This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

FCC CRYOGENIC SYSTEM

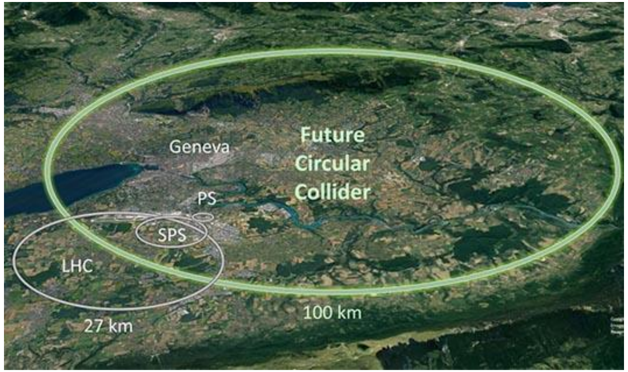
FCC-ee LAYOUT AND IMPLEMENTATION

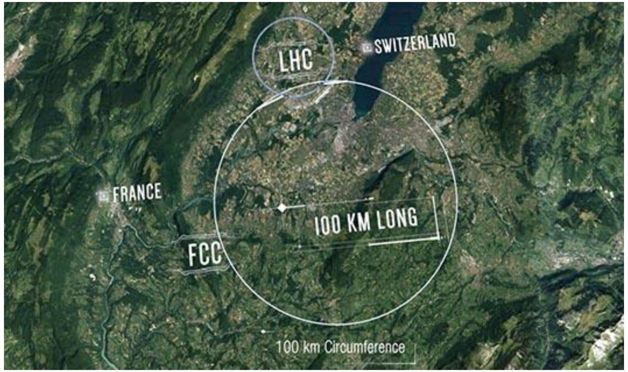
(INCL. COMPATIBILITY WITH FCC-hh)

Boyan Naydenov
on behalf of CERN TE/CRG
16th of May, 2024

Table of contents

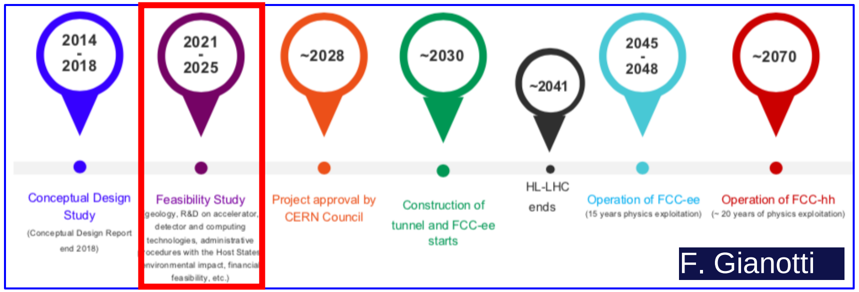
1. **Introduction & status**
2. **FCC-ee**
   - **Cryogenic cooling users**
   - **SRF heat loads**
   - **Cryoplants layout**
   - **Helium inventory**
   - **Electrical power needs**
   - **Operation modes**
   - **Cost estimate and challenges**
3. **FCC-hh compatibility**
4. **Conclusions**



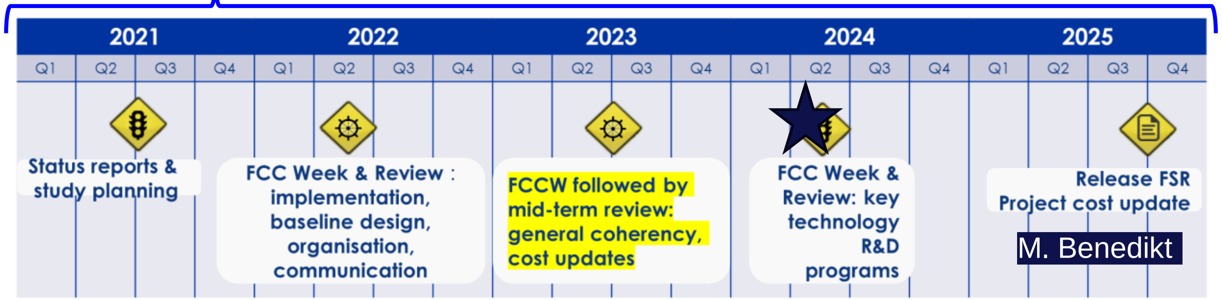


Status

- **FCC Full schedule**



- **FCC Feasibility status:**
  - **Started in ‘21.**
  - **Mid-term review completed in ‘24**
  - **Feasibility Report => May’25**

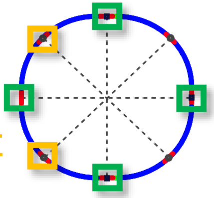


Focus:

- **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.**

Point L – RF Booster

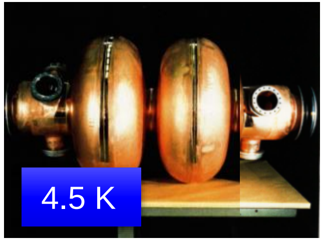
Point H – RF Collider



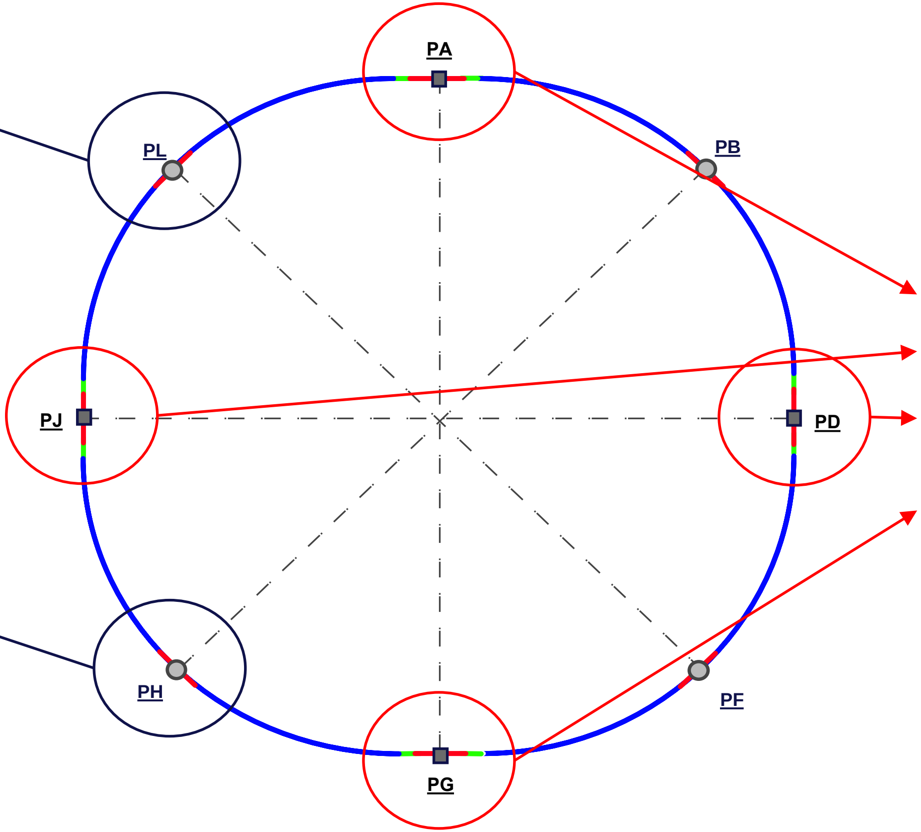
4 IPs

FCC-ee cryogenic cooling users

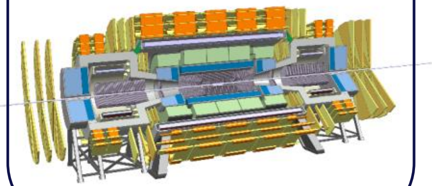
RF **booster** cavities



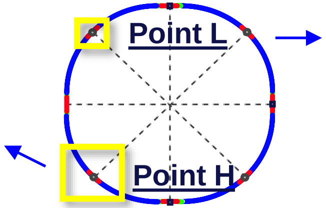
RF **collider** cavities



Detector solenoids and MDI magnets



FCC-ee SRF dynamic and static heat loads



Point H - Collider

String of 1950 m

Strong dynamic/static ratio

Run	Point H - Collider
4y Z	**x28** CM_{400MHz} – **8.7 kW** at 4.5 K
2y W	**x66** CM_{400MHz} – **64 kW** at 4.5 K
3y H	**x66** CM_{400MHz} – **64 kW** at 4.5 K
5y ttbar	**x66** CM_{400MHz} – **64 kW** at 4.5 K **x122** CM_{800MHz} – **22.7 kW** at 2 K

Similar total equivalent cooling power to LHC cryogenics.

Point L - Booster

String of 1300 m

Strong transient heat loads

Run	Point L - Booster
4y Z	**x6** CM_{800MHz} – **0.3 kW** at 2 K
2y W	**x14** CM_{800MHz} – **0.9 kW** at 2 K
3y H	**x27** CM_{800MHz} – **1.9 kW** at 2 K
5y ttbar	**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**
- **50 % margin on heat loads, today**

FCC-ee 3-stages cryoplants layout

RF Points cryogenics

Stage	Point H - Collider	Point L - Booster
Z	1 x 9 kW eq @ 4.5 K	1 x 1 kW eq @ 4.5 K (97% @ 2K)
W&H	2 x 35 kW eq @ 4.5 K	1 x 6 kW eq @ 4.5 K (97% @ 2K)
tt	2 x 67 kW eq @ 4.5 K (55% @ 2K)	2 x 15.5 kW eq @ 4.5 K (97% @ 2K)

Experiment points cryogenics

Detector solenoid :

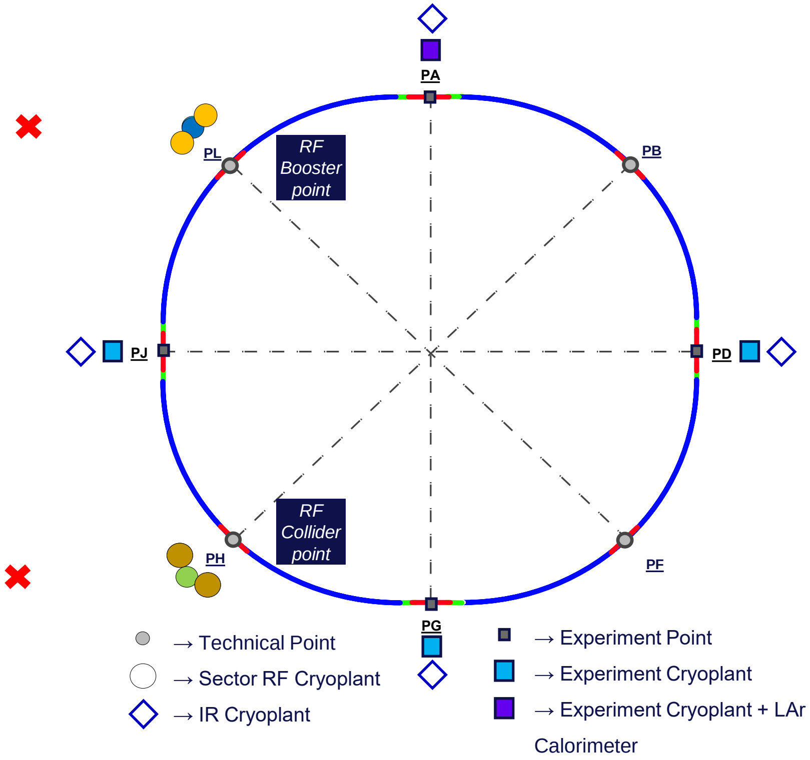
Number of experiments and their heat loads have not been defined yet.

- 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!

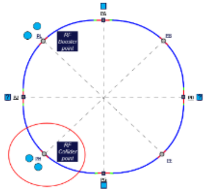


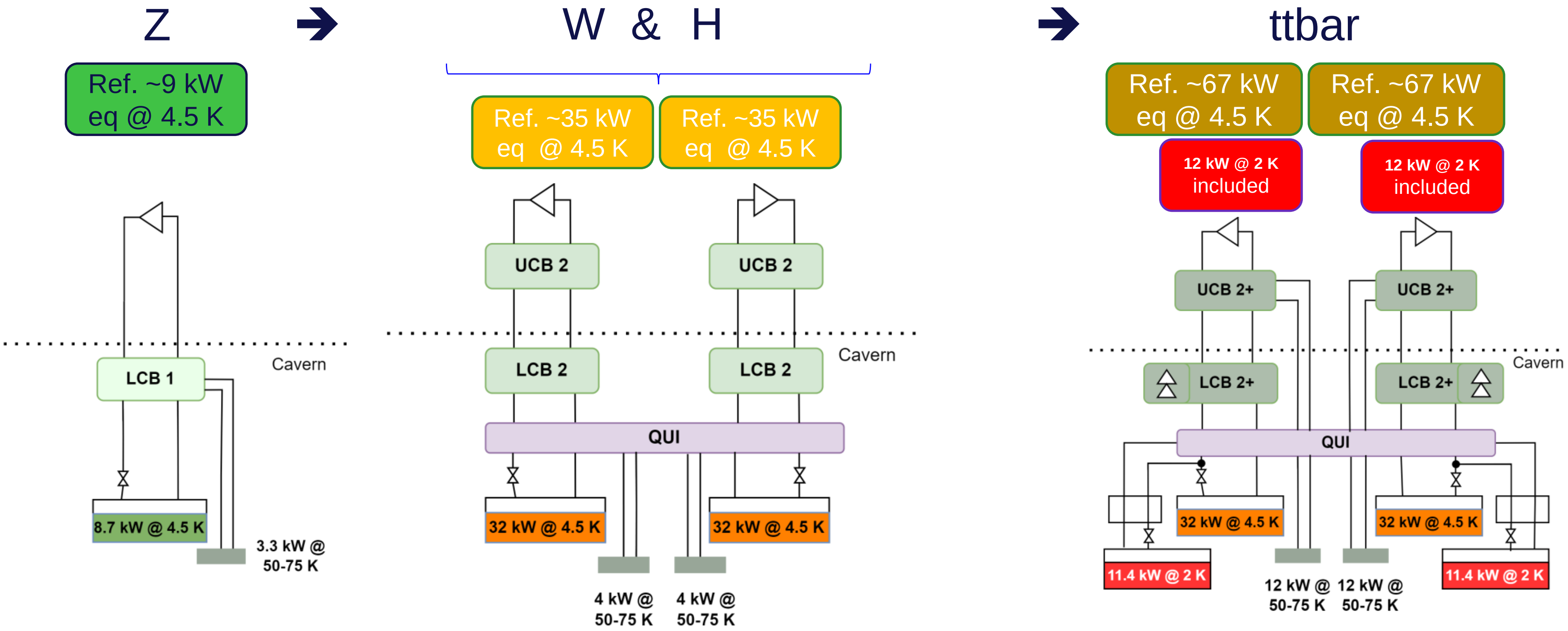
ttbar stage is the driver for surface needs, shaft and tunnel integration.

FCC-ee cryoplants at point H - staging

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

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

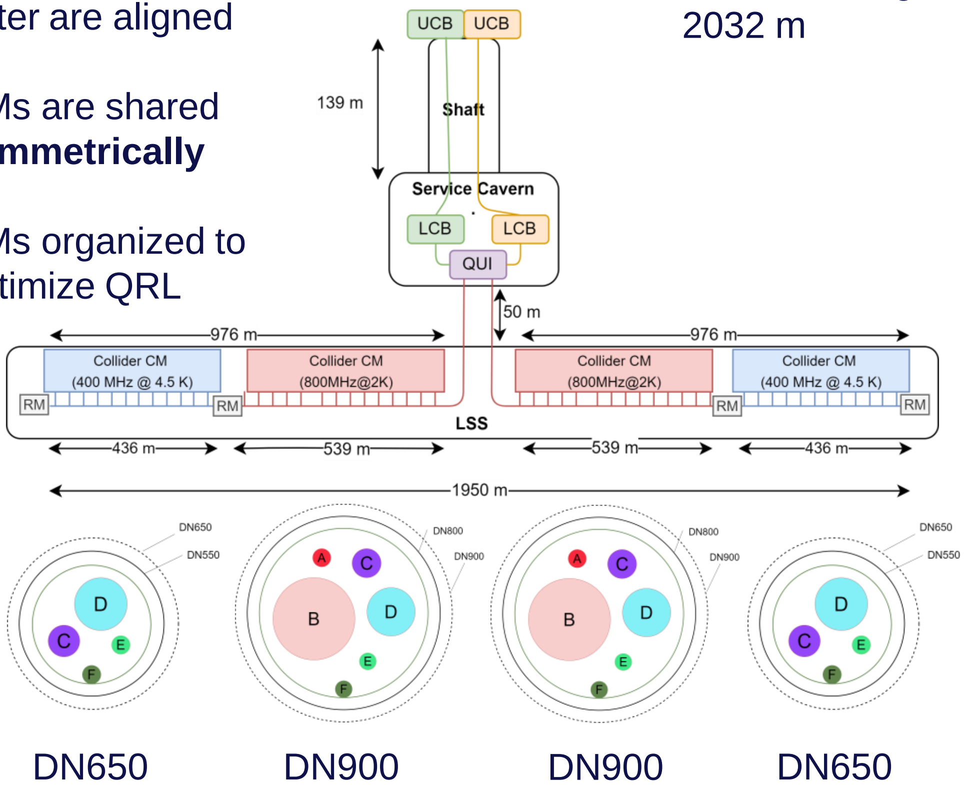




FCC-ee cryo layout at point H (ttbar)

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

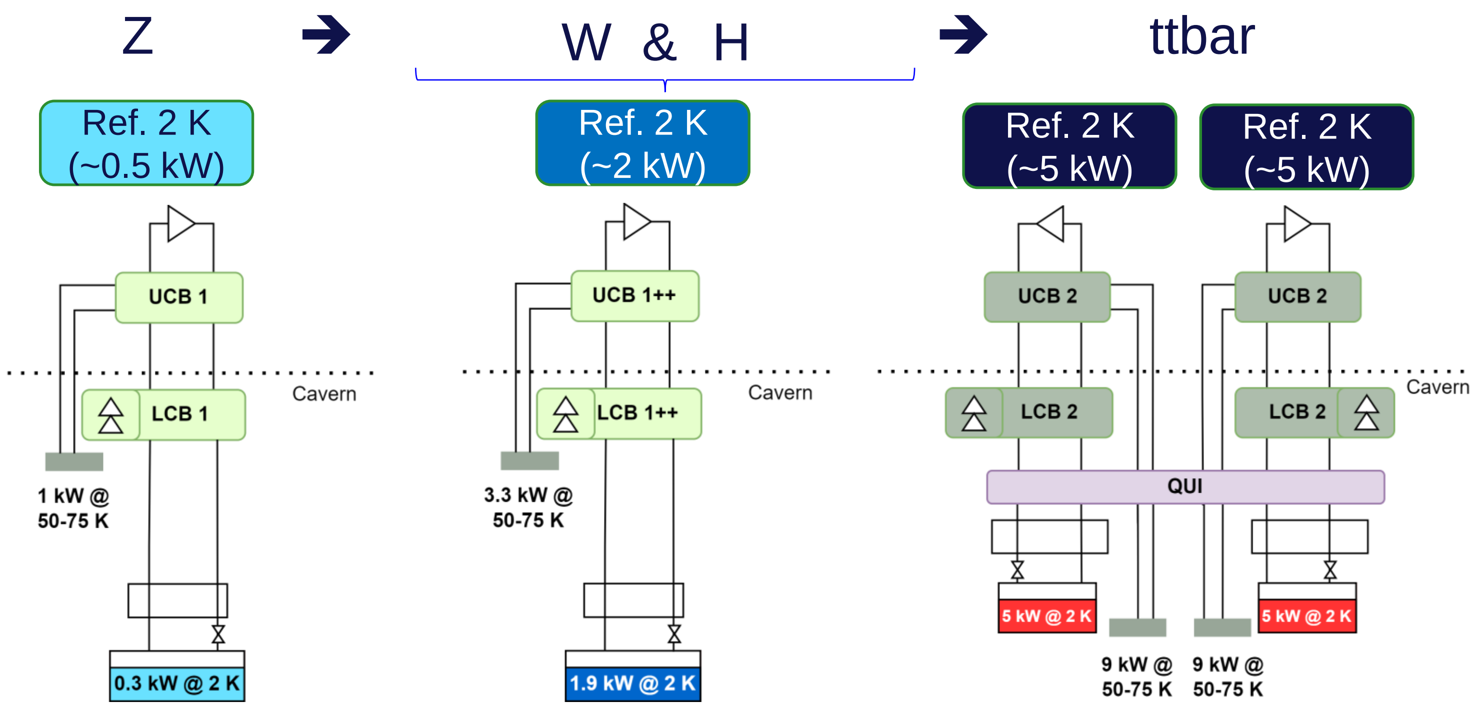
- LSS total length is of 2032 m



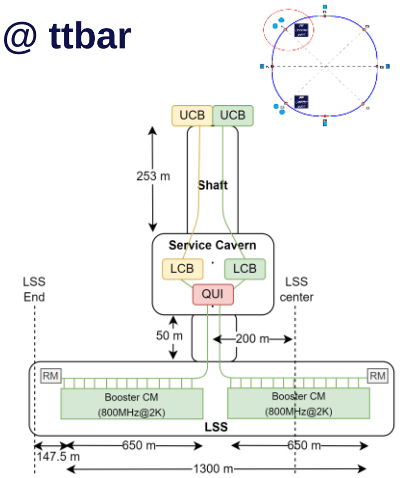
QRL Header & Process values	Diameter (mm)
A : 1.3 bar , 2.2 K (ΔP=25 mbar)	75
B : 30 mbar , 2 K (ΔP=2 mbar)	340
C: 3 bar, 4.6 K (ΔP=130 mbar)	120
D: 1.3 bar, 4.5 K (ΔP=70 mbar)	200
E: 20 bar, 50 K (ΔP=10 mbar)	80
F: 18 bar, 75 K (ΔP=15 mbar)	80
Vacuum jacket (400MHz)	550*
Vacuum jacket (800 MHz)	800*

** +100 mm for bellows and flanges*

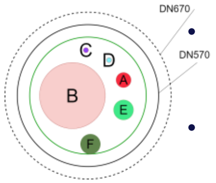
FCC-ee cryoplants at point L: staging



@ ttbar



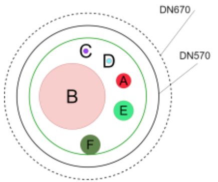
$$Q_{800MHz_{Installed}} = 3.0E+10$$



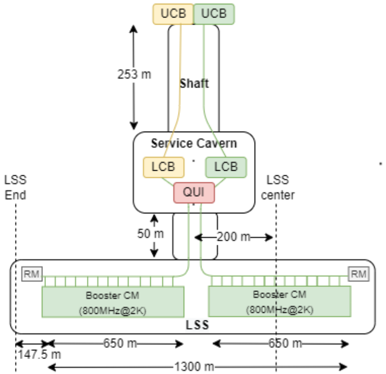
DN670

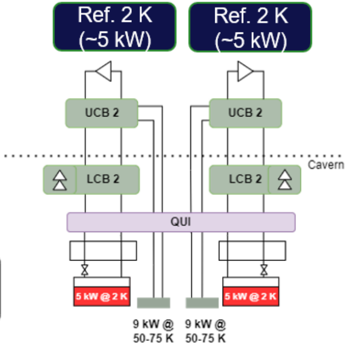
- Line A – 1.3 bar / 2.2 K: **60 mm**
- Line B – 30 mbar/ 2 K: **265 mm**
- Line E – 20 bar / 50 K: **80 mm**
- Line F – 18 bar / 75 K: **80 mm**

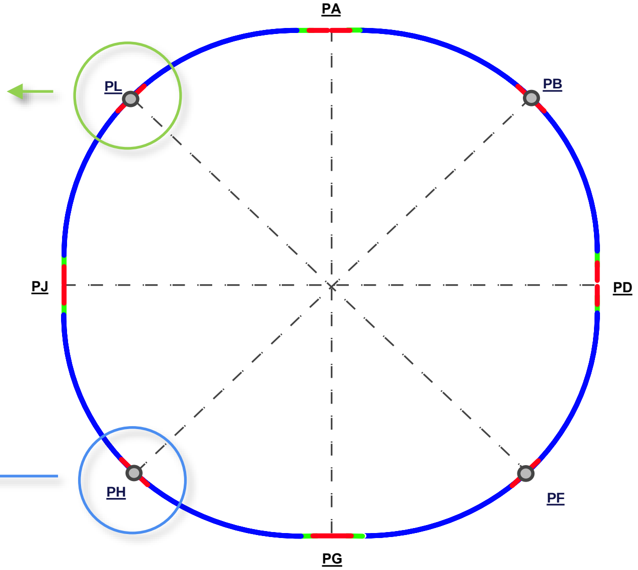
FCC-ee SRF cryogenic system layout summary @ ttbar



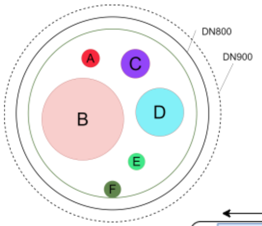
Point L DN670

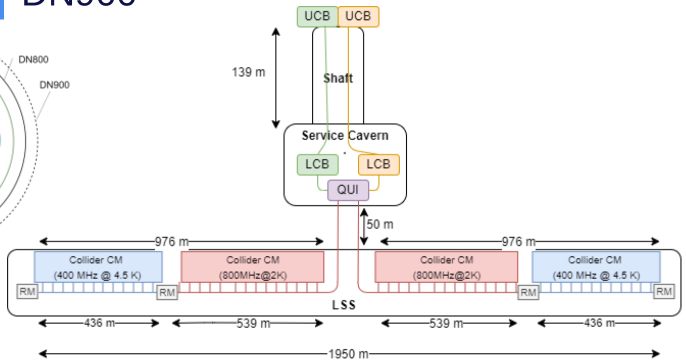


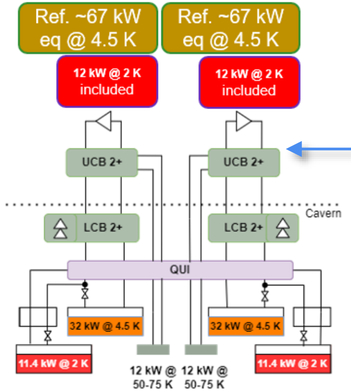




Point H DN900







FCC-ee SRF points H and L - Helium inventory

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

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	0.2 ton	0.2 ton	1.1 ton
Total	1.5 ton	2 ton	2.7 ton	10.4 ton

Point H	Z	W	H	ttbar
Cryomodules	3.2 ton	7.7 ton	7.7 ton	14.4 ton
Distribution (QRL)	2.4 ton	2.4 ton	2.4 ton	4.9 ton
Cryoplants	0.3 ton	2.4 ton	2.4 ton	4.7 ton
Total	5.9 ton	12.5 ton	12.5 ton	24 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

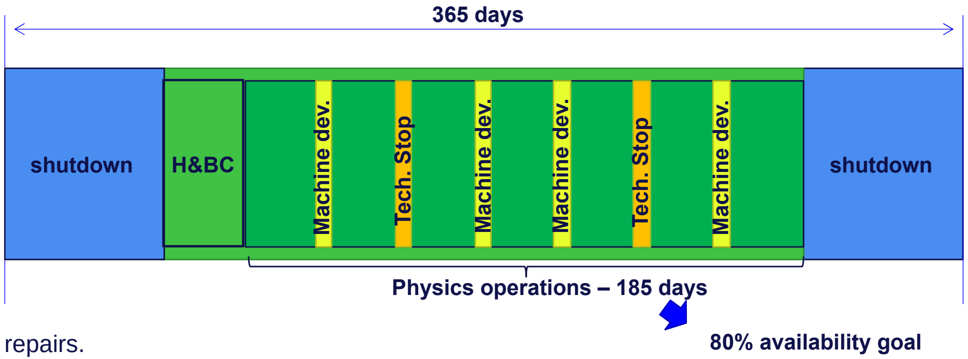
	PH [MW]	PL [MW]	Total (PH+PL) [MW]
Z	2.1 / 1.9 / 1.5	0.23 / 0.21 / 0.17	2.3 / 2.1 / 1.7
W	16.1 / 14.7 / 1.5	1.4 / 1.3 / 1.0	17.5 / 16 / 13
H	16.1 / 14.7 / 1.5	1.4 / 1.3 / 1.0	17.5 / 16 / 13
ttbar	30.8 / 28.1 / 22.8	7.1 / 6.5 / 5.3	38 / 35 / 28

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

FCC operation Modes – typical year

Source: CDS 2645151

- **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.



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

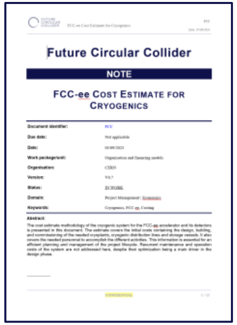
- **Availability target – 80 % of physics operation**
- **The modes will impact the design of the cryoplants and their energy consumption**

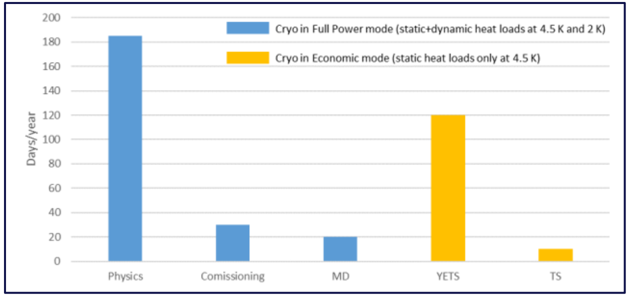
  (30% estimated savings with ECO mode)

FCC-ee cryogenic system cost estimate

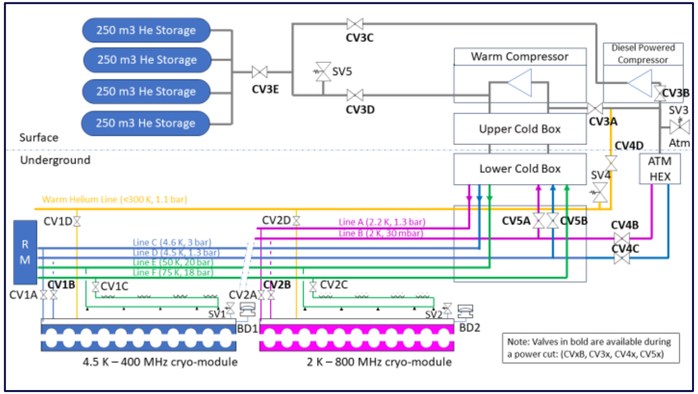
- **Class 4 Cost estimate has been delivered for the Mid-Term Review**
  - Includes SRF cryoplants and 4 detector CMS-like cryoplants.
  - MDI region needs are not accounted!
  - Needs to be updated to include last heat loads and inventory.
- **An FTE estimate has been added.**

EDMS document (confidential)



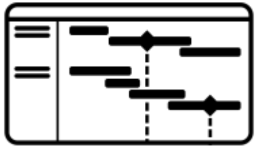


- **A CAPEX-OPEX optimisation is currently addressed:**
  - Cryoplant ECO mode to be included from design stage
    - Current assumption is that all cavities are kept at 4.5 K, without dynamic loads, during the TS and YETS.
  - A Helium Recovery system is proposed for the RF points
    - Addresses a power outage scenario as well as an isolated CM situation.

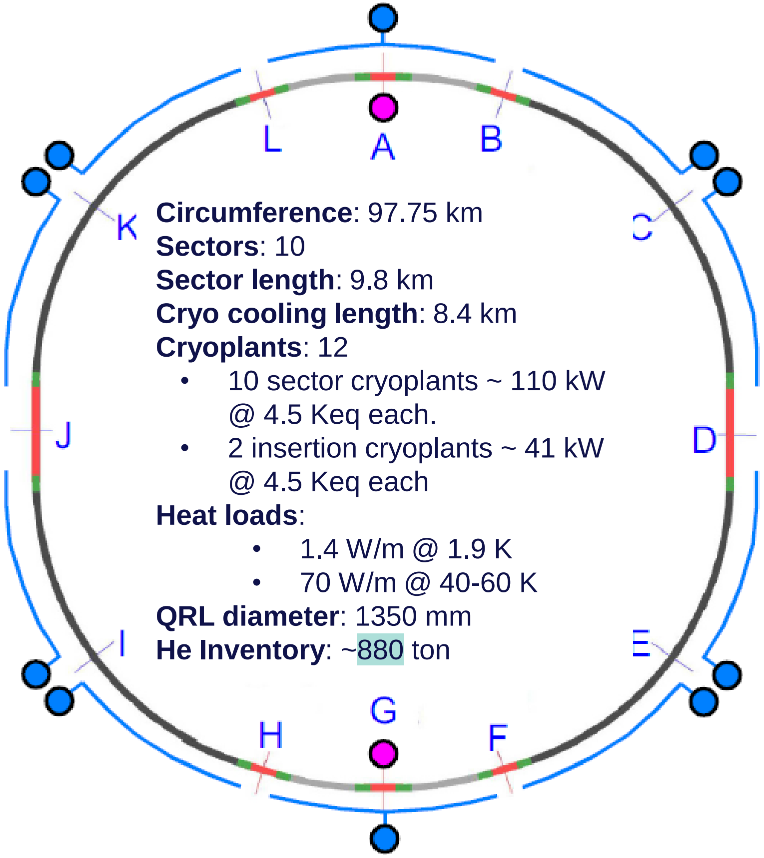


FCC-ee SRF cryogenics challenges

- Cryoplants size. Very large cryoplants needed to optimise for availability. Factor 3 wrt to state-of-the-art units (ITER). Big industrial challenge.
- Heat loads density. Similar cryogenic cooling power to LHC, concentrated at point H.
- Dynamic / static heat loads ratio. Colliders SRF system requires 4 times more dynamic heat loads than static (with current assumptions). LHC dynamic to static ratio is closer to 0.5.
- Transient heat loads management. Booster is operated in a pulsed manner and has different modes: filling from scratch and top up. Impacts cryoplant operation and cryomodules pressure stability.
- Fast cooldown requirements of the cavities between certain temperatures imposes operational constraints and affects the distribution line sizing.
- 2 K system - 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).
- Helium dependency needs to be reduced for future projects. Being addressed with a cryomodule and distribution line optimization, together with a Helium recovery system.
- Sustainability. An optimised cryoplant ECO mode design and operation is required in order to reduce energy consumption. Centrifugal compressors R&D could have a very positive effect too.
- Installation. 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

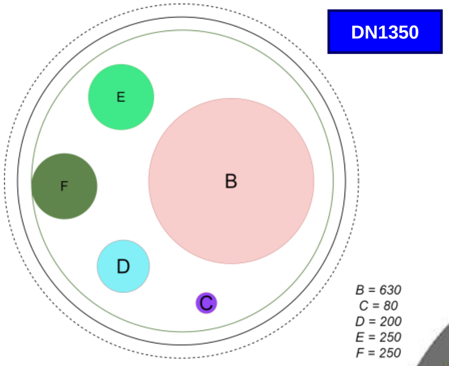
- 10 sector cryoplants ~ 110 kW @ 4.5 Keq each.
- 2 insertion cryoplants ~ 41 kW @ 4.5 Keq each

Heat loads:

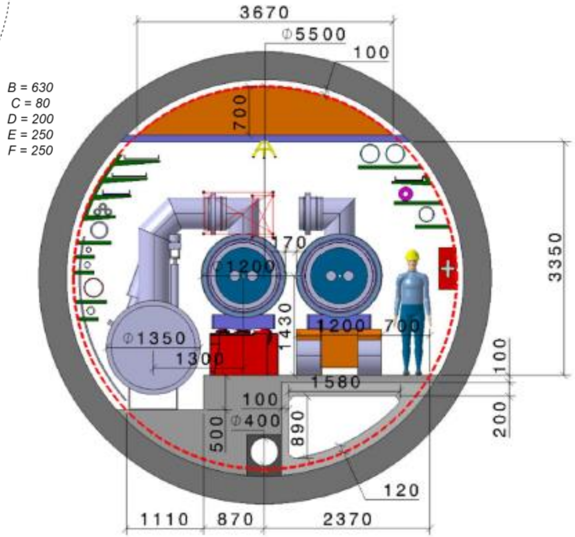
- 1.4 W/m @ 1.9 K
- 70 W/m @ 40-60 K

QRL diameter: 1350 mm
He Inventory: ~880 ton

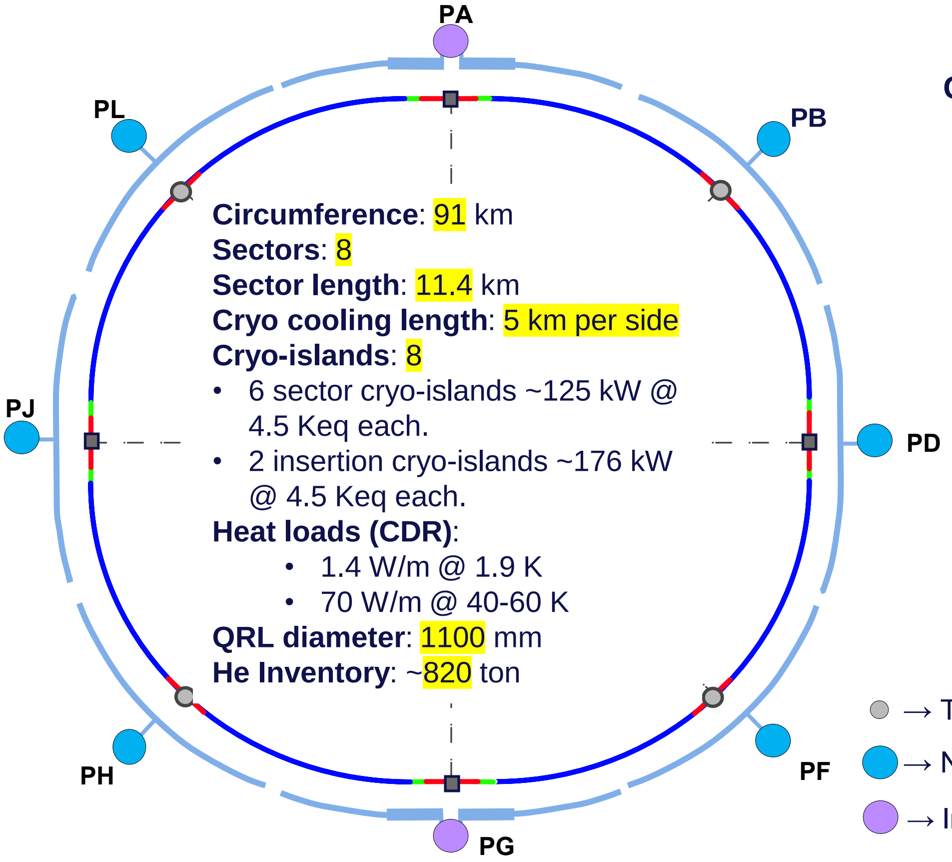
Cryogenic distribution line



FCC-hh CDR



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

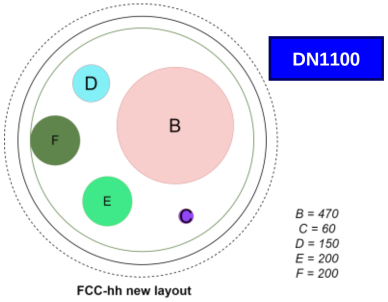


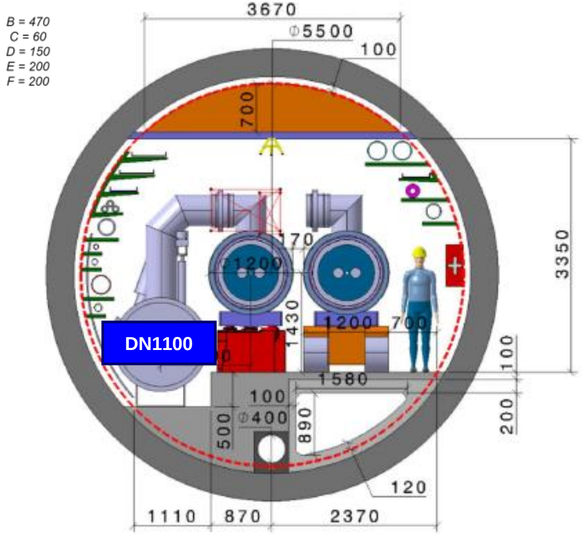
Circumference: 91 km
Sectors: 8
Sector length: 11.4 km
Cryo cooling length: 5 km per side
Cryo-islands: 8
- 6 sector cryo-islands ~125 kW @ 4.5 Keq each.
- 2 insertion cryo-islands ~176 kW @ 4.5 Keq each.

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

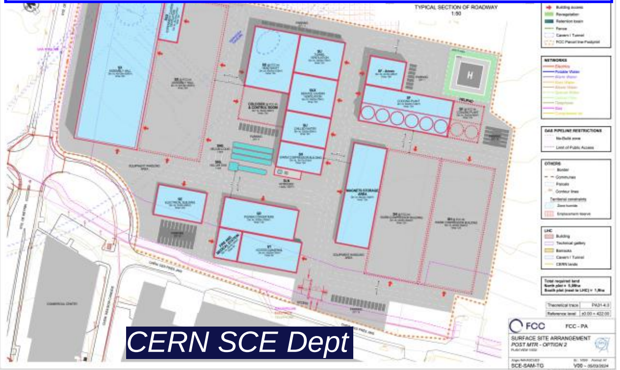
Surface requirements for FCC cryogenics

- **Aboveground surface needs per point:**

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

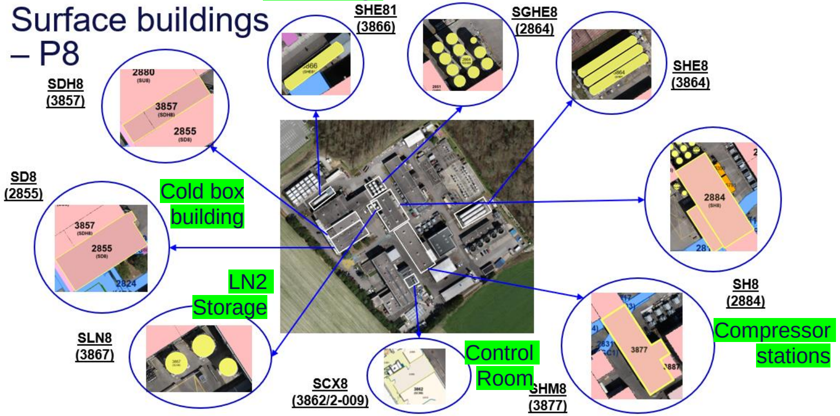
70 m2 control room is included in all points!	Point A & G		Point B & F		Point D & J		Point H		Point L	
	ee (ttbar)	hh	ee (ttbar)	hh	ee (ttbar)	hh	ee (ttbar)	hh	ee (ttbar)	hh
Surface in m2										
Compressor station building	430	5870	x	3200	430	4270	4300	3200	2140	3200
Cold box building	x	600	x	400	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

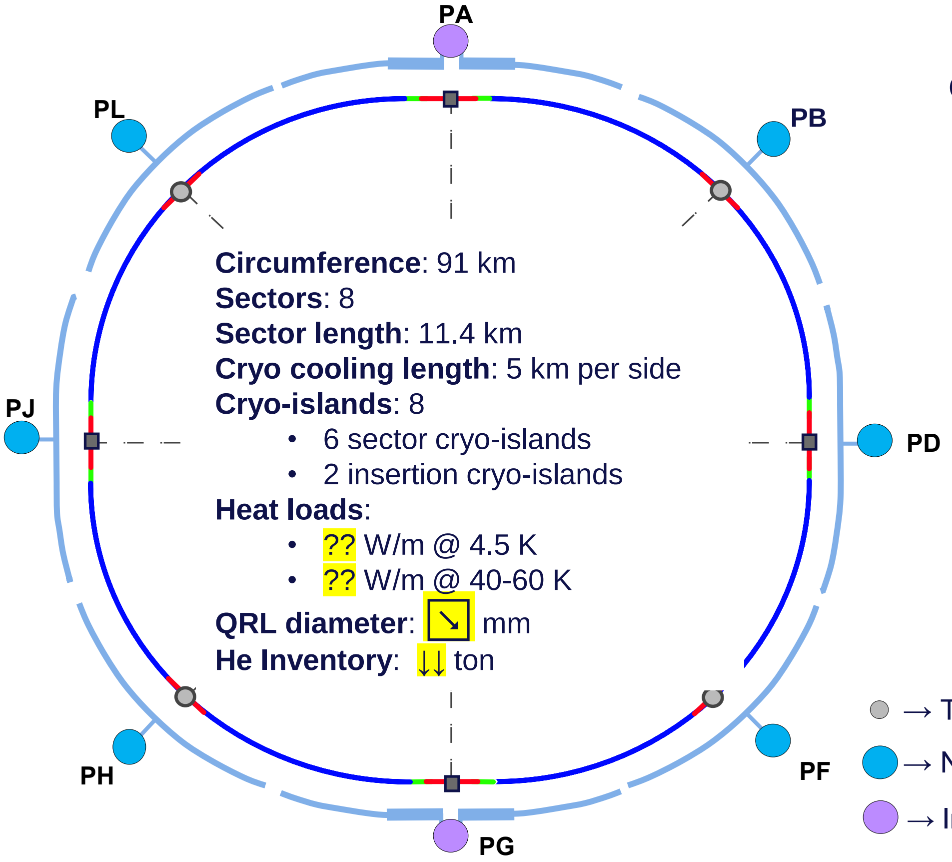


LHC P8 total cryo area of about <u>4600 m2</u>
(as a comparison)

CV and EL surface needs also depend on cryo needs.



FCC-hh cryogenic system updated layout – Nb3Sn @ 4.5 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
- 2 insertion cryo-islands

Heat loads:

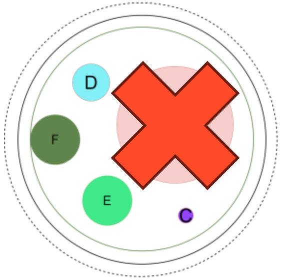
- ?? W/m @ 4.5 K
- ?? W/m @ 40-60 K

QRL diameter: ↘ mm
He Inventory: ↓↓ ton

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

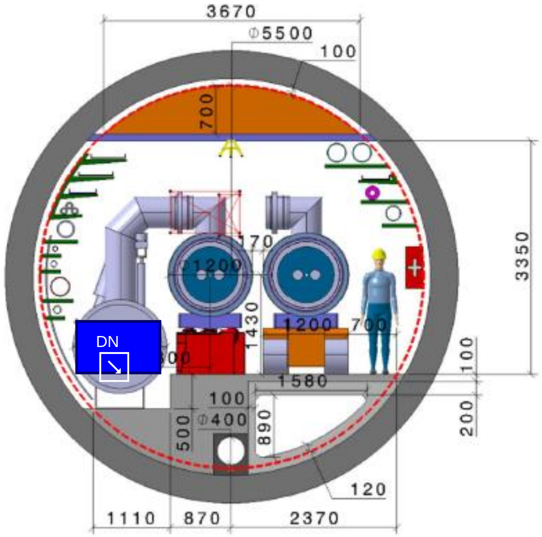
See P. Borges de Sousa talk

Cryogenic distribution line

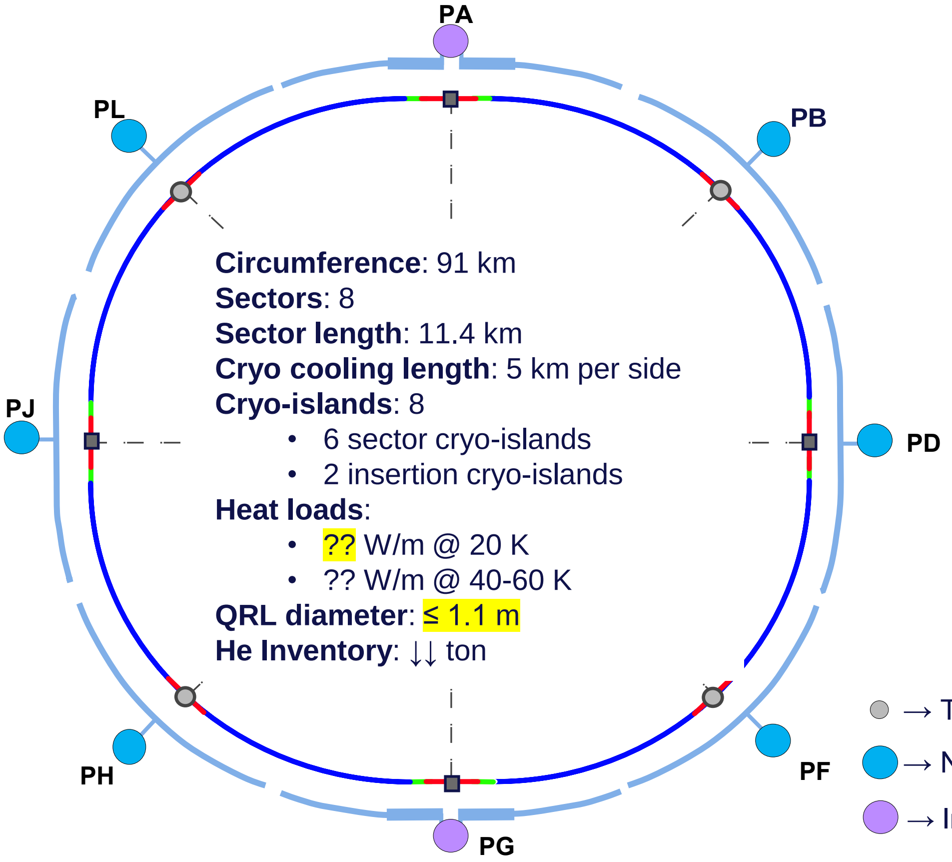


FCC-hh new layout

Line B disappears.
Line D size expected to increase.



FCC-hh cryogenic system updated layout – HTS @ 20 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
- 2 insertion cryo-islands

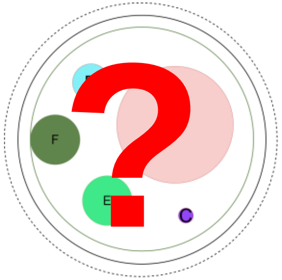
Heat loads:

- ?? W/m @ 20 K
- ?? W/m @ 40-60 K

QRL diameter: ≤ 1.1 m
He Inventory: ↓↓ ton

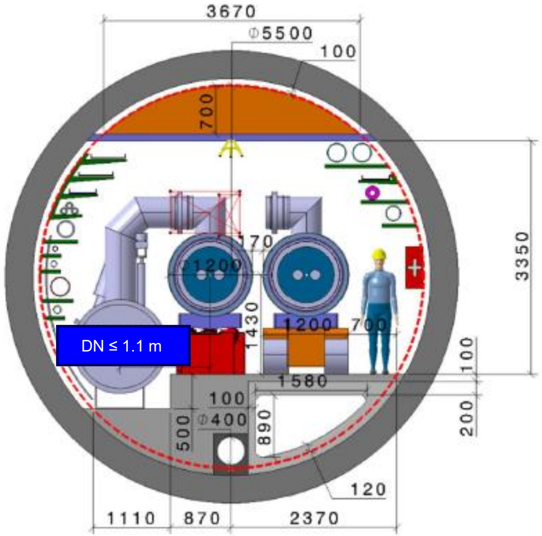
See P. Borges de Sousa talk

Cryogenic distribution line



FCC-hh new layout

Many unknowns at this stage.



- → 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.

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

- 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.

- 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.**

- Mid-Term Review **Cost and FTE estimation** has been delivered (Class 4) – EDMS document (confidential)
  - CAPEX-OPEX topics currently being addressed: ECO mode and He recovery system.

- **FCC-hh compatibility needs to be ensured in terms of land reservation and tunnel integration**. Work in progress. In all configurations (1.9 K, 4.5 K and 20 K), QRL diameter is equal or less than baseline. However, transients (ramping losses) for 20 K to be confirmed.

FCC

THANK YOU FOR YOUR ATTENTION