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Conceptual design of the cryogenic system for the high-luminosity upgrade of the Large Hadron Collider (LHC)

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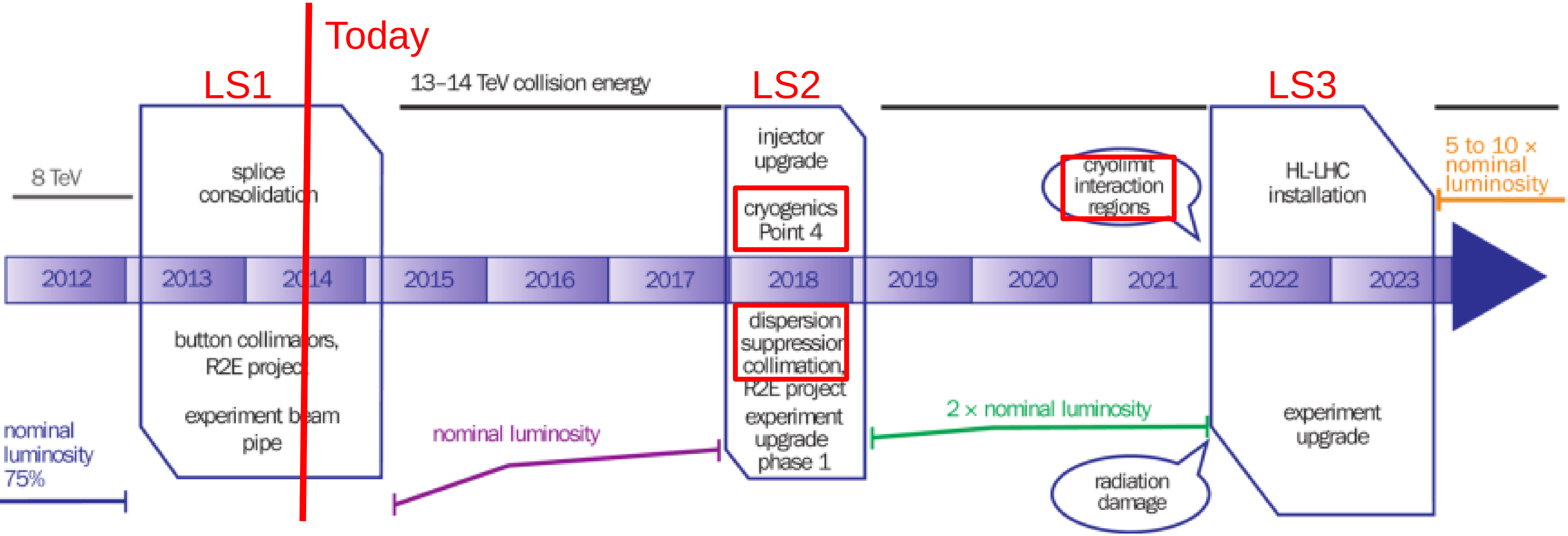
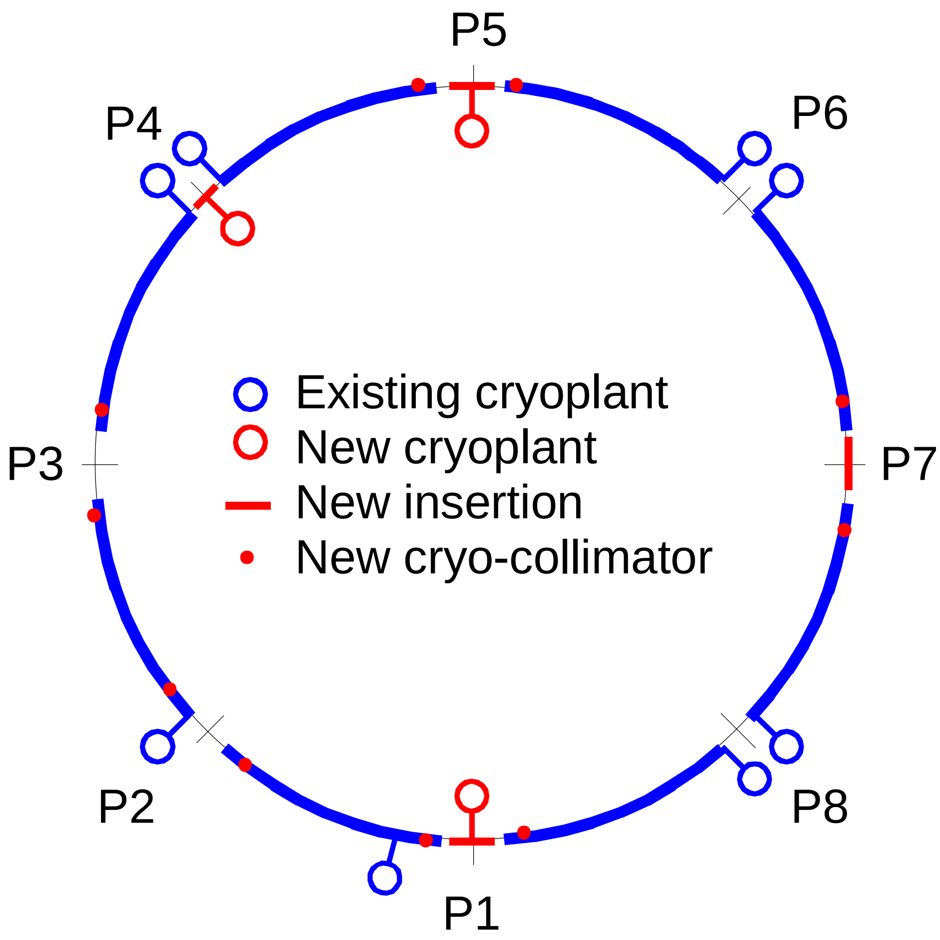
- Introduction
- Review of the upgrade plan
- Operating conditions, cooling methods and heat loads
- Refrigeration capacity requirement of existing-sector and new cryoplants
- Conclusion and main challenges

The CERN 10-year plan (approved early 2011)



Increase of the proton bunch population (~2 times the nominal)
Increase of the luminosity in ATLAS and CMS (~5 times the nominal)
→ Higher beam-induced heating
→ Major upgrade of the cryogenic system

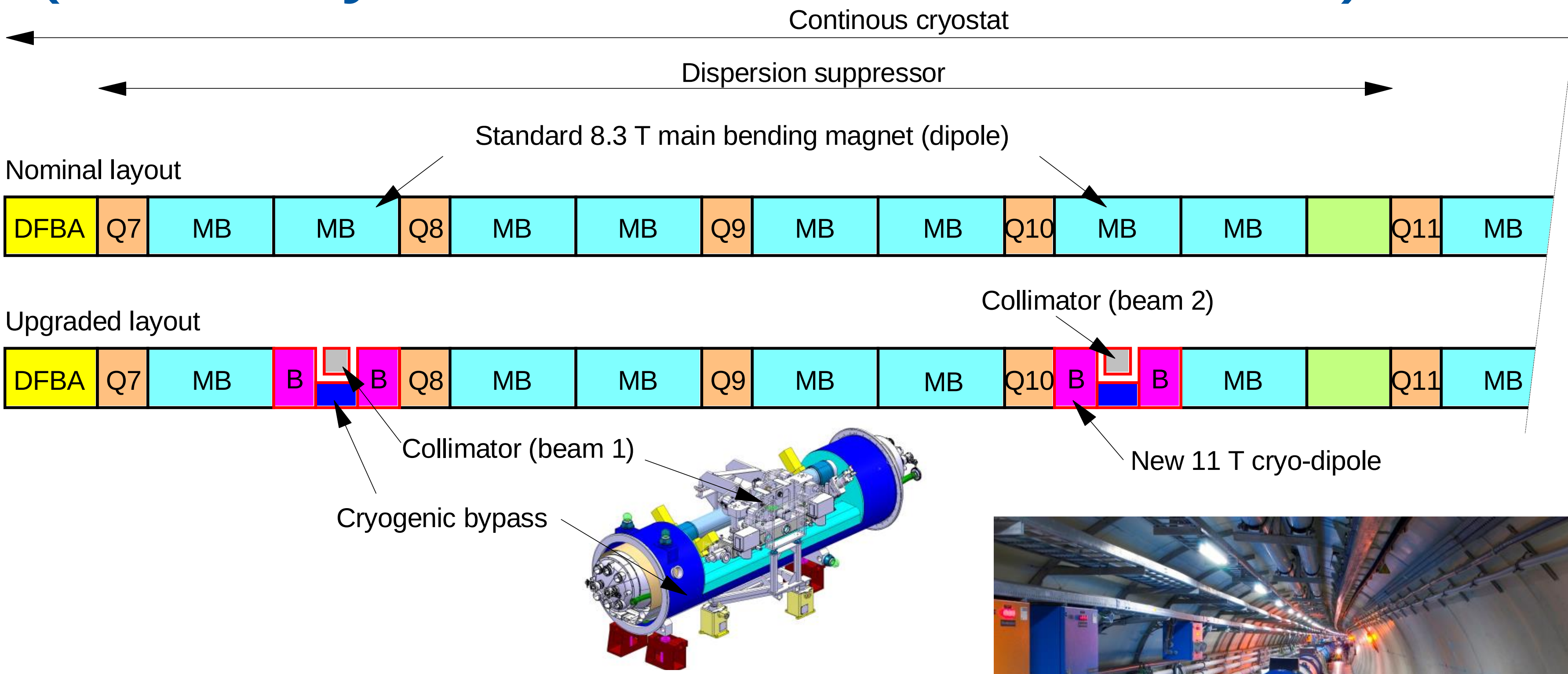
Introduction



HL-LHC cryo-upgrade:

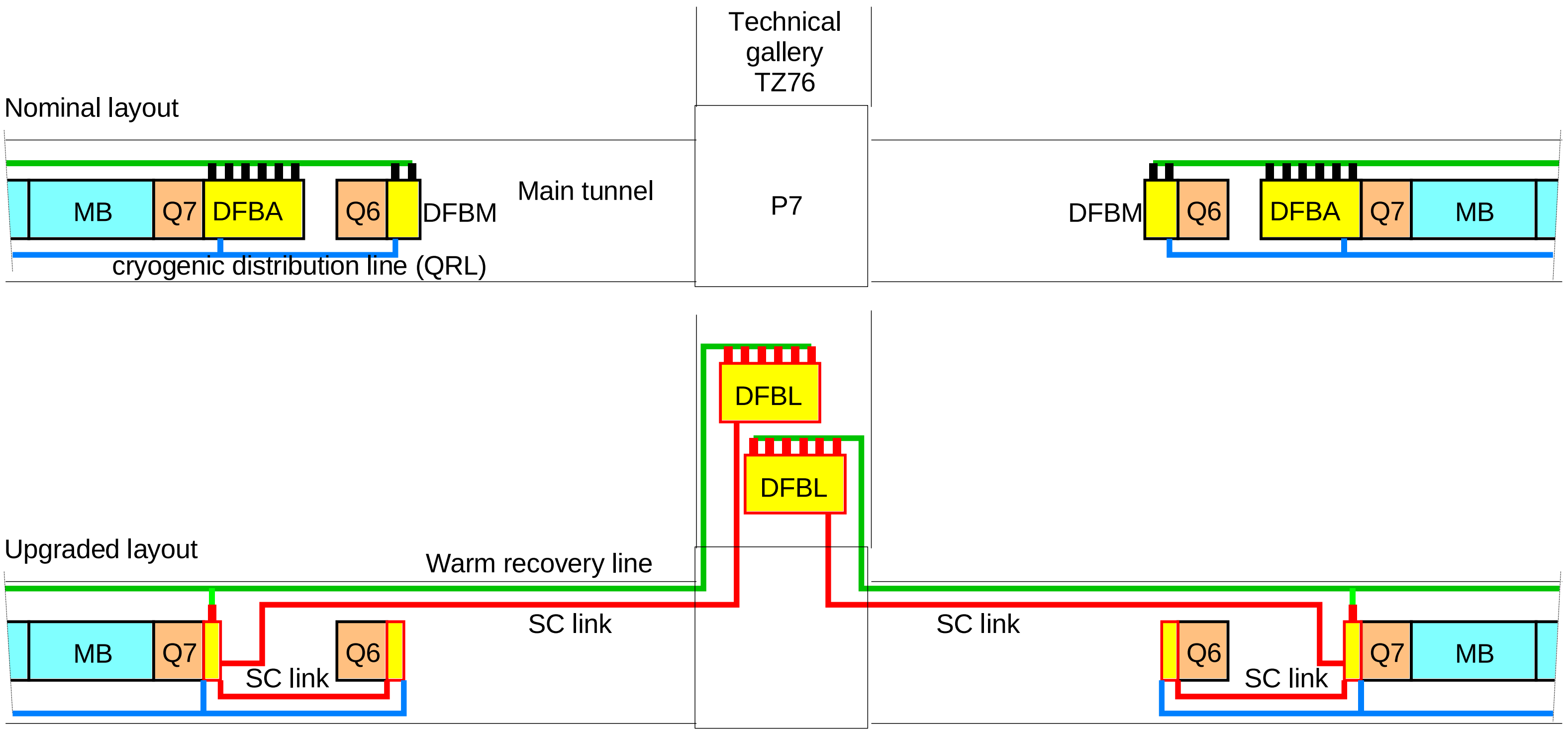
- 2 new cryoplants at P1 and P5 for high luminosity insertions
- 1 new cryoplant at P4 for SRF cryomodules
- New cooling circuits at P1, P5 and P7 for HTS links and deported current feed boxes
- New cooling circuits for cryo-collimators and 11-T dipoles at P2 and P7, and may be also at P3, P1 and P5

Cryo-collimator at P2 and P7 (and may be also at P3, P1 and P5)



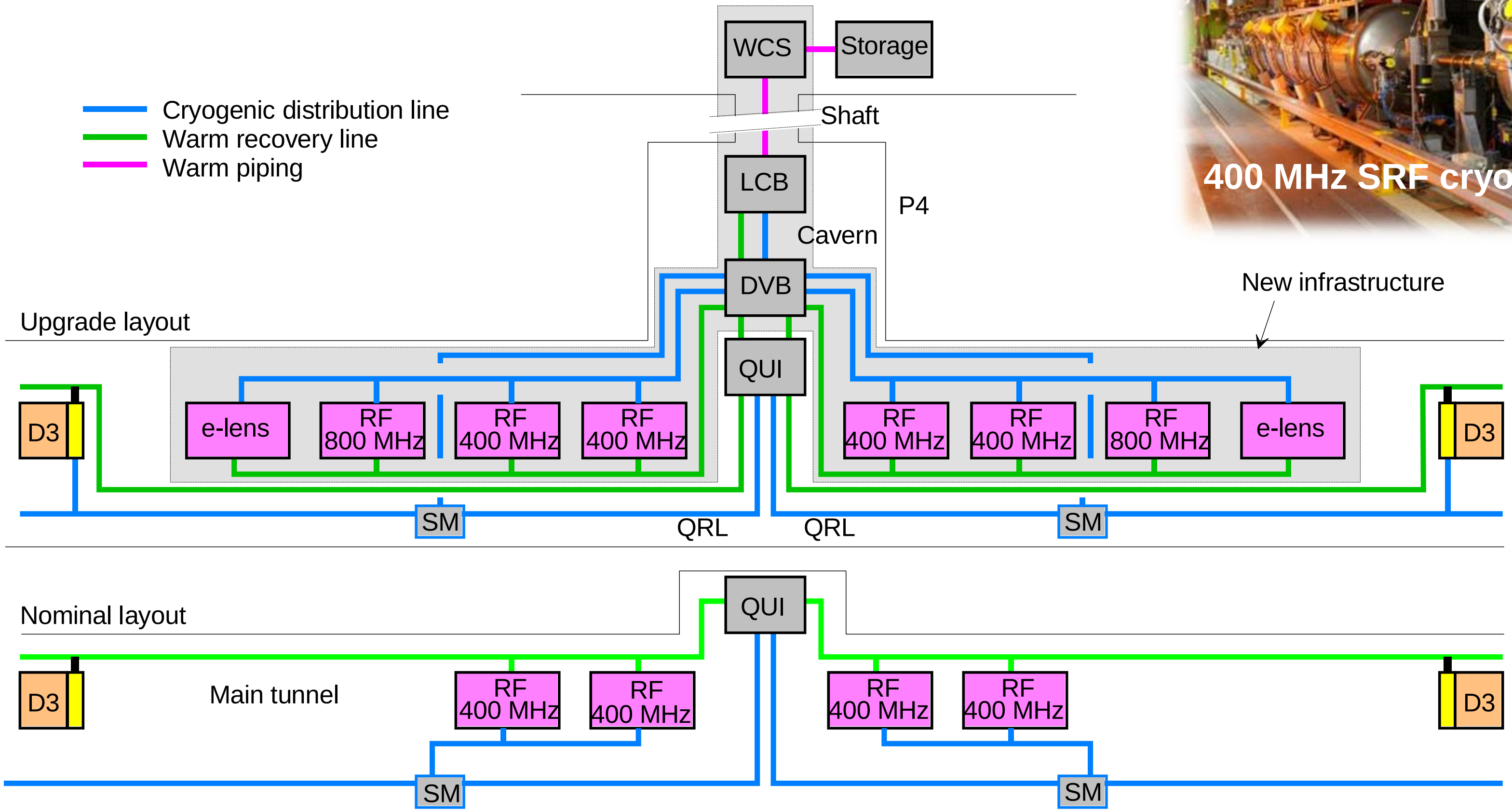
Main cryogenics constraints:
Continuity of the cell cooling (bayonet HX, free section of pressurized HeII), hydraulic impedance for cool-down, warm-up and quench discharge…

New insertion at P7



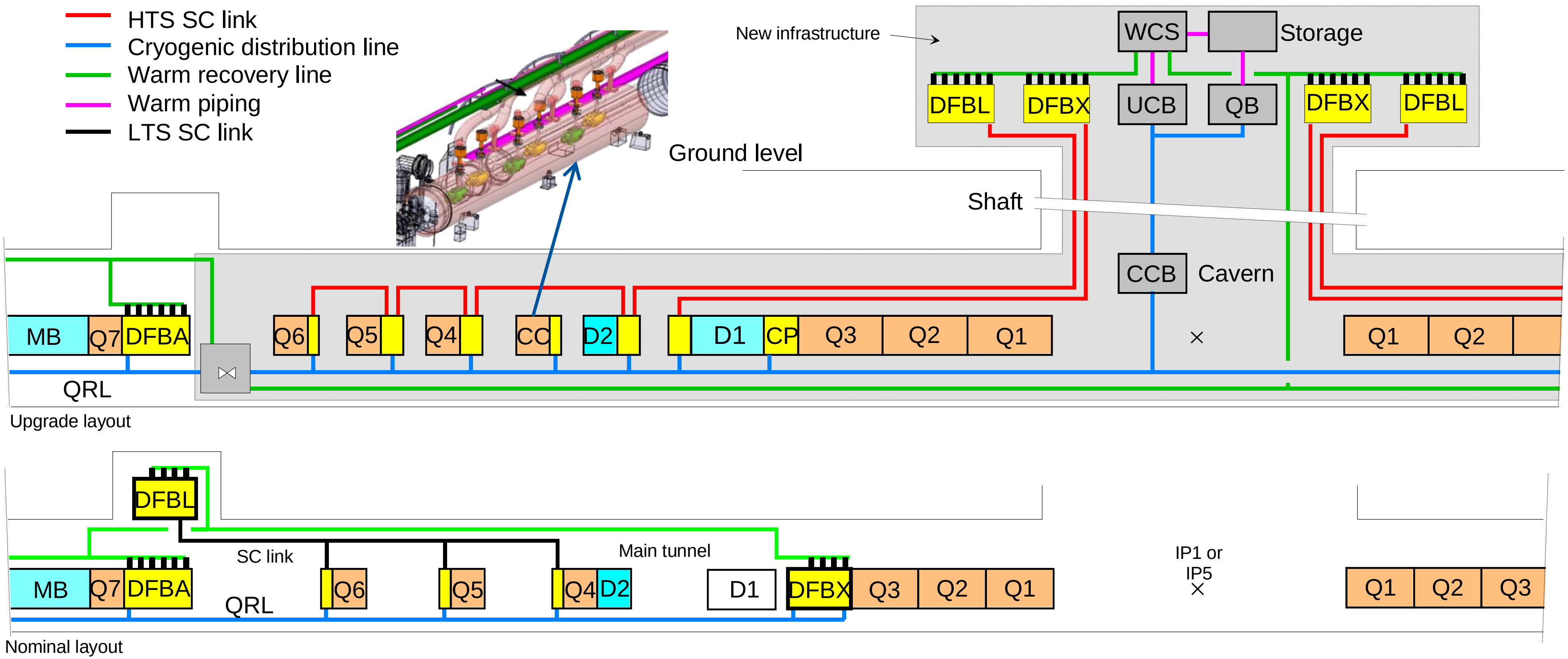
Optimisation of the HTS link cooling taking into account fixed boundary conditions imposed by the existing cryogenic distribution scheme (QRL headers P, T…)

New insertion at P4



- Cryogenics for 800 MHz SRF cryomodules and e-lenses
- 1 warm compressor station (WCS) in noise insulated surface building
- 1 lower cold box (LCB) in UX45 cavern
- 1 valve box in UX45 cavern
- 2 main cryogenic distribution lines
- 2 interconnection lines with existing QRL service modules (redundancy by sector cryoplants)

New insertions at P1 and P5



- Cryogenics for new cryo-assemblies (Crab cavities (CC), insertion cryomagnets, DFBs, HTS links…)
- 1 warm compressor station (WCS) in noise insulated surface building
- 1 upper cold box (UCB) in surface building
- 1 cold quench buffer (QV) in surface
- 1 or 2 cold compressor boxes (CCB) in underground cavern
- 2 main cryogenic distribution lines
- 2 interconnection valve boxes with existing QRL (partial redundancy with sector cryoplants)

Operating conditions and cooling methods

Equipment	Operating condition		Cooling method
	[K]	[bar]	
11-T cryo-dipole (P1, P2, P5 & P7)	1.9	1.3	In static pressurized superfluid helium via a bayonet heat exchanger Φ 54 mm
Cryogenic bypass (P1, P2, P5 & P7)	1.9	1.3	In static pressurized superfluid helium and conduction cooled by adjacent 11-T cryo-dipoles
RF cryo-module 800 MHz (P4)	4.5	1.3	Pool boiling in saturated helium
Electron lens (P4)			
HTS SC link cable (P1, P5 & P7)	4.5-17	1.3-1.2	Force flow in helium gas
HTS SC link screen (P1, P5 & P7)	20-100	1.2-1.1	
HTS current lead (P1, P5 & P7)	20 - 300	1.2-1.15	
Q1-Q2-Q3 string (P1 & P5)	1.9	1.3	In static pressurized superfluid helium via two parallel bayonet heat exchanger Φ 77 mm
D1 & Corrector Package (CP) string (P1 & P5)	1.9	1.3	In static pressurized superfluid helium via two parallel bayonet heat exchanger Φ 49 mm
D2 (P1 & P5)	1.9	1.3	In static pressurized superfluid helium via a bayonet heat exchanger Φ 54 mm
Q4 (P1 & P5)	1.9	1.3	
Crab-cavity module (P1 & P5)	2.0	0.03	Pool boiling in saturated superfluid helium
Q5 (P1 & P5)	4.5	1.3	Pool boiling in saturated helium
Q6 (P1 & P5)	4.5	1.3	

Main Heat loads

- Static heat inleaks: Scaling w/r to specific performance of existing equipment.
- Dynamic heat loads:

Temperature level	Dynamic load		Nominal	Upgrade
4.6-20 K	Synchrotron radiation	[mW/m per beam]	165	310
	Image current	[mW/m per beam]	145	522
	E-clouds (Arc) (with efficient beam scrubbing)	[mW/m per beam]	271	**41**
	E-clouds (Arc) (without efficient beam scrubbing)	[mW/m per beam]	4264	**4097**
	E-clouds (IT)	[W per IT]	200	600
	Secondaries (IT beam screen P1 andP5)	[W per IT]	0	**650**
1.9 K	Beam gas scattering	[mW/m per beam]	24	45
	Resistive heating in splices	[mW/m]	56	56
	Secondaries (IT P1 and P5)	[W per IT]	155	**630**
	Qrf crab-cavities	[W per module]	0	24
4.5 K	Qrf 400 MHz	[W per module]	100	366
	Qrf 800 MHz	[W per module]	-	183
	E-lens	[W per module]	-	2

~ twice the local cooling limitation given by the hydraulic impedance of the beam screen cooling circuits

IT cooling challenge:
~ 13 W/m on 1.9 K cold-mass
~ 23 W/m on beam-screens

Total secondaries: 1270 W shared between beam-screen and cold-mass circuits (beam screens are equipped with tungsten shielding)

Heat loads and refrigeration capacities

Existing sector cryoplants

Temperature level	Heat loads [kW]	Installed capacity [kW]	Over-capacity factor [-]
50-75 K	20.5 (20.5)	33 (31)	1.6 (1.5)
4.6-20 K with efficient beam scrubbing	5.5 (5.9)	7.7 (7.6)	1.4 (1.3)
4.6-20 K without efficient beam scrubbing	**28.5 (28.8)**	7.7 (7.6)	**0.3 (0.3)**
1.9 K	1.1 (0.93)	2.4 (2.1)	2.1 (2.2)
20-290 K (current leads)	33.6 (28.8)	57.5 (37.9)	1.7 (1.3)

Efficient beam scrubbing mandatory !
Overcapacity factors stay correct.

New cryoplant at P4

Temperature level	Static heat inleaks [W]	Dynamic heat load [W]	Installed capacity [W]	Equivalent installed capacity @ 4.5 K [kW]	
4.5 K	1144	1736	5223	5.6	**5.8**
50-75 K	1000	0	2250	0.2	

~ 6 kW @ 4.5 K

New cryoplants at P1 and P5

Temperature level	Static heat inleaks [W]	Dynamic heat load [W]	Installed capacity [W]	Dynamic range [-]	Equivalent installed capacity @ 4.5 K [kW]	
1.9 K	433	1380	**3045**	**7**	12	**18**
4.5 K	196	8	452	2	0.5	
4.6-20 K	154	2668	4348	**28**	2.4	
50-75 K	4900	0	7350	2	0.5	
20-290 K	22200	22200	83200	4	2.6	

~ 18 kW @ 4.5 K
including ~3 kW @ 1.8 K
With large dynamic ranges at 4.6-20 K and 1.9 K

Conclusion

The HL-LHC project will require a large cryogenic upgrade with new cryogenics challenges.

- New cooling circuits must be designed to extract
  - up to 13 W/m on 1.9 K cold-mass superconducting cables while keeping sufficient margin with respect to resistive transition limit
  - up to 23 W/m on inner-triplet beam-screens with possibly a different operating range (40-60 K) and with a large dynamic range which will require specific cryogenic-plant adaptation studies.
  - New cooling method of HTS links, current feed boxes and crab-cavities must be developed and validated.
  - The resistive transition containment and helium recovery via cold buffering must be designed for efficient operation.

- Concerning cryogenic plants, larger 1.8-K refrigeration capacities beyond the present state-of-the-art must be developed including large capacity (1500/3000 W) sub-cooling heat exchangers.

- This upgrade will be implemented within to main phases.
  - During the second long shutdown of LHC in 2018-2019 calendar years, the upgrade at Point 2, Point 7 and Point 4 will be implemented.
  - The remaining part will be implemented during the third long shutdown of LHC in 2023-2025 calendar years.

Thank you for your attention!

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