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Micro channel evaporative CO_2 cooling for the upgrade of the LHCb vertex detector

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ABSTRACT

Local thermal management of detector electronics through ultra-thin micro-structured silicon cooling plates is a very promising technique for pixel detectors in high energy physics experiments, especially at the LHC where the heavily irradiated sensors must be operated at temperatures below −20 °C. It combines a very high thermal efficiency with a very low addition of mass and space, and suppresses all problems of CTE mismatch between the heat source and the heat sink. In addition, the use of CO_2 as evaporative coolant liquid brings all the benefits of reliable and stable operation, but the high pressures involved impose additional challenges on the micro channel design and the fluidic connectivity. A series of designs have already been prototyped and tested for LHCb. The challenges, the current status of the measurements and the solutions under development will be described.

1. Introduction

LHCb is a dedicated flavor physics experiment at the Large Hadron Collider for precision measurements of the decays of charm and beauty hadrons. The Vertex Locator ('VELO') plays a key role in identifying secondary vertices, thanks to its excellent track impact parameter accuracy of 13 μm+25 μm/p_T.

The VELO detector has pioneered the use of evaporative CO_2 cooling for high energy physics since its installation in 2007 [1]. The current VELO has 42 double sided modules, each side equipped with 1 sensor and 16 readout ASICs dissipating around 16 W. The silicon sensors are positioned just 7 mm from the colliding beams and must be kept cool (−10 °C) to limit the effect of significant radiation doses. For this reason the cooling system must not only be radiation resistant but low in mass since the cooling components of the modules are within the LHCb particle acceptance. Also, the unique environment, within the LHC vacuum, requires a perfectly leak tight and robust system.

In 2018 the VELO will be upgraded along with the rest of the LHCb experiment, to operate with a 5-fold increased luminosity (2×10^{33} cm^{-2} s^{-1}) leading to a higher integrated radiation dose ($8 \times 10^{15} n_{1\ \mathrm{MeV}}$ cm^{-2}) after collecting 100 fb^{-1} [2]. The temperature of the sensor nearest to the beam must remain well below −15 °C to avoid thermal runaway. Moreover, the new readout ASICs (VeloPix [3]) will lead to higher total heat dissipation per module ($\sim$36 W) located on top of the sensor. To achieve the lower temperature and increased cooling power a new and efficient thermal management of the module is required and a solution is presented which aims to combine the recent advances in micro channel cooling technology with the experience already gained with CO_2 evaporative cooling.

2. Evaporative CO_2 cooling

The CO_2 liquid, brought very near to the boiling condition, enters a channel where the heat taken from the environment makes it boil. The temperature of this liquid–vapor mix remains constant as long as liquid is available. A 'dry-out' situation can occur when all liquid has been evaporated, because the mass flow is insufficient to absorb the heat flux. CO_2 can boil on any point on the liquid–vapor saturation curve between the triple and critical point in the (P,T) phase diagram and therefore, by controlling the pressure between 5 and 73 bar, the boiling temperature can be set between −56 °C and 31 °C. With a CO_2 cooling system one can

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obtain a very predictable, stable and uniform temperature at the heat exchanger.

2.1. Micro channel cooling plates

Micro channels etched in silicon for high heat fluxes were first realised 30 years ago [4] and the use of two-phase cooling with micro channels was proposed recently [4]. A system of miniature channels, together with an inlet and outlet manifold, are DRIE-etched in a silicon wafer and are sealed by bonding a second silicon wafer (direct fusion bonding) or Pyrex (anodic bonding) on top (Fig. 1). This last process flow is fairly standard and was done by a CERN PH/DT team at the Center of Micronanotechnology (CMI), EPFL lausanne.

These embedded micro channels lead to many advantages:

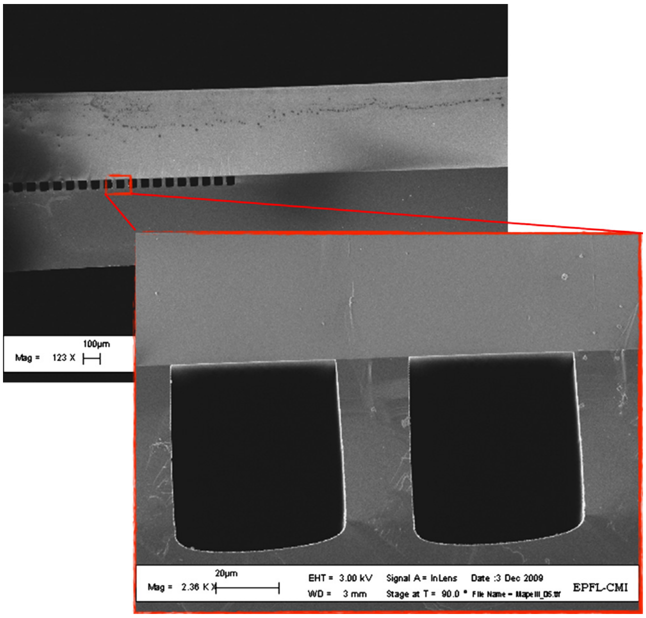

Fig. 1. 50 μm × 50 μm micro channels in Si-Pyrex.

- Obviously, no extra thermal interfaces to the cooling pipe are needed. These interfaces tend to be, despite all efforts, a source of significant thermal resistance and usually represent a non-negligible contribution to the total mass.
- Many parallel small channels represent a large surface for heat exchange.
- One can layout the channel exactly underneath the heat sources. As a consequence, no heat must flow 'in-plane' and the substrate will have smaller temperature gradients and less thermal stress or deformation.
- With silicon detectors and ASICs, the module is all-silicon and no CTE mismatch occurs between parts.

This integrated approach is very attractive for high energy physics detectors and is being pursued in a number of other domains [5,6].

2.2. The new VELO pixel module

The upgraded VELO will have 25 identical stations positioned along a 1 m long beam collision region. Fig. 2 shows a conceptual layout of one station. A station consists of two identical modules,

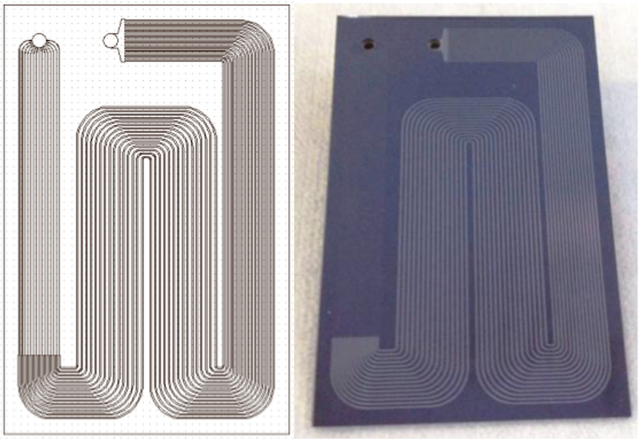

Fig. 3. Drawing and photograph of the "snake" design etched into the silicon substrate.

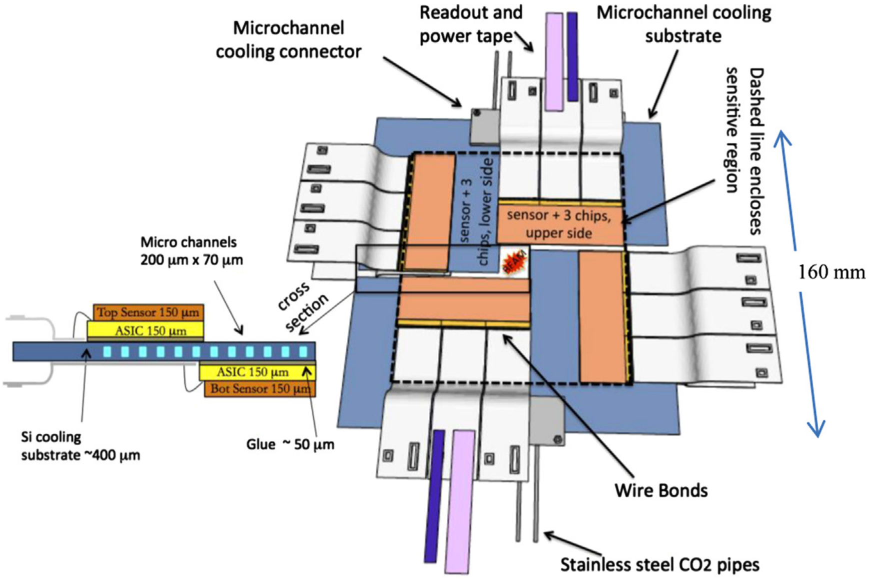

Fig. 2. Conceptual layout of one upgraded VELO station. The left diagram shows the cross section with the micro channels embedded in the substrate underneath the ASICs.

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