



Réunion Suivi de Projets du SERDI

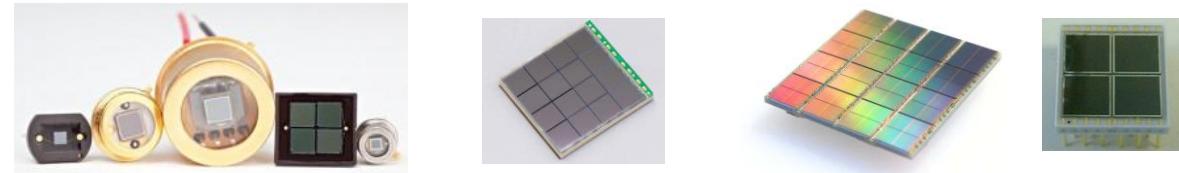
Etudes SiPM

17 janvier 2013 – Vincent Chaumat

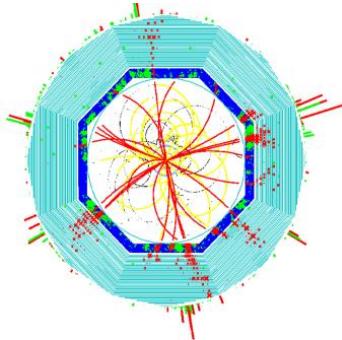
Leonid Burmistrov, Nicoleta Dinu, Véronique Puill, Jean-François Vagnucci

avec la participation de D. Breton, C. Cheikali, J. Maalmi , le SDTM, le DA, le SI (groupe temps réel)

Pourquoi les étudier ?



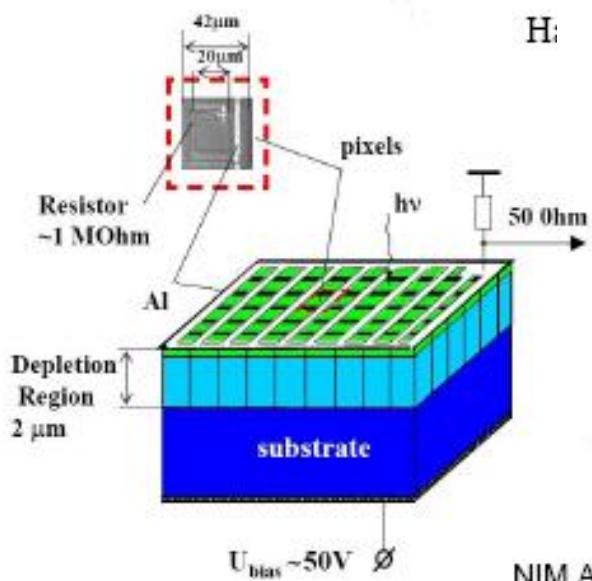
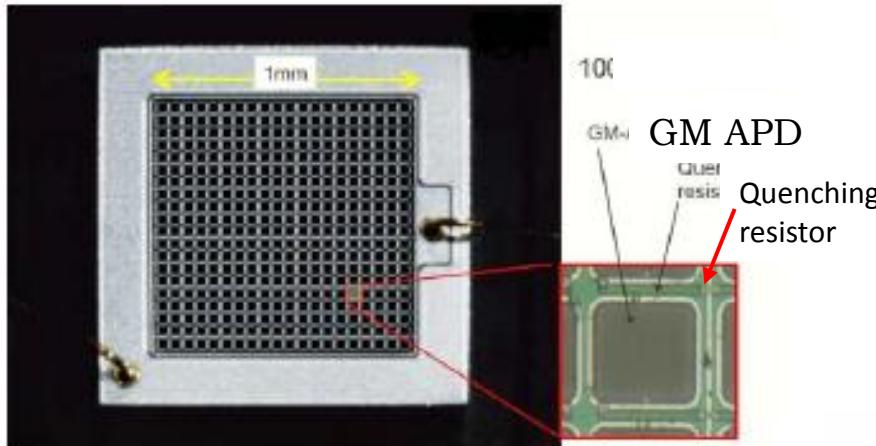
- ❖ Le SiPM est un photo-détecteur au développement récent et en constante amélioration
- ❖ Il pourrait remplacer le photomultiplicateur dans de nombreuses applications :
HEP : calorimétrie, identification de particules, Astrophysique, imagerie médicale,



- ❖ Son fonctionnement est complexe → les phénomènes physiques, qui régissent son fonctionnement , ne sont pas tous compris .
- ❖ les différents développements sont nombreux (provenant de + de 15 sociétés/instituts)

Principe de fonctionnement d'un SiPM

HAMAMATSU MPPC

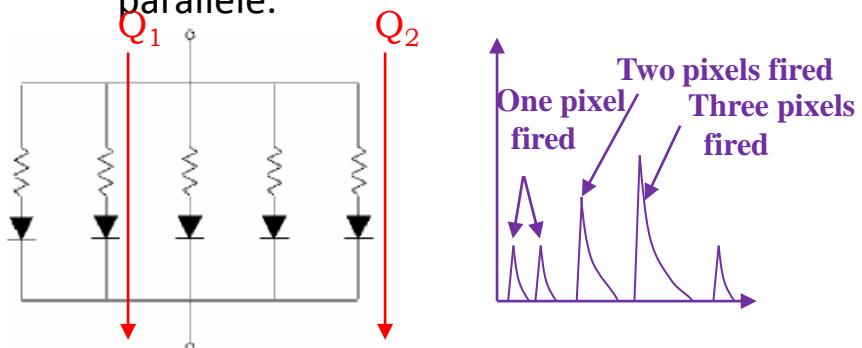


NIM A 504 (2003) 48

- le DéTECTeur SiPM est segmenté en micro cellule GM-APD (de 100 à 40000 pixels/mm²)

- chaque pixel a une résistance de quenching (extinction de l'avalanche)

- tous les pixels sont connectés en parallèle.



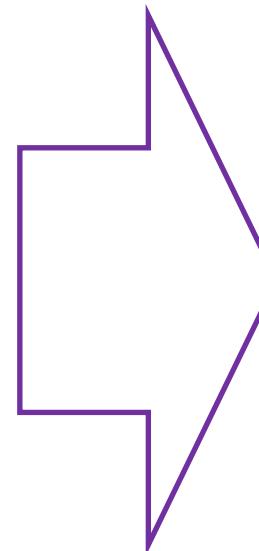
$$Q = Q_1 + Q_2 = 2 \times Q_1$$

charge \propto nombre de pixels allumés

\propto nombre de photons incidents

Caractérisation dans le noir :

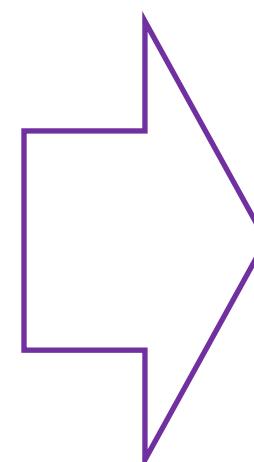
- breakdown voltage
- leakage current
- quenching resistance
- time structure (rise time, recovery time)
- noise (thermal generation, afterpulses, optical cross-talk)
- gain
- capacitance



Bancs de mesure à
l'oscurité

Caractérisation sous lumière :

- Photon Detection Efficiency
- Temporal resolution (1 photoelectron)



Banc de mesure avec
sources de lumière

Projets d'études génériques :

Projet SiPM 1 : image de l'état de l'art des SiPMs de 1 mm² de surface active (5 fabricants, 10 dispositifs)

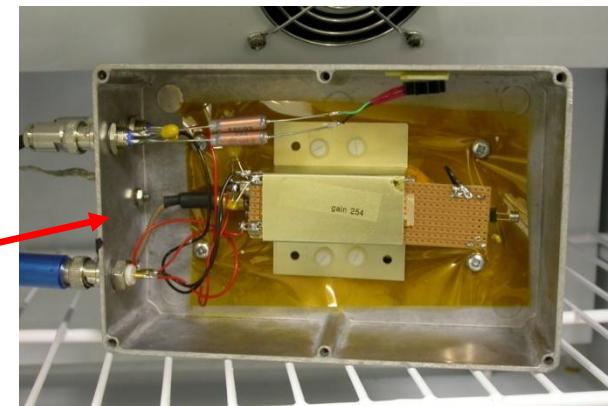
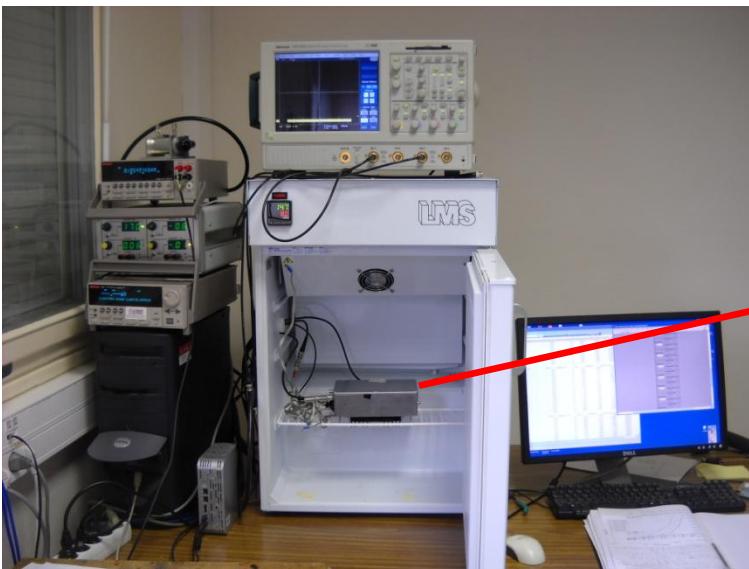
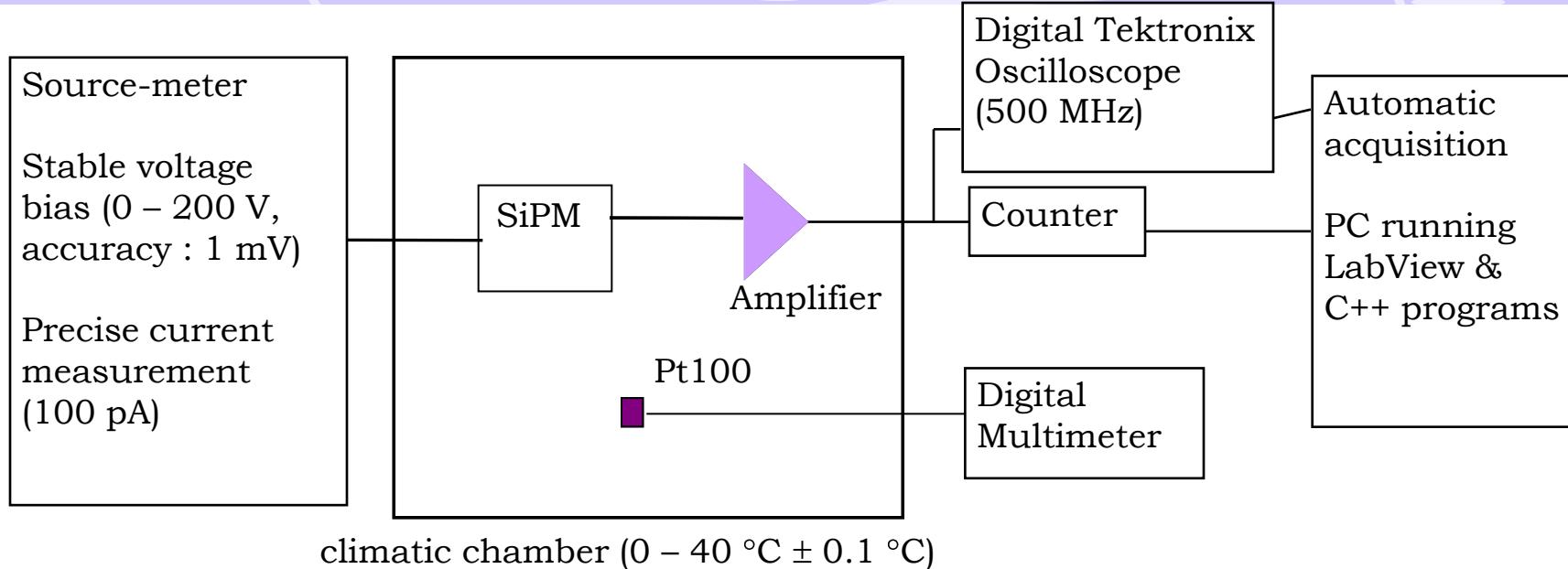
Projet SiPM 2 : caractérisation des SiPMs (1 & 9 mm²) en fonction de la température (de -120 °C à 40 °C) en collaboration avec FERMILAB et l'Université de Kiev ([en cours](#))

Projet SiPM 3 : mesure de la résolution temporelle au photo-électron unique des SiPMs de 1 & 9 mm² (3 fabricants, 13 dispositifs) ([en cours](#), collaboration avec l'Université de Kiev)

Projet SiPM 4 : mesure absolue de la PDE des SiPMs

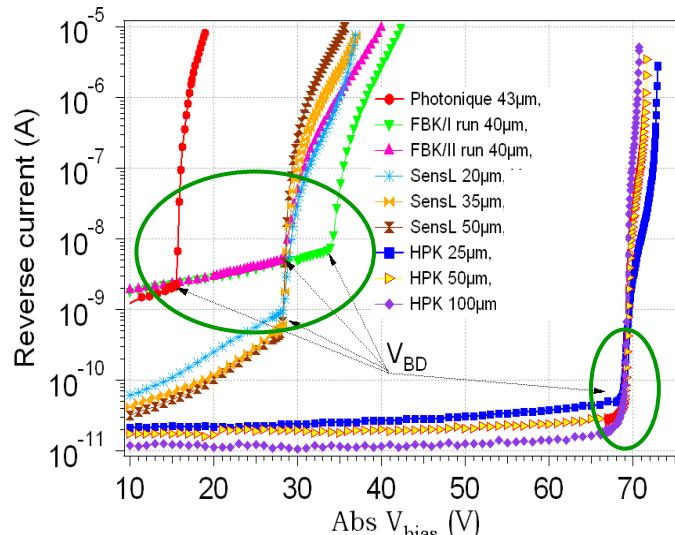
Projets d'application :

- DEMEL (DéTECTeur Matriciel avec Électronique de Lecture) en collaboration avec l'Université de Pise, l'INFN et FBK (Fondation Bruno Kestler)
- SIPMED (SiMed Silicium Photomultiplicateur pour l'Imagerie Médicale) en collaboration avec l'IMNC ([en cours](#))

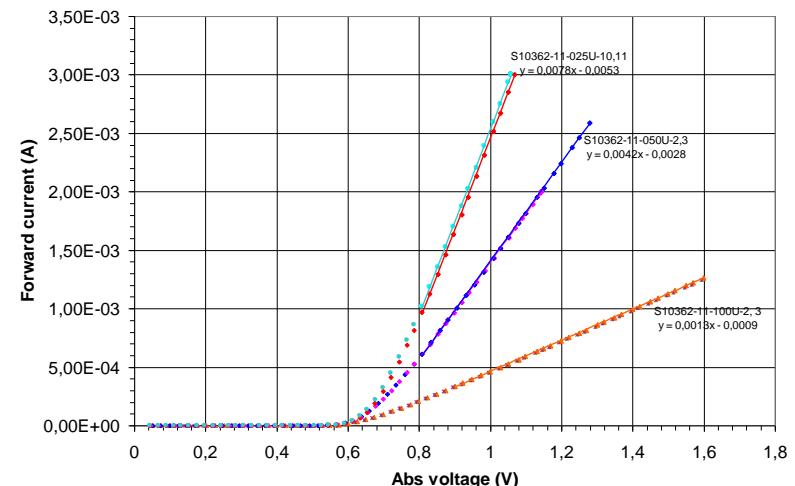


Mesure de la plage de fonctionnement, des paramètres électriques, du gain

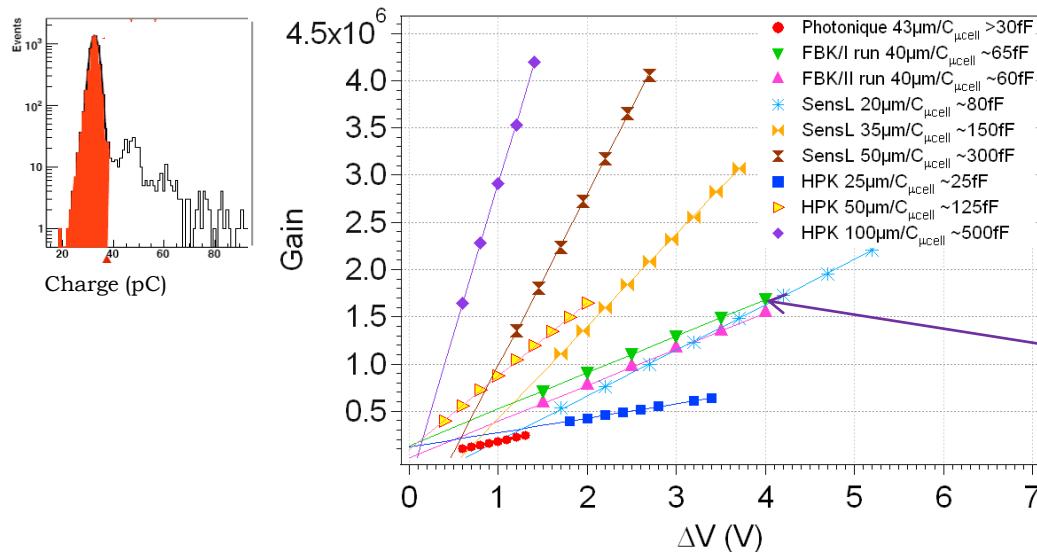
Mesure de l'reverse → Breakdown voltage



Mesure de lforward → Resistance de quenching (pente)



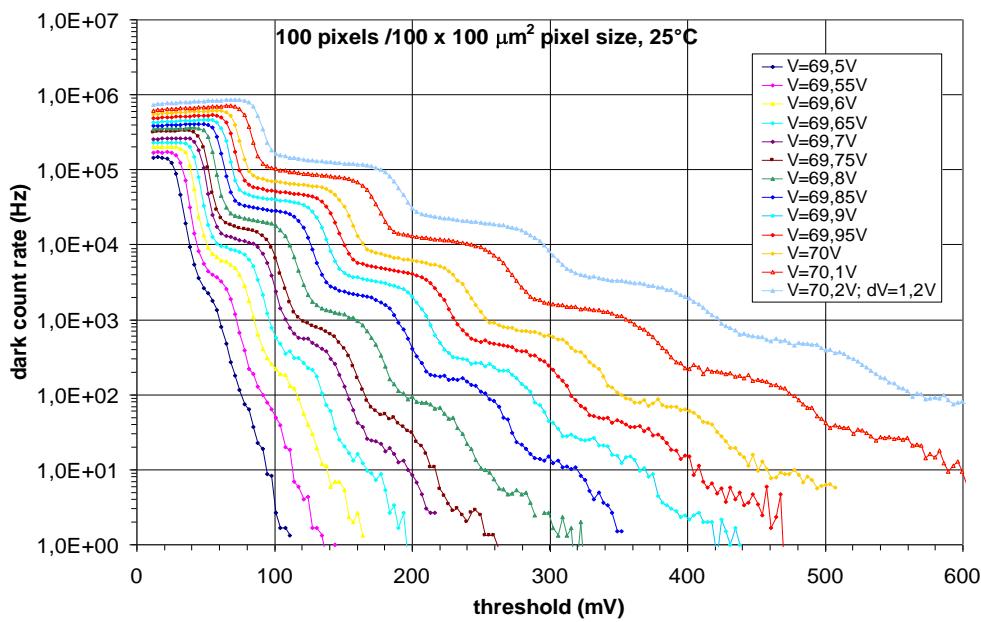
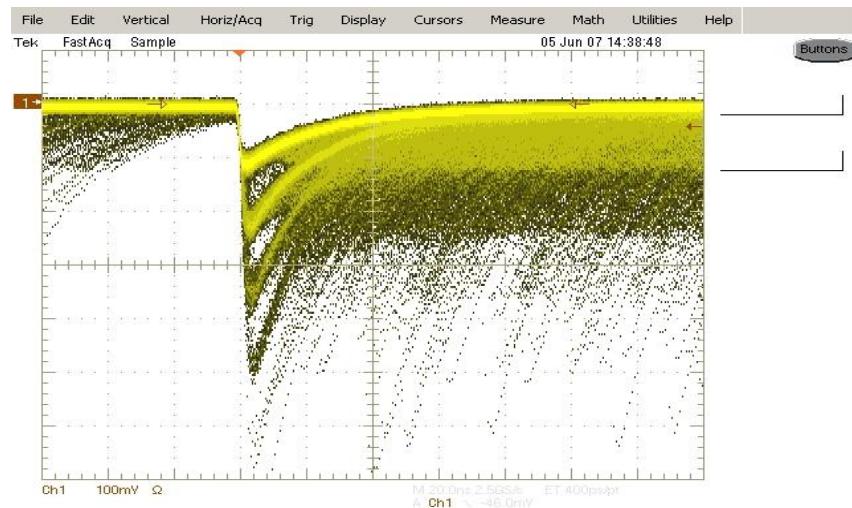
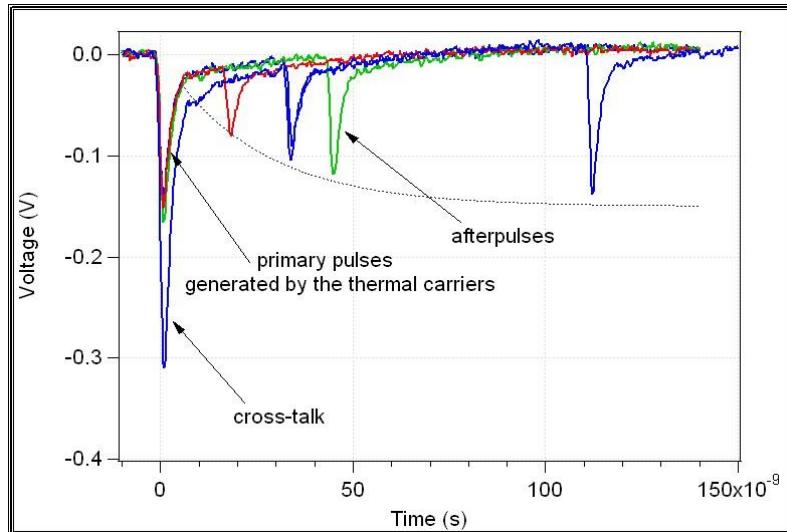
Mesure de la charge → gain

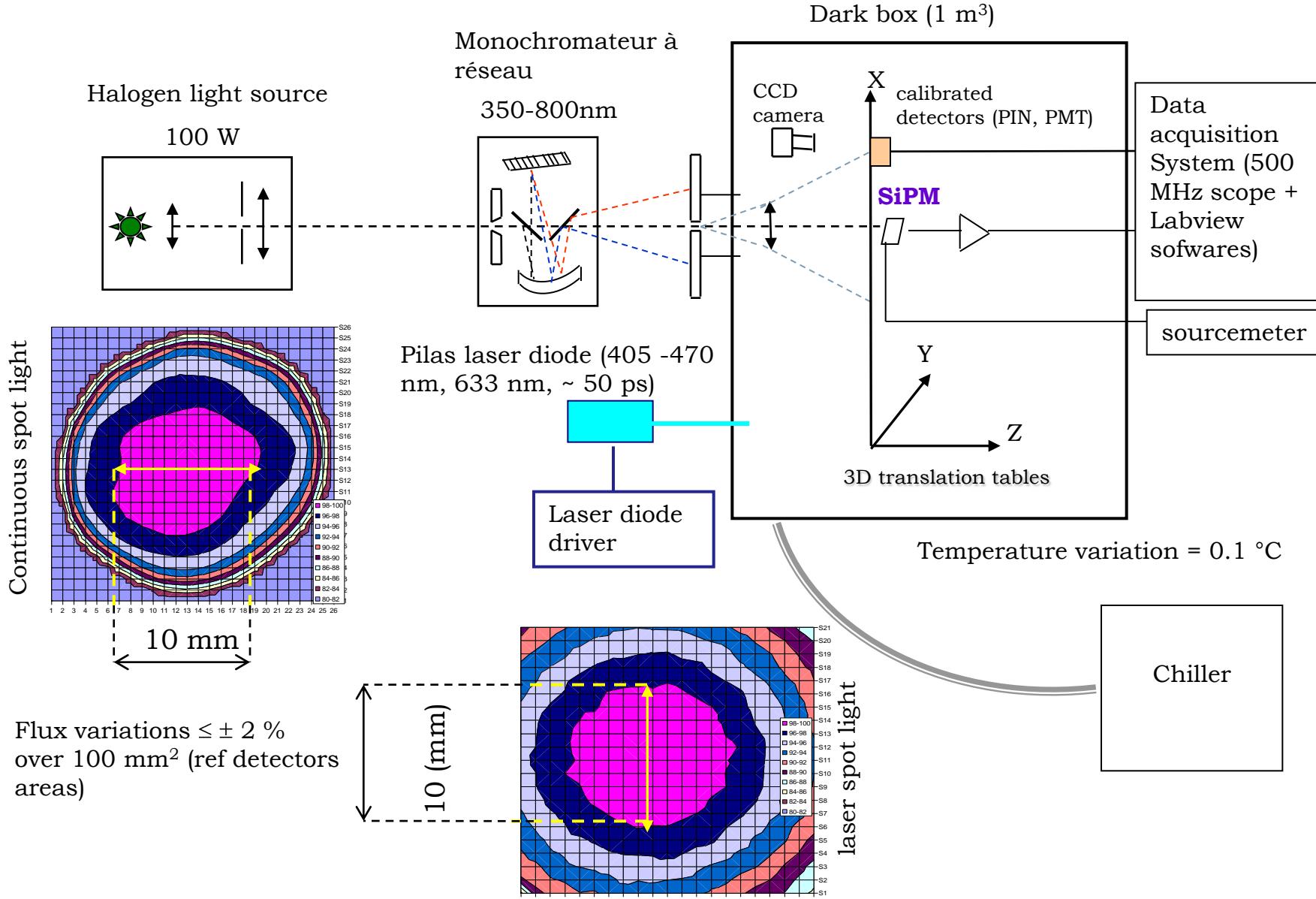


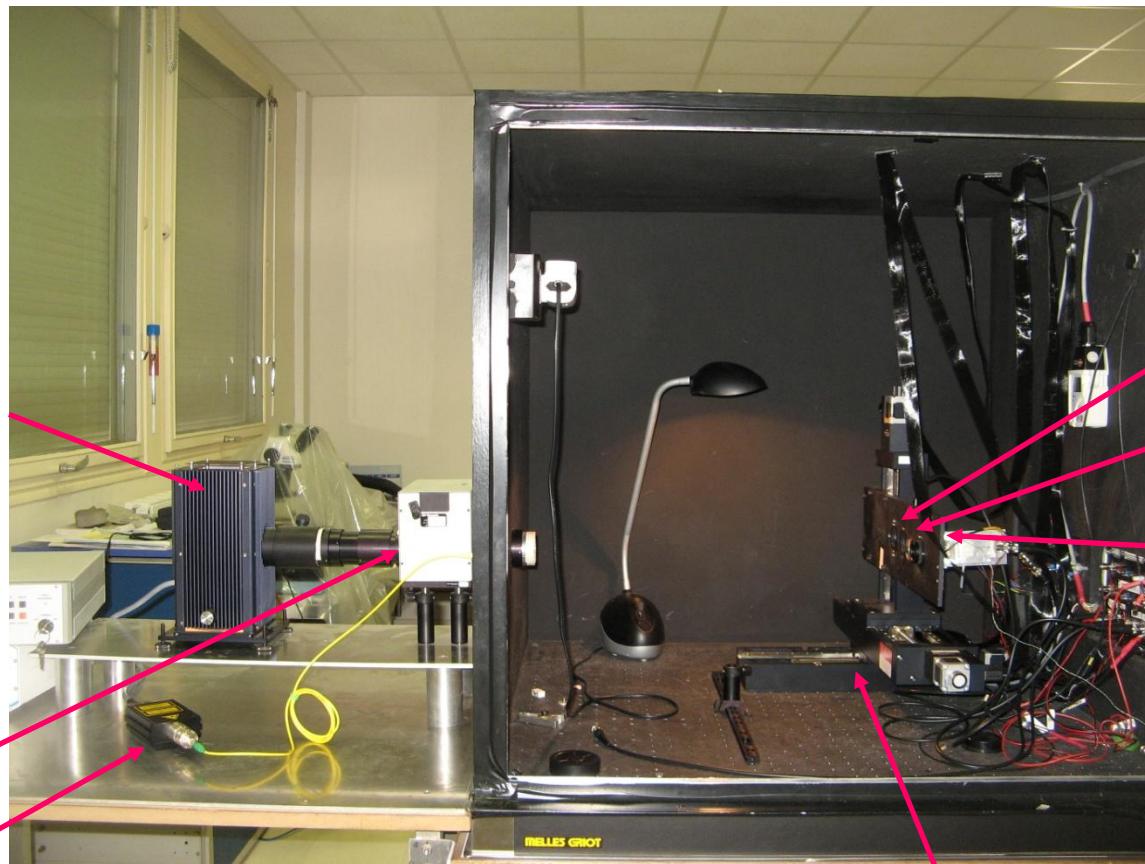
pente de la courbe de gain
→ Pixel capacitance

Mesure du Dark Count Rate, bruits corrélés,

GRED







Lampe Halogen
(100W)

monochromateur
400-800nm

Sources pulsées :
405 - 470 – 532 - 633 nm

Ref PMT calibré
(R7400U-02)

Ref PIN photodiode
(S3590-18)

SiPM + ampli

Table de translation XYZ (0.1 mm precision) pilotée

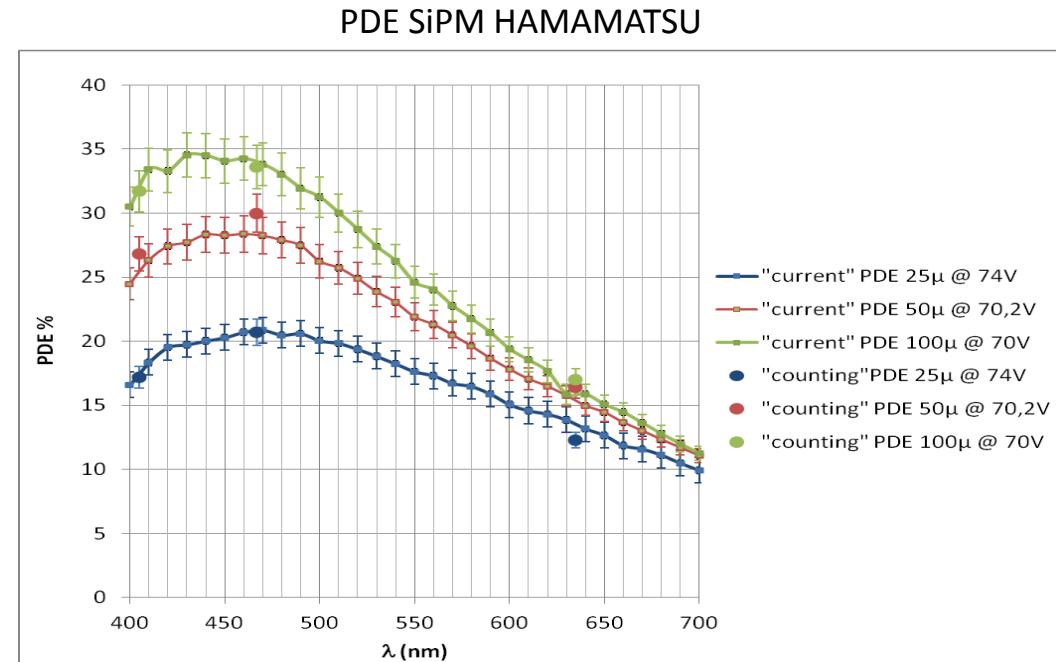
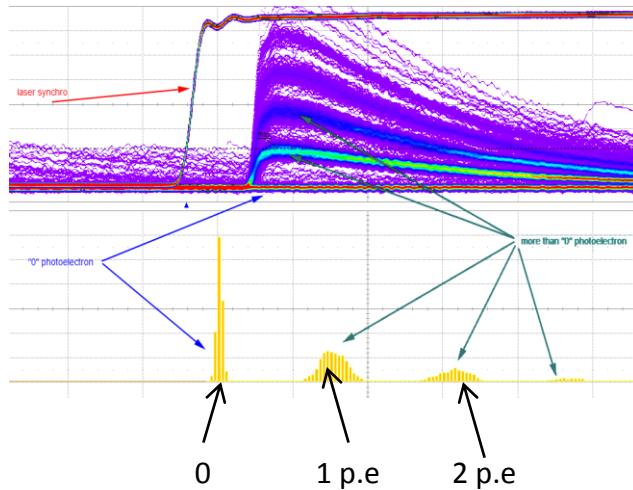
Mesure absolue de l'efficacité de photo-détection (PDE)

GRED

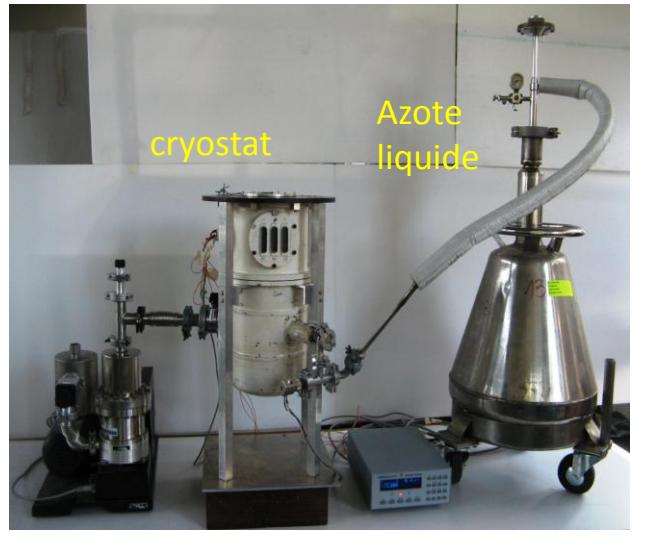
Pour mesurer une efficacité de détection, il faut connaître la nature et le nombre précis de photons incidents sur le SiPM : travail long et difficile → précision des mesure = 6 %

Développement de 2 méthodes de mesure (en lumière continue et pulsée) → amélioration de notre précision sur la mesure du gain → accord entre les 2 méthodes et mesures absolues sur toute la gamme de longueurs d'onde dans le visible

Méthode de comptage à très faible flux

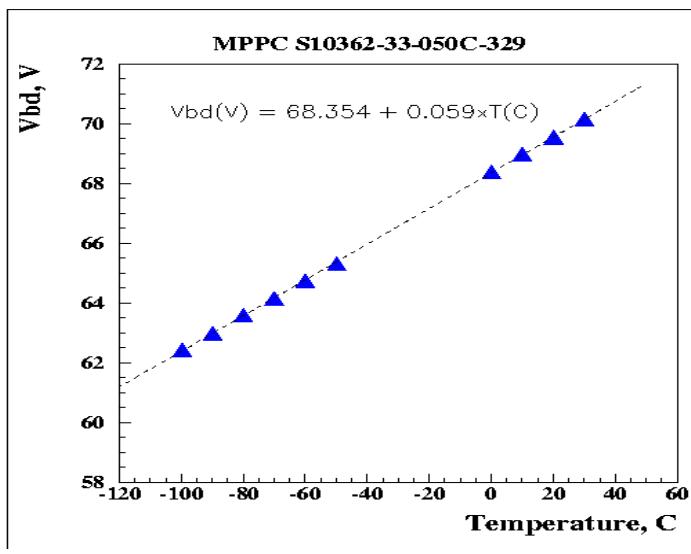


Détermination des variations des paramètres principaux des SiPMs (V_{BD} , résistance, capa, gain, DCR, effets secondaires) en fonction de la température.

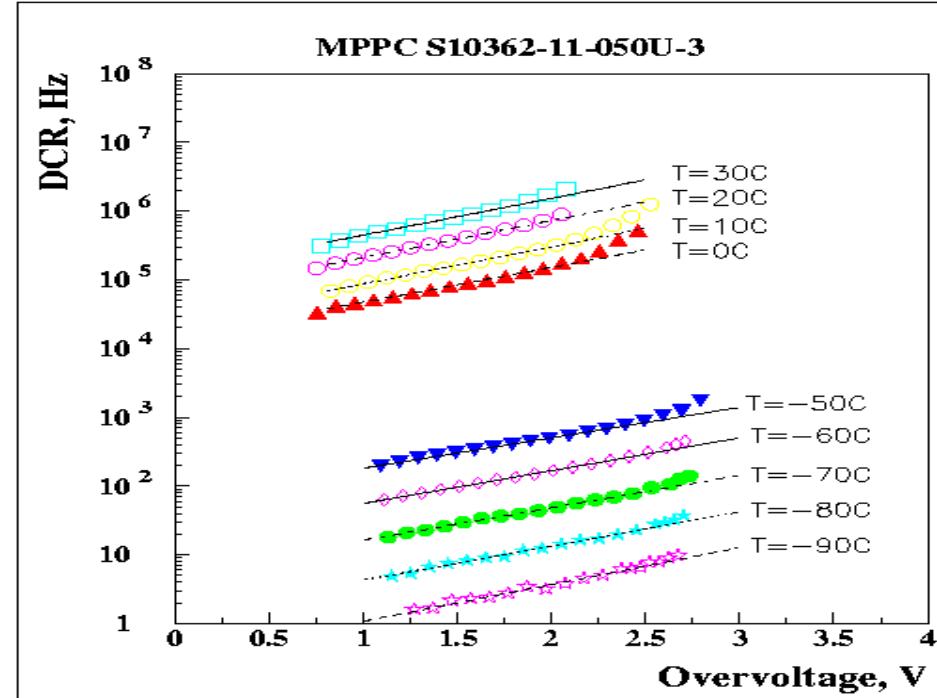


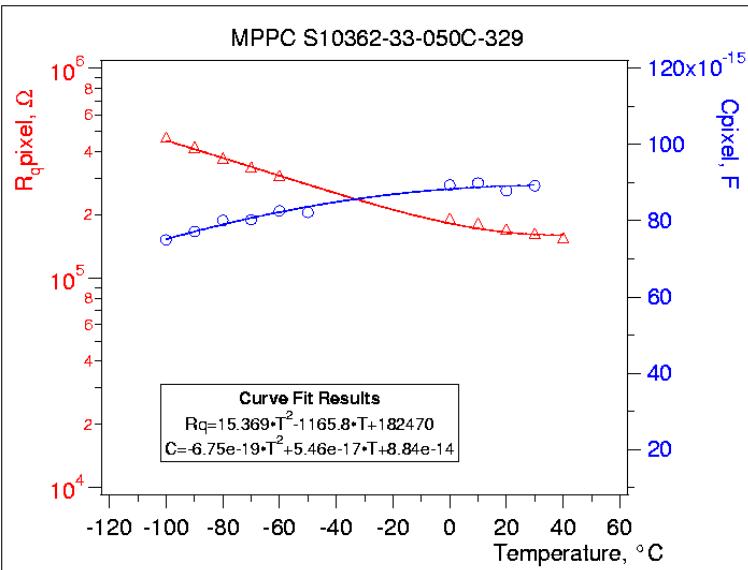
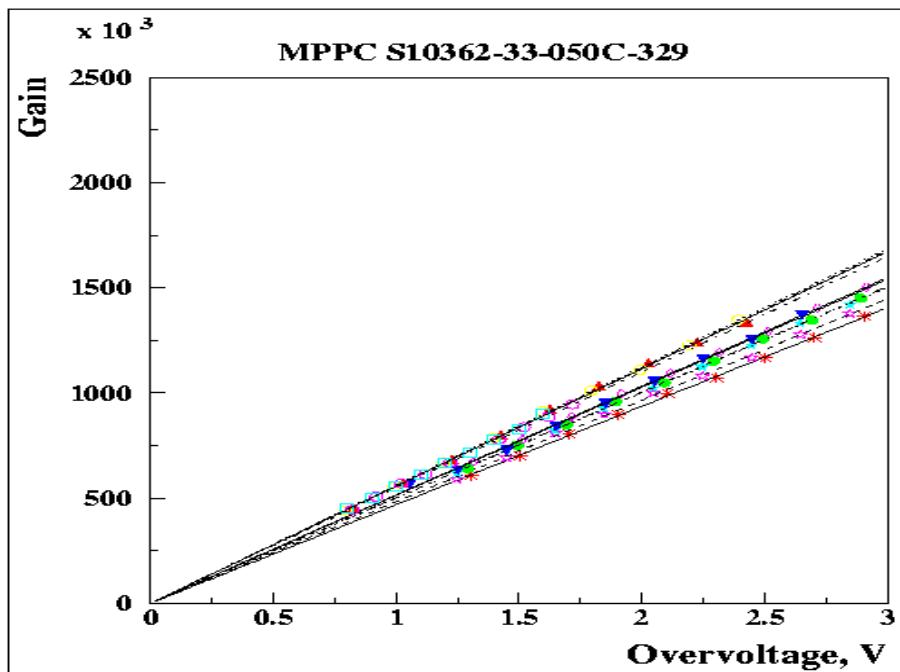
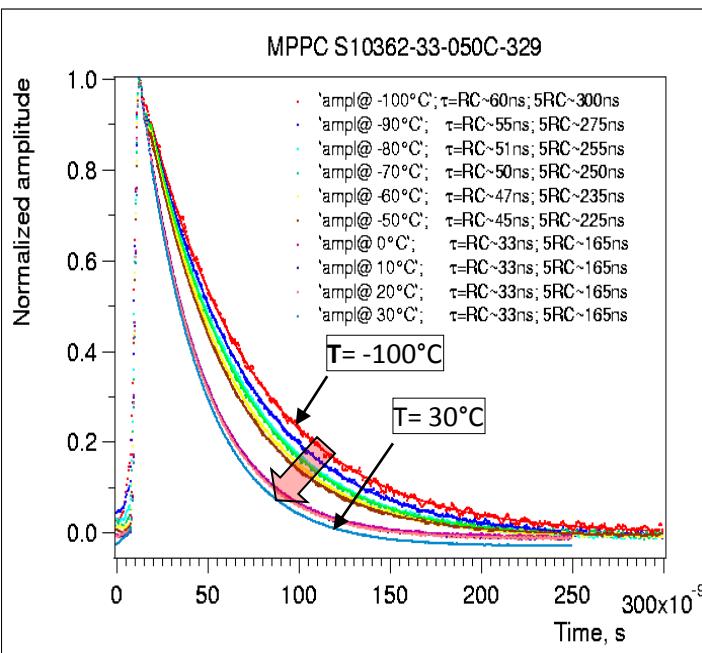
Pompe à vide

Contrôleur de température



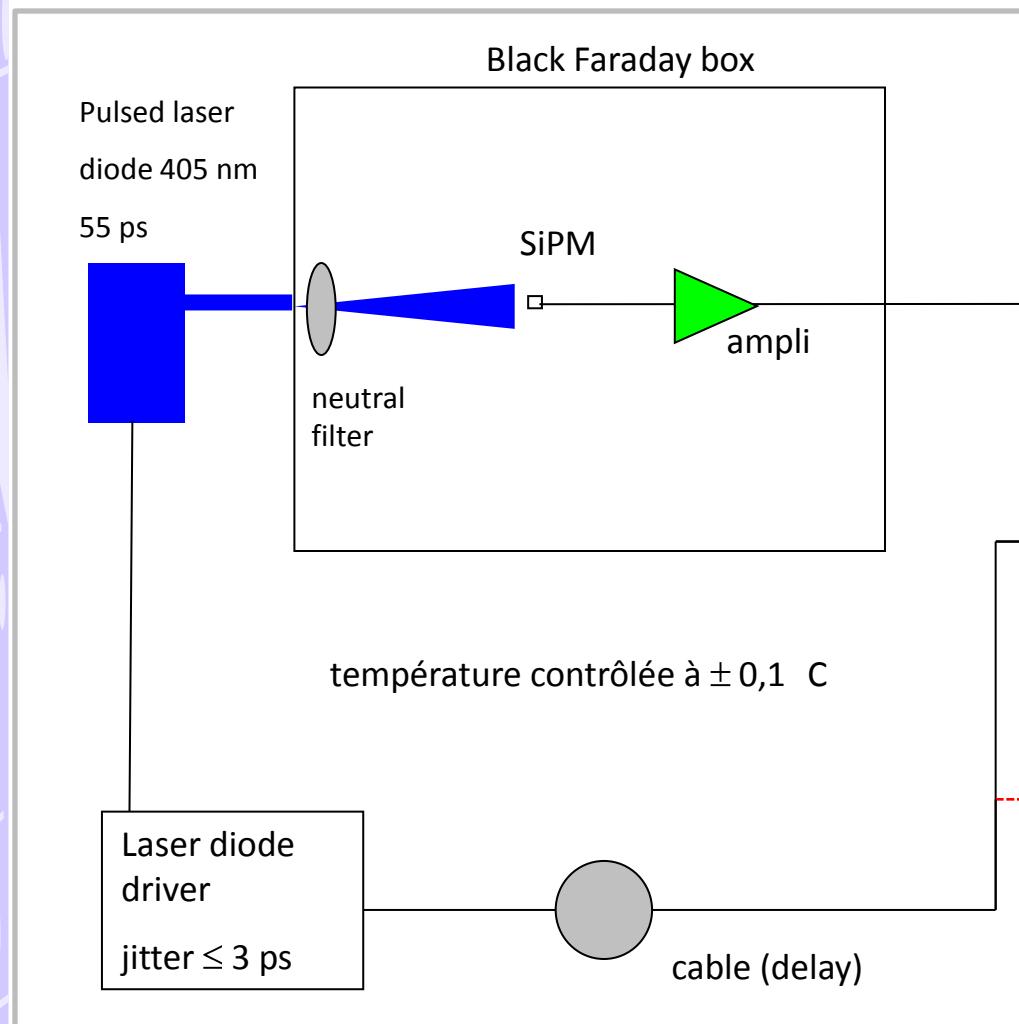
- Cryostat non dédié (développé pour LSST)... pas efficace et bruyant : plage de température (-100 à -50 C)
 - Pas d'automatisation (→ régulation en T difficile)
 - Injection de lumière complexe
- Mesure cohérente avec deux systèmes (enceinte thermostatée et cryostat) différents à 20%
- Collaboration avec FERMILAB : système dédié (-175 C à +55 C)



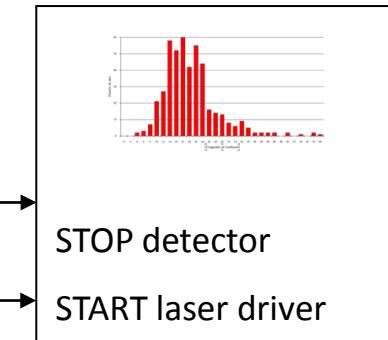


- Variation du recovery time avec la température (diminution de Rpixel, augmentation de Cpixel)
- Gain ~constant avec T au même overvoltage

Temperature and Bias Voltage Dependence of the MPPC Detectors,
N. Dinu et al, NSS IEEE proceedings 2010

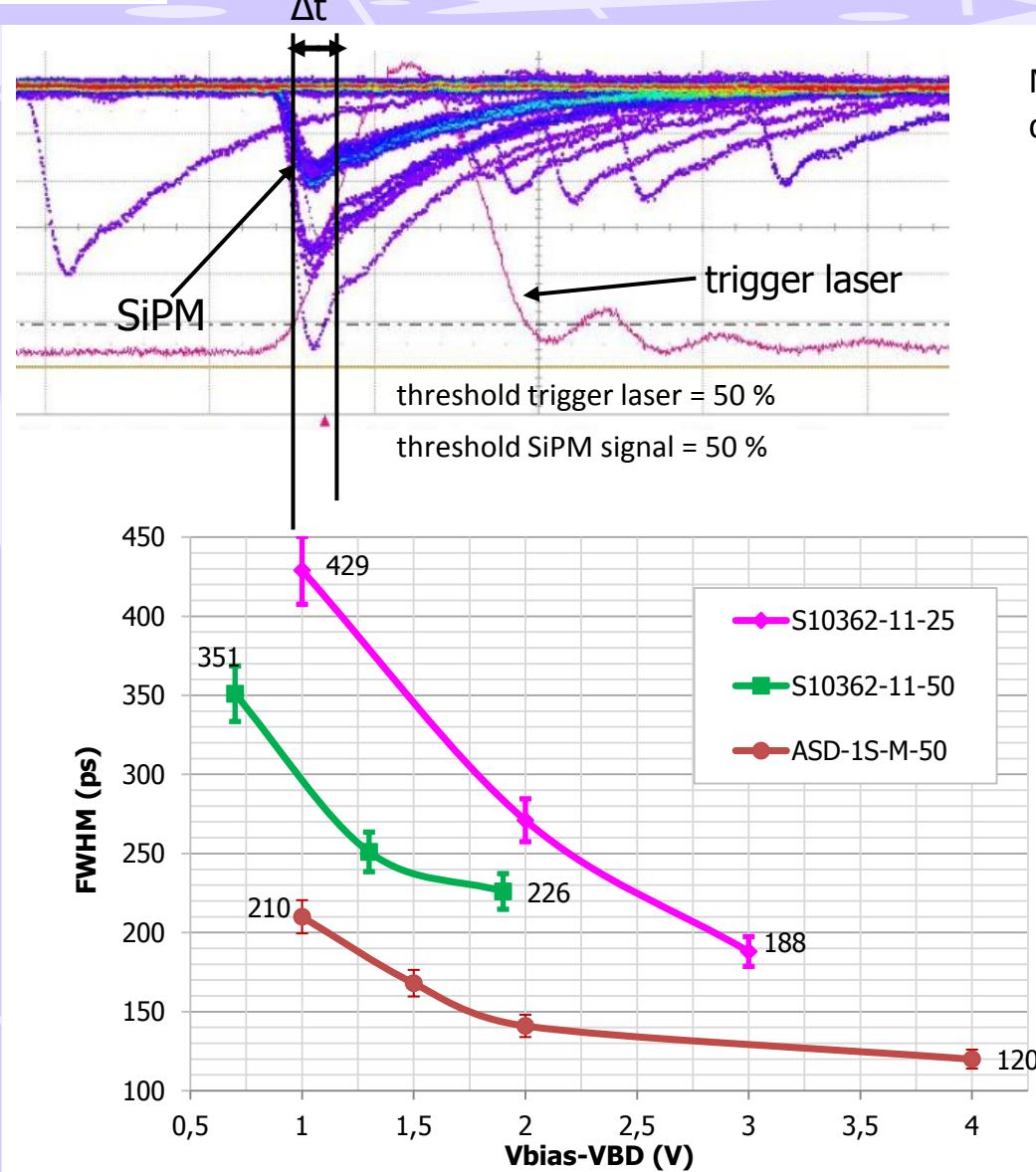


Oscillo Lecroy WAVEPRO 740ZI
4 GHz, 40 Gs/s, 32 Mpts/channel



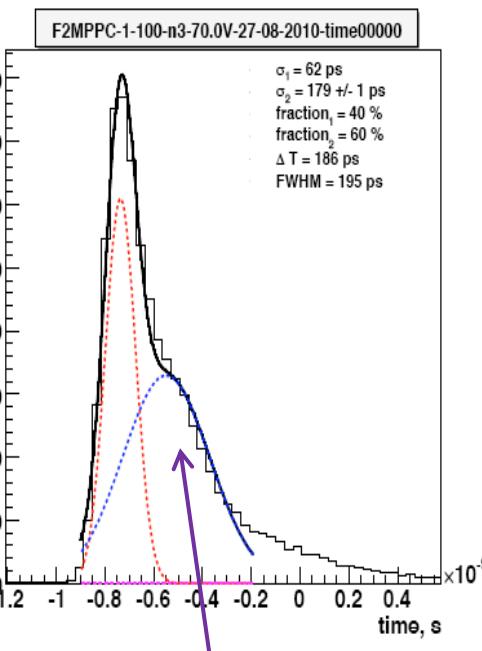
Précision de la mesure = 1 ps avec l'oscillo
8 ps avec le Wavecatcher

Mesure de résolution temporelle au p.e



Mesure en fonction de la température,
de la longueur d'onde, de la tension d'alimentation

MPPC-1-100-n3-70.0V



En cours : compréhension des événements retardés observés dans la distribution temporelle des photoelectrons uniques (collaboration avec l'Université de Kiev)

6 années d'étude sur différents sujets ont permis au groupe :

- de développer plusieurs bancs de test performants.
- d'acquérir une grande expertise des SiPMs → transmission de notre savoir-faire (caractérisation) à d'autres laboratoires (LLR, IMNC, Irfu, APC, Université de Seoul), collaborations (FERMILAB, IMNC, Université de Kiev), proposition de fabricants de SiPMs pour caractériser leurs prototypes (Philips, KETEK, Excelitas)

Prospectives :

Terminer les projets en cours :

- Mesure en température
- SiPMED
- Résolution temporelle

Nouvelles études (quand on aura le temps, l'argent et le personnel) :

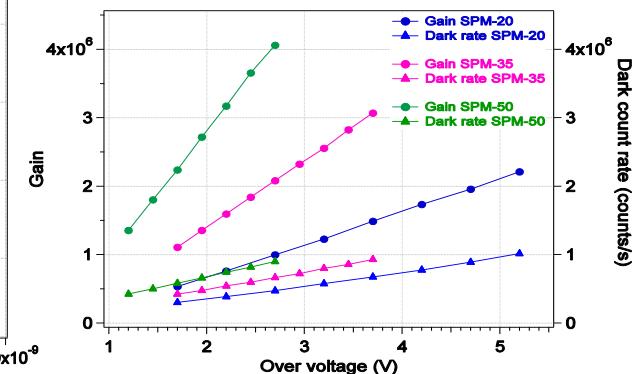
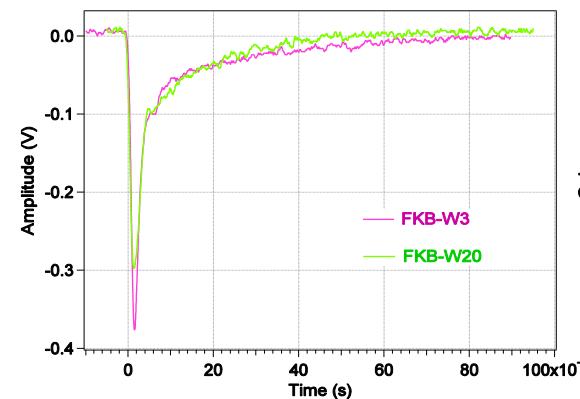
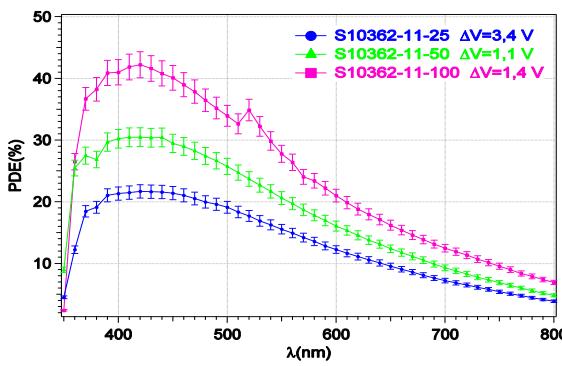
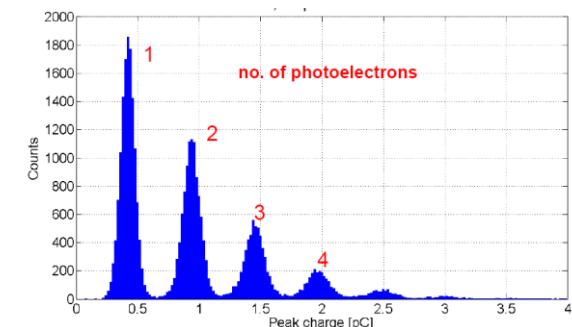
- Détection de lumière Cherenkov (identification de particule, mesure de halo de faisceau)
- Etude des performances des SiPMs sous irradiation en neutrons et gammas (utilisation dans un faisceau de particule, de l'identification de particule, pour la calorimétrie)
- Etude de la résolution en énergie des SiPMs.

Backup

Avantages et inconvénients d'un SiPM

Caractéristiques intéressantes des SiPMs :

- ✓ $10^5 < \text{gain} < 10^7$
- ✓ sensibilité au photon unique
- ✓ $20\% < \text{PDE pic} < 40\%$ (bleu-vert)
- ✓ rapidité (temps montée = 2-5 ns, temps de récupération = 10 ns – 1 μs)
- ✓ résolution temporelle photoélectron unique = 50 à 300 ps



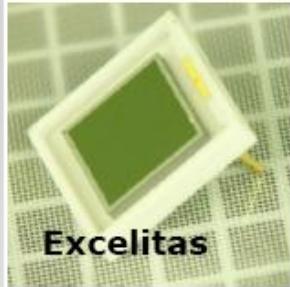
Ce dont on se passerait... :

- courant d'obscurité : de 300 kHz à 2 MHz à 25 °C
- cross-talk : quelques %
- non linéarité (on ne peut détecter un nombre de photons > nb pixel x PDE)
- dépendance du gain avec la température

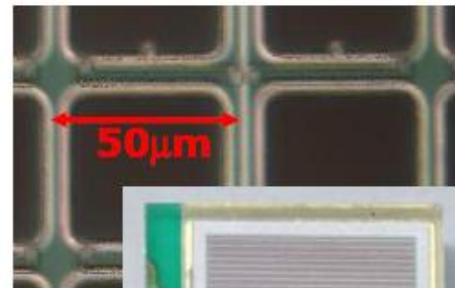
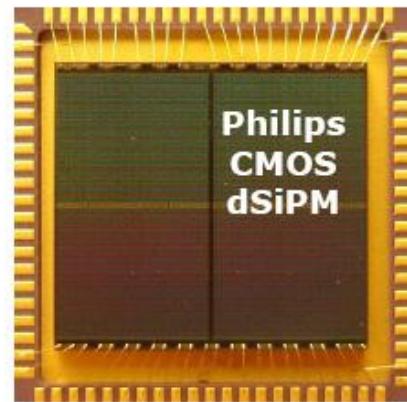
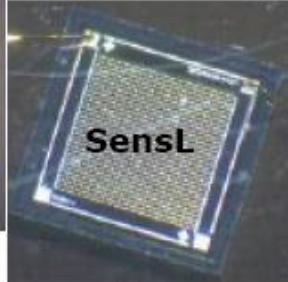
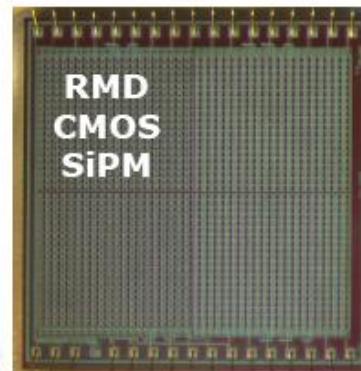
Today

Many institutes/companies are involved in SiPM development/production:

- **CPTA**, Moscow, Russia
- **MePhi/Pulsar** Enterprise, Moscow, Russia
- **Zecotek**, Vancouver, Canada
- **Hamamatsu HPK**, Hamamatsu, Japan
- **FBK-AdvanSiD**, Trento, Italy
- **ST Microelectronics**, Catania, Italy
- **Amplification Technologies** Orlando, USA
- **SensL**, Cork, Ireland
- **MPI-HLL**, Munich, Germany
- **RMD**, Boston, USA
- **Philips**, Aachen, Germany
- **Excelitas** tech. (formerly Perkin-Elmer)
- **KETEK**, Munich, Germany
- **National Nano Fab Center**, Korea
- **Novel Device Laboratory (NDL)**, Beijing, China
- **E2V**
- **CSEM**



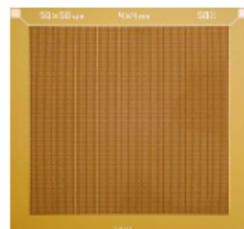
Amplification
Technologies
(DAPD)



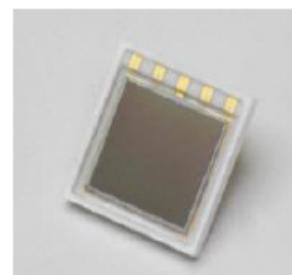
ZECOTEK MAPD-3N



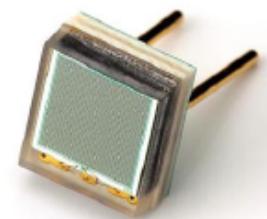
ASD-SiPM4S



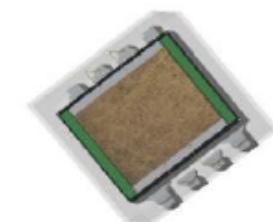
HAMAMATSU S10985



KETEK PM3350



STMicroelectronics



Producer	Reference	Area (mm ²)	PDE max @ 25 °C *	Dark Count Rate (Hz) @ 25°C *	Gain *
ZECOTEK	MAPD-3N	3 x 3	30% @ 480 nm	9.10 ⁵ – 9.10 ⁶	10 ⁵
FBK - AdvanSiD	ASD-SiPM4S	4 x 4	30% @ 480 nm	5.5 10 ⁷ - 9.5 10 ⁷	4.8 10 ⁶
HAMAMATSU	S10985-50C	6 x 6	50% @ 440 nm (includes afterpulses & crosstalk)	6.10 ⁶ – 10.10 ⁶	7.5 10 ⁵
KETEK	PM3350	3 x 3	40% @ 420 nm	4.10 ⁶	2 10 ⁶
STMicroelectronics	SPM35AN	3,5 x 3,5	16% @ 420 nm	7.5 10 ⁶	3.2 10 ⁶

* datasheet data

Ongoing R&D to increase the active area at KETEK, AdvanSiD, Excelitas (6 x 6 mm²)

Other solution to get larger area : connection of several channels of a matrix

SiPMs arrays (discrete 1)

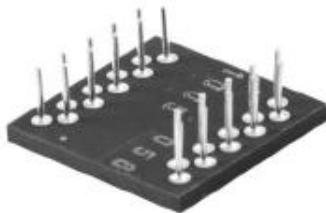
Important effort on the package development



SiPMs are buttable with very small gap



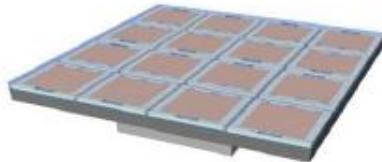
- building of detectors with large surface
- building of compact detectors with large active area



examples of matrix backside

FBK

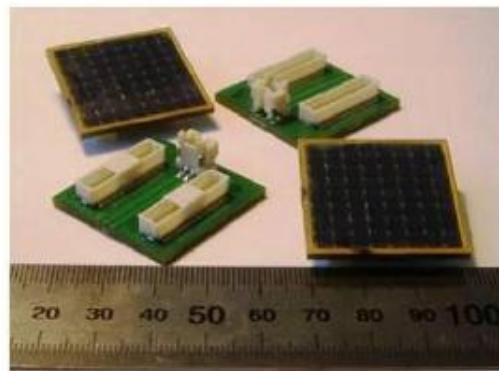
ASD-SiPM4S-P-4x4T-50



4x4 channels

1 channel = $4 \times 4 \text{ mm}^2$

6400 cells ($50 \times 50 \mu\text{m}^2$)
/channel



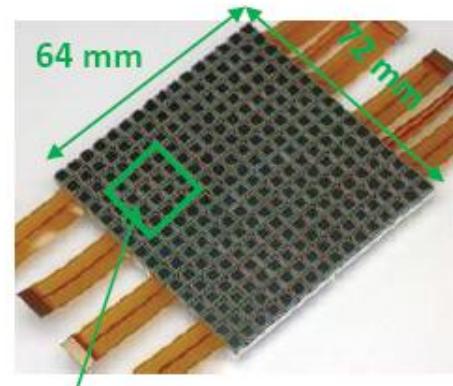
8x8 channels

1 channel = $3 \times 3 \text{ mm}^2$

15000 cells /channel

HAMAMATSU

S11834-3388DF



S11064-025

4x4 channels

1 channel= $3 \times 3 \text{ mm}^2$

14400 cells ($25 \times 25 \mu\text{m}^2$) /channel

- improve spatial resolution and PDE
- simplify the assembly



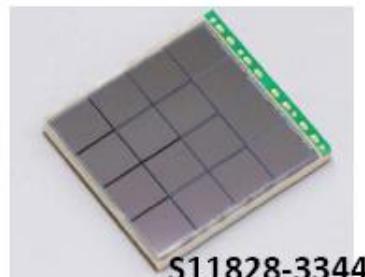
monolithic SiPM matrices

HAMAMATSU

4x4 channels

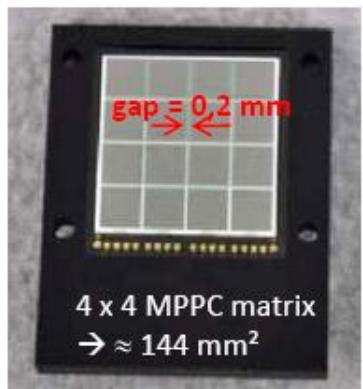
1 channel = $3 \times 3 \text{ mm}^2$

3600 cells ($50 \times 50 \mu\text{m}^2$)/channel



3 sides tileable (4 sides ~~soon now~~)

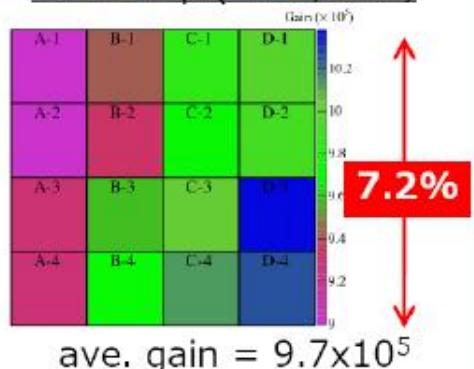
1 cathode – 16 anodes



S10985 - $36 \times 36 \text{ mm}^2$

57600 cells

Gain map (71.9V, 0 °C)

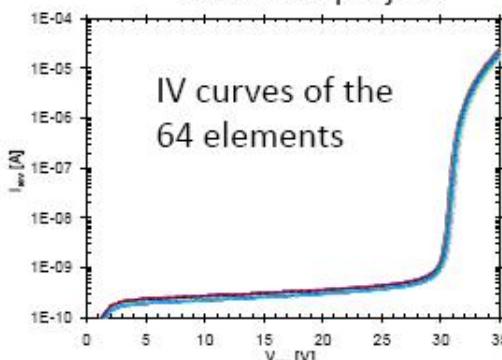


Kato et al, NIMA 638 (2011) 83–91

FBK

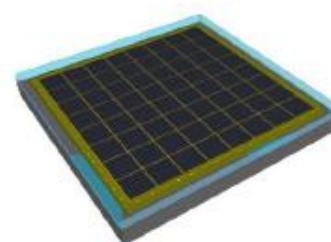


8 x 8 channels

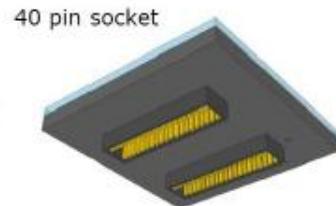


Marcatili et al, NIMA 659 (2011) 494–498

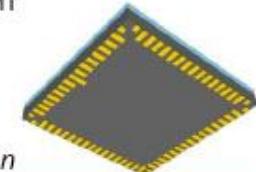
Ongoing R&D at AdvanSiD to improve the performances



64 channels
 $1.5 \times 1.5 \text{ mm}^2$ SiPMs (pixels)



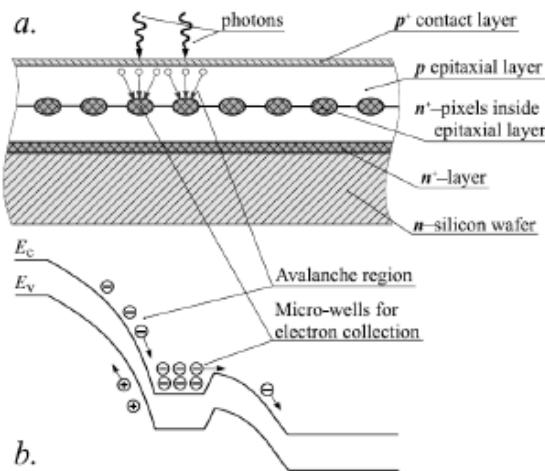
SMT



C. Piemonte, private communication

Very large dynamic range

ZECOTEK



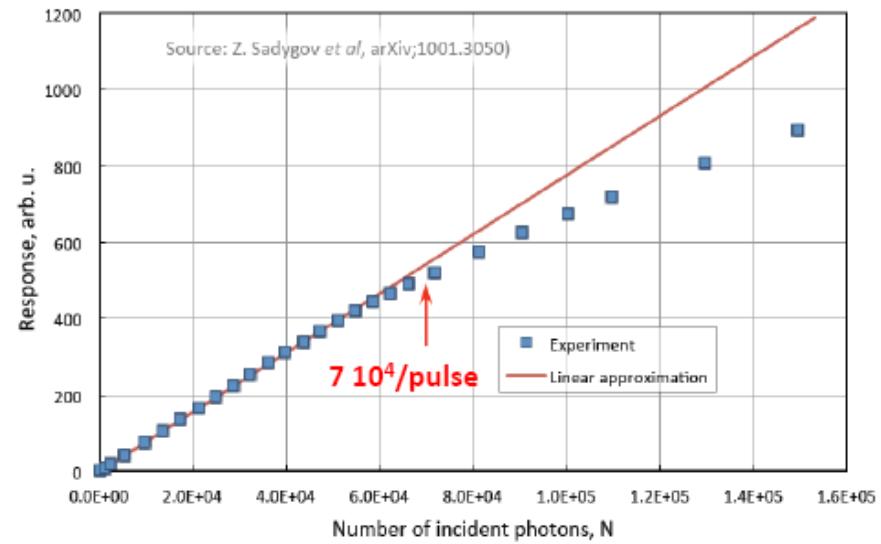
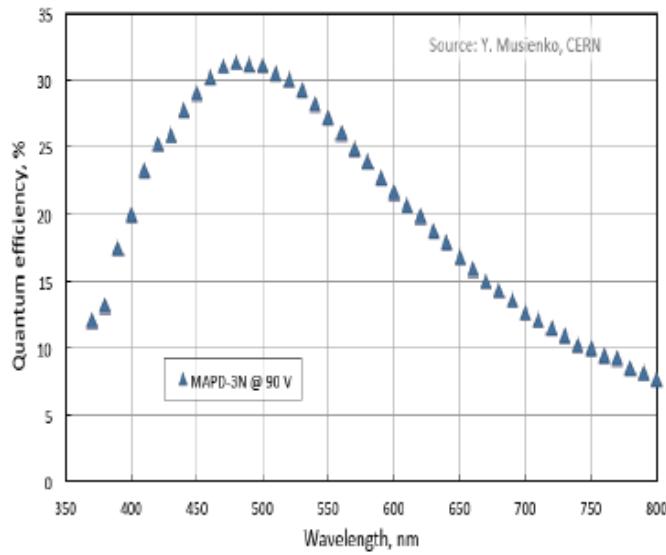
MAPD-3N

$3 \times 3 \text{ mm}^2$

1350000 cells ($15000/\text{mm}^2$)

gain = 10^5

slow cell recovery time : $300 \mu\text{s}$

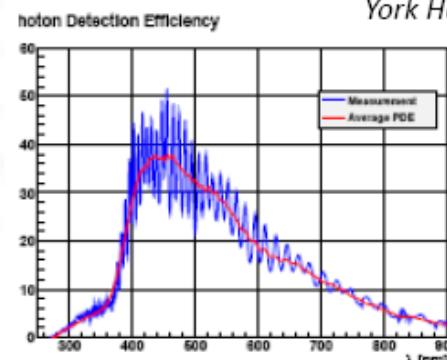
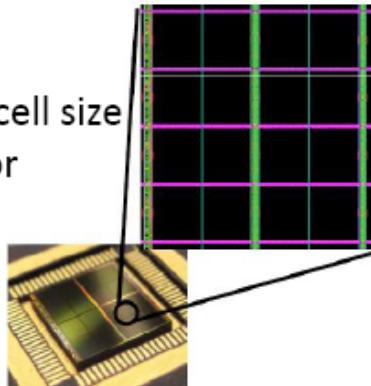


Array of G-APDs integrated in a standard CMOS process. The signal from each pixel is digitized and the information is processed on chip:

- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cell

DLS-3200-22-44

- 3200 cells
- $59 \times 64 \mu\text{m}^2$ cell size
- 78% fill-factor



T. Frach, 2012 JINST 7 C01112

Drawbacks:

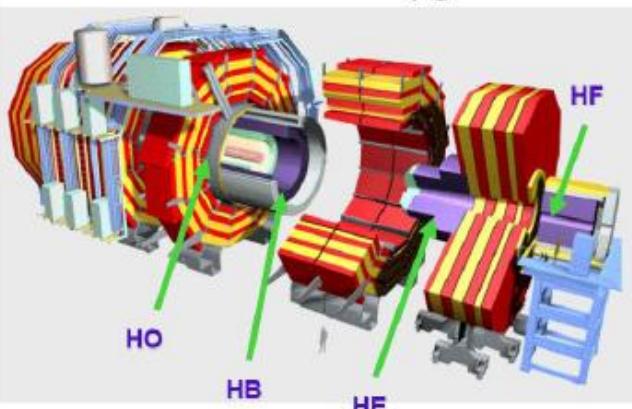
- requires a dedicated readout provided by Philips
- dead space around the sensor
- good arguments in HEP experiments (high numbers of channels) to change that



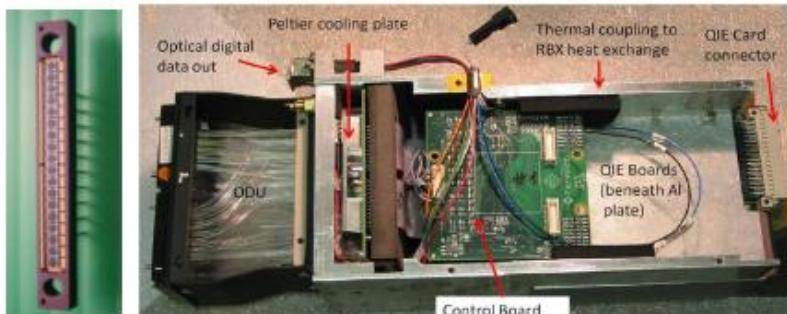
Opened question:

what about the radiation hardness of this device ?

HB & HE upgrade



Prototype HB RM used at 2011 Testbeam



Y. Musienko, NDIP 2011

Temperature dependence → control @ 0.2 °C

Significant progress on the SiPM development over the last 2 years (HAMAMATSU , Zecotek, NDL) → the MPPCs from HAMAMATSU are close to satisfy most of the requirements.

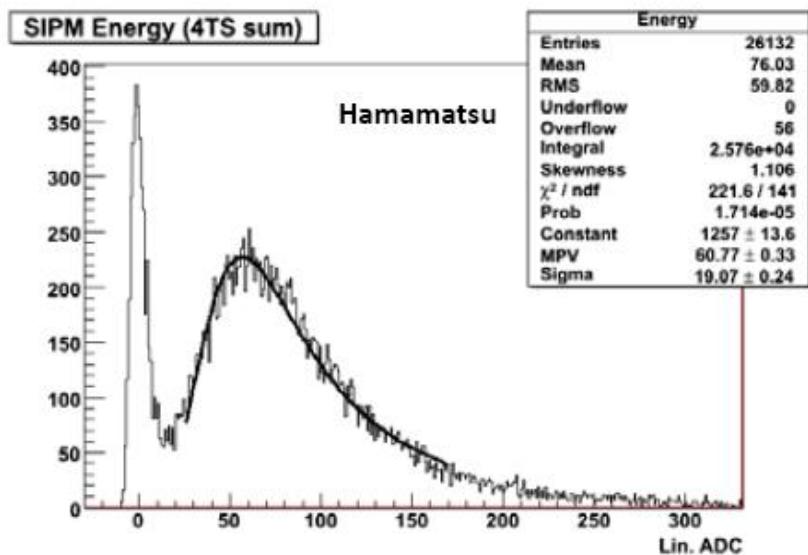
Photodetector requirements (to replace the HPD):

- very large dynamic range: a few p.e → 2500 p.e
- high occupancy in front layers in SLHC → fast recovery time (5 – 100 ns)
- radiation hard up to $3 \cdot 10^{12}$ 1 MeV neutrons/cm² for 3000 fb⁻¹ (Gain * PDE change ≤ 20%)

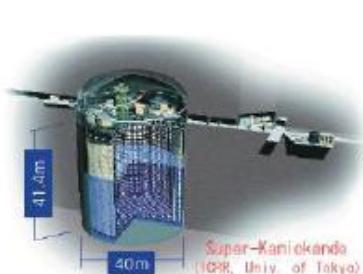
Studied SiPM :

HAMAMATSU, ZECOTEK, FBK, CPTA , ST-Micro, Sensl, NDL, KETEK

Muon response in a single tower of CMS HO



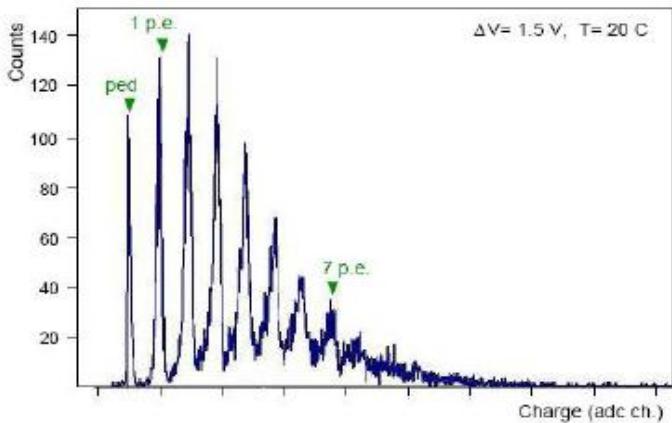
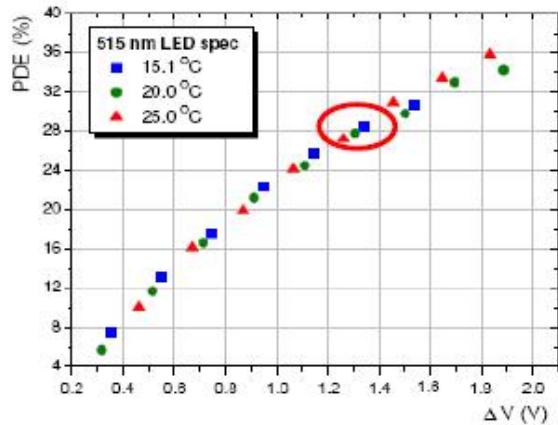
J. Freeman, FERMILAB-CONF-09-601-E



Far detector : Super Kamiokande

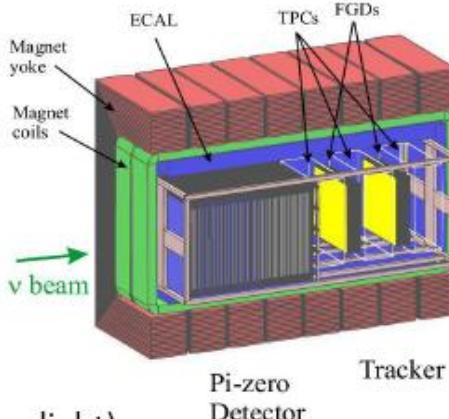
Photodetector requirements:

- insensitive to magnetic field
- coupling with a scintillator + WLS fiber (PDE > 20 % for green light)
- DCR < 1 MHz
- compact



55996 MPPC tested : only 0,16 % rejected

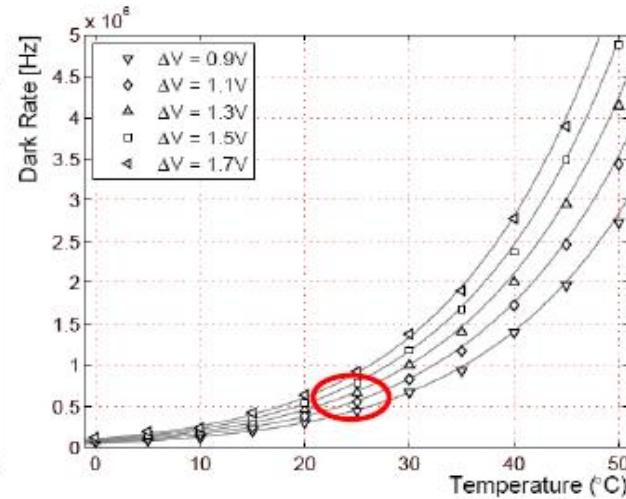
ND280 : near detector complex - neutrino beam flux and spectrum measurements



HAMAMATSU MPPC
customized device



$1.3 \times 1.3 \text{ mm}^2$
667 cells ($50 \times 50 \mu\text{m}^2$)



A. Vacheret, arXiv:1101.1996

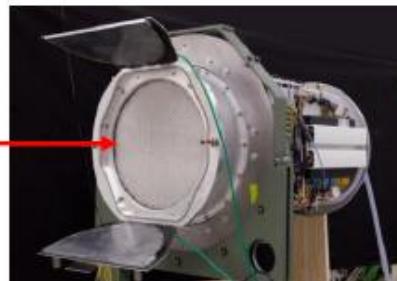
FACT: First G-APD Cherenkov Telescope



MPPC S10362-33-50C
coupled to a cone light
concentrator



1440 channels



Th. Krähenbühl, Photodet
2012

Photodetector requirements:

- PDE > 20 % for blue light
- ability to detect single photons
- stable
- robust
- compact



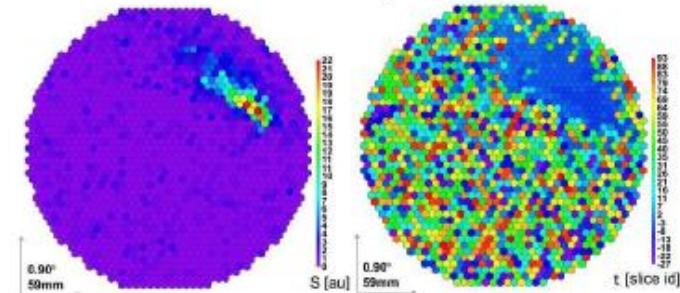
problem with the SiPM V_{BD} temperature dependance
→ regulation of the bias voltage with a feedback system

First operation on the night of October 11, 2011

After one year of routine operation:

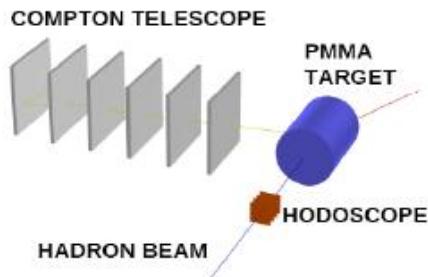
- no indication of any problem or ageing in any SiPM
- temperature as well as ambient-light dependence of SiPM well under control
- operation under very different ambient conditions shows no problem

an Event Seen by FACT

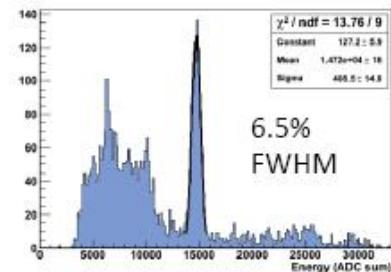
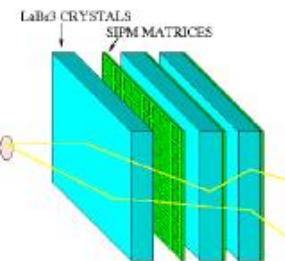


P. Vogler, TWEPP 2012

Compton telescope for dose monitoring in hadron therapy

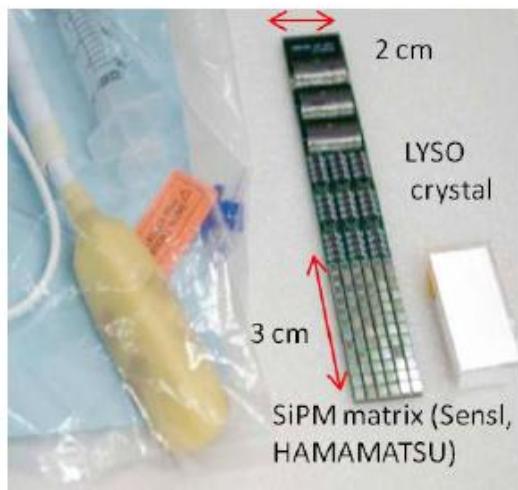


- LaBr₃ continuous crystal
- matrices from HAMAMATSU
- $\Delta E/E \sim 6.5\% \text{ FWHM}$ (at 511 keV)
- $\Delta x = \Delta y \sim 1.2\text{mm FWHM}$
- $\Delta t = 3 \text{ ns}$



G. Llosa, IEEE NSS 2011

Endorectal prostate PET probe



S. Majewski, IEEE NSS 2011

Radio-isotopic probes

Photodetector requirements:

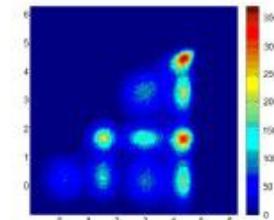
- high fill factor
- low DCR at 37 °C
- low dependence with temp
- compact packaging

Intraoperative probe for beta detection of radiolabeled tumor tissues



T. Ait Imando, N. Dinu
PhotoDet 2012

N. Hudin, PhotoDet 2012



MPPC matrixes
ultra compact electronics