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VELO Module Production - Final Module Metrology

LHCB Technical Note

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Abstract

This note describes in detail the procedures used in the metrology of the completed modules on the Wenzel CMM machine.

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1. Introduction

This is a document to show the mechanical and optical measurement of the LHCb module assembly, using the LH overhead Co-ordinate Measuring Machine (CMM).

There are 3 basic metrology requirements:

1. Perform a touch probe measurement of the bare pedestal, before and after grinding, which is done using a CNC program.

2. Perform a touch probe measurement module assembly after the module has been assembled, using a CNC program.

3. Perform an Optical Measurement of the module assembly at 3 positions, pedestal side, cooling side and top of module.

Note: This document only gives a guide to measuring the module using the CMM and is to be carried out by trained personnel, who know the machine characteristics and operation. Also an in depth knowledge of the software is required, in order to do any troubleshooting and undertake modifications, if needed.

2. Equipment

The picture on the next page shows the LH co-ordinate measuring machine located in the class 10000 open area in the clean room. It is an overhead bridge type machine which has the capacity to measure a full module.

The picture below shows the disk and probe used. This is 2mm dia, probe fitted into a TP200 trigger probe and 60mm steel extensions fitted. The TP200 is fitted into the PH10M motorised probe head. The Module is fitted onto the jig base as shown. (See Figure 1)

2.1. Calibration

The calibration of the probe head is carried out using the automatic probe calibration in the Metromec Software. There are 5 probe positions required, where the numbers are specified in degrees about the horizontal and vertical axes.

Probe Pos	A	b
1	0	0
2	30	-90
3	30	0
4	30	90
5	30	-180

Calibration is to be carried out after an optical measurement of the silicon, or where there has been a large time gap e.g. 2 weeks, between measurements.

2.2. Measuring the Module Jig Base

The module jig base is to be measured using the CNC program in WP52-Mod Jig Metrology. This will provide information about the position of dowel holes and post position relative to dowel.

Figure 1: View of Module and Pedestal on Jig Base with Opitical Probe

2.3. Measuring the Module Assemblies

There are 2 CNC measuring programmes set up in the software. One for measuring the bare pedestal before and after grinding and one with module mounted.

In the database will be 2 CNC programmes:

1. Bare Pedestal Measurement
2. Module and Pedestal measurement.

2.3.1. Bare Pedestal Measurement (before and after grinding):

1. Create a new workpiece and add titles accordingly
2. Using the database, copy the CNC sentences from **program 1:Measure bare paddle without module** to the new workpiece.
3. Position probe to the far right hand corner , then right click over the lower screen and run program with new measurement.
4. After measurement, copy the summary measurement and the cooling face detail measurement to a floppy disc and add to the data base.

2.3.2. Pedestal Measurement with Module:

1. Create a new workpiece and add titles accordingly
2. Using the database, copy the CNC sentences from **program 2:Measure paddle with module** to the new workpiece.
3. Position probe to the far right hand corner , then right click over the lower screen and run program with new measurement.
4. After measurement, copy the summary measurement to a floppy disc and add to the data base.

2.3.3. Optical measurement of Module Assembly:

1. Change Probe to the VPN Optical Probe
2. Create a new workpiece and add titles accordingly
3. Each Measurement must be finely focussed using a slow ‘tortoise’ at about 12% speed.
4. Once a point has been accurately positioned then it is ‘taken’ by manually pressing the X button on the **Renishaw VPU2.**
5. Datums should be saved as they can be retrieved at a later date.

NOTE: The R and Phi silicon can be either side of the Module i.e. each can be placed on the Cooling Side or Pedestal Side (See Figure 2 **and** Figure 3 **)**

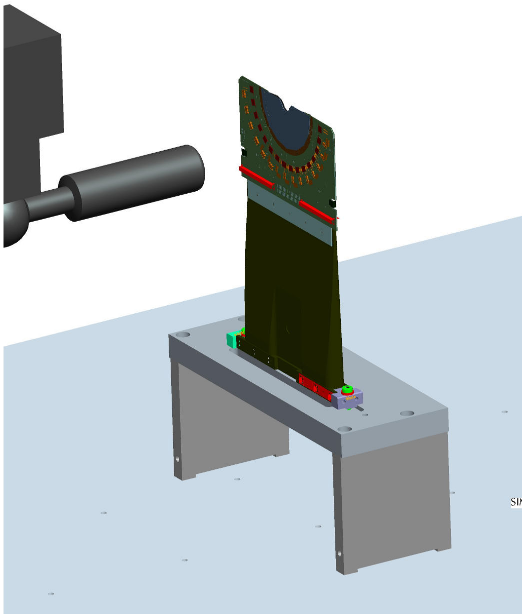

Figure 2: Cooling Side of Module

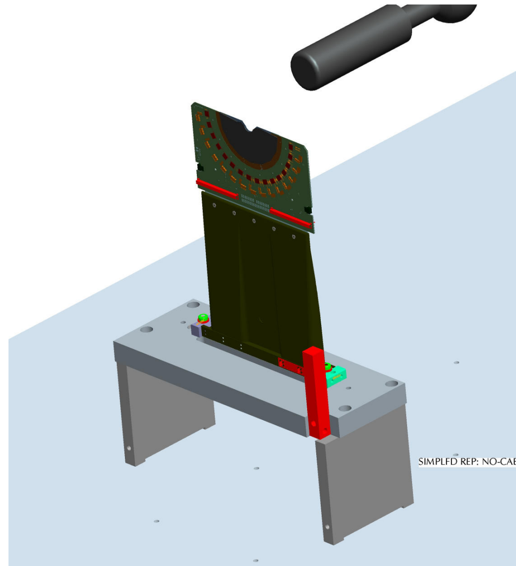

Figure 3: Pedestal Side of Module

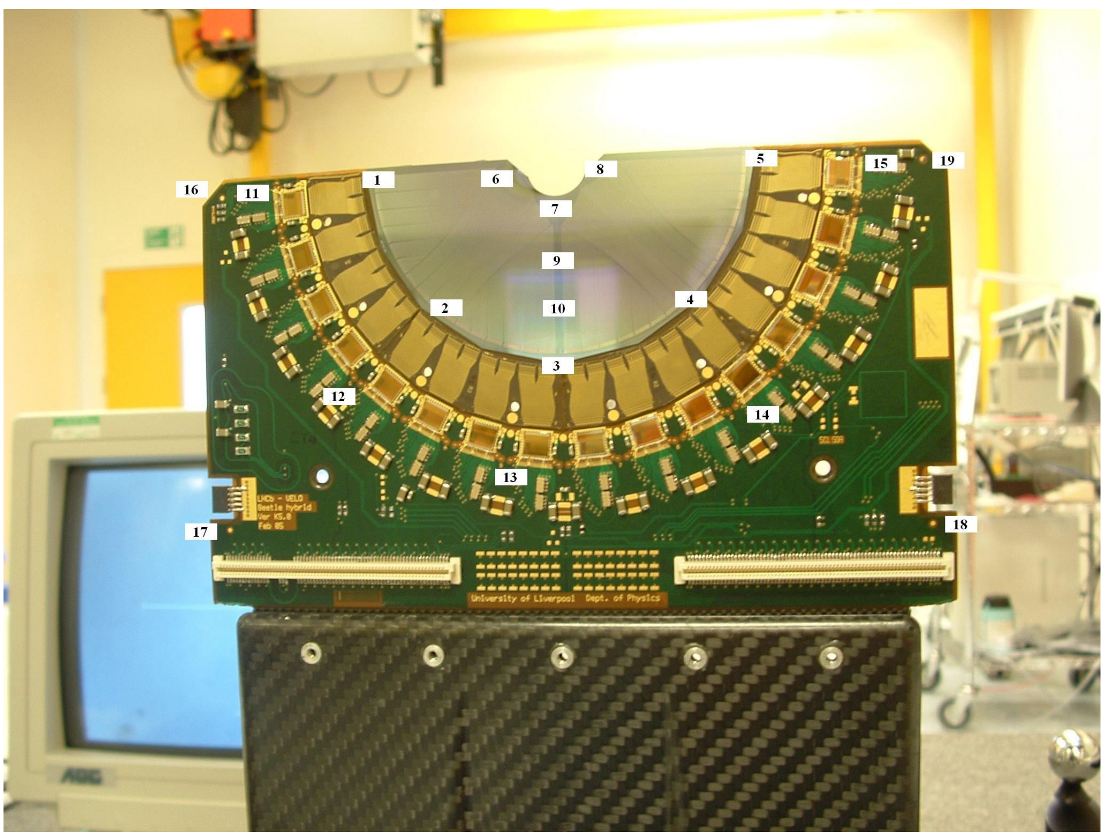

Figure 4: Measuring the Pedestal **Side**

2.3.4. Measure R Side

1. Change the probe position to 1001.
2. Move Probe to module and measure the cooling side.
    a. Take 4 Points on base of jig:
        i. Take 4 points on base.
        ii. Save as primary datum Z
        iii. Save as origin Y
    b. Take 4 points on vertical Pillar
        i. Take 4 points
        ii. Save as Origin X
        iii. Save datum 1

    d. The following measurements need to be made with reference to **Table 1 or 2**.The table gives approximate Y,Z positions of the measurement point Each X,Y Coordinate shows the approximate position of the measurement, so the operator can quickly traverse to the relevant place.

    c. Make a 10 point plane and take a measurement plane of the following points on the silicon.
        i. Starting from the right hand side take 5 fiducial points. (**1,2,3,4,5**)
        ii. Take 3 points on inner rim (**6,7,8**)
        iii. Take 2 further points either on the vertical 'line' of the R silicon or anywhere on central on the Phi silicon. (**9,10**)
    d. Make a 9 point measurement plane of the hybrid surface.
        i. Measure 5 gold + marks near the chips (270, 235, 180, 135 and 90 deg.) (**11,12,13,14,15**)
        ii. Measure the centre of the 5 gold circles. (**16,17,18,19**)

2.3.5. Measure Phi Side:

1. Change the probe position to 1002
2. Move Probe to module and measure the cooling side.
    a. Take 4 Points on base of jig:
        i. Take 4 points on base.
        ii. Save as primary datum Z
        iii. Save as Origin Y
    b. Take 4 points on vertical Pillar
        i. Take 4 points
        ii. Save as Origin X
        iii. Save datum 1

    d. The following measurements need to be made with reference to **Table 1 or 2**. The table gives approximate Y,Z positions of the measurement point Each X,Y Coordinate shows the approximate position of the measurement, so the operator can quickly traverse to the relevant place.

    c. Make a 10 point plane and take a measurement plane of the following points on the silicon
        i. Starting from the right hand side take 5 fiducial points. (**1,2,3,4,5**)
        ii. Take 3 points on inner rim (**6,7,8**)
        iii. Take 2 further points either on the vertical 'line' of the R silicon or anywhere on central on the Phi silicon. (**9,10**)
    d. Make a 9 point measurement plane of the hybrid surface.
        i. Measure 5 gold + marks near the chips (270, 235, 180, 135 and 90 deg.) (**11,12,13,14,15**)
        ii. Measure the centre of the 5 gold circles. (**16,17,18,19**)

2.3.6. Measure Top Side:

1. Change Probe Position to 1003
2. Move probe to measure right hand Dia 5.85 Hole.
    a. Save as primary Datum XY
3. Move probe to measure left hand Dia 5.85 Hole
4. Create a N point line between 2 holes.
    a. Save as secondary datum Y
5. Move Probe to module to measure top edges.
    a. Take 6 points on edge of R side silicon.
    b. Take 6 points on edge of Phi side of silicon.

2.4. Outputting Results

All the sets of results should be added to the database [1] as follows:

2.4.1. Pedestal Update

***Before Grinding**:*

- Enter Action: MET 1
- Add base paddle metrology summary file.

***After Grinding**:*

- Enter Action: MET 2
- Add base paddle metrology summary file.

2.4.2. Module Update:

First Full Metrology:

- Phi Summary
- Phi Silicon Plane
- Phi Hybrid Plane
- R Summary
- R Silicon Plane
- R Hybrid Plane
- Top Summary
- Top Phi Edge
- Top R edge

Second Metrology after Cable Attachment:

- Top Summary
- Top Phi Edge
- Top R edge

Final Metrology after Burn in:

- Top Summary
- Top Phi Edge
- Top R edge

3. Measurement Analysis

Measurement analysis is provided by the web interface of the database program, once the metrology data files have been uploaded using the database web input pages, links are automatically created that allow the data files to be inspected and analysed [1]. The results being displayed directly back to the user via the web browser.

The use of the pedestal data before and after grinding is discussed in the note on Hybrid-Pedestal matching [2].

The first full metrology of the module provides the data that allows the relative and absolute alignments of the R and Phi silicon sensors to be calculated. These data can be combined with the final metrology of all the installed modules at CERN to determine the absolute locations of all the silicon sensors in the final experiment.

In the measurements on the R-side and Phi-side (2.3.4 and 2.3.5) the five fiducials on each silicon sensor plus five additional points were measured in a co-ordinate system with respect to the mounting dowel hole in the foot on the base and the two sides were related to each other by the measurements on the common vertical pillar. Analysis software in the web interface code used these measurements to calculate the absolute position x, y, z and orientation Vx, Vy, Vz of each silicon sensor in the LHCb co-ordinate system and hence also the relative alignment between the two sensors.

The position and orientation of every silicon sensor for the 44 production modules is tabulated below.

Module	Sensor	x (mm)	y (mm)	z (mm)	V_x (mrad)	V_y (mrad)	V_z (mrad)
4	R	0.014	-0.001	-0.766	0.025	4.905	-0.024
	Phi	0.009	-0.005	1.385	0.01	3.006	0.021
5	R	0.004	0.005	-1.13	-0.514	-1.136	-0.024
	Phi	0.010	-0.003	1.019	-0.548	-2.319	-0.035
7	R	-0.006	-0.006	1.001	-1.441	-3.791	0.000
	Phi	-0.012	-0.009	-1.156	-1.929	-2.11	0.008
21	R	0.003	0.011	0.927	0.293	-1.813	-0.270
	Phi	-0.002	0.012	-1.253	0.259	-0.756	-0.237
23	R	0.009	0.028	-0.781	1.392	1.791	-0.179
	Phi	0.012	0.072	1.552	1.091	4.357	-0.264
24	R	0.006	0.023	-0.985	-0.027	-0.604	-0.194
	Phi	0.002	0.028	1.138	0.107	-1.763	-0.176
25	R	0.001	0.012	-0.984	-0.549	2.16	-0.355
	Phi	-0.004	-0.002	1.25	-0.774	0.954	-0.344
26	R	0.009	0.014	-1.044	1.108	-0.87	-0.254
	Phi	-0.003	0.032	1.067	1.449	-1.816	-0.180
27	R	-0.009	0.007	0.716	1.813	-4.672	-0.341
	Phi	-0.017	-0.036	-1.415	1.424	-3.345	-0.214
28	R	-0.009	0.033	1.066	0.641	-0.852	-0.267
	Phi	-0.005	0.032	-1.112	0.666	0.345	-0.232
29	R	0.002	0.014	1.091	0.195	-1.028	-0.213
	Phi	0.002	0.007	-1.08	0.218	0.115	-0.165
30	R	-0.017	0.018	-1.393	-0.411	-4.751	-0.234
	Phi	-0.002	0.019	0.765	0.195	-6.226	-0.282
31	R	-0.010	0.030	0.899	-0.087	-2.74	-0.249
	Phi	0.011	0.042	-1.403	-0.26	-3.556	-0.212

Module	Sensor	x (mm)	y (mm)	z (mm)	V_x (mrad)	V_y (mrad)	V_z (mrad)
32	R	0.002	0.017	-0.719	0.238	3.382	-0.220
	Phi	-0.009	0.017	1.463	0.552	2.439	-0.312
33	R	0.000	0.017	1.178	-0.091	0.639	-0.220
	Phi	-0.005	0.013	-1.029	0.216	1.247	-0.153
35	R	-0.001	0.009	-1.023	0.983	0.305	-0.115
	Phi	0.000	0.002	1.132	1.072	-0.639	-0.206
36	R	-0.001	0.022	1.11	0.702	0.4	-0.252
	Phi	-0.011	0.031	-1.078	0.45	0.72	-0.188
37	R	-0.016	-0.009	-1.282	1.029	-1.363	-0.212
	Phi	-0.005	-0.006	0.939	1.758	-1.938	-0.285
38	R	0.000	0.013	-0.775	-0.463	0.974	0.058
	Phi	-0.009	0.021	1.408	-0.354	0.462	0.082
42	R	-0.001	0.013	-0.924	1.405	1.857	0.052
	Phi	-0.009	0.014	1.219	1.731	1.147	-0.094
44	R	-0.013	0.012	1.298	0.538	2.274	0.038
	Phi	-0.009	0.013	-0.869	0.51	3.387	0.093
45	R	-0.004	0.006	-0.727	1.293	3.228	-0.021
	Phi	-0.010	0.009	1.362	1.235	1.892	-0.038
47	R	-0.006	-0.003	-0.927	1.324	0.827	0.010
	Phi	-0.005	0.003	1.179	1.809	-1.001	0.110
48	R	0.008	-0.007	0.916	2.004	-2.394	-0.011
	Phi	-0.001	-0.010	-1.282	2.238	-1.31	0.015
49	R	-0.010	-0.007	1.189	1.326	0.748	0.062
	Phi	-0.008	-0.004	-0.956	1.565	1.73	0.205
50	R	0.001	0.000	1.209	1.162	0.737	0.000
	Phi	-0.004	0.007	-0.959	1.39	1.553	0.046
51	R	-0.002	-0.009	1.095	-1.004	-0.473	0.001
	Phi	-0.014	-0.010	-1.041	-0.976	0.049	0.001
52	R	0.002	-0.016	1.013	-0.3	-1.816	-0.057
	Phi	-0.002	-0.012	-1.146	-0.247	-1.227	0.053
53	R	-0.001	-0.009	1.176	-0.03	1.589	-0.019
	Phi	-0.009	-0.007	-0.98	-0.064	2.545	0.112
54	R	-0.007	0.003	-1.083	0.539	-0.799	0.031
	Phi	-0.001	-0.002	1.046	0.964	-2.585	-0.061
55	R	-0.001	-0.003	1.286	0.539	1.021	0.038
	Phi	-0.001	0.001	-0.843	0.378	2.206	0.130
56	R	-0.007	0.000	-0.683	0.003	5.456	0.077
	Phi	-0.016	-0.004	1.452	-0.362	4.117	-0.182
58	R	0.000	-0.009	-1.109	-0.063	0.726	0.109
	Phi	-0.005	0.000	1.017	0.469	-0.969	0.014
59	R	-0.013	-0.002	-1.388	-1.68	-5.84	0.034
	Phi	-0.007	-0.007	0.767	-1.478	-7.405	0.003
60	R	-0.018	0.000	1.361	0.075	2.965	0.024
	Phi	-0.001	-0.001	-0.786	0.467	4.73	0.113
61	R	0.004	-0.017	1.446	2.261	3.978	-0.088
	Phi	0.003	-0.014	-0.718	1.999	4.869	0.176
62	R	0.006	-0.001	-0.823	0.404	2.66	0.112
	Phi	-0.002	0.001	1.359	0.378	2.534	-0.114

Module	Sensor	x (mm)	y (mm)	z (mm)	V_x (mrad)	V_y (mrad)	V_z (mrad)
63	R	0.009	0.006	1.289	-0.651	1.829	-0.026
	Phi	0.015	-0.001	-0.837	-0.38	3.232	-0.020
64	R	0.007	0.003	-0.816	-0.895	1.681	0.037
	Phi	0.002	0.001	1.393	-0.74	1.269	0.007
71	R	0.009	-0.021	0.807	-0.517	-3.308	-0.095
	Phi	-0.003	-0.015	-1.359	-0.657	-2.179	0.018
72	R	0.008	-0.002	-1.148	-0.199	-1.746	0.090
	Phi	0.005	0.009	1.012	-0.216	-2.573	0.005
73	R	0.014	-0.014	0.833	-0.029	-2.928	-0.015
	Phi	0.006	-0.009	-1.29	0.218	-1.941	0.004
74	R	0.010	-0.005	-0.789	1.463	3.279	0.015
	Phi	0.006	-0.004	1.431	1.509	2.557	-0.087
75	R	0.019	-0.011	1	-0.065	-0.881	-0.037
	Phi	0.021	-0.011	-1.124	-0.298	0.946	-0.010
	Mean	-0.001	0.004	0.060	0.350	0.140	-0.069
	StDev	0.008	0.016	1.109	0.920	2.657	0.136
	Minimum	-0.018	-0.036	-1.415	-1.929	-7.405	-0.355
	Maximum	0.021	0.072	1.552	2.261	5.456	0.205

At the end of the above table, the mean, standard deviation, minimum and maximum values are given for each of the six parameters. These are discussed further below.

3.1. x, y Positions

The production target was that the [x, y] position of the silicon centre should be within 20 µm of the nominal [0,0]. This criteria was well satisfied in x with just one sensor being 1 µm over the criteria, it was less well satisfied in y with the early modules being systematically offset positive and about 12 sensors outside the 20µm criteria before this was corrected. The [x, y] positions of the silicon centres are plotted for the R and Phi sensors in Figure 5.

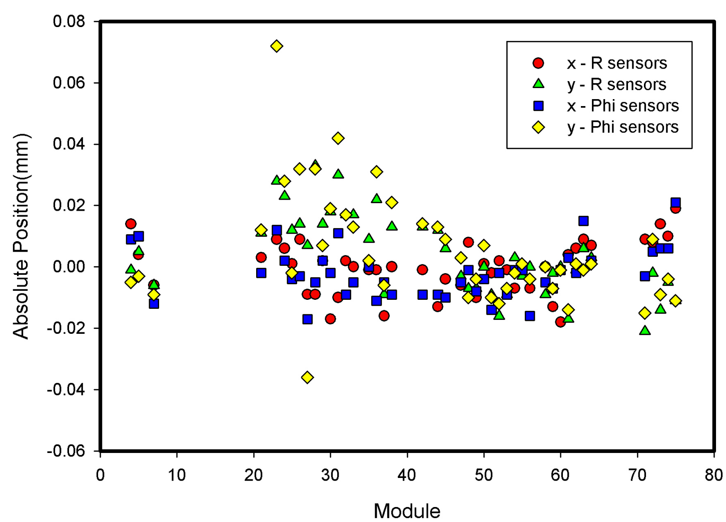

Figure 5: [x, y] of Silicon centres for R and Phi sensor

The same [x, y] silicon sensor centre data is presented in Figure 6 as a contour plot of the distributions in the xy plane separately for the R and Phi sensors. During the construction the primary target was to place the R sensor closest to nominal and the Phi sensor within 20 µm of the R sensor. This was to satisfy online triggering algorithms which use the R sensors. The distributions show that the majority of sensors were placed within the 20 µm tolerance, they also indicate that a precision of 10 µm could be achieved if the small systematic shifts could be reduced by the calibration and fine-tuning of the gluing procedures [3].

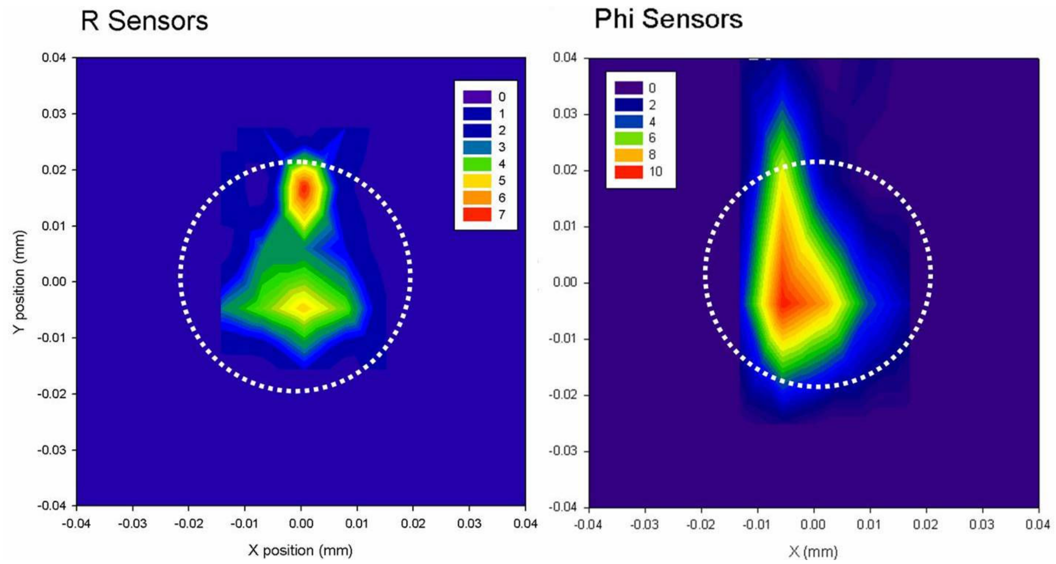

Figure 6: Silicon centre position in xy plane for R and Phi sensors.

3.2. z Position

The mean z is a measure of the average tilt of the modules away from vertical, at +60µm, this looks reasonable. However additional metrology measurements were made to look at the tilt specifically. These were measurements along the front sensitive top edge of each silicon sensor looking down vertically on the mounted module. These measurements were analysed to give a measure of the tilt of the module away from vertical. Ideally the front edges of the two sensors should be symmetrically placed about the z=0 centre line. i.e. the average for the two sensors should be zero. The deviations from zero for the initial tilt were broadly distributed between ±400µm as shown in Figure 7

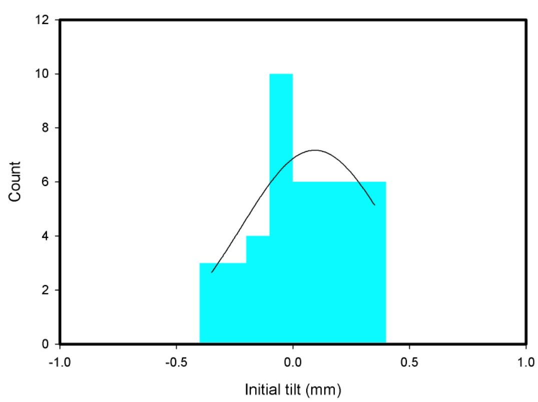

Figure 7: Initial tilt of production modules.

This metrology along the silicon top edges was repeated after the attachment of cables to the module and again when the cables were removed for transport. These partial repeat metrology measurements showed that the attachment and removal of the cables changed the tilt significantly and could increase the tilt range of the module to ±500µm. The distribution of the initial tilt versus the cabled tilt and the distribution of the initial tilt versus the un-cabled tilt are shown in Figure 8 and indicate that the module does not necessarily return to its original position.

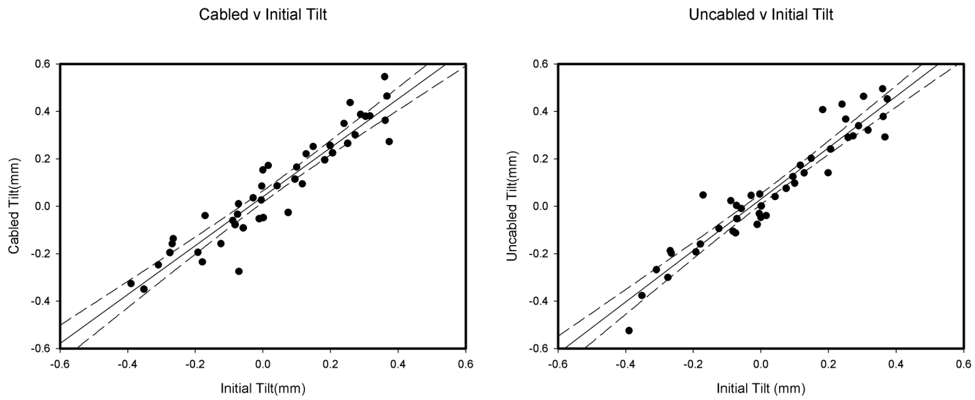

Figure 8: Cabled Tilt vs. Initial Tilt and Un-cabled vs. Initial Tilt of the production modules

The changes in tilt between initial and after cabling, between cabled and un-cabled and between initial and un-cabled are shown in Figure 9. Thus, the process of attaching the cables increases tilt by an average of 62µm, with a sigma of 52µm. Removing the cables decreases the tilt by an average of 10µm but with an increased sigma of 92 µm showing that individual modules move by significant amounts. Finally the process of attaching the cables and then removing them changes the original tilt by an average pf 24µm with a sigma of 52µm, confirming that individual modules can change by more than 100µm from their original position.

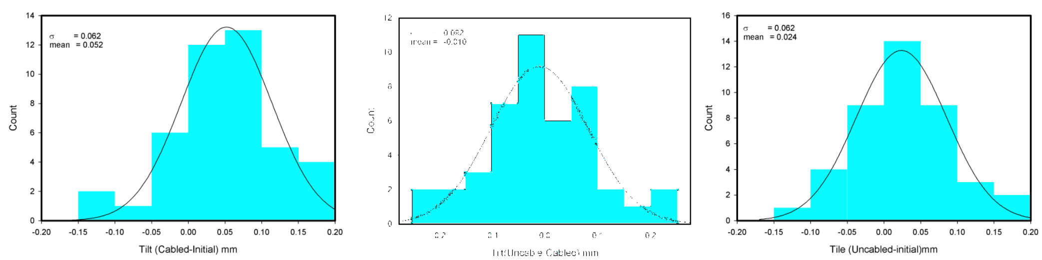

Figure 9: Change in tilt due to attaching and removing cables.

The ±400µm variation was already larger than anticipated and the desired tolerance of ±100µm. For this reason a mechanical constraint system was designed, fabricated and installed to insure that the tilt was mechanically limited to be less than ±100µm on the final installation at CERN.

3.3. V_x, V_y Rotations about x, y

The rotations about x and y, the parameters V_x and V_y, depend upon the shape of the hybrid (twist) and the mounting onto the pedestal and there was no fine control. The measured values are acceptable and the deviations are limited in the final installation by the constraint system discussed above.

3.4. V_z Rotation about z

The final parameter, V_z, measures the rotation of the silicon sensors about the z-axis. This was controlled by the procedures for gluing the sensors to the hybrids [3] and the requirement was to have a zero rotation. The distribution of V_z for the production modules is shown in Figure 10, this shows that there was clear systematic offset for the early production modules (with numbers in the range 21-37). This systematic offset was noted during the Mid-Term Review that was held after the first 15 modules and was corrected for the remainder of the production modules. The offset in the early modules corresponds to maximum deviations of ±30µm at the top silicon corners and is well within tolerances.

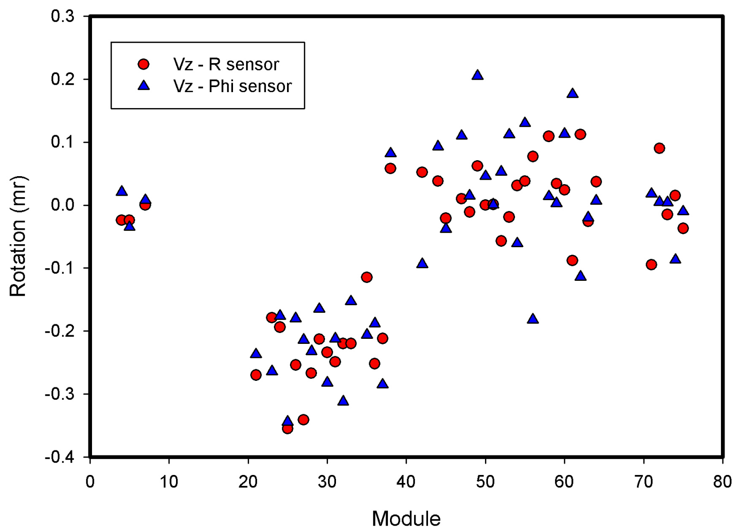

Figure 10: Silicon rotation about Z axis (V_z)

The final set of modules was transported to CERN and 42 of them were installed onto base plates in two halves. A full metrology of the installed modules was carried out at CERN and the analysis of the CERN metrology data and comparisons with the Liverpool metrology will be presented in a subsequent note.

4. References

1. Patel, G.D., et al., *VELO Module Production - Quality and Process Control.* LHCb Internal Note, 2007(088).
2. Carroll, J.L., et al., *VELO Module Production - Hybrid to Pedestal Matching.* LHCb Internal Note, 2007(086).
3. Carroll, J.L., et al., *VELO Module Production - Module Assembly.* LHCb Internal Note, 2007(076).

Appendix - Co-ordinate Tables

Table 1

Module Phi glued (R COOLING SIDE/PHI PEDESTAL SIDE)

R SILICON

Fids	X	Z
1	-174.5	276.0
2	-161.7	244.0
3	-130.0	230.5
4	-98.5	244.0
5	-85.5	276.0

Top edge		
1	-103.0	276.0
2	-152.0	276.0

Center		
1	-130.0	267.0
2	-130.0	257.0
3	-130.0	247.0

PHI SILICON

Fids	X	Z
1	-86.5	274.0
2	-100	243.5
3	-131.2	231.5
4	-161.8	245.0
5	-173.5	276.5

Top edge		
1	-155.0	274.5
2	-103.0	275.5

Center		
1	-130	267.0
2	-145	257.0
3	-115	257.0

R HYBRID

Crosses		
1	-197.3	274.0
2	-185.3	236.5
3	-127.8	207.0
4	-74.7	236.5
5	-62.6	274.0

Dots		
1	-212.0	273.0
2	-212.0	192.5
3	-48	192.5
4	-48	273.0

PHI HYBRID

Crosses		
1	-62.6	274.0
2	-74.7	236.5
3	-127.8	207.0
4	-185.3	236.5
5	-197.3	274.0

Dots		
1	-48	273.0
2	-48	192.5
3	-212.0	192.5
4	-212.0	273.0

Table 2

Module R glued (R PEDESTAL SIDE/PHI COOLING SIDE)

R SILICON

Fids	X	Z
1	-85.5	276.0
2	-98.5	244.0
3	-130.0	230.5
4	-161.7	244.0
5	-174.5	276.0
Top edge		
1	-152.0	276.0
2	-103.0	276.0
Center		
1	-130.0	267.0
2	-130.0	257.0
3	-130.0	247.0

PHI SILICON

Fids	X	Z
1	-173.5	274.0
2	-160.0	243.5
3	-128.7	231.5
4	-98.3	245.3
5	-86.5	276.5
Top edge		
1	-103.5	275.0
2	-155.5	275.5
Center		
1	-130	267.0
2	-145	247.0
3	-115	247.0

R HYBRID

Crosses		
1	-62.6	274.0
2	-74.7	236.5
3	-127.8	207.0
4	-185.3	236.5
5	-197.3	274.0
Dots		
1	-48	273.0
2	-48	192.5
3	-212.0	192.5
4	-212.0	273.0

PHI HYBRID

Crosses		
1	-197.3	274.0
2	-185.3	236.5
3	-127.8	207.0
4	-74.7	236.5
5	-62.6	274.0
Dots		
1	-212.0	273.0
2	-212.0	192.5
3	-48	192.5
4	-48	273.0