Chapter 7

Summary and conclusions

The most important features of a cryogenic module design have been described and characterized, and here we shall summarize the main conclusions. The module is fully operational from a thermoelastic point of view. Further effort is being carried out to operate the readout electronics down to 130 K.

Cryogenic module

The design of a module for the LHC experiments is constrained by the requirements on radiation hardness, minimal mass (low multiple scattering). The starting point was the design of the modules of ATLAS and CMS, which feature radiation hardness up to the neutron equivalent fluence of $3 \cdot 10^{14}$ cm^{-2}, and are presently the most radiation-hard and fastest tracking detectors.

By operating the detectors at cryogenic temperatures the radiation hardness can be improved by a factor 10. This requires the use of current injected sensors and 0.25 μm CMOS readout electronics. Many additional advantages arise from the cryogenic operation of the silicon detectors in heavy radiation environment: suppression of the leakage current, low full-depletion potential, higher carrier drift mobility, charge collection efficiency increase, faster readout electronics and lower noise.

However, this requires improved thermal and thermomechanical performance of the module since neither the ATLAS nor the CMS modules can be cooled below their operating design temperatures without risks: the thermal stresses developed during cool-down would lead to the camber of the sensors, to the peeling of Kapton®, and ultimately to the fracture of the most fragile components, such as the sensors. The choice of the component materials for our cryogenic module was guided by the properties of the silicon sensors, and the main criteria include best possible matching of the thermal dilatation, high thermal conductivity and appropriate elastic properties, in addition to the radiation resistance.

Operation at low temperatures enables to reduce the mass of the module. By using two-phase fluid cooling, the module power can be absorbed by a microtube embedded in the module structure as close as possible to the heat sources (readout electronics). No additional heat spreader is required for the sensor thanks to the high thermal conductivity of silicon at low temperature and because of the low leakage current.

The large stress induced at the silicon sensor can be reduced to a minimum if silicon is glued on silicon or on another material matching its thermal dilatation, using only a thin layer of epoxy. This choice leads also to small temperature gradients and a uniform temperature distribution in the module, as described above. Therefore, both the support plate and the pitch adapter were processed in silicon. The high voltage insulation on these components was provided by a SiO_2 layer grown when processing these components on silicon wafers. Future design options may feature hybrids processed using thick-film techniques on silicon. The module could be built out of this material almost entirely by integrating the cooling into microchannels directly micromachined into the hybrid support plate. Then the pitch adapter could be also printed on the silicon hybrid support plate.

Cooling system

A minimized impact and mass contribution of the cooling system to the detectors are the main requirements. The best performance and highest degree of integration in a device is achieved with two-phase flow and forced circulation of the coolant through capillary pipes. Thermal simulations of the prototype detector modules suggest that the coolant flowing in a single microchannel inside the module needs to be at a temperature less than 10 K below the 130 K design temperature of the sensors; this leads us to the choice of methane or argon with a saturation pressure of 15 bar (124 K). A room-temperature compressor has proven to be a reliable cooling system, making of it a good candidate for beam and irradiation tests, and final experiments in the tunnel close to the interaction point.

Heat transfer in microtubes

Modeling of local heat transfer coefficients in microtubes is essential for the design of evaporator heat exchangers that are integrated in the detector modules. The results from experiments [27] recently carried out at CERN with circular microtubes suitable for cooling cryogenic tracking detectors have been presented. The experiments were focused on nucleate boiling dominated heat transfer, which is the common regime in the applications. However, the two-phase heat transfer measurements were preceded by single-phase measurements with liquid Argon in order to characterize and calibrate the test section of the microtube exchanger.

The results on single-phase (laminar and turbulent liquid, and turbulent vapor) heat transfer showed that there is no physical difference in heat transfer mechanisms between macro tubes and microtubes. The enhancement of heat transfer coefficients in microtubes compared to conventional correlations is explained with the increased influence of roughness, or the relative increase of the wetted surface compared to the volume.

The local flow-boiling heat transfer coefficient α is calculated as a function of the local convective boiling heat transfer coefficient α_{c} and the local nucleate boiling heat transfer coefficient α_{nb}. The heat transfer coefficients in two-phase flow are one order of magnitude higher than those measured in single-phase flow.

Thermal performance of a mechanical module

A series of thermal tests were carried out in a mechanical module built in silicon (detector, pitch adapter and support plate), alumina (readout electronics) and carbon fiber composite (spacer) with thin Araldite® 2011 glue layers. These tests have proven that silicon is an excellent heat spreader and its use as a structural material leads to a uniform temperature distribution in the detector and support plate. Such a module went through a large number (> 30) of thermal cycles without sensor or substrate breaking, thus validating the thermoelasic design.

The maximum temperature difference between the module and the bulk temperature of the fluid was of the order of 25 K for a heat load on the module equivalent to 6 APV25. The thermal resistance due to the glue layers dominates the thermal behaviour. In order to achieve smaller temperature differences, continuous and thin glue layers should be applied. The finite element simulations can be used as a tool to predict the temperature distribution of the module.

Epoxies

Due to the lack of data in literature on the thermoelastic properties of the epoxies, which is a key factor in the cryogenic module design, a series of measurements were conducted at CERN. The thermoelastic properties of Araldite® 2011 (Ciba), Stycast® 1266 (E&C) and Type L (R&G) epoxies filled with fused quartz powder were measured as a function of temperature. The choice of the epoxy and filling factor depends on the geometry and materials to glue.

The measurements showed that filling these epoxies with fused quartz powder considerably reduces their thermal dilatation, nearly matching that of metals. This is very convenient in our application, since less stress is induced when cooling down. However, the filling increases the Young modulus of the composite, which is not convenient in our application. The tensile tests confirm that pure epoxies become brittle at low temperatures, when their elastic modulus increases and the elongation at break is reduced. The Young modulus at 77 K is between 4 and 8 times higher than that measured at 300 K. The tests have shown that the increase of the Young modulus at low temperature for the pure material is larger than the increase due to the change of temperature when the resin is filled. Similar embritteling effects were found when filling the epoxy.

These measurements were used for numeric modeling and comparison of silicon-epoxy-silicon joints. According to the simulations, the critical adhesive layer, which would lead to the silicon substrate cracking in a thermal cycle to 77 K, is of the order of 600 µm. As thin layers as possible should be used to induce the minimum stress on the silicon substrate. Based on these results, unfilled Araldite® 2011 was chosen for the prototype module assembly.

Alignment

There are two main aspects concerning the alignment of a module: the alignment of the module components with respect to each other; and the alignment of the modules with respect to the beam and to other detector modules.

For prototype module assembly, precision gluing jigs were designed and produced. The tooling precision is given by the accuracy of the mechanical edges of the components and the positioning of the alignment pins, which is about 20 µm. The repeatibility of the system is better than 3 µm.

The alignment of the module with respect to the beam is done using a warm support plate, placed between the module and the vacuum chamber. The module is attached to this support structure through three thermally isolating precision support posts with dowels. These go through an alignment hole and a slot that are located on the carbon fiber spacer, and through a third point at the hybrid end. The position of the module and its readout strips is thus accurately referred to the vacuum chamber, which itself can be aligned in the test beam line using optical targets fixed to it.

Electrical performance at low temperature

A first electrical prototype module was assembled using a 50 µm pitch silicon microstrip sensor with an active area of 32.5 cm^2. Pitch adapter and support plate were processed on silicon. The CMS ceramic hybrid with APV25 readout chips was characterized at low temperature. First results were obtained down to 210 K, showing a decrease of the rise time and an increase of the pulse peak height with respect to the room temperature behaviour. The noise also decreases with temperature, though this effect is not seen directly because of the increase of the bandwidth. Further tests are ongoing to characterize the electronics at cryogenic temperatures. A high voltage filter for the sensor biasing was also designed and produced on ceramic.

Edgeless silicon detectors

Measurements in a high-energy beam of the sensitivity of the edge region in planar silicon pad diode detectors have been presented. A high-resistivity silicon p^+-i-n^+ planar diode detector, of 0.25 cm^2 active pad area, was diced through its front p^+ implant to produce two halves of edgeless diode pad sensors. A large surface current on such an edge prevents the normal reverse biasing of this device above the full depletion voltage, but the current can be sufficiently reduced by the use of a suitable cutting method, followed by edge treatment and by operating the sensor at low temperature. A pair of these edgeless silicon diode pad sensors was exposed to the X5 high-energy pion beam at CERN, in order to determine the edge sensitivity. The signal of the detector pair triggered a reference telescope made of silicon microstrip detector modules. The gap width between the edgeless sensors, determined using the tracks measured by the reference telescope, was then compared with the results of precision metrology. It was concluded that the depth of the dead layer at the diced edge is compatible with zero within the statistical accuracy of 8 µm and systematic accuracy of 6 µm.