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FCC CRYOGENICS

STATUS, LAYOUT, AND IMPLEMENTATION STUDIES



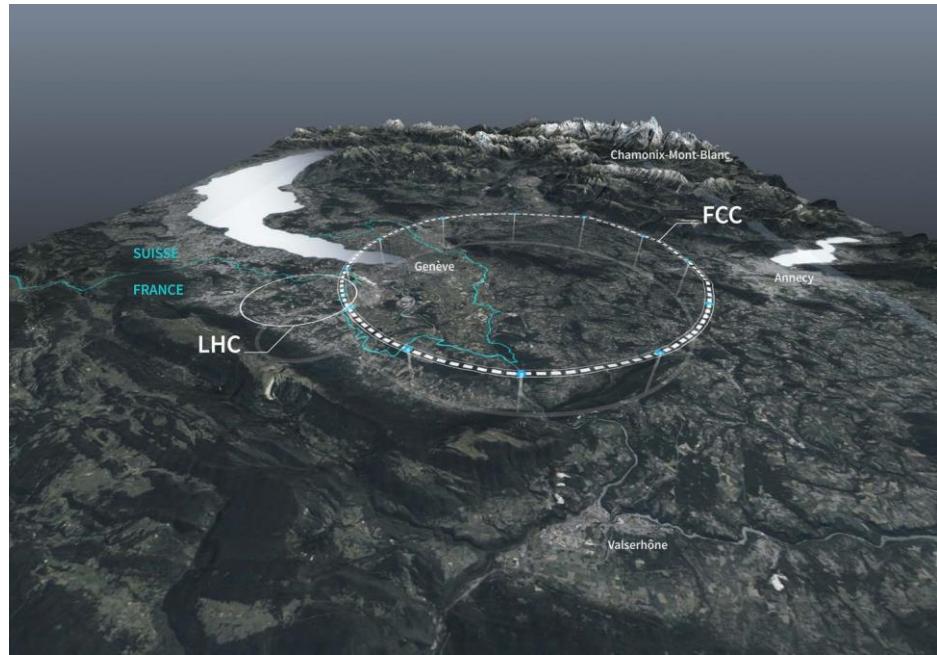
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On behalf of the CERN cryogenics group

FCC Week 23' – London – June 5th-9th 2023

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Status

M. Benedikt

- First surface estimation requirements for cryo (buildings, alcoves, and caverns) system provided to civil engineering team.**

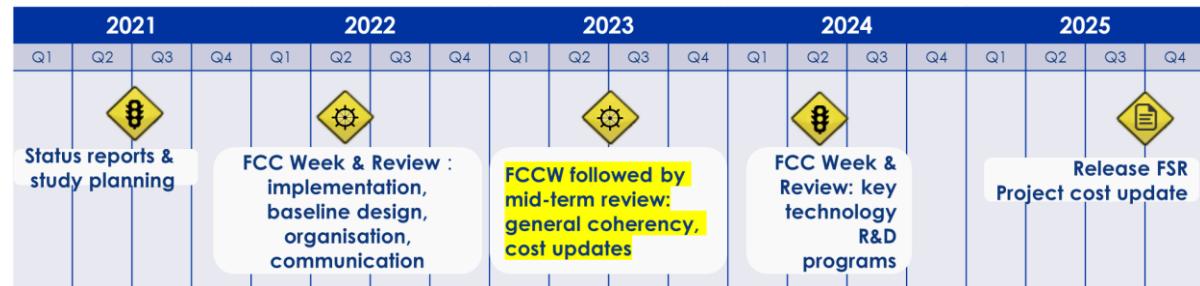
- Collaboration with FNAL.

- New baseline PA31-3.0 (25-01-23)**

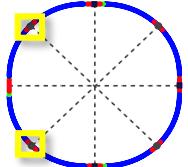
- Long Straight Section (LSS) reduced from 2160 m to 2032 m.
- New cryomodules (CM) distribution: all booster CMs at point L and all collider CMs at point H.
- Four scenarios for point L – shaft at 0 m, 300 m, 600 m and 1000 m of the IP – see slide 8.
- Point H changed from asymmetric to symmetric – see slide 7.
- FCC-ee cryoplants design and staging are being adapted – see slides 6 and 10.

- Narrowing down, together with SRF team, operating scenarios, heat loads (slide 4) and CM design concept with its integration implications (slide 11).**

- Understanding machine booster operation, its differences with the collider and its impacts on the cryogenics system.**
- Soon starting a second iteration of exchanges with industrial partners where focus will be put on FCC-ee.**



Point L – RF Booster



Point H – RF Collider



FCC-ee SRF heat loads

Z
↓
W
↓
H
↓
ttbar

Point H - Collider

Total of 1950 m

Symmetric

x28 CM_{400MHz} – 4.1 kW at 4.5 K

x66 CM_{400MHz} – 48 kW at 4.5 K

x66 CM_{400MHz} – 48 kW at 4.5 K

x66 CM_{400MHz} – 48 kW at 4.5 K
x122 CM_{800MHz} – 20 kW at 2 K



Point L - Booster

Total of 1300 m

Asymmetric

x6 CM_{800MHz} – 0.3 kW at 2 K

x14 CM_{800MHz} – 0.8 kW at 2 K

x27 CM_{800MHz} – 1.7 kW at 2 K

x150 CM_{800MHz} – 8.6 kW at 2 K

Assumptions

400 MHz cavities :
 $Q_{installed} = 2.7E+9$

800 MHz cavities :
 $Q_{installed} = 3.0E+10$

30 % margin on heat loads, today

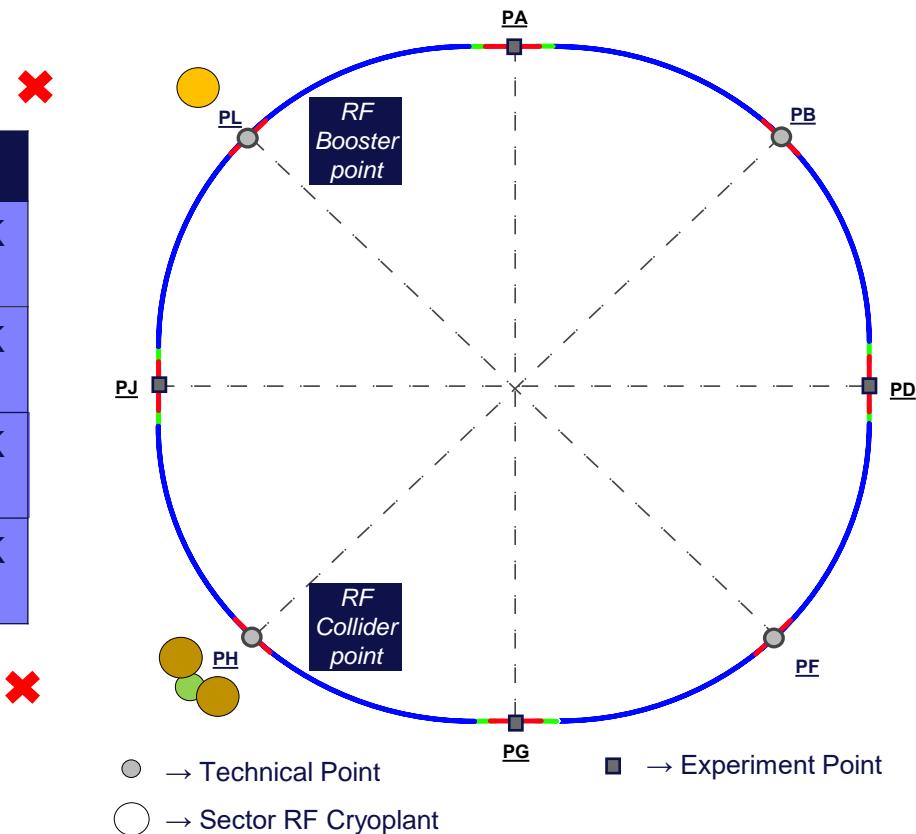
Last update of above values 12/05/2023

FCC-ee machine cryoplants layout

RF points – PH and PL

Stage	Point H - Collider	Point L - Booster
Z	1x 5 kW _{eq} @ 4.5 K	1x 1.5 kW _{eq} @ 4.5 K (98% @ 2K)
W		1x 3.5 kW _{eq} @ 4.5 K (98% @ 2K)
H	2x 25 kW _{eq} @ 4.5 K	1x 6.5 kW _{eq} @ 4.5 K (98% @ 2K)
tt	2x 60 kW _{eq} @ 4.5 K (60% @ 2K)	1x 32 kW _{eq} @ 4.5 K (98% @ 2K)

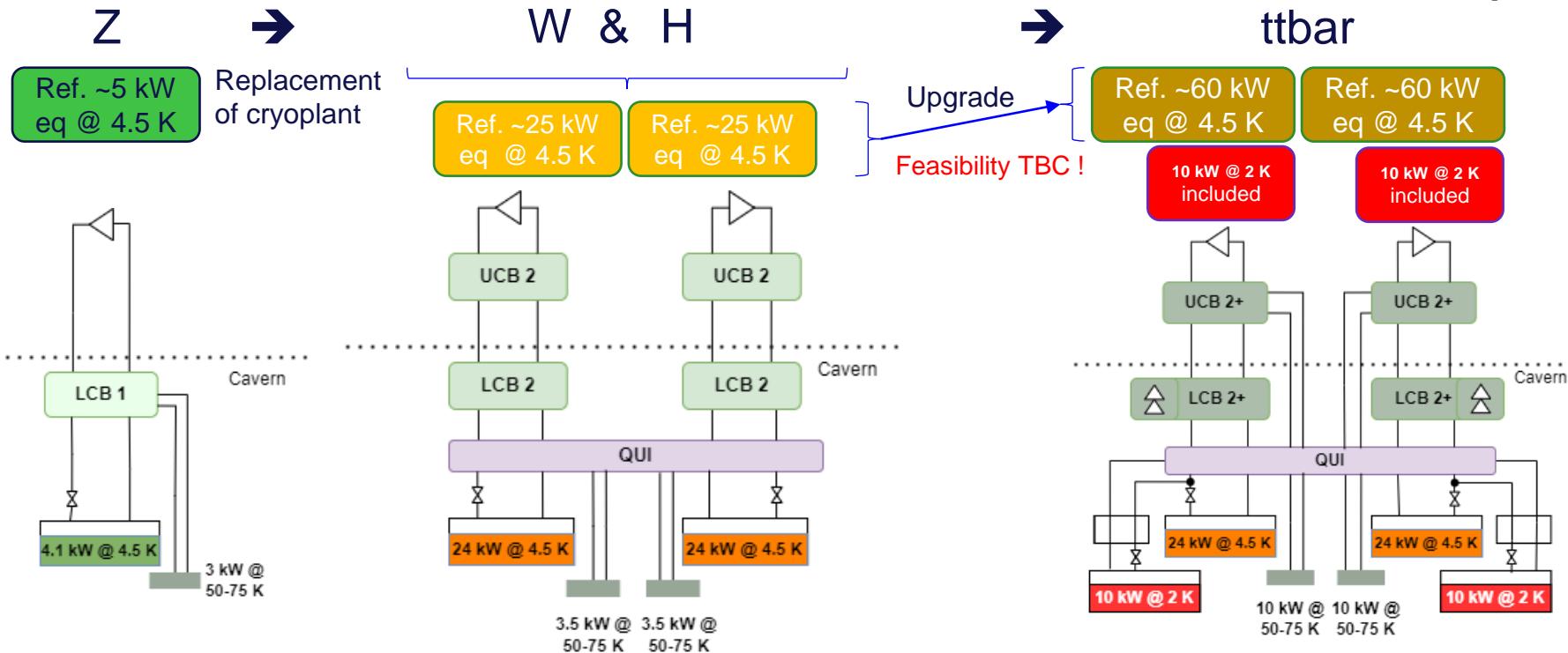
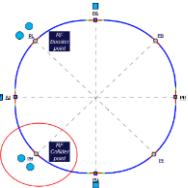
MDI magnets linked to detector position definition – not considered here



FCC-ee cryoplants at point H - staging

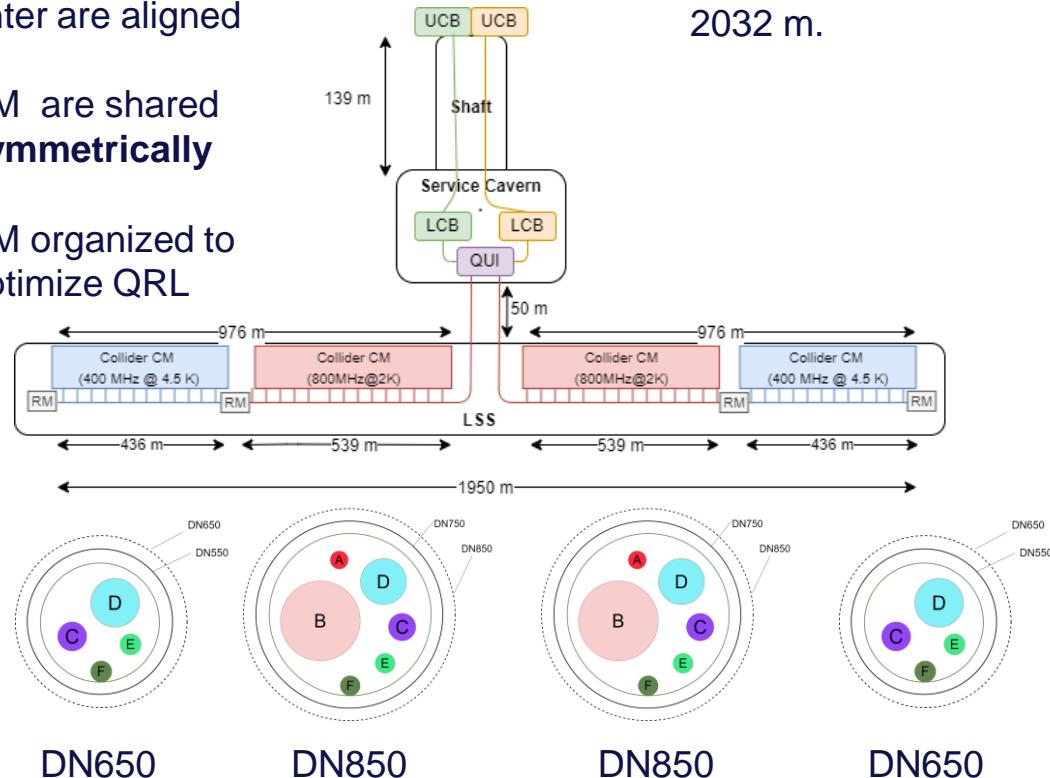
- **Staging at point H**
 - Increased staging complexity.

$$Q_{800MHz_{Installed}} = 3.0E + 10 // Q_{400MHz_{Installed}} = 2.7E + 9$$



FCC-ee cryo layout at point H (ttbar)

- Service cavern & LSS center are aligned
- CM are shared **symmetrically**
- CM organized to optimize QRL



- LSS total length is of 2032 m.

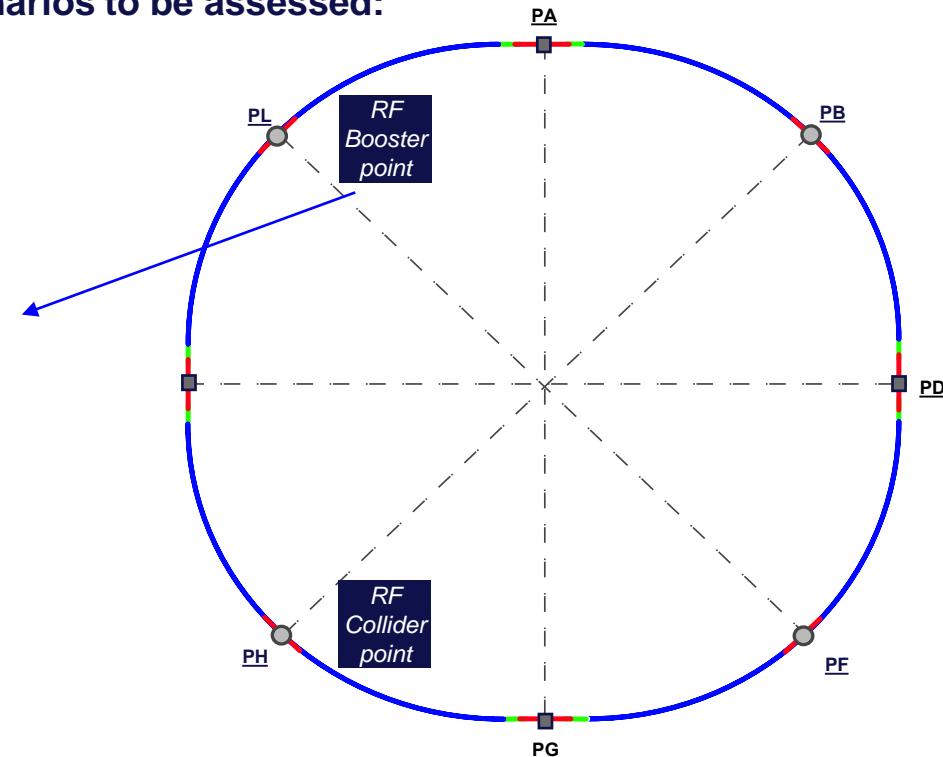
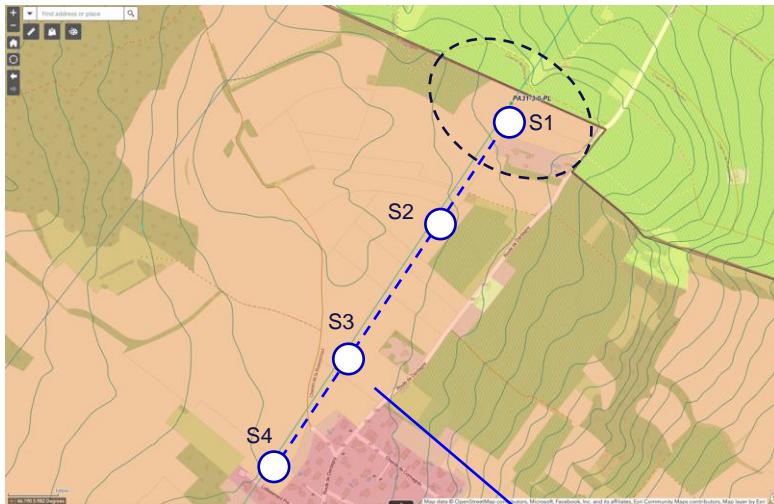
QRL Header & Process values	Diameter (mm)
A : 1.3 bar , 2.2 K ($\Delta P=25$ mbar)	72
B : 30 mbar , 2 K ($\Delta P=2$ mbar)	320
C: 3 bar, 4.6 K ($\Delta P=130$ mbar)	110
D: 1.3 bar, 4.5 K ($\Delta P=70$ mbar)	185
E: 20 bar, 50 K ($\Delta P=10$ mbar)	80
F: 18 bar, 75 K ($\Delta P=15$ mbar)	80
Vacuum jacket (400MHz)	550*
Vacuum jacket (800 MHz)	750*

* +100 mm for bellows and flanges

Point L

PA31-3.0: shaft location is uncertain. Different scenarios to be assessed:

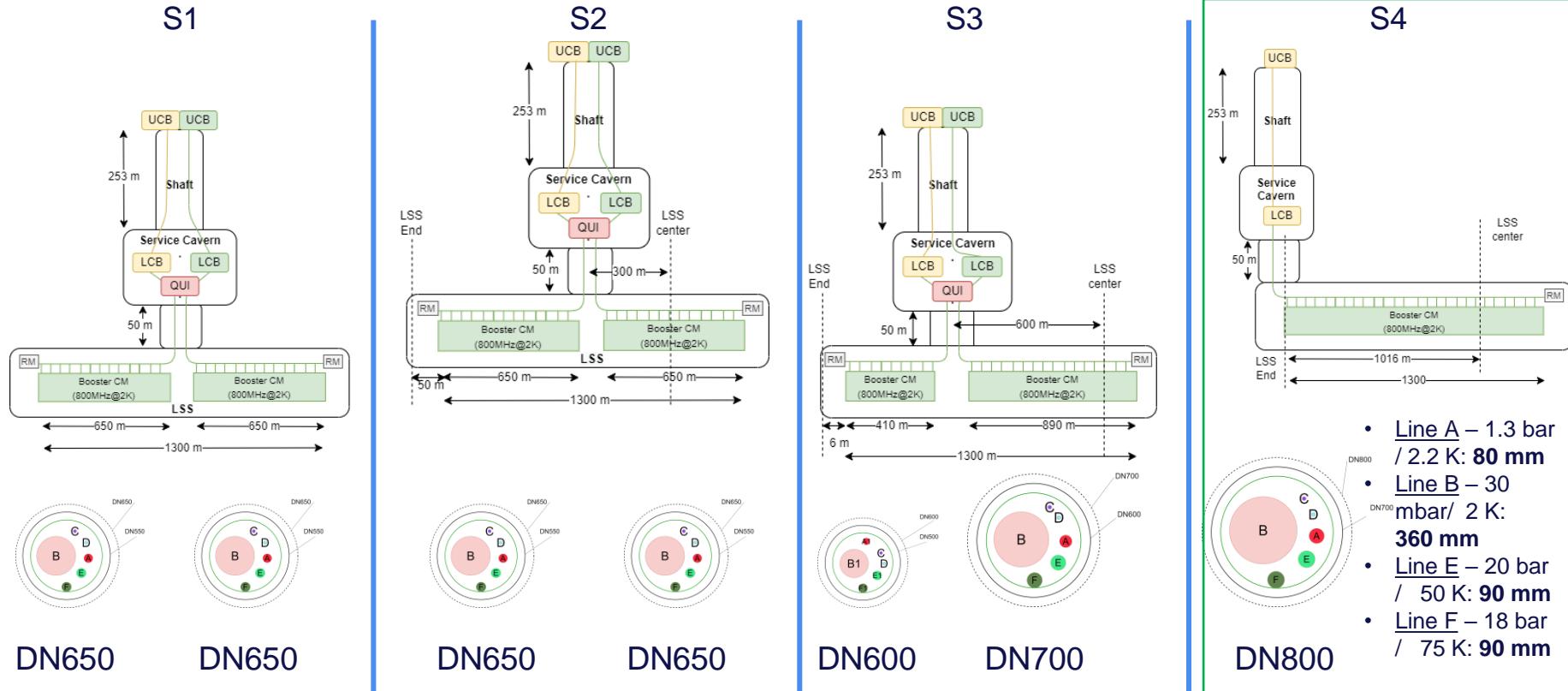
- S1: Shaft at nominal point
- S2: Shaft at 300 m
- S3: Shaft at 600 m
- S4: Shaft at 900 m



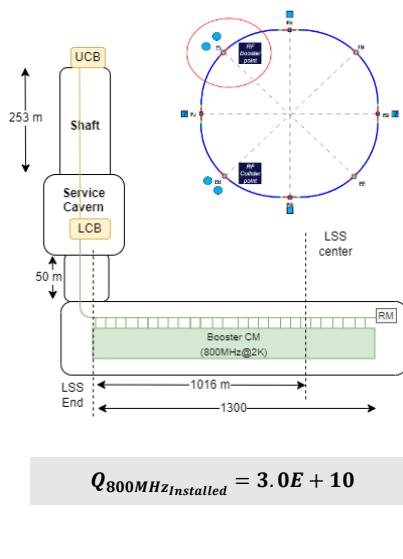
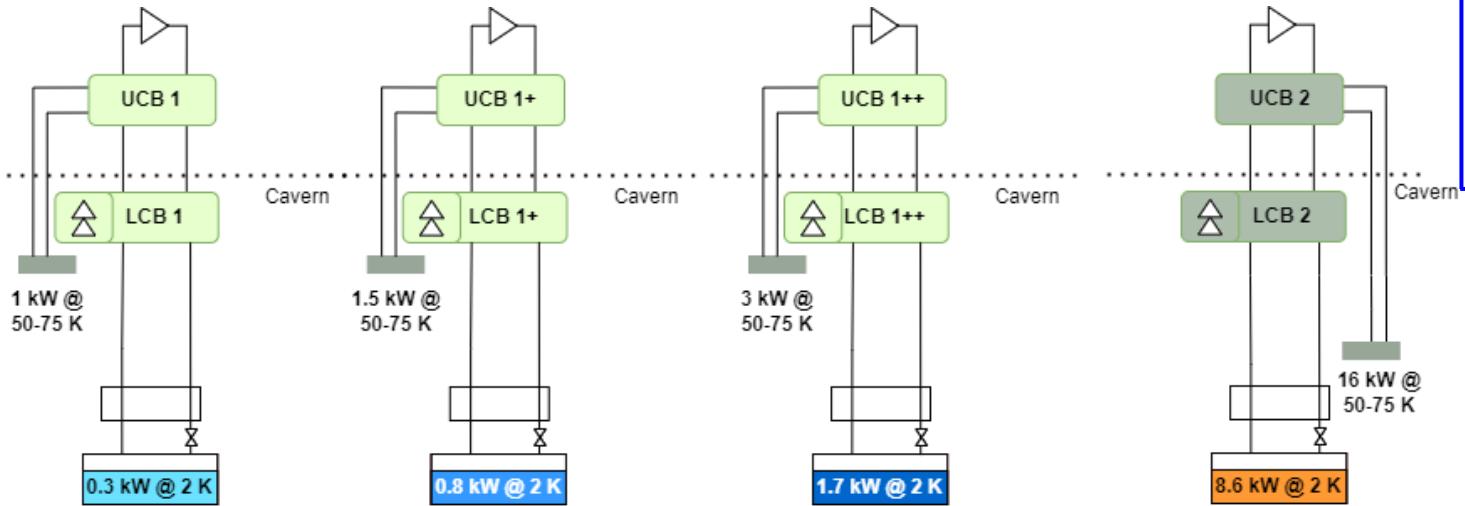
Difficult point containing the booster SRF section – limited integration space

FCC-ee cryo layout at point L (ttbar)

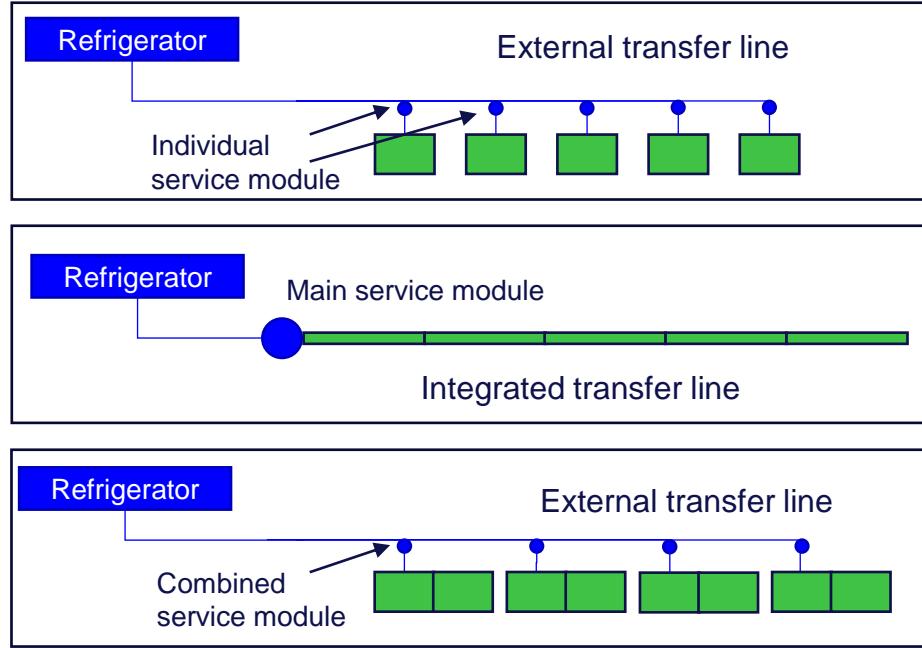
$$L_{LSS} = 2032\,m$$



FCC-ee cryoplants at point L / S4: staging

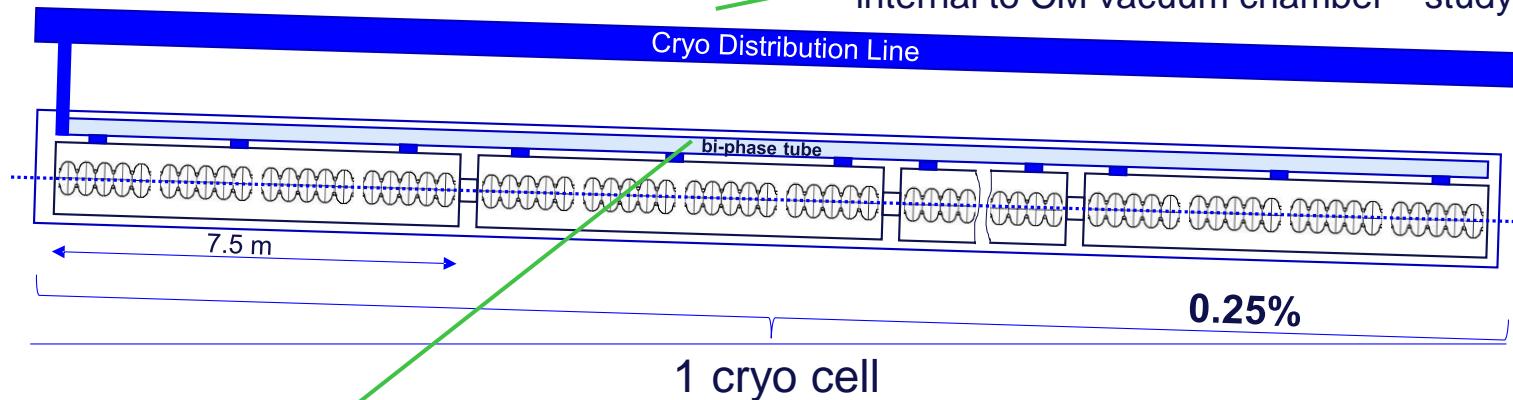


FCC-ee collider/booster CM sectorization at RF points

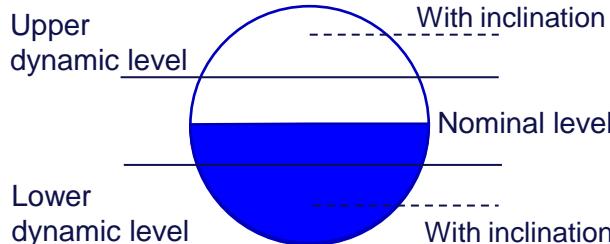
- Cryo-RF working group has been set in January 2024 to address the cryomodule design of the cavities.
 - Current discussions are focused on the sectorization concept of the 2 K Cryomodules for the 800 MHz bulk Nb cavities.
 - Several options are being weighted:
 - Fully segmented approach
 - Ex: ESS or PIP-II
 - Continuous/Integrated cryostat approach
 - Ex: XFEL or LCLS-II
 - Hybrid approach (vacuum not addressed)
- 

FCC-ee 800 MHz CM bi-phase tube study

Cryo distribution line can be both external or internal to CM vacuum chamber – study in progress



Bi-phase tube

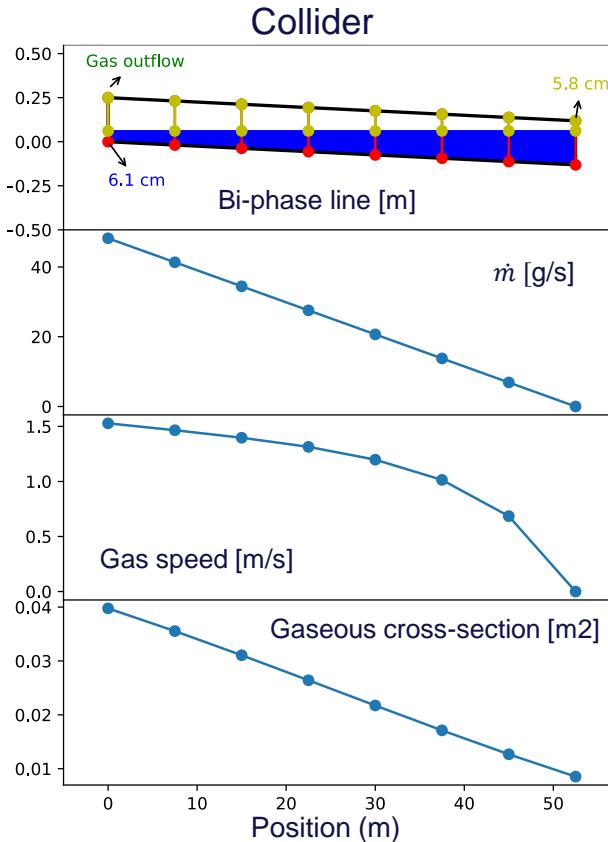


1 cryo cell

The analysis aims to answer:

- What is an optimum cell length?
- What is the right bi-phase tube size for such cell, given the heat loads?

FCC-ee 800 MHz CM bi-phase tube study

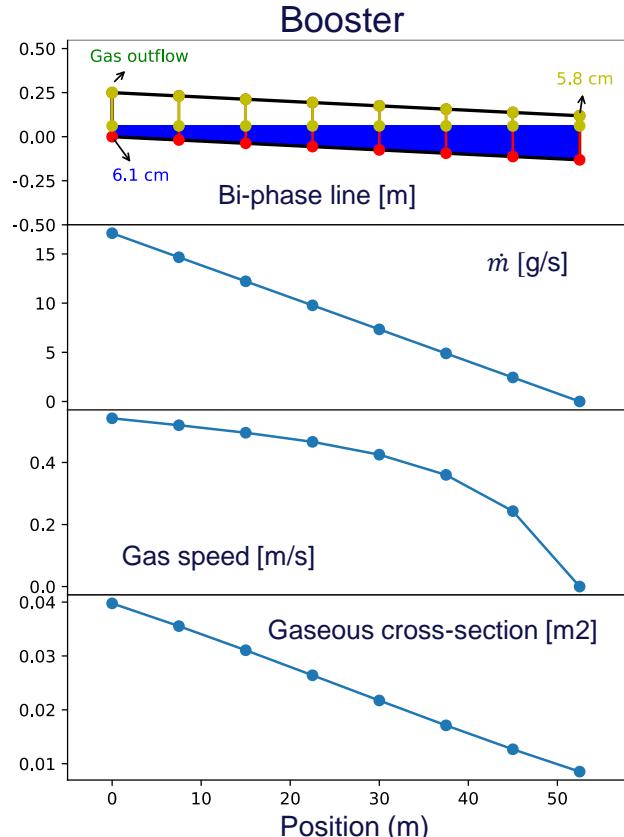


Preliminary proposal:

- A cryo cell length of 52 m (6 CM per cell) – coherent with warm quadrupoles spacing
- A bi-phase tube diameter of 25 cm

First results:

- If supply fails, the highest module will dry in about 30 min
- Evacuation gas speed does not exceed 1.5 m/s (within limits)
- Bi-phase line diameter for booster will be refined once transients are better understood



Points H and L He Inventory

Baseline CM assumption with a two-phase helium pipe and a bath around the cavity: **40 kg LHe per CM**

Point L/S4	Z	W	H	ttbar
Cryomodules	0.3 ton	0.6 ton	1.1 ton	6 ton
Distribution (QRL)	1.4 ton	1.4 ton	1.4 ton	1.4 ton
Cryoplants	0.1 ton	0.1 ton	0.2 ton	1.1 ton
Total	1.8 ton	2.1 ton	2.7 ton	8.5 ton

Point H	Z	W	H	ttbar
Cryomodules	2.2 ton	2.6 ton	2.6 ton	7.5 ton
Distribution (QRL)	4.3 ton	4.3 ton	4.3 ton	4.3 ton
Cryoplants	0.2 ton	1.7 ton	1.7 ton	4.5 ton
Total	6.7 ton	8.6 ton	8.6 ton	16.3 ton

➤ Total helium inventory for technical points at FCC-ee (ttbar) ~ 25 ton

Electricity power requirements – Installed power

➤ Three scenarios are considered:

- **Conservative**: 230 Wel/W or 28.8 % of Carnot efficiency (LHC-like – CDR values) the baseline!
- **Intermediate**: 210 Wel/W or 31.5 % of Carnot efficiency (With an optimized process) appears not achievable
- **Optimistic**: 170 Wel/W or 39 % of Carnot efficiency (With centrifugal compressors) strong R&D effort needed



	PH [MW]	PL [MW]	Total [MW]
Z	1.2 / 1.1 / 0.9	0.35 / 0.32 / 0.26	1.6 / 1.4 / 1.2
W	11.5 / 10.5 / 8.5	0.8 / 0.7 / 0.6	12.3 / 11.2 / 9.1
H	11.5 / 10.5 / 8.5	1.5 / 1.4 / 1.1	13 / 11.9 / 9.6
ttbar	27.6 / 25.2 / 20.4	7.4 / 6.7 / 5.4	35 / 32 / 26

In “high” mode



-26% of consumption with centrifugal compressors - **R&D needed.**

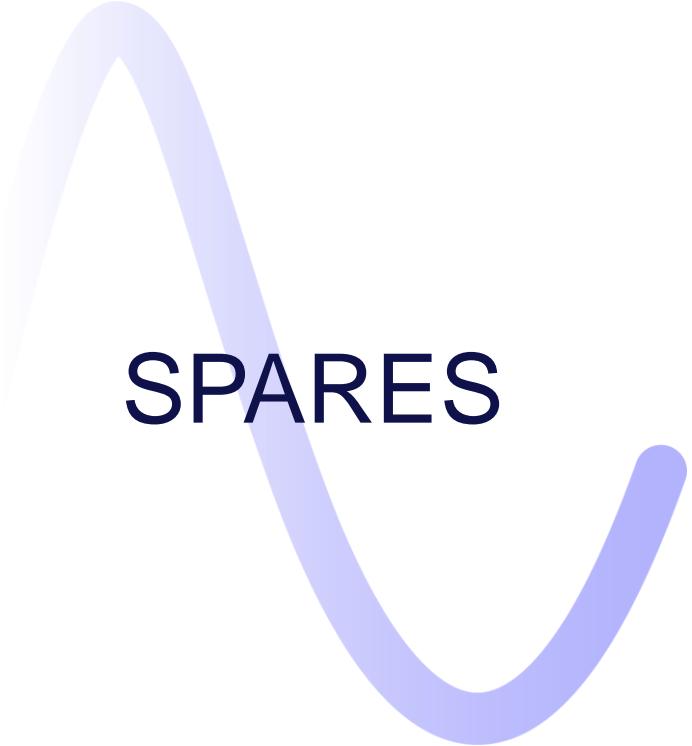
Conclusions and Upcoming activities

- Cryogenics study is on track in collaboration with RF and TIWG colleagues
 - Staging of the machine cryoplants and concept of the cryogenic distribution were defined following Z, W, H and ttbar machine
- Cryo for detectors/MDI under study -> main assumptions still to be transmitted to cryogenics for further study of the design concept
- Surface needs (on ground, alcoves and caverns) have been transmitted to civil engineering
- Further study the operation modes of the booster and the related heat loads with RF/optics experts
- Define the operation modes of the cryoplants according to the machine modes (e.g. Economic mode, maintaining a wide range of operability)
- Conclude on RF points (H & L) layout:
 - PL position of the access shaft wrt the LSS-center to be confirmed
 - Number of CMs, heat loads and sectorization strategy
- Update the feasibility study with industry
- Investigate open points : safety aspects, installation and waste heat management.





THANK YOU FOR
YOUR ATTENTION



SPARES

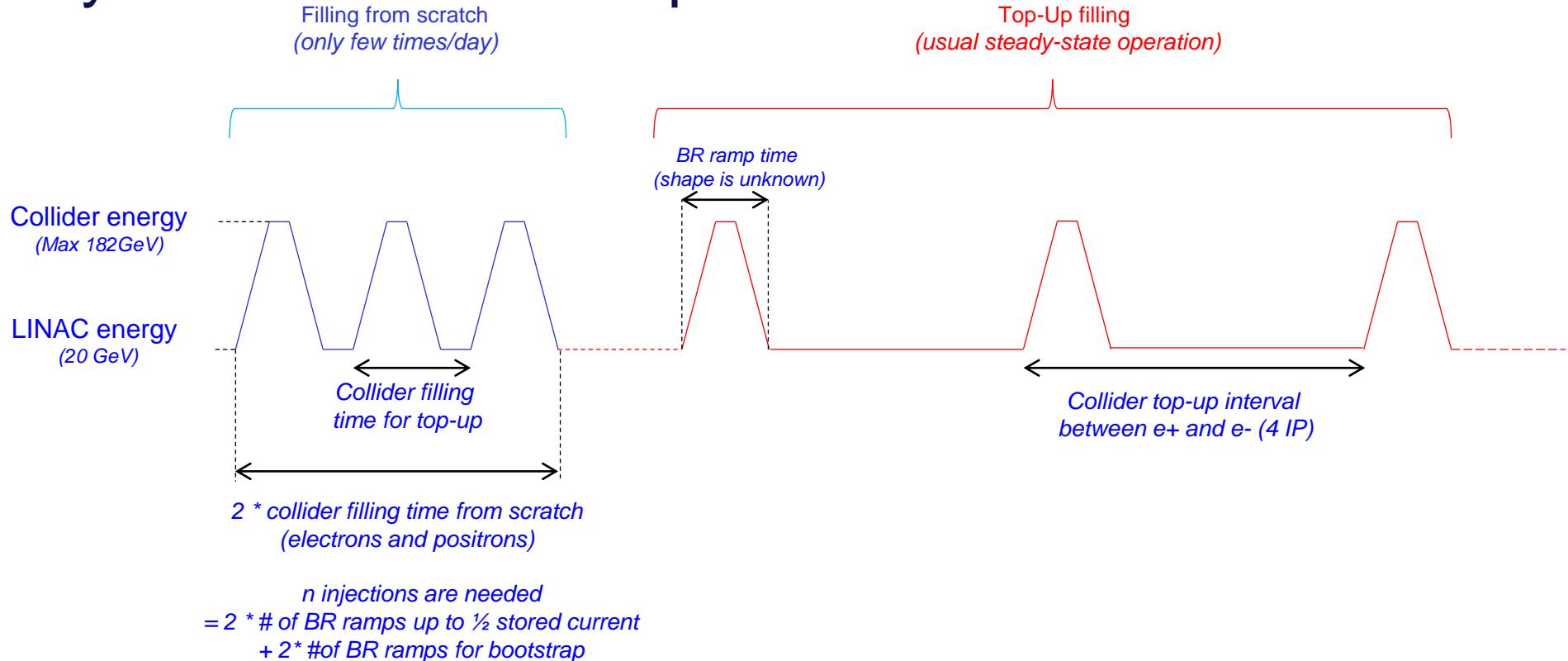
BOOSTER CYCLES IMPACT ON CRYOGENICS

Last booster cycle specifications from

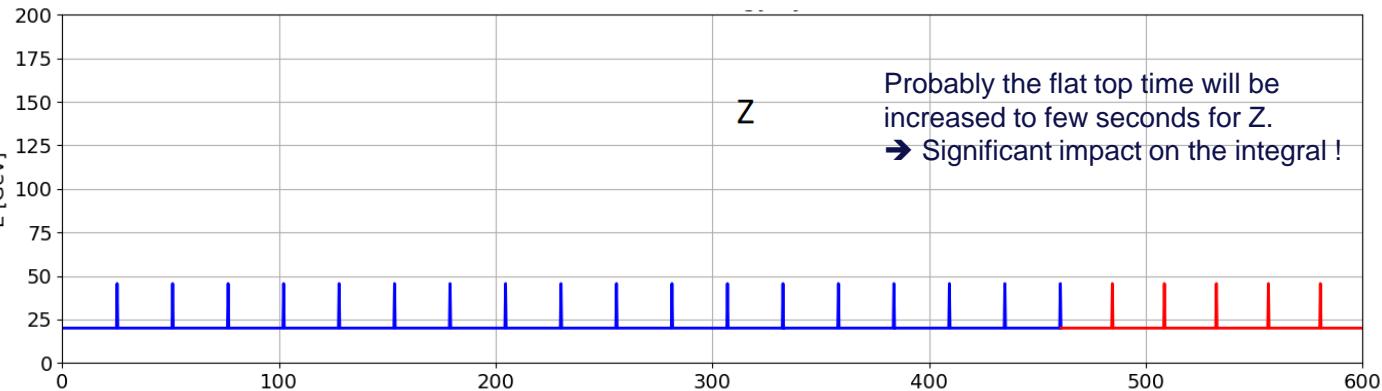
K. Oide (24th Nov. 2022)

Injection time for each specie (20 GeV Linac, 4 IP)			
	Z	WW	ZH
Collider energy [GeV]	45.6	80	120
Collider & BR bunches / ring	10000	880	248
Collider particles / bunch N_b [10^{10}]	24.3	29.1	20.4
Allowable charge imbalance Δ [$\pm\%$]	5		3
Injector particles / bunch N_{max} [10^{10}]	$\leq 3.0^*$		
Bootstrap particles / bunch [10^{10}] = $2N_b\Delta$	2.43	1.746	1.224
# of BR ramps (up to 1/2 stored current, with N_{max})	3	3	3
# of BR ramps (bootstrap with $2N_b\Delta$)	6	8	6
BR ramp time (up + down) t_{ramp} [s]	0.6	1.5	2.5
Linac bunches / pulse	2		
Linac pulses needed n_p	5000	440	124
Linac repetition frequency [Hz] f_{rep}	200		50
Collider filling time from scratch [s]	230.4	113.3	44.82
Collider filling time for top-up [s] = $n_p/f_{rep} + t_{ramp}$	25.6	10.3	4.98
Lum. lifetime (2 IP) [s]	2258		
BS lifetime (2 IP) [s]	100000	100000	2130
Lattice lifetime (2 IP) [s]	1260	2400	3000
Collider lifetime (2 IP) τ_2 [s]	802.2	2140	465.7
Collider top-up interval (between e+ and e-) (2 IP) [s] = $\tau_2\Delta$	40.1	64.2	13.971
Lum. lifetime (4 IP) [s]	1129	1070	596
BS lifetime (4 IP) [s]	100000	100000	1065
Lattice lifetime (4 IP) [s]	840	1600	2000
Collider lifetime (4 IP) τ_4 [s]	479.3	1070	382.1
Collider top-up interval (between e+ and e-) (4 IP) [s] = $\tau_4\Delta$	24.0	32.1	11.463
			16.284

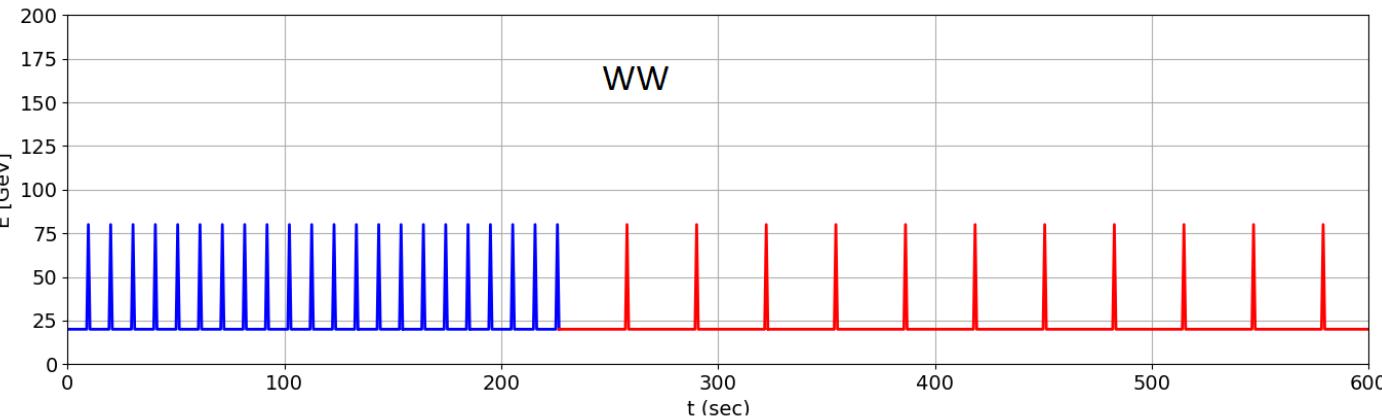
Cycle modes and shapes



Result for Z & W machines



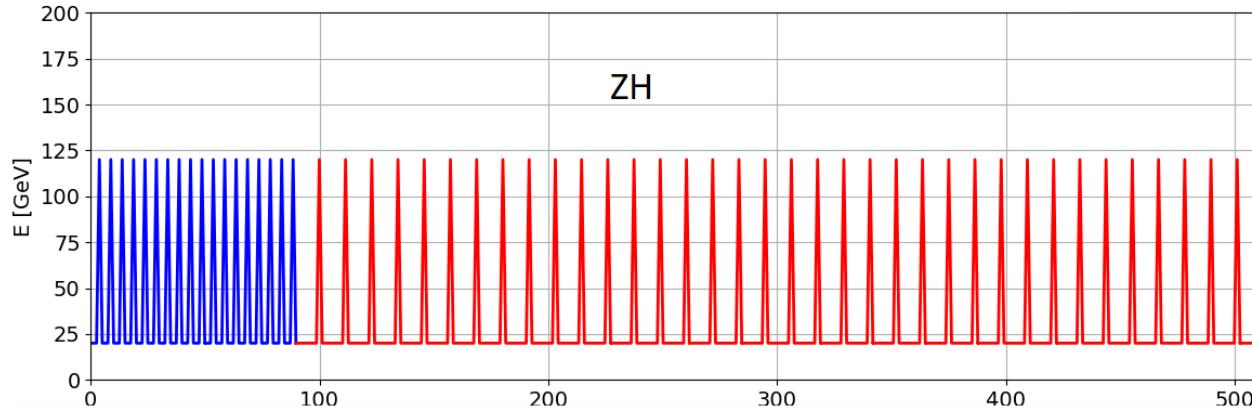
α (from scratch) = 1%
 α (top-up) = 1%



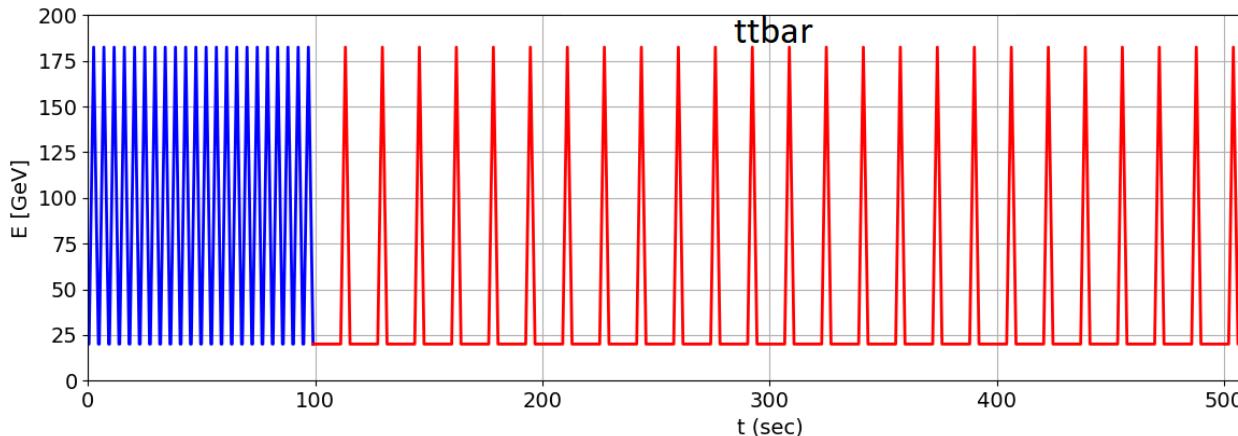
α (from scratch) = 7%
 α (top-up) = 2%

$$\alpha = \frac{\int E - E_{inj}}{\int E_{top} - E_{inj}}$$

Result for H & tt machines



α (from scratch) = 25%
 α (top-up) = 11%



α (from scratch) = 46%
 α (top-up) = 13%

$$\alpha = \frac{\int E - E_{inj}}{\int E_{top} - E_{inj}}$$

Implication for cryogenics

- Cryogenic dynamic heat load is varying during ramp-up/down
- How cryo power evolves during the transient? If we assume that it is proportional to the square of particle energy:

$$P_{\text{dyn}} = \frac{1}{(R/Q)_{\text{lin}}} \frac{V_{\text{tot}}}{E_{\text{acc}}} E_{\text{acc}}^2 l_{\text{cav}}$$

Machine	α for filling from scratch (Energy / cryo power)	α for top-up mode (Energy / cryo power)
Z	1% / 1 %	1% / 1%
WW	7% / 6%	2% / 2%
ZH	25% / 19%	11% / 8%
ttbar	46% / 34%	13% / 9%

- We must consider the filling from scratch mode
- The relationship between the energy cycle and the dynamic heat load could be refined
 - *Allow to not oversize the cryo system.*
 - *Allow to better understand the dynamics.*
- Next steps
 - *Cryo team will perform some dynamic simulations to evaluate the impact of the filling from scratch.*
 - *Some additional helium buffers at the cryomodule level and at the refrigerator level could be mandatory.*

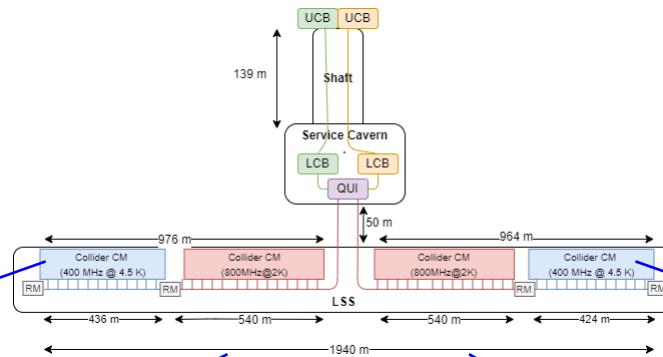
FOCUS ON RF POINTS

Updated RF heat loads for FCC-ee

O. Brunner, F. Peauger

12-May-23	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.72	6.23	10.61	20.01	10.61	20.76	10.61	20.12	20.10
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	7.95	18.75	7.95	19.44	7.95	18.85	18.83
#cells	56	120	264	280	528	540	528	2440	3000
# cavities	56	24	132	56	264	108	264	488	600
# CM	14	6	33	14	66	27	66	122	150
+ #CM	14	6	33	8	0	13	0	122	123
- #CM	-	-	14	-	-	-	-	-	-
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	19	0.3	129	3	129	4	129	23	3
stat losses/cav * [W]	8	8	8	8	8	8	8	8	8
Qext	5.8E+04	3.1E+05	9.2E+05	7.6E+06	9.1E+05	1.6E+07	4.5E+06	4.2E+06	8.1E+07
Detuning [kHz]	9.885	4.385	0.575	0.140	0.106	0.012	0.009	0.056	0.002
Pcav [kW]	901	210	378	89	382	47	78	163	8
energy loss / turn ** [MV]	39.40	39.40	370.00	370.00	1890.00	1890.00	10100.00	10100.00	10100.00
cos phi	0.33	0.28	0.35	0.35	0.90	0.90	0.98	0.86	0.89
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

FCC-ee cryoplants at point H (ttbar)



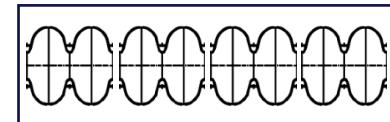
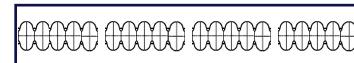
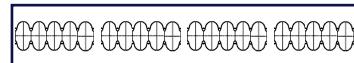
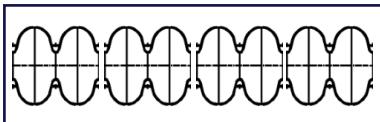
CM = 188

- 33 CM @ 4.5 K
- 11.4 m/CM
- 4 cavities/CM
- 8 cells/CM

- 61 CM @ 2 K
- 7.5 m/CM
- 4 cavities/CM
- 20 cells/CM

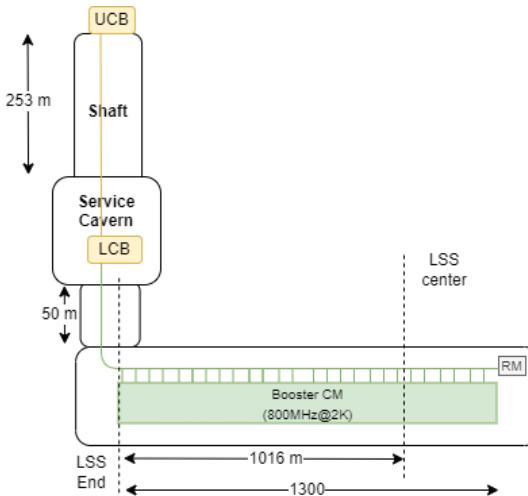
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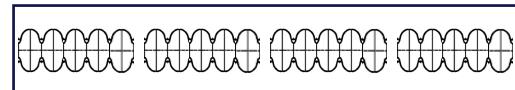
Diagrams not to scale

FCC-ee cryogenics at point L/S4 (ttbar)



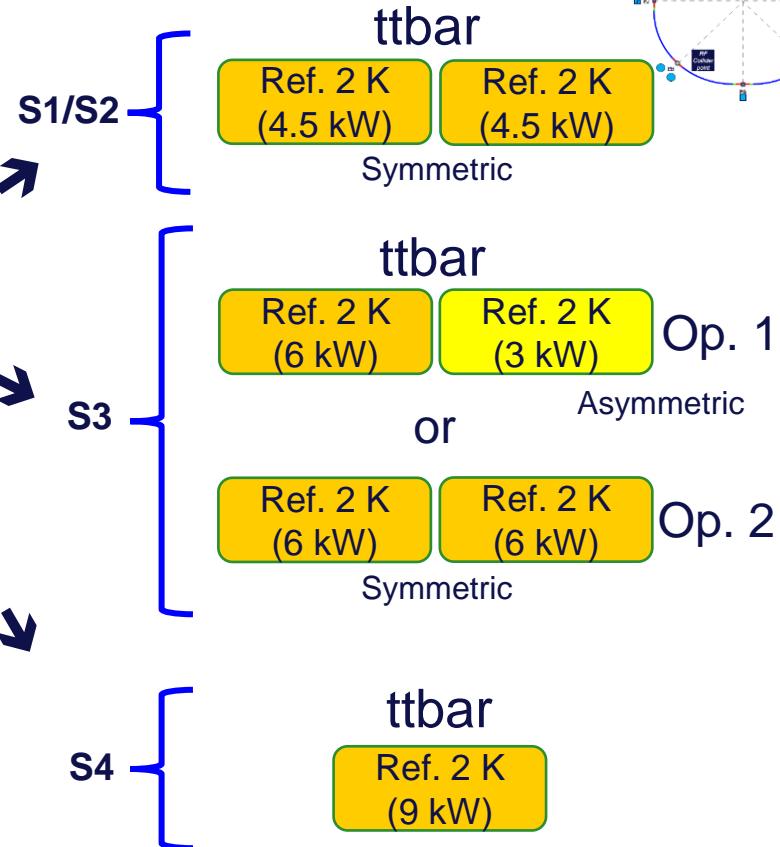
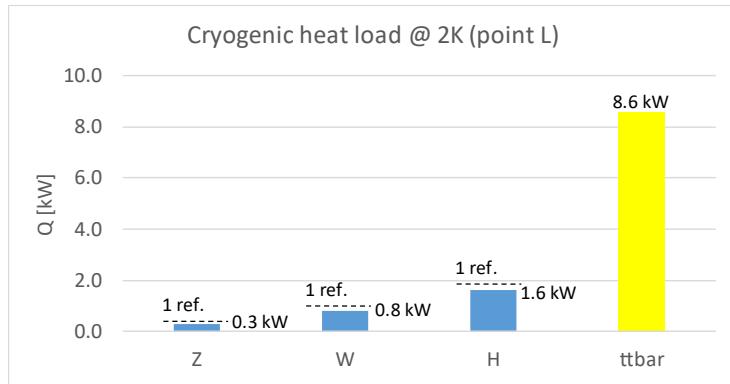
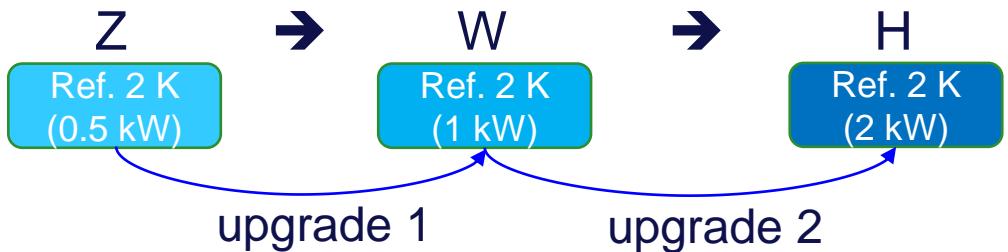
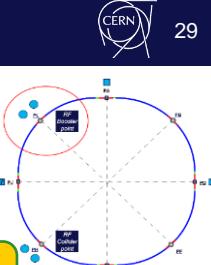
CM = 150

- 150 CM @ 2 K
- 7.5 m/CM
- 4 cavities/CM
- 20 cells/CM



Diagrams not to scale

FCC-ee cryoplants at point L : staging





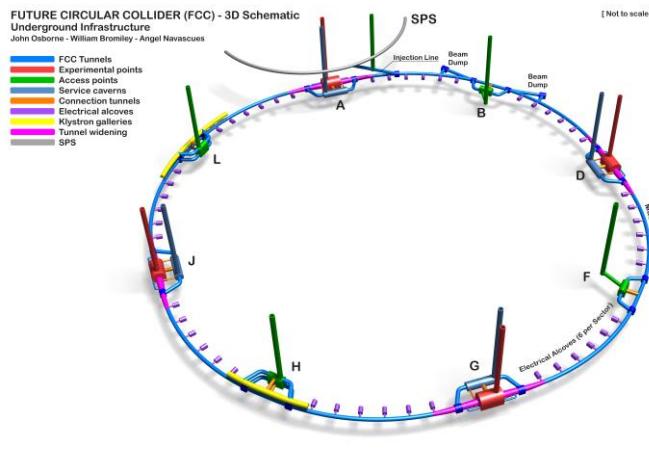
SURFACE NEEDS FOR CIVIL ENGINEERING

Surface requirements for cryo

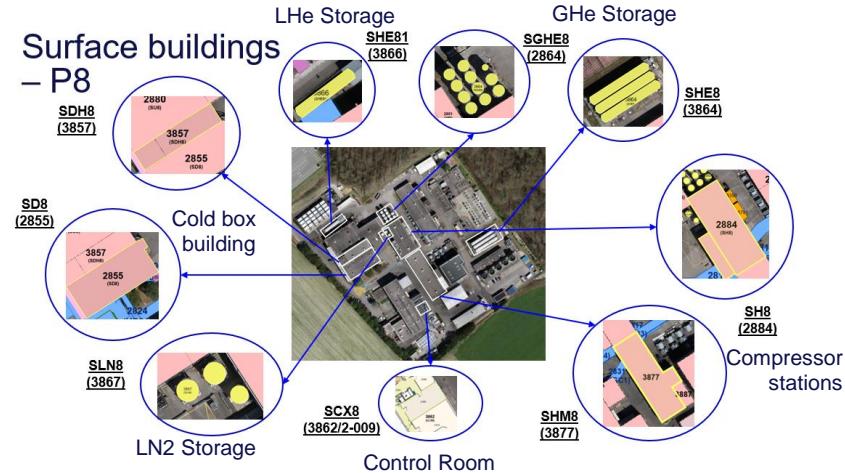
- Aboveground surface needs per point:

Estimations based on industrial studies for FCC-hh
@ CDR baseline and LHC experience.

	Point A & G ee (ttbar)	Point B & F ee (ttbar)	Point D & J ee (ttbar)	Point H ee (ttbar)	Point L ee (ttbar)
Surface in m ²	hh	hh	hh	hh	hh
Compressor station building	430	4300	x	6400	N/A
Cold box building	x	400	x	800	
LN ₂ storage	42	42	x	42	
GHe storage	400	2000	x	2900	
LHe storage	x	1080	x	2200	
Total aboveground	872	7822	x	12342	
				8862	12342
				4452	12342

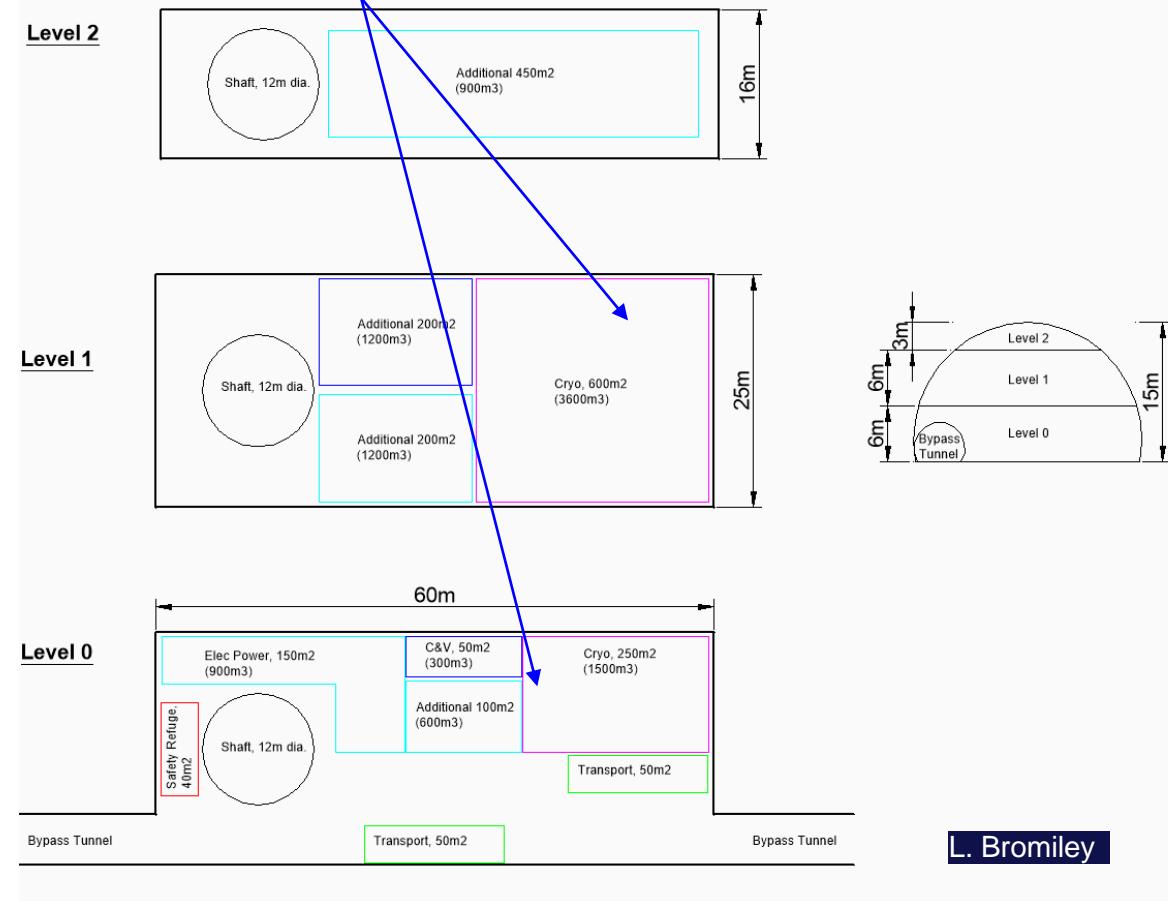


LHC P8 total
cryo area of
about 4600 m².



Surface requirements for cryo – Service Caverns

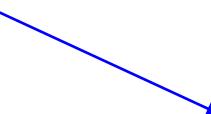
- Service cavern sizes - Points B, F, H and L
 - 850 m² for cryo.
 - Driven by FCC-hh assumptions.
 - Accounts for cold boxes, interconnection boxes and auxiliary racks.
 - Does not account for instrumentation which will be located in:
 - Alcoves (racks)
 - Tunnel (crates)
 - FCC-ee cryoplants should fit within.



Surface requirements for cryo - Alcoves

Instrumentation and Control – main alcoves requirements driver

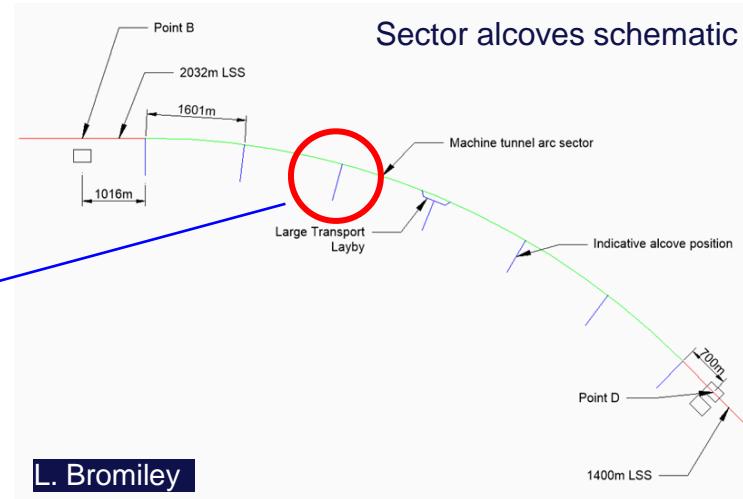
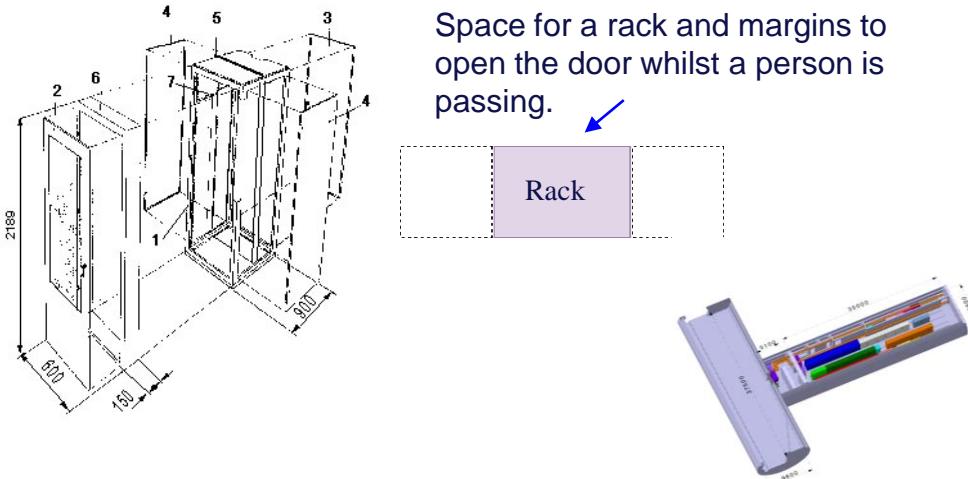
- **Cryogenic control system and instrumentation:**
 - **Sensors** - in the LHC it manages more than 16000 sensors (thermometers, pressure sensors and level gauges).
 - **PLCs running control loops, alarms and interlocks.**
 - **Actuators:**
 - Control valves (analog), quench valves and pressure valves (digital)
– more than 3000 in the LHC.
 - Heaters – more than 2400 in the LHC.
- **Racks and crates house electronic cards for:**
 - reading the temperature, pressure and liquid helium level measurements
 - supplying electrical power to the heaters
 - reading the digital valves status



Surface requirements for cryo - Alcoves

7 alcoves per sector (EDMS - 2822196)

- 16.5 m² of surface in each alcove based on FCC-hh requirements.
 - It is assumed that crates will be kept next to the magnets where radiation is expected to reach 200 Gr/yr (20 – 200 times the LHC values).
 - R&D on radiation resistant ASIC chips and processors is required but deemed realistic.
 - No requirements coming from FCC-ee at this stage as instrumentation will be mostly located in the Klystron galleries.

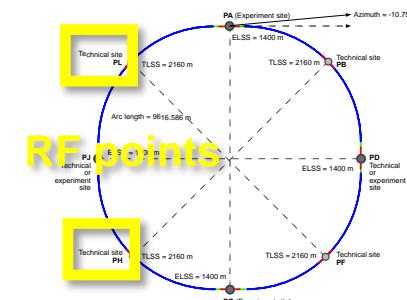




UTILITIES NEEDS

Water- and air-cooling needs for FCC-ee cryo

- **Air needs:**
 - Underground areas @ ttbar :
 - **0.1 MW** for point L ($1 * 9 \text{ kW} @ 2 \text{ K installed}$)
 - **0.2 MW** for point H ($2 * 10 \text{ kW} @ 2 \text{ K installed}$)
 - Surface areas @ ttbar:
 - **0.5 MW** for point L ($1 * 9 \text{ kW} @ 2 \text{ K installed}$)
 - **2 MW** for point H ($2 * 60 \text{ kW eq} @ 4.5 \text{ K installed}$)
- **Water needs:**
 - Underground areas @ ttbar :
 - **0.8 MW** for point L ($1 * 9 \text{ kW} @ 2 \text{ K installed}$)
 - **1.8 MW** for point H ($2 * 10 \text{ kW} @ 2 \text{ K installed}$)
 - Surface areas @ ttbar:
 - **10 MW** for point L ($1 * 9 \text{ kW} @ 2 \text{ K installed}$)
 - **40 MW** for point H ($2 * 60 \text{ kW eq} @ 4.5 \text{ K installed}$)



RF points

13 MW per cryo-point in the LHC

Waste heat recovery assessment to be started with CV.