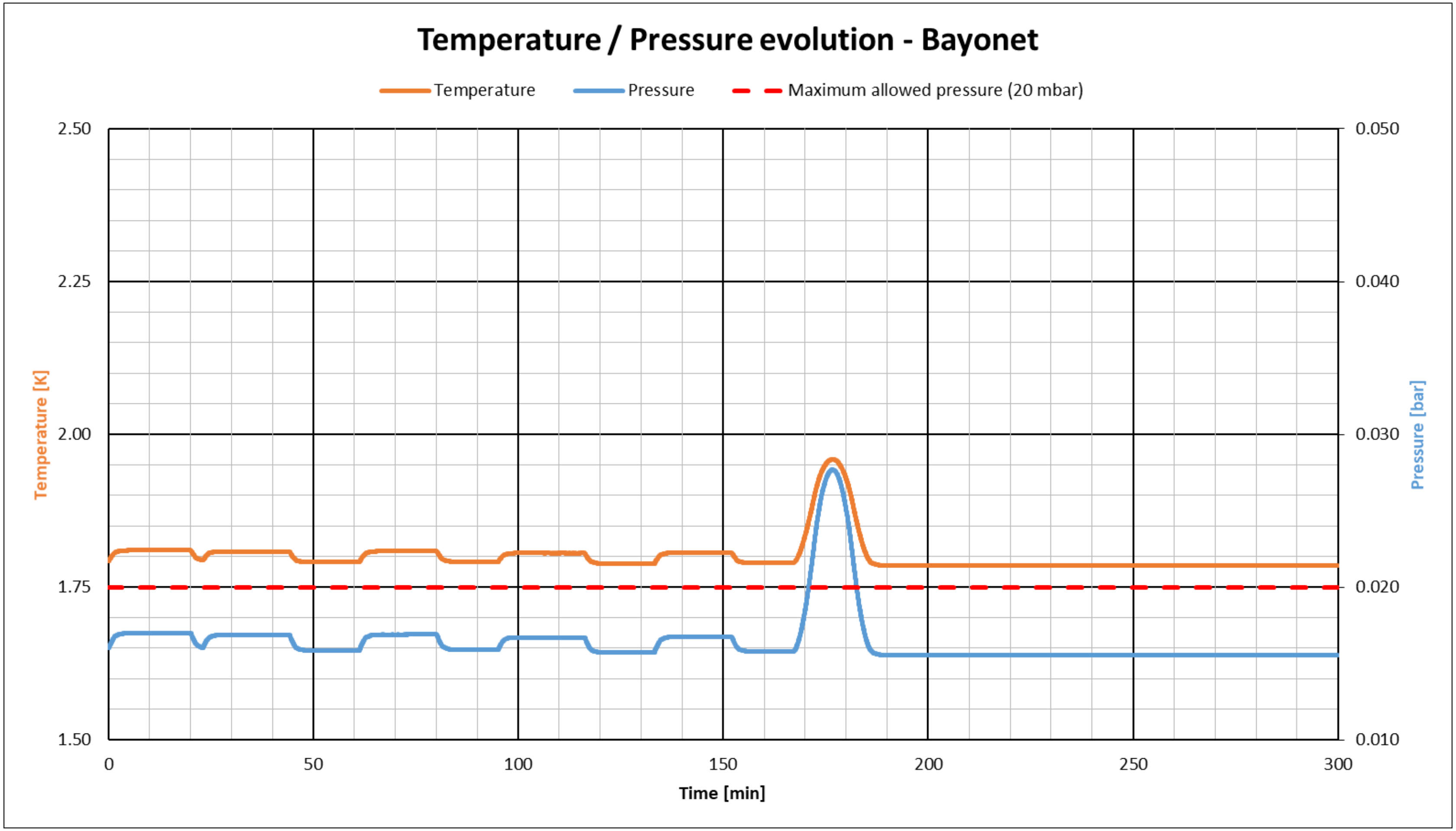


Energy deposition



$$\text{Case} \begin{cases} CC\ acceleration = 5\ g/s/min \\ Pre-load = 0\ W \\ Collision\ ramp = 5\ min \end{cases}$$

Effect on header B



Case
$$\begin{cases} CC\ acceleration = 5\ g/s/min \\ Pre - load = 0\ W \\ Collision\ ramp = 5\ min \end{cases}$$

Cryo parameters evolution when colliding

Limited impact of header B volume, Big impact of flow rate

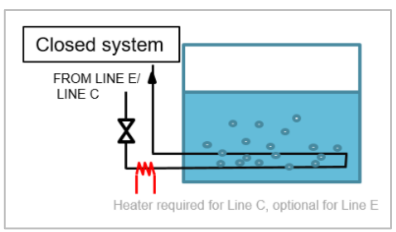
DN 250 → service galleries

DN 200 → tunnel level

#1: Acceleration

#2: Pre-load + active controls

	DESIGN ESTIMATION		No pre-load on cold mass			50% pre-load on cold mass		
			Cryostat	**Bayonet**	**Header B**	**Cryostat**	**Bayonet**	**Header B**
LHC Spec.	5 g/s/min	Max temperature [K]	2.01	1.96	4.98	1.9	1.87	4.44
		Max pressure [mbar]	1304	27.7	27.7	1307	20.8	20.8
		Min pressure [mbar]	1127	0.016	0.016	1224	0.016	0.016
LHC now	10 g/s/min	Max temperature [K]	1.91	1.88	4.51	1.87	1.84	4.24
		Max pressure [mbar]	1343	21.7	21.7	1306	18.6	18.6
		Min pressure [mbar]	1205	0.016	0.016	1255	0.016	0.016
Out of reach …	15 g/s/min	Max temperature [K]	1.9	1.87	4.46	1.87	1.84	4.24
		Max pressure [mbar]	1384	21.1	21.1	1328	16.5	16.5
		Min pressure [mbar]	1213	0.02	0.016	1255	0.016	0.016



Collision ramp-up time → **secondary effect**

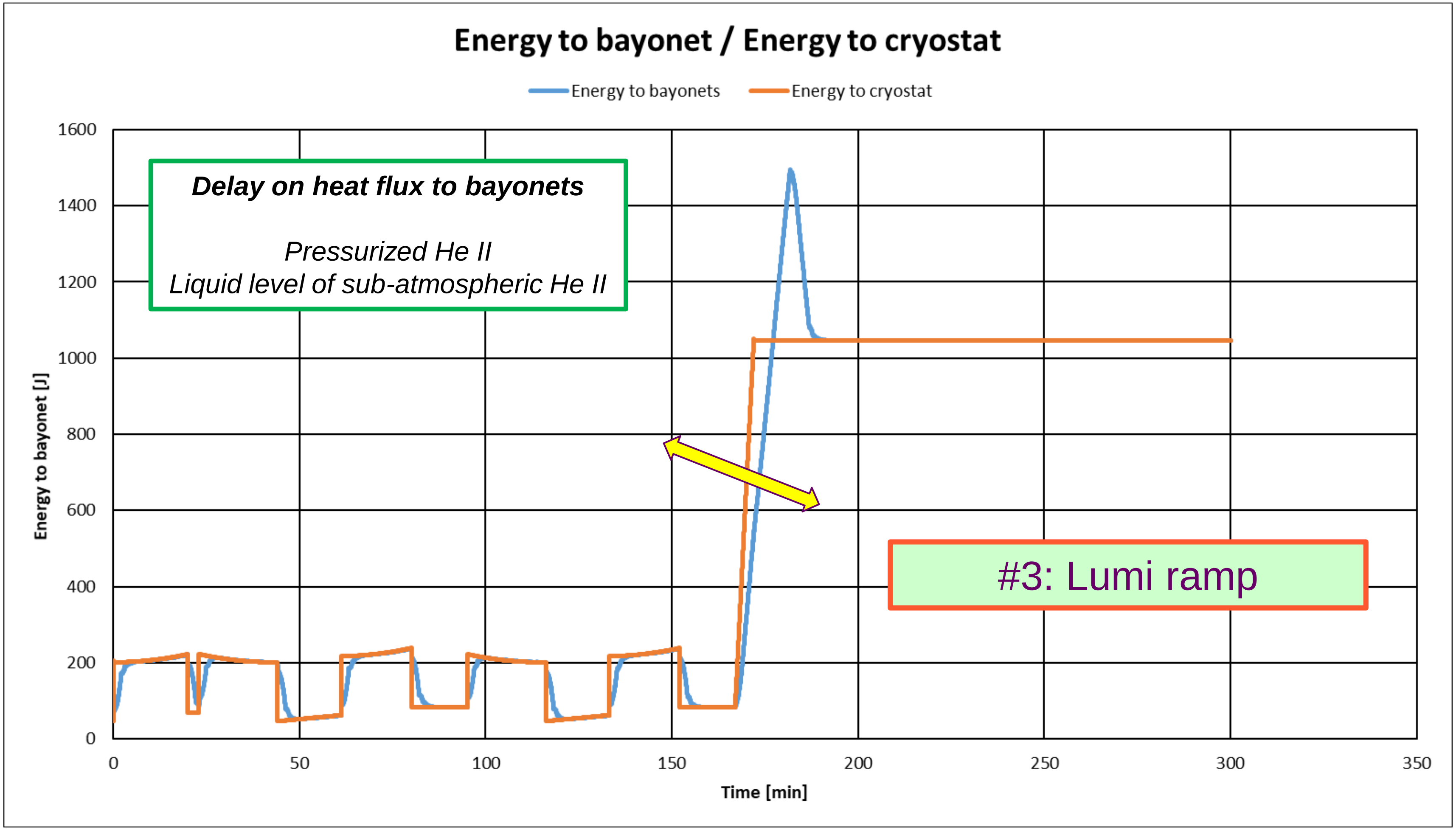
Header B available volume → **negligible effect**

Minimum pre-load of 50 %
strongly recommended

Active controls required with pre-load (heating),
GHe heating more robust than electrical systems required,
And 5-10 min to reach peak luminosity appreciated !

#3: Lumi ramp

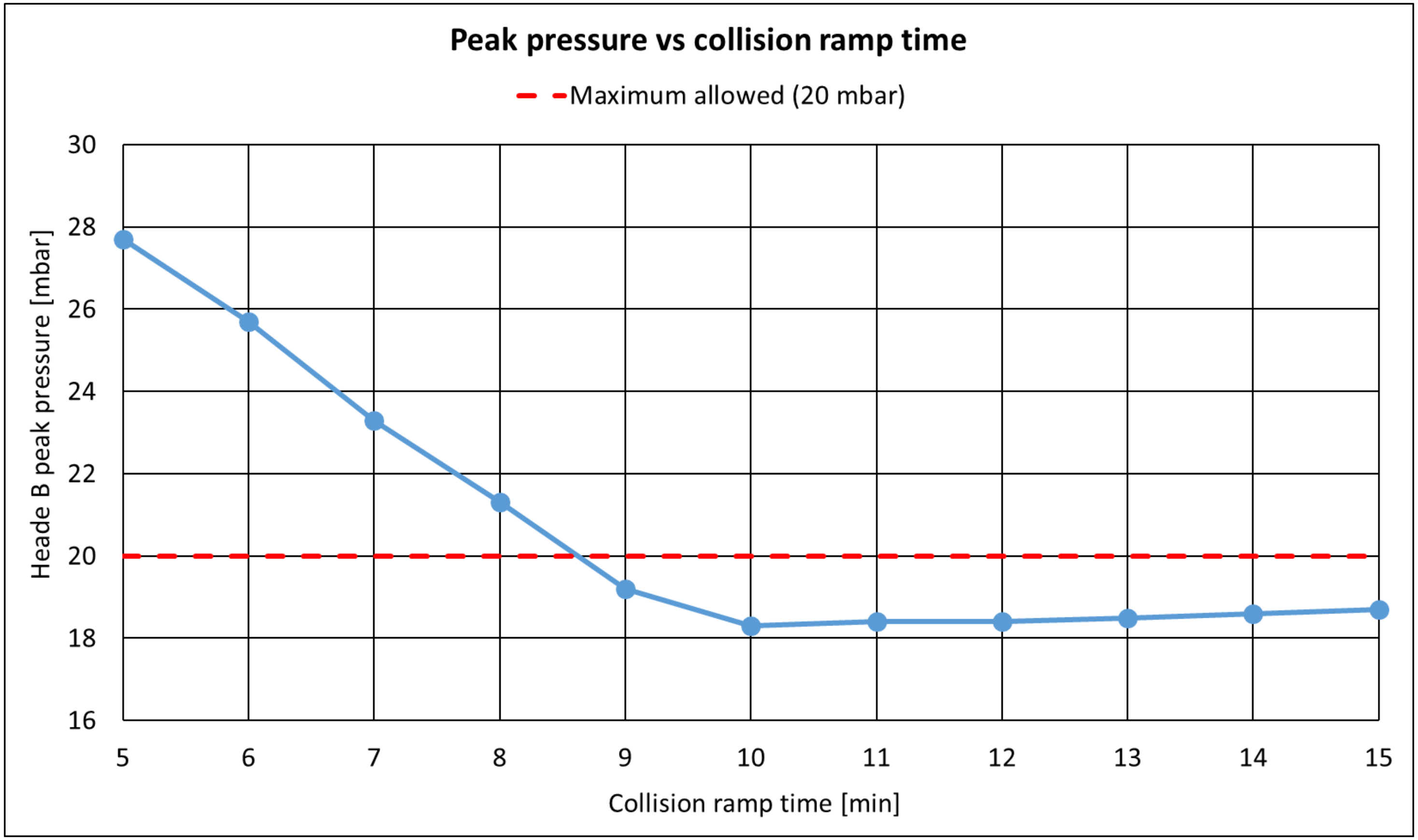
Energy deposition



$$\text{Case} \begin{cases} CC\ acceleration = 5\ g/s/min \\ Pre - load = 0\ W \\ Collision\ ramp = 5\ min \end{cases}$$

Collision ramp time - parametric

Example for CC acceleration equal to **5 g/s/min** with **no pre-load**



As soon as the collision ramp-up time "match" CC acceleration, the maximum pressure in header B became almost flat

Strategy to manage transients

- Cold compressors acceleration
  (not much to expect by buffering effect)

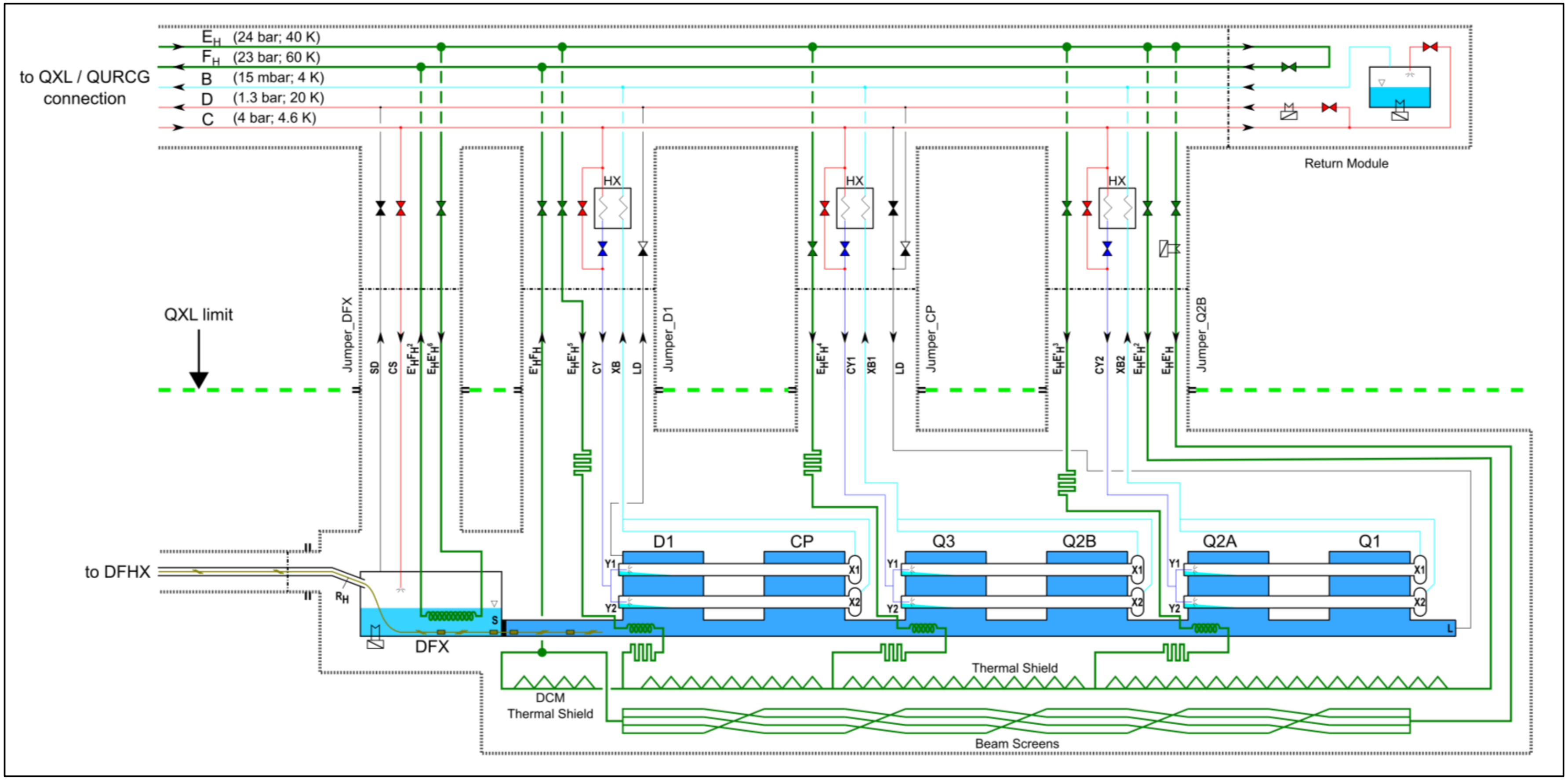
- Pre-load and active controls
  (in high TID area, test & developments ongoing)

- Ramp on Luminosity
  (1e34 within ~sec, 5-7.5e34 within ~10min)

- A mix of all that to start with, and tuning-optimisation will tell what is best, but “knobs” will be there for that

Bonus Slides

Inner Triplet pre-load serpentines



1st Evaluation of Heat Loads

Table 3. Heat load table for mayor components on the magnet side of HL-LHC LSS.R5.

No longer since MSO

1000 W

1200 W

Component Length [m] (thermal shield)	Q1 10.140 (10.640)	Q2A 9.785	Q2B 9.785	Q3 10.140	CP 6.016	D1 7.370	Intercon. 5.800 (5 units *)	DFX 2.435 (2.935)	DFM 4.000	D2 13.025 (14.025)	CC 4 module units †	Q4 9.062 (10.062)	Q5 8.010 (9.010)	Q6 6.610 (7.610)
Cold Mass														
Temperature [K]	1.9	1.9	1.9	1.9	1.9	1.9	1.9	4.5	4.5	1.9	2	1.9	1.9	1.9
Total Heat Load [W]	185.9	147.6	186.7	195.4	90.2	120.4	65.5	1.7	tbd	55.0	123.8	14.4	11.3	4.0
Avg. Heat Load [W/m]	18.34	15.08	19.08	19.27	15.00	16.33	6.13	0.72	tbd	4.22	30.94 W pu	1.59	1.42	0.60
Data: Static [W/m]	*0.82*	*0.83*	*0.83*	*0.82*	*0.87*	*0.83*	*0.13*	*0.72*	tbd	*0.28*	12.5 W pu	*0.29*	*0.32*	*0.36*
Data: Resistive [W/m]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	-	tbd	tbd	tbd
Data: Beam Induced [W/m]	*0.16*	*0.05*	*0.06*	*0.11*	tbd	*0.17*	tbd	tbd	-	*0.10*	0.5 W pu	*0.19*	*0.23*	*0.24*
Data: Collision Induced [W/m]	*17.36*	*14.21*	*18.19*	*18.34*	*14.13*	*15.33*	*6 W pu*	tbd	tbd	*3.84*	0.34 W pu	*1.10*	*0.87*	tbd
Data: RF Induced [W/m]	-	-	-	-	-	-	-	-	-	-	17.6 W pu	-	-	-
Beam Screen														
Temperature [K]	40-60	40-60	40-60	40-60	40-60	40-60	40-60	tbd	-	4.5-20	-	4.5-20	4.5-20	4.5-20
Total Heat Load [W]	271.1	118.9	158.2	161.2	107.4	117.9	110.0	1.3	-	16.7	-	21.7	14.3	3.0
Avg. Heat Load [W/m]	26.74	12.15	16.17	15.90	17.85	16.00	22 W pu	0.55	-	1.28	-	2.40	1.79	0.45
Data: Static [W/m]	*0.14*	*0.14*	*0.14*	*0.14*	*0.23*	*0.19*	-	*0.55*	-	*0.00*	-	*0.15*	*0.17*	*0.21*
Data: Resistive [W/m]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	-	tbd	-	tbd	tbd	tbd
Data: Beam Induced [W/m]	*1.25*	*0.25*	*0.39*	*0.67*	*tbd*	*1.29*	*tbd*	tbd	-	*1.08*	-	*2.08*	*1.60*	*0.24*
Data: Collision Induced [W/m]	*25.35*	*11.75*	*15.64*	*15.09*	*17.62*	*14.52*	*22 W pu*	tbd	-	*0.20*	-	*0.17*	*0.02*	tbd
Thermal Shield														
Temperature [K]	40-60	40-60	40-60	40-60	40-60	40-60	40-60	40-60	40-60	40-60	80	40-60	40-60	40-60
Total Heat Load [W]	56.6	53.2	53.2	54.3	33.8	38.2	18.6	24.1	tbd	68.1	1528.0	48.1	44.7	40.2
Avg. Heat Load [W/m]	5.32	5.44	5.44	5.36	5.63	5.18	3.21	8.21	tbd	4.85	382 W pu	4.78	4.96	5.28
Data: Static [W/m]	*5.32*	*5.44*	*5.44*	*5.36*	*5.63*	*5.18*	*3.21*	*8.21*	tbd	*4.85*	252 W pu	*4.78*	*4.96*	*5.28*
Data: RF Induced [W/m]	-	-	-	-	-	-	-	-	-	-	130 W pu	-	-	-

Maturity level of the source data: estimated = *italic*; calculated = normal; measured = underlined.
tbd = to be defined; "-" = not applicable; W pu = Watts per unit.
* Length of each interconnection unit is 1 m, except between Q3-CP which is 1.8 m.
† A module unit contains 2 crab cavities.

Heat loads to be revisited as well for CC (1.9K, thermal shield, Beam-Screen)

To be revisited following design of cryostats and updated heat deposition studies

Updated heat loads table for HL-LHC

Component	Q1	Q2A	Q2B	Q3	CP	D1	Int.	DFX	DFM	D2	CC	IT	DFX + DFM	D2	CC	TOTAL per SIDE		Mass Flow per SIDE	
Cold Mass																			
Temperature [K]	*1.9*	*1.9*	*1.9*	*1.9*	*1.9*	*1.9*	*1.9*	*4.5*	*4.5*	*1.9*	*2*	*1.9*	*4.5*	*1.9*	*2*	*1.9-2*	*4.5*	*1.9-2*	*4.5*
Total Design [W]	237.4	209.5	263.2	267.3	149.1	169.9	60.0	12.4	13.5	95.3	160.0	1356.4	25.9	95.3	160.0	1611.7	25.9	68.8	1.4
Total Ultimate [W]	198.1	173.5	226.8	228.1	115.4	136.5	48.7	4.1	4.5	73.7	100.0	1127.2	8.6	73.7	100.0	1300.9	8.6	55.5	0.5
Total Nominal [W]	141.1	123.0	158.8	161.1	88.4	97.0	38.2	4.1	4.5	55.7	100.0	807.7	8.6	55.7	100.0	963.4	8.6	41.1	0.5
Dynamic - Ultimate [W]	180.9	156.9	210.1	211.0	104.4	120.3	46.9	0.0	0.0	65.9	93.3	1030.6	0.0	65.9	93.3	1189.8	0.0	50.8	0.0
Dynamic - Nominal [W]	123.9	106.4	142.1	144.0	77.4	80.8	36.4	0.0	0.0	47.9	93.3	711.1	0.0	47.9	93.3	852.3	0.0	36.4	0.0
Static [W]	17.2	16.7	16.7	17.1	11.0	16.2	1.8	4.1	4.5	7.8	6.7	96.6	8.6	7.8	6.7	111.0	8.6	4.7	0.5
Beam Screen																			
Temperature [K]	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*-*	*-*	*4.5-20*	*4.5-20*	*60-80*	*-*	*4.5-20*	*4.5-20*	*60-80*	*4.5-20*	*60-80*	*4.5-20*
Total Design [W]	341.7	158.5	228.8	207.6	102.3	111.0	548.0	0.0	0.0	332.2	0.1	1697.9	0.0	332.2	0.1	1697.9	332.3	16.1	3.2
Total Ultimate [W]	311.4	138.3	201.2	177.0	97.8	100.6	401.4	0.0	0.0	222.6	0.1	1427.6	0.0	222.6	0.1	1427.6	222.7	13.6	2.1
Total Nominal [W]	226.4	104.3	151.2	137.0	66.8	72.6	365.4	0.0	0.0	221.5	0.1	1123.6	0.0	221.5	0.1	1123.6	221.5	10.7	2.1
Dynamic - Ultimate [W]	310.0	136.9	199.8	175.6	96.4	99.2	401.4	0.0	0.0	222.6	0.1	1419.3	0.0	222.6	0.1	1419.3	222.7	13.5	2.1
Dynamic - Nominal [W]	225.0	102.9	149.8	135.6	65.4	71.2	365.4	0.0	0.0	221.5	0.1	1115.3	0.0	221.5	0.1	1115.3	221.5	10.6	2.1
Static [W]	1.4	1.4	1.4	1.4	1.4	1.4	0.0	0.0	0.0	0.0	0.0	8.4	0.0	0.0	0.0	8.4	0.0	0.1	0.0
Thermal Shield																			
Temperature [K]	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*60-80*	*80.0*	*60-80*	*60-80*	*60-80*	*80.0*	*60-80*	*80.0*	*60-80*	*80.0*
Total Design [W]	99.9	79.8	79.8	81.5	50.8	154.8	33.3	52.4	57.0	229.6	585.0	579.9	109.4	229.6	585.0	918.9	585.0	8.7	5.6
Total Ultimate [W]	66.6	53.2	53.2	54.3	33.8	103.2	22.2	34.9	38.0	153.1	390.0	386.6	72.9	153.1	390.0	612.6	390.0	5.8	3.7
Total Nominal [W]	66.6	53.2	53.2	54.3	33.8	103.2	22.2	34.9	38.0	153.1	390.0	386.6	72.9	153.1	390.0	612.6	390.0	5.8	3.7
Dynamic - Ultimate [W]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0	0.0	0.0	0.0	40.0	0.0	40.0	0.0	0.4
Dynamic - Nominal [W]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0	0.0	0.0	0.0	40.0	0.0	40.0	0.0	0.4
Static [W]	66.6	53.2	53.2	54.3	33.8	103.2	22.2	34.9	38.0	153.1	350.0	386.6	72.9	153.1	350.0	612.6	350.0	5.8	3.3

Thermal Shield & Current Leads

$$\dot{Q}_{design} = MAX\left[F_{ov} \cdot \dot{Q}_{nominal} \; ; \; \dot{Q}_{ultimate}\right]$$

Cold mass & Beam Screen

$$\dot{Q}_{design} = MAX\left[F_{ov} \cdot \left(F_{un} \cdot \dot{Q}_{static} + \dot{Q}_{dy.nominal}\right) \; ; \; F_{un} \cdot \dot{Q}_{static} + \dot{Q}_{dy.ultimate}\right]$$

$$F_{ov} = F_{overcapacity} = 1.5$$

$$F_{un} = F_{uncertenties} = 2$$

Summary table for HL-LHC heat loads

PER POINT - EQUIVALENT CAPACITY @ 4.5 K							
Group name	Cold Mass	DFs	SA Beam Screen	IT Beam Screen	Thermal Shield	Current Leads	
Temperature levels [K]	1.9	4.5	4.5-20	60-80	60-80	4.5-300	
Total Design Load [W]	3868	0	665	3396	6270	30135	
Total Design Flow [g/s]	165	0	6.3	32.3	59.6	20	
Conversion factor	3.2	1	0.5	0.07	0.07	125	
Equivalent @ 4.5 K [kW]	**12.38**	**0**	**0.33**	**0.24**	**0.44**	**2.5**	**15.89**

Contains ~ 20% flash due to expansion across J-T valves

Contains heat loads due to ~ 750 m of the distribution system

Reference thermodynamics for headers		
HEADERS	Temperature [K]	Pressure [bar]
Header Eh	60	24
Header Fh	80	23
Header B	4	0.016
Header D	20	1.3
Header C	4.6	4
WRL	293	1.3

Estimates are intended to be on the safe side

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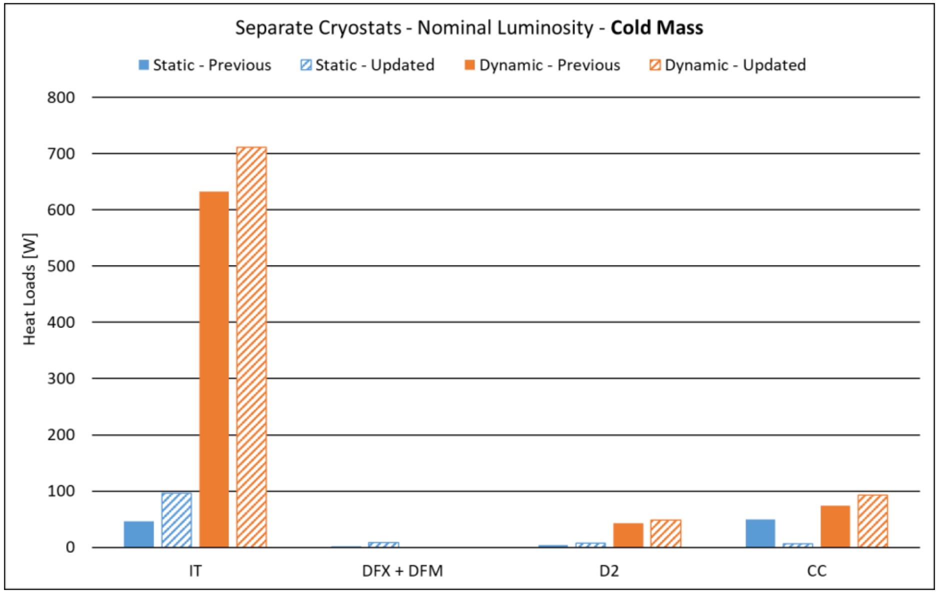
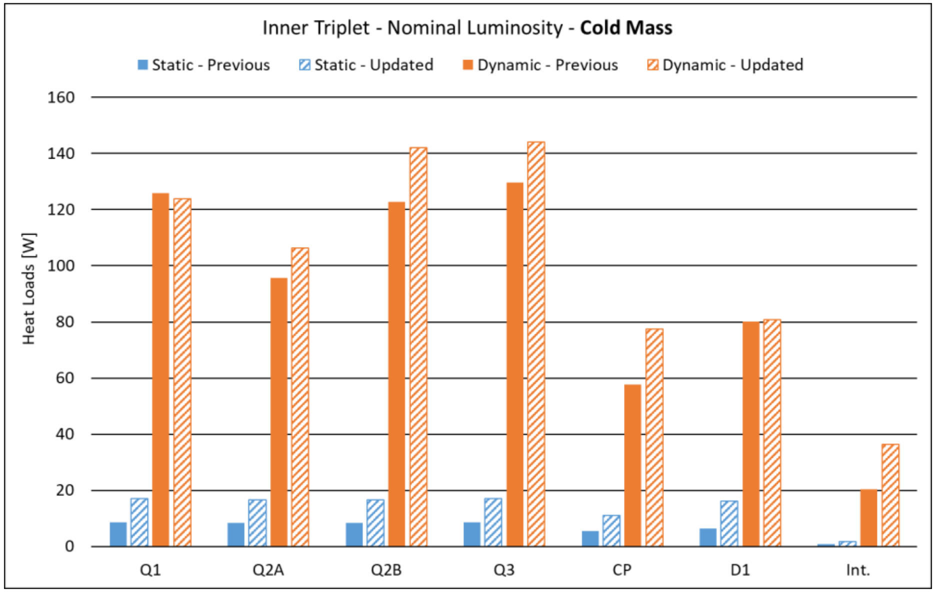
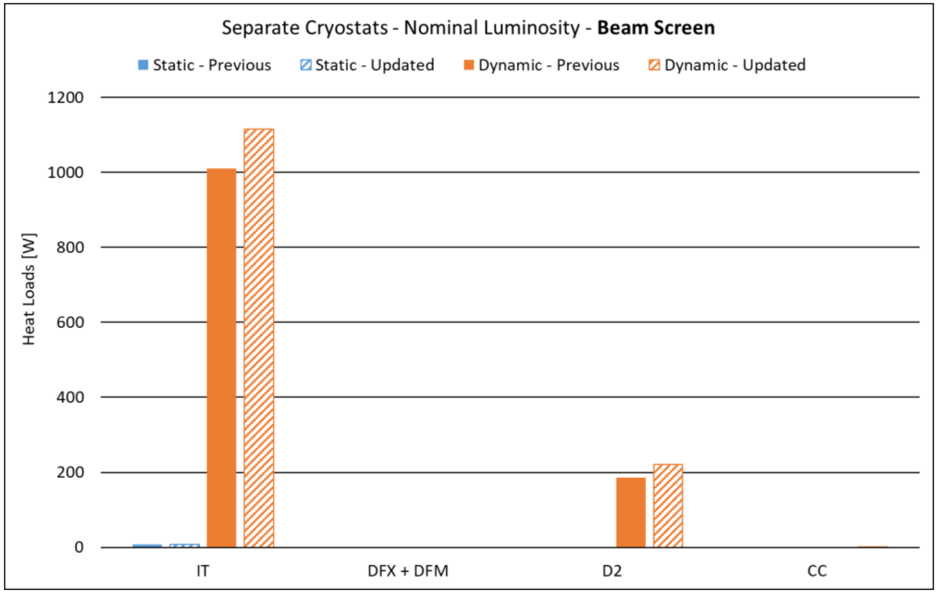
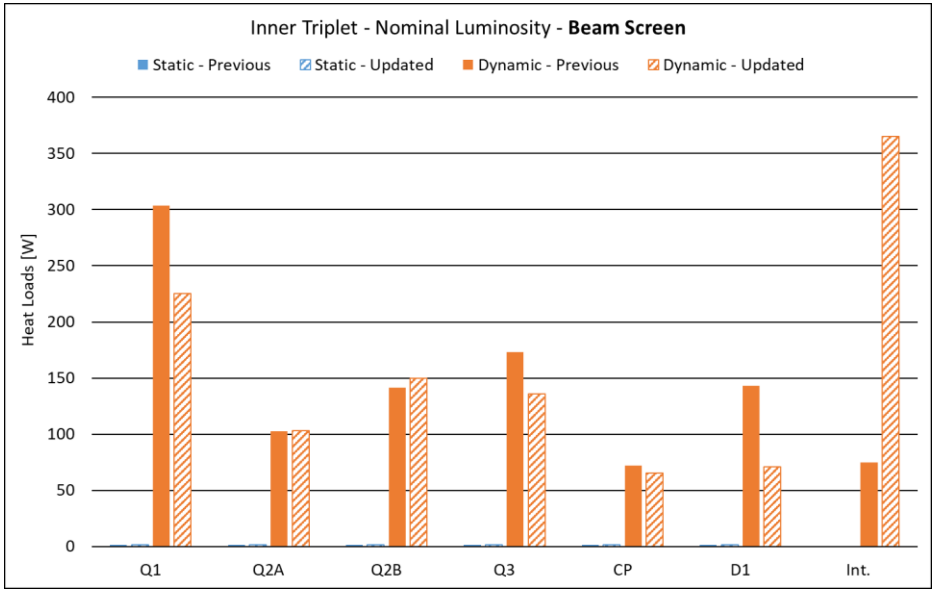
Cold Mass loads – Groups & IT





Beam Screen loads – Groups & IT





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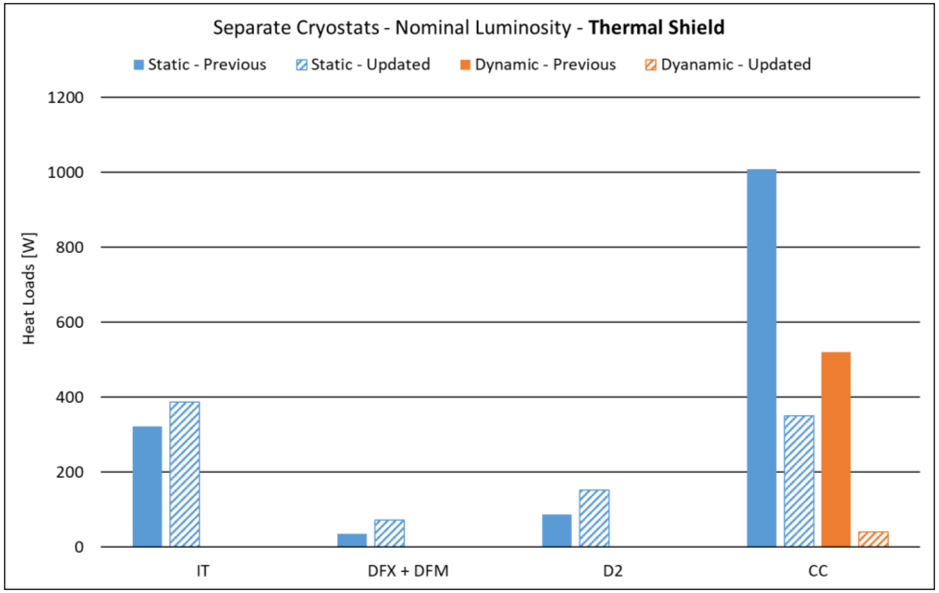
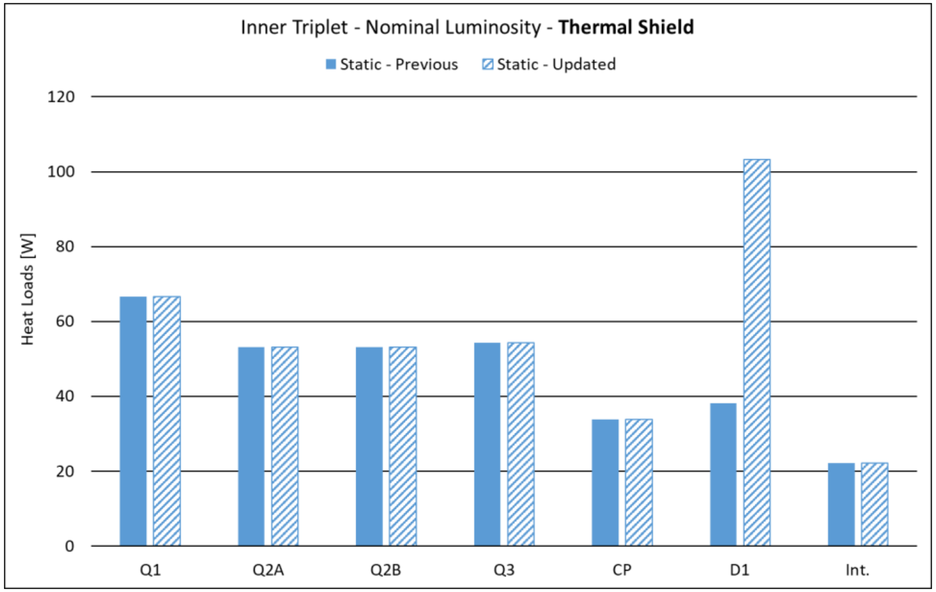
Thermal Shield loads – Groups & IT





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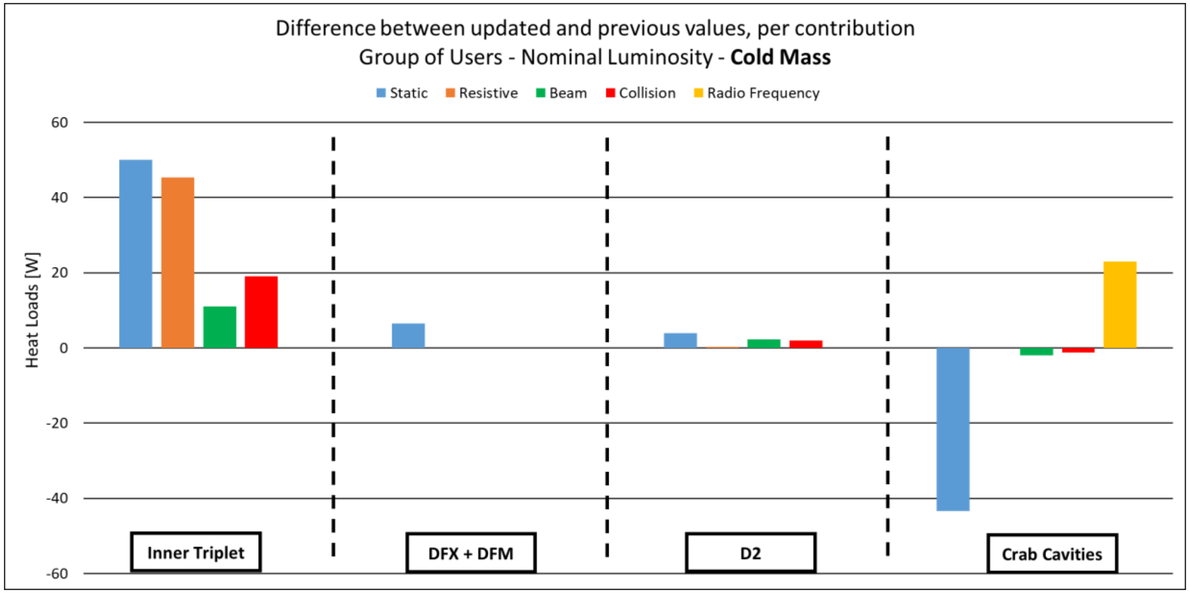
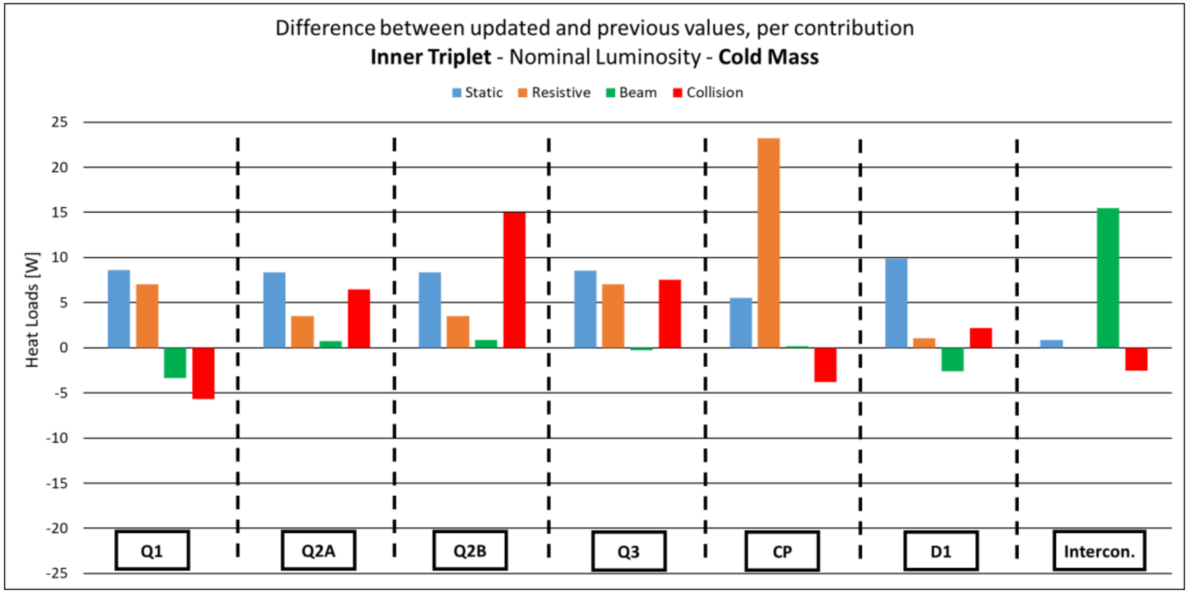
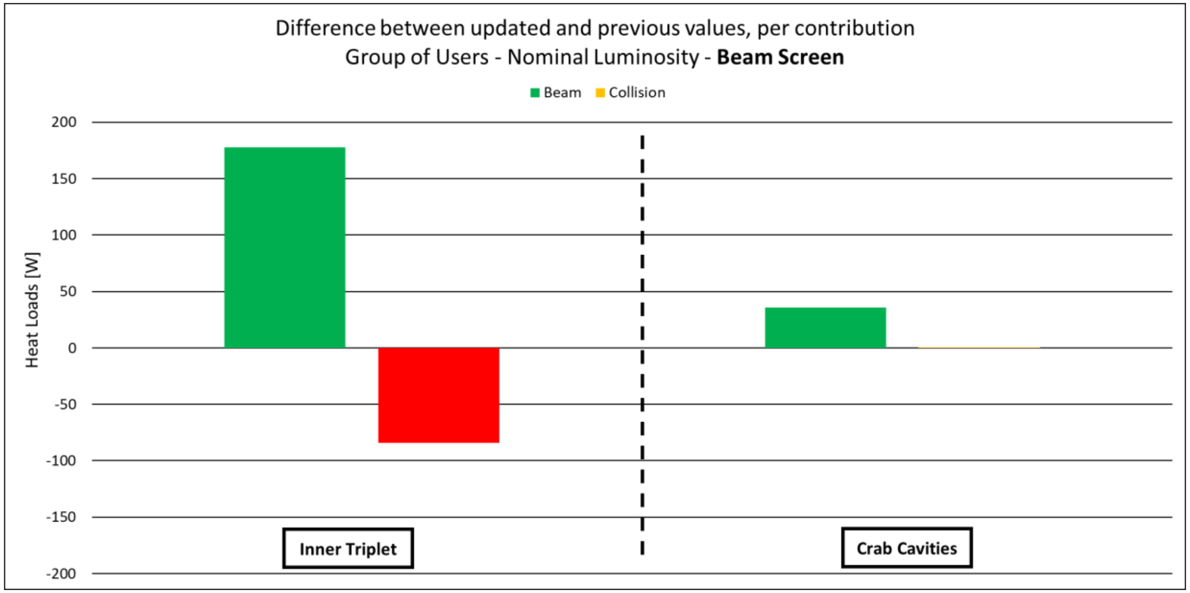
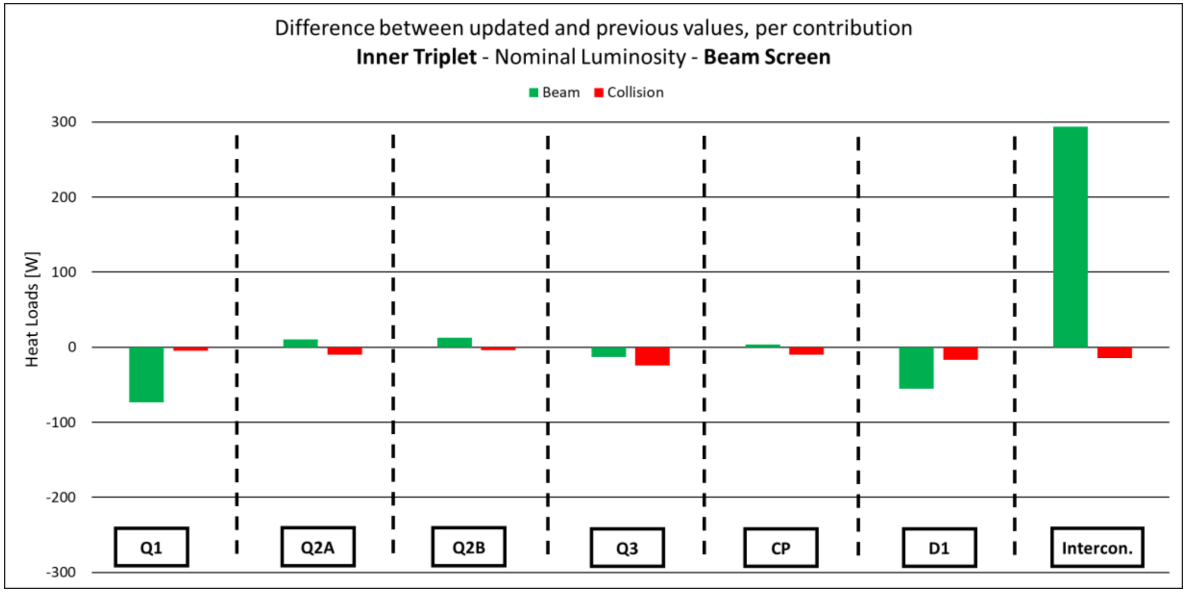
Difference with previous – Cold Mass





Difference with previous – Beam Screen

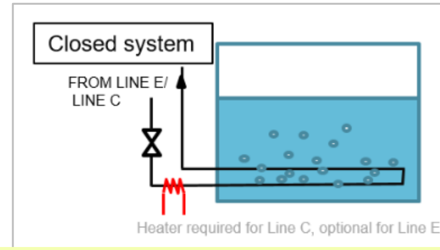




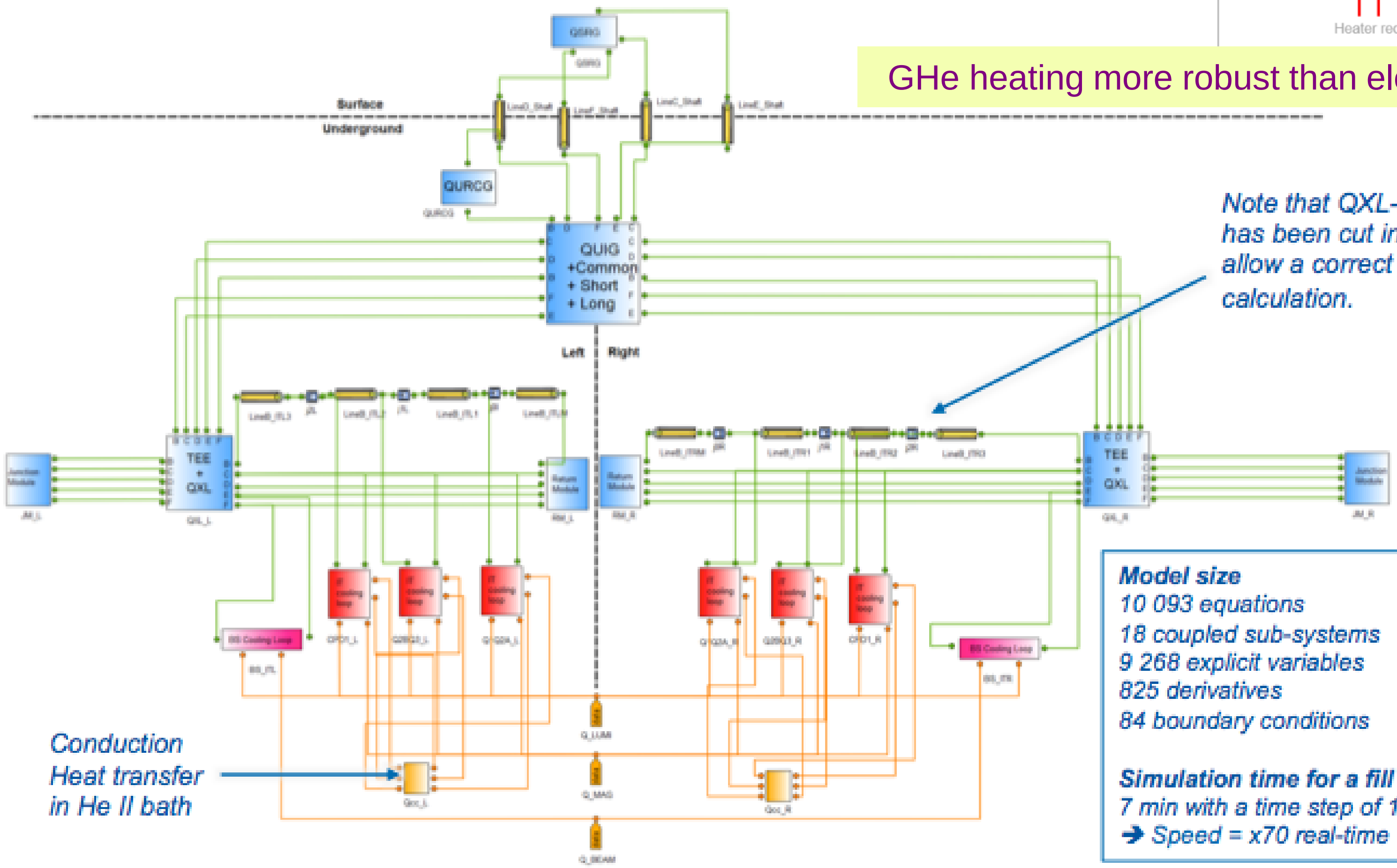
Model for dynamic process control studies

General EcosimPro schematic

Details of each schematic are given in Annex



GHe heating more robust than electrical systems



Note that QXL-B in LSS has been cut in 4 pieces to allow a correct pressure drop calculation.

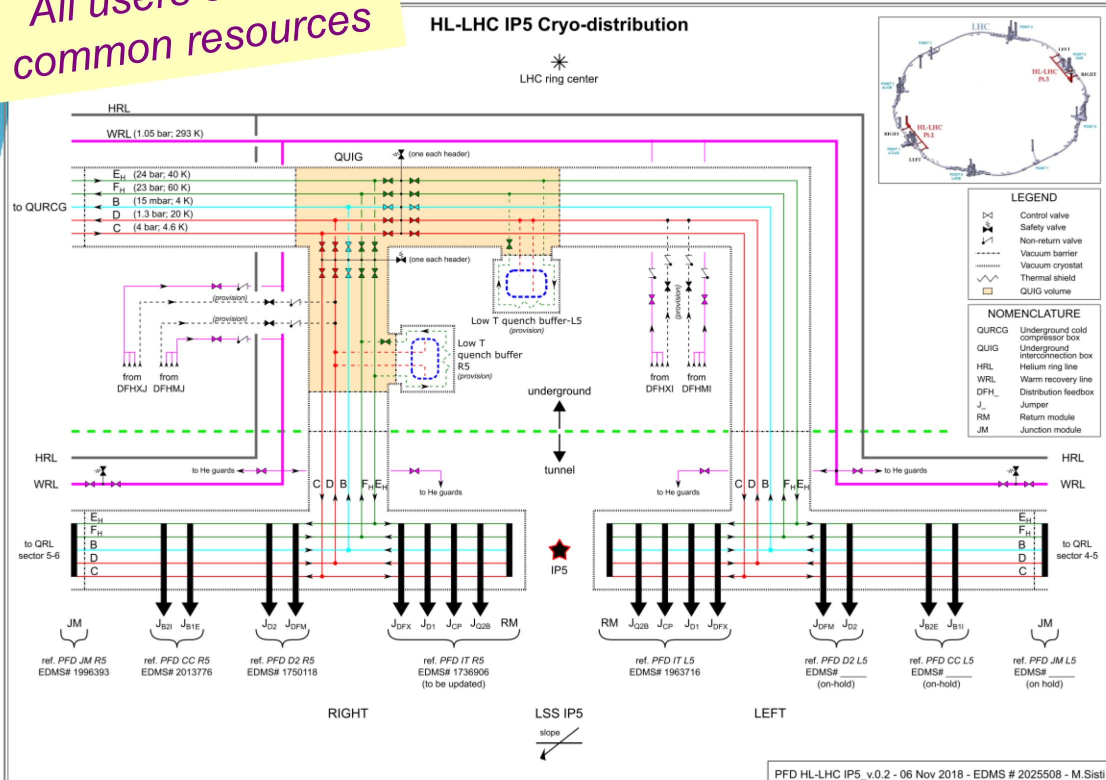
Conduction Heat transfer in He II bath

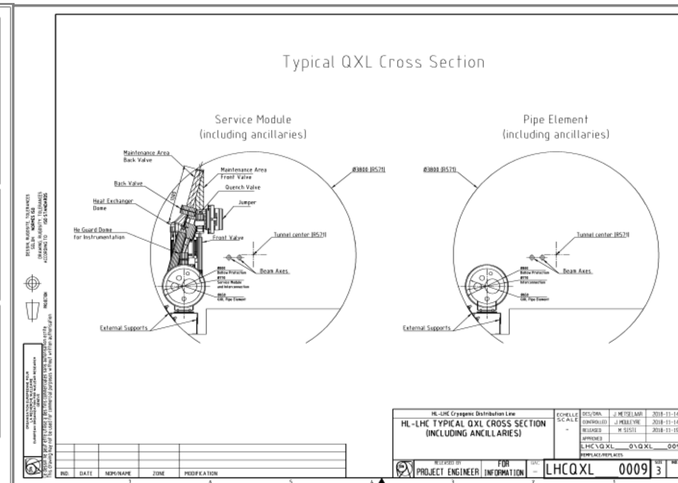
Model size
10 093 equations
18 coupled sub-systems
9 268 explicit variables
825 derivatives
84 boundary conditions

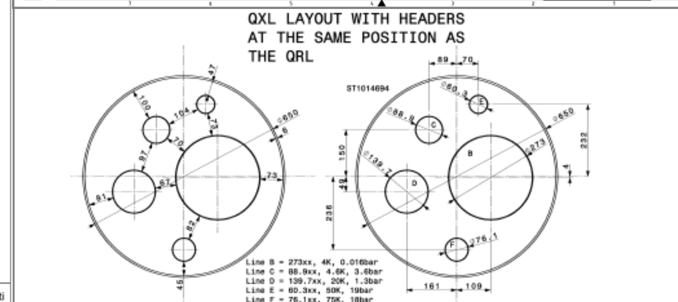
Simulation time for a fill of 8 hours
7 min with a time step of 1sec (laptop)
➔ Speed = x70 real-time

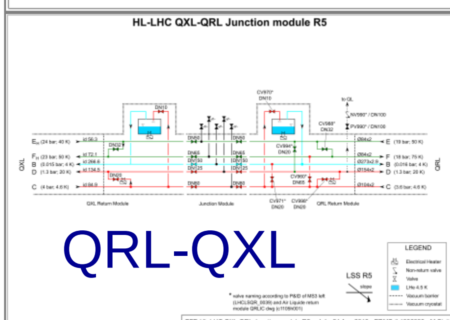
Cryo-distribution reference

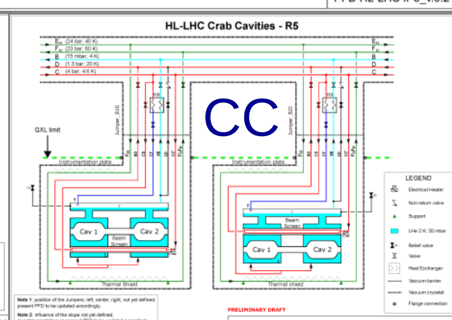
All users sharing common resources

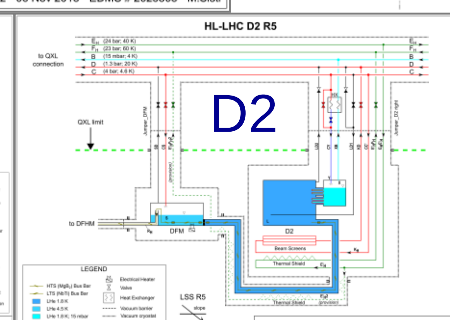


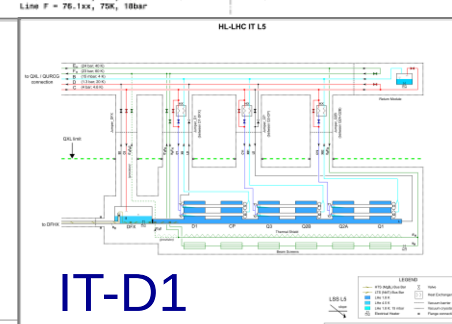








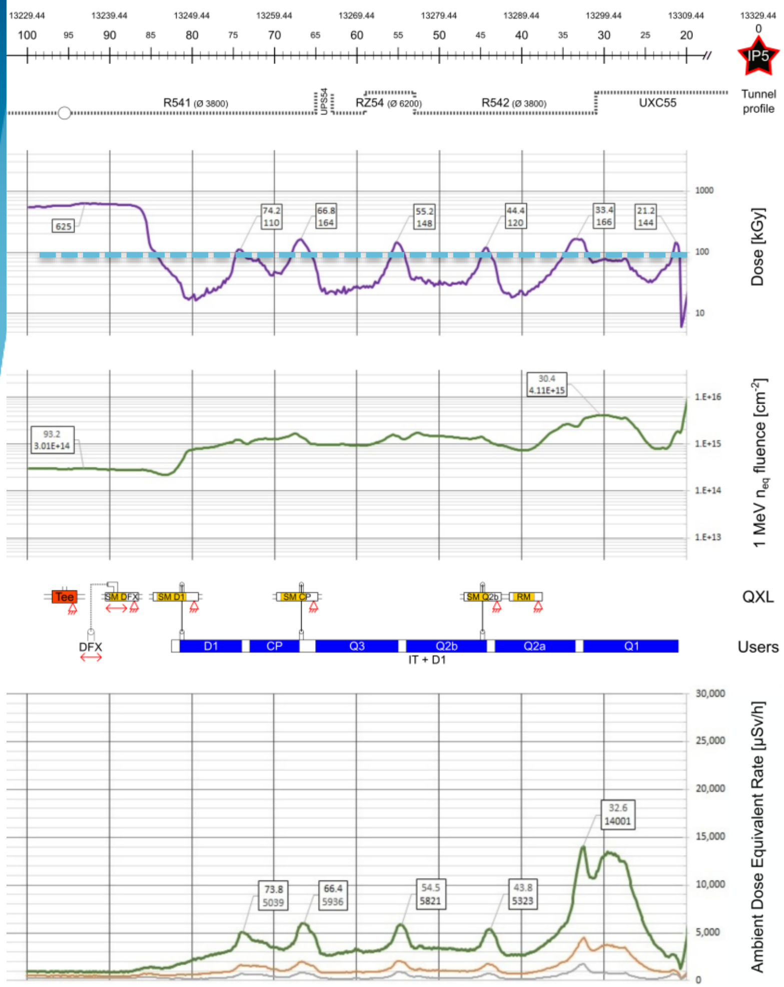


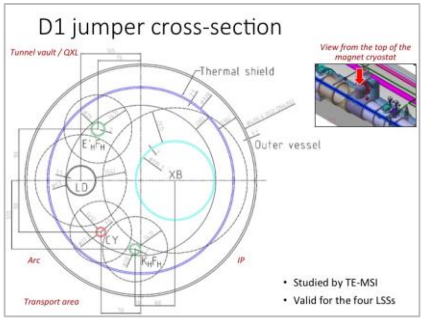


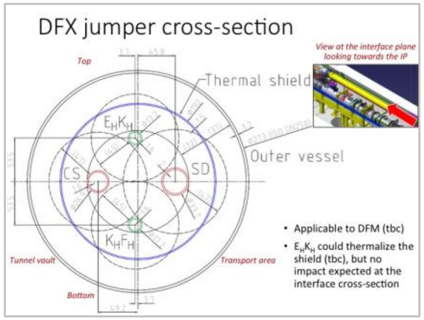
Reference established, optimised considering project requirements and CRG expertise

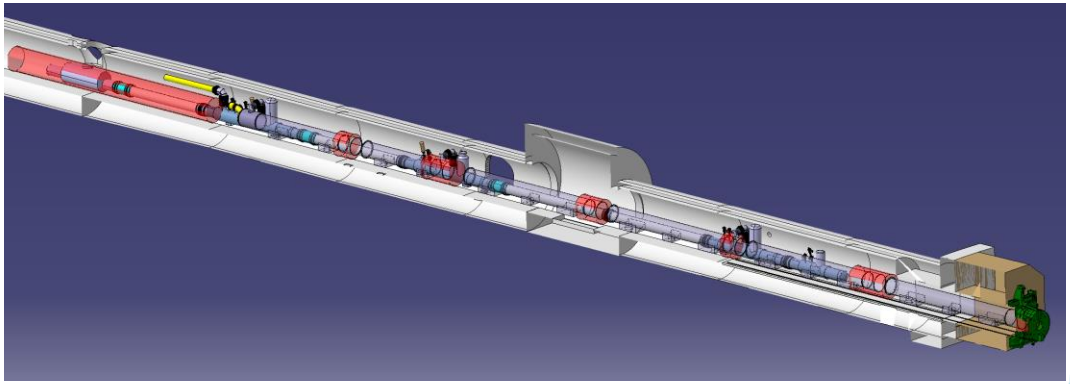
HiLumi HL-LHC PROJECT

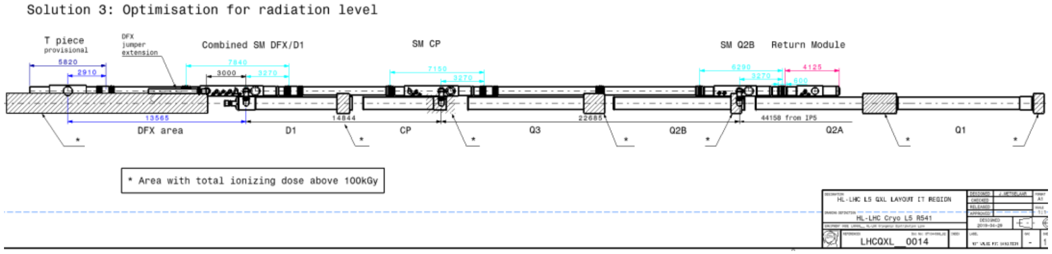
QXL Cryoline integration & interfaces







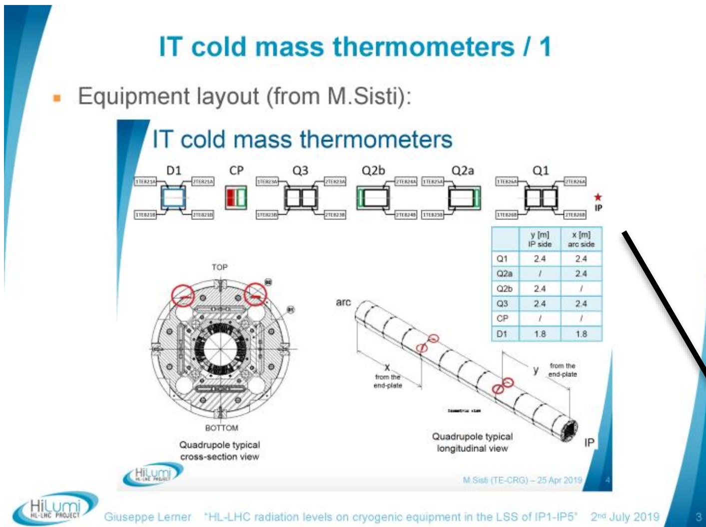


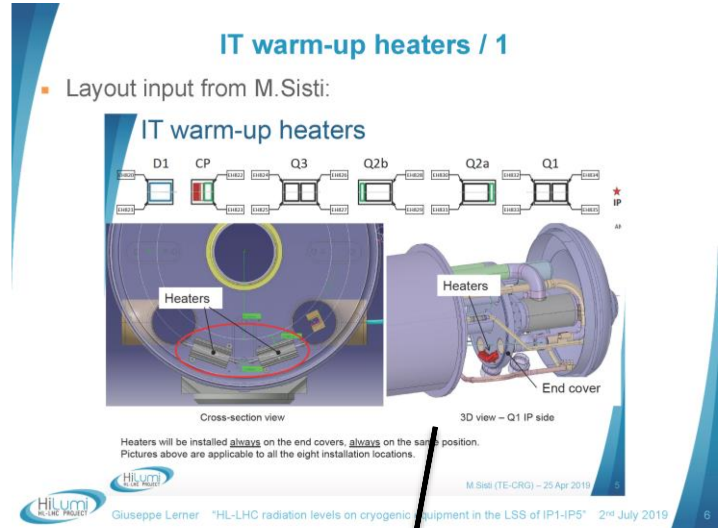


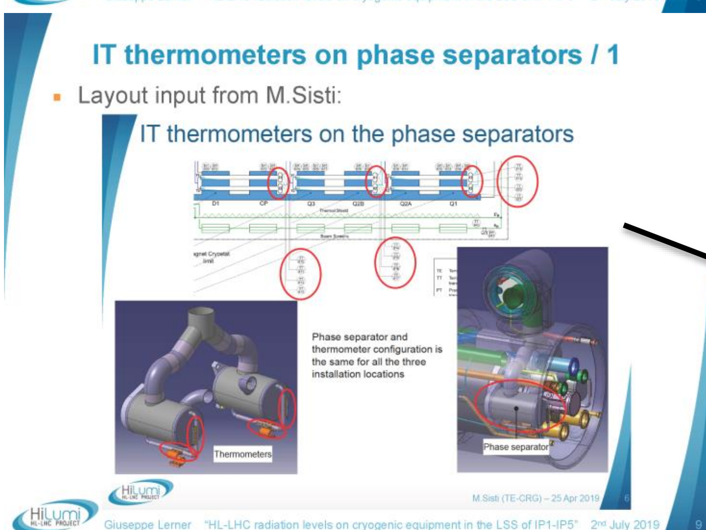
Radiation level: instrumentation considered OK up to 100kGy

TID on Cryo instrumentation

Thanks to G. Lerner and EN-STI team







Summary table

- Upper limits on the dose per equipment type for 4000 fb^{-1} (ultimate HL-LHC scenario) based on the results in the previous slides:

Equipment	Dose upper limit / 4000 fb^{-1} [kGy]	
IT cold mass thermometers	200	OK
IT warm-up heaters	1500	NotOK, alternative!
IT thermometers on phase separators	2000	Ok for less
IT beam screen heaters and thermometers	750	accurate
D2 beam screen heater and therm., and heat exchanger level gauges	200	technology

Giuseppe Lerner "HL-LHC radiation levels on cryogenic equipment in the LSS of IP1-IP5" 2nd July 2019 15