Cryogenic refrigeration for the LHC

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MaTeFu Spring Training School
Cadarache, 5-9 April 2009
The largest scientific instrument in the world...
...based on advanced technology

23 km of high-field superconducting magnets
operating in superfluid helium at 1.9 K
Superconductors for high-field magnets

Graph showing the critical current density ($J_c$) vs. magnetic field ($B$) for different superconductors:

- NbTi @ 4.5 K
- NbTi @ 1.8 K
- Nb3Sn @ 4.5 K

The graph includes data points for LHC Spec Cable 1 and LHC Spec Cable 2.

At +3 tesla, the graph shows a critical current density of approximately 1500 A/mm² for NbTi @ 4.5 K.
Cryogenic system layout

- 5 cryogenic islands
- 8 cryogenic plants, each serving adjacent sector, interconnected when possible
- Cryogenic distribution line feeding each sector
Configuration of cryogenics at LHC even point

Odd point
- MP Storage

Even point
- MP Storage
- New 4.5 K Refrigerator
- Warm Compressor Station
- Cold Box
- Interconnection Box
- Existing 4.5 K Refrigerator
- Warm Compressor Station
- Upper Cold Box
- Lower Cold Box
- 1.8 K Refrigeration Unit
- Warm Compressor Station
- Cold Compressor box

Odd point
- MP Storage

Distribution Line
- Magnet Cryostats, DFB, ACS

LHC Sector (3.3 km)
Cryogenic plants

4.5 K refrigerators
(18 kW @ 4.5 K)

1.8 K refrigeration units
(2.4 kW @ 1.8 K)
Cryogenic storage and distribution

- GHe storage
- LIN storage
- Cryo-magnet string
- Distribution line
- Interconnection box
- Vertical transfer line
Analysis & management of heat loads

**Analysis**

- **Heat inleaks**
  - Radiation
  - Residual gas conduction
  - Solid conduction

- **Joule heating**
  - Superconductor splices

- **Beam-induced heating**
  - Synchrotron radiation
  - Beam image currents
  - Acceleration of photoelectrons
  - Beam halo

**Management**

- 70 K shield, MLI
- Vacuum < $10^{-4}$ Pa
- Non-metallic supports
- Heat intercepts
- Resistance < a few nΩ
- 5-20 K beam screens
- absorbed in cold mass
Steady-state heat loads [W/m]
(Cryomagnets and distribution line in LHC arcs)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>50-75 K</th>
<th>4.6-20 K</th>
<th>1.9 K LHe</th>
<th>4 K VLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat inleaks*</td>
<td>7.7</td>
<td>0.23</td>
<td>0.21</td>
<td>0.11</td>
</tr>
<tr>
<td>Resistive heating</td>
<td>0.02</td>
<td>0.005</td>
<td>0.10</td>
<td>0</td>
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<tr>
<td>Beam-induced nominal**</td>
<td>0</td>
<td>1.58</td>
<td>0.09</td>
<td>0</td>
</tr>
<tr>
<td>Beam-induced ultimate**</td>
<td>0</td>
<td>4.36</td>
<td>0.11</td>
<td>0</td>
</tr>
<tr>
<td>Total nominal</td>
<td>7.7</td>
<td>1.82</td>
<td>0.40</td>
<td>0.11</td>
</tr>
<tr>
<td>Total ultimate</td>
<td>7.7</td>
<td>4.60</td>
<td>0.42</td>
<td>0.11</td>
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</tbody>
</table>

* no contingency

** Breakdown

<table>
<thead>
<tr>
<th></th>
<th>nominal</th>
<th>ultimate</th>
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</thead>
<tbody>
<tr>
<td>Synchrotron radiation</td>
<td>0.33</td>
<td>0.50</td>
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<tr>
<td>Image current</td>
<td>0.36</td>
<td>0.82</td>
</tr>
<tr>
<td>Beam-gas Scattering</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Photoelectron</td>
<td>0.89</td>
<td>3.07</td>
</tr>
</tbody>
</table>
## Scaling laws for LHC dynamic loads

<table>
<thead>
<tr>
<th>Beam parameter</th>
<th>Energy $E$</th>
<th>Bunch current $I_{\text{bunch}}$</th>
<th>Bunch number $n_{\text{bunch}}$</th>
<th>Bunch length $\sigma_z \ [\text{r.m.s.}]$</th>
<th>Luminosity $L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive heating</td>
<td>$E^2$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Synchrotron radiation</td>
<td>$E^4$</td>
<td>$I_{\text{bunch}}$</td>
<td>$n_{\text{bunch}}$</td>
<td>$\sigma_z^{-3/2}$</td>
<td>-</td>
</tr>
<tr>
<td>Image current</td>
<td>-</td>
<td>$I_{\text{bunch}}^2$</td>
<td>$n_{\text{bunch}}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photo-electron cloud</td>
<td>-</td>
<td>$I_{\text{bunch}}^3$</td>
<td>$n_{\text{bunch}}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beam gas scattering</td>
<td>-</td>
<td>$I_{\text{bunch}}$</td>
<td>$n_{\text{bunch}}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Random particle loss</td>
<td>$E$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$L$</td>
</tr>
<tr>
<td>Secondaries</td>
<td>-</td>
<td>$I_{\text{bunch}}^2$</td>
<td>$n_{\text{bunch}}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RF losses</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Uncertainty & overcapacity factors

- Uncertainty factor $F_{\text{in}}$:
  - Lack of reproducibility in construction (e.g. MLI wraps)
  - Variance of thermal processes at work (e.g. insulation vacuum)
  - Evolution in time (ageing, contamination of reflective surfaces)
  ⇒ applied to static loads only, dynamic loads and their scaling known from first principles

- Overcapacity factor $F_{\text{oc}}$:
  - Cooldown in finite time
  - Refrigerator loading < 100 %
  - Variability of machine performance
  ⇒ applied to sum of static load with uncertainty and dynamic load
  ⇒ no overcapacity applied to ultimate conditions
Overall factor on installed refrigeration

- Installed refrigeration power

\[ Q_{\text{installed}} = \text{Max} \left[ F_{\text{oc}} \left( F_{\text{in}} Q_{\text{stat}} + Q_{\text{dyn \, nom}} \right); \left( F_{\text{in}} Q_{\text{stat}} + Q_{\text{dyn \, ult}} \right) \right] \]

- Values of uncertainty & overcapacity factors
  - \( F_{\text{in}} = 1,5 \) at beginning of project
  - \( F_{\text{oc}} = 1,5 \)
  - \( F_{\text{in}} \) gradually lowered following refinement of project configuration and improved knowledge of component thermal performance
Evolution of estimated heat loads & installed refrigeration capacity per LHC sector

Heat load @ 50-75 K [kW]

Heat load @ 5-20 K [W]

Heat load @ 1.9 K [W]

CL cooling [g/s]
## Installed cooling duties in the LHC sectors

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>High-load sector</th>
<th>Low-load sector</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-75 K</td>
<td>33000</td>
<td>31000</td>
<td>[W]</td>
</tr>
<tr>
<td>4.6-20 K</td>
<td>7700</td>
<td>7600</td>
<td>[W]</td>
</tr>
<tr>
<td>4.5 K</td>
<td>300</td>
<td>150</td>
<td>[W]</td>
</tr>
<tr>
<td>1.8 K</td>
<td>2400</td>
<td>2100</td>
<td>[W]</td>
</tr>
<tr>
<td>3-4 K</td>
<td>430</td>
<td>380</td>
<td>[W]</td>
</tr>
<tr>
<td>20-280 K</td>
<td>41</td>
<td>27</td>
<td>[g/s]</td>
</tr>
</tbody>
</table>
Evolution of installed power to heat load ratio

- 50-75 K
- 5-20 K
- 1.9 K
- CL cooling

Overcapacity target
Procurement from industry

- European industry (Air Liquide & Linde Kryotechnik) had demonstrated their competency and know-how in manufacturing turnkey helium refrigerators of medium or large capacity
  - HERA (10 kW)
  - LEP2 (6 kW, 12 kW)
- Most efficient approach was therefore to procure via a functional and interface specification
  - Transform sector cooling requirements into refrigeration duties which can be reception-tested at cryoplant interface
  - Clearly define interfaces to cryogenic and other systems
  - Promote energy-efficient solutions
- Oligopolistic nature of market & desire to balance industrial returns among Member States led to split procurement under constraints
  - Align prices to satisfy CERN lowest-bidder purchasing rule
  - Impose convergence of non- or less-proprietary part of supply, i.e. compressor station and control system
Conversion of cooling duties from LHC sector to 4.5 K refrigerator
Specified refrigeration capacity for the LHC 4.5 K refrigerators

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>Unit</th>
<th>New refrigerator</th>
<th>Upgraded refrigerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-75 K</td>
<td>[W]</td>
<td>33000</td>
<td>31000</td>
</tr>
<tr>
<td>4.5-20 K</td>
<td>[W]</td>
<td>20700</td>
<td>19500</td>
</tr>
<tr>
<td>4.5 K</td>
<td>[W]</td>
<td>4400</td>
<td>4150</td>
</tr>
<tr>
<td>20-280 K</td>
<td>[g/s]</td>
<td>41</td>
<td>27</td>
</tr>
</tbody>
</table>
Scaling laws for cost of cryogenic He refrigerators 
(single cold box, no LIN precooling, controls excluded)

Cost[1998 MCHF] = 2.6 * (Capacity[kW@4.5K])^{0.7} \quad (1)
Cost[1998 MCHF] = 2.2 * (Capacity[kW@4.5K])^{0.6} \quad (2)
How to specify an efficient He refrigerator

- Include capital & operating costs over amortization period (10 years) in adjudication formula
- Operating costs dominated by electricity
- Include externalities in electricity costs => 60 CHF/MWh
  - distribution & transformation on CERN site
  - heat rejection in aero-refrigerants
- Establish shared incentive in the form of bonus/malus on measured vs. quoted electrical consumption
- Break "high efficiency = high investment" pseudo-rule: for given (specified) output, a more efficient plant is smaller, resulting in lower investment (direct & indirect) as well as cheaper operation
How to make an efficient refrigerator
(exemplified on Carnot cycle schematic)

Widen the low-temperature end of the cycle as shown in the T-S diagram
Process cycle & T-S diagram
of 18 kW @ 4.5 K cryoplant
Compressor station of 4.5 K refrigerator

Electrical power consumption: 4 MW

1680 g/s @ 20 bar
880 g/s @ 3.9 bar
800 g/s @ 1.05 bar

Identical installation for both suppliers
Compressor station of 4.5 K refrigerator
(Power input ~ 4 MW)
Cold box of Air Liquide 4.5 K refrigerator
Cold box of Air Liquide 4.5 K refrigerator
Cold box of Linde 4.5 K refrigerator

- HP
- MP
- LP

Temperature Levels:
- 300 K
- 90 K
- 75 K
- 50 K
- 20 K
- 4.5 K

Connections:
- 4.5 K supply
- 20 K return
- 50 K supply
- 75 K return
Cold box of Linde 4.5 K refrigerator
## Guaranteed vs measured performance of the new LHC 4.5 K refrigerators

<table>
<thead>
<tr>
<th>LHC location</th>
<th>PA18</th>
<th>PA4</th>
<th>PA6</th>
<th>PA8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier</td>
<td>Air Liquide</td>
<td>Air Liquide</td>
<td>Linde</td>
<td>Linde</td>
</tr>
<tr>
<td>Guaranteed energy consumption [kW]</td>
<td>4204</td>
<td>4204</td>
<td>4275</td>
<td>4275</td>
</tr>
<tr>
<td>Measured energy consumption [kW]</td>
<td>4297</td>
<td>4474</td>
<td>3964</td>
<td>4095</td>
</tr>
<tr>
<td>Measured cryogenic capacity [% of specified]</td>
<td>97.3</td>
<td>101.5</td>
<td>100.1</td>
<td>99.3</td>
</tr>
<tr>
<td>COP [W/W]</td>
<td>248</td>
<td>247</td>
<td>222</td>
<td>231</td>
</tr>
</tbody>
</table>
C.O.P. of large cryogenic helium refrigerators

C.O.P. [W/W @ 4.5K]

TORE SUPRA
RHIC
TRISTAN
CEBAF
HERA
LEP
LHC

Carnot Limit
• Each 3.3 km sector has a mass of 4625 t to be cooled in few weeks
• Corresponding power 600 kW, must be generated by vaporization of 1250 t LIN at rates of up to 5 t/h
• LIN precooling not foreseen for steady-state operation, but may also be used to boost helium liquefaction
First cooldown of LHC sectors

First beams around LHC

- Simultaneous Cryo start/maintain
- All sectors at nominal temperature
- UX85 Ph1 works

Christmas and water maintenance shutdown

Short in connection cryostats and repairs

Temperature [K]

Challenges of power refrigeration < 2 K

- Compress large mass-flow rate of gaseous helium across high pressure ratio ⇒ \textit{maximum density at suction, i.e. cold}
- Non-lubricated, contact-less machinery ⇒ \textit{hydrodynamic compressor, multistage}
- Heat of compression rejected at low temperature ⇒ \textit{high thermodynamic efficiency}
Main Features of LHC Cold Compressors

- Active magnetic bearings
- 3-phase induction electrical motor (rotational speed 200 to 700 Hz)
- Fixed-vane diffuser
- Spiral volute
- Axial-centrifugal impeller (3D)
- 300 K under atmosphere
- Cold under vacuum
- Pressure ratio 2 to 3.5
Cold hydrodynamic compressors for the LHC

IHI-Linde

Air Liquide
Specification of LHC 1.8 K refrigeration units

Steady state operation modes:
- Installed pumping capacity 125 g/s at 15 mbar (i.e. ~2.4 kW @ 1.8 K)
- Turndown capability: 1 to 3 without extra liquid burning
- Cold return temperature to the 4.5 K refrigerator below 30 K (reduced capacity) to 20 K (installed capacity).
- Capacity check in standalone mode (Interface B closed)
1.8 K refrigeration cycles for the LHC

1.8 K Refrigeration Unit Cycles

Air Liquide Cycle

IHI-Linde Cycle

4 K, 15 mbar
124 g/s

20 K, 1.3 bar
124 g/s
Isentropic efficiency of cold compressors

\[ \eta_{is} = \frac{H^2 - H_1}{H_2 - H_1} \]

Temperature (T)

Entropy (s)

P₂

P₁

1

2

2'

Isentropic efficiency [%]

LHC

CEBAF

Tore Supra

1985

1993

2000

Year of construction
C.O.P. of LHC 1.8 K refrigeration units

[Diagram showing COP values for Air Liquide and IHI-Linde, with a Carnot Limit line]

- 4.5 K refrigerator part
- 1.8 K refrigeration unit part
### Controls for LHC cryogenics
#### Challenges & solutions

<table>
<thead>
<tr>
<th></th>
<th>Tunnel</th>
<th>4.5 K refrigerators</th>
<th>1.8 K units</th>
<th>QUI</th>
<th>Common</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Inputs</td>
<td>12136</td>
<td>5216</td>
<td>2640</td>
<td>1128</td>
<td>216</td>
<td>21336</td>
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<tr>
<td>Analog Outputs</td>
<td>4856</td>
<td>1140</td>
<td>608</td>
<td>292</td>
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<td>7008</td>
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<tr>
<td>Digital Inputs</td>
<td>4536</td>
<td>8100</td>
<td>3984</td>
<td>1144</td>
<td>592</td>
<td>18356</td>
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<tr>
<td>Digital Outputs</td>
<td>1568</td>
<td>956</td>
<td>1184</td>
<td>232</td>
<td>272</td>
<td>4212</td>
</tr>
<tr>
<td>Closed Loop Controllers</td>
<td>3680</td>
<td>548</td>
<td>328</td>
<td>100</td>
<td>48</td>
<td>4704</td>
</tr>
</tbody>
</table>

**UNICOS framework providing**
1. Programmable logic controllers (PLC) and associated hardware
2. Programming rules and code library for common objects
3. Automated tools for writing control code
4. Gateways based in industrial PC for WorldFIP-based signal conditioners
5. Communication via Ethernet gateways <-> PLC and PLC <-> PLC
6. Event-driven communication protocol between PLC <-> SCADA
7. SCADA based in PVSS with generic widgets, look-and-feel and shared data server
**Control system architecture**

- **Supervision layer**
  - Interface for operation team
  - All operators’ actions are taken from this level

- **Process control layer**
  - PLC: the control logic is performed at that level
  - Programmers act on that level

- **Field layer**
  - Interface to process direct I/O Boards, Fieldbuses
Operator-friendly SCADA

Animated synoptics

PID controllers

Alarm & event lists

Trend charts
Some references


