Thermal/mechanical measurements of Forward SCT Modules with two alternative hybrids

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1 Introduction

We would like to start by thanking Sally Brind, Ozy Morris and Martin Gibson of the RAL group for their help and for taking a large proportion of the measurements reported here.

This note [1] describes measurements made on two dummy forward SCT modules. The aim was to find out if one of the alternative hybrid technologies could be ruled out for thermal or mechanical reasons, before using up valuable front-end chips to test its electrical performance. Therefore we have built two dummy modules which are as far as possible identical apart from their hybrids. The same set of tests was run on each module; to find out the operating temperature of the hybrid, the ability of the module to stand up to thermal cycling, and the thermal distortion of the module as it is cooled from room temperature to -20 °C.

2 The modules

The modules were asssembled in Manchester from components supplied by Freiburg, Liverpool, MPI, RAL and Valencia groups. The assembly system has already been described in ref [2]. Module M009 contains the hybrid made with gold and glass layers on a beryllia substrate. It has already featured in our report on the assembly system where it was noted to have a slight (20 micron) misalignment of the wafers because of a vacuum failure during glueing. This will not have any effect on its thermal or mechanical properties. Module M010 contains a hybrid made with a copper/kapton circuit wrapped around a carbon fibre substrate. The alignment of the wafers in M010 is expected to be within specifications but we have not actually surveyed it yet.

Both hybrids were populated with their passive components and equipped with resistive heaters in place of chips. Some platinum resistance thermometers (pt100) were glued on to a few key points on each hybrid. Both the heaters and the pt100s were supplied through the real connector, so we got some experience of plugging in and out of this socket without breaking the module.

3 The test box

The aim of the test box was to hold a module in a thermal-mechanical environment which is the same as it will experience in ATLAS, while being able to measure it optically with a measuring microscope.

Our solution is shown in Figures 1 and 2. It consists of an insulated plastic box with a double glazed window for thermal isolation. Within the box is a cross shaped structure of invar which provides a mechanical reference with near zero c.t.e. . A fiducial mark is glued on to the end of each arm of the cross. Two cooling blocks are fixed on to the long arms of the cross. We ensure that the cooling surfaces are flat and parallel to each other by skimming them after they have been fixed to the cross. The blocks are cooled from the back with a peltier device and the hot terminal of the peltier is itself cooled with a chilled fluid. The use of peltiers is not strictly necessary for the tests described here but we find them convenient; they enable us to tune the two cooling block temperatures seperately, and to reach lower temperatures than our chiller can manage.

4 Thermal distortion

All measurements were made with the Smartscope at RAL, which in principle has an accuracy of about one micron in the X and Y directions, and about 5 microns in the Z direction.

4.1 Method

The Smartscope allows the user to start the survey by measuring three points and defining a plane which passes through them. All subsequent Z measurements are reported relative to that plane. We used the fiducials on three of the invar arms to define our Z plane. We re-defined the Z plane every time we made new set of measurements so that our results are independent of any movement of the invar structure within the box.

In principle, the cooling blocks surface should move with the invar but we checked this. We measured the height of the cooling block surface at the six points shown in Figure 3 when they were at 21 °C and again at -20 °C. The two temperatures gave results which are marginally different, if one accepts a Z error of 5 microns, so we fitted them seperately to define a different cooling block plane at +21 from -20, and we interpolated between the two to get a result for 0 °C. All Z values were corrected offline to be relative to the cooling block plane at the appropriate temperature.

Similarly to the Z plane, the Smartscope allows the user to define an origin and direction for the X axis using measured features. We chose a fiducial mark on the wafer close to the main cooling block as our origin and a similar mark at the far end of the module to define the direction. As before, these axes are re-defined at the start of each series of measurements, so we are insensitive to movements of the module as a whole within its box.

The sequence of measurements was as follows;

1. The BeO module was put in the test box and measured when the cooling blocks were at +21°C, 0°C and -20 °C. Then, without changing the cooling system settings, the hybrid power was switched on to 7 W and another measurement was done. Powering the hybrid has the effect of warming the hybrid block to about -10 °C while the far end block is almost unaffected, but we refer to these conditions as "-20 °C +7 W" and we correct the Z values to the cooling block plane measured at -20 °C.
2. The CF module was put in the test box and the same series of measurements were made.
3. Both modules were put in an environment chamber and cycled 13 times between +40 and -20°C (Figure 4).
4. The CF module was put back into the test box and measured at +21, 0, -20, -20+7W and finally back at +21 °C.
5. The BeO module had its turn in the box and the same series of measurements were made.

4.2 Caveats

We believe that Z measurements on the silicon wafers are probably accurate to better than 5 microns because the microscope was used with its full magnification and there were clear fiducials to focus on. This is confirmed by the good agreement between the Z values of the nearby pairs of fiducials at the wafer break ($x = 65, y = \pm 31$) in Figure 5 for example. However, Z measurements on the hybrid suffer from having no sharp features to focus on and from being done with low magnification. We have made an estimate of their accuracy by looking at the correlation between the pair of points near ($x = -10, y = -40$) which are rather close together; an accuracy of 10 microns seems reasonable.

X, Y measurements on the silicon wafers could in principle be accurate to 1 micron but in practice there was poor etching and/or dirt on the wafers and the Smartscope software is not good at coping with imperfect images. So the resulting accuracy is probably about 3 microns and sometimes much worse. In some cases the Smartscope was searching for circular spots of known diameter and reporting the position and diameter of the spot which it found; this allowed us to make a quality cut on the reported diameter and reject points which were obviously wrong. The rejected points appear as asterisks in our figures. In other cases however, the Smartscope was searching for corner features and no such quality cut was possible. We tried to make some X, Y measurements on the hybrid with limited success. The Smartscope was able to recognise the two farthest corners of the BeO substrate and also the corners of some solder pads on both hybrids. The accuracy of these measurements is unlikely to be as good as those on the wafers.

4.3 Results on BeO module

Figure 5 shows the result of measurements of the BeO module before thermal cycling, while Figure 6 shows it after cycling and Figure 7 compares the room temperature measurements from before and after cycling. You will need to read the captions carefully and spend some time staring at these numbers before they begin to make sense.

Taking the book value of the c.t.e. of silicon of 2.6 ppm, we would expect the high x end of the module to move by about -13 microns in x when cooled by 40 degrees. We do see shifts of this magnitude, the point at $(x = 122, y = 0)$ is particularly clear. If this expected shrinkage is taken out then the remaining movements of the wafers in the X, Y directions are generally less than 5 microns and in our opinion are consistent with zero.

There is clearly some movement of the wafers in the Z direction. The upper edge points (y=30 to 36) drop by 30 to 50 microns when the module is cooled, while the two points near the cooling blocks hardly move and the lower edge moves by less than 20 microns. Figure 11 shows an alternative way to describe these movements as tilt and sagitta along various lines. There are three points across the hybrid end of one wafer which can be used to calculate a tilt and sagitta (circles). Similarly, three points across the far end of the other wafer are plotted with squares. Finally, the two long edges of the module are averaged together and used to calculate the points marked with triangles. The results show that there is very little tilt along the length of the module because it is well constrained by the cooling blocks. The tilt across the module shows a similar variation with temperature as the correction to the cooling block plane. This means that if we had not attempted to correct the block tilt we would have got "better" results, and it makes us suspect that the correction is at fault. The lower plot of Figure 11 shows that sagittas of up to 50 microns are present but that they do not change by more than 20 microns with temperature.

We could take the view that it does not matter what the hybrid does as long as the wafers stay still, but maybe we should try to understand the hybrid too. However, this is difficult because the hybrid appears to jump up and down in Z between one run and the next, in a way which is not proportional to temperature. The movements can be as much as 100 microns up or down. Nor is there any correlation between runs at with nominally identical conditions before and after cycling, except that the final measurement at room temperature is (by chance?) rather close to the very first room temperature measurement (last column, Figure 7).

4.4 Results on CF module

Figures 8 and 9 10 show similar results for the module with a carbon fibre hybrid. This module has a known problem at the far end at $(x = 122, y = -35)$ where the glue failed to join the wafer to the AlN cross bar. Apart from that corner the remainder of the wafers area behaves very similarly to the BeO module. The movements in the X, Y direction are probably consistent with zero and there is a similar drop of 30 to 70 microns of the upper edge in the Z direction.

Because of the unglued corner of the CF module we can only plot the tilt and sagitta across the hybrid end and along one edge (Figure 12). The results are rather similar to the BeO module, showing that the apparent tilt may be due to a collong block mis-correction and that the sagitta down not change by more than 20 microns.

It may be significant that the Z movement of both the BeO and CF modules is larger after thermal cycling than it was before. However this difference may not be caused by the cycling. It is more likely to be caused by the fact that a different person mounted the modules into the test box before and after cycling. In order to get more consistent results we should specify the torque to be used to screw the module down.

5 Temperature of the hybrids

The temperature of each hybrid was measured with pt100 sensors at the four points shown in Figure 15. Measurements were made both before and after thermally cycling the modules. We also recorded the temperature of the hybrid while its thermal distortion was being measured and got results which are consistent with our other measurements, but we do not report them here because they do not match the conditions defined in the hybrid decision document [3]. The document asks that the measurement be done with the cooling block at 10 C in an environment at 22 C, avoiding drafts. We found that running our module test box with the block at 10 C and the lid closed, caused the environment inside to stabilise at around 19 C which is close enough. In these conditions we estimate that when the hybrid runs at 7 W it will lose about 0.44 W to the environment by convection and radiation, and lose a further 0.26 W by conduction through the fan-ins.

We also measured the temperature of each of the dummy chips with a hand held infra-red probe [4]. The IR probe is expected to be much less accurate then the pt100 measurements: in these conditions it has a repeatability of about 0.5 degrees and a possible systematic error of order 1 degree, however the systematic part of the error should be the same for both hybrids.

5.1 Results

Table 1 shows several sets of temperature measurements, taken both before and after the moduels were thermally cycled. It can be seen that the results are very self-consistent and there is no evidence of any change caused by thermal cycling.

We were surprised to find that the CF hyrid runs significantly hotter than the BeO hybrid, so we did a simple FEA simulation [5] to understand it. The simulation solves the 2 dimensional equation for the temperature of the hybrid substrate $T(x,y)$;

$$\kappa(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) + Q_i(x,y) - Q_o(x,y) = 0$$

The source term Q_i is zero everywhere except in the area of the dummy chips where it has a constant value giving 6.3 W total input, corresponding to the real input minus the estimated loss through the environment and fan-ins. The sink term is zero everywhere except in the area of the cooling contact where it is given by $Q_o = H(T - T_{block})$. For the BeO hybrid we put in *a priori* values of all parameters; $\kappa = K_{BeO} \times t_{BeO} = 280\ \mathrm{Wm^{-1}K^{-1}} \times 0.5$ mm and $H = K_{grease}/t_{grease} = 0.5\ \mathrm{Wm^{-1}K^{-1}}/0.02\ \mathrm{mm} = 25000\ \mathrm{Wm^{-2}K^{-1}}$. The result is in reasonable agreement with our measurements (Figure 13 and Table 1).

For the CF hybrid we only know one value *a priori*; $t_{CF} = 0.5$ mm, so we tuned the values of K_{CF} and H to match the data. The best values were $K_{CF} = 310\ \mathrm{Wm^{-1}K^{-1}}$ and $H = 6500\ \mathrm{Wm^{-2}K^{-1}}$. The resulting match is shown in Table 1. We are confident that the grease thickness is not much different between the two modules so most of the temperature difference must be due to a high transverse thermal resistance in the CF material, or else to a thin layer of poorly conducting material on the surface of the CF.

In Table 1 the simulated results in the "chips" columns are the expected temperatures of the substrate immediately below the corresponding chip. The temperature of the dummy chips relative to the substrate is clearly different in the two types of hybrid. It can be seen that on the CF hybrid the chips are 5 to 6 degrees above the substrate while on the BeO hybrid they are 2 to 3 degrees above the substrate. This difference could also be due to high thermal resistance of the CF material in the transverse direction.

6 Conclusions

There is no significant difference between the observed thermal distortions of the two modules as they are cooled from room temperature to -20 C.

When the expected contraction of the silison is taken into account, remaining movements of the wafers in the X,Y direction are generally less than 5 microns and we attribute the few larger movements to pattern recognition errors. We conclude that real X,Y movements are no more than 5 microns and are consistent with zero.

Both modules show some real movement of the wafers in the Z direction when thay are cooled. One edge of the module drops by 30 to 70 microns while the parts near the cooling blocks stay fixed and the other edge moved up or down by less than 20 microns. These movements are not only at the hybrid end of the module so we assume that they are not driven by movements of the hybrid; they are presumably a property of the wafers+spine structure. We can not be certain that this apparent tilt in the Z versus Y direction is really a feature of the module. It could be due to a false correction for the cooling block tilt. In that case the only real distortion of the module would be a bowing of less than 20 microns. Thse numbers are all within the ± 115 micron Z specification of the forward modules but we should take care that they do not combine with a module assembly error to put a module outside specification.

Module	Power	pt100 measurements (C)				IR probe of chips (C)					
	(W)	L	R	E	M	1	2	3	4	5	6
CF before	7	26.3	26.5	17.8	11.9	32.7	29.8	24.7			
CF after	7	26.7	26.6	17.8	11.4	31.7	30.6	21.4	24.8	30.3	31.5
CF after	0	1.3	1.4	1.3	0.6						
CF again	7	26.6	26.9	18.0	11.9	32.6	30.6	24.3	24.4	30.5	33.1
CF again	0	0.9	1.1	0.7	0.5						
CF simulated	7	26.5	26.5	19.5	12.0	27.0	24.1	18.8	18.8	24.1	27.0
BeO before	7	19.4	19.2	12.0	4.8						
BeO before	0	1.0	0.7	0.7	0.4						
BeO before	7	19.5	19.1	11.9	4.8	21.2	17.9	11.4			
BeO after	7	19.9	19.1	12.4	4.7	22.1	19.8	14.1	13.5	19.6	22.6
BeO after	0	0.9	0.9	0.7	0.4						
BeO simulated	7	21.2	21.2	13.5	5.3	21.3	18.3	12.2	12.2	18.3	21.3

Table 1: Temperature measurements of the hybrid and the dummy chips. All temperatures are relative to the main cooling block. The far end cooling block was always kept within one degree of the main block and the environment was always about nine degrees warmer.

The hybrid themselves clearly move in the Z direction when they are cooled down, and move again when 7 W power is switched on. These movements are up to 160 microns in the far corners but only 30 microns near the centre. Since the movement appears not to be transmitted to the detectors we do not care about it.

There is a clear difference in the thermal performance of the two hybrids; the CF version runs about 30 percent hotter than the BeO version under the same conditions. We attribute the difference to poor transverse thermal conductivity of the carbon fibre material. However, both hybrids are within the thermal specifiations and we believe that both modules could be cooled adequately with the baseline cooling system.

Both modules have survived 13 cycles from +40 to -20 C without any measureable change in their thermal or mechanical properties. The only exception is one corner of the CF module where an incomplete glue joint between a wafer and the AlN cross bar sprang open further during cycling.

Both modules have also survived abrupt switching of the hybrid power from zero to 7 W, and back again, without any sign of damage from thermal shock.

References

[1] `http://hepwww.ph.man.ac.uk/groups/atlas/module/index.html` The link labelled “thermo-mechanical” points to this note.

[2] `http://hepwww.ph.man.ac.uk/groups/atlas/module/index.html` Pointer to the note on our assembly jig.

[3] Note circulated by Mike Tyndel, “Specification and decision criteria for the SCT hybrid/module technology”, dated 06/07/99.

[4] Infra red probe from Exergen, model D 501-RS-AO.

[5] FlexPDE version 2.13c from `http://www.pdesolutions.com/`

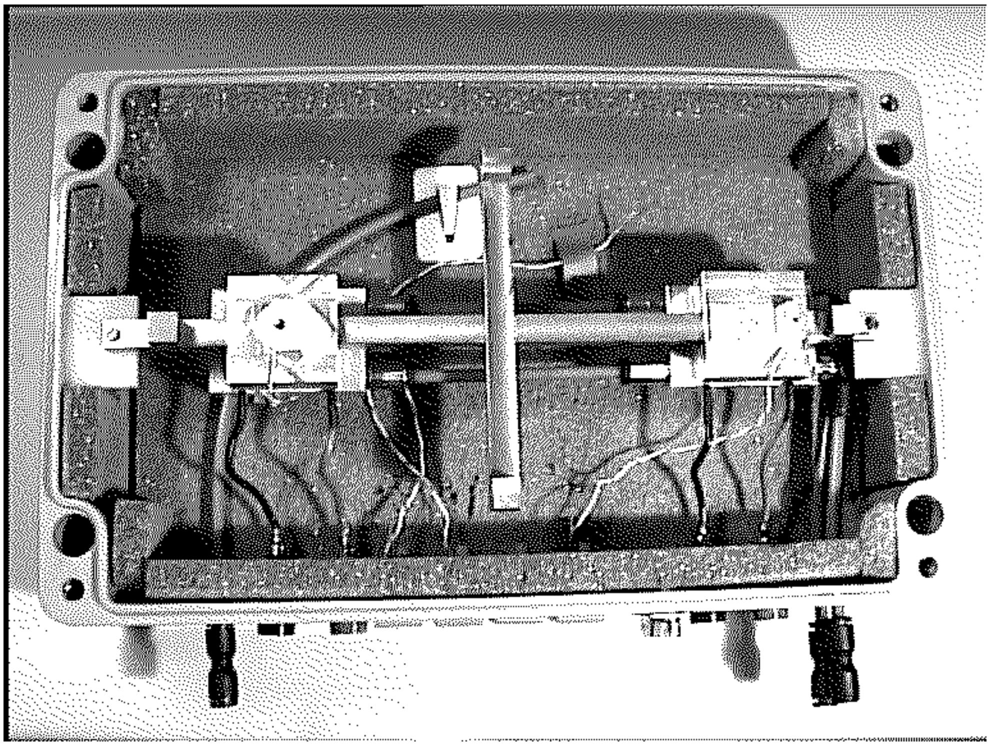


Figure 1: The thermal test box.

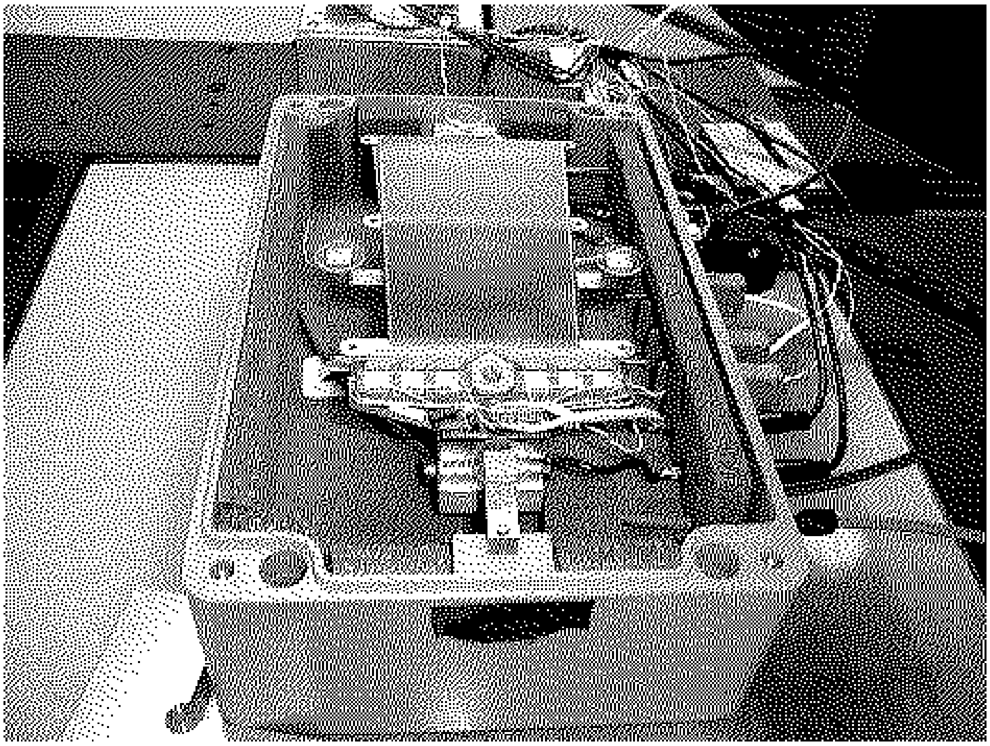
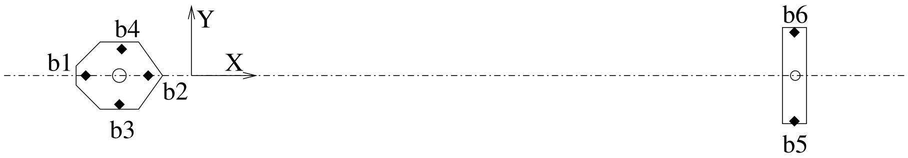


Figure 2: A thermal module in the test box.



point	X	Y	Z at 21C (fit)	Z at -20 C (fit)
b1	-23.5	-0.2	-1.055 (-1.065)	-1.062 (-1.060)
b2	-5.7	0.1	-1.060 (-1.048)	-1.043 (-1.043)
b3	-15.4	-6.4	-1.040 (-1.045)	-1.039 (-1.043)
b4	-15.5	6.3	-1.075 (-1.070)	-1.064 (-1.062)
b5	126.7	-9.3	-0.901 (-0.898)	-0.898 (-0.896)
b6	126.7	9.3	-0.932 (-0.936)	-0.921 (-0.923)

Fit at +21 C: Z = -1.042 + (0.988*X - 2.017*Y)/1000.
Fit at -20 C: Z = -1.037 + (1.006*X - 1.461*Y)/1000.

Figure 3: The fit of a plane to the cooling block surface.

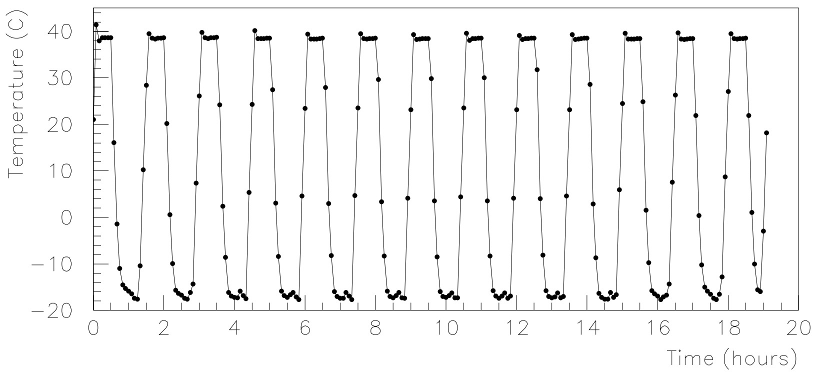


Figure 4: Temperature cycles experienced by the modules in the environment chamber.

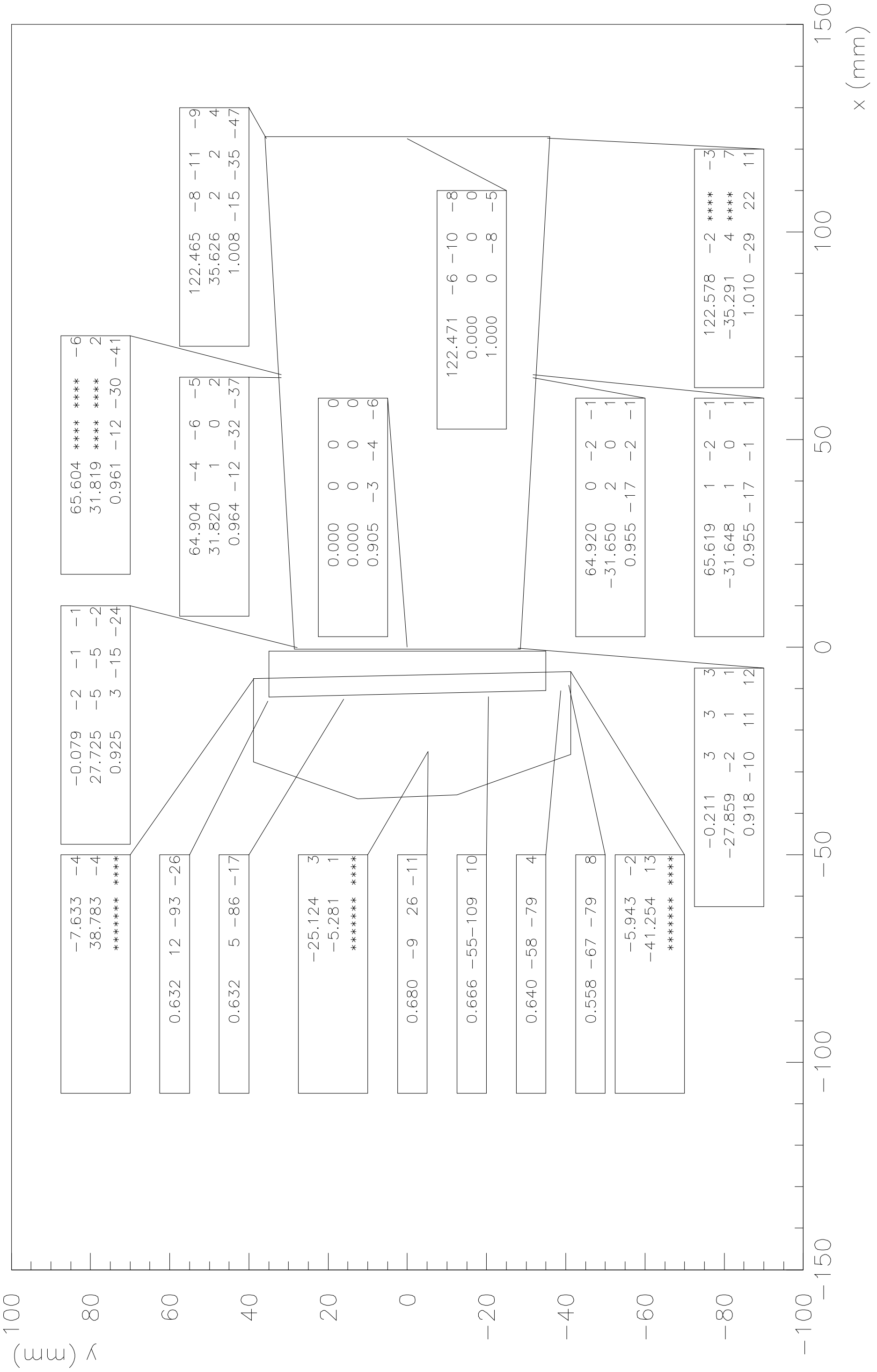


Figure 5: This figure shows the distortion of the module with a **beryllia hybrid** as it goes through a series of temperature changes. These measurements were made **before** the module was thermally cycled 13 times. The three rows of numbers in each box are, from top to bottom, the X, Y and Z coordinates of a feature on the module. Where there is only one row it is the Z coordinate. The four columns of numbers are, from left to right, measurements taken at +21 C, 0 C, -20 C and -20 C +7 W. The first column gives the absolute value of the coordinate in units of mm and the remaining columns give offsets in microns relative to the first column.

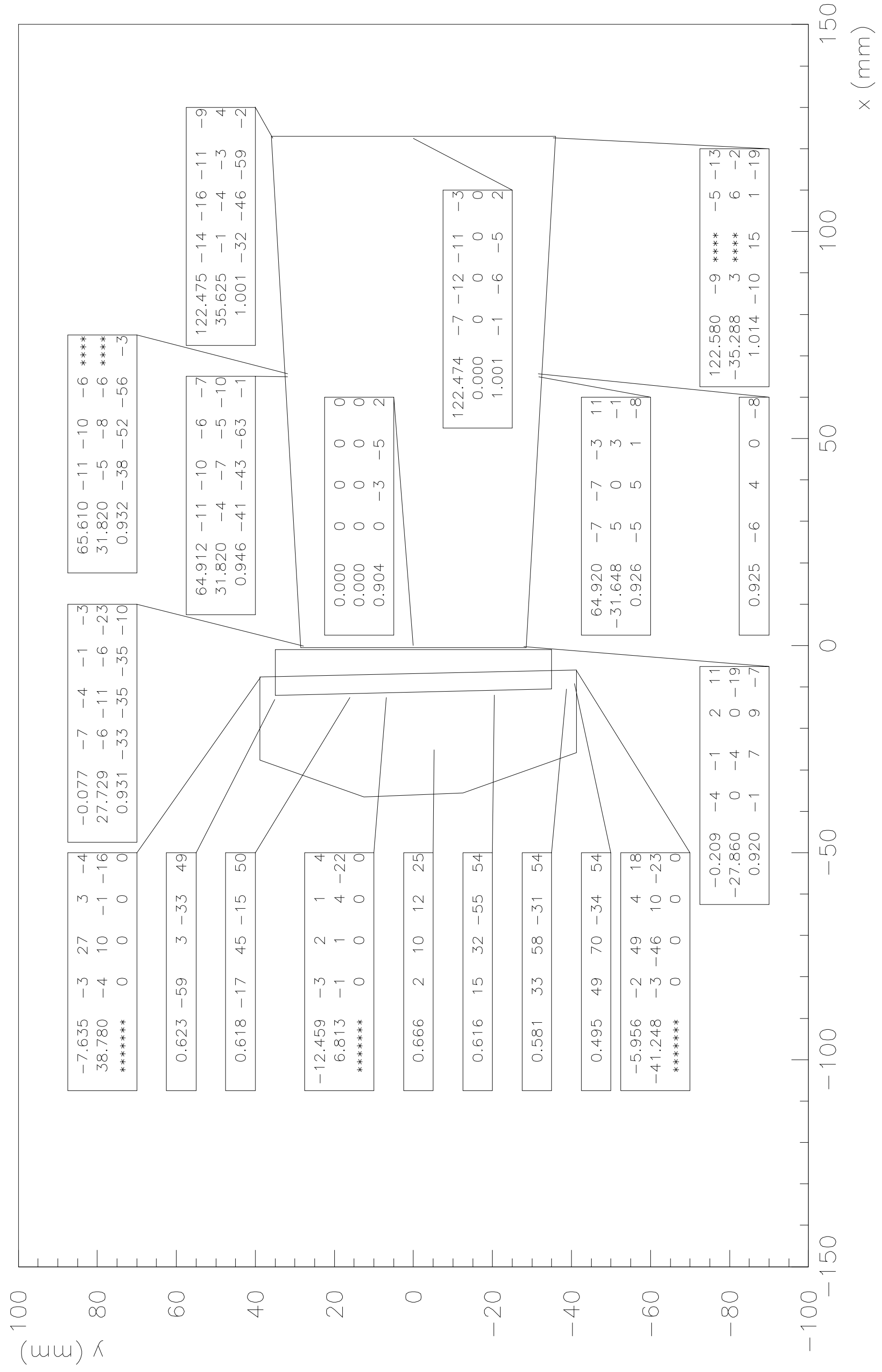


Figure 6: This figure shows the distortion of the module with a **beryllia hybrid** as it goes through a series of temperature changes. These measurements were made **after** the module was thermally cycled 13 times. The three rows of numbers in each box are, from top to bottom, the X, Y and Z coordinates of a feature on the module. Where there is only one row it is the Z coordinate. The five columns of numbers are, from left to right, measurements taken at +21 C, 0 C, -20 C, -20 C +7 W and 21 C. The first column gives the absolute value of the coordinate in units of mm and the remaining columns give offsets in microns relative to the first column.

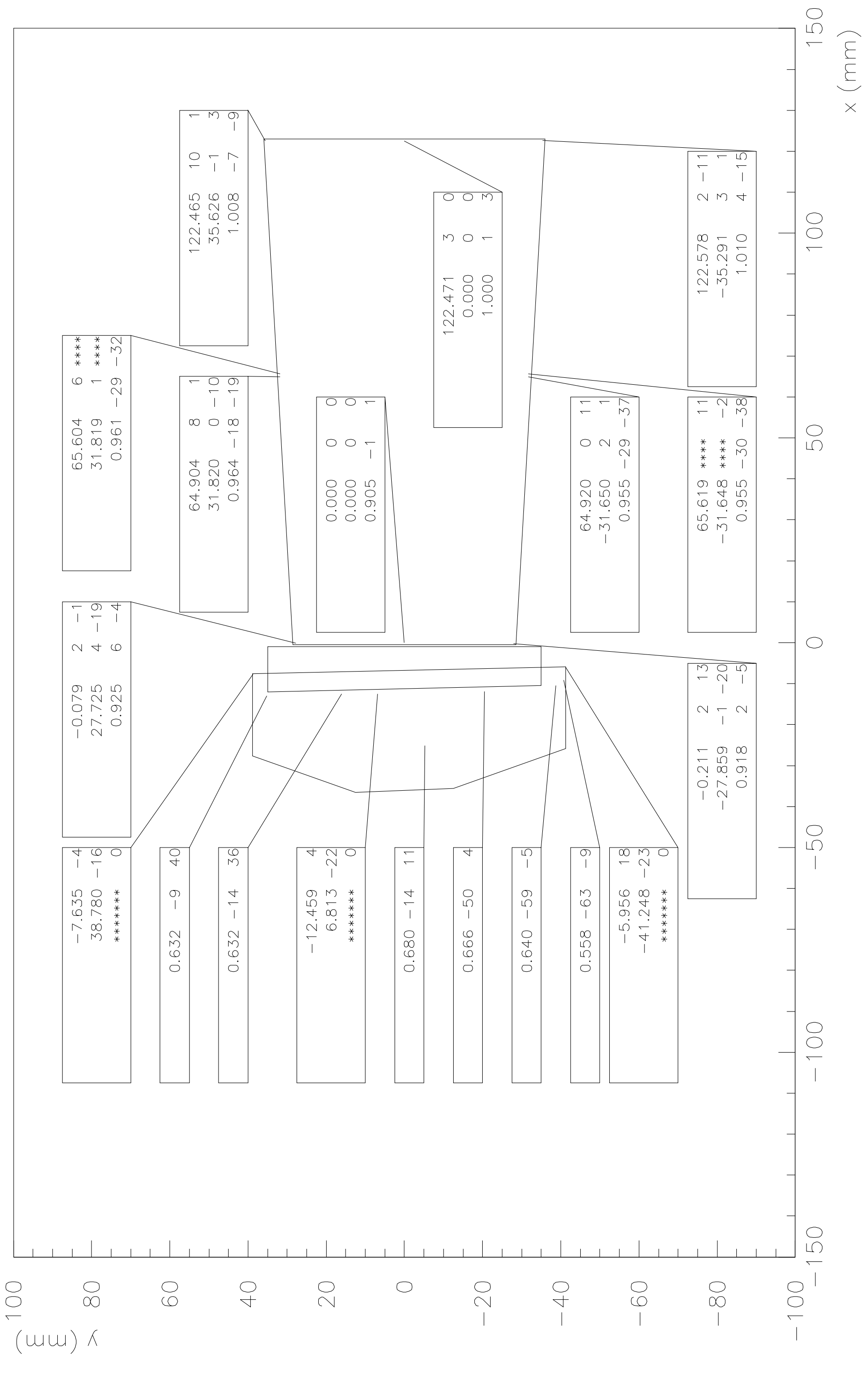


Figure 7: The distortion of the module with a **beryllia hybrid** versus time. All measurements were taken at +21 C. The three rows of numbers in each box are, from top to bottom, the X, Y and Z coordinates of a feature on the module. Where there is only one row it is the Z coordinate. The three columns of numbers are, from left to right, measurements taken before thermal cycling, after 13 cycles from +40 to -20 C, and after a final cycle down to -20 C. The first column gives the absolute value of the coordinate in units of mm and the remaining columns give offsets in microns relative to the first column.

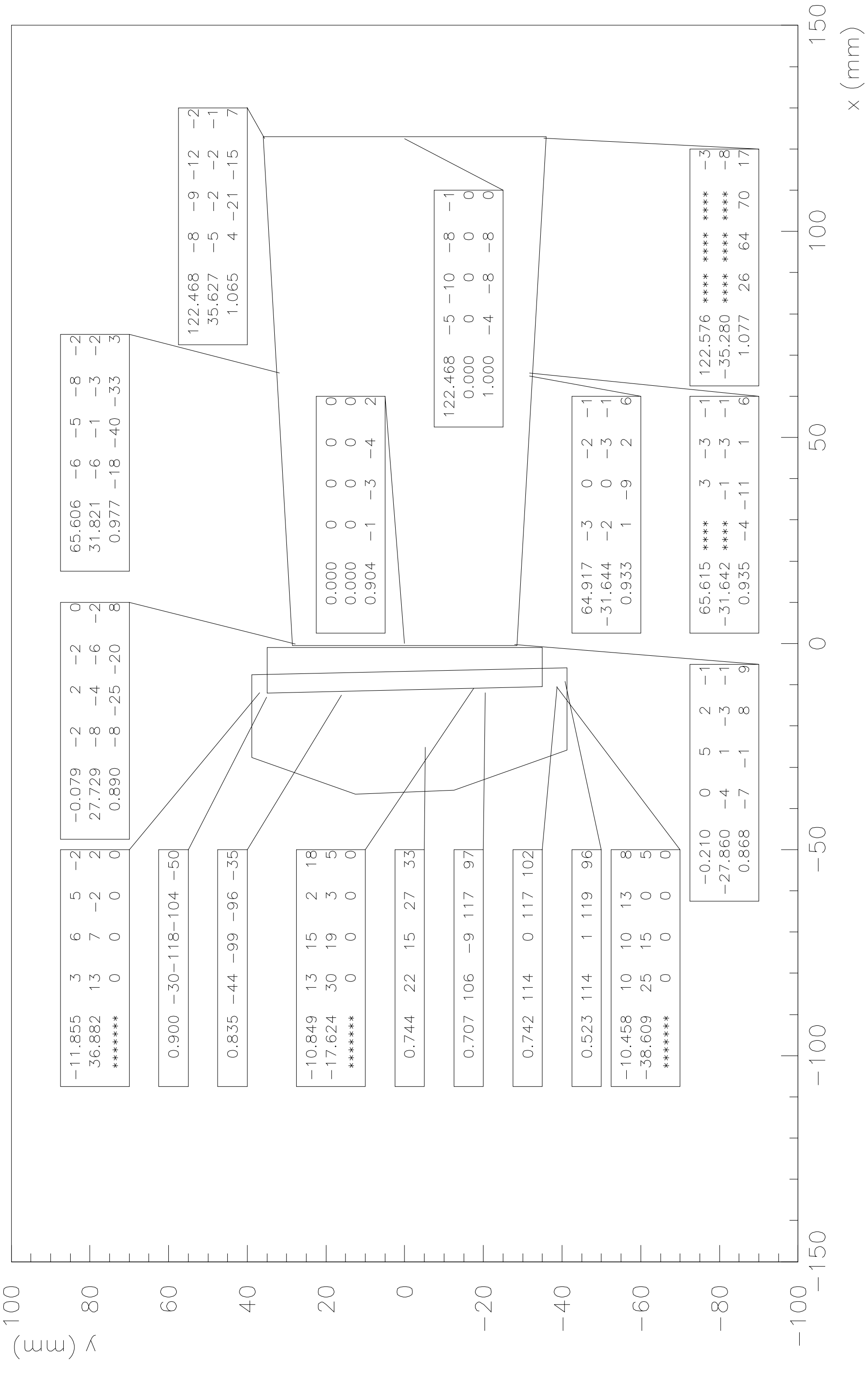


Figure 8: This figure shows the distortion of the module with a **carbon fibre hybrid** as it goes through a series of temperature changes. These measurements were made **before** the module was thermally cycled 13 times. The four rows of numbers in each box are, from top to bottom, the X, Y and Z coordinates of a feature on the module. Where there is only one row it is the Z coordinate. The four columns of numbers are, from left to right, measurements taken at +21 C, 0 C, -20 C, -20 C +7 W and +21 C. The first column gives the absolute value of the coordinate in units of mm and the remaining columns give offsets in microns relative to the first column.

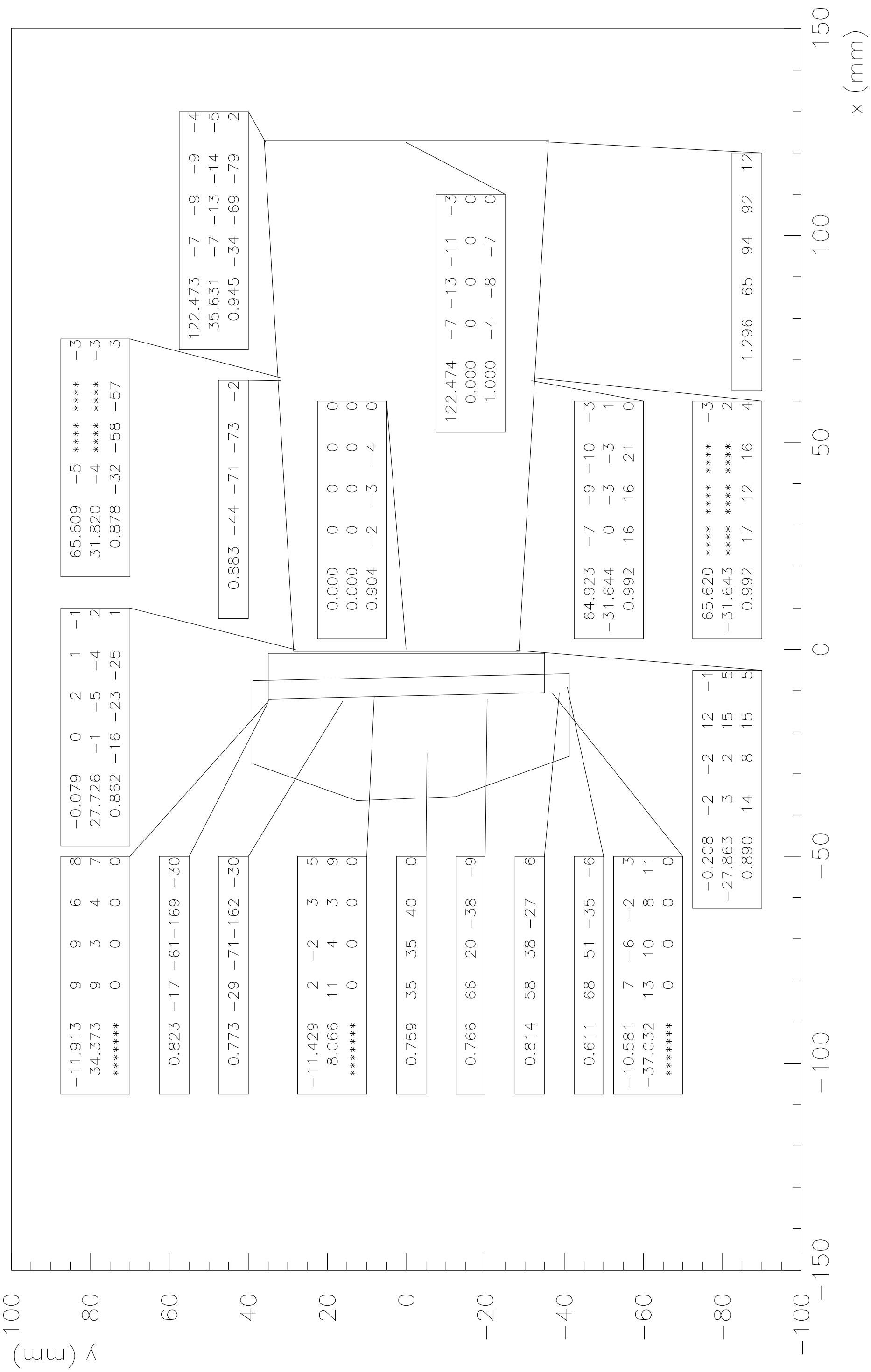


Figure 9: This figure shows the distortion of the module with a **carbon fibre hybrid** as it goes through a series of temperature changes. These measurements were made **after** the module was thermally cycled 13 times. The three rows of numbers in each box are, from top to bottom, the X, Y and Z coordinates of a feature on the module. Where there is only one row it is the Z coordinate. The five columns of numbers are, from left to right, measurements taken at +21 C, 0 C, -20 C, -20 C +7 W and 21 C. The first column gives the absolute value of the coordinate in units of mm and the remaining columns give offsets in microns relative to the first column.

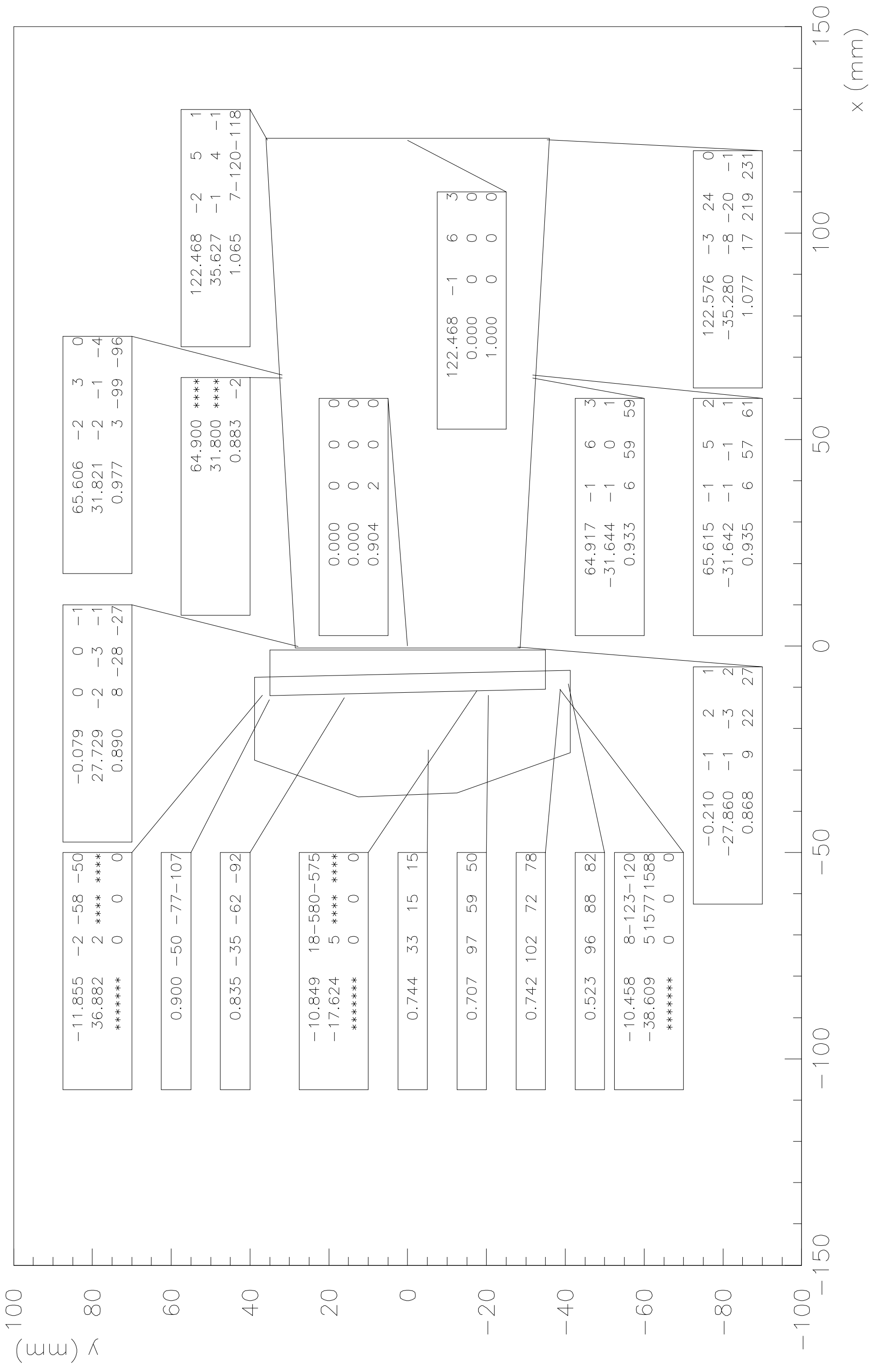


Figure 10: The distortion of the module with a **carbon fibre hybrid** versus time. All measurements were taken at +21 C. The three rows of numbers in each box are, from top to bottom, the X, Y and Z coordinates of a feature on the module. Where there is only one row it is the Z coordinate. The four columns of numbers are, from left to right, two measurements taken before thermal cycling and two taken after thermal cycling. The first column gives the absolute value of the coordinate in units of mm and the remaining columns give offsets in microns relative to the first column.

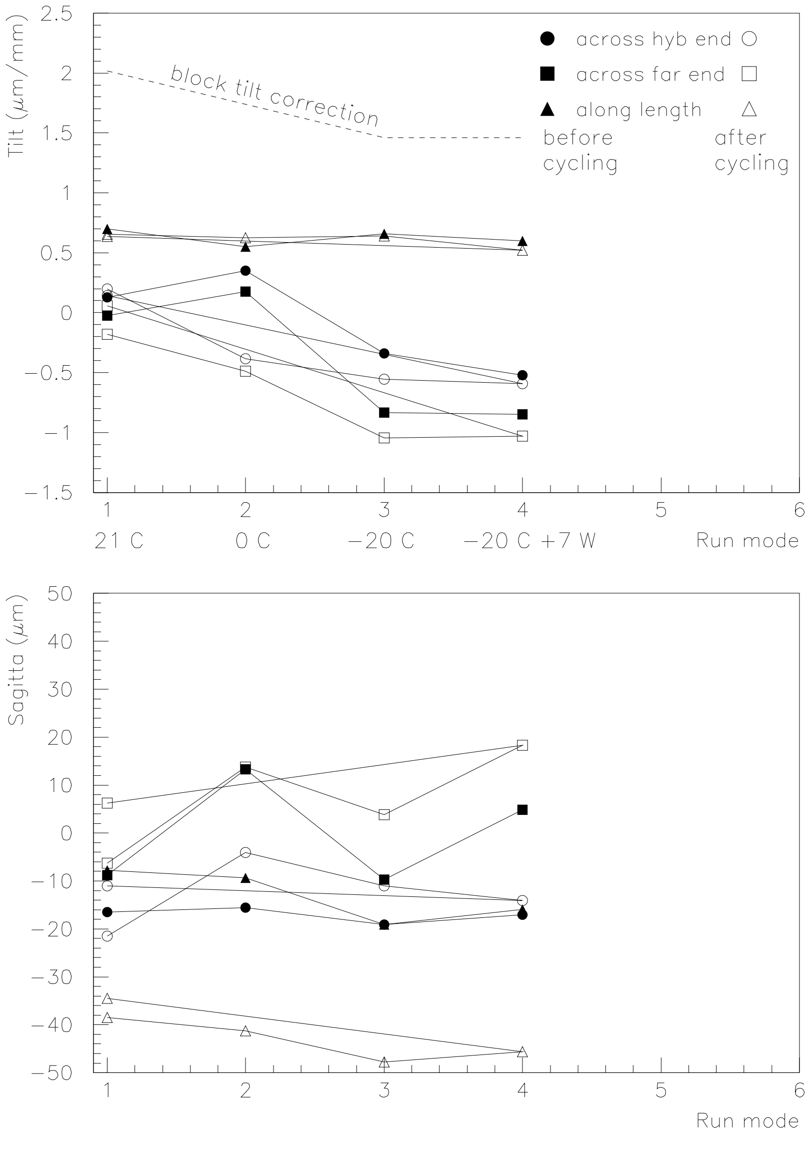


Figure 11: Tilt and sagitta of the BeO module.

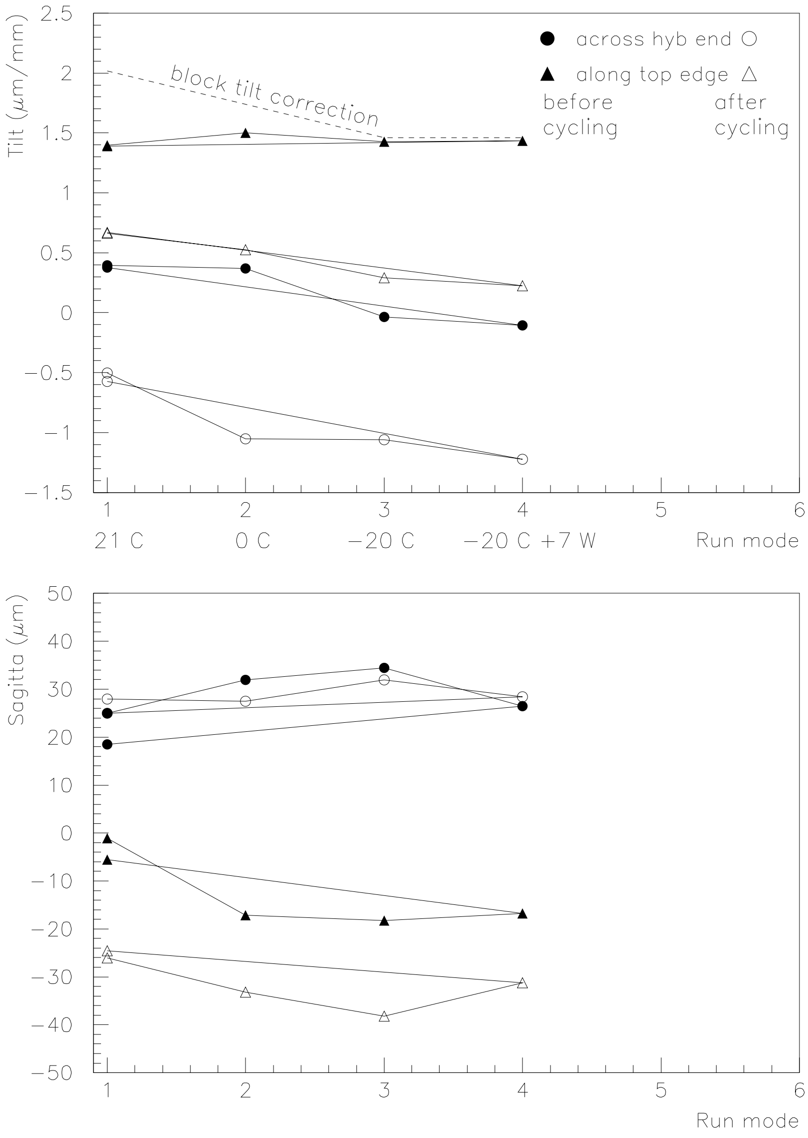


Figure 12: Tilt and sagitta of the carbon fibre module.

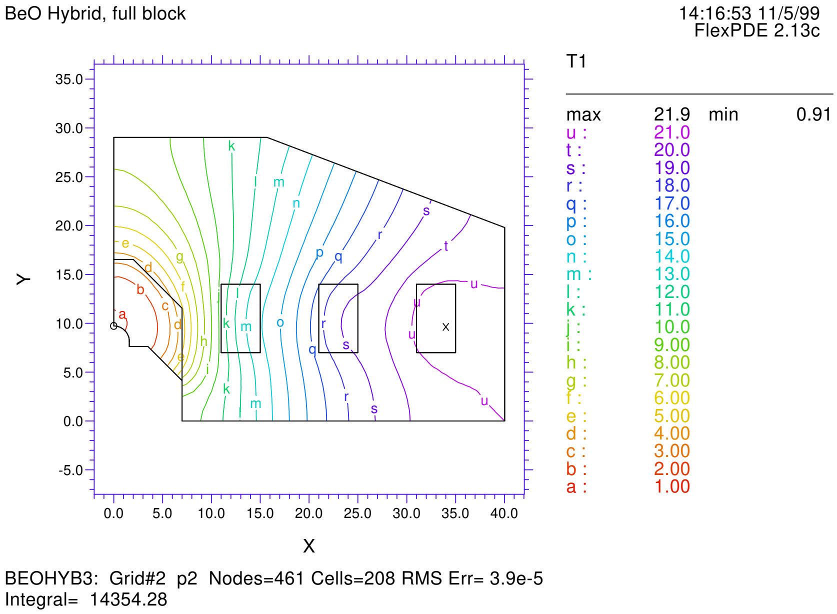


Figure 13: Thermal simulation of the BeO hybrid.

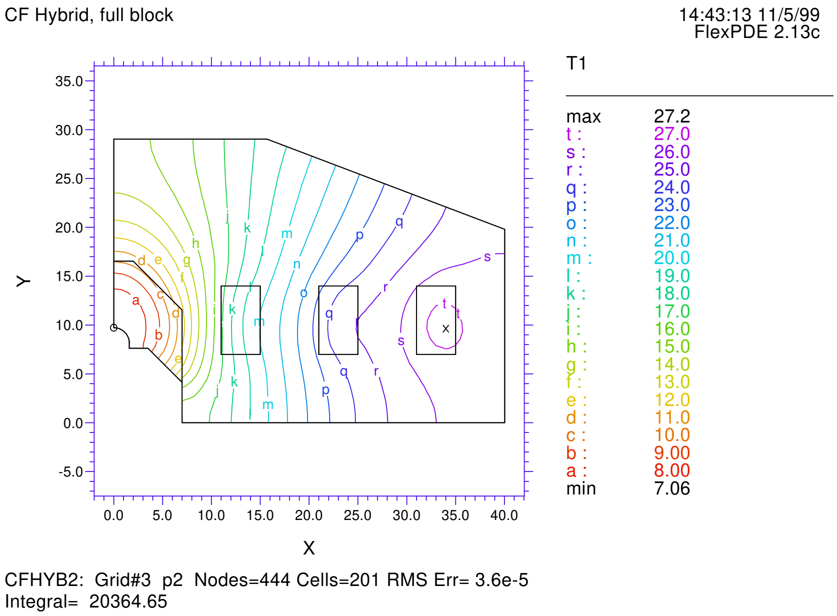


Figure 14: Thermal simulation of the CF hybrid.

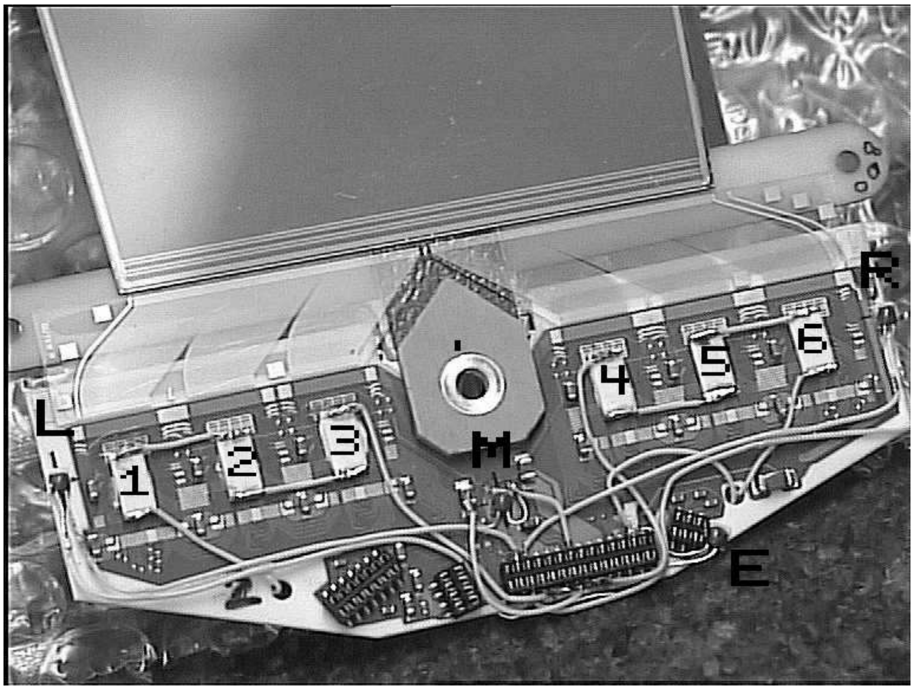


Figure 15: A view of the BeO hybrid showing the positions of the four pt100's, labelled Left, Right, Edge and Mid. The numbering of the six dummy chips is also shown.