Heat loads and cryogenics

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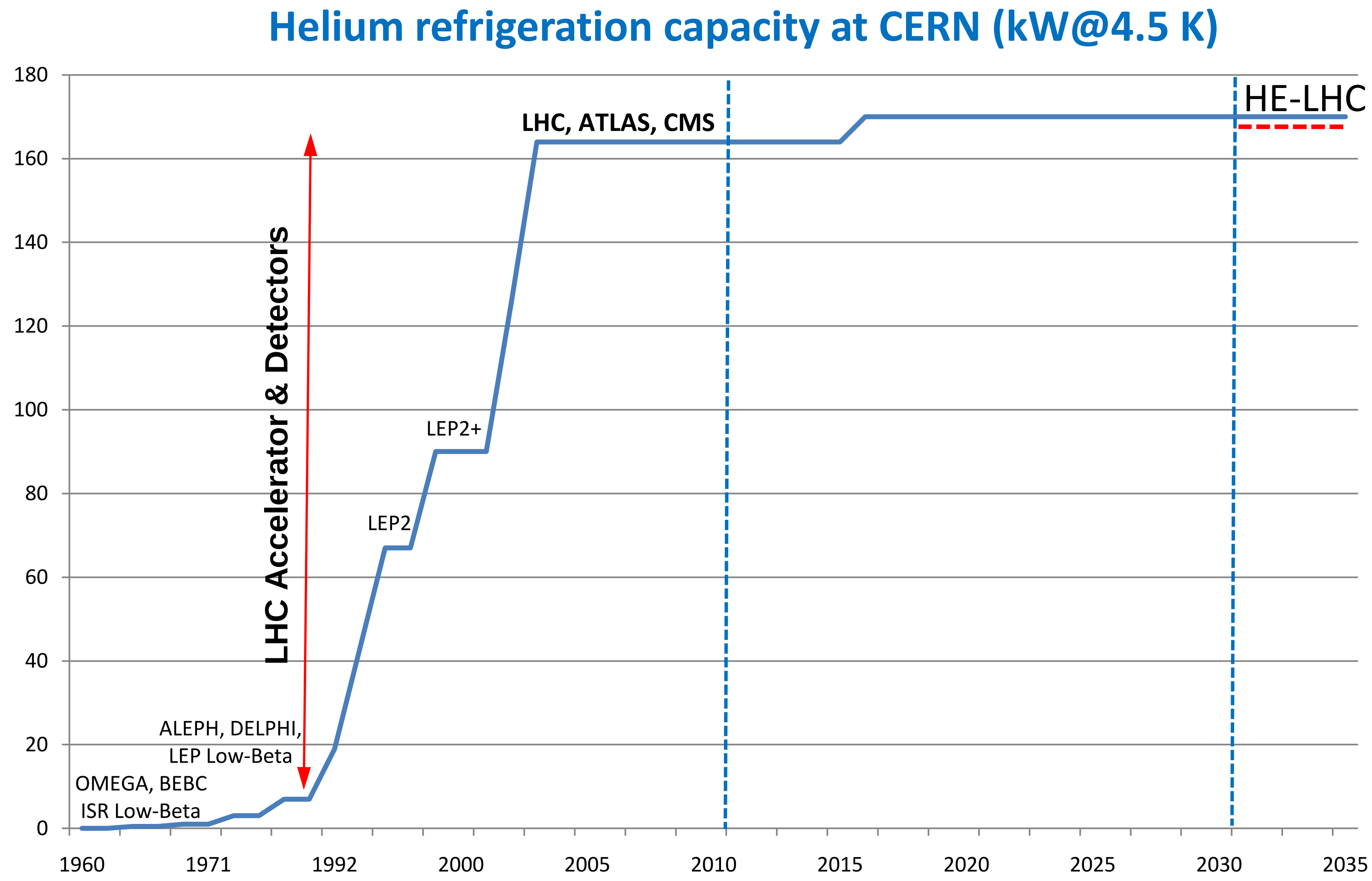
Cryogenics at CERN



Introduction

- Scaling from LHC loads
- Three main temperature levels
  - Thermal shield (TS): 50 and 75 K
  - Heat intercept (HI): 4.6 K & Beam screen (BS): 4.6-20 K (40-60 K or 85-100 K as an alternative compatible with vacuum specification)
  - Cold mass(CM): 2 K
- 8 cryogenic sectors
  - One cryogenic plant per continuous cryostat (arc + dispersion suppressors)
  - Dedicated cryogenic plants for high-load insertions (RF, IT…) as for HL-LHC
- Continuous cryostat (arc + dispersion suppressors) only considered in the following

Heat inleaks (w/o contingency)

- Assumption: thermal performance of the HE-LHC cryostat (magnet + cryogenic distribution QRL) similar to the one of the LHC cryomagnet.

Temperature level		LHC	HE-LHC
TS (50-75 K)	[W/m]	7.7	7.7
HI (4.6 K)	[W/m]	0.23	0.23
CM (2 K)	[W/m]	0.21	0.21

✓Contingency (on heat inleaks); Reminder: LHC contingency factor = 1.5
✓Overcapacity (on cryogenic plant's refrigeration power)

Resistive heating in SC splices

- Resistive heating proportional to:
  - the square of the magnet current,
  - the splice electrical resistance
  - the number of splices

		LHC nominal	HE-LHC
Main magnet current	[kA]	12	18
Splice resistance	[nOhm]	0.5	0.5
Number of splice per arc	[-]	2500	3750
Resistive heating on CM	[W/m]	0.1	**0.34**

Current lead cooling

- Assumptions:
  - HE-LHC is using the same type of HTS current lead as the LHC with the same cooling performance, i.e. 54 mg/s per kA of helium between 20 and 300 K
  - as the optics of the HE-LHC are not yet fully defined the number of individually powered magnets is not known → total current entering or exiting proportional to the main magnet current
  - as for the LHC, it is assumed that high-load sectors enter two times more current than low-load sectors

		LHC nominal	HE-LHC
Main magnet current	[kA]	12	18
Total current in/out	[kA]	2750	4130
Total current high load sector CC	[kA]	460	690
Total current low load sector CC	[kA]	230	345
Specific CL cooling flow	[mg/s per kA]	54	54
High-load sector CL cooling flow	[g/s]	25	**37**
Low-load sector CL cooling flow	[g/s]	12	**19**

Beam-induced load: Scaling laws

Beam-induced load	Energy E	Bunch Population N_{bunch}	Bunch Number n_{bunch}	Bunch Length σ_z [rms]	Beam-screen aperture b	Temp. Level
Synchrotron radiation	E^4	N_{bunch}	n_{bunch}			BS
Image current		N_{bunch}^2	n_{bunch}	$\sigma_z^{-3/2}$	b^{-1}	BS
Photo-electron cloud		N_{bunch}^3	n_{bunch}		b^{-2}	BS
Beam gas scattering		N_{bunch}	n_{bunch}			CM

Beam-induced loads (for BS operating between 4.6 and 20 K)

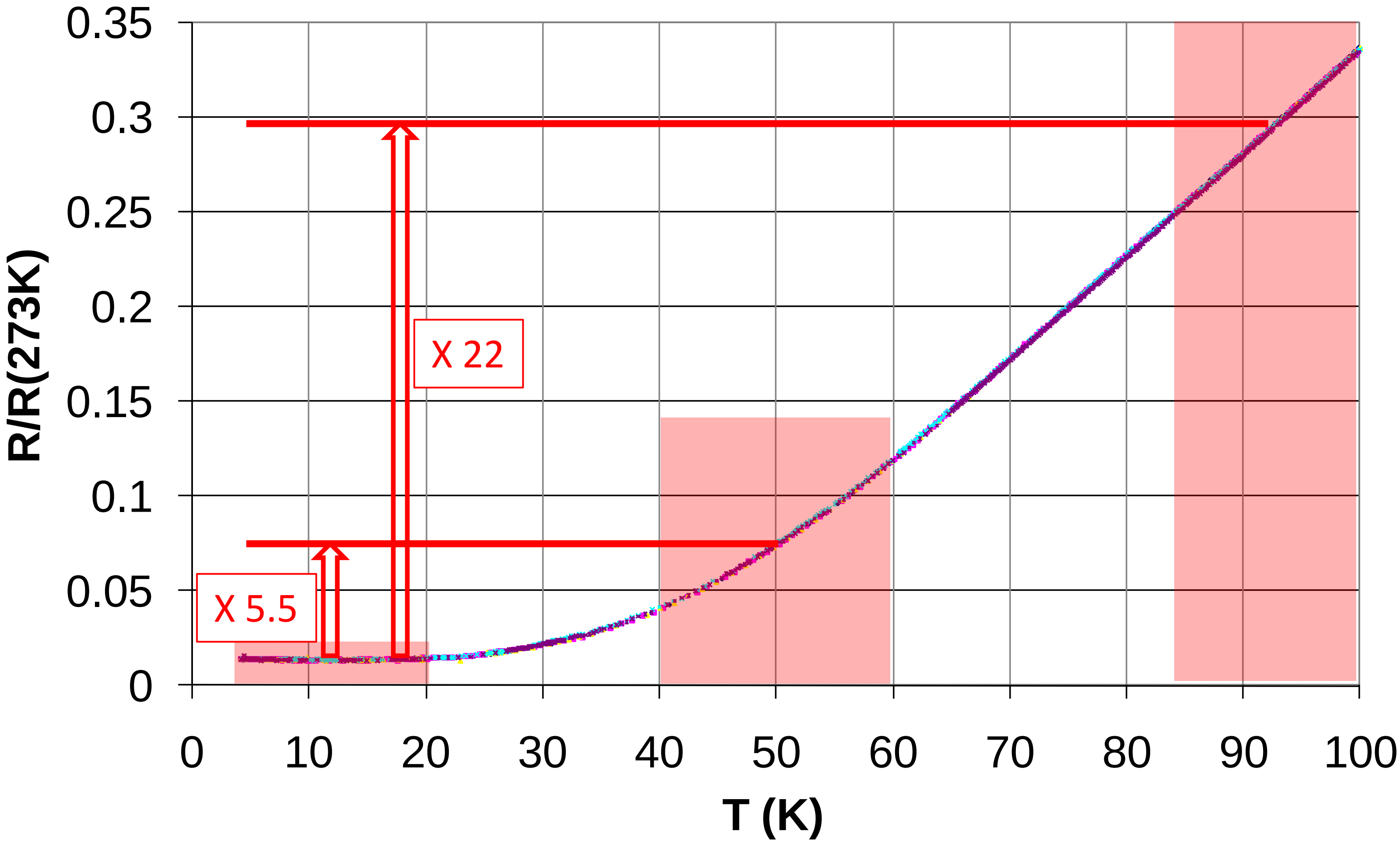
		LHC nominal	HE-LHC
Beam energy, E	[TeV]	7	16.5
Bunch population, N_{bunch}	[10^{11} p]	1.15	1.29
Bunch number, n_{bunch}	[-]	2808	1404
Bunch length, σ_z [rms]	[cm]	7.55	6.55
Beam-screen aperture radius, b	[cm]	2	1.3
Synchrotron radiation	[W/m]	0.33	**5.71**
Image current	[W/m]	0.36	**0.44**
Photo-electron cloud	[W/m]	0.90	**1.50**
Beam gas scattering	[W/m]	0.05	**0.03**

- The biggest change concerns the synchrotron-radiation load, which increases by a factor 17 !

Operating the beam screen at higher temperature

- Operating beam screen at higher temperature will reduce the specific entropic cost of refrigeration, but:
  - As the electrical resistivity of the copper on the beam-screen surface increases with the temperature, the image-current load will also increase proportionally
  - The temperature difference between the beam screen and the cold bore will increase, i.e. the heat inleaks on the cold mass will increase as well
  - Changing the operating conditions and the specific heat load has a direct impact on the cooling capillary diameter
- Two alternative temperature ranges compatible with vacuum requirement:
  - 40-60 K
  - 85-100 K

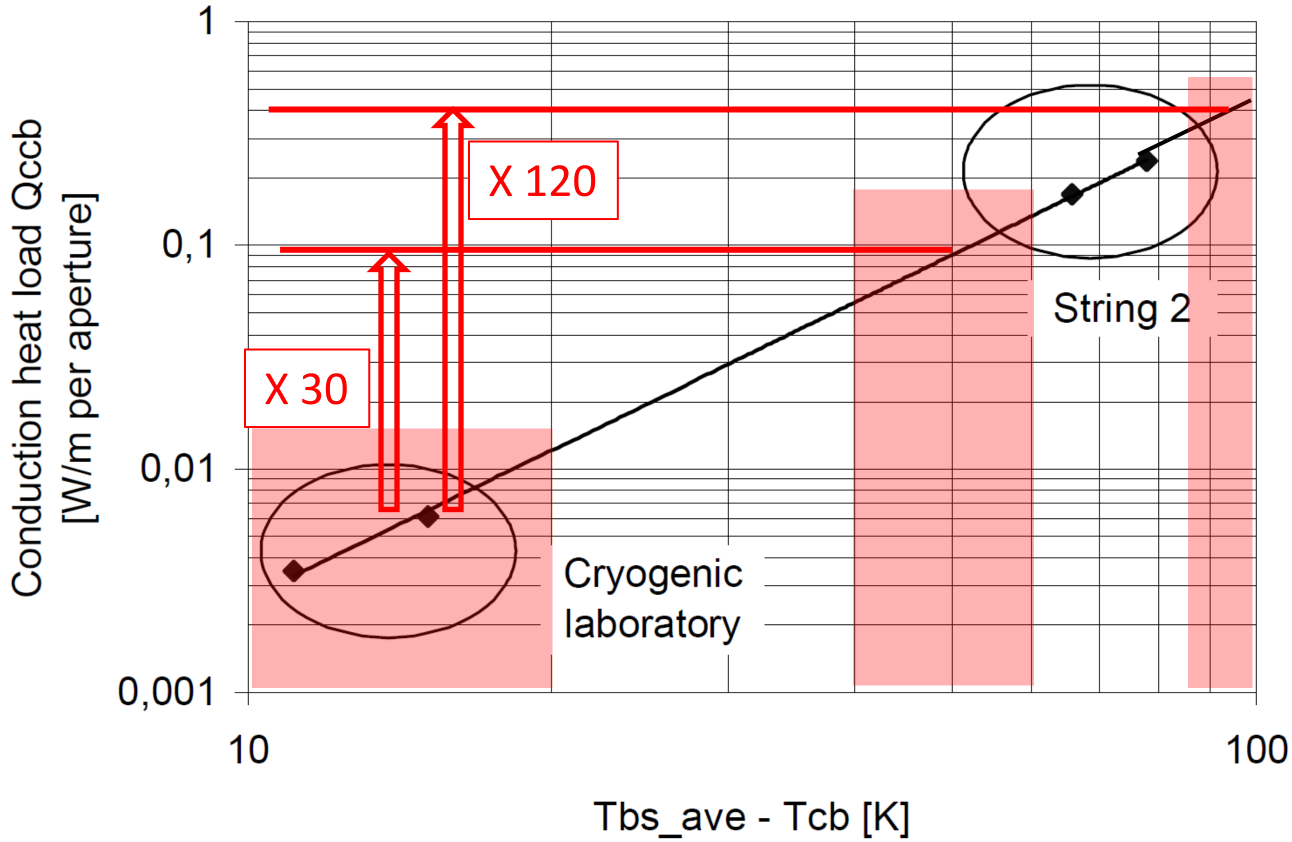
Copper electrical resistivity



- Image current: 0.44 W/m for 4.6-20 K temperature range
  2.4 W/m for 40-60 K temperature range
  9.8 W/m for 85-100 K temperature range

CM heat load vs. BS temperature

(See LHC Project Note 330)



- Cold bore heat load: 0.006 W/m for 4.6-20 K temperature range
  0.17 W/m for 40-60 K temperature range
  0.71 W/m for 85-100 K temperature range

Beam screen cooling capillary

	LHC	HE-LHC		
BS@	4.6-20 K	4.6-20 K	40-60 K	85-100 K
Inlet temperature [K]	4.6	4.6	40	85
Inlet pressure [bar]	3.0	3.0	20	20
Outlet temperature [K]	20	20	60	100
Outlet pressure [bar]	1.3	1.3	18	18
Specific heat load [W/m]	4.8	7.65	9.45	16.3
Loop length [m]	50	50	50	50
Number of capillary per aperture	2	2	2	2
Capillary inner diameter [mm]	3.7	**4.4**	**3.8**	**6.0**

- 40-60 K temperature range → minimum diameter !

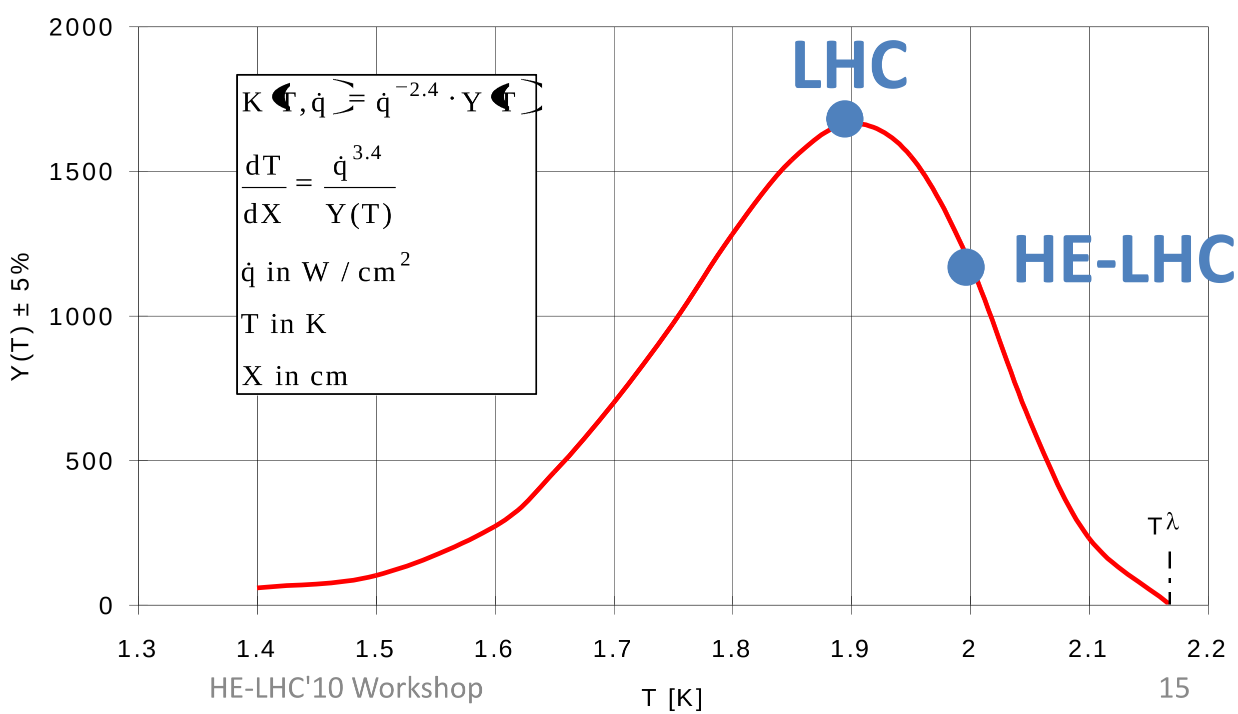
Summary of specific cryogenic heat loads

Temp. level	Heat load source		LHC nominal	HE-LHC BS @ 4.6-20 K	HE-LHC BS @ 40-60 K	HE-LHC BS @ 85-100 K
TS	Heat inleaks	[W/m]	7.7	7.7		
	Total TS	[W/m]	**7.7**	**7.7**		
HI	Heat inleaks	[W/m]	0.23	0.23		
	Total HI	[W/m]	**0.23**	**0.23**		
BS	Heat inleaks	[W/m]	0	0	-0.17	-0.71
	Synchrotron radiation	[W/m]	0.33	5.71	5.71	5.71
	Image current	[W/m]	0.36	0.44	2.40	9.81
	Photo-electron cloud	[W/m]	0.90	1.50	1.50	1.50
	Total BS	**[W/m]**	**1.82**	**7.65**	**9.45**	**16.3**
CM	Heat inleaks	[W/m]	0.21	0.21	0.38	0.92
	Resistive heating	[W/m]	0.10	0.34	0.34	0.34
	Beam-gas scattering	[W/m]	0.05	0.03	0.03	0.03
	Total CM	**[W/m]**	**0.36**	**0.58**	**0.74**	**1.29**

Cold mass cooling

- LHC cooling scheme limited to 0.9 W/m (sub-cooling heat exchanger), i.e. not compatible with the 85-100 K BS temperature range.
- Cooling at 2 K: reduced conduction in superfluid helium to extract the heat from the coil.

Apparent thermal conductivity of superfluid helium



Continuous cryostat cooling capacity per sector

(values in brackets: equivalent entropic capacity in kW at 4.5 K)

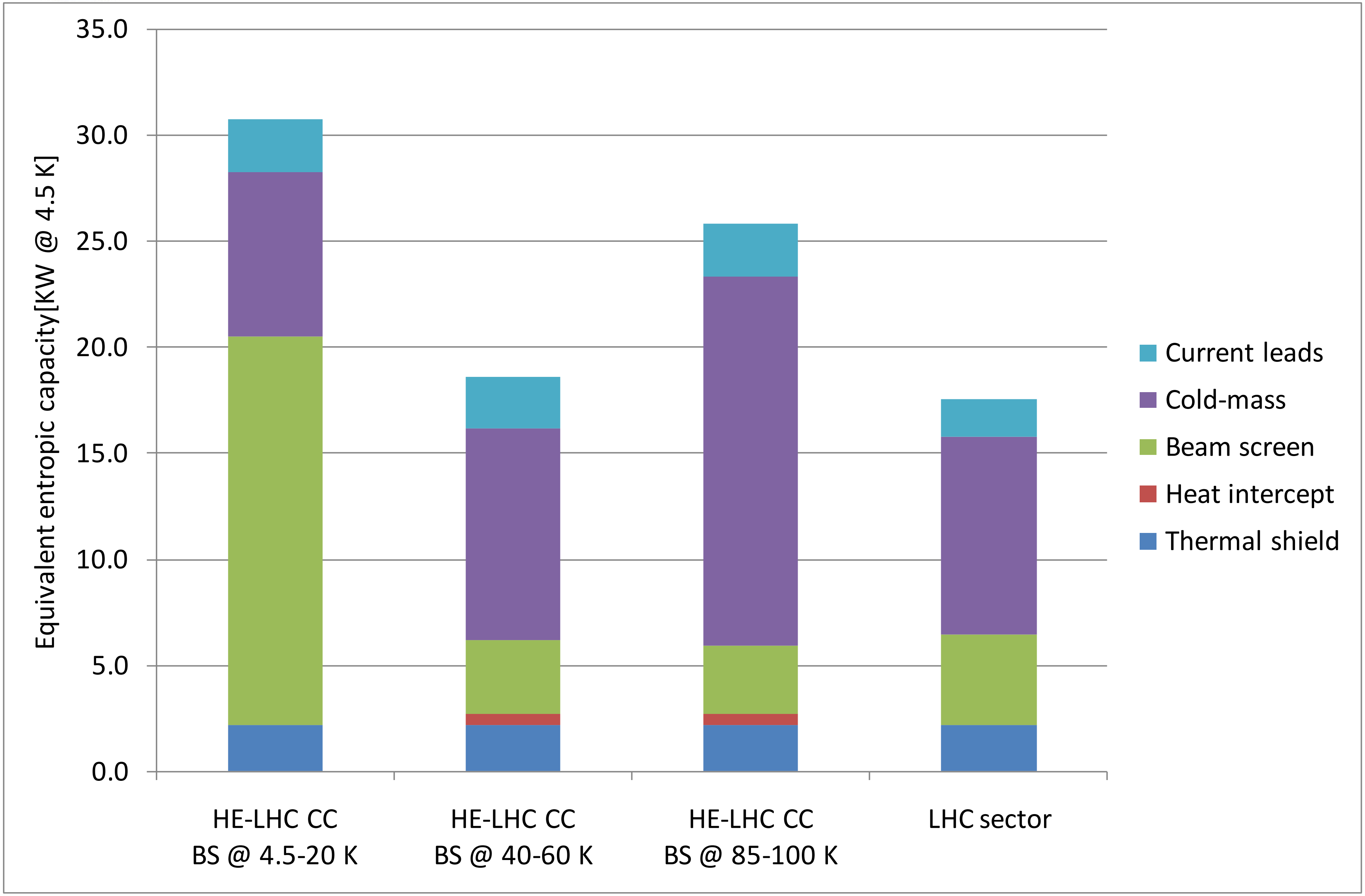
•Assumptions:

- Continuous cryostat length: 2800 m
- Overcapacity factor: 1.5 (for each temperature level) as for LHC plants

Temperature level	HE-LHC continuous cryostat			LHC high-load sector
	BS @ 4.6-20 K	BS @ 40-60 K	BS @ 85-100 K	BS @ 4.6-20 K
TS (50-75 K) [kW]	32 (2.2)			33 (2.2)
HI (4.6-20 K) [kW]	33 (18.4)	1.0 (0.5)	1.0 (0.5)	7.7 (4.3)
BS [kW]		40 (3.5)	69 (3.3)	
CM (2 K) [kW]	2.4 (7.8)	3.1 (10.0)	5.4 (17.4)	2.7* (9.3)
CL [g/s]	56 (2.5)			41 (1.8)
Total equivalent entropic capacity	(30.8)	(18.6)	(25.8)	(17.6)

*: 2.4 kW at 1.8 K plus 0.3 kW at 4.5 K

Equivalent entropic capacity



Electrical input power for continuous-cryostat refrigerators

		HE-LHC CC refrigerator			LHC refrigerator
		BS @ 4.6-20 K	BS @ 40-60 K	BS @ 85-100 K	
Electrical input power per refrigerator	[MW]	7.7	4.7	6.5	4.4
Number of refrigerator	[-]	8	8	8	8
Total electrical input power	[MW]	**62**	**37**	52	35

Assuming a performance coefficient factor of 250 W/W (electrical / @4.5 K)

Concluding remarks [1/2]

- No contingency has been introduced in the numbers
- A lot of assumptions have to be confirmed (e.g. the splice resistance and number, the main magnet current, the current-leads distribution and number, and the cryostat performance)
- The optimization of the refrigeration cycle has still to be done (wrt temperature levels)
- Transient heat loads (ramp/de-ramp, fast de-ramp, quench), have still to be considered in order to define the correct level of buffering
- The insertion loads have still to be considered (dedicated new cryoplants as for HL-LHC)

Concluding remarks [2/2]

- Depending on the cooling scenario, up to 9 temperature levels have to be distributed along the continuous cryostats to supply or recover the different cooling loops
→ A rationalization study has to be done for reducing the number of distribution headers like:
  - operating the beam screen and the thermal shield with the same temperature range (40-60 K)
  - cooling the resistive part of HTS current lead with a helium flow at a higher temperature and pressure (e.g. 40 K, 20 bar)
- At the end of the LHC (2030), the LHC (& former LEP) cryogenics will reach 30 to 40 years operation; Initially specified for a 20-year operation, major overhauling has to be considered for the equipments re-affected to the HE-LHC project (cryoplants, QRL, distribution boxes…)

Additional slide
Rationalization options

•Temperature range (9 levels)

Inlet: 50 K (TS), 40 K (BS), 20 K (CL), 4.6 K

Outlet: 300 K (CL), 75 K (TS), 60 K (BS), 4 K (Very Low Pumping)

Quench recovery T

•Rationalization options:

TS & BS @ 40-60 K

CL LHC 20-300 K (but regulated @ 50 K, saving distribution headers)

CL HE-LHC @ 40-300 K, 20b (taking profit from the TS & BS option)

Leading to reduced Temperature range (6 levels)

Inlet: 40 K, 20 b (TS, BS, CL), 4.6 K

Outlet: 300 K (CL), 60 K (TS, BS), 4 K (Very Low Pumping)

Quench recovery T