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VELO Module Production – Bare Hybrid Metrology

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Abstract

This note describes in detail the procedures for the metrology of the hybrids, from bare substrate stage through to their completion.

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Table of Contents

1. Introduction

This note describes the procedures used for the metrology of the hybrids. An initial metrology is performed of the bare substrate before it is sent for circuits to be bonded to the two sides. Upon return three scans of each hybrid are made before the hybrid is populated: all three scans are repeated after components have been attached.

2. Substrate Metrology

Before despatch for the addition of the circuits [1] all the substrates are measured. Experience with the prototypes showed that extremely twisted substrates gave rise to twisted hybrids. The twist of the substrate is defined for LHCb to be how much the centre line of the hybrid deviates from the nominal (plane). It is measured across the whole length of the hybrid i.e. it is twice the deviation of a single end from the nominal position. (See Figure 1). In order to avoid wasting good circuits extremely twisted substrates were rejected. In addition the substrates are measured to determine their thickness.

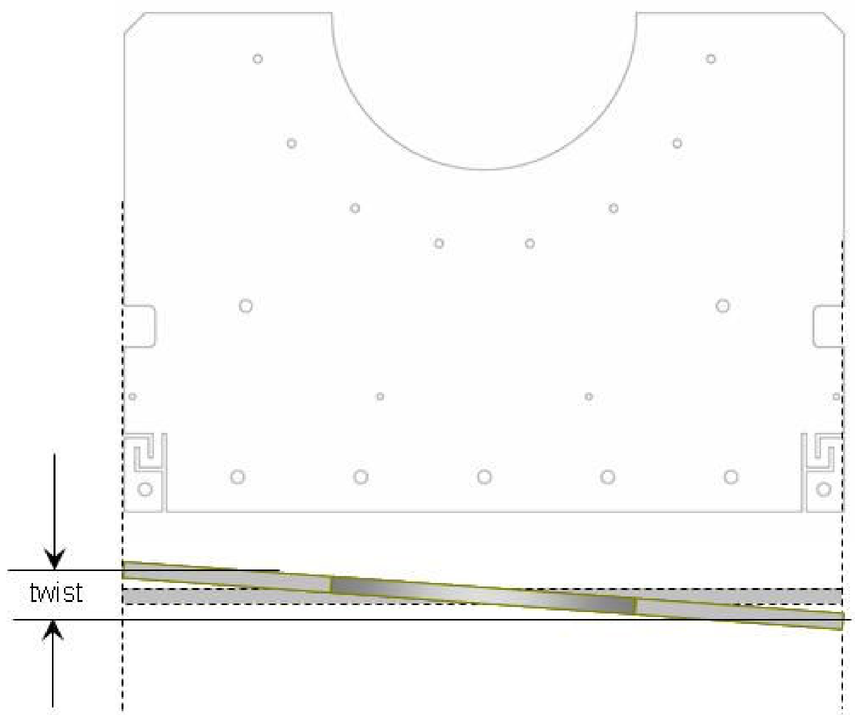

Figure 1: Figure (top) showing "side view" of (routed) substrate. The twist of a substrate or a hybrid is shown at the bottom of the figure where the substrate is viewed "end on".

2.1. Measure four corners to find twist

The following outlines the process used on the "Smartscope" in the metrology part of the assembly areas[2]. One method of (approximately) measuring the twist is to measure the three corners of substrate. One can define plane based on these three points. The deviation of the fourth corner from the plane is a measure of the twist.

- System/reset. Do Not Save changes
- Place the substrate centrally on the Aluminium platen of the Smartsope, with the long axis running left to right, and with the cut-out towards the back. The substrate can be either side up.

- Position on the first (back, left) corner, Focus [i.e. focus tool [plus sign in a square] left mouse button].
- Measure point [[spanner symbol] Enter, Again]
- Position on second (front, left) corner, Focus, Enter, OK
- Position on third (front, right) corner, Focus, Enter, OK
- Construct/plane; Select the previous three points with left mouse button; OK.
- Construct/datum/level; Select side of rectangle with left mouse button; OK
- Image; position on fourth (back, right) corner; Focus
- Twist is given by z value in mm.

This data must then be entered into the database [3].

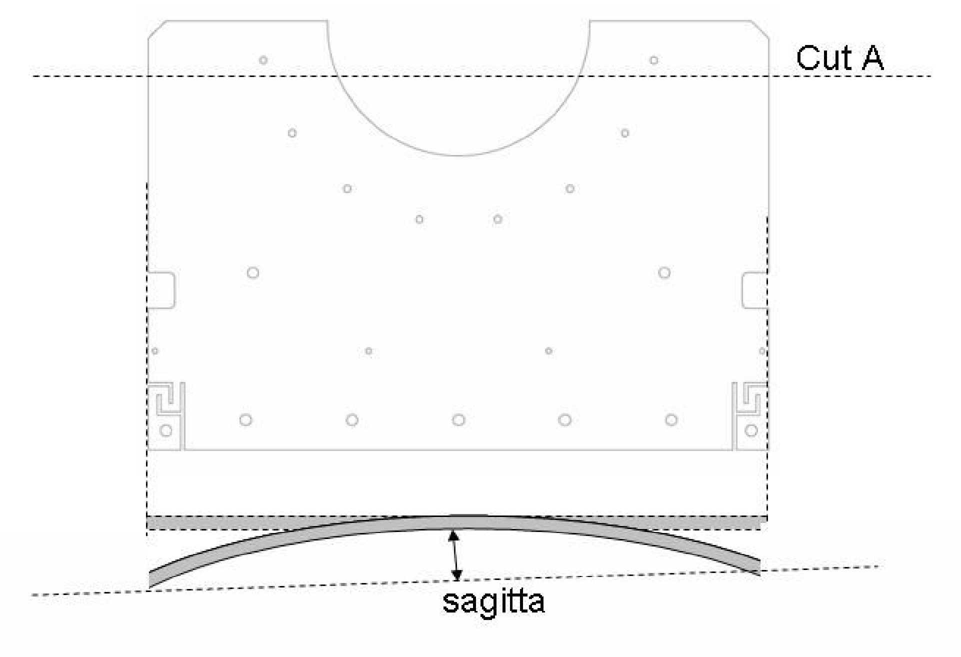

Figure 2: Figure showing "side view" of (routed) substrate. The "sagitta" of a substrate or a hybrid is shown at the bottom of the figure where the substrate is viewed end on. The sagitta can be determined for any Cut (e.g. A) but in general the sagitta 10mm from the top of hybrid is used.

3. Hybrid Metrology

3.1. Introduction

Three scans of each hybrid are made before the hybrid is populated: all three scans are repeated after the circuits have been populated. The scans are:

1. Twist of r-side
2. Height of r-side
3. Height of phi-side

The following outline the procedures used on the Smartscope to measure the twist of the hybrid.

3.2. Twist of r-side

a Mount the hybrid on the frame in a horizontal plane, with the holes towards the front, and the labelled side (the r-side) uppermost. Locate the two outside holes on the alignment pins; place the retaining plate above the hybrid and tighten the two nuts finger-tight.

b Load the SmartScope programme "hybrid_twist"
c Run the programme, select "OK".
d The programme will halt with the cursor close to the front, left corner of the hybrid. Move the hybrid, using the joystick, to align the front, left corner with the cursor. Select "Enter" on the joystick keypad.
e The programme will halt with the cursor close to the front, right corner of the hybrid. Move the hybrid, using the joystick, to align the front, right corner with the cursor. Select "Enter" on the joystick keypad.
f The programme will halt with the cursor close to the back, left edge of the hybrid. Move the hybrid, using the joystick, to align the back, left edge with the cursor. Select "Enter" on the joystick keypad.
g The programme will halt with the cursor close to the back, right edge of the hybrid. Move the hybrid, using the joystick, to align the back, right edge with the cursor. Select "Enter" on the joystick keypad.
h When the programme prompts for a file name, enter a name of the form M59-r-twist2 where the digits immediately after "M" are the module number and the number after "twist" makes the filename unique. "1" is omitted, so the file name for initial measurements ends "-twist", the file name for second measurements ends "-twist2". Hit "return".
i The programme will measure a few points. Select "OK"

3.3. Height of r-side

a If this measurement immediately follows the measurement of r-side twist, as is customary, the hybrid will already be mounted correctly. Otherwise follow the instructions in "a" under "Twist of r-side".
b Load the SmartScope programme "hybrid_height"
c Run the programme, select "OK".
d The programme will halt with a circular cursor close to a circular alignment mark near to the front, left corner of the hybrid. Move the hybrid, using the joystick, until the alignment mark is aligned with the cursor. Select "Enter" on the joystick keypad.
e The programme will measure the height of a second alignment mark near to the back of the hybrid, and then it will halt with the cursor close to a third, circular, alignment mark near to the front, right corner of the hybrid. Move the hybrid, using the joystick, until the alignment mark is aligned with the cursor. Select "Enter" on the joystick keypad.
f When the programme prompts for a file name, enter a name of the form M59-r-height2 where the digits immediately after "M" are the module number and the number after "height" makes the filename unique. "1" is omitted, so the file name for initial measurements ends "-height", the file name for second measurements ends "-height2". Hit "return".
g The programme will measure about 180 points.
h If the programme fails to measure any point automatically, move the error box to reveal the co-ordinates. Note the co-ordinates. Move the hybrid, using the joystick, to the nearest feature. Focus on the feature by clicking the left mouse button when the cursor is within the green rectangle. Move the stage back to the saved coordinates. Click "enter" on the joystick keypad. The programme will continue.
i Select "OK"

3.4. Height of phi side

a Measurement of the height of the phi-side differs only slightly from measurement of the height of the r-side.
b Firstly, the hybrid must be mounted with the unlabelled side (the phi side) uppermost.
c Secondly, the file name has the form M59-p-height2, where "p" denotes the phi-side.

3.5. Data Entry

a Logon to the database.
b Select "Update" alongside "Module"
c Select the module by clicking on its number with the left mouse button.
d Alongside "CURV measurements for Phi side:" browse to the p-height file.
e Alongside "CURV measurements for R side:" browse to the r-height file.
f Alongside "HEIGHT measurements for R side:" browse to the r-twist file.
g Enter the fourth z coordinate from the r-twist file alongside "4th corner Deviation".
h Enter any relevant comment.
i Select "Add Metrology measurements"

4. Performance

The following measurements were made before the substrate was sent to the Stevenage for laminations of the circuits.

4.1. Substrate

4.1.1. Thickness

Data on the thickness of substrates are shown in Figure 3 and Figure 4. The average thickness of the substrates was 0.925±0.020mm. The substrates were manufactured at Liverpool and the evenness of the production process is demonstrated by the small spread of values.

An additional plot included here for reference (Figure 5) shows the difference of this thickness from a measurement of the cooling tongue thickness (at the base of the hybrid and essentially another independent remeasure of the hybrid thickness) at a much later time. The interval between the substrate construction and the measurement of the cooling tongue thickness was up to a year for the last hybrids. Note the small (~5%) evident thickening of the substrates as a function of time. This is attributed to two separate effects.

First it is possible that the substrates absorb water over time. Although the hybrids are stored in dry conditions they are exposed to ~40% humidity when being worked upon. A second cause is that the pressure of the circuit lamination process was reduced during the production run. This could have the effect of leaving the circuits thicker.

4.1.2. Twist

The substrate twist is shown in Figure 6 and Figure 7. The twist was measured to be -0.209±0.115 mm. It is interesting to note that there is a significant "chirality" to the twist. During production the carbon fibre lay-up over the TPG core was explicitly designed to be symmetric. The directions of the fibres were also laid down to ~1° so it is not believed that the CF cladding itself causes the average non-zero twist. The only component that could introduce twists into the final process is the frame around the hybrid. This 7mm wide CF frame surrounds the TPG. It is inserted into the laminate to reduce the probability of delamination between the cladding and the TPG. It has also been observed on the basis of small statistics that making larger "frames" introduces more twist. Therefore it is hypothesized that some feature of the CF lay-up of the frame initiates the substrate twist.

4.2. Unpopulated Hybrids

The following measurements were made on the reception of the hybrid after lamination before population with components. This corresponds to Stage 3 of the hybrid production process [3].

4.2.1. Thickness

The hybrid thickness was measured at 16 points corresponding to the chip positions. (See Figure 8). As a function of production number the hybrid thickness increases from about 1.42 to 1.48mm. This thickness is attributable to the same two reasons as given for the increase in substrate thickness above.

Knowing the hybrid thickness and the (original) substrate we can infer the thickness of the double layer of circuit, see Figure 9.

4.2.2. Hybrid Twist

The fourth corner deviation of the hybrids is shown in Figure 10 and Figure 11. The twist is approximately -0.158±0.236mm. It still shows the chirality of the substrates but the distribution is noticeably wider.

The fourth corner deviation measured can be compared with the twist of the original substrate before the circuits were bonded. The correlation plot is shown in Figure 12. A histogram of the difference of twists (Figure 13) shows in more detail that the mean stays more or less the same (0.012mm) but there is a large individual spread (~0.200mm). Some of this may be attributed to uncertainties in the production process. Although every effort was made to label substrates (by gentle engraving) on CF in many cases there remained an ambiguity (due to epoxy reflow) in the original substrate numbering on reception of the hybrid, Up to 20% of the associations could be faulty.

At the same time the 4th Corner Deviation measurement is made, deviations from a plane defined by the original three points are determined for a point close to the centre of the hybrid. This is called the "Centre Deviation" – see Figure 14. It as an early attempt to measure the sagitta and is only included for completeness here.

4.2.3. Phi and R side measurements

The hybrids also had their twist and sagitta measured independently on the Phi and R sides. These data are shown in Figure 15. The differences of the Phi and R side measurements are histogrammed separately in Figure 16 and Figure 17. The fits to the data show that the measurements on either side correlate very closely with each other.

It is thus possible to consider average values of the Phi and R side measurements of the twist and sagitta to be our best estimates of the twist and sagitta of the hybrid.

The average twist is compared with 4th Corner Deviation method Figure 18 and a strong correlation observed. The twist calculated from the average of the two sides is considered to be a superior measurement of the twist as it has many times more measurements than the single point 4CD measurement. For completeness of comparison of the average sagitta compared with (known to be inaccurate) Centre Deviation method of estimating the sagitta is shown Figure 19.

4.3. Populated Hybrids

The following measurements were made on the reception of the hybrid after population. This corresponds the Stage 7 of the hybrid production process [3].

4.3.1. Hybrid Twist

The hybrid twist (4th Corner Deviation) and "sagitta" (Centre Deviation) are shown in Figure 20.

These can now be compared directly with the pre-population numbers see Figure 21 to Figure 23. The difference in twist as measured by the deviation method is -0.021±0.138mm and the difference in the "sagitta" -0.029 ±0.0.610mm. These differences are smaller than those for the bare substrate to circuit lamination phase. This is partially due that it was required that all soldering of components (i.e. the population) was done by hand. This removes the stresses involved with flowing solder over the whole circuit simultaneously.

4.3.2. Phi and R side measurements

Just as measurements were made on both sides for the pre-populated hybrids, they were repeated post-population, see Figure 24. This can be used to compare the 4CD measurement of twist with average Phi and R twist (Figure 25).

These values are also believed to be more accurate than the "deviation" methods of estimating curvature and twist. Thus a better estimate of the change of shape of the hybrid is given by comparing the average Phi and R values for pre and post-population. See Figure 26 to Figure 28. During the population process the mean sagiita changes by only 0.002±0.013mm and the mean twist by 0.004±0.080mm.

5. Summary

Careful measurements of the hybrid shapes were made during production to try and ensure thy remained flat and undistorted.

The mean twist of the hybrids only changes however by 12microns during lamination of the circuits onto the substrate and 4 microns after population of the circuits. During the last phase of production, i.e. the population of the hybrids, individual hybrids "move" and can twist in either direction of their nominal by about 80 microns.

The mean twist of the hybrids is approximately 200microns. Note that this corresponds to the nominal "top edge" of the hybrid being no more ~100 microns from the nominal (and desired) flatness over an area of over $200cm^2$.

Based on the data selecting flat substrates produces essentially flat hybrids. In any future production further work will be done on the manufacture of the Carbon Fibre frame to see if the average twist of the hybrids can be reduced.

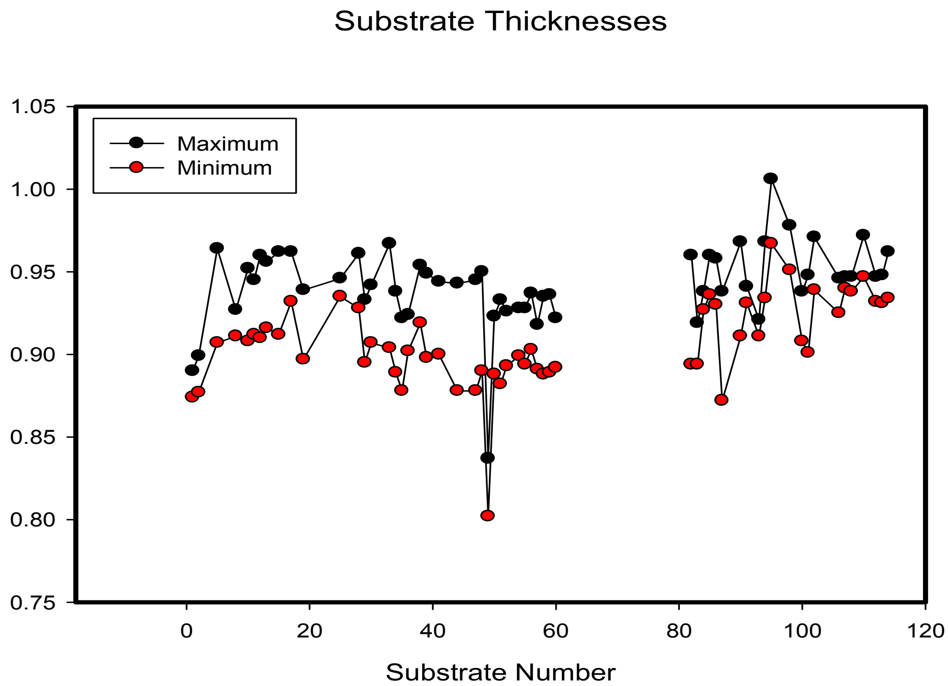

Figure 3: Plot of substrate minimum and maximum thicknesses.

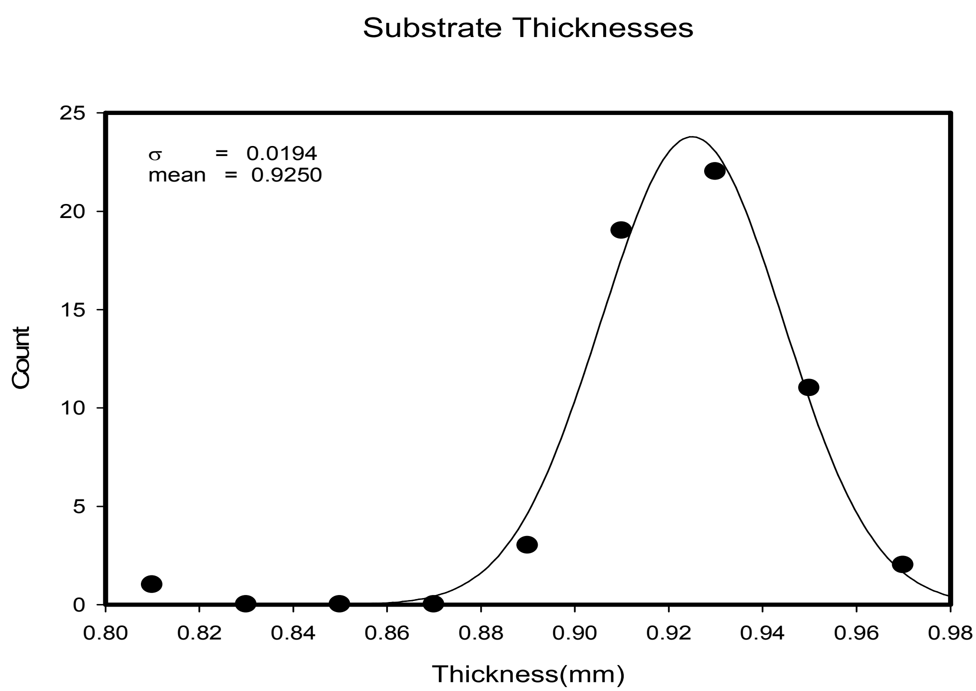

Figure 4: Histogram (with fit) of average thickness of substrates.

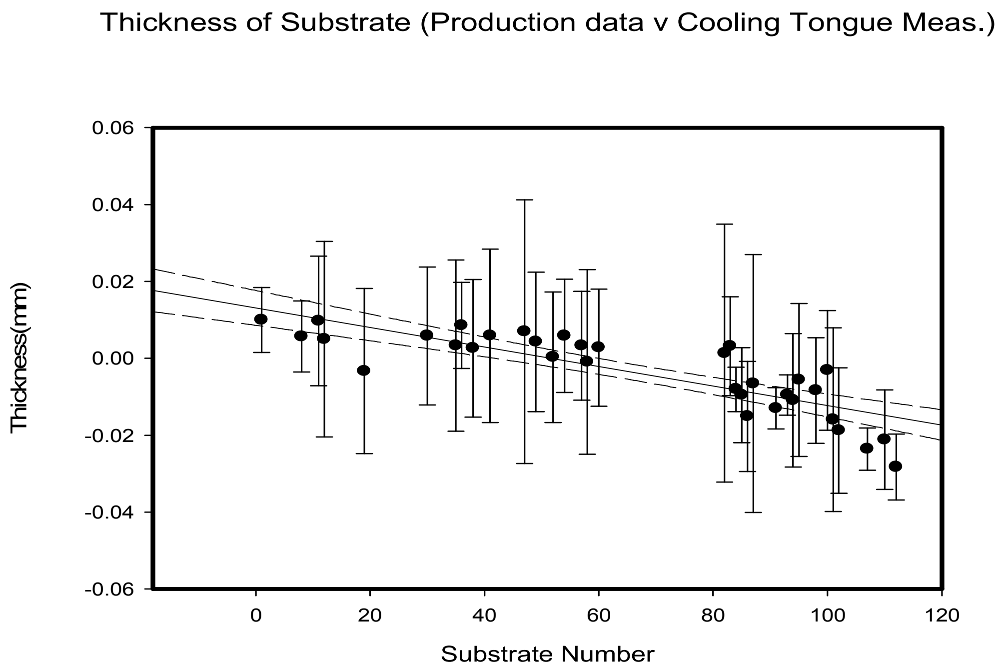

Figure 5: Difference of thickness measured at production time and thickness of cooling tongue post-production. i.e. ($Thick_{sub}$-$Thick_{cooling}$). The data have been fitted to a straight line and the 95% c.l. are shown.

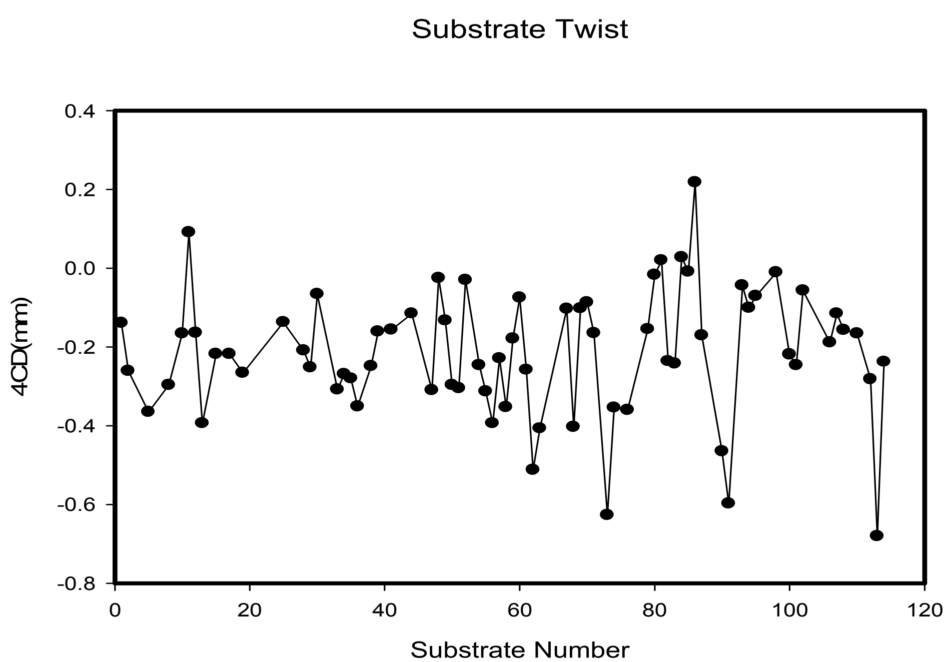

Figure 6: Plot of the substrate twists measured by the 4^{th} corner deviation method.

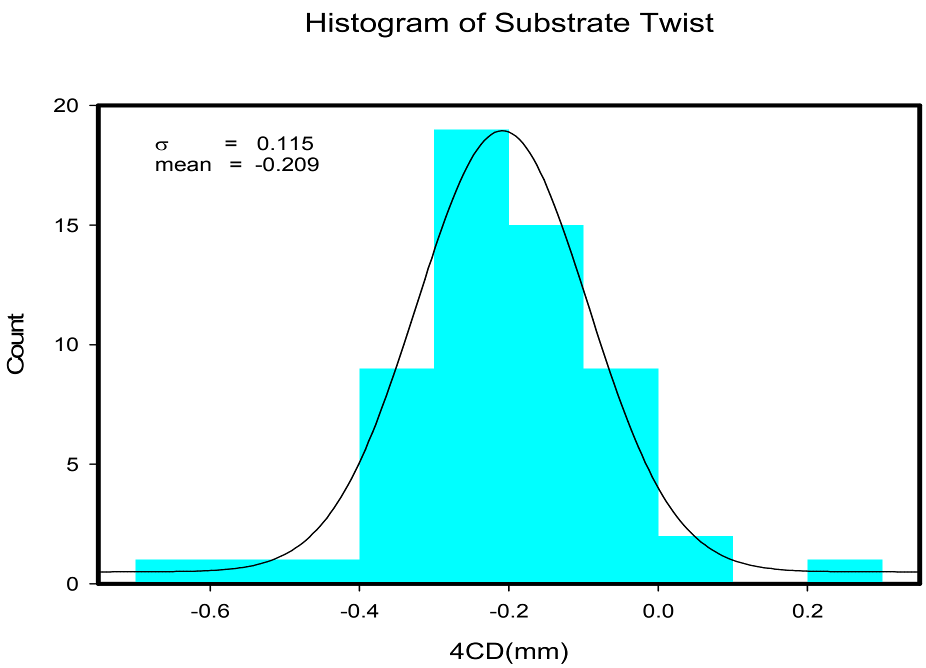

Figure 7: Histogram of substrate twist

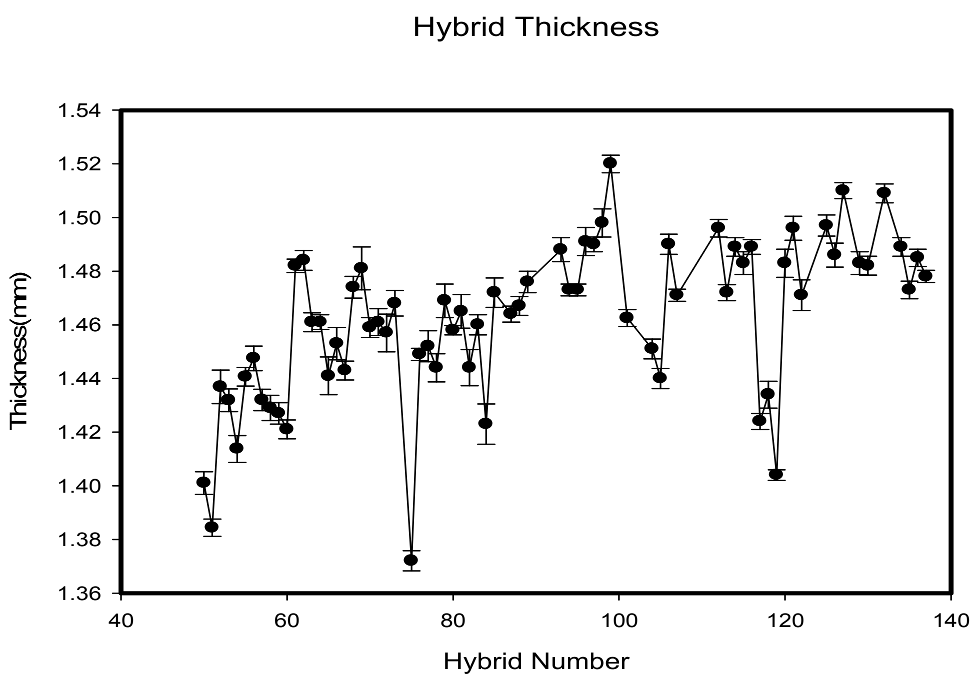

Figure 8: Total Hybrid thickness as a function of hybrid number. Note the gradual increase in thickness. During this period the pressure used in hybrid production was reduced.

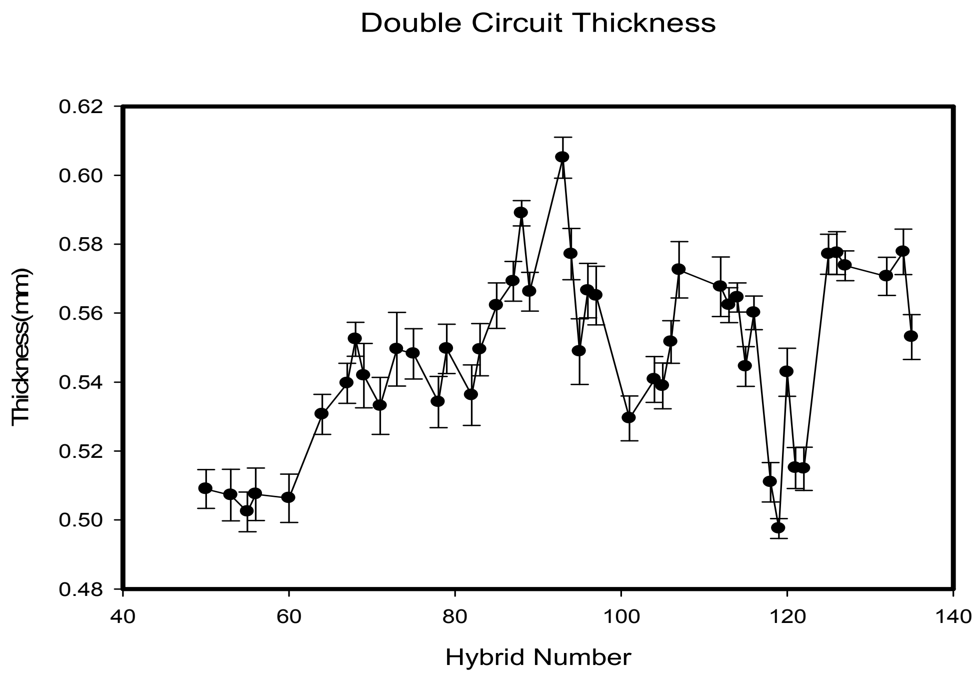

Figure 9: The thickness of the hybrids minus the thickness of the substrates.

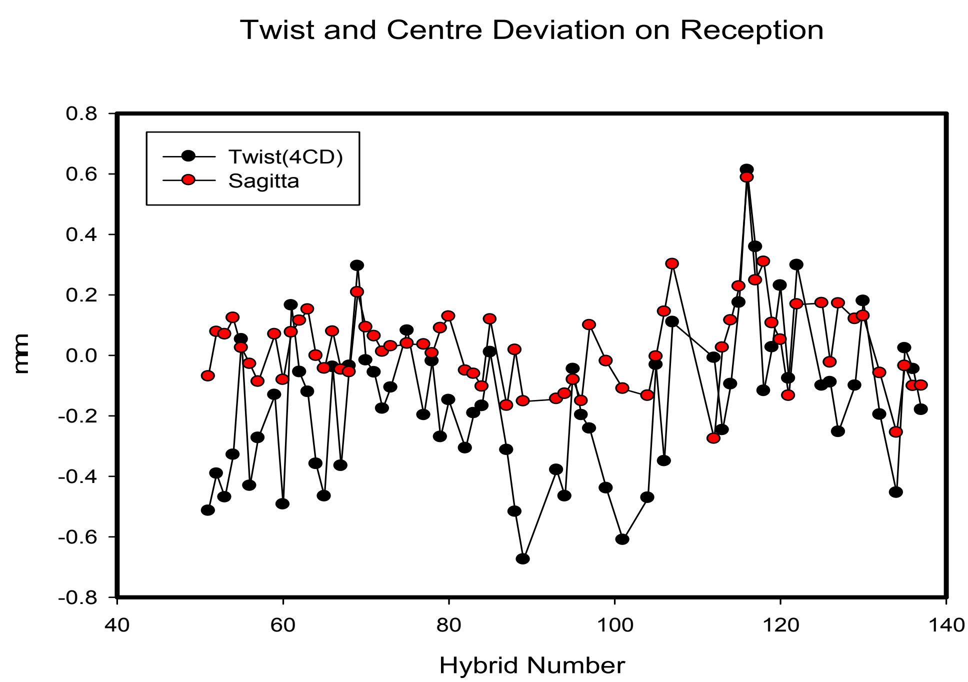

Figure 10: Plot of the twist (from 4th corner deviation) and centre deviation at the first reception of the hybrids.

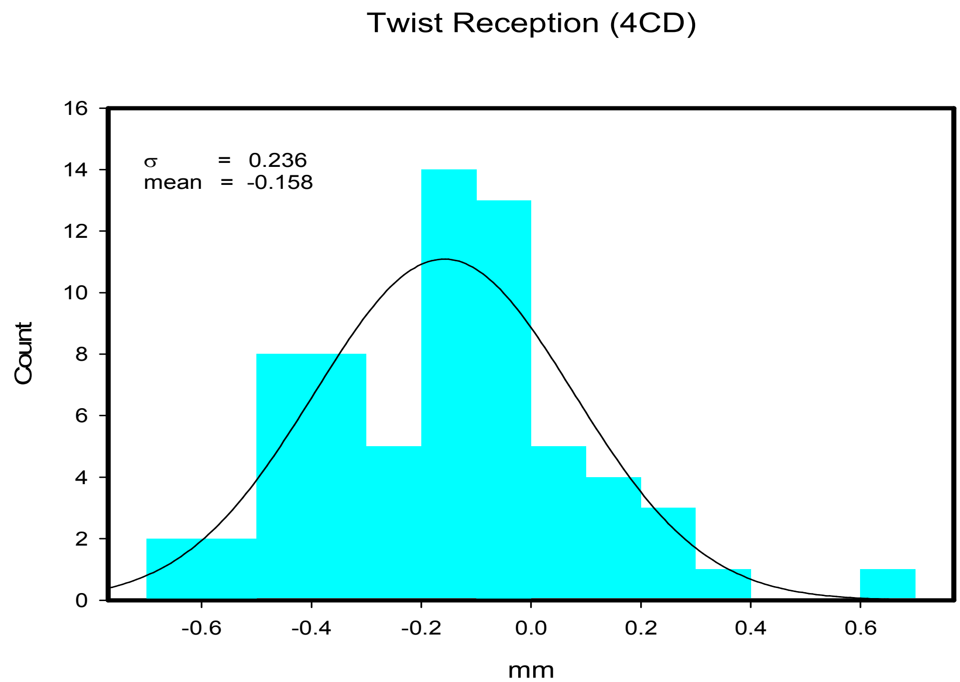

Figure 11: Histogram of the twist of the hybrids at first reception,

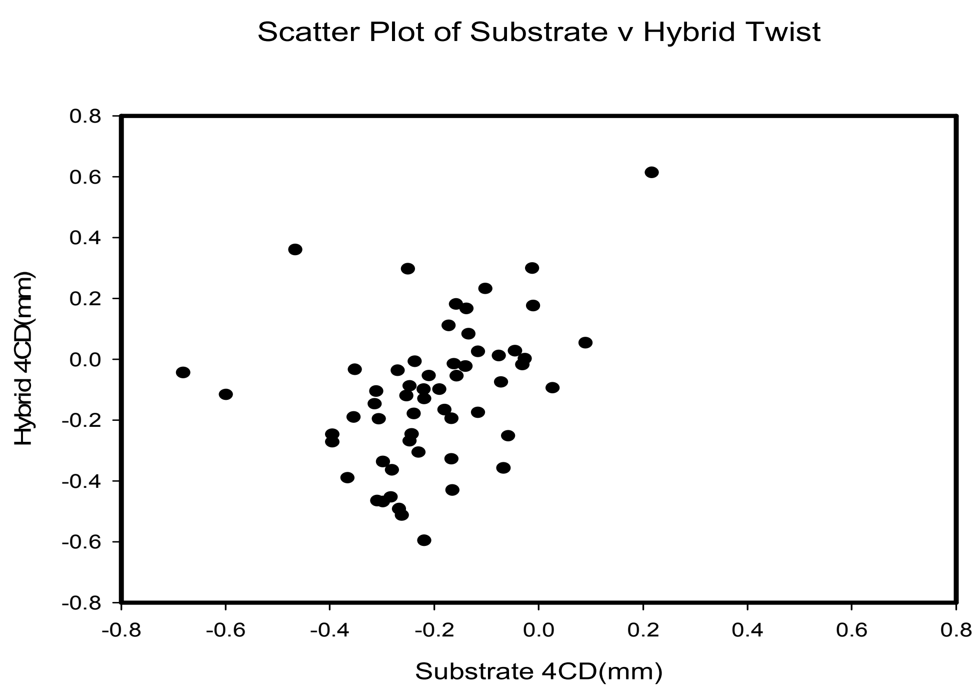

Figure 12: Twist of the substrate versus the twist of the hybrid at reception.

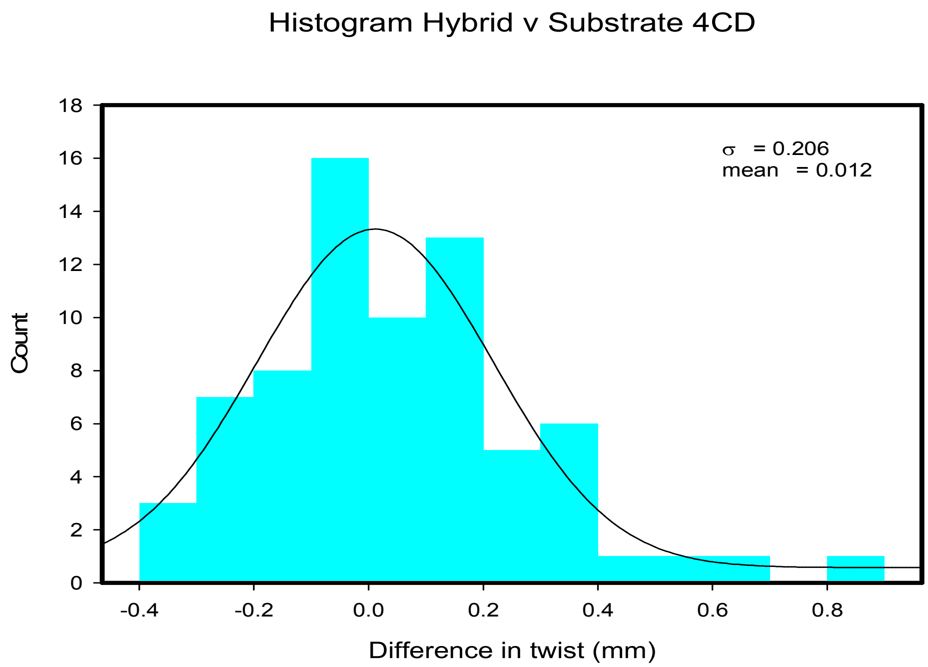

Figure 13: Histogram of the difference between the hybrid twist and substrate twist. The abscissa plots ($Twist_{hybrid} – Twist_{substrate}$). Here the twist and heights are measured from the 4CD technique.

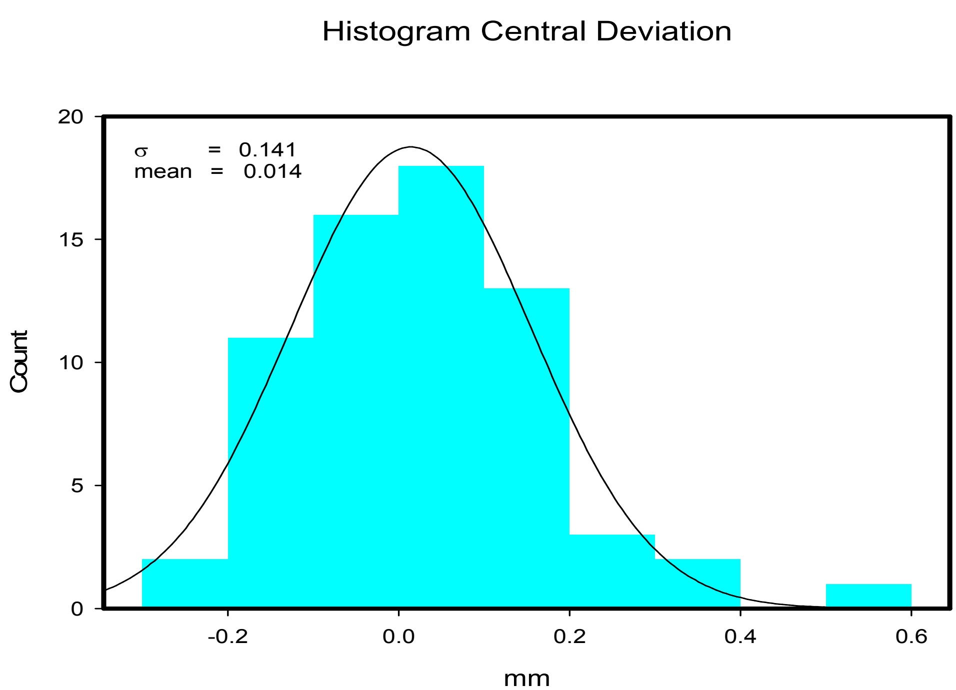

Figure 14: Histogram of the Central Deviation of the hybrid on reception. This is a measure of the sagitta of the hybrid. (See text).

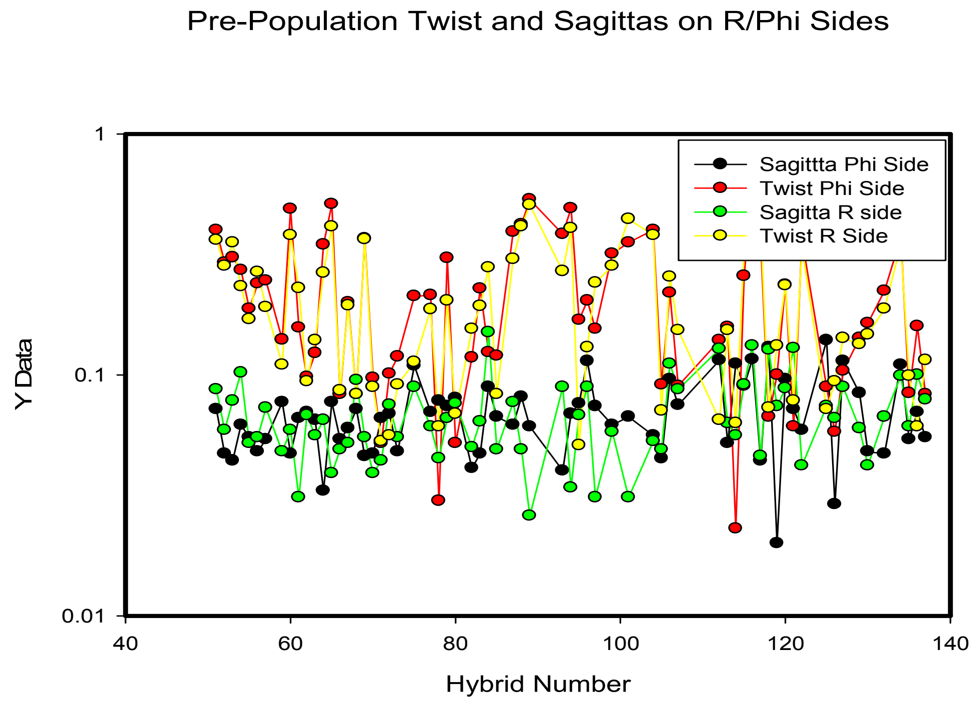

Figure 15: Each hybrid has the twist and sagitta measured on each side separately. Here these are plotted for all hybrids. There exists a close correlation between both sides.

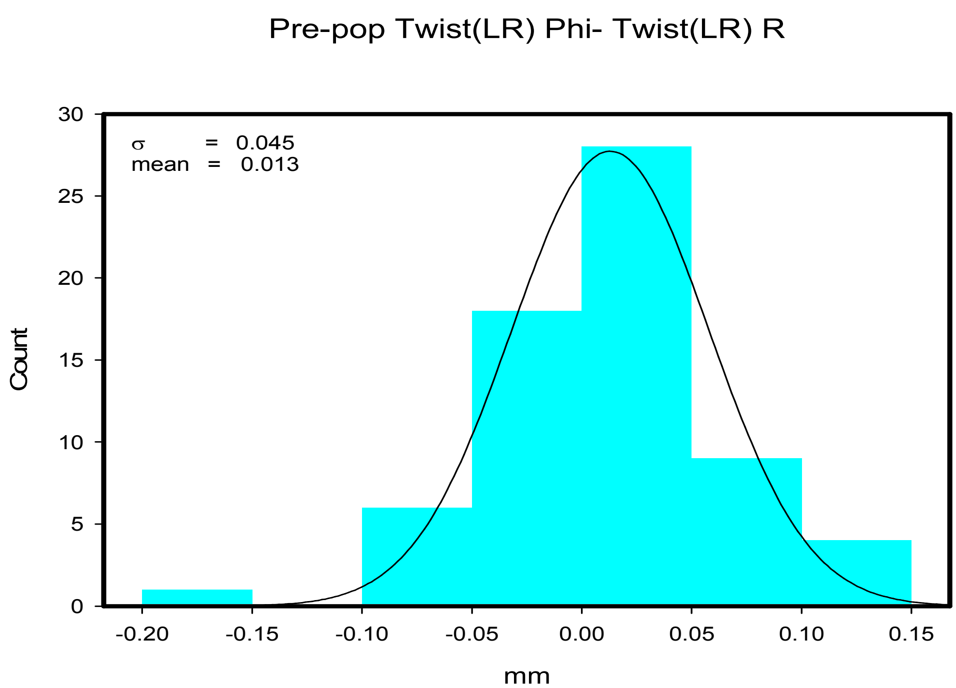

Figure 16: Histogram of the difference between the twist measured on the phi side compared with that on the R side. These measurements are before the hybrids are populated.

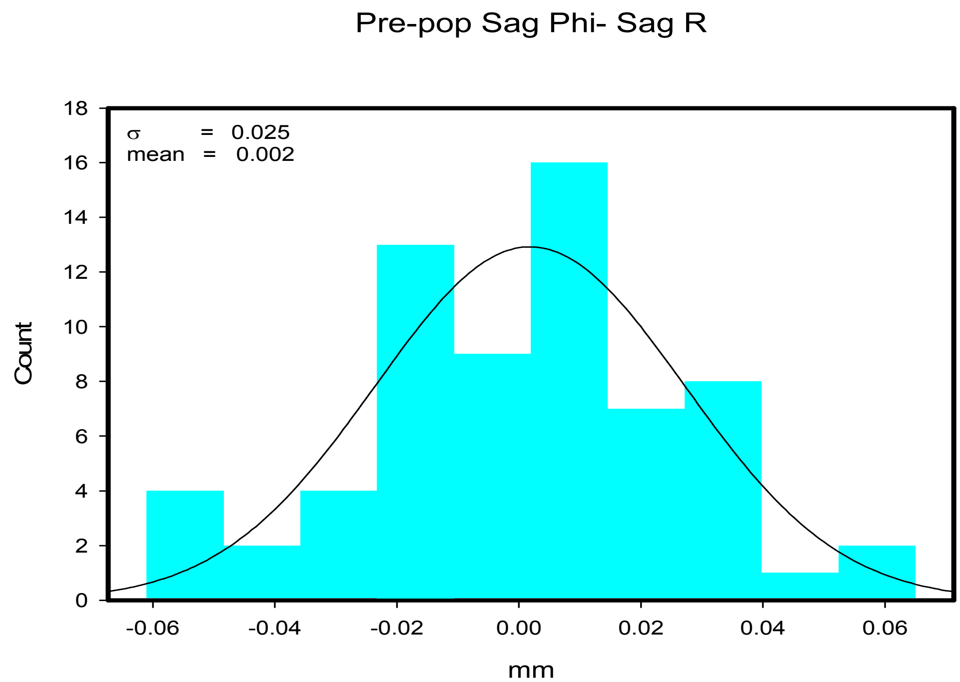

Figure 17: Histogram of the difference between the Phi and R-side measurements of sagitta pre-population.

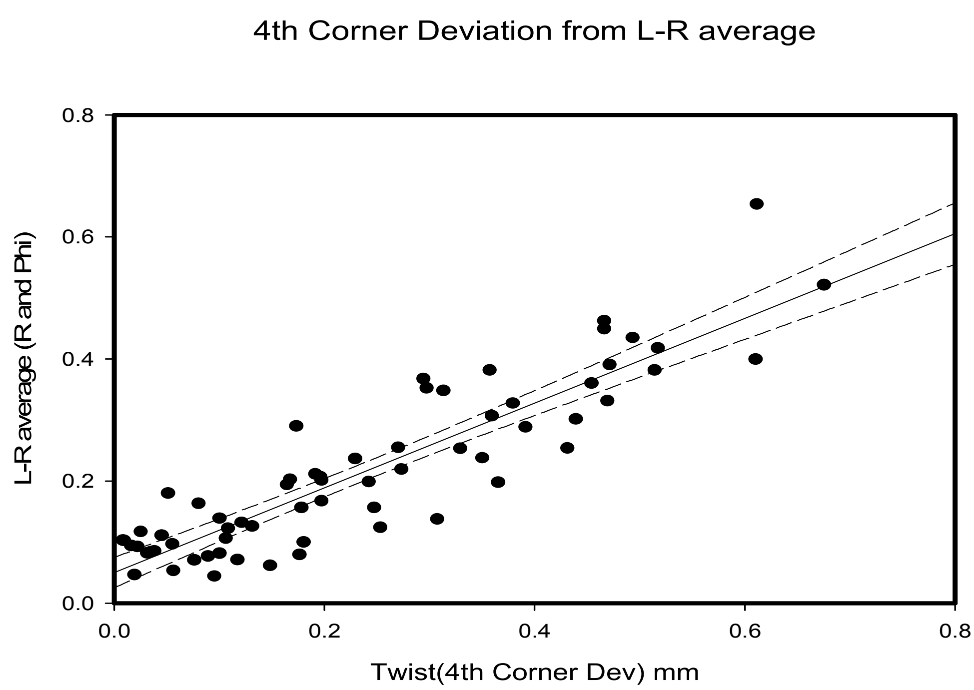

Figure 18: Scatter plot of the twist as measured by 4^{th} Corner Deviation method and the average of the twist measured on the Phi and R sides. A linear fit to the data (and 95% c.l.) are shown. The 4^{th} Corner method consistently appears to give a higher value than the average Phi-R estimate.

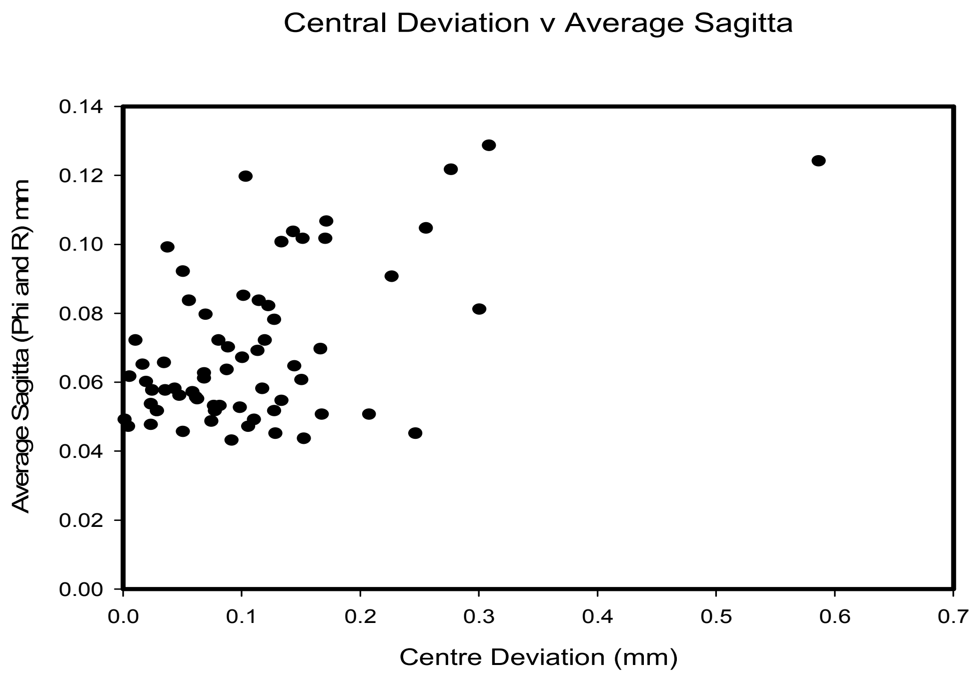

Figure 19: Scatter plot of Sagitta as measured by the Central Deviation compared with the sagitta from the average on the phi and R sides.

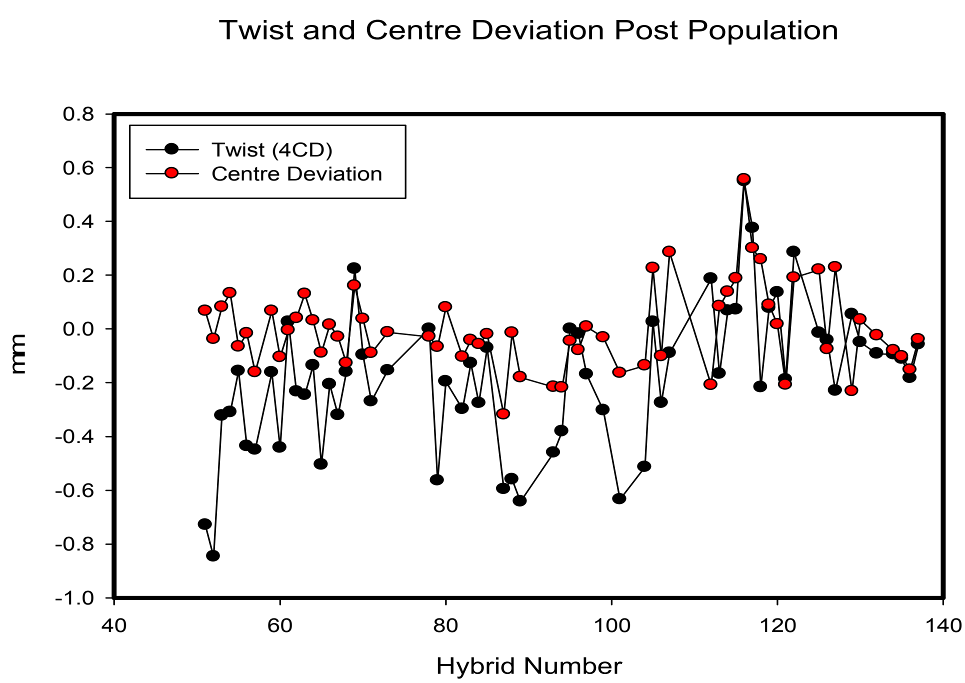

Figure 20: Plot of the Centre Deviation and the Twist (4^{th} Corner Deviation) measured on the hybrid post-population.

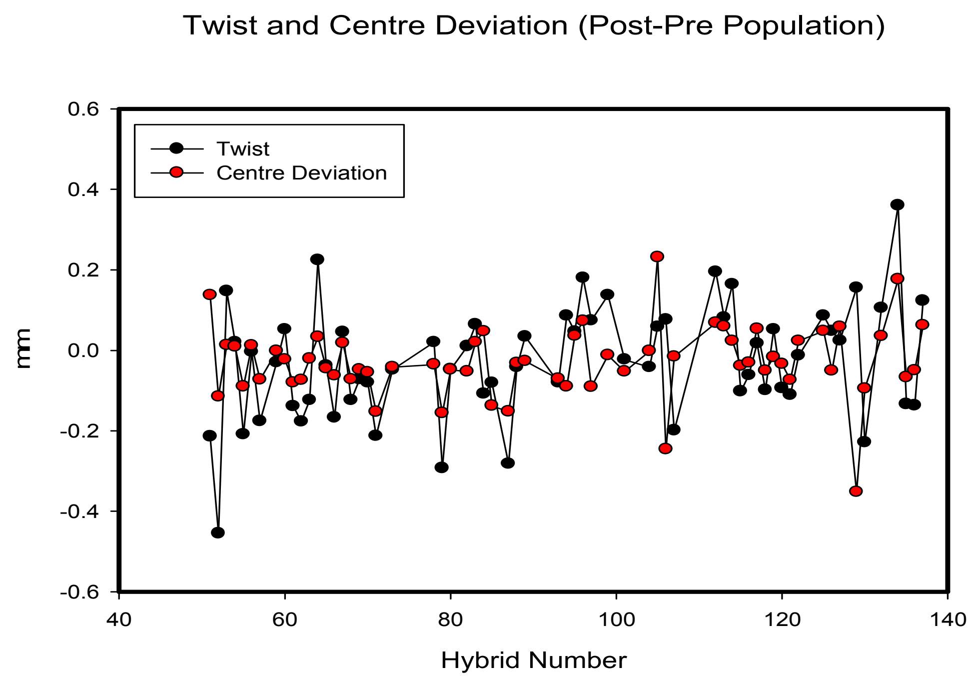

Figure 21: The difference between the measured twist and centre deviations before and after population.

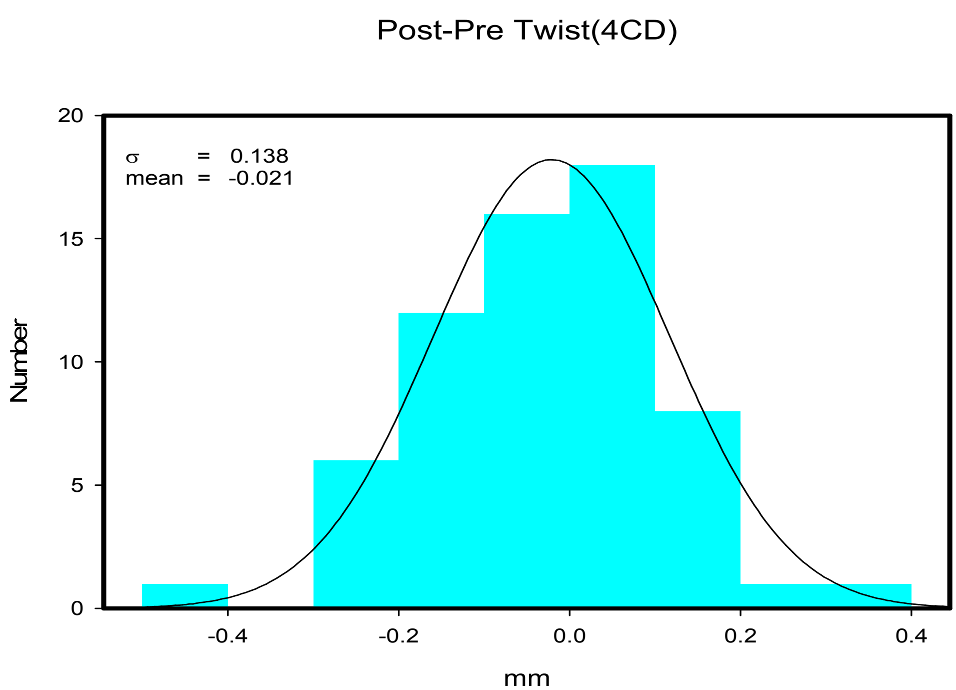

Figure 22: Difference between the post population twist and the pre-population twist.

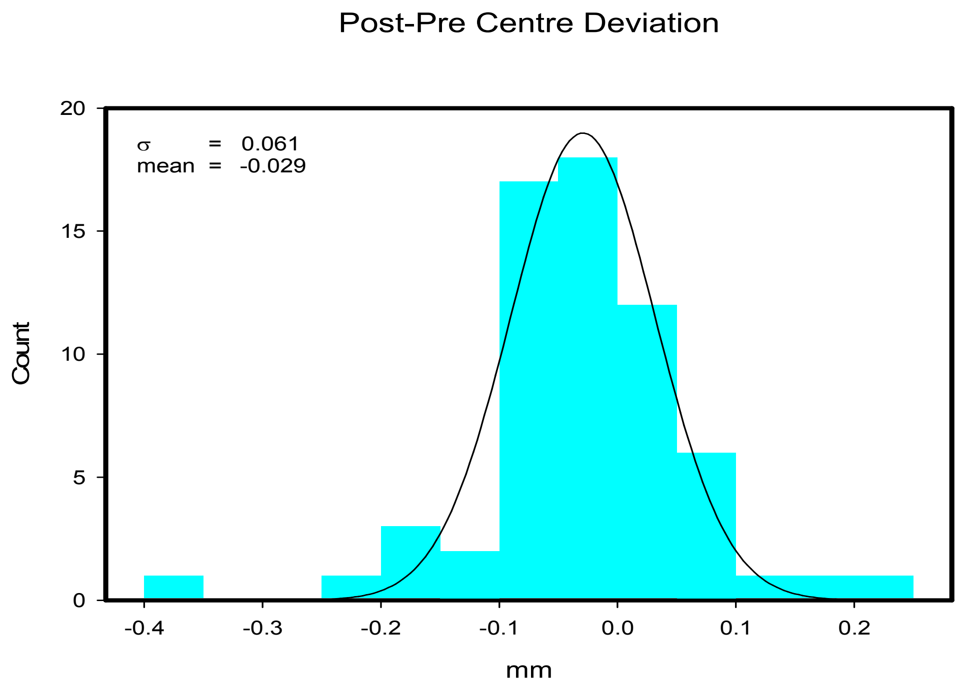

Figure 23: Histogram of the Centre Deviation after and before population

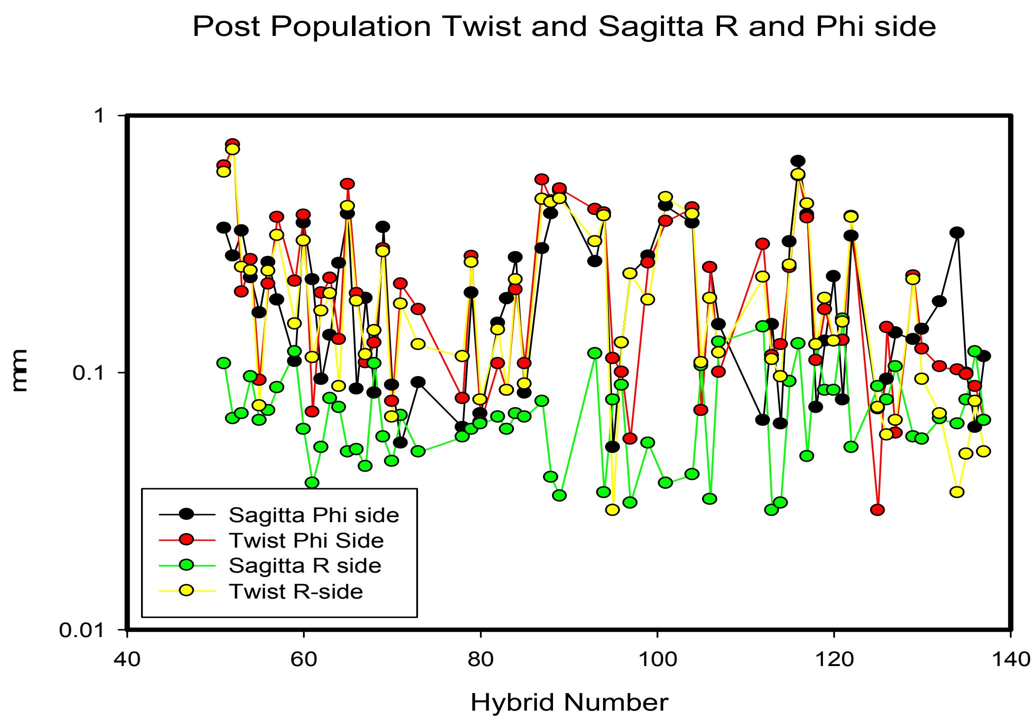

Figure 24: The post population twist and sagitta on both sides of the hybrid

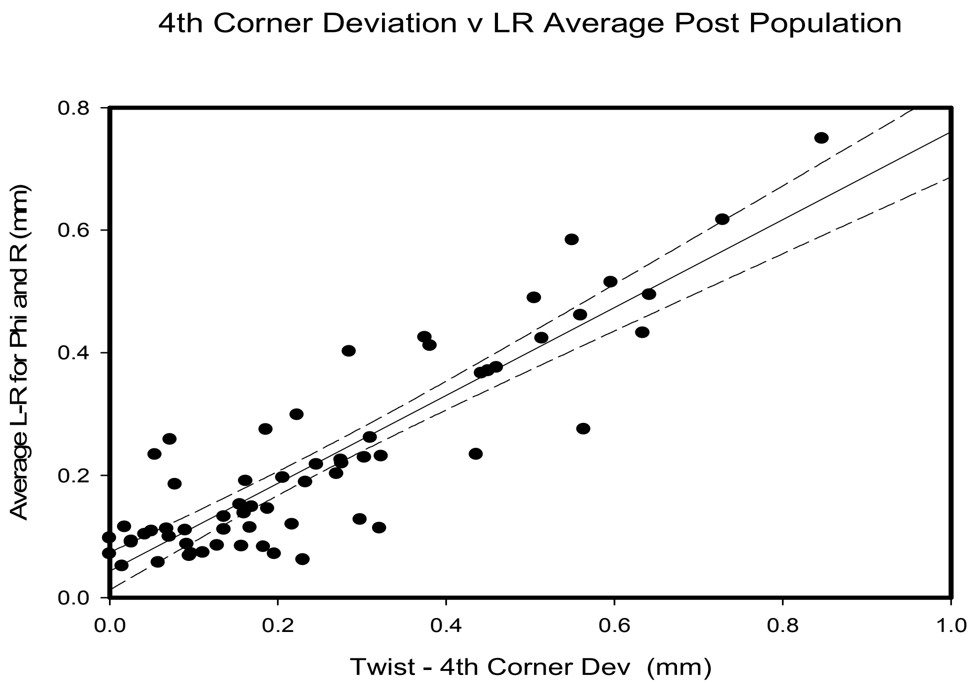

Figure 25: Scatter plot of the 4th Corner Deviation before and after population

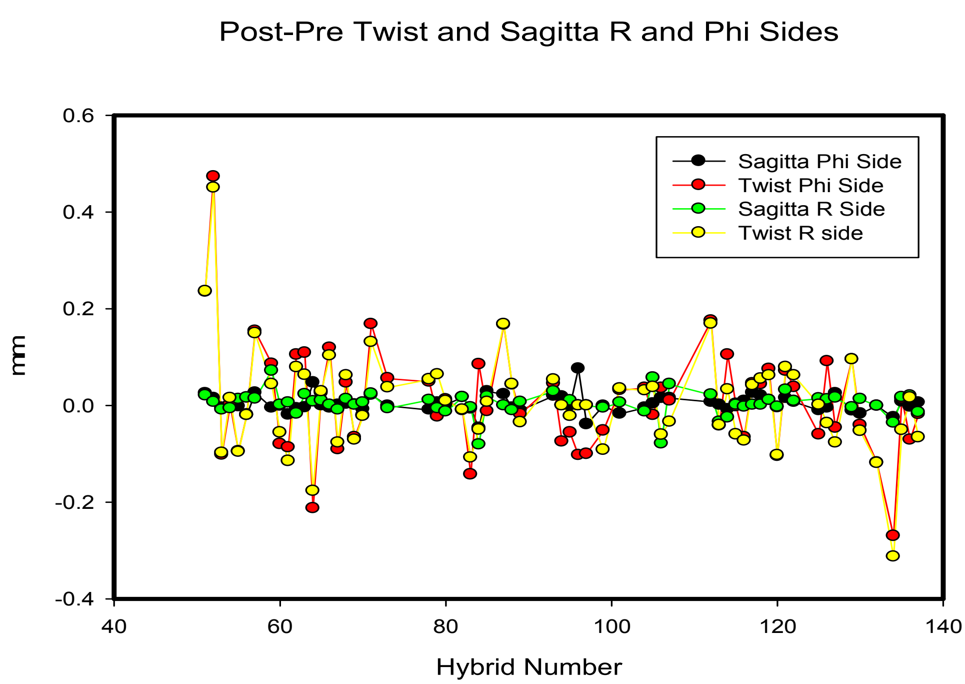

Figure 26: The difference between the post and pre-population sagittas and twists on both sides of the hybrid.

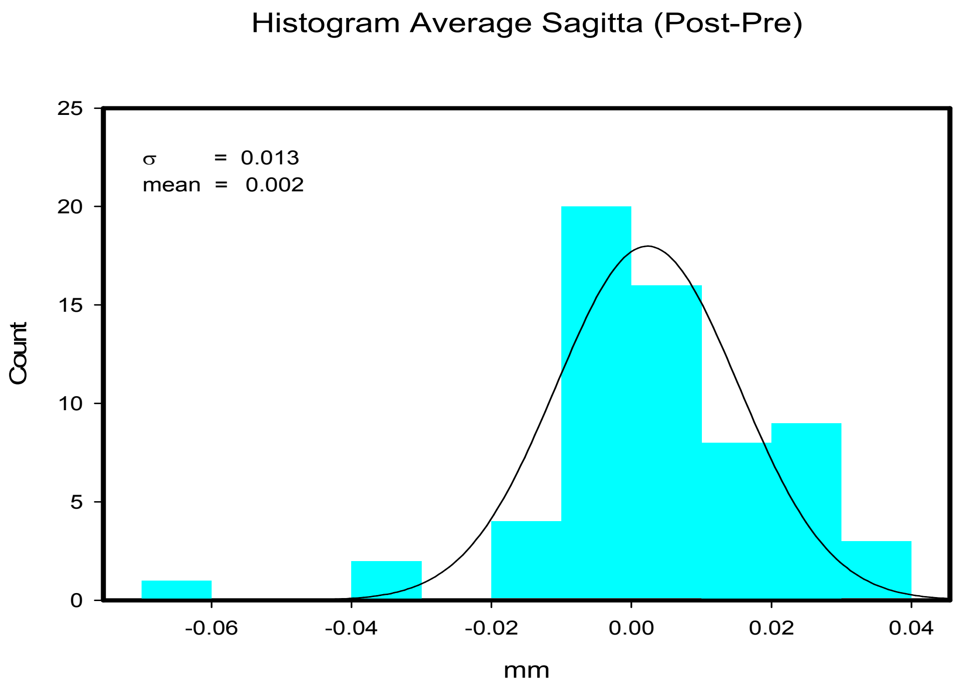

Figure 27: Histogram of the difference average (R&Phi) sagitta before and after population.

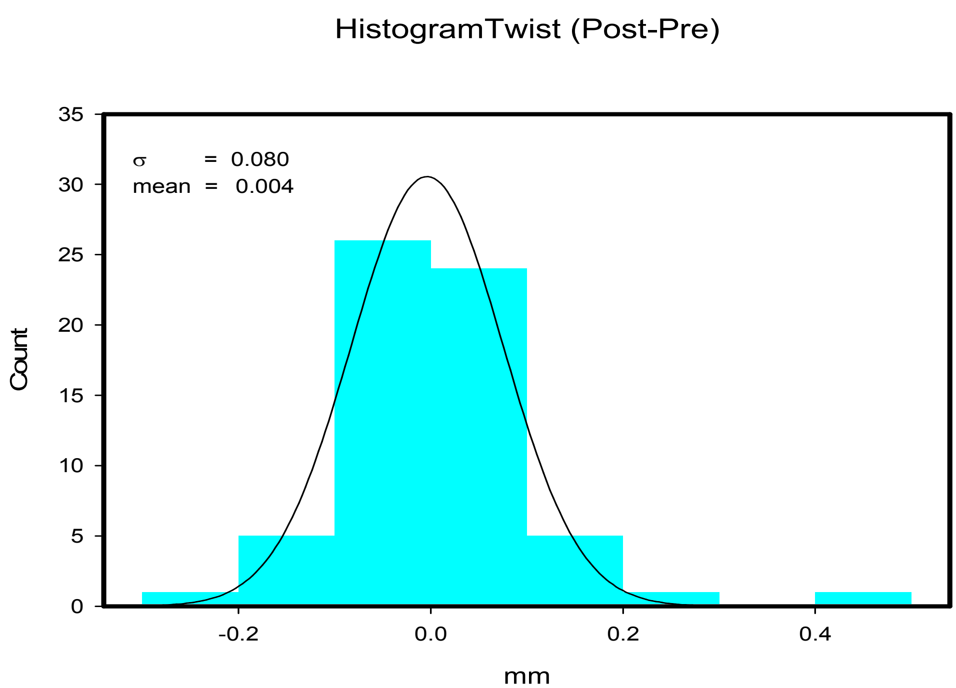

Figure 28: Histogram of the difference average (R&Phi) twist before and after population

6. References

1. *LHCb VELO Hybrid*, http://hep.ph.liv.ac.uk/lhcb/html/k-05.html
2. Lockwood, M., *et al.*, *VELO Module Production - Clean Room Procedure.* LHCb Internal Note, 2007(070).
3. *LHCb VELO production database*, http://hep.ph.liv.ac.uk/lhcb/html/database.html

Appendix: Tables of metrology data

Substrate Metrology

Hybrid#	Mod	Substrate#	T Max (mm)	T min (mm)	Twist (mm)	Tchip (mm)	σ Tchip mm
50		1	0.890	0.874	-0.139	1.401	0.017
51		2	0.899	0.877	-0.261	1.384	0.013
52		5	0.964	0.907	-0.365	1.437	0.025
53		8	0.927	0.911	-0.297	1.432	0.017
54	19	10	0.952	0.908	-0.166	1.414	0.020
55	24	11	0.945	0.912	0.091	1.441	0.014
56	27	12	0.960	0.910	-0.164	1.448	0.018
57	34	13	0.956	0.916	-0.394	1.432	0.016
58	15	15	0.962	0.912	-0.218	1.429	0.019
59	17	17	0.962	0.932	-0.218	1.427	0.016
60	26	19	0.939	0.897	-0.266	1.421	0.014
61	25	25	0.946	0.935	-0.137	1.482	0.010
62	28	28	0.961	0.928	-0.209	1.484	0.015
63		29	0.933	0.895	-0.252	1.461	0.014
64	31	30	0.942	0.907	-0.066	1.461	0.011
65		33	0.967	0.904	-0.308	1.441	0.028
66		34	0.938	0.889	-0.269	1.453	0.024
67	37	35	0.922	0.878	-0.280	1.443	0.014
68	29	36	0.924	0.902	-0.351	1.474	0.016
69	25	38	0.954	0.919	-0.249	1.481	0.032
70	21	39	0.949	0.898	-0.161	1.459	0.015
71	28	41	0.944	0.900	-0.156	1.461	0.020
72		44	0.943	0.878	-0.115	1.457	0.028
73	33	47	0.945	0.878	-0.310	1.468	0.019
74		48	0.950	0.890	-0.025		
75	41	49	0.837	0.802	-0.133	1.372	0.015
76		50	0.923	0.888	-0.297	1.449	0.009
77		51	0.933	0.882	-0.305	1.452	0.023
78	30	52	0.926	0.893	-0.030	1.444	0.021
79	32	54	0.928	0.899	-0.246	1.469	0.025
80		55	0.928	0.894	-0.313	1.458	0.007
81		56	0.937	0.903	-0.394	1.465	0.025
82	35	57	0.918	0.891	-0.229	1.444	0.027
83	44	58	0.935	0.888	-0.353	1.460	0.015
84	36	59	0.936	0.889	-0.179	1.423	0.030
85	38	60	0.922	0.892	-0.075	1.472	0.022
87	48	61			-0.258	1.464	0.012
88	45	62			-0.512	1.467	0.014
89	47	63			-0.407	1.476	0.016
93	42	67			-0.103	1.488	0.018

Hybrid#	Mod	Substrate#	T Max (mm)	T min (mm)	Twist (mm)	Tchip (mm)	σ Tchip mm
94	61	68			-0.403	1.473	0.009
95	54	69			-0.102	1.473	0.009
96	53	70			-0.087	1.491	0.021
97	52	71			-0.165	1.490	0.011
98		73			-0.627	1.498	0.021
99	58	74			-0.354	1.520	0.013
101	49	76			-0.360	1.463	0.012
104	50	79			-0.155	1.451	0.015
105	51	80			-0.017	1.440	0.015
106	55	81			0.020	1.490	0.015
107	56	87	0.938	0.872	-0.171	1.471	0.009
112	59	82	0.960	0.894	-0.236	1.496	0.013
113	62	83	0.919	0.894	-0.242	1.472	0.012
114	63	84	0.938	0.927	0.028	1.489	0.014
115	64	85	0.960	0.936	-0.009	1.483	0.017
116	7	86	0.958	0.930	0.218	1.489	0.011
118	74	91	0.941	0.931	-0.598	1.434	0.020
119	71	93	0.921	0.911	-0.044	1.404	0.008
120	72	94	0.968	0.934	-0.101	1.483	0.021
121	60	95	1.006	0.967	-0.071	1.496	0.018
125	73	100	0.938	0.908	-0.219	1.497	0.016
126	75	101	0.948	0.901	-0.246	1.486	0.018
127	4	102	0.971	0.939	-0.057	1.510	0.012
135	5	107	0.947	0.940	-0.115	1.473	0.013
134	6	112	0.947	0.932	-0.282	1.489	0.014
122		98	0.978	0.951	-0.011	1.471	0.023
129		106	0.946	0.925	-0.189	1.483	0.017
132		110	0.972	0.947	-0.166	1.509	0.014
130		108	0.947	0.938	-0.157	1.482	0.014
136		113	0.948	0.931	-0.680	1.485	0.013
137		114	0.962	0.934	-0.238	1.478	0.009
117		90	0.968	0.911	-0.465	1.424	0.012

Table 1: Metrology on the substrate. Thickness of the hybrid (substrate with the circuits attached) at the chips sites is included. Some data is missing.

Pre-population Hybrid Metrology

Hybrid#	Mod	4th Dev (mm)	Centre Dev (mm)	Sag(Phi) (mm)	Twist(Phi) (mm)	Sag(R) (mm)	Twist(R) (mm)
50		-0.025	0.087	0.034	0.054	0.041	0.078
51		-0.515	-0.070	0.072	0.399	0.087	0.363
52		-0.392	0.077	0.047	0.292	0.059	0.283
53		-0.470	0.069	0.044	0.307	0.078	0.354
54	19	-0.330	0.123	0.062	0.272	0.102	0.233
55	24	0.052	0.024	0.055	0.188	0.052	0.170

Hybrid#	Mod	4th Dev (mm)	Centre Dev (mm)	Sag(Phi) (mm)	Twist(Phi) (mm)	Sag(R) (mm)	Twist(R) (mm)
56	27	-0.432	-0.029	0.048	0.239	0.055	0.267
57	34	-0.274	-0.088	0.054	0.246	0.073	0.191
58	15	-0.598	-0.116	0.064	0.387	0.057	0.452
59	17	-0.132	0.069	0.077	0.140	0.048	0.110
60	26	-0.494	-0.082	0.047	0.488	0.059	0.380
61	25	0.165	0.075	0.066	0.157	0.031	0.229
62	28	-0.056	0.114	0.070	0.098	0.068	0.094
63		-0.122	0.151	0.065	0.123	0.056	0.139
64	31	-0.360	-0.002	0.033	0.347	0.065	0.265
65		-0.467	-0.044	0.077	0.511	0.039	0.412
66		-0.039	0.078	0.054	0.083	0.049	0.086
67	37	-0.366	-0.048	0.060	0.200	0.052	0.194
68	29	-0.036	-0.056	0.072	0.083	0.095	0.083
69	25	0.295	0.208	0.046	0.368	0.055	0.365
70	21	-0.017	0.092	0.047	0.097	0.039	0.089
71	28	-0.057	0.063	0.066	0.052	0.044	0.053
72		-0.177	0.011	0.069	0.101	0.075	0.056
73	33	-0.107	0.029	0.048	0.119	0.055	0.091
74		0.000	0.039	0.071	0.063	0.071	0.089
75	41	0.081	0.038	0.109	0.212	0.089	0.113
76		-0.339	-0.145	0.062	0.319	0.065	0.221
77		-0.198	0.035	0.070	0.214	0.061	0.187
78	30	-0.020	0.006	0.078	0.030	0.045	0.061
79	32	-0.271	0.089	0.074	0.305	0.066	0.203
80		-0.149	0.128	0.080	0.052	0.076	0.069
81		-0.249	0.111	0.084	0.183	0.111	0.171
82	35	-0.308	-0.051	0.041	0.118	0.050	0.155
83	44	-0.192	-0.062	0.047	0.228	0.064	0.193
84	36	-0.168	-0.104	0.089	0.124	0.150	0.279
85	38	0.010	0.118	0.067	0.120	0.049	0.083
87	48	-0.314	-0.167	0.062	0.392	0.077	0.302
88	45	-0.518	0.017	0.081	0.421	0.049	0.413
89	47	-0.676	-0.153	0.061	0.534	0.026	0.507
93	42	-0.380	-0.145	0.040	0.384	0.089	0.269
94	61	-0.467	-0.128	0.069	0.491	0.034	0.406
95	54	-0.046	-0.081	0.076	0.169	0.068	0.051
96	53	-0.198	-0.152	0.114	0.203	0.089	0.130
97	52	-0.243	0.099	0.074	0.155	0.031	0.241
98		-0.760	-0.194	0.065	0.428	0.045	0.520
99	58	-0.440	-0.020	0.062	0.318	0.058	0.283
101	49	-0.611	-0.111	0.067	0.354	0.031	0.443
104	50	-0.472	-0.134	0.056	0.399	0.053	0.380
105	51	-0.032	-0.005	0.045	0.091	0.049	0.071
106	55	-0.351	0.144	0.096	0.219	0.111	0.255
107	56	0.109	0.301	0.075	0.090	0.087	0.153
112	59	-0.009	-0.277	0.115	0.139	0.128	0.065

Hybrid#	Mod	4th Dev (mm)	Centre Dev (mm)	Sag(Phi) (mm)	Twist(Phi) (mm)	Sag(R) (mm)	Twist(R) (mm)
113	62	-0.248	0.025	0.052	0.158	0.063	0.153
114	63	-0.096	0.115	0.111	0.023	0.056	0.063
115	64	0.174	0.227	0.090	0.257	0.091	0.321
116	7	0.612	0.587	0.116	0.647	0.132	0.659
118	74	-0.118	0.309	0.130	0.067	0.127	0.073
119	71	0.026	0.106	0.020	0.100	0.074	0.132
120	72	0.230	0.051	0.096	0.236	0.088	0.235
121	60	-0.077	-0.134	0.072	0.061	0.129	0.078
125	73	-0.101	0.172	0.139	0.089	0.074	0.072
126	75	-0.090	-0.024	0.029	0.058	0.066	0.094
127	4	-0.254	0.171	0.114	0.104	0.089	0.142
135	5	0.023	-0.036	0.054	0.084	0.061	0.099
134	6	-0.455	-0.256	0.110	0.372	0.099	0.347
122		0.298	0.168	0.059	0.365	0.042	0.338
129		-0.101	0.120	0.084	0.142	0.060	0.134
132		-0.197	-0.059	0.047	0.223	0.067	0.188
130		0.179	0.129	0.048	0.164	0.042	0.147
136		-0.046	-0.102	0.070	0.159	0.100	0.061
137		-0.181	-0.101	0.055	0.083	0.079	0.115
117		0.358	0.247	0.044	0.353	0.046	0.409

Table 2: Hybrid Metrology pre-population

Post-population Hybrid Metrology

Hybrid#	Mod	4th Dev (mm)	Centre Dev (mm)	Sag(Phi) (mm)	Twist(Phi) (mm)	Sag(R) (mm)	Twist(R) (mm)
50		0.000	0.000				
51		-0.729	0.067	0.097	0.634	0.108	0.599
52		-0.847	-0.038	0.062	0.765	0.066	0.733
53		-0.323	0.082	0.039	0.205	0.069	0.256
54	19	-0.310	0.132	0.062	0.274	0.096	0.248
55	24	-0.157	-0.066	0.053	0.093	0.065	0.074
56	27	-0.436	-0.017	0.028	0.220	0.071	0.247
57	34	-0.450	-0.161	0.080	0.400	0.087	0.340
58	15	0.000	0.000				
59	17	-0.162	0.067	0.072	0.226	0.120	0.154
60	26	-0.442	-0.105	0.046	0.408	0.060	0.324
61	25	0.026	-0.005	0.047	0.070	0.037	0.114
62	28	-0.233	0.040	0.064	0.203	0.051	0.173
63		-0.246	0.130	0.061	0.232	0.079	0.202
64	31	-0.136	0.031	0.080	0.134	0.073	0.088
65		-0.505	-0.089	0.077	0.537	0.049	0.441
66		-0.206	0.015	0.049	0.202	0.050	0.189
67	37	-0.321	-0.030	0.061	0.109	0.043	0.117
68	29	-0.160	-0.128	0.075	0.130	0.108	0.145
69	25	0.223	0.160	0.048	0.302	0.056	0.294

Hybrid#	Mod	4th Dev (mm)	Centre Dev (mm)	Sag(Phi) (mm)	Twist(Phi) (mm)	Sag(R) (mm)	Twist(R) (mm)
70	21	-0.097	0.037	0.039	0.077	0.045	0.067
71	28	-0.270	-0.090	0.088	0.220	0.068	0.184
72		-0.164	-0.017	0.047	0.084	0.071	0.040
73	33	-0.155	-0.013	0.047	0.175	0.049	0.128
74		0.000	0.000				
75	41	0.114	0.065	0.087	0.236	0.079	0.195
76		0.000	0.000				
77		0.073	-0.232	0.062	0.233	0.045	0.214
78	30	0.000	-0.029	0.069	0.079	0.056	0.115
79	32	-0.564	-0.067	0.080	0.282	0.060	0.267
80		-0.196	0.080	0.081	0.064	0.063	0.078
81		0.000	0.000				
82	35	-0.298	-0.104	0.058	0.108	0.067	0.146
83	44	-0.128	-0.042	0.040	0.085	0.060	0.085
84	36	-0.276	-0.057	0.042	0.209	0.069	0.229
85	38	-0.071	-0.020	0.096	0.108	0.067	0.090
87	48	-0.596	-0.319	0.085	0.559	0.077	0.470
88	45	-0.560	-0.015	0.076	0.464	0.039	0.457
89	47	-0.642	-0.180	0.051	0.516	0.033	0.472
93	42	-0.460	-0.216	0.060	0.429	0.118	0.322
94	61	-0.381	-0.218	0.087	0.416	0.034	0.406
95	54	0.000	-0.045	0.075	0.113	0.078	0.029
96	53	-0.018	-0.079	0.190	0.100	0.089	0.130
97	52	-0.169	0.008	0.035	0.055	0.031	0.241
98		0.000	0.000				
99	58	-0.303	-0.032	0.061	0.266	0.053	0.191
101	49	-0.634	-0.164	0.050	0.386	0.037	0.478
104	50	-0.514	-0.136	0.051	0.435	0.040	0.411
105	51	0.026	0.226	0.049	0.071	0.106	0.109
106	55	-0.275	-0.102	0.111	0.255	0.032	0.194
107	56	-0.090	0.285	0.090	0.100	0.131	0.119
112	59	0.186	-0.209	0.122	0.314	0.150	0.234
113	62	-0.167	0.084	0.053	0.116	0.029	0.112
114	63	0.068	0.138	0.103	0.128	0.031	0.096
115	64	0.072	0.188	0.093	0.255	0.092	0.261
116	7	0.550	0.556	0.125	0.581	0.129	0.586
118	74	-0.217	0.258	0.150	0.111	0.128	0.128
119	71	0.078	0.089	0.031	0.175	0.085	0.194
120	72	0.136	0.017	0.092	0.132	0.085	0.132
121	60	-0.188	-0.208	0.087	0.133	0.161	0.157
125	73	-0.015	0.220	0.129	0.029	0.088	0.073
126	75	-0.042	-0.075	0.024	0.149	0.078	0.057
127	4	-0.230	0.229	0.139	0.058	0.105	0.065
135	5	-0.111	-0.103	0.062	0.098	0.078	0.048
134	6	-0.095	-0.080	0.085	0.102	0.063	0.034
122		0.285	0.191	0.066	0.403	0.051	0.400

Hybrid#	Mod	4th Dev (mm)	Centre Dev (mm)	Sag(Phi) (mm)	Twist(Phi) (mm)	Sag(R) (mm)	Twist(R) (mm)
129		0.054	-0.232	0.073	0.237	0.056	0.229
132		-0.092	-0.024	0.046	0.105	0.066	0.069
130		-0.050	0.034	0.031	0.123	0.055	0.094
136		-0.183	-0.152	0.067	0.088	0.120	0.077
137		-0.058	-0.039	0.061	0.065	0.065	0.049
117		0.375	0.300	0.070	0.398	0.047	0.451

Table 3: Hybrid Metrology post-population