Microfabricated silicon on-detector cooling systems

Alessandro Mapelli
Two years ago we showed how, based on Prof. Thome’s talk at TWEPP 2009, PH-DT had started studying and developing on-detector microfluidic cooling systems with a particular focus on the NA62 GigaTracKer.

Since then this system has been approved by the NA62 experiment. It has also been recently selected by for the upgrade of the LHCb VeLo and it is under consideration as an alternative for ALICE ITS upgrade.

In this talk we will review the current status of these three developments with a focus on microfabrication, integration and fluidic connectivity.
Issues to be addressed when designing on-detector cooling systems

1. Minimization of material budget
2. Efficient thermal management
3. Minimization of $\Delta T$ between heat source and heat sink

Integration of cooling and detector lay-out

The cooling has to be considered as an integral part of the detector and the experiment, therefore physicists and engineers shall collaborate from the beginning of the conceptual design of the systems, with an overall view on all subparts.
Integrating Cooling in Support Structures... 
...or somewhere in the Silicon?

ATLAS IBL

ALICE ITS Upgrade

IN-MECHANICS APPROACH

SILICON COOLING MICROCHANNELS

$\Delta T$ between heat source and heat sink for power dissipations of $\sim 1\text{W/cm}^2$

(currently installed systems $\sim 15^\circ\text{C}$)
Silicon Microfluidic Cooling out of the HEP world

Direct Liquid jet impingement

Arrayed jets, distributed return

Biological vascular systems are optimized for the mass transport at low pressure

Cooling of up to 350 W/cm²

Direct Liquid Jet Impingement Cooling with Micron-Sized Nozzle Array and Distributed Return Architecture, T. Brunschwiler et al., ITERM 2006

SEM cross-section of two-level jet plate with diameter of 35 μm

Direct Liquid Jet-Impingement Cooling with Micron-Sized Nozzle Array and Distributed Return Architecture, T. Brunschwiler et al., ITERM 2006

Water-Cooled IBM BladeCenter HS22

Credit: IBM Research – Zurich
CERN PH-DT Microfabrication @EPFL

http://cmi.epfl.ch/

class 100 MEMS cleanroom
4” wafers
(6” wafers)

operation on 50 machines
Photolithography
Etching
Thin Films
Bonding
Thinning
Metrology

output
120 photolithography masks
1000 processed wafers
NA62-GTK

Hadron Beam 800 MHz

Veto
Photons and Muons

Total Length 270 m

3 Stations

 decay region 65 m

Straw Tracker

Hadron Beam 800 MHz

NA62-GTK

3D schema = drawing of the GTK module

support and alignement structure

Cooling plate

Readout chip
(12 x 20 mm), heat production ca. 3.2 W per chip (2 W/cm²)

Sensor, silicon pixels
(30 x 60 mm)

Pixel Matrix 0.4 W/cm²

EoC 2.5 W/cm²

150 µm thick Silicon substrate with microchannels

Gigatracker* Module

Cooling* Plate*

Readout* Chip*

(12 x 20 mm), heat production ca. 3.2 W per chip (2 W/cm²)

PH-DT
Detector Technologies

TWEPP 2013

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Silicon Cooling Plate

**distribution manifolds**
- 280 µm deep

**fluidic inlets**
- 1.6 mm

**150 microchannels**
- 200 x 70 µm
- pitch 400 µm

**fluidic outlets**
- 1.6 mm

**recollection manifolds**
- 280 µm deep
Microfabrication

Prototypes fabricated at EPFL by PH-DT.
Six pre-production modules outsourced to IceMOS.

- Si wafer
- Plasma etching of channels & manifolds
- Bonding of Si cover
- Plasma etching of fluidic openings
- Wet etching of acceptance

Embedded microchannel in thin silicon cooling plate

150 µm

200 x 70 µm

Thicker Silicon out of acceptance
Fluidic Connectors

Common development with LHCb VeLo Upgrade

Brazing of fluidic connectors

Limitation of the test set-up read-out at 600 bars
Limitation of the pump 700 bars
No failure of the solder joint

Silicon thickness 525 µm
Inner diameter 1.6 mm

Solder joint withstands 700 bar!
Si thickness = 500 um
Exposed Si surface is 2mm hole

Gold 200nm
Nickel 50nm
Titanium 20nm

Copper plating

SnPb 0.1 mm foil

Kovar CTE 6 ppm/ºC
Silicon CTE 3 ppm/ºC

preliminary prototypes size reduction and different geometries under study
Assembly to Sensor/TDCPix

TDCPix (x10)

Sensor

Thermal Interface

Cooling Plate
Experimental Validation

Liquid Cooling C$_6$F$_{14}$

Nominal Power Dissipation 24 W
Results presented for extreme scenario 48 W

C$_6$F$_{14}$: 7g/s, -19°C AT INLET
Digital Power 38 W
Analog Power 10 W

Sensor Dummy
200 µm thick Si

TDCPix Dummy
100 µm thick Si
20 metal lines to simulate power dissipation of analog and digital parts of 10 TDCPix chips

Cooling Plate
150 µm thick Si
High pressure "emergencies" need be avoided / protected / interlocked ...

- Structure needs to withstand static room-temperature conditions (Critical P & T = 74bar & 31°C)
- Common boundary condition for all lines is the pressure drop between the receiving and outlet lines, which need to be small as well due to small available space and the requirement of low mass. The accessible zone can still be far away. Therefore silicon detector cooling lines can have relatively long. They also have in general long in and outlet connections.

- Experimental caverns are inaccessible during running of the LHC beam. All manifolds allow access or shutting accessible areas. That's why the plant with all the controls is very hard to access. The manifolds are therefore often far away from the cooling pipes of the silicon detectors in areas which can be reached in case of problems with individual cooling lines.

- As a result of more than one silicon detector in the central part of detector structures, silicon detectors are located in a safe zone far away from the experimental cavern. The localization of silicon detectors is very hard to access. The manifolds are therefore often far away from the cooling pipes. The long lines with different pressure drop characteristics need to be connected to each other in series (2 loops).

- For the detection of particles, the cooling lines can only be accessed periodically. For flow distribution of the individual lines a passive method is preferred above a controlled one for reliability reasons. For the silicon detectors, the likelihood of problems is small. The silicon detectors are the central part of detector structures. They are located in a safe zone near the experiment during an LHC intervention is enough as well as possible in flow distribution.

- This specific way of circulating and conditioning the fluid inside the cooling lines is called evaporative cooling. This method controls the system as used in particle detector cooling.

- Transition from inlet restrictions to evaporative microchannels brings the liquid/vapour 2-phase accumulator which is heated or cooled. A heat exchanger is needed that is exchanging heat between the incoming liquid and the outgoing gas. The temperature of the incoming liquid is reduced by the condensation of the gas, and the temperature of the outgoing gas is increased by the evaporation of the liquid. This method controls the system as used in particle detector cooling.

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LHCb VeLo Upgrade

1. operating pressure at low temperature ~15 bar
2. pressure at room temperature start-up ~60 bar
3. validation pressure with safety factor ~150 bar

Hydrophilic Bonding vs. Hydrophobic Bonding

Hydrophilic bonding:
- Water molecules coat the surface
- Gives a good quality, even bond
- Highest quality bond with no oxide layer; but more sensitive surface preparation

Hydrophobic bonding:
- Water molecules coat the surface
- Gives a good quality, even bond
- Highest quality bond with no oxide layer; but more sensitive surface preparation

Samples produced by Leti-3s

Si 165 µm vs. Si 400 µm

Round 1 of pressure tests on Si-Si samples sourced from industry

Hydrophilic samples often break laterally across the bond layer

Round 1
- Rupture at 400 bars due to delamination
- Hold 700 bars
- Limitation of pump

Round 2
- No delamination
- Samples produced by Leti-3s

Delamination + Si Rupture

No Delamination

Rupture at 400 bars due to delamination with improved connector (R. Dumps)
LHCb VeLo Upgrade

final design

cooling substrate retracted from module tip

3 ASICs per sensor

Dashed line indicates sensitive region

sensor (4 per module)

Microchannel cooling substrate 400 μm silicon

restrictions at cooling input

Microchannel cooling connector

Fabrication by CEA Leti-3s

Prototyping at EPFL on 4” wafers
ALICE ITS Upgrade

Inner Layers

Baseline Solution

Silicon Alternative

C. Gargiulo et al.
ALICE ITS Upgrade

Bridge interconnections

Fluid path

4 frames are required for a stave from 4” wafers.
Only 2 frames required with single interconnection from 6” wafers (TMEC, Thailand).

9x silicon dummy chips with thin metal film (heater) glued on top of the stave.
Thermo-fluidic preliminary tests have started demonstrating the principle of operation.
Conclusions

Low-mass on-detector cooling systems can be integrated in light support structures and in silicon.

Silicon Microchannel Cooling has been selected as the baseline solution for

- the NA62 GigaTracker with liquid $C_6F_{14}$
- the upgrade of the LHCb VeLo with evaporative $CO_2$

A great effort is currently undertaken at CERN to study and develop reliable connectivity solutions both in-plane and out of plane