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VELO Module Production - Back End Bonding

LHCB Technical Note

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Abstract

This note describes in detail the procedures used in the bonding of the ASICs (Beetle 1.5 chips) to the hybrid for the LHCb VELO detector modules.

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1. Introduction

During back end bonding, all the wire connections between the Beetle[1, 2] readout ASICs and the hybrid are made. This forms the 12 and 13th step [3] in the production of VELO modules and the first wire bonding steps. During this step approximately 70 wire connections are made per chip. The back end bonds are crucial to the smooth running of the chip; if one wire has not been bonded it could lead to the malfunction of the whole chip. The bonding pattern for each chip is slightly different in order to set its unique hardware address, see appendix B, which allows remote chip control & configuration. Two Hesse and Knipps Bondjet 710 bonding machines (labelled 710A and 710B) and a Kulicke & Soffa 8090 were used for the VELO production.

The ultrasonic wedge bonding process is performed with aluminium alloy wire on either aluminium or gold pad metallization. Pure aluminium wire is too soft to be drawn into fine wire, so it is often alloyed with small percentages of silicon or magnesium to increase strength. For this production wire from Williams advanced materials was used with Ø25µm Al 99% and Si 1%.

Wedge bonding utilizes ultrasonic energy and pressure to create a bond between the wire and the bond pad. Wedge bonding is a low-temperature process that uses frequencies up to 120 kHz for fine pitch applications. This cold welding process deforms the wire into the flat elongated shape of a wedge. At Liverpool the Hesse and Knipps bondjet 710s use 100 kHz transducers and the Kulicke and Soffa 8090 uses a 120 kHz transducer.

During bonding wire is fed through a hole in the back of the "wedge"; it then passes beneath the bonding face of the wedge tool, the second bond must be placed in-line with the first to ensure correct location beneath the tool. The tools used for our 710 machines were sourced from Small Precision Tools[1] . A typical wedge bond can be determined (in most cases) by the degree of deformation of the wire. The width of the flattened area should be approximately 1.7×the diameter of the wire, e.g. for 25µm diameter wire, the width should be 42µm. On our 710's we are able to use 38% deformation (1.4× diameter) this gave us a pad width of approximately 35µm.

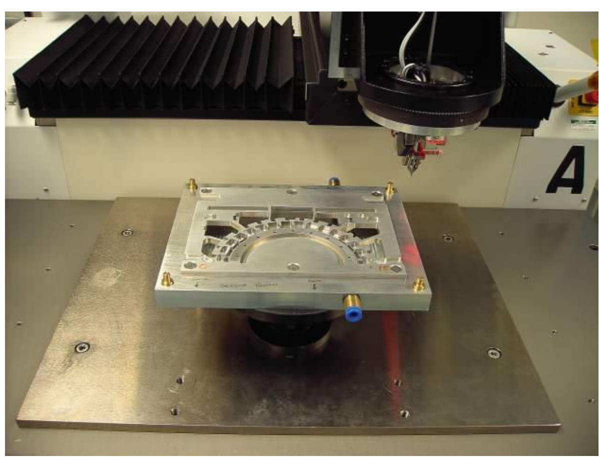

Figure 1: Photograph of the LHCb jig mounted on the H&K 710 bonding machine chuck

[1] The specification was from SPT: FP 45A-W-2020-1.00-C W=VW=003 VR=006; the tool specification for the K&S 8090 was a Kulicke & Soffa bonding tool 4WFM4-2025-W6C-M00.

2. Mechanical Setup

As shown in Figure 1 the bonding jig [4, 5] is mounted onto the bonding machine with the chips toward the operator prior to starting back end wire bonding. The jig is positioned to allow the operator to visually inspect the bonds as they are formed.

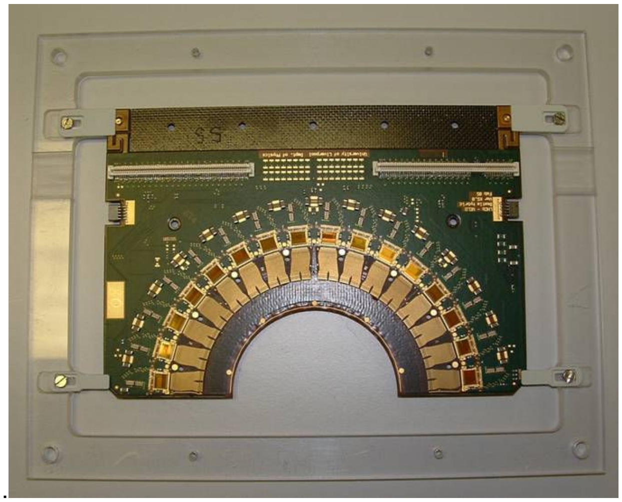

Figure 2: Photograph of the handling frame holding a module.

The hybrid is mounted onto the bonding jig while being held in its handling frame. The handling frame, see Figure 2, locates the hybrid relative to the jig so that the other side of the hybrid is not damaged during bonding. Vacuum is then applied to give the necessary support during bonding. Without adequate vacuum, the hybrid bounces during the bonding process, leading to non-sticking wire bonds as well as low strength wire bonds. The quality of the vacuum was provided by using dedicated oil free pump for each machine. The H&K 710A machine was equipped with a 50 litre vacuum tank reservoir along with ID 12mm tubing to improve its vacuum.

3. Quality Assurance & Calibration

Prior to bonding the readout ASICs on each side of a hybrid, a set of 7 test wire bonds are placed on a large gold pad located on the left hand side of a hybrid as shown in

Figure 3. Since these bonds are made using the same bonding parameters as are used on the hybrid side of the backend wire bonds, the quality of these bonds should be representative of the production backend bonds. These test wire bonds are then measured to destruction using a Dage 4000 series wire bond pull tester. During this test, the force needed to break each wire (in grams) as well as the location and type of the wire break is determined. By using test bonds, the need to destructively sample bonds on the production pads of each hybrid is removed. Anomalous results are indicative of a problem with the wire bonding machine, the bonding fixture, poor vacuum or with the surface quality of the hybrid.

As an additional quality control measure, the hybrid part number, the wire spool number and the total number of bonds performed by the wedge in use are stored prior to starting bonding. With this information, future bond failures can be tracked to a given wire bond machine, wire spool, operators or time. The wedge is replaced when the bond quality deteriorates due to wear-and-tear on the wedge surface; this is after about 40000 wire bonds on average.

The location of the wirebond foot placement on the pads is monitored both for the test wires and the final bonds. If they are not placed with the precision needed, approximate 10 microns, a set of "axle" and "wedge" geometry calibrations are run which place test wires in the large gold pad.

3.1. Bonding map for back end bonds

After pull testing and calibrating the bonding head, the appropriate wire bonding program is loaded.

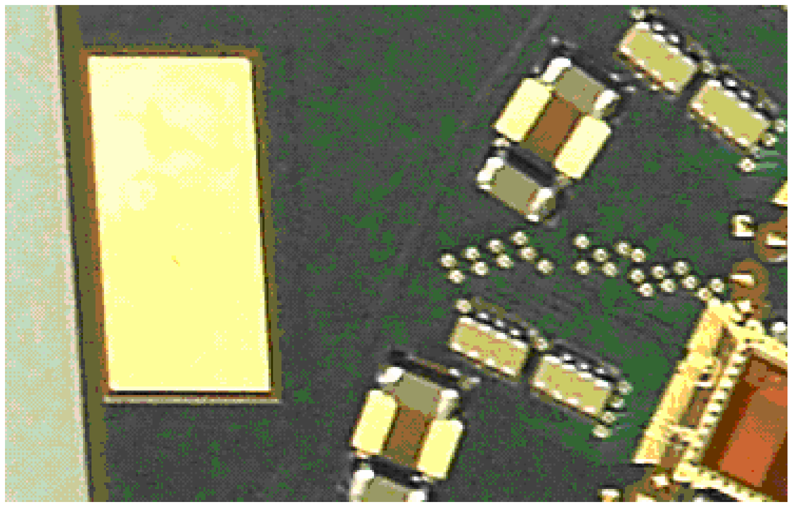

Figure 3: Photograph of the gold pad which forms the test bonding area on the hybrid circuit. The pad is at the left of this photograph.

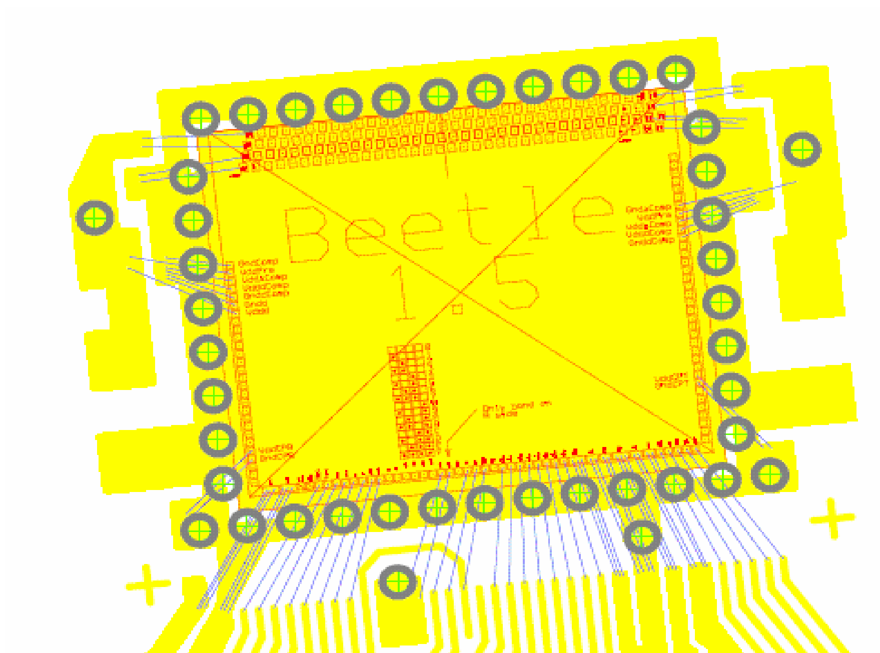

Figure 4: Schematic of the Beetle chip showing bonds (blue lines) which connect the backend of the chip to the hybrid. Note the large angles some bond make with respect to the bottom edge of the chip.

Within the program, the locations and heights of the bonds for all 16 chips are stored. The schematic bonding map of a chip is shown in Figure 4. Within the database[6, 7], any problems during bonding are logged and mapped to this wirebond numbering scheme.

A complete list of the chip-to-hybrid connections are tabulated in Appendix A. The bonds are numbered sequentially for the given hybrid side, ranging up to 1104 for the R-side and 1088 for the Phi-side.

3.2. Bonding reference systems

3.2.1. Hesse and Knipps Bondjet 710

The H&K 710 wire bonding program has 17 separate reference systems as shown in Figure 5 the hybrid itself is reference system #1. Each chip has its own reference system (#2-17). The absolute location of each reference system is found using the fiducial markers; those for the hybrid are shown in Figure 6 a, b those for the chips in Figure 6 c, d

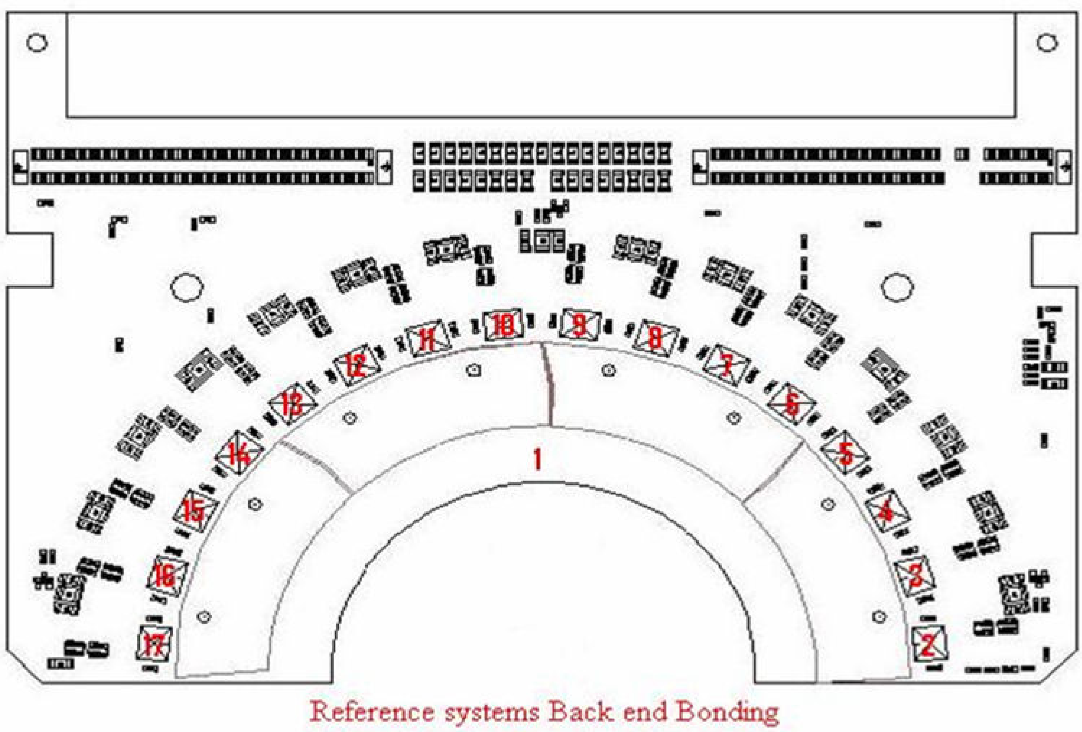

Figure 5: Schematic of the hybrid showing the 17 references frames

3.2.2. Kulicke & Soffa 8090

The program has been written so each chip is a separate device there are 4 saws each with 4 devices giving a total of 16 devices shown in Figure 7. The absolute location of each reference system is found using the fiducial markers; those for the hybrid are shown in

Figure 8 (a, b) those for the chips in

Figure 8 (c, d).

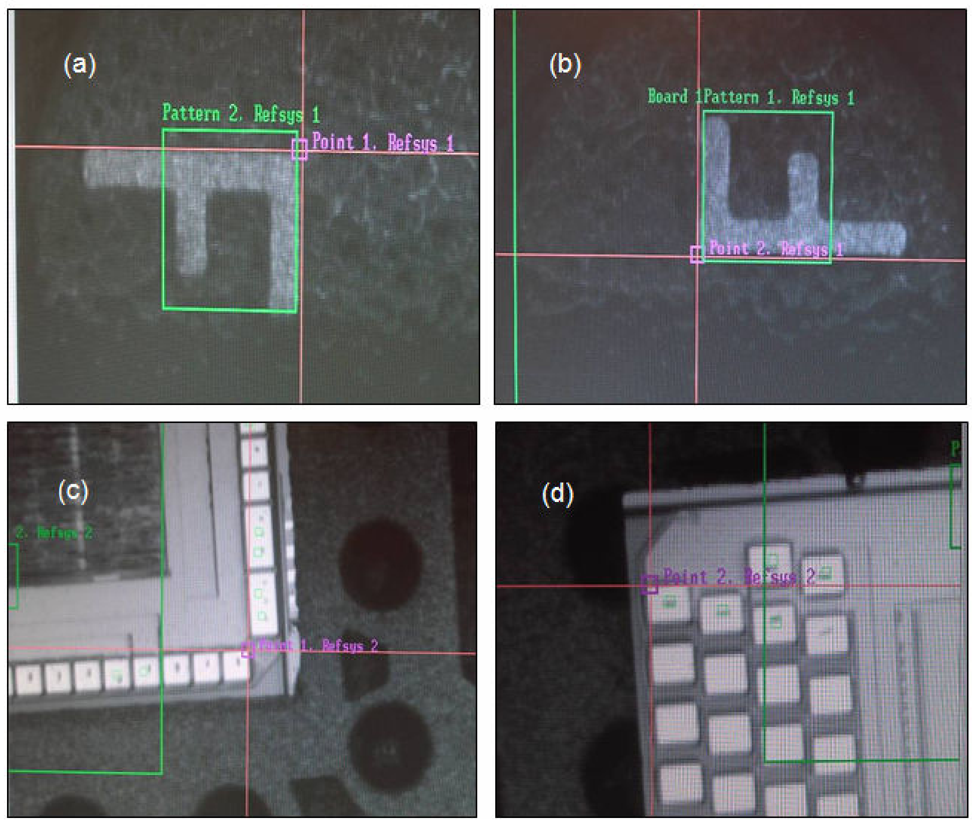

Figure 6: (a, b) Show the fiducial markers used to find the locations of the hybrid; (c, d) Show the fiducial markers used to find the location of each chip

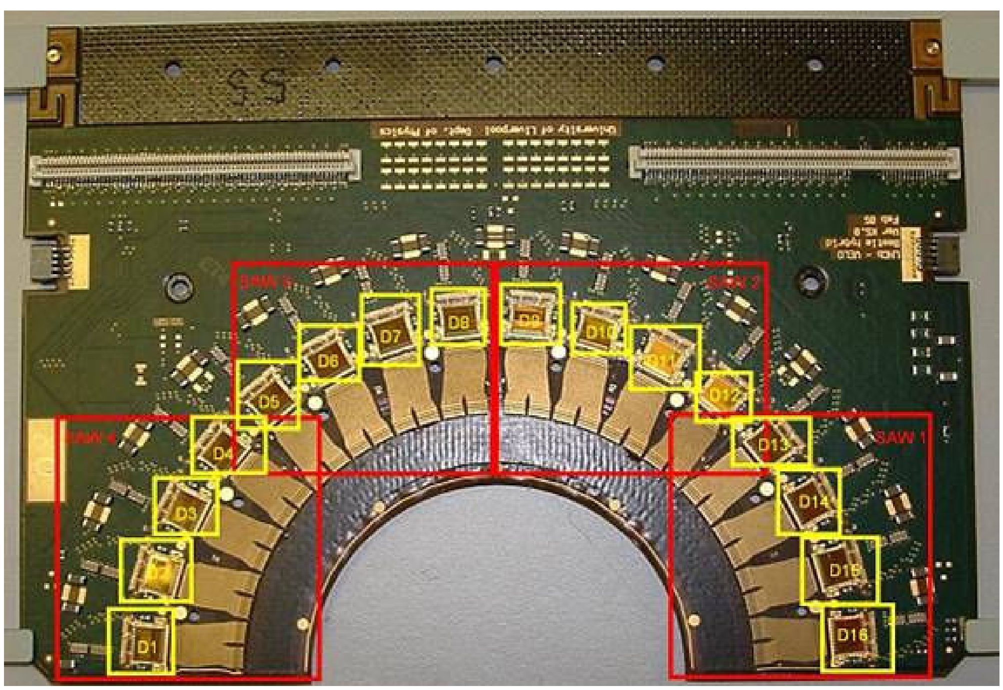

Figure 7: Schematic of the hybrid showing the references frames

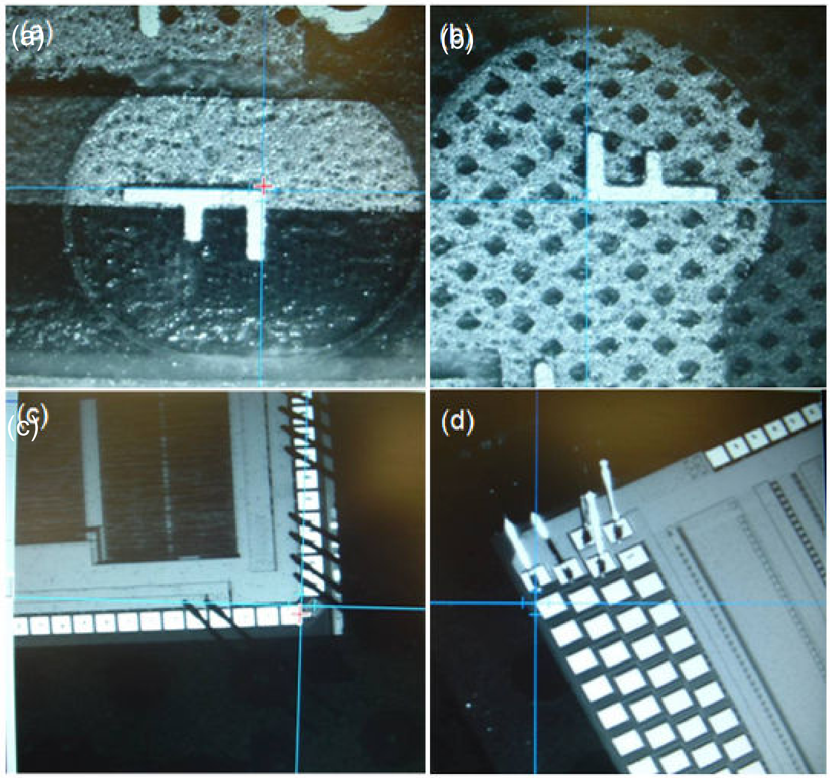

Figure 8: (a, b) Show the fiducial markers used to find the locations of the hybrid; (c, d) Show the fiducial markers used to find the locations of each chip.

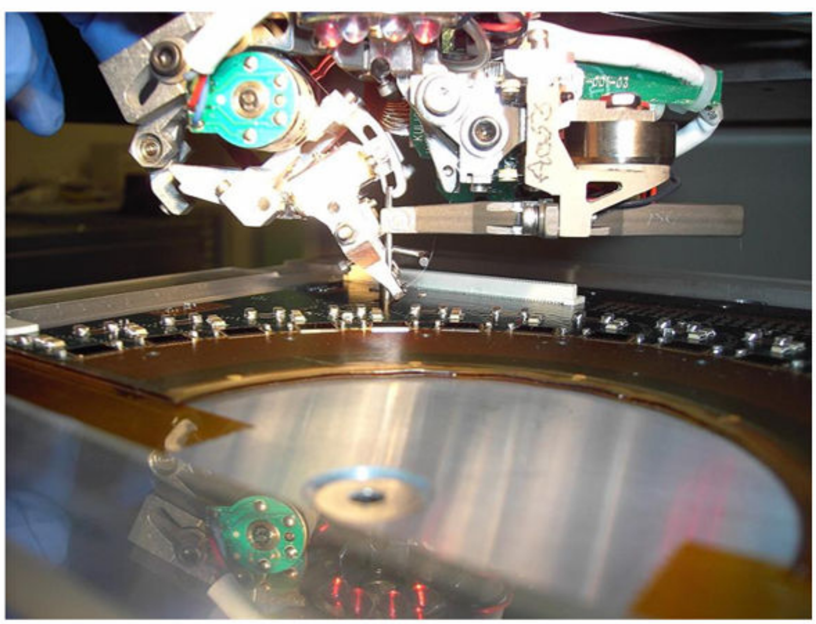

Figure 9: Back end bonding underway on the K&S 8090.

3.3. Bonding procedure

Both the H&K and the K&S machines use pattern recognition to find the fiducials that are identified by the wire bonder's pattern recognition software. The chips are then aligned to the hybrid reference systems in software. If the wire bonder's pattern recognition software fails to find any of the alignment points, the point can be manually aligned using the fiducial markers see Figure 6 and

Figure 8. Once aligned, the wirebonds can then be placed quickly in a semi-automatic fashion, see Figure 9. Note the edge of the chip all the way around is not passivated (so it is electrically active). Thus it is important to a void touching bond feet to the edge of the chip. Checking for contact is done using a multimeter by measuring resistance (Ω) across one capacitor behind the chip check one capacitor in each block of 4 chips the reading should be 1.2-1.4kΩ. The pad sizes for the backend were as follows: Beetle chip 1.5 communication channels 95μm×95μm, amplifier channels 95μm×120μm.

All back end bonds are crucial to the proper functioning of the chip. Thus, all wire bond failures have been repaired during the VELO production. Some limited redundancy and protection against bond failures is achieved by having multiple power and ground bond. The locations of the problem bonds are noted in the database in order to track future failure and for general quality control purposes. All parameters used within the bonding programs are shown in the appendices C & D.

There are 1,104 wires placed in bonding an r-detector and 1,088 wires for the phi detector. Thus a total number of 2,192 back end bonds are placed on each complete hybrid, see Figure 10.

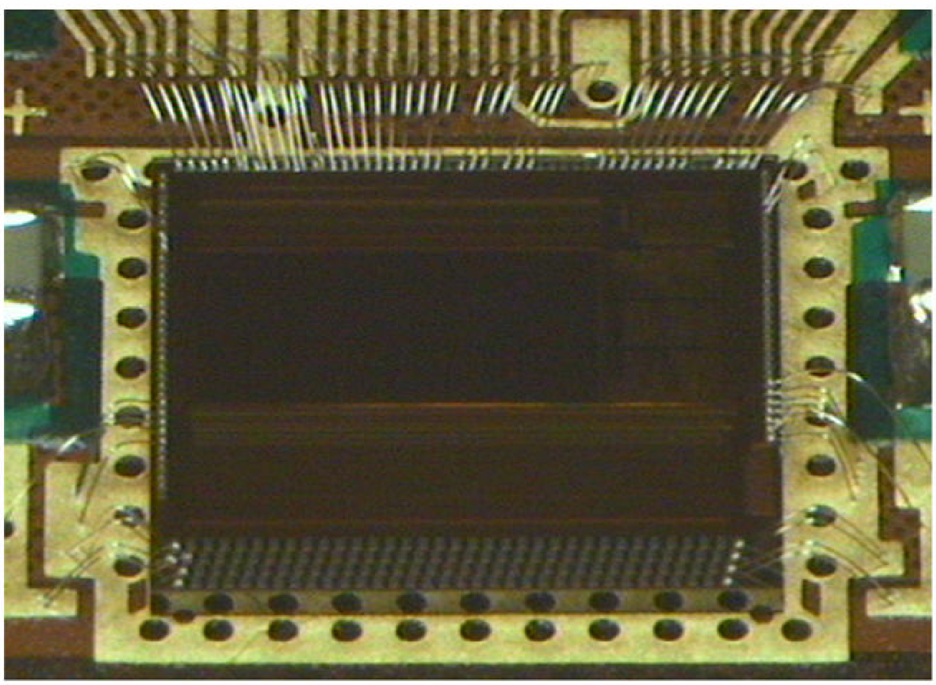

Figure 10: Photograph of a back end bonded chip. Note the long, high bond wires to the right and left of the chip and the large angles the bond wires make with the perpendicular to the chip edge.

4. Bonding Results

4.1. Bonding times

The K&S 8090 requires calibration at the beginning of every session which takes about 1.5 hours before production bonding may be started and reduces the effective working time in a day. In addition the pattern recognition on the 8090 is not capable of reliably recognizing all the requisite fiducial marks. This is was a shortcoming of the design of the pitch adaptors and hybrid. The result was that all patterns had to be manually aligned; the alignment process took about 15 minutes per side. The bonding process is extremely rapid with the 8090 being able to put down approximately 5 bonds per second. However visual inspection on completion of bonding and repair work to wires took on average 1 hour per side of a hybrid. On this machine approximately three hybrids (six sides) could be bonded per working day which represents approximately 1/14 of the VELO complement of hybrids.

Back end bonding on the H&K 710 was slow. Because of the stretching of the circuit on the hybrid the position of the end point (or destination) bonds have to be manually aligned and the bond heights have to be manually set prior to bonding. This process took on average about 1 hour. The bonding the 16 chips then took approximately 20 minutes. Visual inspection and repairs takes approximately 1 hour. Typically about one hybrid (two sides) could be bonded per day on the H&K machines. Approximately 48% of the modules were bonded on the 8090 and 710A machines each and 4% on the 710B.

4.2. Bond Pull strengths

The back-end bonding was performed on two H&K 710 machines, labelled A and B, and a K&S 8090. Samples of test bonds on each hybrid were measured prior to bonding on each machine. Wherever possible, several complete chips worth of production wire bonds have been tested destructively prior to faulty chip replacement or on faulty hybrids removed from the production chain. The results for the three machines from data taken during the VELO production are shown in Figure 11.

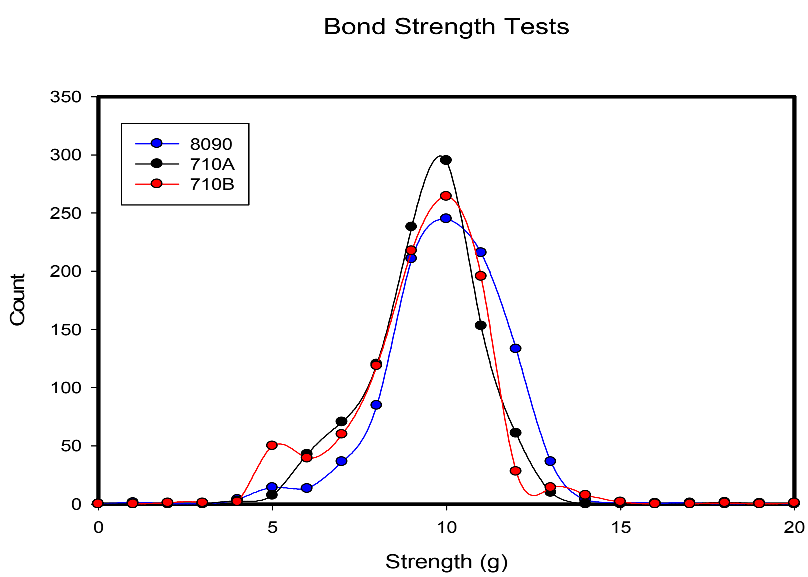

Figure 11: Average pull strengths for bonds during the production on all three machines. The sampling presented here is from the test bond pads on the hybrids.

The mean and the standard deviation of the pull strengths for the three machines, on the test bond pads, were: 8.9 ± 1.6 g, 8.8 ± 1.8 g and 9.5 ± 1.7 g for the 710A, 710B, and 8090 wire bond machines, respectively. The width of these distributions reflects the difficulty of bonding to large, flexible, double-sided hybrids with angled wire bonds. Prior to the beginning of production, the target of having greater than 6 gram pull strengths was set. This target was achieved for 99%, 95% and 98% of the test bonds made with the 710A, 710B and 8090 wire bonding machines.

4.3. Bonding Failures

There was a requirement that all the bonds between the chip and the hybrid had to be made, in order to ensure the proper functioning of the chip. Where a bond failed, repeated attempts were made to complete the bond and the information that a bond required multiple attempts was logged in the database. In the worst case, where an essential bond could not be made, the chip was replaced and bonding re-done. For these chips destructive tests of the back-end bond strength could be made. (See Figure 12). This subset samples the achieved back-end bond strengths on the hybrids. For this data the 8090 achieve mean (and rms) pull strength of 10.0±1.5g and the 710A and 710B machines (with much more limited statistics) 9.4±1.5g and 8.9±1.9g. On the three machines (8090, 710A and B) about 1.5, 0.5 and 2.5% of bonds were tested with a pull strength of less than 5g. These figures reflect the problems encountered in bonding double sided large hybrids which are not rigidly held down.

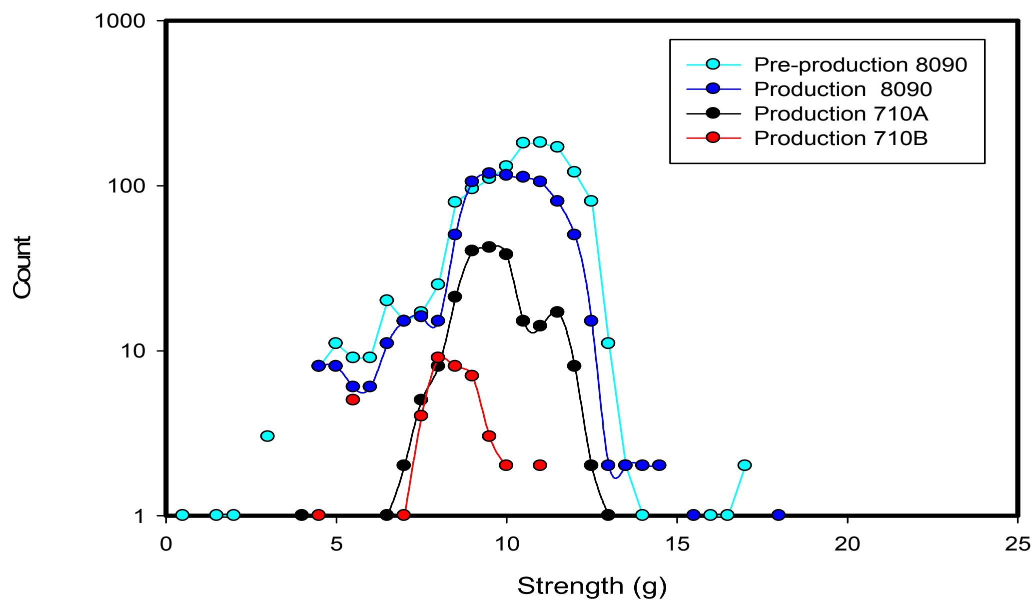

Figure 12: An analysis of the bond pull strengths on back end bonds from samples of hybrids where chips had to be replaced. The 8090 has much larger samples for both pre-production and production.

The database contains full information on the back end bonding performance over the 44 production modules. Of the almost 100000 back end wire bonds made multiple attempts were required on 0.50% and 0.76% of the wire bonds for the R-side and Phi-side respectively as shown in Table 1.

BEB		
	R-side	**Phi-side**
No of modules	**44**	**44**
No of bonds/module	**1104**	**1088**
Total Bonds	**48576**	**47872**
No of modules		
with bond problems	**34**	**35**
No of problem bonds	**241**	**363**
% problem bonds	**0.50**	**0.76**

Table 1: Backend bonding results for the VELO production modules.

The difference seen in the failure rates between the R and Phi sides is of marginal statistical significance. In addition, the distribution of the location of the problem bonds has been studied. In Figure 13 the number of problems bonds as function of chip number is shown. Severe problems with hybrid bounce would manifest themselves as increased levels of bad bonds around chips 1 and 15. There exists only limited evidence for this. In Figure 14 details of the problems per chip are displayed. No obvious correlation with bond length or direction could be found. The bond heights are different on the 8090 and the 710 and are not plotted. The full frequency table is given in Appendix A. One of the VddPre bonds had the most problems bonding.

We note that in the Liverpool production environment the 8090 was faster but less reliable than either of the 710 machines.

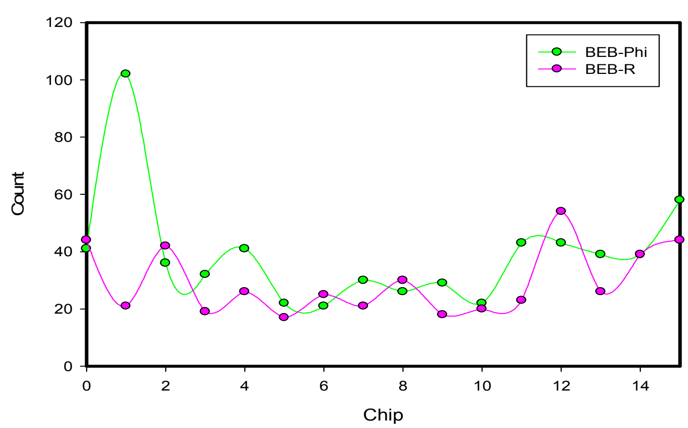

Figure 13: Plot of problems with back end bonds as a function of chip number. The peak around chip 1 is almost entirely due to one module. There is limited evidence for an increased number of problems in the edge regions where the bounce is the greatest.

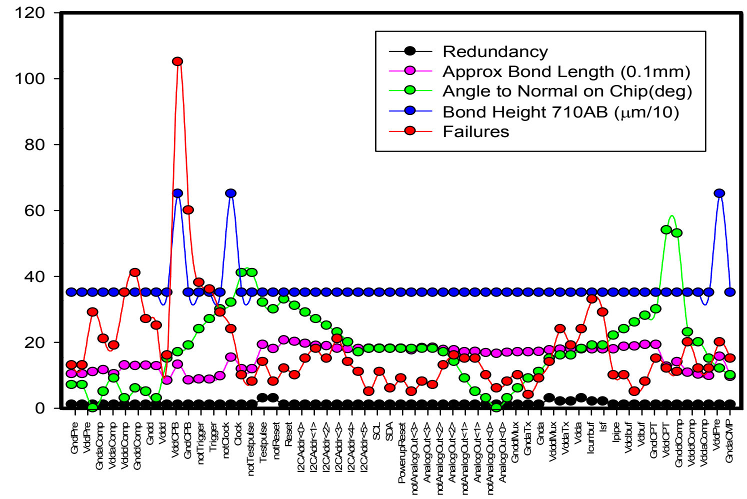

Figure 14: Plot of the total number of bond failures on the back end. Also plotted are the bond lengths and the angle the bond makes with respect to the normal of the chip surface together with the bond heights (710 only). The 710 bond head made a 180º at the peak around VdddComp and sometimes damaged adjacent bonds.

A further plot, Figure 15, shows the plot failures as a function of module production order. The plot shows some limited evidence for the improvements in the back end bonding as function of place in the production line.

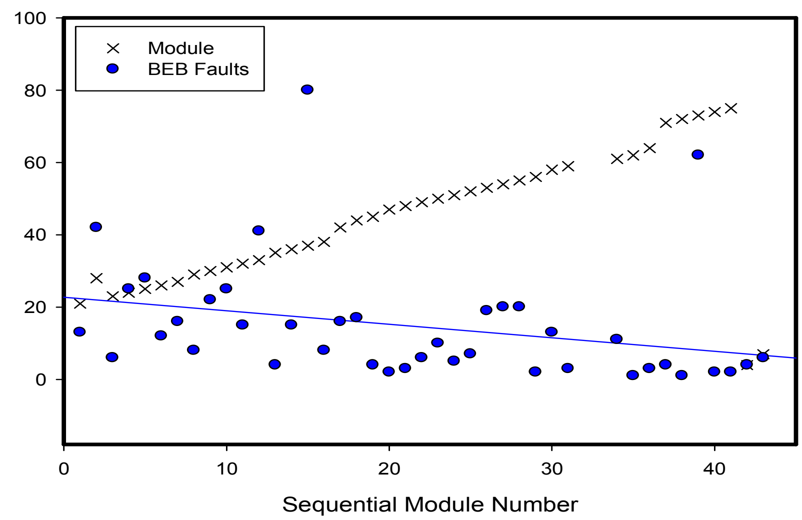

Figure 15: Plot failures per module as function of production order. Modules <10 were the last constructed otherwise the modules are approximately in production order. The plot is indicative of an improvement in variability during the process.

5. Conclusions

The connections between the hybrid and readout ASICs are made during backend wirebonding. During the production, over 96000 backend wirebond were made using 2 H&K 710 wire bonders and a K&S 8090 wire bonder. Design of the hybrid to benefit from the high speed bonding capability of the 8090 would have greatly reduced production time, although reliability of the 8090 impeded production.

Only 0.6% of the production bonds needed more than one bonding attempt. The bonding pull strengths seen are representative of the difficulty of bonding such a large, flexible hybrid. The only improvement foreseen for future productions is improving the hybrid support by modification of the bond jig and adding vacuum reservoirs to the H&K 710B machine and the K&S 8090.

6. References

1. Agari, M. et.al., *Beetle: A radiation hard readout chip for the LHCb experiment.* Nucl. Instrum. Meth., 2004. **A518**: p. 468-469.

2. Lochner, S. and M. Schmelling, *The Beetle Reference Manual.* LHCb Internal Note, 2006(105).

3. *Summary of stages in module production*, http://hep.ph.liv.ac.uk/lhcb/html/summary.html

4. Carroll, J.L., *Bonding Jig Base Plate*, 2005, Liverpool, np31-02-171

5. Carroll, J.L., *Bonding Jig Top Plate*, 2005, Liverpool, np31-02-173

6. Patel, G.D., *et al.*, *VELO Module Production - Quality and Process Control.* LHCb Internal Note, 2007(088).

7. *LHCb VELO production database*, http://hep.ph.liv.ac.uk/lhcb/html/database.html

Appendix A Chip-to-hybrid wire numbers

The RefNo and Pin Name of all chips bonds are listed in the table below. Also given is the frequency of rebonds for each logged in the database during the production. Figure 16 below shows the layout of the pads for these bonds on the surface of the chip.

RefNo	Pin Name	Number of repairs
1	GndPre	13
2	GndPre	13
3	VddPre	29
4	VddPre	21
5	GndPre	19
135	VddPre	35
136	VddPre	41
137	GndPre	27
138	GndPre	25
139	GndaComp	16
140	VddPre	105
141	VddaComp	60
142	VdddComp	38
143	GnddComp	36
144	Gndd	29
145	Vddd	24
164	VddCPB	10
165	GndCPB	8
169	Vddd	14
170	Gndd	8
173	notTrigger	12
174	Trigger	10
175	notClock	15
176	Clock	18
177	notTestpulse	15
178	Testpulse	21
179	notReset	14
180	Reset	11
183	I2CAddr<0>	5
184	I2CAddr<1>	11
185	I2CAddr<2>	6
186	I2CAddr<3>	9

RefNo	Pin Name	Number of repairs
187	I2CAddr<4>	5
188	I2CAddr<5>	8
190	SCL	7
191	SDA	13
192	PowerupReset	16
194	notAnalogOut<3>	15
195	AnalogOut<3>	15
196	notAnalogOut<2>	10
197	AnalogOut<2>	6
198	notAnalogOut<1>	8
199	AnalogOut<1>	10
200	notAnalogOut<0>	4
201	AnalogOut<0>	9
202	GnddMux	14
203	GndaTx	24
204	Gnda	19
205	VdddMux	24
206	VddaTx	33
207	Vdda	29
208	Icurrbuf	10
209	Isf	10
210	Ipipe	5
211	Vdclbuf	8
212	Vdbuf	15
220	GndCPT	12
221	VddCPT	11
238	GnddComp	20
239	VdddComp	12
240	VddaComp	12
241	VddPre	20
242	GndaComp	15
	Total	1137

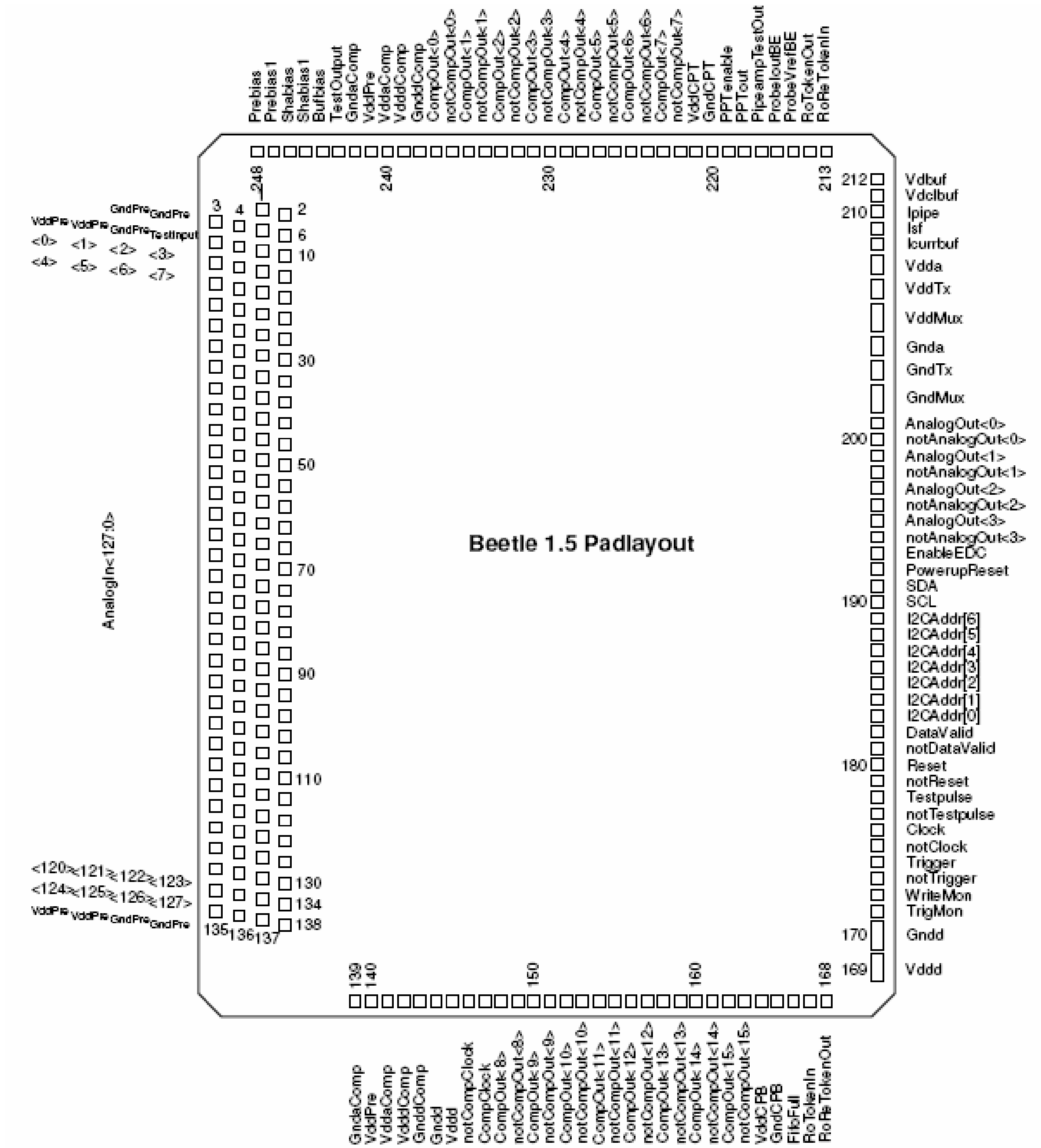

Figure 16: From the Beetle Users Manual: layout of the pads. The backend pads are on the top, right and bottom of the schematic.

Appendix B Chip Addressing Table

Pin Ref No 183-188 were the 6 chip address bits that uniquely identified the 32 chips on a hybrid, as chips 0-15 on the R-side and chips 0-15 on the Phi side. Each wire bond had an assigned machine wire bond number and the chip address bits that were bonded for each chip are shown by the assigned machine wire number in the table below.

Phi

Chip	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
First Bond	1	71	140	209	277	346	414	482	549	618	686	754	821	889	956	1023
I2CAddr<0>	26		165		302		439		574		711		846		981	
I2CAddr<1>	27	96			303	371			575	643			847	914		
I2CAddr<2>	28	97	166	234					576	644	712	779				
I2CAddr<3>	29	98	167	235	304	372	440	507								
I2CAddr<4>																
I2CAddr<5>	30	99	168	236	305	373	441	508	577	645	713	780	848	915	982	1048
Last Bond	70	139	208	276	345	413	481	548	617	685	753	820	888	955	1022	1088

Rad

Chip	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
First Bond	1	72	142	212	281	351	420	489	557	627	696	765	833	902	970	1038
I2CAddr<0>	26		167		306		445		582		721		858		995	
I2CAddr<1>	27	97			307	376			583	652			859	927		
I2CAddr<2>	28	98	168	237					584	653	722	790				
I2CAddr<3>	29	99	169	238	308	377	446	514								
I2CAddr<4>	30	100	170	239	309	378	447	515	585	654	723	791	860	928	996	1063
I2CAddr<5>	31	101	171	240	310	379	448	516	586	655	724	792	861	929	997	1064
Last Bond	71	141	211	280	350	419	488	556	626	695	764	832	901	969	1037	1104

Appendix C Bond parameters for Hesse and Knipps 710

1.Reference pattern:	
Position:	X = -169.910 mm, Y = -0.645 mm
Image information	
algorithm:	pattern recognition for chips
search area:	400 X 400 Pixel
Image size:	64 X 64 Pixel
accuracy:	good
Subpixel search:	off
save search:	off
2.Reference pattern:	
Position:	X = -84.437 mm, Y = -3.986 mm
Image information	
algorithm:	pattern recognition for chips
search area:	400 X 400 Pixel
Image size:	64 X 64 Pixel
accuracy:	good
Subpixel search:	off
save search:	off
1.Reference point:	X = -84.464 mm, Y = -3.968 mm
2.Reference point:	X = -169.885 mm, Y = -0.670 mm
Focus height:	-1.485 mm
Tolerance:	0.100 mm
Lighting (Upon):	0.00 %
Lighting (Ring):	68.00 %
Touchdown data:	
Touchdown height:	-17.993 mm
Touchdown area:	0.100 mm
Lower Tolerance:	0.300 mm
velocity:	2.000 mm/s
Welding parameters:	
US-threshold 1:	3.000 %
Bond force 1:	13.000 CN
US-threshold 2:	17.000 %
Bond force 2:	18.000 CN
Change at:	7.000 ms
US-channel:	A
Max. deformation:	38.000 %
Max. bond time:	110 ms
Positioning parameters:	
Offshoot:	0.020 mm
Delay:	10 ms
Accuracy:	
Working area:	0.003 mm
Height:	0.200 mm
Radius:	0.100 mm
Loop parameters:	
Start height:	0.500 mm
Height:	0.375 mm
Form:	85.000 %
Clamp closed after apex	Tear Off:
Method:	Wire Clamp

General parameters	
Working height:	-1.623 mm
Wire buffer:	70.000 %
Holder:	CICOHEIZUNG
Ultrasonic generator	
Channel A	
Ramp:	15
Boost:	0.000 °s
Delay:	2.000 ms
Channel B	
Ramp:	15
Boost:	0.000 %
Delay:	2.000 ms
Mode of adjustment:	per Board
Off-bond:	per Substrate

Appendix D Bond parameters for Kulicke and Soffa 8090

There are 2 different groups of wires most fall in to group 1, wires 4,11 and 61 (depending on chip number) fall in to group 2 these must be higher than all other wires to avoid shorting.

Bond parameters for group1

First bond	Tip	500 µm
	C/V	.30mps
	USG bond time 25ms	
	USG mode	constant current
	USG current	50mA
	Force	25g
	Hold	25g
	Bond at	wire angle
Second bond	Tip	500 µm
	C/V	.30mps
	USG bond time 25ms	
	USG mode	constant current
	USG current	50mA (range 45-65mA)
	Force	30g
	Hold	30g
	Bond at	wire angle
Loop	Loop height	375µm
	Loop shape	square
	Clamp close at loop	
	Loop peak Coeff	65%
	Tail	75

Bond parameters for group 2

First bond	Tip	575 µm
	C/V	.30mps
	USG bond time 25ms	
	USG mode	constant current
	USG current	50mA
	Force	25g
	Hold	25g
	Bond at	wire angle
Second bond	Tip	500 µm
	C/V	.30mps
	USG bond time 25ms	
	USG mode	constant current
	USG current	50mA (range 45-65mA)
	Force	30g
	Hold	30g
	Bond at	wire angle
Loop	Loop height	575µm
	Loop shape	square
	Clamp close at loop	
	Loop peak Coeff	75%
	Tail	75

Appendix E Programmes used for bonding

Programmes used for bonding on Hesse and Knipps 710

Program name	Description
lhcbhybr	LHCb Hybrid Rad side
lhcbhybp	LHCb Hybrid Phi side

Programmes used for bonding on Kulicke and Soffa 8090

Program name	Description
1LHCBHYBR	LHCb Hybrid Radial side
1LHCBHYBP	LHCb Hybrid Phi side