Technology progress and R&D on detector cooling

L. Zwalinski – CERN EP/DT/FS
October 4th, 2016

European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland
Outline

- Detector cooling roadmap to HL-LHC.
- Recent experience with CO$_2$ cooling systems.
- Evaporative CO$_2$ R&D programs.
- Mono-phase R&D programs.
- Conclusions.
- Outlook.
# Detector cooling projects towards HL-LHC

## Evaporative CO$_2$
- **LHCb Velo & UT**
  - 2x7kW @ -30°C.
  - Will use current state-of-the-art technologies, no R&D required.
- **ATLAS ITk**
  - ~300kW @ -40°C and below
  - Requires R&D on low temperature, high capacity units and cooling loop complexity.
- **CMS TK Phase II**
  - ~100kW @ -35°C.
  - Requires R&D on high capacity units and loop complexity.
- **Common development for ATLAS and CMS**

## Mono-phase
- **ALICE ITS**
  - Leakless water system @ <30°C.
  - No R&D required.
- **LHCb SciFi**
  - 9.0kW @ -50°C.
- **Replacement of fluorocarbons**
  - Requires R&D on new refrigerants with similar properties to fluorocarbons with special focus on NOVEC fluids family.

---

**CMS HGC**

Evaporative CO$_2$ vs Mono-phase evaluation study has been launched.
Detector cooling R&D roadmap towards HL-LHC

Evaporative CO₂ is the common development for all experiments.
Cooling pipes and module temperature stable in 2016; variation below 0.2°C threshold

(<0.05 °C RMS)

** Please note that the temperatures values shown from 2015 have not yet been corrected with the calibration constants defined in April 2015. As a consequence cooling pipe sensors shown are ~1.5°C too high, Module temperatures ~0.5°C
ATLAS IBL operation experience

<table>
<thead>
<tr>
<th>Period</th>
<th>CO$_2$ System failure</th>
<th>Chiller or primary cooling issue</th>
<th>Software modification</th>
<th>NO cooling for the detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSS Interlock</td>
<td>Automatic swap</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data taking</td>
<td>Beam</td>
<td>1x (Flow meter failure)</td>
<td>4x</td>
<td>5x</td>
</tr>
<tr>
<td>No beam</td>
<td>1x (Initiated swap for maintenance followed by a trip of the 2nd system due to threshold conflict in the start-up stepper)</td>
<td>6x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No beam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TS</td>
<td>1x due to global ATLAS DSS alarm</td>
<td>6x</td>
<td>6x</td>
</tr>
<tr>
<td></td>
<td>MD</td>
<td></td>
<td>1x</td>
<td>1x</td>
</tr>
</tbody>
</table>

- The IBL CO$_2$ cooling system had an excellent track record: **0% downtime** during physics (1.5 year).
- Very limited number of interventions needed (mostly done in TS & MD).
- 3 incidents during detector operation:
  - 1 hardware failure with a **successful back-up procedure**.
  - 1 system failure during controlled swap.
  - 1 cooling plant trip due to global ATLAS DSS interlock. **NO cooling for the detector**
Recent experience with evaporative CO$_2$ cooling systems #3

ATLAS IBL flexible transfer lines experience

- Challenge: limited space **required small diameter insulation.**
  - Ø18mm vacuum vs. Ø70mm foam.
- Custom made flexible vacuum insulated tri-axle transfer lines have been developed.
  - Required **constant pumping** (min. vacuum level $10^{-3}$ mbar)
- Very positive experience! => easy to lay down in packed environment.

Flex transfer lines cross section

C. Bortolin Forum on Tracking Detector Mechanics 2015, Amsterdam
Recent experience with evaporative CO$_2$ cooling systems #5

CMS Tracker rigid static vacuum transfer line experience

- 3 different piping sections with different types of vacuum insulated concentric lines to minimize required space.
- Type 1 and 2 based on industrial standards.
- Type 3 custom made small diameter static vacuum lines with a distance of 7mm between cold and warm surface.

Identified problem for type 3:
- Surface $T < 13^\circ C$ when cold CO$_2$ circulates.
- Static pressure degraded in time; summer 2015 the best lines @ $10^{-3}$, the worst one few mbar.
- Installed getter pump system => hybrid solution.
- Careful design & TESTING needed for “out of standard” sizes.
Recent experience with evaporative CO$_2$ cooling systems #4

CMS Tracker large capacity experience

Normal operation:

- Requirements 2 x 7.5 kW @ -23°C.
- Achieved 2 x 11.0 kW @ -23°C.
- Achieved 2 x 7.0 kW @ -32°C.
- Maximum load of 6.5 kW on each plant reached at +15°C.

Limitation factor was the primary chiller @ CMS shared between many users.
Summary for the recent experience

1. The evaporative CO$_2$ cooling systems show high detector temperature stability with variations less than 0.2°C.

2. Very positive experience with small diameter triaxle vacuum insulated transfer lines has been gained.

3. Static vacuum insulated rigid transfer lines are a suitable solution for the future although careful attention should be given to non-standard sizes.

4. High cooling power capabilities were well proven by CMS.

5. Detector cooling systems are not simple fridges but are advanced technical units that always have to be treated as an integral part of the detector. The complex cooling distribution inside the detector directly influences its thermal performance and hence data quality.
CO$_2$ R&D programs
Sometimes boiling is not triggered, and reduced cooling performance is observed (bad heat transfer). We are trying to understand what causes this phenomena and how we can improve it.

A test set-up containing a real size stave pair including flex lines and its orientation has been made in SR1 to investigate the phenomena.

This study is highly important for Phase II upgrades of both ATLAS and CMS:

- Is this effect due to tube material? (IBL tests were performed with stainless steel)
- Do we need surface treatment?
- How can we control boiling in a passive way inside the detector?
- What can be done at the level of the accessible manifolds?

CMS Phase 1 will use pre-heating provided by DC/DC converters as additional boiling trigger. Long term behaviour will be validated during operation starting in 2017.

B. Verlaat The International Workshop on Semiconductor Pixel Detectors for Particles and Imaging (Pixel 2016)
Is the “warm nosing concept” with a by-pass loop the solution for Phase II??

- Control the temperature of the CO$_2$ in front of the manifold via back-pressure controlled by-pass loop.
- All controlled hardware is placed in accessible manifold location.
- Multiple loops can be controlled with 1 by-pass loop.
CO$_2$ R&D program #3

DEMO common ATLAS & CMS effort for pre-production large capacity cooling plant for HL-LHC

Time scale for results: 2020

Goal: Workout common CO$_2$ cooling unit fulfilling ATLAS and CMS requirements.

Challenges and sub R&D programs:

- Study and define redundancy scheme.
- Accumulation and CO$_2$ storage.
- High capacity pumps.
- Transfer lines & complex distribution.
  - Foreseen number of evaporators is $\sim$100x larger than in current evaporative CO$_2$ systems.
- HW components, outsourcing, QA.
  - Constant market survey is required due to industrial evolution.
  - Phase II will require $\sim$15+ large cooling plants to be constructed.
  - Industrial outsourcing will be required: suitable QA procedures must be put in place!
- Optimization for minimum temperature at high cooling capacity.

For more details please see ECFA 2014 “CO2 Cooling” P. Petagna
Baby DEMO small scale low temperature demonstrator – why, what and when?

R&D for ATLAS ITk low temperature CO₂ cooling (DEMO plant prototype).

Program time span: May 2016 – Dec 2017

Plant + chiller design and construction: outsourced to CUT (PL)

CMS declared their interest in BD effort and accepted financial contribution.

Goals:

• Provide input to the Pixel TDR about **minimum attainable cooling temperature** by the end of 2017 as it will have an impact on technological choices for the detector sensing elements.

  *Minimum attainable cooling temperature - is the minimum evaporation temperature inside the detector. This is not the cooling plant temperature as it must be lower due to pressure drop in the transfer lines.*

Challenges:

• Demonstration of a typical 2-PACL CO₂ plant to operate at the lowest temperature ever achieved!

• Investigate capability to reach an operational temperature down to -45°C. (at -56°C CO₂ freezes + CO₂ pumps require to operate safe sub cooling margin).

• The target is to bring the on evaporator temperature down to -40°C or lower, if possible!

• Typical distribution beyond PP2 manifold is required as it is the critical path due to pressure drop.
**Baby DEMO – how and where?**

BD1: the design, construction and operation of an R&D cooling plant (with cooling power of one PP2 branch)

BD2: the design, construction and R&D on a full scale “PP2 distribution line”, including manifolds with realistic height variations, to be coupled to the produced BD1 cooling plant.

A suited space at CERN has been made available by ATLAS for this activity; (proposed B180 full scale ATLAS mock-up already moved into required position).
Both CMS and ATLAS IBL use vacuum insulated transfer lines. Reduced size and more reliable insulation wrt to foam. Would it be possible to scale up the IBL flexible triaxle lines into Phase II suitable sizes? Looks feasible, first design ready, prototyping will start very soon.

What would be the cooling capacity vs diameter ratio? Simulations showed that 50mm flex line can have a 7.5kW capacity.

Designed by S. Vogt, MPI Munich
Dynamic simulations tools for 2-PACL systems

Time span: May 2016 – April 2019.

Dedicated PhD program at Manchester launched by EP-DT, supported 50-50 by ATLAS and CMS.

The main goal of the project is to build up a software tool that will allow for **modelling the time varying behavior** of cooling plants and distributions under any operational conditions.

Benefits for cooling system lifecycle.
- Design phase.
- Commissioning phase.
- Operation phase.

Dedicated use of CORA CO\textsubscript{2} cooling plant.

**Existing and well verified with real detector data, CoBra models** will be extended and implemented into Ecosim Pro commercial software.

---

**Example of use at CERN (BE-ICS)**

**Cryogenics**
Helium cryogenics for LHC and experiments

**Objective:** Cryo operator Training / Control optimization
Industrialization of the I-2PACL CO2 portable laboratory detector cooling units

- Industrial evolution of TRACI to MARTA (Mono-block Approach for Refrigeration Transportable Apparatus).
  - Optimization of cost and size.
  - Industrial manufacturing standards and techniques – mono-block.
  - Improved cooling capacity to ~300W @ -30°C.
  - Industrialization of LUCASZ cooling plants is also under consideration.

Signed Collaboration Agreement between CERN, KT and Polish consortium of CUT-PONAR-CEBEA

First prototype shall be ready by the end of 2016 with final price quotation.
Mono-phase R&D programs
NOVEC (649 and 7100)

Alternatives “GREEN” refrigerants as possible replacement of environmental unfriendly liquid fluorocarbons for detector cooling applications at CERN.

Project launched in 2015

Interdepartmental R&D (EN, EP, TE, HSE)

Scope of the R&D:

- **Radiation tests**
  - Check the fluid destruction/degradation rate.
  - Determine products of radiolysis.
  - Which of them are detrimental to the cooling system and personnel (corrosive, toxic)?

- **Material compatibility laboratory testing**
  - Testing of rubbers and plastics.
  - Measurement of absorption/extraction rate.
  - Measurement of mechanical properties.

- **Endurance test bench**
  - Evaluation of filtering and purification methods.
  - Evaluation of maintenance procedures.
  - **Evaluation of possible drop-in replacement for the existing systems.**
  - Monitoring of component performance and compatibility – long term operation.

---

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>GWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
</tr>
<tr>
<td>NOVEC 649</td>
<td>1</td>
</tr>
<tr>
<td>NOVEC 7100</td>
<td>320</td>
</tr>
<tr>
<td>C₆F₁₄</td>
<td>7400 !!!</td>
</tr>
</tbody>
</table>

---

*Endurance test bench in SR1*
Evaporative CO$_2$ or mono-phase cooling the solution for detectors other than trackers?

CMS HGCAL is planning to be equipped with silicon sensors therefore **cold detector cooling system is required**.

- Evaporative CO$_2$ cooling is proposed in the Technical Proposal as synergy with CMS and ATLAS Trackers.
- Feasibility study to understand if evaporative CO$_2$ or mono-phase detector cooling concept is the most suitable solution has been launched in EP-DT on request of CMS Endcap Calorimeter.
- Challenges:
  - Large mass of the detector.
  - High radiation doses.
  - Integration.
Conclusions

**Evaporative CO\textsubscript{2}**

- Relevant experience and an important standardization approach to CO\textsubscript{2} cooling for HEP detectors has been growing @ CERN since 2009.
- **Short term objectives:**
  - 4x LUCASZ cooling systems (first unit ready in 2016).
  - ATLAS low temperature R&D cooling system, Baby-Demo (ready by Q4 2017).
- **LS2 objectives:**
  - 2 x 7 kW @ T< -30 °C for LHCb Velo + UT
- **LS3 objectives:**
  - Large capacity & low temperature cooling unit of 30-45 kW @ T< -30 °C for ATLAS ITk, CMS TK + (HGCal) very demanding, requiring dedicated prototyping and technical studies, DEMO.

**Mono-phase**

- New refrigerants as possible replacement of C\textsubscript{6}F\textsubscript{14} are under investigation. NOVEC radiation resistance and material compatibility are the key issues addressed into ongoing R&D. At the moment NOVEC can not be considered as a drop in replacement for existing systems.
- **LS2 objectives:**
  - SciFi mono-phase cooling system based on NOVEC 649.
Outlook

- The path ahead is quite clear. Many goals for different detectors are similar which allows that currently developed techniques and standardization can be put in place for the upcoming LS2 challenges.

- Common ATLAS-CMS R&D projects for HL-LHC have been launched. (Baby-Demo and DEMO)

- Upcoming operation of new CMS PIXEL detector will allow to gain additional long term experience with high power 2PACL unit.

- Cold mono-phase cooling requires more environmental friendly dielectric refrigerants. The NOVEC study is well on route.

- The cooling community is slowly but surely growing. Effort ahead requires even more active participation from collaboration institutes and manpower.
Why evaporative CO$_2$ in pumping cycle for HEP?

- **Significant saving of cooling hardware**
  - (material budget) into the detector due to the physical properties:
    - large latent heat of evaporation
    - low liquid viscosity
    - high heat transfer coefficient
    - high thermal stability due to the high pressure
- Very practical fluid to work (environmental friendly, not activated)
- Practical range of the detector application -45$^\circ$C to +25$^\circ$C
**CO₂ facts and safety**

CO₂ has a high pressure (10-100bar) but this does not have to be an increased safety issue.

**Pressure Equipment Directive (PED):**
- Stored energy determines the safety class.
- Stored Energy = Pressure x Volume

CO₂ is environmentally friendly, non-toxic and cheap.

CO₂ in large concentrations is asphyxiating, be careful with venting CO₂ in unventilated small spaces.

CO₂ does not exist as liquid in atmospheric conditions. It is released as -78°C solid (Like a fire extinguisher). => Cold burn risk.

<table>
<thead>
<tr>
<th></th>
<th>ID</th>
<th>Design Pressure</th>
<th>Stored energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1.4mm</td>
<td>100 bar</td>
<td>15.4 J/m</td>
</tr>
<tr>
<td>C₃F₈</td>
<td>3.6mm</td>
<td>15 bar</td>
<td>15.3 J/m</td>
</tr>
</tbody>
</table>
ATLAS IBL pump:
- Triple head with out of phase gear box
- Reduced flow and pressure pulsations
- Heads in contact with cold CO$_2$
- Heater needed to keep hydraulic oil fluid
  - Significant heat input in the system increasing the required subcooled margin
- Insulation needed around heads

CMS PIXEL pump:
- Single head
- Damper needed to absorb pulsations
- Remote head
- Easy access for maintenance
- Installed in cold box dry volume
  - No insulation needed
  - No heat input into the system