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FCC CRYOGENIC SYSTEM

FCC-ee Layout and Implementation

(*incl. compatibility with FCC-hh*)

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On behalf of the CERN Cryogenics Group

ICEC/ICMC
29th International Cryogenic Engineering Conference
International Cryogenic Materials Conference 2024
July 22-26, 2024, Geneva, Switzerland

ICEC29/ICMC 2024 – CERN, Geneva, Switzerland – July 22nd to 26th

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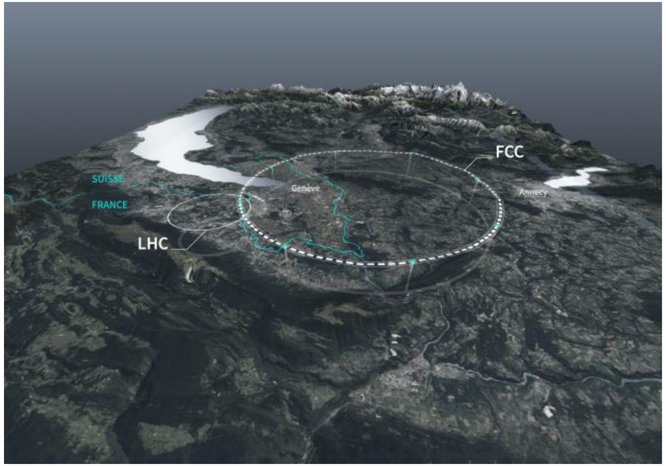
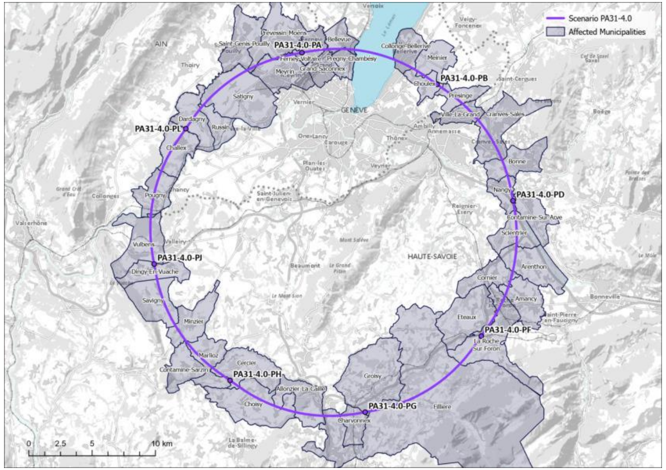
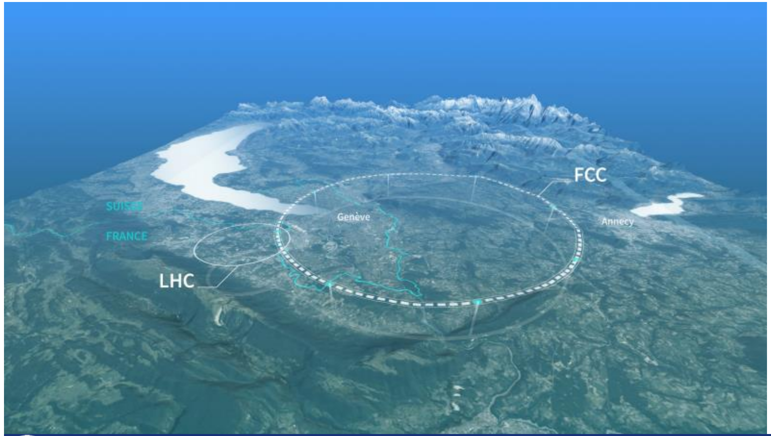




What is FCC?



FCC IN A NUTSHELL

Timeline

- **2025**: Completion of the FCC Feasibility Study
- **2027–2028**: Decision by CERN Member States and international partners

Tunnel

- **90.7 km** circumference
- **200 m** average depth
- **8 surface points** (7 in France, 1 in Switzerland)

Two stages

- **FCC-ee** (precision measurements) about 15 years from the **mid-2040s**
- **FCC-hh** (high energy) about 25 years from the **2070s**

Costs/benefits

- **15 billion CHF**, spread over at least **15 years** for FCC-ee with four experiments
- Estimated benefit–cost ratio of **1.66**
- About **800 000** person-years of employment created

https://home.cern/science/accelerators/future-circular-collider

FUTURE CIRCULAR COLLIDER

FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam.
- Independent vacuum systems for electrons and positrons
- full energy booster ring with top-up injection, collider permanent in collision mode

- ❑ x 10-50 improvements on all EW observables
- ❑ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ❑ x10 Belle II statistics for b, c, τ
- ❑ indirect discovery potential up to ~ 70 TeV
- ❑ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

FUTURE CIRCULAR COLLIDER

FCC-hh main machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significant amount of time for high-field magnet R&D, aiming at highest possible collision energies

- Target field range for cryo-magnet R&D

Formidable challenges:

- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ optimization of energy consumption: → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays (γγ, Zγ, μμ)
- ❑ Final word about WIMP dark matter

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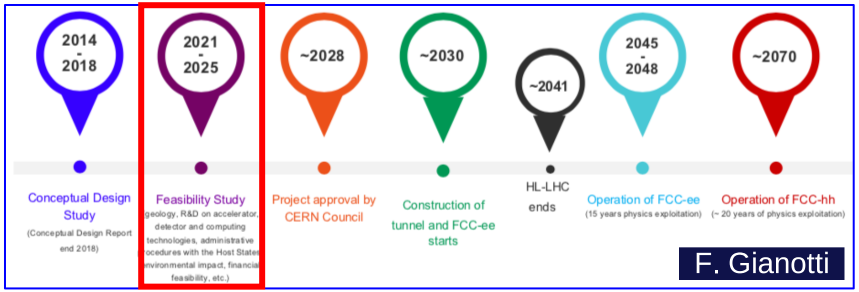
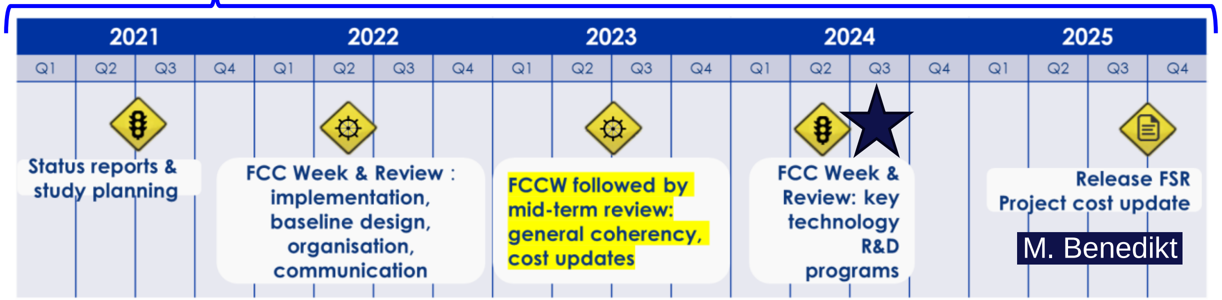
Status

- FCC Full schedule



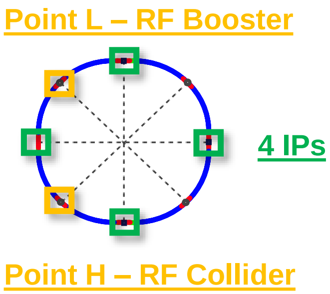
1st stage collider FCC-ee: electron-positron collisions 90-360 GeV: electroweak and Higgs factory
2nd stage collider FCC-hh: proton-proton collisions at ~ 100 TeV

- **FCC Feasibility status:**
  - **Started in '21.**
  - **Mid-term review completed in '24**
  - **Feasibility Report => March'25**

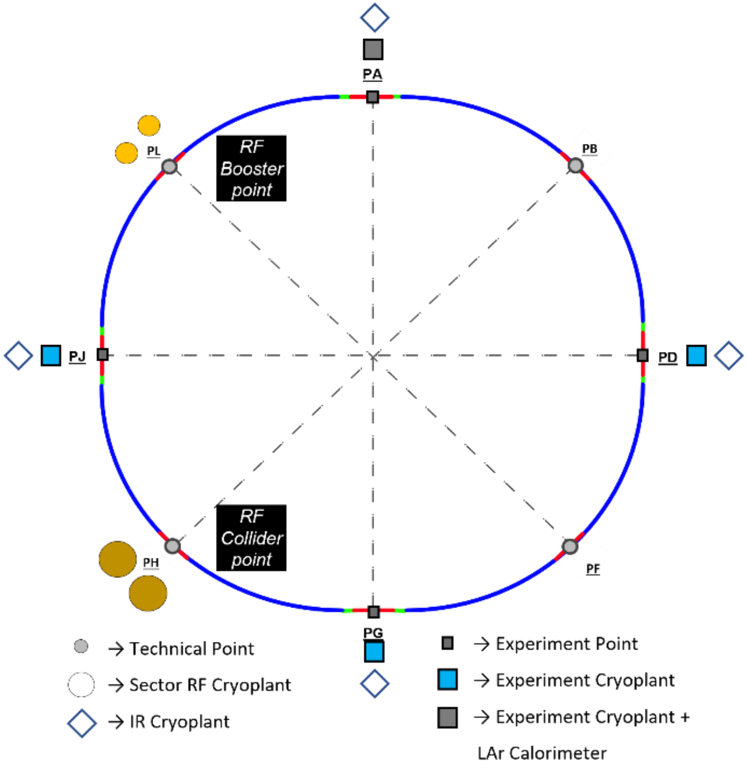


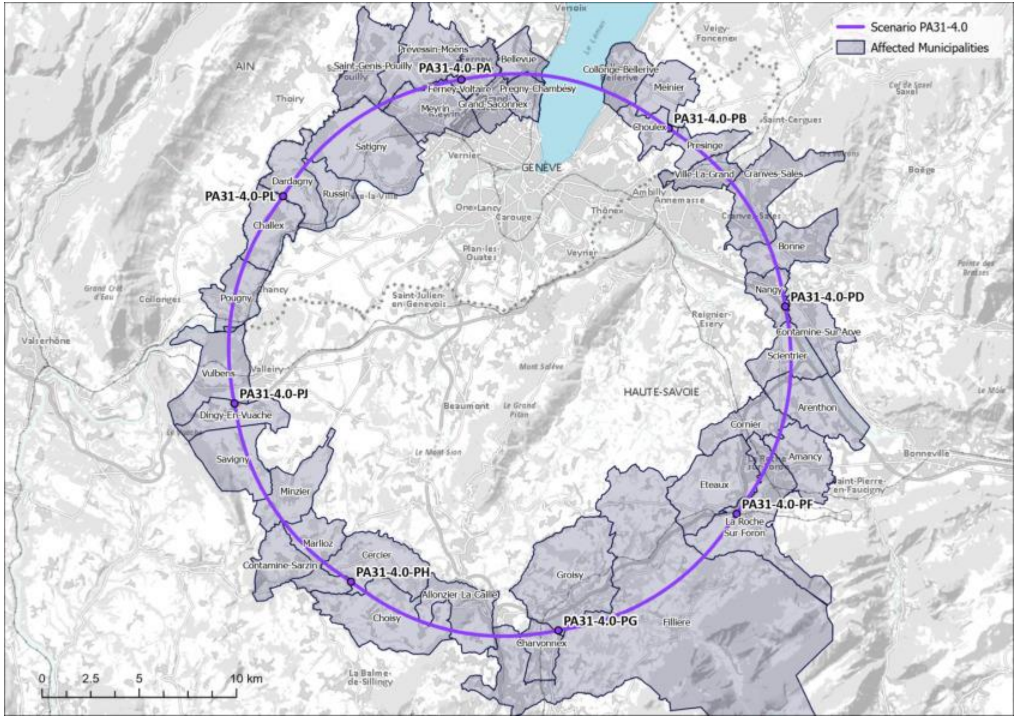
Focus:

- **Cryomodules Helium inventory refinement.**
- **Updated static loads for 4.5 K cryomodules.**
- **New layout at point L – becomes symmetric again.**
- **FCC-hh layout adjusted with integration constraints (PH, PB and tunnel diameter).**
  - **Utilities needs are also being adjusted.**



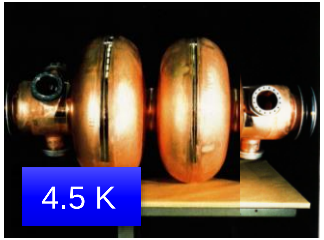
FCC-ee cryogenics



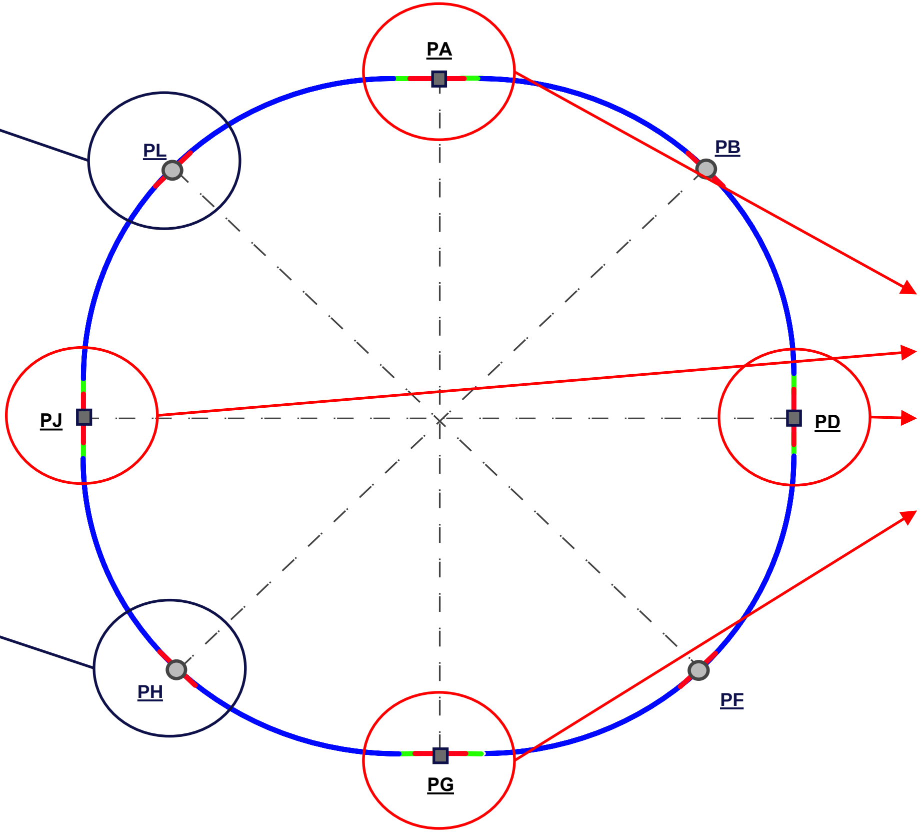


FCC-ee cryogenic cooling users

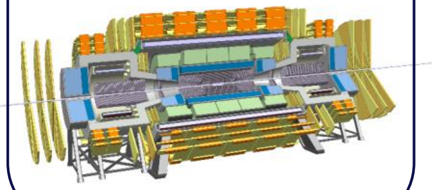
RF **booster** cavities



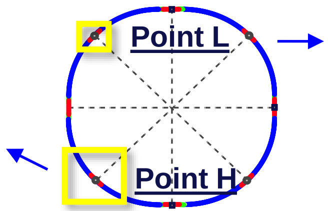
RF **collider** cavities



Detector solenoids and MDI magnets



FCC-ee SRF dynamic and static heat loads



		String of 1950 m — **Point H - Collider**: Strong dynamic/static ratio	**Point L - Booster**: Strong transient heat loads — String of 1300 m
4y	Z	**x28** CM_{400MHz} – **7 kW** at 4.5 K	**x6** CM_{800MHz} – **0.3 kW** at 2 K
2y	W	**x66** CM_{400MHz} – **64.1 kW** at 4.5 K	**x14** CM_{800MHz} – **0.9 kW** at 2 K
3y	H	**x66** CM_{400MHz} – **64.1 kW** at 4.5 K	**x27** CM_{800MHz} – **1.8 kW** at 2 K
5y	ttbar	**x66** CM_{400MHz} – **64.1 kW** at 4.5 K **x122** CM_{800MHz} – **22.7 kW** at 2 K	**x150** CM_{800MHz} – **9.9 kW** at 2 K

Assumptions

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

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

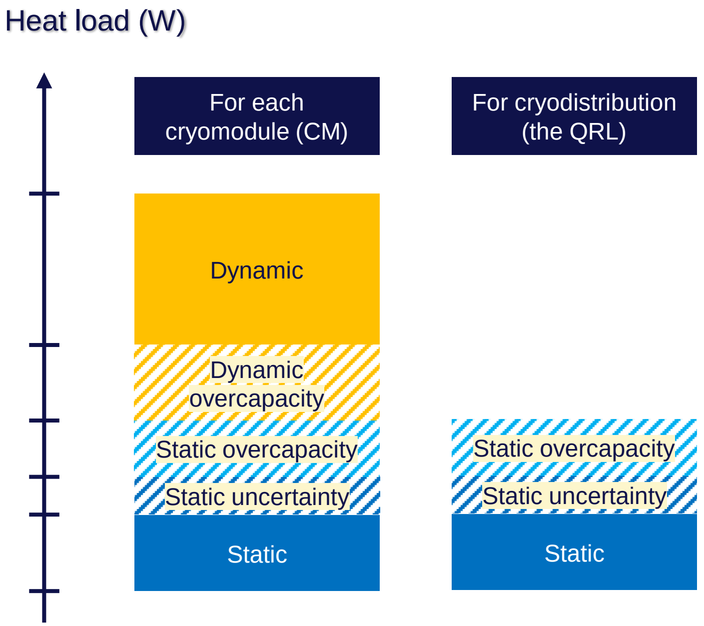
Static & dynamic heat loads on He bath + 50 % margin

- **Couplers**
- **HOMs**
- **Thermal shields**

= not shown here

Sizing the cryoplants and QRL

- Margins to be added to the raw heat loads of cryomodules (CM) and cryogenic distribution line (QRL)
- Approach based on HL-LHC heat load review performed in April 2021
- Uncertainty factor (F_{un}):
  - To cover design uncertainty, engineering changes, tolerances
  - Evolves with maturity of the design
  - 50%, applied to all static heat loads (CM and QRL)
- Overcapacity factor (F_{ov}):
  - To ensure nominal performance by covering the risks, for instance cryoplant ageing, and operational flexibility
  - 50% applied to [static + static uncertainty]
  - 50% applied to [CM dynamic heat load]



FCC-ee 3-stages cryoplants layout

RF Points cryogenics

Stage	Point H - Collider	Point L - Booster
Z	1 x 15 kW eq @ 4.5 K	1 x 2 kW eq @ 4.5 K (77% @ 2K)
W&H	2 x 40 kW eq @ 4.5 K	1 x 9 kW eq @ 4.5 K (80% @ 2K)
ttbar	2 x 84 kW eq @ 4.5 K (47% @ 2K)	2 x 26.5 kW eq @ 4.5 K (81% @ 2K)

Experiment points cryogenics

Detector solenoid :

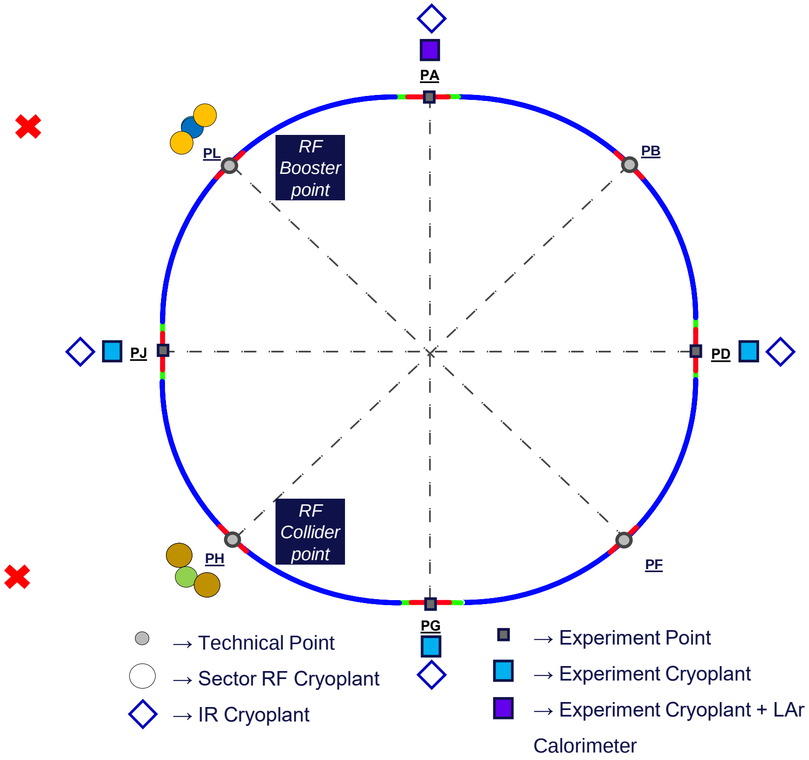
Number of experiments and their heat loads have not been defined yet.

- Option 1 (baseline):
  - 4 “CMS-like” cryoplants, one of which has a LAr calorimeter.
- Option 2:
  - 2 “CMS-like” cryoplants, one of which has a LAr calorimeter.

Insertion Region magnets:

- Unknown heat loads.

Not covered!

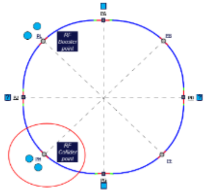


ttbar stage is the driver for surface needs, shaft and tunnel integration.

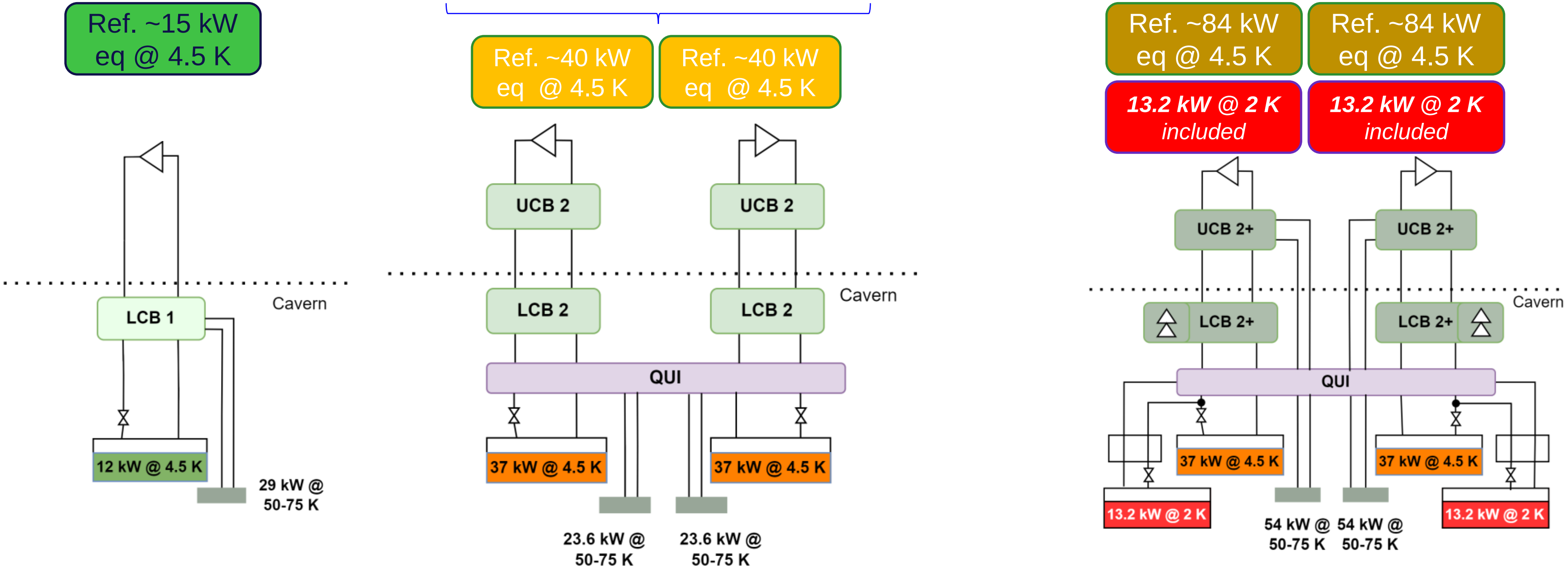
FCC-ee cryoplants at point H – staging

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

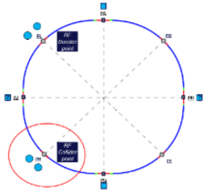
$$Q_{800MHz_{Installed}} = 3.0E+10 \,//\, Q_{400MHz_{Installed}} = 2.7E+9$$



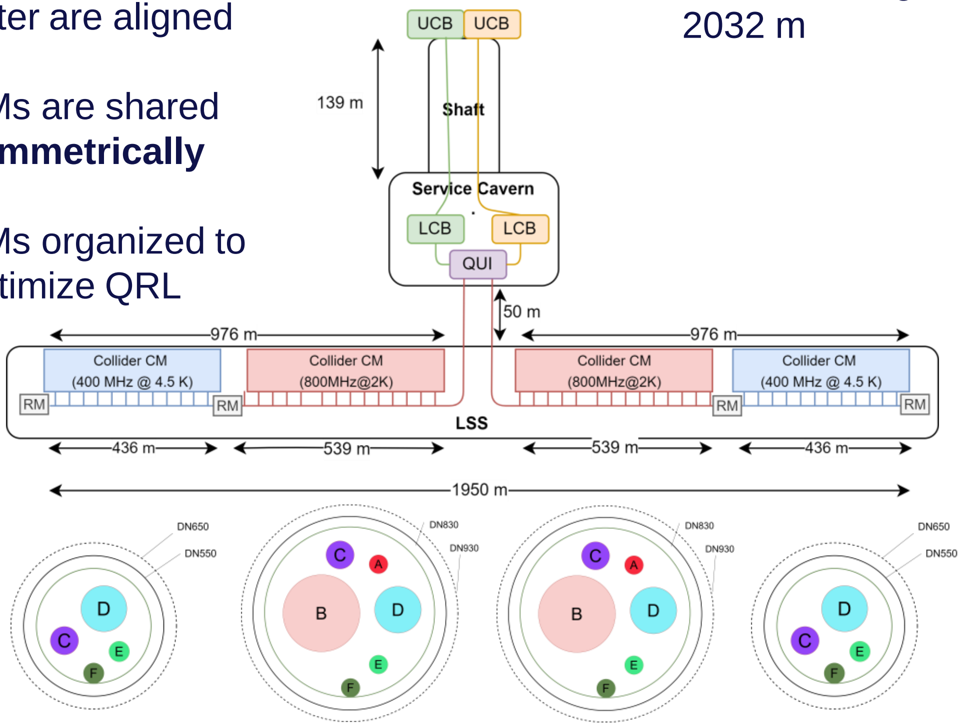
Z ➔ W & H ➔ ttbar



FCC-ee cryo layout at point H (ttbar)



- Service cavern & LSS center are aligned
- CMs are shared **symmetrically**
- CMs organized to optimize QRL
- LSS total length is of 2032 m

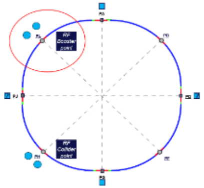


DN650 DN930 DN930 DN650

QRL Header & Process values	Diameter (mm)
A : 1.3 bar , 2.2 K (ΔP=25 mbar)	80
B : 30 mbar , 2 K (ΔP=2 mbar)	330
C: 3 bar, 4.6 K (ΔP=130 mbar)	120
D: 1.3 bar, 4.5 K (ΔP=70 mbar)	200
E: 20 bar, 50 K (ΔP=100 mbar)	80
F: 18 bar, 75 K (ΔP=100 mbar)	80
Vacuum jacket (400MHz)	550*
Vacuum jacket (800 MHz)	830*

** +100 mm for bellows and flanges*

FCC-ee cryoplants at point L – staging



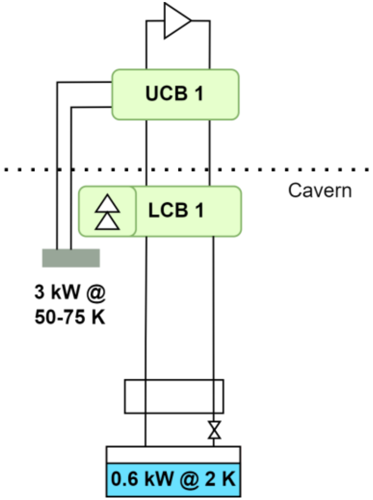
$$Q_{800MHz_{Installed}} = 3.0E+10$$

Z ➔ W & H ➔ ttbar

Z

Ref. ~2 kW eq @ 4.5 K

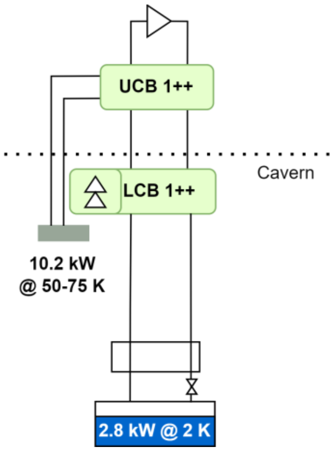
~0.6 kW @ 2 K included



W & H

Ref. ~9 kW eq @ 4.5 K

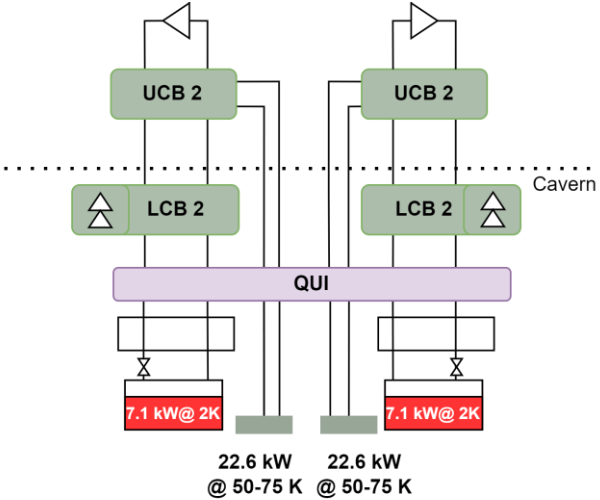
~3 kW @ 2 K included



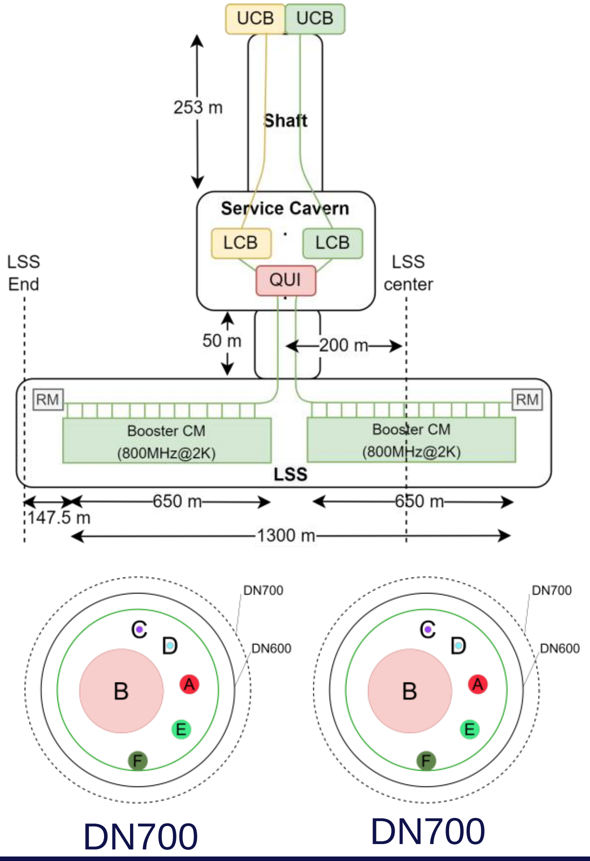
ttbar

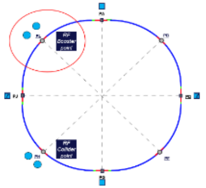
Ref. ~26.5 kW eq @ 4.5 K | Ref. ~26.5 kW eq @ 4.5 K

7.1 kW @ 2 K included | ***7.1 kW @ 2 K included***



FCC-ee cryo layout at point L (ttbar)



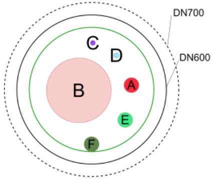


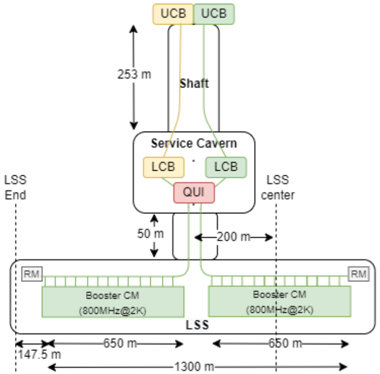
QRL Header & Process values	Diameter (mm)
A : 1.3 bar , 2.2 K (ΔP=25 mbar)	60
B : 30 mbar , 2 K (ΔP=2 mbar)	260
C: 3 bar, 4.6 K (ΔP=130 mbar)	20
D: 1.3 bar, 4.5 K (ΔP=70 mbar)	20
E: 20 bar, 50 K (ΔP=100 mbar)	80
F: 18 bar, 75 K (ΔP=100 mbar)	80
Vacuum jacket (800 MHz)	600*

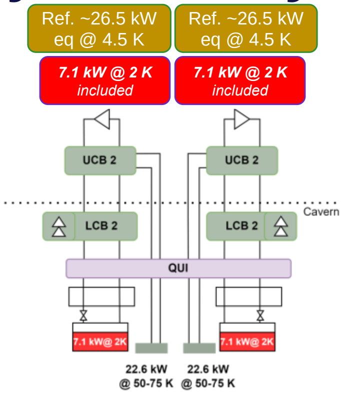
** +100 mm for bellows and flanges*

FCC-ee SRF cryogenic system layout summary @ ttbar

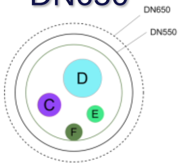
Point L

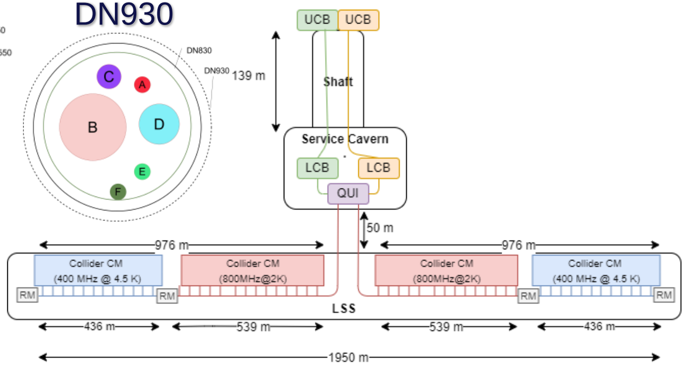


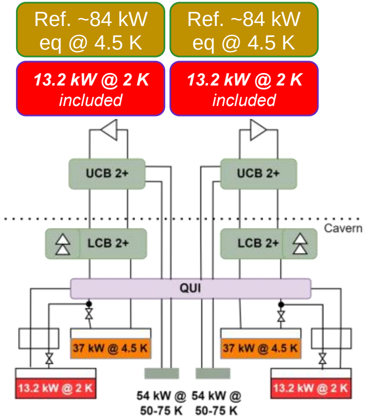


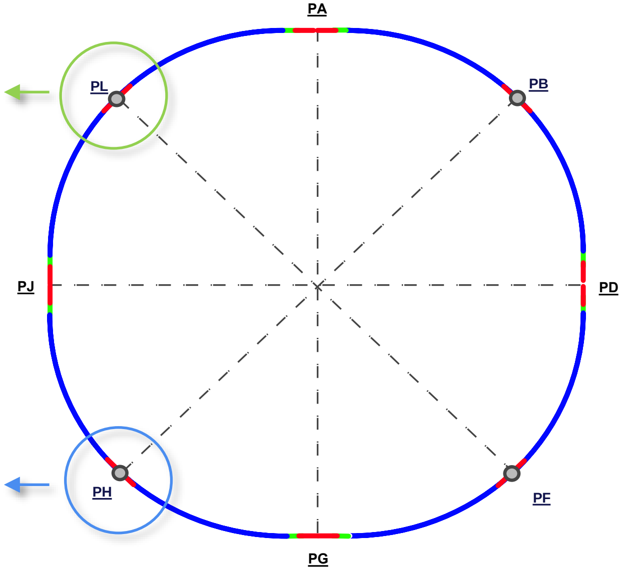


Point H

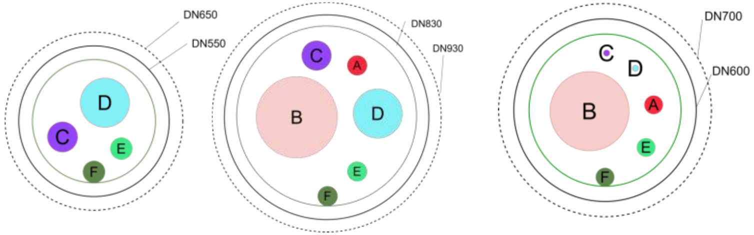








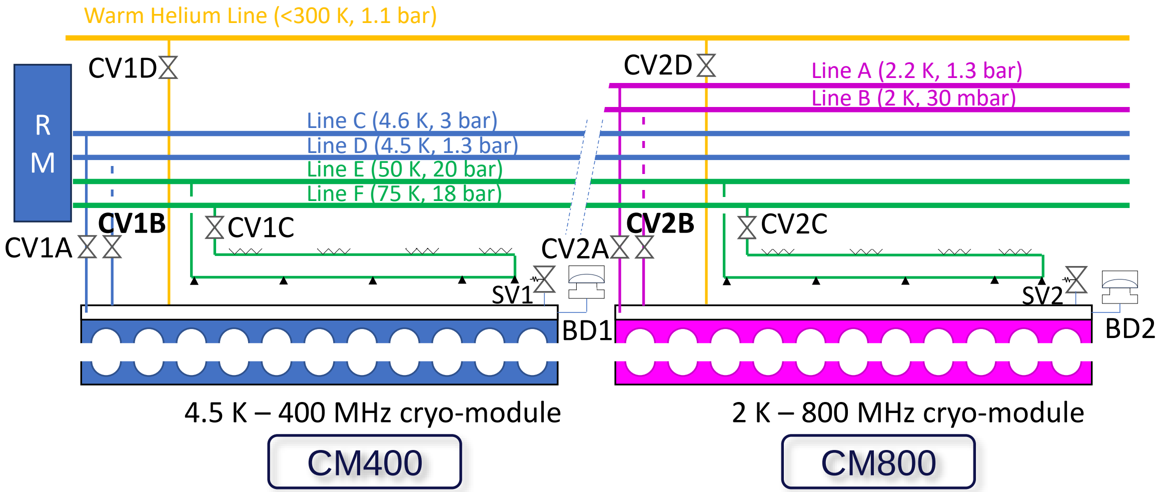
FCC-ee cooling scheme and cryodistribution

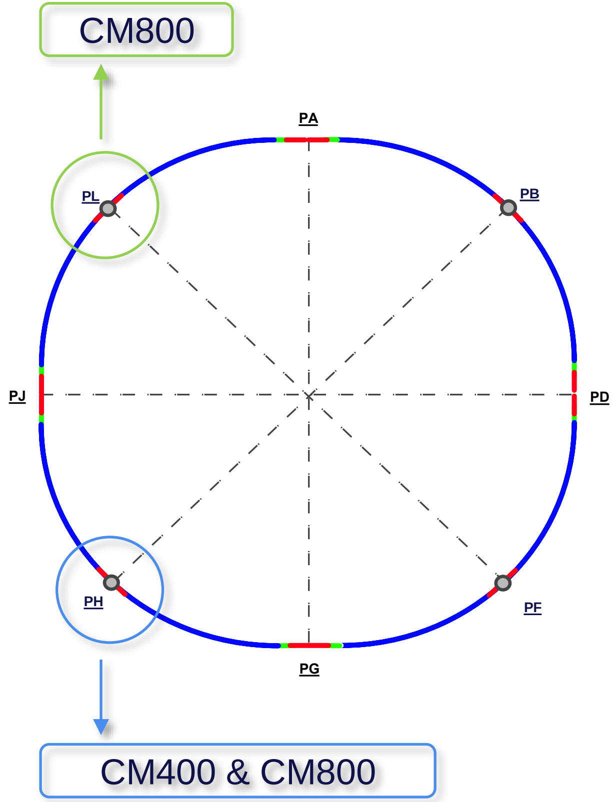


Point H
CM400 QRL
DN650

Point H
CM800 QRL
DN930

Point L
CM800 QRL
DN700





FCC-ee SRF points H and L – Helium inventory

Updated CM inventories: $116\ kg\ LHe\ per\ CM\ @\ 4.5\ K$ $55\ kg\ LHe\ per\ CM\ @\ 2\ K$

He preservation: see B. Naydenov talk

Point L	Z	W	H	ttbar
Cryomodules	0.4 ton	0.8 ton	1.5 ton	8.3 ton
Distribution (QRL)	1 ton	1 ton	1 ton	1 ton
Cryoplants	0.1 ton	0.3 ton	0.3 ton	1.6 ton
Total	1.5 ton	2.1 ton	2.8 ton	10.9 ton

Point H	Z	W	H	ttbar
Cryomodules	3.2 ton	7.7 ton	7.7 ton	14.4 ton
Distribution (QRL)	1.7 ton	1.7 ton	1.7 ton	4.2 ton
Cryoplants	0.5 ton	2.6 ton	2.6 ton	5.5 ton
Total	5.4 ton	12 ton	12 ton	24.1 ton

- **Total helium inventory for technical points at FCC-ee (ttbar) ~ 35 ton**

FCC-ee SRF points H and L – Installed EL 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

In "high" mode

	PH [MW]	PL [MW]	Total (PH+PL) [MW]
Z	3.4 / 3.1 / 2.5	0.46 / 0.42 / 0.34	3.9 / 3.5 / 2.8
W	17.8 / 16.3 / 13.2	2.1 / 1.9 / 1.5	19.9 / 18.2 / 14.7
H	18.2 / 16.6 / 13.5	2.1 / 1.9 / 1.5	20.3 / 18.5 / 15.0
ttbar	38.6 / 35.3 / 28.6	12.2 / 11.1 / 9.0	50.8 / 46.4 / 37.6

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

Surface requirements for FCC cryogenics

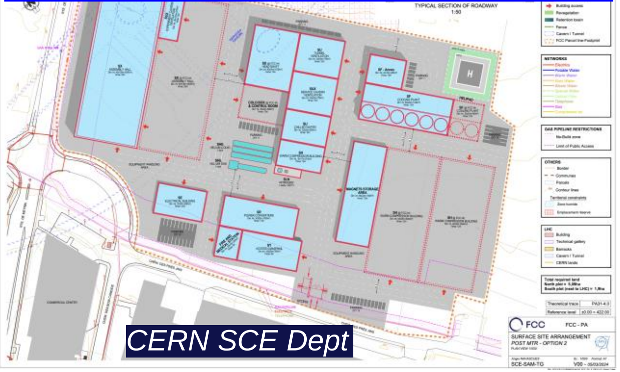
Estimations based on industrial studies for FCC-hh @ CDR baseline and LHC experience.

- **Aboveground surface needs per point:**

70 m2 control room is included in all points!

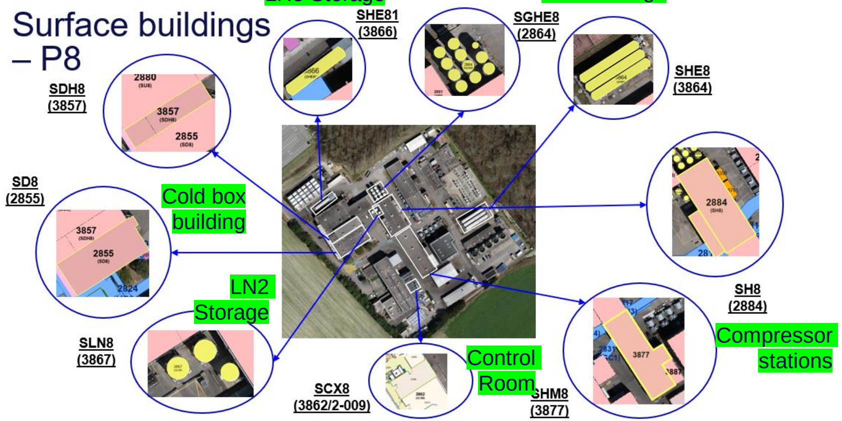
Surface in m2	Point A & G ee (ttbar)	Point A & G hh	Point B & F ee (ttbar)	Point B & F hh	Point D & J ee (ttbar)	Point D & J hh	Point H ee (ttbar)	Point H hh	Point L ee (ttbar)	Point L hh
Compressor station building	430	5870	x	3200	430	4270	4300	3200	2140	3200
Cold box building	x	600	x	400	x	400	800	400	400	400
LN2 storage	302	102	x	102	102	102	102	102	102	102
GHe storage	405	3240	x	1215	405	2430	2430	1215	1215	1215
LHe storage	X	2880	x	1440	x	1440	X	1440	x	1440
Total aboveground	**1207**	**12762**	**x**	**6427**	**1007**	**8712**	**7632**	**6427**	**3857**	**6427**

FCC surface site arrangement in point A



LHC P8 total cryo area of about <u>4600 m2</u> (as a comparison)

CV and EL surface needs also depend on cryo needs.

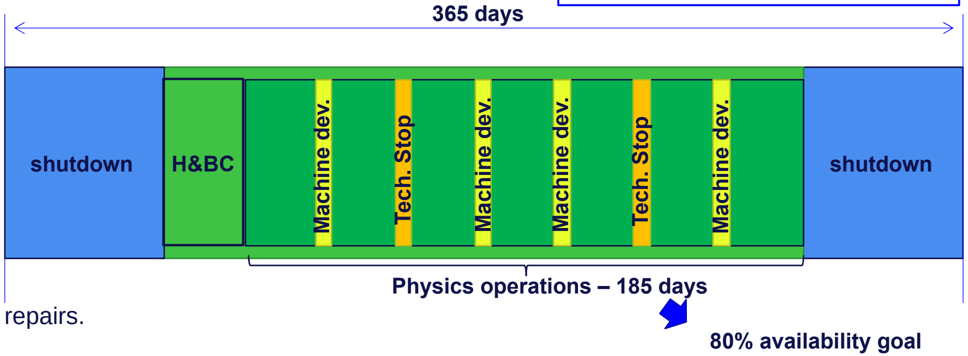


FCC operation Modes – typical year

Source: CDS 2645151

A total of 14 years of expected life-cycle:
- 4 years in Z stage
- 2 years in W stage
- 3 years in H stage
- 5 years in ttbar stage

- **Phases in a typical year – 365 days**
  - Shutdown phase – 120 days (33%) — Cryo in ECO mode
    - The machine is stopped and open for upgrade works, maintenance and repairs.
  - Operation phase – 245 days (67%)
    - Hardware and beam commissioning – 30 days
      - All systems are restarted and tested before operation.
    - Physics operation – 185 days
      - Beam is stable and collides for experiments.
    - Technical stops – 10 days — Cryo in ECO mode
      - Planned stops during operation to perform maintenance and repairs.
    - Machine development – 20 days
      - Planned activities with beam operation to improve beam performance.



Points H & L cryoplants elec consumption	Z	W	H	ttbar
Full power [MW elec]	3.5	17.4	18.8	46.4
Eco power [MW elec]	3.4	6.7	7.1	13.9
Elec energy/year w/o an eco mode [GWh]	31.0	152.6	164.4	406.5
Elec energy/year with an eco mode [GWh]	31.0	119.1	128.0	305.0
Corresponding energy saving in eco mode	N/A	22%	22%	25%

- **Availability target – 80 % of physics operation**
- **The modes will impact cryoplants' design and energy consumption**

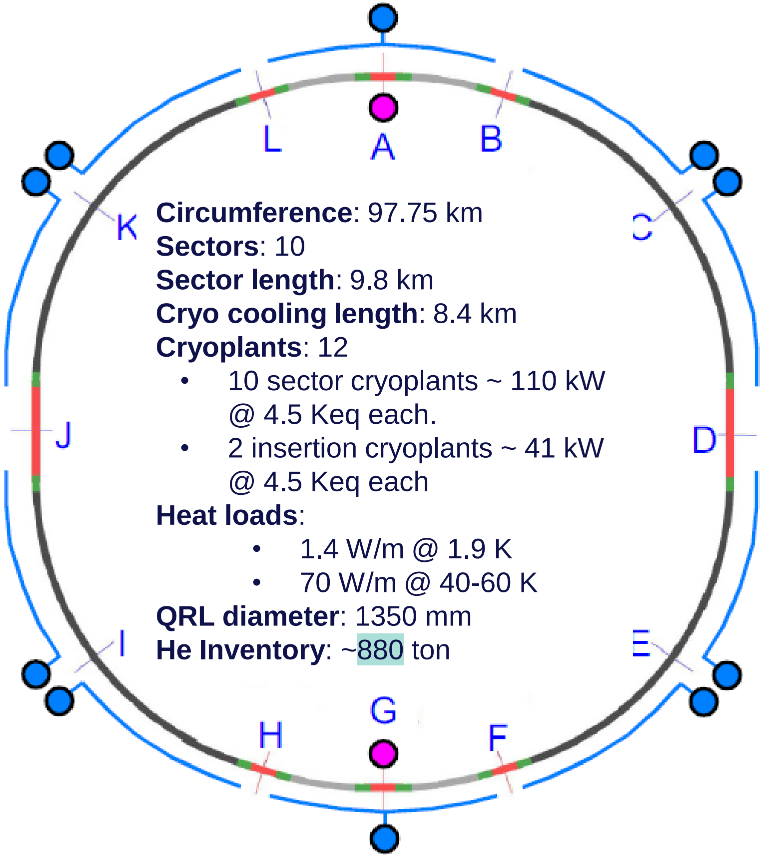
  (about 25% estimated savings with ECO mode)

FCC-ee SRF cryogenics challenges

- <u>Cryoplants size.</u> Very large cryoplants needed to optimize for availability. Factor 3 wrt to state-of-the-art units (ITER). Big industrial challenge.
- <u>Heat loads density.</u> Similar cryogenic cooling power to LHC, concentrated at point H.
- <u>Dynamic / static heat loads ratio</u>. Collider SRF system requires 2 times more dynamic heat loads than static (with current assumptions). LHC dynamic to static ratio is closer to 0.5.
- <u>Transient heat loads management</u>. Booster is operated in a pulsed manner and has different modes: filling from scratch and top up. Impacts cryoplant operation and cryomodules pressure stability.
- <u>Fast cooldown requirements</u> of the cavities between certain temperatures imposes operational constraints and affects the distribution line sizing.
- <u>2 K system</u>: +500 g/s for the collider at 30 mbar. R&D needed as factor 2 wrt to current state-of-the-art (HEX + cold compressor).

- <u>Helium dependency</u> needs to be reduced for future projects. Being addressed with a cryomodule and distribution line optimization, together with a Helium recovery system.
- <u>Sustainability</u>. An optimized cryoplant ECO mode design and operation is required to reduce energy consumption. Centrifugal compressors R&D could have a very positive effect too.
- <u>Installation</u>. The cryogenic distribution line should be installed to cover from Z to ttbar. Complex optimization and integration in the tunnel. Moreover, the cryoplant size doubles between H and ttbar, leading to a challenging staging in a tight schedule.

FCC-hh compatibility – CDR cryogenic layout



Circumference: 97.75 km
Sectors: 10
Sector length: 9.8 km
Cryo cooling length: 8.4 km
Cryoplants: 12

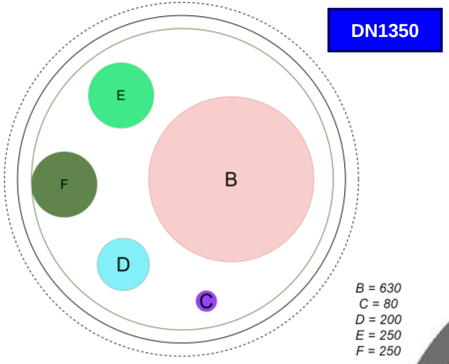
- 10 sector cryoplants ~ 110 kW @ 4.5 Keq each.
- 2 insertion cryoplants ~ 41 kW @ 4.5 Keq each

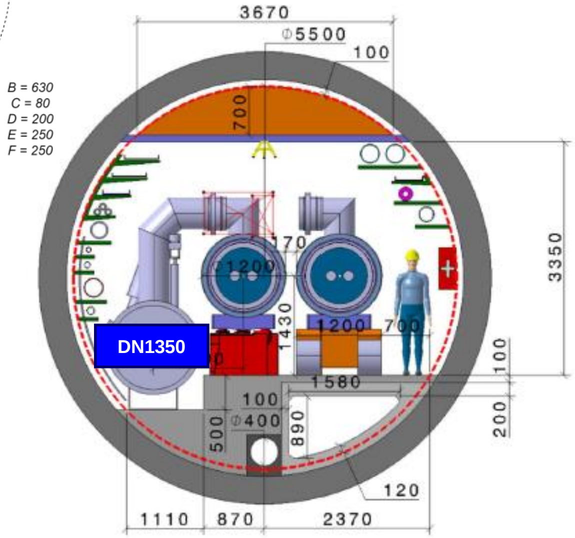
Heat loads:

- 1.4 W/m @ 1.9 K
- 70 W/m @ 40-60 K

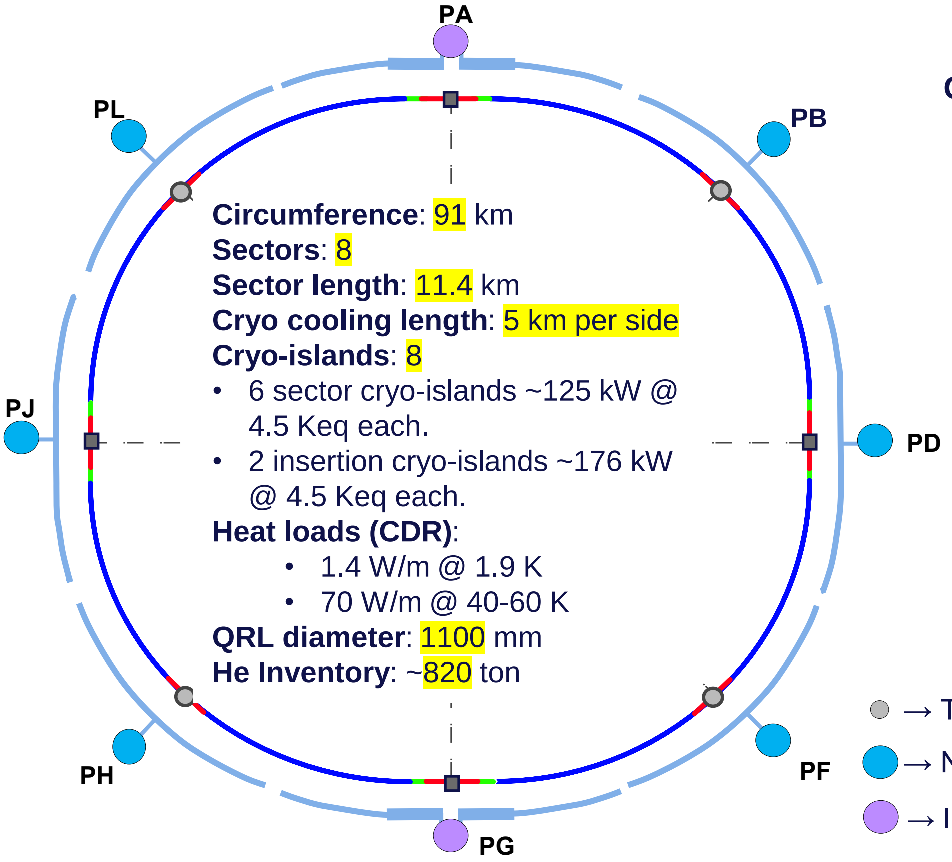
QRL diameter: 1350 mm
He Inventory: ~880 ton

Cryogenic distribution line





FCC-hh cryogenic system updated layout – Nb3Sn @ 1.9 K

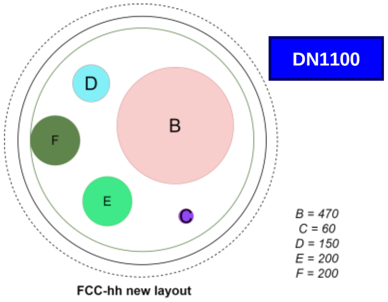


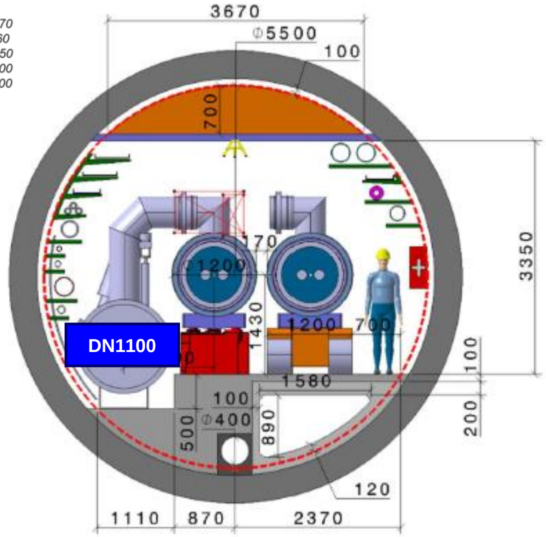
Circumference: 91 km
Sectors: 8
Sector length: 11.4 km
Cryo cooling length: 5 km per side
Cryo-islands: 8
- 6 sector cryo-islands ~125 kW @ 4.5 Keq each.
- 2 insertion cryo-islands ~176 kW @ 4.5 Keq each.

Heat loads (CDR):
- 1.4 W/m @ 1.9 K
- 70 W/m @ 40-60 K

QRL diameter: 1100 mm
He Inventory: ~820 ton

Cryogenic distribution line





→ Technical Point
→ Normal sector cryo-island
→ Insertion sector cryo-island

Conclusions and upcoming activities

- Progress on **preliminary cryomodule design** led to updates on heat loads and He inventory.

- **Service cavern location** at point L changed, making the point symmetric again.

- FCC-ee cryogenics study is on track in **collaboration with different stakeholders**
  - SCE team regularly updated with surface needs – current focus on land reservation.
  - EN/EL and EN/CV updated with cryogenic needs.
  - Integration: regular iterations to optimize FCC-ee layout to fit in a 5.5 m tunnel.

Impact on the cryogenic system sizing, layout and staging. Updated values were presented here.

- Cryo for detectors under study with user inputs to be transmitted to cryogenics for further development of the associated design. **Detectors are accounted for land reservation only. MDI is not accounted anywhere from cryo side.**

- **FCC-hh compatibility needs to be ensured in terms of land reservation and tunnel integration**. Work in progress:
  - In 1.9 K configuration, QRL diameter is less or equal than CDR baseline, with distribution system (vs FCC-ee tunnel) compatible
  - In 4.5 K & 20 K configurations, many unknown parameters (W/m @ 4.5 K, 20 K, 40-60 K ?, transients, ramping losses ?). Compatibility of distribution system (vs FCC-ee tunnel) needs to be investigated.

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THANK YOU FOR YOUR ATTENTION

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Spare slides

Heat load margins management bibliography

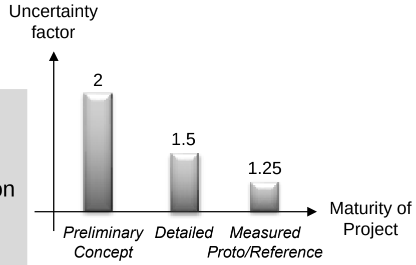
Name & Definition

Static heat load:
Raw static heat load from calculation or measurement without contingency.

Dynamic heat load:
Raw dynamic heat load from calculation or simulation without contingency.

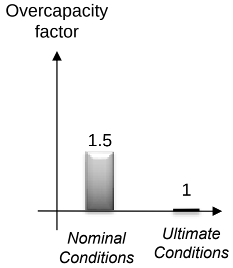
Design heat load:
Heat load including uncertainty and overcapacity margin

Installed local cooling capacity :
Capacity that is installed at the user interface



Uncertainty factor ($_{un}$)
Evolved during the project lifetime. On **static heat loads** only.
To cover:
- uncertainty in the design (material, installation…)
- Engineering change
- Tolerances
- Room for growth

Uncertainty factor evolves with maturity of design.

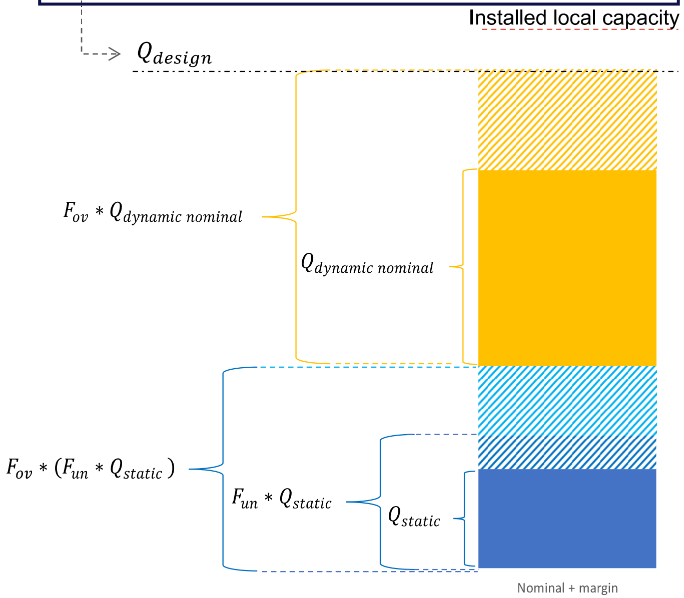


Overcapacity factor ($_{ov}$)
On static + dynamic.

To ensure nominal performance by covering the risk; for example, reduced performance, uncertainty due to modelling.

No margin taken on Ultimate Conditions.

$$Q_{design} = F_{ov} * (F_{un} * Q_{static} + Q_{dynamic\ nominal})$$



*graph not to scale

Heat load margins management bibliography

- 1998 LHC Project Note 140
- 2008 ICEC22 LHC Project Report 1171
- 2013 ICEC24 Energy efficiency of Large Cryogenic Systems
- **2021** HL-LHC Heat Load Review EDMS document 2560556 v.2 and Indico 1019569
- **2022**
  - Heat Load Definition for the HL-LHC project on EDMS 1610730
  - Capacity requirements for the HL-LHC Refrigerators on EDMS 2747548

Main drivers for FCC-hh compatibility

Courtesy P. Borges de Sousa

Option	Cryogen content	Power consumption	Able to handle transient loads?	ΔT along arc cell?	Size of QRL
FCC at 1.9 K (Nb_3Sn) Baseline	≈ 10^6 kg He	262 MW [2]	Yes (via c_p of He II)	Extremely low gradient with He II operation (≈ mK)	≈ Ø1.1 m (8 points)
FCC at 4.5 K (Nb_3Sn)	↓↓ Intrinsically lower, no liquid bath	↓↓ Carnot + no cold compressors	In principle yes (might need liquid reservoirs at end of sector)	↑ Will require moderate ΔT (≈ K)	↓↓↑ No VLP line required but could have large $\dot{m}$; lower ΔT means larger QRL (but still < Ø1.1 m)
FCC at 20 K (HTS)	↓↓ Only gas if He; two-phase flow confined in pipes if H_2	↓↑ Carnot + no cold compressors; could be still high if transients are also high	Unclear if using He (c_p of cold mass insufficient)	↑↑ Will require sizeable ΔT (≈ 5+ K)	↓↓↑ No VLP line required but could have large $\dot{m}$; lower ΔT means larger QRL (but still < Ø1.1 m)

As an output we'd like to have a 3D plot of QRL size as a function of heat loads to magnets (steady-state + transient) and allowed temperature gradient along an arc cell

CERN TE Department, FCC-ee workshop