CO₂ cooling experience in the LHCb Vertex Locator

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Outline

- VeLo Introduction
- VELO CO$_2$ Cooling system
- Evaporator Lab performance
- Cooling plant operation
- Major challenges
- Final Cooling plant performance
- Module Thermal performance
- Conclusions
VErtex LOcator

- Vacuum vessel
- rectangular bellows
- Silicon sensors
- exit window
- rf-box
- kaptons
- wake field suppressor
VELO detector half

- Manifold
- Kaptons
- 21 + 2 silicon sensors
- Beam (7mm)
- Cooling pipes + cookies

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VELO cooling requirements

- Harsh non-uniform radiation environment
  - avoid thermal runaway in silicon
  - hold reverse annealing
  - radiation hard refrigerant
- Vacuum
  - Direct contact between cooling and module
  - No connections but failsafe orbital welds
- In LHCb acceptance → low mass system
- No mechanical stress on the module
- Cooling capacity up to 800W/half

Temperature silicon sensors
-5°C at all times
→ cooling temperature of -25°C

VELO Thermal Control System
based on CO₂ Evaporator
The CO2 cooling principle

Tertiary System: two-phase accumulator controlled system

No local evaporator control, evaporator is passive in detector

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The CO2 cooling cycle

Transfer tube heat exchange brings evaporator pre expansion per definition right above saturation

Capillary expansion brings evaporator blocks in saturation

Accumulator pressure = detector temperature

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The implementation

Accessible and a friendly environment

Inaccessible and a hostile environment

Cooling plant:
- Sub cooled liquid CO₂ pumping
- 12.5 kg CO₂ per half
- CO₂ condensing to a R507a chiller
- CO₂ loop pressure control using a 2-phase accumulator
- Redundancy with spare pump and backup chiller
- Control of the system by Siemens PLC

Evaporator:
- VTCS temperature ≈ -25°C
- Total Evaporator load ≈ 0-1600 Watt
- Completely passive
The cooling plant

Accumulators

Heat exchanger

3 CO₂ pumps

2 Compressors (Air and water chiller)

CO₂ unit

Freon chiller

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Installation at CERN

July - August 2007

Controls PLC

CO₂ Unit

Freon Unit

July - August 2007
The Evaporator

23 parallel evaporator stations + Al cast cooling blocks

Vacuum feed through capillaries and return hose

PT100 cables

Capillaries $\phi_{\text{inner}} = 0.5\text{mm}$

Liquid inlet

Vapor outlet

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The Evaporator

- Vacuum feed through capillaries and return hose
- 23 parallel evaporator stations + Al cast cooling blocks
- Liquid inlet
- Vapor outlet
- PT100 cables
- Capillaries $\Phi_{\text{inner}} = 0.5\text{mm}$
Evaporator Lab Performance

nominal flow = 12 g/s

dry out

annular gas+liquid flow

heat load 1.4x nominal
From room temperature to set-point of -25 °C

Operation: start-up
Major Challenges

Hardware concerns

Pumps

• problems for cold start-up → sphere valve secured by a spring
• pump-membrane failure as result of vacuuming → pump filling now done by flushing.
• pump discharge burst discs replaced by spring relieves

Heat exchanger

• from food industry (no mixing between coolants) + reinforced to withstand 200bar

Safety Procedures

Accu working pressure 130bar, V =14l → European directive for high pressure vessels → CE certification

PLC control loops

Accu control see next slides
VTCS Accumulator Control

Accumulator Properties:
- Volume 14.2 liter (Loop 9 Liter)
- Heater capacity 1 kW
- Cooling capacity 1 kW

Cooling spiral for pressure decrease (*Condensation*)

Decrease heater power near critical point to prevent dry-out

Thermo siphon heater for pressure increase (*Evaporation*)

2PACL Start-up

Accumulator Pressure (Bar)

Heather temp. (ºC)

Accu Level (%)

Liquid temp. (ºC)

Heater power (%)

Pump head (Bar)

Pump inlet (ºC)

Thermal Resistance (mK/W)

Accumulator pressure (bar)

Thermal Resistance @ 1000, 750, 500, 400 & 250 W
VTCS Accumulator Control

Accu PID control loop not adequate → temperature oscillations of a few degrees

Needed tuning of PID control loop to solve problem
VTCS Evaporator performance

Stability and response to heat-load changes

@Setpoint = -25°C:
Accumulator temp: -24.8°C
Evaporator temp (No Load): -23.4°C
Evaporator temp (600 W Load): -23.0°C
Stabilization time from 0 to 600 Watt: ca. 7min
Temperature stability: <0.25°C

Temperatures stable without pressure change
Module Cooling

2 NTCs to monitor temperature on hybrid

Cooling system at -25 °C

Total Chip Power: ~19W
Module Cooling & Performance

\[ \Delta T (\text{Setpoint} - \text{NTC1}) \]
Cooling system to silicon

\[ \Delta T (\text{Cool. Cookie-NTC0}) \]
Transfer cool-module

\[ \Delta T (\text{NTC0-NTC1}) \]
Module performance

\[ \Delta T (\text{setpoint-cool. Cookie}) \]

\( <T_{\text{silicon}} > \) with setpoint of -25°C:

\((-4.2 \pm 1.4) \, ^\circ\text{C}\)

Min. -7.2 °C Max. -1.0 °C

Measurement conditions not exactly as! final system (vacuum, not all modules cooled simultaneously, …)

Small variations in power consumption, modules assembly, evaporator stations \( \rightarrow \) variations in \( \Delta T \)

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Conclusions

- All stringent requirements met
  - Setpoint temperatures go down to ~ -35°C
  - System proves stable operation:
    - without loads/with loads up to 800W
  - Module thermal performance + CO2 cooling at -25 °C
  - All modules at all times below 0°C
  - Low mass system without mechanical stress on module
  - Redundancy built in
- VELO CO2 cooling system is installed and commissioned
- PLC control successful
  - all routines implemented
  - 1 button start/stop for main system

Looking forward to enter the final commissioning phase with the VELO installed!
Back Up Slides
The cooling plant: CO$_2$ unit

- Accumulator
- CO$_2$-part
- Heat exchanger
- 3 CO$_2$ pumps
The cooling plant: Freon unit

2 Compressors (Air and water chiller)
VELO detector half

Graph:

- Station 7
- Station 25

Dimensions:

- Axis: radius [cm]
- Y-axis: $n_{eq}$/cm$^3$ per year

标注:

- kaptons
- manifold
- cooling pipes + cookies
- Beam (7mm)
- 2 silicon sensors
Stand-alone test results of the VTCS cooling plant
(No external evaporator, cooling over by-pass)

Main chiller performance
- Dynamic range of main chiller works properly.
- Full operational range (0 to 1800 Watt) possible in evaporator range (-25°C to -30°C)
- Isolation needs improvement around injection valves
- CO2 condensers/ Freon evaporator works beyond expectation
  (Hardly no dT between Freon and CO2)

Back-up chiller performance
- Able to maintain an un-powered CO2 evaporator at -10°C
Transfer line Operation
(Internal heat exchanger)

Transfer line temperature profile

A: Condenser and evaporator single phase

B: Evaporator 2-phase, condenser single phase

C: Both evaporator and Condenser 2-phase

[1] Pump inlet (°C)
[5] Evaporator liquid in (°C)
[10] Evaporator pressure (Bar)
[13] Condenser Inlet (°C)
[14] Accumulator pressure (Bar)
[10] Evaporative temp. (°C)