Evaporative CO$_2$ microchannel cooling for the LHCb VELO Pixel Upgrade

Oscar Augusto on behalf of the VELO Group and CERN PH-DT

PIXEL2014
Outline

- Current LHCb VErtex LOcator (VELO)
- Module cooling for the upgrade
- First prototype and cooling performance
- First Si-Si samples and resistance to pressure
- Cyclic stress tests
- Towards the final microchannels layout
- Fluidic connector attachment
- Conclusion
Current LHCb VELO
LHCb experiment:
- One of the 4 major experiments at LHC
- Forward spectrometer designed to measure CP violation, study rare decays of c and b hadrons and search for new physics.

VELO:
- Vertex reconstruction and tracking
- 88 Si-strip sensors surrounding the interaction point
- Modules are moved away during the beam injection
- Excellent impact parameter resolution (down to 11.6 µm)
- Excellent single hit resolution ~4 µm
- ~16.5W/module
Module Cooling for the upgrade
Upgrade cooling requirements

- The closest distance to LHC beam will be 5.1 mm (down from 8.2 mm).
- Very high \(8 \times 10^{15} n_{eq}/\text{cm}^2\) for 50 fb\(^{-1}\) & non-uniform radiation \((\sim r^{-2})\)
- Huge data bandwidth: up to \(\sim 15\) Gbit/s for central ASICs and 2.9 Tbit/s in total.
- Sensor temperature < -20°C \((\text{CO}_2 \@ -35°C)\)
- Total maximum power dissipation/module is \(\sim 43\) W
  - \(\sim 3\) W/ASIC, \(\sim 2\) W on the innermost sensors and 5 W on the hybrid
  - Active cooling area \(\sim 24\) cm\(^2\)
  - Power density: 1.8 W/cm\(^2\)
- Minimal material: cooling substrate is retracted 5 mm at the inner region.

More details in Eddy Jans’s talk on “The VELO Pixel Upgrade” and in Tuomas Poikela’s talk on “VeloPix: The Pixel ASIC for the LHCb VELO Upgrade”
Advantages of evaporative CO$_2$ microchannel cooling in silicon

<table>
<thead>
<tr>
<th>Evaporative Cooling</th>
<th>CO$_2$</th>
<th>Microchannels in Silicon</th>
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<tbody>
<tr>
<td>- Isothermal (low temperature gradient)</td>
<td>- High latent heat</td>
<td>- Cooling fluid is immediately underneath the heat source</td>
</tr>
<tr>
<td>- Easy to control by regulating the pressure</td>
<td>- Low viscosity</td>
<td>- Low mass – The cooling substrate is also the mechanical support</td>
</tr>
<tr>
<td>- Very Stable: Temperature is quite insensitive to the variation of heat load</td>
<td>- Non-toxic and environment friendly</td>
<td>- No mismatch of expansion coefficients</td>
</tr>
<tr>
<td></td>
<td>- Chemical inert</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Radiation hard</td>
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</table>
First prototype and cooling performance
First prototype

- Produced at CMI (EPFLausanne) by CERN PH/DT

- Geometry:
  - Size 4 x 6 cm² (380 µm Si / 2 mm Pyrex)
  - Channel dimensions*
    - Restrictions: 70 µm x 30 µm
    - Main channels: 70 µm x 200 µm
    - In/out-let holes 1.6 mm diameter

- The restrictions are required to
  - trigger the boiling (high pressure drop)
  - equalize the flow (main fluidic resistance)
  - Prevent flow instabilities (coupling between channels)

- For pressure resistance, it is critical to minimize the area of the manifold.

*The diameter of the human hair is between 17µm and 181µm
Cooling performance

Thermal mockups made of 300 µm Si metallized to simulate the heat density.
The end of lifetime expectation for half of a module corresponds to ~13W (11.5W ASIC and 1.5W on inner sensor) and in this condition the $\Delta T < 7^\circ C$ across the module.

{It was not possible to test up to maximum power of 21.5W because of the insufficient CO$_2$ flow}
Cooling performance

ANSYS simulation:
1) 3W/ASIC (36W/module)
2) No power consumption on the sensors
3) CO₂ at -30°C
4) 100 µm styrcast® 8550 FT + catalyst 9 (1.25W/mK)
5) ΔT ~ 5°C {Due to the 5 mm overhang}
First Si-Si samples and resistance to pressure
First Si-Si bonded samples

- Manufactured at LETI (Grenoble @ France)
- Four test structures (P1...P4)
  - Same channels dimensions of the first prototype
  - 500 µm diameter inlet
  - 30 x 15 mm
  - P3 and P4 have the highest resistance to pressure

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manifold</td>
<td>700 µm</td>
<td>700 µm</td>
<td>200 µm</td>
<td>No</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>200 µm</td>
<td>400 µm</td>
<td>200 µm</td>
<td>200 µm</td>
</tr>
</tbody>
</table>
Microchannels fabrication

1. DRIE etching of channels
2. Si - Si direct bonding
3. Thinning
4. Plasma etching of fluidic inlets
5. Metalization for soldering connectors

Hydrophilic bonding

Hydrophobic bonding
Pressure resistance tests

Hydrophilic bonding

The bond was not strong enough!

The hydrophilic samples exploded with a maximum pressure around 400 bars.

Hydrophobic bonding

No delamination in the bonding plane!

The hydrophilic samples resisted up to 700 bars (pump limit).

Maximum required pressure is 170 bars (> 2 x CO₂ pressure @ 25°C is ~65 bars).

Pressure test was done on 33 out of 100 samples
Rupture pressure as function of the Si cover thickness

Channel width

- silicon "cover" thickness 25-200 μm
- microchannels: depth 70 μm
- 2 mm glass layer

Graph showing rupture pressure in bars versus cover thickness in μm.

- 100 μm width
- 200 μm width
- 500 μm width

LHCb nominal cover thickness

04/09/14
Cyclic stress tests
Cyclic stress tests

- Pressure: between 1 and 200 bar
- Using compressed air
- Temperature: between -40°C and +40°C
Pressure cycle between 1-170 bars

Thousands of temperature and pressure cycles were performed on microchannels samples without any sign of rupture due to accumulated stress or fatigue.

Temperature cycle between -40 - +40°C
Towards the final microchannels layout
New channels dimensions

Optimizations to reduce fluidic resistance (by a factor ~4) while maintaining resistance to pressure:

- Main channels have the same width (200 µm) but increased depth (120 µm)
- Restrictions made squared (60 µm x 60 µm) to avoid clogging

Considering the CO$_2$ is at -20°C and assuming 30% vapour quality, we need a flow of 0.52g/s to dissipate 43 W/module. The pressure drop will be ~ 3 bar.
New connector and manifold

- No manifolds in Silicon
  - Each channel has its own inlet and outlet
- Manifolds are moved inside metallic connector.

Restrictions

Alignment holes
All 19 channels have nearly the same length and fluidic resistance.
Fluidic connector attachment
Fluidic connector attachment

- **Requirements:**
  - Adherence force required is 212 N @ 65 bars (safety factor 2)
  - No flux (prevent corrosive effects on long term and clogging effects)
  - Hermetic
  - No creep effect

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**Metallization**

- **Pyrex with patterned metallization**
- **Eutectic Sn/Pb solder Preform (55 µm)**
- **Connector, with coating**

**Kovar Connector**

**Silicon**

**1 mm**

**0.6 mm**

**100 µm step**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
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<tbody>
<tr>
<td>Ni</td>
<td>4 µm</td>
</tr>
<tr>
<td>Au</td>
<td>1 µm</td>
</tr>
<tr>
<td>SnPb</td>
<td>55 µm</td>
</tr>
<tr>
<td>Au</td>
<td>1 µm</td>
</tr>
<tr>
<td>Ni</td>
<td>1 µm</td>
</tr>
<tr>
<td>Ti</td>
<td>0.2 µm</td>
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</tbody>
</table>
Reflow soldering in vacuum

- Top Heater
- Bottom Heater
- Integrated Pt100
- Copper plate for cooling
- Teflon for controlled conduction (thickness)

Temperature:
- ~183°C
- 195°C
- ~1°C

Time:
- 45-90 s

Pressure of ~10^{-3} mbar

~0.7 °C/s
Soldering prototypes

- Voids should be reduced in size and number
  - The pressure exerts force and potentially creates a leak path
- Adherence force was validated up to 580 N (8 N/mm$^2$)
  - Considering the soldered area, it should hold > 1200 N (safety factor 10)
- Creep test is being prepared
- Work in progress (aimed at reducing voids/ control the solder flow)
Future

- R&D will continue until the end of 2014
  - Soldering
    - Controlling voids formation
    - Evaluation of the creep effects
  - Stress tests on the fully assembled microchannels
  - Final cooling and fluidic performance

- Prepare the steps towards full production

- Review and start of production mid 2015
  - 52 modules installed + spares and development => ~80 cooling plates
Conclusion

- The microchannel CO$_2$ evaporative cooling fulfills the requirements for the VELO upgrade
  - Pressure resistance
  - Cooling performance
- No fatigue or accumulated stress effects have been observed by doing cyclic stress tests
- A new optimized layout of the microchannels has been designed and the prototype will be tested soon
- A fluidic connector, that can be attached on silicon, has been developed
  - Reliability is still under tests

Thank you!!!
BACKUP SLIDES
Preform foil soldering technique with frame (with slits)
Stress tests

Power supplies and NI chassis

Chiller

Compressed air

Compressed Air

Test samples

Peltier

Heat exchanger
The edge-to-edge spacing between the microchannels was chosen to be 500 µm.

ANSYS simulation:
- CO\textsubscript{2} kept at -30°C
- 3W on each ASIC

Criteria:
- Maximum ΔT < 1°C
- Efficient heat exchange along three sides of channel
The edge-to-edge spacing between the microchannels was chosen to be 500 µm.

**ANSYS simulation:**
- CO₂ kept at -30°C
- 3W on each ASIC

**Criteria:**
- Maximum ΔT < 1°C
- Efficient heat exchange along three sides of channel
Surface preparation

- Old Cleaning procedure
  - Neutral soap
  - Distilled water (18 MOhm)
  - Ultra pure ethanol (99.8%)
  - Nitrogen blow drying

- Changed to plasma cleaning

- The entire procedure is done on a clean room environment (TPG lab)

- After the cleaning, the samples are stored in a dryer to prevent oxidation and to keep them clean (1-10 mbar)
Connector attachment Progress

Xray pictures of the soldered connector
Optical zoom 1000x on void in solder layer

Original sputtered Ni(350)Au(200nm)

- Added Ni (4um)
- Intermetallic NiSn

Sn/Pb

- Length 42.09 µm
- Length 1.36 µm
- Length 3.75 µm

Pyrex

Void

Sn/Pb/Ag

Silicon

- Silicon
- All Ni(350nm) is consumed in intermetallic

Intermetallic NiSn

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Preform foil soldering technique with frame: components

Frame in Stainless Steel 50 µm (laser cut @ CERN)

Solder foil 50µm (made in our lab)

1mm gap

The connector and the silicon with the slits are plasma cleaned before the soldering

Small aluminium “washers” (D=2.46 mm)

Connector

Silicon with the slits pattern on the metallization
Preform foil soldering technique with frame: stack up

Alignment holes

2.5 mm
1.35 mm
50 µm
50 µm
525 µm

Metallized connector
Aluminium washers
Sn63Pb37 (Solder foil)
Frame (Stainless Steel)
Metallized Si

We verify after the soldering that the total thickness corresponds to the sum of the individual components heights (10 µm precision!)
Fluidic connector.

- Soldering:
  - with eutectic Pb/Sn
  - in vapor phase oven,
  - no use of flux
  - with brass (large CTE mismatch with Si). Later with Invar.

- 3 samples were produced:
  - All hold pull force of 580N. None break.
  - Leak test with water up to 400bar: no leak observed.