Cryogenics for LHC Experiments

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with contributions from: Johan Bremer, Udo Wagner
LHC experiments: ATLAS and CMS

general-purpose particle physics experiments run by international collaborations installed at the CERN LHC 100 m underground

Source: © CERN / BUL-PHO-2009-064-3
ATLAS: A Toroidal LHC ApparatuS

Calorimeters for measuring energies

Diagram of particle paths in the detector

Large superconducting magnets for bending charged particles trajectories and measuring momenta

Detector characteristics
- Width: 44m
- Diameter: 22m
- Weight: 7000t

Source: © CERN-GE-0803012-05, CERN-EX-1301009
Tracker and Calorimeters placed inside the coil
15 separate «slices»
Where to find cryogenics in LHC experiments

- as a cooling source for detector superconducting magnets
- as active “medium” of detectors for particles energy measurements like Liquid Ionization Chambers (liquefied rare gases detectors)
Content

- The ATLAS and CMS experiments
- Cryogenics for detector superconducting magnets
  - Magnets characteristics
  - Cryogenic system requirements
  - CMS solenoid: thermosyphon cooling scheme CMS
  - ATLAS toroids: forced flow cooling scheme
  - Operational experience
- Cryogenics for rare liquefied gases detectors
  - ATLAS liquid argon calorimeter
  - Requirements
  - Cryogenic system
  - Operational results
- References
Cryogenics for detector superconducting magnets
Detector superconducting magnets

- What is special about detector magnets:
  - have often to deliver a magnetic field in a large volume (sensitive volume CMS solenoid: 370 m³);
  - are often enclosed in the experiment. In this case the magnet system shall be made as “transparent” as possible, to diminish the possibility that particles will be adsorbed in the magnet “mass”;
  - are non-series magnets
Detector superconducting magnets

Common characteristics

- Coil support, thermal shield, cooling channels made out of Aluminum
- Al-stabilized NbTi-Cu conductors
- Operating temperature 4.5 - 4.8K
- Indirect cooling w 2-phase helium

Cryo requirements

- Cool-down with a max. temperature gradient of 40K
- Cool cold mass, current leads and thermal shields
- Accommodate static and dynamic heat loads
- Ensure slow dumps
- Limit fast dumps
- Limit thermal cycling
Solenoid magnets with thermosyphon cooling

- **ATLAS central solenoid**
  - 5.3 m length, 2.4 m diameter
  - 5 t cold mass
  - 2 T field, 7.73 kA nominal current
  - 38 MJ stored energy
  - Shares the calorimeter insulation space volume

- **CMS solenoid**
  - 12.5 m length, 7 m o.d.
  - 225 t cold mass
  - 4 T field @ IP, 2 T @ iron yoke
  - 18 kA nominal current
  - 2.7 GJ stored energy
  - the largest of its kind
CMS thermosyphon cooling

- Possible with a geometry allowing sufficient pressure head to drive the flow & avoiding high points with risk of vapour lock
- Driving force created by the difference in density between the liquid supply and the two phase return column: self sustained natural boiling convection
- Natural circulation, no cold mechanical pump needed
- When sufficient liquid available: magnet system can go into slow-dump in case of power failure
CMS refrigeration scheme

At 4.5K

Refrigerator data - 1.5 kW @ 4.5 K equivalent:
800 W @ 4.5K
4.5 kW @ 70K for thermal shield
4 g/s liquefaction load for current leads
CMS fast dump

Helium loss: 180 kg
CMS fast dump recovery

Time from fast dump to cryo-ready: 95 hours
Toroid magnets
with forced flow cooling

ATLAS:

- **Barrel Toroid**
  - 8 separate race track flat coils
  - 25.3 m length, 20.1 m o.d.,
  - 370 ton cold mass,
  - 1T (4 T on superconductor),
  - 20.5 kA nominal current;
  - 1.08 GJ stored energy;

- **2 End-cap Toroid**
  - 8 coils in common cryostat each
  - 5.0 m length, 10.7 m o.d.,
  - 160 ton cold mass,
  - 1T (4 T on superconductor),
  - 0.25 GJ stored energy

Source: © CERN
ATLAS Toroid forced flow cooling refrigeration scheme

6 kW @ 4.5K
1.1 b 19.4 b 500 g/s
Main refrigerator compressors
Main refrigerator cold box
4.5 K
4.5 K

20 kW @ 60K
1.25 b 18.0 b 320 g/s
Shield refrigerator compressors
Shield refrigerator cold box
40 K
80 K
40 K
80 K

Underground radiation-free cryogenic cavern
Surface building

80 K
40 K
4.5 K
4.5 K
80 K
40 K
4.5 K
4.5 K
4.5 K

Distribution valve box

Underground detector cavern

Centrifugal pump
1.2 0.7 kg/s / 300 mbar
Toroid proximity cryogenics

Buffer volume covering slow dump

Buffer volume for decoupling from toroid
Solenoid proximity cryogenics
ATLAS toroid fast dump

![Graph showing ATLAS toroid magnet fast dump](image-url)
ATLAS toroid fast dump recovery

Diagram showing the recovery process of the ATLAS toroid magnet, including data on Dewar level, Magnet Temperature, Phase separator level, Magnet Current, Cooling loop pressure, and the total recovery time of 94 hours. The timeline and values are plotted against time with specific markers for important events.
Performances of ATLAS cryogenics

<table>
<thead>
<tr>
<th>Year</th>
<th>2011</th>
<th>2012-13</th>
<th>2015</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total average availability (%)</td>
<td>96.5</td>
<td>98.3</td>
<td>92.5</td>
<td>97.1</td>
<td>98.3</td>
</tr>
</tbody>
</table>

Helium losses < 2 kg/d
Performances of CMS cryogenics

<table>
<thead>
<tr>
<th>Year</th>
<th>2011</th>
<th>2012-13</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total av. availability (%)</td>
<td>98.3</td>
<td>96</td>
<td>52.7</td>
<td>97.9</td>
<td>98.9</td>
<td>99.989</td>
</tr>
</tbody>
</table>

Helium losses < 0.2 kg/d
## Operational experience ~10 y

<table>
<thead>
<tr>
<th>Main causes for down-time</th>
<th>Main consolidations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity to power cuts:</strong></td>
<td>Detailed fault chain analysis</td>
</tr>
<tr>
<td>- “Glitches”, typically &lt;120 ms</td>
<td>Readjustment of hard and soft safety to be tolerant to power losses of &lt; 120 ms.</td>
</tr>
<tr>
<td>- Long term cuts, typically &gt;300 ms to black-out</td>
<td>Now most of the glitches are seen by the client system</td>
</tr>
<tr>
<td><strong>Control &amp; instrumentation</strong></td>
<td>Modification of hard wired safety chain</td>
</tr>
<tr>
<td>- Electrical contact error, element failure</td>
<td>Replacement of aging electrical cabinets (ATLAS), aging elements, aging PLCs, standardization,</td>
</tr>
<tr>
<td>- Mistakes or shortfalls in programmed controls</td>
<td></td>
</tr>
</tbody>
</table>
## Operational experience ~10 y

<table>
<thead>
<tr>
<th>Main causes for down-time</th>
<th>Main consolidations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil contamination 2015: Installations with well performing oil separators and coalescers suffered little</td>
<td>YETS 2015-16:</td>
</tr>
<tr>
<td>Major impact on CMS availability (52%!)</td>
<td>1. Exchange the final oil separator (generous design)</td>
</tr>
<tr>
<td></td>
<td>2. Exchange the coalescer stages (generous design)</td>
</tr>
<tr>
<td></td>
<td>3. Exchange the oil adsorbent material</td>
</tr>
<tr>
<td>Cumulated effect:</td>
<td>4. Exchange the high pressure piping between compressor station and cold-box</td>
</tr>
<tr>
<td>▪ Change of coalescers cartridges brand during 2013-14 preventive maintenance</td>
<td>5. Clean the cold box circuits</td>
</tr>
<tr>
<td>▪ bad choice of the adsorbent material of the final oil adsorber during 2013-14 preventive maintenance</td>
<td>6. Exchange the 20 K and 80 K adsorbers</td>
</tr>
<tr>
<td>▪ Under-sizing of the final oil separator of CMS</td>
<td>Better prevent than cure!</td>
</tr>
</tbody>
</table>

*YETS: year end technical stop ~3 months
## Operational experience ~10 y

<table>
<thead>
<tr>
<th>Main other limitations</th>
<th>Main improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaseous impurities and regular filter clogging:</td>
<td>Improved procedures. We live with periodic warm-up of turbine inlet filters (on-line, no down-time) and regeneration of adsorber / cold box (stop during TS)</td>
</tr>
<tr>
<td>- due to temperature excursions, accumulated gaseous impurities migrate to the 80K adsorber outlet, desorb, and clog the turbine inlet filters</td>
<td></td>
</tr>
<tr>
<td>- Single 80K adsorber without bypass</td>
<td></td>
</tr>
<tr>
<td>1st heat exchanger clogging twice a year (CMS): intervention in TS, no down time:</td>
<td>Install dryer units at both CMS and ATLAS in order to live 1 full year run without cold-box warm up</td>
</tr>
<tr>
<td>- Water from top up oil</td>
<td></td>
</tr>
<tr>
<td>- We rely on purges and oil adsorber heating to remove water during a start-up phase.</td>
<td></td>
</tr>
</tbody>
</table>
And more improvements

- Installed redundancy of all compressor stages
  - diminish down-time in case of large equipment failure

- de-coupling of ATLAS toroid and solenoid system with added 11000 liter dewar to solenoid system
  - diminish the effect of an eventual toroid fast-dump on the physics measurements
Cryogenics for liquefied rare gas detector
the ATLAS Liquid Argon Calorimeter
The ATLAS liquid argon calorimeter

A noble liquid ionization chamber

- Accordion shaped lead adsorber plates alternating with HV copper electrodes immersed in liquid argon bath
- Interactions with the adsorbers transform the incoming particle energy into a shower of secondary particles which in turn ionize the liquid argon
- The electrons created are accelerated in the HV field and this electrical “current” is measured by the electrodes.
- This allows to establish both the position and the energy of the incoming particle.

© CERN

Module of the accordion shaped electromagnetic calorimeter being assembled

Electrons shower in the calorimeter

© CERN
The ATLAS liquid argon calorimeter

- three Al cryostats
- total cold mass 550 t
- total liquid argon volume 100 m³ in underground
- temperature around 88.3 K
- cooled by forced flow evaporating liquid nitrogen
- 228000 signal wire feed-through
- operational 365/365 since 2005

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Length</th>
<th>Heat Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3 m</td>
<td>3 m</td>
<td>2.5 kW</td>
</tr>
<tr>
<td>(≈ 25% cold electronics)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Requirements

- **Cool-down**
  - keep $\Delta T$ within strict $T^\circ$ dependant limits ($<6K..45K$) to avoid any excessive stresses or displacements of the detector composite structure

- **Steady-state**
  - No gas bubble formation in liquid bath
  - Liquid argon bath temperature constant at about 88.4 K
    - Temperature stability not well defined in TDR
  - Temperature gradient across bath $< 0.7$ K
  - Argon purity $< 2$ ppm(v) of O2-equivalent
  - Safe and uninterrupted functioning over the life-time of the experiment
  - Prevent any condensation of water on the electrical feed-throughs

Energy measurement sensitivity: 2 % per K
Forced flow of evaporating liquid nitrogen

- Nitrogen circulated through heat exchangers via a centrifugal pump;
- 2-phase nitrogen flow regulated to the same pressure in all 12 heat exchangers placed in the baths;
- Wetting of heat exchanger ensured
- Nitrogen re-liquefied by refrigerator;
- System backed up by 100 m3 N2 storage at the surface;
LAr bath sub-cooled with 4 K to 7 K

Ar and N₂ saturation curves

Steady state

Pmin N₂ = 2.1 bar

Ar triple point
T = 83.8 K
P = 0.69 bar

No boiling (no gas production, no noise)
Time to recover from cooling failure

h barrel ≈ 3.4 m
h end-cap ≈ 2.4 m
expansion vessel

End-cap A

CERN

01/10/2019, TE-CRG/Caroline Fabre
2019 EASISchool 2 on Cryogenics
Cryogenics for LHC Experiments
Result 2010 data taking period

Temperature uniformity over detector volume: < 70 mK rms

Temperature stability: < 5 mK rms

LAr bath sub-cooled with 4.2 K to 7.7 K. No argon gas bubble

Argon purity: between 0.1 and 0.3 ppm of O2-equivalent
Un-interrupted functioning

Redundancies:

- LN2 pumps (x3)
- LN2 supply services (x3)
- all essential devices on backed-up electrical power system: EDF/EOS network, diesel generators, UPS
- compressed air and cooling water backed up
- Warm back-up for each of the PLCs (not really redundant)

Displacement of end-caps over 12 m for access to inner part
Safety aspects

Special features related to safe handling of large volume of cryogenic liquids in underground area:

- Argon volume of the three cryostats can be emptied into 2 x 50 m$^3$ argon storage tanks by:
  - gravity
  - cryogenic pump
- Argon tanks are equipped with LN2 condenser and kept cold
- Items containing large volumes are:
  - equipped with safety valves collected to a dedicated DN 500 pipe going to surface
  - placed above retention pits
- Gas constantly renewed from the retention pits by surface extraction system
- Insulation vacuum levels are monitored
- Oxygen detectors
Conclusion

These cryogenic systems have been designed, constructed and installed by international collaborations:

- CMS cryogenics: CEA-SACLAY, CERN
- ATLAS magnet cryogenics: CEA-SACLAY, CERN, INFN, KEK, RAL
- ATLAS calorimeter cryogenics: BNL, CEA, CERN, LAL, LPSC and NTNU
Some references

- Brédy Ph., *Challenges and limitations of thermosiphon cooling*, Symposium for the Inauguration of the LHC Cryogenics, CERN, 31/05 & 01/06 2007.
- Rabbers J.J. et al., *Theoretical and experimental investigation of the ramp losses in conductor and coil casing of the ATLAS Barrel Toroid Coils*,
- Fabre C., *Cleaning and consolidation of the CMS helium refrigerator after hydrocarbon contamination*, CryoOps workshop, Batavia, USA, 2016.
Back-up slides
ATLAS Barrel toroid cross section → Slow dump

- Vacuum Vessel
- Double Pancake
- Coil Casing
- Thermal Shield
- Cooling Pipes at 4.5 K
- Quench Heaters
- Cryogenic Stops
- Cooling Pipes at 60-80 K
- Tie Rod

When the current changes in the coil eddy currents are induced and the heat load of the cold mass increases

**Slow dump** is always preferred to fast dump

**Slow dump** is at constant $dI/dt$

Source: © Ruggero Pengo
# ATLAS design & measured heat loads

## Thermal loads at 4.5 K

<table>
<thead>
<tr>
<th>Component</th>
<th>Design (W)</th>
<th>Measured (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Static</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel toroid</td>
<td>660</td>
<td>510</td>
</tr>
<tr>
<td>Both End-Cap toroid</td>
<td>360</td>
<td>290</td>
</tr>
<tr>
<td>Central solenoid</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td>Pump</td>
<td>650</td>
<td>670</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>450</td>
<td>215</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2170</td>
<td>1702</td>
</tr>
<tr>
<td><strong>Dynamic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel toroid (2 hr)</td>
<td>350</td>
<td>360</td>
</tr>
<tr>
<td>Both End-Cap toroid (2 hr)</td>
<td>220</td>
<td>140</td>
</tr>
<tr>
<td>Central solenoid (20 min)</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>590</td>
<td>525</td>
</tr>
</tbody>
</table>

### Liquefaction load

- Design: \((1.6 \times 6 + 1.2) \text{ g/s} = 10.8 \text{ g/s}\)
- Measured: \((1.85 \times 6 + 1.2) \text{ g/s} = 12.3 \text{ g/s}\)

Source: © Giorgio Passardi
Operation of LHC detectors cryogenics

365 day operation
3 Technical Stops (~1 week) per year run for planned interventions
1 Year End Technical Stop for maintenance and improvements

- Detectors dedicated operation 2008 to 2016
  - Dedicated team of 5 CERN staff operators/team leader ensuring
    - Daily site operation
    - On-call service for outside of working hours interventions
  - back-up by 2nd line “Best Effort” support:
    - for operational or expert support in exceptional situation
    - for assistance of other support services (controls, electricity, maintenance…)

- LHC and its detectors common operation 2017 to 2019
  - Common team of 15 CERN staff operators/team leaders ensuring
    - Daily site operation
    - 24h Shift service from the Cern Central Control room for monitoring and 1st line interventions
  - 10 industrial support operators ensuring:
    - Daily operation
    - On-call service for outside of working hours 2nd line interventions
  - back-up by 2nd line “Best Effort” support
# Helium losses 2012

<table>
<thead>
<tr>
<th></th>
<th>Nominal inventory (kg)</th>
<th>Strategic inventory (kg)</th>
<th>Total losses 2012 (kg)</th>
<th>Perman ent losses (kg)</th>
<th>Losses due to stops (kg)</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>900</td>
<td>1200</td>
<td>-1600</td>
<td>330 (~27% of SI)</td>
<td>660 (~ 80 kg / stop)</td>
<td>610 (purges)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>2600</td>
<td>3500</td>
<td>-3350</td>
<td>1095 (~30% of SI)</td>
<td>740 (~185 kg / stop)</td>
<td>1515 (purges + CP6 installation)</td>
</tr>
</tbody>
</table>