# Analysis of Silicon Module Thermal Runaway for Stave Geometry with Embedded Cooling Tubes

## Model Description

In the 10cm wide module design[1] there are 10 electronic chips per each hybrid. A module is 10cm long, divided into 4-segments, providing strip lengths of 2.5cm. There are 4-hybrids per 10cm module. This arrangement is configured in the FE model as a 2.5cm long unit with 5chips (1/2 width model), with the stave middle being a plane of symmetry, Figure 1. The final plane of symmetry is the mid-plane of the cooling tubes, making overall a ¼ actual size model.

The cooling tubes in this study run in the stave axial direction with a symmetrical transverse spacing dependent on the number of back-forth coolant passages. For a single U-Tube (down once and back) the stave lateral dimension is divided into two equal transverse thermal zones with respect to the chips. Each cooling tube is thus placed ¼ of the distance from the outboard stave edge. This provides a symmetrical distribution of the electronic chip heat zones, as shown in Figure 1.

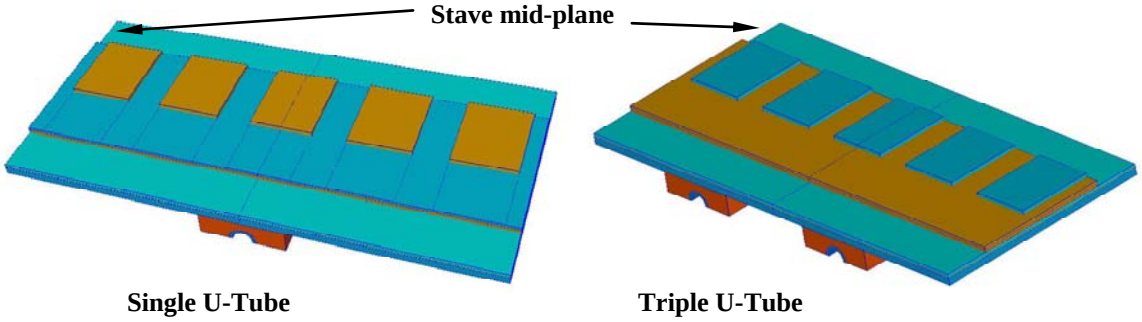


**Figure 1: FEA models for the Single and Triple U-Tube cooling system.**

Stave geometry with a Triple U-Tube cooling tube, makes four passes, and exits at the same end as it entered. In this case, the transverse spacing with respect to chip layout is equally divided into 6 (3 spaces about mid-plane). As one might expect, this latter case can tolerate higher leakage current induced surface heating before thermal runaway occurs.

Thermal runaway occurs when the silicon module temperature dependent leakage current heating exceeds a critical value for a given prescribed geometry. As one anticipates, the furthermost point on the module from a cooling tube becomes the hottest point. This hot spot generates more leakage current, thus eventually leading to an unstable thermal gradient in silicon module.

## Leakage Current Temperature Dependency

The leakage current and leakage current temperature dependency was extracted from a presentation [1] (Allport) and a technical note [2] (Sadrozinski, et al. Reference [1] provided information on a 3cm long 300µm thick module operating with a bias

[1] Basic layout of chips, heat spreading effects of the composite facings and BeO are discussed in previous notes

voltage of 600VDC. Reference [2] provides data for short strip detectors of 320 µm thickness with a 500VDC bias. As a matter of completeness, thermal runaway was assessed for both surface heating profiles.

To facilitate the analysis the standard temperature dependency relationship is used. In the expression below $q$ is the equivalent induced heat flux for a typical short strip 300micron wafer in SLHC.

(1) $q = q_o(\frac{T}{T_{ref}})^2 \exp(-\frac{E}{2k_B}(\frac{T_{ref}-T}{T_{ref}T}))$ Where it is normal to use $T_{ref} = 293K$; the constants are $E = 1.2V$ and $k_B = 8.617 * 10^{-5} V/K$. However, in this thermal analysis the leakage current equivalent heat flux ($q_o$) at -40ºC was used (1.8mW/cm$^2$ ref. [1] and 0.7mW/cm$^2$ ref. [2]) as a means to define the input curves, with a corresponding $T_{ref}$ = -40ºC. Figure 2 depicts a comparison between the two surface heating. The consistent difference in surface heating between the two sources is a factor slightly >2.57. No one anticipates that the actual surface heating will lie outside the region encompassed by these two curves.

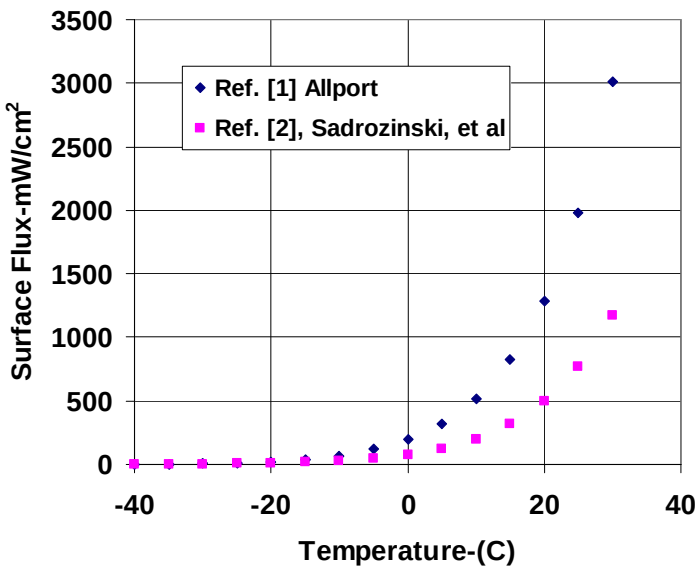


**Figure 2: Short Strip Module surface heating from leakage current, references [1] and [2].**

**Procedure for Determining Thermal Runaway---Independent Variables**

The data contained in Figure 2 is used to construct an input table for module surface heat flux. This permits a temperature dependent solution for the stave geometries shown in Figure 1; a constant applied chip heat load 0.5W was used in each solution. This steady state solution follows the same technique used when only the constant chip heat load is applied.

It is possible to extract peak silicon module temperature and average module surface heat flux from each steady state solution. One can simply obtain the peak module edge temperature through inspection; this is the region of interest. Fortunately, the

program used, CFDesign, permits simple inspection and recording of surface temperatures by simple screen selection. Any point on a surface can be selected. It also calculates an average surface temperature for any "screen selected" surface defined by the user's mouse. However, obtaining the corresponding heat flux from the leakage current effect is not quite as direct. The step involves using the total "exit" heat load at the cooling tube surface.

CFDesign will calculate the total heat at any surface, again by screen selection, which in our case is a tube surface for a Single U-Tube cooling, or two tubes in the case of the Triple U-tube. Subtracting the chip heat load from this value leaves the component heat term from the module surface heating. This dissipated heat term is then averaged by the module area to extract the value of $mW/cm^2$ resulting from the thermal solution.

It is generally accepted to show thermal runaway as a function of initial coolant tube surface temperature. In this manner, solving the thermal equilibrium problem for each discrete "input" coolant tube surface temperature[2] provides a measure of "head-room" between the proposed coolant bulk temperature and that bulk fluid temperature for which thermal runaway will occur. One should stress that a series of solutions is made for each fixed leakage current temperature dependent curve.

**Thermal Runaway Results: Single U-Tube**

Figure 3 represents successive thermal FEA solutions for the Single U-Tube configuration shown in Figure 1. As noted, the solution progresses by applying discrete surface temperatures for the coolant tube. Heat load on the model is comprised of both the chip load (0.5W/chip) and the temperature dependent leakage current heating shown in Figure 2 ([1] and [2]).

First, it is noticed (Figure 3) that surface heating value which is associated with thermal runaway is the same for both basic curves. The only difference is the "headroom[3]". For [1] thermal runaway will occur at a coolant surface inner temperature of nominally -22.5ºC and for [2] an inner surface tube surface temperature of approximately -13.2ºC. From our convection analyses with the $C_3F_8$ coolant the film temperature drop is nominally 3ºC, hence the bulk fluid temperature for these two points of thermal runaway would be approximately -25ºC and -16ºC respectively.

Implications derived from these two solutions for the Single U-Tube is as follows:

- If the leakage current module surface heating is as described in [2], then the stave could be cooled with $C_3F_8$ using -25ºC coolant and still have 9ºC of "headroom"
- Alternatively, if the leakage current surface is 2.57 times higher, [1], a much lower coolant temperature would be required, most likely -35ºC.

It is our understanding at this juncture that the representative curve for surface SLHC heating would be reference [2], judged to have a confidence level of within 20% based on experimental module testing.

---

[2] Eventually the coolant tube surface temperature input leads to an unstable solution.

[3] Defined as the temperature difference between the "chosen" cooling tube operational temperature and the cooling tube input temperature, which results in thermal runaway.

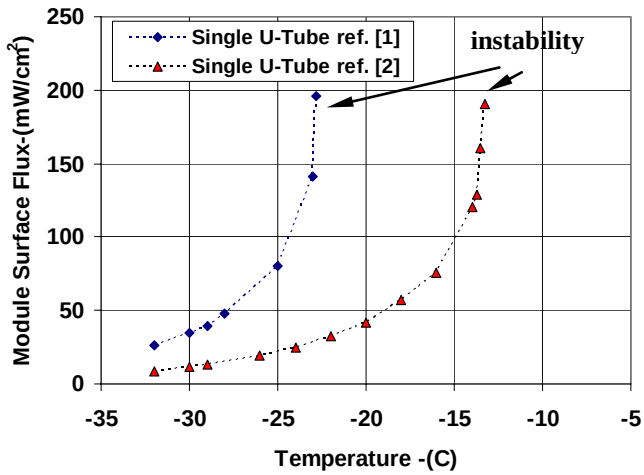


**Figure 3: Thermal solution with tube surface temperature as independent variable with silicon module temperature dependent surface heating per Figure 2.**

To precisely tie down the exact points of thermal runaway for the two different surface heating curves in Figure 3 will require further small incremental adjustments in the input temperatures, and adding more data points in the temperature dependent surface heating "look-up" table near the point of thermal runaway. This exercise is hardly worth the effort, since visually we can see the limiting heat flux is in the neighborhood of 200 mW/cm$^2$ for this particular stave/cooling geometry.

**Thermal Runaway Results: Triple U-Tube**

From the standpoint of "head-room" the Triple U-Tube has a decided advantage over a Single U-Tube as becomes evident in comparing Figure 3 and Figure 4. This is as one would suspect since the distance from any point on the silicon module to the cooling tube centerline has been reduced from 2.5cm to 1.67cm.

Now, the two points of instability for Triple U-Tube geometry, using [1] and [2] inputs, correspond to a coolant tube surface temperature of -12.45ºC and -2.4 ºC respectively. The surface heating flux induced by the leakage current in both cases is nominally 312mW/cm$^2$. This flux is about 60% greater than derived for the Single U-Tube at the point of instability.

One can conclude:

- $C_3F_8$ at -25ºC and surface heating from [2] will provide 19.6ºC "headroom" and with surface heating from [1] "headroom" of 9.5ºC
- In either case, it seems clear that high pressure $CO_2$ coolant is not required to prevent thermal runaway.

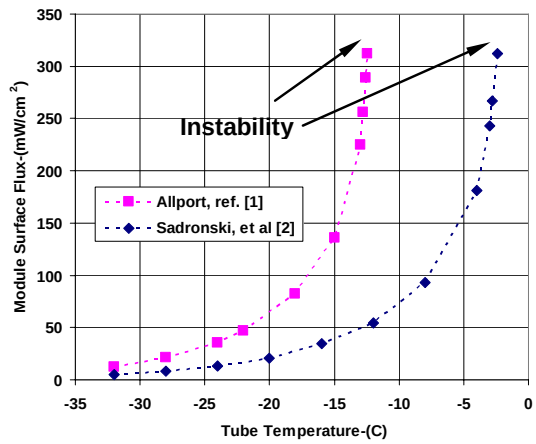


**Figure 4: Thermal runaway comparison for the Triple U-Tube for two values of temperature dependent surface heat flux, references [1], and [2], as function coolant tube surface temperature.**

## Conclusions

The foregoing (Figures 3 and 4) were intended to show that assuming that one must use coolant fluid temperatures 20ºC below LHC to offset the 10 fold increase in leakage power is an over simplification. It appears quite possible to operate a Single U-Tube or a Triple U-Tube in our present stave design with -25ºC bulk coolant, without any impact on the current SCT cooling system.

As mentioned earlier, the flux at which instability is reached is a function of the thermal gradient in the structure and the coolant tube surface temperature. What defines the thermal gradient in the module and sandwich facing depends on:

- Overall thermal path length from furthest point on the module,
- Various materials making up the thermal path, and
- Their thickness and conductivities

In our opinion, the Single U-Tube can provide adequate protection against thermal runaway, assuming surface heating is defined by reference [2]. If there is some other need for maintaining -25ºC throughout the silicon module, the Single U-Tube concept would require an approximate bulk fluid temperature of - 40ºC and the Triple U-Tube -35 ºC. These two bulk fluid temperatures would necessitate using $CO_2$.

In closing, the reason for choosing $CO_2$ as an evaporative coolant for a stave design configured as we propose would not be based on a need to avoid thermal runaway, even with a Single U-Tube design, but rather on some other criterion.

## References

1. P. Allport, “Atlas at the Super LHC”, Internet link:
hep.ph.liv.ac.uk/~green/silc/talks/AllportAtlasAtSLHC.pdf

**2.** C. Betancourt, M. K. Petterson, H.F.-W. Sadrozinski, M. Bruzzi, “Expected Leakage Current for the ATLAS Upgrade Silicon Detectors”, SCIPP UC Santa Cruz, Santa Cruz,

CA 95064, USA, and Dept. Energetic, University of Florence and INFN, via S. Marta 3, I-50139, Firenze, Italy