



Семинар отдела физики высоких энергий ИЯИ
24 января 2012

Кремниевые фотоумножители: состояние дел и ближайшие перспективы

Попова Елена Викторовна

(elenap73@mail.ru)

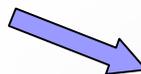
НИЯУ МИФИ

Экспериментальная физика для регистрации света слабой интенсивности использует вакуумные ФЭУ



Основные недостатки ФЭУ:

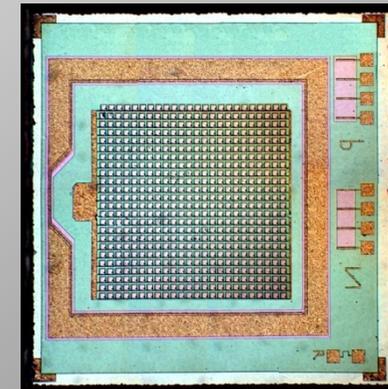
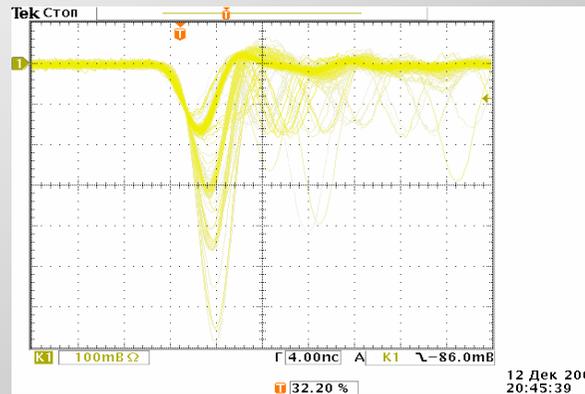
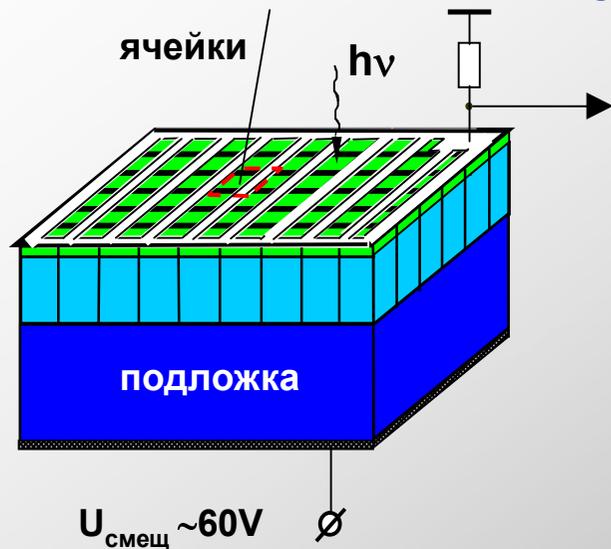
- большие размеры,
- высокое напряжение питания
- чувствительность к магнитным полям



 **Нужен детектор нового типа – замена вакуумного ФЭУ.
Изобретен в России в конце 20 века (В.Головин, З.Садыгов,
Н.Юсипов патент #1702831 от 10/11/1989)**

МИФИ - группа проф.Б.А.Долгошеина – одни из первых разработчиков – 1993г.

Новый фотодетектор: кремниевый фотоэлектронный умножитель (SiФЭУ)



SiФЭУ – основные особенности:

Ячейки одинаковые!

Ячейки должны быть независимые! – кроссток - основная проблема SiФЭУ

Ячейка – стандартный сигнал – состояние 0 или 1

SiФЭУ – суммарный сигнал на выходе – аналоговый

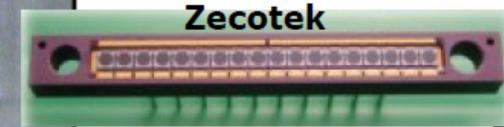
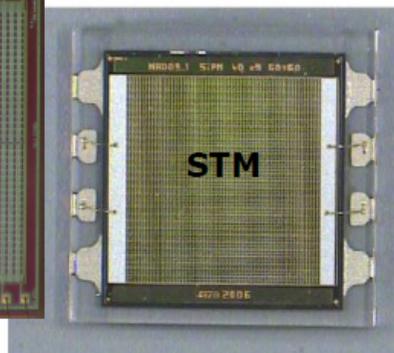
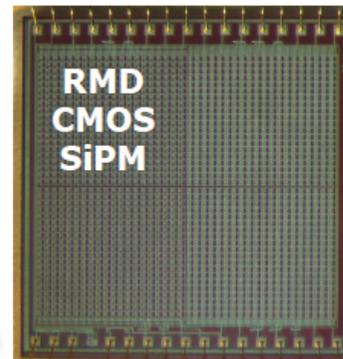
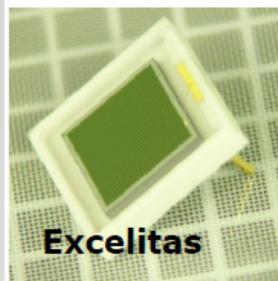
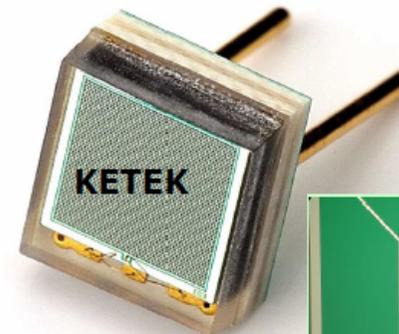
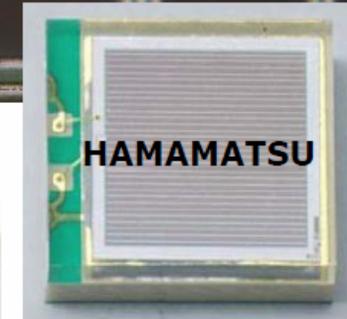
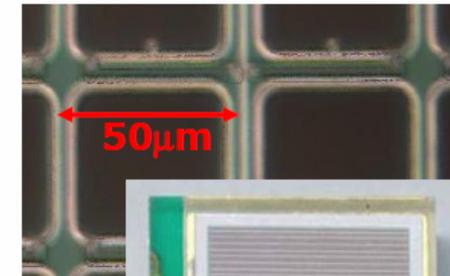
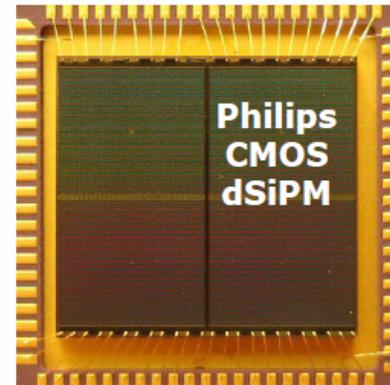
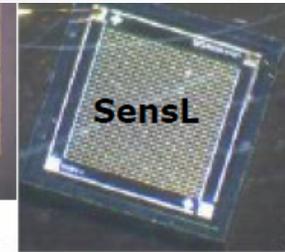
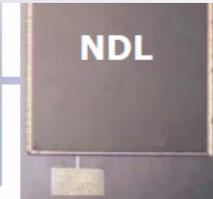
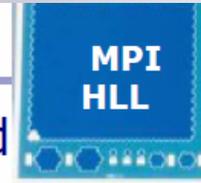
Ячейка – p-n- переход в гейгеровском режиме

SiФЭУ - твердотельный аналог ФЭУ

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**





Направления развития SiФЭУ

- SiФЭУ большой площади
- Матрицы и линейки
- SiФЭУ с максимальной (рекордной) эффективностью
- SiФЭУ, чувствительные к глубокому (вакуумному) УФ
- SiФЭУ, чувствительные к зеленому свету
- SiФЭУ с большим динамическим диапазоном
- Радиационно-стойкие SiФЭУ
- «Быстрые» SiФЭУ



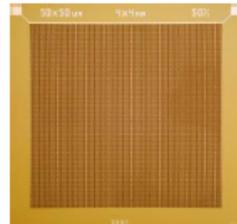
Large Area SiPMs



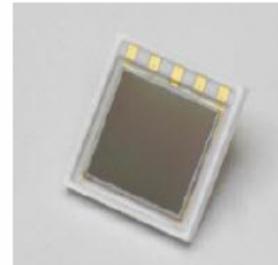
ZECOTEK MAPD-3N



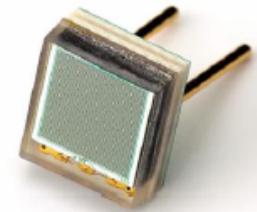
ASD-SiPM4S



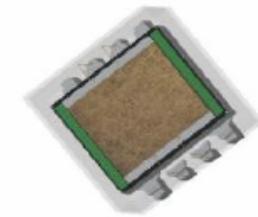
HAMAMATSU S10985



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 <i>матрица 2x2</i>	50% @ 440 nm (includes afterpulses & crosstalk)	6.10 ⁶ – 10.10 ⁶	7.5 10 ⁵
KETEK	PM3350	3 x 3 <i>6x6</i>	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

Excelitas 5x5mm²

* 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

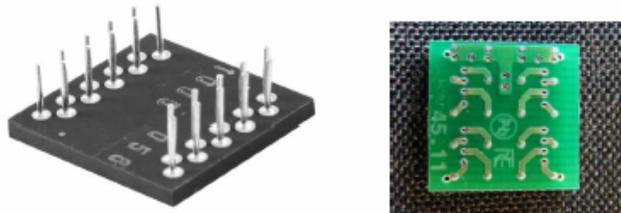


SiPMs arrays (discrete 1)



Important effort on the package development

➔ SiPMs are buttable with very small gap

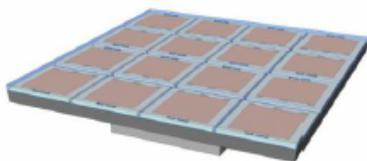


examples of matrix backside

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

FBK

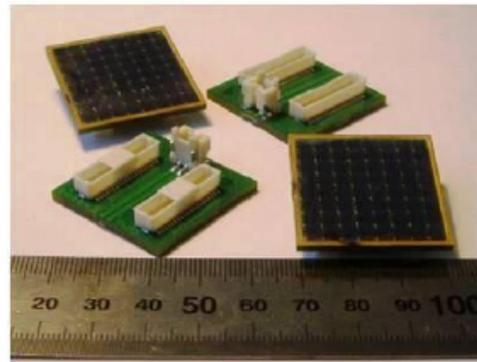
ASD-SiPM4S-P-4x4T-50



4x4 channels

1 channel = $4 \times 4 \text{ mm}^2$
6400 cells ($50 \times 50 \mu\text{m}^2$)
/channel

Zecotek

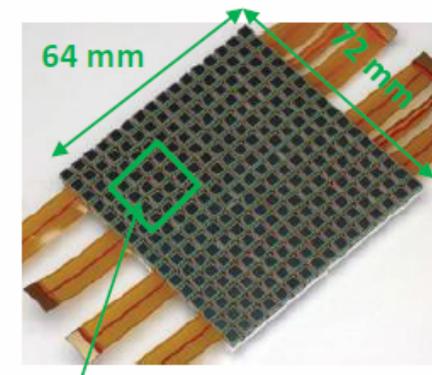


8x8 channels

1 channel = $3 \times 3 \text{ mm}^2$
15000 cells /channel

HAMAMATSU

S11834-3388DF



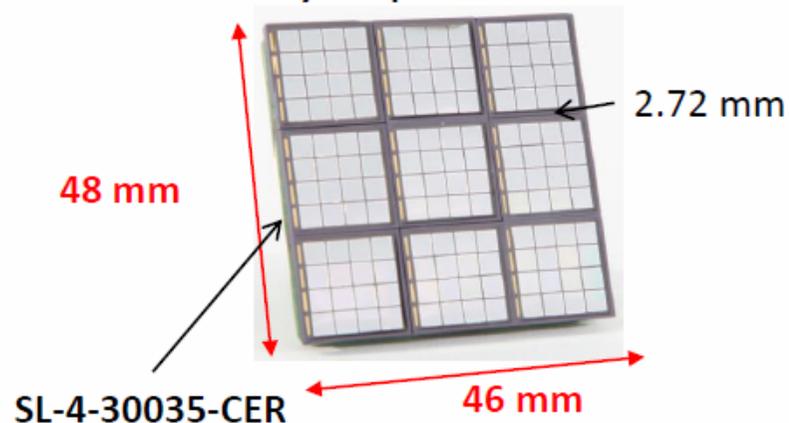
S11064-025

4x4 channels

1 channel = $3 \times 3 \text{ mm}^2$
14400 cells ($25 \times 25 \mu\text{m}^2$) /channel

Sensl

ArraySL-4p9-30035



SL-4-30035-CER

4x4 channels

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

4774 cells ($35 \times 35 \mu\text{m}^2$) /channel

ArraySM-8



8x8 channels

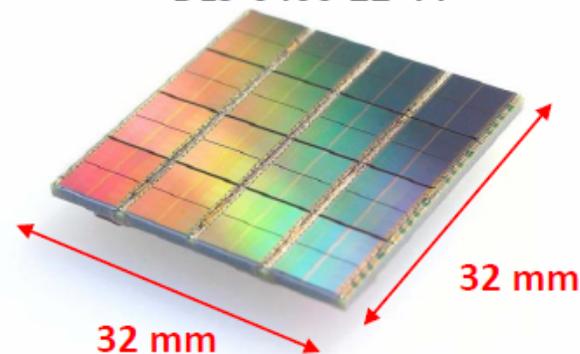
1 channel = $6 \times 6 \text{ mm}^2$

18980 cells /channel

new surface mount package

Philips Digital Photon Counting

DLS-6400-22-44

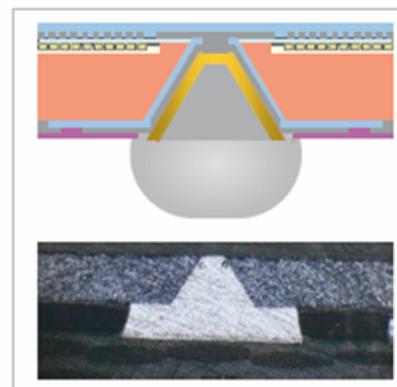


8x8 channels

1 channel = $3.9 \times 3.2 \text{ mm}^2$

6396 cells ($59 \times 32 \mu\text{m}^2$) /channel

Electronics embedded



through silicon
vias

development

Hamamatsu

KETEK



SiPMs arrays (monolithic)



- improve spatial resolution and PDE
- simplify the assembly



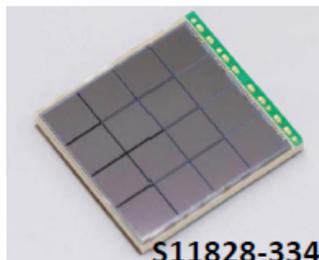
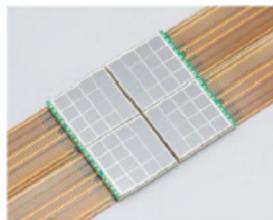
monolithic SiPM matrices

HAMAMATSU

4x4 channels

1 channel = 3x3 mm²

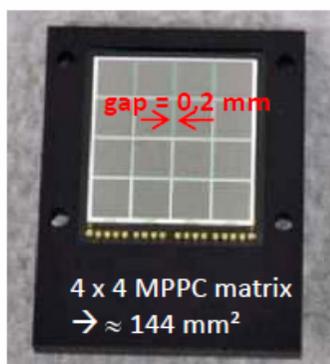
3600 cells (50x50 μm²)/channel



S11828-3344

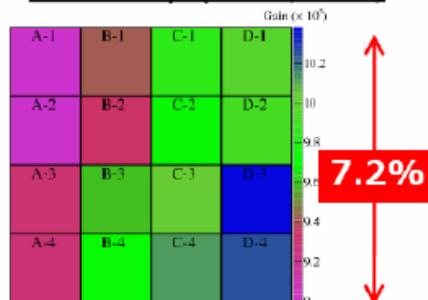
3 sides tileable (4 sides soon now)

1 cathode – 16 anodes



S10985 - 36x36 mm²
57600 cells

Gain map (71.9V, 0 °C)



ave. gain = 9.7×10^5

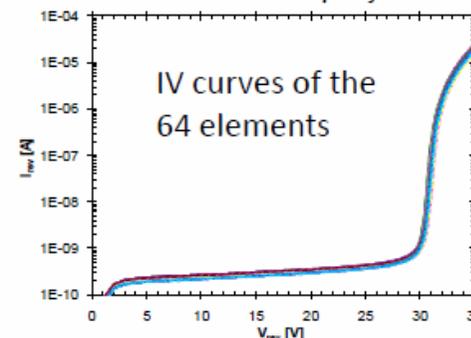
Kato et al, NIMA 638 (2011) 83–91

FBK



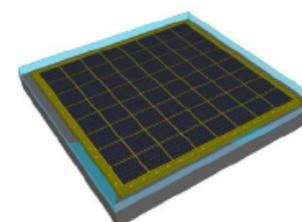
8 x 8 channels

DASiPM2 project

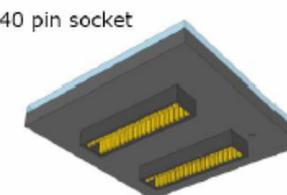


Marcatili et al, NIMA 659 (2011) 494–498

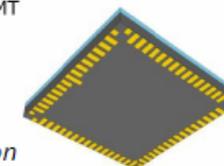
Ongoing R&D at AdvanSiD to improve the performances



64 channels
1.5x1.5 mm² SiPMs (pixels)



SMT



C. Piemonte, private communication

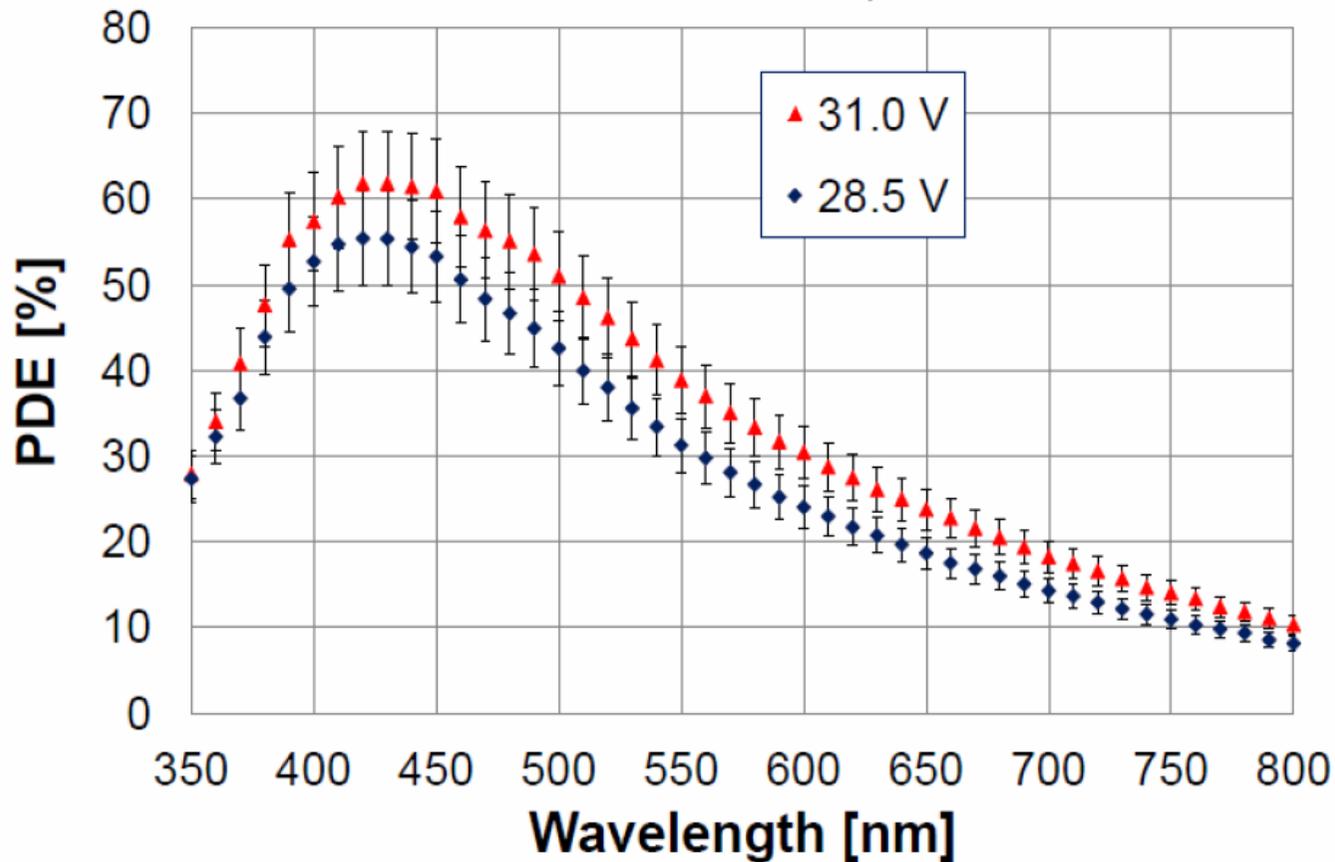
SiФЭУ с максимальной (рекордной) эффективностью



PDE vs. Wavelength

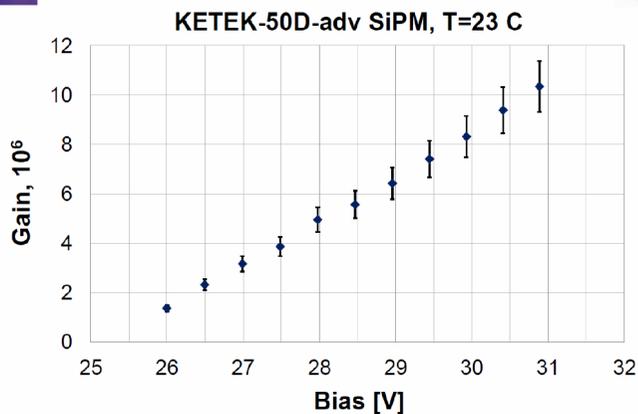


KETEK-50D-adv SiPM, T=23 C

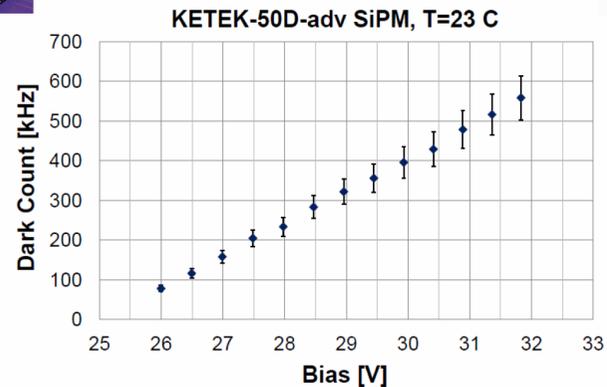




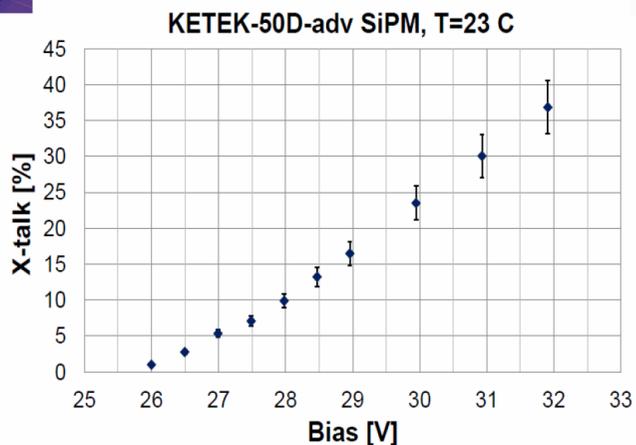
Gain vs. Bias



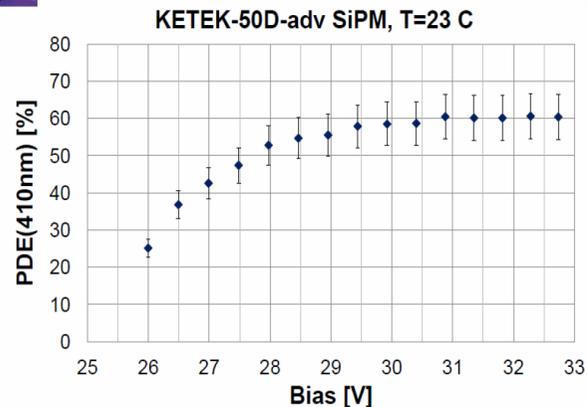
Dark Count vs. Bias



X-talk vs. Bias



PDE vs. Bias



Статус разработки микропиксельных лавинных фотодиодов для адронного калориметра эксперимента CMS
 24.12.12 Ю.В. Мусиенко (ИЯИ РАН, Москва) Семинар ИЯИ Е.Попова

Нейтринные эксперименты на жидком ксеноне (аргоне) – 178нм (128нм)

Глубина поглощения коротковолнового света (<200 нм) ~5 нм

Эффективность регистрации света ε :

$$\varepsilon = T * QE * G(U) * A,$$

где

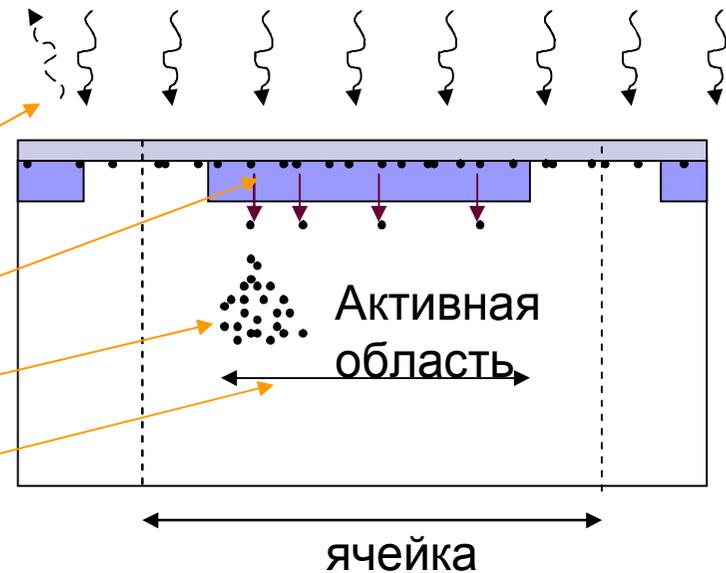
T-коэффициент пропускания света,

QE- внутренняя квантовая эффективность,

G(U) – вероятность развития гейгеровского разряда,

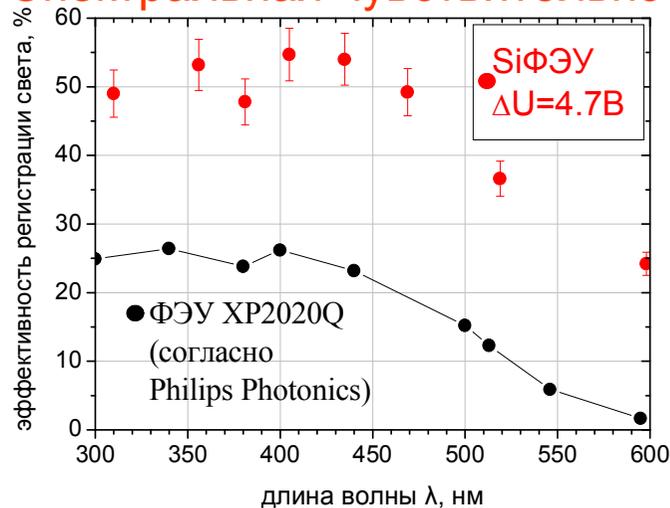
A – доля активной площади ячейки SiФЭУ

Возможна независимая оптимизация всех факторов

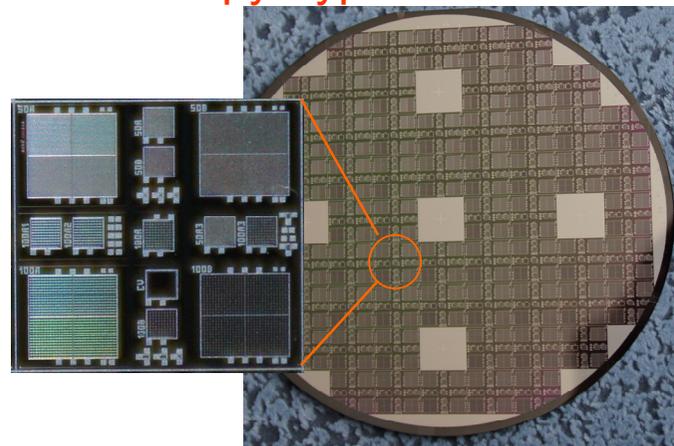


Параметры SiФЭУ (МИФИ/МРІ совместно с Excelitas)

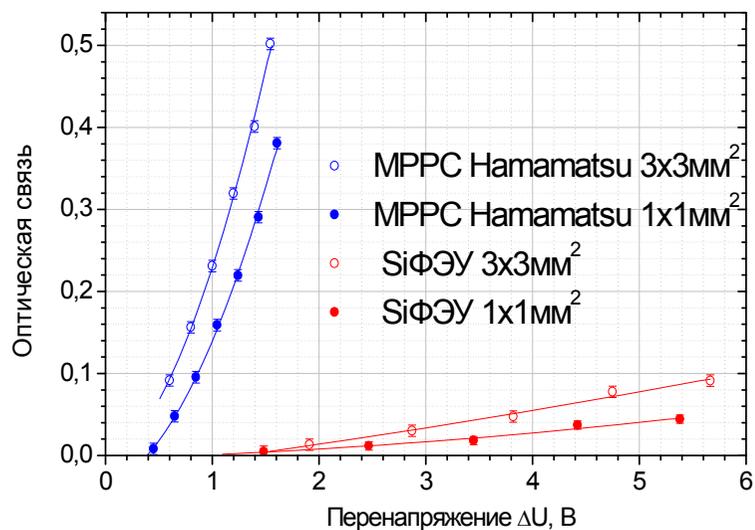
Спектральная чувствительность



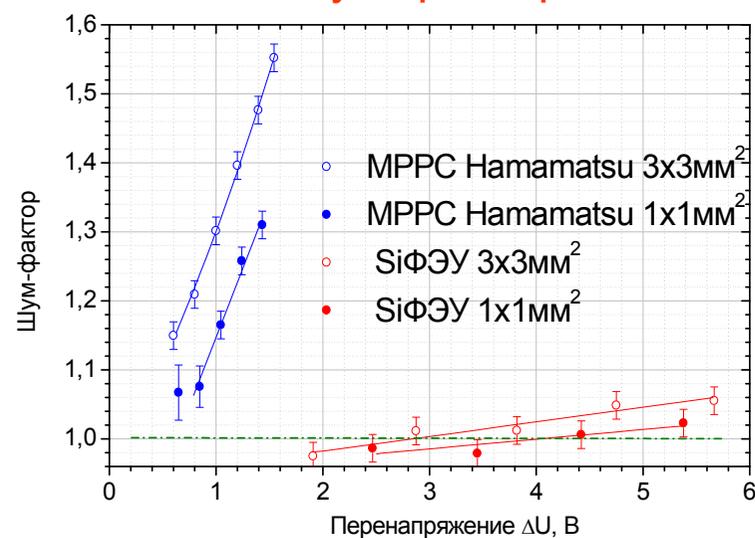
Кремниевая пластина со структурами SiФЭУ



Оптическая связь



Шум-фактор

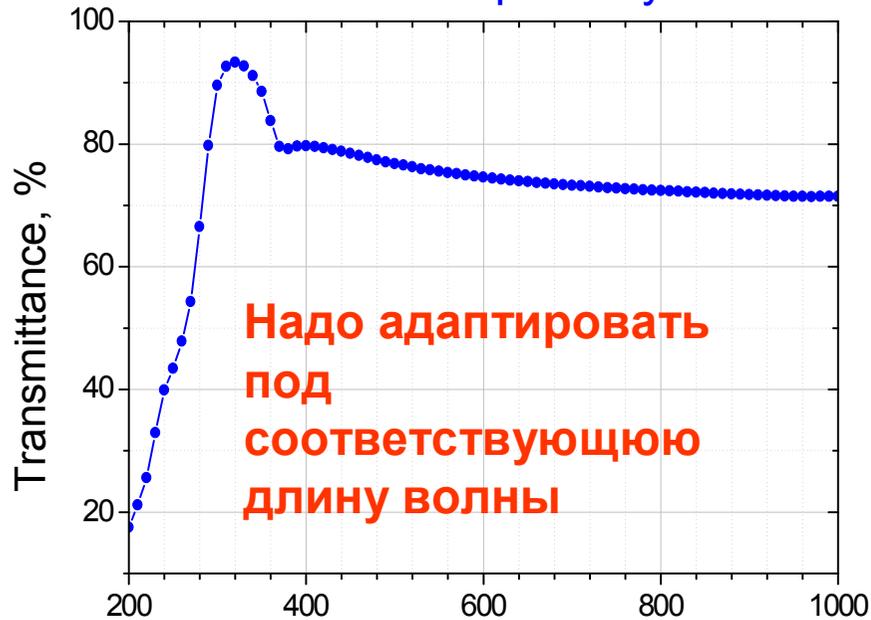


GERDA requirements. Task 1: VUV sensitivity

- AR coating
- High internal quantum efficiency (abs. length for 128nm ≈ 5 nm)

actual MEPhi/MPI/Excelitas SiPMs

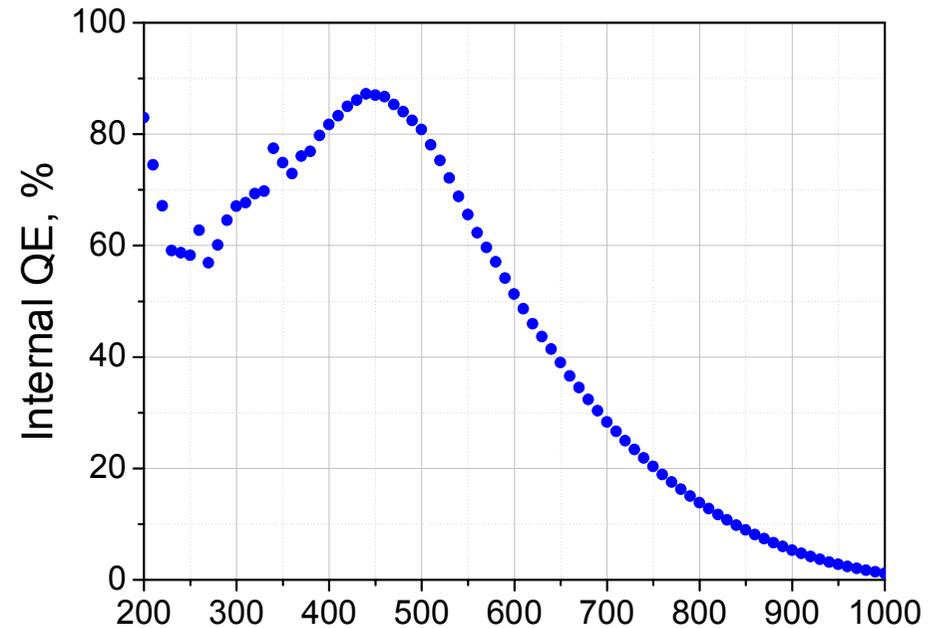
ARC transparency



**Надо адаптировать
под
соответствующую
длину волны**

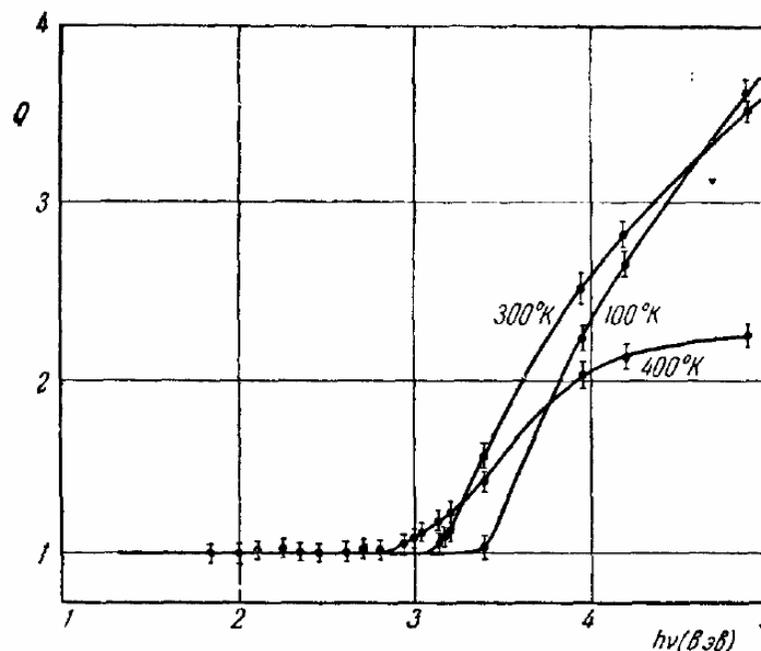
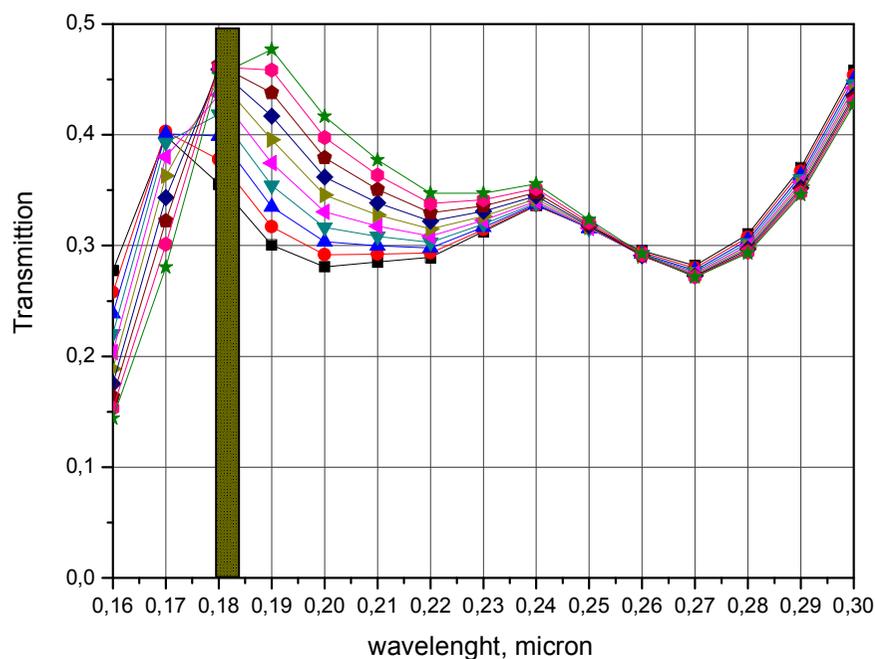
ARC should be shifted to 128nm

Internal QE



internal QE already is quite high

Расчет просветляющего покрытия Квантовый выход (двойная ионизация) (ARC)



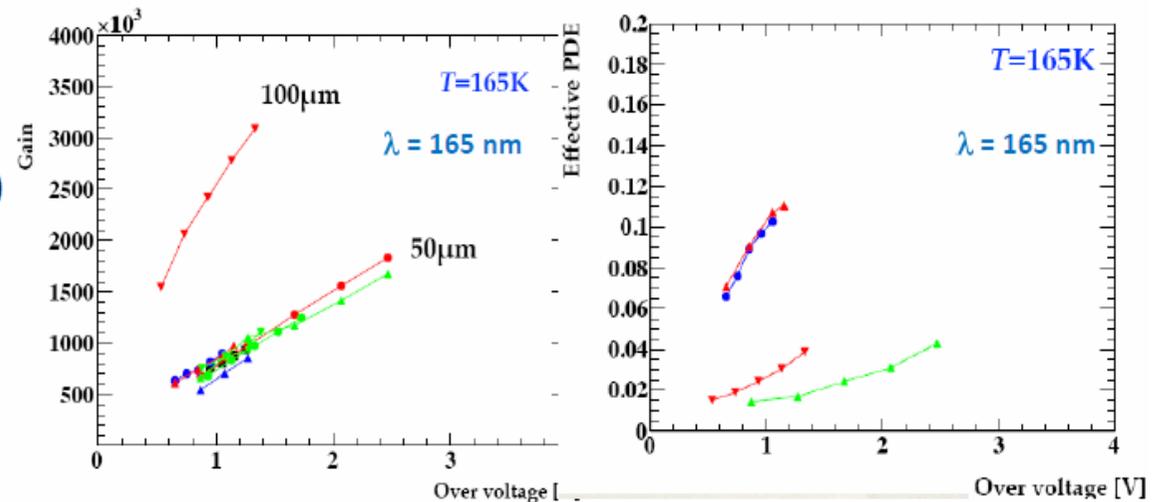
178nm – 7эВ

Расчеты, проведенные в МИФИ, показывают, что для 178 нм возможно ARC~40%, что, принимая во внимание, двойную ионизацию при фотоэффекте, позволяет надеяться получить PDE~40-50%

HAMAMATSU

UV-enhanced MPPC under development (collaboration between Hamamatsu, ICEPP and KEK) : removal of the protection coating and optimization of the MPPC parameters → currently sensor size: $3 \times 3 \text{ mm}^2$ (cell size = $50 \mu\text{m}$)

- ❖ PDE (165 nm) = 10 % (best sample)
- ❖ Gain $\approx 10^6$ @ 165 K
- ❖ DCR = 0 @ 165 K
- ❖ large $R_q \rightarrow$ long tail ($\approx 150 \text{ ns}$)



W. Ootani, PhotoDet2012

11

V. Puill, IEEE NSS Conference, Anaheim, Nov 1 2012

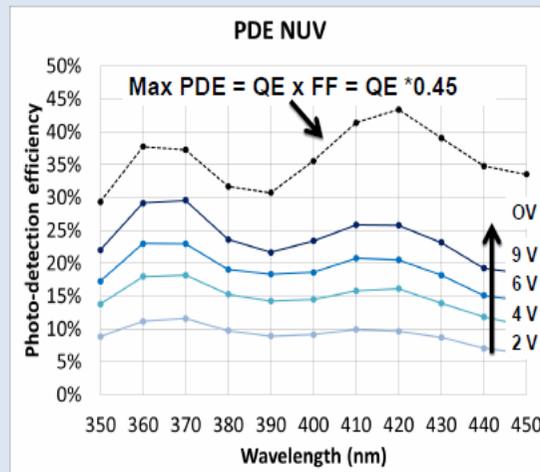
First results on NUV-SiPMs at FBK

Alessandro Ferri¹, Alberto Gola¹, Claudio Piemonte¹, Tiziana Pro¹, Nicola Serra¹, Alessandro Tarolli¹, Nicola Zorzi¹

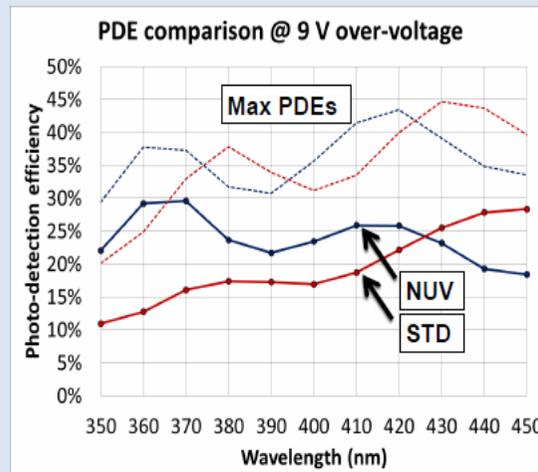
¹Fondazione Bruno Kessler, Trento, Italy

Transition from n-on-p to p-on-n

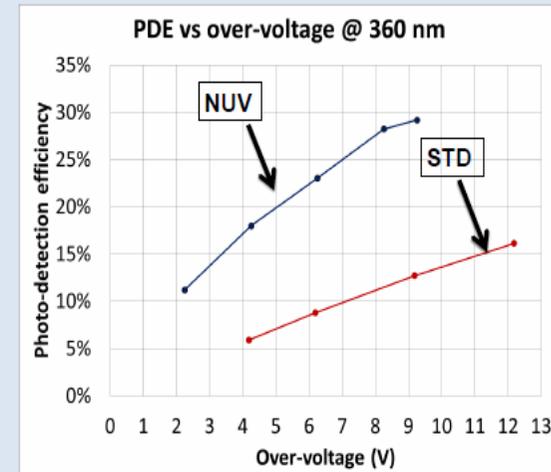
PDE results and comparison with Standard n-on-p technology



QE measured on test photo-diode allows us to evaluate max PDE (higher plot).
PDE=30% is measured at 360 nm, 9 V OV.



At the same 9 V over-voltage the **NUV PDE is a factor ~ 2.5 greater** than standard n-on-p technology.



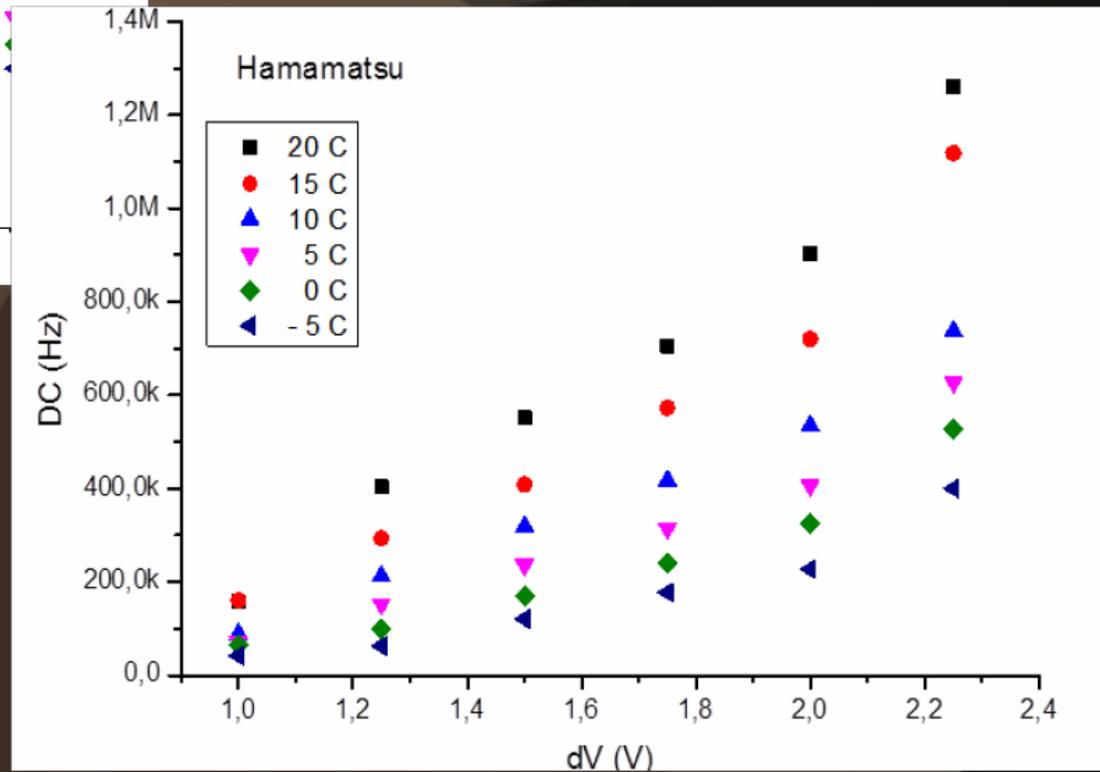
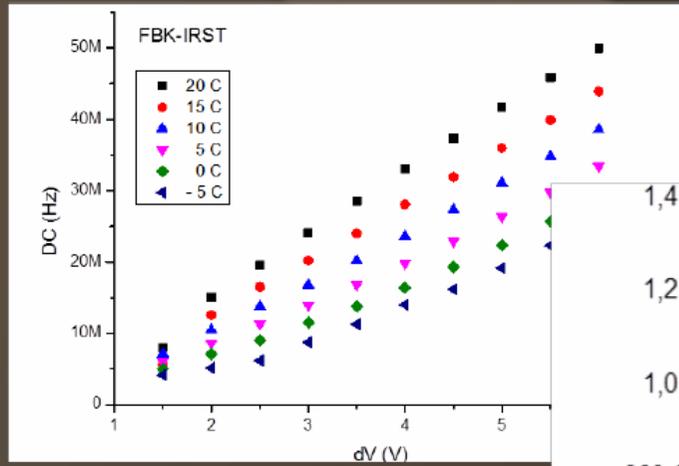
In NUV SiPM PDE **increases faster** with OV w.r.t STD since the avalanche is triggered by electrons instead of holes.

Conclusions: We presented the first results of the Near Ultra Violet SiPM technology (NUV-SiPM) produced at FBK. The functional measurements on a 1x1mm² 50x50um² SiPM show that the device is working properly. The optical characterization of a SPAD with the same cell structure of the SiPM evidences a PDE as high as 30% at 360nm and 9 V over-voltage which is a rather good value considering a FF=45%. For the same over-voltage and wavelength, PDE in NUV-SiPM is a factor ~ 2.5 greater than in standard technology. We are currently working to improve the noise and after-pulse performance of this new technology.

Темновой счет SiФЭУ от FBK

SiPM characterization

Signal characterization with single-channel custom preamplifier



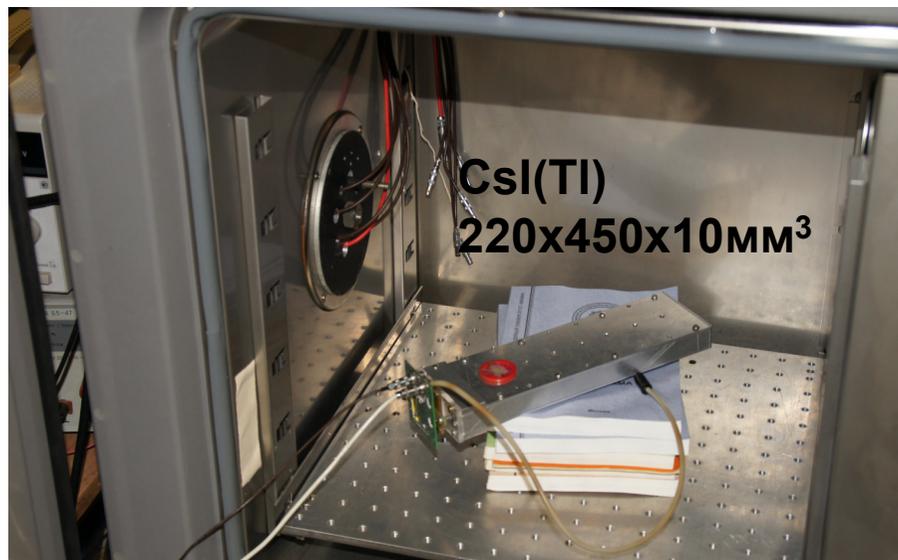
R.D'Alessandro
(Università di Firenze e INFN-Firenze)

SiФЭУ, чувствительные к зеленому свету

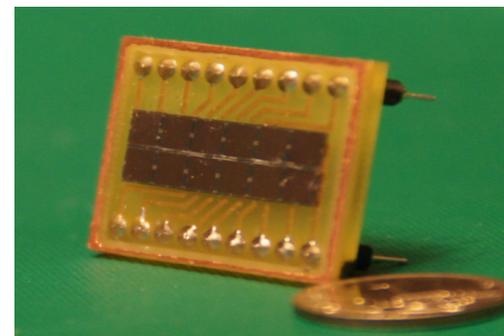
Области применения:

Спектросмещающие волокна $\sim 500\text{nm}$

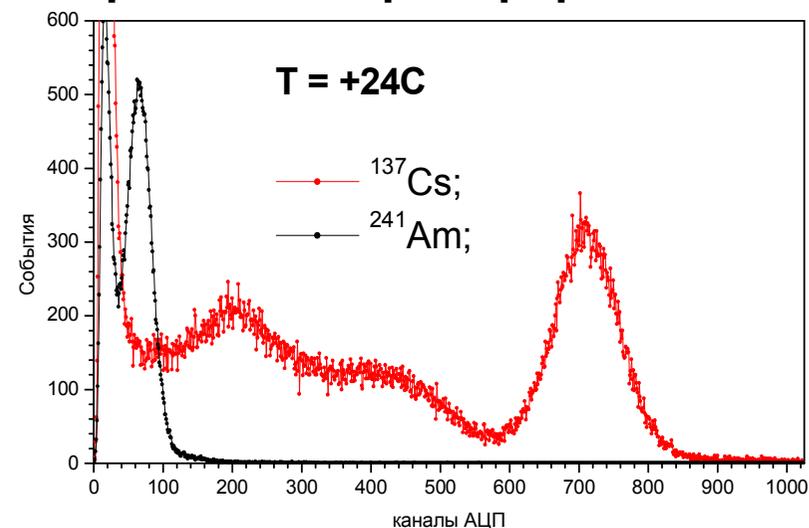
Кристаллы сцинтилляторов (CsI(Tl)) $\sim 550\text{ nm}$



Макет радиационного монитора



Сборка детекторов фирмы КЕТЕК

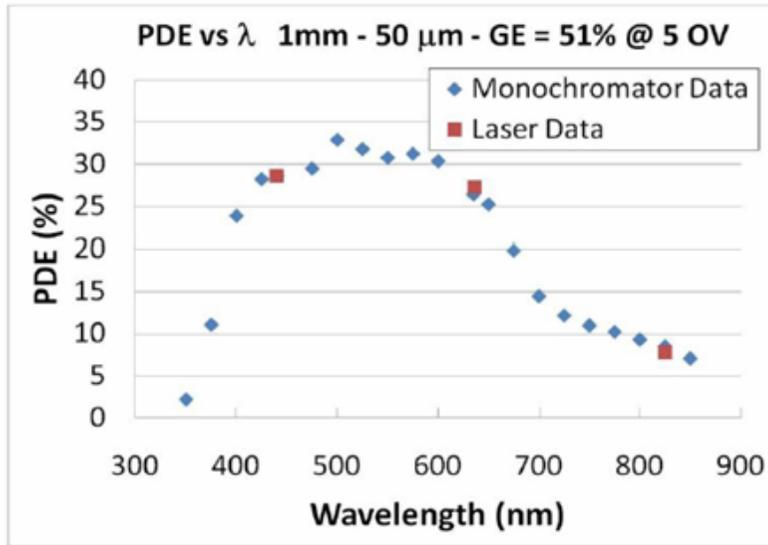


Особенности конструкции «зеленых» SiФЭУ:

Соответствующее просветление (ARC)

Глубокая обедненная область (высокое напряжение пробоя)

Excelitas technologies

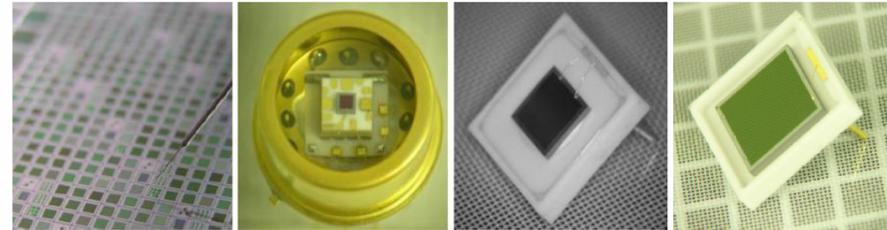


Broad responsivity spectrum

Ubreakdown 90-140V

Almost ready for market! Final product in end of 2012

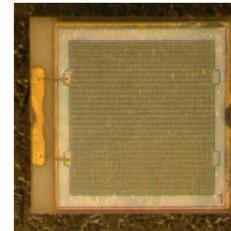
2nd Gen SiPM- Packaging Development



Wafer of chips

TO-can, cooler

Ceramic Header 3x3, 5x5



SMT package (tile-able)

Packaging Development progressing alongside, 1,3 and 5 mm chip sizes

EXCELITAS TECHNOLOGIES

20

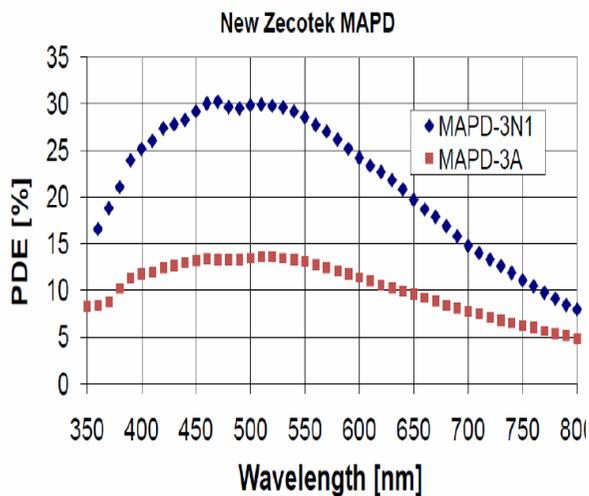
Addressing the needs of molecular imaging and PET communities.

SiFЭУ с большим динамическим диапазоном

HCAL CMS свет 500nm

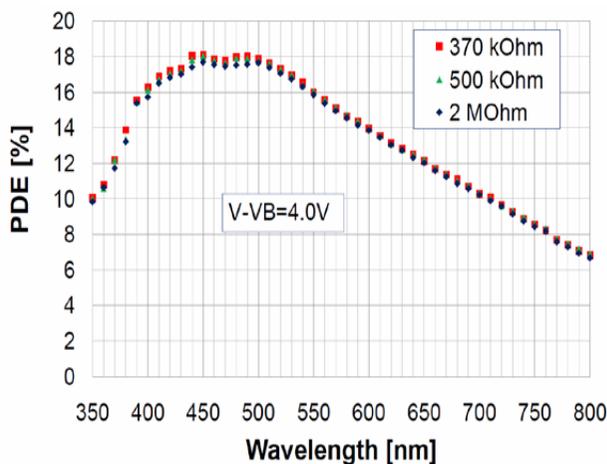
Zecotek

>15000 ячеек/мм²



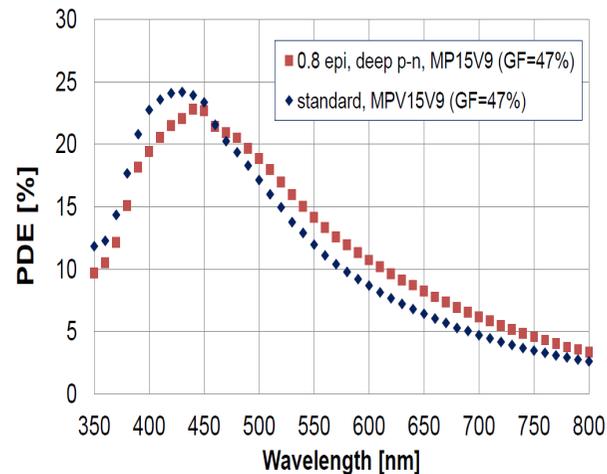
Hamamatsu

до ~4489 ячеек/мм²



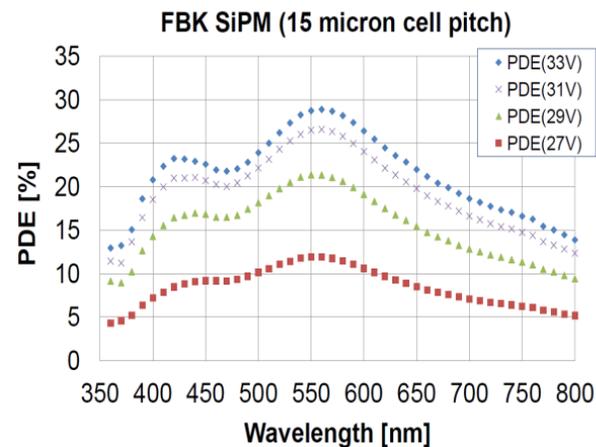
4384 ячейки/мм²

KETEK SiPMs, V-VB=4.0V



FBK
RGB-SiPM-HD

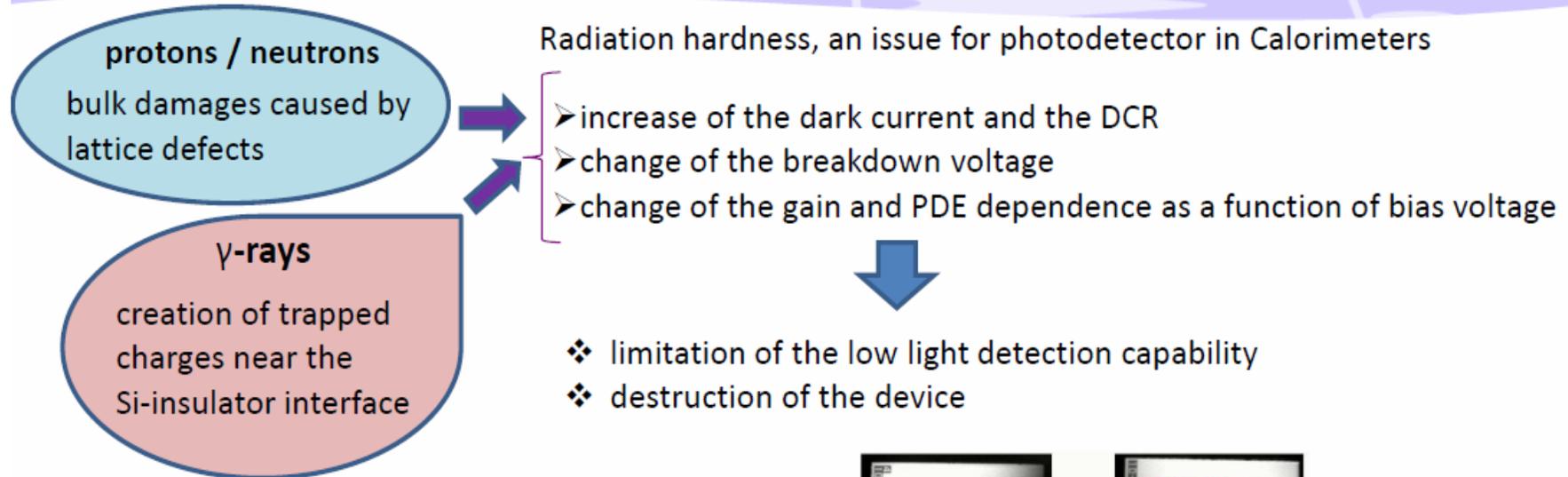
4404 ячейки/мм²



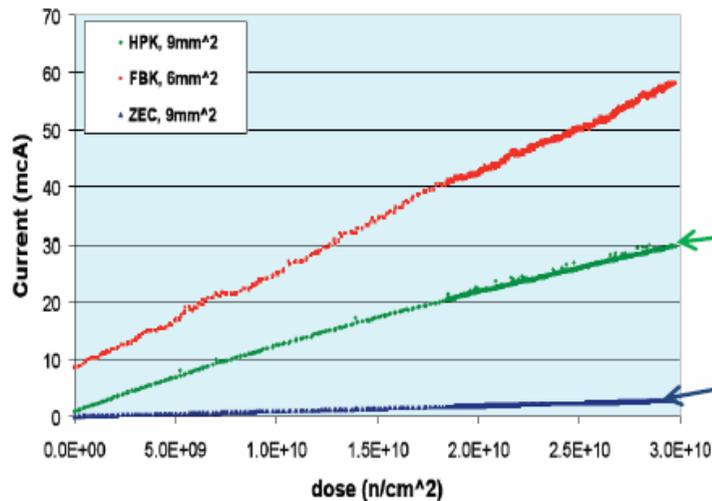
Измерения Ю.В. Мусиенко (ИЯИ РАН, Москва)



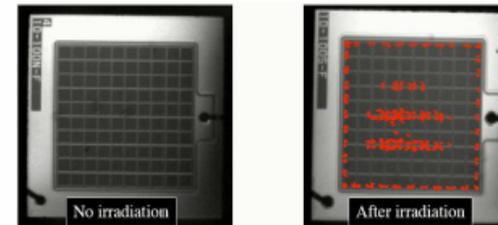
Rad-hard SiPMs (1)



1MeV Neutron dose vs leakage current



Y. Musienko, LHC on the March workshop 2011



HAMAMATSU have developed new MPPC more resistant to irradiation

MAPD have a good behavior under irradiation but its recovery time is long (300 μ s)

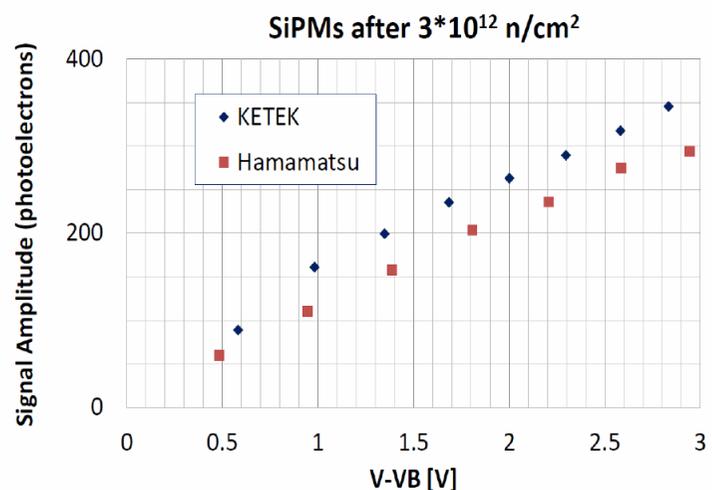
Радиационная стойкость детекторов для апгрейда CMS. Нейтронное облучение



MPPC&KETEK:
Amplitude in p.e. vs. dV

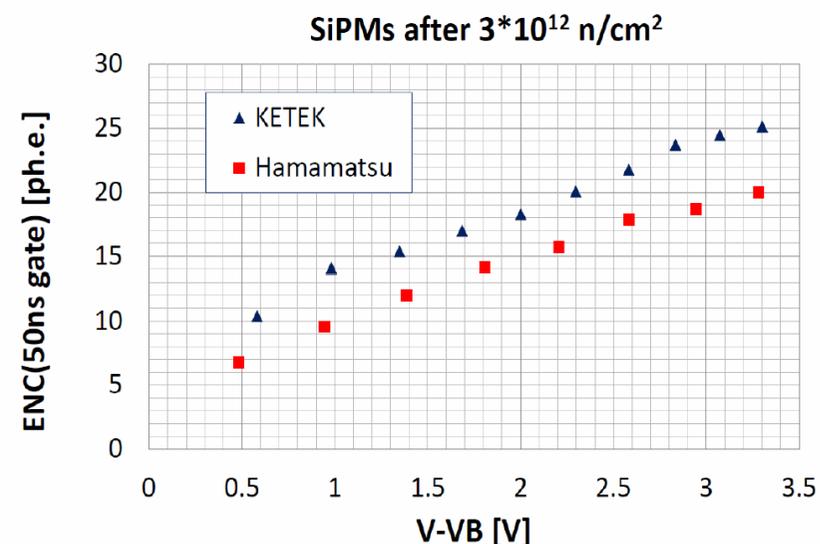


MPPC&KETEK: ENC vs. dV



Амплитуда сигнала после облучения, выраженная в фотозелктронах, выше для МЛФД КЕТЕК (из-за большего геометрического фактора)

53

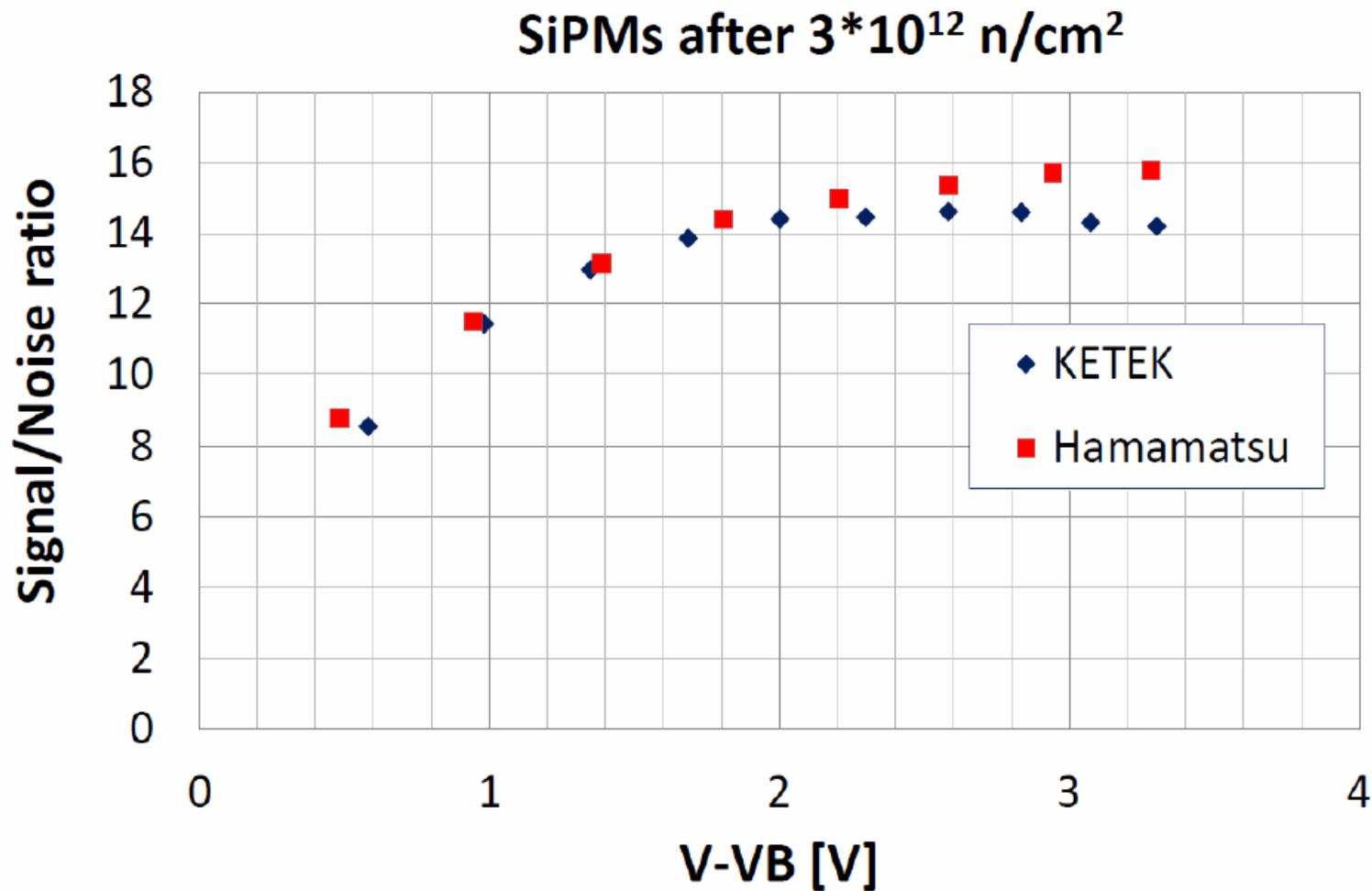


Шум МЛФД КЕТЕК после облучения несколько выше, чем шум Hamamatsu MPPC (в основном из-за лучшего геометрического фактора)

52



MPPC&KETEK: S/N ratio vs. dV

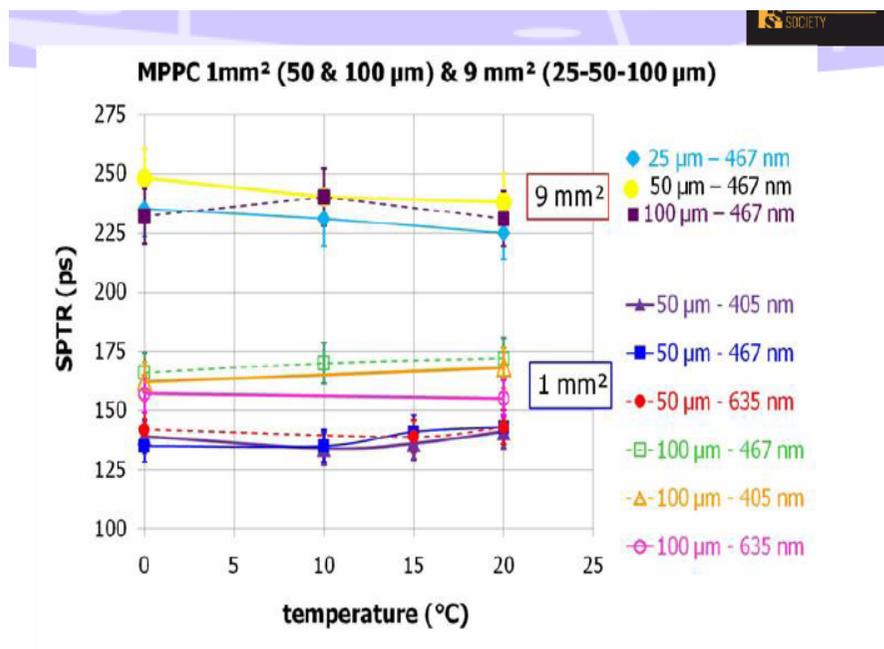
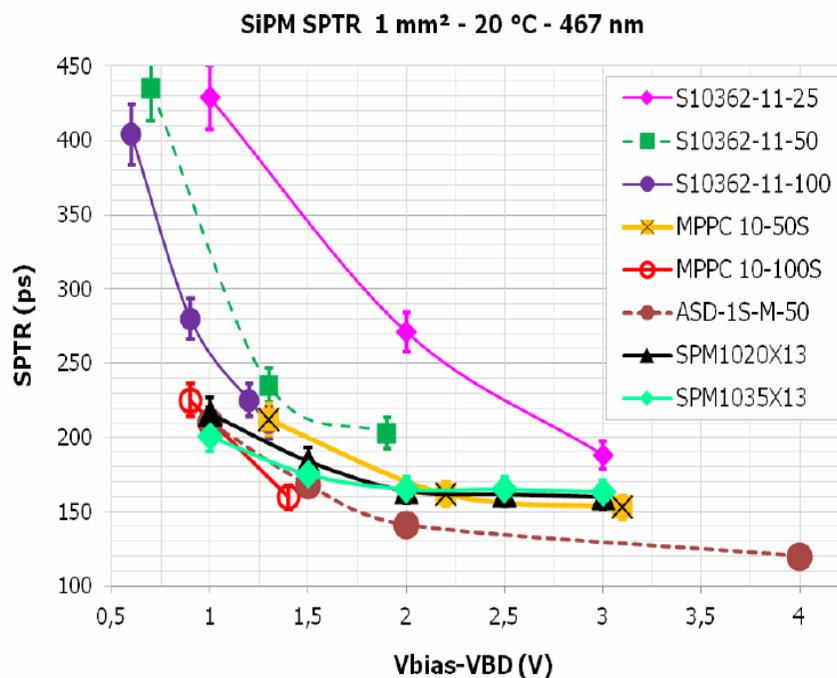


Отношение сигнал/шум после облучения нейтронами одинаково для KETEK и Hamamatsu МЛФД

Временное разрешение различных SiФЭУ (ПШПВ)



SiPM Single PhotoElectron timing Resolution

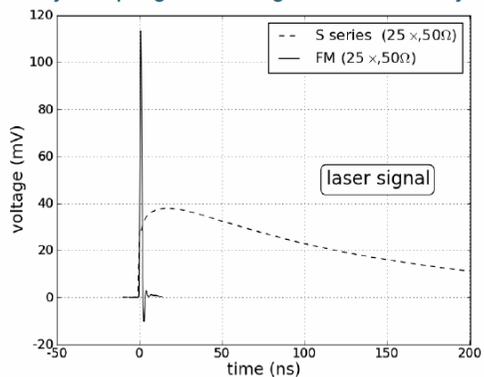


V. Puill et al, Single Photoelectron Timing Resolution of SiPM as a function of the bias voltage, the wavelength and the temperature, NIMA 54094, NDIP2011 Proceedings

«Быстрые» SiФЭУ от SensL

Introduction – Fast Pulses with SPM

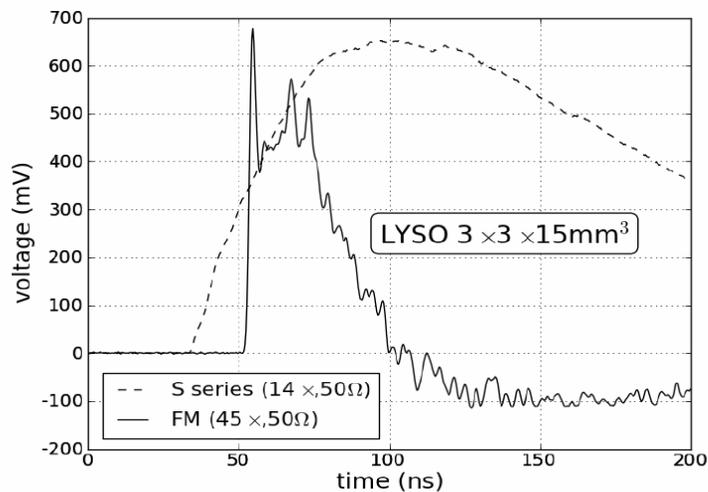
- SensL's new technology creates fast pulses without sacrificing PDE
- This new technology is described in SensL's international patent application no. WO2011117309
- MicroFM family sampling now with general availability Q3 2012



sensL
sense light

2

FM Signal with L(Y)SO Output

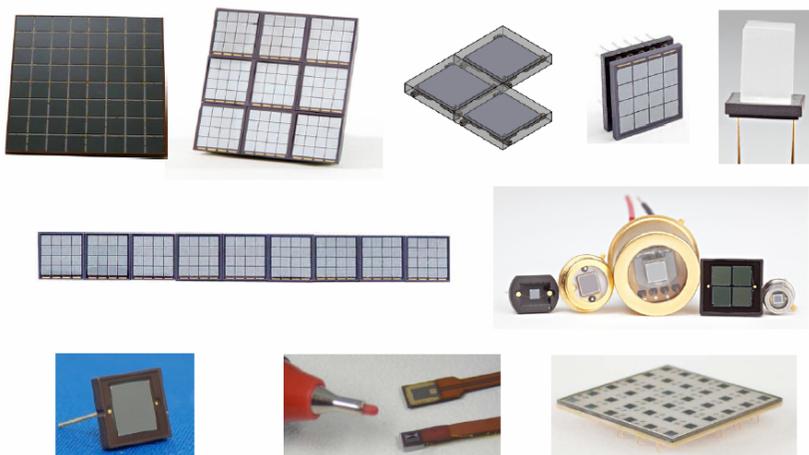


- Superior ability to trigger from the first photoelectron
- Less dependence on PDE

sensL
sense light

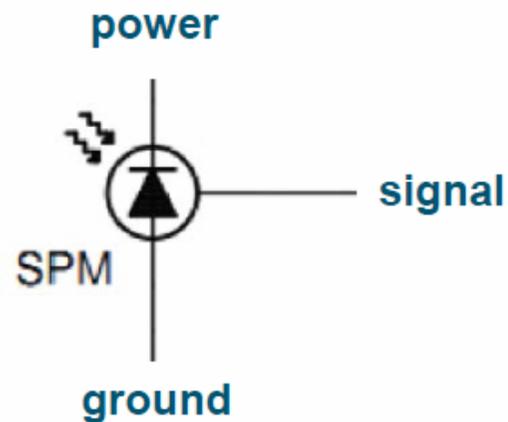
4

SensL Products



sensL
sense light

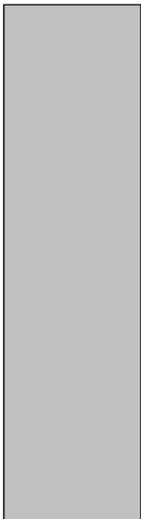
19



ИЯИ Е.Попова



VNIVERSITAT
D VALÈNCIA



Overview of Multicell Geiger-mode Avalanche Photodiodes (SiPM) Applications

Gabriela Llosá,

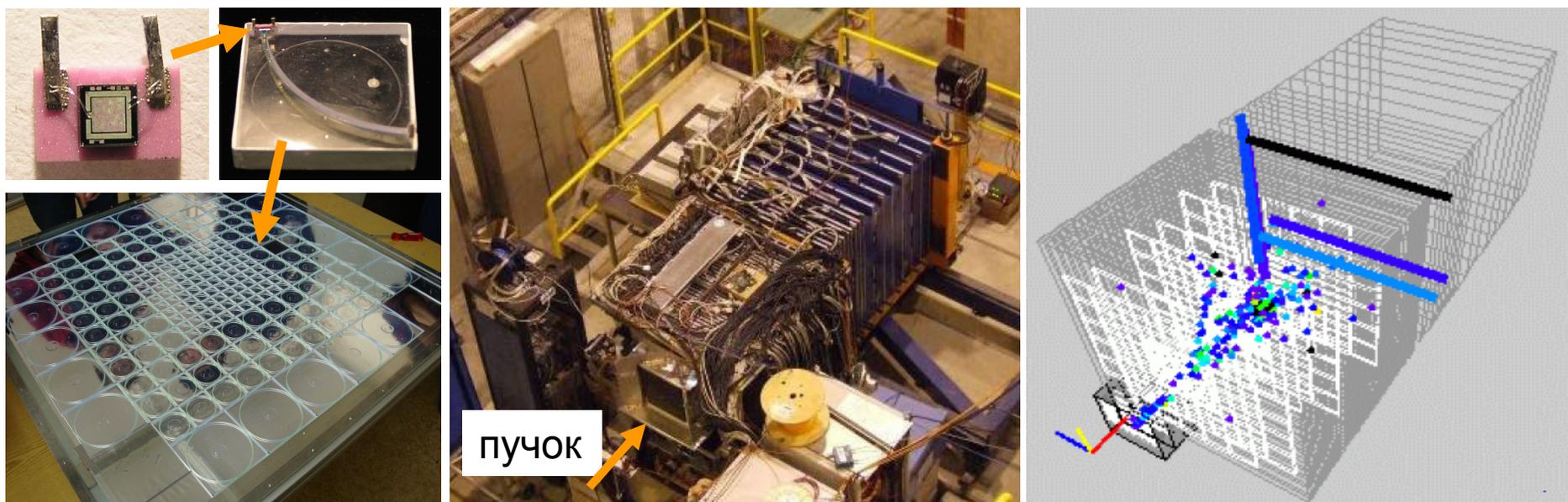
Instituto de Física Corpuscular - IFIC (CSIC-UV), Valencia, Spain

IRIS group <http://ific.uv.es/iris>

Photodet 2012, Orsay, 13-15 June 2011

Разработка прототипа тайлового адронного калориметра на основе SiФЭУ для международного линейного коллайдера

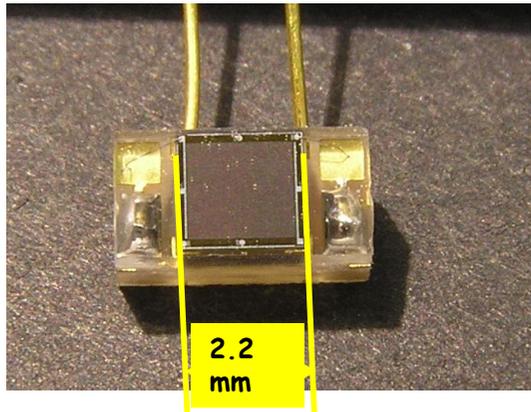
(коллаборация CALICE, 2007)



7620 SiФЭУ – первое в мире массовое применение

SiФЭУ изготовлены совместно МИФИ-ПУЛЬСАР

KETEK SiPM



Sensitive area - 2.2x2.2 mm²

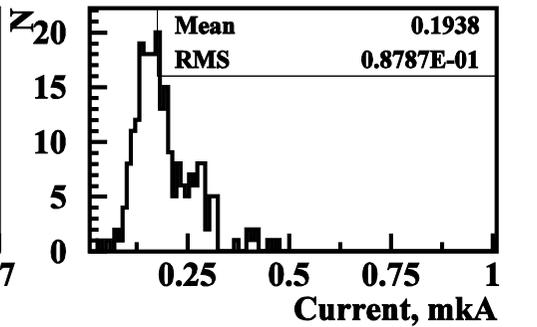
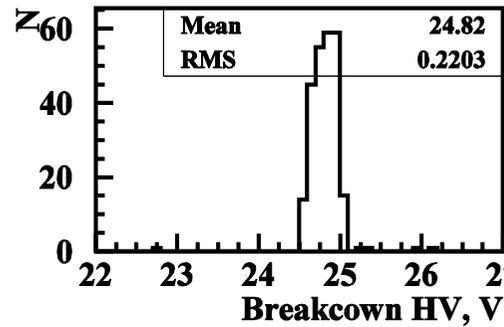
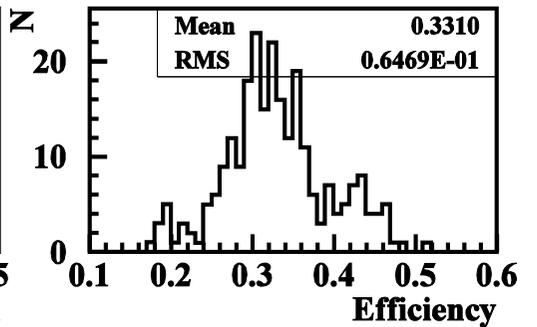
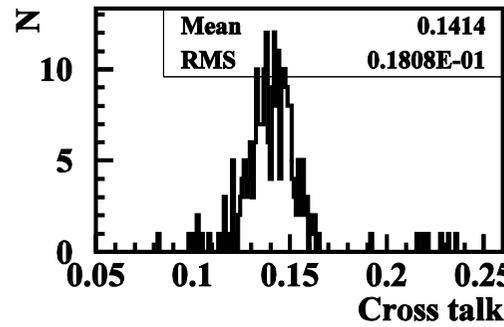
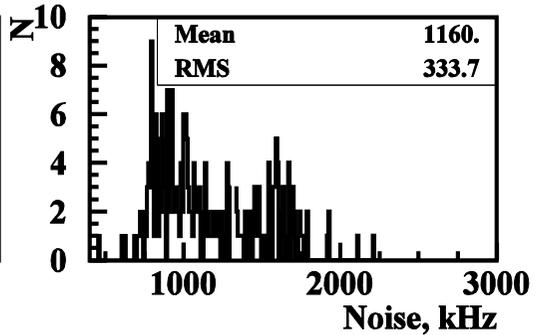
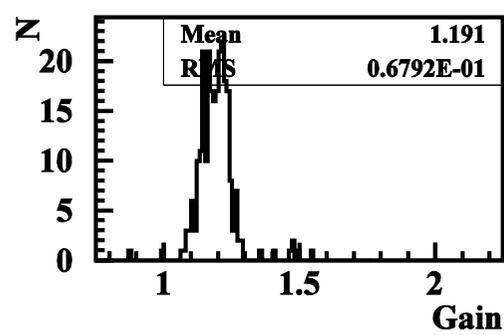
Pitch - 20 μ --> 12100 pixels

Package size (LxHxD) - 5.4x2.9x2.0 mm³

Breakdown HV ~ 24.6 V

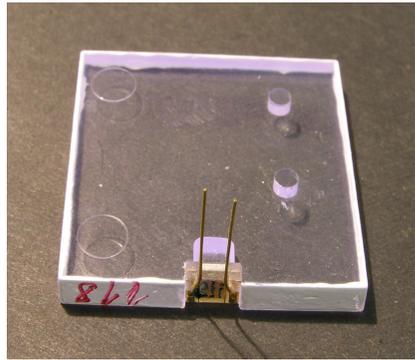
Operation voltage - 32.5 V

Due to high operating overvoltage week dependence on temperature!

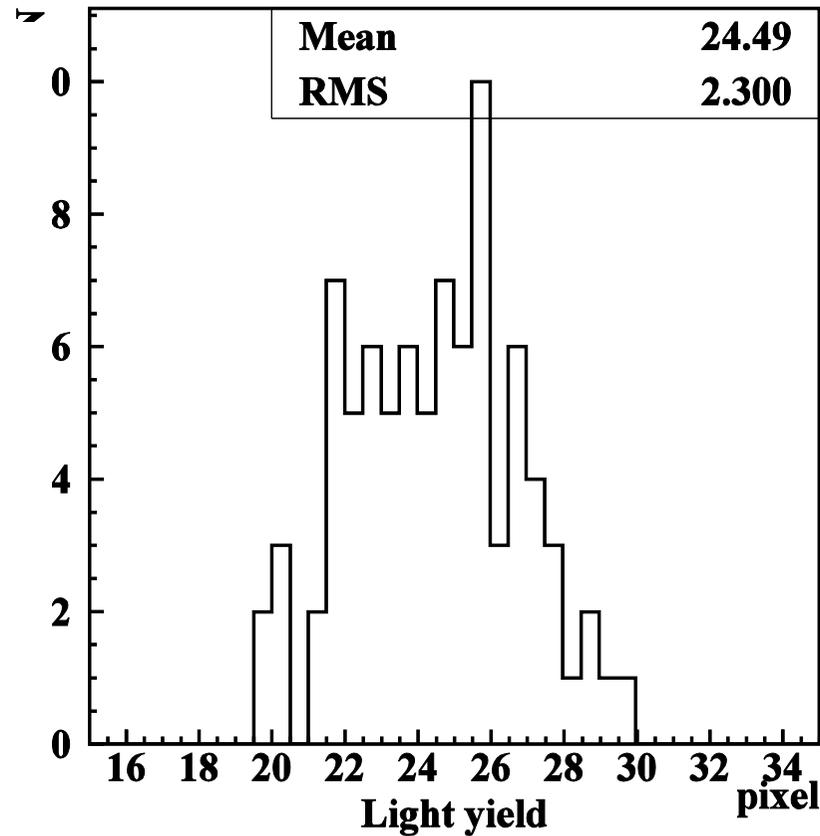
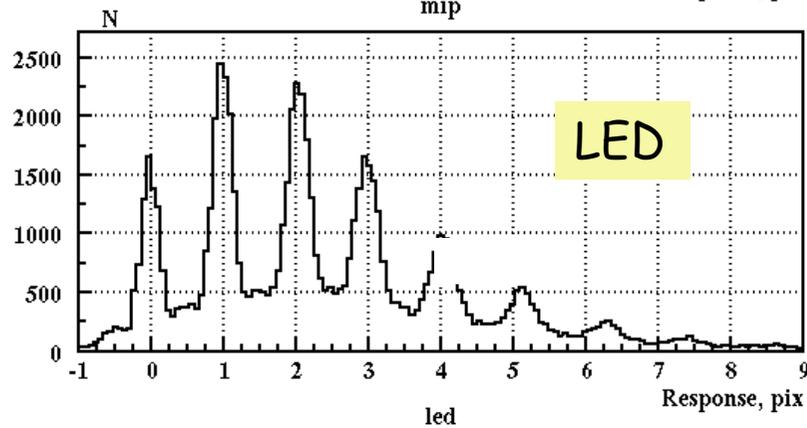
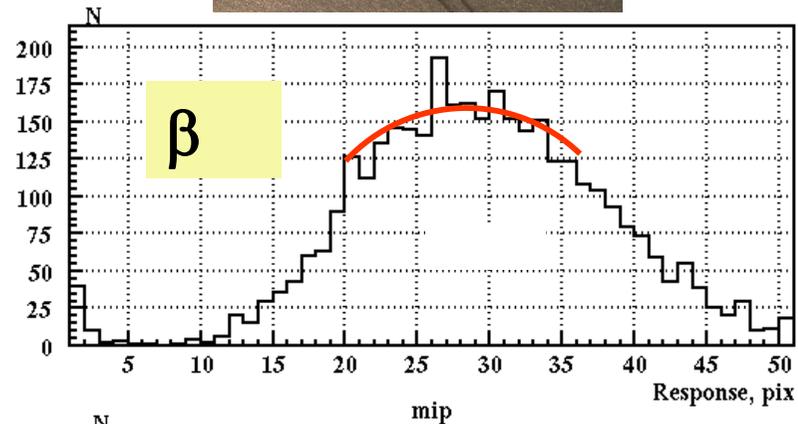


CALICE
ITEP data

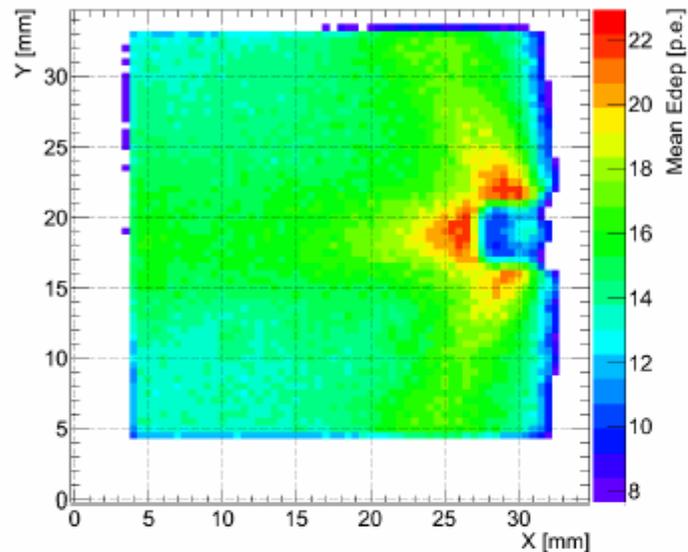
Response of a tile with KETEK SiPM to β -particle from ^{90}Sr



Distribution of MPV for tile response



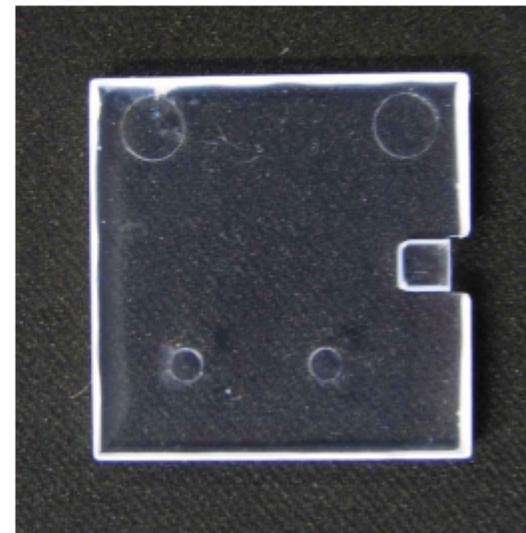
Results: ITEP tile ($3.0 \times 3.0 \times 0.3 \text{ cm}^3$)



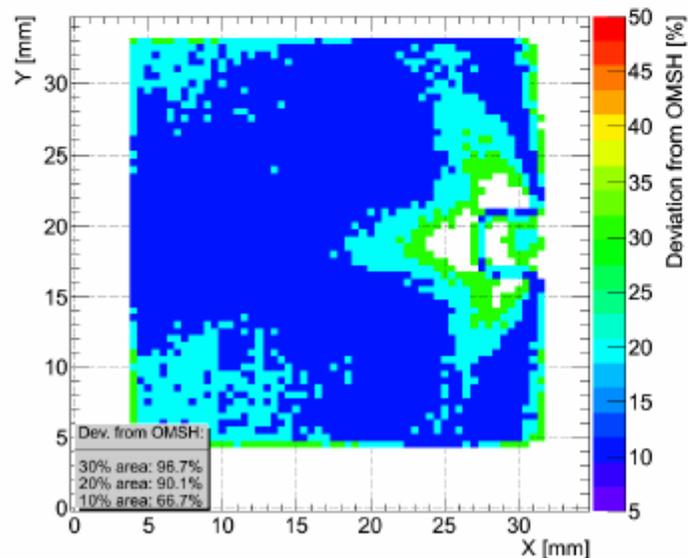
Homogeneity:

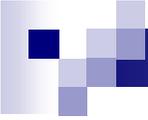
- 30% around mean: 97% area
- 20% around mean: 90% area
- 10% around mean: 66% area

Photograph



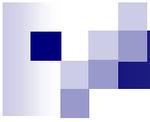
**CALICE
MPI data**





Заключение:

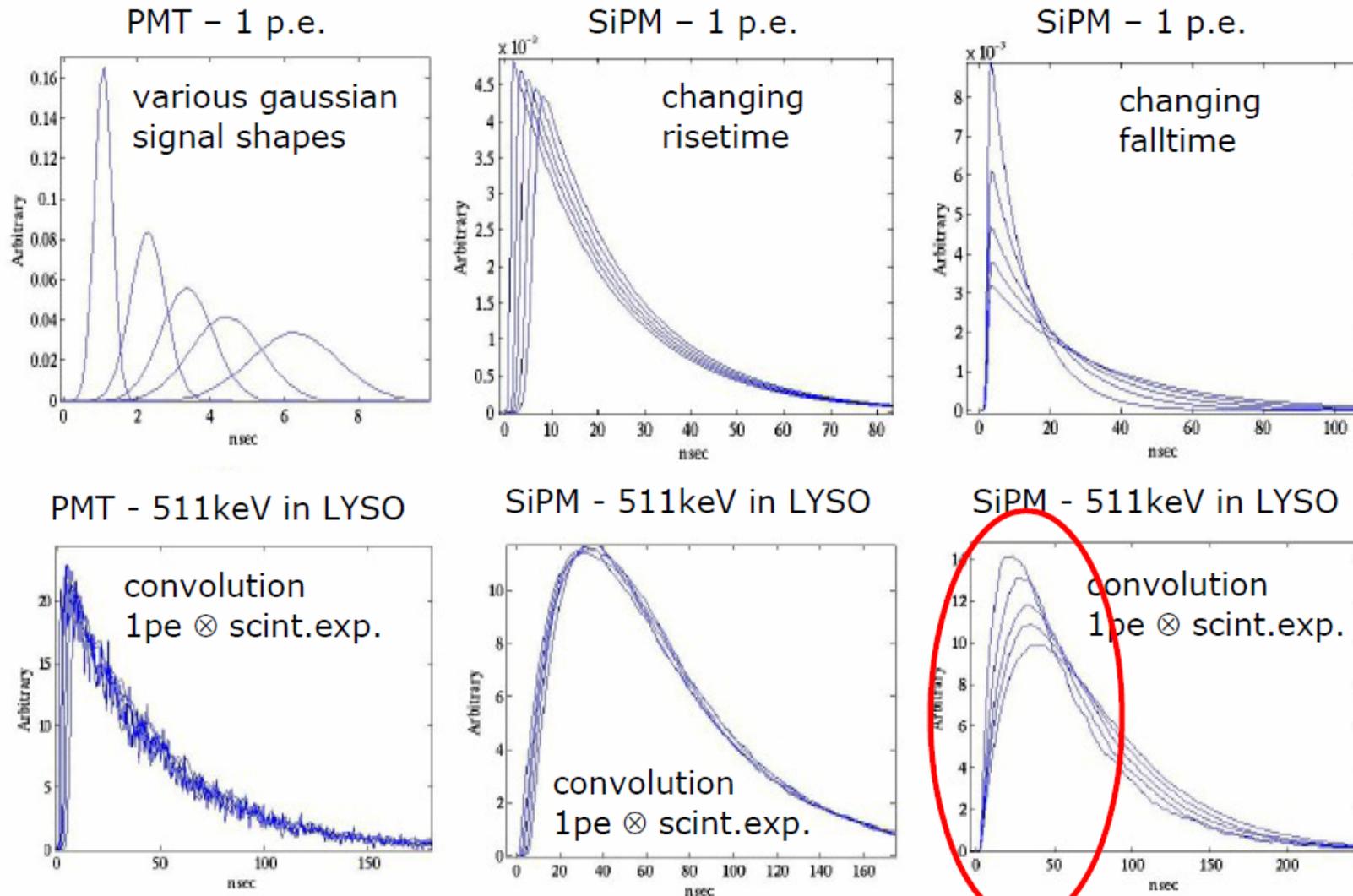
- SiФЭУ очень перспективные, быстроразвивающиеся твердотельные фотодетекторы
- Эффективность регистрации света посредством SiФЭУ превысила эффективность квантовых фотоумножителей ($>60\%$)
- Огромное количество различных модификаций как самих SiФЭУ, так иборок на основе SiФЭУ
- SiФЭУ уже доступны коммерчески и используются в реальных экспериментах



■ Backup slides

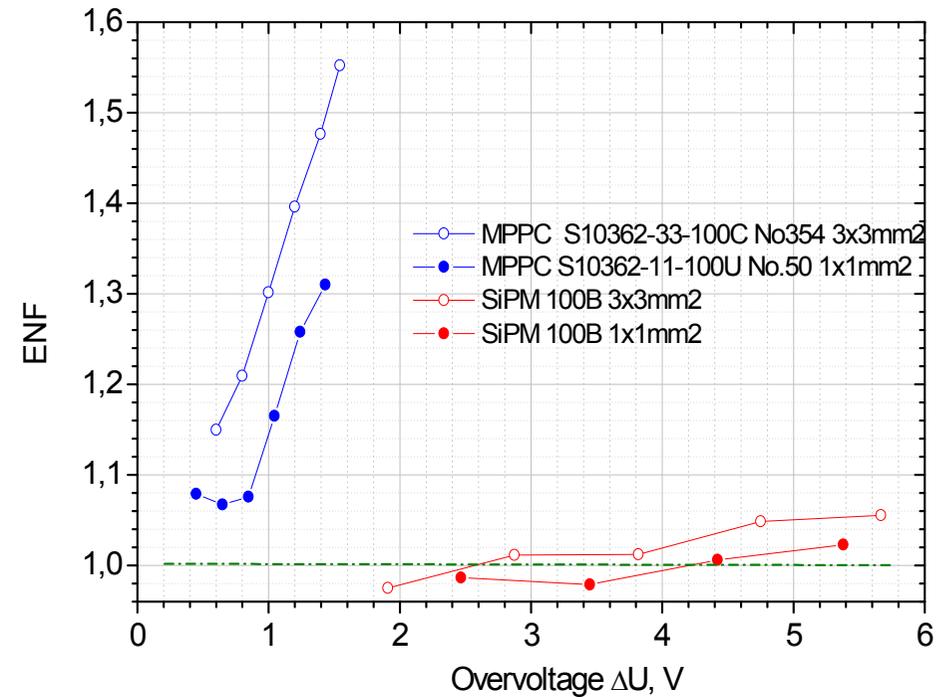
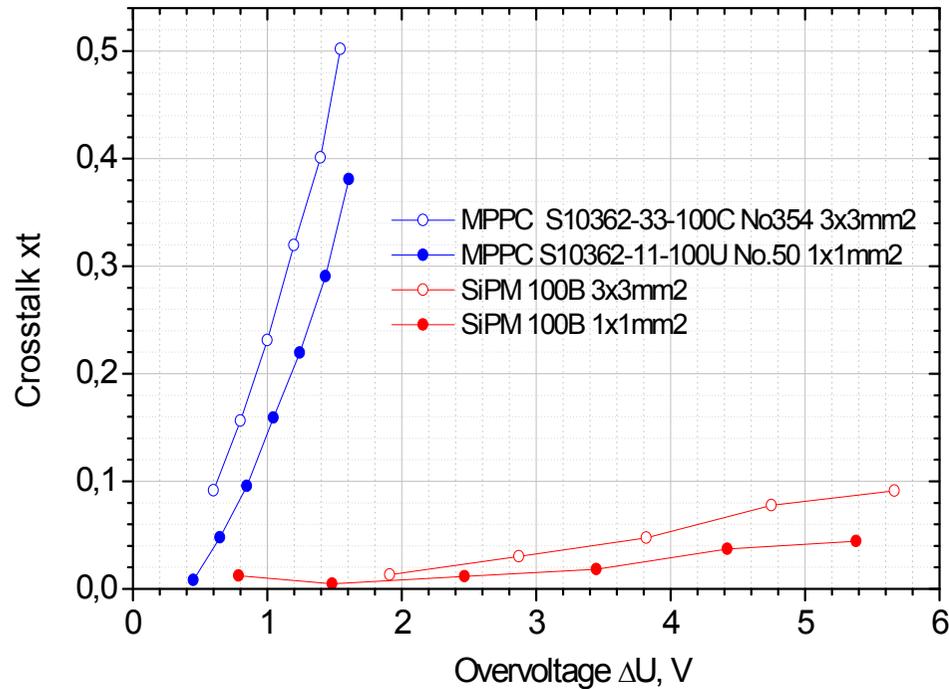
Signal shape for timing - many photons

Single p.e. signal **slow falling-time** component $\tau_{\text{fall}} = R_q (C_d + C_d)$
 strongly affects **multi-photon signal risetime**



Crosstalk and Excess noise factor

For light distributed according to Poisson law



$$ENF \equiv \left(\frac{\sigma_{out} / A_{out}}{\sigma_{in} / A_{in}} \right)^2$$

$$ENF = N_0 \cdot \left(\frac{\sigma}{\langle Mean \rangle} \right)_{\text{exper}}^2$$

$$N_{\text{fired_pixels}} = \frac{N_0}{1 - xt}$$

$$N_{\text{fired_pixels}} = \frac{\langle Mean \rangle}{A_{1e}}$$

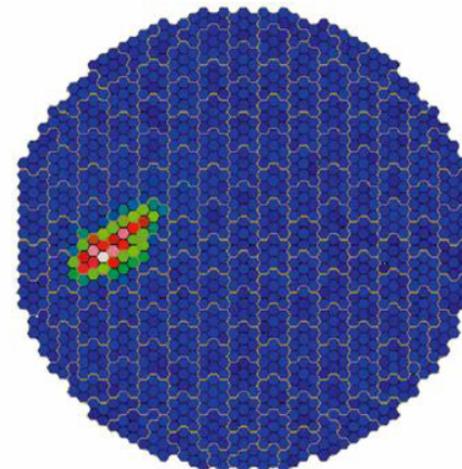
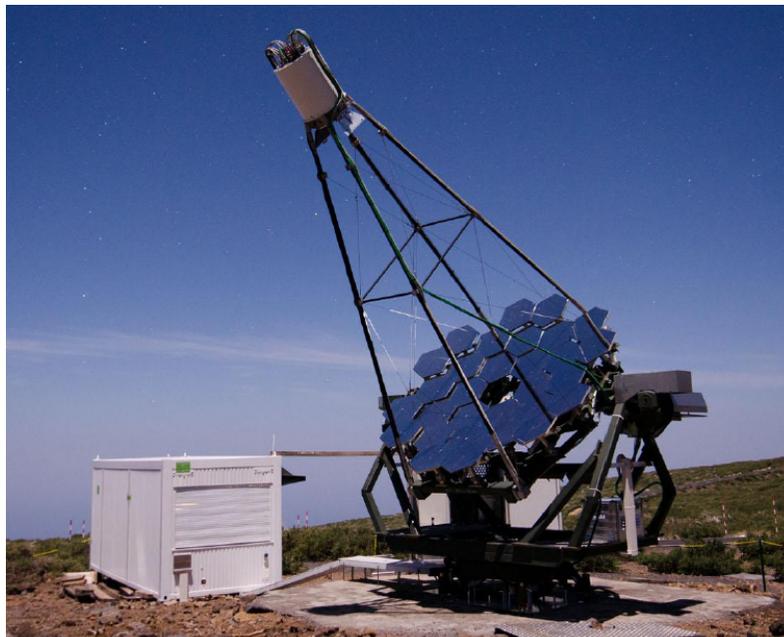
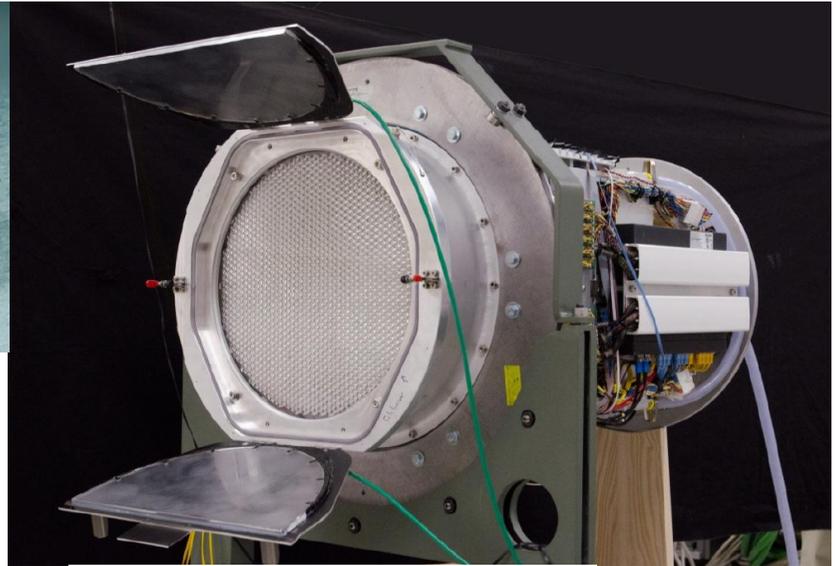
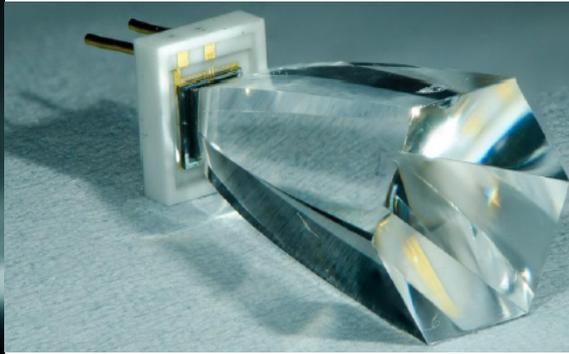
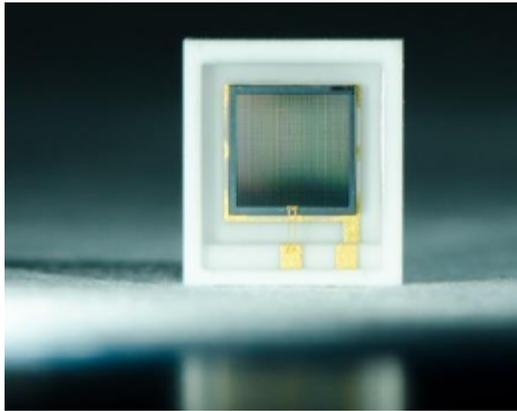
N_0 initially fired pixels calculated from "0" probability

Xt crosstalk

A_{1e} amplitude of single pixel

FACT camera (First G-APD Cherenkov Telescope)

Hamamatsu MPPC



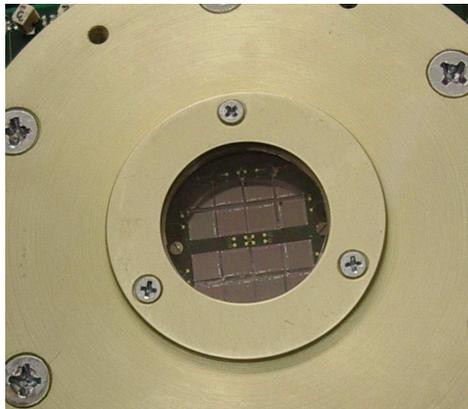
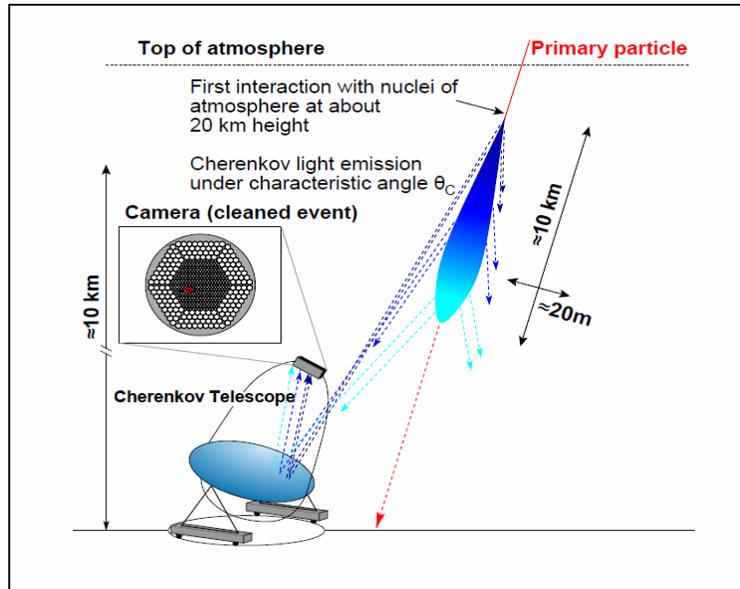
Th. Krähenbühl for the FACT collaboration

PhotoDet2012 - International Workshop on New Photon-detectors

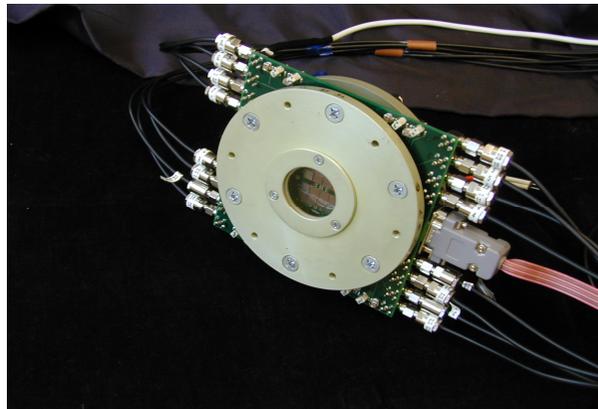
Paris – France, June 13-15, 2012

Cooled SiPM matrixes modules for astropartical applications

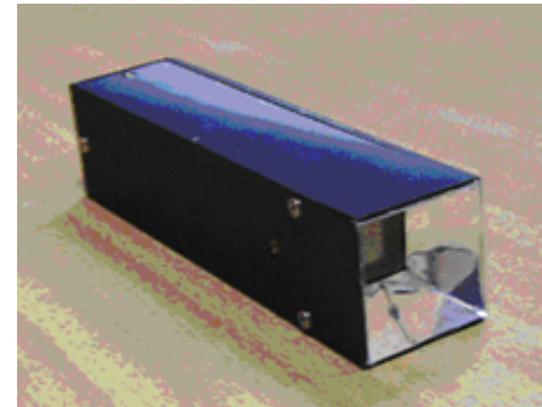
MEPhi/MPI for Physics (Munich) SiPMs with area $5 \times 5 \text{mm}^2$ and FE electronics



24.12.12

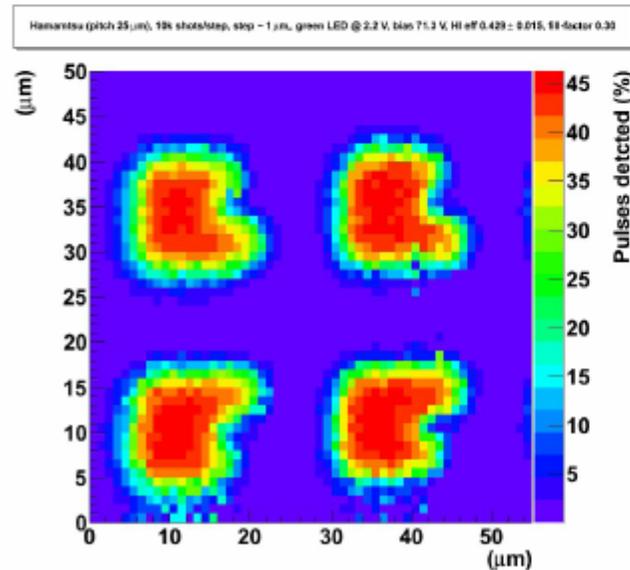
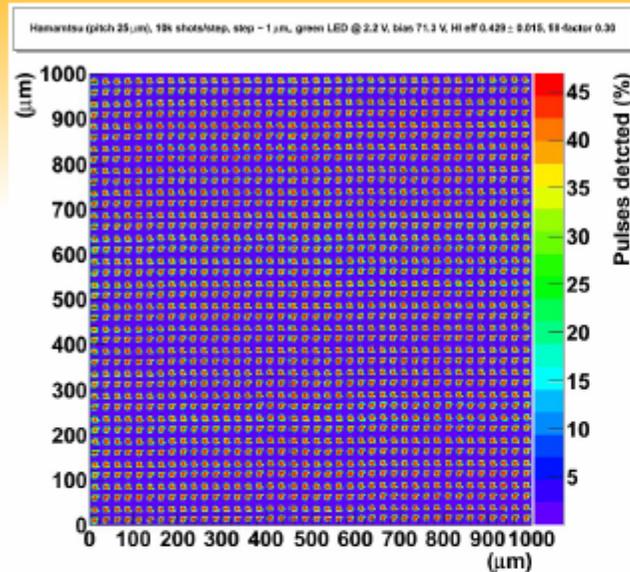


Семинар ИЯИ Е.Попова



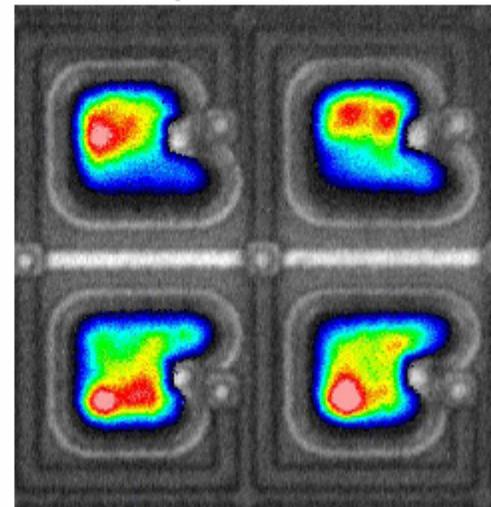
37

Results: Hamamatsu (MPPC) (25 μm pitch)



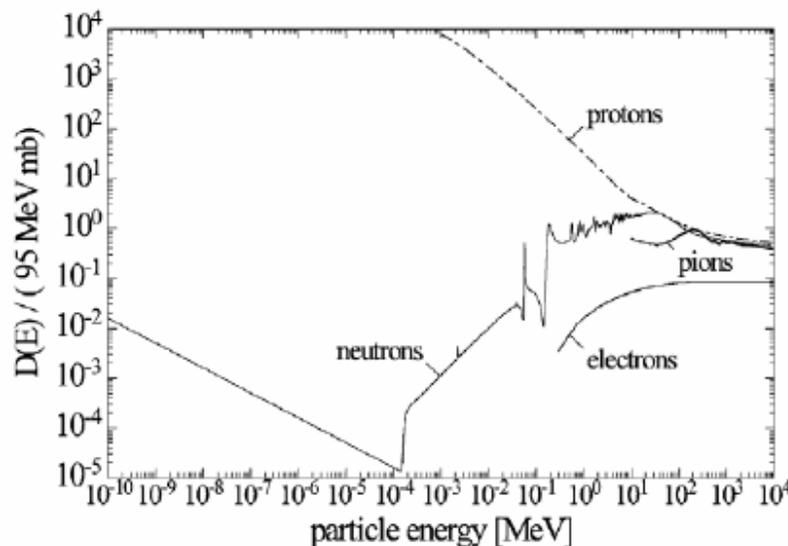
- whole of SiPM area
- resolution 1 μm
- LED peak wavelength 520 nm
- geometrical fill-factor 31%

Photo + photoemission image

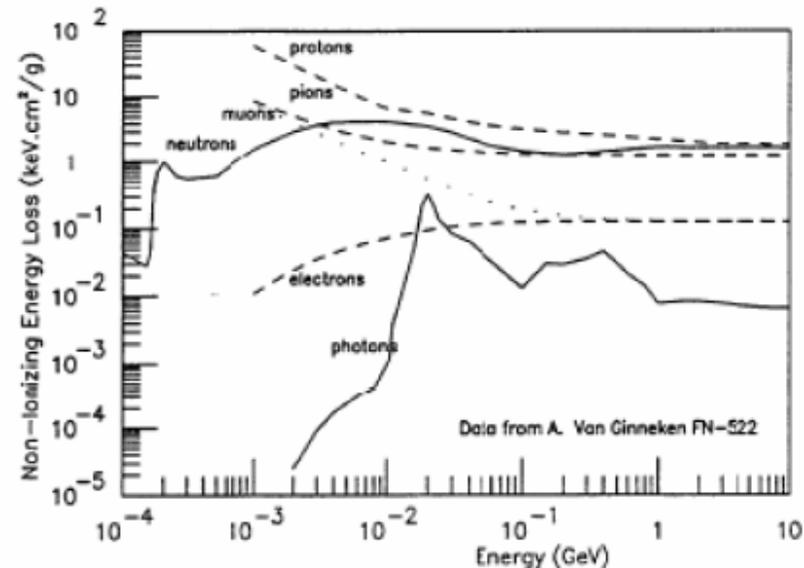


Bulk damage and NIEL function

Bulk damage scales linearly with the amount of Non Ionizing Energy Loss (NIEL hypothesis), which is very dependent on the particle type and its energy



A. Vasilescu, Fluence normalization based on the NIEL scaling hypothesis, 3rd ROSE Workshop on Radiation Hardening of Silicon Detectors, DESY Hamburg 12-14 February 1998, DESY-PROCEEDINGS-1998-02.



A. Van Ginneken, Fermilab Note, FN-522 (1989).

$$\text{NIEL}(1 \text{ MeV gammas}) \sim 10^{-5} * \text{NIEL}(1 \text{ MeV neutrons})$$