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LHC cryogenic system upgrade for various luminosity upgrade scenarios

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Beam parameters for various upgrade options

Effective luminosity for various upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep}[ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
longitudinal profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	ß* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [μrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
IBS growth time	$\tau_{x,IBS}$ [h]	106	72	42	75
nuclear scatt. lumi lifetime	τ_N/1.54 [h]	26.5	17	8.5	5.2
lumi lifetime (τ_{gas} =85 h)	τ_L [h]	15.5	11.2	6.5	4.5
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.4	0.8	2.4	1.9
($T_{turnaround}$=10 h)	T_{run} [h] optimum	14.6	12.3	8.9	7.0
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.5	1.0	3.3	2.7
(T_{turn}=5 h)	T_{run} [h] optimum	10.8	9.1	6.7	5.4

Beam parameters and heat load data

Scenario		Nominal	Ultimate	Short-bunch	Long-bunch
energy, E	[TeV]	7	7	7	7
beam current, I	[A]	0.58	0.86	1.72	1
bunch number, nb	[-]	2808	2808	5616	936
bunch spacing, sb	[ns]	25	25	12.5	75
bunch current, Ib	[mA]	0.2	0.3	0.3	1.1
rms bunch length, s_z	[mm]	75.5	75.5	37.8	144
luminosity, L	[$cm^{-2}.s^{-1}$]	10^{34}	$2.3.10^{34}$	$9.2.10^{34}$	$8.9.10^{34}$
resistive heating	[W/m]	0.1	0.1	0.1	0.1
synchrotron radiation	[W/m]	0.34	0.50	1.0	0.58
image currents	[W/m]	0.30	0.66	3.7	1.9
beam gas scattering	[W/m]	0.076	0.11	0.23	0.13
average e-clouds	[W/m]	2.1	2.1	**27**	0.52
RF losses per half insertion	[W]	214	480	1000	2040
secondaries per half insertion	[W]	190	440	**1770**	**1710**

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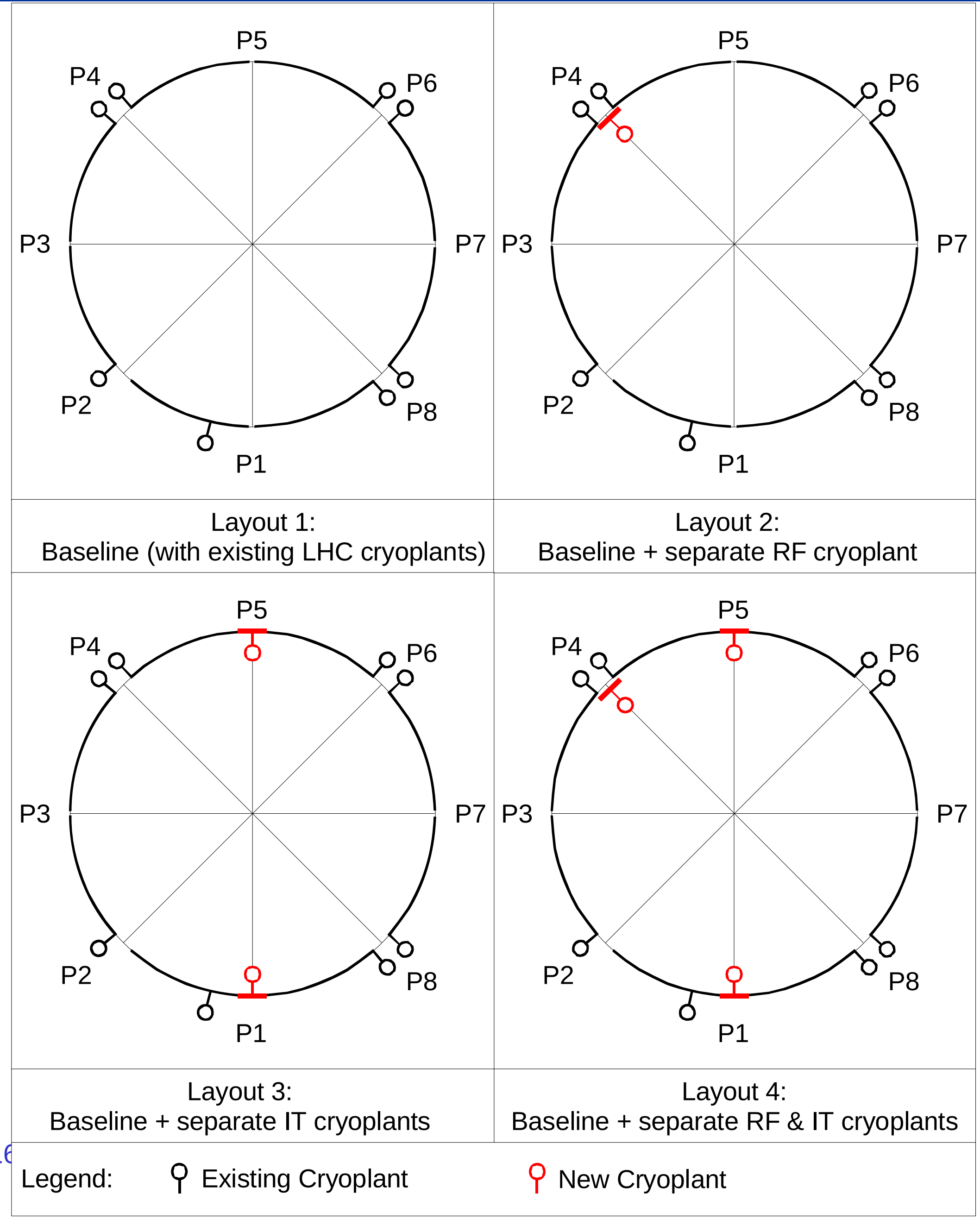
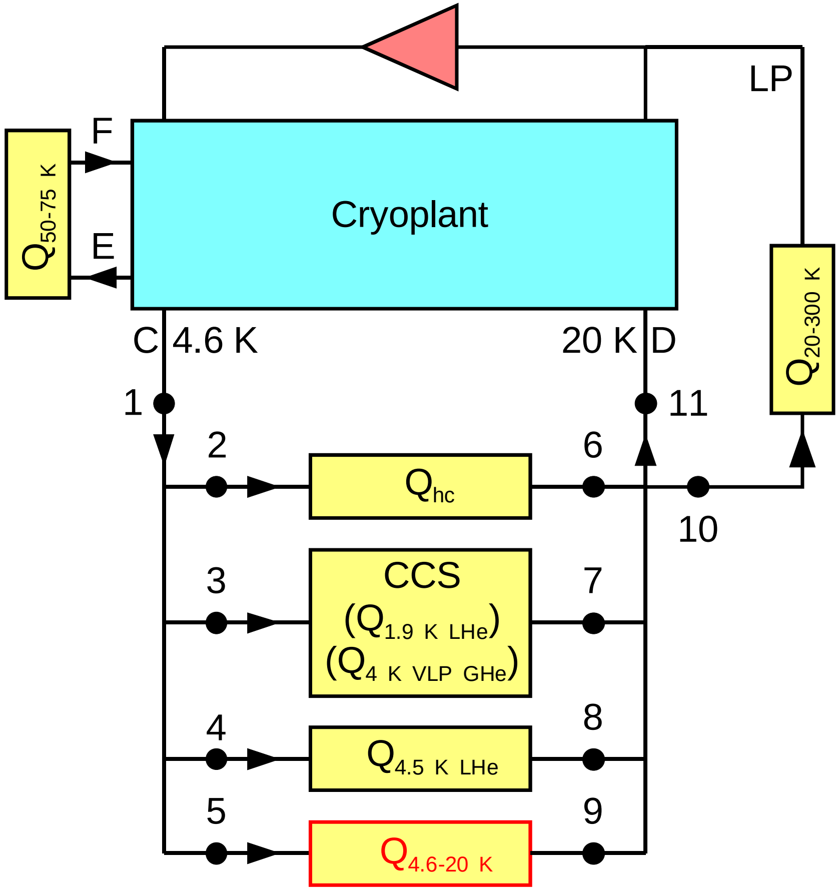
Cryogenic layout configurations



Existing cryoplant model



(BS cooling loop)

Q_{hc}: QUI phase separator for line C recooldown after hydrostatic compression
$m_2 = 0.09 * m_1$ for new cryoplant,
$m_2 = 0$ for Ex-LEP cryoplant

CCS: Cold compressor system seen by the cryoplant as 4.6 - 20 K loads
$m_3 = 0.1254 * Q_{1.9\ K\ LHe} / 2400$
$m_{3min} = 0.04$ kg/s (CC adaptation)

$Q_{4.5\ K\ LHe}$: Standalone magnets, DFBs and Cavities
$m_4 = Q_{4.5\ K\ LHe} / (H_8 - H_C)$
H_8: Saturated GHe @ 4.5 K

$Q_{4.6\text{-}20\ K}$: BS cooling loop load
$m_5 = m_1 - m_2 - m_3 - m_4$
$Q_{4.6\text{-}20K} = m_5 * (H_9 - H_C)$
$T_9 = 20$ K

$Q_{20\text{-}300\ K}$: Current lead cooling loop load

$Q_{50\text{-}75\ K}$: Thermal shield cooling loop load

Required cryoplant capacity (Without contingency)

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Scenario	Layout	Existing LHC Cryoplant margin			New Cryoplant capacity	
		1.8 K unit		4.5 K Cryoplant	RF Cryoplant	IT Cryoplant
		IT @ 1.8 K	IT @ 4.5 K			
		[kW @ 1.8 K]		[kW @ 4.5 K]	[kW@ 4.5 K]	[kW @ IT Temp.]
Nominal	**Layout 1**	**1.0**	**N/A**	**1.2**	**N/A**	**N/A**
Ultimate	Layout 1	0.6	1.1	**-1.2**	N/A	N/A
	Layout 2	**0.6**	**1.1**	**0.2**	**1.4**	N/A
	Layout 3	1.1	1.1	**-0.1**	N/A	0.9
	Layout 4	1.1	1.1	1.3	1.4	0.9
Short-bunch	Layout 1	**-1.8**	0.0	**-51**	N/A	N/A
	Layout 2	**-1.8**	0.0	**-48**	2.4	N/A
	Layout 3	0.0	0.0	**-47**	N/A	3.5
	Layout 4	0.0	0.0	**-44**	2.4	3.5
Long-bunch	Layout 1	**-0.7**	1.1	**-9.0**	N/A	N/A
	Layout 2	**-0.7**	1.1	**-3.1**	4.5	N/A
	Layout 3	1.1	1.1	**-4.5**	N/A	3.4
	Layout 4	**1.1**	**1.1**	**1.4**	**4.5**	**3.4**

Blue: Possible layout | **Blue Bold: Recommended layout**

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Local cooling limitations

Scenario	BS cooling loop [W/m/aperture]	1.9 K cooling loop [W/m]
Nominal	1.5	0.40
Ultimate	1.7	0.44
Short-bunch	**16**	0.81
Long-bunch	1.6	0.45
Local limitation	2.4 *	0.9 **

*: limited by the hydraulic impedance of the cooling channels and calculated for a supply pressure (header C) of 3 bar.

**: limited by the sub-cooling heat exchanger capacity

Remark: In the BS, 16 W/m can be extracted with a supply pressure (header C) of 20 bar. However, this supply pressure of 20 bar will also increase from 17 to 60 % the gas fraction produced in the final expansion of the 1.9 K cooling loop and will jeopardize the 1.9 K refrigeration capacity.
An alternative to keep the supply at 3 bar is to change the BS in all the magnet and increase the cooling channel diameter to 8 mm → beam aperture issue ?

Intermediate conclusion

- If the e-clouds heat loads are well estimated:
  - » The consideration of both overall capacity and local cooling requirements shows that the Short-bunch scenario is not feasible from the cryogenic point of view.
  - » Concerning the upgrade of the RF cooling, in order to avoid two consecutive upgrades for the Ultimate and for the Long-bunch scenarios, it is recommended to upgrade the cryogenic system directly with the Long-bunch cavities requirements.
  - » Consequently, in the following, only the Long-bunch scenarios will be studied and cost estimated.

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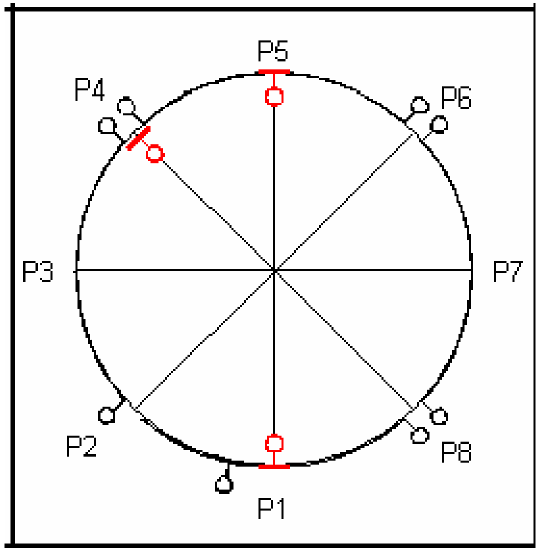
Equivalent installed capacity at 4.5 K of additional cryoplants



Layout 4:
Baseline + separate RF & IT cryoplants

- The choice of the SC material for the IT magnets is still open.
- In addition, even if Nb3Sn is chosen, sub-cooling of He could be required for heat extraction.

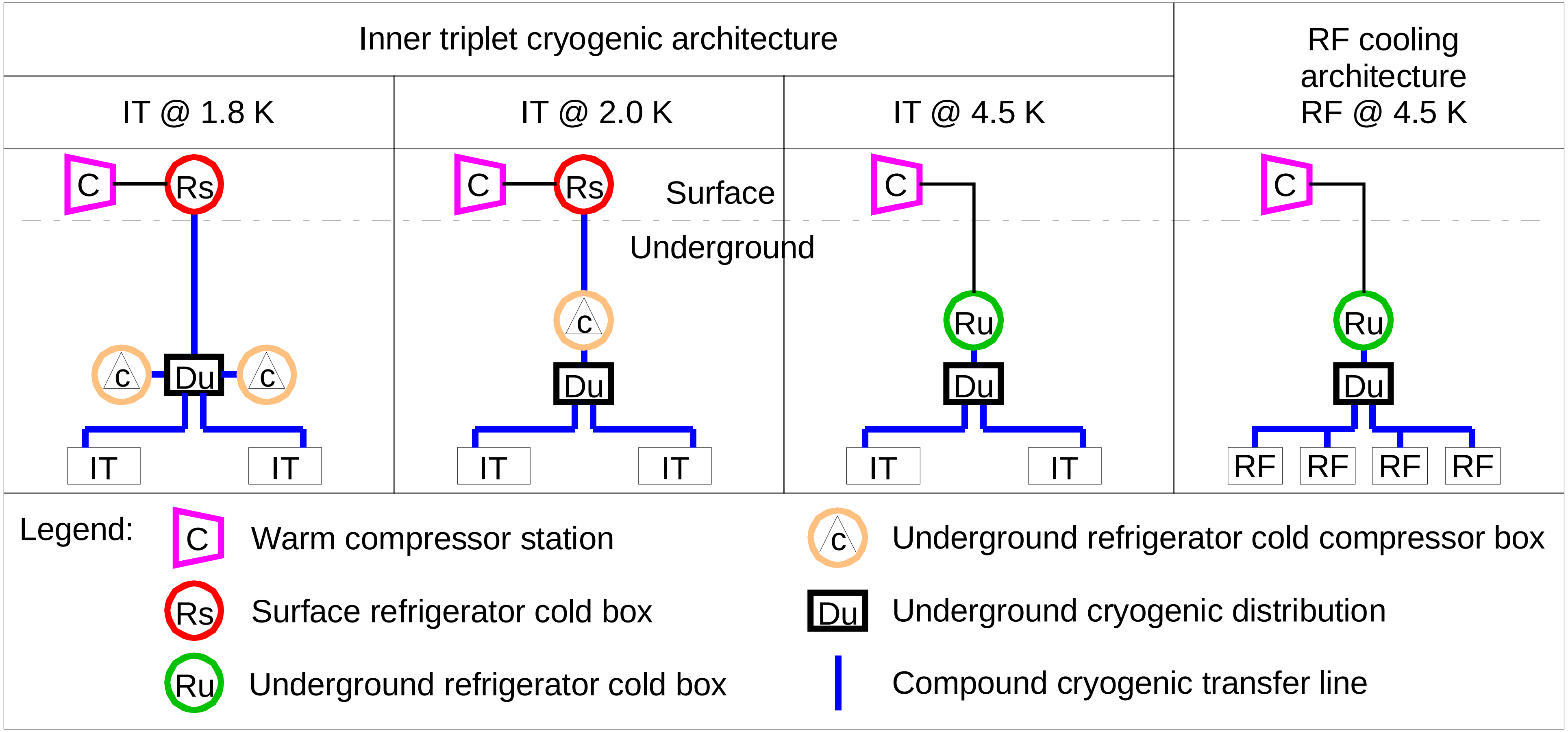
→ Study with 3 different temperatures: 1.8, 2 & 4.5 K

Cryoplant		Inner Triplet cryoplant			RF cavities cryoplant
Operating temperature	**[K]**	**1.8**	**2.0**	**4.5**	**4.5**
Power to be extracted	[kW]	3.4			4.5
Contingency coefficient	[-]	1.5			
Installed capacity	[W]	5.1			6.7
Equivalent capacity @ 4.5 K	**[kW]**	**18.3**	**16**	**5.1**	**6.7**

Basic assumptions for cryoplant architecture

- To cope with large hydrostatic head due to high elevation difference in access shafts, refrigeration at 2 K or below requires installing the cold compression in underground caverns.
- For refrigerators with an equivalent capacity at 4.5 K smaller than about 6 kW, the whole cold box can be located in underground caverns.
- For refrigerators producing isothermal refrigeration at 4.5 K or refrigeration below 2 K with an equivalent capacity higher than 7 kW, the cold box has to be split in two. In case of cold compression, the splitting temperature must be higher than the outlet temperature of the last cold compression stage.
- The warm compressor station is installed at ground level in a noise-insulated building.
- The maximum capacity of a cold compressor set is 2.6 kW at 1.8 K and 5.2 kW at 2 K. Above these values, the cold compressor set must be duplicated for parallel compression.

Cryogenic architecture for IT and RF cooling

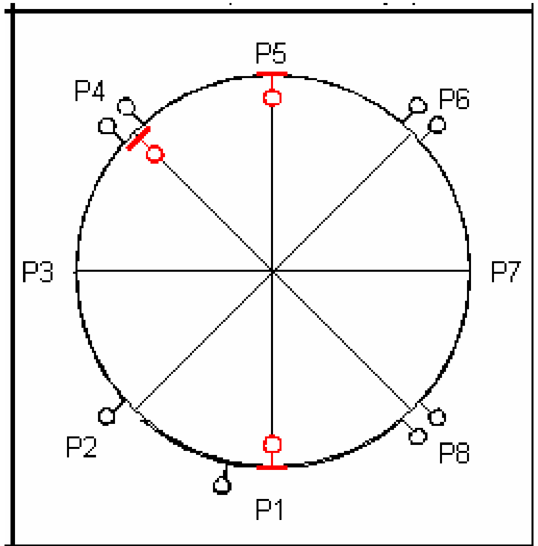


Cost breakdown of cryogenic system for Long-bunch luminosity upgrade

Cryogenic system		Inner triplet			RF cavities
Operating temperature	**[K]**	**1.8**	**2.0**	**4.5**	**4.5**
Refrigerator	['98 MCHF]	13	12	5.9	6.9
Cold compressor	['98 MCHF]	6.5	2.6	0	0
Underground distribution	['98 MCHF]	1.4	1.3	0.7	0.8
Vertical transfer line	['98 MCHF]	2.0	2.0	0	0
Local transfer line	['98 MCHF]	0.5	0	0	0
Tunnel transfer line	['98 MCHF]	2.0	2.0	2.0	1.0
Technical service module	['98 MCHF]	0.80	0.80	0.80	0.80
Storage vessel	['98 MCHF]	0.60	0.60	0.60	0.20
Interconnecting piping	['98 MCHF]	1.1	1.0	0.57	0.65
Dryer	['98 MCHF]	0.80	0.75	0.43	0.49
Additional infrastructure	['98 MCHF]	0.20	0.20	0.20	0.20
Industrial control	['98 MCHF]	0.60	0.60	0.40	0.40
Tunnel Instrumentation	['98 MCHF]	0.13	0.13	0.13	0.13
Total/cryoplant	['98 MCHF]	29	24	12	12
Cumulated indices from 1998 to 2005	[-]	1.183			
Total/Cryoplant	**[MCHF]**	**35**	**28**	**14**	**14**

Total cost of cryogenic upgrade for Long-bunch scenario with two ITs and one RF section (without contingency)

IT operating temperature	IT upgrade	RF upgrade	Total
[K]	[MCHF]	[MCHF]	[MCHF]
1.8	69	14	**83**
2	56	14	**70**
4.5	28	14	**42**



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Baseline + separate RF & IT cryoplants

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Building and general service requirements

Cryogenic system			Inner triplets			RF cavities
Operating temperature		[K]	1.8	2	4.5	4.5
Warm compressor building	Surface	[m2]	700	600	500	500
	Crane	[t]	20	20	20	20
	Electrical power	[MW]	4,6	4,0	1,5	2,0
	Cooling water	[m3/h]	540	450	174	227
	Compressed air	[Nm3/h]	30	30	20	20
	Ventilation	[kW]	250	200	100	100
	Type	[-]	Noise-insulated (~108 dB_A)			
Surface "SD" building	Surface	[mxm]	30x10	30x10	N/A	N/A
	Height	[m]	12	12	N/A	N/A
	Crane	[t]	5	5	N/A	N/A
	Electrical power	[kW]	50	50	N/A	N/A
	Cooling water	[m3/h]	15	15	N/A	N/A
	Compressed air	[Nm3/h]	90	90	N/A	N/A
Cavern	Volume	[m3]	840	432	360	300
	Local handling	[t]	2	2	2	2
	Electrical power	[kW]	100	70	20	20
	Cooling water	[m3/h]	20	10	20	20
	Compressed air	[Nm3/h]	40	20	30	30

Personnel resource requirement for Long-bunch luminosity upgrade scenario (without contingency)

Year			2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
IT cryogenic upgrade	Definition & studies & development	Cat 2	1,5	1,5	1,5	1,5	1,5	1,5				**9**
		Cat 3-4	2	2	3	3	2	2				**14**
	Specification	Cat 2				1	2					**3**
		Cat 3-4				1	2					**3**
	Procurement & Fabrication	Cat 2						5	5	3		**13**
		Cat 3-4						3	3	3		**9**
	Installation & Commissioning	Cat 2							1	3	6	**10**
		Cat 3-4							3	3	6	**12**
		FSU							6	6	6	**18**
	Total IT cryogenic upgrade	Cat 2	1,5	1,5	1,5	2,5	3,5	6,5	6	6	6	**35**
		Cat 3-4	2	2	3	4	4	5	6	6	6	**38**
		total	3,5	3,5	4,5	6,5	7,5	11,5	12	12	12	**73**
RF cryogenic upgrade	Definition	Cat 2				0,5						**0,5**
		Cat 3-4										**0**
	Specification	Cat 2					1					**1**
		Cat 3-4					0,5					**0,5**
	Procurement & Fabrication	Cat 2						1	1	1		**3**
		Cat 3-4						1	1	1		**3**
	Installation & Commissioning	Cat 2							1	1	2	**4**
		Cat 3-4							2	2	3	**7**
		FSU							3	3	3	**9**
	Total RF cryogenic upgrade	Cat 2	0	0	0	0,5	1	1	2	2	2	**8,5**
		Cat 3-4	0	0	0	0	0,5	1	3	3	3	**10,5**
		total	**0**	**0**	**0**	**0,5**	**1,5**	**2**	**5**	**5**	**5**	**19**
Total cryogenic upgrade for Long-bunch scenario		Cat 2	1,5	1,5	1,5	3	4,5	7,5	8	8	8	**43,5**
		Cat 3-4	2	2	3	4	4,5	6	9	9	9	**48,5**
		total	**3,5**	**3,5**	**4,5**	**7**	**9**	**13,5**	**17**	**17**	**17**	**92**

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Conclusion

- **Cryogenic system upgrades for three LHC luminosity upgrade scenarios have been studied:**
  - » The **Ultimate** scenario can be performed by adding a dedicated cryoplant for the cooling of the RF cavities.
  - » The **Short-bunch** scenario requires an increase of the sector cooling capacity by a factor 4 and shows local limitations in the beam screen cooling circuits. These two showstoppers render this scenario cryogenically unfeasible.
  - » The **Long-bunch** scenario requires to add dedicated cryoplants for the cooling of the RF cavities and of the inner triplets located at the high luminosity interaction points.

- **The total cost of the cryogenic upgrade, which varies from 42 to 83 MCHF, depends strongly on the choice of inner triplet operating temperature.**

- **The need in personnel resources is about 92 person.years spread over 9 years, including 4 years for construction.**

- **The operating temperature of the inner triplets has to be defined. For this purpose, heat transfer simulations and measurements have to be performed on representative coil geometry and cable insulation with specific heat fluxes up to 10 W/m.**