Introduction to Cryogenics for accelerators

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CAS on Vacuum for Particule Accelerators
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Préambule

Reference
Great thanks to predecessors for this type of exercice, particularly to Ph. Lebrun and his “legacy” of slides

Disclaimer
Being more an experienced engineer than “teacher”, I will try to share with you some information with emphasis on “applied cases” with a “pragmatic approach” rather than only a theoretical one.

There are plenty of books, previous CAS courses with lot’s of formulas and various equations. I leave it to you to check bibliography if this is what you are looking for!
Contents

• Introduction
• Cryogenic fluids
• Heat transfer & thermal insulation
• Cryogenic distribution & cooling schemes
• Refrigeration & liquefaction
• Trends and future machines
• Concluding remarks, references
• **cryogenics**, that branch of physics which deals with the production of very low temperatures and their effects on matter

*Oxford English Dictionary*

• **cryogenics**, the science and technology of temperatures below 120 K

*New International Dictionary of Refrigeration*
3rd edition, IIF-IIR Paris (1975)

Temperature in Celsius (C): unit defined with 0 C (ice) and 100 C (vapour)
Temperature in Kelvin (K): 1 K = 1 C, but 0 K = -273.15 C (absolut zero)
Densification, liquéfaction & séparation des gaz

LNG

130 000 m³ LNG carrier with double hull

LIN & LOX

Air separation by cryogenic distillation
Up to 4500 t/day LOX

Rocket fuels

Ariane 5
25 t LHY, 130 t LOX
Cooling of superconducting devices

- LHC Accelerator
- ITER Reactor
- Power cables
- Medical imaging
Cryogenics is an ENABLING technology for superconductivity

Operating temperature & performance of superconductors

- Superconductivity only exists in a limited domain of temperature, magnetic field and current density
- Electrotechnical applications require transport current and magnetic field
- Operating temperature of the device must therefore be significantly lower than the critical temperature of the superconductor
Main advantages from superconductivity & cryogenics

For accelerators in high energy physics

• Compactness through higher fields

\[ E_{\text{beam}} \approx 0.3 \cdot B \cdot r \quad E_{\text{beam}} \approx E \cdot L \]

\[
\text{[Gev]} \quad \text{[T]} \quad \text{[m]} \quad \text{[Gev]} \quad \text{[MV/m]} \quad \text{[m]}
\]

At design stage, working at highest possible temperature is always considered, but often not selected to maximise beam energy and overall cost ...

Cryogenic systems takes longer to recover from failures than conventional ones!

(operational availability is a key issue, and there is work on it!)

• Saving operating energy

Electromagnets:

Resistive: \( P_{\text{input}} \approx E_{\text{beam}} \)

Superconducting: \( P_{\text{input}} \approx P_{\text{ref}} \)

Acceleration cavities

\( P_{\text{input}} \approx R_s \cdot L \cdot E^2/w \)

\( R_s \approx R_{\text{BCS}} + R_o \)

\( R_{\text{BCS}} \approx (1/T) \exp(-BT_c/T) \)
Limiting energy stored in beam

- Energy $W$ stored in the beams of circular accelerators and colliders

  \[ W \, [kJ] = 3.34 \, E_{\text{beam}} \, [GeV] \, I_{\text{beam}} \, [A] \, C \, [km] \]

  $C$ circumference of accelerator/collider

  ⇒ building compact machines, i.e. producing higher bending field $B$
  limits beam stored energy

- Example: the LHC

  \[ E_{\text{beam}} = 7000 \, \text{GeV} \]
  \[ I_{\text{beam}} = 0.56 \, \text{A} \]
  \[ C = 26.7 \, \text{km} \]

  ⇒ $W = 350 \, \text{MJ}$!
Low impedance for beam stability

- Transverse impedance
  \[ Z_T(\omega) \sim \rho \ r / \omega \ b^3 \]
  \(\rho\) wall electrical resistivity
  \(r\) average machine radius
  \(b\) half-aperture of beam pipe

- Transverse resistive-wall instability
  - dominant in large machines
  - must be compensated by beam feedback, provided growth of instability is slow enough
  - maximize growth time \(\tau \sim 1/ Z_T(\omega)\) i.e. reduce \(Z_T(\omega)\)

\[ \Rightarrow \] for a large machine with small aperture, low transverse impedance is achieved through low \(\rho\), i.e. low-temperature wall
Cryopumping maintains good vacuum

Vapour pressure at cryogenic temperatures

Saturation pressure of all gases except helium vanish at cryogenic temperature

Cryopumping maintains good vacuum
Rationale for superconductivity & cryogenics in particle accelerators

Cryopumping

Beam vacuum

Beam stability

Cryogenics

Superconductivity

Beam impedance

Compactness

Reduce cost

Limit beam stored energy

Reduce power consumption

Zero resistance
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Useful range of cryogens, and potential applications

Superconducting materials: increased performance for demanding/compact applications, but cryogenic cooling required!

Low temperature sc (LTS)  High temperature sc (HTS)
## Characteristic temperatures of cryogens

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>Triple point [K]</th>
<th>Normal boiling point [K]</th>
<th>Critical point [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>90.7</td>
<td>111.6</td>
<td>190.5</td>
</tr>
<tr>
<td>Oxygen</td>
<td>54.4</td>
<td>90.2</td>
<td>154.6</td>
</tr>
<tr>
<td>Argon</td>
<td>83.8</td>
<td>87.3</td>
<td>150.9</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>63.1</td>
<td>77.3</td>
<td>126.2</td>
</tr>
<tr>
<td>Neon</td>
<td>24.6</td>
<td>27.1</td>
<td>44.4</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>13.8</td>
<td>20.4</td>
<td>33.2</td>
</tr>
<tr>
<td>Helium</td>
<td>2.2 (*)</td>
<td>4.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

(*): \( \lambda \) point
Vaporization of normal boiling cryogens under 1 W applied heat load

\[ \text{Power} \approx \dot{m}' \cdot \text{Latent Heat} \]  
\[ [\text{W}] \quad [\text{g/s}] \quad [\text{J/g}] \]

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>[mg.s(^{-1})]</th>
<th>[l.h(^{-1})] (liquid)</th>
<th>[l.min(^{-1})] (gas NTP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>48</td>
<td>1.38</td>
<td>16.4</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>5</td>
<td>0.02</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Staging considered to minimise LHe consumption …
### Amount of cryogens required to cool down 1 kg iron

Power \( \approx m' \cdot \text{Latent\_Heat} \quad \text{Power} \approx m' \cdot \text{Specific\_Heat} \cdot \Delta T \)

<table>
<thead>
<tr>
<th>Using</th>
<th>Latent heat only</th>
<th>Latent heat and enthalpy of gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHe from 290 to 4.2 K</td>
<td>29.5 litre</td>
<td>0.75 liter</td>
</tr>
<tr>
<td>LHe from 77 to 4.2 K</td>
<td>1.46 litre</td>
<td>0.12 litre</td>
</tr>
<tr>
<td>LN2 from 290 to 77 K</td>
<td>0.45 litre</td>
<td>0.29 litre</td>
</tr>
</tbody>
</table>

Cold vapor considered to minimise LHe/LN2 consumption …
Phase diagram of helium

- **Solid**
- **He I**
- **He II**
- **Vapour**
- **Critical Point**
- **Pressureized He II**
  (Subcooled liquid)
- **Saturated He II**
- **Saturated He I**
- **Super-Critical**
<table>
<thead>
<tr>
<th>Phase domain</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated He I</td>
<td>Fixed temperature High heat transfer Two-phase flow Boiling crisis</td>
<td></td>
</tr>
<tr>
<td>Supercritical</td>
<td>Monophase Negative J-T effect Non-isothermal Density wave instability</td>
<td></td>
</tr>
<tr>
<td>He II</td>
<td>Low temperature High conductivity Low viscosity Second-law cost Subatmospheric</td>
<td></td>
</tr>
</tbody>
</table>
Contents

• Introduction
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• Heat transfer & thermal insulation
• Cryogenic distribution & cooling schemes
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• Concluding remarks, references
Typical heat transfer coefficients at cryogenic temperatures

3 mechanisms involved:
- Conduction
- Radiation
- Convection
Heat conduction in solids

Fourier’s law:

\[ Q_{\text{con}} = k(T) \times S \times \frac{dT}{dx} \]

\[ k(T) : \text{thermal conductivity} \ [\text{W/m.K}] \]

Integral form:

\[ Q_{\text{con}} = \frac{S}{L} \times \int_{T_1}^{T_2} k(T) \timesdT \]

\[ k(T) \timesdT : \text{thermal conductivity integral} \ [\text{W/m}] \]

Thermal conductivity integrals for standard construction materials are tabulated

Risks associated with “optimisation”:
- small section \( S \): towards limit for material resistance
- long length \( L \): towards limits for mechanical stability
- insulators (large) \( K \): difficulties with transfer of forces
### Thermal conductivity integrals, selection of materials [W/m]

<table>
<thead>
<tr>
<th>From vanishingly low temperature up to</th>
<th>20 K</th>
<th>80 K</th>
<th>290 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFHC copper</td>
<td>11000</td>
<td>60600</td>
<td>152000</td>
</tr>
<tr>
<td>DHP copper</td>
<td>395</td>
<td>5890</td>
<td>46100</td>
</tr>
<tr>
<td>1100 aluminium</td>
<td>2740</td>
<td>23300</td>
<td>72100</td>
</tr>
<tr>
<td>2024 aluminium alloy</td>
<td>160</td>
<td>2420</td>
<td>22900</td>
</tr>
<tr>
<td>AISI 304 stainless steel</td>
<td>16.3</td>
<td>349</td>
<td>3060</td>
</tr>
<tr>
<td>G-10 glass-epoxy composite</td>
<td>2</td>
<td>18</td>
<td>153</td>
</tr>
</tbody>
</table>

Several orders of magnitude between materials …
Thermal conductivity of materials at cryogenic temperatures

Graph to illustrate the global picture, a help to select (or avoid) a material

For design, data available in various codes
Non-metallic composite support post with heat intercepts for LHC magnets

Cooling intercepts, a complementary method to further reduce conductive heat loads

5 K cooling line (SC He)

Aluminium intercept plates glued to G-10 column

Aluminium strips to thermal shield at 50-75 K
Thermal radiation

- **Wien’s law**
  - Maximum of black body power spectrum
  \[ \lambda_{\text{max}} \cdot T = 2898 \, [\mu\text{m.K}] \]

- **Stefan-Boltzmann’s law**
  - Black body
  \[ Q_{\text{rad}} = \sigma A \, T^4 \]
  \[ \sigma = 5.67 \times 10^{-8} \, \text{W/m}^2\cdot\text{K}^4 \]
  (Stefan Boltzmann’s constant)
  - “Gray” body
  \[ Q_{\text{rad}} = \varepsilon \, \sigma A \, T^4 \]
  \[ \varepsilon \] emissivity of surface
  - “Gray” surfaces at \( T_1 \) and \( T_2 \)
  \[ Q_{\text{rad}} = E \, \sigma A \, (T_1^4 - T_2^4) \]
  \( E \) function of \( \varepsilon_1, \varepsilon_2 \), geometry

Best would be to have a reflective (high \( E \)) “shelter” to intercept \( T^4 \), or a series of shelters ...
## Emissivity of technical materials at low temperatures

<table>
<thead>
<tr>
<th></th>
<th>Radiation from 290 K Surface at 77 K</th>
<th>Radiation from 77 K Surface at 4.2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel, as found</td>
<td>0.34</td>
<td>0.12</td>
</tr>
<tr>
<td>Stainless steel, mech. polished</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>Stainless steel, electropolished</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>Stainless steel + Al foil</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Aluminium, as found</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>Aluminium, mech. polished</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>Aluminium, electropolished</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Copper, as found</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>Copper, mech. Polished</td>
<td>0.06</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Residual gas conduction

- **Viscous regime**
  - At high gas pressure \( \lambda_{molecule} \ll d \)
  - Classical conduction \( Q_{res} = k(T) A \frac{dT}{dx} \)
  - Thermal conductivity \( k(T) \) independant of pressure

- **Molecular regime**
  - At low gas pressure \( \lambda_{molecule} \gg d \)
  - Kennard’s law \( Q_{res} = A \alpha(T) \Omega P (T_2 - T_1) \)
  - Conduction heat transfer proportional to pressure, independant of spacing between surfaces
    \( \Omega \) depends on gas species
  - Accommodation coefficient \( \alpha(T) \) depends on gas species, \( T_1, T_2 \) and geometry of facing surfaces

\( \lambda_{molecule} \) : mean free path of gas molecules

Best would be to avoid residual gas ...
Multi-layer insulation (MLI)

30 layers at least once, 2nd blanket could be with 10 layers, Minimum 1-2 on coldest surface, to minimise brutal heat loads in case of vacuum degradation

- Complex system involving three heat transfer processes
  - \( Q_{MLI} = Q_{rad} + Q_{sol} + Q_{res} \)
  - With \( n \) reflective layers of equal emissivity, \( Q_{rad} \sim 1/(n+1) \)
  - Due to parasitic contacts between layers, \( Q_{sol} \) increases with layer density
  - \( Q_{res} \) due to residual gas trapped between layers, scales as 1/n in molecular regime
  - Non-linear behaviour requires layer-to-layer modeling

- In practice
  - Typical data available from (abundant) literature
  - Measure performance on test samples
## Typical heat fluxes at vanishingly low temperature between flat plates [W/m²]

<table>
<thead>
<tr>
<th>Description</th>
<th>Heat Flux [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black-body radiation from 290 K</td>
<td>401</td>
</tr>
<tr>
<td>Black-body radiation from 80 K</td>
<td>2.3</td>
</tr>
<tr>
<td>Gas conduction (100 mPa He) from 290 K</td>
<td>19</td>
</tr>
<tr>
<td>Gas conduction (1 mPa He) from 290 K</td>
<td>0.19</td>
</tr>
<tr>
<td>Gas conduction (100 mPa He) from 80 K</td>
<td>6.8</td>
</tr>
<tr>
<td>Gas conduction (1 mPa He) from 80 K</td>
<td>0.07</td>
</tr>
<tr>
<td>MLI (30 layers) from 290 K, pressure below 1 mPa</td>
<td>1-1.5</td>
</tr>
<tr>
<td>MLI (10 layers) from 80 K, pressure below 1 mPa</td>
<td>0.05</td>
</tr>
<tr>
<td>MLI (10 layers) from 80 K, pressure 100 mPa</td>
<td>1-2</td>
</tr>
</tbody>
</table>
Cross section of a LHC dipole

LHC DIPOLE
CROSS SECTION

- Low thermal radiation (shield)
- Low conduction (insulator)
- Insulation vacuum
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Transport of refrigeration in large distributed cryogenic systems
Cryogenic distribution scheme: design issues

- Monophase vs. two-phase
  - temperature control
  - hydrostatic head & flow instabilities
- Pumps vs. no pumps
  - efficiency & cost
  - reliability & safety
- $\text{LN}_2$
  - cooldown and/or normal operation
  - capital & operating costs of additional fluid
  - safety in underground areas (ODH)
- Lumped vs. distributed cryoplants
- Separate cryoline vs. integrated piping
- Number of active components (valves, actuators)
- Redundancy of configuration
Thermal contraction for cryo lines

3 mm / m of thermal contraction => Compensation required!

Thermal compensation

This is THE delicate part in the design of a cryogenic line, as thermal performance can only be considered once the line withstand mechanical forces!!!
LHC vertical lines

Specified “bellows free” in vertical shaft, with relaxed thermal requirements.

Very important cross-section control for 3D lines.

S. Claudet - 31Oct'07
CERN Experience with Transfer Lines & Valve boxes
LHC vertical lines

Strategy and tooling for installation: a must!
8 QRL sectors

- each QRL sector
  - continuous cryostat of
  - ~3.2 km length: from the cryogenic interconnection box to the return module
  - no header (4 or 5) sectorization
  - 9 vacuum sub-sectors
  - repetitive pattern of straight pipe elements and service modules
  - connection to the superconducting magnets every 107 m
LHC distribution scheme

8 x 18 kW @ 4.5 K
1'800 SC magnets
24 km and 20 kW @ 1.9 K
36'000 tons @ 1.9 K
135 tons of He

Cryogenic plant

Typical LHC Cross-section

Cryoplants at five points, separate ring cryoline, 107 m long strings
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Thermodynamics of cryogenic refrigeration

First principle [Joule]

\[ Q_0 = Q_i + W \]

Second principle [Clausius]

\[ \frac{Q_0}{T_0} > \frac{Q_i}{T_i} \]

(= for reversible process)

Hence, \( W \times T_0 \times \frac{Q_i}{T_i} = Q_i \)

which can be written in three different ways:

1. \( W \times T_0 \times \frac{Q_i}{T_i} = Q_i \) introducing entropy \( S \) as

\[ \Delta S_i = \frac{Q_i}{T_i} \]

2. \( W \geq Q_i \times \left( \frac{T_0}{T_i} \times 1 \right) \) Carnot factor

3. \( W \times \Delta E_i \) introducing exergy \( E \) as

\[ \Delta E_i = Q_i \times \left( \frac{T_0}{T_i} \times 1 \right) \]
The Carnot Factor

Graph for $T_{\text{warm}} = 300$ K

For low temperatures:

$$\frac{T_w}{T_c} \approx 1 \quad \frac{T_w}{T_c}$$

- Use of low temperatures if no alternative
- Better intercept heat at higher temperatures

- He II: $1.8K - 166$
- He: $4.5K - 65.7$
- H2: $20K - 14$
- N2: $77K - 2.9$
Helium refrigerators

The efficiency w.r.t Carnot does not depend on the temperature, but rather on the size.

The largest possible, the best!
Consider the extraction of 1 W at 4.5 K, rejected at 300 K

The minimum refrigeration work (equation 2) is:

\[
W_{\text{min}} = Q_i \cdot \left(\frac{T_0}{T_i} \cdot 1\right) = 1 \cdot \left(\frac{300}{4.5} \cdot 1\right) = 65.7 \text{ W}
\]

In practice, the most efficient helium refrigerators have an efficiency of about 30% w.r. to the Carnot limit.

\[
W_{\text{real}} = \frac{W_{\text{min}}}{\zeta} = \frac{65.7}{0.3} = 220 \text{ W}
\]
C.O.P. of large cryogenic helium refrigerators

Time (left to right) is not the only factor for improvement

Contract adjudication with industry based on Capital+Operation(10yrs) costs
Elementary cooling processes on T-S diagram

- **Isobar (heat exchanger)**
- **Isentropic**
- **Isenthalpic (Joule-Thomson valve)**
- **Adiabatic (expansion engine)**

Points:
- **A**
- **B₁**
- **B₂**
- **B₂'**
- **B₃**

Pressures:
- **P₁**
- **P₂ (< P₁)**

Heat exchanger (heat exchanger)

Expansion engine (expansion engine)

Joule-Thomson valve (Joule-Thomson valve)
Log $T$-$s$ Diagram for Helium

- Like ideal gas
- $H \# T$
- Non-ideal gas
### Maximum Joule-Thomson inversion temperatures

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>Maximum inversion temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>43</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>202</td>
</tr>
<tr>
<td>Neon</td>
<td>260</td>
</tr>
<tr>
<td>Air</td>
<td>603</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>623</td>
</tr>
<tr>
<td>Oxygen</td>
<td>761</td>
</tr>
</tbody>
</table>

While air can be cooled down and liquefied by JT expansion from room temperature, helium and hydrogen need precooling down to below inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines).
T-S diagram for helium (non-ideal part)
Two-stage Claude cycle
Claude-cycle helium refrigerators/liquefiers (Air Liquide & Linde)

<table>
<thead>
<tr>
<th></th>
<th>HELIAL SL</th>
<th>HELIAL ML</th>
<th>HELIAL LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Liquefaction capacity without LN2</td>
<td>25 L/h</td>
<td>70 L/h</td>
<td>145 L/h</td>
</tr>
<tr>
<td>Max. Liquefaction capacity with LN2</td>
<td>50 L/h</td>
<td>150 L/h</td>
<td>330 L/h</td>
</tr>
<tr>
<td>Compressor electrical motor</td>
<td>55 kW</td>
<td>132 kW</td>
<td>250 kW</td>
</tr>
<tr>
<td>Specific consumption for liquefaction w/o LN2</td>
<td>645 W/W</td>
<td>552 W/W</td>
<td>505 W/W</td>
</tr>
<tr>
<td>% Carnot</td>
<td>10%</td>
<td>12%</td>
<td>13%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Without LN₂ precooling</th>
<th>With LN₂ precooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>L70</td>
<td>20 - 35 l/h</td>
<td>40 - 70 l/h</td>
</tr>
<tr>
<td>L140</td>
<td>45 - 70 l/h</td>
<td>90 - 140 l/h</td>
</tr>
<tr>
<td>L280</td>
<td>100 - 145 l/h</td>
<td>200 - 290 l/h</td>
</tr>
<tr>
<td>LR70</td>
<td>100 - 145 Watt</td>
<td>130 - 190 Watt</td>
</tr>
<tr>
<td>LR140</td>
<td>210 - 290 Watt</td>
<td>255 - 400 Watt</td>
</tr>
<tr>
<td>LR280</td>
<td>445 - 640 Watt</td>
<td>560 - 900 Watt</td>
</tr>
</tbody>
</table>
Refrigerator

Compressor

Cold Box

LOAD

$T_0 = 300 \text{ K}$

$T_1 = 4.5 \text{ K}$

$Q_1$

$1 \text{ g.s}^{-1} \text{LHe } 100 \text{ W @ 4.5 K}$

$LHe$

isobar (1.3 bar)

$125 \text{ W @ 4.5K} \approx 1 \text{ g/s LHe}$

Liquefier

Compressor

Cold Box

LOAD

$T_0 = 300 \text{ K}$

$T_1 = 4.5 \text{ K}$

$Q_1$

$R$

$18.8 \text{ J.g}^{-1}$

$1543 \text{ J.g}^{-1}$

$4.5 \text{ K}$

$4.2 \text{ J.g}^{-1}.\text{K}^{-1}$

$23.1 \text{ J.g}^{-1}.\text{K}^{-1}$

$S$
Process cycle & T-S diagram of LHC 18 kW @ 4.5 K cryoplant
Process diagram, LHC compressors 18 kW @ 4.5 K

Oil lubricated screw compressors, water cooled, oil separation included

Machine derived from industrial refrigeration (or compressed air)
No more piston (high PR, low flow), not yet centrifugal (high flow, low PR)
Compressor station of LHC 18 kW@ 4.5 K helium refrigerator

4.2MW input power
Bldg: 15m x 25m

Oil/Helium Coolers  Compressors  Motors
Oil-injected screw compressor

(derived from Industrial refrigeration, compressed air)
Process diagram, LHC refrigerator 18 kW @ 4.5 K

LN2 (cool-down)

Heat exchangers

Adsorbers (remove impurities)

Turbines

300 K  75 K  50 K  20 K  4.5 K

20 K return
50 K supply
75 K return
LHC 18 kW @ 4.5 K helium cryoplants

33 kW @ 50 K to 75 K, 23 kW @ 4.6 K to 20 K, 41 g/s liquefaction

Diameter: 4 m
Length: 20 m
Weight: 100 tons
600 Input/Output signals
Brazed aluminium plate heat exchanger

Largest used: 1.4 m x 1.4 m x 8 m
(10 tons)
Cryogenic turbo-expander
Specific technology “contact free” gas bearings operated at 120’000 rpm

Wheel diameter: 5-15 cm
Shaft length: 20 cm
Rotation: 60’000 to 150’000 rpm
Challenges of power refrigeration at 1.8 K

- Compression of large mass flow-rate of He vapor across high pressure ratio ⇒ intake He at maximum density, i.e. cold
- Need contact-less, vane-less machine ⇒ hydrodynamic compressor
- Compression heat rejected at low temperature ⇒ thermodynamic efficiency
1.8K Units with cold compressors (x8)

Cold Compressor

3-phase induction Electrical motor (rotational speed: 200 to 800 Hz)

Fixed-vane diffuser

Spiral volute

Axial-centrifugal Impeller (3D)

Active magnetic bearings

Pressure ratio 2 to 4

Cold under vacuum

300 K under atmosphere

Inlet

Outlet

Specific technology to allow large capacity below 2K
Contents

• Introduction
• Cryogenic fluids
• Heat transfer & thermal insulation
• Cryogenic distribution & cooling schemes
• Refrigeration & liquefaction
• Trends and future machines
• Concluding remarks, references
New LINACS (Project, construction, Commissioning)

International Linear Collider (ILC)

e+ e- linear collider
Collision energy 500 GeV c.m. initially, later upgrade to ~1 TeV c.m.
Overall length 31 km
Key technology: SC RF cavities

Global Design Effort
No central laboratory
World-wide collaboration
Site-specific studies conducted on sample sites

2K superconducting RF Linacs, with cryogenic systems mostly based on existing technologies with variants or improvements
HiLumi LHC

Beam Screen

Cold Mass

Assembly (IT.R5)

LHC

CERN

Fermilab

Cryostat

N\textsubscript{b}-Ti + single cooling channel at 1.8K

Tungsten shielding

CERN

Fermilab

Assembly

N\textsubscript{b}-3Sn + double cooling channel at 1.8K

Cryogenics mostly based on existing technologies with variants or improvements

S. Claudet

LHC Cryogenics at CERN over decades
Future Circular Collider studies

A really new project, pushing to go beyond today’s state-of-the-art technologies for Cryogenic as well: 1MW class cooling below 40K, new gas mixture Ne-He, new machinery ....
LHC Cryo operator in Cern Central Control room

Feasibility, Demonstrated capacity, Availability

Fully automated, supervised by a single operator!
Concluding remarks

- Cryogenics serving superconducting systems is now part of all major accelerators and future projects (linear, circular).

- While advanced applications tend to favor “below 2K”, many almost industrial applications are based on “4.5K” and RnD (or demonstrators) continues for “high temperature” applications.

- If cryogenic engineering follows well defined rules and standards, there are variants depending on boundary conditions, continents, time of a project...

I could only recommend that demonstrated experience be evaluated and adapted to specific requirements you may have!

Thanks for your attention, and hoping you would (now) be more aware with cryogenics !!!
Some references

  - U. Wagner, *Refrigeration*
  - G. Vandoni, *Heat transfer*
  - Ph. Lebrun, *Design of a cryostat for superconducting accelerator magnet*
  - Ph. Lebrun & L. Tavian, *The technology of superfluid helium*
- Proceedings of ICEC and CEC/ICMC conferences
Bonus slides
Safety notes

- Major risks associated with cryogenic fluids at low temperatures:
  - **Asphyxiation**: Oxygen is replaced by a pure
  - **Cold burns**: in case of contact with cold surfaces
  - **Explosion**: pressure rise in case of warm-up at constant volume
    (1 l Liq $\approx$ 700 l gas)
  - **Embrittlement**: Thermal contractions, potential fragile at cold

- Be informed about valid standards, like for pressure vessels, safety
  devices, transport of cryogens, ...
Bulk Liquid & Gaseous cryogen storage solutions

Deliveries in Liquid form:
- 60 trucks LN2 to cool a LHC sector to 80K (14 days - 1’200t)
- 20 trucks for external storage of helium (4 months - 90tons)

250m3 Gaseous He
(20B - 850kg He)
How to deal with impurities

• Any liquid or gas other than helium would solidify during the cooling process. This could block the helium flow or degrade moveable components (valves, turbines)

• Typical treatment applied for: Water, air (N2 and O2), H2 (adsorption on porous medium like activated charcoal, molecular thieve)

Recommendation:
⇒ evacuation of air once circuits are leak-tight (pur helium)
⇒ on-line treatment of what could remain or arrive during operation, with target of fraction of ppm(v)
Thermometry

Industrial instrumentation whenever possible, specific developments when necessary

6’000 units, +/- 10 mK @ 2K in LHC radiation conditions

From ‘sensor’ to ‘thermometer’ with signal processing
Industrial Control Architecture

Industrial Supervision Layer
- Interface to operators (Monitoring & Command emission)
- Real time DB & Archiving

Industrial Control layer
- Control Logic Actions

Industrial Field layer
- control system connection to the process directly or through field-buses

Operator Consoles
- SCADA Servers

Accelerator Presentation Tier

Accelerator Middle Tier

Accelerator Resource Tier
- 4 x 30 PLC’s
- 4 x 15,000 I/O
- 8 x 500 PID loops

Fieldbus Networks
Superfluid Helium:
- Lower viscosity
- Larger heat transfer capacity
LHC sector cooling scheme

Pressurized/saturated He II

37'500 tons at 1.9 K

$Q_{\text{dist}} = 450 \text{ W}$

$Q_{\text{load}} = 2400 \text{ W}$

$T_{\text{sink}} = 1.8 \text{ K}$

$T_{\text{load\_max}} = 1.9 \text{ K}$
Electrical Feed Box for current leads

- Low current module 6kA & 600A leads
- High current module 13kA & 6kA leads
- Shuffling module
- Vacuum equipment VAA
- Current lead chimneys
- Removable door
- Supporting beam
- Jumper cryo connection to QRL
- SHM/HCM interconnect
- HCM/LCM interconnect

LHC: 3.4 MAmp

x 16
2 per LHC Point

1.9K
4.5K

Rearmov: 3.4 MAmp
Beating the WFL law: HTS current leads

- The WFL law essentially states that good electrical conductors are also good thermal conductors.
- Current leads need good electrical conductors with low thermal conductivity.
- Superconductors are bad thermal conductors with zero resistivity.
- Build current lead with superconductor up to temperature as high as possible, i.e. HTS.
Electrical feed boxes for current leads

48 Boxes, 1200 leads

More than 10’000 Amperes per chimney, from room temperature down to 4.5K in about a meter
## HTS vs. normal conducting current leads

<table>
<thead>
<tr>
<th>Type</th>
<th>Resistive [W/kA]</th>
<th>HTS (4 to 50 K) Resistive (above) [W/kA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat into LHe</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total exergy consumption</td>
<td>430</td>
<td>150</td>
</tr>
<tr>
<td>Electrical power from grid</td>
<td>1430</td>
<td>500</td>
</tr>
</tbody>
</table>

For LHC, using HTS allowed to save the equivalent of 1 large 18kW@4.5K refrigerator!
Standard cells (≈27/sector)

- Cool-down using mostly Flow controllers
- P, T, L controllers at operating conditions
1/8e of the LHC: refrigeration - distribution - cooling cells

Total 8 sectors:
Compressors: 64
Turbines: 74
Cold Comp.: 28
Leads: 1’200
I/O signals: 60’000
PID loops: 4’000

- Initial test of all sub-systems (at least one per type)
- Global functional analysis, interlocks, PID controllers, automatism to capitalise experience, procedures, training
- Computerised maintenance management

x 13.5
Basic thermodynamics at low temperature

- Minimum refrigeration work $W_{\text{min}}$ to extract heat $Q$ at temperature $T$ and reject it at ambient temperature $T_a$

  $$W_{\text{min}} = Q \left(\frac{T_a}{T} - 1\right) = T_a \Delta S - Q$$

- At cryogenic temperature $T \ll T_a$

  $$W_{\text{min}} \asymp Q \frac{T_a}{T} \ll T_a \Delta S$$

- Entropy is a good measure of the cost of cryogenic refrigeration
- Strategies minimizing $\Delta S$ improve cryogenic design
Cryogenic design strategies

Cooling scheme

Insulation

Shielding, heat interception

Q refri

Q device

Q shield

T refri

T device

T shield

Temperature

Cooling Power

Increasing S

Ln Q

Ln T
Operation, indicators

Global availability

Efficiency

Alarms

Powering

It works !!!
2016 Cryogenic Availability for LHC (Cryo Maintain signal)

LHC CRYO AVAILABILITY SUMMARY FROM RUN 1 TO RUN 2

<table>
<thead>
<tr>
<th>Year</th>
<th>CRYO</th>
<th>CRYO PLC</th>
<th>CRYO SEU</th>
<th>SUPPLY</th>
<th>66 kV transf.</th>
<th>USERS</th>
<th>RUN TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>5.2%</td>
<td>4.2%</td>
<td>3.4%</td>
<td>3.5%</td>
<td>0.9%</td>
<td>0.5%</td>
<td>98.6%</td>
</tr>
<tr>
<td>2011</td>
<td>94.8%</td>
<td>2.5%</td>
<td>1.2%</td>
<td>0.5%</td>
<td>95.5%</td>
<td>1.0%</td>
<td>95.3%</td>
</tr>
<tr>
<td>2012</td>
<td>2.7%</td>
<td>93.3%</td>
<td>2.1%</td>
<td>1.1%</td>
<td>95.5%</td>
<td>1.0%</td>
<td>95.3%</td>
</tr>
<tr>
<td>2015</td>
<td>98.6%</td>
<td>0.7%</td>
<td>0.5%</td>
<td>2.1%</td>
<td>95.5%</td>
<td>1.0%</td>
<td>94.4%</td>
</tr>
<tr>
<td>2016</td>
<td>1.7%</td>
<td>3.5%</td>
<td>1.5%</td>
<td>1.0%</td>
<td>94.4%</td>
<td>1.0%</td>
<td>94.4%</td>
</tr>
</tbody>
</table>

Quite a successful year

<table>
<thead>
<tr>
<th>Year</th>
<th>Total downtime [Duration: h]</th>
<th>Total downtime [Cryo Maintain lost: quantity]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>273</td>
<td>164</td>
</tr>
<tr>
<td>2016</td>
<td>79</td>
<td>19</td>
</tr>
</tbody>
</table>
In average, the helium consumption has been ~ 0.9 t / month during physic run 2016. During eYETS period, helium consumption is expected ~ 1.1 t/month