Introduction to Cryogenics

T. Koettig, P. Borges de Sousa, J. Bremer

Contributions from S. Claudet and Ph. Lebrun

CAS@ESI: Basics of Accelerator Physics and Technology, 7 - 11 Oct. 2019, Archamps
Introduction to cryogenic installations

Safety aspects => handling cryogenic fluids

Motivation => reducing thermal energy in a system

Heat transfer and thermal insulation

Helium cryogenics, He I => He II

Conclusions

References
Overview of cryogenics at CERN - Detectors

- Superconducting coils of LHC detectors @ 4.5 K (ATLAS, CMS)
- LAr Calorimeter - LN$_2$ cooled
- Different types of cryogens (Helium, Nitrogen and Argon)
Overview of cryogenics at CERN - LHC

- Helium at different operating temperatures (thermal shields, beam screens, distribution and magnets, …)
- Superconducting magnets of the LHC accelerator
- Accelerating SC cavities
Safety aspects in cryogenics
<table>
<thead>
<tr>
<th>Fluid</th>
<th>$^4\text{He}$</th>
<th>$\text{N}_2$</th>
<th>$\text{Ar}$</th>
<th>$\text{H}_2$</th>
<th>$\text{O}_2$</th>
<th>$\text{Kr}$</th>
<th>$\text{Ne}$</th>
<th>$\text{Xe}$</th>
<th>$\text{Air}$</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling temperature (K) @ 1.013 bar</td>
<td>4.2</td>
<td>77.3</td>
<td>87.3</td>
<td>20.3</td>
<td>90.2</td>
<td>119.8</td>
<td>27.1</td>
<td>165.1</td>
<td>78.8</td>
<td>373</td>
</tr>
<tr>
<td>Latent heat of evaporation @ $T_b$ in kJ/kg</td>
<td>20.9</td>
<td>199.1</td>
<td>163.2</td>
<td>448</td>
<td>213.1</td>
<td>107.7</td>
<td>87.2</td>
<td>95.6</td>
<td>205.2</td>
<td>2260</td>
</tr>
<tr>
<td>Volume ratio gas($273$ K)/ liquid</td>
<td>709</td>
<td>652</td>
<td>795</td>
<td>798</td>
<td>808</td>
<td>653</td>
<td>1356</td>
<td>527</td>
<td>685</td>
<td>------</td>
</tr>
<tr>
<td>Volume ratio saturated vapor to liquid (1.013 bar)</td>
<td>7.5</td>
<td>177.0</td>
<td>244.8</td>
<td>53.9</td>
<td>258.7</td>
<td>277.5</td>
<td>127.6</td>
<td>297.7</td>
<td>194.9</td>
<td>1623.8</td>
</tr>
<tr>
<td>Specific mass of liquid (at $T_b$) – kg/m³</td>
<td>125</td>
<td>804</td>
<td>1400</td>
<td>71</td>
<td>1140</td>
<td>2413</td>
<td>1204</td>
<td>2942</td>
<td>874</td>
<td>960</td>
</tr>
</tbody>
</table>
Cryogenic hazardous events – Discharge of helium

- Displacement of oxygen \(\Rightarrow\) Asphyxiation risk!
- Opposite behavior for e.g. argon and nitrogen!

Safer location on the floor

Simulated blow out in the LHC tunnel cross section

10-Oct-19

T. Koettig TE/CRG
Technical risks

Embrittlement

- Some materials become brittle at low temperature and rupture when subjected to mechanical force (carbon steel, ceramics, plastics)

Thermal contraction (293 K to 80 K)

- Stainless steel: 3 mm/m
- Aluminum: 4 mm/m
- Polymers: 10 mm/m
- Requires compensation for transfer lines, QRL ...

Condensation of atmospheric gases

- Inappropriate insulation or discharge of cryogens
- Observed at transfer lines and during filling operations (liquid air ~50 % O₂ instead of 21 % in atmospheric air)
Cryogenics and Superconductivity
## Characteristic temperatures of low-energy phenomena

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debye temperature of metals</td>
<td>few 100 K</td>
</tr>
<tr>
<td>High-temperature superconductors</td>
<td>~ 100 K</td>
</tr>
<tr>
<td>Low-temperature superconductors</td>
<td>~ 10 K</td>
</tr>
<tr>
<td>Intrinsic transport properties of metals</td>
<td>&lt; 10 K</td>
</tr>
<tr>
<td>Cryopumping</td>
<td>few K</td>
</tr>
<tr>
<td>Cosmic microwave background</td>
<td>2.7 K</td>
</tr>
<tr>
<td>Superfluid $^4$He</td>
<td>2.17 K</td>
</tr>
<tr>
<td>Bolometers for cosmic radiation</td>
<td>&lt; 1 K</td>
</tr>
<tr>
<td>ADR stages, Bose-Einstein condensates</td>
<td>~ µK</td>
</tr>
</tbody>
</table>
Superconductivity

- H. Kamerlingh Onnes

- Liquefied helium in 1909 at 4.2 K with 60 g He inventory

- Observed in 1911 for the first time superconductivity of mercury

- Nobel prize 1913

Historic graph showing the superconducting transition of mercury, measured in Leiden in 1911 by H. Kamerlingh Onnes.
Cryogenic application: Dipole magnets of the LHC

All circuits are cooled by helium

LHC main cryostat
(Cross-section)

Alignment targets

Multi layer insulation (MLI)

Vacuum vessel

Thermal shield

Beam screen

Magnet support posts (GFRE)

External supports (jacks)

Bottom tray
(50-65 K feed line
~ 19.5 bar)

5-20 K support post
heat intercept

CERN

10-Oct-19

T. Koettig TE/CRG
13
Heat Transfer and Thermal Insulation
Heat transfer: General

- **Solid conduction:**

- **Thermal radiation:**
  *(with and without MLI)*

- **Natural convection:**
  *Negligible with insulation vacuum for $p < 10^{-6}$ mbar*

Source: Edeskuty, Safety in the Handling of Cryogenic Fluids
Choosing the right materials in terms of mechanical strength and low-temperature properties is essential.
Heat capacity of materials

Discrete lattice vibrations $\Rightarrow$ Phonon

Metals have a contribution of free electron gas $\Rightarrow$ dominant at very low temperature

Source: Enss, Low temperature physics.

Source: Ekin, Experimental Techniques for Low-Temperature Measurements.
Thermal conductivity, solid conduction

Heat transport in solids

Fourier's law: \[ \dot{Q} = -\lambda(T) \frac{A}{l} \nabla T \]

Pure dielectric crystals: phonons

Dielectrics/Insulators: phonons

Pure metals: free electron gas and phonons

Alloyed metals: electrons and phonons

From: Cryogenie, Institut International du Froid, Paris
Radiative heat transfer – Black body

- Wien’s law (Maximum of black body power spectrum)

\[ \lambda_{\text{max}} T = 2898 \, \mu\text{m} \, \text{K} \]

\[ \Rightarrow 10 \, \mu\text{m} \, \text{for} \, T = 300 \, \text{K} \]

Radiative heat transfer

• Wien’s law (Maximum of black body power spectrum)

\[ \lambda_{\text{max}} T = 2898 \, \mu m \, K \]

\[ \Rightarrow 10 \, \mu m \quad \text{for} \quad T = 300 \, K \]

• Stefan-Boltzmann’s law

- Black body

\[ \dot{Q}_{\text{rad}} = \sigma A T^4 \]

\[ \sigma = 5.67 \times 10^{-8} \, W/(m^2 \, K^4) \]

(Stefan-Boltzmann’s constant)

- “Gray” body

\[ \dot{Q}_{\text{rad}} = \varepsilon \sigma A T^4 \]

\[ \varepsilon - \text{emissivity of surface} \]

- “Gray” surfaces at \( T_1 \) and \( T_2 \)

\[ \dot{Q}_{\text{rad}} = E \sigma A (T_1^4 - T_2^4) \]

\[ E - \text{function of} \ \varepsilon_1, \varepsilon_2, \text{geometry} \]
## Emissivity of technical materials at low temperatures

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Surface at 77 K</th>
<th>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>0.02</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>

Condensed layers from gas phase easily vary these values!
Multi-layer insulation (MLI)

Complex system involving three heat transfer processes

- \( Q_{\text{MLI}} = Q_{\text{radiation}} + Q_{\text{solid}} + Q_{\text{residual}} \)
- With \( n \) reflective layers of equal emissivity, \( Q_{\text{radiation}} \approx \frac{1}{(n+1)} \)
- Parasitic contacts between layers, \( Q_{\text{solid}} \) increases with layer density
- \( Q_{\text{residual}} \) due to residual gas trapped between layers, scales as \( 1/n \) in molecular regime
- Non-linear behavior requires layer-to-layer modeling

Large surface application
# Typical heat fluxes between flat plates (cold side vanishingly low)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black-body radiation from 293 K</td>
<td>420</td>
</tr>
<tr>
<td>Black-body radiation from 80 K</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Refrigeration and Liquefaction
Thermodynamics of cryogenic refrigeration

\[ Q_0 = Q_i + W \]

First principle [Joule]

Second principle [Clausius]

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

(= for reversible process)

Hence,\[ W \geq T_0 \cdot \frac{Q_i}{T_i} - Q_i \]

which can be written in different ways:

1. \[ W \geq T_0 \cdot \Delta S_i - Q_i \]
   introducing entropy \( S \) as \[ \Delta S_i = \frac{Q_i}{T_i} \]

2. \[ W \geq Q_i \left( \frac{T_0}{T_i} - 1 \right) \]
   Carnot factor
Thermodynamics of cryogenic refrigeration

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

For low temperatures:

\[ \frac{T_w}{T_c} < 1 \quad \frac{T_w}{T_c} > 1 \]

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

<table>
<thead>
<tr>
<th>Gas</th>
<th>Cold Temperature [K]</th>
<th>Carnot factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>He II</td>
<td>1.8 K - $\varepsilon_c = 166$</td>
<td></td>
</tr>
<tr>
<td>He</td>
<td>4.5 K - $\varepsilon_c = 65.7$</td>
<td></td>
</tr>
<tr>
<td>H$_2$</td>
<td>20 K - $\varepsilon_c = 14$</td>
<td></td>
</tr>
<tr>
<td>N$_2$</td>
<td>77 K - $\varepsilon_c = 2.9$</td>
<td></td>
</tr>
</tbody>
</table>
Elementary cooling processes in a T-s diagram

- Isobar (heat exchanger)
- Isentropic
- Isenthalpic (Joule-Thomson valve)
- Expansion engine
Maximum Joule-Thomson inversion temperatures

- Air can be cooled down and liquefied by J-T expansion from room temperature,
- Helium and hydrogen need precooling down to below the inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

Source: http://faculty.chem.queensu.ca/people/faculty/mombourquette/Chem221/3_FirstLaw/ChangeFunctions.asp
Two-stage Claude cycle
Process cycle & T-s diagram of LHC 18 kW @ 4.5 K cryoplant

20 K - 280 K loads
(LHC current leads)

50 K - 75 K loads
(LHC shields)

4.5 K - 20 K loads
(magnets + leads + cavities)

LN2 Precooler

Adsorber

201 K
75 K
49 K
32 K
20 K
13 K
10 K
9 K
4.4 K
0.1 MPa
0.4 MPa
1.9 MPa
0.3 MPa

T

S

from LHC loads

To LHC loads

T. Koettig TE/CRG
COP of large cryogenic helium refrigerators

Size of the plant matters

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

<table>
<thead>
<tr>
<th>Plant</th>
<th>C.O.P. [W/W @ 4.5K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TORE</td>
<td>466</td>
</tr>
<tr>
<td>RHIC</td>
<td>466</td>
</tr>
<tr>
<td>TRISTAN</td>
<td>466</td>
</tr>
<tr>
<td>CEBAF</td>
<td>350</td>
</tr>
<tr>
<td>HERA</td>
<td>280</td>
</tr>
<tr>
<td>LEP</td>
<td>200</td>
</tr>
<tr>
<td>LHC</td>
<td>200</td>
</tr>
</tbody>
</table>

- TORE: Tokamak in France
- RHIC: Heavy ion collider US
- TRISTAN: e+e- Accel. in Japan
- CEBAF: LINAC ring US
- HERA: Circular acc. Germany
- LEP: e+e- Accel. CERN
- LHC: Hadron Acc. CERN

Carnot Limit
LHC 18 kW @ 4.5 K helium cryoplants

- Th. shields: 33 kW @ 50 K to 75 K
- Beam screen: 23 kW @ 4.6 K to 20 K
- Current leads: 41 g/s liquefaction
- 4 MW compressor power
- COP 220-230 W/W @ 4.5 K

Air Liquide

Linde
LHC 18 kW @ 4.5 K helium cryoplants

8 x 18 kW @ 4.5 K
1800 SC magnets

24 km and 20 kW @ 1.9 K
36,000 ton @ 1.9 K
96 ton of He

Air Liquide

Linde

Cryogenic plant
$^4$He phase diagram

SC cavities are cooled in a 4.5 K saturated LHe bath

Source: CERN, LHC design report, ch. 11
Cryogenic Fluid Properties

He I and He II
Normal fluid helium => He I
- Like a standard fluid: viscosity etc.

Superfluid helium => He II
- Temperature < 2.17 K
- Peak in heat capacity $c_p$ at $T_\lambda$
- Very high thermal conductivity
- Low / vanishing viscosity

Murakami, Experimental study of thermo-fluid dynamic effect in He II cavitating flow, Cryogenics, 2012.
Phase diagram of $^4$He

$T_\lambda \approx 2.1768 \text{ K}$ @

$p_\lambda \approx 50.41 \text{ mbar}$

Glass cryostat set-up

Boiling effects during cooldown / Pumping on the He vapour
How to explain that unique behaviour?

Two fluid model of L. Tisza:

He II is composed of two components
Two-fluid model of He II by Tisza, 1938

Formal description of He II as the sum of a normal and a superfluid component.

Ratio $\rho_s/\rho_n$ depends on temperature.

Superfluid component:
- no entropy: $S_s = 0$
- zero viscosity: $\eta_s = 0$

Normal component:
- carries total entropy: $S_n = S$
- finite viscosity: $\eta_n = \eta_n$
He II in practice
Superleak below $T_\lambda$

1963 film by Alfred Leitner, Michigan State University
Critical heat flux in He II

Heat and mass flow are limited by a critical velocity:

\[ v > v_{cr} \]

Superfluid behavior becomes non-linear (mutual friction)

Formation of vapor bubbles at the surface of the heater

In He II re-condensation of the vapor

Surface tension let the bubbles implode

Implosion speed exceeds \( v_1 \)

Shock wave \( \Rightarrow \) cavitation
Critical heat flux in He II (T<Tₜₐₜ)
Normal fluid cooling ($T>T_\lambda$)
Concluding remarks

• Cryogenics serving superconducting systems is now part of all major accelerators and future projects,

• While advanced applications tend to favour “T< 2 K”, many almost industrial applications are based on “4.5 K” and R&D continues for “high temperature” applications,

• Even though cryogenic engineering follows well defined rules and standards, there are still variants depending on boundary conditions, continents, project schedule …

• I could only recommend that demonstrated experience is evaluated and adapted to specific requirements you may have!
Some references

- Proceedings of *CAS School on Superconductivity and Cryogenics for Particle Accelerators and Detectors*, Erice (2002)
  - 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
- CERN, HSE, Cryogenic Safety courses 1-3
Thank you for your attention.
Spare slides
Overview of cryogenics at CERN - Infrastructure

- Refrigeration plants (warm compressor stations and cold boxes – e.g., LHC, ATLAS, CMS)
- Refrigeration units (e.g., LHC cold compressor units)
- Liquefiers (Central Liqu., SM18, ISOLDE, CAST...)
Overview of cryogenics at CERN - Infrastructure

- Storage vessels: GHe or LHe
- Networks of distribution lines (warm and cryogenic)
- Q stands for Cryogenics

GHe 20 bar
LHe at 4.5 K
LN$_2$ at 80 K

QRL
Liquid or gaseous cryogens are odourless and colourless. Surface temperatures are not obvious. The human senses do not warn!

OFTEN ONLY secondary signs:

- Ice, water, air condensation (!) → indicates cold surfaces
- Fog → may indicate a leak of liquid or gaseous cryogens
- Risk of cold burn / Frost bite

Vapor pressure curves of common gases

1.85 K @ 19.5 mbar

Source: Haefer; Kryovakuumtechnik, 1981
Thermo-acoustic oscillations

Quarter wave resonator “resonance at one open end”

From: openstax college, Rice University, Sound Interference and Resonance, Download for free at http://cnx.org/content/col11406/latest/.
Thermo-acoustic oscillations (TAO or Taconis)

Gas in contact with a wall that is subjected to a temperature gradient

\[ Y_C = r \cdot \sqrt{\frac{\nu_1 \cdot \rho_{vap}}{l_{cold} \cdot \nu_{vap}}} \]

\[ \alpha = \frac{T_{hot}}{T_{cold}} ; \quad \xi = \frac{l_{hot}}{l_{cold}} \]

Typical frequencies 10 to 40 Hz

Conditions:

Stand pipe of a transfer line

\[ T_{warm} = 280 \text{ K} \]
\[ T_{cold} = 2.1 \text{ K saturated bath} \]
\[ L_{cold} = 0.35 \text{ m} \]
\[ L_{warm} = 0.35 \text{ m} \]
\[ r_{Tube} = 5 \text{ mm inner tube radius} \]

Thermo-acoustic oscillations (TAO or Taconis)

- Oscillations are more likely and stronger at lower pressure
- $\Delta p = \pm 0.3$ bar
- Reduction/attenuation by:
  - restriction and warm buffer
  - insert in tube
  - closing bottom of tube by liquid
Heat capacity of materials vs. cooldown

Amount of cryogen required to cool down 1 kg iron to sat. temperature

<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 liter</td>
<td>0.75 liter</td>
</tr>
<tr>
<td>LHe from 77 to 4.2 K</td>
<td>1.46 liter</td>
<td>0.12 liter</td>
</tr>
<tr>
<td>LN₂ from 290 to 77 K</td>
<td>0.45 liter</td>
<td>0.29 liter</td>
</tr>
</tbody>
</table>

Vaporization of normal boiling cryogens under 1 W applied heat load

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>[mg/s]</th>
<th>[l/h] (liquid)</th>
<th>[l/min] (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>
Emissivity of technical materials at low temperatures

Emissivity of cold surface coated with water condensate dependent on layer thickness

<table>
<thead>
<tr>
<th>Layer thickness d</th>
<th>Emissivity $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$1$</td>
<td>0.9</td>
</tr>
<tr>
<td>$10$</td>
<td>0.8</td>
</tr>
<tr>
<td>$10^2$</td>
<td>0.7</td>
</tr>
<tr>
<td>$10^3$</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cold surface, 77 K</th>
<th>Gas inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al + Cat-a-Lac, Uniform over time, 0.06 Pa</td>
</tr>
<tr>
<td>2</td>
<td>Ni + Black Velvet 101-C10/3M, Sporadic</td>
</tr>
<tr>
<td>3</td>
<td>Ni + Black Velvet 101-C10/3M, Uniform over time, 0.1 Pa</td>
</tr>
<tr>
<td>4</td>
<td>Al, polished, $\varepsilon = 0.07$, Uniform over time, 0.06 Pa</td>
</tr>
<tr>
<td>5</td>
<td>Ni, polished, Sporadic</td>
</tr>
<tr>
<td>6</td>
<td>Ni, polished, Uniform over time, 0.1 Pa</td>
</tr>
</tbody>
</table>

Source: Haefer, Kryovakuumtechnik, 1981
Superconductivity – Properties

Three essential parameters of SC:

- **Critical Temperature**: $T_c$
  For $T_c > 23.2 \, K$ one calls it *High Temperature Superconductivity (HTS)*

- **Critical magnetic field strength**: $H_c$

- **Critical current density**: $j_c$

- Lowering the temperature allows for higher current density and higher magnetic field strength.
- Temperature stability and homogeneity are crucial.
LHC cryogenic distribution scheme - QRL

Pressurized/saturated He II

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}

37'500 tons at 1.9 K
Interface heat transfer at very low temperature

Source: Ph. Lebrun, Cooling with Superfluid Helium
The effectiveness of J-T expansion

Source: Ph. Lebrun, Cooling with Superfluid Helium
Refrigerator

LOAD
Cold Box
LP
HP
Compressor

$T_0 = 300 \text{ K}$

$T_1 = 4.5 \text{ K}$

$Q_1$

$T = 300 \text{ K}$

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

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

$4.5 \text{ K}$

$4.5 \text{ K}$

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

Isobar (1.3 bar)
For refrigerators/liquefiers with the same efficiency:

\[
1 \text{ g.s}^{-1} \text{ LHe} \equiv 100 \text{ W} @ 4.5 \text{ K}
\]
Process diagram, LHC refrigerator 18 kW @ 4.5 K

LN2 (cool-down)

Heat exchangers

Adsorbers (remove impurities)

Turbines

4.5 K supply
20 K return
50 K supply
75 K return

300 K 75 K 50 K 20 K 4.5 K
CERN in total is around 200 MW with LHC contributing to 115 MW

When the LHC is up and running the total average power for the whole CERN site will peak during July at about 180 MW of which:

- LHC cryogenics 27.5 MW (40 MW installed)
- LHC experiments 22 MW
Heat capacity – Lambda point

Minimum specific volume or maximum density occurs at $T = T_\lambda + 6 \text{ mK}$.

The saturated vapor pressure (SVP) is indicated.

$\frac{dv}{dT} \approx 30\%$ from 2.17 to 4.5 K.

Data from NIST, Hepak.