REPORT ON THE SCT FORWARD ELECTRICAL MODULE PROGRAM

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IN THE CONTEXT OF THE ATLAS SCT FORWARD HYBRID PROGRAM, THREE ELECTRICAL DETECTOR MODULES HAVE BEEN BUILT. THIS NOTE DESCRIBES THE ASSEMBLY AND SUMMARISES THE MECHANICAL AND ELECTRICAL PROPERTIES OF THESE MODULES. SOME COMMENTS ON THE SPECIAL REQUIREMENTS OF THE PRODUCTION OF A REAL MODULE AS COMPARED TO DUMMY MODULES ARE GIVEN. A LIST OF OPEN QUESTIONS ARISING FROM THIS ASSEMBLY RUN IS APPENDED.

All three electrical modules have been built at Freiburg University using the Manchester/Valencia/Freiburg system of chucks and software. The first one was assembled during a meeting of the proponents of this assembly system at Freiburg.

The following equipment was used in the production process:

- Assembly system built up from Newport stages and controllers, using a turn plate and associated tooling from Valencia and an adapted version of the LabVIEW assembly software from Manchester
- Asymtek Century Series glue dispenser with a pressure-driven dispense head
- Leica VMM 200 automatic measuring microscope, which has an accuracy of 2 μm in x,y,z
- F&K Delvotec 6400 wire bonder, using 17.5 μm aluminium wire
- Read-out system, which is described in detail below

The following components were built into these modules:

- 6 W31 and 6 W32 detectors from CiS
- 3 TPG/AlN spines produced at MPI Munich
- 6 Fan-in sets
- PEEK washers provided by Manchester
- Two Kapton-hybrids produced by DYCONEX
- One BeO-hybrid provided by Liverpool
- 36 ABCD2T chips
- 3 DORIC and 3 VDC chips provided by Oxford

The following table gives an overview of the three modules.

#	Serial Number	Hybrid	Comment
1	FR_R_002	Kapton K64	assembled during workshop
2	FR_R_003	BeO	
3	FR_R_004	Kapton K81	

PREPARATION OF ELECTRONIC HYBRIDS

HYBRIDS IN KAPTON/COPPER/CARBON-FIBER TECHNOLOGY

Hybrids were supplied by DYCONEX in a state in which the Dycostrate multilayer flexible circuit is bonded to the K1100 carbon fibre substrate and electrically tested. These hybrids have been populated with passive components, using a solder paste with a low melting point and a reflow oven. Afterwards their electrical quality has been checked on an automated test bench. Two hybrids have then been populated with 12 ABCD2T read-out chips each. Using conductive epoxy (Polytec H20E), the chips were glued onto analogue ground pads on the hybrid. Then the wire bond connections on the hybrid were made. Analogue and digital ground have been connected on the hybrid near each chip. The carbon fibre substrate was connected to analogue ground. A final read-out test showed that these hybrids were of good quality and that they could be used for the modules to be built.

HYBRIDS IN BERYLLIUM OXIDE TECHNOLOGY

One hybrid in BeO technology was supplied by the University of Liverpool, including the passive components. Obeying the same testing procedures as for the Kapton hybrids, the BeO hybrid was populated with 12 ABCD2T chips. Again, the chips were conductively glued onto the foreseen analogue ground pads on the hybrid. The wire bond connections on the hybrid were made, including the connection of analogue and digital ground near each chip on the top (connector) side. A read-out test qualified also this hybrid for module assembly.

COMMENT ON THE SELECTION OF ABCD2T CHIPS

The chips for the three hybrids have been selected randomly from the total of 40 chips which was supplied to Freiburg.

ASSEMBLY OF THE MODULES

ALIGNMENT OF WAFERS

The wafers have been aligned on the assembly system with respect to each other and to the mounting pins. The module geometry is defined by

- a 700 μm gap between the fiducials on the two detectors on each side
- a symmetric 20 mrad tilt of the detectors on both sides resulting in a stereo angle of 40 mrad
- the point in the middle of the gap between the detectors is located 80.137 mm away from the hybrid side mounting pin in the direction of the second mounting pin, and 80 μm offset from the line connecting the two mounting pins in the direction of the stereo angle tilt

Some specific comments on the assembly procedure can be found in the list of open questions at the end of this report.

GLUING OF DETECTORS ONTO THE SPINE

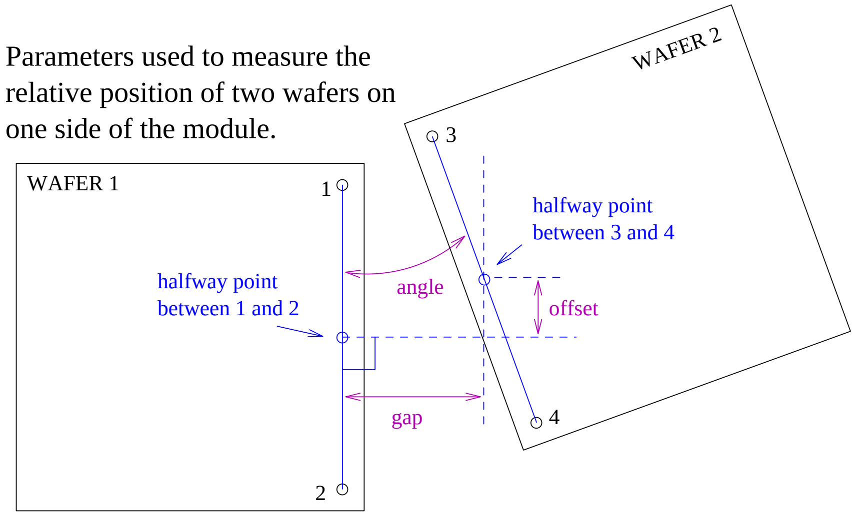
For gluing the detectors onto the spine, a boron-nitride filled glue was used, consisting of 5 parts Araldite resin (AW106), 4 parts Araldite hardener (HV953U), and 4 parts boron-nitride. The glue was mixed for two minutes and then filled in a syringe. Dispensing was done between 10 and 20 minutes after the mixing had started. The glue was dispensed on the spine using the Asymtek glue dispenser with an EFD needle of 1.54 mm inner diameter. The pressure was set to 3 bar. Two different glue beads were dispensed. Over the long TPG sections of the spine a thick bead of glue was dispensed. The amount of glue was tuned in such a way as to just cover the width of the spine, provided the glue layer thickness is 100 μm. This was achieved at a dispense speed of 5 mm/s. Over the transverse AlN parts of the spine, thin glue beads have been applied which for the nominal glue layer thickness of 100 μm would be 2 mm wide. This was obtained at a dispense speed of 25 mm/s. On the central part where the W31 and W32 detectors join, two of the thin glue beads were placed in order to have a gap in the glue distribution beneath the gap between the detectors. This scheme has been tested using an aluminium spine and two plexiglas plates, which were lowered on the spine, down to the nominal glue layer thickness. Nevertheless, on the first module glue was spilling out between the detectors and, filling the small gap between the detector surface and the transfer plate chuck, covered a large part of the guard rings next to the gap. The excess volume of glue which is necessary to cause this problem is very small compared to the amount of glue which has to be applied in order to insure a good bonding. A small deviation of the glue layer thickness from the nominal value is sufficient to cause this glue excess. In order to avoid this problem, the other two modules were equipped with a 2mm wide strip of Kapton tape, which was attached to the back side of the detectors and which covers the gap between the detectors. This works fine. As an additional precaution, the second and third module was assembled in two steps. First the detectors were glued onto the spine, and only after proper gluing and proper alignment was confirmed, the electronics hybrid, the fan-ins and the PEEK washers have been attached to the module.

VERIFICATION OF THE ALIGNMENT

The alignment was checked on an independent measuring microscope (Leica VMM 200). The modules were surveyed while they were still sitting in the turn plate. Therefore the glass fiducials in the turn plate could be used for referencing the front to the back side. Table 1 gives an overview of the measured alignment of the modules. The first module (FR_R_002) is slightly out of specifications in the back-side offset and the stereo angle. The other two modules show an improved alignment, although, taking the tight tolerances quoted in the table, they are still not completely in specs. The most critical parameter seems to be the Xfb, which is the front-to-back offset in the direction transverse to the strips. It is currently being discussed whether these tolerances could be relaxed without compromising the physics performance of the tracker.

	Front-side			Back-side			front-to-back		
	gap (μm)	offset (μm)	angle (10^{-5}rad)	gap (μm)	offset (μm)	Angle (10^{-5}rad)	Xfb (μm)	Yfb (μm)	stereo angle (mrad)
Nominal	700	0	0	700	0	0	-160	3	40.00
Tolerance	4	4	7	4	4	7	8	8	0.15
FR_R_002	702	1	0	702	8	-8	-139	-4	40.39
FR_R_003	700	2	0	698	-1	-6	-143	-31	40.14
FR_R_004	697	2	-6	701	1	-15	-171	-2	40.09

Table 1 Alignment of the three electrical modules. The variables are defined in the following figure.



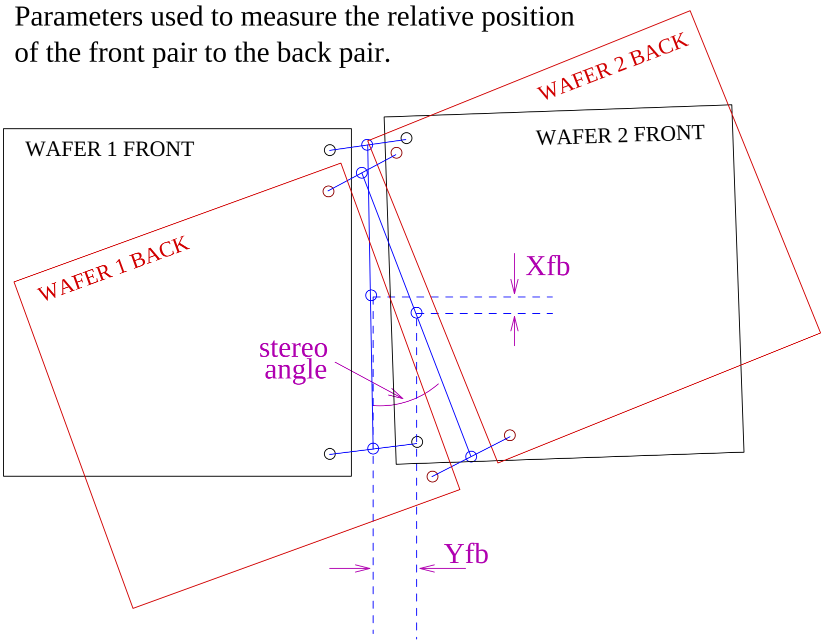


Figure 3: The upper plot shows how Gap, Offset and Angle are derived from the measured positions of two fiducials on each wafer. The lower plot shows how Xfb, Yfb and Stereo-angle are defined in a similar way, based on lines joining measured fiducial positions and the mid-points of these lines.

PLACEMENT OF HYBRID, FAN-INS AND PEEK WASHERS

After alignment and proper gluing had been verified, the fan-ins, PEEK washers and electronics hybrids have been attached to the detectors. These components were placed and positioned by hand, using a vacuum pen for the fan-ins, and tweezers for the washers and the hybrid. Standard Araldite 2011, which was manually applied with a syringe, was used for these glue connections.

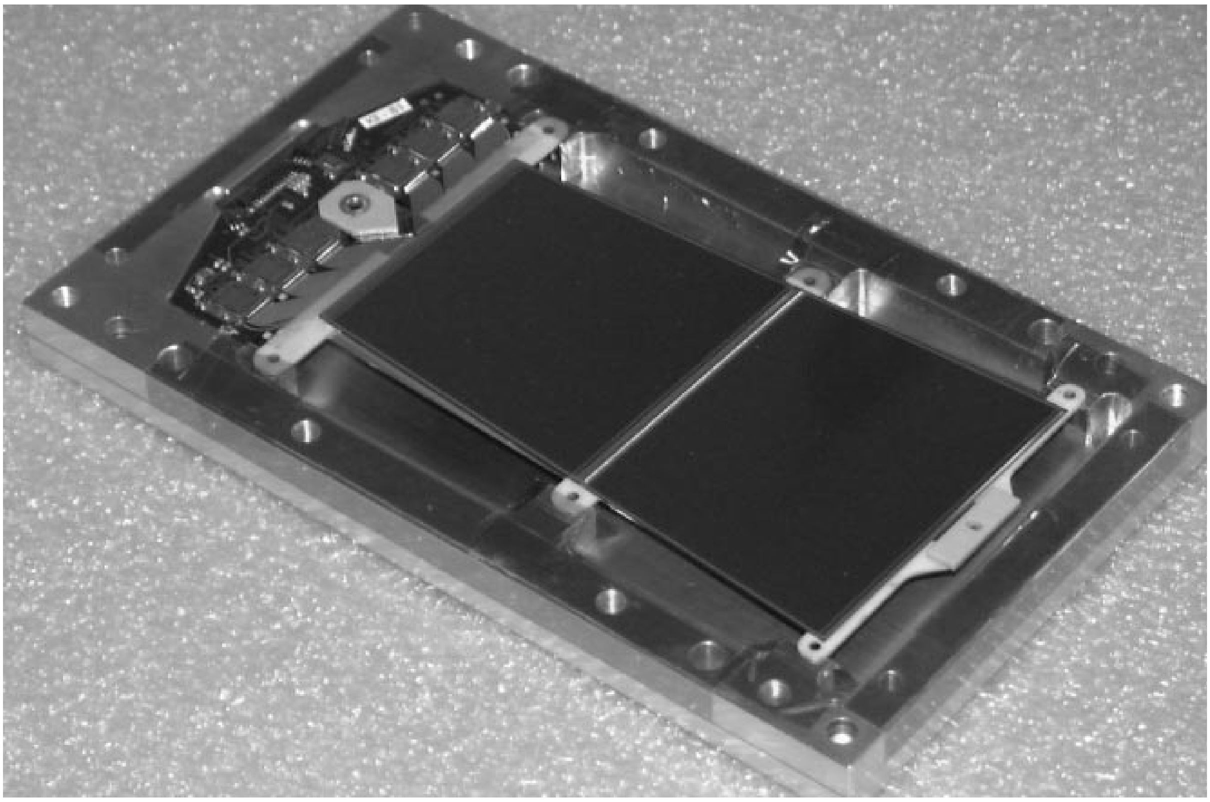
BIAS VOLTAGE SUPPLY

For these modules, the bias voltage is supplied to the detectors through wire bonds from the hybrid via the fan-in to the front side bias pads of the first wafer, and subsequently from the first to the second wafer. This biasing scheme deviates from the baseline design, which aims at a bias voltage supply through the TPG spine. As this scheme is not yet sufficiently tested on real modules and as there is no way to cut the connection between spine and detector backside once the module is made, it was decided that for this first set of real modules the front-side biasing would be used. The CiS detectors which were used for these modules have the P+ edge implant which allows for this way of bias supply, even after irradiation.

WIRE BONDING OF MODULES

All wire bond connections were done using the F&K Delvotec 6400 wedge bonder available at Freiburg and using 17.5 μm aluminium wire. During bonding the modules were held in an aluminium frame, which supports it at the outer edges of the hybrid and at the ceramic ends of the spine. No technical problems were found during the wire bonding of theses modules.

On the second and third module (FR_R_003 and FR_R_004) all read-out channels were connected to the full 12 cm strip length. For the first module (FR_R_002) this was not possible for all channels due to the glue on the detector front side. For most of the channels only the strips on the first wafer could be connected to the electronics.



The Module FR_R_004 (K81) after all assembly steps.

COMMENTS ON THE ASSEMBLY OF REAL MODULES

During this program, for the first time a (yet small) series of real forward modules has been assembled. Compared to the assembly of dummy modules, of which many have been made in many places, there are issues and problems which only show up when working with the real parts. The following – certainly not exhaustive – list gives some indications of the experience gained during this program.

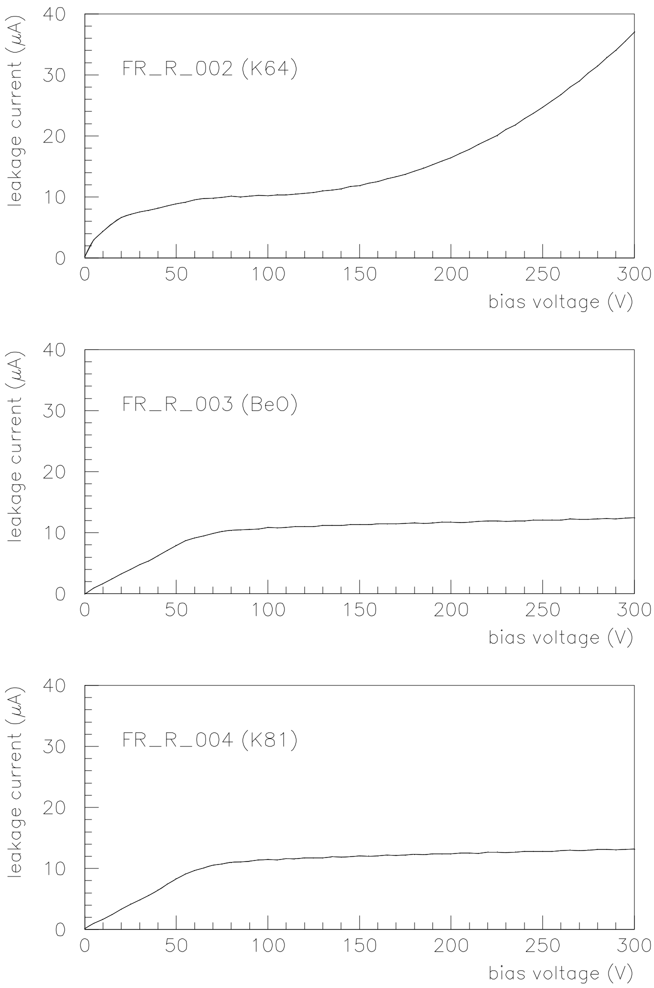
- handling of parts: although this seems to be a triviality, the additional care which is needed when handling real parts represents a significant effort:
  - parts have to stay in the clean room; if they have to be taken out (e.g. for testing) they have to be properly protected
  - operators have to wear face masks
  - all surfaces and tools need to be clean
  - parts may not be touched, except with a vacuum pen or tweezers
  - handling operations which seemed to be safe when exercising with dummies appeared to be unsafe for the real parts
- some operations become delicate on real modules because of the vicinity of fragile parts: e.g. the fan-ins have to be placed in between the detector edge and the read-out chips with a small clearance to both; in addition the glue must not spill out to any side.
- in particular the operation of taking the assembled module out of the turn-plate is extremely delicate as the module has no handles at which it could be safely picked up. For mass production special tooling will be needed
- fixing problems during assembly is much more difficult for real modules:
  - in general the compromise between potential benefits and risks of a certain operation looks different; repair work for which the risk seems acceptable for dummy modules is often unacceptable for real modules
  - due to the special handling requirements, some operations are just impossible for real parts

ELECTRICAL EVALUATION OF THE MODULES

MEASUREMENT OF THE LEAKAGE CURRENT

As a first electrical test after assembly, the modules have been biased. It was noticed that sometimes there was an electrical connection between detector back-side and the aluminium frame in which the modules was held. It turned out that this problem was caused by the fact that the cutting edges of the AlN parts of the spine were conductive. This happens if the AlN parts are not properly cleaned after cutting. In addition it must mean that there is an electrically conductive connection between the detector back-side and the spine, which for a perfect glue layer covering the full spine should not be the case (N.B. the glue used for the detectors is not conductive). After isolating the spine from the aluminum frame the problem was fixed and IV-curves were recorded. The figure below shows the IV-curves of these modules. Apparently, the first module shows soft breakdown starting at around 150 V. Although this issue needs further investigation, it is very likely that this is caused by the glue reaching over the guard structures on the front side of the detectors. The second and third module show a very stable behaviour and no sign of breakdown up to 300V, which was the highest voltage in this measurement.

Given the time pressure of the program, the read-out tests described in the following were focussed on the second and third module (one of each hybrid technology), and the first module was left aside for the moment.



The leakage current measured on the three modules after assembly (at room temperature).

READ-OUT TESTS

The readout system at Freiburg consists of the following setup:

- PC/NT - 200MHz Pentium, PCI/VXI - Interface
- DSP/SLL , BC96 - supply and driver, external linear power supplies
- SC97 - LVDS driver card, new ABC GAL's on SLL card
- self burned with code from Tom Fahlands webpage
- Software : ABCDAQ version 0.62 by Peter Phillips
- X1X level mode
- Edge detect off
- Any bin mode
- BinRal by Peter Phillips and then EXCEL and PAW
- KEK and RAL kumacs

For all read-out tests the modules have been operated with the following settings:

- bias voltage of 150 V
- strobe delay 0
- Vcc = 3.5V (on support card)
- Vdd = 4.15V (on support card)

The following measurements have been made:

- charge injection and threshold scans at several FE_Bias current settings from 128 to 285 uA
- noise occupancy scans to identify possible low-threshold-instabilities
- most of the scans were taken without trimming (loading trimDAC with 0)- the chip response is very uniform
- trimming was also tested, did not improved the gain/noise figures, only the response uniformity

A summary of the results is given in the following table:

module	FEB current (μA)	FES current (μA)	gain at 2 fC (mV/fC)	noise (electrons)	Oscillations	Vth at zero noise occupancy (mV)
FR_R_004 (K81) untrimmed	248	34.7	65	1400	weak, Vth<75mV	75
FR_R_004 (K81) untrimmed	285	27.6	50	1500	no	70
FR_R_004 (K81) trimmed	285	27.6	50	1400	no	150
BeO untrimmed	285	34.6	60	1400	yes, Vth<100mV	100

From these measurements, the following preliminary conclusions are drawn:

- uniform ABCD2T chip response (untrimmed response matching about 7%)
- Kapton module
    - stable at FEB 285 and gain 50 mV/fC, this means
        - no bumps, no maxima, etc. in noise occupancy curves
        - 50% noise occupancy values show Gaussian spread (Mean 46 mV, RMS=8.6 mV for untrimmed)
        - many curves start at the same threshold, but there is no steep rise to 100%, but rather many slow increases. This may be perhaps explained by a good channel-to-channel uniformity
    - below 75 mV at FEB 248 μA (gain 65 mV/fC) some instabilities observed
        - at these conditions 9 chips are perfectly stable
    - trimming works, no effect on gain/noise/stability, full range of trimDAC 160 mV (step=ca.10mV), too gross for fine trimming
- BeO module
    - gain and noise the same as kapton, stronger instabilities observed below 100 mV, at the same conditions any set of 6 chips works stably
    - additional bonds between AGND and DGND near each chip on the top side crucial for the level of instabilities (without these bonds instabilities occur at 250 mV)

OPEN QUESTIONS

- **Glue dispensing:** Although an automatic way of glue dispensing was used, we were unable to avoid that glue can spill out of the gap between the detectors. The problem is that the variations of the glue bead thickness within the tolerances of spine and detector thickness are more than sufficient to generate a surplus of glue flowing to the detector front side. It is unclear whether a fine tuning of the glue volume – possibly taking into account the thickness of the actual spine and detectors in each module – can be a viable and safe way to guarantee that the amount of glue is neither marginal nor too big. Given that in both cases the module is lost without a chance of rework we were looking for additional measures. For the second and third module in this assembly run we covered the gap between the detectors by a 2mm wide strip of Kapton tape, which guarantees success. Is this step affordable during production?

- **Biasing:** The baseline design is to bias the detectors through the spine. However, the detectors in the modules of this assembly run are biased through their front-side edge contact, as the aim of this program was the evaluation of the hybrid technologies and there was not enough confidence that biasing through the spine would not have negative effects on the performance of the module. On the other hand this front-side biasing is not possible for detectors from all vendors. Therefore it is high time to gain working experience with real modules biased through the spine. Resources should be made available soon to build at least two modules with this biasing scheme and check in detail that it works as expected.

- **Coating of spine:** It was noticed, in particular at higher bias voltages, that electrical connections between the detector back-side and the spine can occur, although the used glue is not conductive. It seems that just the glue layer is not sufficient to ensure electrical insulation of the detectors from the spine. A little piece of TPG on the surface of the spine, which is loose at one end and not covered by glue, is able to act as a (voltage dependent) switch. Although the spine will probably be at bias voltage anyway this unstable behaviour of the bare TPG should be taken serious and a coating of the spine should be considered. This would also avoid that TPG particles fall off the spine and cause damage in other parts of the module.

- **Placement of fan-ins:** Currently there is no satisfactory tool available for the placement of the fan-ins in this assembly scheme. In this assembly run the fan-ins were placed manually with a vacuum pen, which is certainly impossible during mass production. Better tooling is needed.

- **Fixation of turn plate on the assembly station:** For the assembly run described here, the scheme has been adopted in which the three feet of the turn plate (3mm diameter stainless steel balls) are sitting in V-shaped grooves. The grooves are oriented in such a way that they are all pointing to a spot in the centre of the turn plate. Continuously measuring the location of a fiducial in the turn plate and at the same time doing some operations on the plate (e.g. inserting the transfer plates) has shown that movements of the turn plate relative to the assembly station can be kept at the level of 1μm if the operations are done with great care. If operations are done with less care, movements of tens of microns were observed. Obviously this means that the success of the alignment depends very much on the skills of the operator. This problem can be dealt with by an additional measurement step in the assembly process which either proves that (in particular after insertion of the transfer plates) the alignment has not been distorted, or tells the operator to repeat the alignment procedure. This is time consuming and implies additional handling steps for the detectors. Improvements on this issue are under consideration.

- **Handling of real modules:** The only places where a module can be held are the AlN ends of the spine, the outer edges of the hybrid and the cooling block contact surface. Given that in any kind of mounting most of these areas will be blocked it is obviously very difficult to move a module from one mounting (e.g. turn plate) to the other (e.g. storage frame, bonding jig etc.). Probably the only safe way is to lift the module by means of a vacuum chuck attached to one of the detectors. Testing of this procedure is needed.