The Pad HPD as Photodetector of the LHCb RICH Detectors

LHCb Note

Reference LHCb 2000-063 RICH

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The Pad HPD as Photodetector of the LHCb RICH Detectors

Mini-Proposal

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for the

Pad HPD team

21 October, 1999

Contents

Other sources of information:

The Pad HPD web page: http://lhcb.cern.ch/rich/html/pad-hpd/Pad_HPD.html

Large-area hybrid photodiodes with enclosed VLSI readout electronics
A. Braem et al, Proceedings of the Beaune conference, 1999
http://lhcb.cern.ch/documents/presentations/conferencetalks/postscript/1999presentations/beaunefilthaut.ps

An apparatus for the fabrication of large area hybrid photo-diodes
A. Bream et al., LHCb 98-007, RICH
http://lhcb.cern.ch/notes/postscript/98notes/98-007.ps

1. Overview of the baseline option

The design of the Pad HPD

Figure 1: Photograph of the Pad HPD.

The Pad HPD is a round photodetector of 127 mm (5 inch) diameter (see Figures 1 and 2) with a 114 mm diameter active area visible-light transmittive bialkali photo-cathode. Hexagonal close packing of the HPDs results in an active area coverage of 69%. The spherical entrance window of the HPD is made of an UV extended borosilicate glass (T = 50% at λ = 250 nm). The window and the tube body are joined by a Kovar skirt in order to adapt to the slightly different thermal expansion coefficients of the glass types. A set of 4 stainless steel ring electrodes defines a fountain shape electrostatic configuration, which de-magnifies the photocathode image by a factor $\approx$ 2.5 onto a silicon sensor of 50 mm diameter. The sensor comprises 2048 pads of size$1 \times 1\text{mm}^2$ and is read out by multiplexed analogue electronics enclosed in the vacuum envelope. The resulting readout granularity at the HPD entrance window perfectly matches the LHCb requirements. Both the sensor and the electronic chips are mounted on a ceramic carrier, which is wire bonded to the vacuum feedthroughs of the stainless steel base plate. The design of the Pad HPD is also strongly motivated by the chosen fabrication process, which consists of an external photocathode evaporation followed by an in-situ cold indium sealing of the base plate to the HPD envelope. The Pad HPD is fabricated in a dedicated UHV evaporation plant designed and built at CERN.

The complete design of the Pad HPD has been coherently optimized for use at the LHCb RICH detectors:

- The active diameter of the HPD is 90% of the total diameter. Hexagonal close packing including 0.9mm μ-metal shields provides a filling factor of 69%.
- The bialkali photocathode combined with a UV extended borosilicate entrance window represent a very good compromise between sensitive bandwidth and chromatic error.
- The granularity of the silicon sensor and the demagnification of the electron optics result in a pixel error which matches the other error contributions.
- The electron optics is characterized by an almost purely linear and adjustable demagnification. The practically constant E-field gradient along the tube axis distribution E-field combined with the fountain focussing scheme result in a comparably weak sensitivity to magnetic fields.
- The n^+ and Al contact layer of the Si sensor backside have been thinned to obtain a minimum energy loss.
- The analog readout scheme, guarantees a robust operation at optimum efficiency. Continuous online pedestal adaptation and subtraction is able to cope with possible common mode noise. Experience from many silicon tracking detectors demonstrates that this feature is essential for the fast readout of small signals. The availability of the charge amplitude helps in addition to resolve ambiguities in case of overlapping rings or ionization due to traversing charged particles.
- The tube design and the chosen fabrication technology allows to re-open sealed tubes and to re-use all components without degradation of performance.
- The fabrication inside the LHCb collaboration allows to exploit available resources and represents a very cost effective solution.

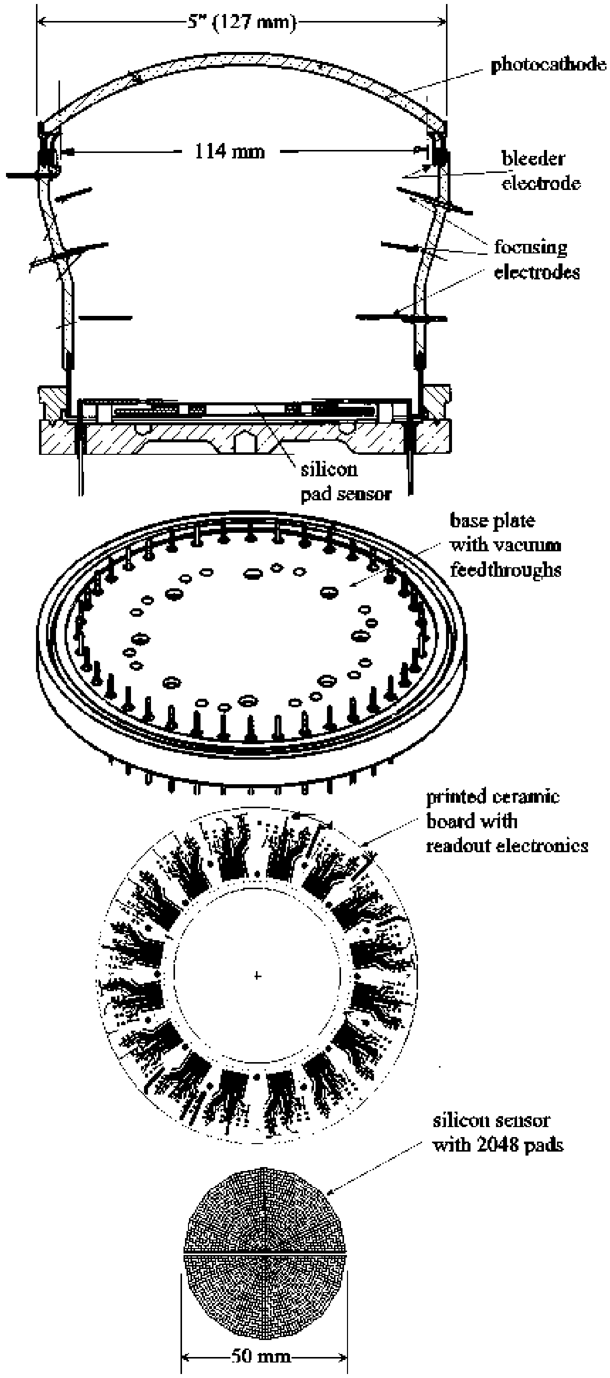


Figure 2: View of the Pad HPD components. From top to bottom: HPD assembled, baseplate, ceramic carrier, silicon sensor.

Summary of the Pad HPD characteristics

General:

total diameter	127 mm (5")
active diameter	114 mm
granularity at entrance window	2.3 x 2.3 mm^2
entrance window type	UV-extended borosilicate glass
entrance window transmission	T=50% at ca. 250 nm, T=0 at ca. 200 nm
photocathode	bialkali K_2CsSb, semitransparent
quantum efficiency	> 20% at 390 nm

Electrostatics:

electrodes	4 concentric ring electrodes
focusing	fountain type
demagnification	2.3, constant over full active diameter

Silicon sensor:

Si sensor diameter	50 mm active diameter
Si sensor thickness	300 µm (160 µm will be tested, which will result in a faster charge collection)
segmentation	2048 pads of 1 x 1 mm^2, no dead space
E-loss in dead layer (n+ + Al)	ca. 1 keV

Readout electronics:

Level-0 readout	Analog readout scheme. 16 SCTA128 chips, inside tube
SCTA128 features	comply with LHCb specifications (25 ns peaking time, 4µs L0 latency, 32 fold multiplexing)

Operation:

max. cathode voltage	-25 kV
signal	6600 e- (expected)
pedestal noise	650 e- (expected)
S/N ratio	10 (expected)
single el. det. efficiency	92.8%, 4 sigma cut (expected)

Mounting:

Tube arrangement	Hexagonal close packing
Total number of tubes	216
gap between tubes	3 mm (allowing for µ-metal shielding)
active area fraction	69%

Fabrication:

Silicon sensor	CSEM, Neuchatel, Switzerland
SCTA128LC	TEMIC Semiconductors
glass envelope	SVT, Viry Chatillon, France
baseplate	SVT, Viry Chatillon, France
Evaporation + encapsulation	LHCb/CERN or industry

2. *Main results from R&D (laboratory measurements + test beam results)*

The R&D programme of the Pad HPD is carried out in several partly overlapping phases. The **initial phase** was devoted to the development of the concept, the design and fabrication of all components (1996-1997). In the **2nd phase** (1997) the electron optical characteristics of the HPD have been verified and the operation of the silicon sensor and the Viking VA electronics in vacuum have been demonstrated. These tests were performed with a pumped HPD equipped with a UV sensitive CsI cathode. In the **3rd phase** (1997-1998) the evaporation plant for the fabrication of bialkali photocathodes and tube encapsulation has been designed, built, and commissioned. In the **4th phase** (1998-1999) the tube fabrication process has been developed and optimized. Several sealed tubes have been built using the Viking VA electronics. Two tubes have been tested in a test bean using a Cherenkov radiator set-up. The main goal of the **5th phase** (1999-2000) is to fabricate tubes with the final LHCb electronics.

Most of the results discussed below have been obtained in laboratory measurements. The quantum efficiency of a HPD is determined on an optical bench using a calibrated light source and a set of interference filters. Another light-tight set-up has been built which allows to precisely scan a collimated light spot coming from a hydrogen flash lamp across the HPD surface.

- **Fabrication process**
  The fabrication plant and the fabrication process of the Pad HPD (component preparation and cleaning techniques, vacuum generation, photocathode deposition, getter activation, sealing) have been developed and optimized. All individual techniques are now mastered with high repeatability. The production yield (ignoring the HV problem discussed below) is of the order 80% (see table 1). At the current stage a tube is considered as successful if it has reasonable Q.E., no leaks and fully operational electronics. The problems with leaking tubes (PC52 and PC58) could be correlated with a technology change by the tube manufacturer (RF heating rather than flame heating). The supplier improved its technique and is convinced that the problem is solved.
  It has been proven that <u>all</u> HPD components (except the cheap non-evaporable getter strip) can be re-used after opening a sealed HPD without loss of performance.

Table 1. Overview of photocathodes and sealed tubes fabricated during the last 7 months.

No.	Comment	Result
PC47	1st co-evaporation test	
PC48	2nd co-evaporation test	
PC49	1st sealed 5" tube with encapsulated readout electronics (256 channels)	Operational and tested in beam, however low Q.E.
PC50	Test evaporation	
PC51	Test evaporation	
PC52	2nd sealed tube, full electronics (2048 ch.)	Tube leaks
PC53	3rd sealed tube, full electronics	Operational but HV limitation
PC54	4th sealed tube, full electronics	Operational but HV limitation
PC55	5th sealed tube, full electronics (test evaporation)	Operational but HV limitation
PC56	6th sealed tube, full electronics, getter	Tube succesful, however electronics accidentally damaged during getter activation.
PC57		Tube not sealed because of mechanical problem
PC58	7th sealed tube, full electronics,	After baking tube leaks at Kovar skirt
PC59	8th sealed tube, full electronics (2048 ch.), getter	Operational but HV limitation, tested in beam
PC60	9th sealed tube, no electronics, getter (test evaporation)	Succesful, no HV limitation, QE curve not measured.
PC61	10th sealed tube, full electronics, getter	Operational but HV limitation
PC62	11th sealed tube, full electronics, getter	Operational but HV limitation
PC63	12th sealed tube, full electronics, getter	Operational (HV tested up to 20 kV), S/N(at 18 kV) = 16

- **Quantum efficiency and uniformity of the photocathode**
  Since spring 1999 a state-of-the-art co-evaporation technique is employed. The quantum efficiency of recently produced Pad HPD photocathodes reached peak values up to 23%. The uniformity of the cathode is better than ±10%. None of the last 10 photocathodes had a peak Q.E. below 14%. The laboratory Q.E. measurements were cross-checked with test beam data (PC59).In the measurments with a 180 cm long C_4F_{10} gas radiator 12.5% more photoelectrons (N_{pe} = 54) were found than expected (N_{pe} = 48).
  The photocathode statistics presented in Figure 4 lists all photocathodes fabricated during the last 7 months. Some of the cathodes were fabricated as test cathodes without full optimization. Futher experience and a number of small modifications of the set-up is expected to result in a further Q.E. increase and a reduction of the spread. No indication has been found for a degradation of sealed photocathodes.
  The Q.E. is measured online during photocathode processing. If during the series production a non-acceptable cathode (e.g. Q.E. < 18%) is produced, the processing would be stopped without sealing the tube. All HPD components could be used in one of the next evaporations.

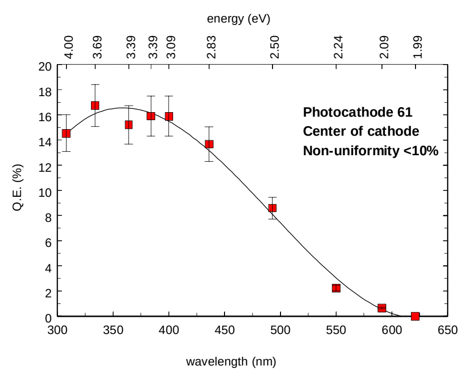


Figure 3: Quantum efficiency curve of a typical sealed Pad HPD.

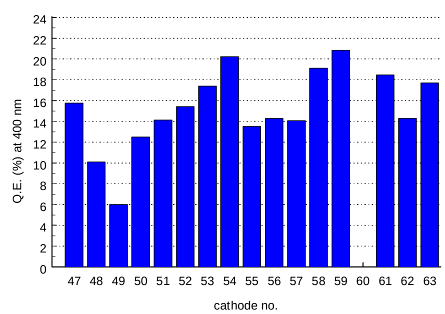


Figure 4: Quantum efficiency at 400 nm of all photocathodes fabricated by the co-evaporation process.

- **Electron optics of the Pad HPD**
  The Pad HPD electron optics is characterized by a tunable linear demagnification over the full active diameter of 114 mm. Fit residuals of a linear fit are of the order 200 µm.

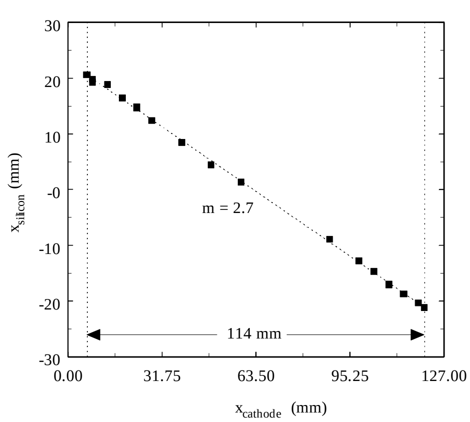


Figure 5: Mapping between radial coordinate of the photon on the photocathode and the silicon sensor. The demagnification is tunable over a large range by the voltage of the 2nd electrode.

- **Point spread function**
  The point spread function of the Pad HPD has been measured for various cathode voltages up to 24 kV. At voltages below 23 kV the point spread function is larger than the pixel error (288 μm). The extrapolation to 25 kV gives a point spread function of $230 \pm 30\mu m$ (measured on the silicon plane).

- **Influence of a grounded hexagonal mu-metal shield on electron optics**
  The Pad HPD has been operated inside a grounded hexagonal 0.9 mm thick mu-metal shield of 128 mm inner diameter and 110 (160) mm length. No influence on the electron optics has been observed. Hence no optical distortions are expected when close packing the Pad HPD.

- **Influence of magnetic field + shielding on electron optics**
  Up to now tests in an axial (E||B) homogenous B-field of up to 32 Gauss have been performed. In the unshielded case a rotation of the image by $\Phi = B(\Phi_o - r_B \cdot U_C)$ with $\Phi_o = 38.5$ mrad/Gauss and $r_B = 0.84$ mrad /(Gauss·kV) has been found. In addition a small radial dilatation of the image has been observed: $\Delta r/r \approx 0.3\text{-}0.4$ %/Gauss.
  A hexagonal mu-metal shield of 160 mm length and 0.9 mm thickness was mounted such that the shield extended 65 mm over the HPD entrance window. The shield reduces the rotation by a factor ≈12. The dilatation becomes negligible. Measurements with a shorter shield (110 mm) which extended only 15 mm over the entrance window gave a reduction factor of 2.5, however not uniform over the HPD surface. A short shield seems therefore to be inadequate, if there is not already an efficient global focal plane shielding reducing the B-field to levels well below 10 Gauss. Measurements with non-axial field orientation are under way.

- **Signal-to-noise ratio with Viking electronics**
  When operated with Viking electronics (VA3, $\sigma_{noise} = 285\ e^-$ ENC), a signal-to-noise ratio of 19 has been measured in a sealed tube (PC49) at 20 kV. The single photoelectron detection efficiency under these conditions is estimated to be 94%.

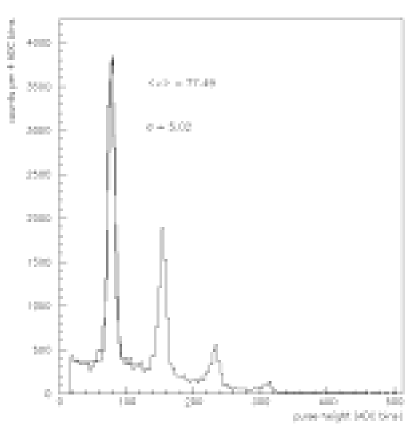


Figure 6: Pulse height spectrum measured with PC49 (bialkali PC) at 20 kV.

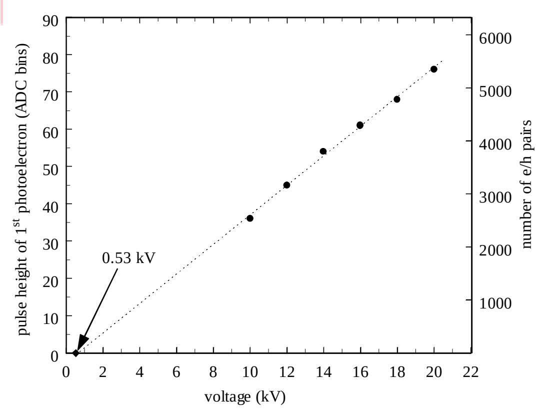


Figure 7: Variation of amplitude of 1st photoelectron peak with cathode voltage. The intersect with the x-axis indicates an energy loss of 0.53 keV in the dead layers of the silicon sensor.

- **Maximum High Voltage**
  The Pad HPD envelope has been operated with a CsI photocathode at cathode potentials up to 30 kV without observing discharges. In sealed tubes, equipped with a visible light sensitive bialkali

cathode, voltage limitations in the range 8-25 kV have been observed. The effect has been shown to be caused by deposition and chemical reaction of K and Cs vapor with impurities on the tube side wall leading at a later stage, when high voltage is applied, to atomic excitation associated with light emission. A clear correlation with imperfect envelope cleaning and preparation has been established. The cleaning procedure of the HPD envelope has recently been improved employing a sequence of acid baths. Our recent experience (PC60 and PC63) is that 'perfectly' cleaned envelopes may well reach the full design voltage, however without a comfortable safety margin. We plan to solve this problem by shielding the tube side wall during evaporation with a removable mask. A mask technique has been developed and will be tested and implemented during the next 3 weeks.

- **Beam tests**

  Two tubes (PC49 and PC59) have been used in test beams using a Cherenkov gas radiator set-up (1.8 m radiator length, spherical mirror with 1 m focal length). Cherenkov rings could be clearly detected, but due to deficiencies of both tubes (PC49: low Q.E., only 256 electronic channels mounted; PC59: HV limited to 9 kV) only a reduced set of tests could be performed: HV scans, verification of Q.E., Cherenkov radiator pressure scan, exposure of the HPD to direct beam. Figs. 8 and 9 show two examples of observed Cherenkov rings with tube PC59. We are currently preparing a set of fully equipped HPDs (3 or 4) which are planned to be used in the 'Aerogel testbeam' (Nov. 1999).

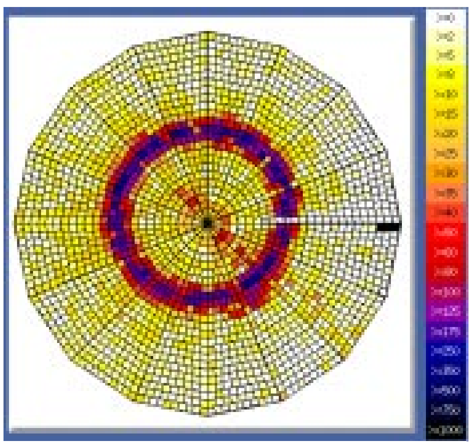


Figure 8: Accumulated Cherenkov rings observed with PC59 for a C_4F_{10}/air mixture.

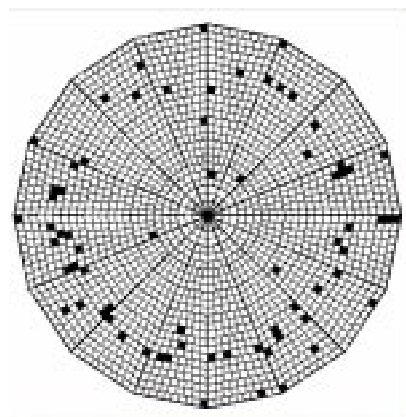


Figure 9: Cherenkov ring (single event) observed with PC59 for C_4F_{10} (1000 mbar).

- **Exposure to direct charged particle**

  Exposure of the HPD to direct beam (120 GeV π^-) has been studied with the beam traversing the HPD under 0^o and 25^o entering through the front window. In both cases the Cherenkov light produced in the entrance window was found concentrated on a round spot described by a sigma of 1.2 mm (measured on Si surface). The rest of the HPD surface remains unaffected. Charged particles and light can be easily distinguished by the charge deposition in the Si sensor. The test beam results confirm the simulations performed by M. John.

- **First tests of the SCTA128 chips**

  The currently available high capacity version of the SCTA128 chip has been demonstrated to operate in good agreement with the expected performance (peaking time, fast multiplexing, noise). Recently the chip has been successfully used in a beam test of the LHCb microvertex team).

  A new ceramic carrier for the Pad HPD and the corresponding readout card has been developed and fabricated in order to test the SCTA128 in the Pad HPD. All necessary components to start the tests discussed in chapter 3 are now available.

3. Future R&D programme

Besides further optimizations of the evaporation process, the R&D programme of the next 9 months will be focused on the fabrication of a sealed Pad HPD incorporating the final LHCb readout electronics.

Current status of the level-0 electronics

The SCTA128 chip, which is produced using the DMILL process, relies upon a fast bipolar shaper with 25ns peaking time and semi-gaussian shaping. This is followed by an analogue pipeline and some control logic to read out samples which are taken at 40MHz. While the chip was originally designed for the ATLAS SemiConductor Tracker, also the LHCb microvertex detector and the MAPMT proposal for the RICH propose to use this circuit.

In order to use this chip for the read-out of the Pad HPD, several modifications of the original design are required:

- Analog front-end (FE)
  For the readout of the comparably small signals produced by a single photoelectron (ca. 6500 e^-) the pedestal noise variations have to be as low as possible. The front-end of the SCTA128 is currently being modified such that it is practically identical with the front-end of the binary ABCD chip. The achieved performance of the ABCD front-end promises noise values around 650 e- (ENC) when the chip is connected to the Pad HPD Silicon sensor. It is expected that this new front-end will allow to use a single SCTA128 version both for the LHCb Silicon tracker and the Pad HPD. Since the design of the front-end is practically ready for submission the chip is expected to be available by beginning of 2000.

- Digital back-end (BE)
  1. The principal modifications required for LHCb are
  2. 4 x 32 fold multiplexing rater than 1 x 128 fold multiplexing
  3. Increase of the L0 pipeline length from 3.2 μs to 4 μs
  4. Reduction of the set-up time

  According to information from the Heidelberg group (M. Schmelling 7/10/99) the LHCb conform multiplexing has been already implemented in the design, however the pipeline extension remains to be done. Submission of the design is expected for February 2000. The sharing of the costs has to be defined by the LHCb management.

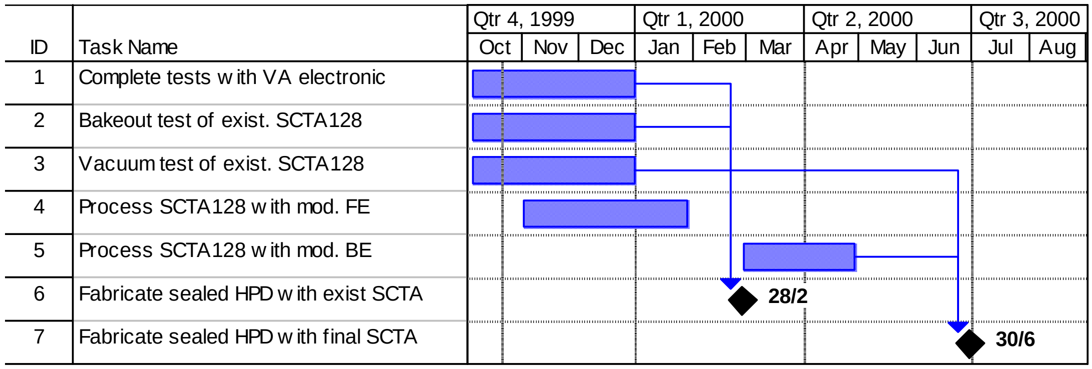
Future Pad HPD R&D tasks

- Test of existing SCT128A chips, connected to a standard Pad HPD silicon sensor with single photoelectrons under vacuum (CsI photocathode). Goal: Proof of vacuum operation and determination of operational characteristics (noise, gain).
  (October - December 1999)

- Test bakeout of SCT128A following typical bakeout cycle (72 hrs at 160°C). Goal: Proof of compatibility with Pad HPD standard bakeout cycle.
  (October - December 1999)

- Fabricate sealed HPD with existing SCTA128 chips
  (before March 2000)

- Fabricate sealed HPD with final SCTA128 (LHCb specifications) chips
  (before July 2000 if modified SCTA128 is available as foreseen).



List of future R&D tasks

4. Detector cost estimate

The baseline scenario for the detector cost estimate is to fabricate the Pad HPD at CERN. In annex 1 a detailed cost breakdown and fabrication schedule is given. We estimated the costs of 250 tubes (216 + 34 spares).

- The cost for producing 250 tubes is 2.3 MCHF.

The price includes all materiel costs (processing plants and HPD components) and labor costs of technicians, required for preparing the components and carrying out the HPD production.
Two physicists are required to supervise the component preparation/testing and the processing of the tubes. Two further physicists are required for the characterization of the electronics before tube fabrication and the final testing of the HPD. Their salaries are not included in the cost estimates.

We are also investigating the possibility of having the tubes produced by industry. As discussed in annex 1 the company Thomson Tubes Electroniques (Grenoble, France) has worked out an offer for the production of 250 tubes

- The cost for the production of 250 tubes by Thomson is 3.7 MCHF.

The price includes all component costs, the preparation and mounting of the Silicon sensor + electronics, and the tube fabrication by Thomson.

One physicist is required to supervise the component preparation/testing. Two further physicists are required for the characterization of the electronics before tube fabrication and the final testing of the HPD. Their salaries are not included in the cost estimates.

For the final characterization of the photodetectors and the electronics one or two largely automated test set-ups are required. As a preliminary estimate we adopt the figures proposed in the UK funding bid, although we expect the actual costs to be lower since part of the required components are already available.

- The price of one test station (photodetector + electronics) is 153 kCHF. (UK funding bid)

5. *Production schedule*

<u>Assumptions:</u>

The installation of the LHCb experiment starts in autumn 2003. All 250 photodetectors have to be available by mid of 2004. The fabrication of all tubes at CERN is assumed as baseline.

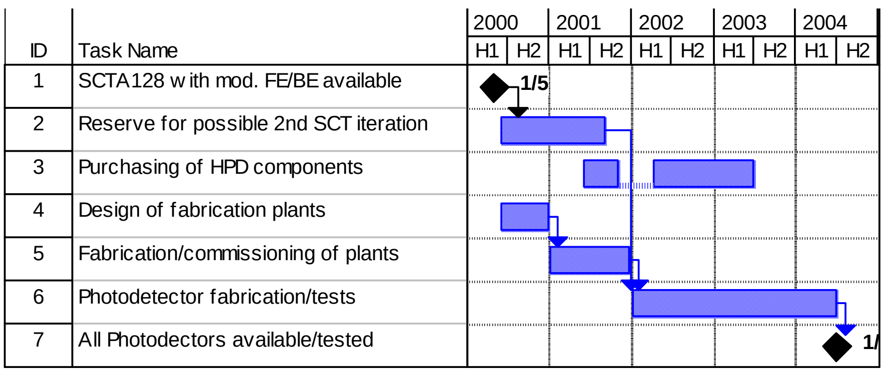
As discussed in annex A1., the required 250 Pad HPD detectors can be fabricated within 24 months, independent whether production at CERN or by industry is chosen. The HPD production has therefore to start no later than summer 2001.

<u>Electronics:</u>

The encapsulation of the level-0 electronics inside the HPD requires the final electronics to be available by summer 2001.The SCTA128 chip requires one iteration of modifications to fulfill all LHCb requirements. The submission of the modified design to the foundry is scheduled for February 2000.

Normal processing time is 10 weeks.

In case of unexpected problems with the modified version, there is about 12 months reserve for a second iteration. The reserve could be extended by compensating it afterwards with a higher tube production rate. This would however lead to increased production costs.



Production schedule for the Pad HPD. The chart has been made for the production at CERN. In case of an industrial production, the tasks 4 and 5 are replaced by an industrial pre-series phase of similar duration.

Annex A1.

Detailed production and costing document

C. Joram, 14 April 1999
Last update: 21 October 1999

Production, testing and commissioning of the Pad HPD for the LHCb RICH 1 and RICH 2

I. Number of required detectors

Assumptions:

- overall detector diameter = 127 mm,
- sensitive detector diameter = 114 mm
- hexagonally closed packing
- distance centre–centre = 130 mm, 3 mm left for HV insulation and possible magnetic shielding.

The resulting active area fraction is 0.69
Number of required detectors: 216 + 34 spares = 250

II. Pad HPD hardware costs

	Unit price
• 250 envelopes with borosilicate window	913 Euros
• 250 base plates	273 Euros
• 250 Silicon sensors, "full moon"	400 CHF*)
• 250 ceramic PCBs	500 CHF**)
• 250 SCT128A chip sets (16 chips)	1940 CHF***)
• total	4750 CHF

1 Euro = 1.61 CHF (May 1999)

*) Price based on pessimistic yield. Could be 30% less if a good yield is achieved. Could be in addition 30% less if half moons are used.

**) This price includes: the ceramic PCB (ca. 400 CHF), Laser drilling at CERN(62 CHF), mounting components other than the SCT chips (20 CHF) and ceramic testing is about 27 CHF/piece.

***) Price based on pessimistic yield and order volume estimates. Could be more than a factor 1.5 less. The price of the SCT128A chips depends on the total CERN order volume at TEMIC in the year of the order.

III. Pad HPD production

The installation of the LHCb experiment is foreseen to start in autumn 2003. All photodetectors are expected to be available and tested by mid 2004. The photodetectors should therefore be produced in 2002 and 2003. The years 2000 and 2001 are used to optimize the HPD design and to prepare the production facilities.

We see 3 possible production scenarios, which will be discussed in more detail below:

A. Production of all detectors at CERN
B. Production of detectors shared between CERN and another partner (laboratory or industry)

C. Production by industry

We discuss first scenario A.

Scenario A. Production of detectors at CERN

The HPD production consists of the following sequence of steps:

1. Cleaning of all components
2. Galvanic deposition of Nickel (baseplate groove)
3. Pre-fusion of Indium in Vacuum (baseplate groove)
4. Wire bond Silicon sensor + readout chips to ceramics PCB
5. Test of Silicon sensor + readout chips
6. Wire bond ceramics to baseplate
7. Test baseplate
8. Mount getter strip
9. Galvanic deposition of Nickel (envelope knife edge)
10. Evaporation of gold film (envelope knife edge)
11. Evaporation of Al pads (envelope window)
12. Photocathode evaporation, getter activation + sealing
13. Test HPD with pulsed light source (quantum efficiency, mapping of the electron optics, dark current, stability, magnetic field effects)

In case of an industrial production of the HPD, the steps 4 to 7 and 13 would probably still have to be performed at CERN or a similarly equipped laboratory.

III.1 Component preparation and testing

The preparatory steps are carried out in the laboratories of the TA1/TFG section (Andre Braem) and by the surface treatment service EST/SM (Alain Lasserre).

The galvanic treatment of the baseplate (step 2.) and the envelope (step 9.) of the prototype HPDs can be done at CERN by EST/SM. We assume the cost for an envelope and baseplate which we have paid up to now: 300 CHF per HPD.

The cleaning of all components (step 1.), and the required evaporations and Indium-premelting (steps 3., 10. and 11.) can be done in the TA1/TFG labs. Andre Braem estimates an initial investment of 10 kCHF to be required for upgrading the existing facilities, in order to allow in-parallel processing of several components.
In addition 10 kCHF have to be spent on consumables like Indium and Gold.

The TA1/TFG labs can also be used to recuperate HPD components, which have undergone evaporation and possibly also encapsulation. In this case 5 kCHF will have to be spent for special cleaning chemicals.

The work in the TA1/TFG labs can be carried out to a large extent by the technician team discussed in section III.2. For additional assistance by the TA1/TFG personnel a total flat rate of 10 kCHF is estimated.

Based on the available experience, for the steps 4 to 7 a total working time of 8 hours are required (ca. 600 CHF)

Preliminary estimate of steps 1 – 8: 1000 CHF / HPD (+ costs included in section III.2).

III.2. Photocathode evaporation and tube encapsulation

Assumptions:
- 40 production weeks per year
- Failure rate 20%

The production of 250 operational HPDs requires to fabricate 3 to 4 HPDs per week. This can be achieved with 2 evaporation plants. Compared to the currently available system, the processing time can be reduced by

- reducing the volume and surface of the pumped set-up
- shorter bake-out cycle with faster ramps (becoming possible for a smaller system)
- optimising the system in view of pumping conductance
- optimising the evaporation sources for fast exchange and cleaning

As indicated in the table below, the two plants are run by two operators in parallel (E = Evaporation, S = Sealing, L = Loading, B = Bake-out, P = Preparation). The bake-out cycles during the weekend and from Tuesday afternoon to Thursday morning are performed under computer control and do not require any intervention. This leaves 2 working days per week for the preparation of the envelopes, base plates and the cleaning of the replacement sources.

HPD production schedule with 2 parallel plants

day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Plant 1	E S	L B	B B	B E	S L	B B	B B
Plant 2	E S	L B	B B	B E	S L	B B	B B
Other		P	P P	P			

Cost estimate:
The total cost for the processing and sealing 250 HPDs is estimated to be 840 kCHF (as listed below). This corresponds to 3360 CHF/tube.

- 2 optimised evaporation plants, assuming that material (electrical + mechanical feedthroughs, viewports, pumping system, etc.) of the existing set-up can be re-used. 300 kCHF
- 2 technicians for 2.5 years 500 kCHF
- consumables (joints, evaporation sources) 20 kCHF
- maintenance + repairs (pumps, controllers) 20 kCHF

- total 840 kCHF

Scenario B. Production of detectors shared between CERN and other laboratories

The HPD production as discussed in scenario A. can be partly or completely transferred to or shared with another laboratory or an industrial partner. Depending on the available infrastructure the complete production sequence (steps 1 - 13) or only the photocathode deposition and tube encapsulation (step 12) are shared with the outside partner, the remaining steps are carried out at CERN.
Shared production at an outside laboratory is an attractive option if the laboratory has available workshop (plant construction) and manpower resources, so that the production costs could be significantly reduced compared to scenario I.
On the other hand the production is more efficient if carried out at a single place, since the know-how and experience is concentrated. Also the required packaging and shipment of equipment, followed by tests after reception, consumes sizeable resources.

Scenario C. Production by industry

We are currently discussing the possibility of an industrial HPD production with three phototube manufacturers.

- Thomson Tubes Electroniques (TTE), Grenoble, France. After two detailed discussions of the project, one in Grenoble and one at CERN, TTE has worked out a quotation for the production of 250 tubes. This quotation (dated 23 August 1999) comprises component preparation (except of sensor + electronics mounting), photocathode evaporation and sealing of the HPD. All components are provided by the LHCb experiment. The baseplate is assumed to be delivered with the sensor and electronics mounted. Thomson proposes to start with a pre-series phase of 12 months duration in order to adapt their production techniques and processing set-ups. After this phase the required

250 HPD detectors can be produced within 24 months after receipt of the order for the series production.

- PHOTEK, St Leonards-on-Sea, England. PHOTEK met us at CERN (4 June 1999) for a first discussion. They expressed their strong interest in the project. Many questions have been discussed by e-mail exchange, however a second meeting at PHOTEK is believed to be necessary before they can prepare a reliable quotation (panned for October 1999)

- Matsusada Precision Inc, Japan, is setting up a plant for the production of 10" HPDs and has expressed interest in the production of 5" HPDs, as well.

IV Pad HPD testing

Each HPD has to be tested after production (or delivery) to determine the following characteristics:

- Quantum efficiency as a function of wavelength
- Uniformity of sensitivity
- High voltage capability
- Electron optics (demagnification, mapping out distortions)
- Noise (Pedestals of electronics, dark current)

For these tests one or several automated test benches have to be built. A bench consists of a light tight chamber, which is flushed with dry Nitrogen. The quantum efficiency is determined by measuring the photocurrent between the photocathode and the focusing electrodes at a given pre-calibrated illumination. The wavelength is scanned by a monochromator. The uniformity of the sensitivity, as well as the electron optical characteristics are measured by observing the image produced by a pattern of optical fibres. For these tests the HPD is read-out via the Silicon sensor and its own electronics. Under these conditions also the maximum high voltage and the noise of the HPD are determined.

Rough price estimate: ca. 40 kCHF for one unit (including monochromator, PC controlled).

The tests have to be repeated after some months to filter out tubes, which show signs of deterioration.

Cost summary: scenario A, before final testing

	price/HPD	price/channel	price for 250 units
HPD hardware	4'750.00	2.319335938	1'187'500.00
Preparation + testing	1'000.00	0.48828125	250'000.00
Evaporation + sealing	3'360.00	1.640625	840'000.00
HPD complete	9'110.00	4.448242188	2'277'500.00

Cost summary: scenario C, before final testing, Thomson Tubes Electroniques)

The TET quotation comprises the processing (photocathode evaporation) and sealing of 250 HPDs. TET quotes per-tube-costs between 4500 and 5000 Euros (for the table 4500 Euros have been used).

All hardware components are made available by LHCb. The baseplate is assumed to be equipped with the sensor and the electronics at CERN (or another LHCb laboratory). TET proposes the production of a pre-series (in the range of 5-20 tubes, depending on the achieved yield). The cost of this test phase (263.000 Euros, ca. 423.000 CHF) is included in the price of the 250 HPDs. The cost of the hardware components and the cost of the baseplate preparation and testing are assumed to be identical to scenario A.

	price/HPD	price/channel	price for 250 units
HPD hardware	4'750.00	2.319335938	1'187'500.00
Preparation + testing	1'000.00	0.48828125	250'000.00
Evaporation + sealing	8'894.00	4.342773438	2'223'500.00
HPD complete	14'644.00	7.150390625	3'661'000.00

Annex A1.

Replies to the detector performance questions (R. Forty)

The Pad HPD baseline detector

- 127 mm overall diameter
- 114 mm active diameter
- bialkali photocathode with >20% peak efficiency
- SCTA analog chips, modified to match the LHCb requirements (32 way multiplexing, 4 µs Level-0 latency, etc.).

1. Pixel size at entrance window

The pixel size is defined by the size of the Si pads (1 x 1 mm^2) and the demagnification factor. The latter can be tuned in a rather wide range (>=2 .. <4) by varying the voltage of the second electrode. A pixel size of 2.3 x 2.3 mm^2 is feasible without problems.

Other contributions to the effective pixel size:
Point spread function. Unfortunately our measurements (performed with PC49) are not yet fully conclusive. An upper limit for the point spread function measured on the silicon plane is 400 µm (sigma) at 20 kV. We envisage to operate the detector at U > 20 kV, so that the point spread function may fall well below the pixel error (288 µm sigma).

Optical distortions:
Measurements with the CsI HPD and PC49 demonstrate that a linear imaging can be achieved over the full active diameter. Typical fit residuals are smaller than the pixel error.

Variations in the silicon pad shape:
The nominal pad dimensions are 1 x 1 mm. However the pads at the edges of the 16 sectors deviate from the square shape (see... http://lhcb.cern.ch/rich/html/padhpd/mapping_HPD.htm) and can be a bit wider or smaller than 1 mm. I tried to count and find 32 of the 128 pads / sector to be a bit smaller (10-20 % in area) and 13 of the 128 pads / sector to be a bigger (10 - 20 % in area). Histogramming the pad area distribution one finds an average pad of 0.96 mm^2 (± 0.13 mm^2 RMS)

2. Chromatic dispersion contribution to error

The Pad HPD will be equipped with a bialkali photocathode (baseline). If there are strong arguments (what I don't believe), we should be able to switch to S20 cathodes. Fortunately we have Hank's expertise. The front window of the Pad HPD consists of a UV extended borosilicate glass which starts to drop in transmission at about 300 nm and has 50% transmission at 250 nm. (T-curve can be provided). Concerning the window in front of the aerogel: HERMES is using a lucite window (cut-off at 290 nm). Mylar is cutting around 350 nm. Has Lucite been studied , tested in LHCb ? I don't think so.

3. Fraction of active area covered at detector plane

To achieve 73% active area fraction, hexagonal close packing without any gaps would be required. This doesn't seem completely realistic, not only in case we need mu-metal shielding. A more realistic packing would leave 3 mm gaps between tubes. 2 x 0.9 mm would be used by the mu-metal shielding, 1.2 mm would be left for HV insulation between the tube and the shield and for compensation of mechanical imperfections. With a centre-centre distance of 130 mm, the resulting active area coverage would be 69%.

4. Integral QE(E)dE (QE = detected photon efficiency within active area)

I consider the Q.E. curve in the TP as by far too optimistic. Values around 28% (as shown in the TP) can only be achieved in photo multipliers when light reflected from the 1st dynode or a special reflection cone around the 1st dynode is detected. This is clearly not the case neither for a HPD nor for a MAPMT. This is most likely the reason why the Q.E. of MAPMT is in general considerably lower than for single anode Pmts. Our latest photocathodes achieved peak Q.E. above 20%. We have to confirm these values with Cherenkov photons under realistic conditions. We think however that our DC method in the lab probably even underestimates the QE. A scale factor of 0.8 compared to the curve shown in the TP seems realistic.

5. Signal/Noise, common-mode noise tolerance, dark count rate

The noise figures of the SCTA128LC is not yet precisely known. From measurements with the SCTA128LC when connected to silicon pixels and from tests with calibrated charge injection, pedestal noise figures between 600 and 700 electrons are expected when connected to the Pad HPD silicon sensor. For the following table we assume 650 e pedestal noise, an energy loss of 1 keV in the dead layer of the sensor and a back-scattering fraction of 18%.

U (kV)	S/N ratio	N_{sigma} cut	Efficiency
20	8	3	93.25
20	8	4	91.
25	10.2	3	94.6
25	10.2	4	92.8
30	12.3	3	95.6
30	12.3	4	94.2

We will try to operate the detector at the highest voltage which is possible from power supply, cabling, insulation and stability limitations. We propose to use 25 kV with a 4 sigma cut as baseline. Consequently we would expect a detection efficiency of 92.8%.

We believe that the readout of small signals (5000 e) at very high speed is best done by means of an analogue electronic chain. Short pedestal runs allow to measure the amplitude and the spread (i.e. the gain of the electronics) of the pedestal in regular intervals. The analogue readout chain has the potential to be common-mode noise tolerant to a high extent. Adaptation to common-mode noise in an online way is possible with the scheme proposed by the vertex group (see chapter 7.6 in the TP).

Dark count rate: Pure thermionic emission from the photocathode should not play any role at a peaking time of 25 ns. According to the Philips PMT handbook, the dark count rate of a bialkali cathode at 30^{o}C is 100 Hz/cm. This results in a hit probability of $1.25 \cdot 10^{-7}$/pad/25ns. (For a S20 cathode the effect is more than 2 orders of magnitude larger, because of the increased red sensitivity.)

There may however be other sources contributing to the background count rate: Field emission (is expected to be stronger in a HPD than in a PMT because of the much higher electric fields), radioactive background radiation (e.g. radioactive K isotopes in the glass) and micro corona discharges on the tube walls and electrodes.

From measurements with PC49 we find a random hit probability of less than 1% for a peaking time of 1.3 μs. This value is a factor 1000 higher than what one expect from pure thermionic emission alone. But even this value becomes completely negligible (hit probability $2 \cdot 10^{-4}$ /pixel/25ns) for the fast readout.

6. Backscattering effect

The BS effect is taken into account in point 5. The probability that a backscattered electron hits the silicon sensor is very small. A rough ballistic calculation gives a chance of about 1-2%. Multiplied with the backscattering probability of 16-20%, we expect less than 0.5% backscattered p.e. per 'primary' photoelectron. This estimates are in agreement with the measurements with the 256 pad CsI HPD (E. Chesi et al., NIM A387 (1997) 122). The distribution of the background is rather flat, both in space and energy.

7. Channel-to-channel uniformity

C-to-c variations in gain, pedestal etc. are in general small and are taken into account automatically by performing pedestal runs, which determine the pedestal noise amplitude and its spread.

8. Effect of traversing charged particles

Under study in test beam.

9. Sensitivity to magnetic fields

Studies in preparation. A Helmholtz coil magnet has been built which allows to produce a uniform magnetic field of up to 30 Gauss (>30 Gauss for short time periods) over a volume of about 10 x 10 x 10 cm^3. From simulations drastic efficiency losses are expected for longitudinal (E||B) fields > 15 Gauss and transverse fields > 5 Gauss. 20 Gauss longitudinal could already cost 30% efficiency! Hexagonal mu-metal shieldings of different length have been fabricated to study the influence of the shielding. The loss in geometrical efficiency has been discussed above.

Annex A2.

Replies to the detector integration questions (O. Ullaland)

Information concerning the photon detector integration and cabling issues

Define a unit / cluster	1 Pad HPD
Number of read-out channels for each unit	64
Cables and Connectors Is standard (LEP) copper twisted pair suitable for your read-out	Yes
Will cheap connectors (like CANNON DCC-37S-FO) be adequate	Yes. (Also cheap connectors of other types).

Low Voltage

Number of LV channels for each unit	3 LV channels: +4 and +- 6V
How many units can be daisy chained	~10 (1 row or column)
What is the low voltage stability requirements	Better than +- 100 mV
What is the current on each of the LV lines	Total current per HPD is about 1A. Splitting between various lines not yet precisely known.
Do you require local voltage monitoring	Yes
Do you need high quality earth return path	Analog signal is differential -> little sensitive earth variations. High quality earth is desirable anyway.
Do you need local temperature monitoring	Local, i.e. tube by tube, monitoring is not required.

High Voltage

Number of HV channels for each unit	4 (+1) bleeder We need ultra low ripple power supplies: 2 X 30 kV 1 x 15 kV 1 x 6 kV
Assume there is a HV patch panel less then 20 cm away	OK
Do you require local HV monitoring for each unit	No
What is the current in each HV line	~nA
Can the HV be daisy chained	Yes. As for the LV supplies, one set of power supplies could power 1 column (row) of tubes (~10).
Resistor or a HV fuse for each unit	50 MΩ resistors for each of the HV lines as close as possible to the tubes.
Will you require high dielectric strength atmosphere	at least dry N2
Cooling	at least N2 circulation 1 HPD is expected to consume about 3.5W. Count 50 HPD's per side. Add some extra power for electronics cards.

Magnetic and/or electrostatic shielding
To be considered as an integral part of the unit

	Shielding is probably required

Mechanical specifications

Please indicate the weight of a unit and a basic footprint	HPD: ca. 1.5 kg Shielding: ca. 0.3 – 0.5 kg (depends on length) Footprint: 127 mm round
How can a unit be fixed to a supporting structure	Squeezed by pads or ring
Do you provide/need internal to external alignment pins	Yes

Lifetime

	Everything depends on the vacuum tightness of the tube. Getter will compensate undetectable ‘nano’ leaks. Long term experience is of course missing for the time being.

Annex A3.

Replies to the detector electronics questions (J. Bibby)

PAD-HPD (on the basis of 216 tubes)

Front-end, Level 0:

• Number of readout channels.	216*2048 = 442.368
• Number of active channels.	216*2048 = 442.368
• Your Proposed chip.	SCTA128
• Expected cost per chip. (CHF)	45 to 120
• Binary/Analogue?	Analogue
• Acceptable noise from FE chip	< 800 e-
• Detector signal shape.(Baseline width).	Few ns, not relevant
• Required shaping time before pipeline	25 ns
• Dynamic range (up to 4 photons before saturation!!)	~ 30000 e-
• ADC bit resolution.	~ 60 e-
• Dynamic range. (ADC bits)	9 bits
• Threshold range.	n.a.
• Power rails. Will these need to be remotely sensed.	Yes.
• What is the expected tolerance on power supplies?.	20-30 mV
• Currents from each supply and ground current.(per chip)?	50-60 mA/chip
• Monitoring (thresholds, power supplies. Temperature!!)?	PS: yes, T:no(?)
• Power dissipation./chip?.	200 mW / chip
• Cooling.	N2 circulation
• Pipeline length.	4 us (see LHCb FE 99-29, J. Christiansen)
• Derandomizer depth	16
• Overhead in clock cycles in the read-out of data.	4
• Differential signal out?	Yes
• Does the signal require output buffer drivers.	No
• Output multiplexing grouping	32
• Output multiplex rate.	40Mhz
• Module grouping.	2048
• Clock and trigger levels required.	LVDS.
• Number of pins to be accommodated by the adapter board per module.	~80
• Modes of operation.	
• Testing-Calibration modes?	Yes
• Failure report and recovery modes?	Yes
• Control protocol (IIC/JTag etc..)	No

Adapter Board: (Interface board)

• How many units.(Depends on grouping.)	216
• Does this board need buffers to drive the data links to level 1?	Yes
• Are these to be differential?	Yes
• Rad tolerant types required?	Yes
• What services (low voltage distribution/ filtering; High Voltage!!) Does this board need to handle/monitor/distribute?	LV: yes, Filter: yes, HV: no.
• What interconnects are to be used for data?	IDC
• What interconnects to be used for power lines.	????
• TTCrx. and fibre links for trigger/clock?	Yes

- How is the clock fanned out to the various FE chips? By 1 LVDS driver
- DCS and interfacing.? To be decided.
- Failure recovery modes?` Part of DCS!
- Does this board have mechanical support structure functions? Yes.

Links: (Requires further discussions and explanations with/by DAQ people)

- Copper or Fibre for output data lines from level 0 to level 1?
- (but to be evaluated when length is confirmed) Copper
- Number of data links. 13824
- Coupling Interconnects and mechanical support for links ?????
- Service panel feed through requirements?. ?????
- Fibre for Trigger and Clocks? Yes.
- Service panel feed through for links? How? ?????

Level 1: (Requires further discussions and explanations with/by DAQ people)

- Is the data at the input to the Level 1 inputs to be Binary or Analogue Analogue
- Dynamic range for ADC in Analogue? 9 bits.
- What are the signal levels? (For receivers). ??????
- Is Zero-Suppression required? yes
- Is some form of Common Mode correction to be done? yes
- How many channels do you plan for per 9U module? 64
- How many modules. 216
- What is the bandwidth for the output data
  with zero-suppression 15 Gb/s
  without zero-suppression 500 Gb/s
- What test modes do you envisage? ????
- How much data space for Algorithms and Modes of operation etc. does the DAQ have to allow for? To be investigated.
- Do your units need to be Rad Hard/tolerant? Rad tolerant!!

Multiplexers: (Example- Francois Bals' Proposal)

- How many Units are required? (Output bandwidth is aimed at 1Gbits/s). 4 .. 14 (To be discussed with DAQ)
- Do you require fibre or Copper links from Level 1? Copper.
- Do the units need to be Rad hard/tolerant? Yes.
- Are the links to the Readout Unit, which will be >80 metres away, Fibre!. (radiation a problem!) Yes.

Front-end Control:

- Crate-resident controller or Remote controller? Remote Controller. ?
- Communication with Level 1 units? To be discussed with DAQ

Power Supplies:

- Do they require to be Rad tolerant? No.
- Location? >80 metres.
- What Voltages? 4V, +-6 V
- Total Currents? 1A
- Safety? To be studied.
- Common Grounds? To be studied.

• Distribution-grouping?	Layout studies.
• Monitoring into the DCS?	?
• Connections and connectivity?	?

Cables:

• Power cables.	?