4.3.2. Sensor design and production.

The sensors have been designed internally and the process is subcontracted to a silicon sensor funder.

The design is done according to the following requirements:

- Pixels should fit the size of the XPAD chip pixels (130 µm x 130 µm)
- The sensor should receive 7 XPAD chips separated by about 400 µm
- The distance between two chips should an exact number of pixels => 4 pixels
- There should be no dead area between chips
  => border pixel size = 130µm x 325 µm
- To avoid leakage current the border of the sensor should include at least one guard ring and a safety distance from the scribe line equal to the thickness of the detector

The sensor drawing of shown on the figure 4.8 satisfy all of these requirements. This design is our standard and it will be used for the proposed detector.

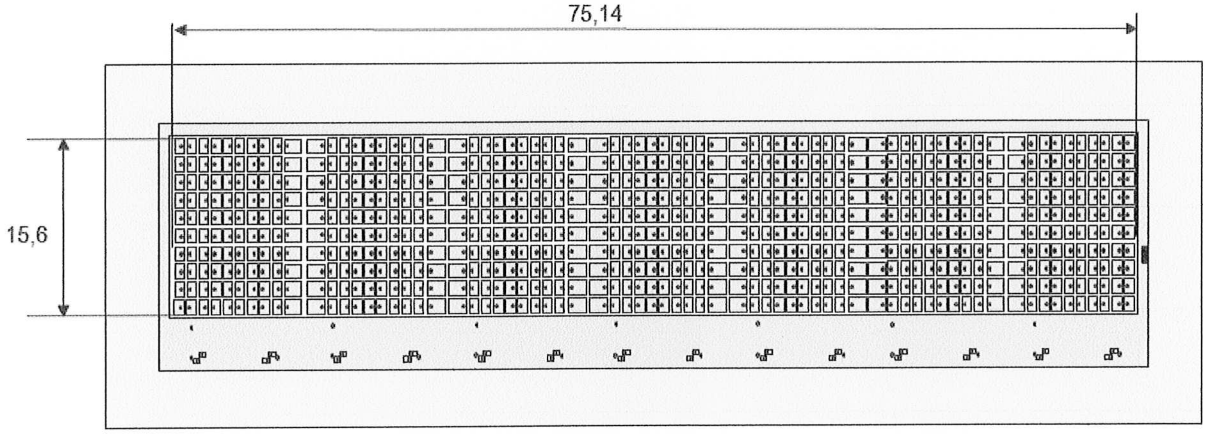

Figure 4.8. Silicon sensor wafer.

The sensors will be subcontracted to the CIS System GmbH, Erfurt, Germany) who is a company that we have a long business history with. This company has produced thousands of sensors for the high energy physics experiment and all the former sensors that we used at the CPPM and imXPAD). The company imXPAD has ordered and will receive a batch of wafers in November 2010. These would be used to start the construction of the U-SHAPED detector.

4.3.3. Detector array.

The detection plate is an array of 7 XPAD chips (see the figure 4.9) which are soldered with one connection by pixel on silicon sensor. The fabrication of this array needs several operations listed below:

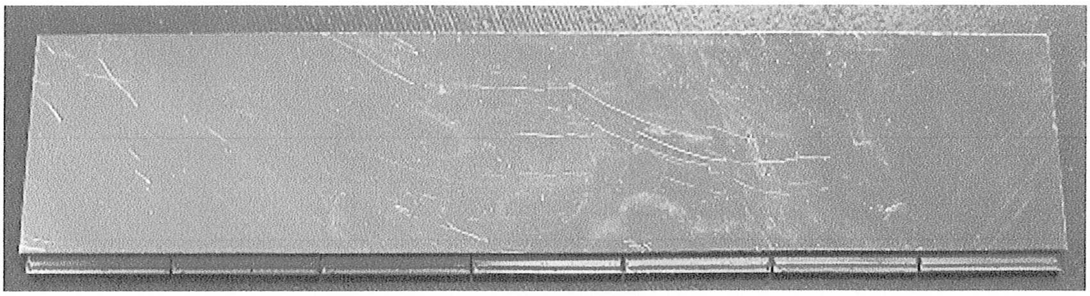

Figure 4.9. Silicon detector array.

XPAD wafer bumping.
On the delivery from IBM the wafers are sent to a subcontractor for bump-bonding . We can rely on several subcontractors for the bump-bonding but we use in priority IZM (Fraunhofer Institut Mikrointegration, Berlin, Germany). This company has had the best results for 2400 modules of the ATLAS experiment (CERN, Geneva) and for our detectors.
After proper metallisation, solder balls are deposited on each pixel contact. The bumping is done on the whole wafers.

XPAD wafer tests and chip selection.
After bumping the XPAD wafers are tested at imXPAD to select the good chips. This is done with a needle probe station rented at CPPM. A program has been written to make all the digital and analogue tests automatically. Test results are recorded for each chip and logged in a file.
The good chips are selected and noted on a table to be taken aside after dicing. The dicing is done at the bump-bonding manufacture.

Sensor wafer metallization and test.
On the delivery from CIS the sensor wafers are sent to IZM for metallization and dicing. Then the sensors are tested at CPPM. The leakage current is measured on the guard ring using a single needle.

Flip-Chip.
This is the final operation. It consists of the alignment of the sensor pixels to the XPAD pixels and to press and heat to reflow the solder bump. This is also done at the IZM company.

4.3.4. Flex design and production.

The role of the flex is to provide connecting pads for the micro-connections to the chip input/outputs and to route the signals and power supplies to/from the backplane. The flex will be designed to support two detector arrays. Actually this is done via a flat strip to ease the connectors manipulations and to have a small flex attached to the module. The design of the flex is simple and does not give any problem.

There are many manufacturers which can produce this flex. Good results are obtained with the "CICOREL" (Switzerland) company for our production and we will continue to order the flex to them.

4.3.5. Support bar design and production.

The bar support will be designed to receive the flex and two detector arrays. The choice of the material is a compromise between two constraints: an excellent heat conduction and the match of the heat extension factor with the silicon. The best candidates are the titan and the graphite. We prefer the graphite because of its smaller weight and lower price.
The support bars will be subcontracted at the company "Graphtech" (Aigueblanche, France) which is specialized on graphite work and has already produced such elements for the XPAD detectors.

4.3.6. Gluing of the flex and the detector arrays on the bar support.

The flex is positioned and glued in such a way that it goes a little under the XPAD chips. This is to secure the gluing of the flex by the stronger attachment of the chip. The positioning of the flex has to be done with an accuracy of about 50 µm.
The gluing of the detector array needs an accuracy as well as less than 20 µm in order to reduce the misalignment between the active areas of the modules. The two sub-modules are mounted on the aluminum support and then the two detector plates are aligned and glued with an exact number of pixels size between their detection area. This space is 0.2 mm between the detector plates and two sensor guard ring (figure 6.3), that is 1.3 mm (10 pixels)
This operation is done with a dedicated robot. The robot makes the deposition of the glue with a controlled volume and pressure (figure 4.10). It also takes the detector array, present it above the bar support, align it with respect to alignment balls situated on the bar support and then apply it with the right pressure on the bar support.

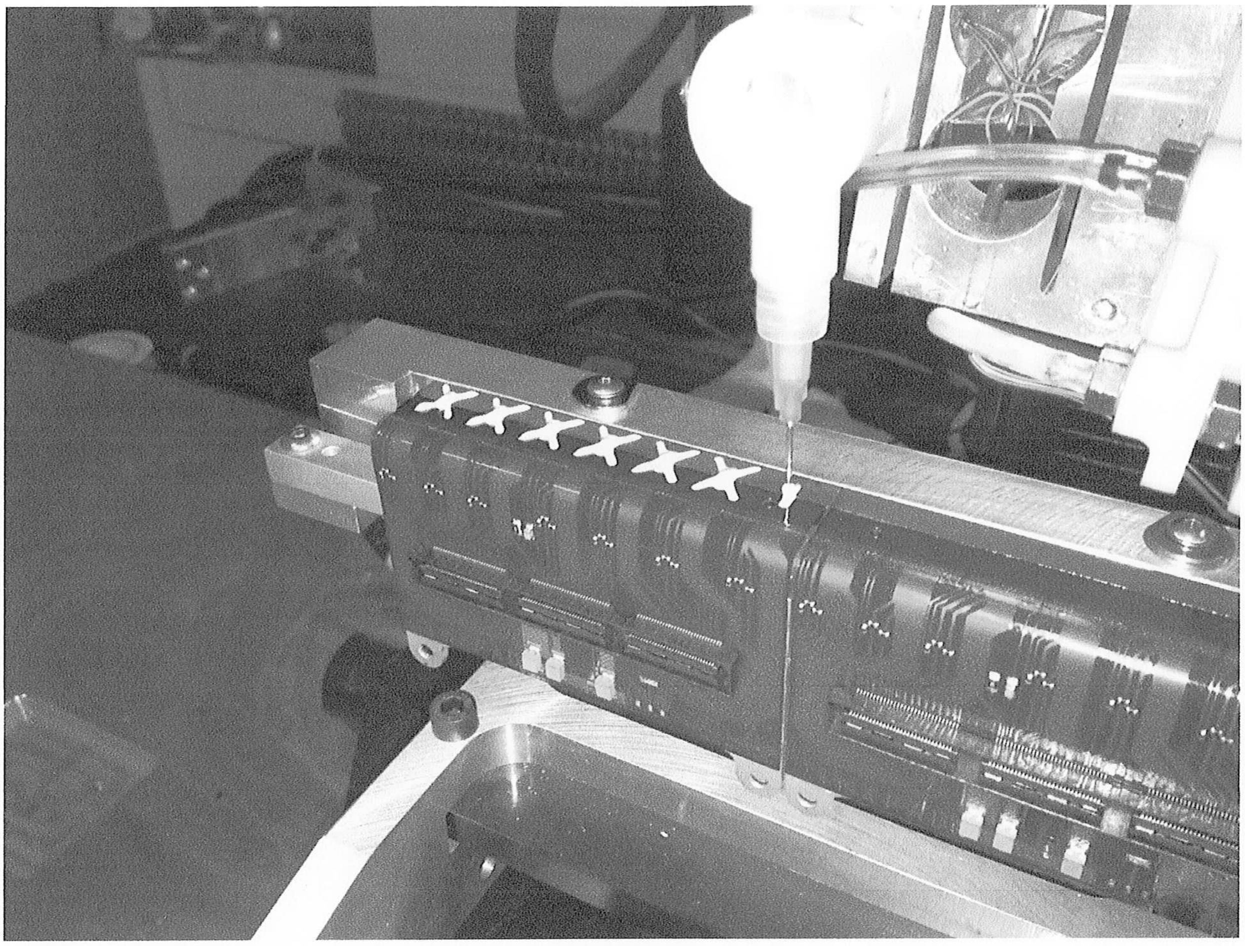

Figure 4.10. Glue deposition by the robot, controlling the volume as a function of the position.

4.3.7. Making the micro-connections.

After gluing we need to make the micro-connections between the XPAD I/O and the flex contact pads. This is done by wire bonding by a company specialized on this operation. For this we use to ask the "HCM" (Perigny, France) company which has already demonstrated their high quality for hundreds of modules.

4.4. Frame design and module mounting.

The material is chosen to be a good heat conductor and easy to machine with high accuracy. We use aluminum for the frame. The fabrication will be done at "Précision Lambescaine" (Lambesc, France).
The modules are mounted on the frame with an accuracy of 20 µm by the use of precise guides. The choice of this method allows for mounting/dismounting on site if necessary. We will obtain a detector assembly as shown on the figure 2.2.

The space between the detection area of two modules is an exact number of pixels: 2.5 mm between the two sensors and two sensor guard rings, that is 3.64 mm (28 pixels).

4.5. Link to the Data acquisition boards

Behind the detector support frame the modules are linked to the C4A DAQ boards by flexible cables as shown on the figure 4.11.

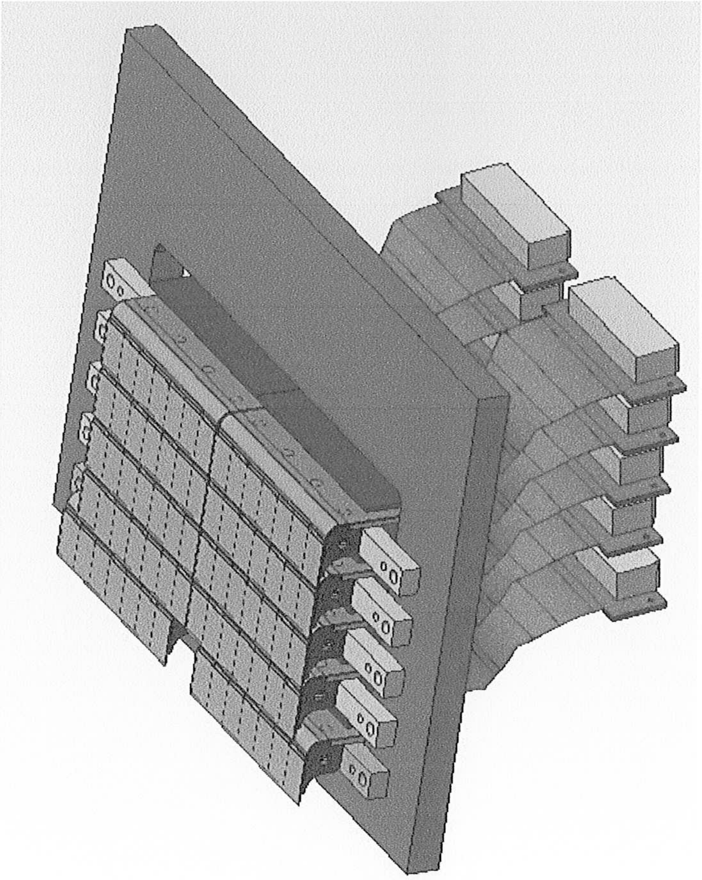

Figure 4.11. Detector part with the link to the DAQ C4A boards.

4.6. Environment box.

All the detector elements will be mounted in a metallic box. This includes:

- the detector assembly
- the DAQ hardware
- the power supplies (electronics LV and sensor HV)
- the air cooling system
-

The overall dimension of the box is shown on the figure 4.12. The weight will be about 10 kg.

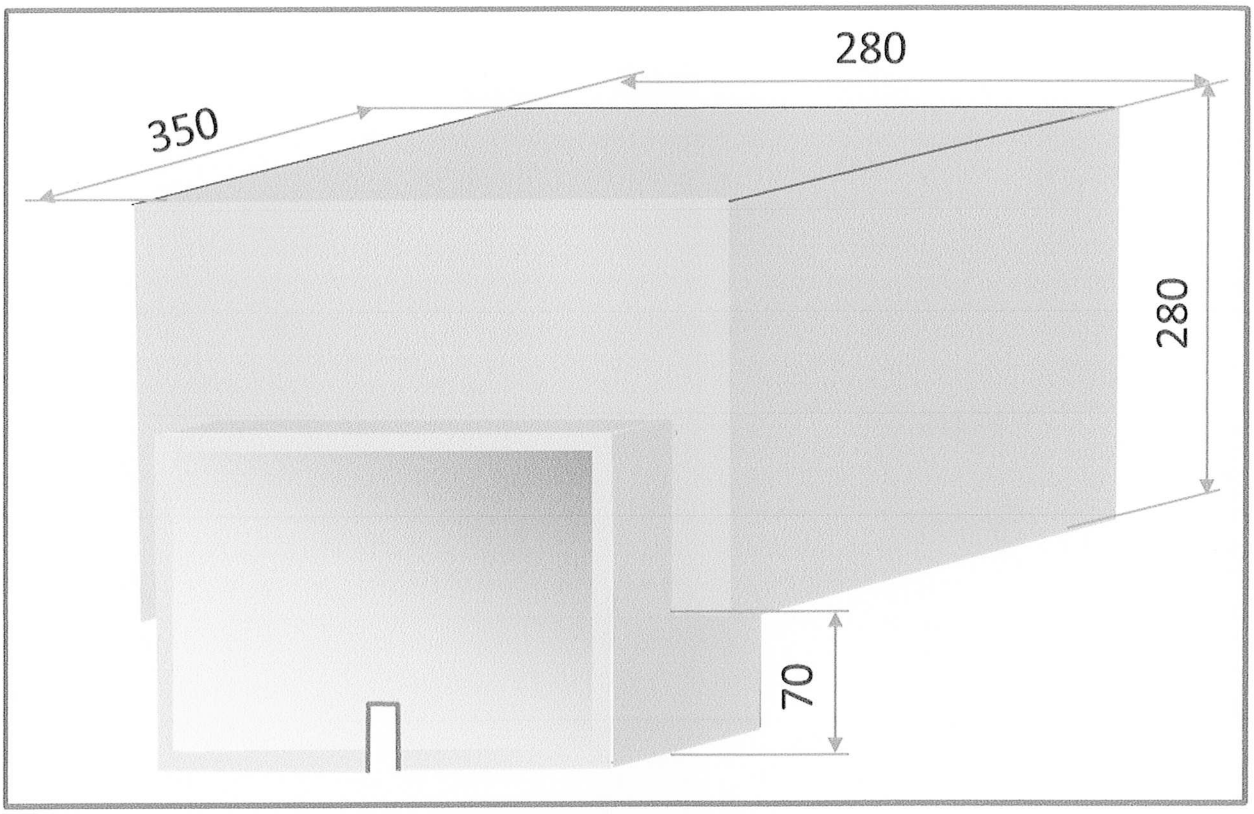

Figure 4.12. Overall dimensions of the detector.

4.7. Metrology and alignment

Here will be 4 reference marks on the front of the detector support frame (figure 4.1). The position of the modules and of the pixel matrix will be measured with a MITUTOYO BH706 3D measurement machine. A report of these measurements will be given to the D2AM team in order to include the data in the image correction program. A control grid will then allow the verification of these corrections.

The 4 reference marks on the front of the detector support frame will be visible for the alignment of the detector. On the demand, special holes for laser tracker mirrors can be provided instead of the reference marks.

5. DATA ACQUISITION SYSTEM (DAQ).

5.1. The DAQ block diagram

The DATA ACQUISITION system (DAQ) of the XPAD detectors has been designed to offer full parallelism. The DAQ for any big size detector is built by putting in parallel several basic blocks. The basic block corresponds to the 70 kpixel detector made of 7 XPAD chips. One CYCLONE IV FPGA based C4 board is used for each 70 kpixel module.
A grouping board is used to gather and dispatch the information from and to the modules.

- The communication between the control PC to and from the detector is done with an optical fiber connection.

- The firmware located in the FPGA takes care of executing the orders from the PC and storing the data from the detector in a local volatile DDR2 memory module (several 100 images)

- Images can be retrieved and stored in the PC under 16 bit or 32 bit format. These are RAW data.

- An external GATE signal is used to be able to control the timing of the photon counting precisely. A gate with a length as low as 100 ns can be used for instance when separating a bunch from the others in a time resolved experiment.

- The detector can work in several operational modes:

    - Loop mode versus single shot mode
    - Internal GATE versus external GATE
    - 16 bit or 32 bit images

C4 Board

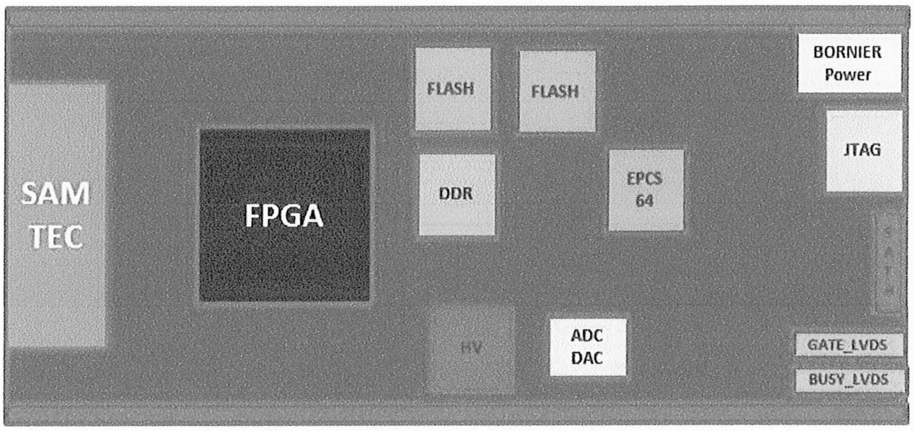

Figure 5.0. Block diagram of C4 board.

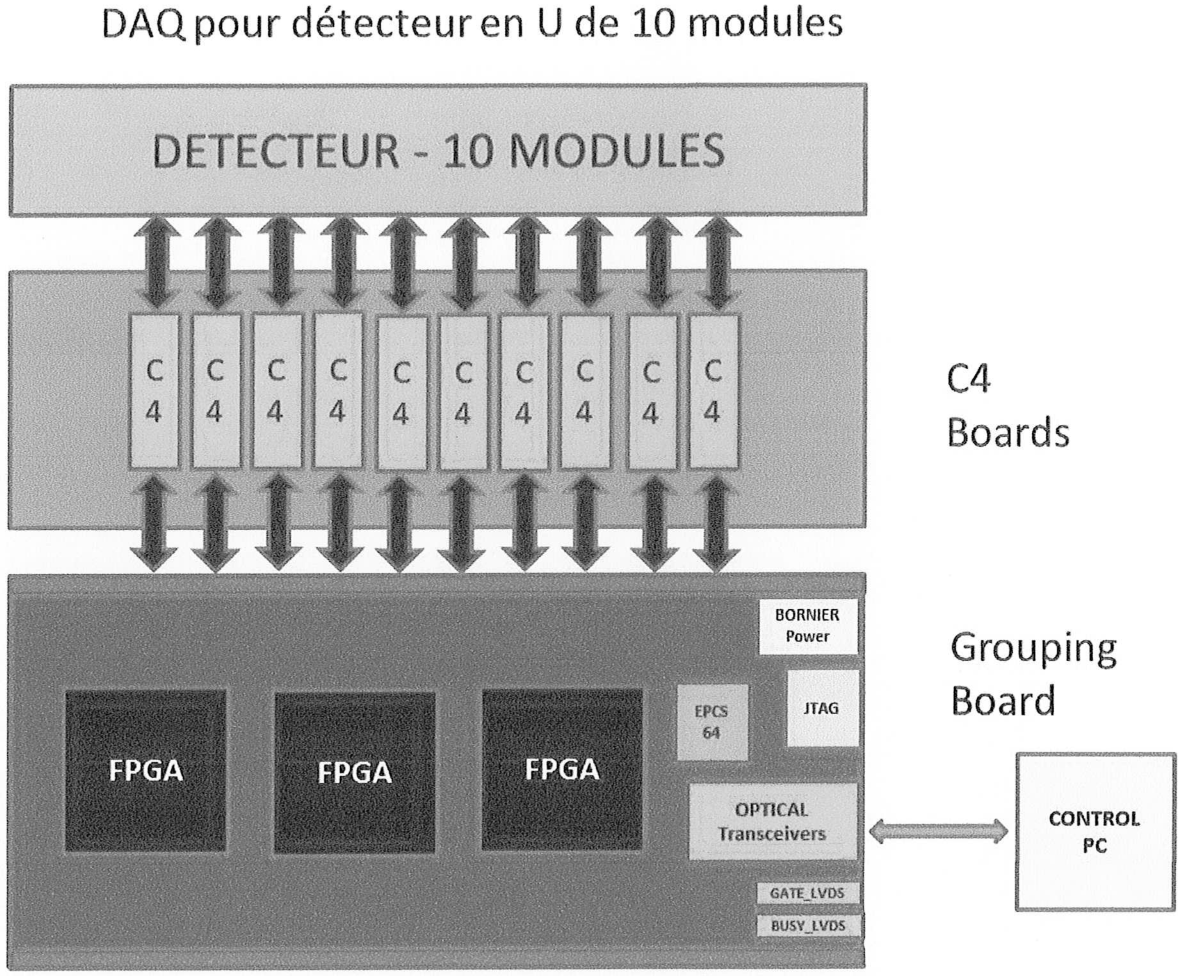

Figure 5.1. Block diagram of the data acquisition system.

5.2. FPGA processing.

The processor (FPGA) located on the CYCLONE Backplane board is a member of the ALTERA CYCLONE IV family. It is a powerful device on which we have developed and embedded a custom firmware. It has a NIOS processor with a C program that controls the on-going processes and a series of specially designed fast wired blocks that are used to exploit the detector at its full speed.

The FPGA can be reprogrammed according to new specifications allowing carrying out in the future experiments that are not even imagined today. This flexibility has already been used in several occasions to our customer's benefit.

The FPGA controls:

- Start-up
- Loading the calibration files
- Setting the operating mode

- Read and store images from the DDR2 memory
- Read and store configuration data

The read out of an image from the detector to the CYCLONE board takes less than 1ms, allowing a fast 1000 images per second frame rate.

5.3. SOFTWARE PACKAGE

Turnkey software is provided with the detector.

It offers the possibility to control and operate the detector through a user friendly and easy to use interface.

The software has been integrated in the TANGO system on the synchrotrons SOLEIL and ESRF .

The files are stored in raw data format. However, other formats can be provided.

6. DETAILS OF THE QUALITY ASSURANCE SCHEME.

6.1. The Quality Assurance at imXPAD

The Quality Assurance scheme used at imXPAD has been put together by a Quality Assurance committee composed of:

- Pierre DELPIERRE.

General Director at imXPAD, Pierre DELPIERRE has been the project leader for the Hybrid Pixel Detector project for the ATLAS experiment at CERN. This position within a R&D project involving 24 institues and a budget of 4 MSFr comprised the interaction with some high layers of CERN management. More generaly, as can be seen on his Curriculum Vitae provided in annex, Pierre DELPIERRE has taken key responsibilities in quite a number of high tech projects where the Quality Assurance was a premium concern. He is worldwidely recognized in the particule physics community for his achievements in the detector technology field.

- Bernard DINKESPILER

President of imXPAD, Bernard DINKESPILER has worked for more than 25 years in the area of electronic design for high energy physics and astroparticle experiments. Bernard DINKESPILER has a wide range of scope covering analog and digital electronics, optoelectronics and data acquisition systems. Very attracted by projects for which Quality Assurance is challenging, Bernard DINKESPILER was offered the responsibility of designing access-less critical systems for the ATLAS Larg calorimeter at CERN and for the ANTARES sub-marine neutrino detector. Bernard DINKESPILER' Curriculum Vitae is provided in annex.

The Quality Assurance plan at imXPAD aims at offering its customers the best products and associated services by putting into practice 4 main aspects:

- Management responsibility
- Management of resources
- Design and manufacturing control
- Process of permanent improvement

The Quality Assurance committee of imXPAD will have the permanent mission of improving the Quality Assurance plan.

6.2. Quality Assurance for the U-shaped detector

As far as the U-shaped detector is concerned, the Quality Assurance plan will be put to practice by the U-shaped detector manager along with an external consultant as auditor. He will ensure:

- An efficient project team:

  A team of professionals devoted to the project driven by a responsible management:
  The planned staff devoted to the project and the corresponding management is described in paragraph 9 as requested.

- A thorough design and manufacturing control via:

6.2.1. A complete understanding of all the aspects of detector

Manufacturing hybrid pixels detectors implies to master the complete line of technical specialties involved:

- Semiconductor sensors: design, purchase and test
- Microelectronics devices: design, purchase and test
- Bump Bonding subcontracting
- Wire bonding subcontracting
- Design and test of fast electronics acquisition systems

Since the U-shaped detector is composed of the same basic modules as the ones used in other detectors in service at ESRF and SOLEIL since several years, we don't expect any bad surprise in the fields listed above. Furthermore, imXPAD has an easy access to an extensive set of experts in the area mentioned above. These experts coming from CPPM, CERN and more generally the worldwide community of high energy physics can be consulted in case of a specific problem.

6.2.2. A complete access to manufacturing tools and equipment

A complete set of manufacturing tool and equipment is accessible to imXPAD for the manufacturing of their detectors either as internal resources or through the access to CPPM equipment thanks to a convention signed with imXPAD for this purpose.

- Clean room
- Probe test machine
- Detector Test Bench
- Measurement equipment

It has been checked forehand that CPPM will grant sufficient access to imXPAD for it's first production to take place. In fact this equipment is very precious and useful to CPPM but seldom used.

6.2.3. An efficient testing program

An efficient testing program is compulsory to deliver a high quality U-shaped detector to D2AM.

- Single chips are tested on wafer with a probe machine
- Leakage currents are measured on sensor wafers
- Bump-bonded modules are tested before assembly
- Metrology tests
- Subsystems are tested before integration
- Complete system test is performed before delivery including compliance test with the applicable norms.

⇨ **A detailed document for each test will be made available at the detailed design review.**

6.2.4. A set of Quality Control procedures concerning:

- The procurement, the verification and acceptance of all components and sub-contracted items and jobs
- The storage and handling of fragile items within the factory
- The shipping and handling policy of fragile and expensive items to the subcontractors

- The testing of all parts, sub-systems and complete detector. This concerns the factory tests, and the acceptance tests at the customer's site.
- The management of abnormal situations.
- The management of changes: design changes, change of provider, change of subcontractor
- The compliance to the norms in force (CE marking, etc…)
- The after sales procedures. How to handle the relationship after the detector's delivery, in the long term.

⇨ **A document for each Quality Control procedure listed above will be made available at the detailed design review.**

6.2.5. A thorough risk analysis:

The main identified risks are listed hereafter:

- Key-contractor failure
- Bad yield on a production
- Single source problem (components , subcontractors …)
- Risk linked to a change, willed or unwilled.
- Delay in the planning
- Shipping and handling problems
- Accidents
- Manpower issue (key person sick …)

⇨ **A document will be provided at the detailed design review with detailed analysis of the risks involved and the corresponding answers.**

6.3. Quality and delays guaranty for key components

Sensors and electronic chips are the two key-components of our detectors.
In general the quality and the delays of the deliveries are granted by a contract.
As far as the key-components are concerned for the U-shaped detector, we feel comfortable since we will have the parts available in advance at imXPAD when the contract is signed.

The sensors are produced with a very good yield and tested by the manufacturer before delivery and by us before acceptance and payment. Good wafers are expected by early November 2010 (Cf annex #12). An additional order would take 8 weeks.

A batch of 25 wafers of **XPAD chips** has been order. Taking into consideration the worst case of yield, we will have far enough chips to build 100 modules, which matches our requirements including the present U-SHAPED detector. An additional order would take 8 weeks.

The subcontractors chosen for the **metallization-bumping**, the **flip-chip** and the **wire-bonding** have been selected during the R&D year at CERN and are considered as the best ones world widely. Second sources are available though.

The **graphite support bars** require high accuracy machining and they are measured using our 3D MITSUMITO machine. Tough acceptance test is performed. Every precise mechanical item undergoes the same procedure.
Mechanical parts are also ordered in advance. They will be available when the contract is signed.

All printed circuit boards (PCB) are standard technology for production and cabling.

6.4. A proper documentation of the project

Several data bases will be created:

- **A design database** will contain all the schematics, drawings, firmware, software used to fabricate and use the detector
- **A test database** will contain all the data concerning the different tests performed in factory
- **A customer database** will be maintained by D2AM on site to record any problems that would occur after delivery
- **A management database** will be maintained at imXPAD to manage the problems encountered at imXPAD and the solutions adopted.

- **A version management database** will be maintained at imXPAD to control the various versions of hardware, firmware, and software.
- **A database** will also be keeping the minutes of all the meetings concerning the project, internal and external.

⇨ **A document will be provided with detailed description of all data bases at the detailed design review.**

7. TECHNICAL SCHEDULE AND DELIVERY ON SITE

7.1. Technical schedule

The table 7.1 shows the technical schedule. This schedule is pessimistic but well in accordance with the required timing.

U-Shaped detector technical schedule (aterix* are for miletones)		
Phases	**Tasks**	**End** (months)
Project definition		
	Agreement on the design and on the tests	T0 + 0,5
Detailed drawings		
	Detailed drawing	T0 + 1,5
	Agreement on drawings*	T0 + 2
Manufacturing and factory tests		
	XPAD3.2 and sensors	T0 + 4
	Bump-bonding and test*	T0 + 6
	Mechanics	T0 + 6
	S4A DAQ boards tested*	T0 + 8
	Detector complete	T0 + 10
	Firmware + software*	T0 + 10
	Factory tests	T0 + 12
Tests at D2AM	Mounting on site*	T0 + 12
Final acceptance	Tests on site	T0 + 15

Table 7.1. Technical schedule

7.2. Delivery and installation on site

The conditioning boxes will be already prepared around the end of the detector fabrication. The imXPAD responsible for the detector installation will visit D2AM well in advance to understand where and how to install the detector and how to process for the alignment. If necessary, adaptation pieces could then be fabricated.

The transport between Marseilles to D2AM will take only half a days, at the end of T0 +12 months. The delivery and installation will be taken care of by imXPAD entirely. Upon the D2AM team authorisation, imXPAD will bring the detector to D3AM by the safest transportation means. The detector will be protected against shocks under imXPAD entire responsibility. Concerning the installation of the detector, imXPAD will follow the set of directions given by D2AM.

Although the complete installation should not take more than a single day, imXPAD will stay at the D2AM team disposal to remain on the site as long as required to give full satisfaction.

8. LIST OF ITEMS THAT WILL BE SUBCONTRACTED

The technology, the providers and the subcontractors that imXPAD will use for the manufacturing of its detectors are the same as those selected by CERN for the ATLAS inner detector. Several square meters of hybrid pixel detectors have been built for the ATLAS tracker and are currently in use. The high level of reliability required for this detector located in a very inaccessible place led to assign this project the highest quality specifications requirements. Extensive reviews have been organized in order to qualify and select the best actors.

The same set of providers and subcontractors have been successfully chosen for the production of the first XPAD detectors currently in use at SOLEIL, NEEL and CPPM.

imXPAD has established fruitful business relationships with these companies.

The subcontracted items are the following:

Sensors	CIS System GmbH (Erfurt, Germany)
XPAD chips	IBM via CMP
Flexs	CICOREL (Switzerland)
Support bars	Graphtech" (Aigueblanche, France)
Bump Bonding	IZM (Fraunhofer Institut Mikrointegration, Berlin, Germany)
Wire Bonding	HCM (Perigny, France)
Module support frame	Précision Lambescaine (Lambesc, France)
PCB manufacturing	EXCEPTION (Calne, Wiltshire, UK)
PCB cabling	EASYTECH (Aix en Provence, France)

9. LIST OF PLANNED STAFF DEVOTED TO THE PROJECT

The company imXPAD will involve the necessary man power in this development. Special efforts will be done on the Quality Assurance to make sure that the detector will have the announced performances and be reliable for a long time.

9.1. Staff devoted to the project

Management:

Pierre DELPIERRE: Project manager and Quality contrôle responsible	50%

Fabrication:

Engineer 1 : subcontractor responsible	20%
Engineer 2 : DAQ hardware and software adaptation and test	50%
Technician 1: Electronic boards fabrication and tests	50%
Technician 2: Mechanical supports fabrication, mounting and measurements	50%
Students (ESIL, ISEN, Université de Provence...): electronic tests	

Engineer: On site installation responsible

Jean-Pierre GUIGNARD: Quality Assurance plan Consultant

CPPM assistance with experts:
Eric VIGEOLAS, Mechanical engineer
Jean-Claude CLEMENS, Sensor expert
Pierre Yves DUVAL, Software integration

Furthermore, imXPAD trains continuously technicians to follow the growth of the company and undertakes to involve them in the project in order to guaranty the schedule.

The Curriculum Vitae of the main persons involved in the project are available in Annex, Chapter 12.

9.2. Organization of the team involved in the project.

The team is organized in such a way that the work and the schedule are continuously under control. If a malfunction or any problem occur, each person knows to whom he should refer.

Laurent VASSE and Arkadiusz DAWIEC follow the work of the technicians under their respective responsibility, day by day, with the help of the CPPM experts. At the end of each week they have a meeting with Pierre DELPIERRE, where they expose the progress, the problems and the proposed solutions.

On each Monday a short follow-up meeting is organized with Bernard DINKESPILER, Pierre DELPIERRE, Laurent VASSE, Arkadiusz DAWIEC and Jean-Pierre GUIGNARD. These meetings are meant to follow the work quality and the schedule and make the necessary decisions about the material procurement, subcontractors or changes of involved persons.

10. LIST OF COMPARABLE PROJECTS AT OTHER 3RD GENERATION SYNCHROTRON FACILITIES.

The imXPAD company has already fabricated and sold photon counting detectors of different size, for example:

Univ. Nancy	S340
SOLEIL, Swing	S540 (under vacuum)
SOLEIL Diffabs	S140
ALBA (Spain)	S140
Xenocs (Grenoble)	S70
NEEL (Grenoble)	S70
SOLEIL, SIXS	S140
SOLEIL, Nanoscopium	S140
NEEL, D2AM	S70
Univ. Rennes	S70
Ecole Centrale, Paris	S140

Under fabrication at imXPAD:

ALBA (Spain)	S1400

11. LIST OF PROPOSED TEST AND INSPECTIONS EQUIPMENT THAT WILL BE USED

1. MITUTOYO BH706 :
    - 3D metrology machine
2. Probe station and its associated DAQ and software package (figure 11.1).
    - Test and selection of XPAD chips
    - Leakage current of sensors

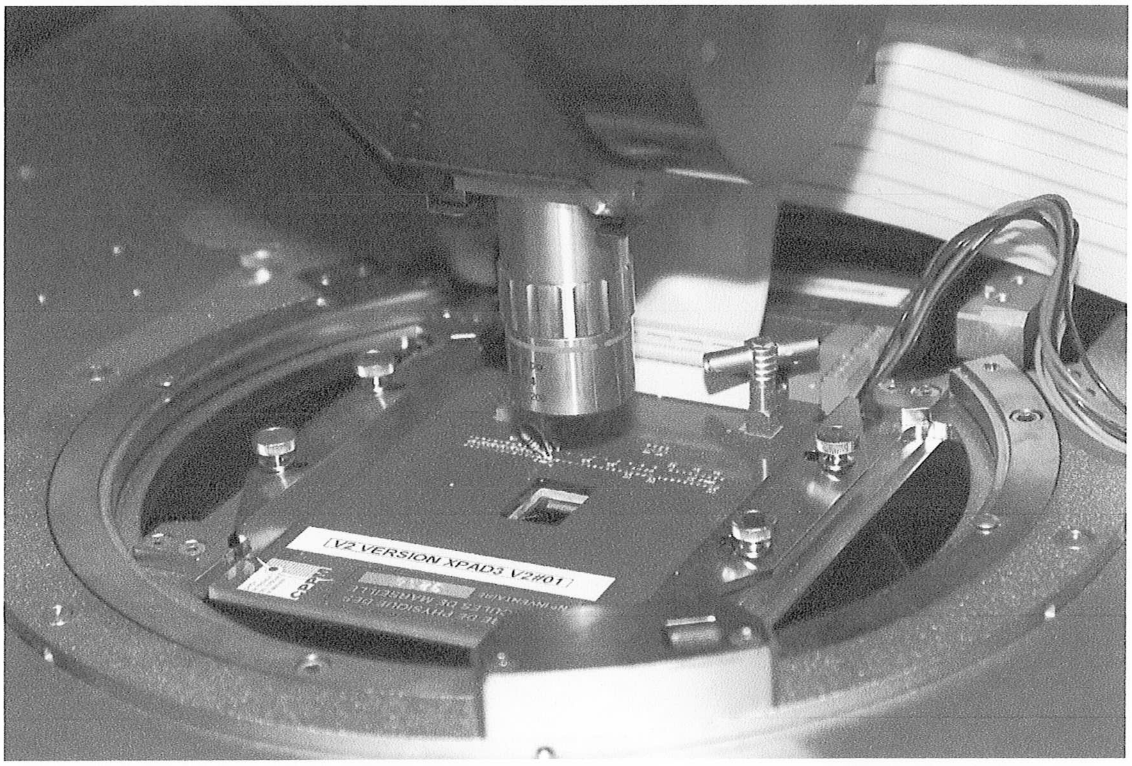

Figure 11.1. Probe station.

3. Wide field binocular (figure 11.2).
    - Bumps survey on XPAD wafers
    - Sensor contacts and edge survey

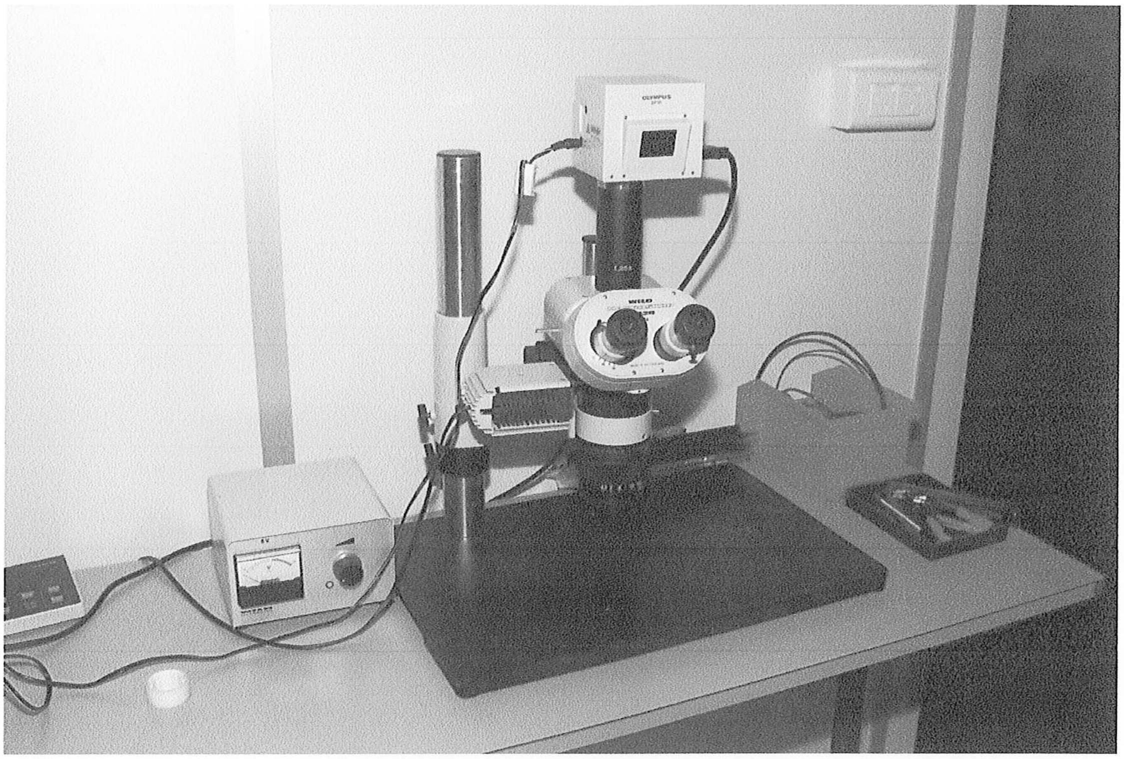

Figure 11.2. Wide field binocular installed in the clean room.

4. Pre-assembly test station:

   - Test of the modules and subsystem before assembly.
   - Calibration with internal test pulse

5. Radioactive source

Test and calibration of the detector with radioactive source will be performed by qualified people under the authority of the CPPM safety department.

6. Clean room that houses:

   - A robot for the flex and sensor gluing
   - The probe station
   - The binocular
   - Tables for module mounting
   - Clean cabinets for the detector elements storage

12. ANNEXES

Annex 1: Curriculum Vitae of the staff members.

Annex 1: Curriculum Vitae of the staff members.

- Mr Pierre DELPIERRE
- Mr Bernard DINKESPILER