Transient modes and their impacts on the cryoplant size and operation margins

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• Introduction: Input from magnets
• AC losses during magnet current ramp
  – Impact on helium inventory
  – Impact on refrigeration capacity at 1.8 K
  – Impact on cryogenic distribution
  – Impact on cryoplant size and cryogenic layout
• Operational margins
• Conclusion
### AC-losses: input for 16 T magnets

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>AC-losses during ramp-up [kJ/m]</th>
<th>AC-losses during ramp-down [kJ/m]</th>
<th>AC-losses during pre-cycle [kJ/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>present state-of-the-art of NB3Sn conductor ((D_{\text{eff}}) of 50 µm)</td>
<td>7.5</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>Case 2</td>
<td>Reduced (D_{\text{eff}}) on low-field external layers ((D_{\text{eff}}) of 20 µm)</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Case 3</td>
<td>Reduced (D_{\text{eff}}) on low-field external layers ((D_{\text{eff}}) of 20 µm) and implementation of new concepts (artificial pinning)</td>
<td>2.5</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>LHC as comparison</td>
<td>0.5</td>
<td>0.5 (10 A/s) 3 (fast discharge)</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Remark: For FCC cable, AC-losses dominated by magnetization losses, i.e. no strong dependence on ramp rate
AC-losses: On-line extraction?

- The nominal current ramp rate is about 10 A/s, i.e.:
  - A ramp-up time of 1600 s (~27 min)
  - A pre-cycle time of 3200 s (~53 min)

On-line extraction not possible → AC-loss energy must be buffered in the cold-mass helium inventory.

Capacity increase by a factor 2 to 4 w/r to steady-state requirement

Ramp-rate : 10 A/s

Ramp-rate : 1 A/s

Capacity increase by up to 33 % w/r to steady-state requirement...
...but ramp-up time of 4.5 h (9 h per pre-cycle) !!!

Steady-state capacity requirement
AC-losses: Buffering in magnet cold-masses

- At 1.9 K, the specific heat of materials is negligible → only helium is taken into account.
- The specific helium inventory required for steady-state operation is 33 l/m
  - 50 % required by the longitudinal free area
  - 50 % required by the laminations void-fraction and end volumes

With the present helium inventory (33 l/m) and an initial temperature of 1.9 K, it is possible to buffer:

- ~ 5 kJ/m if we accept a temperature excursion of 0.2 K (OK for Nb₃Sn)
- ~ 8 kJ/m if we want to stay below Tλ.
AC-losses: Impact on He inventory

- Cryo requirement 1: Remain in LHeII after a pre-cycle (temperature excursion of 0.27 K)
- Cryo requirement 2: Remain below 2.1 K after a ramp-up (temperature excursion of 0.2 K)

→ Both requirements have impacts on He inventory and on the quench recovery line diameter (Line D)

- Requirement 1 is the design case
  - Case 1: + 80 % of cold mass He inventory (+ 300 t for FCC total inventory)
  - Case 2: + 20 % of cold mass He inventory (+ 80 t for FCC total inventory)
  - Case 3: no impact on He inventory (covered by steady-state need).
AC-losses: Impact on 1.8 K cooling capacity

- Cryo requirement 3: Extract deposited energy during ramp-up in less than 2 hours (half-time of a high-luminosity stable-beam plateau)
- Cryo requirement 4: Recovery of a pre-cycle in less than 1 hour (time to wait before Cryo OK for injection)

Both requirements have impacts on installed capacity @ 1.8 K

- Requirement 4 is the design case
- Additional 1.8 K cooling capacity:

<table>
<thead>
<tr>
<th>Case</th>
<th>Requirement 3</th>
<th>Requirement 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>+ 75 %</td>
<td>+ 230 %</td>
</tr>
<tr>
<td>Case 2</td>
<td>+ 50 %</td>
<td>+ 140 %</td>
</tr>
<tr>
<td>Case 3</td>
<td>+ 25 %</td>
<td>+ 40 %</td>
</tr>
</tbody>
</table>
AC-losses: Impact on cryogenic distribution

- Increase of cold-mass helium inventory will impact the size of the cold quench buffer (Line D)
- Increase of the 1.8 K cooling capacity will impact the diameter of the pumping line (Line B)

→ i.e. an increase of the diameter of the cryogenic distribution line

For Case 1 and 2 the cryoline is becoming larger than the magnet cryostats
→ first signs of a design showstopper
→ 10-km sector cooling has to be questioned
AC - losses: Impact on sector cryoplant size and cryogenic layout

• Increase of 1.8 K cooling capacity will impact the sector cryoplant size and the cryogenic layout.

![Graph showing AC losses vs. sector cryoplant size]

- Case 1 and 2: Go for alternative layout (20 cryoplants in 10 technical sites and ½ sector cooling)
- Case 3: Try to keep the baseline layout (10 cryoplants in 6 technical sites)

...but:
- Point J and D with extended LSS (~2 km)
- Point F with a very deep shaft (~600 m)
- Point B in a difficult urban area
AC-losses: Conclusion and baseline input

- **Main project decisions:**
  - The Case 3 (SC conductor with artificial pinning) is taken as the baseline input for cryogenics.
  - Maximum recovery time of 2 hours after a magnet ramp-up is endorsed.
  - Maximum recovery time after a pre-cycle is not required (could be longer than 1 h).

- **Main consequences:**
  - No impact on the helium inventory requirement (remain at 33 l/m)
  - Increase of the sector cooling capacity at 1.8 K from 12 kW at 15 kW (+25 %). This 3 kW extra-capacity is also an operational margin for steady-state operation.
  - Recovery time after a pre-cycle will be 1.2 h
  - The VLP pumping line diameter will increase from 630 to 690 mm; the corresponding vacuum jacket of cryogenic distribution line diameter will increase from 1200 to 1300 mm, i.e.:
    - 1400 mm at the position of local flanges and bellows
    - 1550 mm at the position of service modules (valves, heat exchanger and jumper connection)
  - The unit cryogenic plant size will increase from 100 to 110 kW @ 4.5 K, still compatible with a single-plant per 10-km long sector.
  - The cryogenic layout baseline remains with 10 cryogenic plants in 6 technical sites (PA, PC, PE, PG, PI & PK).
Operational margins

Main project decisions:

– The FCC-hh beam energy (100 TeV c.m.) and bunch current (1E11 ppb) has to be considered as ultimate conditions, i.e. they could be reached without operational margins.

However, a cryogenic system requires a minimum operational margin of 1.3 to guarantee its availability.

What are the beam parameters which give an operational margin of 1.3 with respect to the ultimate conditions?
Scaling laws

- Scaling laws for beam induced heating:

<table>
<thead>
<tr>
<th>Beam parameter</th>
<th>Energy</th>
<th>Bunch population</th>
<th>Bunch number</th>
<th>Temperature level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive heating</td>
<td>$E^2$</td>
<td>-</td>
<td>-</td>
<td>@ 1.9 K</td>
</tr>
<tr>
<td>Synchrotron radiation</td>
<td>$E^4$</td>
<td>$N_b$</td>
<td>$n_b$</td>
<td>@ 40-60 K</td>
</tr>
<tr>
<td>Image current</td>
<td>-</td>
<td>$N_b^2$</td>
<td>$n_b$</td>
<td>@ 40-60 K</td>
</tr>
<tr>
<td>Beam gas scattering</td>
<td>$E$</td>
<td>$N_b$</td>
<td>$n_b$</td>
<td>@ 1.9 K</td>
</tr>
</tbody>
</table>
Operational margins vs beam energy and bunch population

40-60 K Temperature level

Margin w/r to ultimate Center-of-mass Energy [TeV]

14 T
0.5xNb
0.6xNb
0.7xNb
0.8xNb
0.9xNb
Nb

15 T

16 T

1.9 K Temperature level

Margin w/r to ultimate Center-of-mass energy [TeV]

14 T
0.5xNb
0.6xNb
0.7xNb
0.8xNb
0.9xNb
Nb

15 T

16 T

25 % already given by AC-loss recovery capacity
Operational margins: Beam parameters giving an operational margin of 1.3

Operational margin of 1.3 obtained:
- For ultimate beam energy (100 TeV) by reducing the bunch population by 25%.
- For a beam energy of 95 TeV (~5%) and a bunch population of 0.9Nb (~10%).
- For ultimate bunch population by reducing the beam energy by 7.5%.
• AC-losses:
  – AC-losses during magnet current transient are strongly impacting the cryogenic system design.
  – Impacts are limited by the introduction of new concepts in Nb3Sn conductor (artificial pinning), which are now part of the baseline for cryogenic design.
  – The remaining impacts are:
    • the increase of the 1.8 K capacity by 25 % (from 12 to 15 kW per sector)
    • The increase of the pumping line diameter and of the cryogenic distribution line (from 1200 to 1300 mm).

• Operational margins:
  – Present design beam parameter has to be considered as ultimate conditions (without margin)
  – However, a minimum operation margin factor of 1.3 is required to guarantee the cryogenic system availability.
    • A factor 1.25 already is existing at 1.8 K (thanks to AC-losses)
    • With the proposed installed capacity, the cryogenic system can guarantee the following “Nominal Conditions”:
      – 100 Tev & 0.75E11 ppb
      – 95 TeV & 0.9E11 ppb
      – 92.5 TeV & 1E11 ppb
Thank you!