IRST SiPM characterizations and Application Studies

G. Pauletta
for the
FACTOR
collaboration

Outline

1. Introduction (who and where)
2. Objectives and program (what and how)
3. characterizations
4. Applications

FACTOR

3-year project (2007 – 2009) funded by INFN

Participants:

INFN laboratories and/or universities at:Trieste, Udine, Messina

collaborating with

ITC (now Bruno Kessler Foundation) -IRST

Trento, Italy

Background:

2005: INFN funds project (DASiPM) for the development of SiPM devices, mainly for PET application
2007: INFN funds continuation of DASIPM and expands development to other applications (FACTOR)

INFN-Trieste has a long – standing collaboration with IRST in the development of Silicon-based detectors for application in accelerator, underground and space – based experimental particle physics.

Motivations

The FACTOR collaboration interested in the development of the device and in its optimization for application to:

Present application interests:

- Calorimetry with fiber-based optical readout
- Large – area scintillator – based muon counters
- Scintillating fiber – based tracking
- future space experiments for detection of UHECR
- FEL studies and instrumentation
- future large – area, ground – based x-ray telescopes

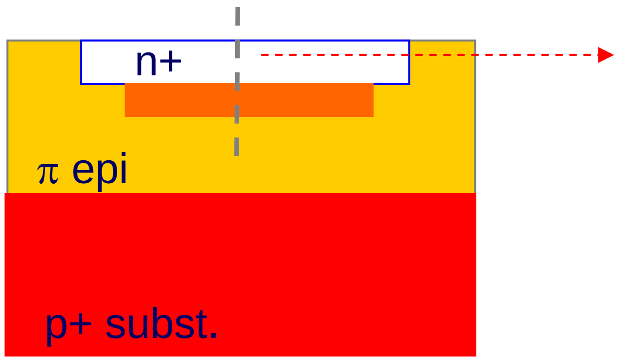
Action Plan:

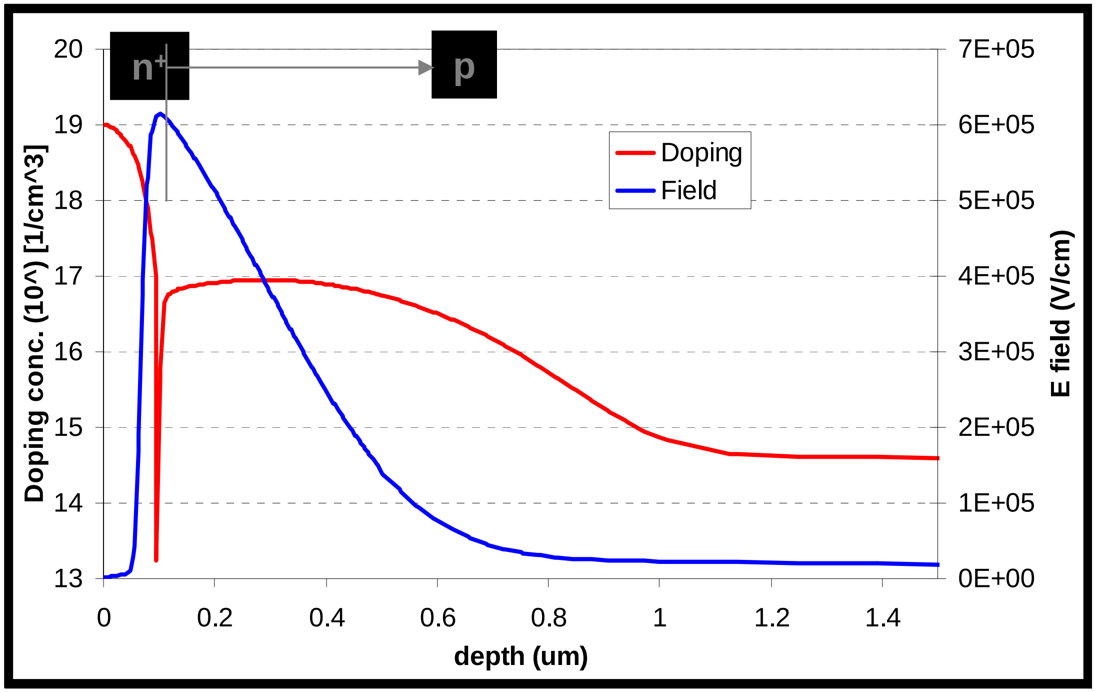
- comparative studies for detailed understanding of device characteristics
- Application tests
- Optimization of properties as a function of application

Present IRST technology*

***C. Piemonte "A new Silicon Photomultiplier structure for blue light detection" NIMA 568 (2006)**

Shallow-Junction SiPM





Distinguishing characteristics:

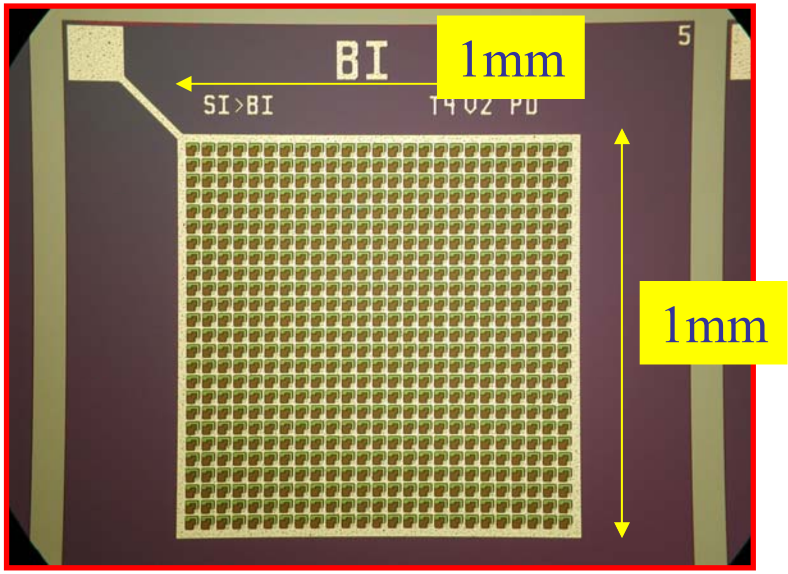
1) **Very shallow junction**
2) **ARC optimized for short wavelenghts (~400nm)**
3) **polysilicon quenching resistors**

Development History

Development started at the beginning of 2005

Baseline geometry

SiPM structure:
- 25x25 cells
- microcell size: 40x40mm²



Geometry of baseline model NOT optimized formaximum PDE (fill factor ~20%) .

Development has continued over last two years: several succeeding production runs to to develop geometries for different applications

and to optmize operational characteristics

Principal characteristics of interest

- Gain
- Noise
  - dark count
  - afterpulsing
  - optical cross-talk
- PhotoDetection Efficiency (PDE)
- Dynamic Range
- Time characteristics
  - rise – time, resolution, recovery time
- Radiation hardness
- Sensitivity to magnetic fiels

Other considerations

- Packaging
- Readout electronics

Device characterization[1,2]

- Static measurents: IV measurements for rapid test of device properties, uniformity and stability

- Dynamic tests: Output signal characterization and stability using noise signals in the dark
  - Signal rise time and fall time
  - Gain
  - Dark count
  - Optical cross – talk
  - Afterpulsing

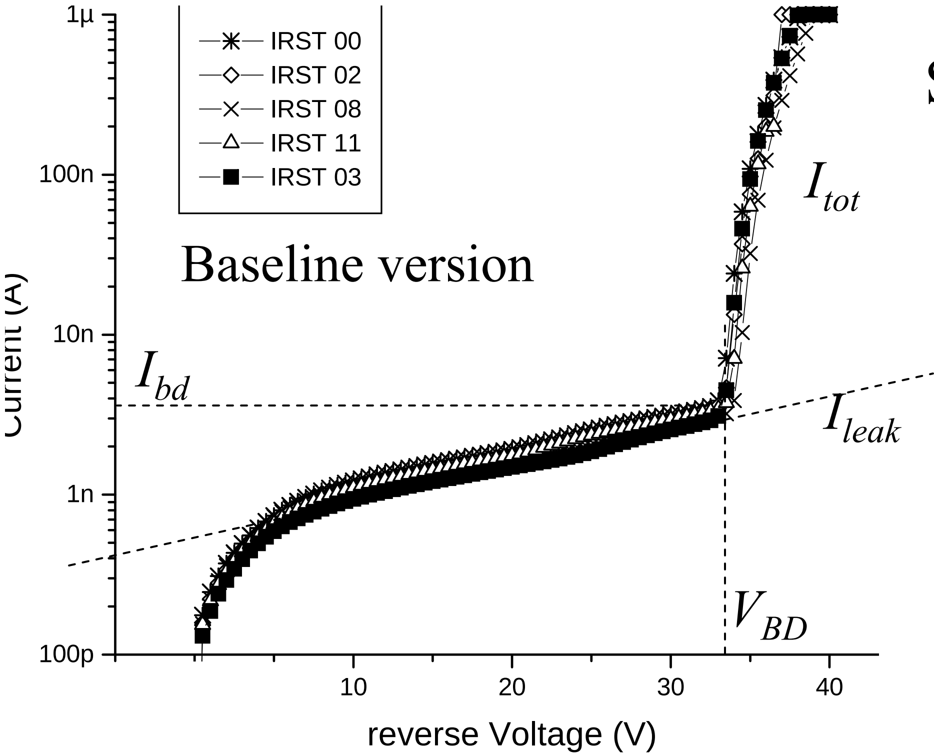
- PhotoDetection Efficiency

1)All characterizations reported here are for 1mm^2 devices
2) for a thorough characterization of the first SiPM prototypes fabricated at ITC-irst see C. Piemonte, IEEE TNS, February 2007

Static measurements-1

Rapid check functionality & uniformity

Sensitive to principal characteristics



dark current $I_{dc} = I_{tot} - I_{leak}$

is prop. to gain G and dark count (DC)

$$I_{dc} \propto G.(DC)$$

and since $G \propto V, \quad DC \underset{\sim}{\propto} V$

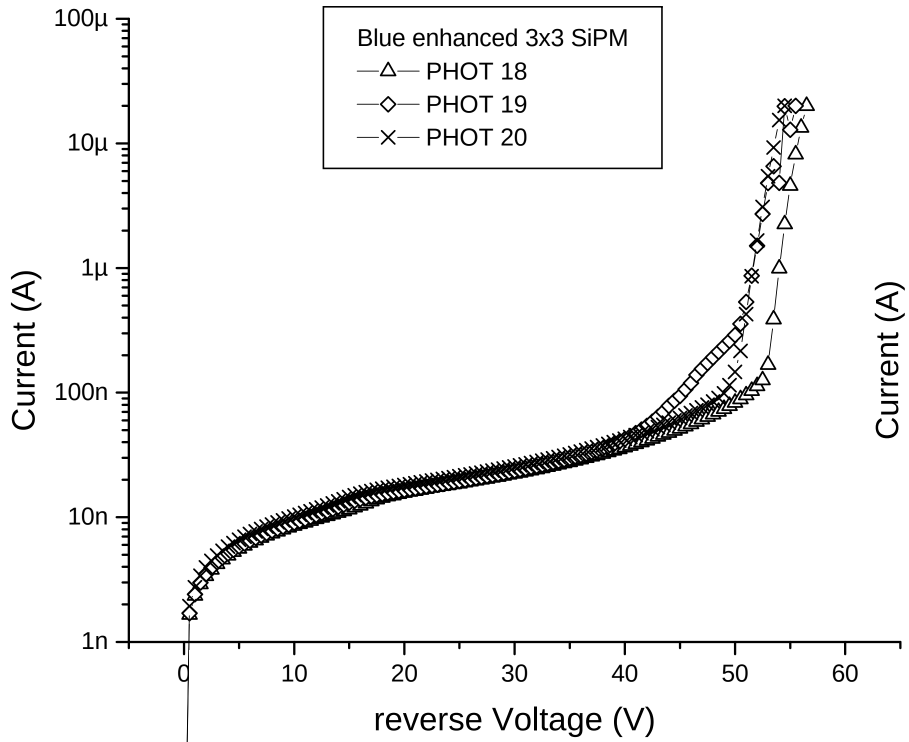
$$I_{dc} \propto V^2$$

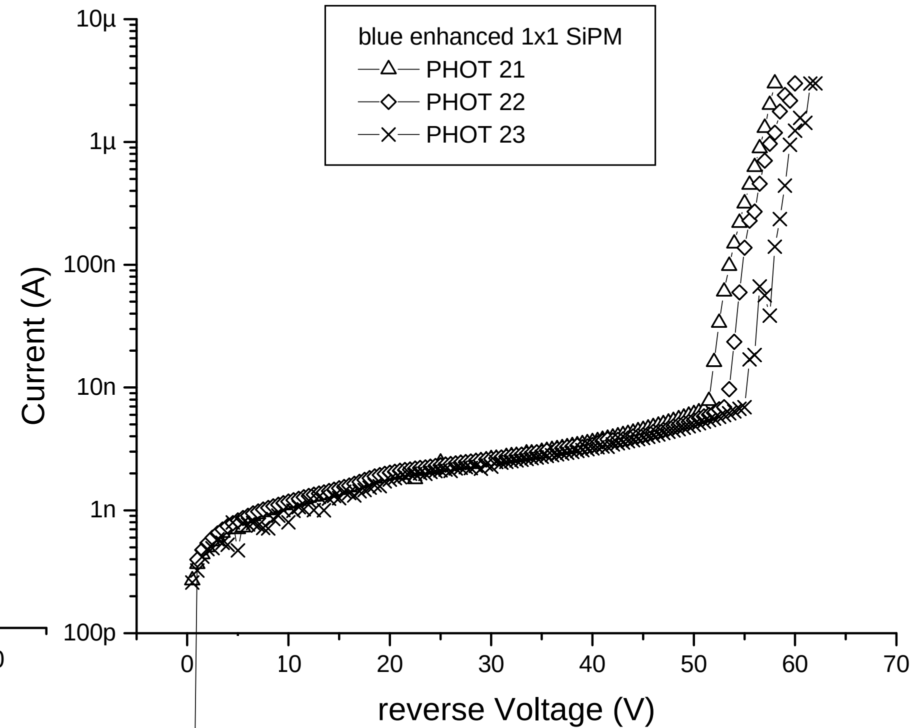
SiPM	Vbd (V)	Ibd (nA)
IRST-00	32,5	3,6
IRST-02	33,0	3,6
IRST-03	33,0	3,1
IRST-08	33,5	3,2
IRST-11	33,5	3,8

IRST 1mm^2 second batch

IRST devices generally very uniform

Static measurements-2



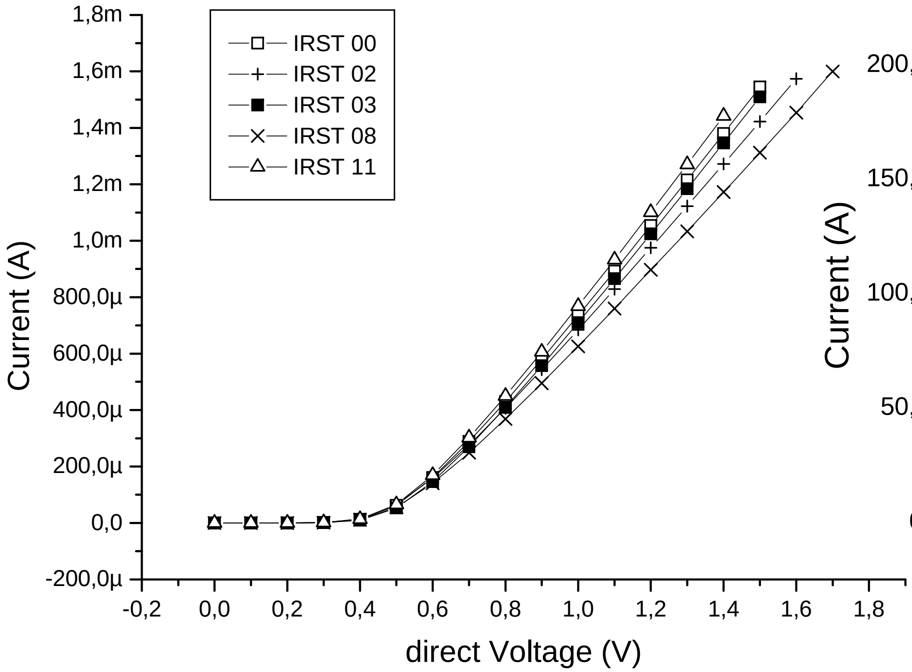


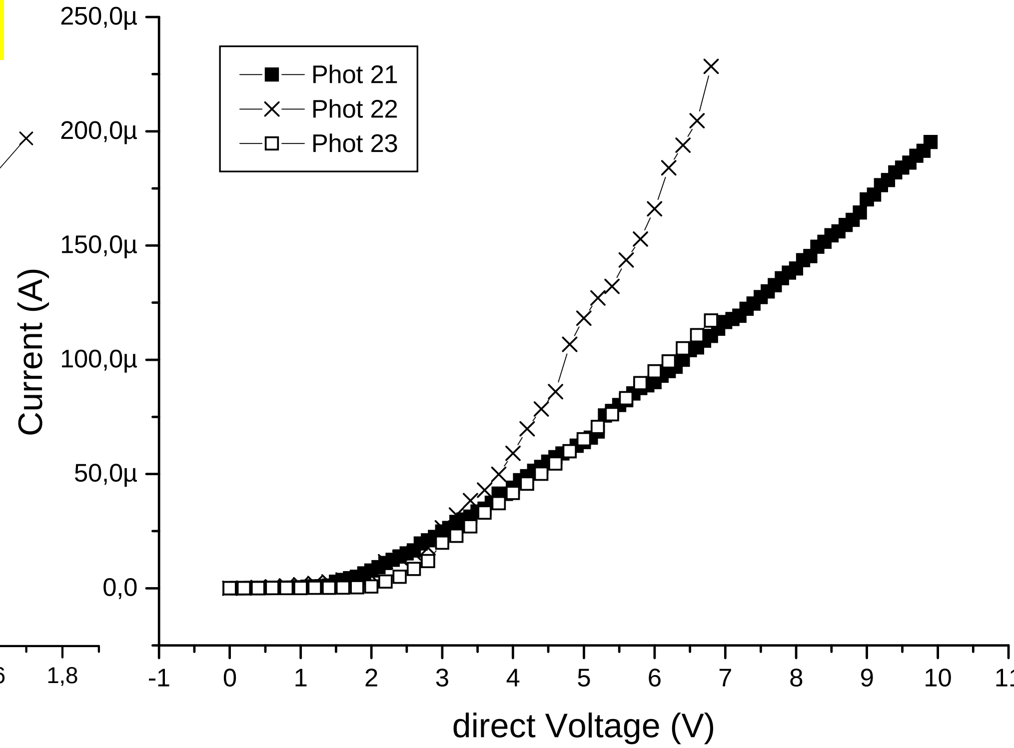
SiPM	Vbd (V)	Ibd (nA)
Phot-18	52,5	125,8
Phot-19	49,5	260,6
Phot-20	49,0	98,7
Phot-21	51,0	6,5
Phot-22	53,0	6,9
Phot-23	55,0	6,0

Photonique 9mm^2
Blue sensitive

Photonique 1mm^2
Green-red sensitive

Static measurements-3





SiPM	Rq (Ohm)
IRST-00	669
IRST-02	612
IRST-03	619
IRST-08	697
IRST-11	590

IRST 1mm^2 second batch

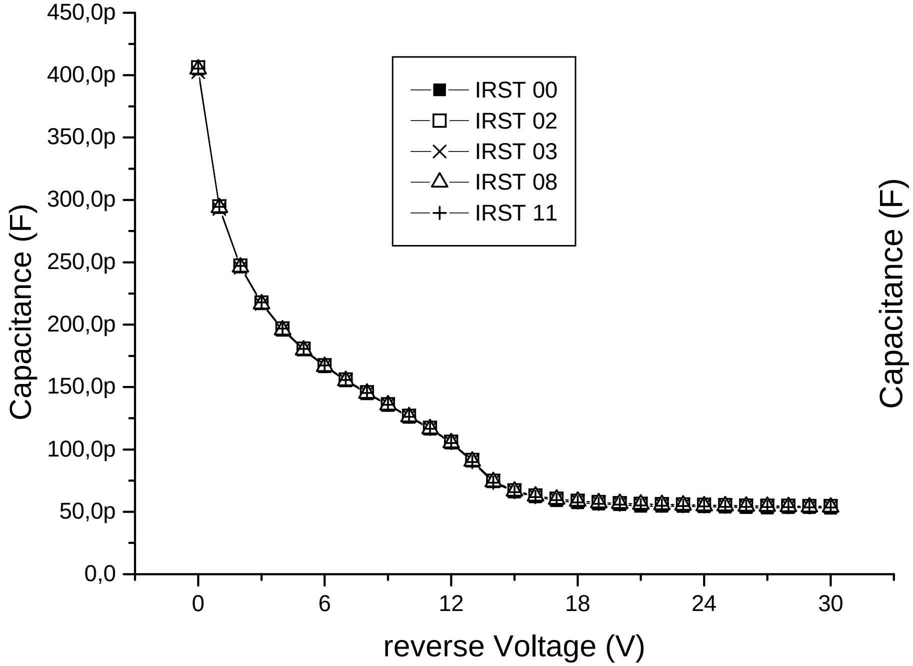
$\times 625 \approx 390k\Omega$

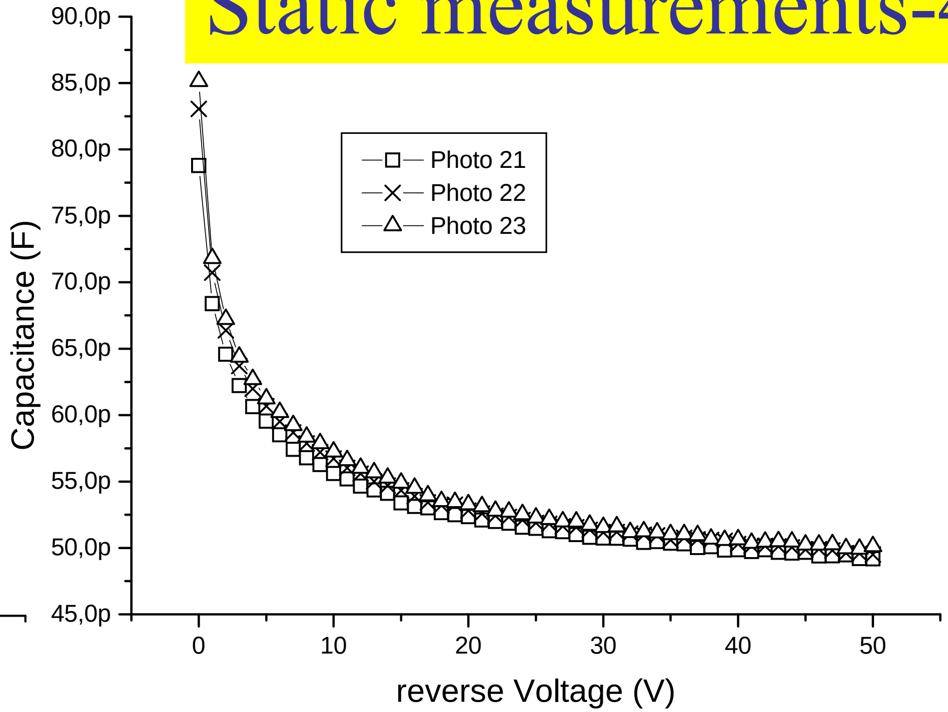
SiPM	Rq (kOhm)
Phot-18	2,29
Phot-19	1,52
Phot-20	1,24
Phot-21	39,8
Phot-22	17,4
Phot-23	37,8

Photonique 9mm^2 Blue sensitive

Photonique 1mm^2 Green-red sensitive

Static measurements-4



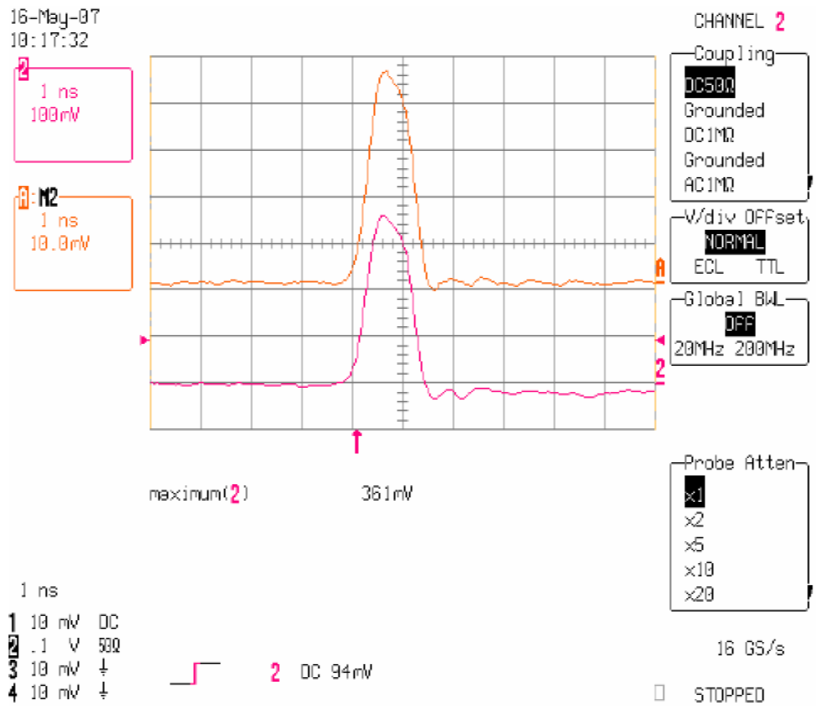


SiPM	Vdep (V)	Cdep (pF)
IRST-00	21	54
IRST-02	21	55
IRST-03	21	55
IRST-08	21	55
IRST-11	21	54

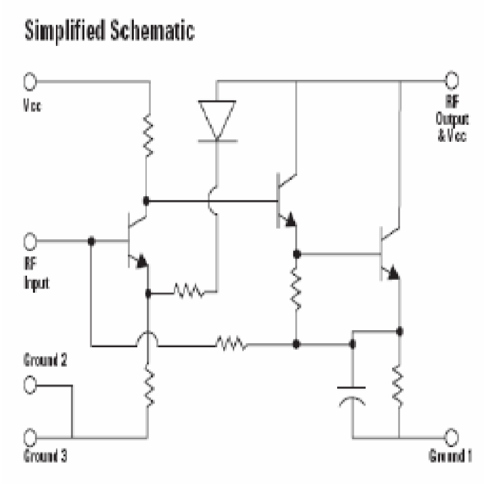
$$\div 625 \approx 90\, fF$$

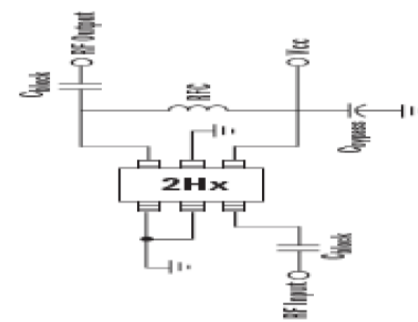
dynamic measurements-1

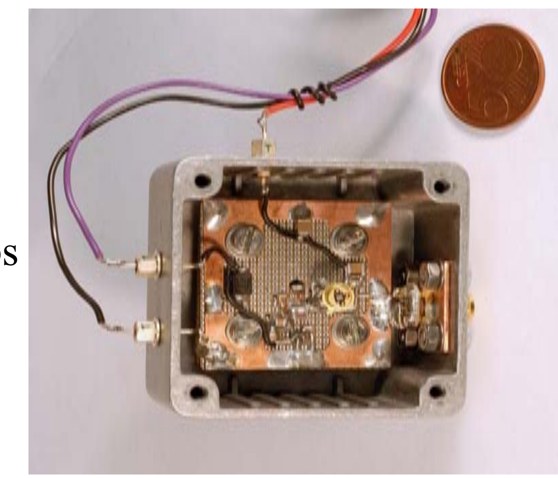
Amplifier used for fast characterization of SiPMs:
Agilent ABA-52563 3.5 GHz RFIC Amplifier
(economic, compact, internally 50-Ω matched, gain ~ 20 dB)
Dimensions 1.8 x 1.8 mm2



Orange trace: input from pulse generator, FWHM = 0.9 ns, tr = tf = 300 ps
Red trace: amplifier’s output

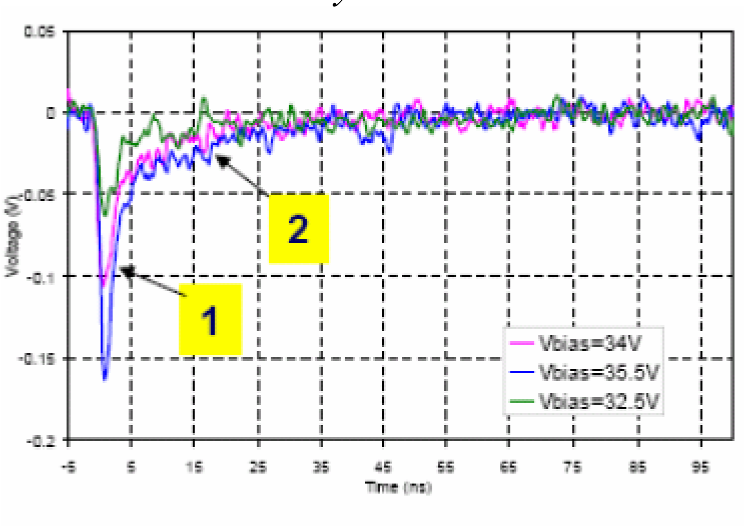


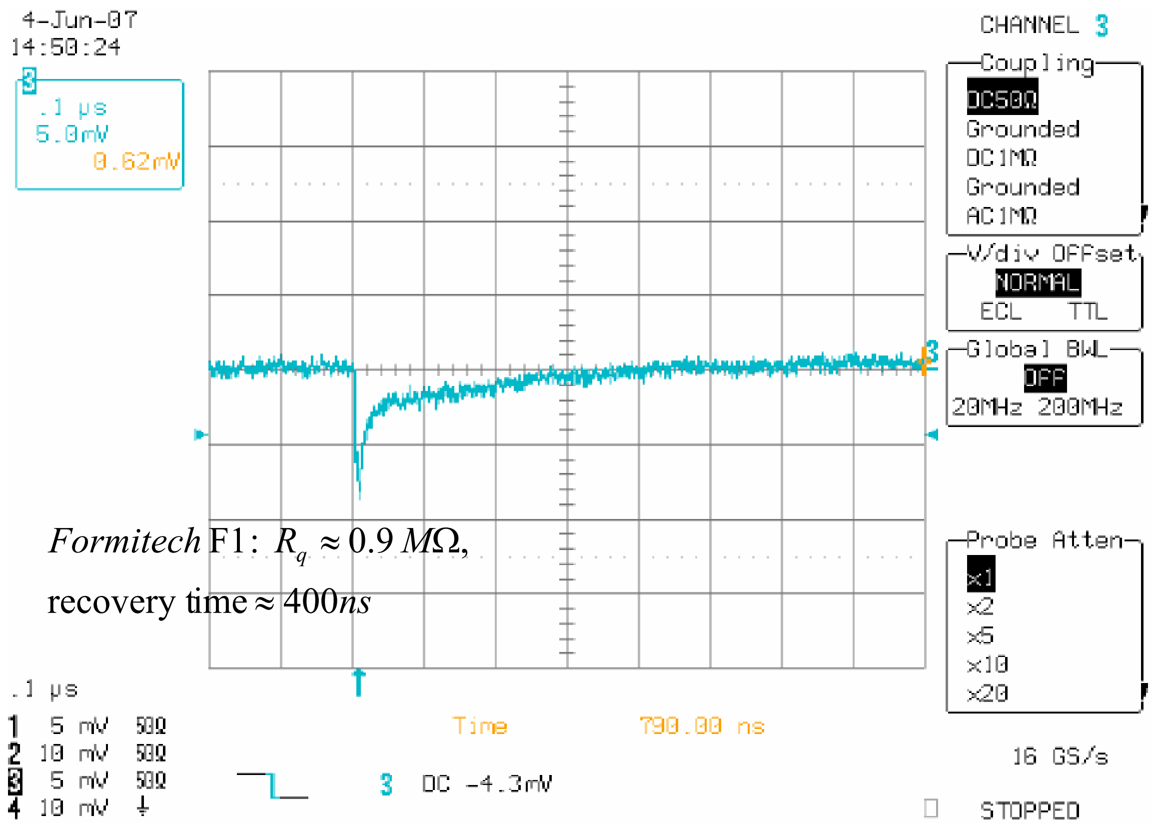




dynamic measurements-2

IRST :recovery time ~70 ns





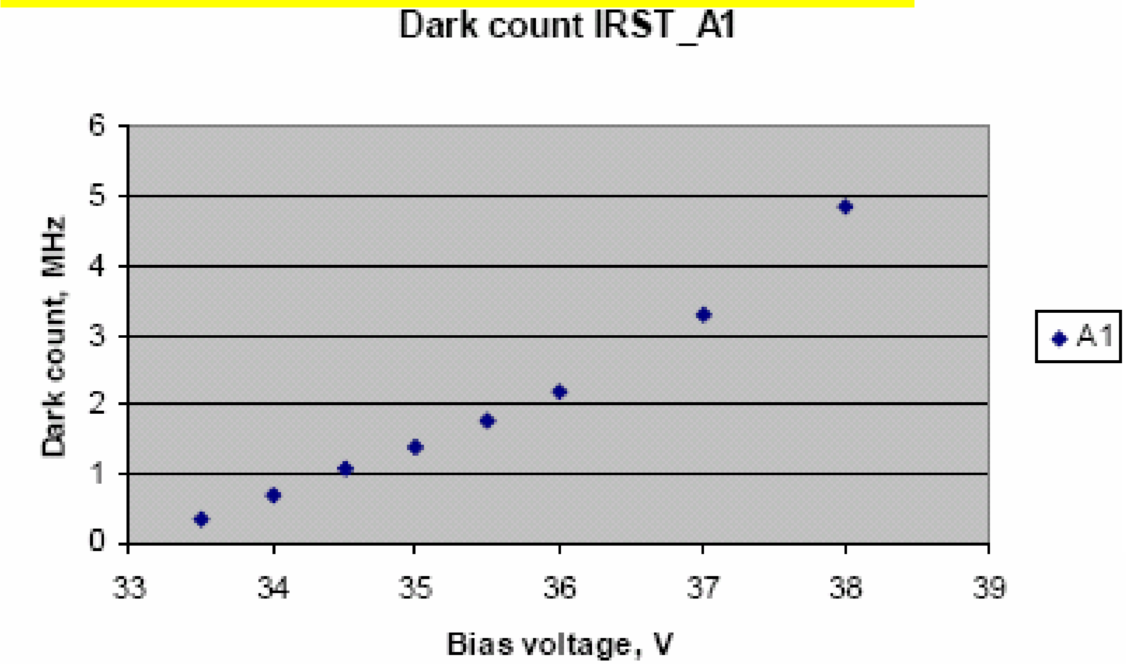
Formitech F1: $R_q \approx 0.9\ M\Omega$,

recovery time ≈ 400*ns*

MRS SiPMs have 2.5 to 50 times larger Rq values than IRST (polysilicon) devices

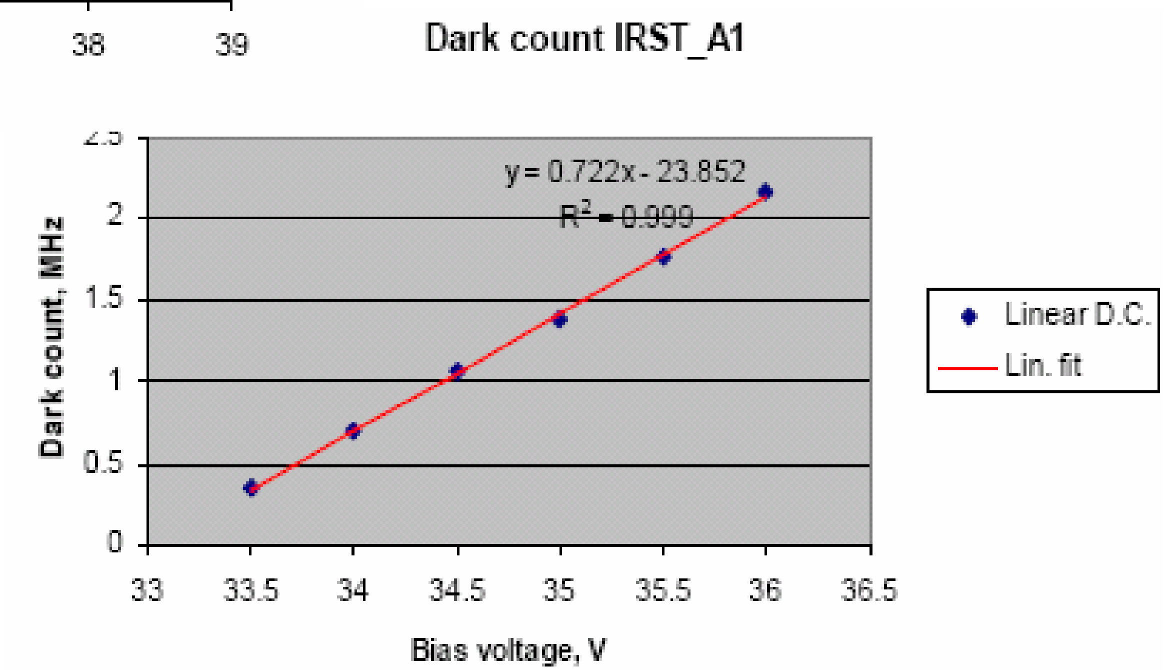
→ longer recovery rimes

dynamic measurements-4

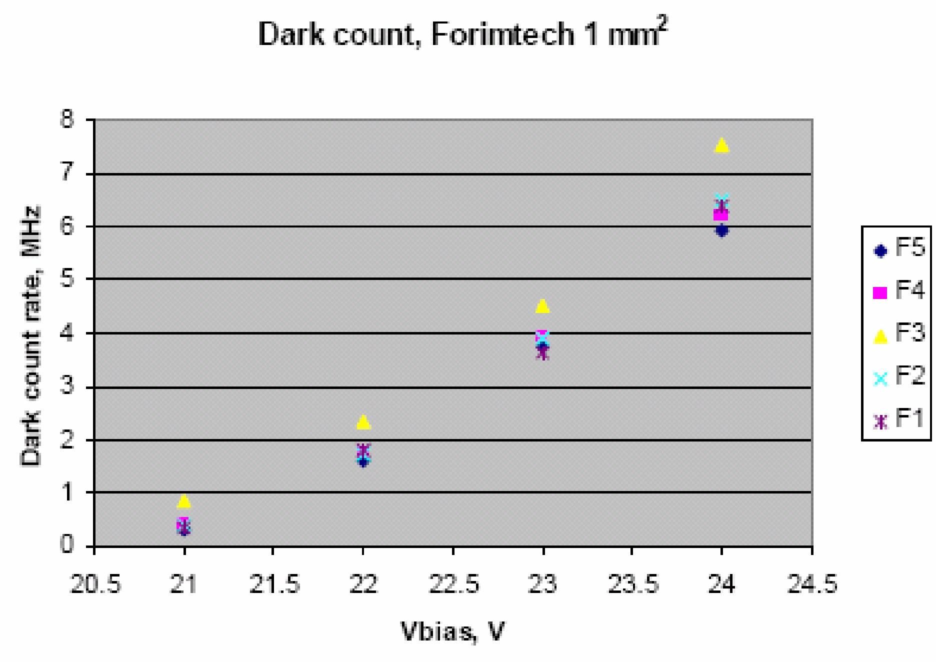


1 mm^2 type A
VBD ≈ 33 V
D.C.(ΔV=2V) ≈ 1.5 MHz

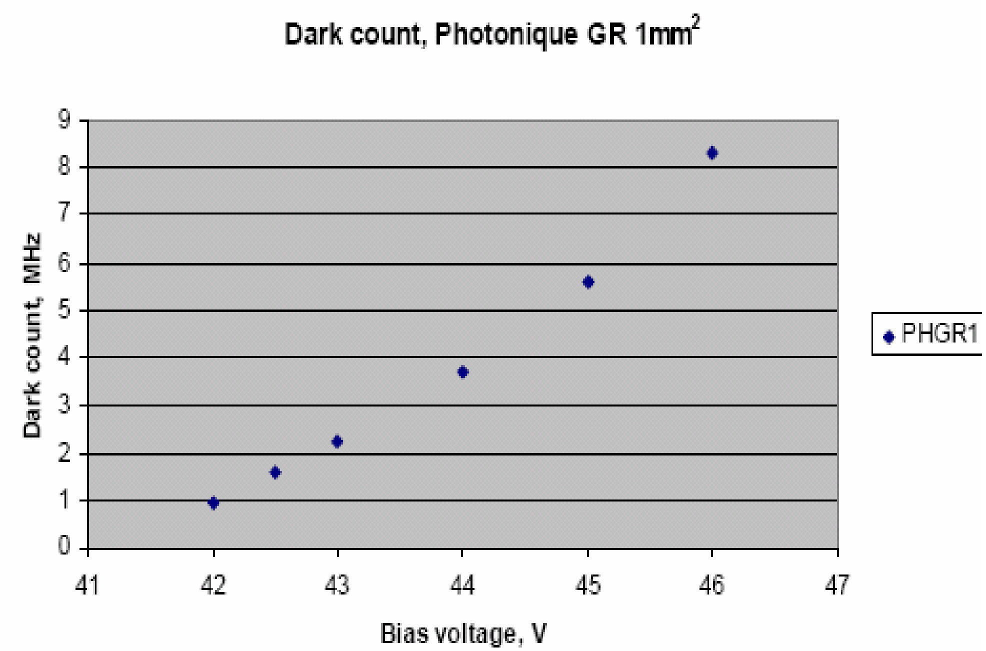
Linear fit intercept with V-axis gives VBD = 33.04 V



dynamic measurements-4

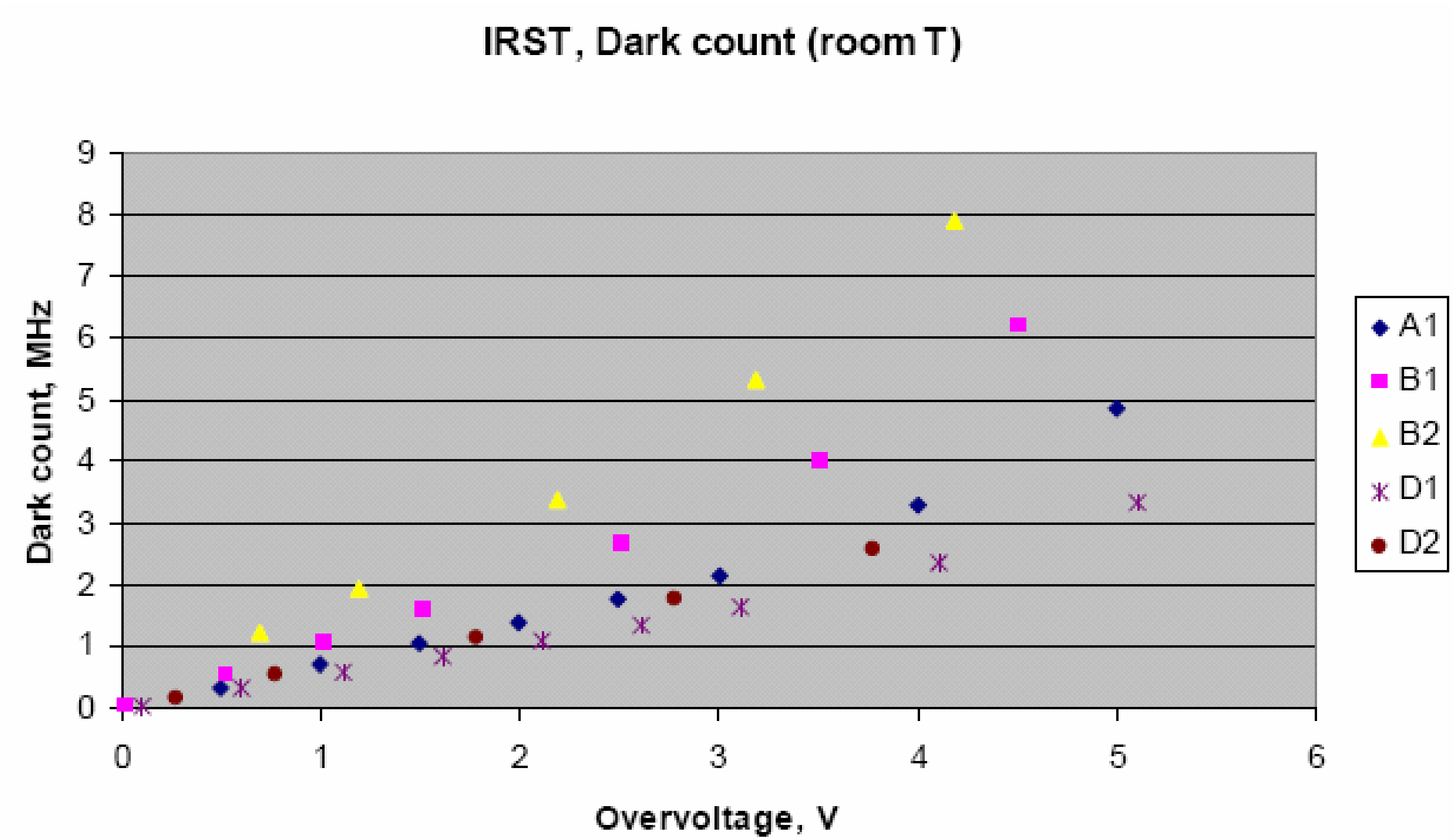


1 mm2 MRS devices
VBD ≈ 20 V
D.C.(ΔV=2V) ≈ 2 MHz



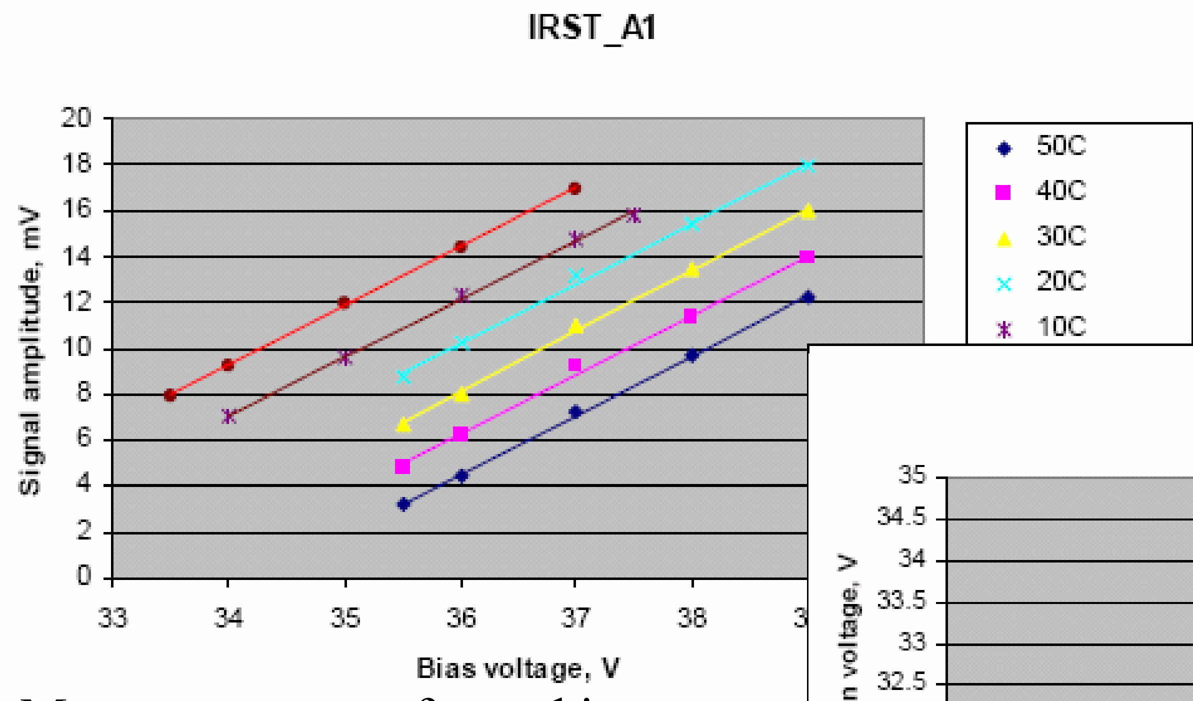
1 mm2 MRS device
VBD ≈ 41 V
D.C.(ΔV=2V) ≈ 2.2 MHz

dynamic measurements-5

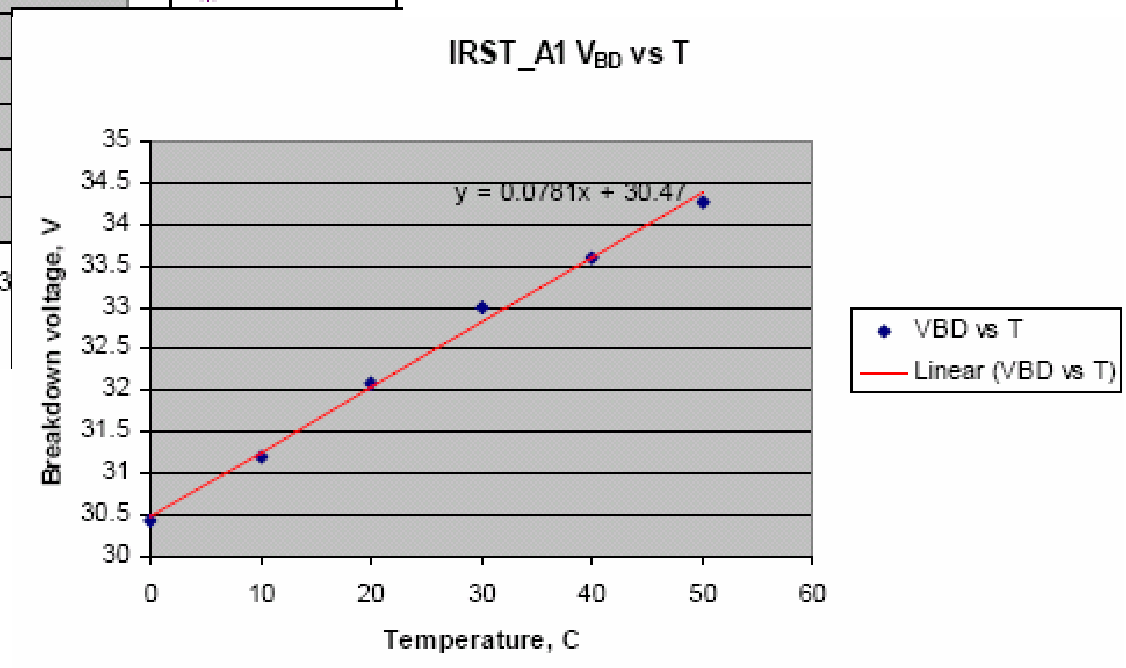


type "A", D.C.(ΔV=2V) ≈ 1.5 MHz
type "B", D.C.(ΔV=2V) ≈ 2- 3 MHz
type "D", D.C.(ΔV=2V) ≈ 1 MHz

dynamic measurements-6



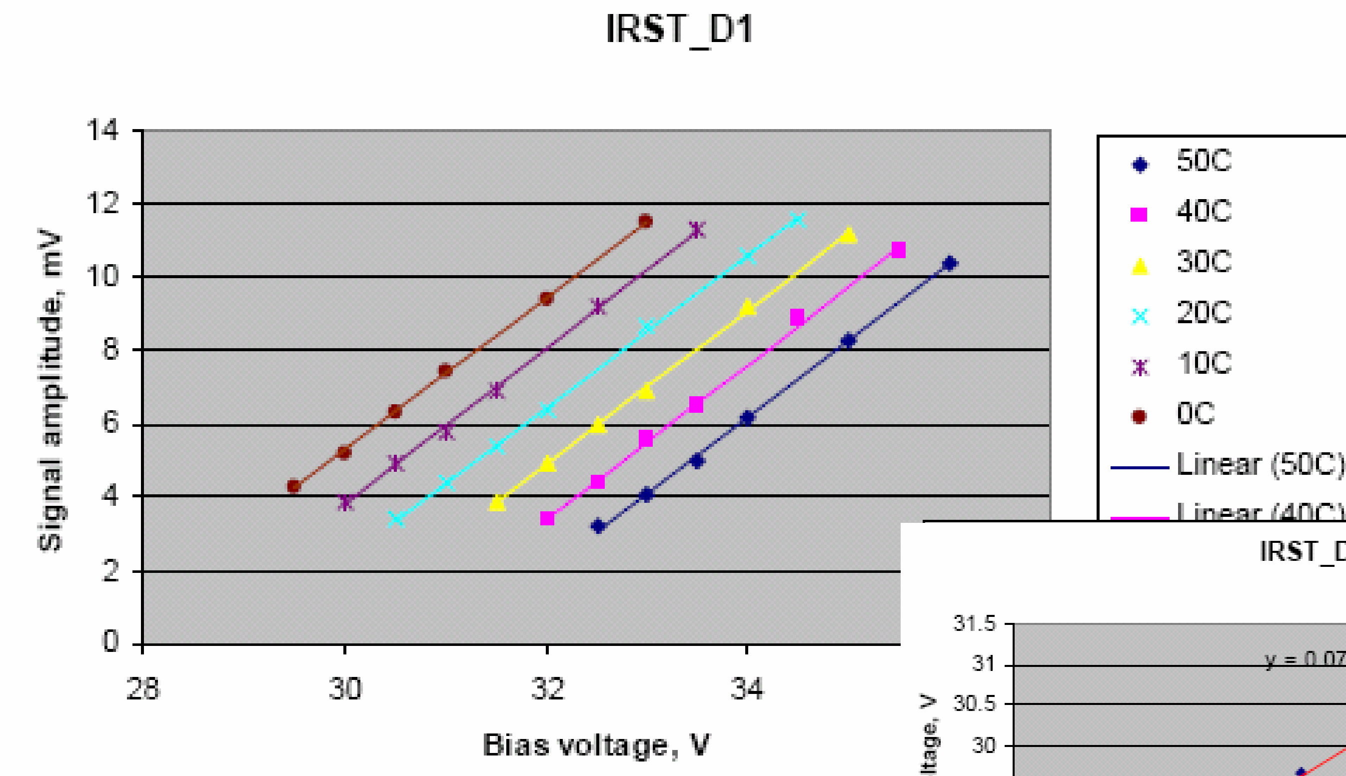
Temperature Dependences - 1



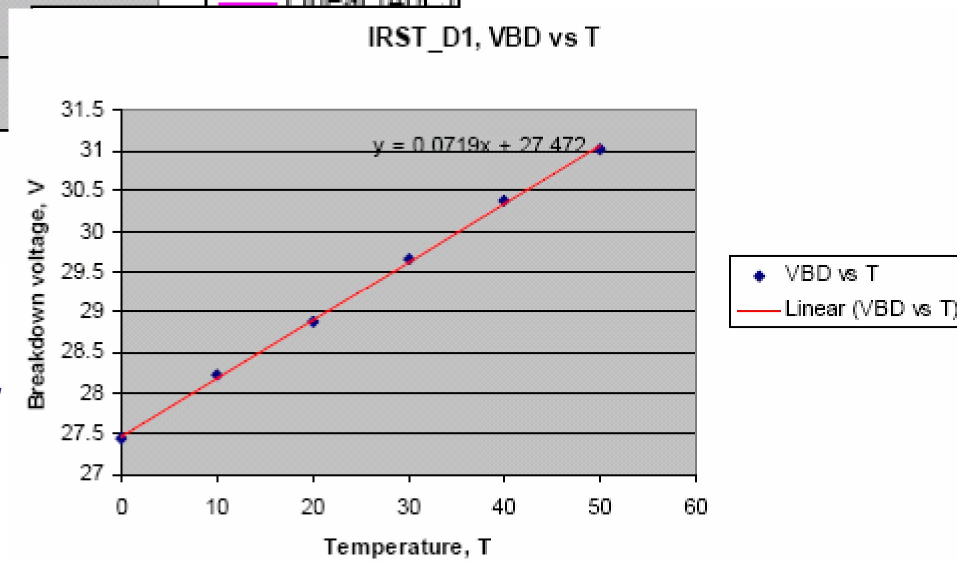
Measurements performed in a climatic chamber (with humidity control)
The amplifier was located outside the chamber, connection via a special 18 GHz ft
50 Ω cable

$dV_{BD} /dT \approx 78\ mV/C$

dynamic measurements-7



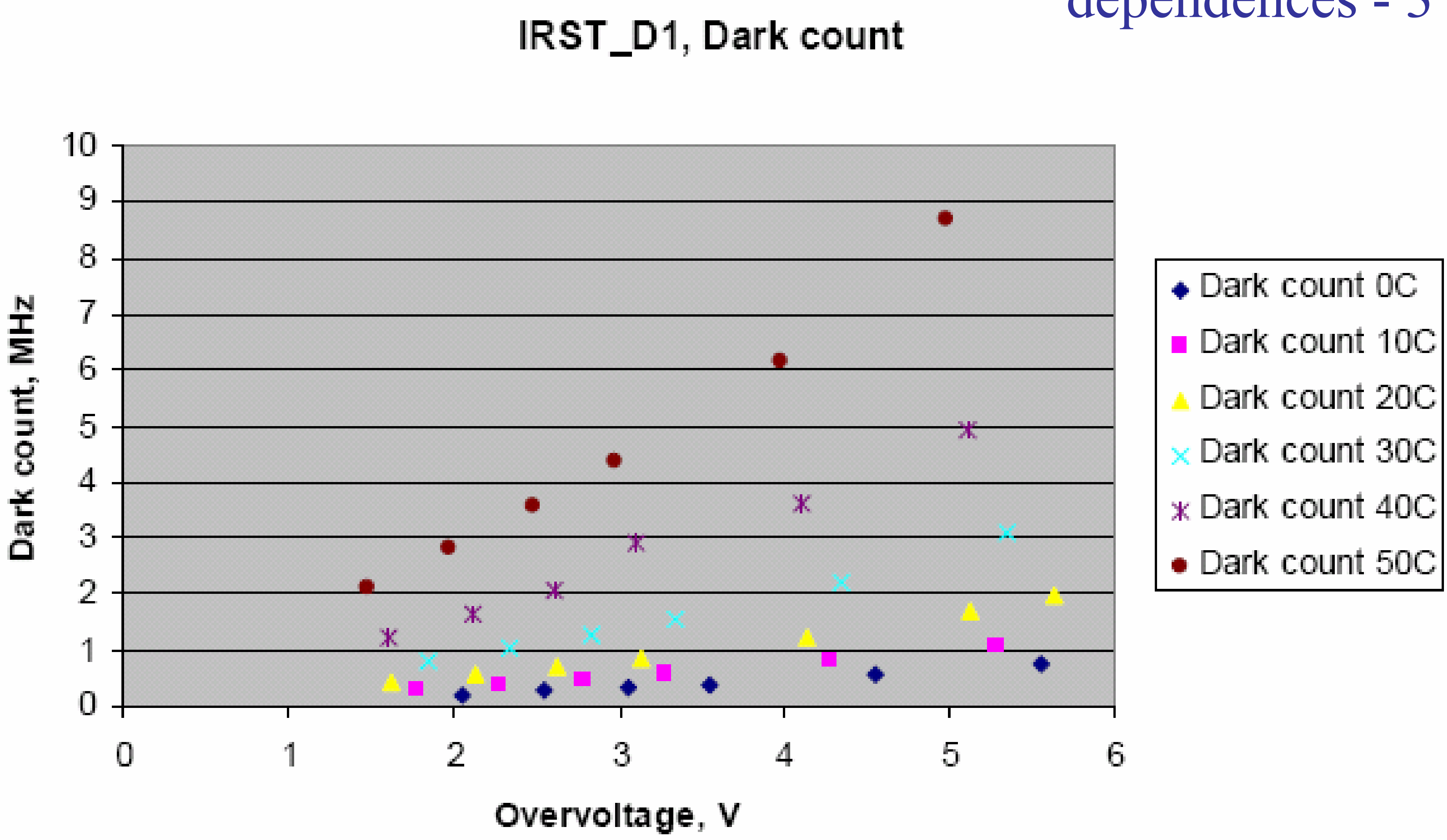
Temperature Dependences - 2



$dV_{BD}/dT \approx 72\ mV/C$

dynamic measurements-8

Temperature dependences - 3

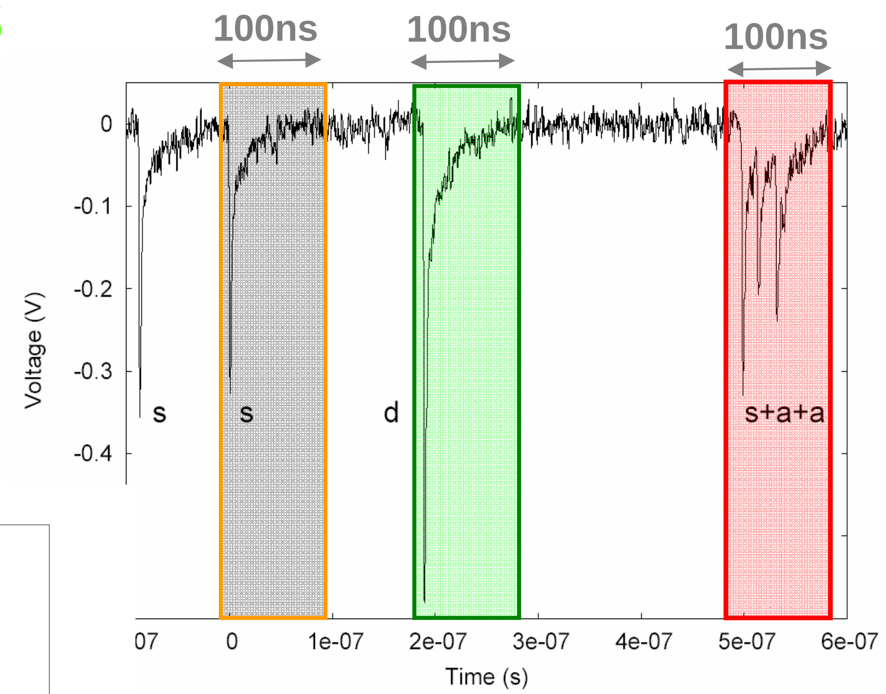


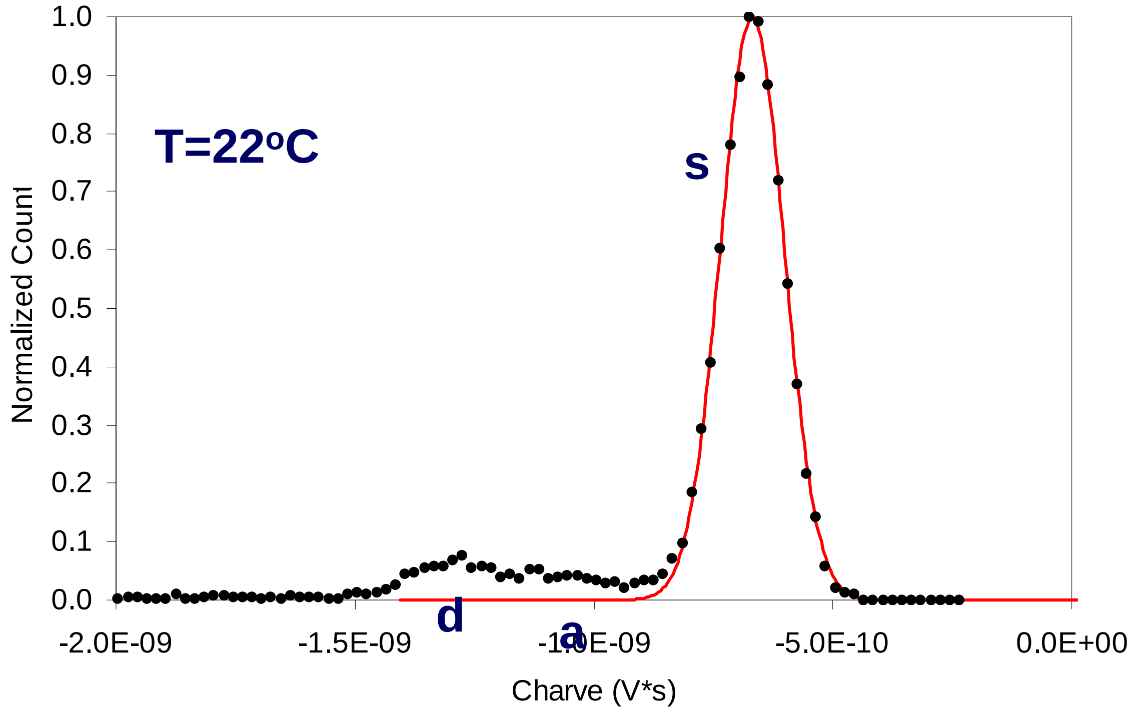
The following are static measurements performed at ITC-IRST and reported on at a recent (June 13^{th} 2007) workshop at Perugia

Signal properties

Charge spectra – T_{int}=100ns

C. Piemonte et al. "Characterization of the first prototypes of SiPM fabricated at ITC-irst"
IEEE TNS, February 2007





Well defined peak of the single pulses.

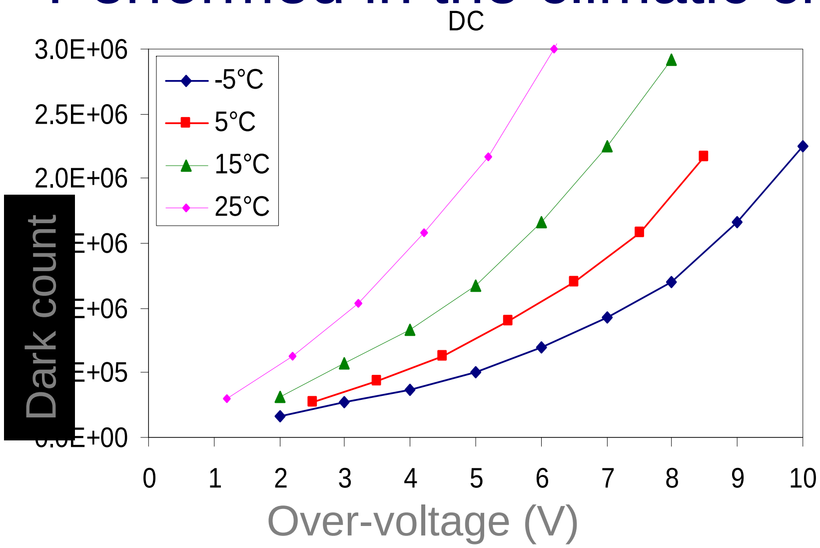
Gaussian distribution width determined by:

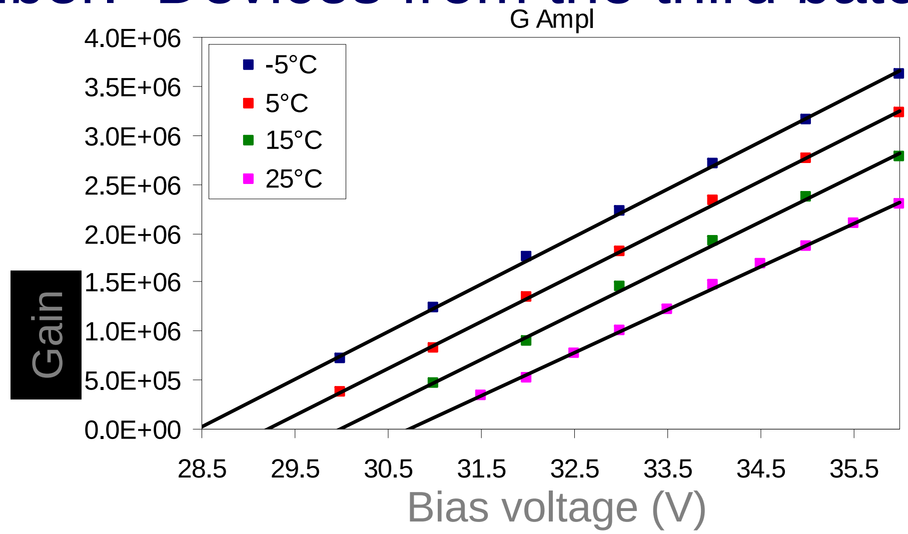
- noise of the system
- tiny gain non-uniformities

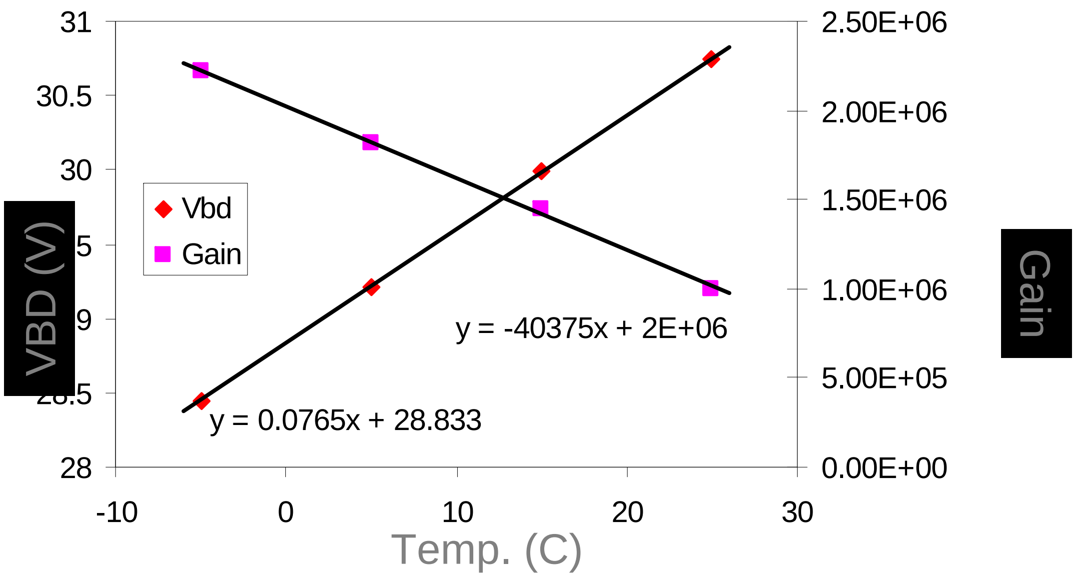
Tails due to:
optical cross-talk + afterpulse

Gain & Dark count

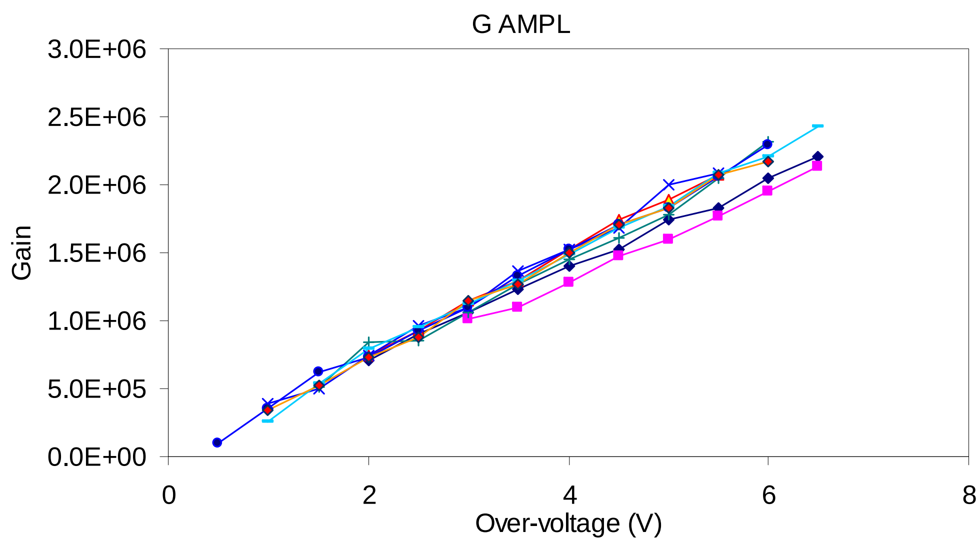
Performed in the climatic chamber. Devices from the third batch

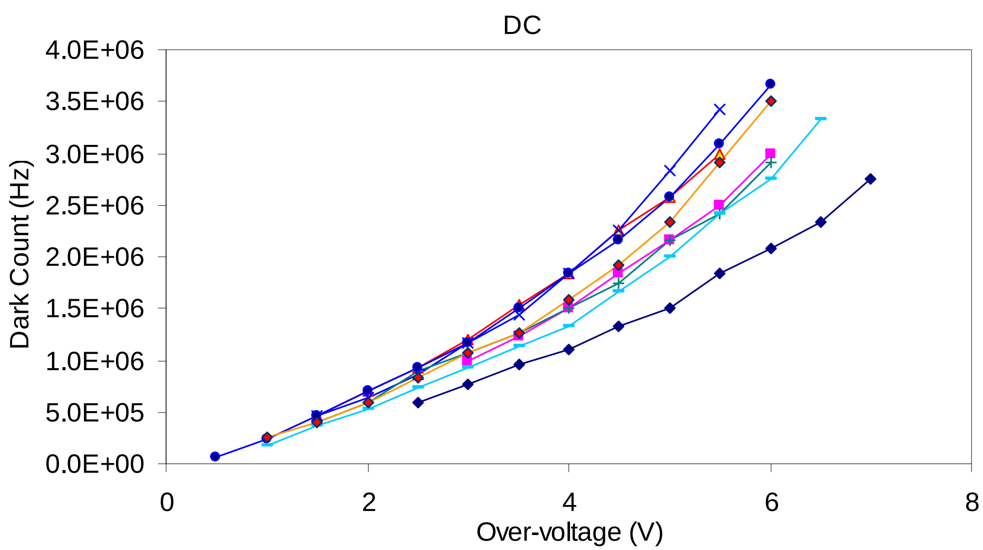






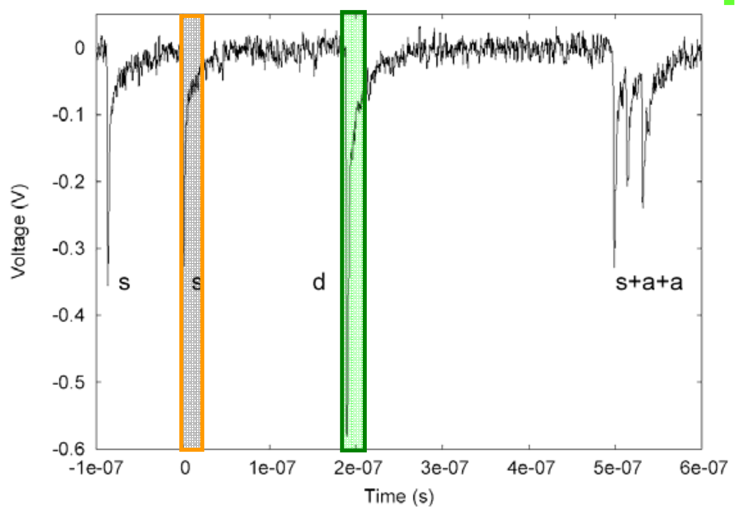
Gain & Dark count (uniformity)





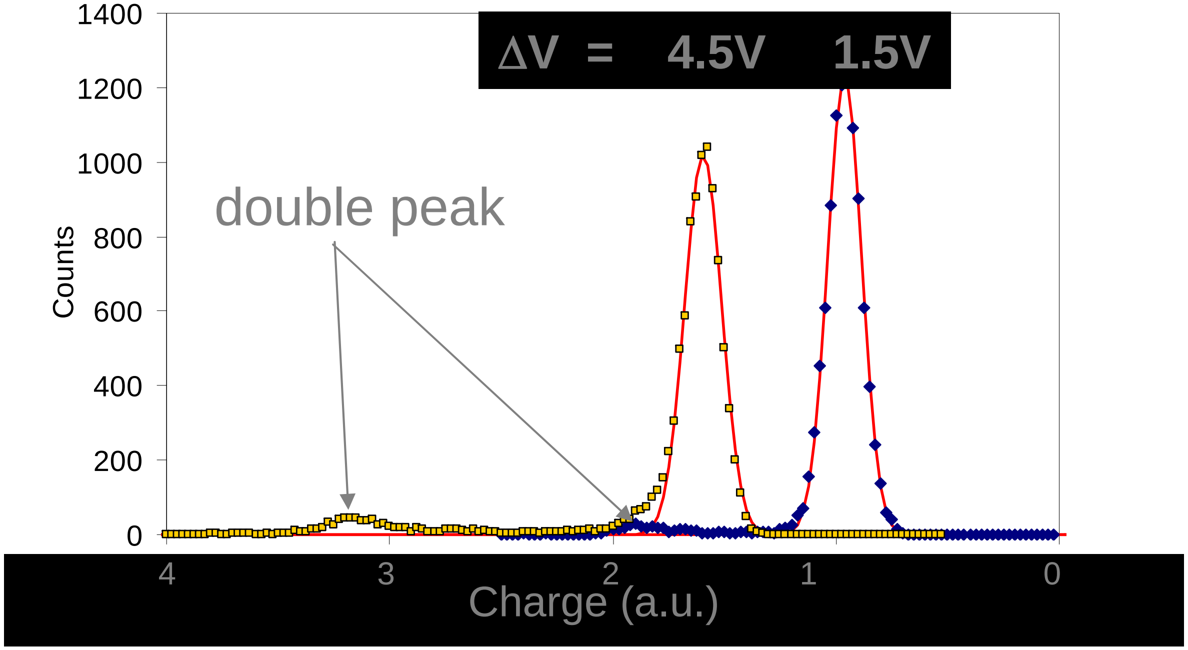
Gain and Dark count measured on devices from the same wafer

Optical cross-talk



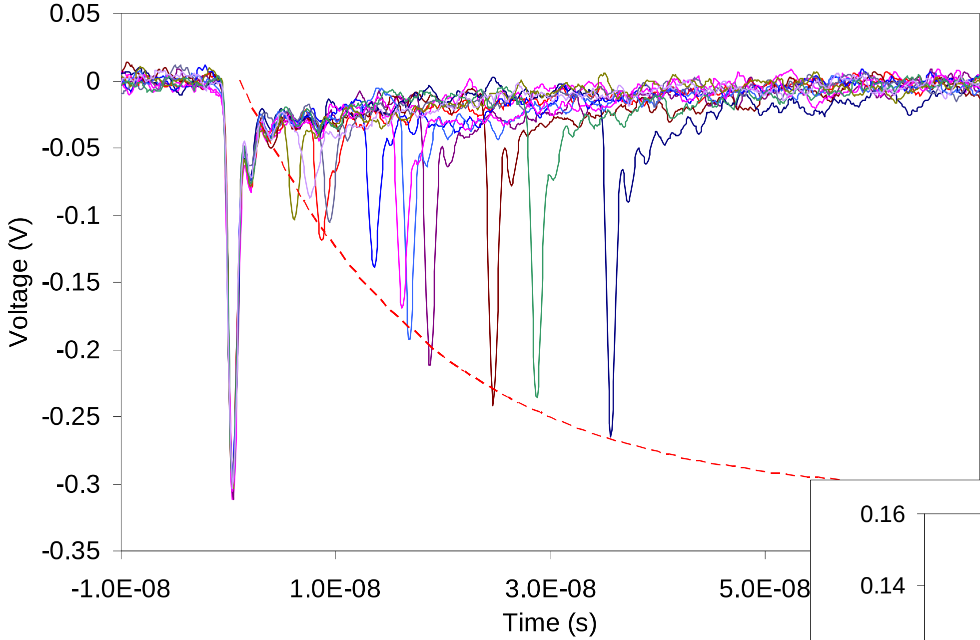
Short integration time
⇒ only single/double/….pulses are counted

Number of events with optical cross-talk increases with voltage



Cross-talk below 5% at 4V over-voltage.

After-pulsing



Events with after-pulse measured on a single micropixel.

The amplitude of the after-pulse increases as the cell recovers to its opertional condition

After-pulse probability *vs* bias

It increases following a parabolic law:

$$P_a = P_c \cdot P_{01}$$

linear with Vbias

linear with Vbias

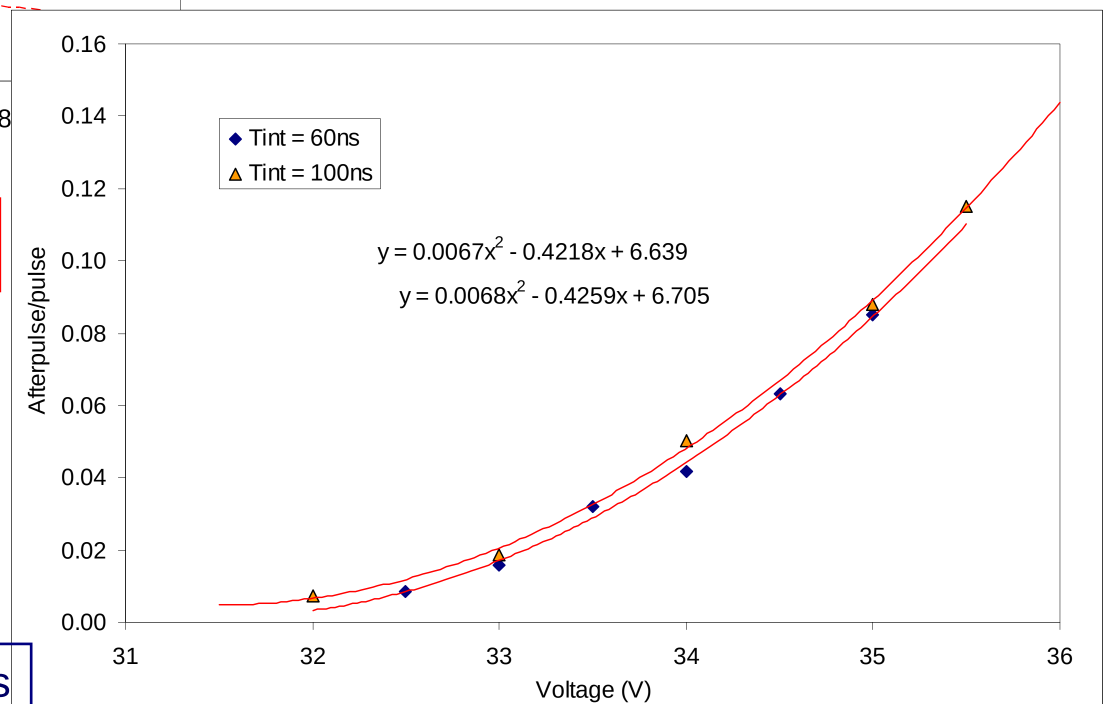


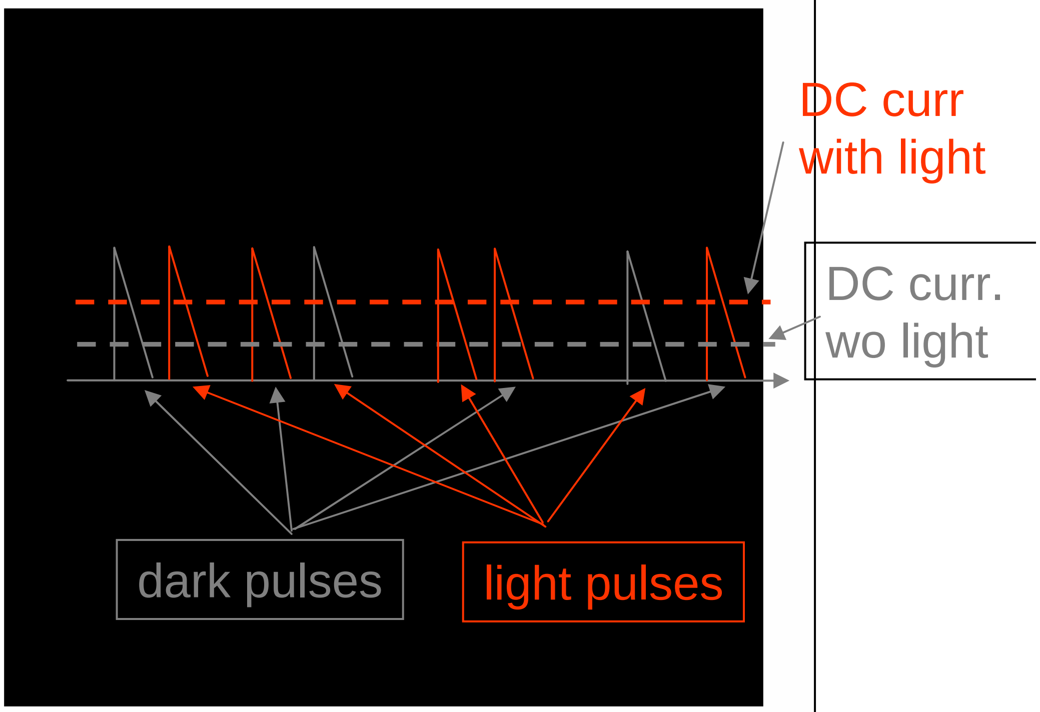
Photo-detection efficiency

Two methods: DC current and Pulses count

$$(1)\quad N_{det.\ photons\ [s^{-1}]} = \frac{I_{light} - I_{dark}}{q \cdot G}$$

$$(2)\quad N_{det.\ photons\ [s^{-1}]} = Rate_{light} - Rate_{dark}$$

$$PDE = \frac{N_{detected\ photons}}{N_{incident\ photons}}$$

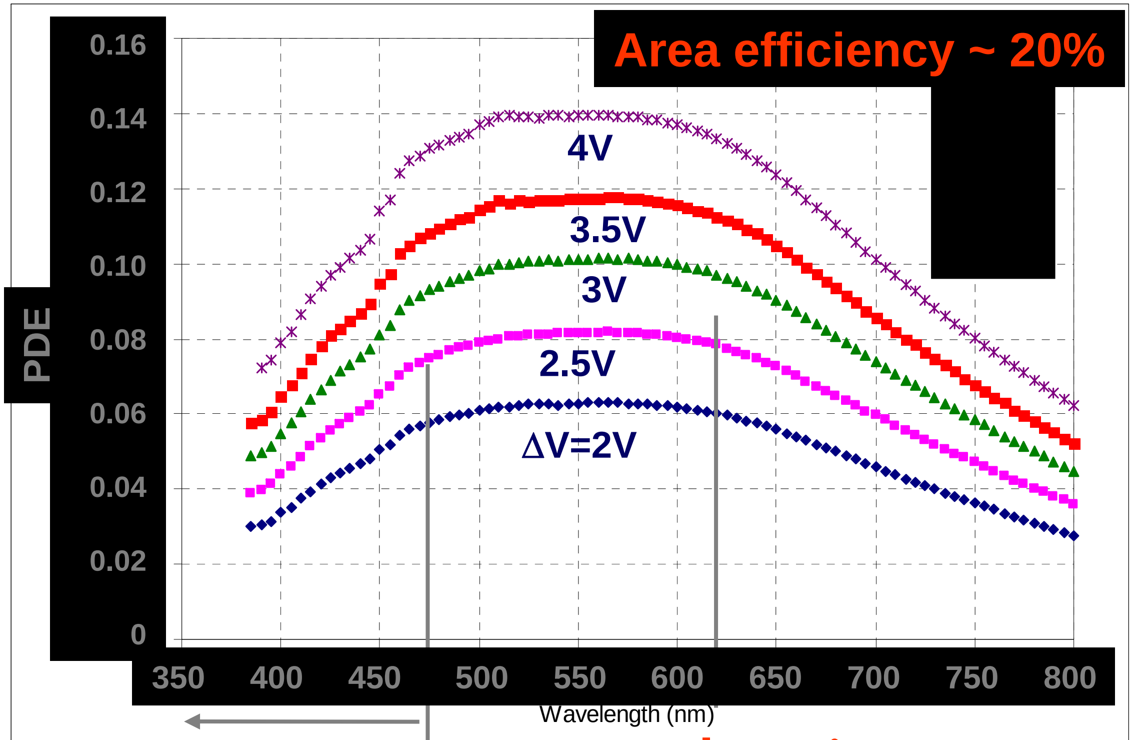


Reference by calibrated detector (photodiode)

$$N_{incident\ photons\ [s^{-1}mm^{-2}]} = \Phi_{[W/mm^2]} \frac{\lambda}{hc}$$

$$\Phi_{[W/mm^2]} = \alpha_{[W/A]} \frac{I_{[A]}}{S_{[mm^2]}}$$

Photodetection efficiency

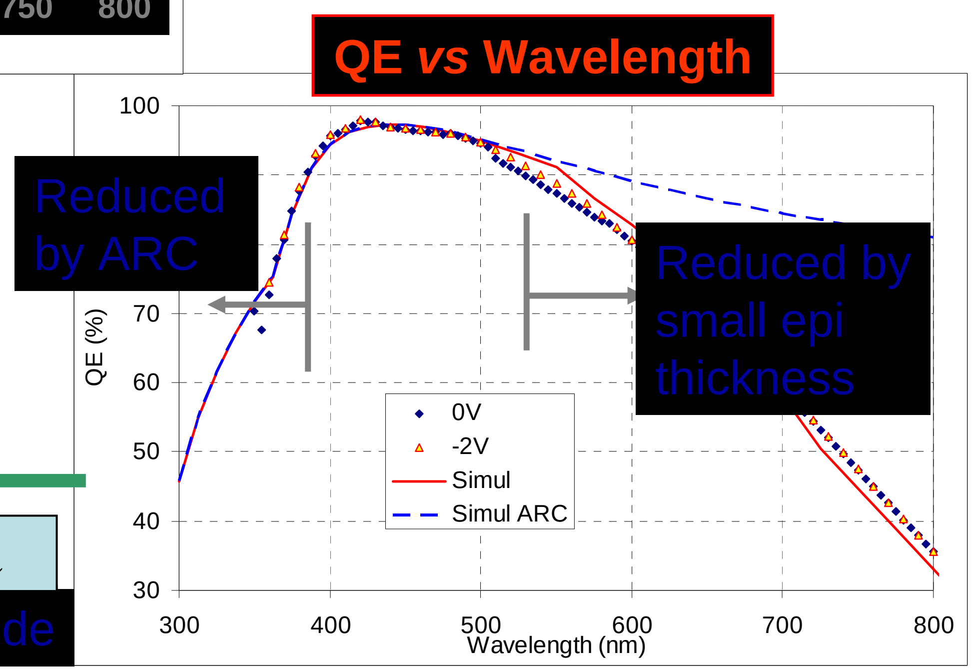


PDE=QE*Pt*Ae

QE=quantum eff.
P_t=avalanche prob.
A_e=area eff.

short λ:
low PDE because avalanche triggered by holes

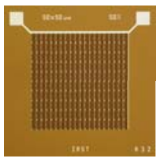
long λ:
low PDE because low QE

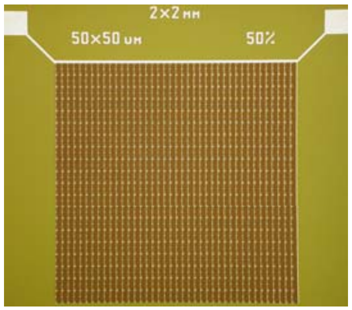


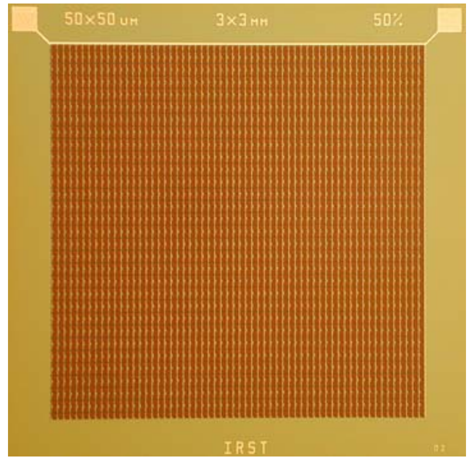
Measured on a diode

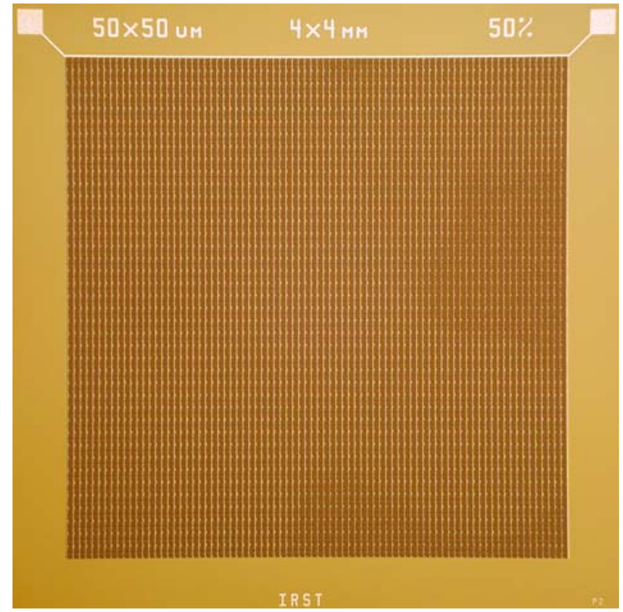
C. Piemonte: June 13th, 2007, Perugia

last batch





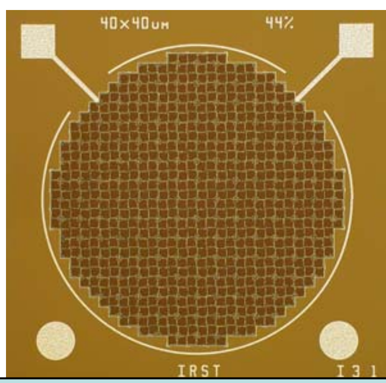




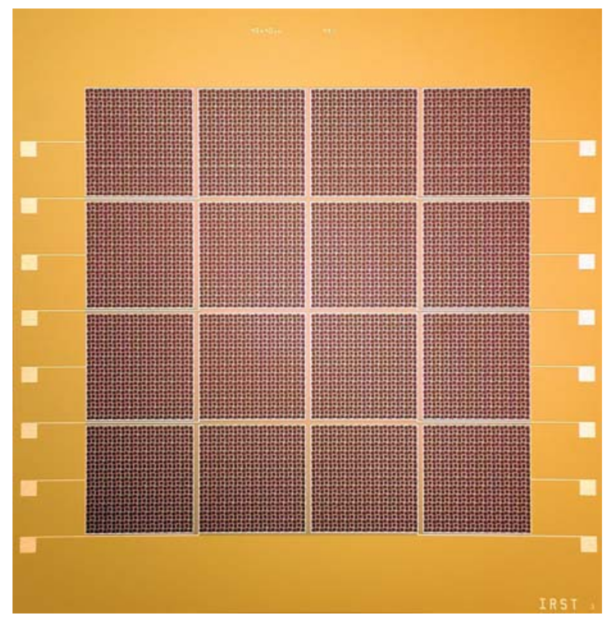
1x1mm 2x2mm 3x3mm (3600 cells) 4x4mm (6400 cells)

increased fill factor:

40x40mm => 44%
50x50mm => 50%
100x100mm => 76%;



Circular (1.2 mm – diameter)

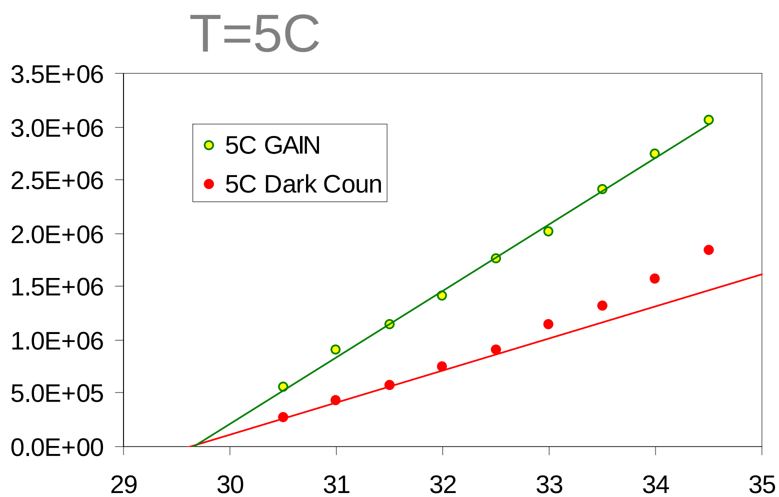


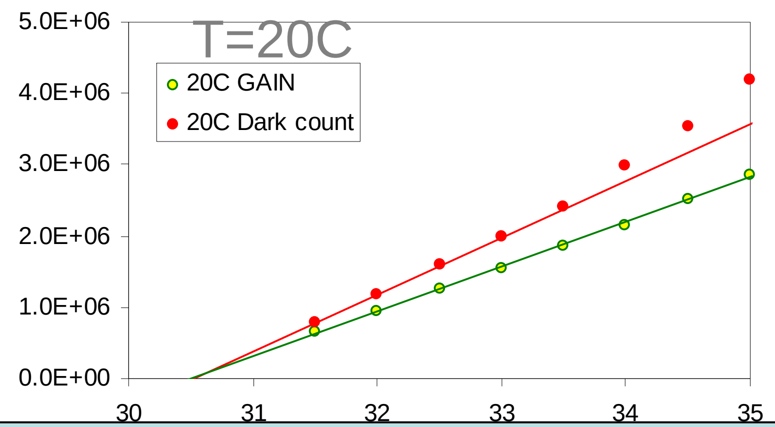
Array

First signal and noise characteristics of the last devices

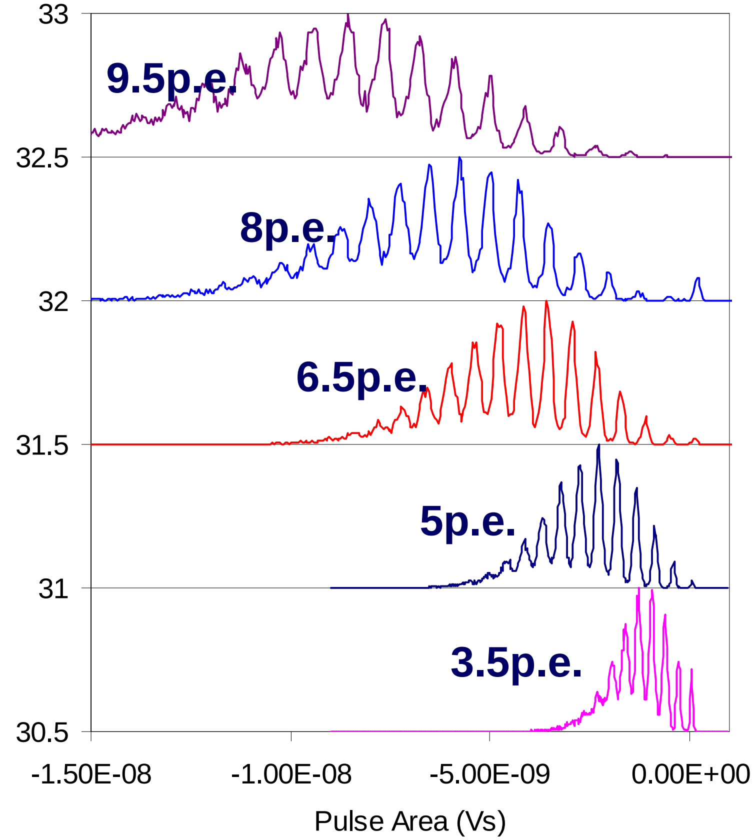
Noise and charge resolution

1x1mm^2 SiPM with 40x40μm^2 cells





Charge spectra at different Voltages with the same light Intensity (pulsed)



resolution limited by electronic noise

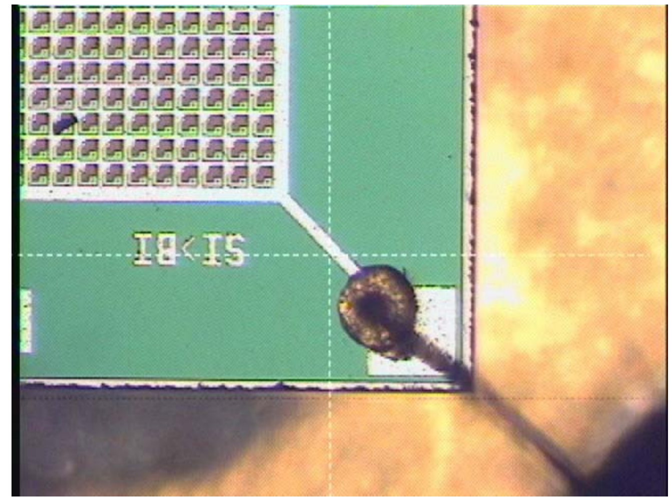
applications

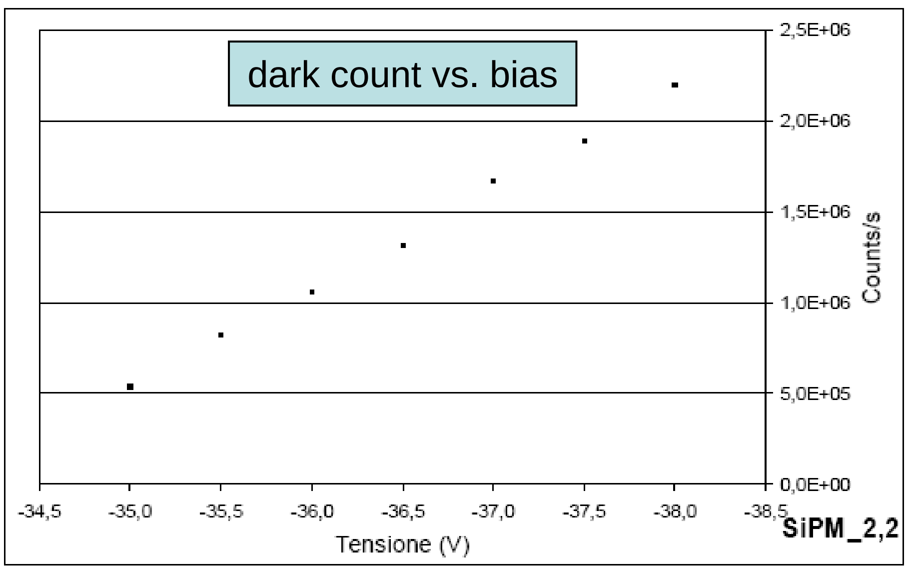
Characterization of SiPMs (1 mm^2 from second batch) used for preliminary at Fnal test beam

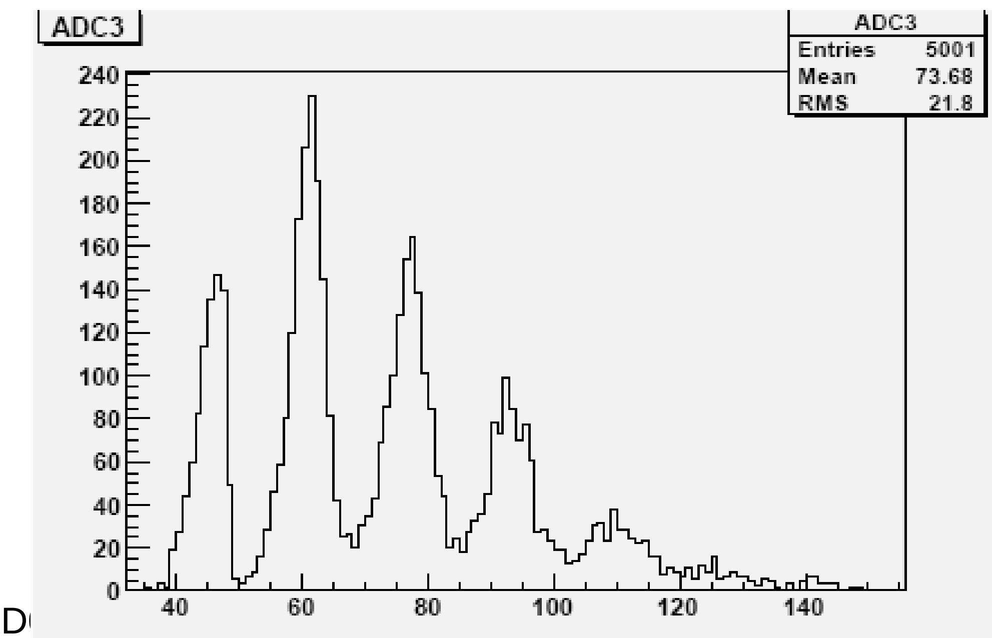
Visual inspectons (SiDet) and dynamic tests at lab 6 prior to use of SiPMs in Test Beam yielded results compatible with IRST measurements:

V_B = 34.1 V

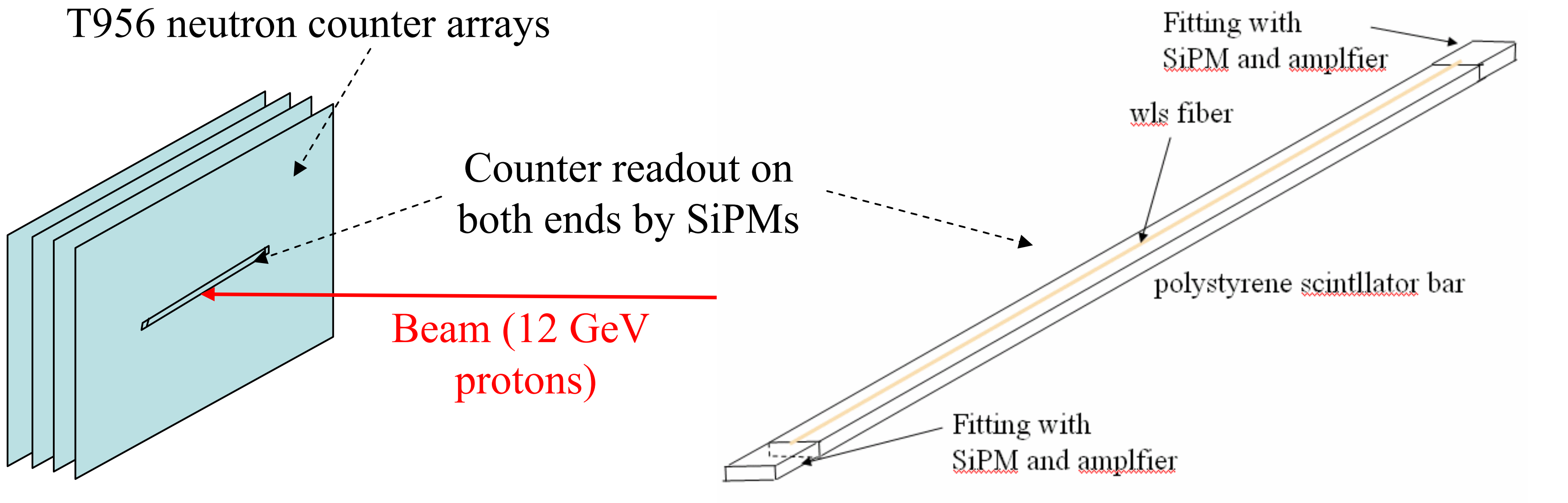
Gains between ~1 and 2 x 10^6

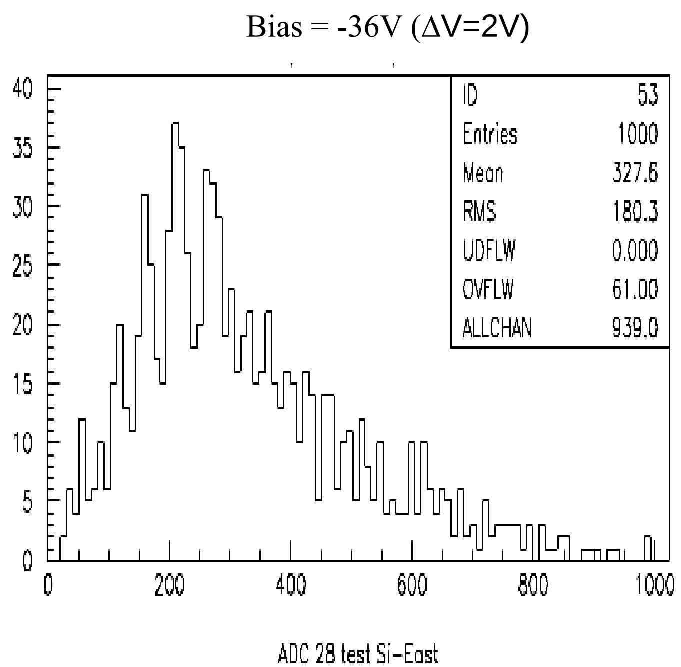






Preliminary study of Scint. Strip viewed by IRST SiPM at the FNAL test beam





Data with 120 Gev proton - beam

$$N_{p.e.} \approx 6.5\,p.e.$$

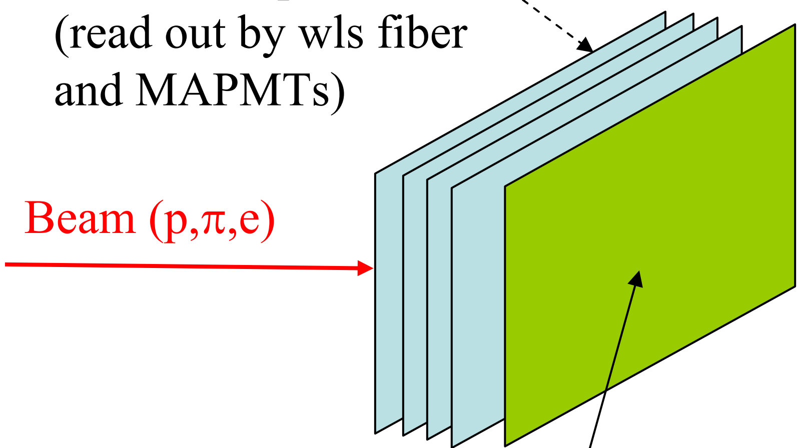
$$\varepsilon = 99\%$$

$$N_{d.c.} \approx 1.5\,MHz$$

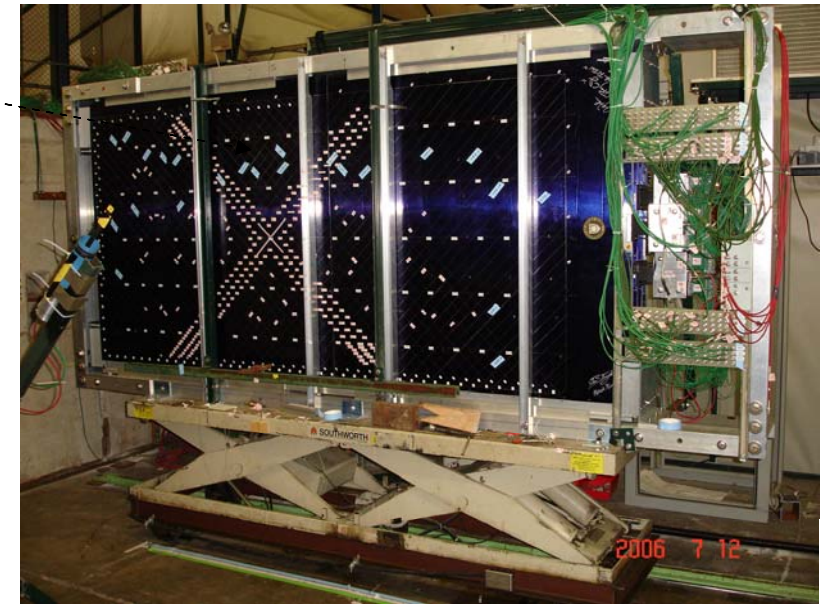
$$G \approx 1.6 \times 10^{6}$$

Future work at fnal

T956 neutron counter arrays:
64 scint strips each
(read out by wls fiber
and MAPMTs)

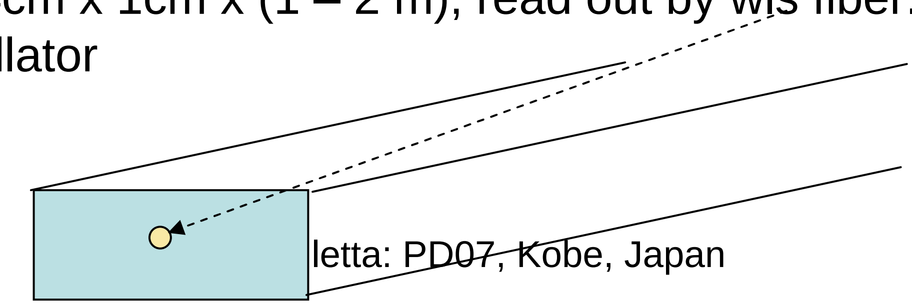


Add one plane
of scint strips read
out by Wls fiber and
SiPMs



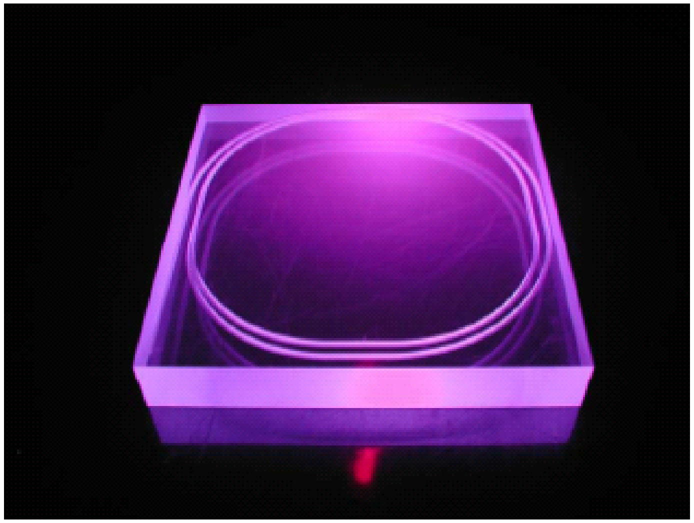
Whole assembly mounted on
movable (x,y) support

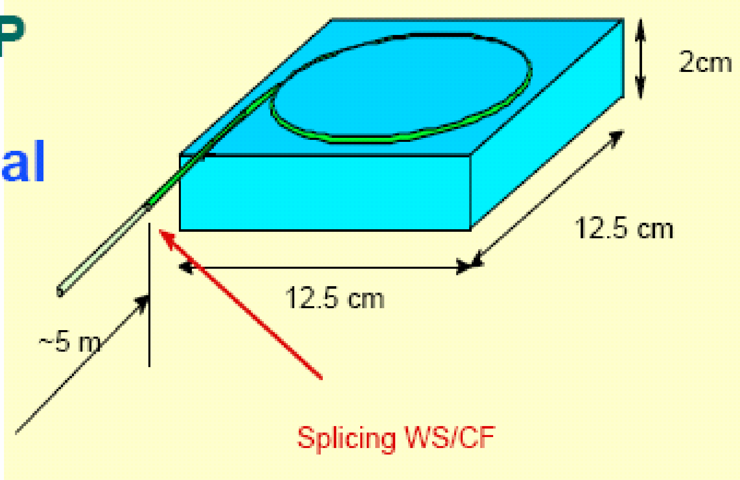
Scintillator strips : 4cm x 1cm x (1 – 2 m), read out by wls fiber. Groove for fiber extruded with scintillator



Tiles used for Ts/Ud tests

- **Dubna scintillator + keyhole/double-spiral groove + 3M super-reflector**
- **Kuraray fiber achieved 37 pe/MIP without optical glue, 44 pe/MIP with glue.**
- **Lose x3-4 along optical path to PMT (attenuation+splice+ connector)**





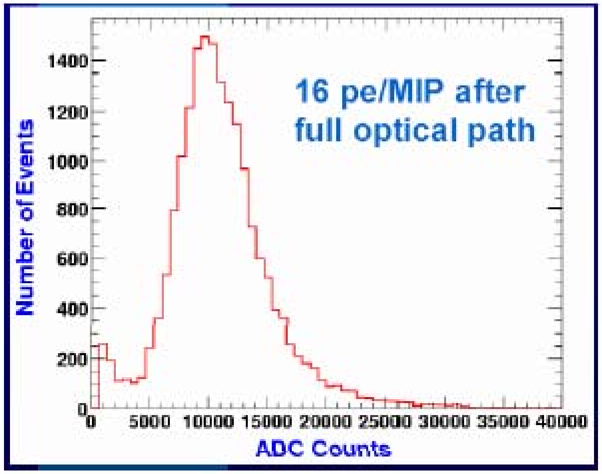
Performance (MIP)

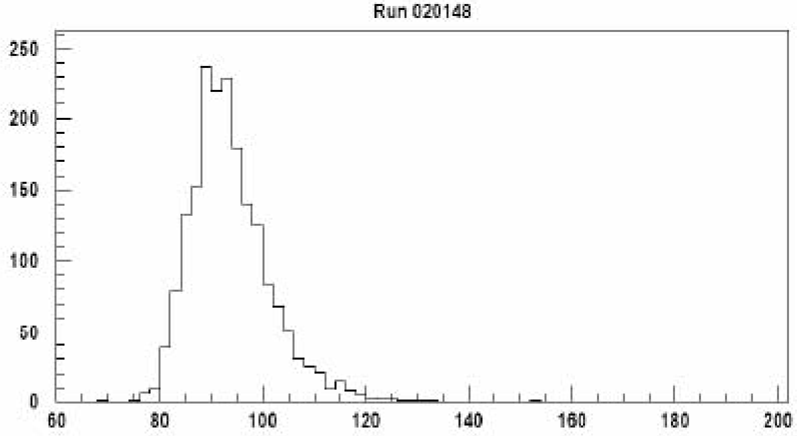
with

PMT

and

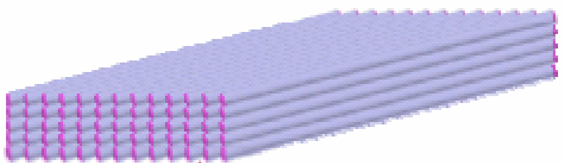
SiPM

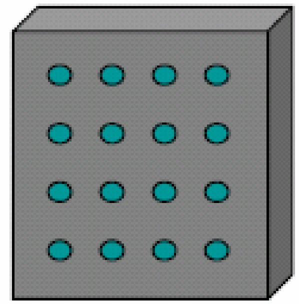


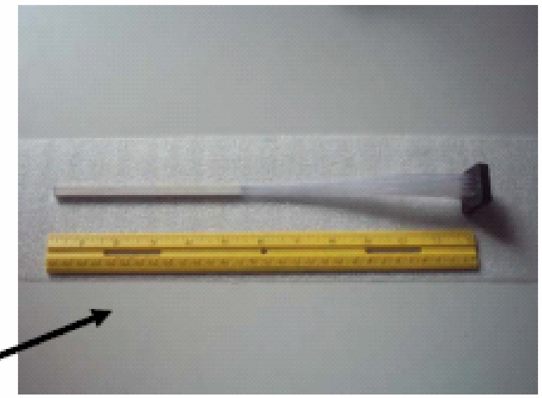


Fiber application study: Fiber Arrays

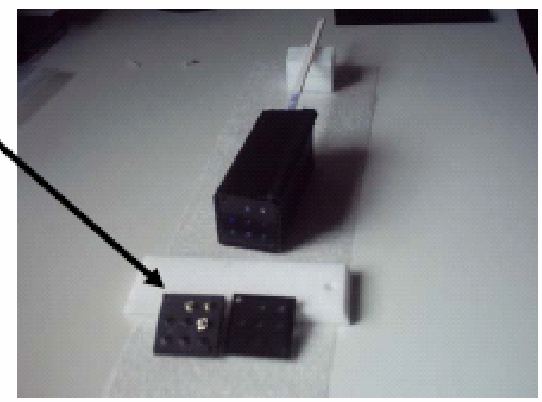
[5 layers of 0.5 mm diameter Fibers]







- **Fiber Array** mapped via a **Template** on a16 channel multi-anode photomultiplier H6568
- A second **Fiber Array** equipped with **SiPM** (8 channels, each corresponding to 2 of the adjacent channels of MAPMT)



The 2 arrays are accurately superimposed and aligned in a PS test beam (T11)