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FCC-HH CRYOGENICS

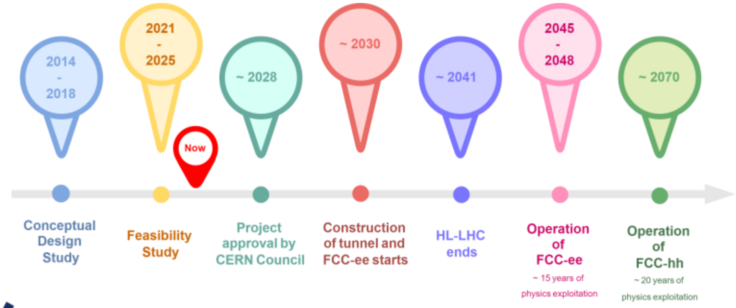
Layout update for 1.9 K and 4.5 K options

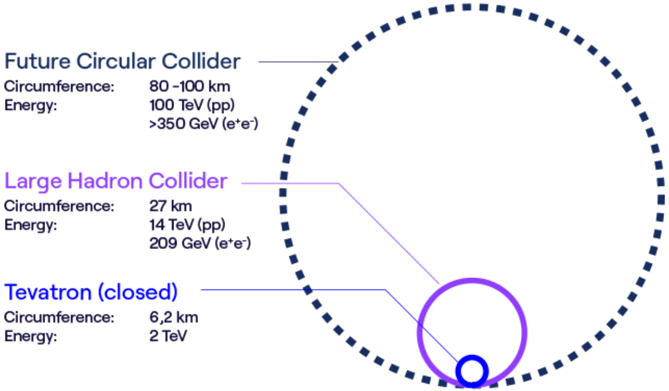
L. Delprat, *A. Petrovic, B. Bradu, P. Borges de Sousa, X. Gallud*

On behalf of the CERN Cryogenics Group

FCC Week 2025 – Vienna – May 19th to 23rd, 2025

1. Introduction & status





2. FCC-hh at 1.9 K

- Layout
- Heat loads distribution
- Summary

3. FCC-hh at 4.5 K

- Why?
- Layout
- Heat loads distribution
- Summary

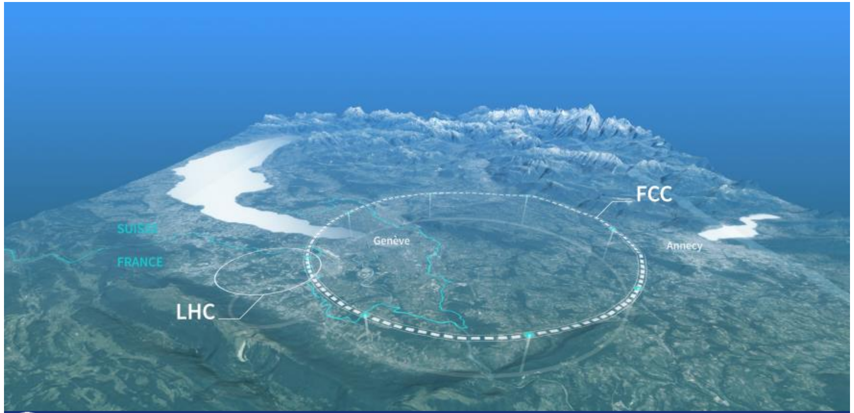
4. Helium inventory and electrical power consumption

- About an economic mode

5. Conclusions

- And perspectives for the pre-TDR phase

The Future Circular Collider



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

From FCC Week 2024

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

F. Gianotti

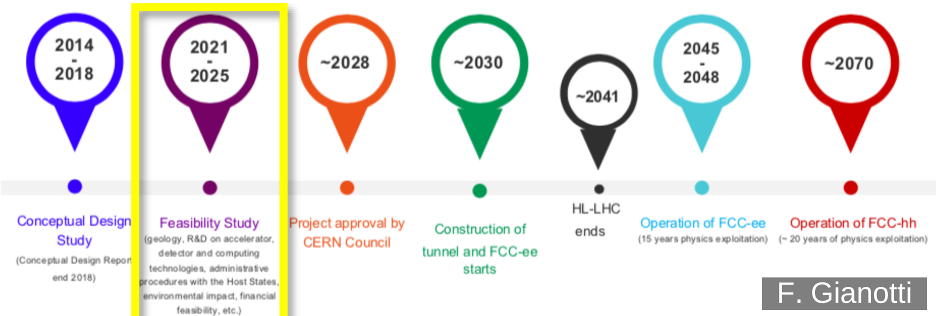
Where we are today

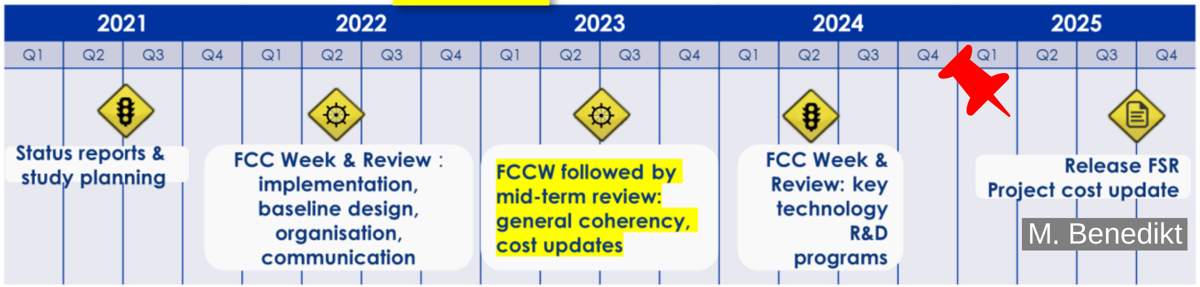
Main objectives:
- Launch the civil engineering procurement right after the approval in 2028
- Complete all the studies deemed necessary to do so
- For cryogenics: refine the design foreseen in the Feasibility Study with industrial partners (2nd round)

Mandate: WP4.6 Cryo pre-TDR description, EDMS 3254016

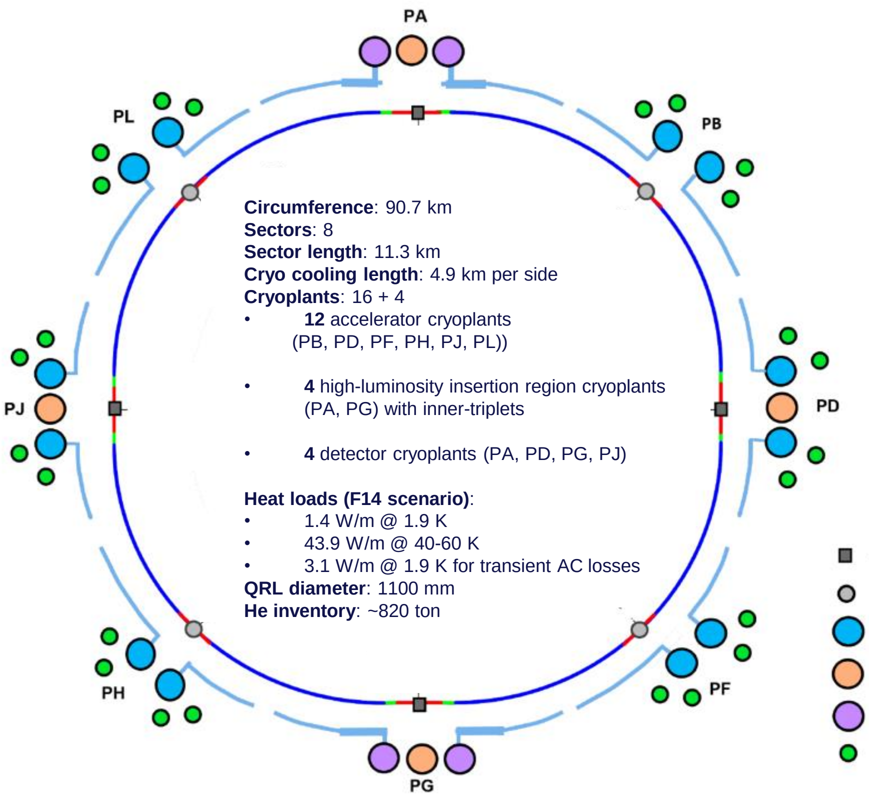
Timeline:

- ☑ **2025:** FCC Feasibility Study completion and beginning of Pre-TDR phase
- **2027:** ESPP update
- **2028:** approbation by the CERN council





FCC-hh @ 1.9 K – Nb_3Sn @ 14T (“F14 scenario”)



Circumference: 90.7 km
Sectors: 8
Sector length: 11.3 km
Cryo cooling length: 4.9 km per side
Cryoplants: 16 + 4

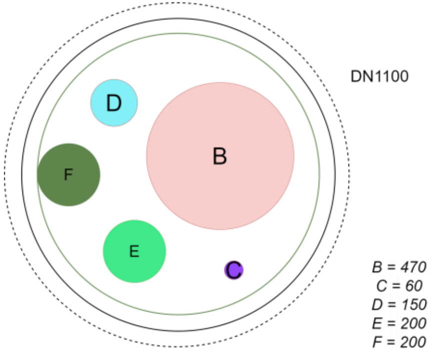
- **12** accelerator cryoplants (PB, PD, PF, PH, PJ, PL))
- **4** high-luminosity insertion region cryoplants (PA, PG) with inner-triplets
- **4** detector cryoplants (PA, PD, PG, PJ)

Heat loads (F14 scenario):

- 1.4 W/m @ 1.9 K
- 43.9 W/m @ 40-60 K
- 3.1 W/m @ 1.9 K for transient AC losses

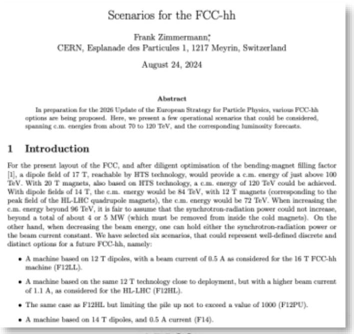
QRL diameter: 1100 mm
He inventory: ~820 ton

Cryogenic distribution line



FCC-hh new layout

“F14 scenario”



Scenarios for the FCC-hh

Frank Zimmermann*
CERN, Esplanade des Particules 1, 1217 Meyrin, Switzerland

August 24, 2024

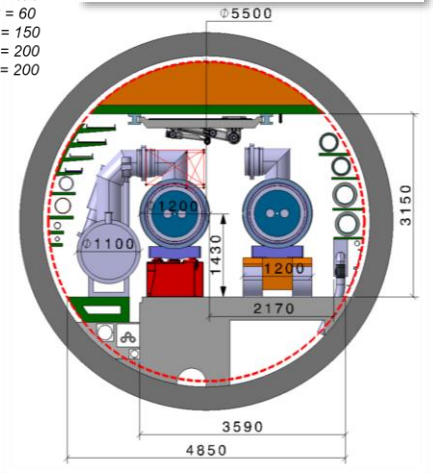
Abstract

In preparation for the 2026 Update of the European Strategy for Particle Physics, various FCC-hh options are being proposed. Here, we present a few operational scenarios that could be considered, spanning c.m. energies from about 70 to 120 TeV, and the corresponding luminosity forecasts.

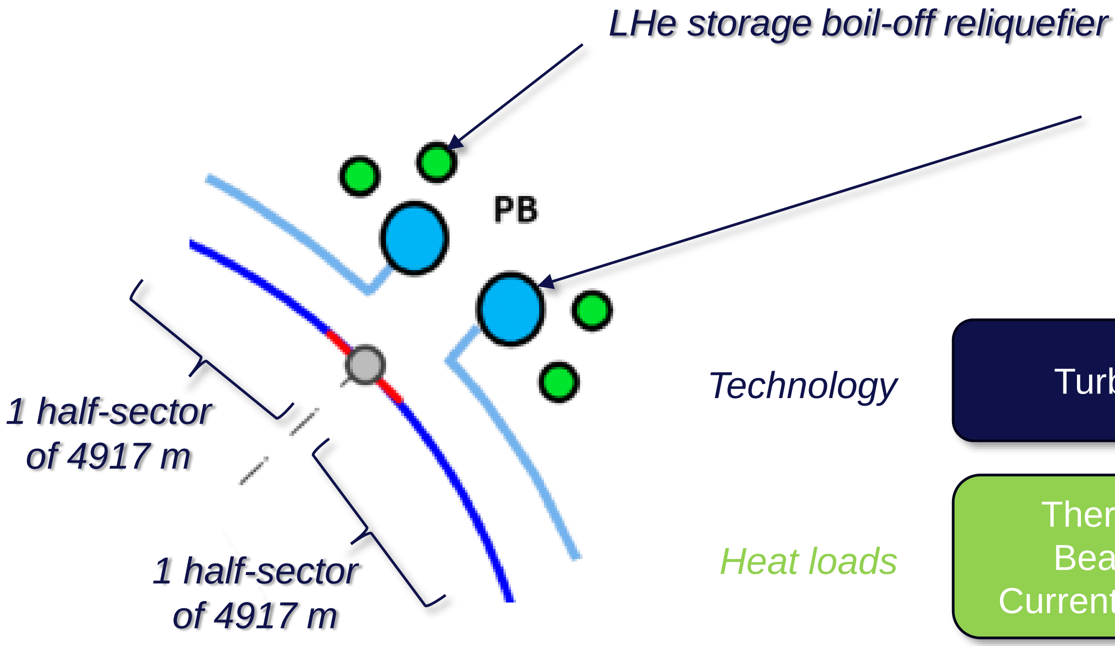
1 Introduction

For the present layout of the FCC, and after diligent optimisation of the bending-magnet filling factor [1], a dipole field of 17 T, reachable by HTS technology, would provide a c.m. energy of just above 100 TeV. With 20 T magnets, also based on HTS technology, a c.m. energy of 120 TeV could be achieved. With dipole fields of 14 T, the c.m. energy would be 84 TeV, with 12 T magnets (corresponding to the peak field of the HL-LHC quadrupole magnets), the c.m. energy would be 72 TeV. When increasing the c.m. energy beyond 96 TeV, it is fair to assume that the synchrotron-radiation power could not increase, beyond a total of about 4 or 5 MW (which must be removed from inside the cold magnets). On the other hand, when decreasing the beam energy, one can hold either the synchrotron-radiation power or the beam current constant. We have selected six scenarios, that could represent well-defined discrete and distinct options for a future FCC-hh, namely:

- A machine based on 12 T dipoles, with a beam current of 0.5 A as considered for the 16 T FCC-hh machine (F12LL).
- A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
- The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
- A machine based on 14 T dipoles, and 0.5 A current (F14).



Typical technical point cryoplants layout (preliminary)



Cryogenic plant for 1 half-sector

Technology	Turbo-Brayton	Helium refrigerator
Heat loads	Thermal shields Beam screens Current leads cooling	Magnets RF cavities
Temperatures	[40 – 60] K g/s @ [40 – 290] K	1.9 K 4 K VLP 4.5 K isothermal

Summary of 1.9 K option – whole FCC

Item	Machine	High luminosity Insertions	Unit	Comments
Turbo-brayton cooling capacity	3454	182.8	kW @ [40-60] K	incl. current leads cooling
Turbo-brayton electrical power consumption	46	2.8	MW_elec	/
Main helium refrigerator cooling capacity	609 *(⇔ 16 * 38.1 kW @ 4.5 Keq)*	95.8 *(⇔ 4 * 24 kW @ 4.5 Keq)*	kW @ 4.5 Keq	/
Main helium refrigerator electrical power consumption	136	21.2	MW_elec	/
Total electrical power consumption	182	24	MW_elec	/
Grand total	206		MW_elec	

**without considering the detectors, generally representing approx. 10% of the accelerator figures

Looking into a 4.5 K option for FCC-hh

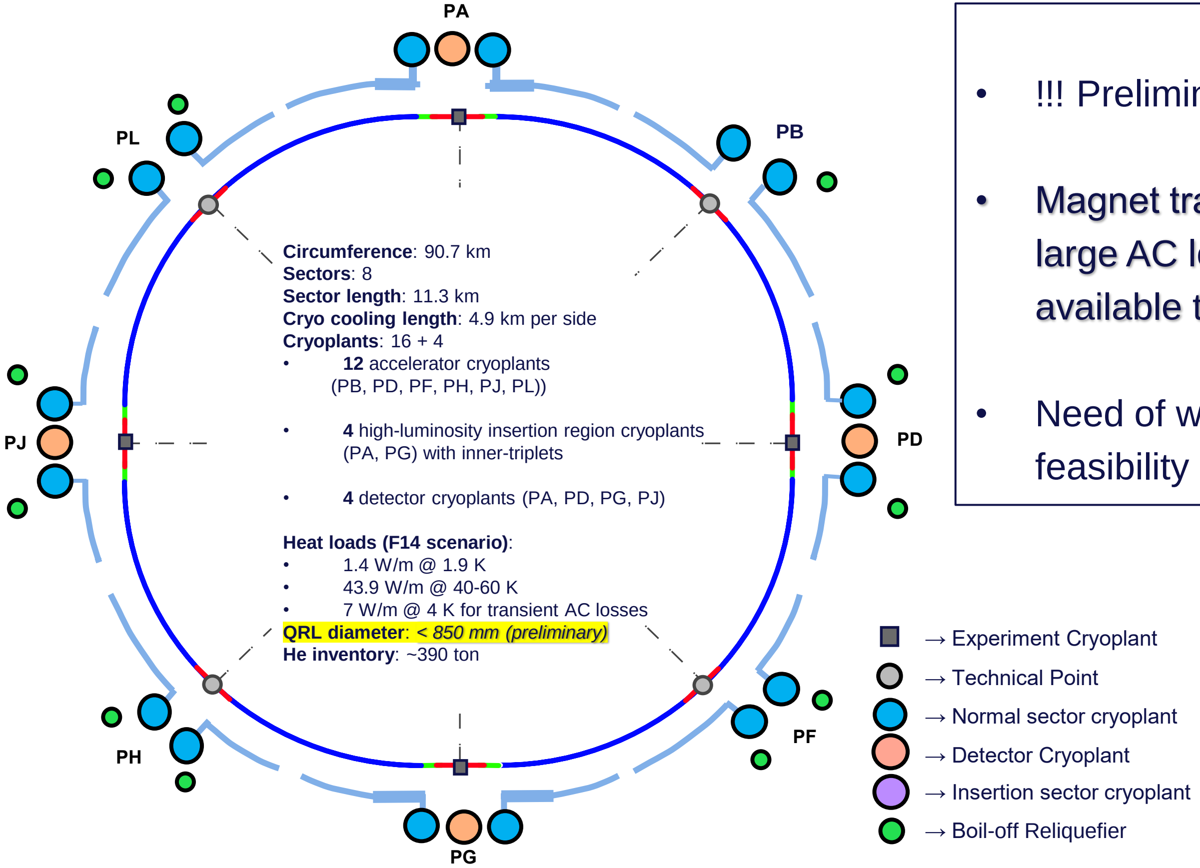
Main drivers for studying the 4.5 K option

- Reduce the capital cost
  - With less cryogenic cooling power installed
- Reduce the operation cost
  - With a reduced electrical power consumption
- Reduce the required cryogens inventory

#######

- Challenging magnets loads transients' management (AC losses)
  - installed capacity of 2.8 W/m (⇔ extra 7 kW per half-sector)
  - … was 2.0 W/m (⇔ extra 3 kW per half-sector) in the feasibility for 1.9 K option

FCC-hh @ 4.5 K – Nb_3Sn @ 14T ("F14 scenario")



Circumference: 90.7 km
Sectors: 8
Sector length: 11.3 km
Cryo cooling length: 4.9 km per side
Cryoplants: 16 + 4

- **12** accelerator cryoplants (PB, PD, PF, PH, PJ, PL))
- **4** high-luminosity insertion region cryoplants (PA, PG) with inner-triplets
- **4** detector cryoplants (PA, PD, PG, PJ)

Heat loads (F14 scenario):

- 1.4 W/m @ 1.9 K
- 43.9 W/m @ 40-60 K
- 7 W/m @ 4 K for transient AC losses

QRL diameter: *< 850 mm (preliminary)*
He inventory: ~390 ton

DISCLAIMER

- !!! Preliminary conceptual design only !!!
- Magnet transients' management challenging: very large AC losses without large He II inventory available to buffer the energy as in the 1.9 K option
- Need of work ahead to produce a technical feasibility report

QRL

$\varnothing_{QRL\ 4.5\ K}$ < 1.9 K option (1100mm)

$\varnothing_{QRL\ 4.5\ K\ expected}$ < 850 mm

- Highly dependent on
  - Magnets cooling scheme
  - Sector length

Summary of 4.5 K option – whole FCC

Item	Machine	High luminosity Insertions	Unit	Comments
Turbo-brayton cooling capacity	3454	182.8	kW @ [40-60] K	incl. current leads cooling
Turbo-brayton electrical power consumption	46	3	MW_elec	/
Main helium refrigerator cooling capacity	299 *(⇔ 16 * 18.7 kW @ 4.5 Keq)*	30.6 *(⇔ 2 * 15.3 kW @ 4.5 Keq)*	kW @ 4.5 Keq	/
Main helium refrigerator electrical power consumption	82	8	MW_elec	/
Total electrical power consumption	128	11	MW_elec	/
Grand total	139		MW_elec	

**without considering the detectors, generally representing approx. 10% of the accelerator figures

FCC-hh 1.9 K and 4.5 K comparison

FCC-hh Parameters	F14 scenario at 1.9 K [2024]	F14 scenario at 4.5 K [2024]
Circumference [km]	90.7	90.7
Dipole field [T]	14	14
Centre of mass energy [TeV]	85	85
Sync. Rad. for 2 beams [MW]	2.4	2.4
Magnet temperature [K] Beam screen temperatures[K]	1.9 [40 – 60]	4.5 [40 – 60]
Helium Cryogenic Capacity @ 4.5 K equivalent [kW]	1040	698
Number of cryo islands [-]	8	8
Number of cryoplants in total [-]	16	16
ARC cooling length [km]	16 x 4.9 = 78.4 km	16 x 4.9 = 78.4 km
Electrical consumption [MW]	206	139
Helium inventory [tons]	820	390

**without considering the detectors, generally representing approx. 10% of the accelerator figures

Helium inventory

- FCC-hh at 1.9 K: 820 tonnes of helium
  - Scaled from the estimate of the Conceptual Design Report (CDR) published in 2019
  - Electrical power consumption in nominal: 206 MW_elec

- FCC-hh at 4.5 K: 390 tonnes of helium
  - Distribution: 214 t
  - Magnets : 130 t
  - Cryoplants: 16 t
  - Gas storage: 30 t
  - Electrical power consumption in nominal: 139 MW_elec

Electrical power consumption and economic mode

- A provisional economic mode was studied (operation scenario not defined yet)

- Assumptions:
  - No dynamic heat load (only static)
  - The ability to handle magnet transients

- Results:
  - FCC-hh at 1.9 K:
    - Nominal: 206 MW_elec
    - Eco mode: 103 MW_elec

    -50%

  - FCC-hh at 4.5 K:
    - Nominal: 139 MW_elec
    - Eco mode: 66 MW_elec

    -53%

DISCLAIMER

- Like LHC, 3 modes could be considered
  - Physics (cryo consumption ⇔ beam energy and intensity)
  - Eco: see on the left
  - Cold standby: neither beam nor magnets powering allowed, machine kept at 20 K in standby (shutdowns)

Conclusion

- All required documentation was delivered on time for the Feasibility Study
  - For -hh at 1.9 K and at 4.5 K configurations
  - With FCC-hh at 1.9 K still being the baseline
- Pre-TDR study is launched
- Potential R&D lines are identified that are of interest for the cryogenic design of FCC-hh
  - With the industry for centrifugal compression and turbo-brayton cycles towards energy savings up to 20%
  - With a new cooling scheme adapted to the FCC-hh at 4.5 K configuration (conduction cooled)
- Full steam ahead towards pre-TDR report completion in 2027!

See P. Borges de Sousa's talk on Thursday 11h30 on FCC-hh accelerator: Optics baseline session

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THANK YOU FOR YOUR ATTENTION

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