11.5 Modules

11.5.0.1 Barrel and Forward module specification

For the SCT barrel, the required tracking precision is obtained by modules with an intrinsic point resolution of 23 µm in the r-ϕ coordinate per single side measurement. The precision is obtained for the binary readout scheme (on-off readout) using detectors with 80 µm readout pitch. A back-to-back detector pair with a stereo rotation angle of 40 mrad gives a precision of 17 µm in the r-ϕ coordinate and 500 µm in the z coordinate from the correlations obtained through fitting.

The severity and consequences of the high accumulated radiation levels for silicon detector operation , increased leakage current and type inversion, need to operate detectors at -7°C. The maximum expected fluence after 10 years of operation in the SCT is 3×10^{14} n/cm^2 (at the upper limit of uncertainity of 50% in the total cross section). The corresponding depletion voltage will be in the range 300-400 volts depending upon warm-up scenarios. This will result in a total leakage current of ~ 0.7 mA for a barrel detector operated at -7°C at a bias voltage of 350 V. The leakage current is dependent on temperature, roughly twice per 7 °C . The detector heat generation requires the knowledge of the temperature of the detectors in the module.

Thermal considerations, and especially concerns of thermal run-away, lead to a module design where the effective in-plane thermal conductivity must be increased beyond that of silicon. In practice this will be achieved by the use of thermal heat spreading materials which are laminated as part of the detector sandwich.

The power consumption of the frontend LSI chips are expected to be 5.5 W nominal and 7.2 W maximum. The thermal design of the module must allow for this.

The mechanical tolerance for positioning wafers within the back-to-back pair must be ~ 5 µm in lateral strip position, 25 µm in module thickness, and 25 µm in z. The forward region measures the longitudinal momentum and the track dip angle. The requirements are very similar to the barrel after allowing for interchange of r and z.

The SCT will undergo temperature cycling over the range -15˚C to +25˚C in a controlled sequence, and it must be safe, in the event of cooling or local power fluctuations, at temperatures up to 50˚C. This requires the module design to have minimal CTE, and to be capable of elastic deformation. The precision of the tracking measurement depends on the modules having a stable profile after changes of the operating conditions. To prevent fracture, permanent deformations should be < 5 µm, and elastic deformations occurring across the full temperature range should be < 50 µm.

The modules specifications are summarized in Table 11-21 and Table 11-22.

After considering the combined electrical, thermal and mechanical requirements, the optimised modules will use centre-tap hybrid readout in the barrel region and end-tap for the forward region.

Table 11-21 Barrel module specification

Detector outer dimension	63.6 mm x 128 mm
Construction	Use four 63.6 mm x 64 mm *n*-on-*n* single sided detectors to form 128 mm long and back-to-back glued detectors
Mechanical tolerance	back-to-back: <5 μm (ϕ), <25 μm (r), <25 μm (z) Fixation point: <50 μm (ϕ), <100 μm (z)
Strip length	126 mm (2 mm dead in the middle)
Strip directions	Axial (along z-coordinate), U/V (40 mrad stereo)
Number of readout strips	768 per side, 1536 total
Strip pitch	80 μm
Hybrid	two single-sided hybrids bridged over the detector
Hybrid power consumption	5.5 W nominal, 7.2 W maximum
Detector bias voltage	350 V (at the detector), >410 V in the module
Operating temp. of detector	-7°C (average)
Uniformity of silicon temp.	<5°C
Detector power consumption	1 W /total at -7 °C, Initial heat flux (300 μm): 120 $\mu W/mm^2$ at 0°C
Thermal runaway	Initial heat flux : >240 $\mu W/mm^2$ at 0 °C
Permanent deformation	<5 μm (after 10 thermal cycles between -20 and +70°C)
Power on-off deformation	<10 μm (Detector & Hybrid)
Dynamical deformation	<50 μm (between -20 and +30°C)

11.5.1 Description of module design

11.5.1.1 The barrel module

In the barrel region, one module is made of four 6.4 cm x 6.36 cm single-sided silicon microstrip detectors. Geometrical dimensions are shown in Figure 11-51 for two detectors butt joined to form a 12.8 cm long mechanical unit. Strips of two of the detectors are electrically connected to form 12.6 cm long active strips. The detectors will be positioned to have a 2 mm gap at their join. In order to form a double-sided readout module, two 12.8 cm long mechanical units are back-to-back aligned and glued with a stereo angle of 40 mrad. One side of the module measures the r-ϕ coordinates ("axial strips") while the other side measures the 40 mrad rotated coordinate (the "stereo strips"). The pitch of the strips is 80 μm and there are 770 strips per measuring plane.

Figure 11-50 is a schematic of the barrel module showing the key features in the design. Figure 11-52 shows an expanded view of all the components. The measuring planes, each formed of a pair of wafers, are glued to a central TPG baseboard with a thermal conductivity of 1700 W/mK. As shown in the figure, the baseboard protrudes out symmetrically on both sides of the module. The exposed tabs are the points at which the readout hybrids attach to the module. The hybrids form mechanical bridges across the silicon, in a design that reduces the thermal

Table 11-22 Forward module specification

Detector outer dimension	**Outer: 56.5 - 71.8 mm x 123.1 mm** **Middle: 56.1 - 75.3 mm x 118.7 mm** **Inner: 43.8 - 55.8 mm x 73.9 mm**
Construction	Use four *n*-on-*n* single sided detectors to form back-to-back glued detectors (two detectors back-to-back in the inner ring)
Mechanical tolerance	back-to-back: <5 µm (ϕ), <20 µm(z), <25 µm (r) Fixation point: <50 µm (ϕ), <100 µm (r)
Strip length	Outer: 121.1 mm (2 mm dead near the middle) Middle: 116.7 mm (2 mm dead near the middle) Inner: 71.9 mm
Strip directions	Fan (along r-coordinate), U/V (40 mrad stereo)
Number of readout strips	768/side, 1536/total
Strip pitch	Outer: 70.8 - 90.3µm, Middle: 70.3 - 94.8 µm, Inner: 54.4 - 69.5 µm
Hybrid	one double-sided hybrid, set at the end of the module
Hybrid power consumption	5.5 W nominal, 7.2 W maximum
Detector bias voltage	350 V (at the detector), >410 V in the module
Operating temp. of detector	-7°C (average)
Uniformity of silicon temp.	<5°C
Detector power consumption	1 W/total @ 0°°C, Initial heat flux : 120 µW/mm^2
Thermal runaway	Initial heat flux : >240 µW/mm^2 at 0 °C
Permanent deformation	<5 µm (after 10 thermal cycles between -20 and +70°C)
Power on-off deformation	<10 µm (Detector & Hybrid)
Dynamical deformation	<50 µm (between -20 and +30°C)

coupling between the front end chips and the silicon without contacting the silicon surface and also avoids gluing to the active surface, given the uncertainties associated with long term ageing and radiation effects.

The cooling contact to the barrel module is made at one side as indicated in the diagrams. The contact point includes dowel pin holes to accurately locate the module on the support structure.

11.5.1.2 The forward module

In the forward region, each module is formed from two measuring planes. In the first plane, the azimuthal angle, ϕ, is measured directly via strips of a radial geometry in which the strip pitch varies along the module length. The second measuring plane, identical to the ϕ plane, is mounted such that there is a 40 mrad rotation with respect to the ϕ plane. The second plane provides a measure of the radial position of a particle when used in conjunction with the ϕ plane. Figure 11-53 shows a schematic of the wafer dimensions and relative positioning for each of the three module types used in the forward region. Each wheel is covered by one to three rings depending on its z position in the tracker.

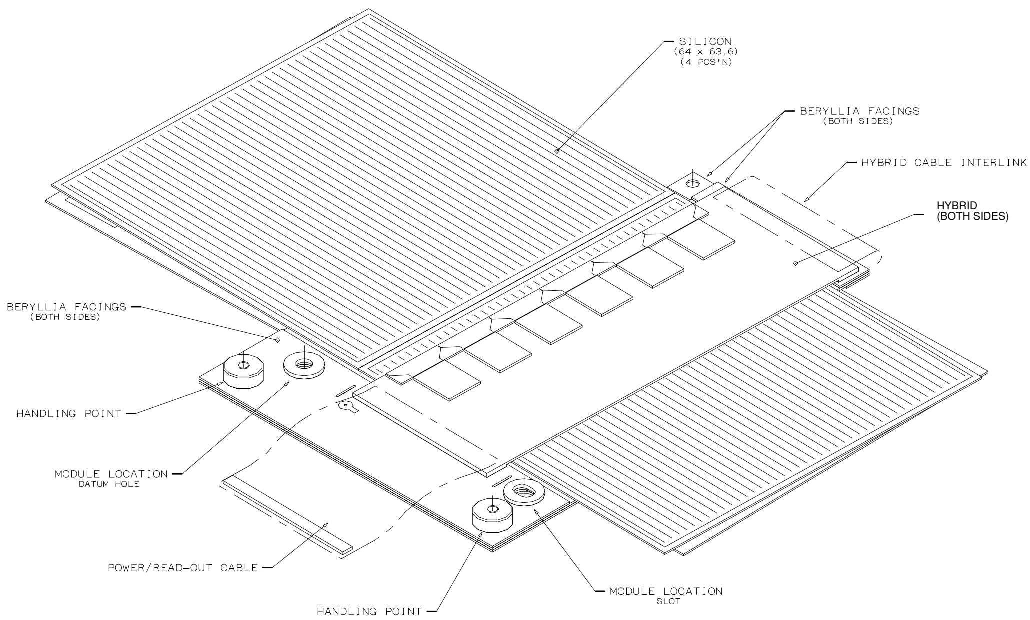

Figure 11-50 Configuration of the barrel module.

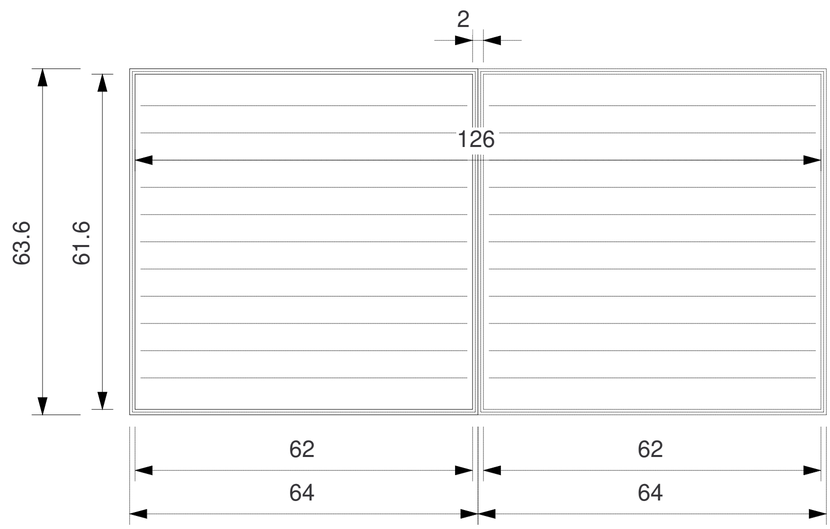

Figure 11-51 Geometry of barrel module detectors and configuration.

There are 770 strips per measuring plane, with the first and last being used for field shaping and not connected to the readout. Each module subtends an angle larger than that required, to allow for a reasonable number of overlapping strips to ensure hermiticity and to facilitate module-to-module alignment using physics tracks. The nominal ϕ angle of a module is covered by strips 10 to 759 where strips 0 and 770 are the field shaping strips.

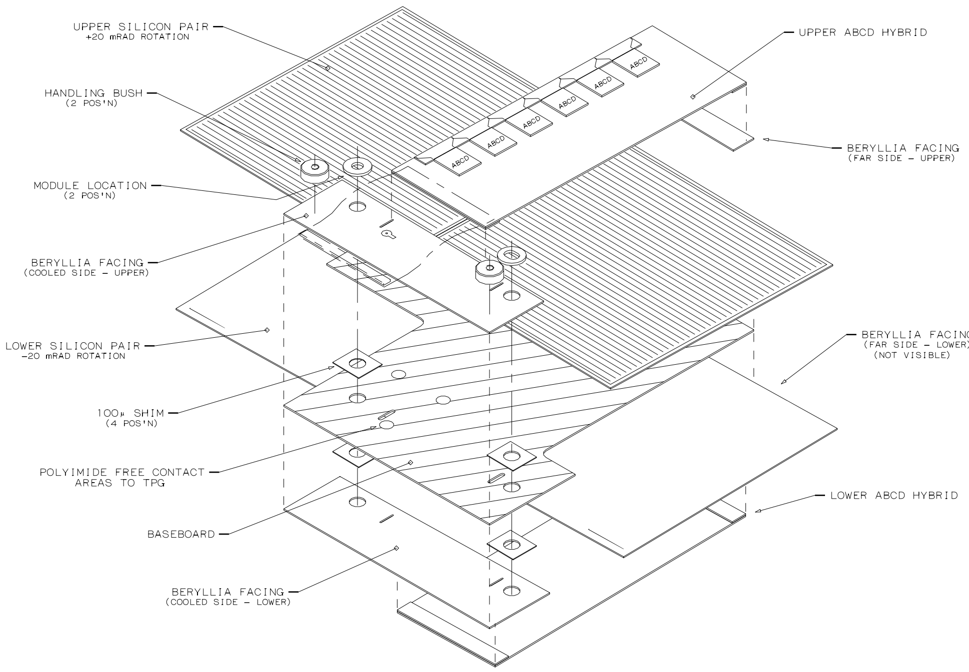

Figure 11-52 Expanded view of barrel module.

Figure 11-54 is a schematic of the forward middle ring module showing the key features in the design. Figure 11-55 is an expanded view of the forward module. The two measuring planes, each formed of a pair of wafers as described in Section 11.5.2.1, are sandwiched around a double sided readout hybrid and a central TPG spine. The TPG spine serves as a mechanical support for the wafers and increases the thermal conductivity along the length of the module. The same double sided hybrid is used for all modules and is formed on a support board into which two slots have been made. The slots act as a thermal break to prevent heat from the front-end electronics from entering into the silicon wafers. The electrical connections from the silicon strips to the readout electronics are made via fan-in structures mounted on either side of the hybrid bridging the thermal break.

The front-end electronics chip-sets are separated into two groups by the primary cooling contact which also serves as the module mounting point. Additional cooling may be provided by a contact to the far end of the spine. The additional cooling contact is used only for full length middle ring modules.

Figure 11-55 shows the details of the component parts for one of the three forward modules. All three designs are similar except for geometry dependent details. In the case of the outer ring, the electronics is mounted in-board the silicon to maximize the radial coverage allowed within the SCT geometry envelope. Furthermore the secondary cooling point, at the outer radius, is not required since the power dissipated in the silicon is much reduced due to the lower radiation dose. The inner ring, having an active length of 72 mm, does not require a secondary cooling contact either.

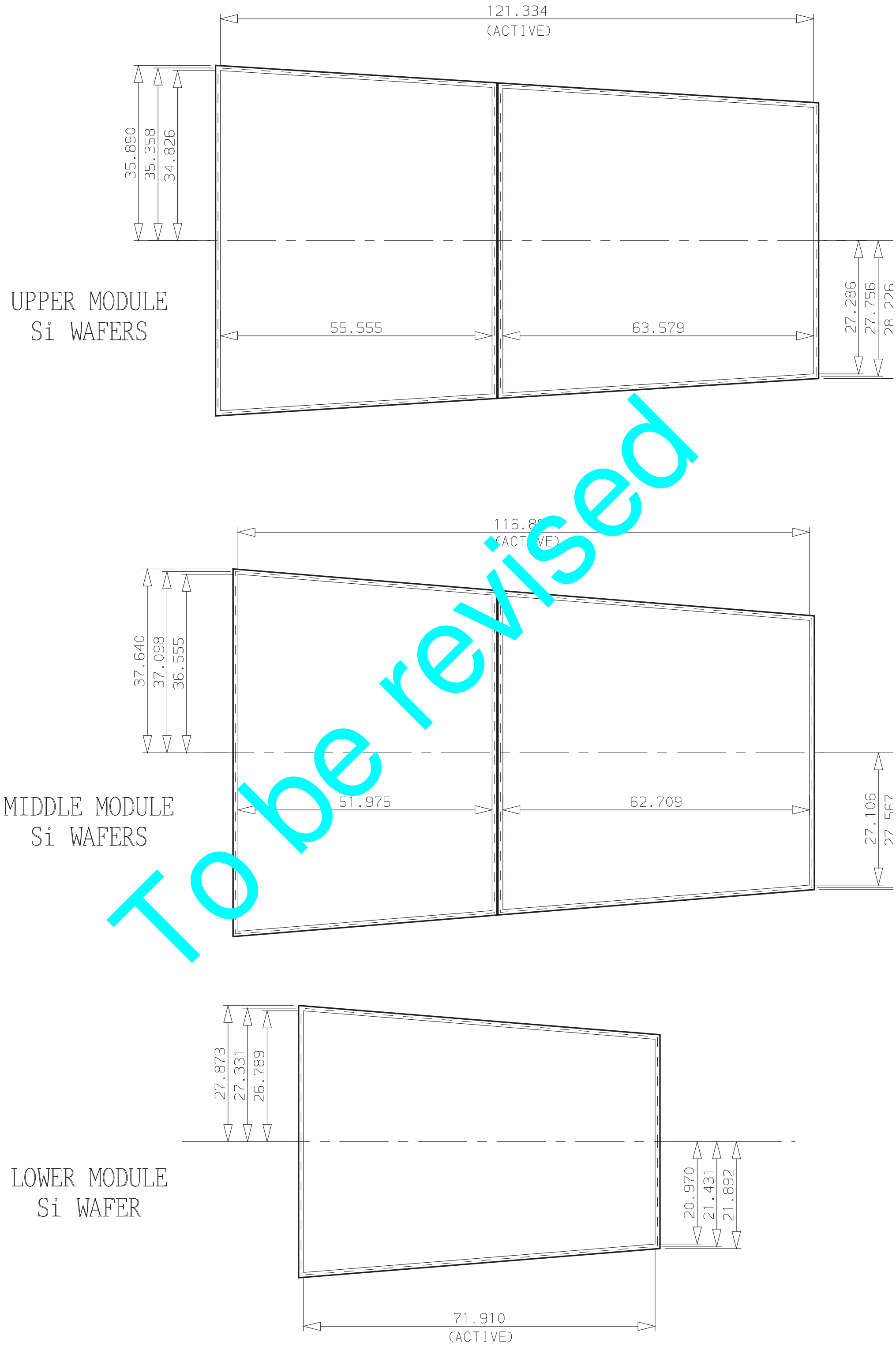

Figure 11-53 Geometry of forward silicon detectors.

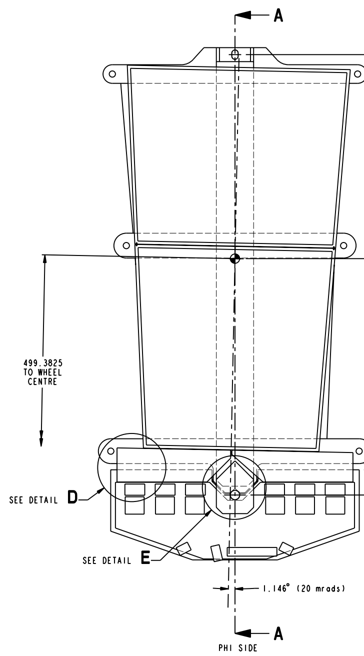

Figure 11-54 Forward module layout: Outer module.

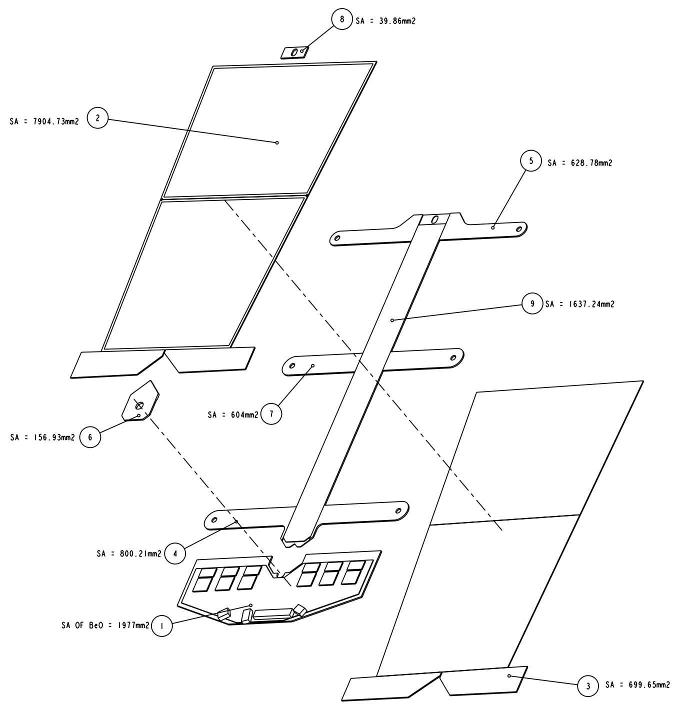

Figure 11-55 Expanded view of a forward outer module.

11.5.1.3 Thermal performance

Barrel modules

The process of thermal runaway has been observed in radiation damaged silicon detectors [11-71]. A silicon strip module was fabricated using two irradiated detectors. A mock hybrid, instrumented with a 3 W heater was placed near the middle of the module. A cooling pipe ran over the edge of the hybrid and the temperature of the furthest corner of the silicon was measured as a function of the bias voltage applied to the irradiated detectors. Heat was therefore generated in both the silicon and the hybrid. In this particular study stable thermal containment was obtained for all relevant bias voltages for cooling/air temperatures below 10º C, and runaway actually occurred at 250 V bias when they were increased to 20º C [11-71].

For the final barrel module design (see Figure 11-50) a thermal simulation was done. Figure 11-56 shows the maximum (T_{si} max) temperature of the silicon detectors in the module as a function of the bulk heat generation, normalized at 0˚C. , for various coolant temperatures. The simulation shows that the thermal runaway of the silicon detector occurs at 220 µW/mm^2 for the 7.2 W chip power. Figure xx-xx shows the coolant temperature dependence of the point of thermal runaway. The bulk heat generation after 10 years of operation at LHC is estimated to be 120 µW/mm^2 in the worst case. The coolant temperature is required to be -17 °C in order to satisfy the heat generation of 240 µW/mm^2, the safety margin of two.

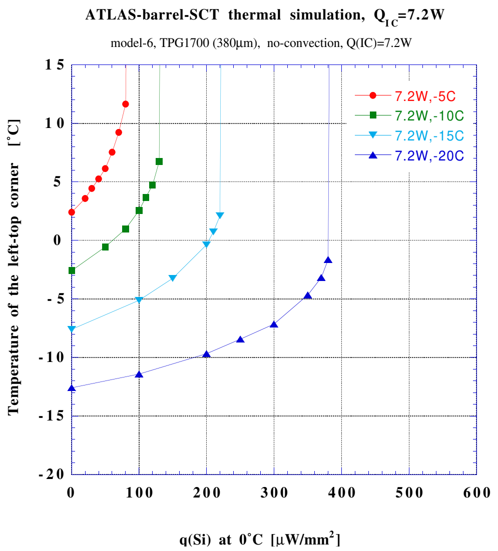

Figure 11-56 **** Sample figure in a double figure on Reference Page.

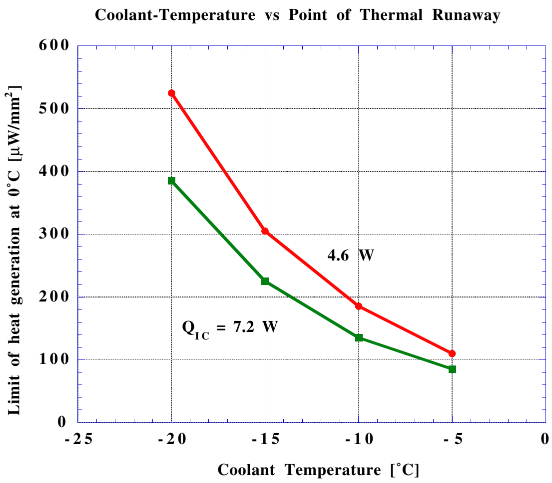

Figure 11-57 **** Sample figure in a double figure on Reference Page.

Forward modules

The thermal properties of the outer module were simulated using FEA analysis. The module is cooled entirely by the cooling blocks. No heat transfer to and from the ambient gas is allowed. The cooling block properties are taken from a separate FEA analysis. The runaway curves for the outer module with 7 W hybrid power is shown in Figure xx-xx. The thermal runaway occurs at 210 µW/mm2 for the coolant temperature of -15 °C. A slight decrease of coolant temperature to -17 °C allows to operate the module at 240 µW/mm2, the safety margin of two.

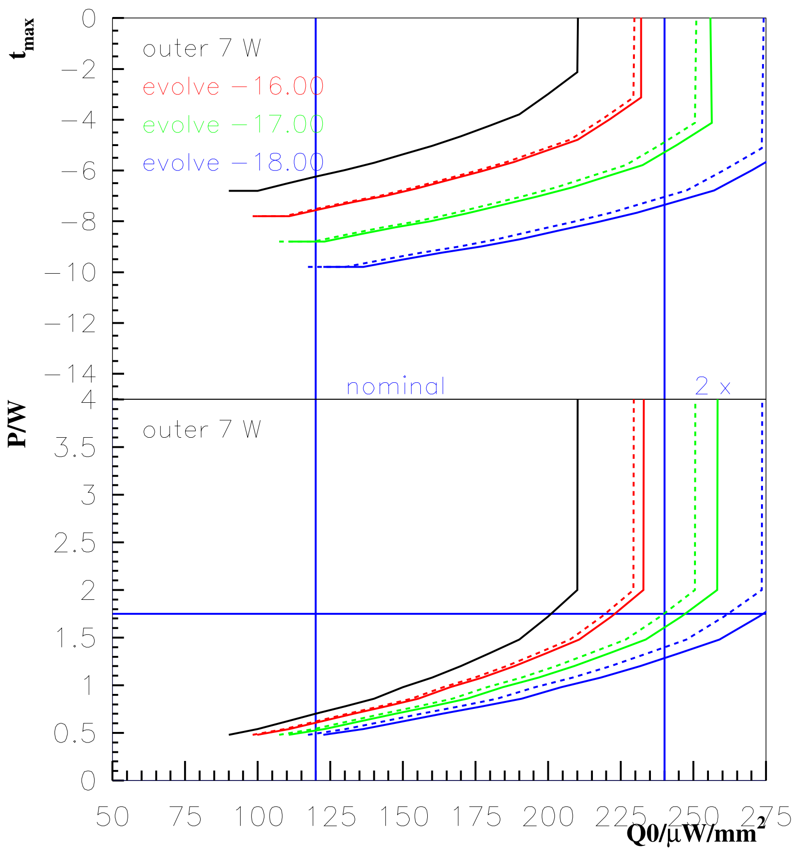

Figure 11-58 Maximum temperature in the detectors and total power in the outer module for various coolant temperatures for the 7 W hybrid power. The curves are derived from the full simulation at -15 °C using a scaling low. The dashed lines indicate the uncertainties of this scaling.

11.5.1.4 Generic components of modules

Generic components of modules are listed in Table 11-23.

Table 11-23 Generic module components

Component	X_0 (%)
(a) Silicon wafers	0.64
(b) adhesives	0.04-0.06
(c) front end chips	0.04-0.05
(d) mechanical baseboard	0.12-0,15
(e) thermal baseboard	0.06-0.08
(f) hybrid, with bonds and electrical planes	0.30-0.32
Summed material	1.20-1.28

When considering variations in module components it is vital to ensure that the constructed device is made with high yield, has stable and well-defined geometry, and shows robust electrical performance. The front end electronics and hybrid, coupled with the detailed electrical properties of the wafer will determine the significance of the digitizing precision through the achievable signal-to-noise ratio. The internal mechanical stability and alignment specifications will then limit the ultimate spatial precision that can be achieved for tracks to be used in physics studies. As indicated in Table 11-23 the typical module contribution is 1.24% X_o. Roughly 20% of the radiation length comes from mechanical items (b,d,e) and 80% from electrically active elements (a,c,f). Of the latter, 65% are fenced by the need for maximum ionization signal. Any future changes will effect 0.48% X_o due to refinements in the electrical and mechanical design of the modules with final readout chips etcetera. The current barrel module design with a material estimate of 1.2% X_o has minimized all possible component items.