Cryogenics overview

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On behalf of the FCC cryogenics study collaboration

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• Introduction: FCC cryogenic study organization

• FCC-hh cryogenics overview

• FCC-ee cryogenics overview

• Conclusion
FCC cryogenics studies

**FCC Cryogenics Studies**

- **Cryoplants**
  - (~50-100 kW @ 4.5 K including 10 kW @ 1.8 K)
  - Ne-He cycle for refrigeration above 40 K
    - TU-Dresden
  - MoU and addendum signed
    - New addendum under discussion

- **Cooling scheme and cryo-distribution**
  - PhD student
    - C. Kotnig
  - Innovative He cycle
    - CEA Grenoble
  - MoU signed
    - Addendum 1 signed
    - Addendum 2 signed*
  - In steady-state

- **Specific studies (CD, WU, Transients...)**
  - Fellow
    - H. Correia Rodrigues
  - Design pressure impact on heat inleaks
    - Wroclaw-TU
  - In steady-state

- **MoU signed**
  - Addendum signed*

*: New w/r to Washington
**FCC-hh (100 km) cryogenic layout**

### Baseline

- 10 cryoplants
- 6 technical sites

### Alternative

- 20 cryoplants
- 10 technical sites

<table>
<thead>
<tr>
<th>Cryoplate</th>
<th>40-60 K [kW]</th>
<th>1.9 K [kW]</th>
<th>40-300 K [g/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>592</td>
<td>11</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>616</td>
<td>12</td>
<td>85</td>
</tr>
</tbody>
</table>

Without operational margin!
## FCC-hh Refrigeration Capacity

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>Cooling circuit</th>
<th>Capacity / Sector</th>
<th>Dynamic range</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-60 K</td>
<td>Beam screen</td>
<td>530 kW</td>
<td>~6</td>
</tr>
<tr>
<td></td>
<td>Thermal shield</td>
<td>90 kW</td>
<td></td>
</tr>
<tr>
<td>40-300 K</td>
<td>Current lead</td>
<td>85 g/s</td>
<td>~2</td>
</tr>
<tr>
<td>1.9 K (4.2 K ?)</td>
<td>Cold-mass</td>
<td>12 kW</td>
<td>~3</td>
</tr>
</tbody>
</table>

- Large cooling capacity required above 40 K \(\rightarrow\) new for particle accelerators
- Large dynamic range required above 40 K (factor \~6) \(\rightarrow\) new for particle accelerators
  \(\rightarrow\) Special effort to develop an efficient and flexible 300-40 K refrigeration cycle
  (see contributions of TU Dresden and CEA Grenoble/SBT).

- Large cooling capacity at 1.9 K (factor 5 w/r to LHC)
  \(\rightarrow\) Special effort to develop large and efficient 1.8-K refrigeration cycle
  (see contributions of CEA Grenoble/SBT).
FCC-hh cryoplant architecture

300-40 K cryoplant
• Beam screen (40-60 K)
• Thermal shield (40-60 K)
• Current leads (40-300 K)
• Precooling of 1.9 K cryoplant

1.9 K cryoplant
• SC magnet cold mass

Contributions of TU Dresden and CEA/SBT
Shaft elevation (h) impacts the hydrostatic head (\( \rho g h \)) and the enthalpy (\( g h \)) variations: The relative variation strongly depends on the operating temperature.

40 K is a good compromise compatible with a Nelium cycle producing the refrigeration capacity down to 40 K and which has to be located at the surface for limiting the Neon inventory (cost).
Design pressure up to 50 bar: See contribution of WrUT for the impacts on heat inleak.
FCC-hh He inventory

Cold mass He inventory: 33 l/m (scaled from LHC)
Distribution inventory dominated by the beam-screen supply and return headers

FCC He inventory: ~800 t! (~6 LHC He inventory)
Process flow diagram

BS cold circulator (CC)

40-4 K LCB

40 K

Shaft Cavern

300-40 K UCB

Ne-He WCS

He WCS

Quench buffer

LNB

GN2

LN2

CWU

300 K

40-4 K

LCB

BS warm circulator (WC) (could also be used for CWU)

Sector

Tunnel

E F G

Qbs CM Qcm

Quench buffer

B C E F D

Qbs CM

Qcl

Qcm

Shaft

Tunnel

Cavern

40 K
Nominal operation

- Cold compressor for He subcooling

- NeHe cycle at ground level

- Thermal shields in series with the BS (~620 kW)

- Cold mass (~12 kW)

- Cold compressor for He subcooling

- CL cooling @ 40-300 K, 1.3 bar (~85 g/s)
Power consumption vs beam-screen pressure drop

\[ \eta_s = 0.7 \text{ (cold circulator)} \]
\[ \eta_s = 0.83 \text{ (warm circulator)} \]
\[ \eta_{th} = 0.42 \text{ (Nelium cycle)} \]

1 MW ≅ 36 MCHF in 10 years of FCC operation

Half-cell cooling
~105 m, ~800 valves

7.4 MW for 618 kW refrigeration

Cold circulator more efficient for DP below 10 bar...
...but warm circulator could be more suitable to handle tricky transients
**Beam-screen transient**

Ramp in energy

Beam dump

SR power (seen by the beam screens)

**Phase 1:**
“Low” luminosity
(10 h of beam physics)

**Phase 2:**
“High” luminosity
(3 h of beam physics)

Heat load seen by the cryoplant (header buffering)

C. Kötnig
Cooldown & warmup studies:
See H. Rodrigues presentation and poster.

- Separate circuit for indirect cool-down and warm-up (no impact on the CM design pressure)
- Bayonnet heat exchanger for Liquid-liquid LHe II
- Thermal shield and heat intercepts on the return headers
- Safety/quench valve spacing : ~100 m (to be validated $\rightarrow$ ~40 MJ per magnets)
- Cold quench buffer (Header D) at 40 K (to be validated (LHC @ 20 K))
Normal He cooling “à la HERA”

Cooling of magnet cold-masses with supercritical helium (SHe) at high heat load (1.5 W/m):
→ See C. Kötnig poster
Magnet cooling: He II vs He I cooling

He II cooling

- Tref
- Tcm (Tref + 0.1 K)
- Qcm: 12 kW
- 4.6 K
- 3 bar
- 4.6 K
- 3 bar
- Trcb
- H
- Tref + 0.1 K (per stage)
- ηis = 75 %
- Qb: 2 kW

He I cooling

- Tref
- Tref + 0.1 K
- Tref + 0.2 K
- Tcm (Tref + 0.5 K)
- Qcm: 12 kW
- 6 bar
- 3 bar
- 6 bar
- 1.3 bar
- ηis = 60 %
- Qb: 2 kW
- Tref
- Tref + 0.1 K
Magnet cooling cost including 10 years of operation

- He II cooling
- He I cooling
FCC-hh electrical consumption

RH: resistive heating
BGS: beam-gas scattering
CM: cold mass heat-inleaks
CL: current lead
BS cir.: Beam screen circulator
TS: thermal shield
IC: image current
SR: synchrotron radiation
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2 main-ring and 1 booster-ring RF module strings
FCC-ee cryogenic capacity
(2 main + 1 booster rings)

Basic input:
- RF-cavity modules installed in the extended straight sections (ESS at Points J and D)
- Baseline: 1-2 cells, 400 MHz RF cavities @ 4.5 K with Q0= 3.1 E9
- Qstat: 5 W/m (main rings and booster ring)
- Qdyn for booster ring: 10 % of one main ring

<table>
<thead>
<tr>
<th>Machine</th>
<th>Q stat [kW]</th>
<th>Q dyn [kW]</th>
<th>Qtot [kW]</th>
<th>Cryoplant #</th>
<th>Cryoplant size [kW@4.5 K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>2.9</td>
<td>0.5</td>
<td>3.4</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>WW</td>
<td>3.7</td>
<td>24</td>
<td>27</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>ZH</td>
<td>14</td>
<td>88</td>
<td>102</td>
<td>4</td>
<td>26</td>
</tr>
<tr>
<td>ttbar</td>
<td>31</td>
<td>154</td>
<td>185</td>
<td>4 (8)</td>
<td>46* (23)</td>
</tr>
</tbody>
</table>

*: Outside State-of-the-Art
FCC-ee: Cryogenic layout

Z machine

WW machine

ZH machine

ttbar machine

~ 10 m-long cryo-modules with cold-warm transitions
Total FCC-ee electrical power to the refrigerator [MW]

FCC-ee: Cryogenics electrical consumption

- Z
- WW
- ZH
- ttbar

- Q RF dynamic
- Q RF static
- Q distribution
- Q shield
Substantial progress in various domains.

Next important steps:
- Cryoplant studies by industrial partners (Air Liquide & Linde)
- Beam-screen transient → local and global controls strategy
- Quench discharge and recovery (impact on CM design pressure and # of quench valves)
- Distribution system (heat in-leaks, INVAR option)
- Freezing of magnet operating temperature