SiPM Applications past and future at FNAL
or
what's been done so far
and what we still hope to do

G. Pauletta
for the
FACTOR
collaboration

Outline

Background
What's been done
Future plans

Motivations

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

Present interests focus on:

- Calorimetry with fiber-based optical readout
- Large – area scintillator – based muon counters
- future space experiments for detection of UHECR

Action Plan:

- comparative studies for detailed understanding of device characteristics
- Application tests
- Optimization of properties as a function of application
- definition of readout parameters and electronics

History

- 2005 -- FBK & INFN fund SiPM development

- 2006 -- first batch (1mmx1mm) IRST devices available
  test of these SiPMs for large – area muon
  counters at FNAL TB (Exp. T956)
  --- FACTOR Proposed and funded (beginning 2007)

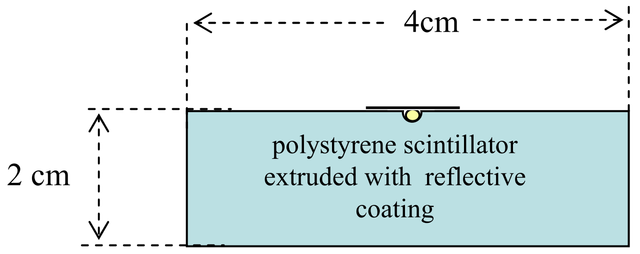
- 2006/2007
  -- plans for new SiPM – equipped plane for T956
  -- FBK (IRST) developes SiPMs for this plane
  (custom geometry and improved fill factor)
  -- FNAL (Rubinov) starts developing f.e. electronics for T.B.
  --SiPM test facility developed at SiDet (Adam)
  -- systematic SiPM character. starts up a Ts/UD
  FBK devices include trenches and gettering

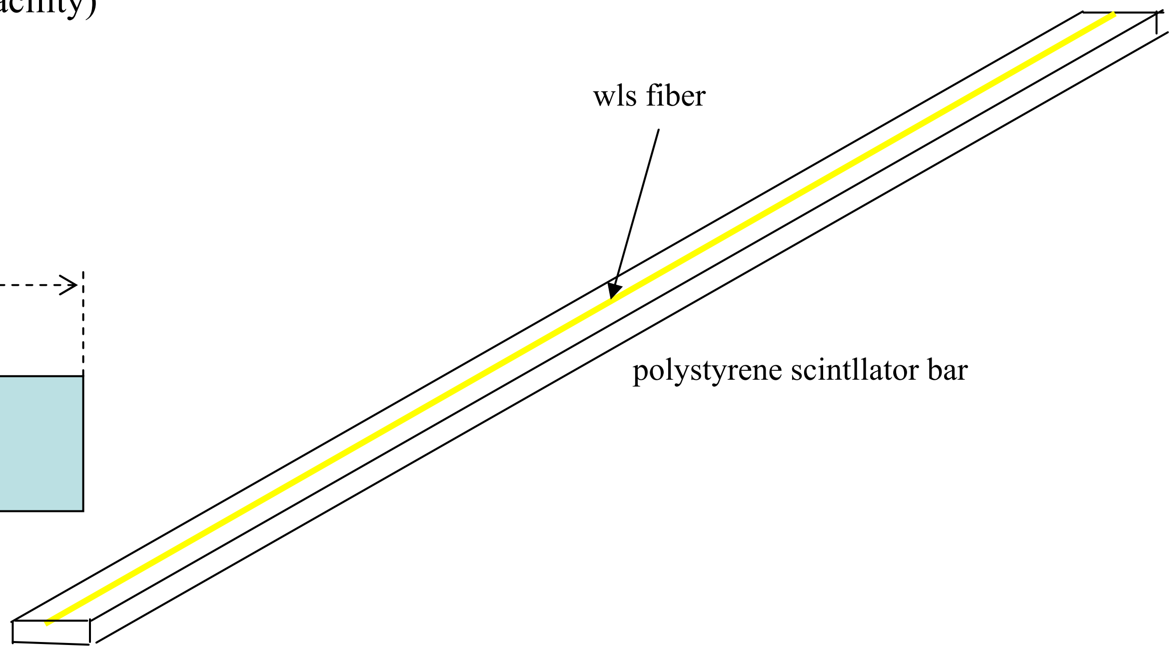
- 2008 -- irradiation tests at Ts/Ud (FACTOR)
  -- dual readout calorimetry an option for SID

T956:LC Scintillator-based Muon/Tail-catcher R&D

Hodoscopes of polystyrene scintillator bars*. Light collected by single 1.2mm wls fiber readout by MAPMT

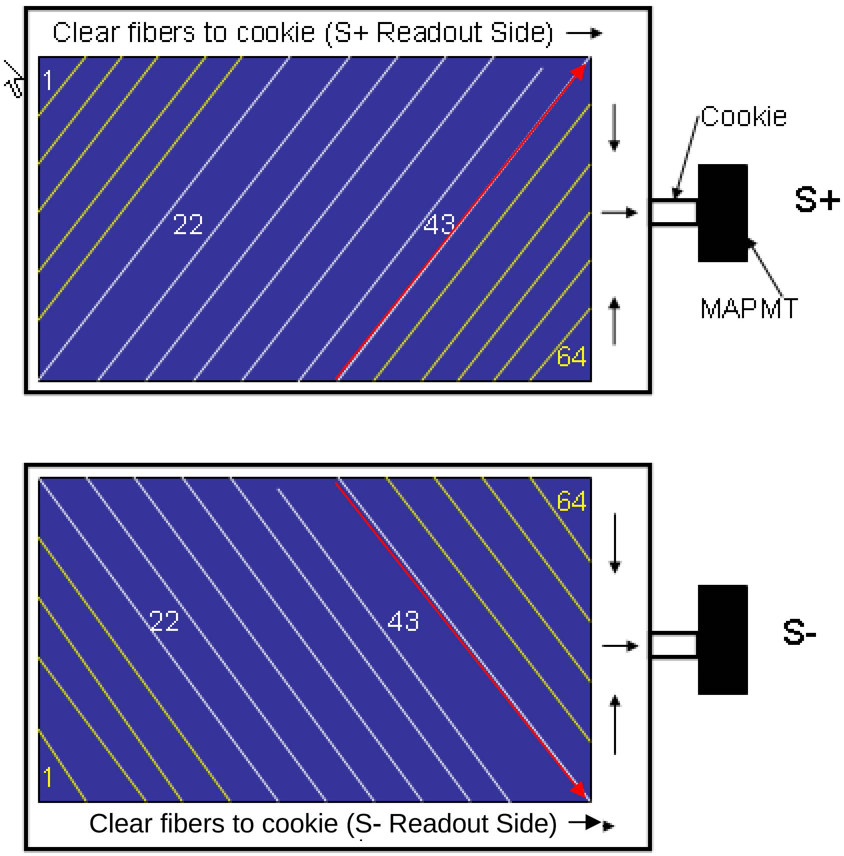
(*developed at FNAL scint. Facility)



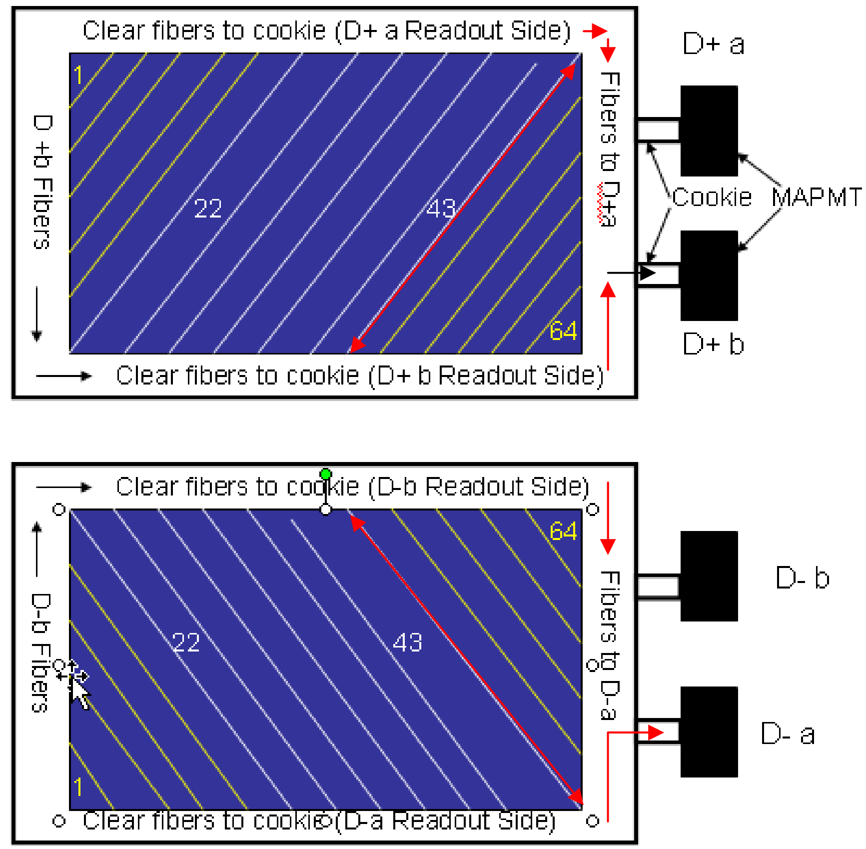


Four Detector planes

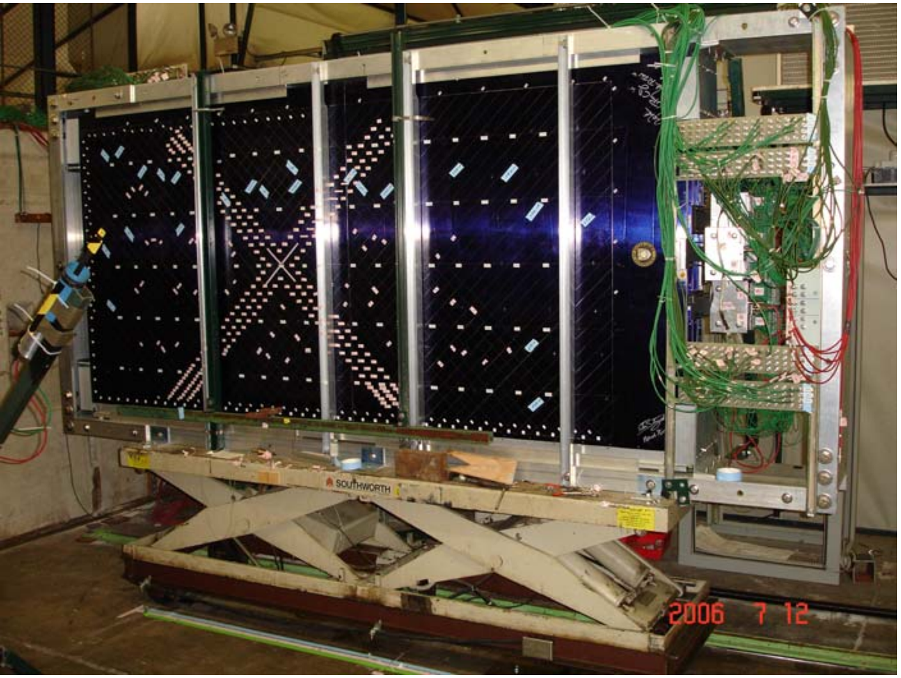
Single ended readout



Dual readout



ILC Muon/Tail Catcher Test Setup



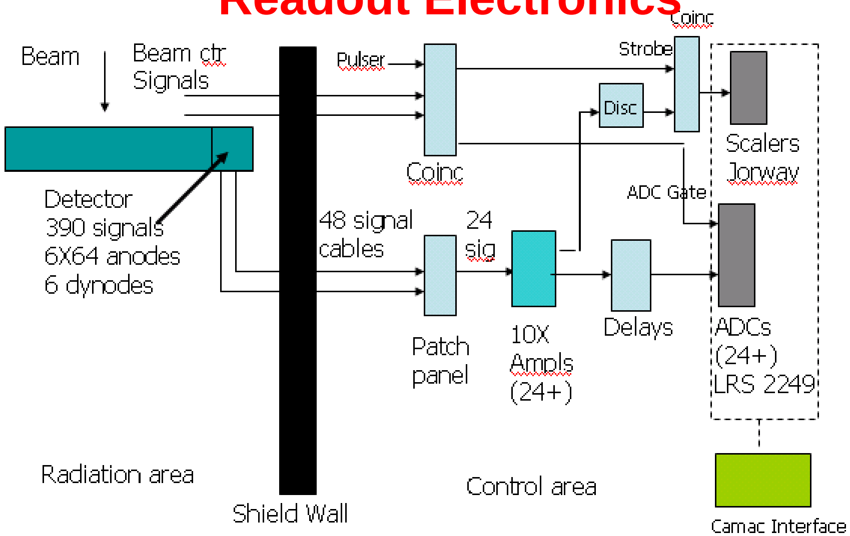
Scintillator-strip planes installed in Fermilab Beam Test Facility

Planes: 1.25m X 2.5m

256 scintillator strips: 4.1cm (W) X 1cm (T) X 1.8m (L). Two planes have single- ended readout and 2 planes have both ends of strips readout.

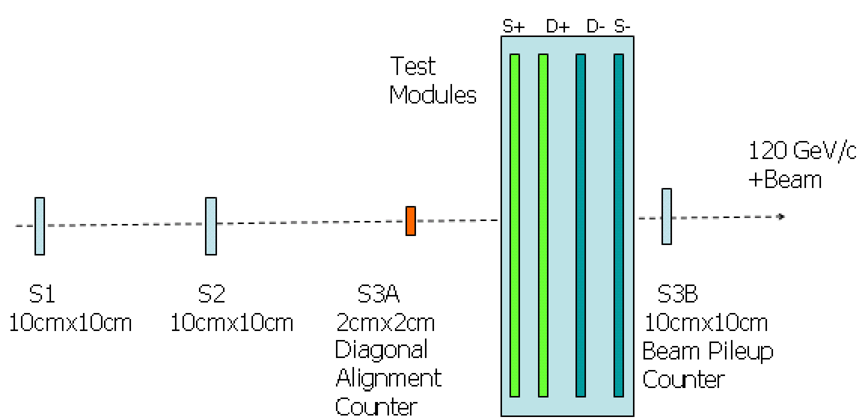
Read out by 384 PMT channels

Readout Electronics



a: TPDPP

Beam Trigger (S1.S2.S3A.S3B)



Beam Operating conditions

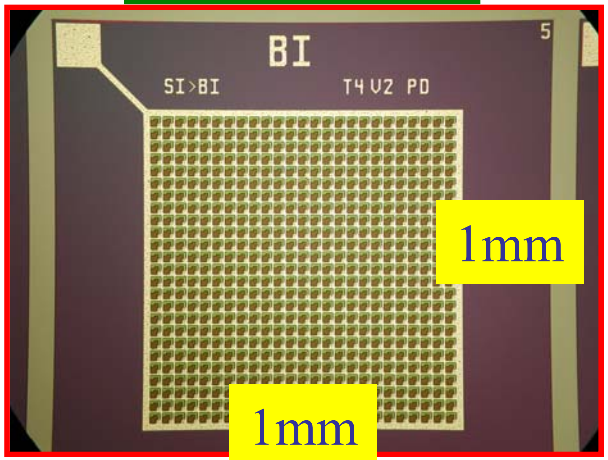
- DAQ triggered on beam; no strips in the trigger.
- When prime user, we had low intensity, ~ 1000p/sec during spill, two 1-sec spills/minute, 12 hours/day.
- When secondary user we operated up to ~20K p/sec.
- DAQ data rate limited < 50Hz. (CAMAC readout)
- Beam spot at +120 GeV/c ~ 1 cm FWHM.
- Additional beam particles within ADC gate (170ns) ~10% of time, even at low rates.
- Offline veto of multiple beam particles using beam counter.

Beam Test Objectives

- Pulse height characteristics
- Measurement of integrated dE/dx charge => $N_{p.e.}$
- Strip longitudinal position response.
- Strip-to-strip response.
- Read out two ends or only one end?
- SiPM confirmation data w/similar strips.

Baseline SiPMs used for T956

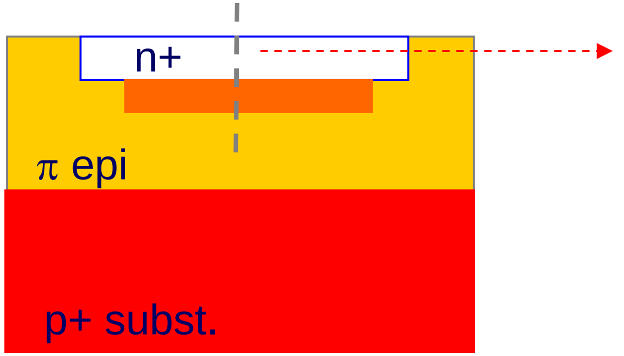
geometry

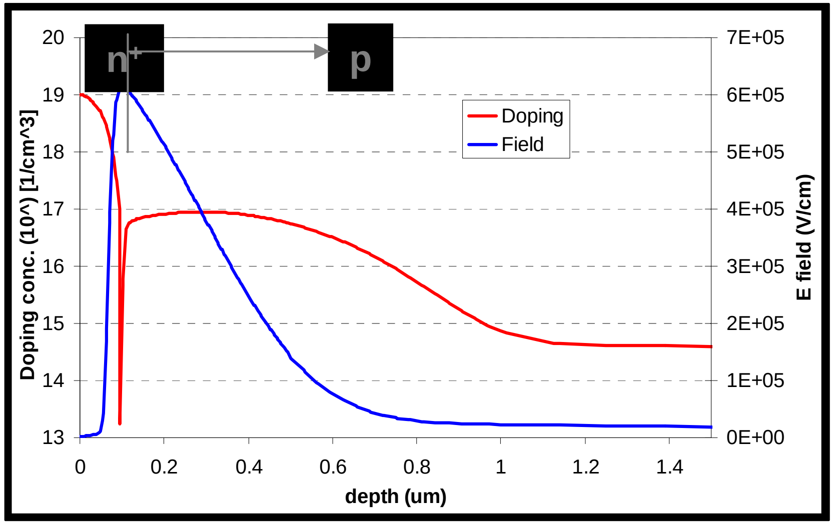


SiPM structure:
- 25x25 cells
- microcell size: 40x40mm²

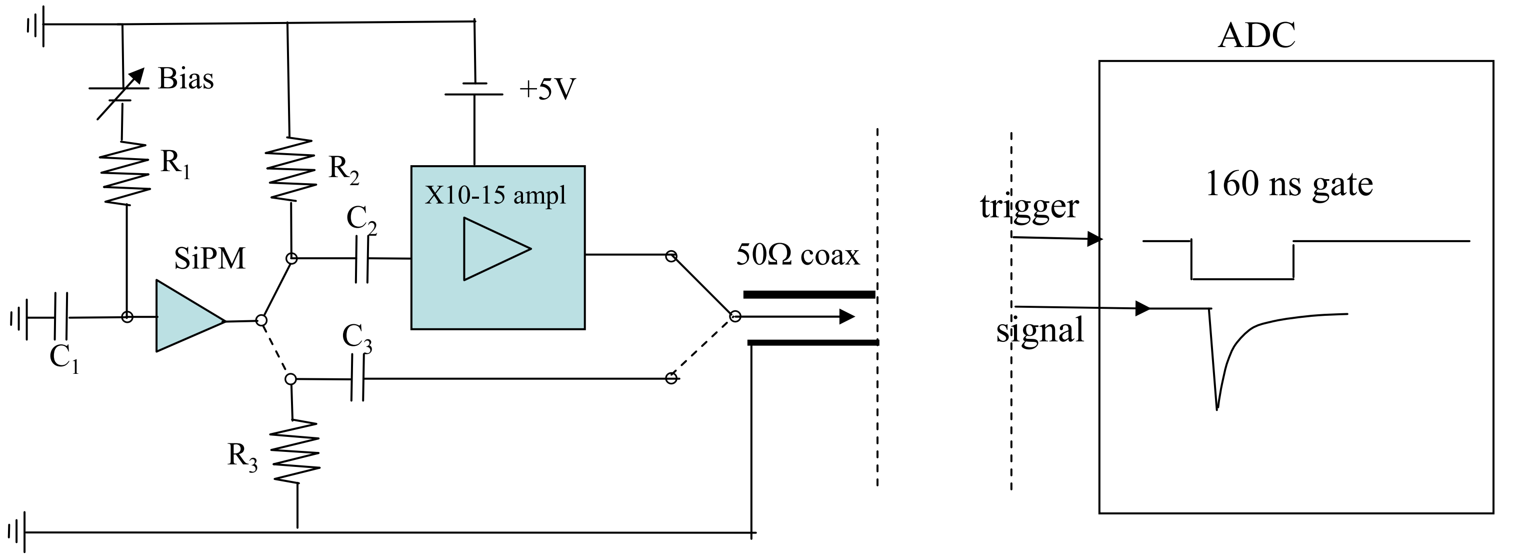
Geometry of baseline model NOT optimized formaximum PDE (fill factor ~20%) .

Shallow-Junction SiPM

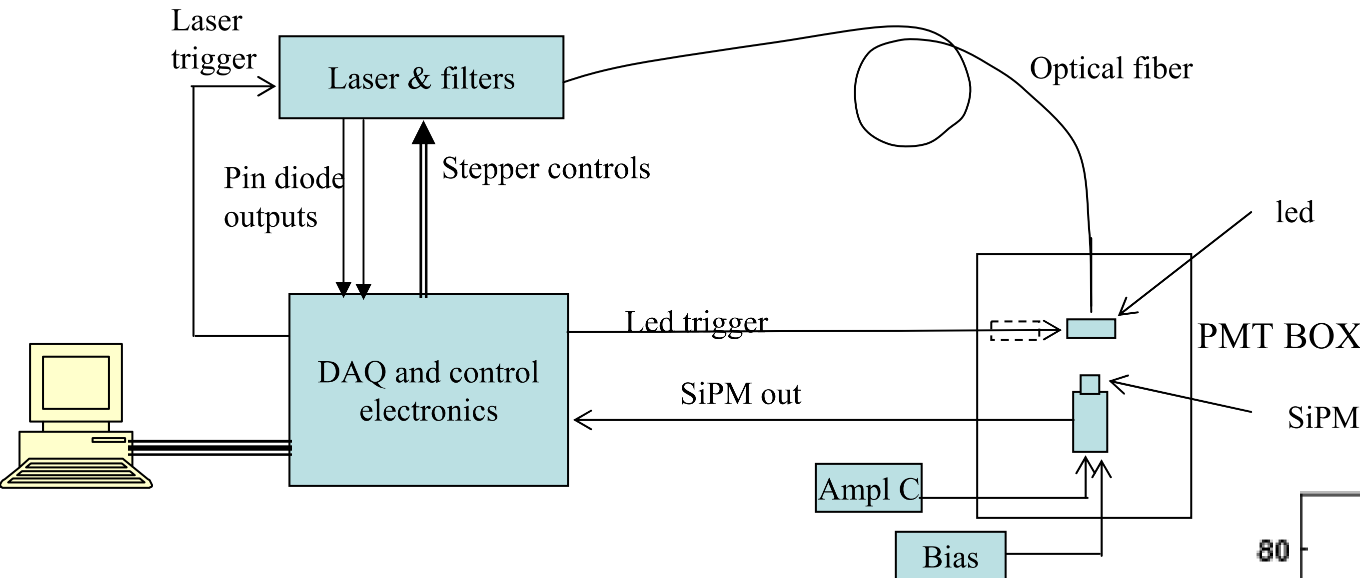


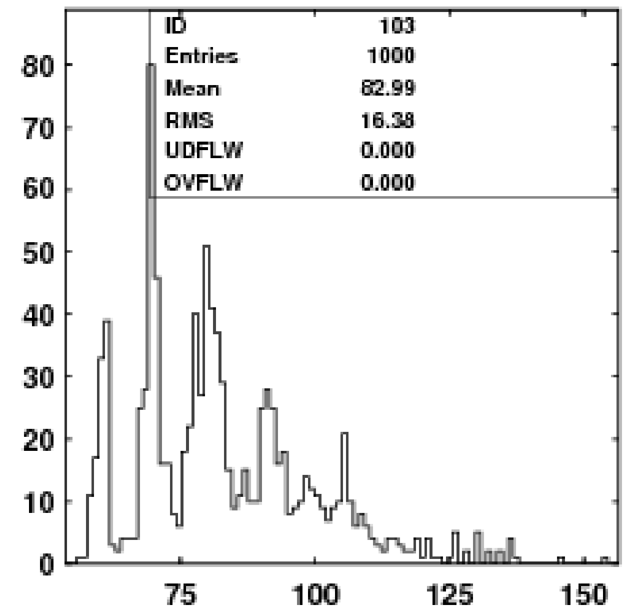


Standard calorimeter – type readout:
- digitize signal in ADC gate
- no waveform digitization



Preliminary bench tests with pulsed light source

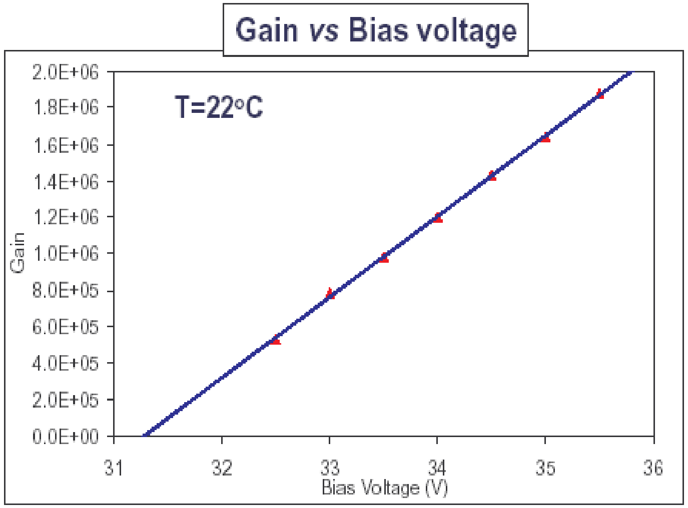




An example of the integrated charge distribution from a weak light source illuminating a SiPM at -35V, accumulated using an ADC with 0.25 pC /channel is shown alongside. From this distribution we deduce that the amplified signal corresponding to 1 photoelectron corresponds to ~ 10 ADC channels, from which we calculate that the overall gain is about

$$\frac{10\times 0{,}25.10^{-12}\,C}{1{,}6\times 10^{-19}\,C} = 1{,}6\times 10^{7}$$

Gain

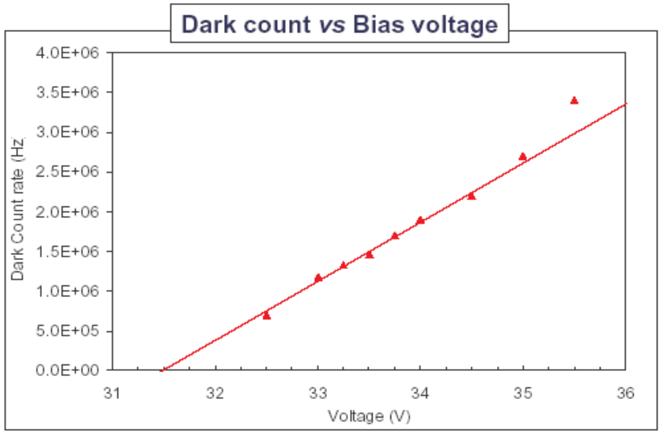


Given an amplifier gain of ~10, that the SiPM gain is ~1,6.10^6 for a Bias voltage of -35V. This value is very close to the expected value given by IRST specifications illustrated below

dark count vs. bias

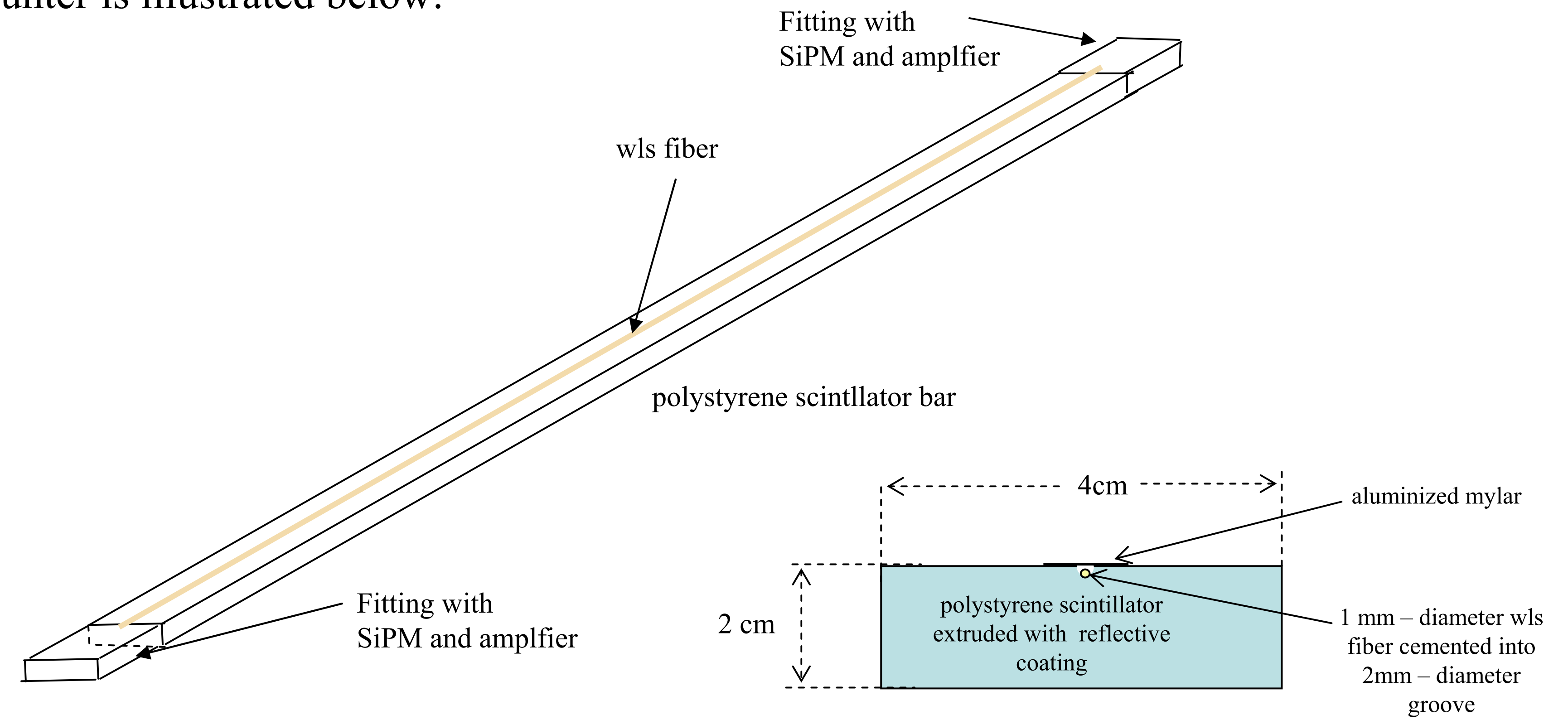
Single thermal photoelectron rates were also found to be consistent with specifications

Dark count



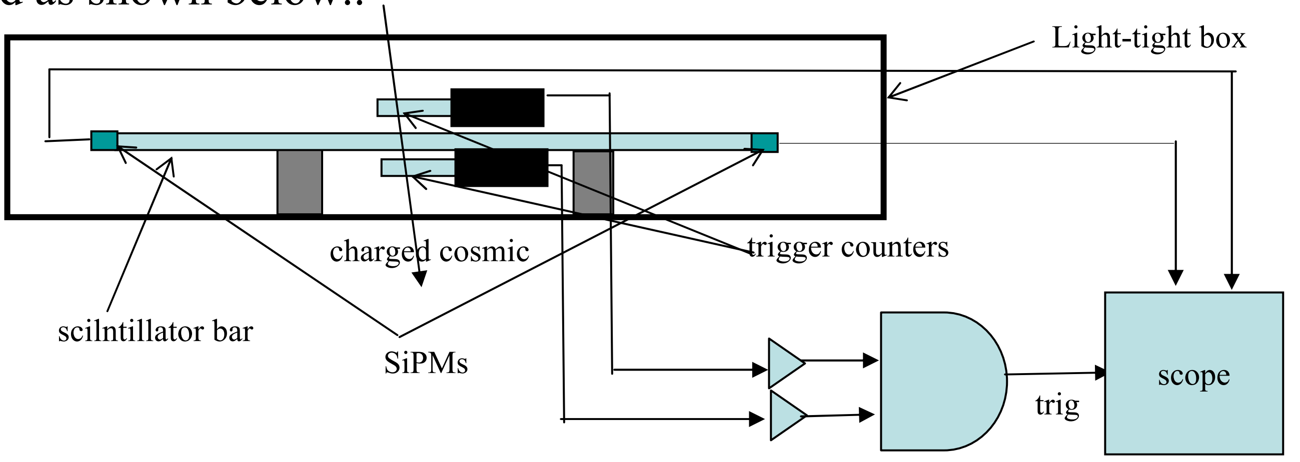
These characteristics did not vary significantly over the sample of SiPMs tested.

Using the same readout circuits and fittings used for the preliminary tests, SiPMs were then mounted to the two ends of a scintillation counter and aligned with the ends of the wavelength-shifting (wls) fiber used to collect and transport the light generated in the scintillator. The counter is illustrated below:

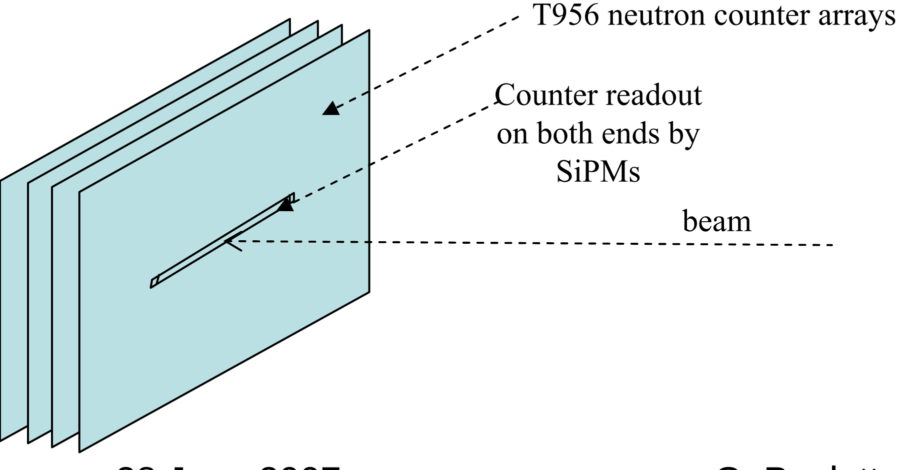


The SiPMs were alligned, by means of an improvised fitting with the ends of the wls fiber, which were polished at both ends at lab 7 prior to cementing the fiber in the groove. The sentive surface of the SiPM was maintained at a distance of ~ 0.5. mm from the polished fiber face . Because the active area of the SiPMs (1 mm^2) is equal to that of the fiber end, alignment is critical

Alignment was optimized by detecting cosmic muons in a light – tight box . Signals corresponding to the passage of charged cosmics, triggered by the conicidence of two trigger counters of width equal to that of the scintillator bar, were used to align the SiPm with the fiber end as shown below..

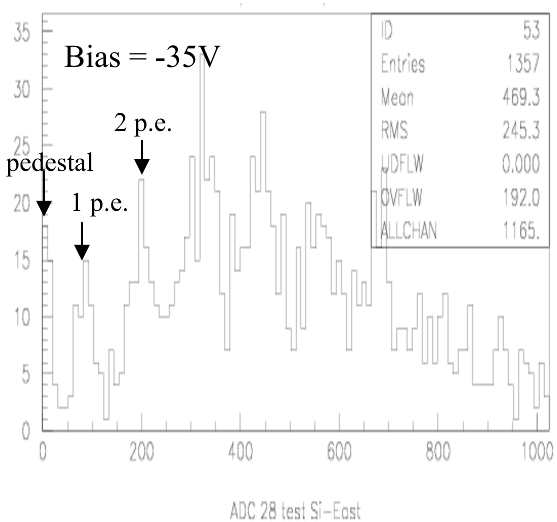


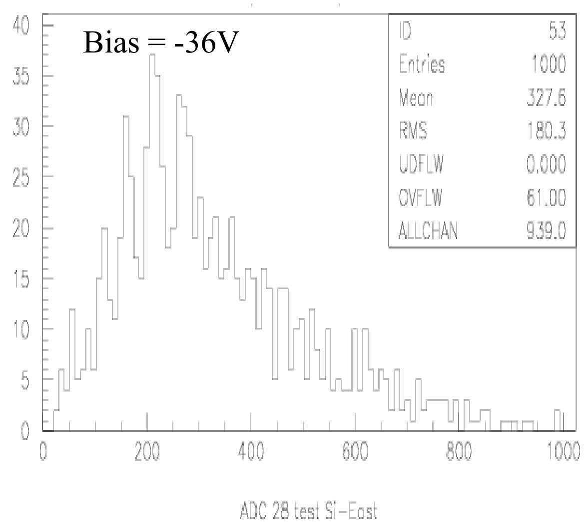
counter was then transported to the MT6 test beam and installed in front of the muon counter array of T956



. The T956 muon counters are mounted on s support structure which allows for both horizontal and vertical (remotely controlled) motion.. The DAQ trigger include 2 Trigger counters just upstream of our counter array which define a $1 cm^2$ effective beam spot at the position of our counter.

Data was taken with both 120 GeV and 60 GeV protons. The signal currents were integrated over gate intervals of 160 ns in ADCs having a sensitivity of 0.25 pC / channel.. Examples of distributions from the West end of the counter are shown below for different bias and amplifier settings.

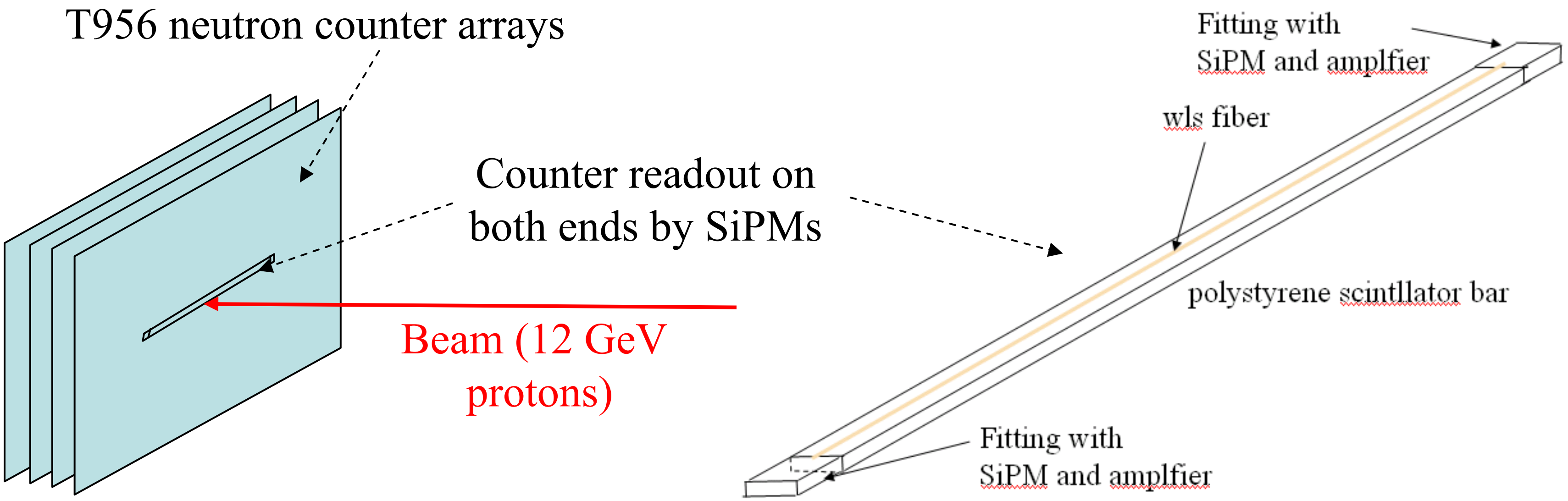




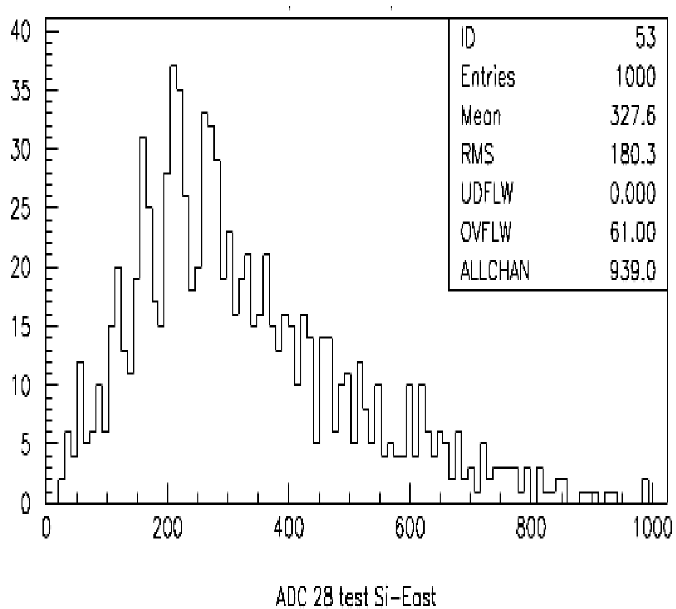
Inefficiency goes from 8% to less than 1% as the bias is raised from 35V to 36V. At the same time, the mean number of photoelectrons per mip goes from 4.6 to 6.5

Pedestal runs were taken in the absence of beam with a free – running pulser substituting the beam trigger (see figures above) These runs also allowed for the measurement accidentals due to the relatively high thermal dark current typical of these devices. The go from ~10% to ~ 20%. Given the ADC gate width of 160 ns, this corresponds to thermal single p.e. dark currents of about 1 – 1.5 MHz

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



Bias = -36V (ΔV=2V)



Data with 120 Gev proton - beam

$$N_{p.e.} \approx 6.5\,p.e.$$
$$\varepsilon = 99\%$$
$$N_{d.c.} \approx 1.5\,MHz$$
$$G \approx 1.6 \times 10^{6}$$

a: TPDPPC, Trieste

Future plans for the muon/Tailcatcher at FNAL:

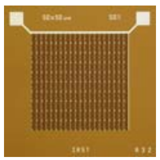
- SiPMs are our future interest

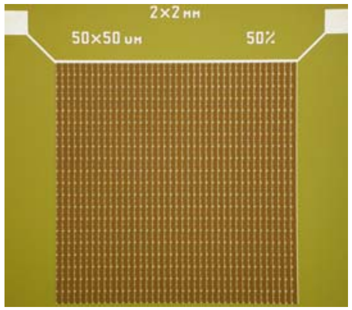
- Begin by instrumenting a full plane with SiPMs (100 Custom SiPMs produced by FBK IRST for the purpouse)

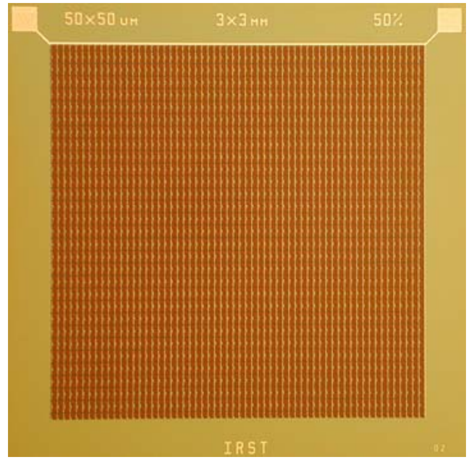
- Bench Tests of Russian, IRST, MPPC and other avalanche photo-diodes have started at Fermilab and are ongoing at NIU and Trieste/Udine.

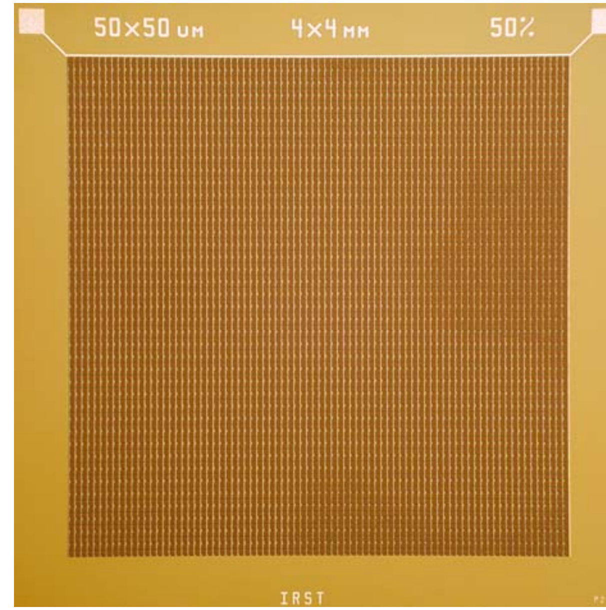
- Electronics development in concert with DHCal are in the

last batch





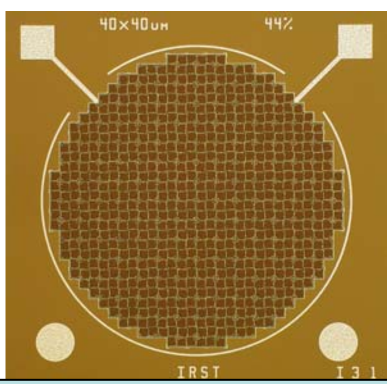




1x1mm 2x2mm 3x3mm (3600 cells) 4x4mm (6400 cells)

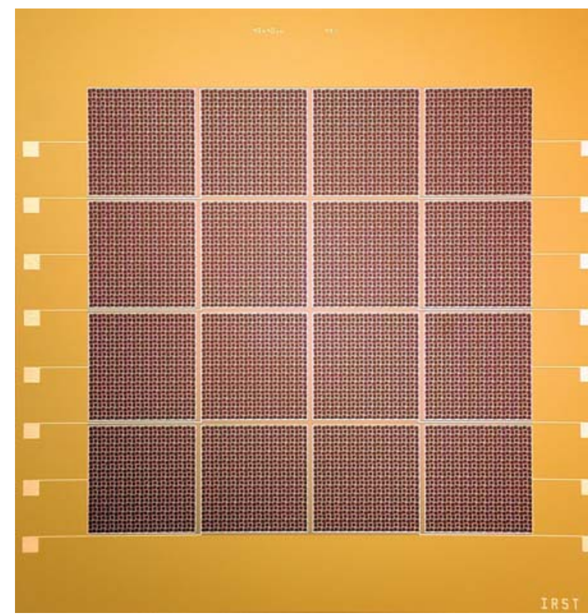
increased fill factor:

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

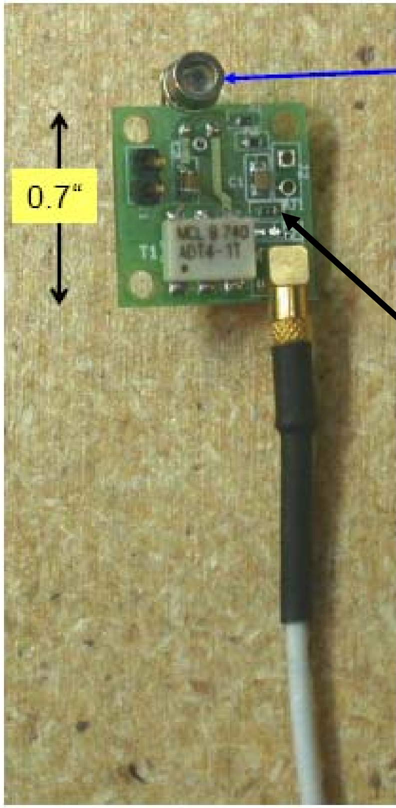


Circular
(1.2 mm –
diameter)

Array



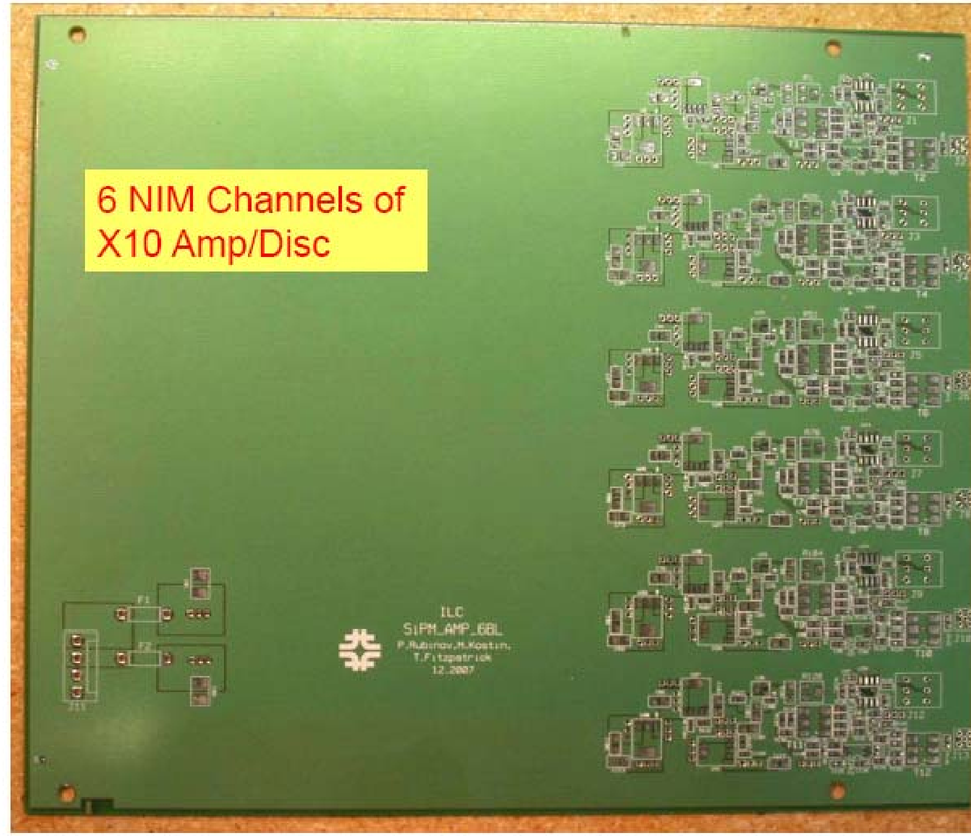
F.E. Electronics development a t FNAL



SiPM

Transformer – coupled filter

Paul Rubinov



…Plans for Calorimetry?

* CALICE (PFA) is already taking data at FNAL TB

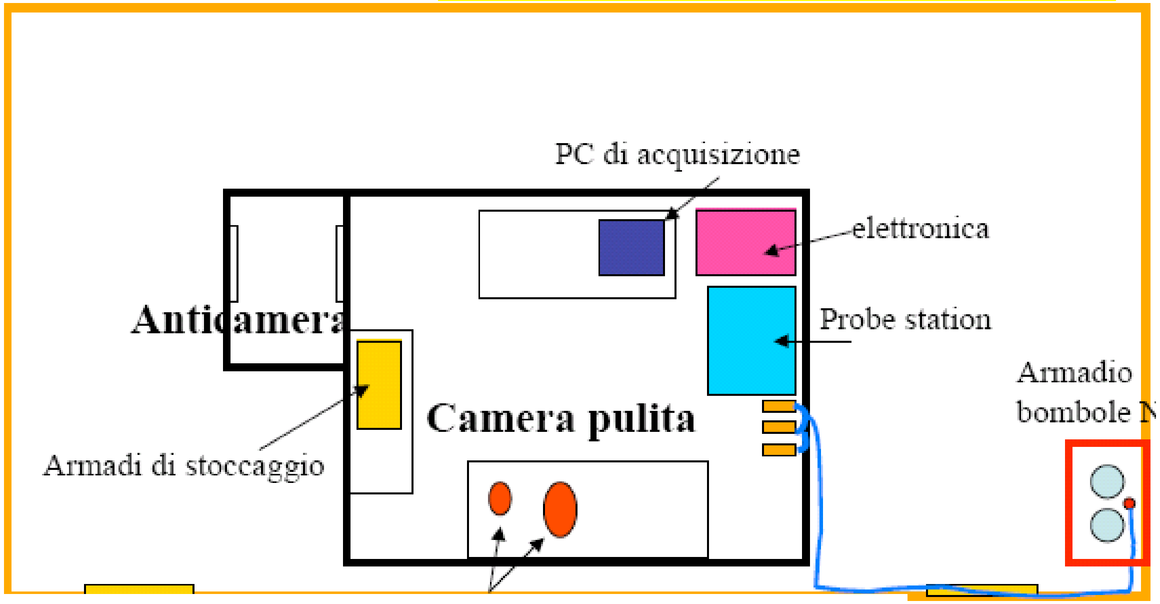
- Dual readout has now been recognized as a possible alternative for SID
- Looks like a total absorption calorimeter with transverse segmentation is the way to go - crystals? - which? – see Adam's talk
- Finer transverse segmentation (PFA?) could be obtained by alternating crystals with Si -detector planes. This would also introduce a measure of longitudinal segmentation.
- Adam is actively investigating crystal tecnology --
- Need to get going going - but available funds insufficient -- proposals submitted both in US and Italy

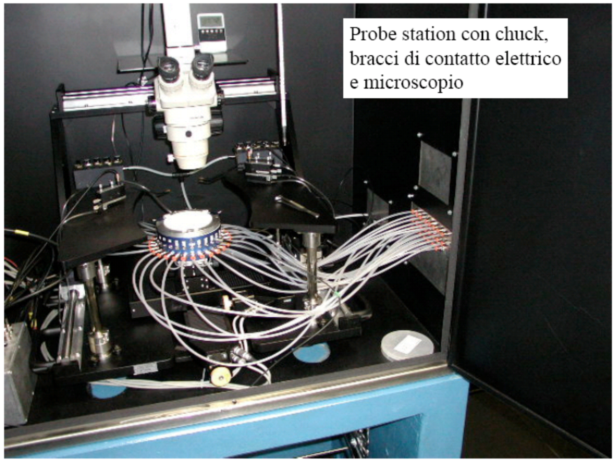
Meantime!

- Simulate --- Adam and collaborators already up and running
- Study light collection schemes --- don't need a full-fledged calorimeter module for that
- Develop SiPMs with extended sensitivity in the blue side of the spectrum (has FBK IRST given up on that?)
- Start developing readout electronics
- ……….and continue with SiPM studies

Area: 18 m²

Si-detector Clean room at UD



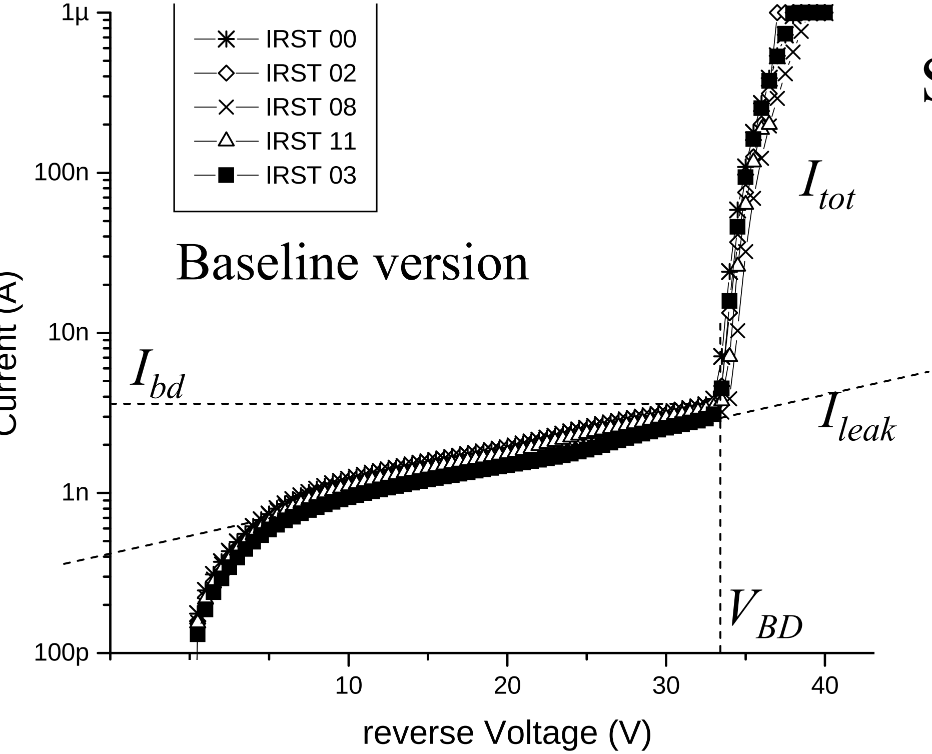


Dotazioni

Object	producer	#
1-side probestation	Maehlum	1
Probe arms	Karl Suss	3
1-kV probe arm	Karl Suss	2
2-side probe chuck	U. Dortmund	1
X-Y+Z table + controller	Micos	1
LCR meter 4284A	HP	1
HV source/measure unit 237	Keithley	1
Electrometer 6514	Keithley	1
Picoammeter/voltage source 487	Keithley	1

* detector development lab with
*3 GHz LeCroy sampling scope
*NIM/CAMAC/VME DAQ electronics
*keithly powe-supplies/pA
*~1ns pulse N-laser
*100 ps pulsed diode-laser
*calibrated detectors
*optical bench

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 $G \propto V, \quad DC \propto V$

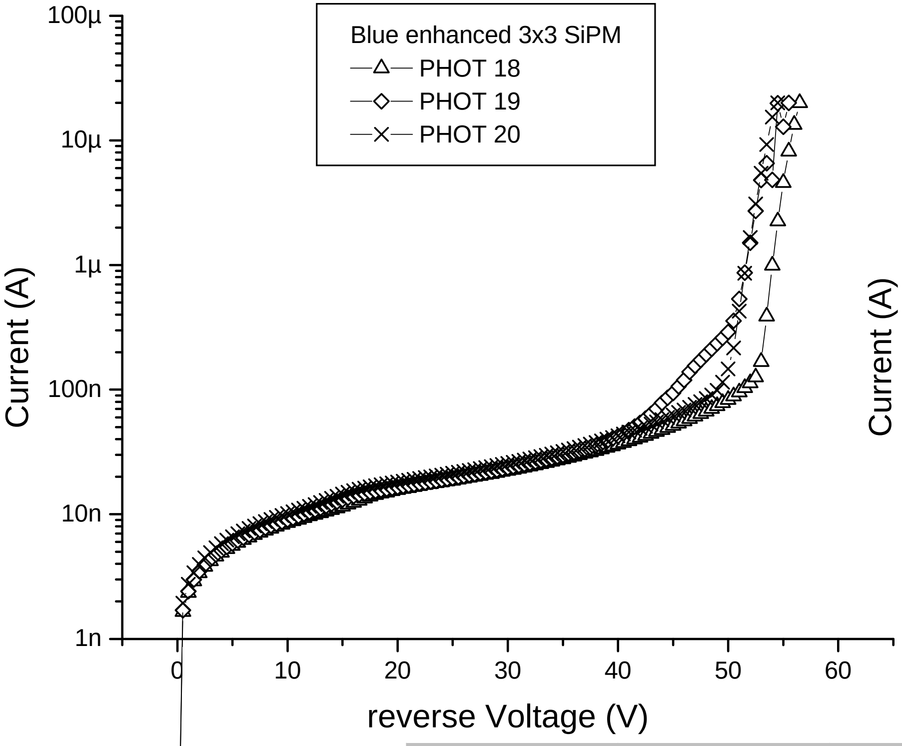
$$I_{dc} \propto V^2$$

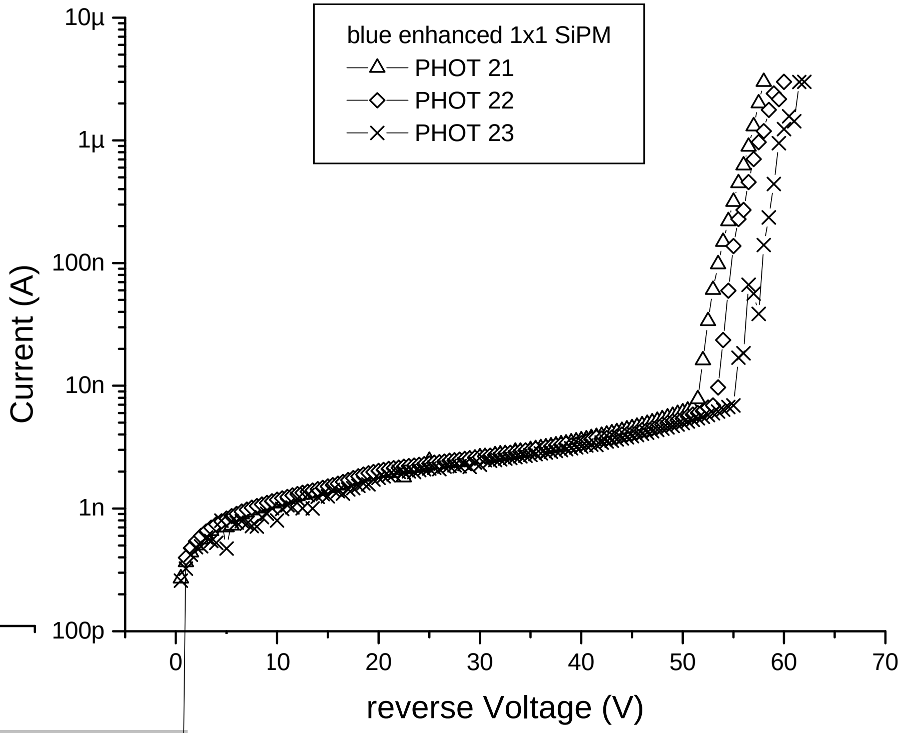
SiPM	Vbd (V)	Ibd (nA)
IRST-00	32,5	3,6
IRST-02	33,0	3,6
IRST-03	33,0	3,1
IRST-08	33,5	3,2
IRST-11	33,5	3,8

IRST 1mm^2 second batch

IRST devices generally very uniform

Static measurements-2



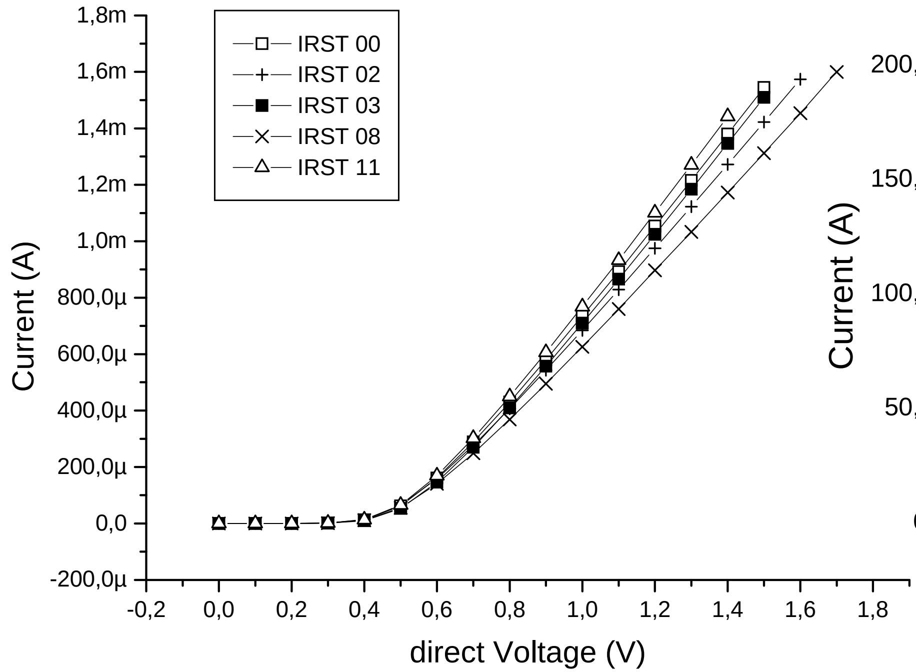


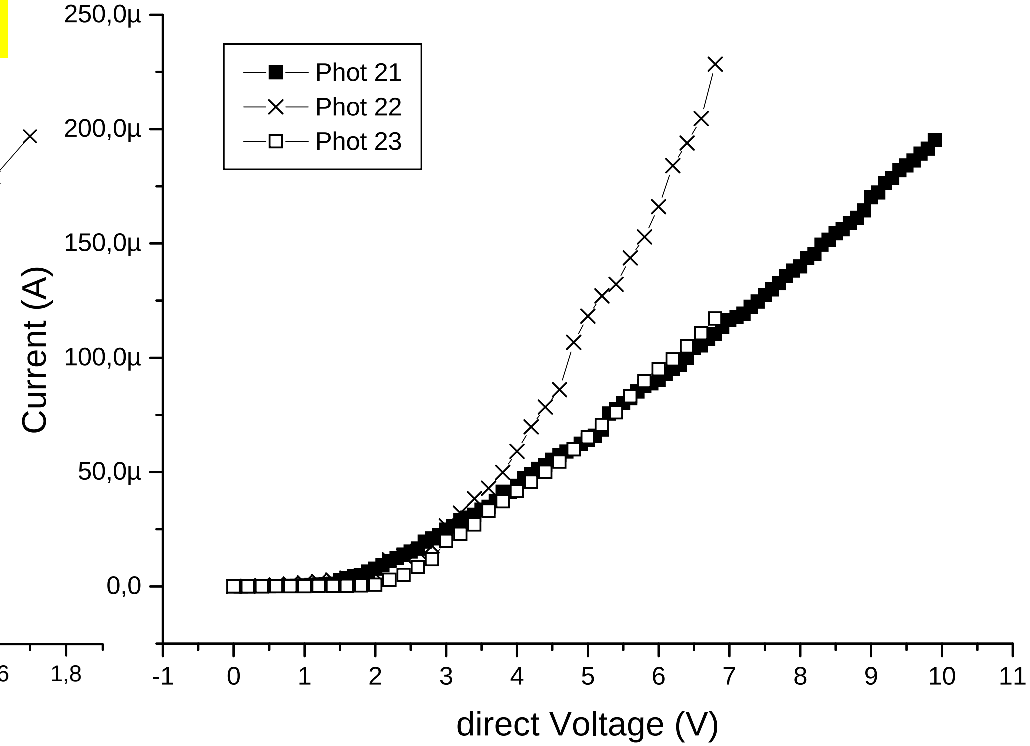
SiPM	Vbd (V)	Ibd (nA)
Phot-18	52,5	125,8
Phot-19	49,5	260,6
Phot-20	49,0	98,7
Phot-21	51,0	6,5
Phot-22	53,0	6,9
Phot-23	55,0	6,0

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

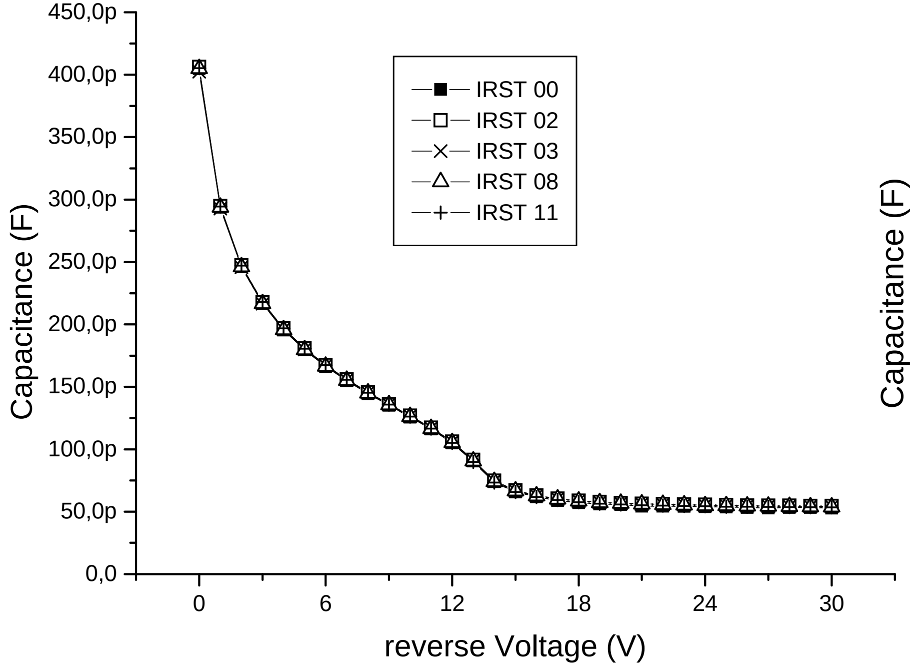
$$\times 625 \approx 390 k\Omega$$

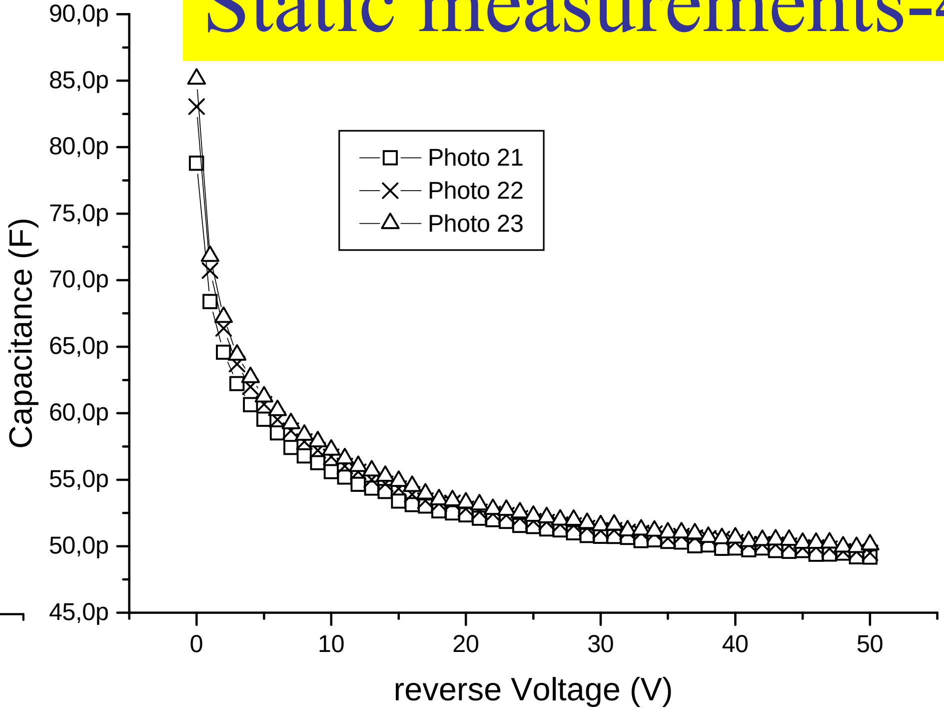
SiPM	Rq (kOhm)
Phot-18	2,29
Phot-19	1,52
Phot-20	1,24
Phot-21	39,8
Phot-22	17,4
Phot-23	37,8

Photonique 9mm^2 Blue sensitive

Photonique 1mm^2 Green-red sensitive

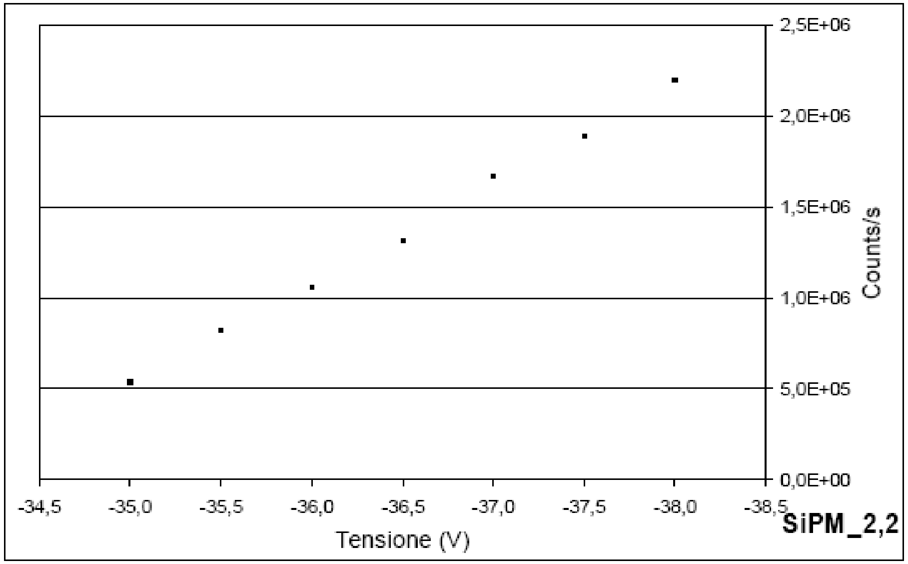
Static measurements-4

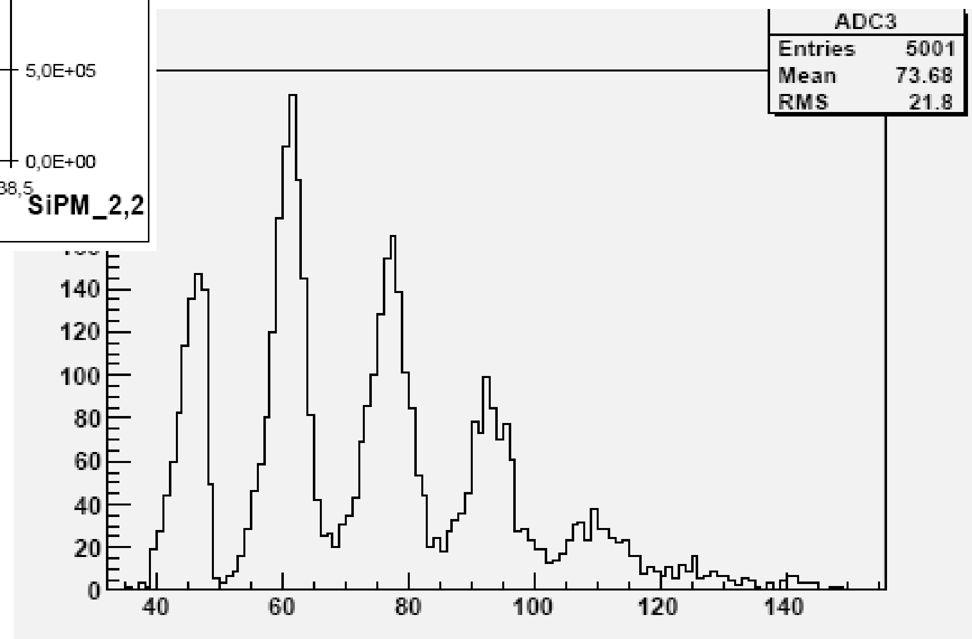




SiPM	Vdep (V)	Cdep (pF)
IRST-00	21	54
IRST-02	21	55
IRST-03	21	55
IRST-08	21	55
IRST-11	21	54

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


2,5E+06
2,0E+06
1,5E+06
1,0E+06
5,0E+05
0,0E+00
Counts/s
-34,5
-35,0
-35,5
-36,0
-36,5
-37,0
-37,5
-38,0
-38,5
Tensione (V)


SiPM_2,2
ADC3
Entries 5001
Mean 73.68
RMS 21.8
140
120
100
80
60
40
20
0
40
60
80
100
120
140

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

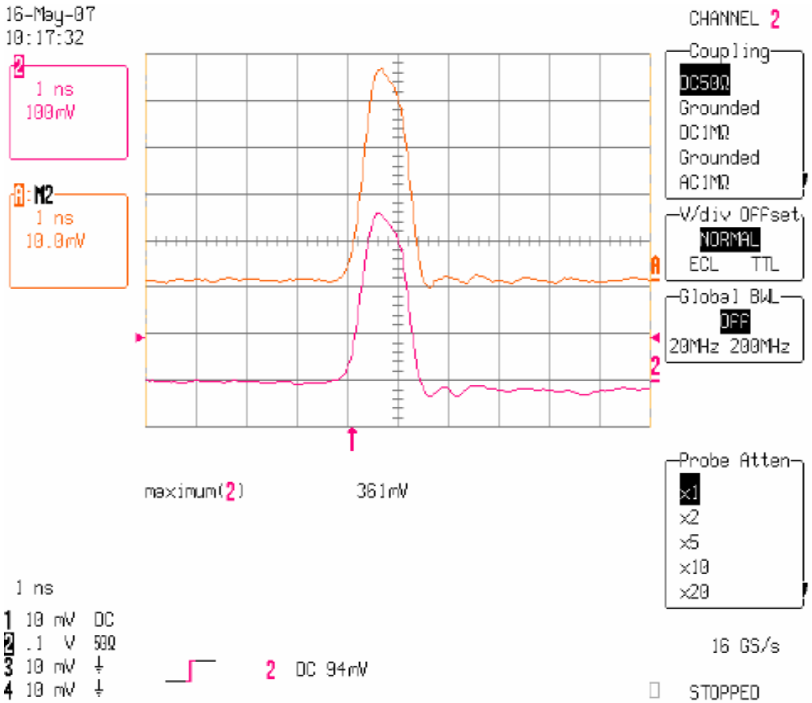
- Signal rise time and fall time
- Gain
- Dark count
- Optical cross – talk
- Afterpulsing

• PhotoDetection Efficiency

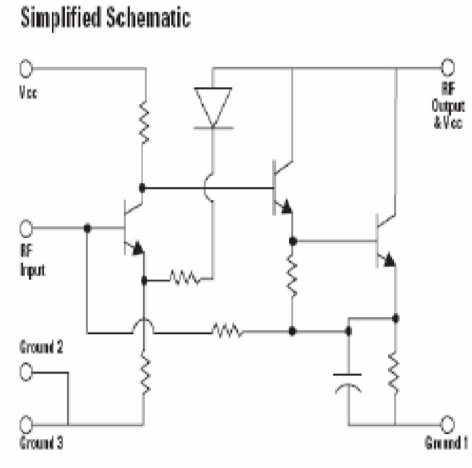
1)All characterizations reported here are for 1mm^2 devices
2) for a thorough characterization of the first SiPM prototypes fabricated at ITC-irst see C. Piemonte, IEEE TNS, February 2007

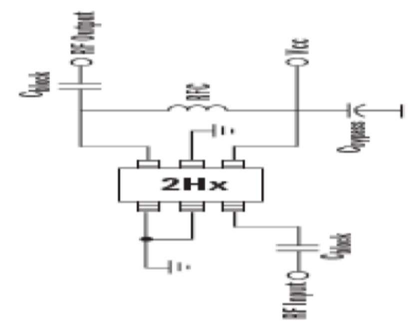
dynamic measurements-1

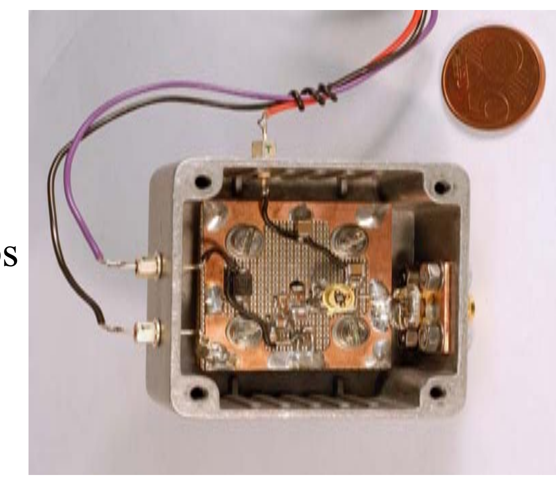
Amplifier used for fast characterization of SiPMs:
Agilent ABA-52563 3.5 GHz RFIC Amplifier
(economic, compact, internally 50-Ω matched, gain ~ 20 dB)
Dimensions 1.8 x 1.8 mm2



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

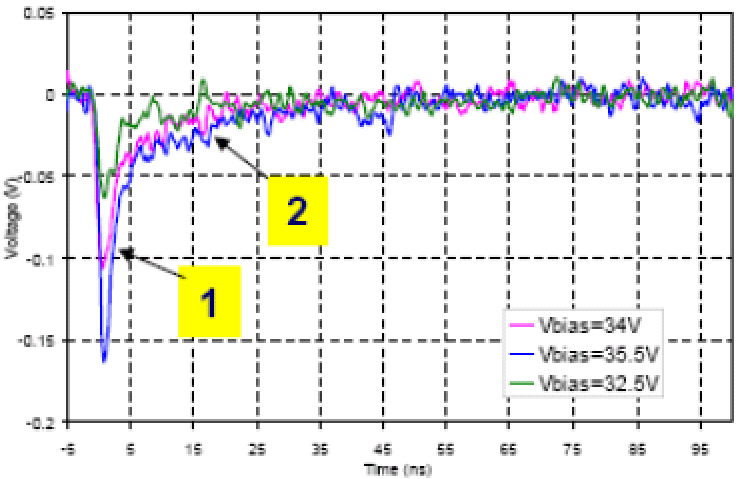


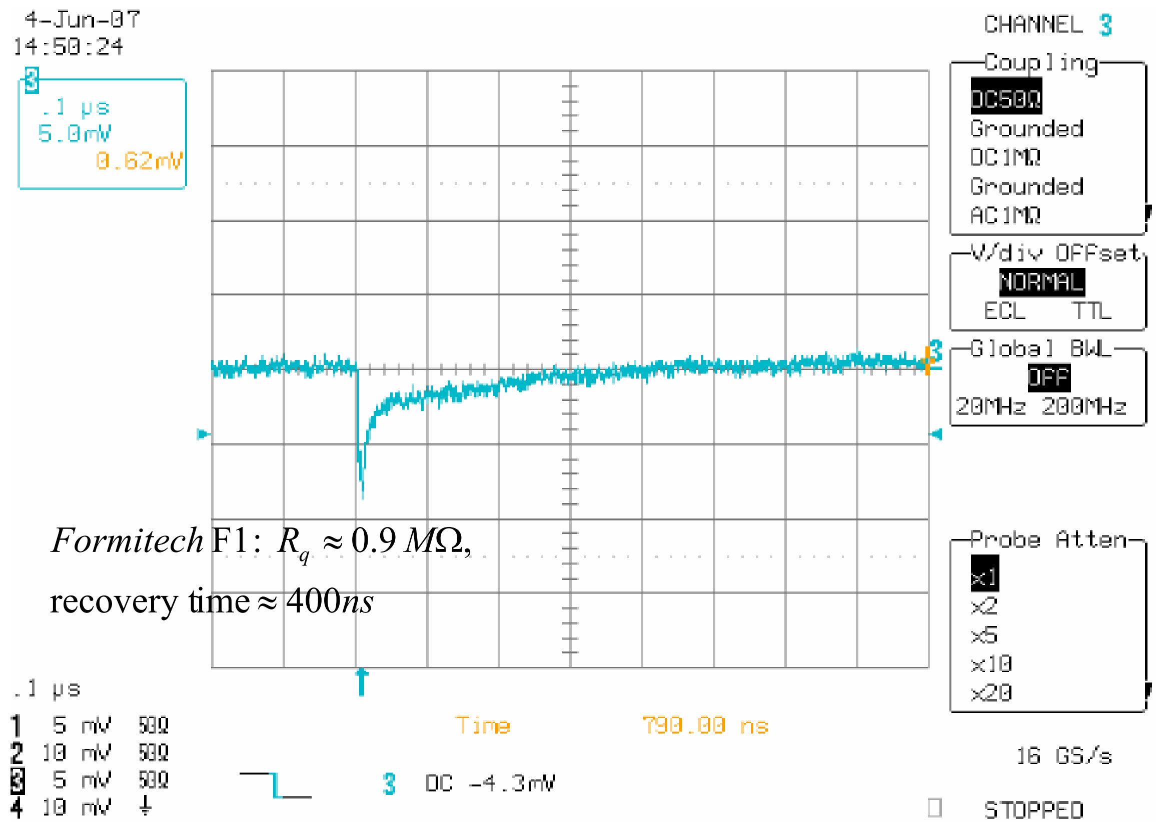




dynamic measurements-2

IRST :recovery time ~70 ns



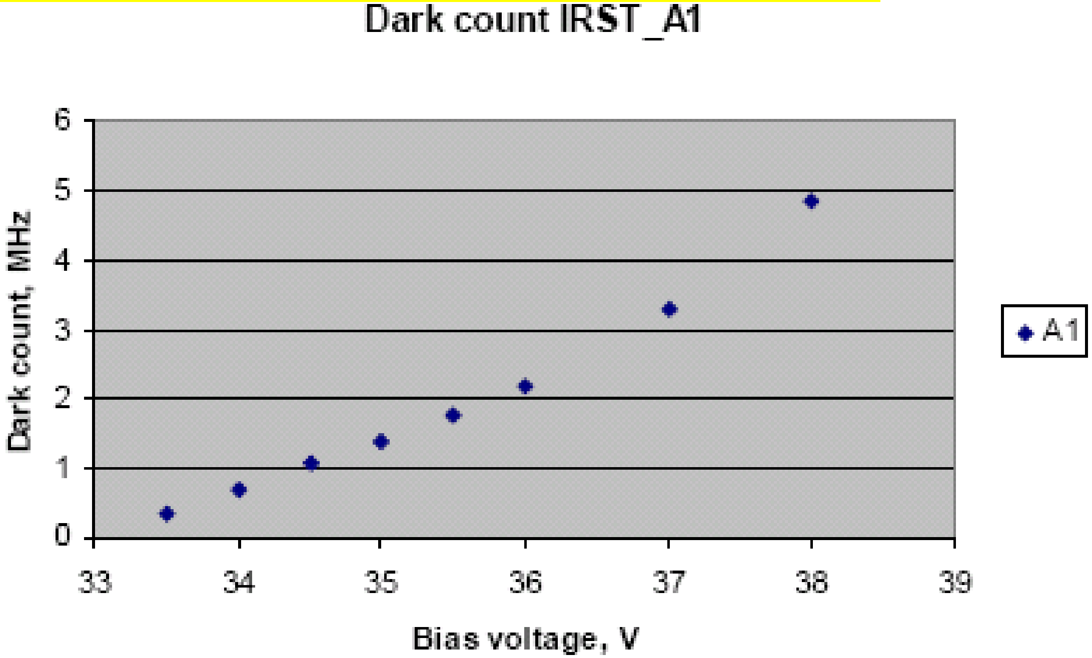


Formitech F1: $R_q \approx 0.9\ M\Omega$,

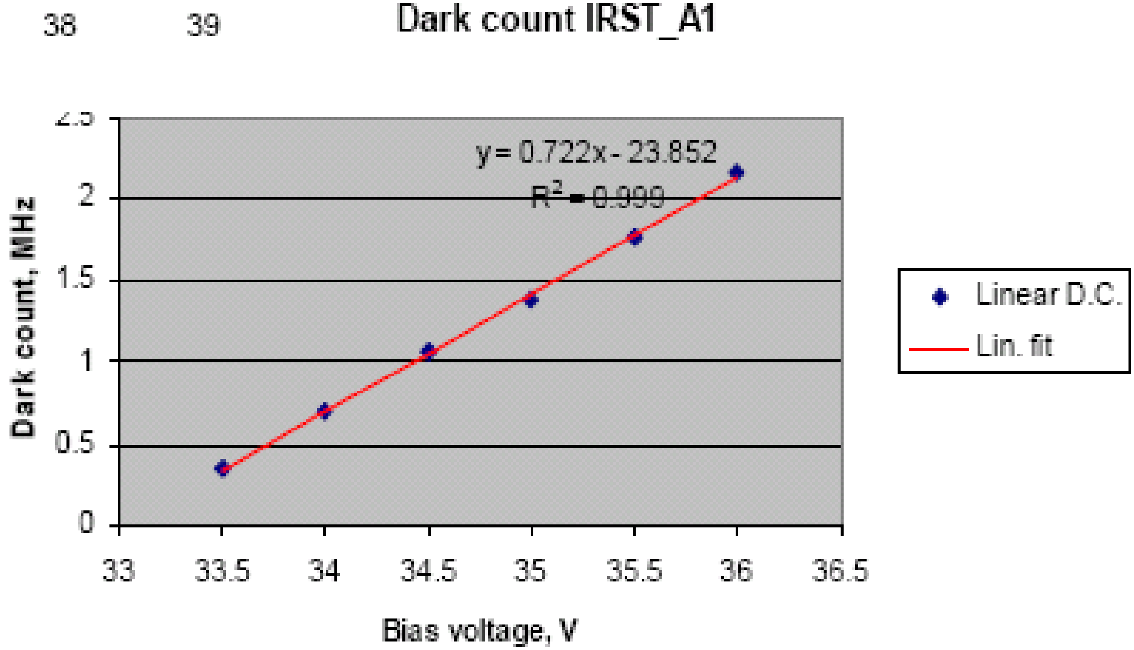
recovery time $\approx 400 ns$

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

dynamic measurements-4

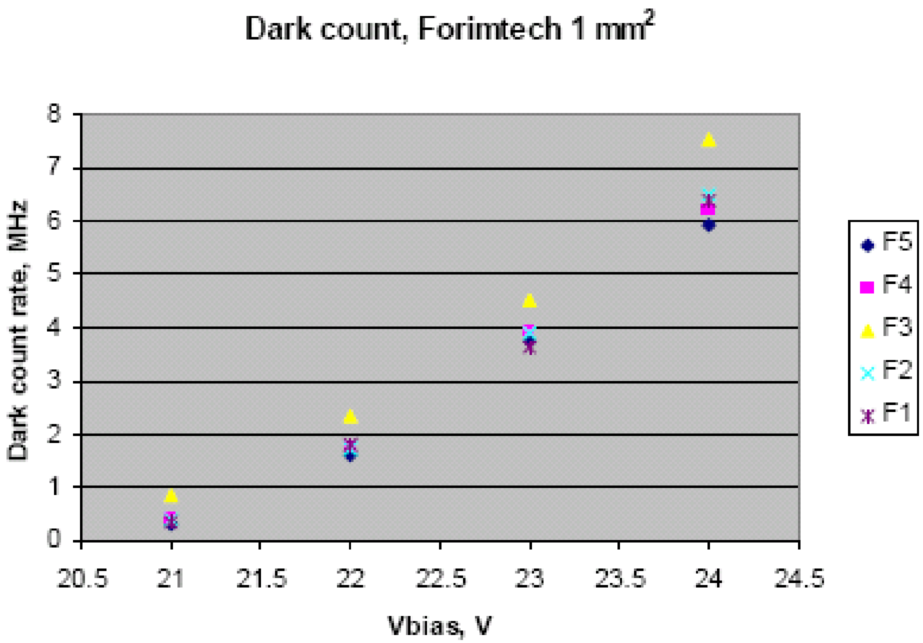


1 mm^2 type A
VBD ≈ 33 V
D.C.(ΔV=2V) ≈ 1.5 MHz



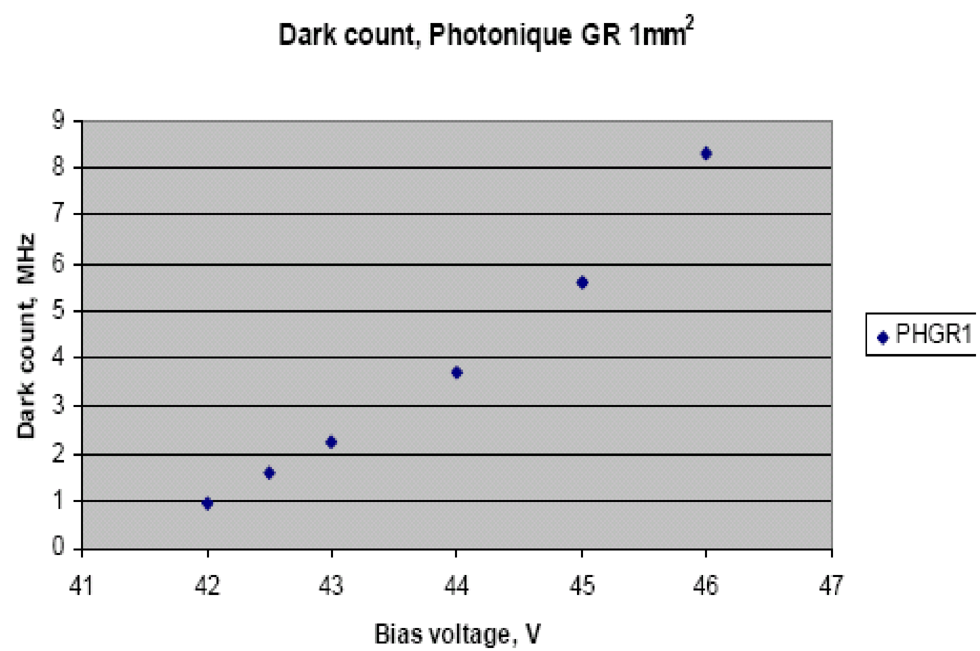
Linear fit intercept with V-axis gives VBD = 33.04 V

dynamic measurements-4

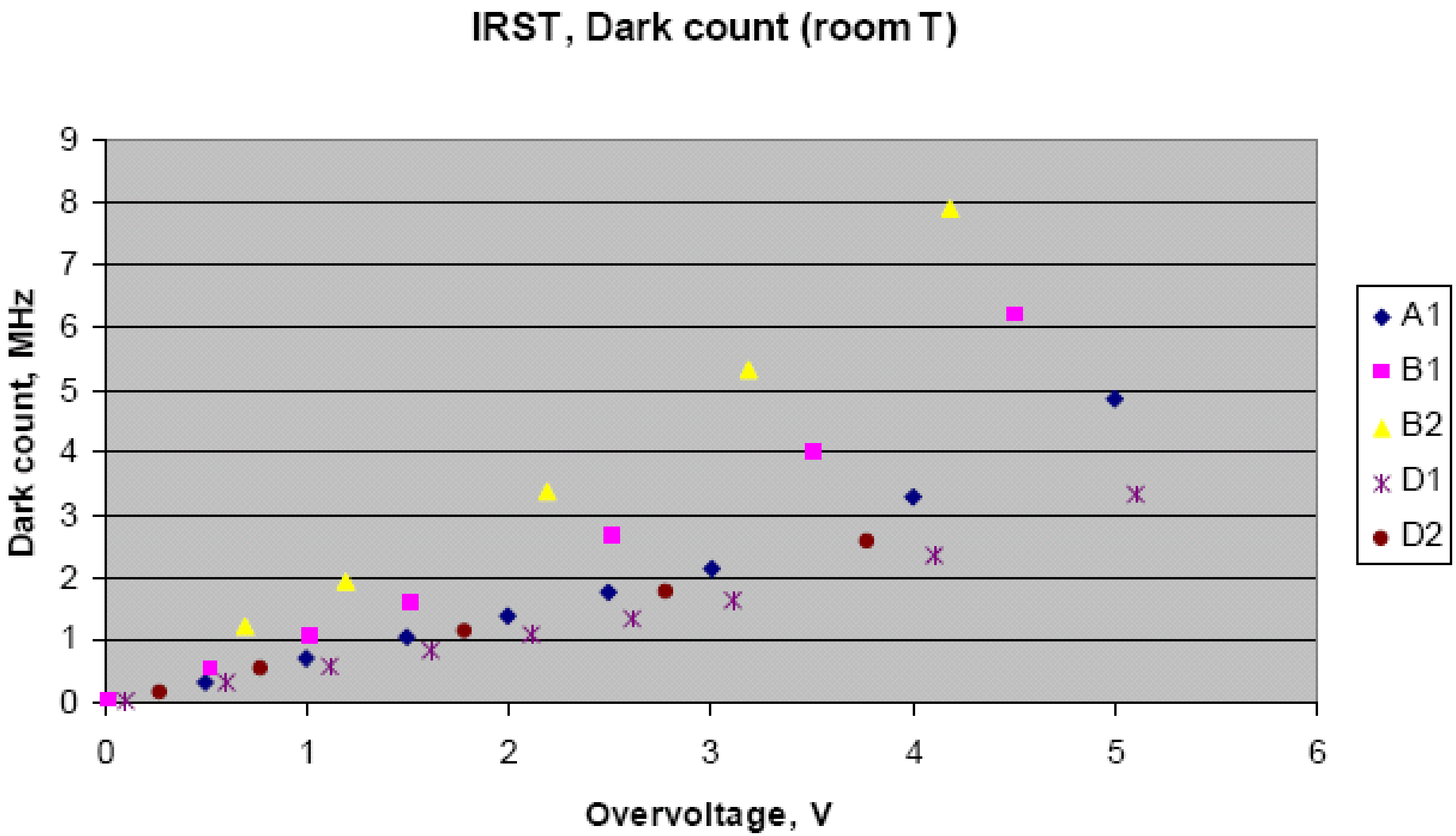


1 mm2 MRS devices
VBD ≈ 20 V
D.C.(ΔV=2V) ≈ 2 MHz

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

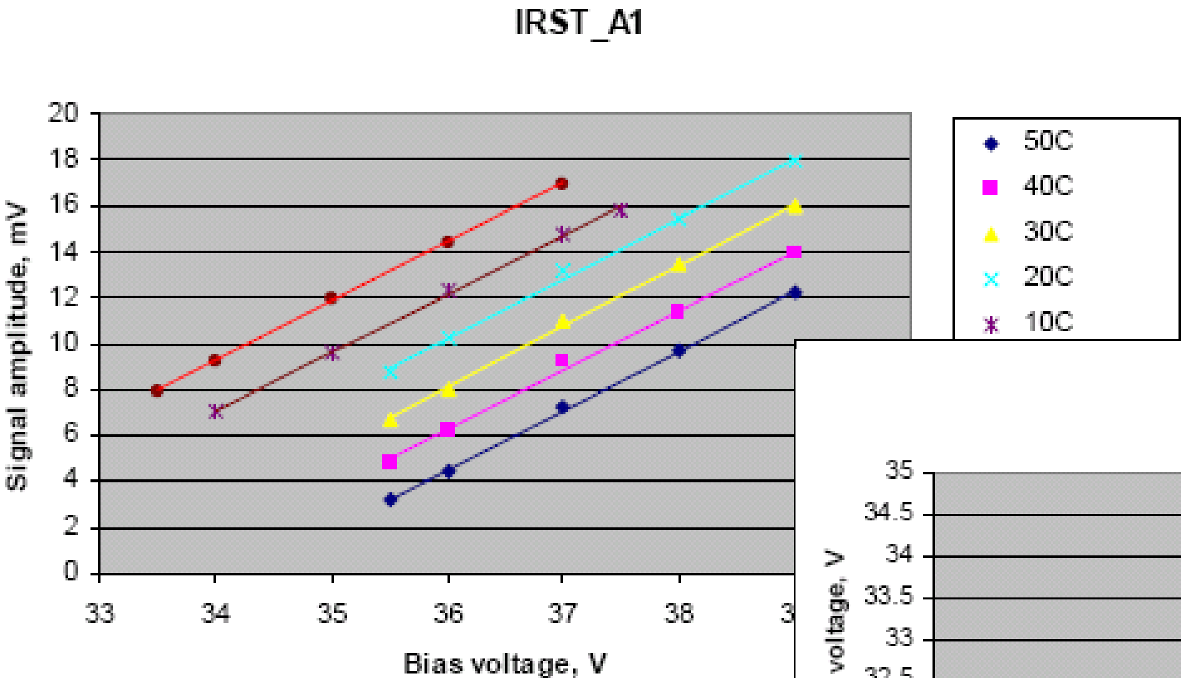


dynamic measurements-5

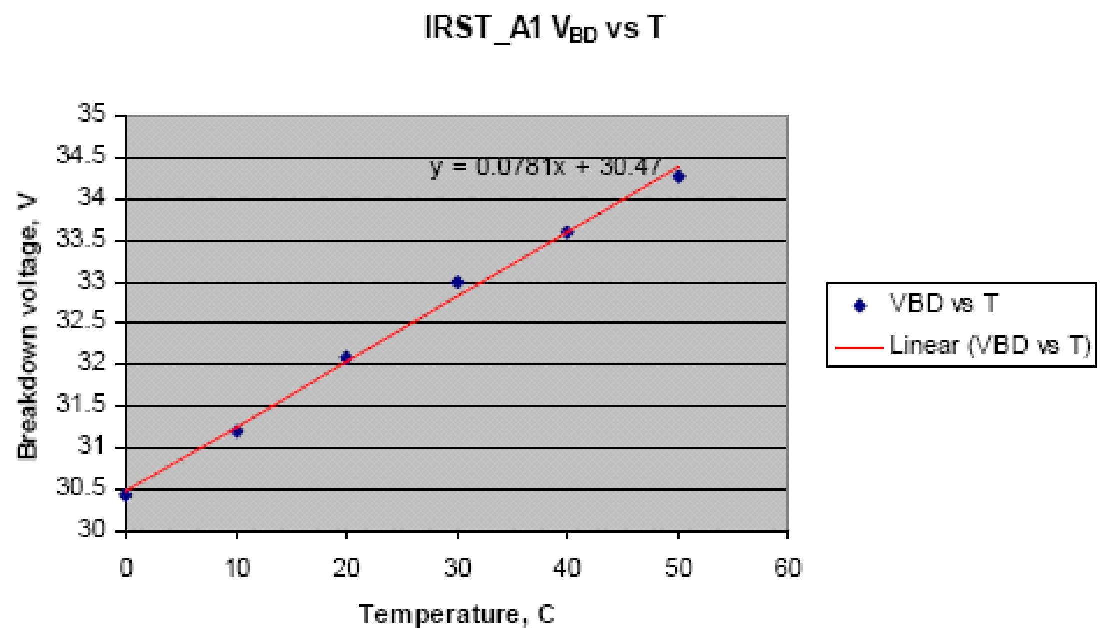


type "A", D.C.(ΔV=2V) ≈ 1.5 MHz
type "B", D.C.(ΔV=2V) ≈ 2- 3 MHz
type "D", D.C.(ΔV=2V) ≈ 1 MHz

dynamic measurements-6



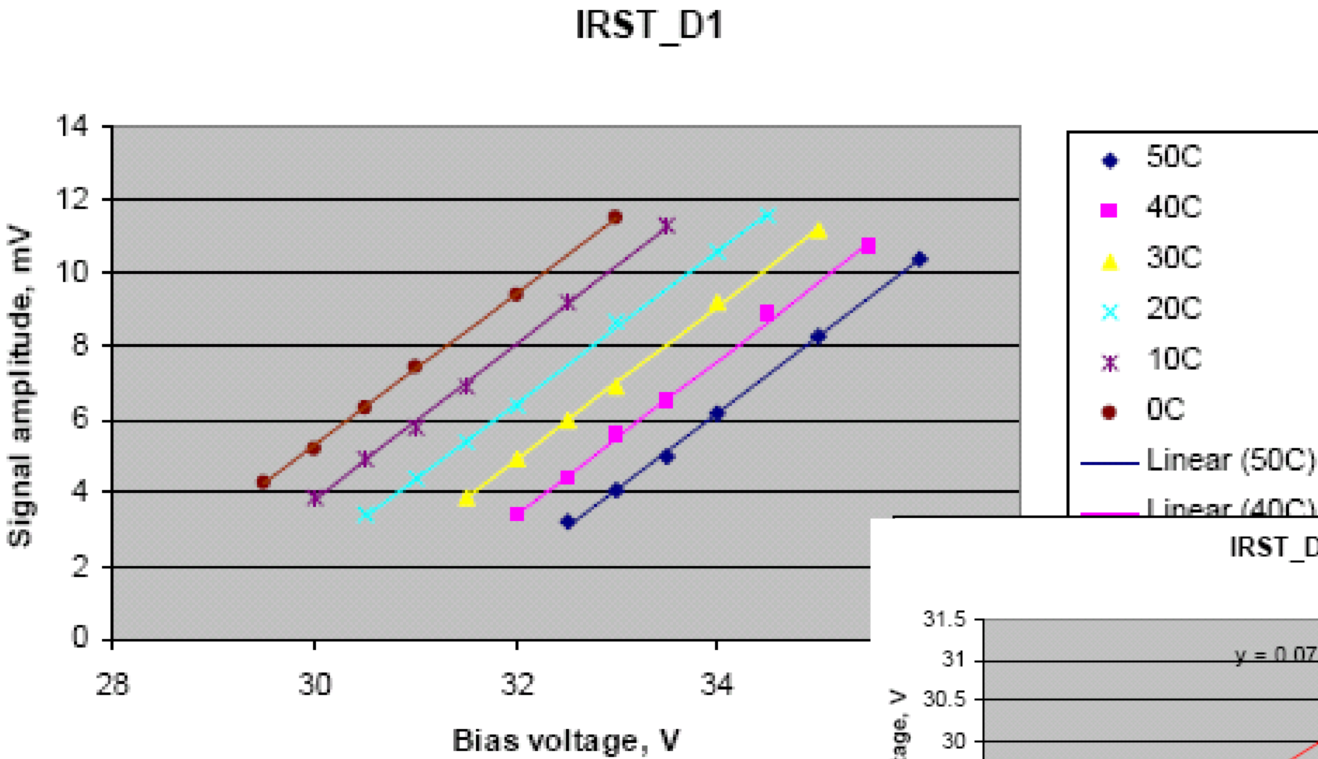
Temperature Dependences - 1



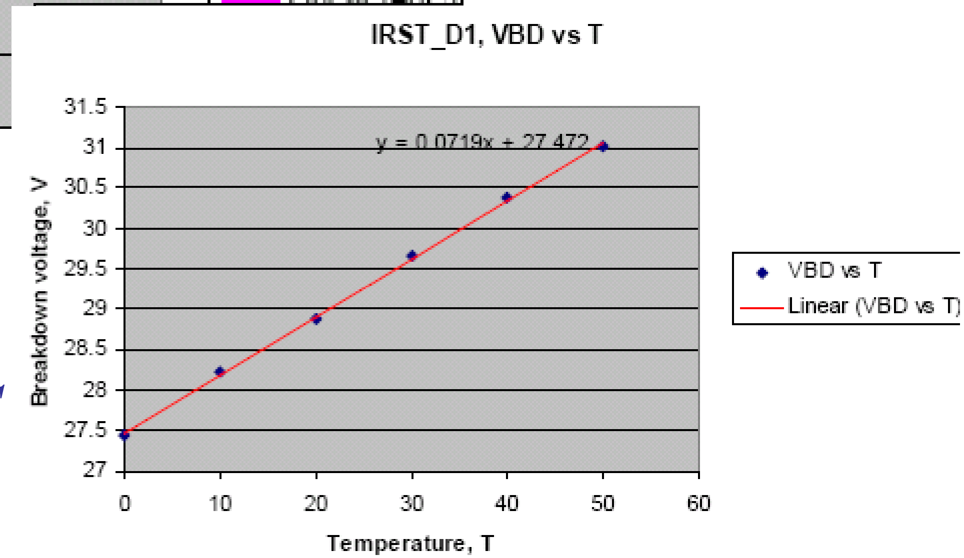
Measurements performed in a climatic chamber (with humidity control)
The amplifier was located outside the chamber, connection via a special 18 GHz ft
50 Ω cable

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

dynamic measurements-7



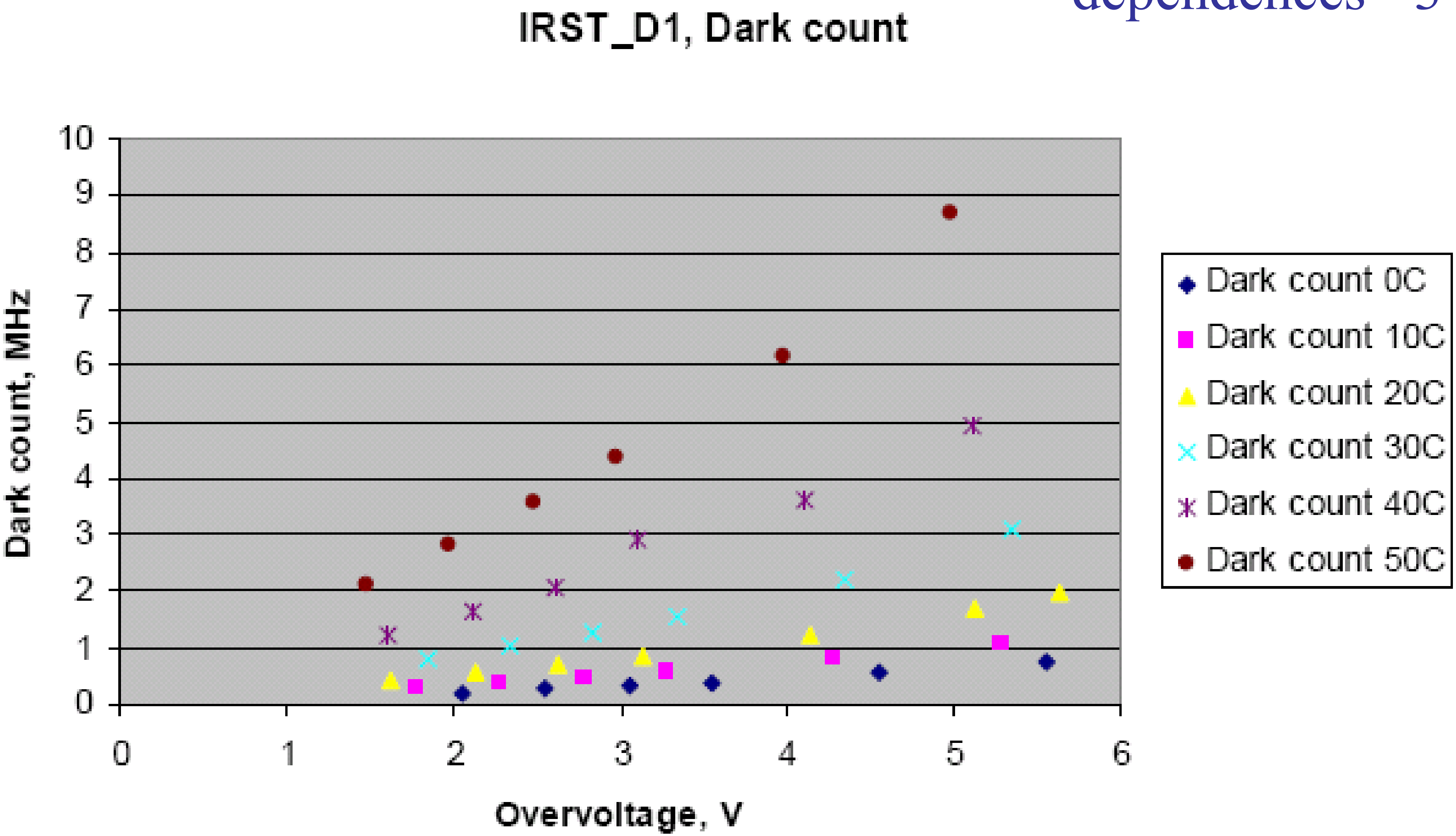
Temperature Dependences - 2



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

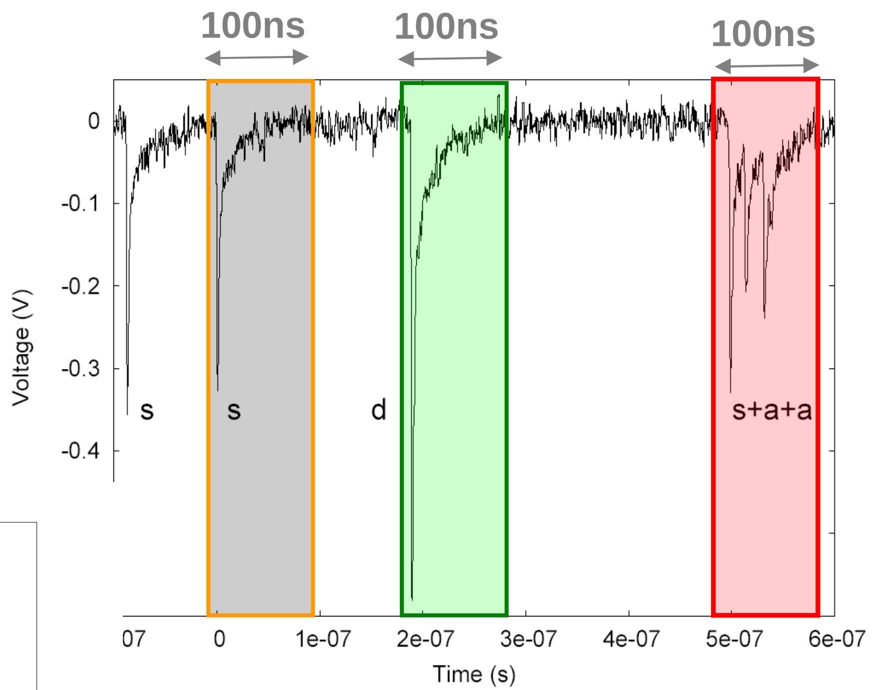
dynamic measurements-8

Temperature dependences - 3



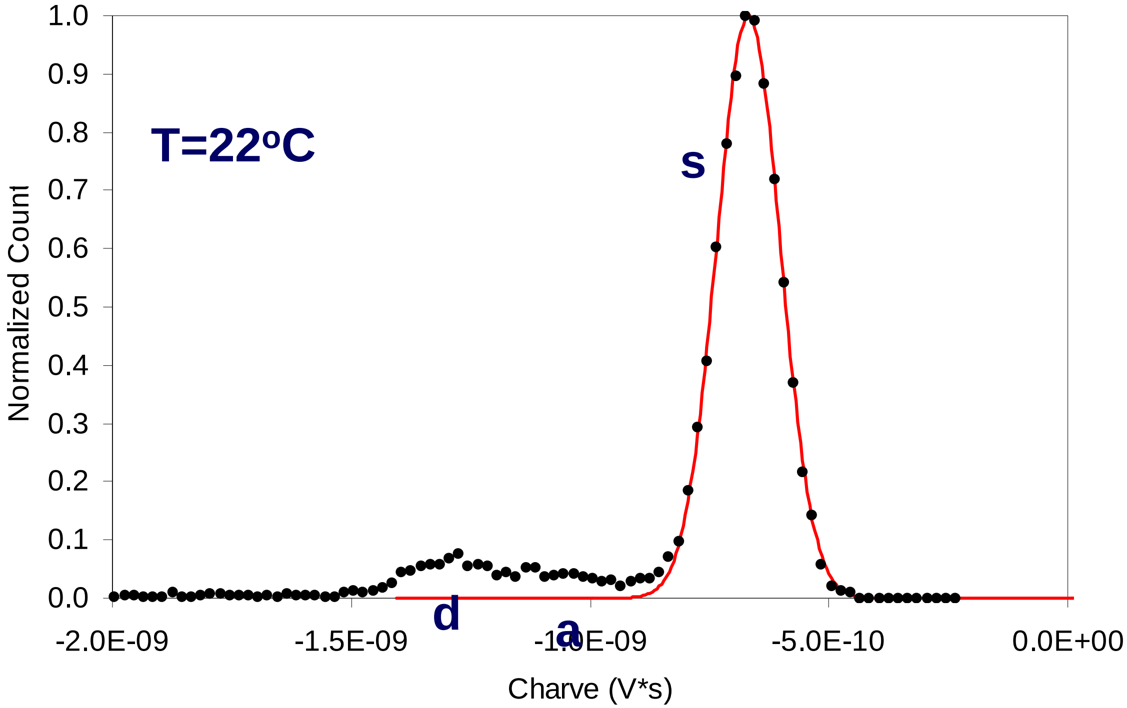
The following are static measurements performed at ITC-IRST and reported on at a recent (June 13th 2007) workshop at Perugia

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



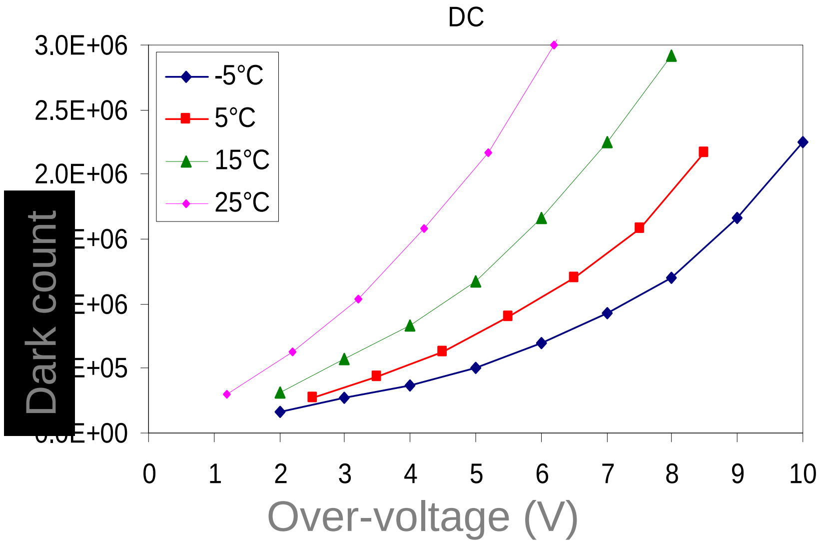
Well defined peak of the single pulses.

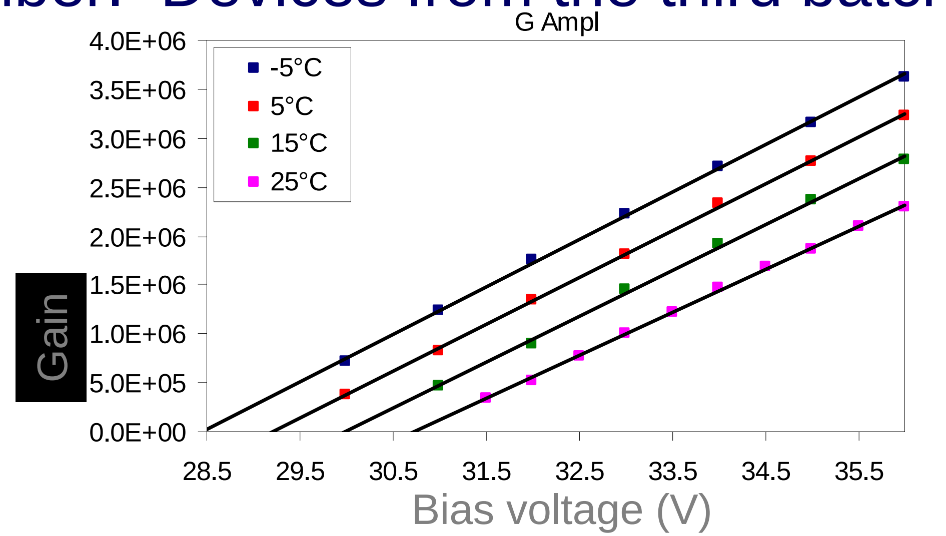
Gaussian distribution width determined by:
- noise of the system
- tiny gain non-uniformities

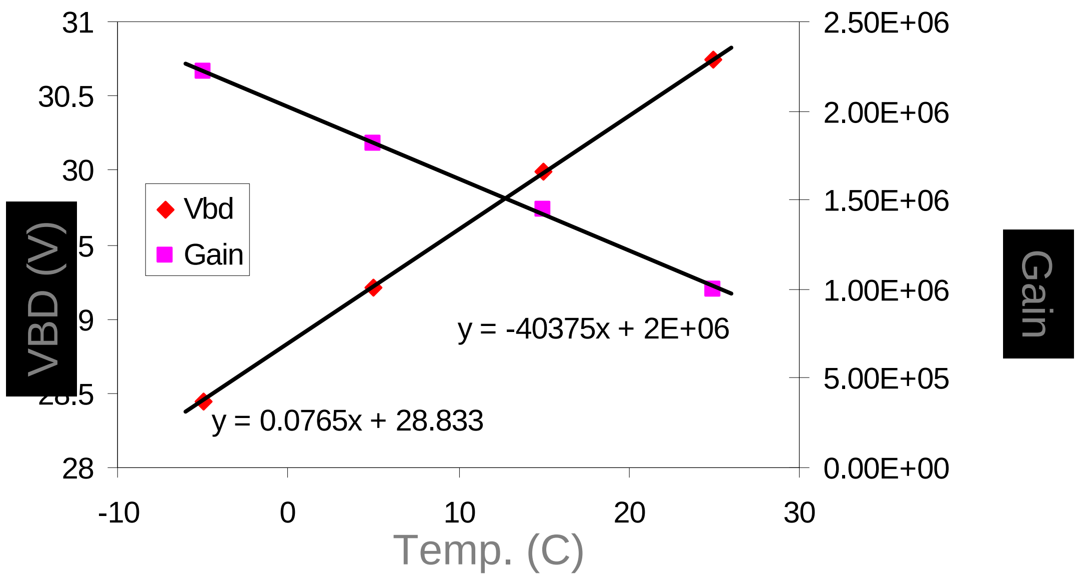
Tails due to:
optical cross-talk + afterpulse

Gain & Dark count

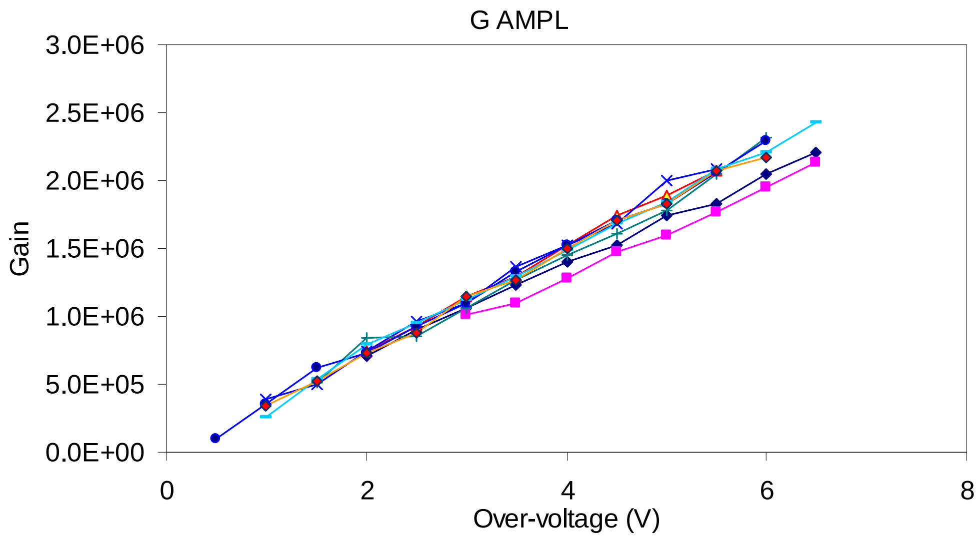
Performed in the climatic chamber. Devices from the third batch

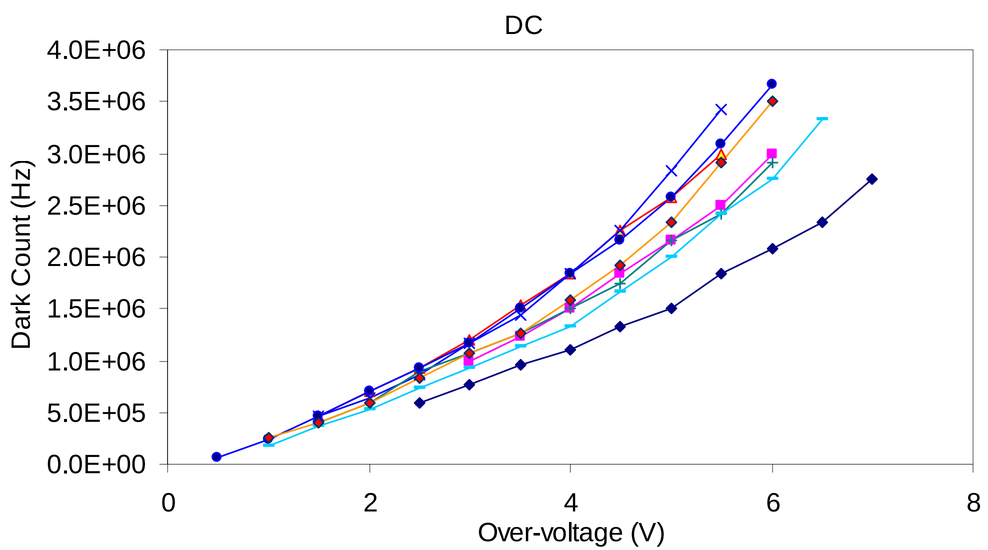






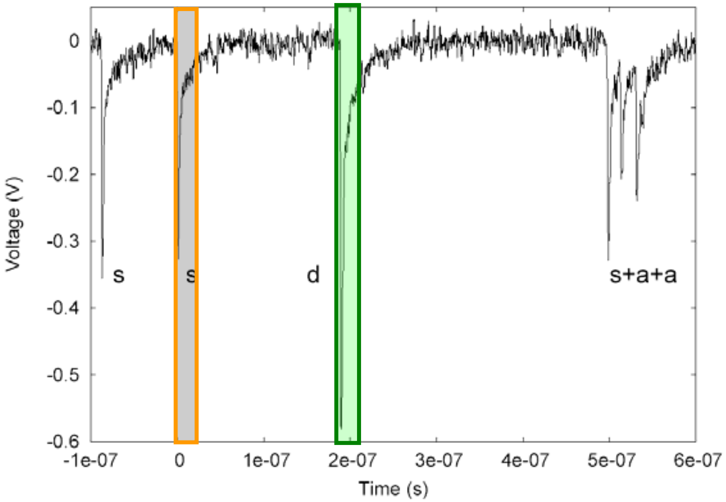
Gain & Dark count (uniformity)





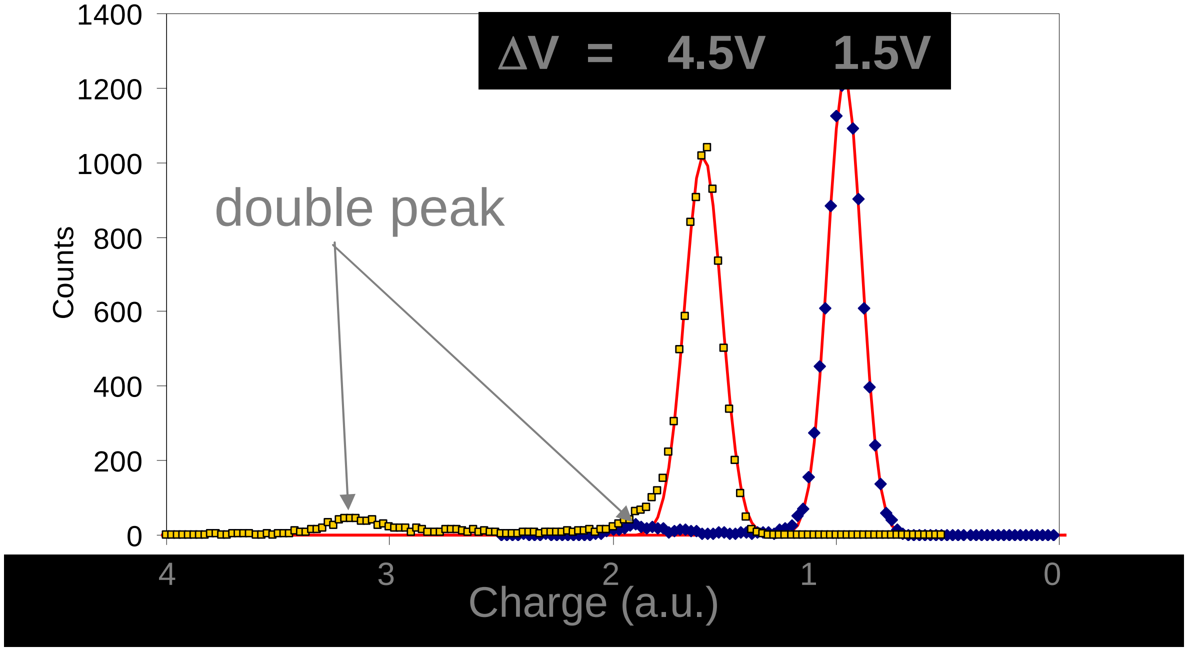
Gain and Dark count measured on devices from the same wafer

Optical cross-talk



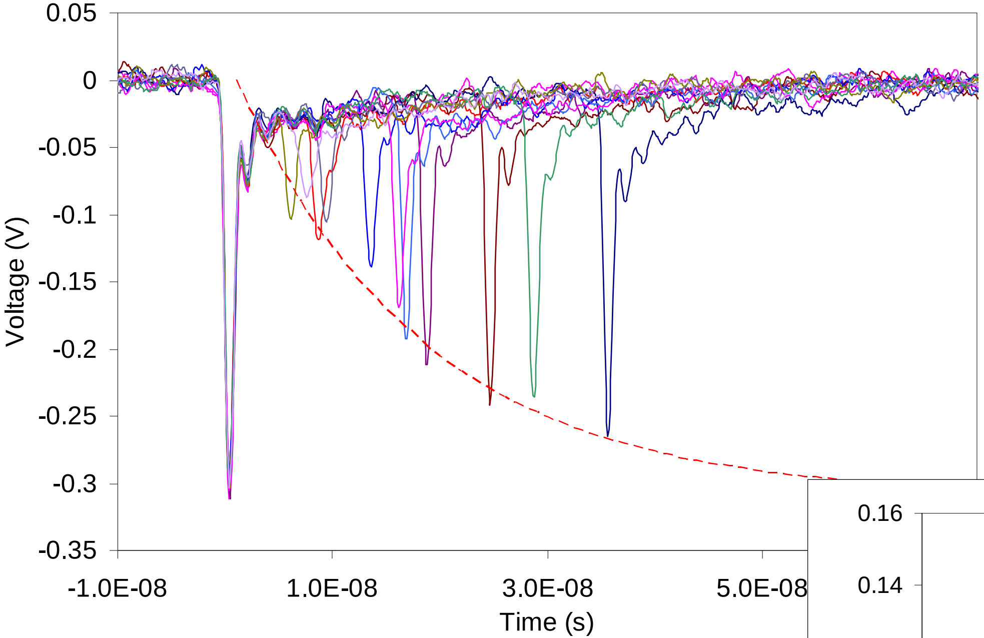
Short integration time
⇒ only single/double/….pulses are counted

Number of events with optical cross-talk increases with voltage



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

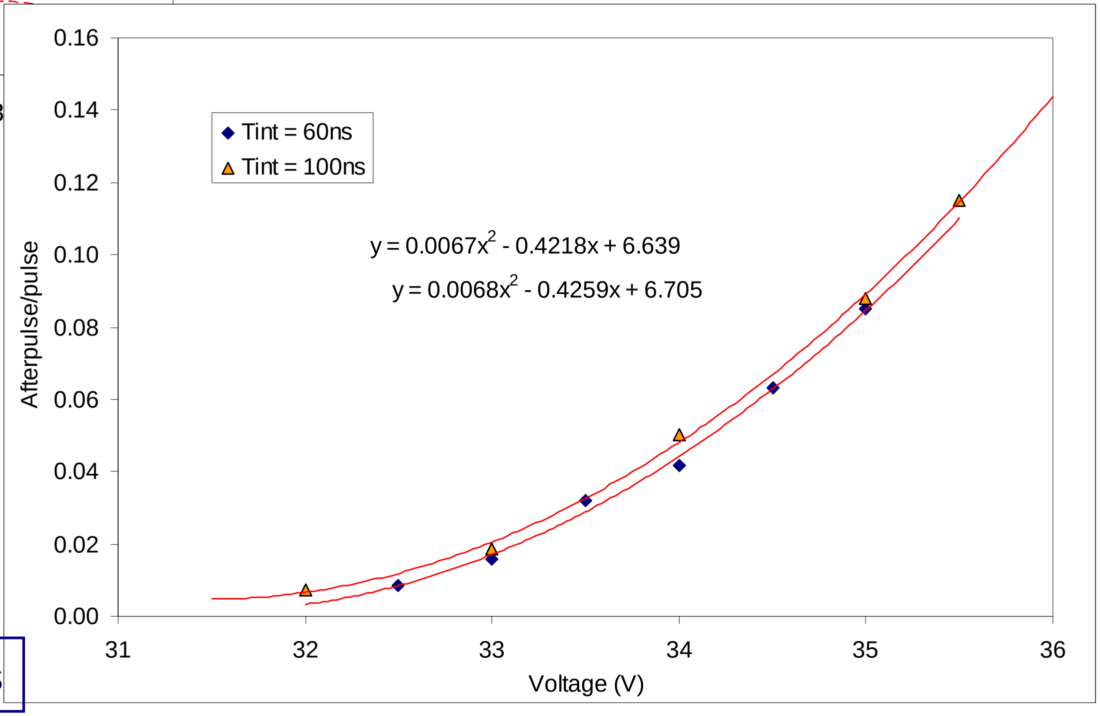
After-pulsing



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

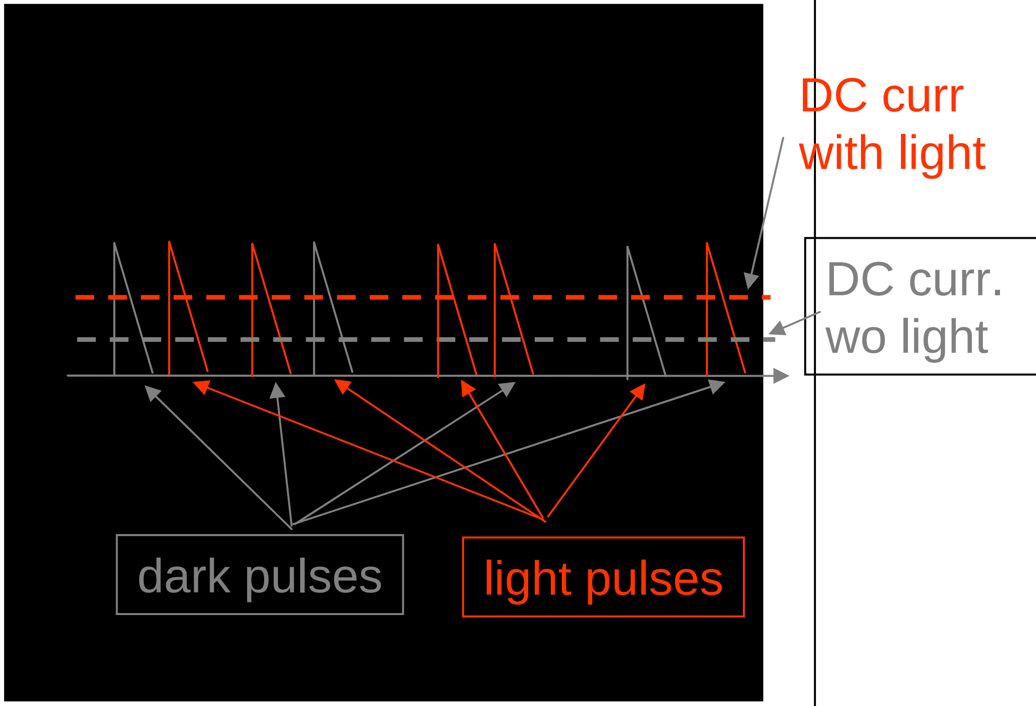
Photo-detection efficiency

Two methods: DC current and Pulses count

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

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

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

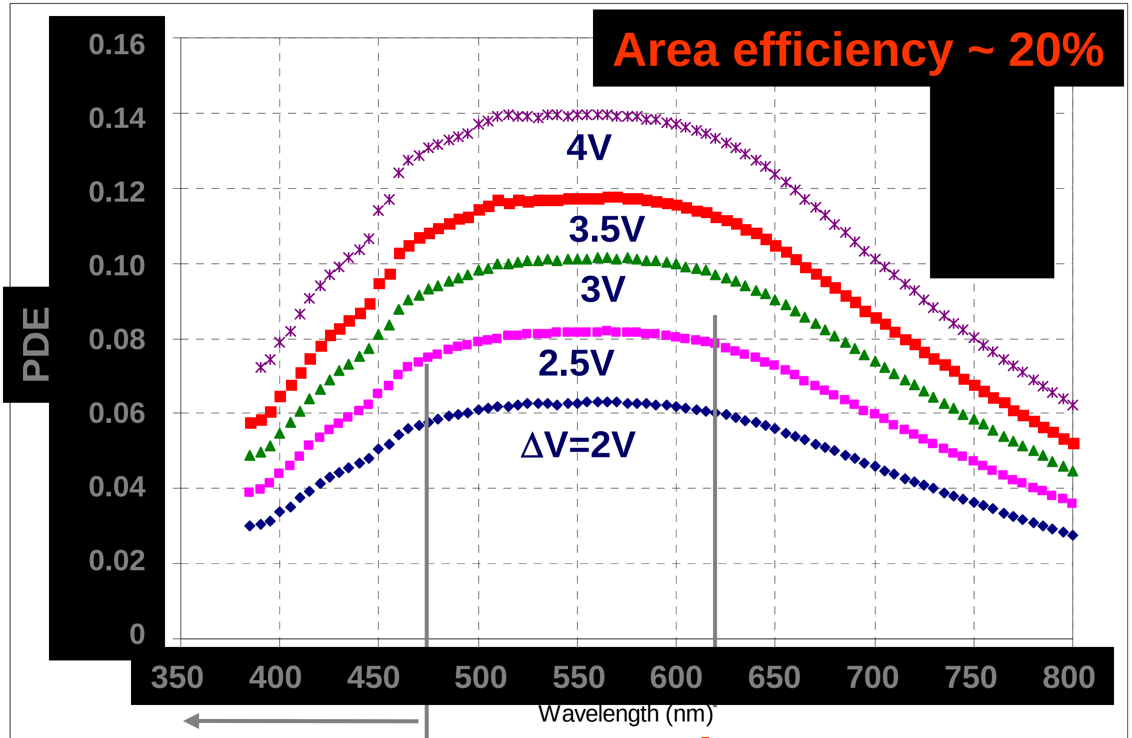


Reference by calibrated detector (photodiode)

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

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

Photodetection efficiency

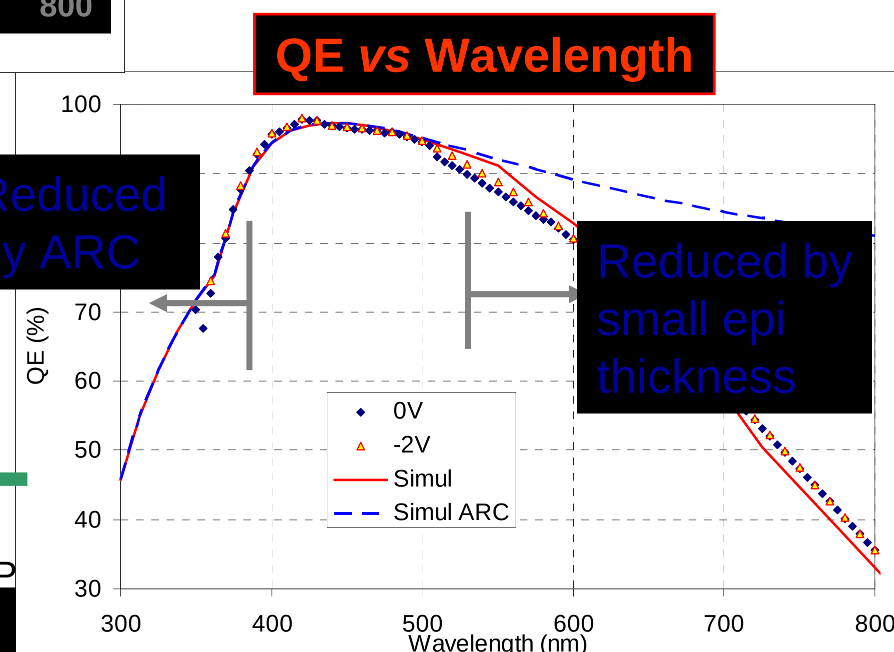


PDE=QE*Pt*Ae

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

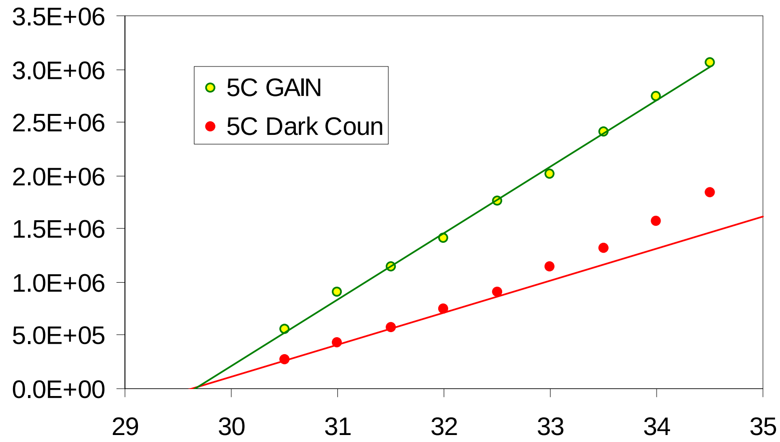


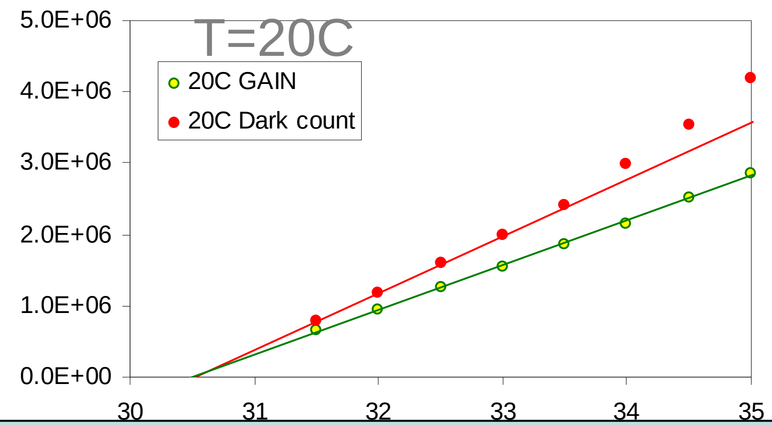
Measured on a diode

Noise and charge resolution

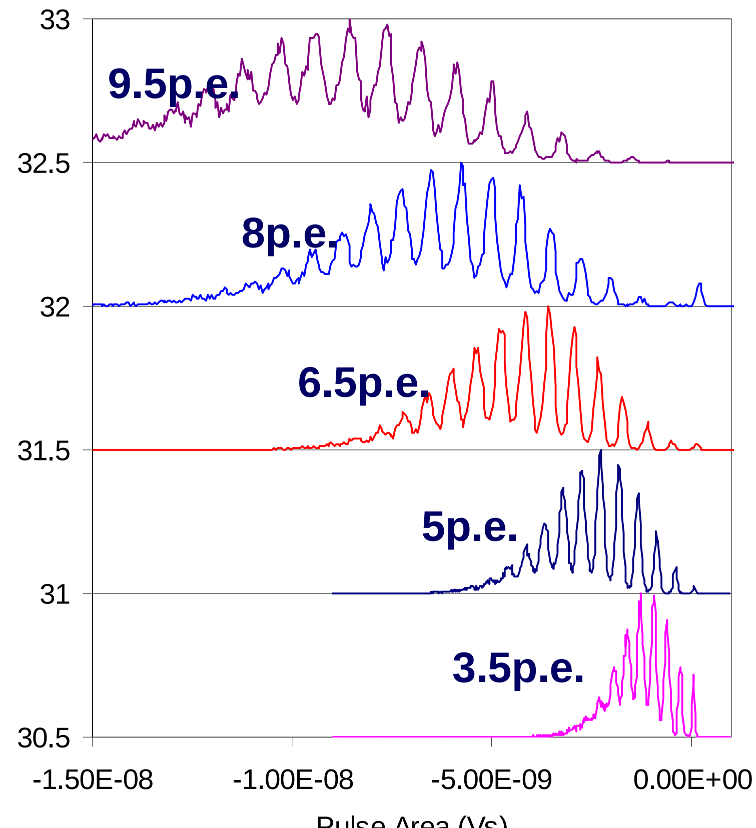
1x1mm² SiPM with 40x40μm² cells

T=5C





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



resolution limited by electronic noise

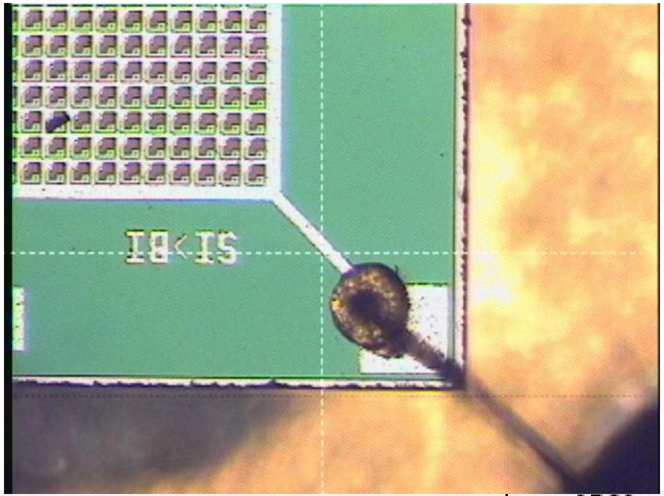
applications

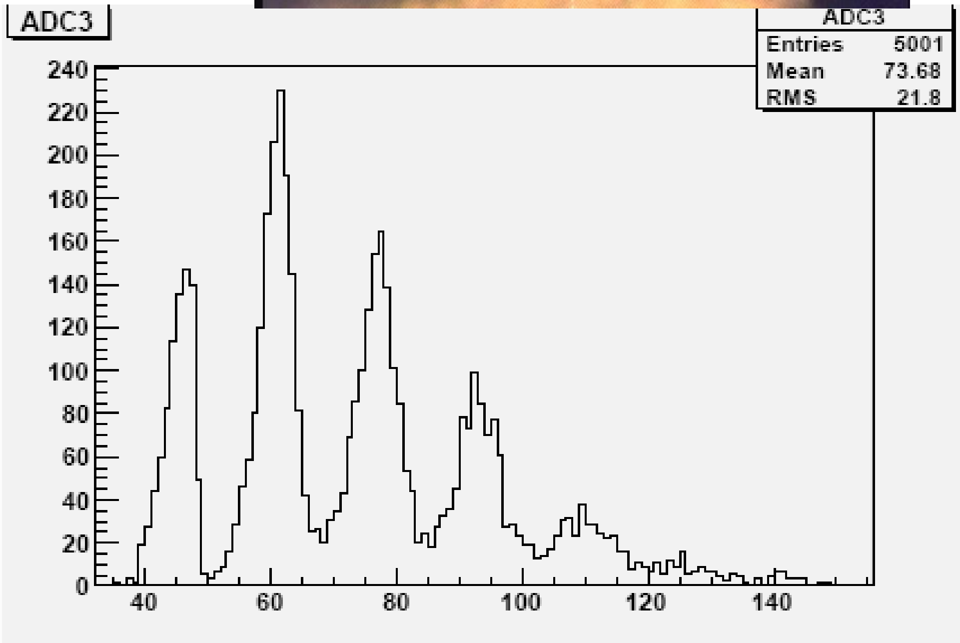
Characterization of SiPMs (1 mm²from second batch) used for preliminary at Fnal test beam

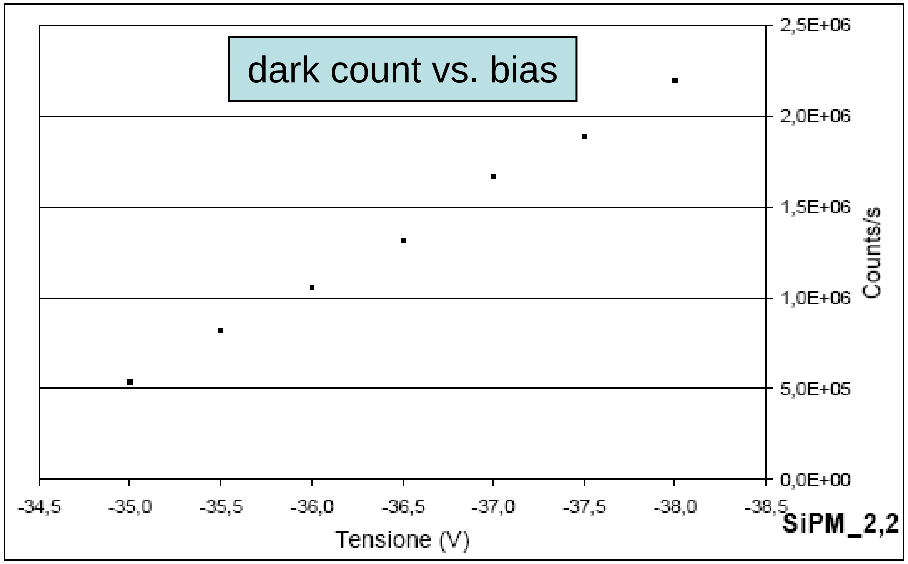
Visual inspectons (SiDet) and dynamic tests at lab 6 prior to use of SiPMs in Test Beam yielded results compatible with IRST measurements:

$V_B = 34.1$ V

Gains between ~1 and 2×10^6



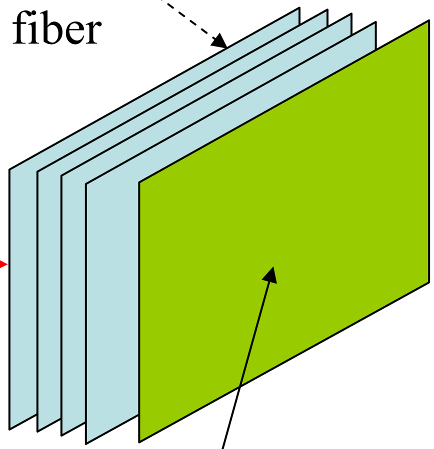




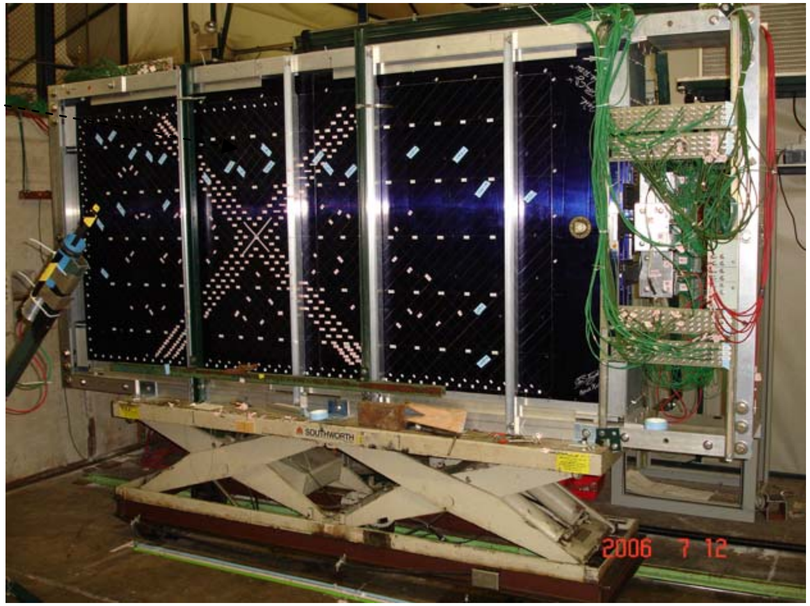
Future work at fnal

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

Beam (p,π,e)

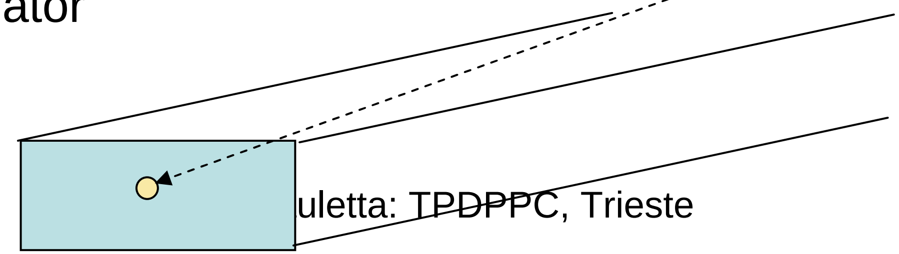


Add one plane
of scint strips read
out by Wls fiber and
SiPMs



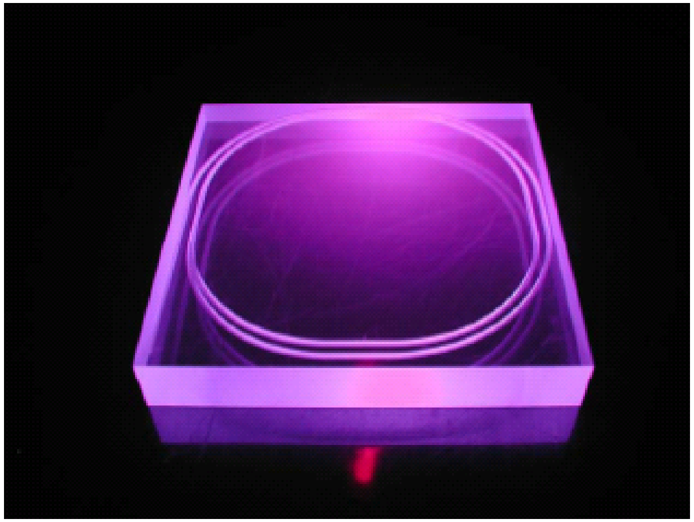
Whole assembly mounted on
movable (x,y) support

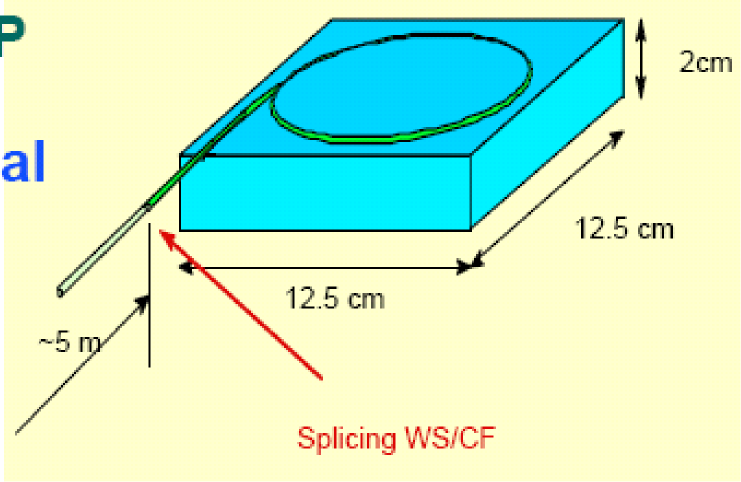
Scintillator strips : 4cm x 1cm x (1 – 2 m), read out by wls fiber. Groove for fiber
extruded with scintillator



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)**





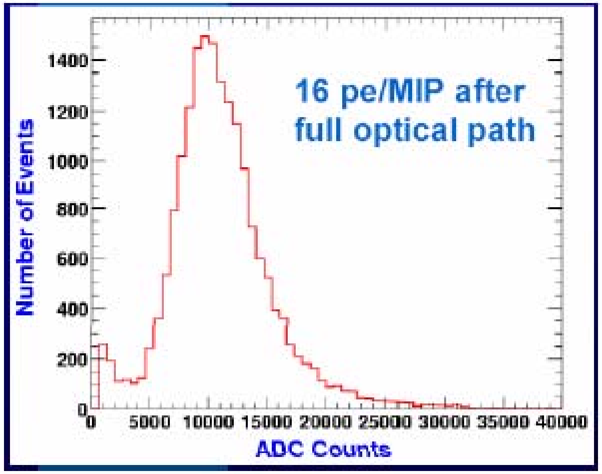
Performance (MIP)

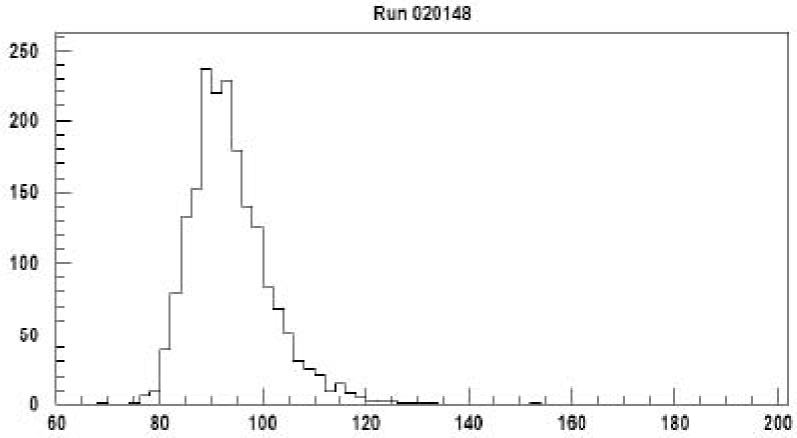
with

PMT

and

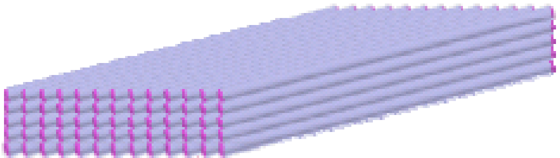
SiPM

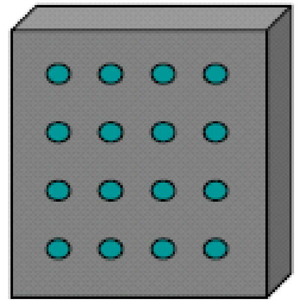


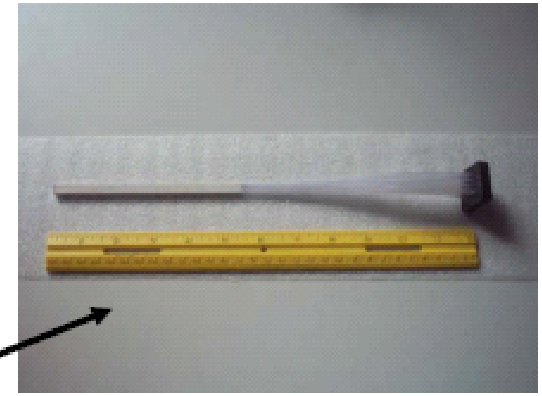


Fiber application study: Fiber Arrays

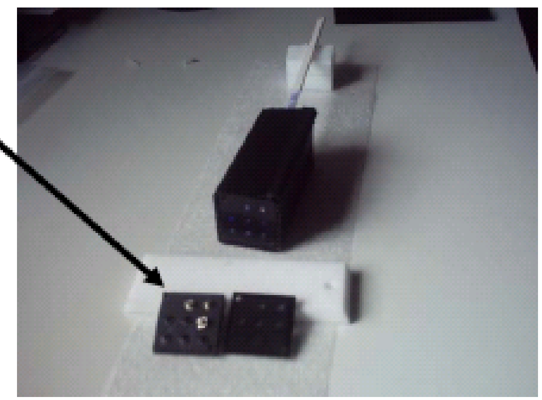
[5 layers of 0.5 mm diameter Fibers]



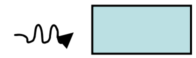




- **Fiber Array** mapped via a **Template** on a16 channel multi-anode photomultiplier H6568
- A second **Fiber Array** equipped with **SiPM** (8 channels, each corresponding to 2 of the adjacent channels of MAPMT)



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



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:

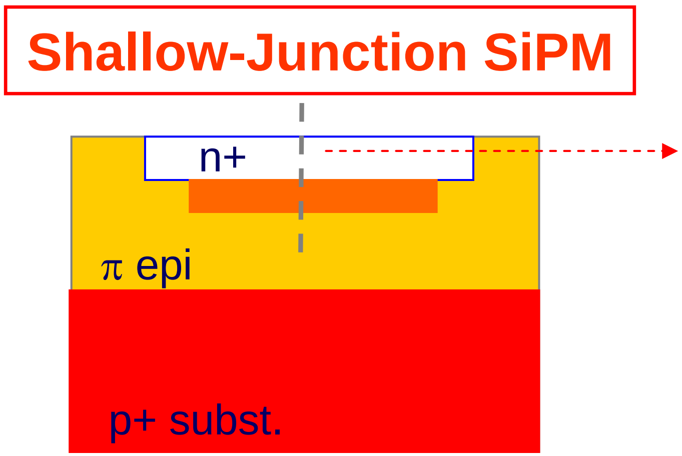
2005: INFN funds project (DASiPM) for the development of SiPM devices, mainly for PET application

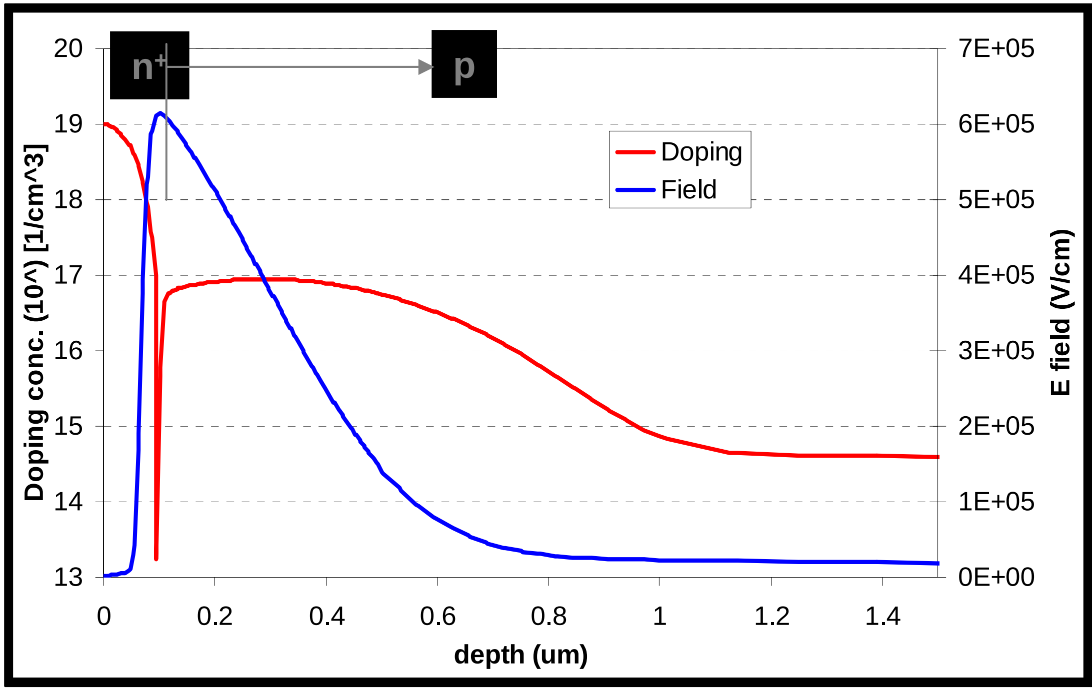
2007: INFN funds continuation of DASIPM and expands development to other applications (FACTOR)

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.

Present IRST technology*

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





Distinguishing characteristics:

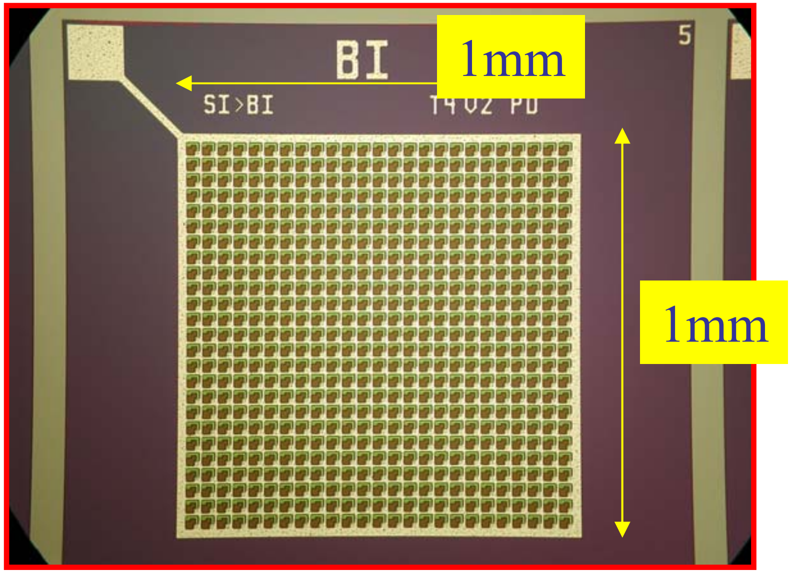
1) **Very shallow junction**
2) ***ARC optimized for short wavelenghts (~400nm)***
3) **polysilicon quenching resistors**

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

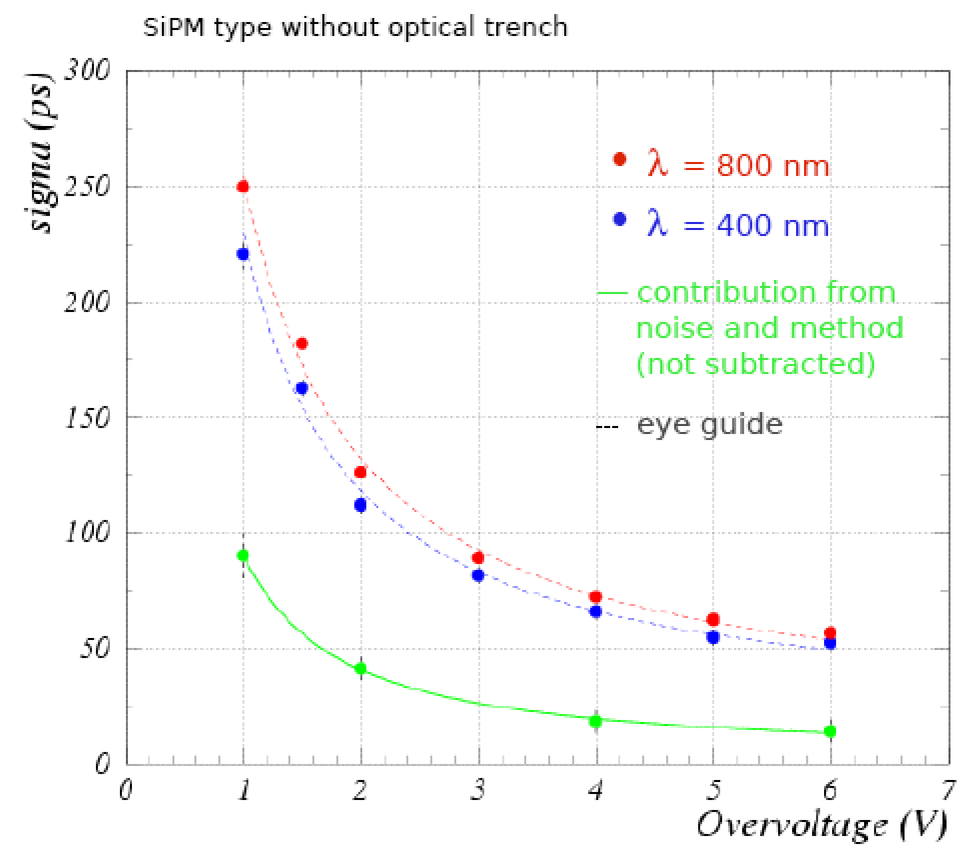
Other considerations

- Packaging
- Readout electronics

backup slides

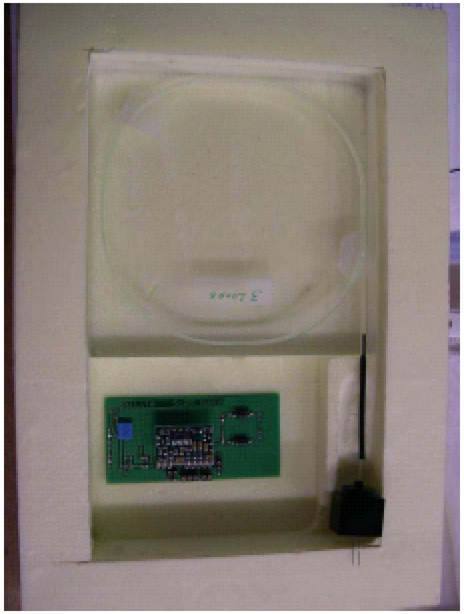
Time resolution

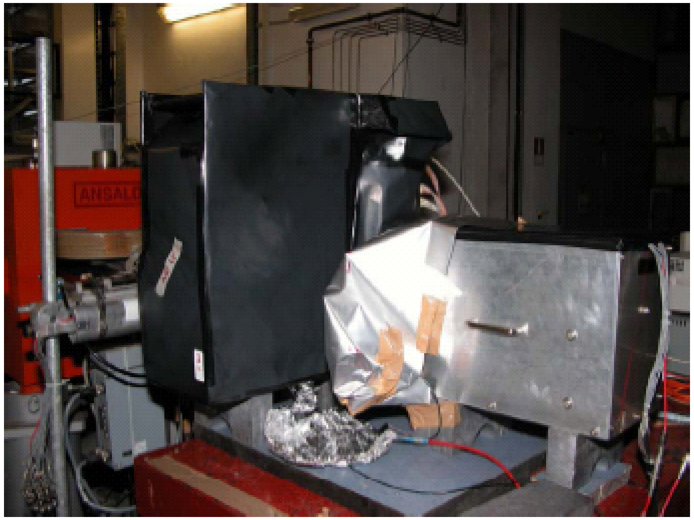
Results on IRST devices: gaussian σ_t



Gianmaria Collazuol VCI 2007 Vienna 19-24 Feb 2007

Tile test setup at Frascati





Erik Vallazza, Michela Prest

Development History

Development started at the beginning of 2005.

September 2005

First batch

- Establish functionality and base-line parameters

May 2006

Second batch

- Verify reproducibility of the first batch
- First attempt to reduce optical cross-talk

October 2006

Third batch

- First attempt to reduce dark count rate

May 2007

Fourth batch

- optimize fill factor
- new geometries for different applications
- continue the study on dark count reduction