FCC Week 2018, Amsterdam

Staging and design of the cryogenic system for FCC-ee and HE-LHC

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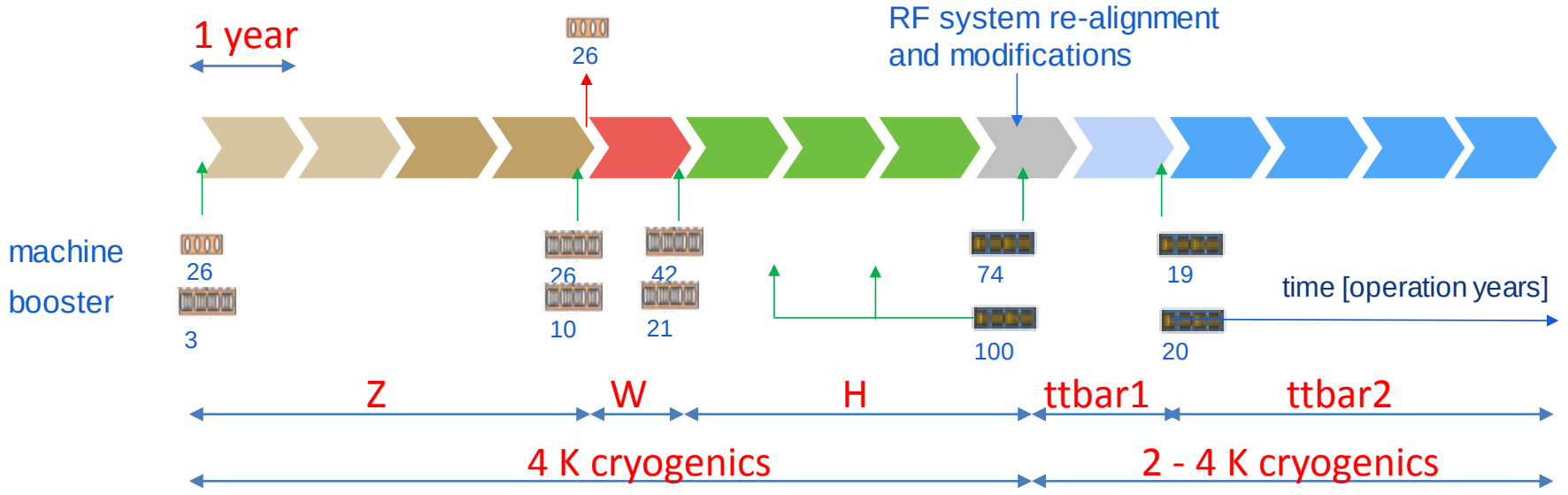
Content

- FCC-ee conceptual design
  - Basic input from SRF
  - Cryogenic plant layout and architecture
  - Staging proposal from Z → W → H → ttbar1 → ttbar2
  - Electrical consumption and helium inventory
- HE-LHC conceptual design
  - Temperature levels, heat loads & installed cooling capacity
  - How to deal with existing LHC tunnel and existing cryogenics?
  - Electrical consumption and helium inventory
- Conclusion

FCC-ee: RF configuration for the different machines

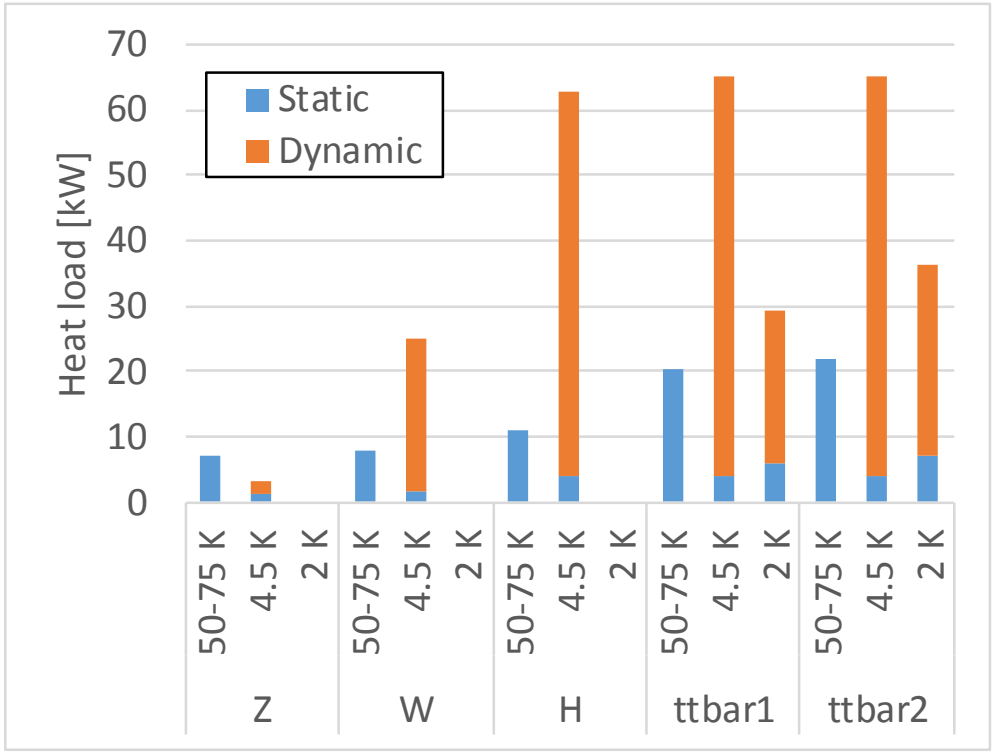
	Machine									
	Z		W		H		ttbar1 (ttbar2)			
	per beam	booster	per beam	booster	per beam	booster	2 beams	booster	2 beams	booster
Frequency - Temperature	400 MHz - 4.5 K								800 MHz - 2 K	
# cell / cav	1	4	4		4		4		5	
# cavities	52	12	52	52	136	136	272	136	296 (372)	400 (480)
# CM	13	3	13	13	34	34	68	34	74 (93)	100 (120)
dynanic losses/cav [W]	14	11	210	26	202	29	210	30	66	10
stat losses/cav [W]	8		8		8		8		8	



FCC-ee: Heat loads per machine

Heat load			Machine Z	W	H	ttbar1	ttbar2
4.5 K static	Main rings	[W]	832	832	2176	2176	2176
	Booster	[W]	96	416	1088	1088	1088
	Distribution	[W]	515	545	734	734	734
	Total	**[W]**	**1443**	**1793**	**3998**	**3998**	**3998**
2 K static	Main rings	[W]	0	0	0	2368	2976
	Booster	[W]	0	0	0	3200	3840
	Distribution	[W]	0	0	0	227	247
	Total	**[W]**	**0**	**0**	**0**	**5795**	**7063**
4.5 K dynamic	Main rings	[W]	1456	21840	54944	57120	57120
	Booster	[W]	132	1352	3944	4080	4080
	Total	**[W]**	**1588**	**23192**	**58888**	**61200**	**61200**
2 K dynamic	Main rings	[W]	0	0	0	19536	24552
	Booster	[W]	0	0	0	4000	4800
	Total	**[W]**	**0**	**0**	**0**	**23536**	**29352**
50-75 K static	Main rings	[W]	817	980	2564	4935	5545
	Booster	[W]	94	490	1282	4486	5127
	Distribution	[W]	6341	6441	7071	10740	11130
	Total	**[W]**	**7252**	**7911**	**10916**	**20161**	**21802**

Grand total 50-75 K [kW]	**[kW]**	**7.3**	**7.9**	**11**	**20**	**22**
Grand total 4.5 K [kW]	**[kW]**	**3.0**	**25**	**63**	**65**	**65**
Grand total 2 K [kW]	**[kW]**	**0**	**0**	**0**	**29**	**36**

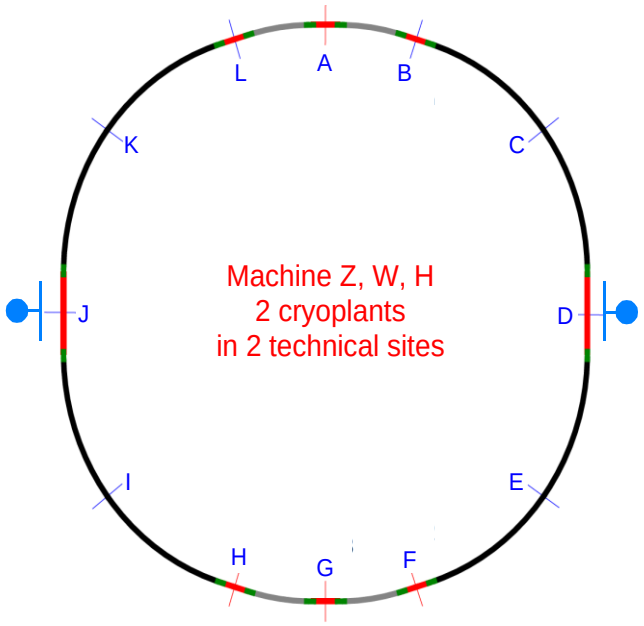


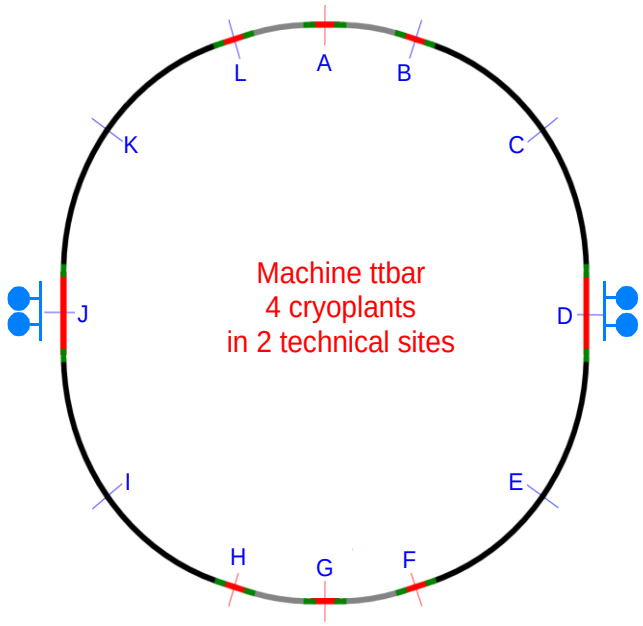
Heat loads largely dominated by dynamic loads

(w/o operational margin)

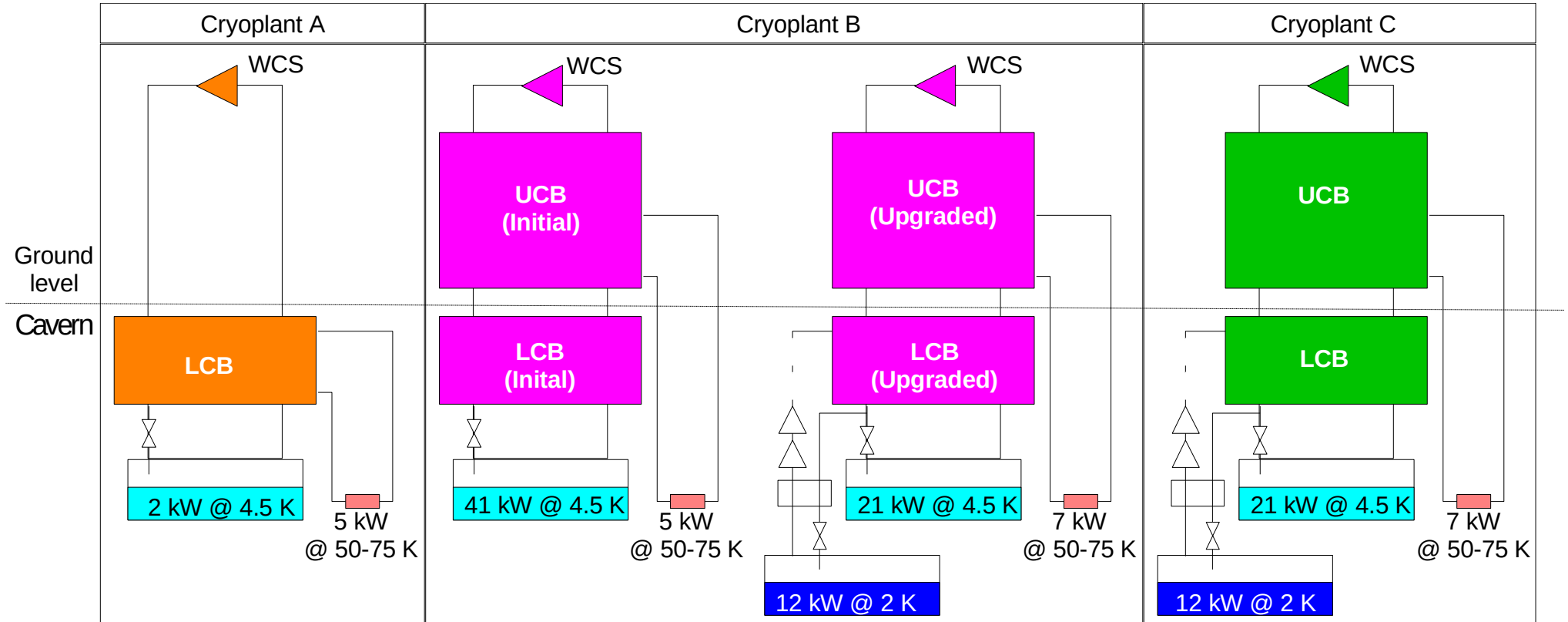
FCC-ee: Cryogenic plant capacity and layout

		Machine				
		Z	W	H	ttbar1	ttbar2
Nb of cryoplants	**[-]**	**2**	**2**	**2**	**4**	**4**
operational magin factor	**[-]**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Total @ 50-75 K	[kW/plant]	4.7	5.1	7.1	6.6	7.1
Total @ 4.5 K	[kW/plant]	2.0	16	41	21	21
Total @ 2 K	[kW/plant]	0	0	0	10	12
Cryoplant size	**[kWeq @ 4.5 K]**	**2.2**	**16**	**41**	**55**	**63**



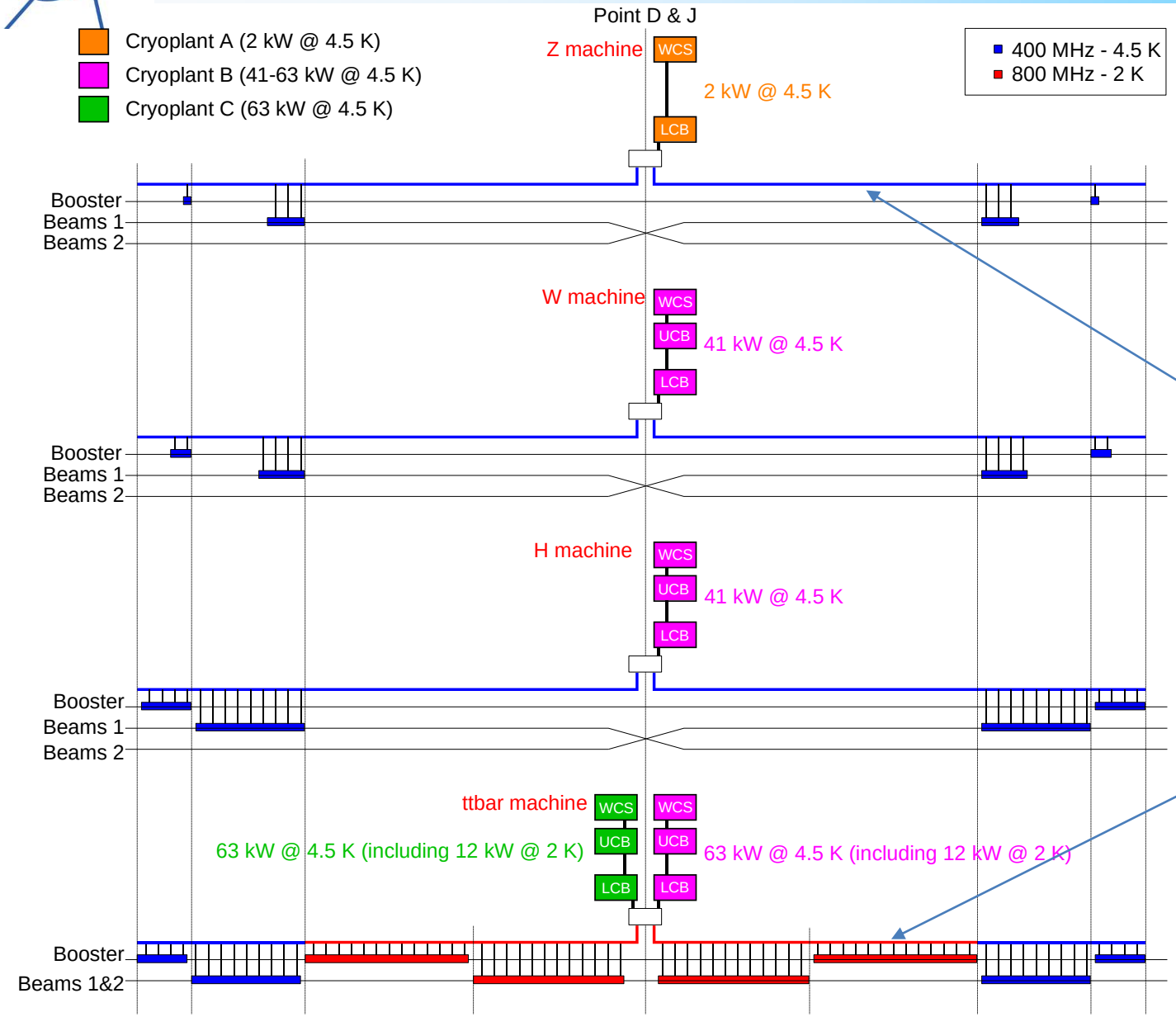


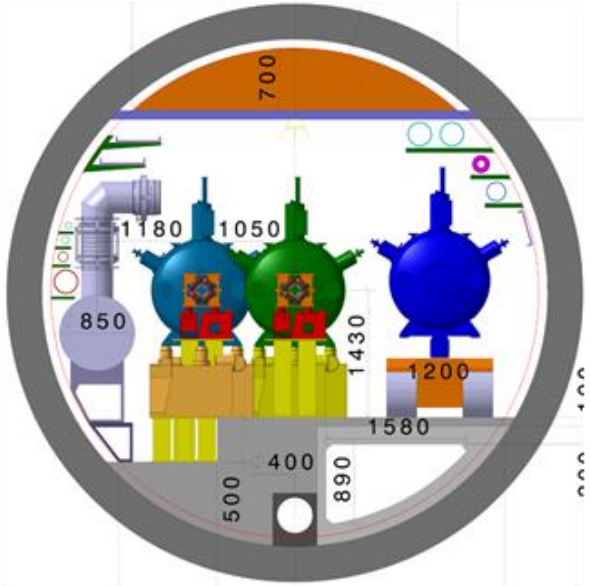
FCC-ee: cryogenic plant architecture

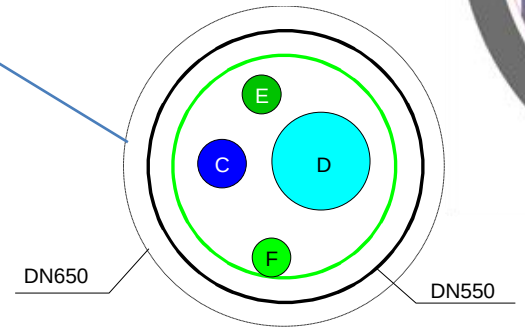


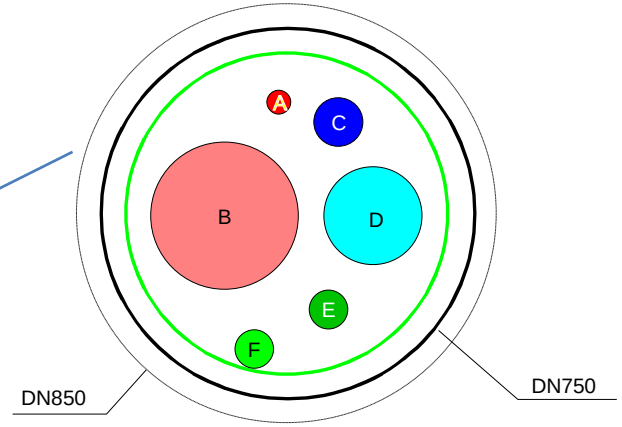
	2 kW @ 4.5 K	41 kW @ 4.5 K upgradable to 63 kW @ 4.5 K		63 kW @ 4.5 K
Z	2			
W		2		
H		2		
ttbar1			2	2
ttbar2			2	2

FCC-ee: Cryogenic architecture

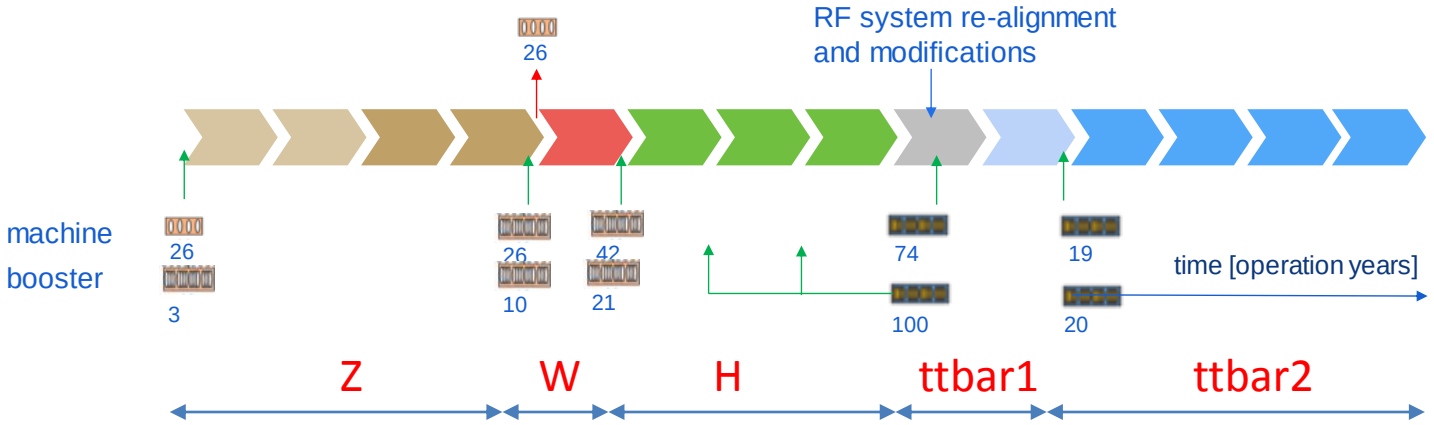




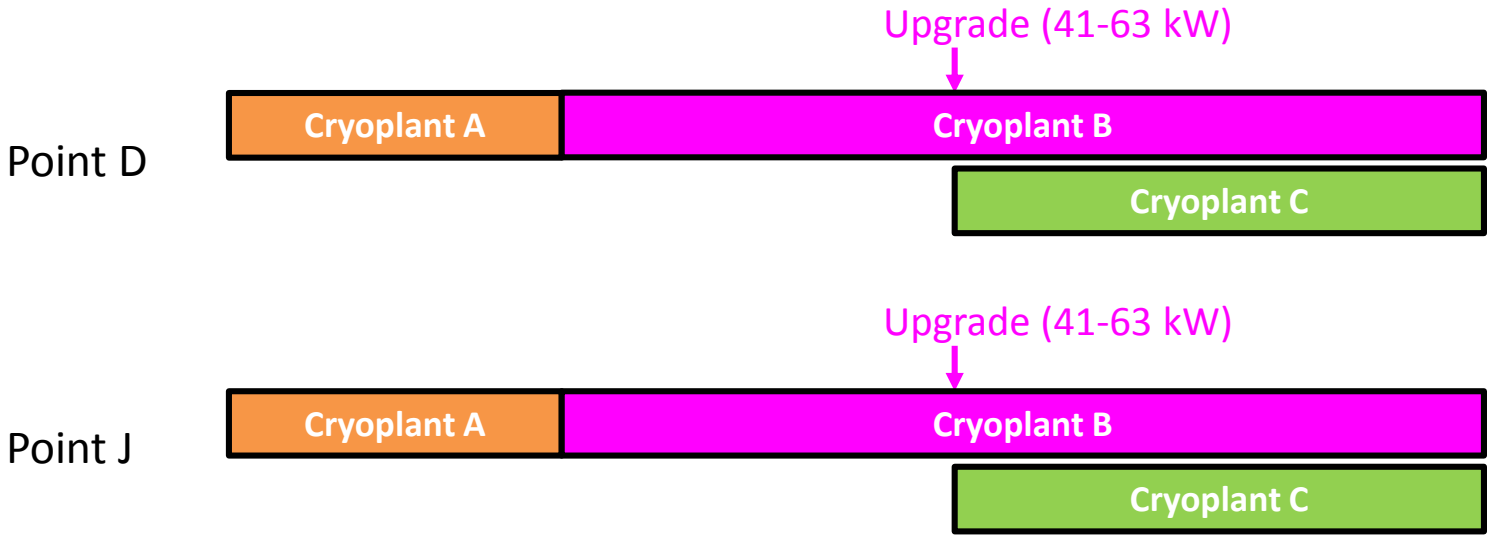




FCC-ee: Cryo-plant staging



Refrigeration need per Point:	2	16	41	55	63



Reminder: Staging scenario similar to LEP-LHC:

- started with two 6 kW plants
- then four 12-18 kW plants (LEP2 – LEP2+); upgraded with 2.4 kW @ 1.8 K units for LHC.
- then four additional 18 kW including 1.8 K units for LHC

FCC-ee: Electrical consumption and He inventory

Electrical consumption

Machine	Installed power				Nominal power			
	per plant [MW]	per site [MW]	Total [MW]	COP [W/W]	per plant [MW]	per site [MW]	Total [MW]	COP [W/W]
Z	0.51	0.51	1.0	230	0.44	0.44	0.89	261
W	9.5	9.5	19	230	5.3	5.3	11	320
H	9.5	9.5	19	230	8.3	8.3	17	261
ttbar1	14	29	58	230	12	23	46	274
ttbar2	14	29	58	230	13	25	50	261

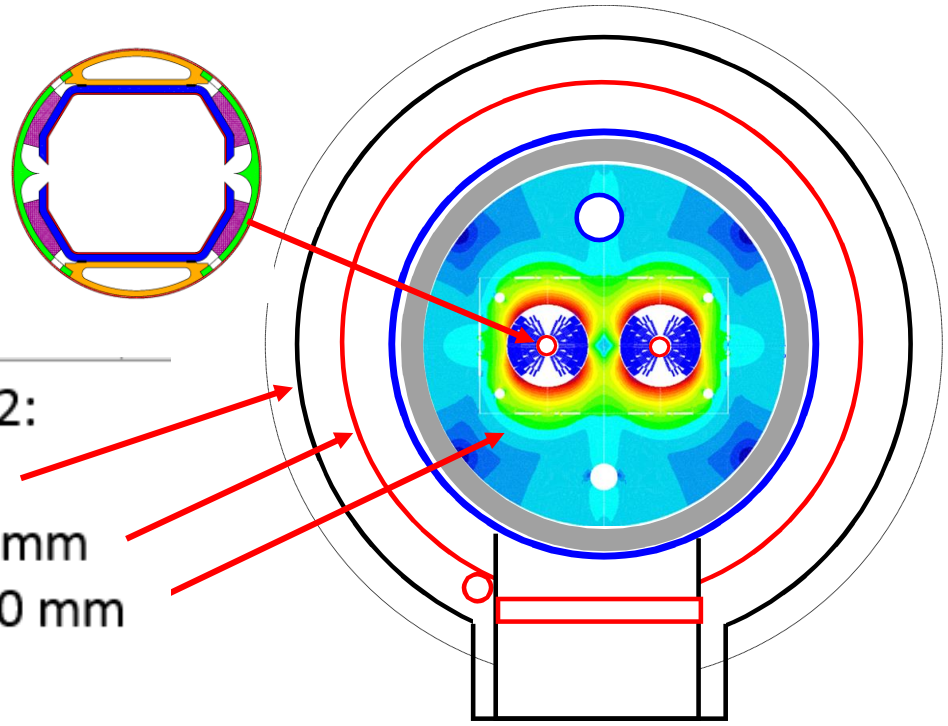
Helium inventory

Machine	Z	W	H	ttbar1	ttbar2
Cryomodule [t]	1.2	1.6	4.1	11.0	12.6
Distribution [t]	7.9	7.9	7.9	8.9	8.9
Cryoplant [t]	1	1	2	4	4
Total [t]	10	10	14	24	26

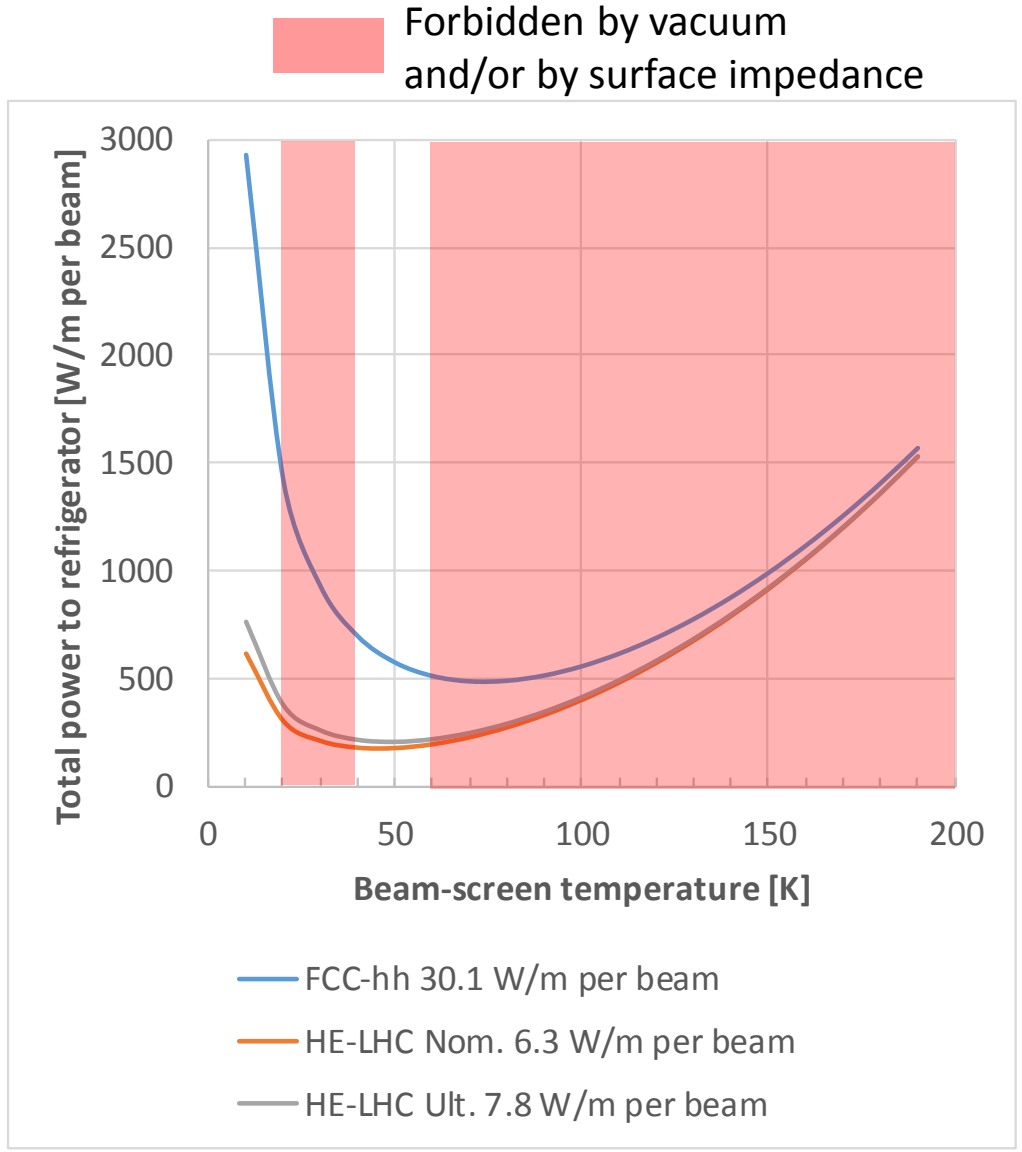
HE-LHC : temperature -pressure level

- Use of FCC-hh cryo-magnet design and cooling principle:
  → T cold-mass @ 1.9 K and 1.3 bar
- Beam screens cooled between 40-60 K, which corresponds to the optimum exergetic efficiency. The reduced specific load (8 W/m per beam) allows to operate at 20 bar.

Beam-screen



HE-LHC/ FCC v2.2:
VV: Φ 1074 mm
Al shield: Φ 890 mm
Cold mass: Φ 740 mm



HE-LHC : heat load in steady-state and transient operation

		FCC-hh [W/m]		HE-LHC [W/m]	
	Temperature level	40-60 K	1.9 K	40-60 K	1.9 K
Static heat inleaks	CM supporting system	2.4	0.13	2.4	0.13
	Radiative insulation		0.13		0.13
	Thermal shield	3.1		3.1	
	Feedthrough & vac. barrier	0.2	0.1	0.2	0.1
	Beam screen		0.12		0.12
	Distribution	3.6	0.1	3	0.1
	Total static	**9.3**	**0.58**	**8.7**	**0.58**
Steady-state dynamic heat loads	Synchrotron radiation	57	0.08	8	0.08
	Image current	3.4		4.46	
	Resistive heating		0.3		0.3
	e-clouds			0.2	
	Beam-gas scattering		0.45		0.18
	Total dynamic	**60**	**0.83**	**13**	**0.56**
	Total	**70**	**1.4**	**21.4**	**1.1**

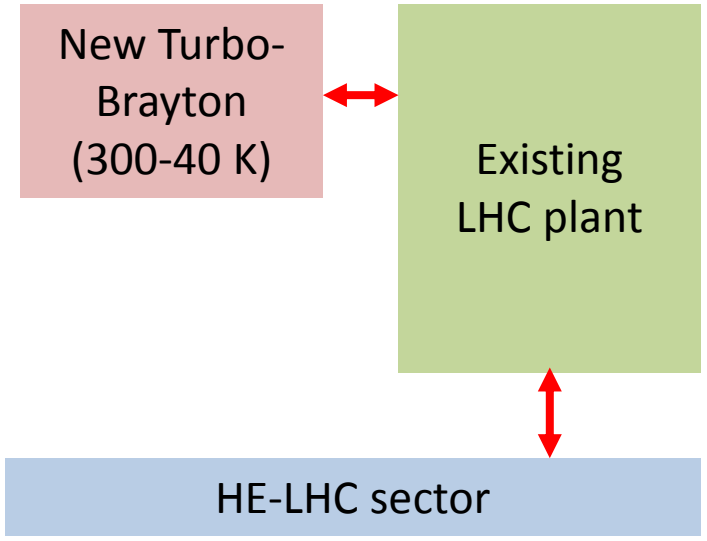
Sector capacity need				
T level	Steady-state	Transient	**Total**	
40-60 K	81		**81**	[kW]
1.9 K	3.3	1.1	**4.4**	[kW]
40-300 K	65		**65**	[g/s]
		Cryoplant size	**25**	**[kWeq @ 4.5 K]**

+ 1.1 kW at 1.9 K per sector to extract deposited energy (AC-losses) during ramp-up in less than 2 hours

(Including operational margins of 1.3 for 40-60 K and 40-300 K temperature level)

HE-LHC : Re-use of LHC cryoplant?

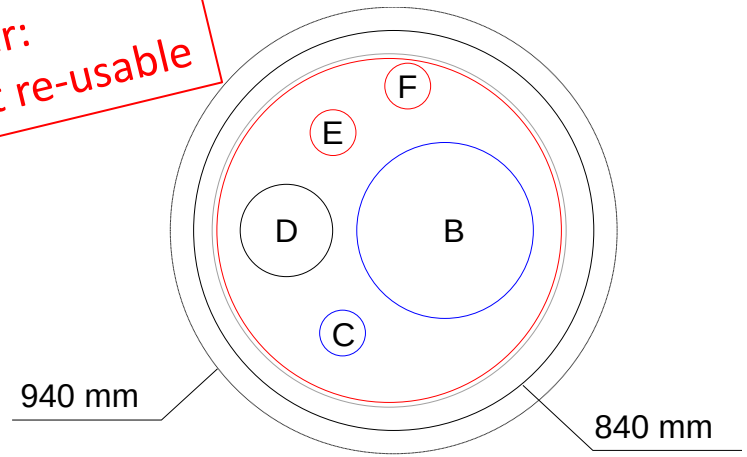
T level	Cooling capacity	**Entropic load [kW @ 4.5 K]**
40-300 K	65 g/s	**2**
40-60 K	81 kW	**7**
1.9 K	4.4 kW	**16**
	Total	**25**



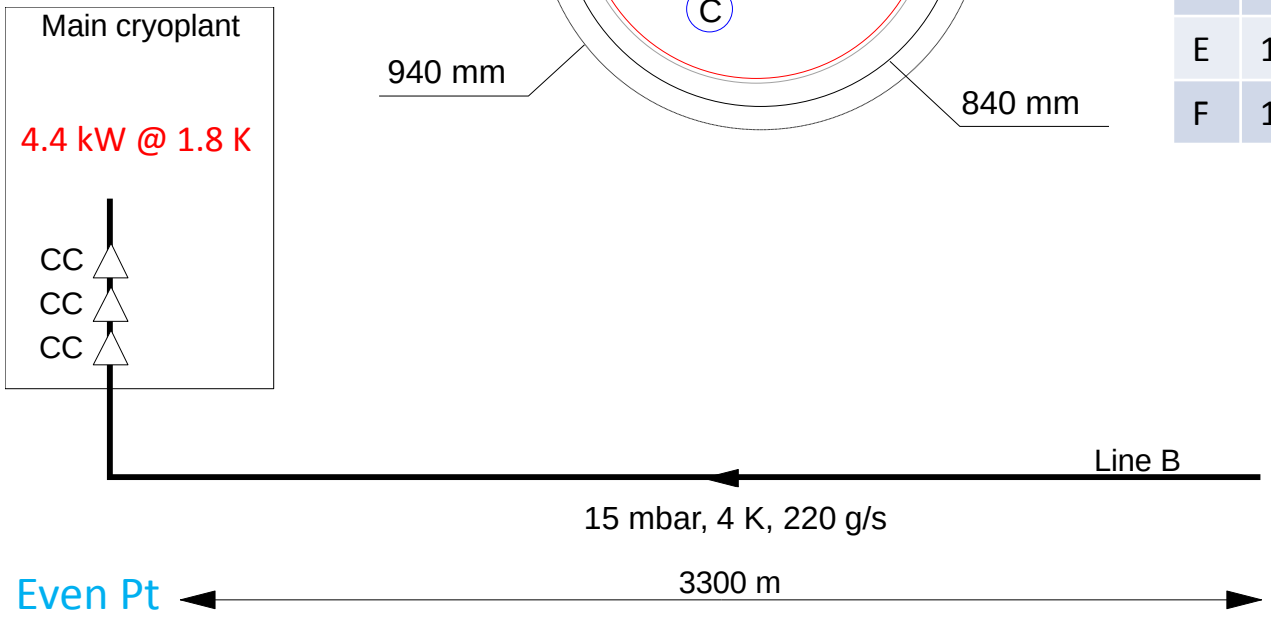
- The total entropic load is not compatible with existing LHC cryo-plants (18 kW @ 4.5 K).
- However, by adding aTurbo-Brayton refrigeration stage to produce the cooling capacity above 40 K (equivalent to 9 kW @ 4.5 K), the remaining capacity to be produced by the LHC plants is reduced to 16 kW @ 4.5 K.
  → The corresponding supercritical mass-flow at 4.6 K and 3 bar to be delivered in the tunnel is 220 g/s per sector, to be compared with 235 g/s for LHCB plants (new LHC) and with 190 g/s for the LHCA plants (Ex-LEP).
- Turbo-Brayton can also be used for precooling of the LHC plant and for sector cool-down.
- The aging of the existing LHC plants must also be taken into account (Ex-LEP plants will be 50-year old in 2040 !).
- Feasibility study to be continued !

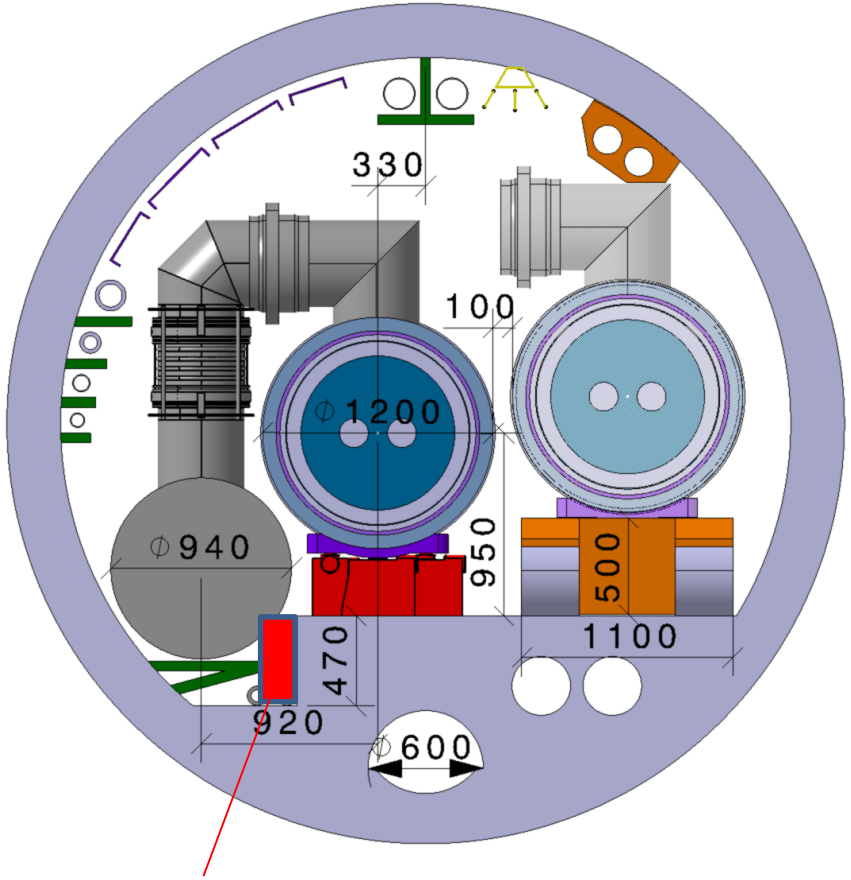
HE-LHC: cryogenics distribution for sector cooling

Reminder:
Existing QRL not re-usable



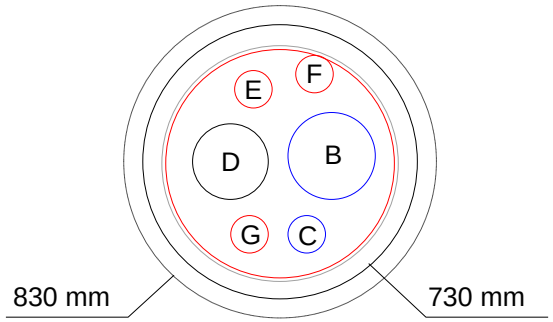
	DN
B	340
C	100
D	200
E	100
F	100





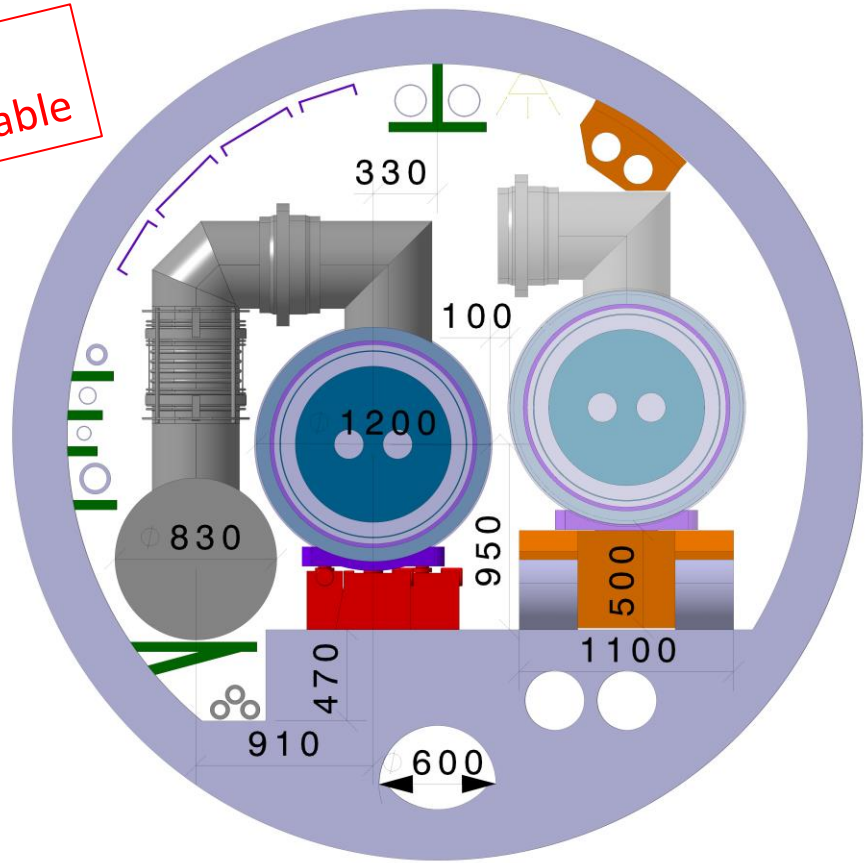
Trench enlargement over 27 km!

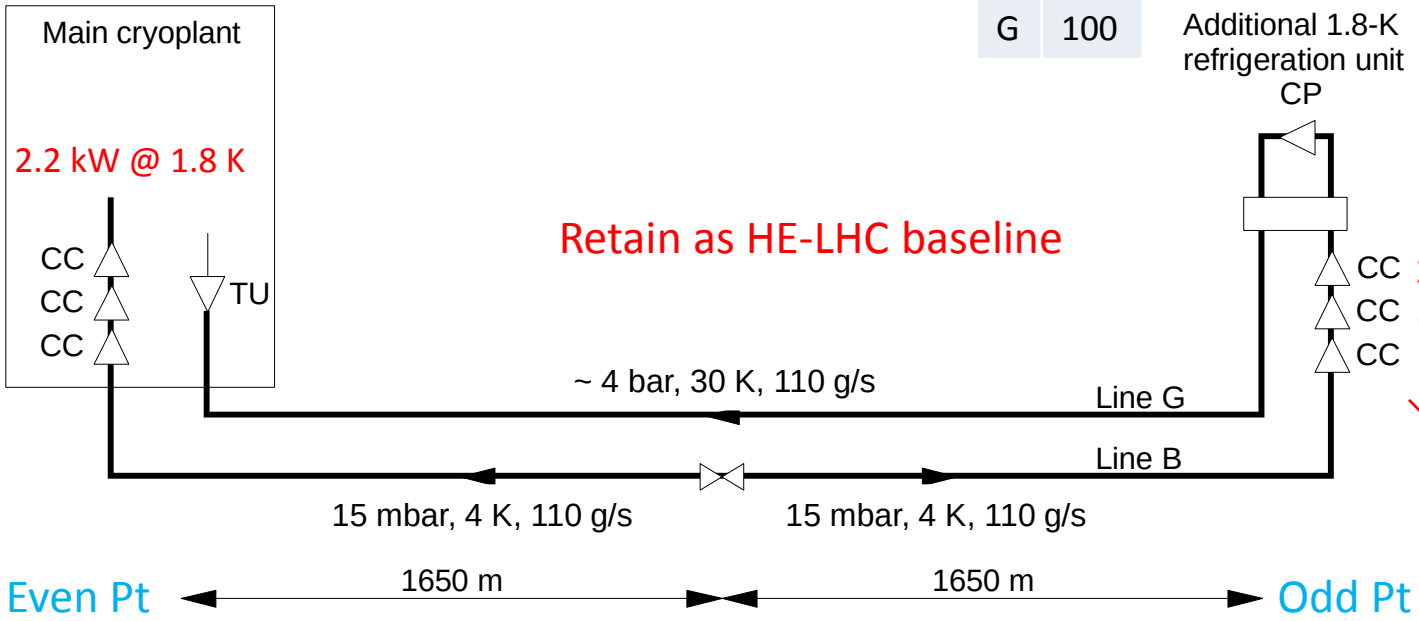
HE-LHC: cryogenics distribution for ½ sector cooling



	DN
B	230
C	100
D	200
E	100
F	100
G	100

Reminder:
Existing QRL not re-usable

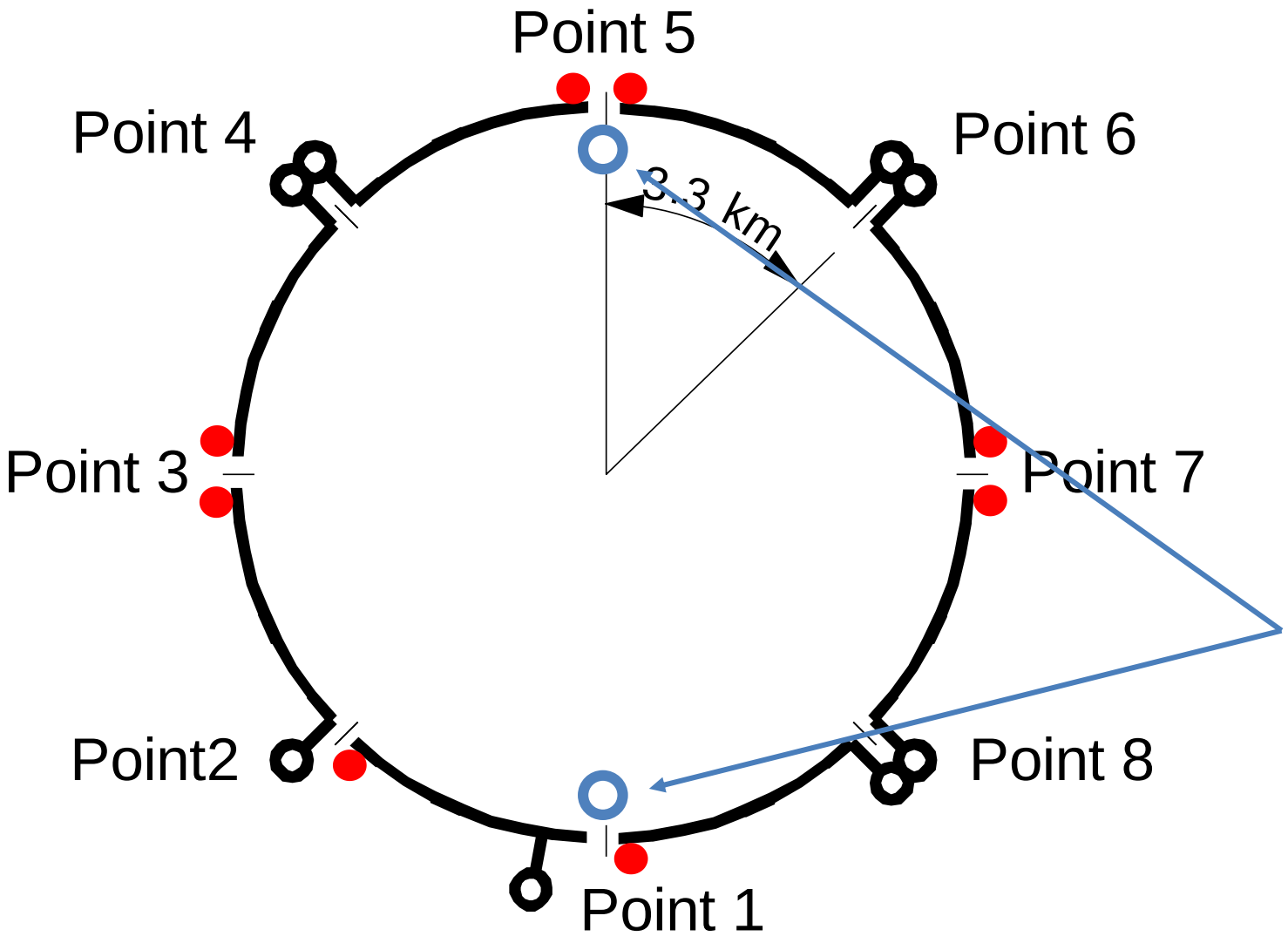




Retain as HE-LHC baseline

More rotating machinery
→ lower global availability
→ But existing LHC 1.8 K refrigeration unit can be reused (2.4 kW @ 1.8 K)

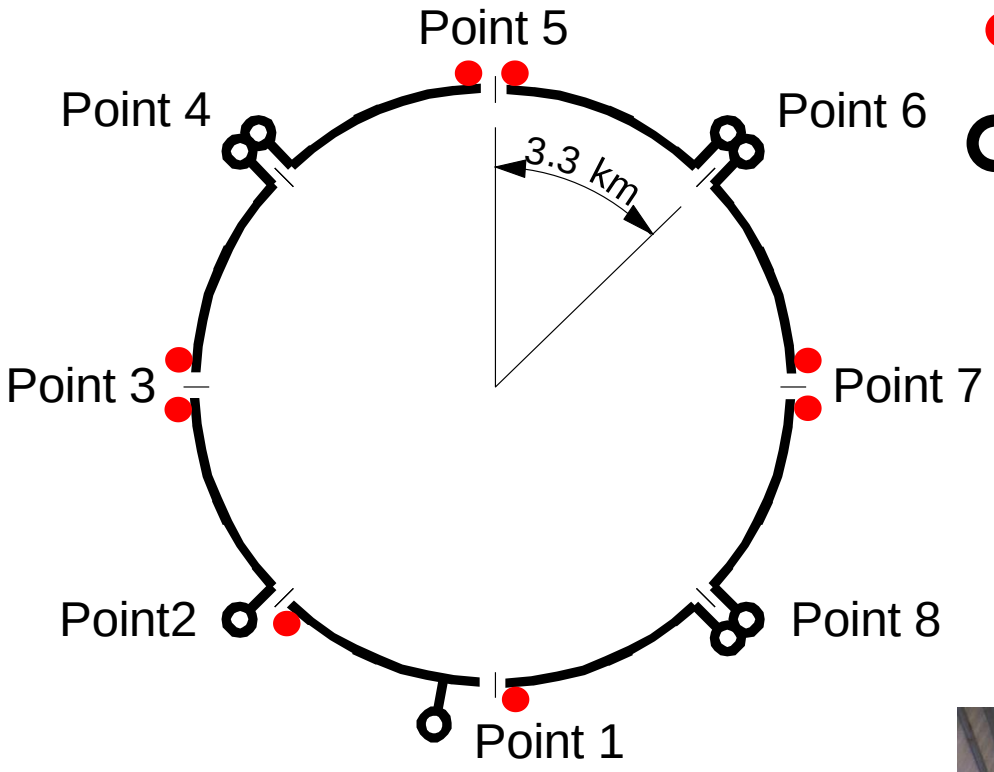
HE-LHC cryogenic layout



- 2.2 kW @ 1.8 K refrigeration unit
- Main sector cryo-plant 23 kW @ 4.5 K including 2.2 kW @ 1.8 K

Remark: specific cryoplants to be probably added at Point 1 and Point 5 for high luminosity insertion cooling (28E34 cm-2.s-1 : reuse of HL-LHC cryo-plants?).

HE-LHC: Additional civil engineering



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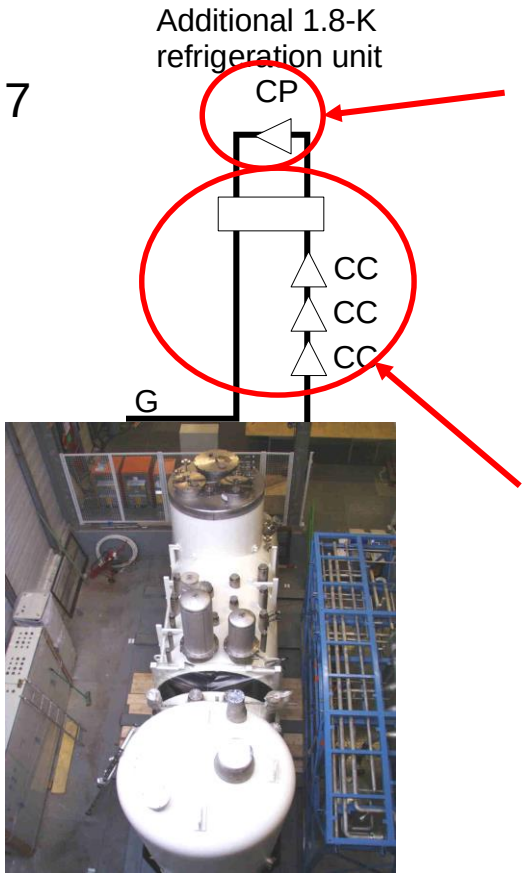


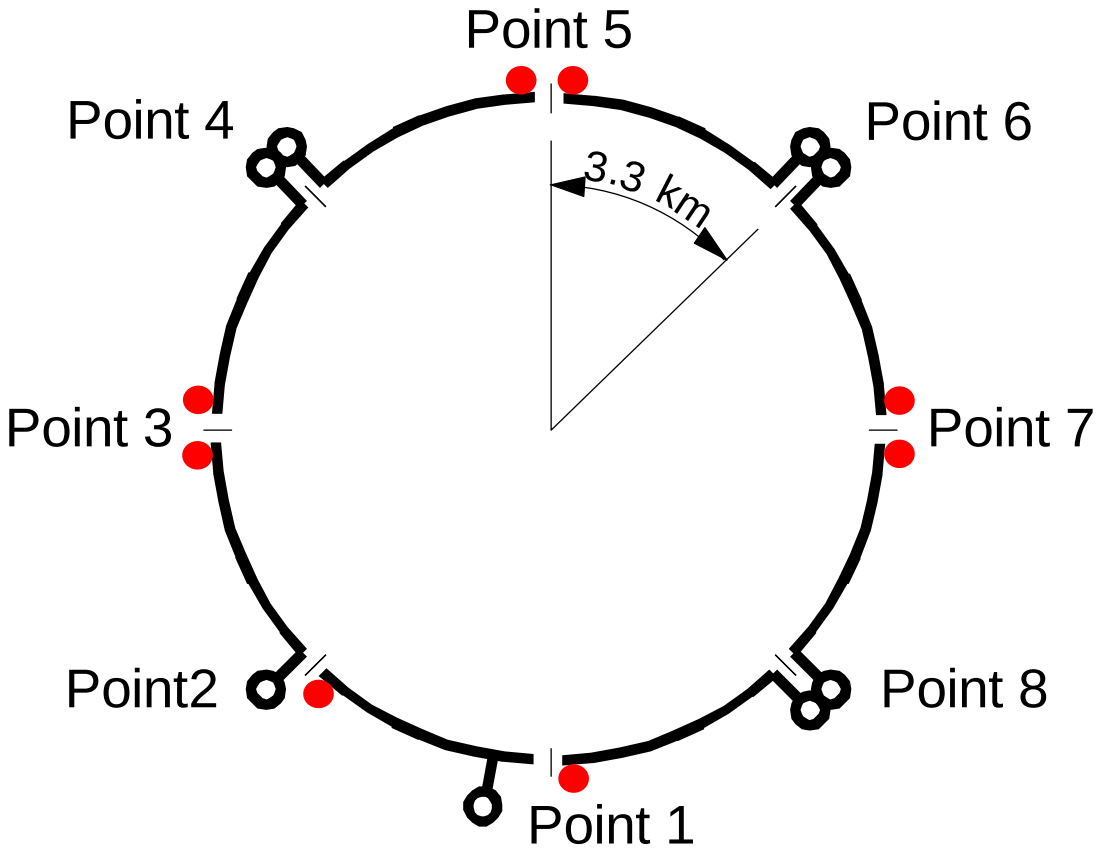
The warm compressor stations must be located in noise-insulated surface buildings:

- Space requirement: ~10 x 30 m^2 per unit
- Reuse available existing space at P1, P2, P5 ?
- New buildings at P3 and P7.

The cold boxes must be located in underground radiation-free alcoves or caverns:

- Space requirement: ~10 x 10 x 10 m^3 per unit
- Reuse available existing space at P1, P2, P5 ?
- New alcoves at P3 and P7.

HE-LHC electrical consumption



Point	Installed power			Nominal power		
	Main	1.8 K unit	**Total**	Main	1.8 K unit	**Total**
Point 1		0.5	**0.5**		0.4	**0.4**
Point 18	5.5		**5.5**	4.7		**4.7**
Point 2	5.5	0.5	**6**	4.7	0.4	**5.1**
Point 3		1	**1**		0.8	**0.8**
Point 4	11		**11**	9.4		**9.4**
Point 5		1	**1**		0.8	**0.8**
Point 6	11		**11**	9.4		**9.4**
Point 7		1	**1**		0.8	**0.8**
Point 8	11		**11**	9.4		**9.4**
Total	**44**	**4**	**48**	**37.6**	**3.2**	**41**

+ additional power for high-luminosity insertion cryo-plants

HE-LHC helium inventory

- Present LHC inventory (135 t)
- Main change due to cold-mass helium inventory:
  → from 25 to 33 l/m, i.e. + 28 t in total
- HE-LHC helium inventory: 163 t
- To store this additional inventory (28 t), 2 additional LHe storage vessels (120 m^3 unit volume) will be required.

Two LHC LHe storage tanks at Point 18

Conclusion

- Conceptual designs of FCC-ee and HE-LHC are completed.
- For FCC-ee:
  - Two to four cryo-plants with unit capacity from 2 to 63 kW @ 4.5 K have been proposed to cover the need of the 5 machines (Z, W, H, ttbar1 & ttbar2)
  - a staging scenario is also proposed (similar to the scenario proposed for LEP2, LEP2+ & LHC).
- For HE-LHC:
  - The integration of the machine in the existing LHC tunnel imposes additional 1.8 K refrigeration units at the odd Points.
  - The unit refrigeration capacity per sector is 25 kW @ 4.5 K. the feasibility study to partially cover this need by the existing LHC plants has to continue.
  - The existing LHC distribution line (QRL) is not reusable (different cooling circuit, cell length, header diameter…).
  - LHC storage infrastructure can be re-used and upgraded by 2 new LHe storage tanks (from 6 to 8).
  - Cryogenic plants for high-luminosity insertions still to be design.

Thank you!