The LUCID luminometer

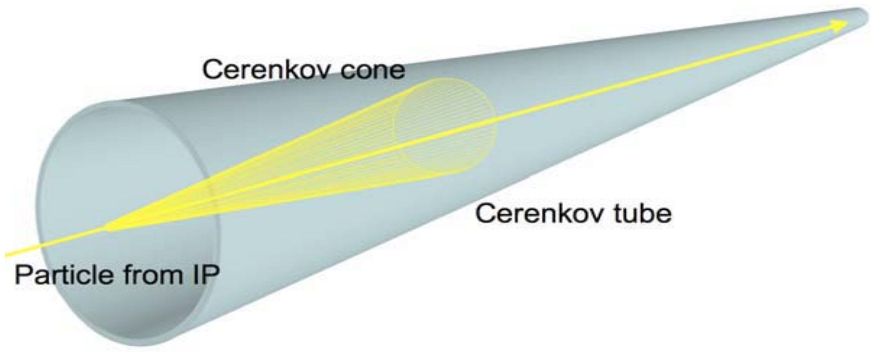
Vincent Hedberg

The LUCID-2 collaboration:

G L. Alberghi, M. Bruschi, D. Caforio, N. Dehghanian, A. Floderus, B. Giacobbe, F. Giannuzzi, P. Grafström, V. Hedberg, F.Lasagni Manghi, M. Negrini, J. Pinfold, C. Sbarra, N. Semprini Cesari, A. Sbrizzi, R. Soluk, G. Ucchielli, S. Valentinetti, O. Viazlo, M. Villa, C. Vittori, A. Zoccoli

The Alberta, Bologna and Lund groups in ATLAS

Introduction



The LUCID-1 detector (2009-2013)

Gas Cherenkov detector

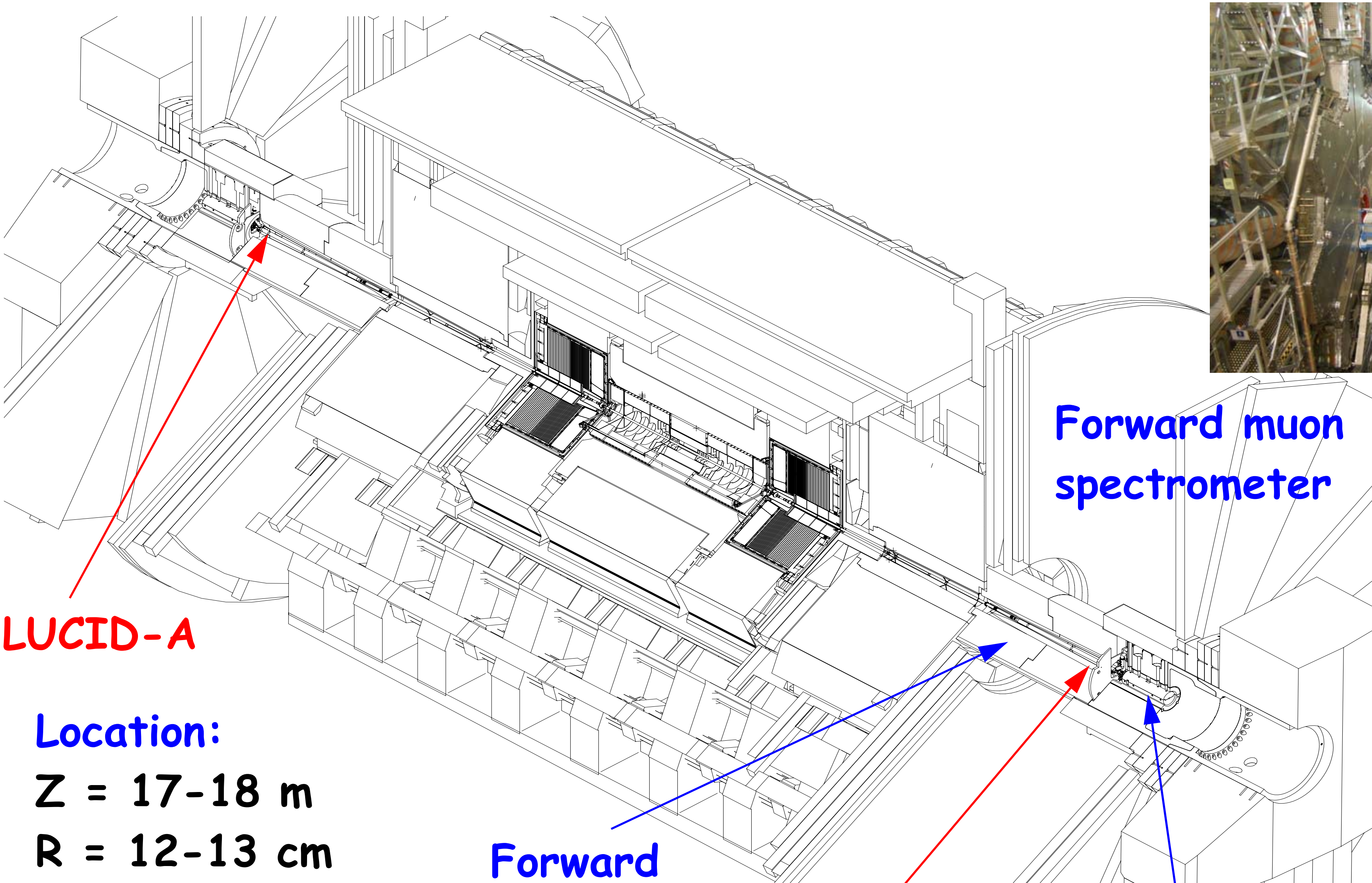
The LUCID-2 detector (2015- ?)

Quartz Cherenkov detector

Location in ATLAS

ATLAS

LUCID surrounds the beampipe on both sides of the IP at a distance of 17-18 m.



Forward muon spectrometer

LUCID-A

Forward Shielding

LUCID-C

TAS collimator

Location:

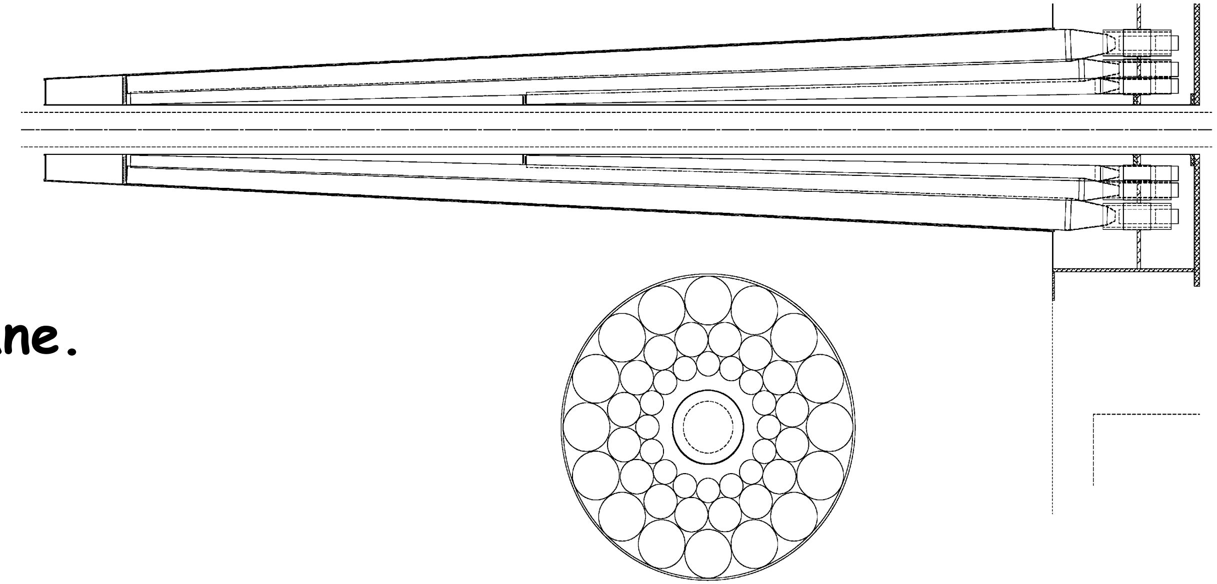
Z = 17-18 m

R = 12-13 cm

η = 5.6

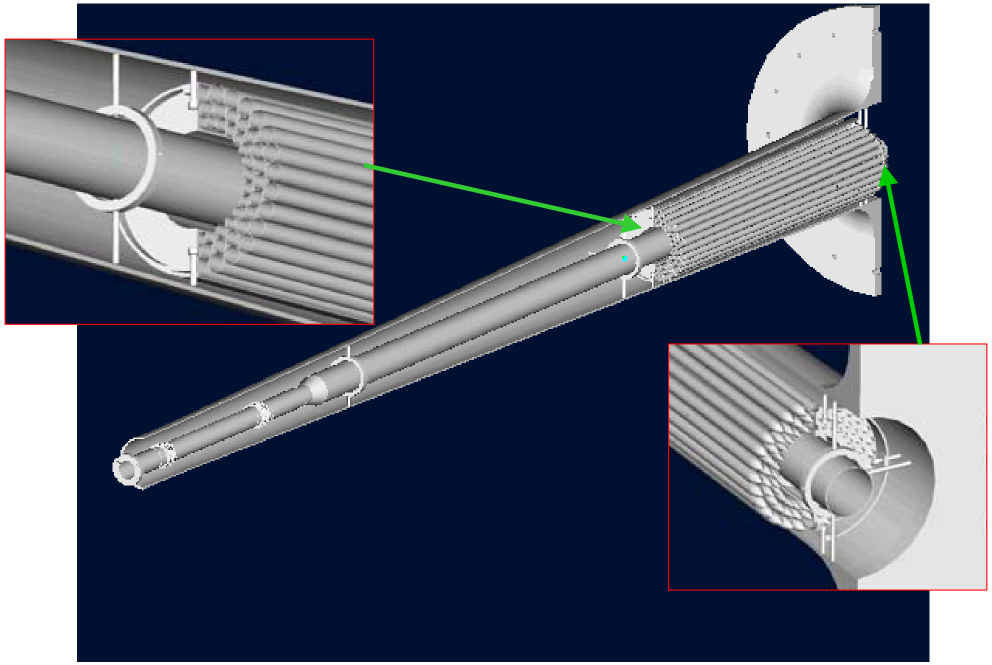
History

The original idea for a gas Cherenkov luminometer came from the CDF experiment. It used two detectors, each with 48 conical tubes pointing towards the IP and filled with isobutane. The Cherenkov light was read-out by photomultipliers at the end of the tubes.



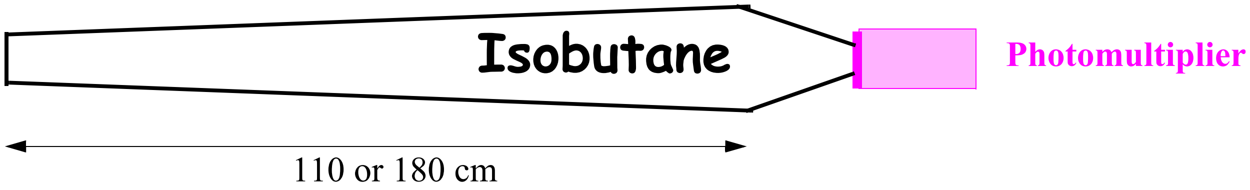
ATLAS designed a similar detector with 2 x 168 tubes where the light was transported by 2 x 6216 quartz optical fibers to a shielded location with low radiation.

It was never built.



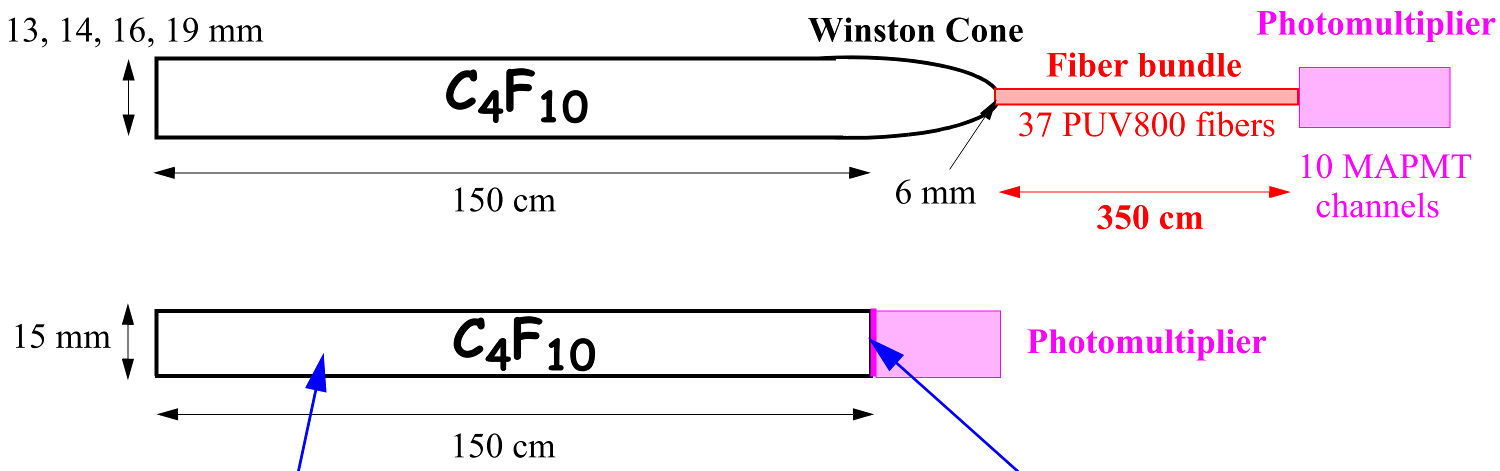
History

The CDF detector



ca. 100 photoelectrons

In ATLAS we did testbeam studies of two types of read-out

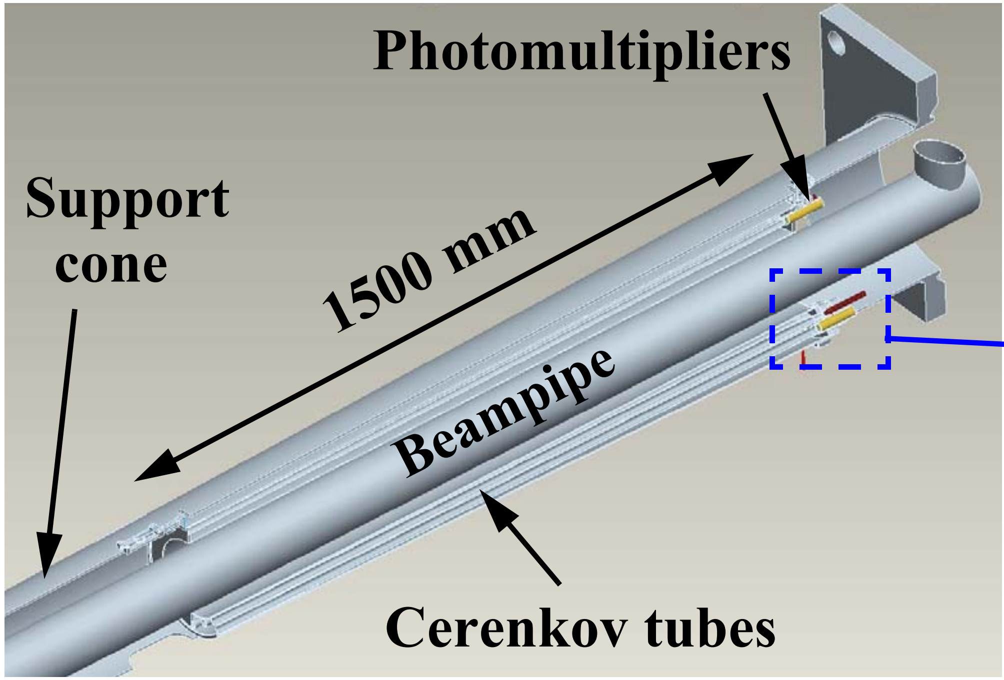


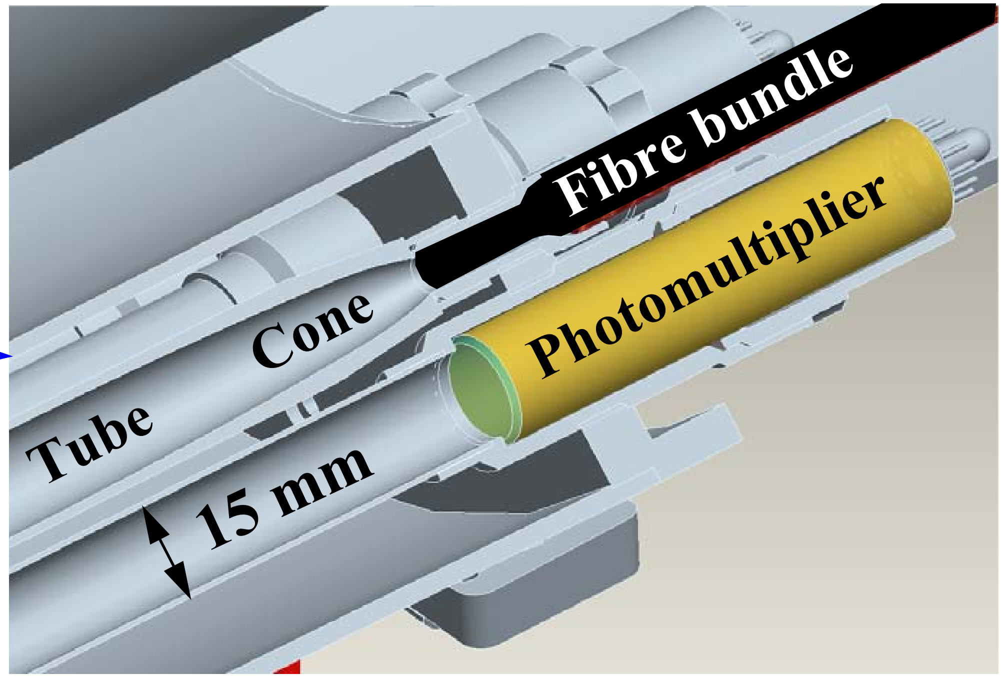
12 photoelectrons

67 photoelectrons from the gas

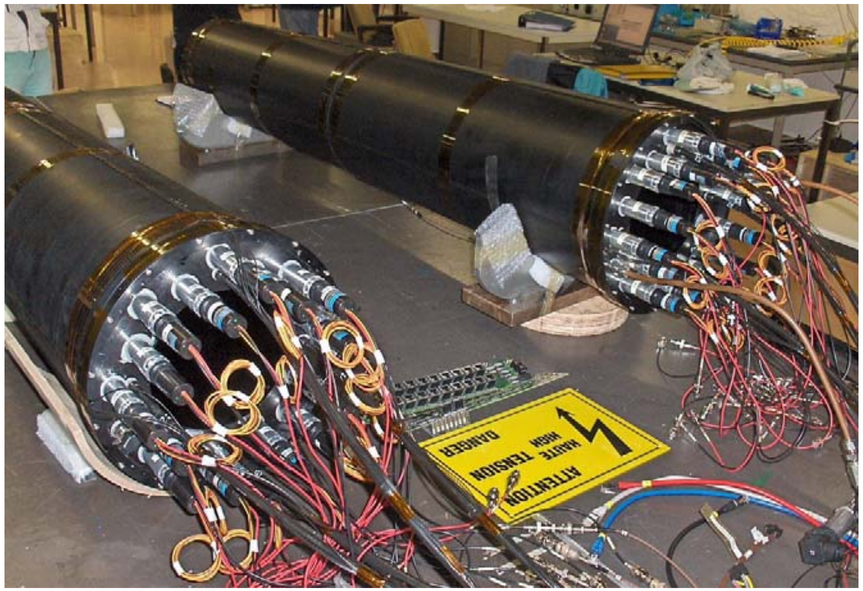
47 photoelectrons from the window

The LUCID-1 detector





The LUCID-1 detector consisted of 4 Cherenkov tubes read-out by fiber bundles and 16 tubes read-out by photomultipliers.

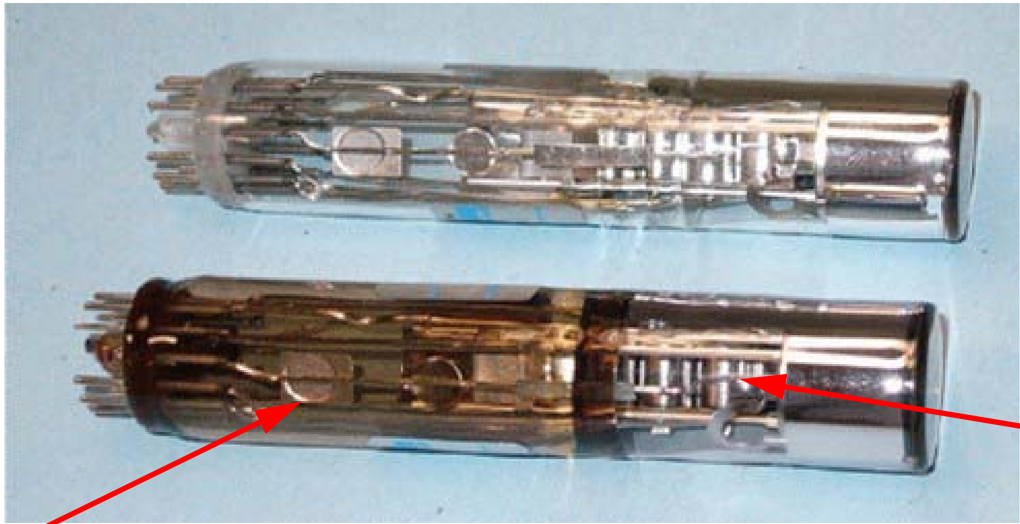


The analog signals were sent to constant-fraction discriminators and the hits from those to special purpose built electronics with logic requirements and scalers.

Radiation hardness

Before radiation exposure

After exposure to 200 kGray



Fused silica glass ("quartz"): 100% SiO_2

Borosilicate glass: 80% SiO_2 + 4% Na_2O + 13% B_2O_3 + 3% Al_2O_3

Photomultipliers with fused silica (quartz) windows are radiation hard.

The LUCID photomultipliers have been exposed to gamma radiation (200 kGray) and neutrons from reactors.

An increase of the dark current was observed but no change of signal size or gain.

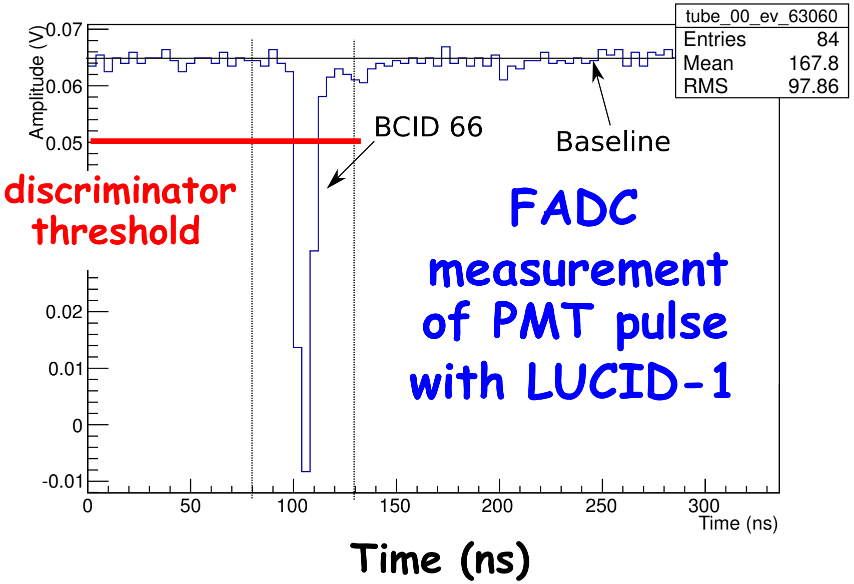
The dose to the photomultipliers in 2015 was measured to be 9.4 kGray.

Pile-up ("migration")

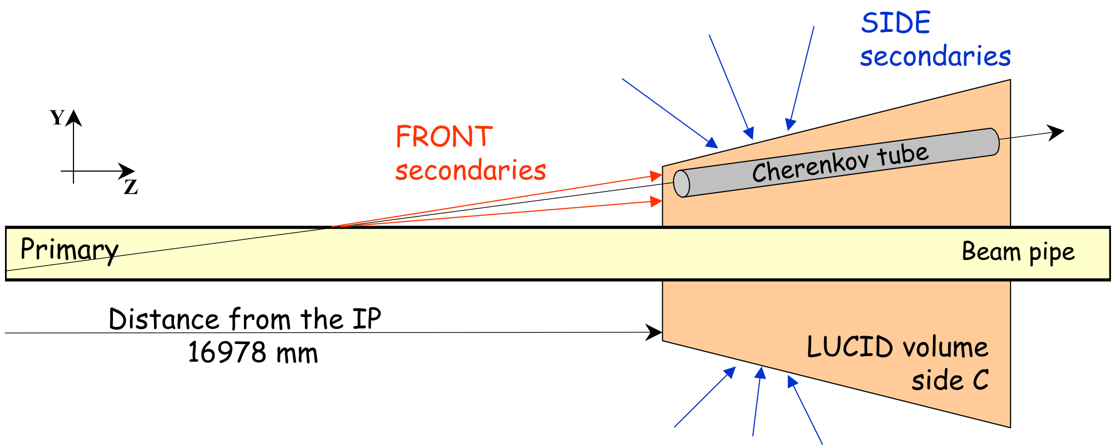
One can calculate the luminosity in a time period called a luminosity block (typically 60s long) from the fraction (f) of bunch crossings with at least one discriminator hit:

$$\mathcal{L}_{BCID} = \frac{-\ln(1 - f)}{\sigma_{vis}} f_{LHC}$$

from VDM



Assumptions:
1. The number of interaction in a BC is Poission distributed.
2. The probability to observe a single int. is always the same.



Signals from different pp-interactions which are below the disc. threshold can add up and give hits.

Pile-up leads to an overestimation of the luminosity at high μ.

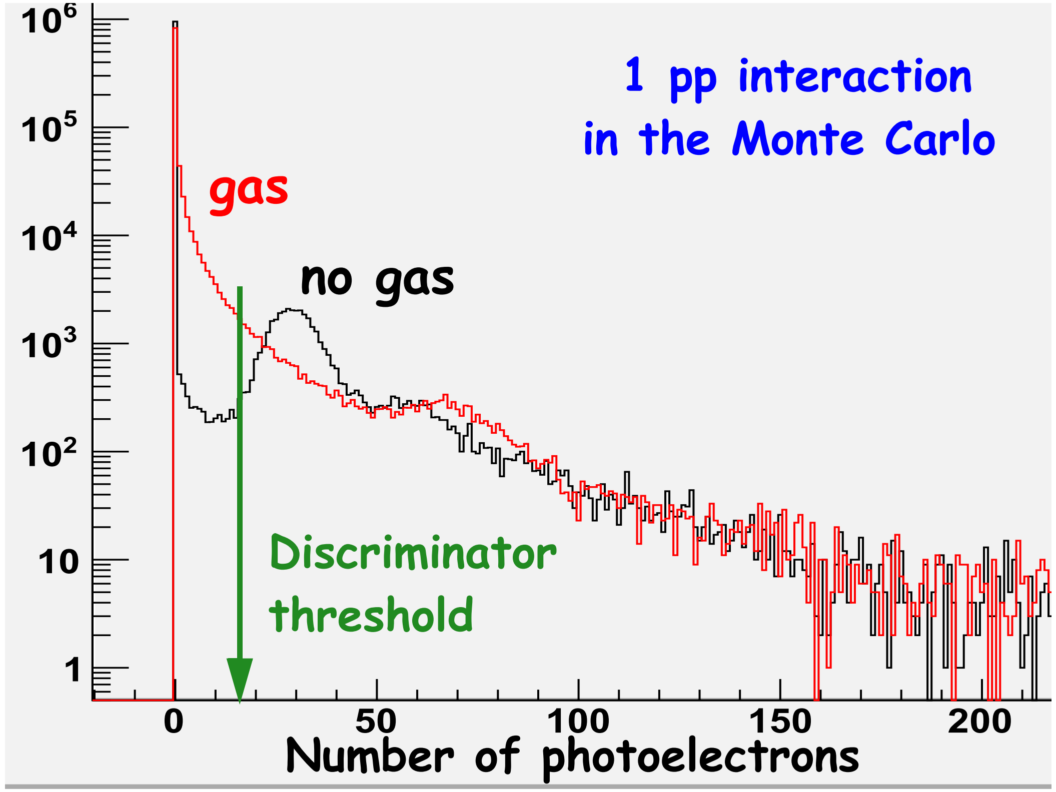
Pile-up ("migration")

The size of the pile-up effect depends on the shape of the pulse-height distribution.

The long Cherenkov tubes resulted in a pulseheight distribution with most signals below the discriminator threshold ⟶ Large pile-up.

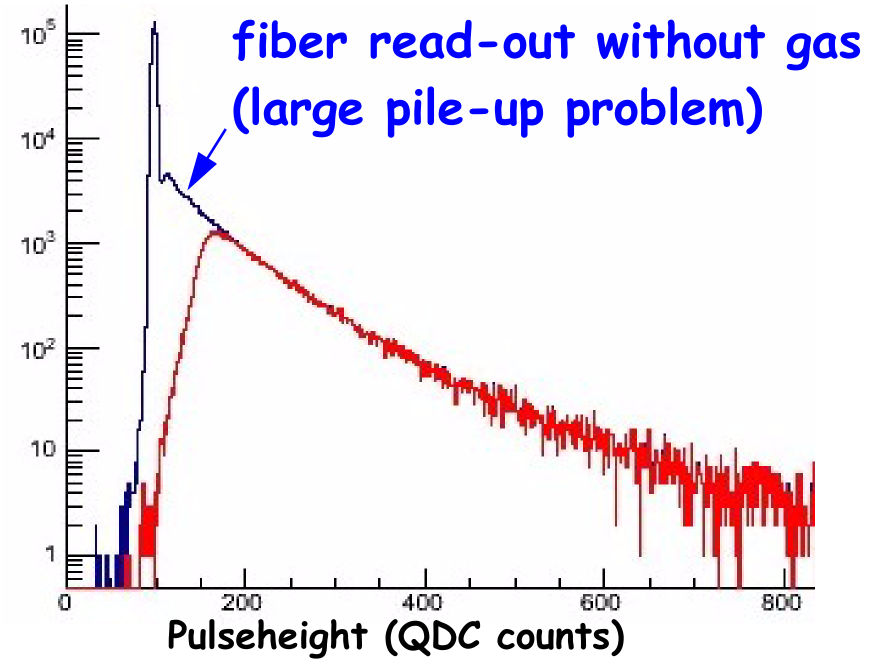
For this reason we started to run without gas in the middle of 2011.

Pulseheight distribution



Pile-up ("migration")

The Cherenkov tubes read-out by bundles of quartz fibers also gave a sizable signal without gas.



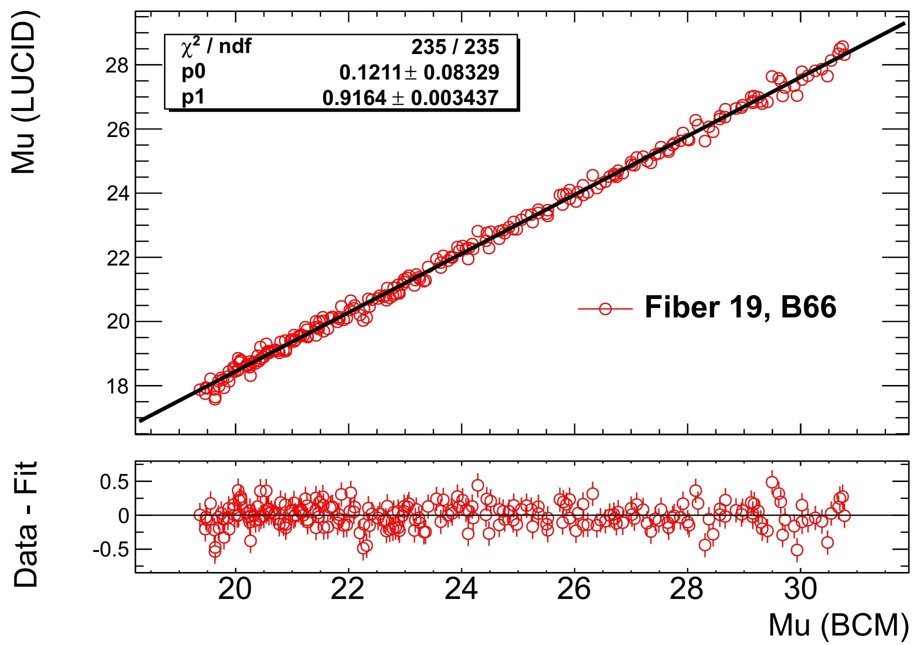
However, counting bunch crossings with hits had large pile-up problems.

CHARGE COUNTING:

Integrate the pulse i.e. measure the charge in the pulse (C).

$$\mathcal{L}_{BCID} = \frac{C}{\sigma_{vis}} f_{LHC}$$

This measurement has no pile-up problem.



Zero-starvation ("saturation")

One wants a luminometer with a large dynamic ranges so that it can measure a μ of 0.001 in the tails of a vdM scan and a μ of 40-100 during physics.

If the detector efficency and acceptance is too large one will experience zero-starvation ("saturation").

$$\mathcal{L}_{BCID} = \frac{-\ln(1 - f)}{\sigma_{vis}} f_{LHC}$$

f = 1

when every bunch crossing during a luminosity block period has at least one hit

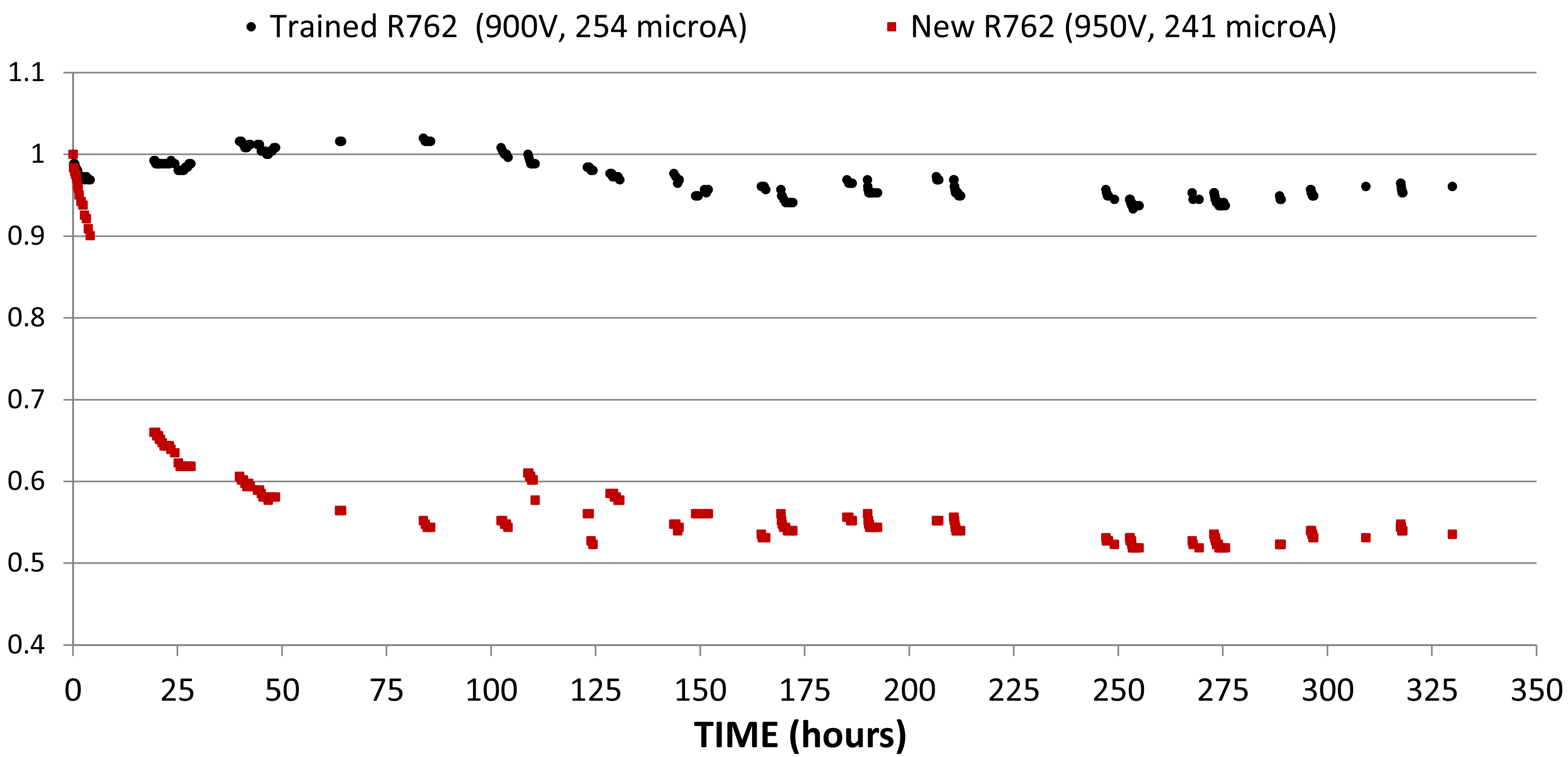
This problem can be solved by increasing the length of the time period, by requiring hits in both detectors (AND requirement) or by reducing the number of photomultipliers used in the OR requirement.

In 2012 the logical OR of 15+13 photomultipliers saturated and one had so use single-sided ORs of 15 and 13 photomultipliers.

Long-term stability

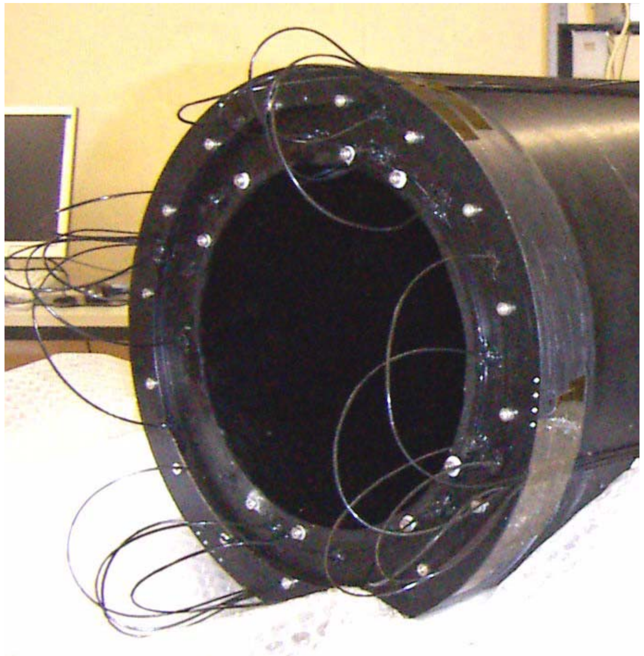
The gain of a photomultiplier goes down with time. The initial gain loss can be very large but the rate of gain loss typically becomes smaller with time.

The change in gain is believed to be caused by a loss of sensitivity in the last dynodes due to erosion of the Cesium on the dynode surfaces due to the electron bombardment.

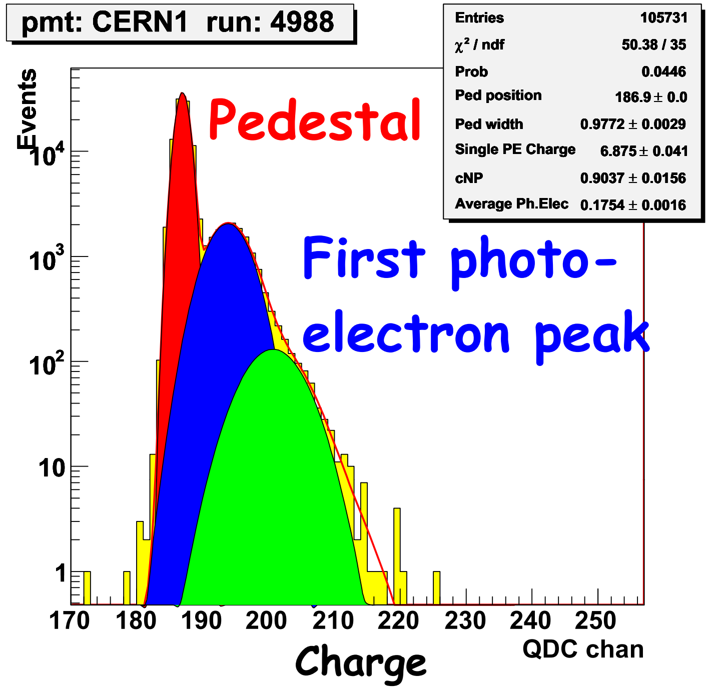


Long-term stability

The detector gain was monitored by injecting small amounts of LED light via optical fibers and then measure the first photoelectron peak.



Typical calibration plot



This method was accurate but could not be used when the activation background became too large.

The LUCID luminosity measurement decreased by 5% in 2012.

Design goals for LUCID-2

1. Use quartz instead of gas as Cherenkov medium to minimize pile-up problems.

2. Build a detector with smaller acceptance to avoid zero-starvation.

3. Install new systems to monitor and correct for gain changes.

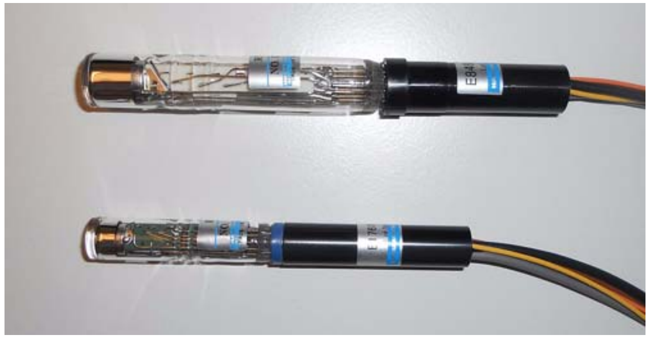
4. Build new electronics that could cope with 25 ns bunch separation and that can measure the pulse shape.

Photomultiplier choice

Two of the smallest Hamamatsu photomultipliers with quartz widows were evaluated by us.

R760

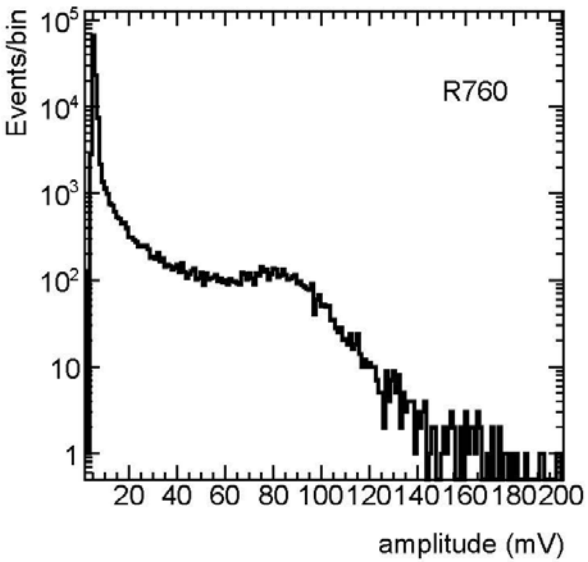
R2496

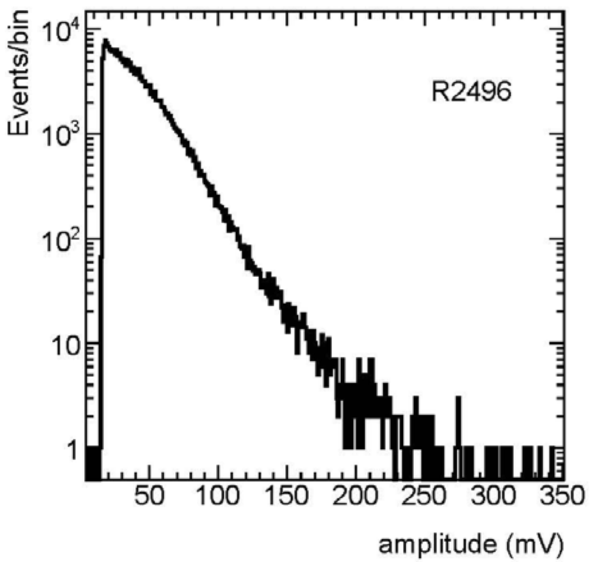


Flat fused silica window: 1.2 x 10 mm

Concave fused silica window: (0.8-1.85) x 8 mm

Pulseheight distribution from cosmics

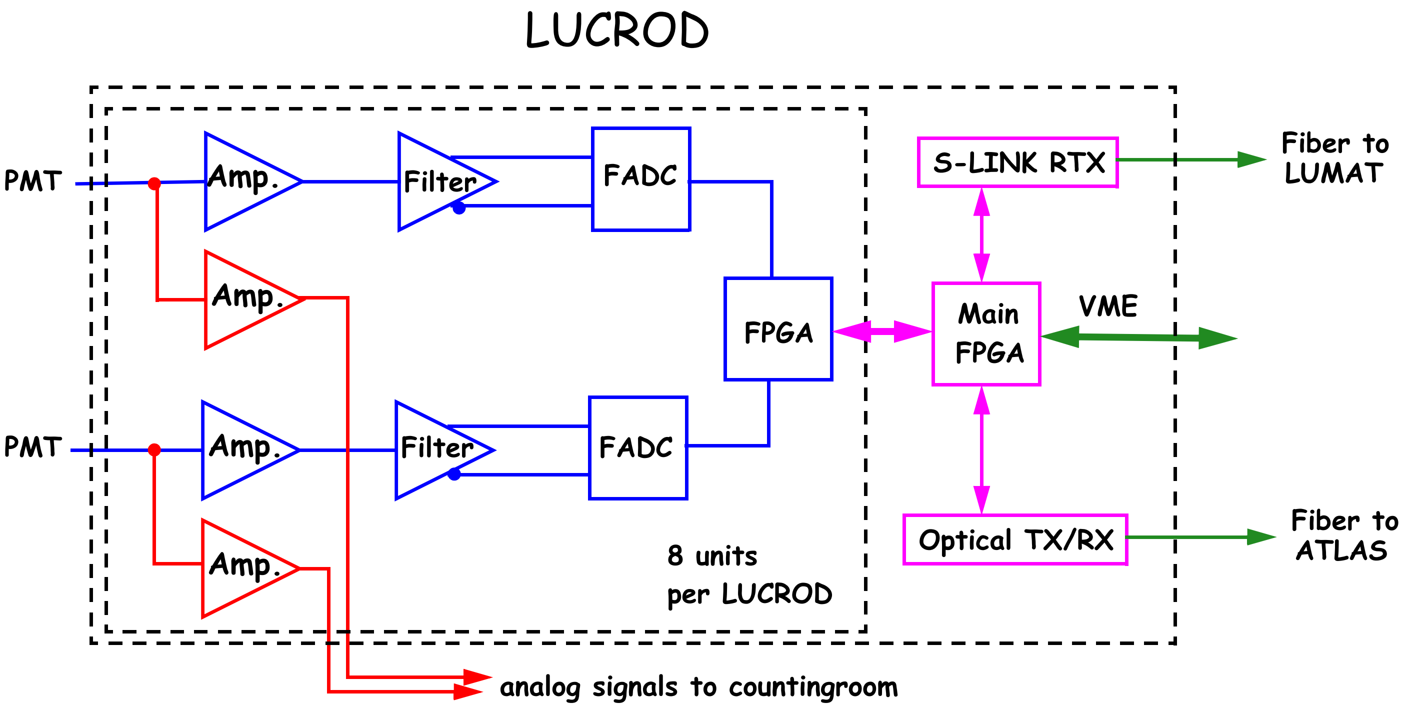




Modified R760 pmts were manufactured for us with a reduced acceptance.

New electronics

New purpose built electronics is measuring the pulseshape of every pulse in 3.125 ns intervals (8 samplings in 25 ns).



Signals above a pre-set threshold ("hits") are recorded as well as the integral of the pulse ("charge").

FPGAs are used to require certain logical conditions:

OR = At least one hit in 4 or 8 photomultipliers

AND = At least one hit in both the A-side and the C-side detector

New electronics

Different types of measurements are provided by the electronics:

Event-counting: The fraction of bunchcrossings fulfilling a requirement of one or more hits.

PMT-counting: The fraction of bunchcrossings with a hit in an single photomultiplier.

Hit-counting: The totals number of hits in one luminosity block period.

Charge-counting: The sum of the integral of all pulses in one luminosity block period.

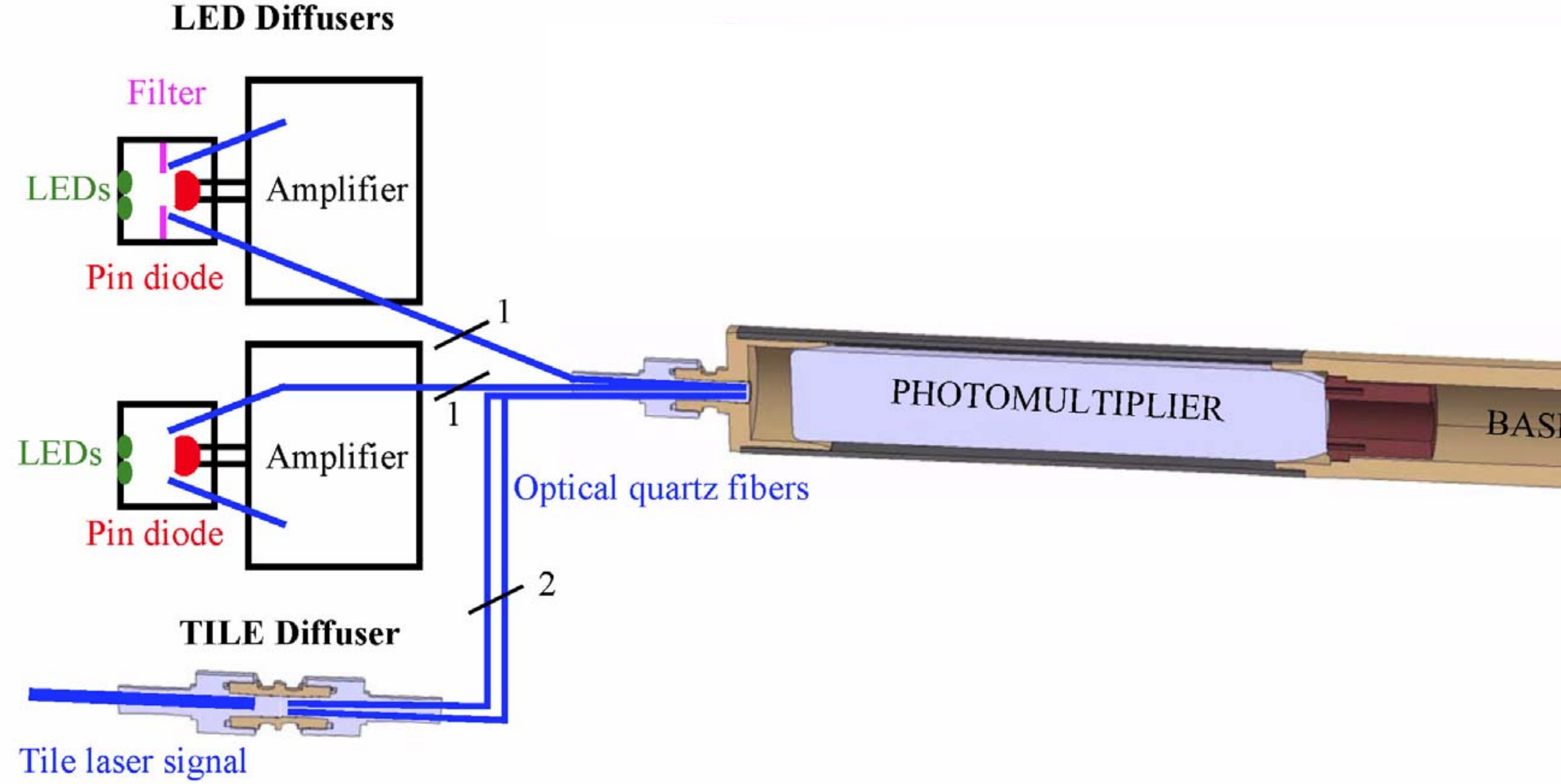
The electronics provides a total of 104 different luminosity measurements.

This measurement is done separately for each of the 3564 BCIDs.

LED system for gain monitoring

LED light and laser light are sent to the front of 32 of the photomultipliers via quartz optical fibers.

The stability of the LEDs are monitored by PIN diodes.



LED calibration runs with a duration of 10 minutes are made between most fills.

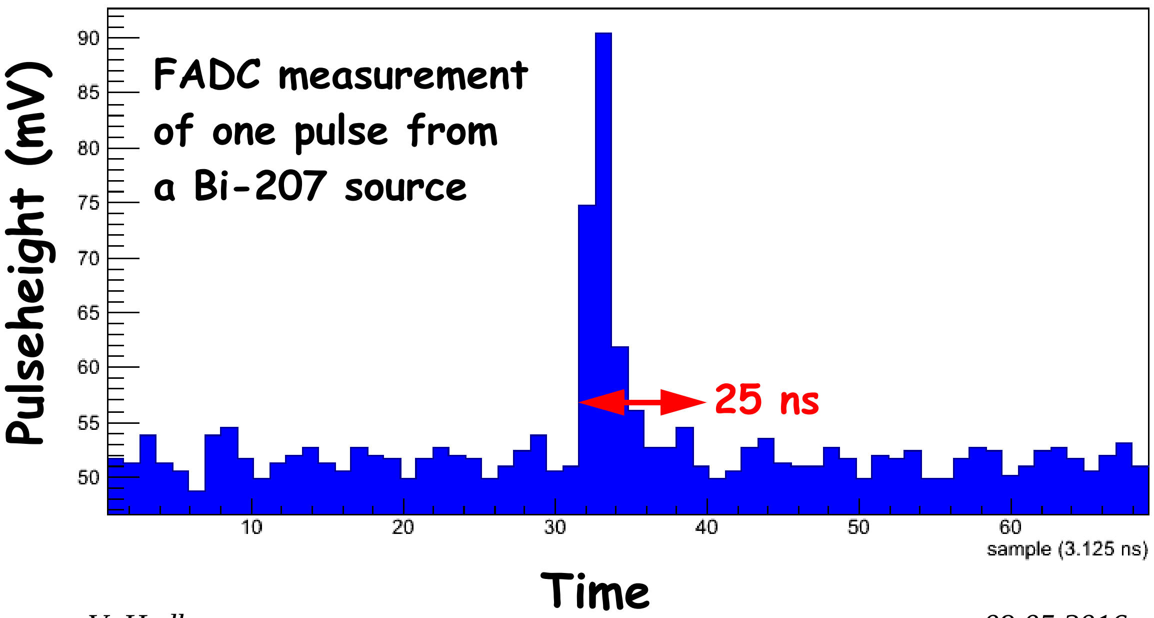
The pulses from the LEDs are integrated (the "charge" is measured) and the mean charge are used to estimate the photomultiplier gain.

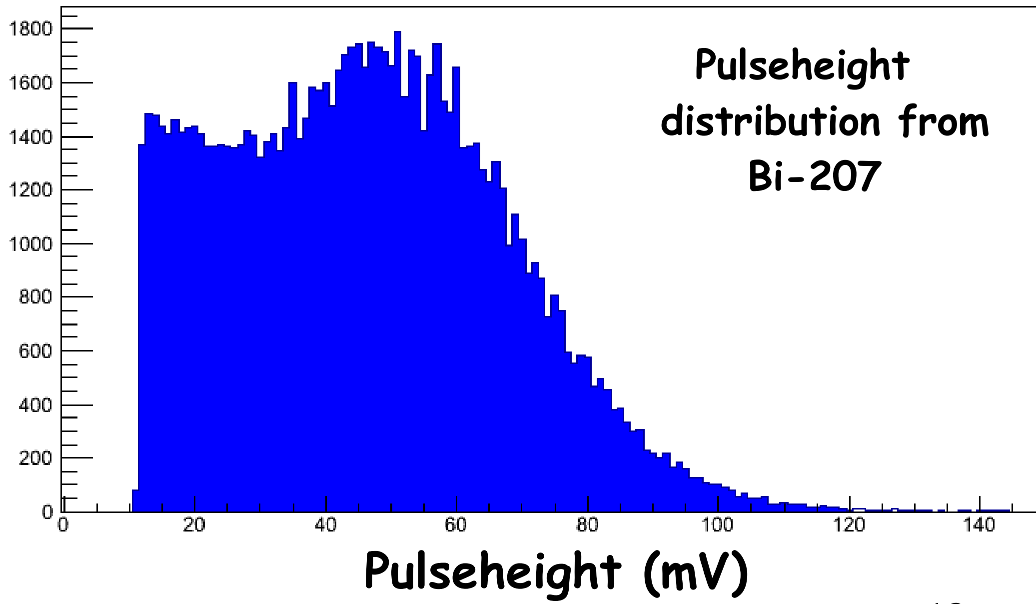
Bi-207 source calibration

1 μCi liquid Bi-207 sources have been applied on to the window of eight photomultipliers.

Peek cap

Bi-207 give monoenergetic electrons from internal conversions with an energy above the Cherenkov threshold in quartz. The half-life is 33 years.





Bi-207 source calibration

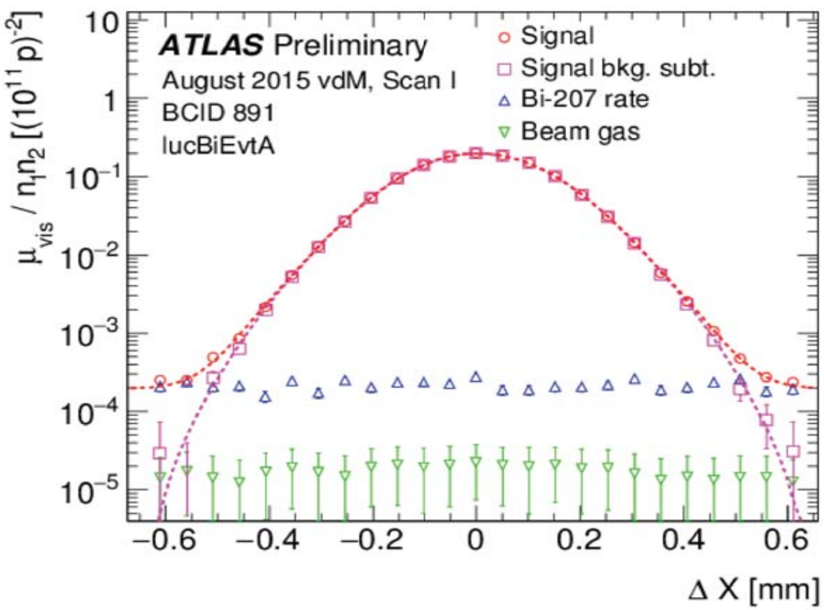
Source calibration runs with a duration of 40 minutes are made between most fills.

The pulses from the Bi-207 are integrated (the "charge" is measured) and the mean charge are used to estimate the photomultiplier gain.

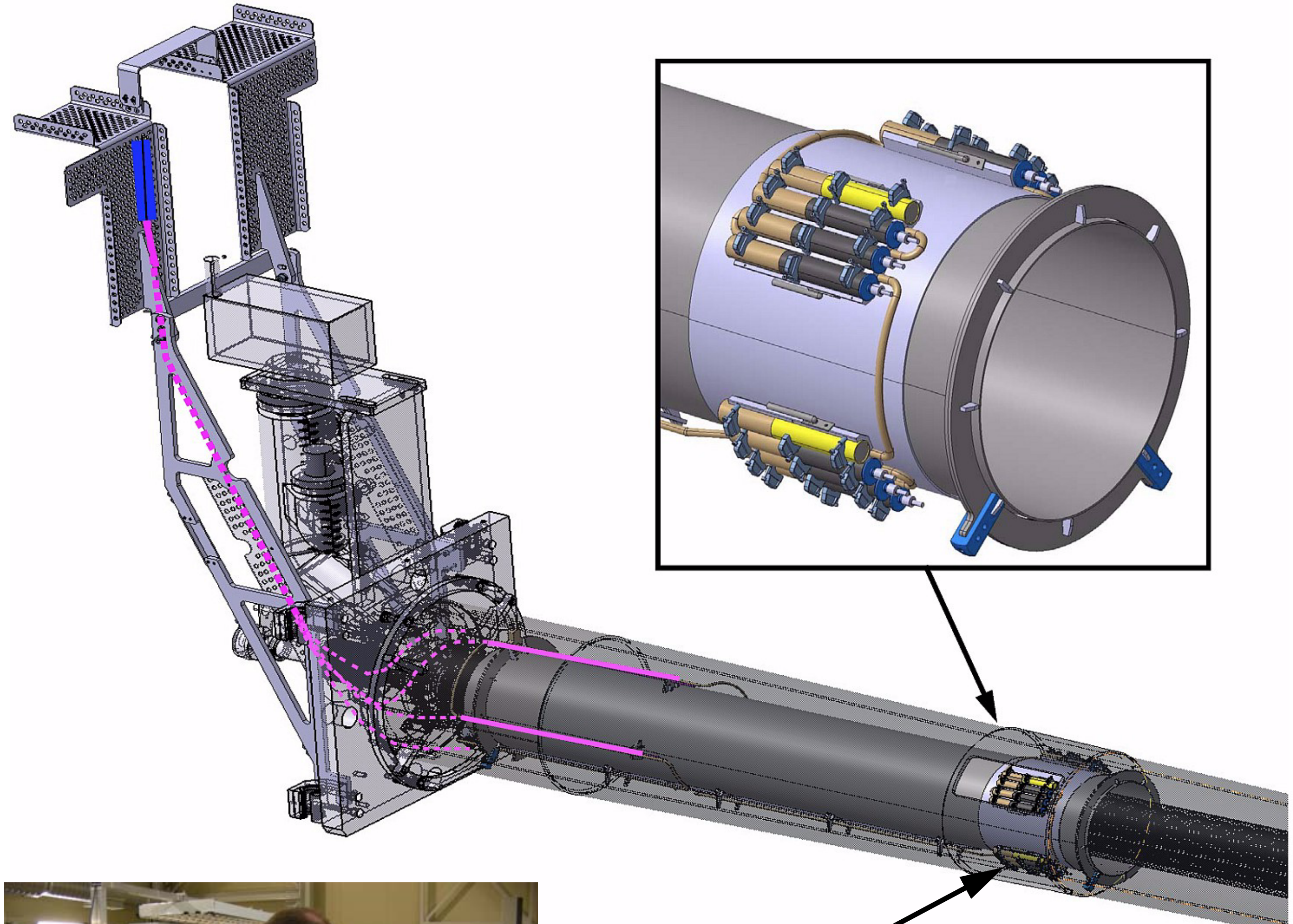
After each calibration run the high voltage of the photomultipliers is automatically changed to compensate for any gain change.

The reason why not all photomultipliers were source calibrated was the concern that the Bi-207 rate would spoil the van der Meer measurements.

However, this was not the case !



The LUCID-2 detector



5 different detectors with 4+4 photomultipliers

BI: Bi-207 calibrated detector

VDM: LED calibrated detector

MOD: Modified pmts

FIB: Quartz fiber detector

SPARE: A spare VDM detector that is not turned on

Performance in 2015

1. Pile-up: A μ-dependence has been observed at a level of 0.1%-0.2% per unit of μ

2. Long-term stability: 1.2% envelope (RMS=0.2%) in run-to-run comparison to TILE and EMEC calorimeters and track counting.

3. Zero-starvation:

Algorithm	σ^{vis} (mb)	ε (%)	μ_{max}	
BI_OR	32.4	40.5	24	4+4 pmts
BI_OR_A	19.3	24.2	41	4 pmts
BI_AND	6.38	8.0	125	4 AND 4 pmts
BI_C9	6.44	8.0	125	1 pmt
MOD_OR	21.7	27.1	36	4+4 modified pmts

4. Background: insignificant

5. Bi-207 monitoring works well but not the LED monitoring which seems to overestimate the gain changes.

Summary

The new LUCID-2 detector monitored by Bi-207 was used as the main luminosity detector in ATLAS during 2015.

The source monitoring system worked better than expected.

The LED monitoring system worked worse than expected.

A large decrease in the gain of the photomultipliers was observed but could be automatically corrected for using the Bi-207 runs.

Pile-up has been observed and will have to be corrected for.

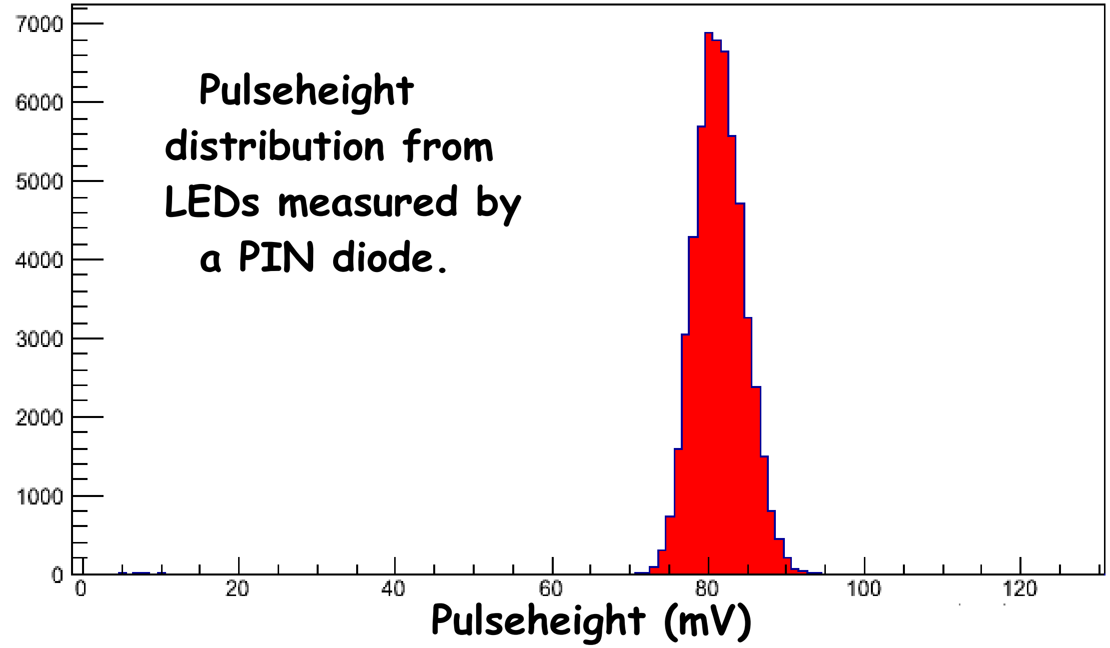
Only a small subset of the many luminosity measurements that the detector provides have sofar been evaluated.

Eight additional Bi-207 equipped photomultipliers have been installed for 2016.

Backup

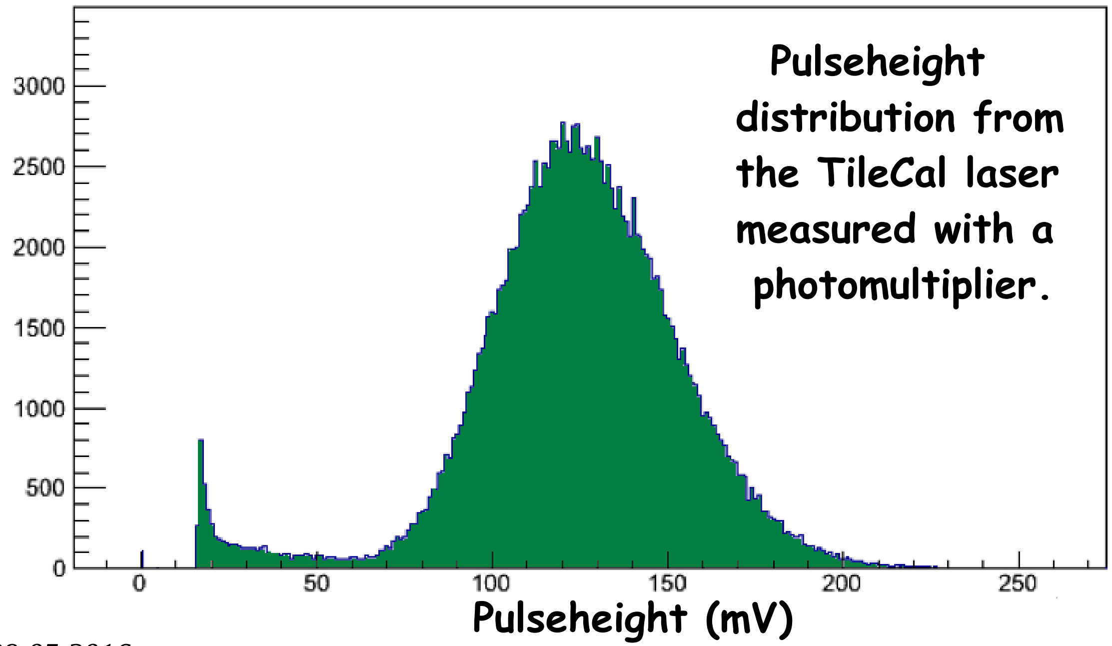
LED and Tile laser calibration

The FADCs in the LUCROD boards have also been used to measure the pulseheight and charge distributions of signals from the LEDs and TileCal lasers.

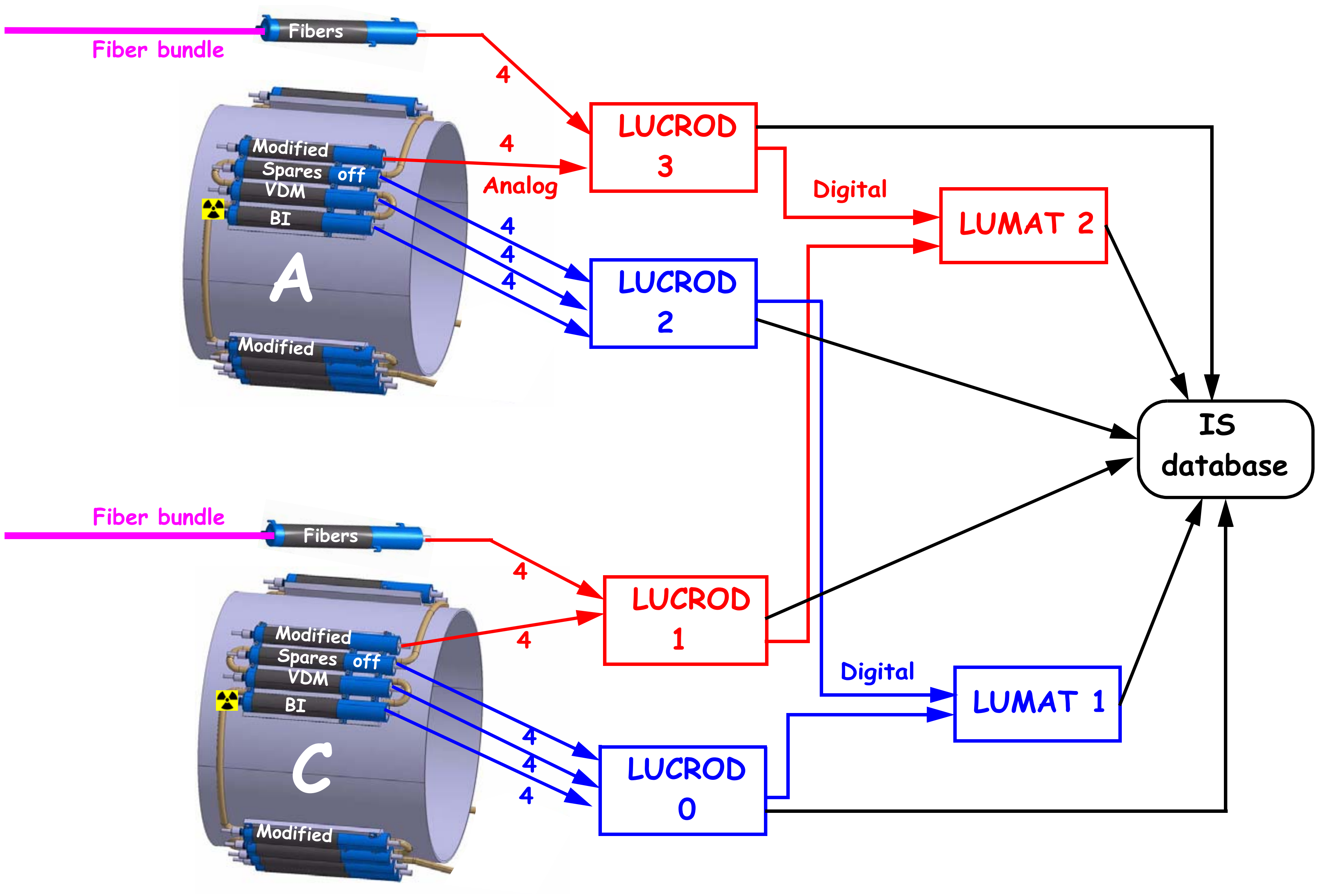


The LEDs give signals simultaneously in the photomultipliers and the PIN diodes.

The TileCal laser signals give signals only in the photomultipliers (not in the PIN diodes).



Electronic modules



Luminosity algorithms

LUCROD 2

BI_A1, A5, A9, A13
BI_CHA_A1, A5, A9, A13
BI_OR_A, BI_HIT_A, BI_CHA_A

VDM_A2, A6, A10, A14
VDM_CHA_A2, A6, A10, A14
VDM_OR_A, VDM_HIT_A, VDM_CHA_A

LUCROD 0

BI_C1, C5, C9, C13
BI_CHA_C1, C5, C9, C13
BI_OR_C, BI_HIT_C, BI_CHA_C

VDM_C2, C6, C10, C14
VDM_CHA_C2, C6, C10, C14
VDM_OR_C, VDM_HIT_C, VDM_CHA_C

LUCROD 3

MOD_A4, A8, A12, A16
MOD_CHA_A4, A8, A12, A16
MOD_OR_A, MOD_HIT_A, MOD_CHA_A

FIB_A17, A18, A19, A20
FIB_CHA_A17, A18, A19, A20
FIB_OR_A, FIB_HIT_A, FIB_CHA_A

LUCROD 1

MOD_C4, C8, C12, C16
MOD_CHA_C4, C8, C12, C16
MOD_OR_C, MOD_HIT_C, MOD_CHA_C

FIB_C17, C18, C19, C20
FIB_CHA_C17, C18, C19, C20
FIB_OR_C, FIB_HIT_C, FIB_CHA_C

LUMAT 1

BI_OR, BI_OR_A, BI_OR_C, BI_AND
BI_HIT_OR, BI_HIT_AND

VDM_OR, VDM_OR_A, VDM_OR_C, VDM_AND
VDM_HIT_OR, VDM_HIT_AND

LUMAT 1

MOD_OR, MOD_OR_A, MOD_OR_C, MOD_AND
MOD_HIT_OR, MOD_HIT_AND

FIB_OR, FIB_OR_A, FIB_OR_C, FIB_AND
FIB_HIT_OR, FIB_HIT_AND

COOL

BI_A1, A5, A9, A13, C1, C5, C9, C13
BI_OR, BI_OR_A, BI_OR_C, BI_AND
BI_HIT_OR, BI_HIT_AND
BI_CHA_A, BI_CHA_C

VDM_OR, VDM_OR_A, VDM_OR_C, VDM_AND
VDM_HIT_OR, VDM_HIT_AND
VDM_CHA_A, VDM_CHA_C

MOD_OR, MOD_OR_A, MOD_OR_C, MOD_AND
MOD_HIT_OR

FIB_CHA_A, FIB_CHA_C