



**ISTITUTO NAZIONALE DI FISICA NUCLEARE**

**Sezione di Catania**

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**INFN/TC-08/07**

**13 October 2008**

**CHARACTERIZATION OF AVALANCHE PHOTO DIODES FOR THE FIRST  
SUPER-MODULE OF THE ALICE ELECTROMAGNETIC CALORIMETER**

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**Abstract**

A status report is given of the ongoing activities in Catania concerning the testing procedures for the Avalanche Photo Diodes (APD) to be used in the first super-module of the ALICE electromagnetic calorimeter. A description of the equipment, testing procedure and protocol, together with results from a first sample of APDs are reported.

PACS.: 06.60.-c , 85.30.-z, 85.60.Dw

*Published by SIS-Pubblicazioni  
Laboratori Nazionali di Frascati*

## 1 INTRODUCTION

To enhance the capabilities of the ALICE detector [1] for jet reconstruction and high momentum photons and electrons, a large acceptance electromagnetic calorimeter (EMCal) is actually under construction, to be added to the ALICE original design. The combination of such additional detector to the existing tracking and identifying detectors in ALICE will greatly improve the reconstruction of particles from low to high  $p_T$ , enabling also an extensive study of jet quenching phenomena at LHC energies.

The design of the EMCal has been planned according to the need to integrate it with the existing ALICE magnet and detectors. The EMCal will be installed inside the solenoidal magnet, in the region between the ALICE space-frame and the magnet coils. Due to the presence of the PHOS and HMPID detectors, it will cover a region of  $110^\circ$  in azimuth and  $\pm 0.7$  units in pseudo-rapidity, and will be located in order to provide a partial back-to-back coverage with the ALICE Photon Spectrometer. Fig.1 shows a basic layout of the detector.

The chosen technology is based on a layered Pb-scintillator sampling calorimeter with longitudinal wavelength shifting fibre light collection. The detector is segmented into 12672 towers, approximately projective in  $\phi$  and  $\eta$  to the interaction vertex, and organized in super-modules, which will be the basic structural units of the calorimeter.

The smallest block in the calorimeter design is the individual module, which contains  $2 \times 2 = 4$  towers, built by 77 alternating layers of Pb (1.44 mm) and polystyrene (1.76 mm), with a front face dimensions of  $6 \times 6 \text{ cm}^2$ .

The scintillation light produced in each tower is collected by an array of 36 wavelength shifting fibres (WLS), which run longitudinally through the Pb/scintillator stack. Each fibre terminates in an aluminized mirror at the front face of the module and it is integrated into a group of 36 fibres joining the photo sensor at the back of the module (Fig.2).

The readout of the modules makes use of large area ( $5 \times 5 \text{ mm}^2$ ) Hamamatsu Avalanche Photo Diodes (APD S8148), which will be operated at room temperature and moderate gain with a low noise and high gain stability.

To ensure an optimal resolution for high energy electromagnetic showers, it is important to have a tower-to-tower relative energy calibration better than 1% in the offline analysis. This will be achieved by cosmics and on beam events. However, even during the data taking, in order to provide a reliable EMCal trigger, the APD gains need to be adjusted to match a relative energy calibration better than 5%. This requires, prior to the installation and data taking, a careful measurement of the individual gains as a function of the APD high voltage, with a calibrated LED pulser system. Since the APD gain drifts with the operating temperature, measurements of the APD gains at different temperatures are in order, to check their temperature coefficient. The use of a LED calibration system will finally ensure a proper monitoring of the system during data taking. A detailed description of the EMCal project is reported in Refs.[2,3].

This Report describes the ongoing activities in Catania, aiming at the development of a

standardized procedure for the test and characterization of a large number of APDs, in the order of a few thousands, to be installed in the ALICE EMCAL super-modules. Sect.2 describes the equipment employed, while Sect.3 discusses the test procedures and reports a set of results obtained on a lot of about 1000 APDs recently tested for the construction of the first super-module.

## **2 EXPERIMENTAL SET-UP**

### **2.1 The Hamamatsu APD devices for the EMCAL**

The active readout elements of the EMCAL towers are  $5 \times 5 \text{ mm}^2$  Avalanche Photo Diodes Hamamatsu S8664-55 (S8148). Such devices are the result of an extensive R&D activity carried out by the CMS Collaboration and Hamamatsu Photonics. They have high quantum efficiency, low dark current and very good stability. Moreover, irradiation studies demonstrated their reliability even with doses much higher than those expected in the ALICE environment after ten years of operation. Their main properties are reported in Table I. Each APD is connected directly by soldering to the back of a Charge Sensitive Preamplifier (CSP) with 0.83 V/pC sensitivity and a maximum range of about 5 pC. The APD and CSP are shown in Fig. 3. The APDs will be operated at moderate gain ( $M=30$ ) for low noise and high gain stability in order to maximize energy and timing resolution. This photodiode has a peak spectral response at a wavelength of 585 nm compared to an emission peak of 476 nm for the optical fibers. However, both the spectral response and the quantum efficiency of the APD are quite broad with the latter dropping from the maximum by only about 5% at the WLS fiber emission peak. At this wavelength, the manufacturer's specification gives a quantum efficiency of 80%.

### **2.2 The laboratory environment**

A laboratory especially designed to test and characterize all the Avalanche Photo Diodes planned for the ALICE EMCAL activity was prepared in our Institute. It has a size of about  $20 \text{ m}^2$ , and it is equipped with air conditioning, proper ground-clean electric power and network connections. A false floor allows a clean passage of cables wherever required.

### **2.3 Basic equipment for the first prototype measurements**

Before proceeding to the massive tests for all the APDs to be mounted in the super-modules of the EMCAL, a series of prototype measurements was carried out with a basic equipment, capable to test individual devices. This equipment includes a chiller, together with a temperature probe, to control and monitor the temperature of the photo diode, low and high voltage power supplies, a LED pulser, and a digital oscilloscope with histogram capabilities. Fig.4 shows the block diagram of the experimental setup, while fig.5 shows a picture of the setup. Such equipment, which is suitable for the characterization of single devices, was

actually used to test a first sample of 64 APDs which were successfully mounted and used during the 2007 beam test of a 64-towers prototype of the EMCal, with PS and SPS hadron and electron beams at CERN. For the laboratory tests, signals from the CSP were collected by a digital oscilloscope, and the results were analyzed on-line through the histogram capabilities of the oscilloscope. Typical results obtained during these first tests are reported in Sect.3.3.

To test however large samples of devices, as required for the construction of the super-modules (in the order of a few thousands), a more suitable system has been developed, to speed up the overall procedure and collect data files for off-line analysis. Such system is described in Sect.2.5.

## **2.4 The chiller and temperature control**

Since it is well known that the gain of Avalanche Photo Diodes is very sensitive to the temperature, the setup includes also a system for the control and monitoring of the APD temperature during the measurements: the liquid from a chiller flows through a pipe inside a copper plate; the APDs are placed in direct contact with this plate and their temperature is continuously monitored by a thermocouple placed on the APD surface. Once the nominal temperature is set through the board controller of the chiller, the APD temperature reaches the desired value after a few minutes, with minor discrepancies when exploring values very different from the ambient temperature, as shown in Fig.6. The use of such system allows a control temperature with precision of 0.1 °C. Fig.7 shows the copper plate and a series of APDs mounted on board during the test procedures which involve the simultaneous testing of 16 devices.

## **2.5 The acquisition system for massive APD testing**

As discussed in Sect.2.3, a large number of devices to be tested requires the use of a suitable system to collect and analyze the data and speed up the procedure. To this aim, a laboratory version of an acquisition system making use of the same hardware and software configuration which will be used during in-beam ALICE data taking has been implemented. The layout of the equipment used during these massive tests is shown in Fig.8. A highly stable blue LED from Kingbright (L7104PCB) with  $\lambda = 470$  nm [4], triggered by an external pulse generator (width 50 ns) with a frequency of 10 Hz is used as light source. To obtain the desired light intensity, a voltage of 400 V is applied. In Fig.9 the basic scheme of the avalanche LED pulser and a photograph of the LED driver are shown. The LED driver card is put in a metallic box to shield the apparatus from electromagnetic noise. The LED is inserted inside the optical connector and its light is delivered to the 16 APDs by a bundle of 1 mm fibers.

Signals from each APD, through its preamplifier, are sent to a T-card which couples the devices to the Front-End (FE) card, where the signals are shaped and sampled by two 10-bit ADCs. Fig.10 shows a block diagram of the readout architecture developed at CERN for the PHOS detector and adapted, with minor modifications, also to the EMCal [5]. A picture of

the electronics boards is shown in Fig.11. The digitized data are transferred, via an optical link, to a computer running the ALICE DAQ (DATE).

### 3 TEST PROCEDURES AND RESULTS

#### 3.1 Characteristics of APDs as measured by Hamamatsu

A series of quantitative measurements concerning each individual APD are carried out by Hamamatsu when supplying the devices. They include the breakdown voltage  $V_B$ , the voltage ( $V_{50}$ ) at which the APD gain equals  $M=50$ , the dark current  $I$  and the capacity  $C$ , all measured at  $T=25$  °C. In previous APD samples, the breakdown voltage was found to be highly correlated with  $V_{50}$ . Fig.12 shows the correlation plot between the breakdown voltage and the voltage  $V_{50}$ , as supplied from Hamamatsu, for a sample of about 1000 APD under test for the construction of the first super-module of the EMCAL. The distribution of the dark current for the same set of devices is shown in Fig.13, while Fig.14 shows the scatter plot between the dark current and the breakdown voltage.

#### 3.2 Assembly and labeling procedure

Each APD comes from Hamamatsu with a 10-digit serial number, which is stamped on the back side of the APD. However, when the APD is soldered to the charge preamplifier, such number cannot be seen, so that it should be recorded together with the preamplifier serial number before connecting them as an entity. Preamplifier serial numbers are not assigned at the production stage, and they must be labeled before connecting them to the APD. Preamplifiers are assigned a 5-digits serial number, to be attached to the outer side of the molex connector and also on the component-less side of the preamplifier.

The APDs were soldered to the preamplifiers with the back surface of the APD flush with the front (component-less) surface of the preamplifier. This can be done by laying the APD active surface on a clean surface and inserting the preamplifier onto the APD leads. The APD leads are located asymmetrically. When the APD is inserted properly on to the preamplifier, the APD will be centered on the preamplifier. The APD leads should be soldered to the preamplifier while the preamplifier is lying on the table with the component side face up. The soldering should be done with a low heat and short duration of contact with the APD leads such that the solder flows well into the APD contact holes, without stressing the device. After soldering, the excess length of the APD solder leads has been trimmed off.

#### 3.3 Testing single devices through the oscilloscope

Typical tests for a single APD consist in the measurement, at a fixed temperature, of the gain dependence on the bias voltage to determine the voltage for which the gain equals  $M=30$ . The gain  $M(V)$  is defined as the ratio between the amplitude at the voltage  $V$  and the amplitude in the plateau (low APD voltages). When testing the APD through a digital

oscilloscope, after collecting a suitable number of events (in the order of 1000) for each voltage, the amplitude extracted from the corresponding histograms (Fig.15) permits to evaluate the gain by a comparison to the amplitude measured at low voltages. The shape of the gain vs voltage curve (Fig.16) is an exponential function and may be well fitted with an exponential plus a constant:

$$M(V) = p_0 + p_1 e^{p_2 V}$$

where  $M(V)$  is the gain at the voltage  $V$ . The low gain plateau value can be determined in different ways. Accurate studies have shown that in our case the best reference value is the amplitude at 50 V. The relative change of the gain with the bias voltage (the voltage coefficient) is a linear function of the gain. In the present case such coefficient turned out to be  $1/M \times dM/dV = 2.3\%/V$  at  $M=30$  (Fig.17). This voltage dependence has a significant effect on the energy resolution of the EMCAL: if the voltage control step is 0.2 Volt/bit, a coefficient of  $2.3\%/V$  would limit the gain calibration to 0.46%.

The EMCAL will be operated at ambient temperature. Recent estimates of the temperature in the EMCAL region inside the L3 magnet give values around 20-21 °C and a temperature uniformity in the order of 1-2 °C. Large differences with respect to such values may be however expected. For this reason the APD behaviour has been studied in the range around the room temperature (from 21 °C to 29 °C). Examples of gain curves, for the same APD, obtained at different temperatures, are shown in Fig.18. The dependence on the temperature is especially evident at higher values of the bias voltage, where the gain undergoes a strong variation with temperature changes. As it can be seen from Fig. 19, where the gain versus temperature is reported for four different APDs, the relation between gain and temperature is approximately linear at a fixed value of the bias voltage. The parameter from the linear fit allows to calculate for each APD the temperature coefficient  $1/M \times dM/dT$ , which is the percentage change in gain per one degree change in temperature. In Fig.20 the temperature coefficient as a function of the APD gain is reported, showing that this quantity is strongly dependent on the gain. At  $M=30$  the temperature coefficient is  $-1.7\%/^{\circ}C$ ; this means that for a variation of  $+1^{\circ}C$ , the gain of 30 will change to about 29.5. Measurements repeated on a significant number of APDs, showed that the voltage and temperature coefficients ( $2.3\%/V$  and  $-1.7\%/^{\circ}C$  at  $M=30$ ) are quite similar for all APDs. For example, the RMS of the temperature coefficient distribution is  $0.1\%/^{\circ}C$ . Conversely, at the same reverse-bias voltage a batch of 170 APDs showed considerable differences in the individual APD gain. For example, applying a bias voltage of 380 V, the distribution of gains ranged from  $M=20$  to  $M=90$ .

### 3.3 Massive test procedures

Massive tests for the characterization of the devices to be installed in the first super-module of the electromagnetic calorimeter were initiated in our lab during September 2008.

The tests involved the determination of the individual gain curves at the (controlled) temperature of 25 °C, by the use of a software procedure which controls the voltage to the APD while data are collected by DATE. After measuring the amplitude at the plateau value ( $V=50$  V), a script running on the DCS card varies the voltage to be sent to the APD in controlled steps, waits a fixed amount of time (in the order of 1-3 minutes, depending on the voltage step) before stepping on, while data are collected and stored by the ALICE DATE software. The trigger is disabled and enabled again during the various voltage steps.

A set of 16 APDs is characterized simultaneously. For reference purposes, one APD was always mounted in the same position on the copper plate (and data were sent always to the same channel), in order to check the results and the reproducibility.

Once the raw data are stored on file, a script is launched and produces a root file for graphical and numerical analysis. Fig.21 shows an example of an overall plot of the gain curves for 16 APDs tested in a single run. Basically, the same procedure is then adopted, as for single APD (Sect.3.3), to extract the quantities of interest (fit parameters and their errors,  $V_{30}$ , voltage coefficient) to be inserted in the database.

### **3.4 Archiving procedure and database**

A proper database must be devised in order to keep track of the Hamamatsu information and of the results obtained from the test procedure for each individual APD. Since the coupling of such information to the physical tower and its location in the EMCAL structure will be defined later, at this stage it will be enough to record the APD+Preamplifier information, together with the information supplied by Hamamatsu, for instance in an EXCEL spreadsheet. This should include the following data: APD and CSP Serial Numbers, status of the assembly, parameters of the fit and their errors,  $V_{30}$ , Voltage Coefficient. Fig.22 shows a section of the database, with the relevant information for a set of APD data.

### **3.5 Statistical analysis of the results**

Here we present a preliminary statistical analysis of the results extracted from a set of about 1000 APDs already tested according to the procedure described in this Section. Fig.23 shows the distribution of the values  $V_{30}$ , i.e. the voltages required to have an individual gain of 30. Such distribution is particularly important, since APDs which require voltages in excess of 400 V cannot be used in the ALICE EMCAL, due to the hardware employed for the power supplies. The distribution shown in Fig.23 points out that the percentage of the devices requiring voltages higher than 400 V is of the order of 20 %, which is higher than expected on the basis of the first test of prototypes (where less than 10% of the devices were found to exhibit a too large  $V_{30}$ ). Moreover, such percentage was found to be strongly dependent on the particular batch of devices provided by Hamamatsu, as it can be seen from Fig. 24, which shows the distribution of the  $V_{30}$  in a series of three different lots tested in Catania. Similar problems are being experienced by the Houston group, who is going to test the APDs for the US Collaboration.

According to this result, a larger amount of spare devices has to be planned to take into account this aspect, or, conversely, a slightly smaller gain has to be decided during data taking. Discussions are going on in the Collaboration to provide the best solution to the problem. No fault device (neither APD nor preamplifier) has been found in this lot of about 1000 assemblies.

A good correlation was found between the value  $V_{30}$  extracted by our tests and the value  $V_{50}$  provided by the manufacturer, as shown in Fig.25, in agreement with the findings obtained during the first tests. A good correlation was also found between  $V_{30}$  and the breakdown voltage provided by the manufacturer. In principle, such correlation allows to predict how many devices will have a too large  $V_{30}$  value in a given batch.

For each APD, the voltage coefficient was also extracted from the results. The distribution of such quantity is shown in Fig.26.

### **3.6 Final assembly**

For the final assembly, each Avalanche Photo Diode must be glued to a truncated pyramid Plexiglas light guide, inserted in a black plastic cylinder, in order to provide a suitable coupling with the fiber bundle. For such operation, a special tool was built, in order to glue and hold simultaneously, for several hours, a set of 10 APDs (Fig.27). It consists of three aluminium plates which may be piled through some vertical guides: the APDs are placed onto the lower plate in proper slots which keep the sensors immobile; the optical glue is injected on the APD surface using a precision dispenser and the coupling with the light guides is carried out piling the second plate, which steadily holds the plastic cylinders; finally, the third plate is put on to press the layers below.

At room temperature, the required time is in the order of 24 hours; however larger temperatures allow reduced times to be used, so after some test, a higher temperature will be used – making use of a small oven - in order to speed up the procedure.

To check the attenuation introduced by the light guide, a series of measurements were carried out on a few samples, before and after the gluing procedure. The results showed that the voltages  $V_{30}$ ,  $V_{50}$  and the voltage coefficient are very close to those obtained before and that the attenuation factor is in the order of 10%. Fig.28 shows a picture of the assembly, ready to be coupled to the fiber bundle.

## **4 CONCLUSIONS**

After about one year of activity, the hardware, software and testing procedures for the characterization of the Avalanche Photo Diodes required for the European super-modules of the ALICE Electromagnetic Calorimeter are ready and fully tested in our site. The main results from such activity were recently published and presented to International Conferences [6,7]. A similar activity has just started in the US, with the same configuration employed in Catania. Starting from September 2008, a lot of more than 1000 devices have been fully



tested and characterized in a relatively short time, with the collaboration of physicists and technicians from our Institution. The functionality of the system and the time required to carry out such tests were demonstrated to be fully compatible with the planned installation of the first super-module of the EMCal at CERN in January 2009.

## 5 ACKNOWLEDGMENTS

The authors warmly thank the Directors of the Department of Physics and Astronomy, F.Porto, and of the INFN, Sezione di Catania, F.Catara and A.Pagano, for their support to the local ALICE activities, and in particular to the organization of the EMCal laboratory for APD testing.

The contribution of M.Mazzeo, G.Platania, A.Rapicavoli and V.Sparti is acknowledged. The assistance of D.Wang, N.Tupikin and O.Parasole during the first tests carried out in Catania is also recognized.

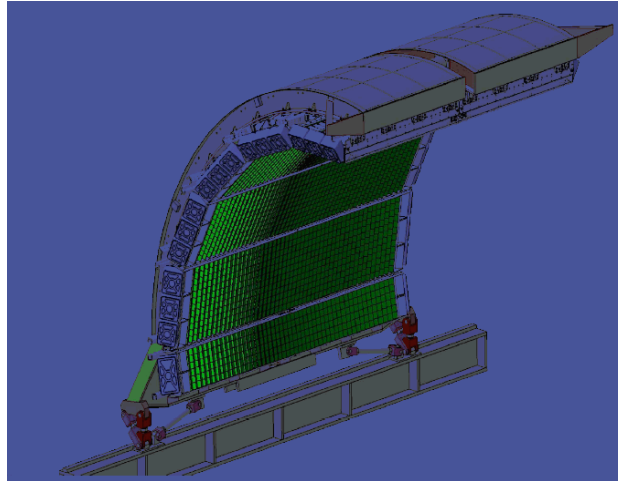
The overall APD testing activity in Catania would not have been possible without the help and the contribution of several colleagues in the ALICE Collaboration. In particular, we are grateful to Terry Awes, Hans Müller and David Silvermyr for their continuous help and for providing us with part of the equipment needed for such task.

## 6 REFERENCES

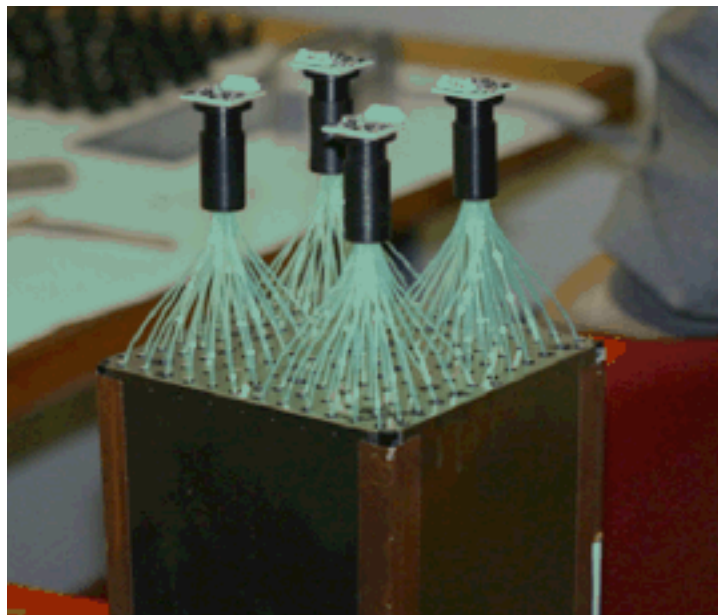
- [1] The ALICE Collaboration, *Journal of Instrumentation*, 2008\_JINST\_3\_S08002 (2008)
- [2] The ALICE Collaboration, *The Electromagnetic Calorimeter*, Addendum to the Technical Design Report, CERN-LHCC-2006-014
- [3] The ALICE Collaboration, *The Electromagnetic Calorimeter*, Technical Design Report CERN-LHCC-2008/014.
- [4] Kingbright, [www.Kingbright.com](http://www.Kingbright.com)
- [5] H.Müller et al., *Nuclear Instruments and Methods in Phys.Research A* 565(2006)768.
- [6] A.Badalà et al., *Nuclear Instruments and Methods in Phys.Research A*, doi 10.1016/j.nima.2008.07.133
- [7] A.Badalà et al., *Proceedings of the NDIP08 Conference, Aix-Les-Bains (2008)*; *Nuclear Instruments and Methods in Phys.Research A*, in press.

*Table 1: Main properties of the Hamamatsu APD S8664-55 (S8148) to be employed in the construction of the ALICE EMCAL.*

Active Area	$5 \times 5 \text{ mm}^2$
Capacitance	80 pF
Wavelength min.	$\sim 320 \text{ nm}$
Wavelength max.	$\sim 1000 \text{ nm}$
Peak wavelength	600 nm
Quantum efficiency	$\sim 80\%$ at 476 nm



*Fig.1: Layout of the overall structure of the ALICE Electromagnetic Calorimeter.*



*Fig.2: A set of four towers with the fiber bundles and the attached APD-preamplifier assemblies.*

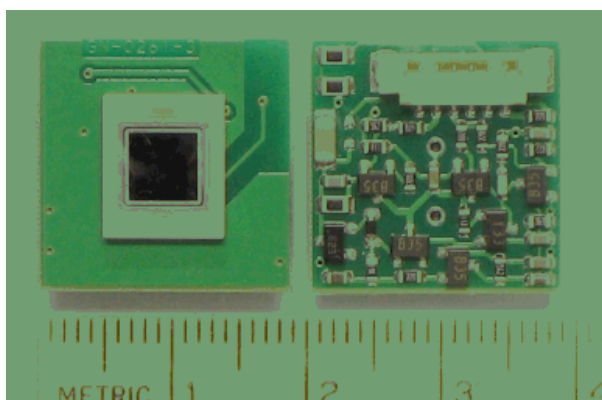


Fig.3: One of the Hamamatsu Avalanche Photo Diode mounted on board of the Charge Sensitive Preamplifier.

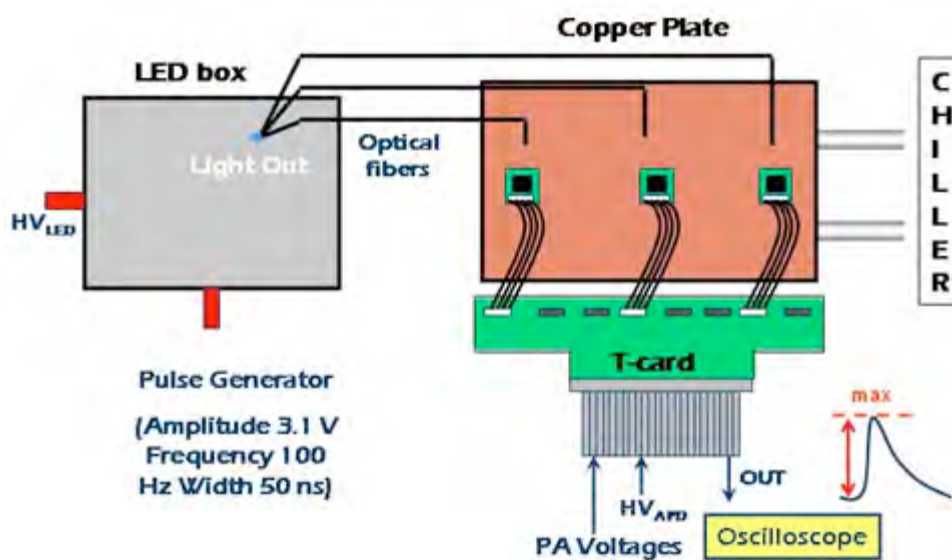
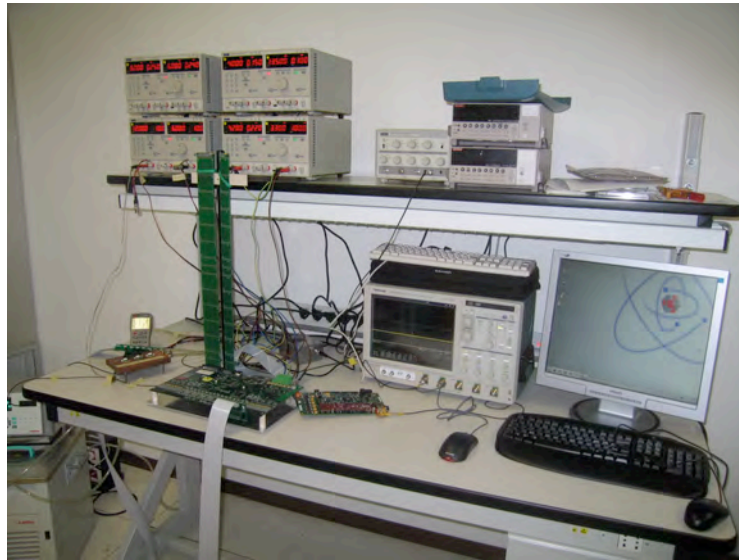
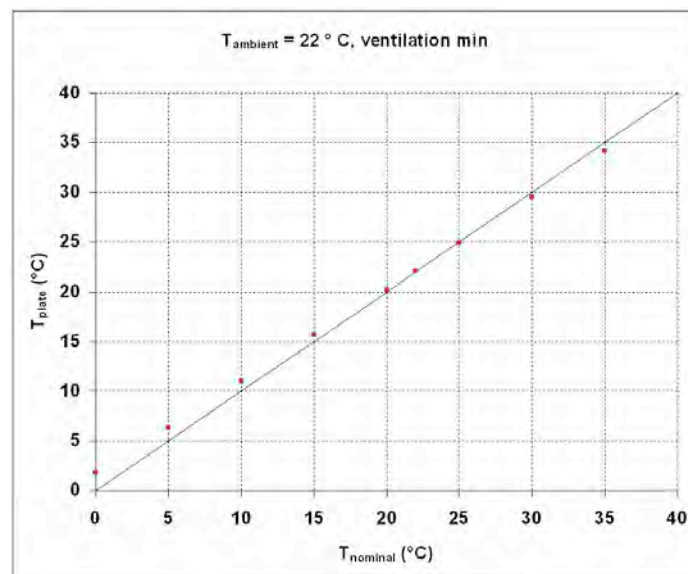


Fig.4: The block diagram of the test setup used in our lab for the first prototype APD characterization.



*Fig.5: A picture of the setup used during the first prototype tests.*



*Fig.6: Temperature measured on the copper plate vs the nominal temperature setting in the chiller.*

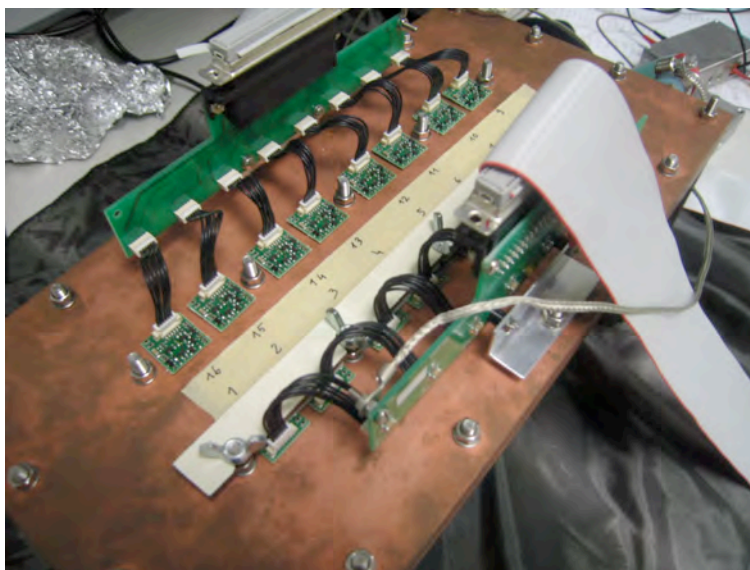


Fig.7: The copper plate ensuring uniformity and control of the APD temperature for a set of 16 APD to be simultaneously tested.

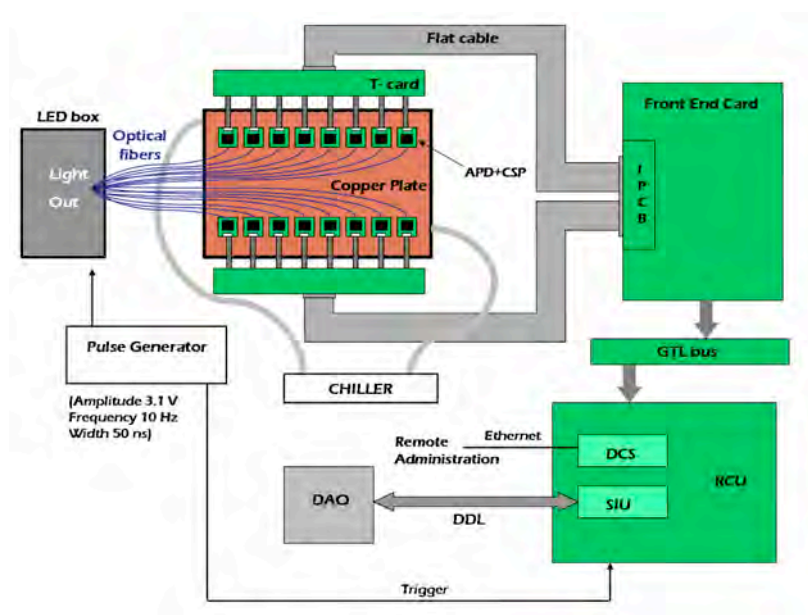


Fig.8: Building blocks of the experimental setup for APD characterization during the massive measurements.

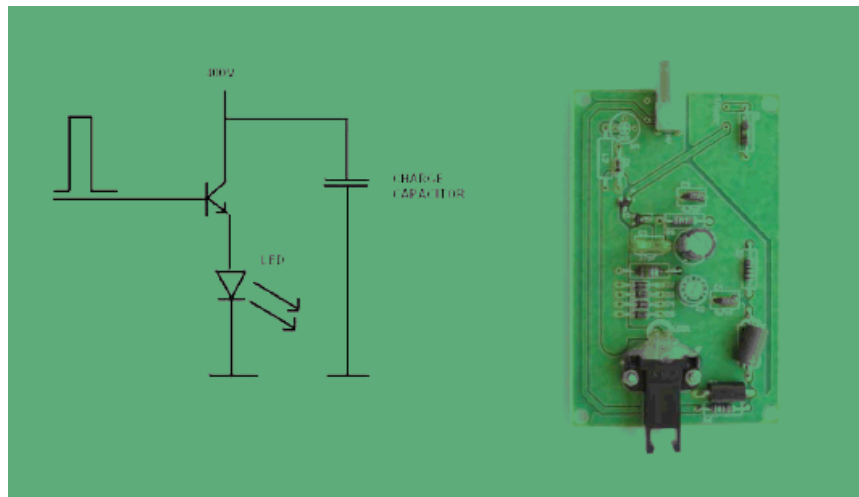


Fig.9: Scheme of the avalanche LED pulser (left) and a photograph of a LED driver (right) [5].

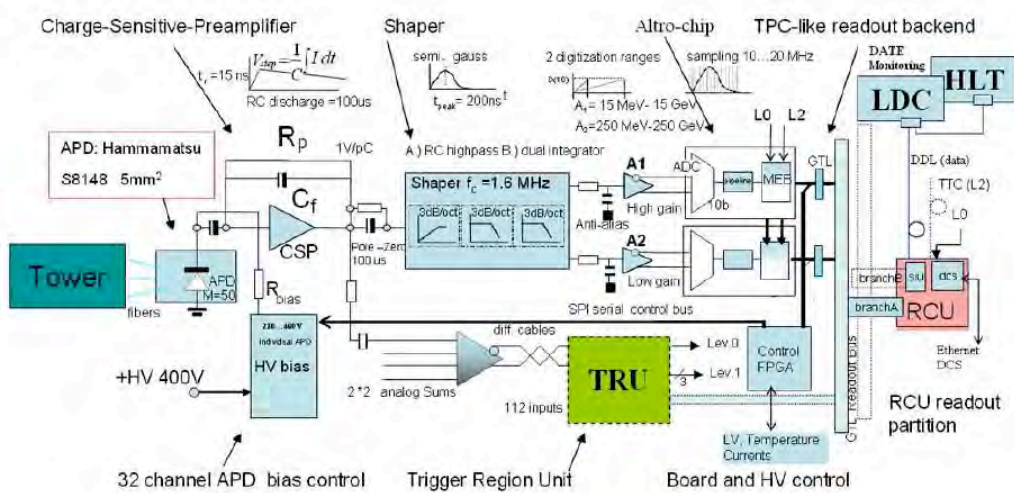


Fig.10: Schematics of the electronics developed at CERN for APD testing [5].



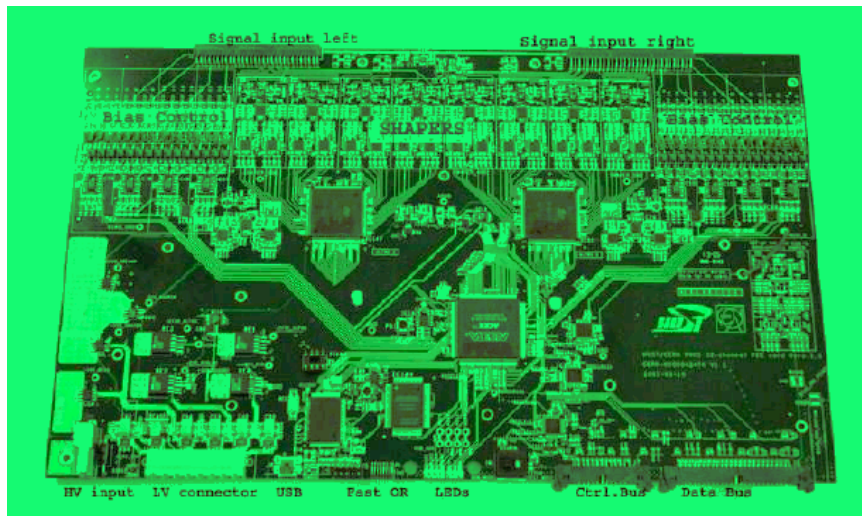


Fig.11: Picture of the DAQ electronics card [5].

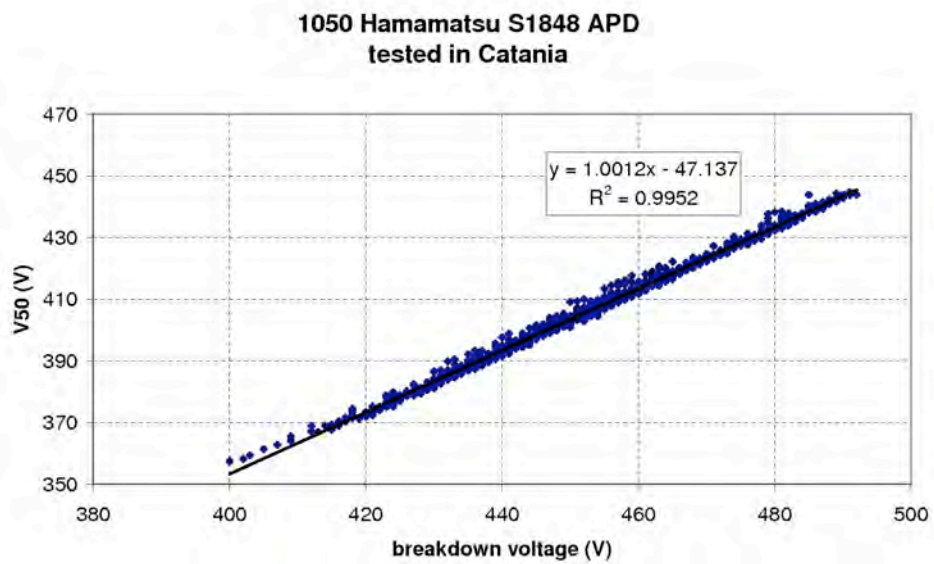


Fig.12: Correlation between the voltage  $V_{50}$  and the breakdown voltage  $V_B$  in a sample of APD devices supplied by Hamamatsu.



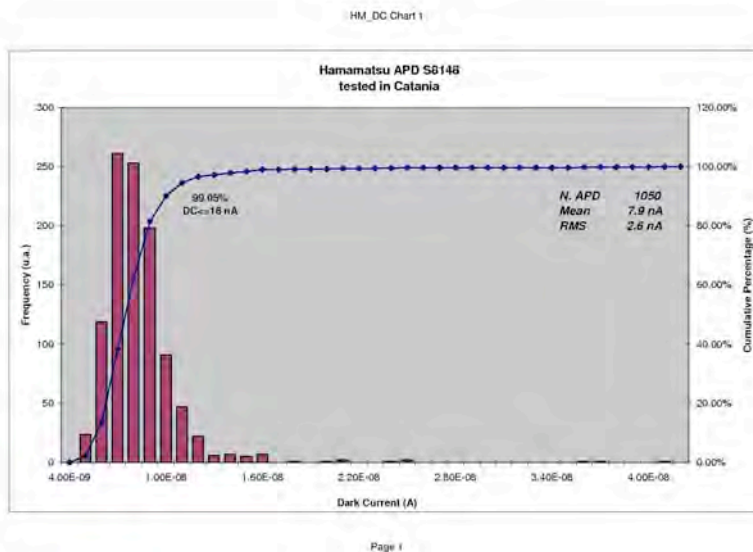


Fig.13: Distribution of the dark current in a sample of APD provided by Hamamatsu and under test for the construction of the first super-module of the EMCAL.

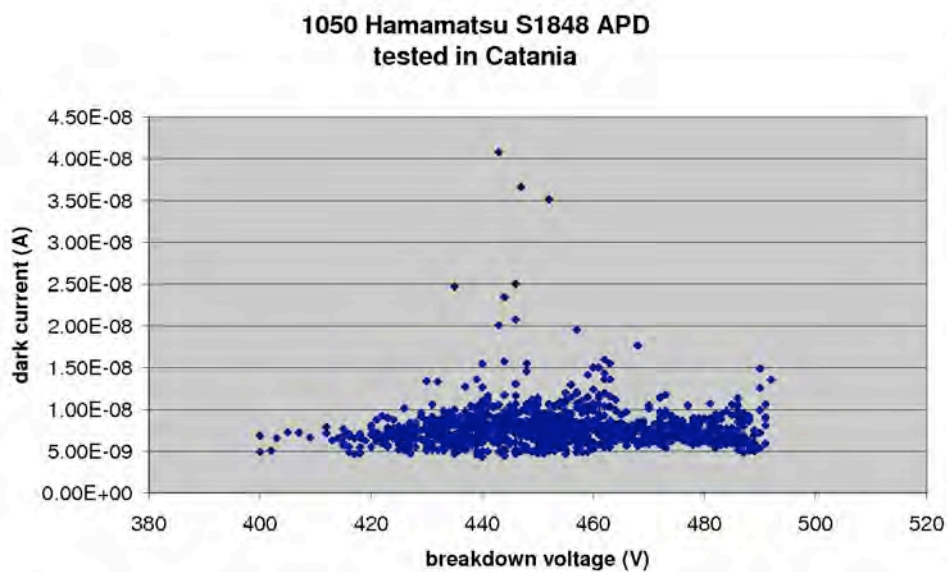


Fig.14: Scatter plot of the dark current vs breakdown voltage.

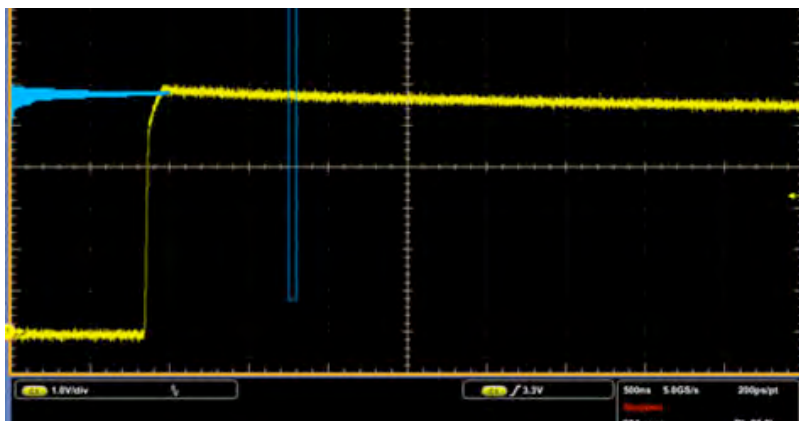


Fig.15: A screenshot from the digital oscilloscope.

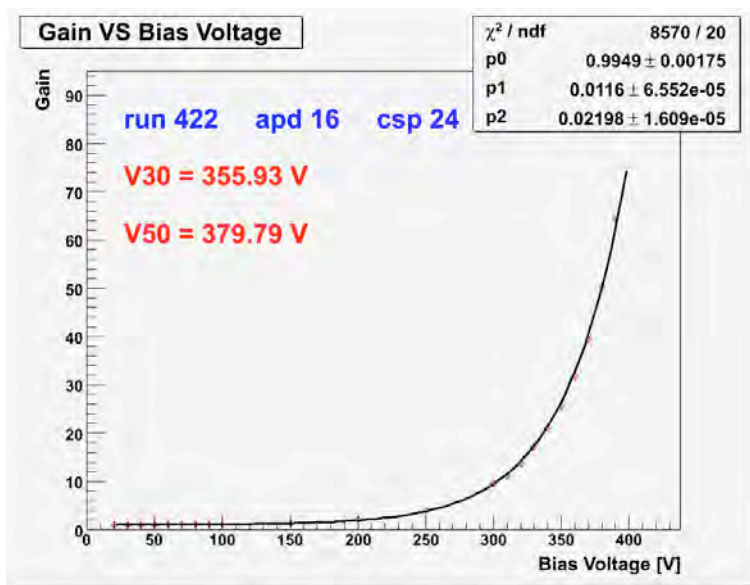


Fig.16: A typical APD gain vs voltage.

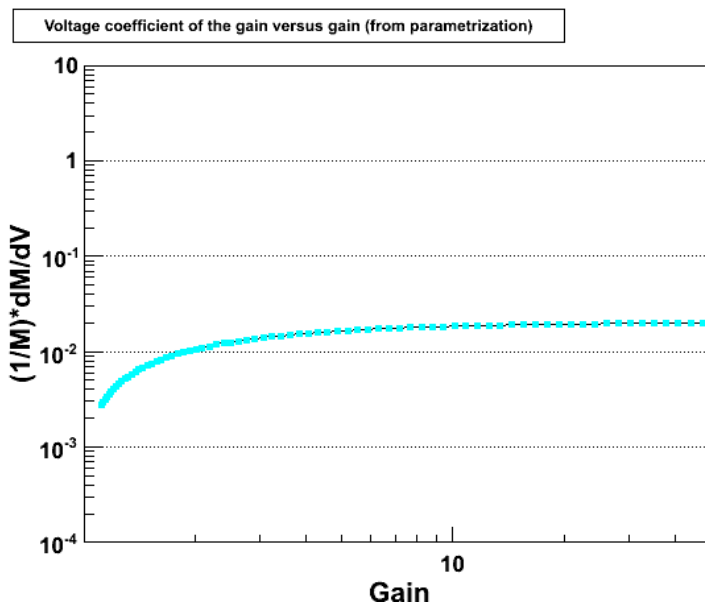


Fig.17: Voltage coefficient as a function of the APD gain.

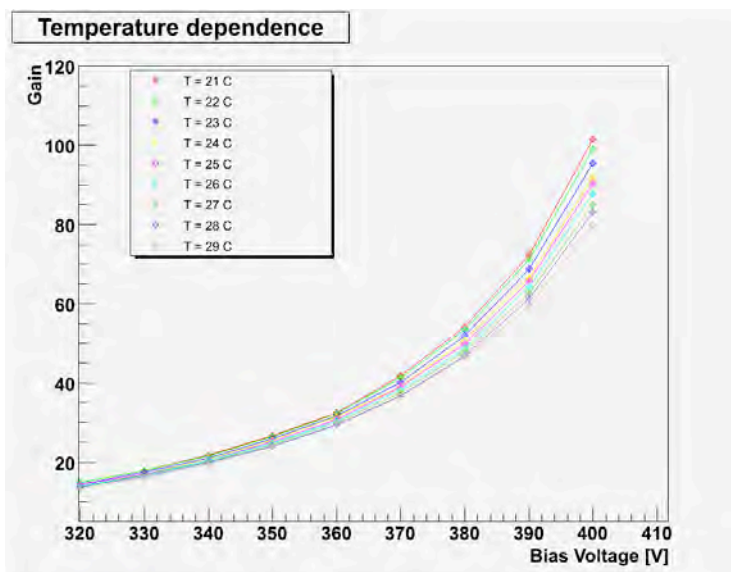


Fig.18: Gain curves measured at different APD temperatures.

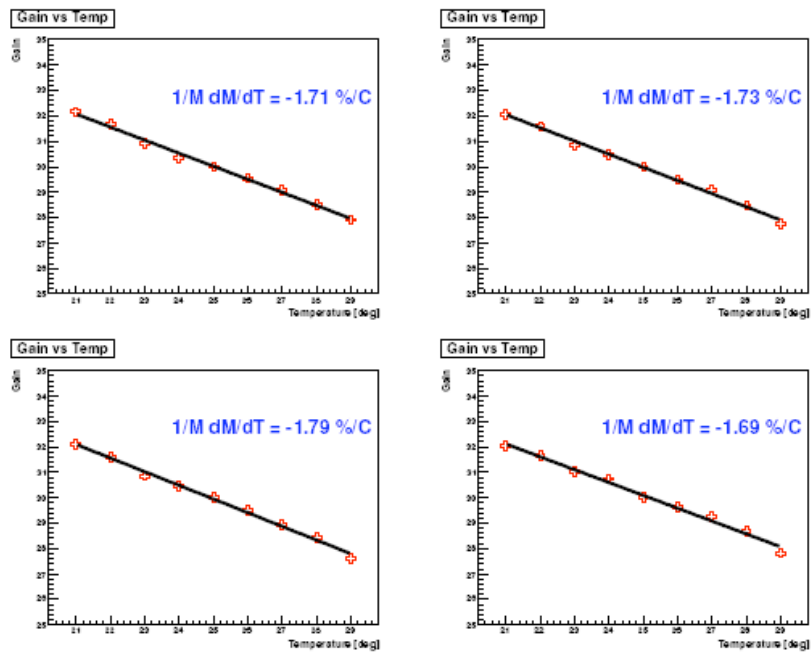


Fig.19: APD gain vs temperature for a set of four APD.

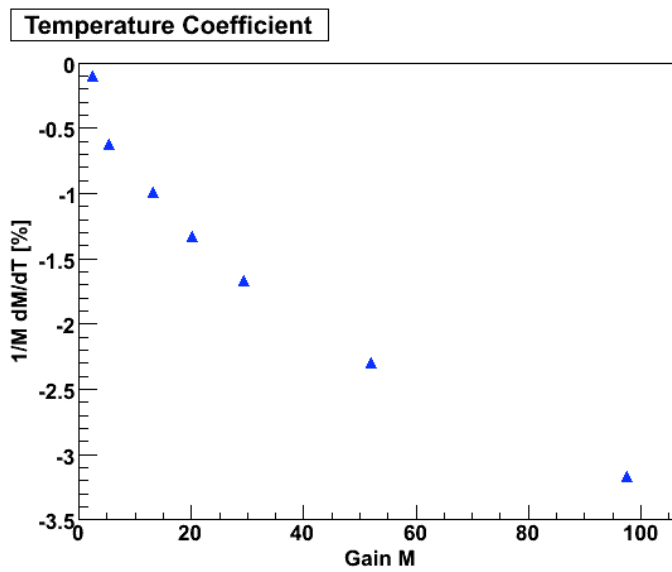


Fig.20: Temperature coefficient vs gain.

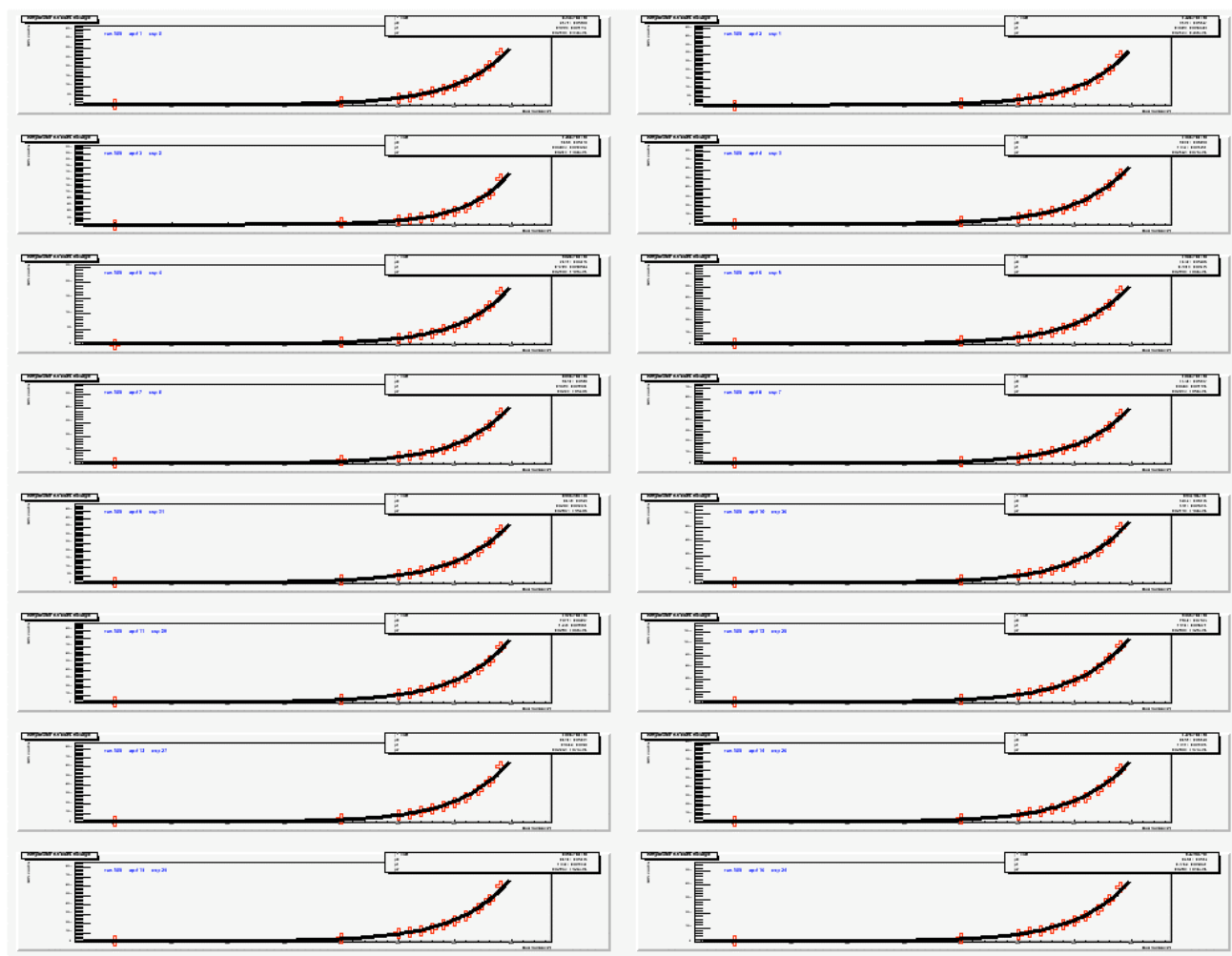


Fig.21: A set of 16 gain vs voltage curves.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	APD_PA number	Serial Number	Status	Present location	Rou number	Caatania Voltage V30 (V) at T = 25°	Caatania Voltage V50 (V) at T = 25°	Voltage Coefficient 1/Ma/μA/V	pe (ft)	pl (ft)	p2 (ft)	eo (ft)	e1 (ft)	e2 (ft)
2	11217	320416600	tested	Catania	642	417,99	440,73	2,16	4,52	6,03E-04	2,55E-02	0,16	1,07E-04	4,20E-04
3	11218	320416601	tested	Catania	642	416,18	436,68	2,38	5,57	1,21E-04	2,92E-02	0,10	1,90E-05	3,49E-04
4	11219	320416602	tested	Catania	642	417,73	441,42	2,08	4,17	1,03E-03	2,42E-02	0,17	1,80E-04	4,03E-04
5	11220	320416603	tested	Catania	642	418,45	443,43	1,99	3,31	2,28E-03	2,24E-02	0,18	3,41E-04	3,49E-04
6	11221	320316604	tested	Catania	642	418,03	446,34	1,78	1,77	1,04E-02	1,89E-02	0,20	6,37E-05	1,43E-03
7	11222	320316605	tested	Catania	642	416,79	438,92	2,22	4,92	4,00E-04	2,65E-02	0,13	6,22E-05	3,68E-04
8	11223	320316606	tested	Catania	642	414,25	443,38	1,75	0,56	1,83E-02	1,78E-02	0,32	2,89E-03	3,55E-04
9	11224	320316607	tested	Catania	642	420,55	445,32	2,00	3,80	1,72E-03	2,29E-02	0,18	2,88E-04	3,92E-04
10	11225	320316608	tested	Catania	642	422,46	448,92	1,82	2,74	5,74E-03	2,00E-02	0,20	8,99E-04	3,60E-04
11	11226	320316609	tested	Catania	642	414,83	441,15	1,90	2,88	4,48E-03	2,10E-02	0,20	6,52E-04	3,38E-04
12	11227	320316610	tested	Catania	643	417,95	442,99	1,98	3,67	2,11E-03	2,26E-02	0,36	6,81E-04	7,48E-04
13	11228	320316611	tested	Catania	643	405,81	430,09	2,03	4,15	1,79E-03	2,36E-02	0,38	5,02E-04	6,54E-04
14	11229	320316612	tested	Catania	643	394,76	415,01	2,34	7,97	7,30E-05	3,19E-02	0,13	9,88E-06	3,18E-04
15	11230	320316613	tested	Catania	643	405,72	430,86	1,97	4,06	2,26E-03	2,27E-02	0,27	4,83E-04	4,42E-04
16	11231	320316614	tested	Catania	643	409,26	434,76	1,94	3,71	2,99E-03	2,22E-02	0,35	7,40E-04	5,79E-04
17	11232	320316615	tested	Catania	643	407,92	431,46	2,08	4,84	1,00E-03	2,48E-02	0,30	2,57E-04	6,05E-04
18	11233	320316616	tested	Catania	643	410,46	431,10	2,35	6,00	1,40E-04	2,94E-02	0,14	2,58E-05	4,41E-04
19	11234	320316617	tested	Catania	643	415,75	440,52	2,00	3,83	1,90E-03	2,29E-02	0,30	4,94E-04	6,04E-04
20	11235	320316618	tested	Catania	643	404,42	428,34	2,05	4,86	1,26E-03	2,45E-02	0,20	1,96E-04	3,63E-04
21	11236	320316619	tested	Catania	643	403,45	429,55	1,92	2,73	5,33E-03	2,11E-02	0,25	7,83E-04	3,31E-04
22	11237	320316620	tested	Catania	643	400,16	421,72	2,24	6,54	2,51E-04	2,86E-02	0,17	3,86E-05	3,67E-04
23	11238	320316621	tested	Catania	643	402,09	429,69	1,83	1,23	1,31E-02	1,91E-02	0,48	2,85E-03	4,98E-04
24	11239	320316622	tested	Catania	643	402,49	426,05	2,08	5,09	1,06E-03	2,30E-02	0,21	1,71E-04	3,84E-04
25	11240	320316623	tested	Catania	643	401,67	427,29	1,95	3,03	4,30E-03	2,17E-02	0,31	7,85E-04	4,06E-04
26	11241	320316624	tested	Catania	643	405,96	431,86	1,93	2,84	4,75E-03	2,13E-02	0,31	8,97E-04	4,39E-04
27	11242	320316625	tested	Catania	644	404,47	428,55	2,04	4,65	1,43E-03	2,41E-02	0,39	4,28E-04	6,88E-04
28	11243	320316626	tested	Catania	644	412,62	437,47	1,99	3,82	2,11E-03	2,28E-02	0,35	5,99E-04	6,38E-04
29	11244	320316627	tested	Catania	644	410,78	430,91	2,40	6,42	8,51E-05	3,05E-02	0,10	1,25E-05	3,52E-04
30	11245	320316628	tested	Catania	644	412,93	438,69	1,93	3,61	3,12E-03	2,19E-02	0,26	6,25E-04	4,67E-04

Fig.22: A section of the EXCEL database with the relevant parameters extracted from the test procedures.



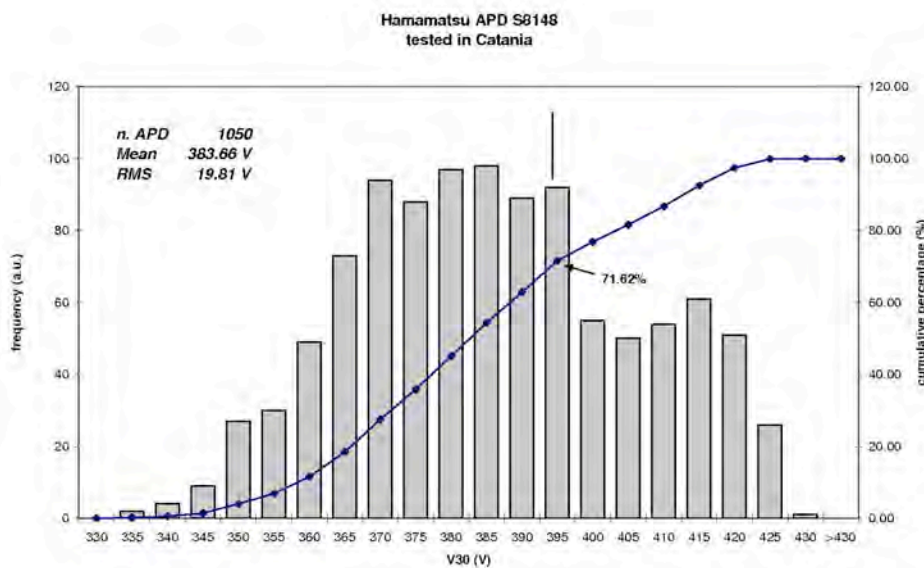


Fig.23: Distribution of the V30 values for a set of 1050 APD as measured in our laboratory

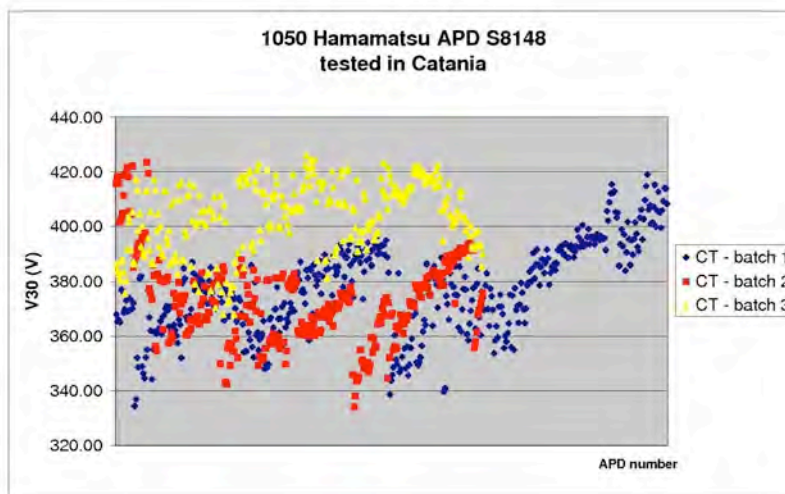


Fig.24: Distribution of the V30 values for three different batches of APD tested in Catania.

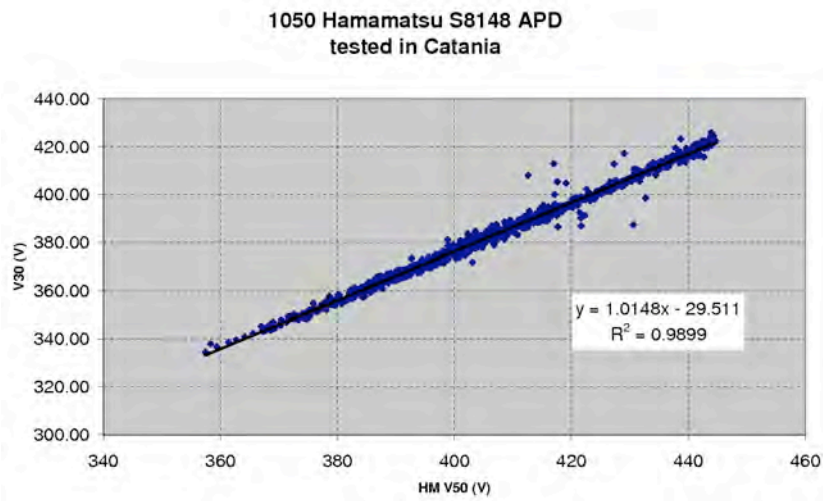


Fig.25: Correlation between the values  $V_{30}$ , as obtained during the tests and the values  $V_{50}$  provided by Hamamatsu.

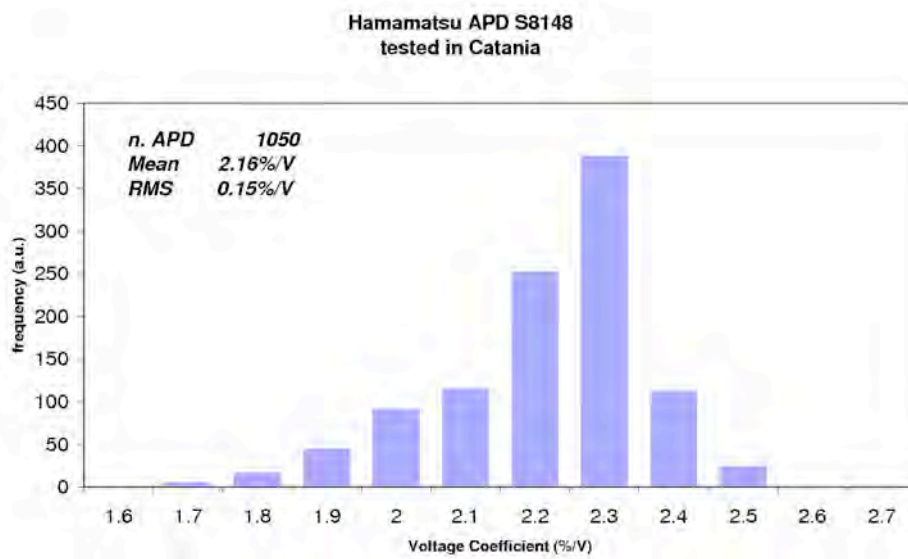
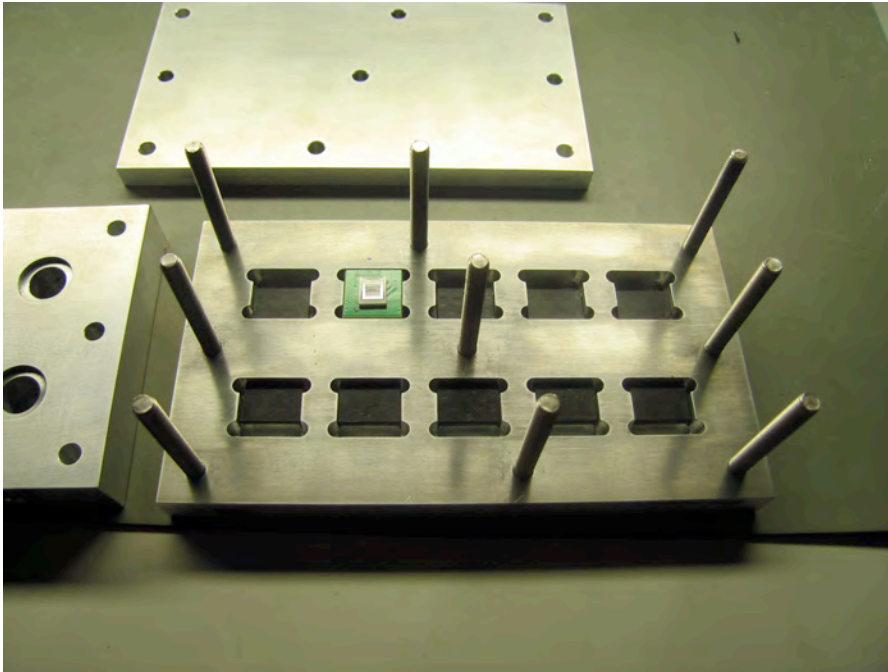


Fig.26: Distribution of the voltage coefficients (%/V) obtained from a lot of 1050 APD tested in our lab.





*Fig. 27: The tool employed to glue the APDs to the Plexiglas light guide.*



*Fig. 28: The light guide after gluing it to the APD.*