Advances in Avalanche Photodiodes

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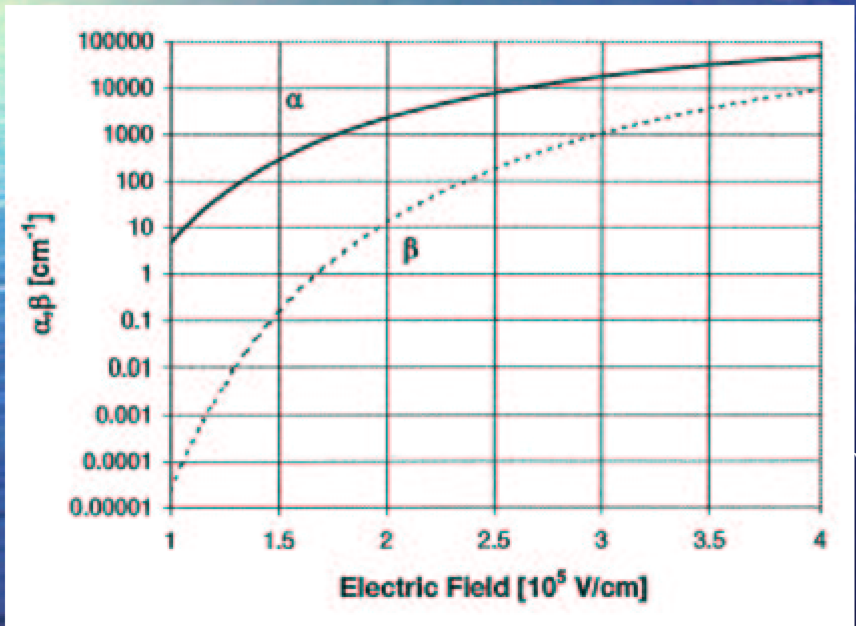
Outline

- *Avalanche multiplication*
- *APD's for supercollider - requirements*
- *Different APD structures*
- *APDs for the CMS ECAL*
- *Radiation hardness and reliability*
- *APDs at low temperatures*
- *New APD developments*
- *Conclusion*

Avalanche multiplication

Avalanche photodiodes are photodiodes with built-in high electric field region. With increasing reverse bias voltage, electrons (or holes) are accelerated and can create additional electron-hole pairs through impact ionization.

Silicon is a good material for APD construction: high sensitivity in visible and UV range, significant difference between ionization coefficients for electrons and holes – smaller positive feedback and smaller multiplication noise



Excess Noise Factor:
$F=k*M+(1-k)(2-1/M)$
$k=\beta/\alpha$ ***(k-factor)***
β***- ionization coefficient for holes***
α***- ionization coefficient for electrons***
(see R.J. McIntyre, IEEE Tr. ED-13 (1972) 164)

Ionization coefficients as a function of electric field in silicon

APD's for supercolliders

- APDs are used in telecommunications > 30 years
- To be used in HEP they should satisfy certain requirements
- Requirements depend on the application

Applications:

- *Calorimetry*
- *SciFi trackers*
- *Cherenkov light detection*
- *TOF*
- *…*

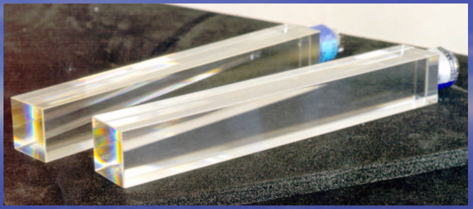
Here I will discuss mainly the applications of the APDs for HEP calorimetry

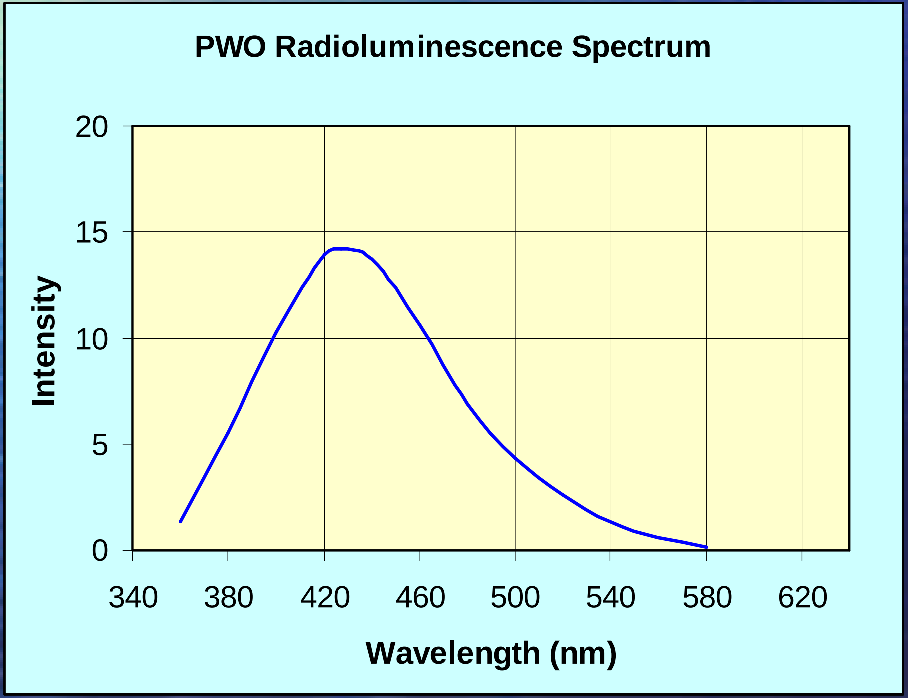
CMS ECAL is a good example

Lead Tungstate Properties

Advantages:
- Fast
- Dense
- Radiation hard
- Emission in visible

Disadvantages:
- Temperature dependence
- Low light yield





Density [g/cm^3]	8.28
Rad length, X_0 [mm]	8.9
Interaction length [mm]	224
Molière radius [mm]	21.9
Decay time [ns]	5(39%) 15(60%) 100 (1%)
Refractive index	2.30
Max emission [nm]	425
Light yield [photon/MeV]	~50
Temp coeff [%/ºC]	-2

Photo Detector Requirements

In the CMS ECAL :

- high radiation levels
- 4T magnetic field
- limited space
- $PbWO_4$ (low light yield, 420-450 nm emission peak)

Photodetector must be :

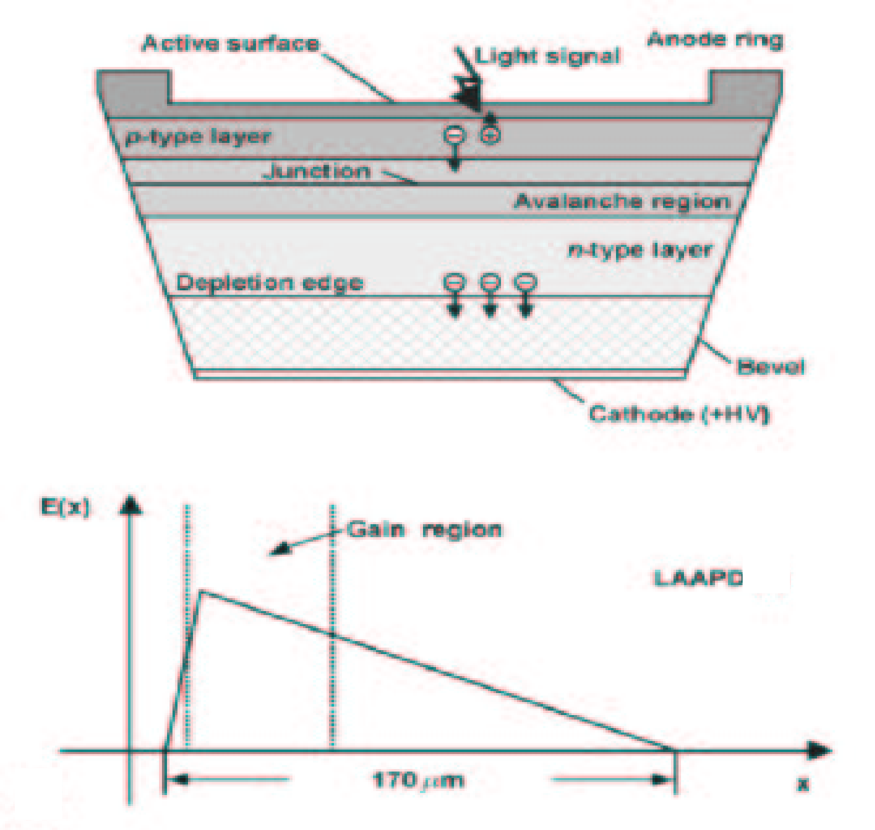
- radiation hard
- operational in high magnetic field
- small nuclear counter effect and reasonable gain
- small excess noise factor
- match the properties of $PbWO_4$ light (high QE, high speed)
- low sensitivity of the gain on temperature and voltage
- high reliability (10 years of LHC) and low price !!!

PIN photodiode has no gain and has high "nuclear counter effect"

→ Avalanche Photo Diode

APDs from several producers had been considered

"Beveled edge" APD (API)

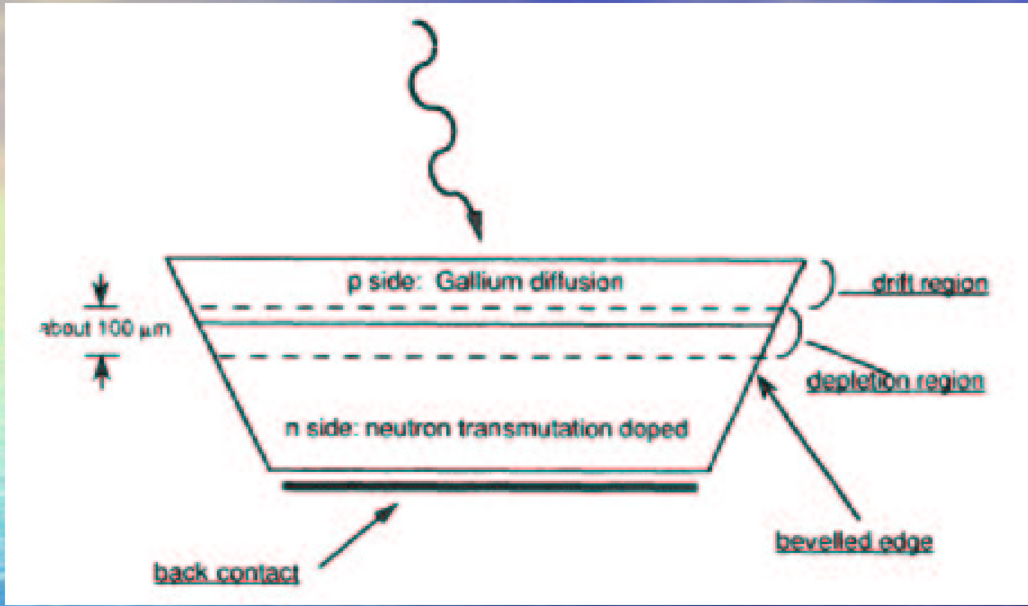


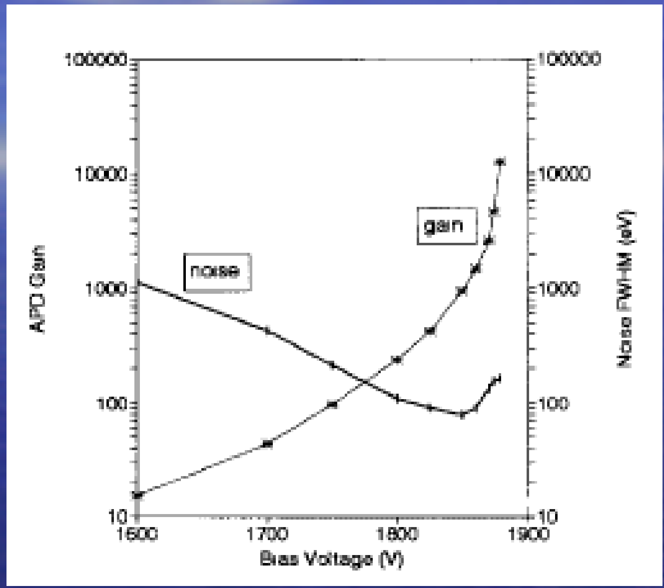
It is made by growing the p-type epitaxial layer on n-type neutron transmutation doped silicon. The broad gain region enables device operation at high gain with low excess noise and excellent gain uniformity.

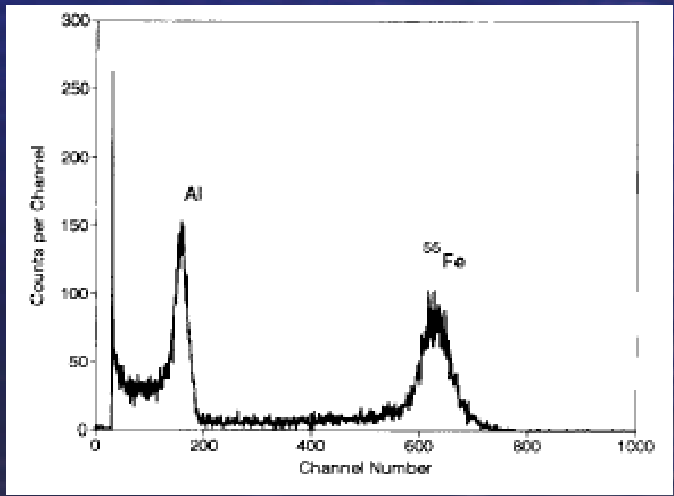
The APD edge (perpendicular to the junction) is beveled in order to reduce the field along the device edge, enabling the device to sustain the high biases necessary for APD operation.

Schematic cross-section and electric field profile, according to Advanced Photonix Inc.
(from M.Moszynski et al., NIM A485 (2002) 504)

Deep-diffused "beveled edge" APD (RMD)



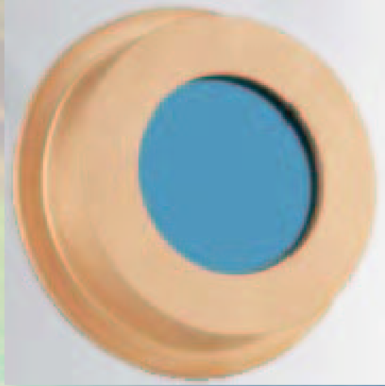




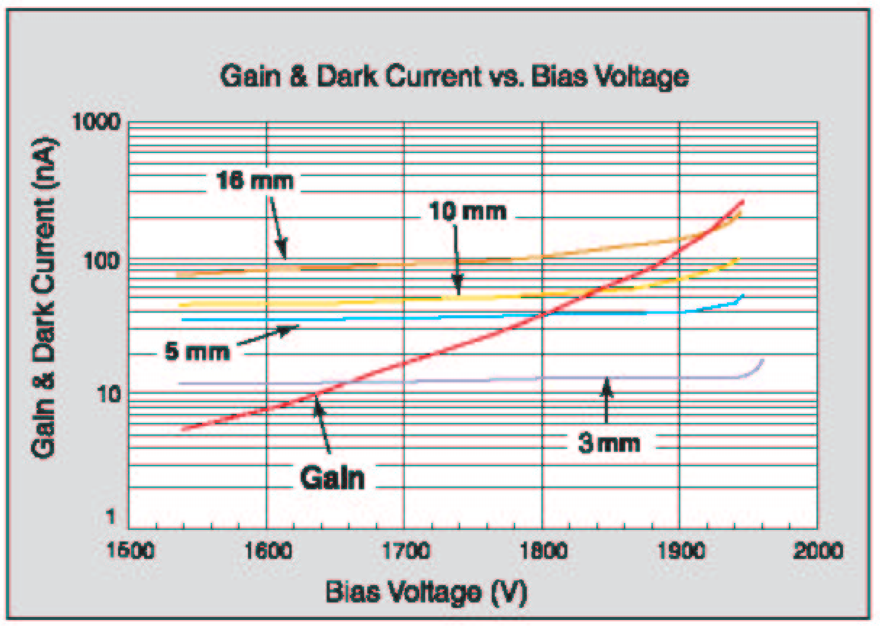
Gain ~10^4 possible
Low energy gamma detection (~200eV threshold)

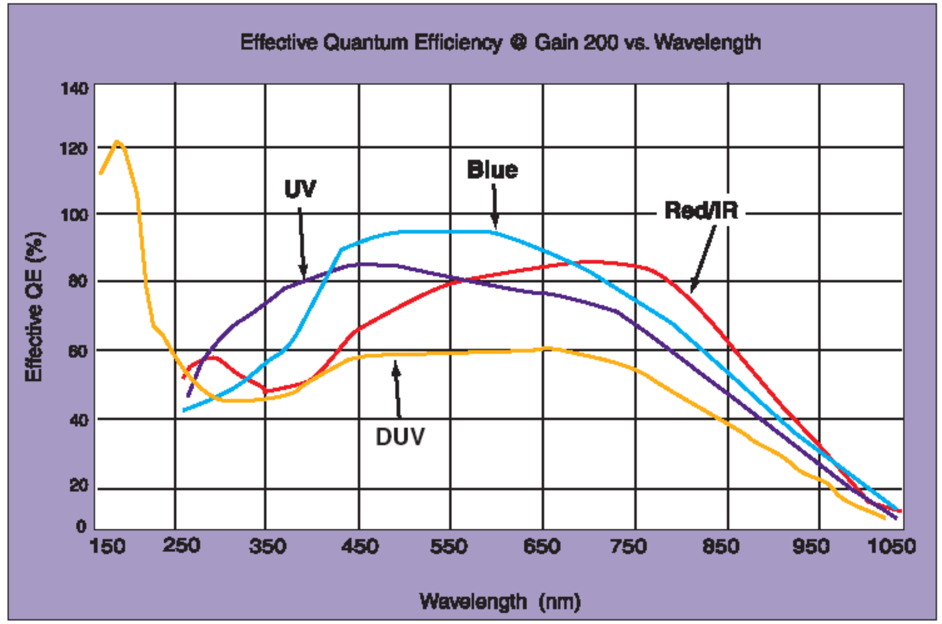
R. Farrell et al., NIM A353 (1994) 176

API APDs (Gain and QE)



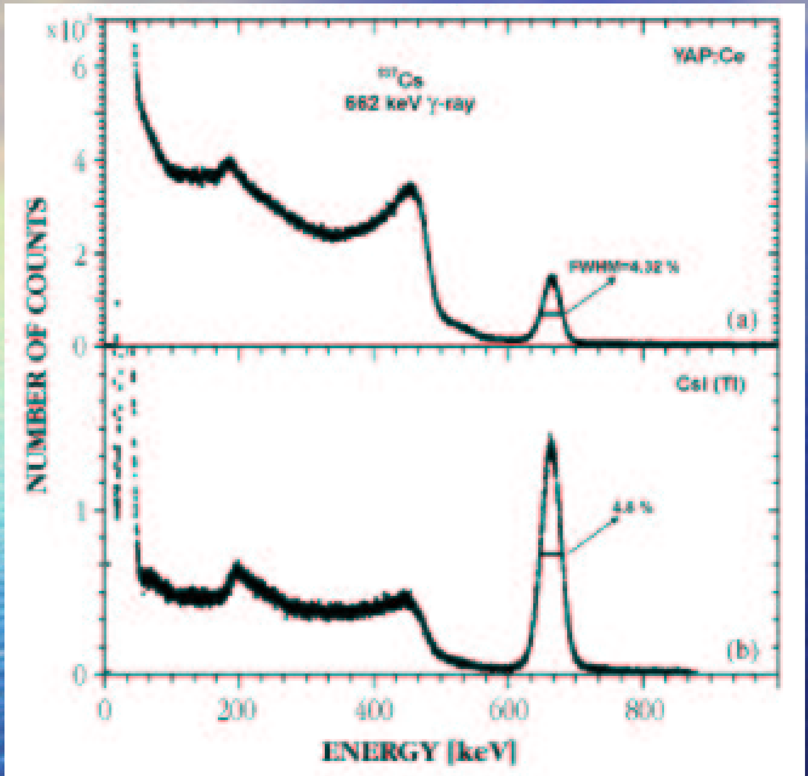
- High gain >100
- Large area – up to 16 mm in diameter
- High QE
- Low excess noise factor



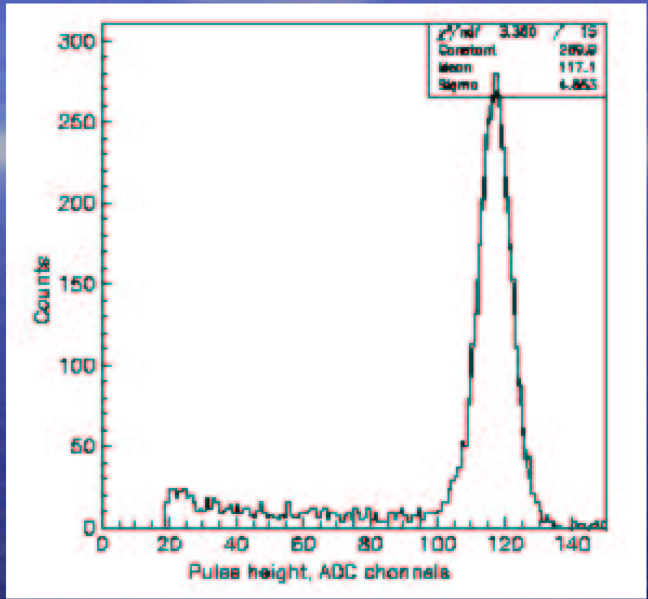


(measured by Advanced Photonix, Inc.)

API APD – Scintillation Light Detection



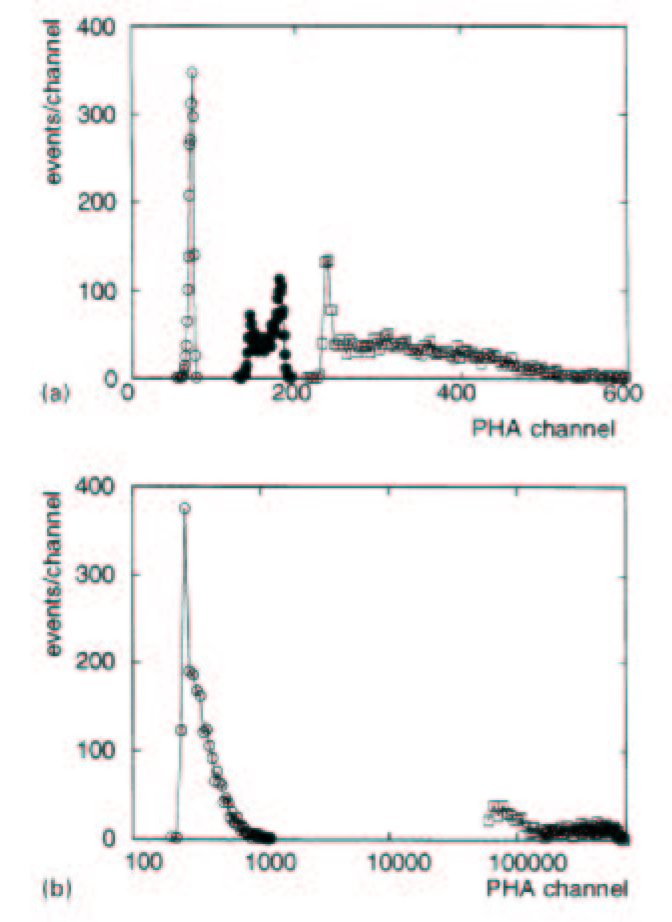
Energy spectrum of 662 keV g-rays measured with CsI(Tl) and YAP:Ce crystals
(M. Moszynski et al., NIM A497 (2003) 226)



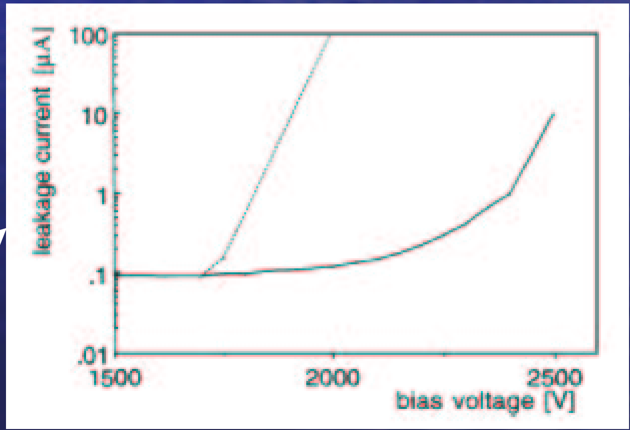
Pulse height spectrum of scintillation due to 5.5 MeV α-particles in liquid Xe (λ=178 nm), measured at T=-102 C and M=120
(V.N. Solovov et al., NIM A488 (2002) 572)

"Beveled edge" APDs in HEP environment

When operating these APDs at high gain in beam line environment, abnormal behavior and eventually permanent damage to the detectors were observed. These abnormal events were probably triggered by rare but highly ionizing nuclear collision events



Pulse height spectra of APD response to α-particles at different bias voltages:
U=1000 V, M=1.2
U=1500 V, M=2
U=1650 V, M=4
U=1700 V, M=5
U=1750 V, M=6



APD leakage current vs. bias voltage before and after lethal a-particles damage

(From G. Anzivino et al., NIM A430 (1999) 100)

"Beveled edge" APD's summary

Excellent photosensor:

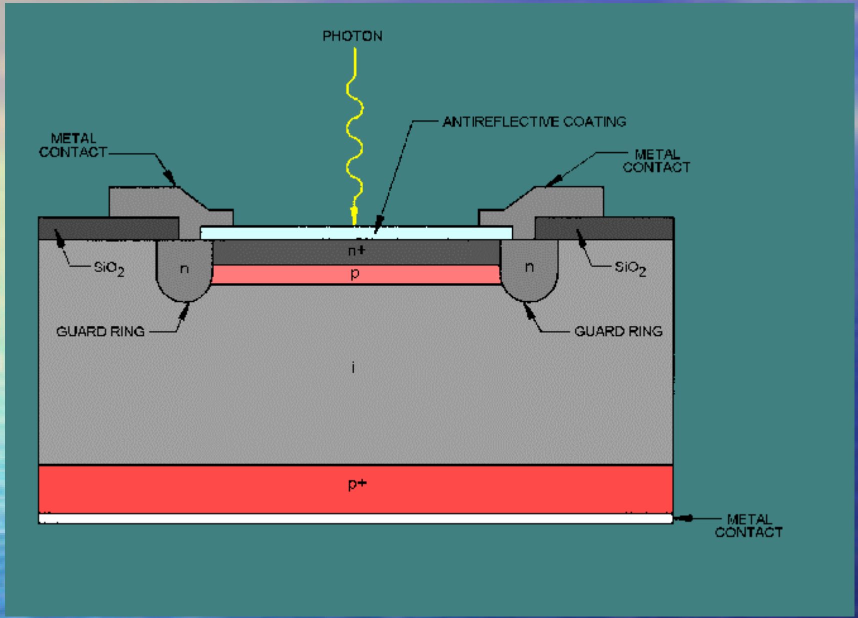
- Large area
- High QE and gain
- Good uniformity over the sensitive area
- Low excess noise factor
- Low voltage and temperature sensitivity

But:

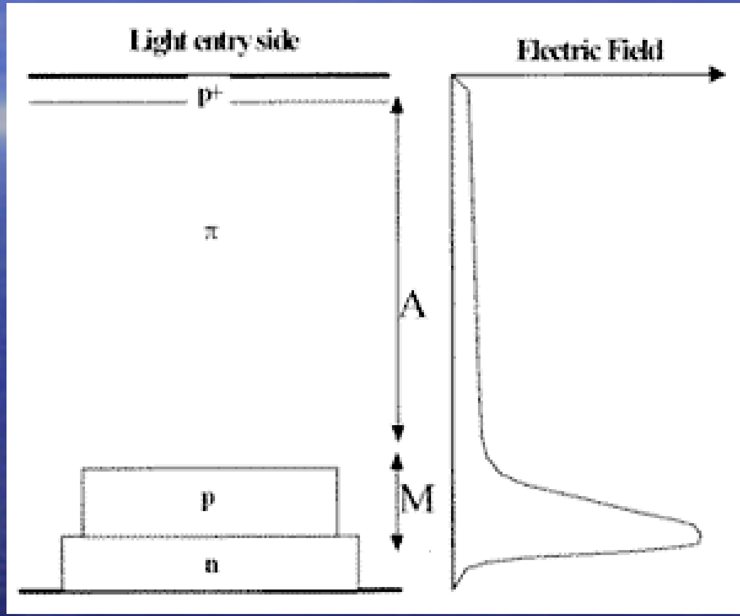
- High operating voltage (~2000 V)
- High sensitivity to heavily ionizing particles
- Structure should be sensitive to hadron irradiation
- Difficult for mass production
- High price

"Reach-through" APD

Schematic cross-section and electric field profile



Structure optimized for red light detection,
(see for example: I. Wegrzecka, M. Wegrzecki, NIM A426 (1999) 212)



Structure with improved sensitivity for blue light
(see for example R. Lecomte et al., NIM A278 (1989) 585

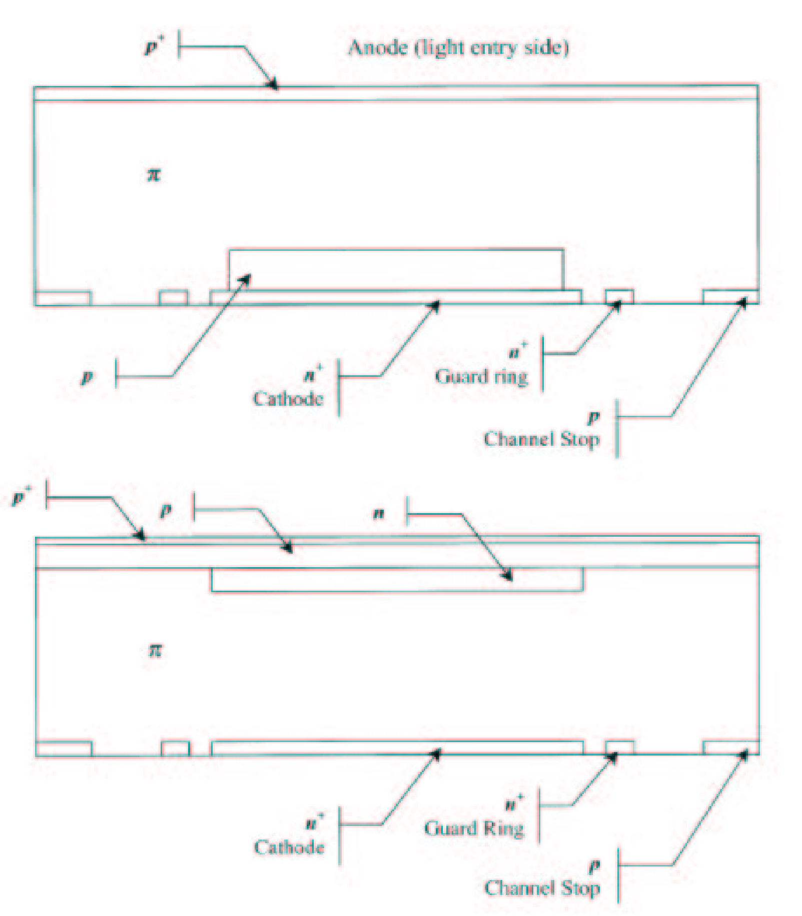
- Guard-ring - to reduce electric field at the edge
- Region with high electric field is thinner than in the case of beveled edge APDs
- Region with low doping - to reduce capacitance and operating voltage (<500 V)

Low operating voltage, easy to produce - good for mass production, but high signal from ionizing particles crossing the APD depletion region ("nuclear counter effect") and high dark current induced by hadron irradiation (thick depletion region)

“Reverse” or “Baried Junction” APD (EG&G)

Standard or “rich-through” APD →

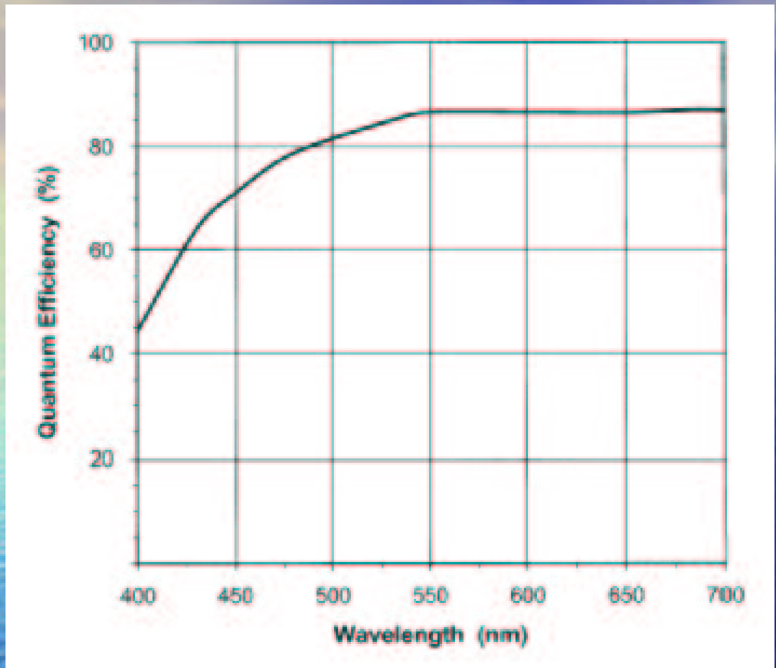
“Reverse” or “baried junction” APD →
The peak field is ~4 µm deep

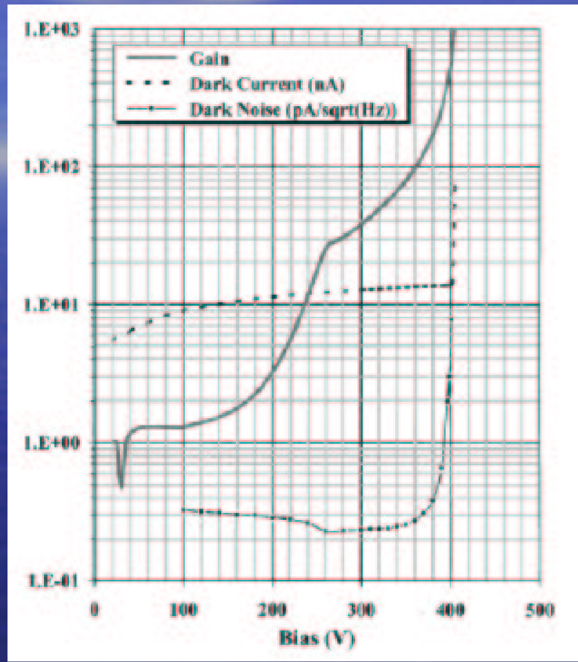


PerkinElmer™ optoelectronics.

R. Lecomte et al., NIM A423 (1999) 92

"Reverse" APD performance





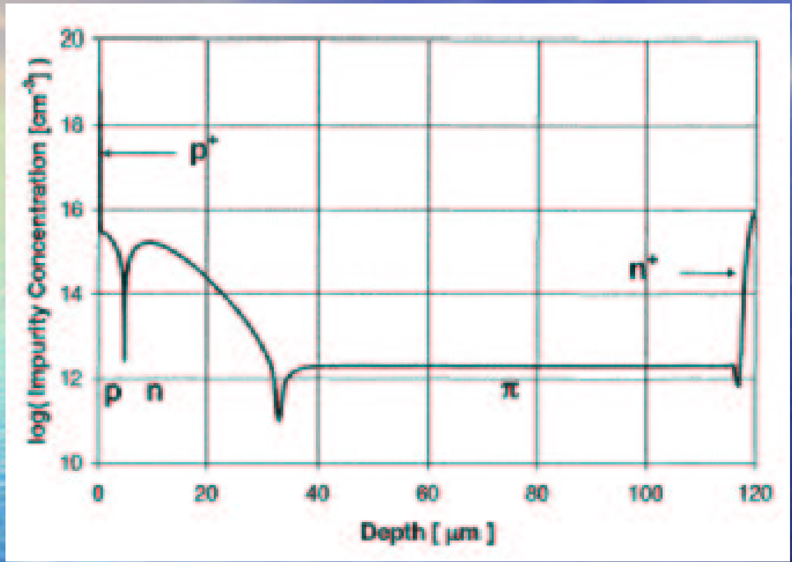
Area: 5x5 mm^2

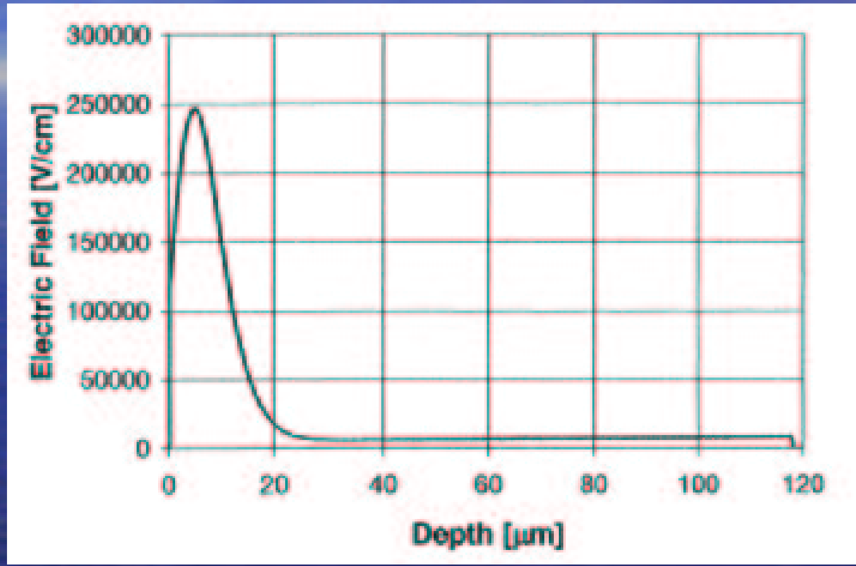
Capacitance: ~30 pF (for 120 μm depletion region)

Excess noise factor (M=50): 3.5

R. Lecomte et al., NIM A423 (1999) 92

Doping profile and electric field distribution (calculated)

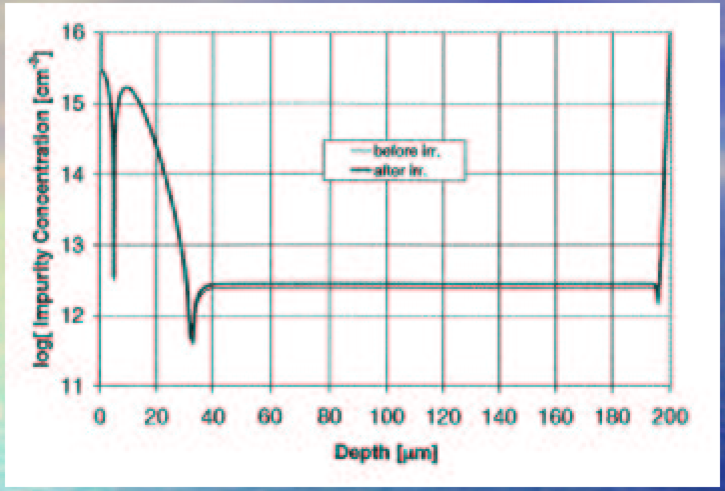


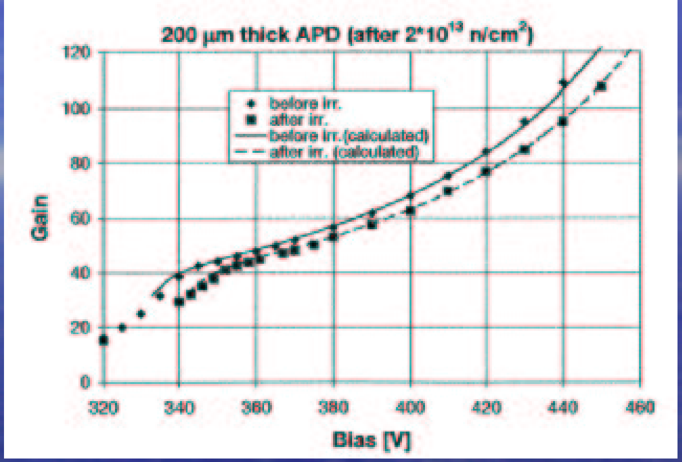


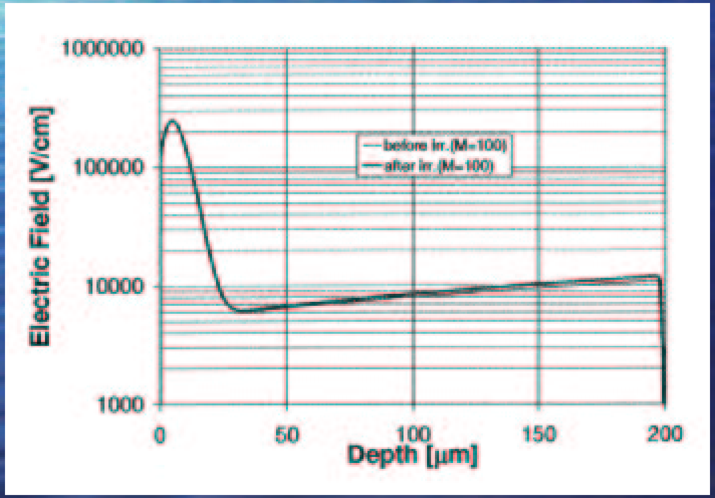
Y. Musienko et al., NIM A442 (2000) 179

APD is made on 120 μm thick high resistivity wafer. For mass production 200 or even 300 μm thick wafer is preferable (lower production cost and better yield)

Thick APDs under neutron irradiation







Calculated

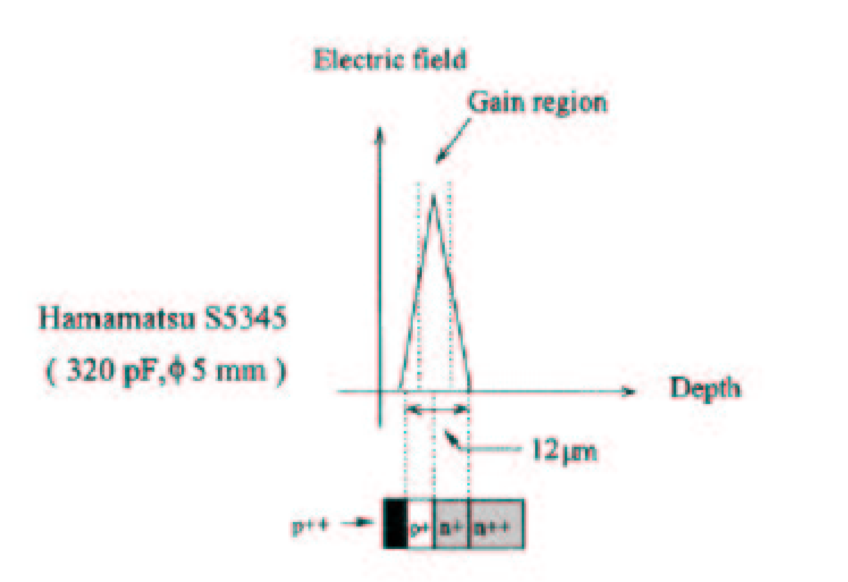
Calculated and measured

Neutrons cause the change of the doping profile, electric field distribution and shift the gain curve. Effect is proportional to the square of the depletion region thickness

APDs with depletion region of ~40-60 µm are optimal

Y. Musienko et al., NIM A442 (2000) 179

"High C" Hamamatsu APD



Sensitive area	19.6 mm²
Operating voltage	~150 V
Excess noise factor	2.0
1/M*dM/dT	-2 %/C
Effective thickness	~4 μm
QE(430nm)	60 %
Capacitance	320 pF
1/M*dM/dV	15 %/V

Produced by epitaxial growth, ion implantation and diffusion – easy to produce

R&D on APD for CMS ECAL

In 1995 there was no APD which was suitable for CMS ECAL

Main goal of R&D – optimize APD structure for the CMS ECAL

1995 - Development contract with Hamamatsu Photonics and EG&G Opto-electronics, they had APDs which were close to the CMS ECAL requirements

Hamamatsu:

small NCE (~4μm), small F, small temperature sensitivity of the gain
high capcitance (320pF for 5 mm in dia. APD), 15%/V change of the gain (when M~50)

Goals of R&D:

- reduce capacitance
- reduce voltage sensitivity of the gain

EG&G:

small capacitance (~30pF for 5x5 mm^2 area), small voltage sensitivity of the gain ~1.5%/V
high F (3.5 for M~50), high temperature sensitivity of the gain

Goals of R&D:

- reduce F
- reduce temperature sensitivity of the gain

Contradiction: low nuclear counter effect → high capacitance, high voltage sensitivity of the gain

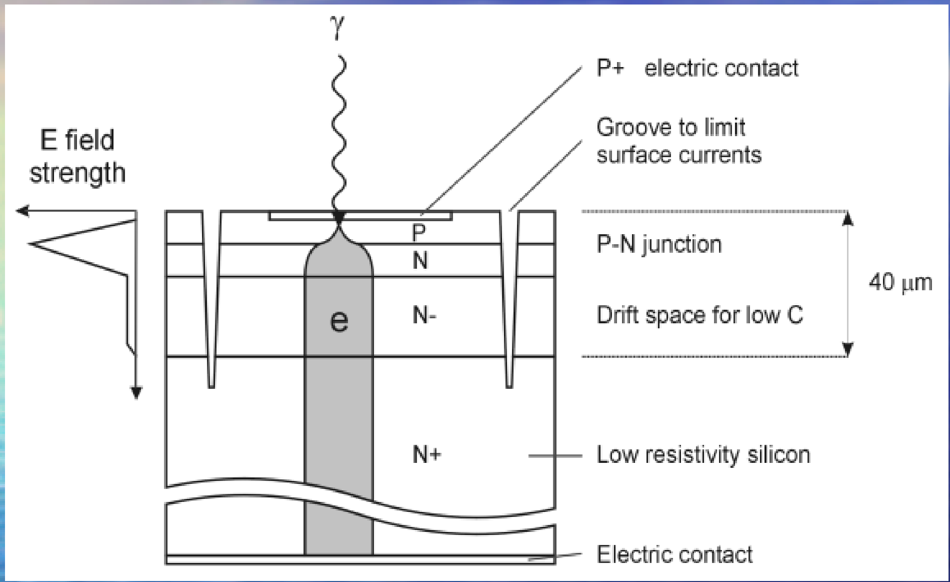
3 years of exciting (!!!) work on CMS ECAL APD development...

Choice between the two vendors made in July 1998 in favour of Hamamatsu Photonics (both producers produced good APDs, but Hamamatsu had better reliability and smaller price)

New R&D contract with Hamamatsu: - reduce capacitance from 120 to 80 pF, larger VB-VR, improve resistance to radiation (~100% survival!)

... 2 more years of R&D ...

Hamamatsu APD structure (final CMS APD)



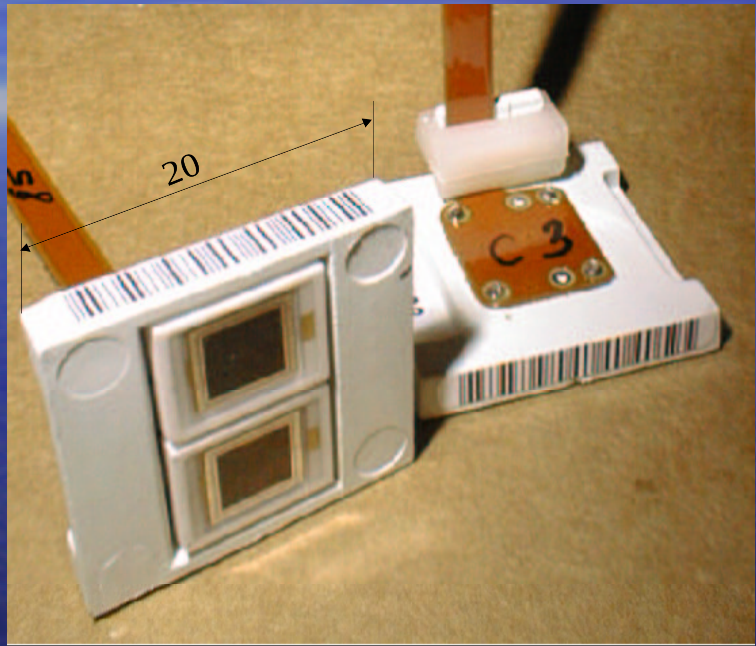
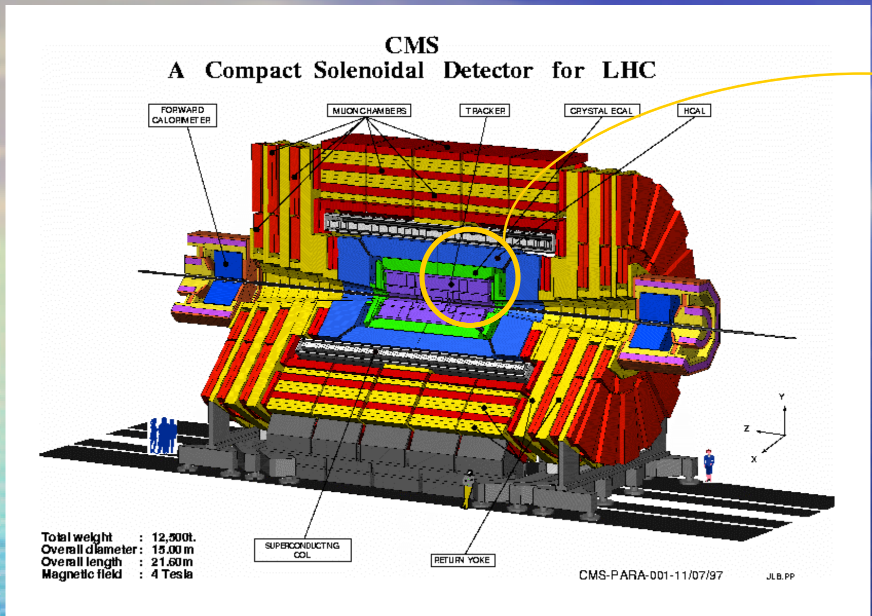


Photo-electrons from THIN p-layer induce avalanche at p-n junction

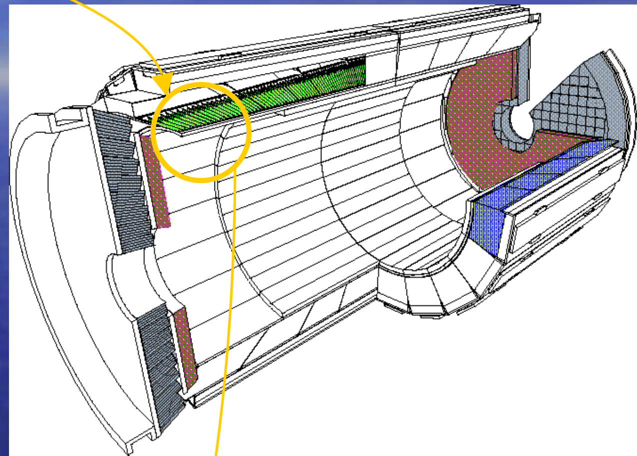
Electrons from ionizing particles traversing the bulk amplified with relatively small gain (M_e=50, M_h=1.5)

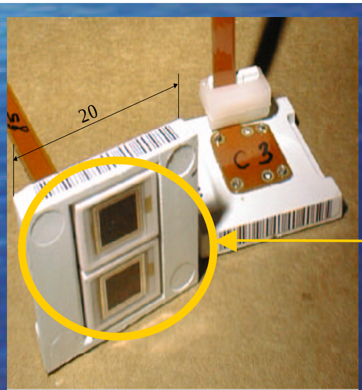
2 APDs (each 5 x 5 mm) mounted in a capsule ready for gluing to a crystal

APD’s in the CMS detector

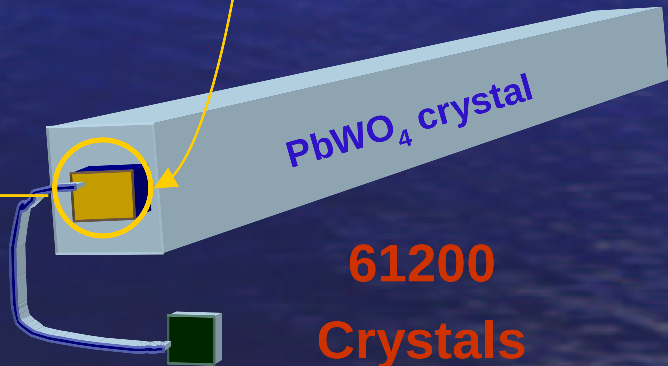


Electromagnetic Calorimter





2 APDs per Crystal



61200 Crystals in Barrel

APD Impact on ECAL Resolution

Resolution:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus b \oplus \frac{c}{E}$$

where, *a* : due to intrinsic shower fluctuations

b : related to stability and reproducibility

c : noise contributions

CMS design goal : *a* ~3%, *b*~0.5%, *c*~200 MeV

APD contributions:

a - photon statistics (area, QE) & excess noise factor

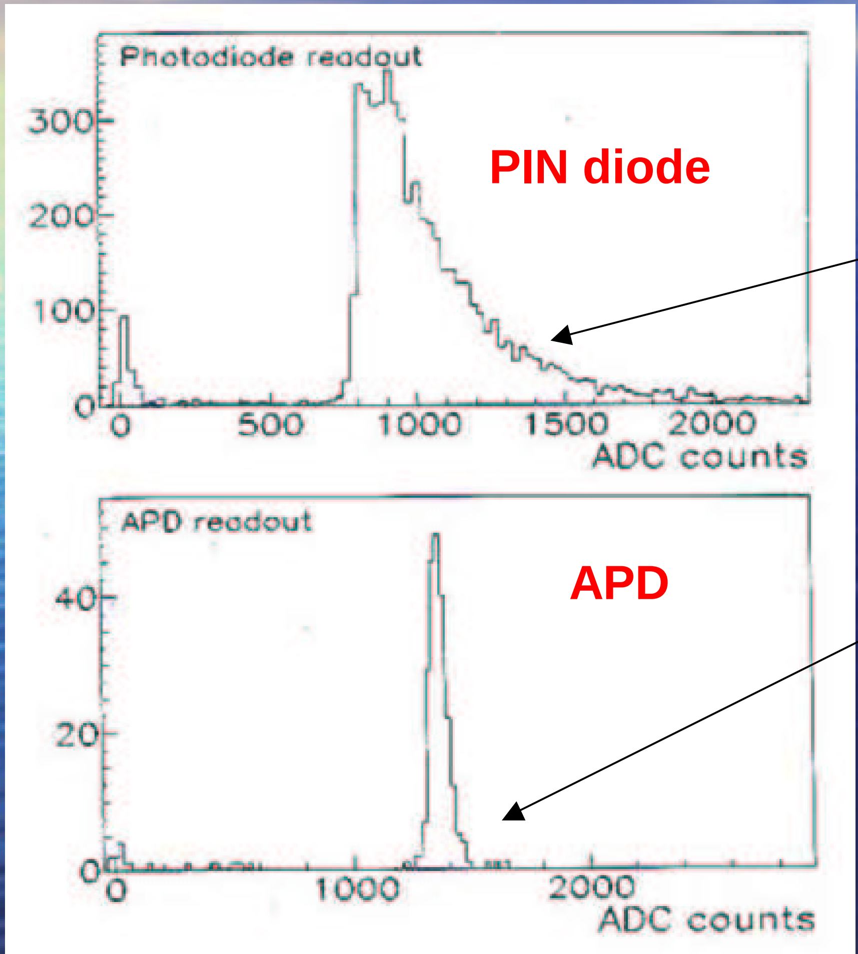
b - gain variation with bias voltage and temperature

c - capacitance as series noise and dark current as parallel noise

Optimise all these parameters to reach design goal

Nuclear Counter Effect

80 GeV electrons in $PbWO_4$ **PIN diode or APD readout**

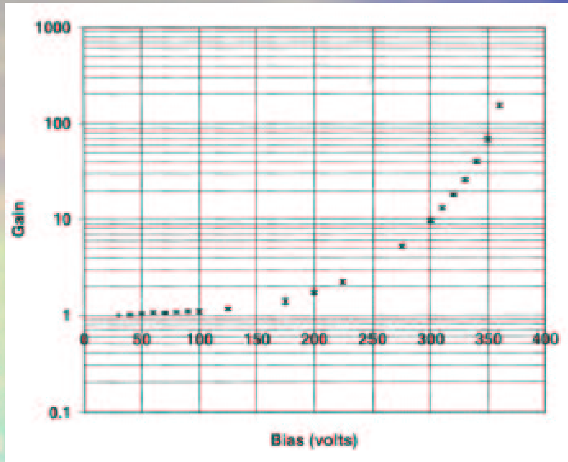


Tail due to particles leaking through crystal and traversing diode

No tail !

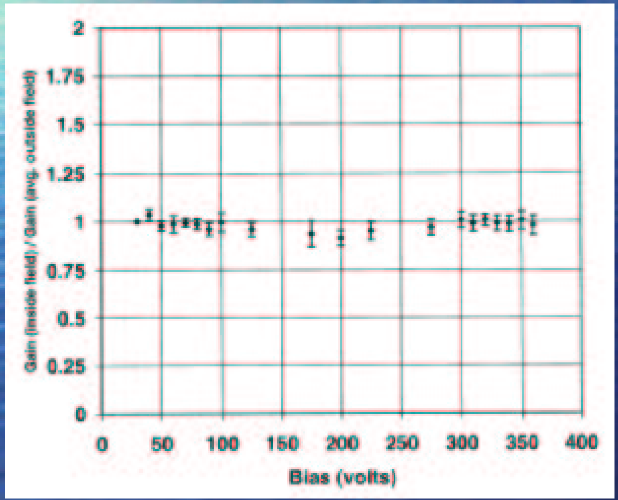
APD effective thickness for traversing particles: ~6 µm

APDs in the magnetic field (7.9 T)

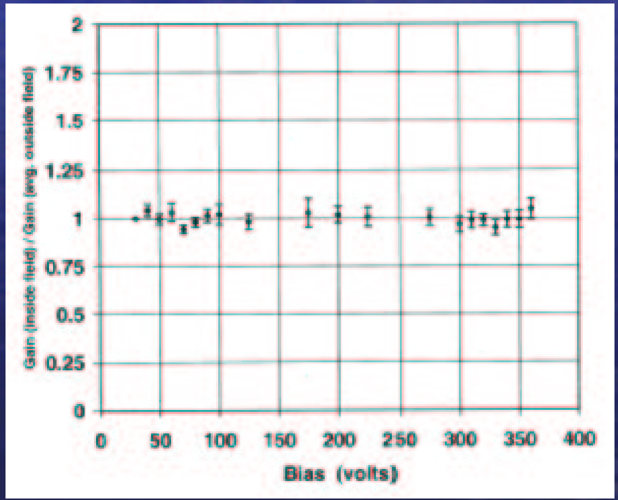


APD gain curve measured outside the field

J.Marler et al., NIM A449 (2000) 311



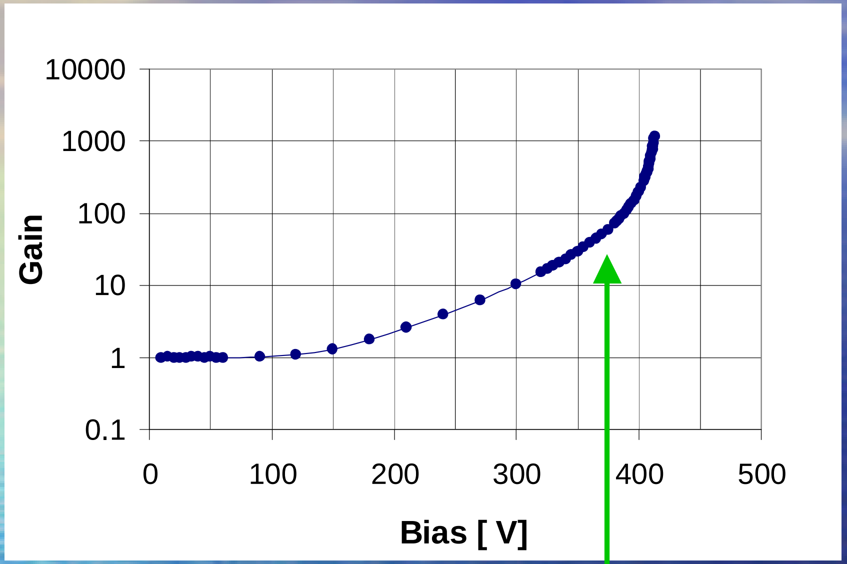
APD surface oriented perpendicular to the field

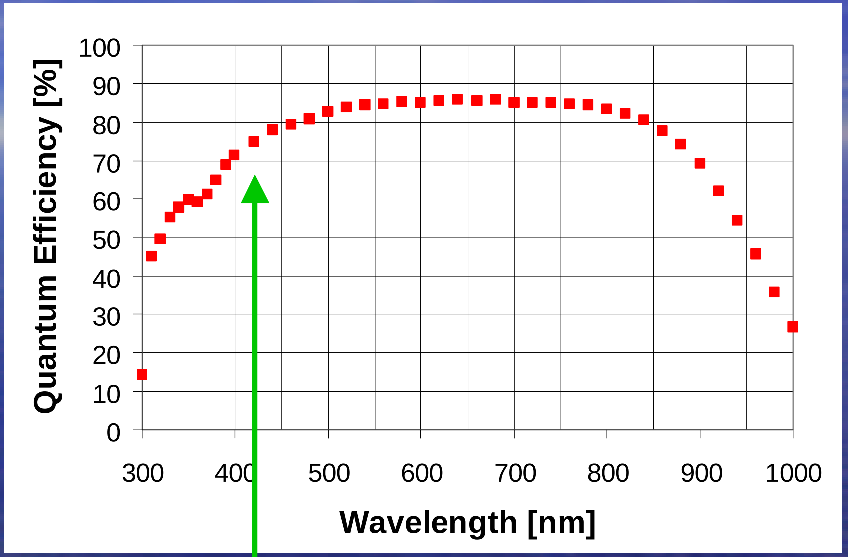


APD surface oriented parallel to the field

Gain of APD is unaffected by the 7.9 T magnetic field

APD Gain, Quantum efficiency





Operating Voltage, M=50

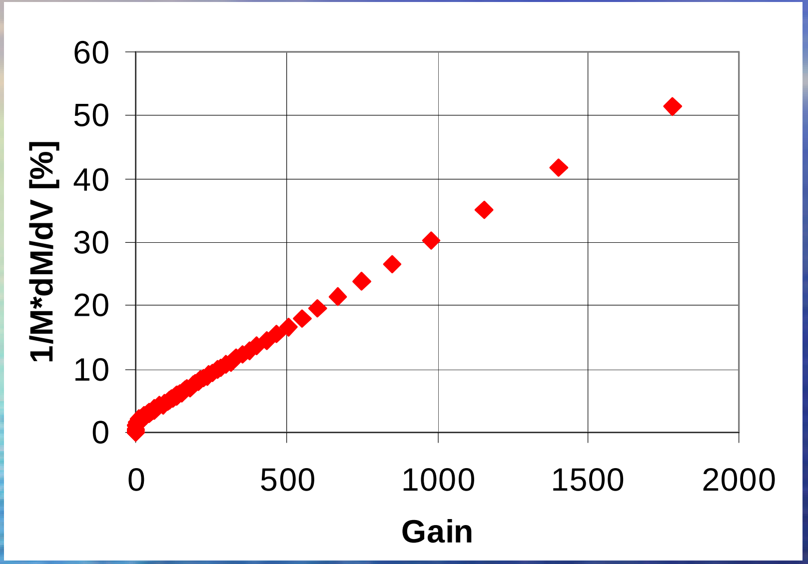
$PbWO_4$ peak emission 420 nm

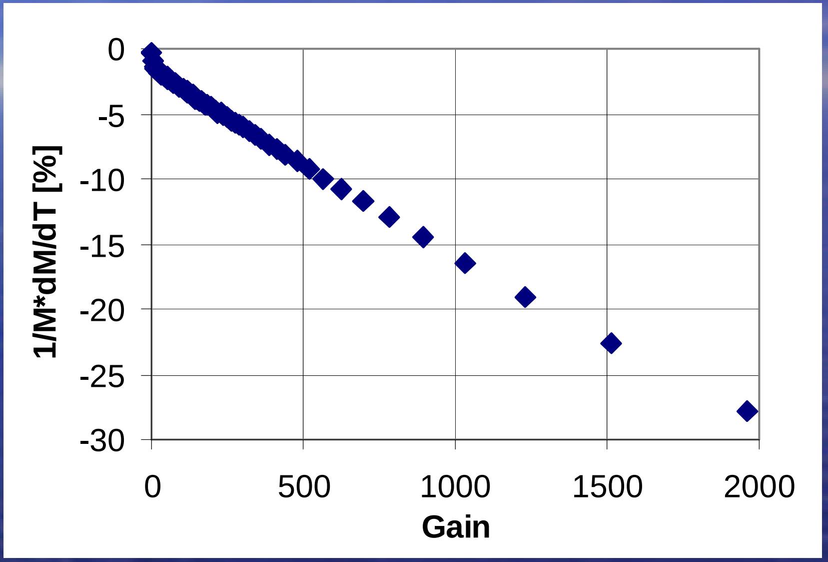
Gains can go to over 1000

We demand good behavior up to gain 400

Q.E. is ~73% at peak emission

Voltage and Temperature Coefficients



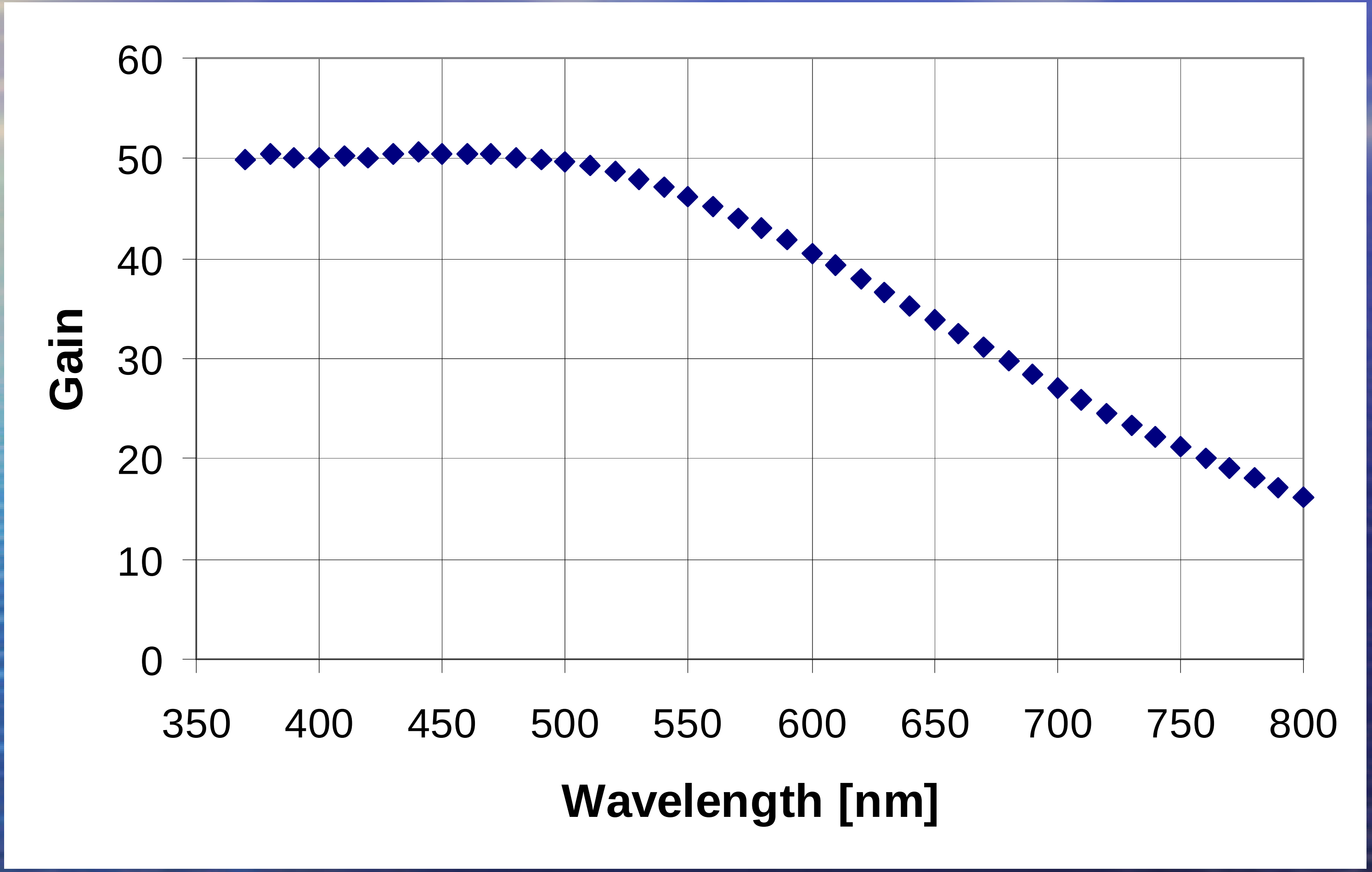


At M=50 :

*dM/dV*1/M =* 3.1 *%/V*

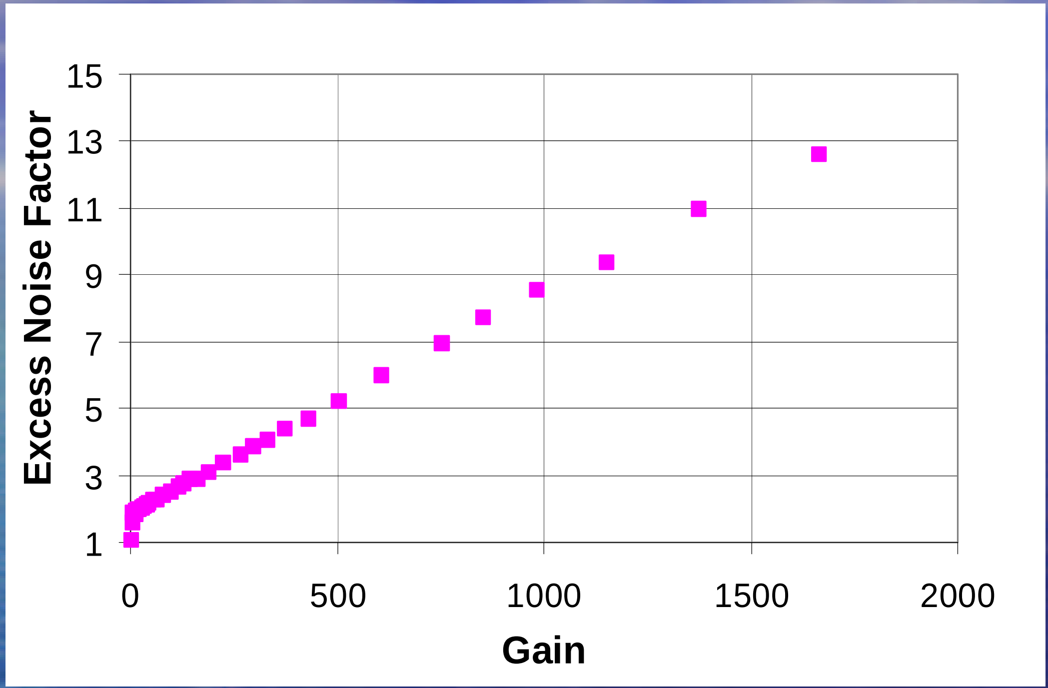
*dM/dT*1/M =* -2.4 *%/C*

Gain vs. Wavelength



Main junction is close to the entrance window – red light has smaller gain

Excess Noise Factor



statistical fluctuations of the avalanche multiplication

$F = k\times M + (2-1/M)\times(1-k)$ (from theory of R. McIntyre)

k - ratio of the ionisation coefficients for holes and electrons, M- gain

Contributes to the stochastic term in energy resolution as: $SQRT(F/N_{p.e.})$

Summary of APD parameters (M=50)

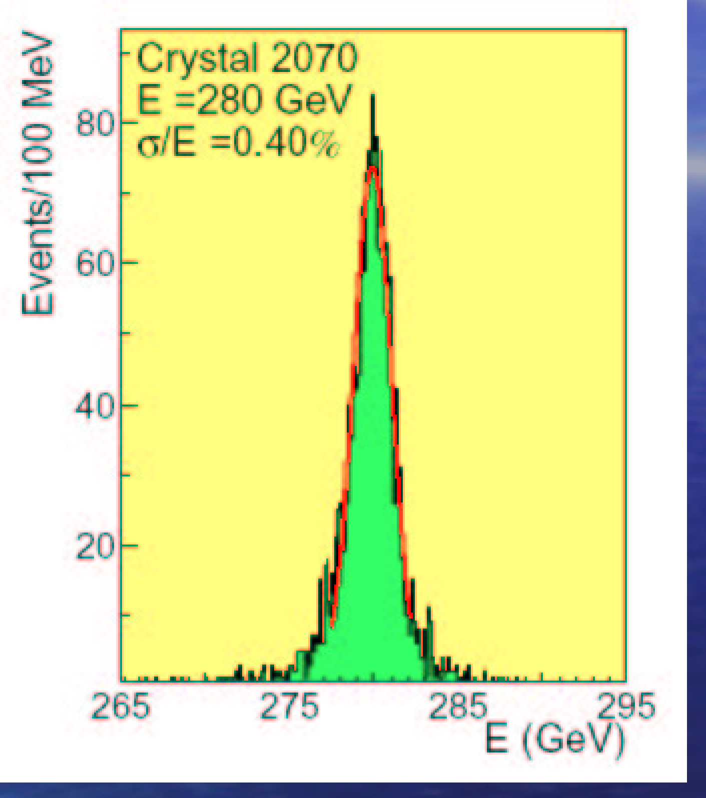
Active area	5 x 5 mm
Operating voltage (T=25C)	< 420 V
Quantum Efficiency (420 nm)	73 %
Capacitance	80 pF
Serial resistance	< 10 Ω
Dark Current (t=25 C)	~3.5 nA
Voltage sensitivity (1/M*dM/dV)	3.1 % / V
Temperature sensitivity (1/T*dM/dT)	- 2.4 % / °C
Excess noise factor	2.1
Breakdown - operating voltage (Vb - Vr)	45 ± 5 V

For GOOD APDs:

RADIATION HARDNESS:
After 10 years of LHC equivalent hadron irradiation, ONLY property to change is the dark current, which rises to ~5 μA at 18 °C

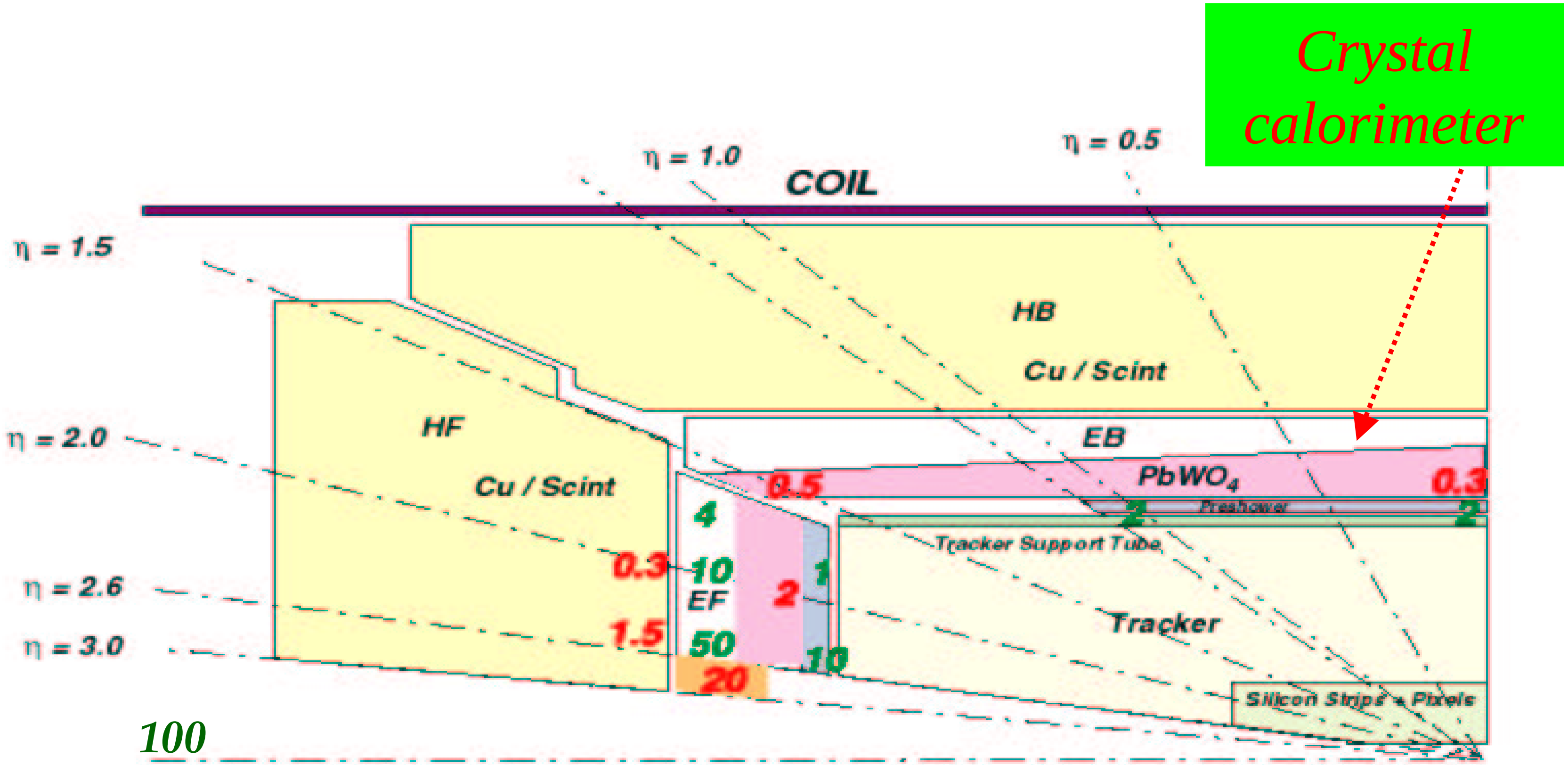
AGING: No effect seen after ~10 years' equivalent in an oven.

Test beam: Energy Resolution



Reconstructed energy with 280 GeV electrons incident on 5x5 crystal matrix

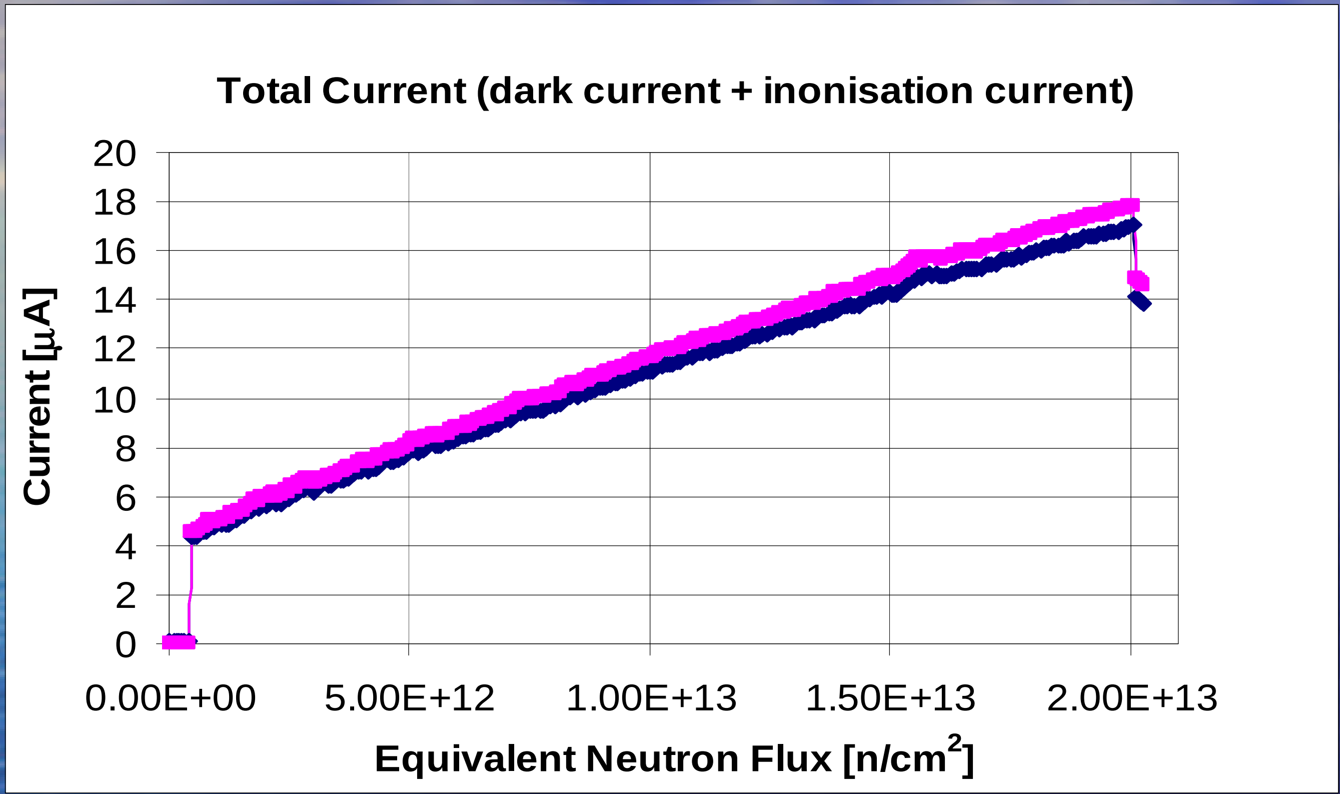
Radiation level after 10 years



Radiation doses are in red, 10^4 Gy.

Neutron fluence is in green, 10^{13} neutrons/cm ^{2} with E > 100 keV.

Irradiation with 70 MeV protons

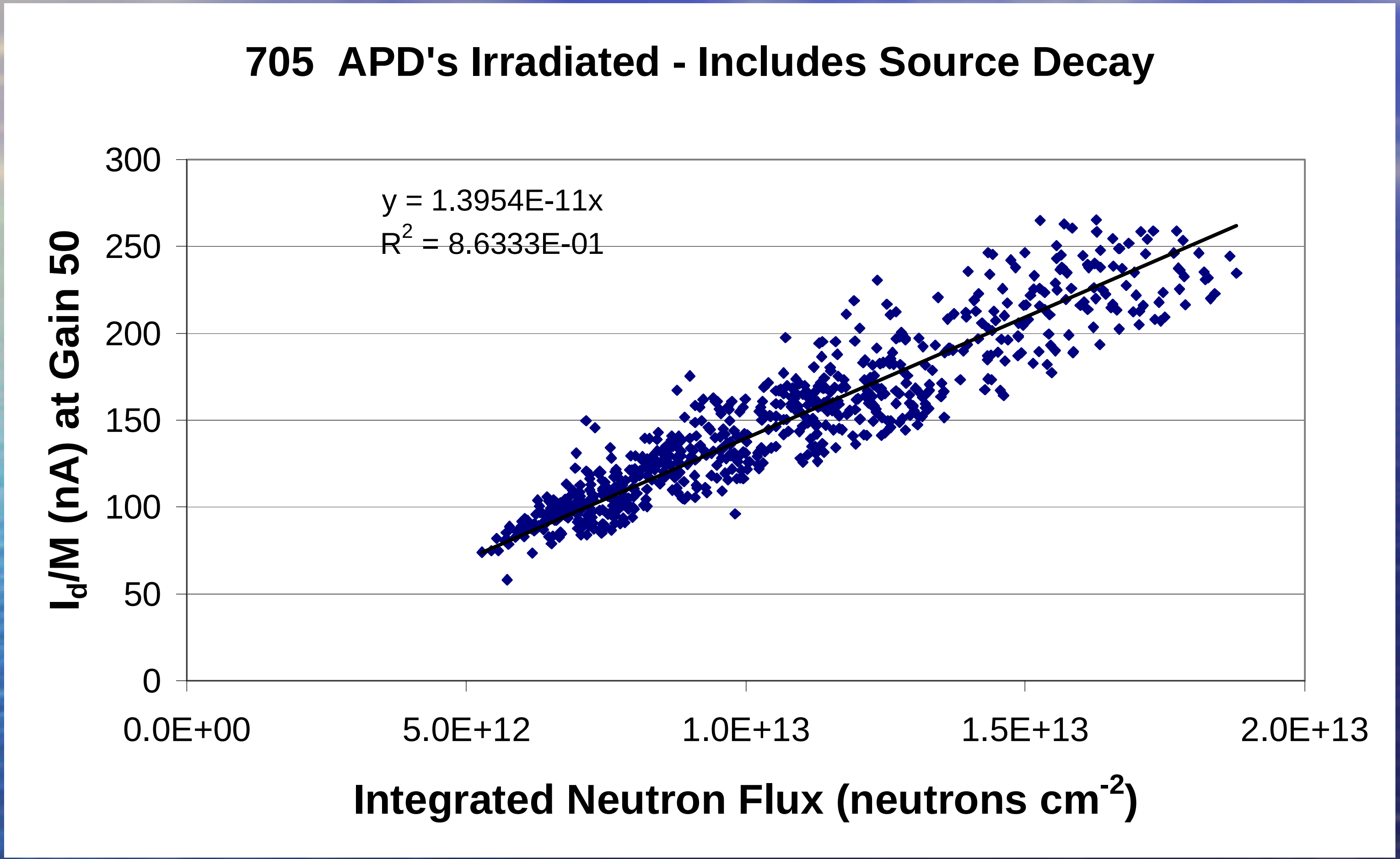


APD's irradiated at PSI 70 MeV proton beam for 105 minutes

$9x10^{12}$ protons/cm^2 ≡ $2x10^{13}$ 1MeV neutrons/ cm^2

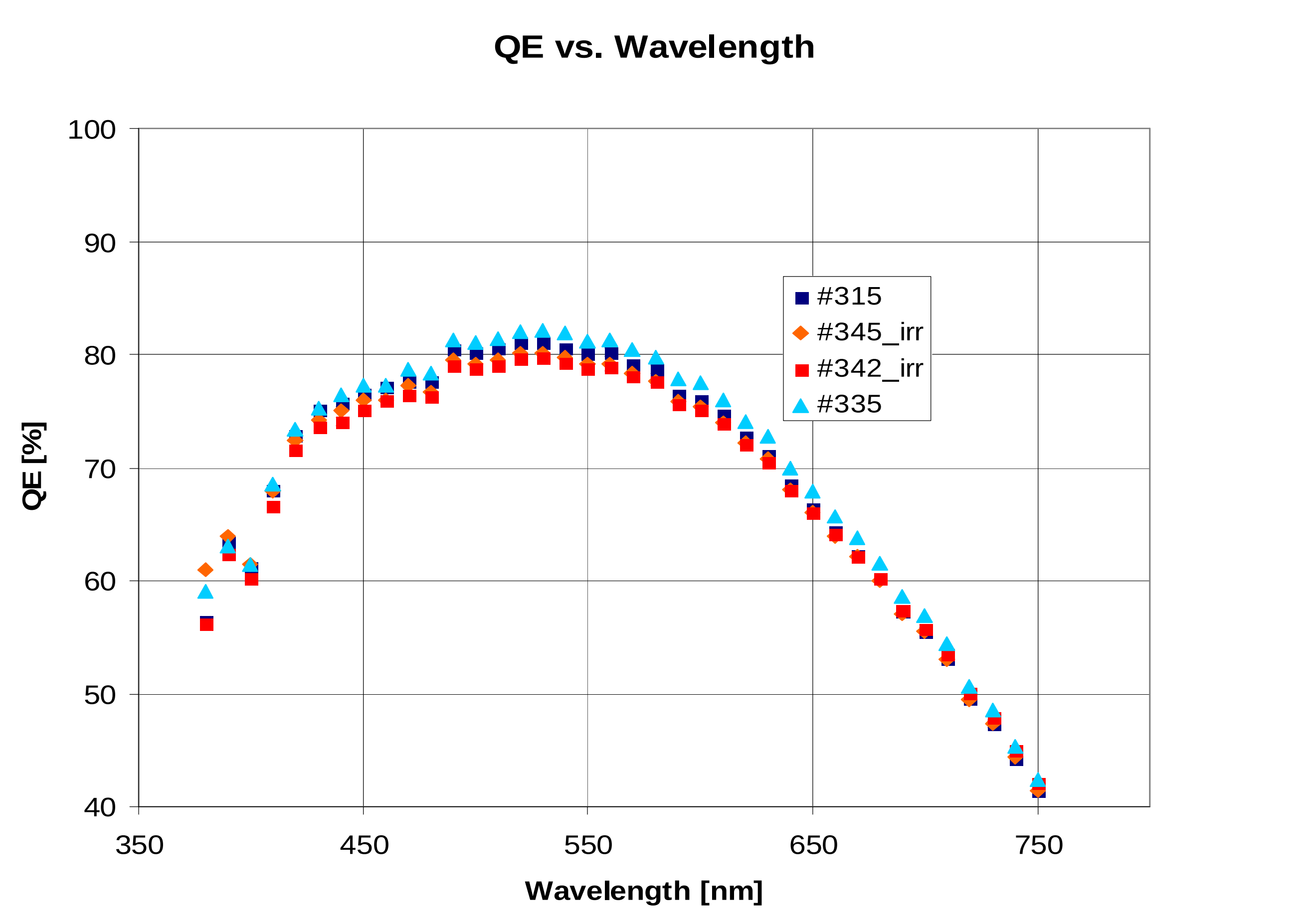
≡ 10 years fluence expected in CMS barrel

Neutron irradiation results



To date >1000 APD's have been irradiated by ^{252}Cf neutrons and all have survived

Effect of Irradiation on Q.E.



No change in quantum efficiency for λ's of interest

Very small change of gain curve and APD breakdown voltage

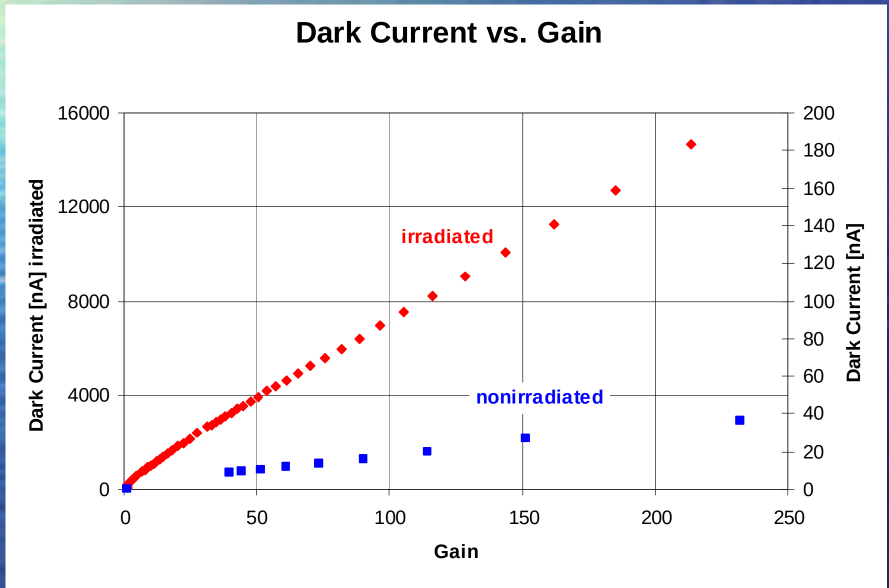
up to 10^{14} n/cm^2

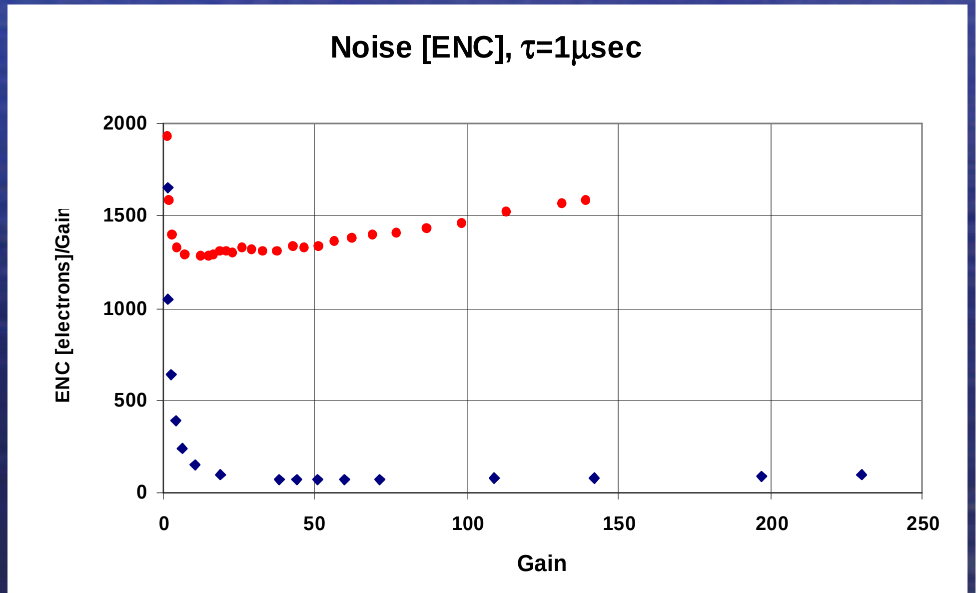
Dark Current & Noise

*After 2*10^13 n/cm^2 and annealing*

Id~5μA @ 18 °C

ENC~12 500 el (τ = 50 ns) → 50 MeV/ch





Radiation Hardness, Stability

Good APDs are very Robust, Radiation Hard

They still work after more rigorous tests (some "violent")

BUT

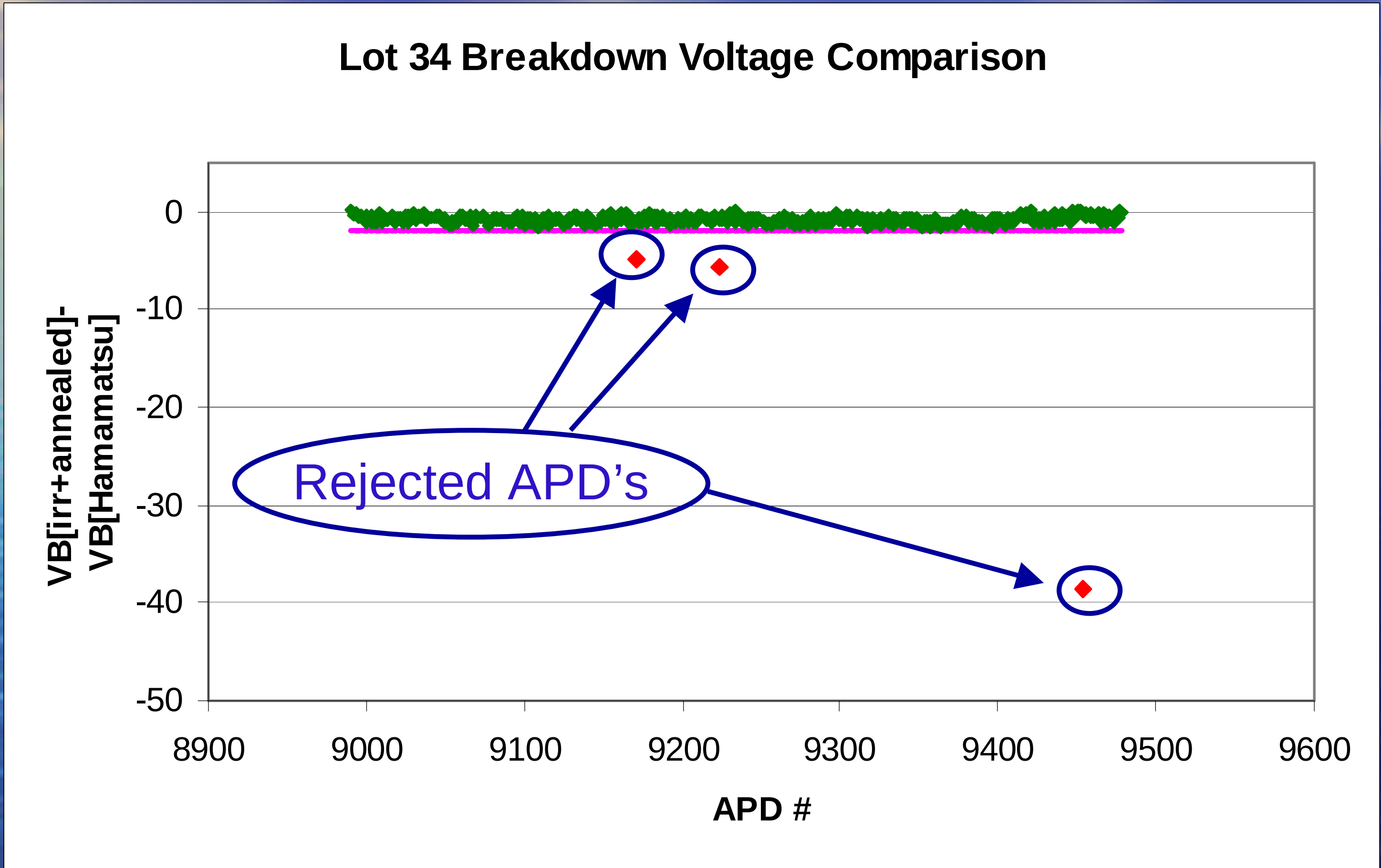
Despite heroic effort by Hamamatsu

- few % die or get sick under gamma irradiation
- a few more in an extended "burn-in" at 80 °C

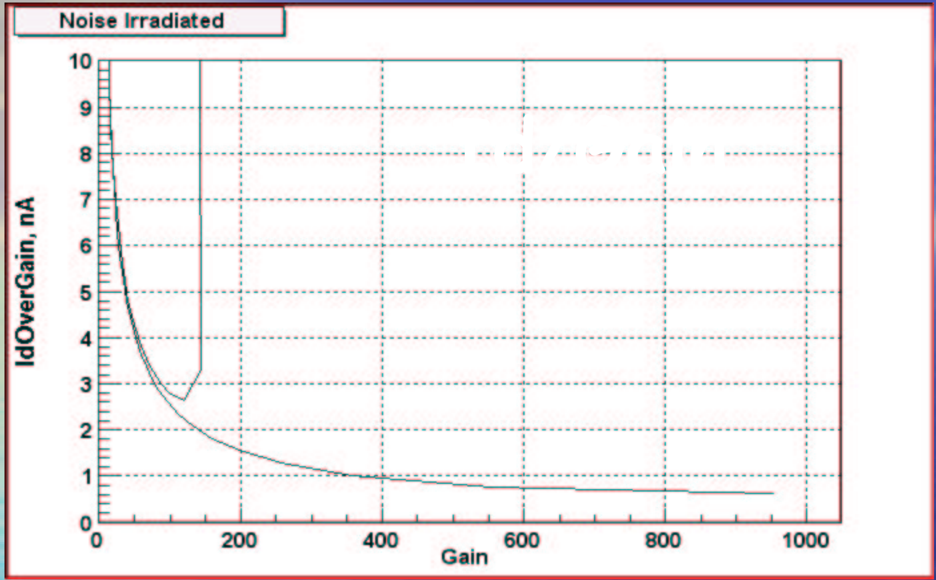
Reliability goal 99.9%, for 10 years of LHC

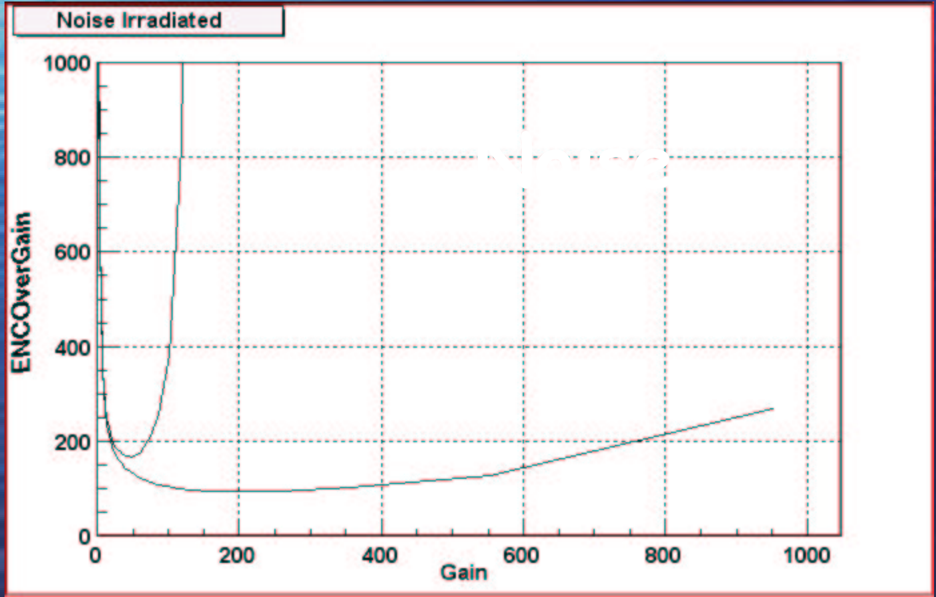
==> Screen all APDs

Change of VB after irradiation and annealing



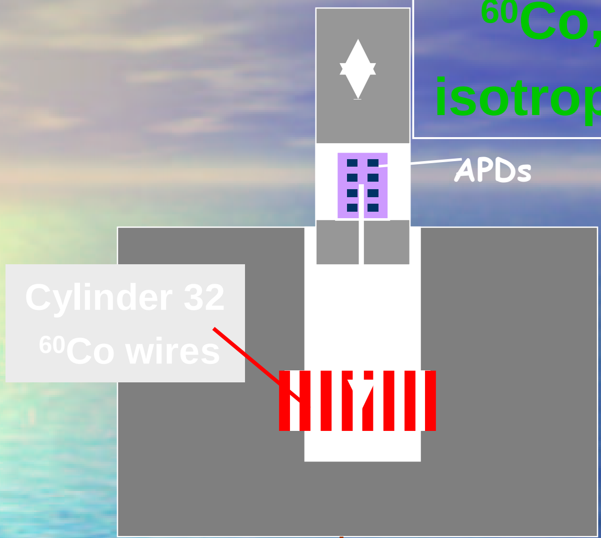
Dark Current and Noise





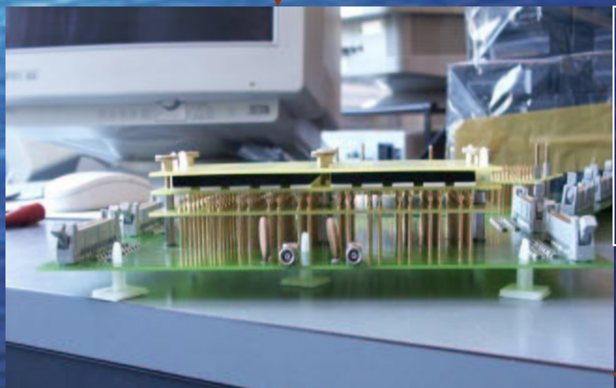
APD with a significant shift of Vb after ^{60}Co irradiation shows abnormal behavior of Id/Gain curve and high noise

Screening Procedure



^{60}Co, 5 kGy, isotropic (2 hrs)

PSI



Measure Vb, Id
1 day later;
Noise > 1 week

Cook at 80 °C
for 4 weeks
under bias

CERN

Measure Vb, Id

Select, pair

Make Capsule
Measure Noise

Lyon

Rejection Criteria

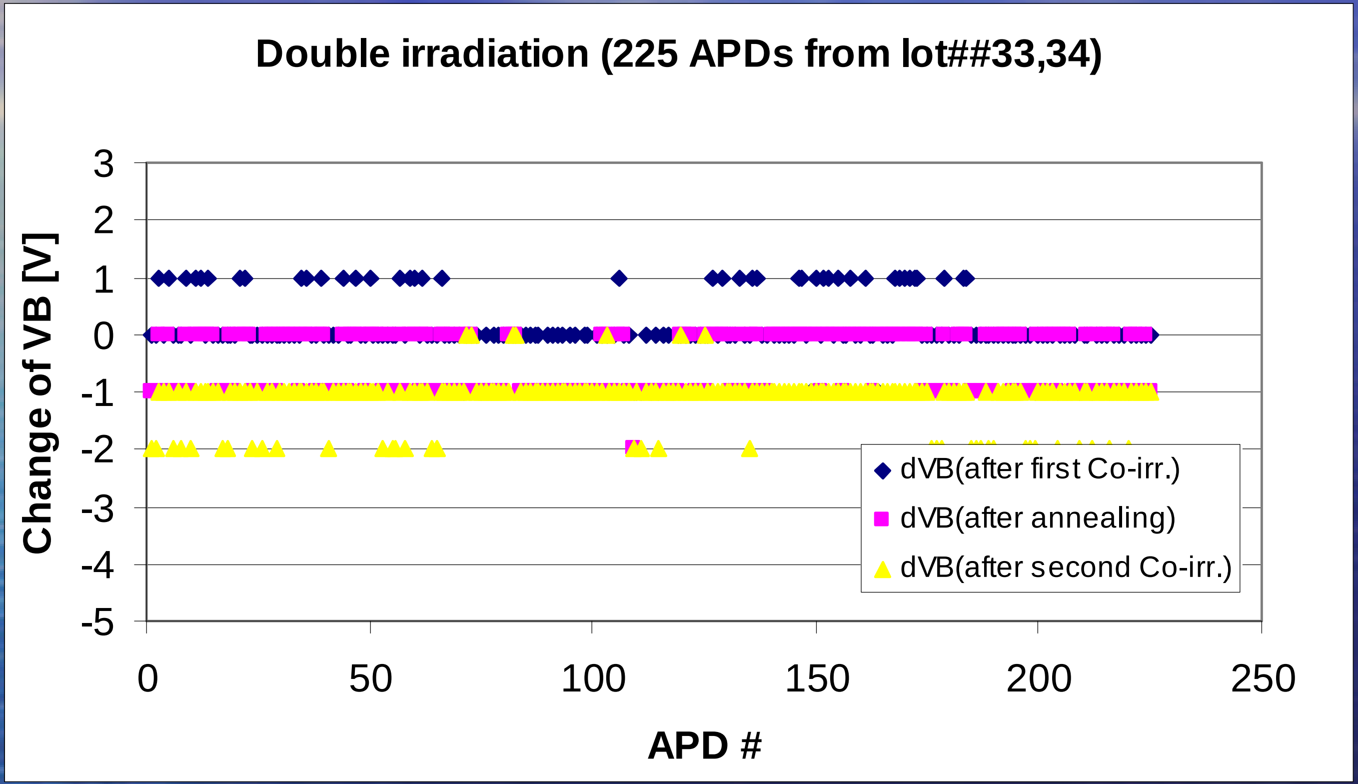
APDs are rejected if after irradiation or cooking:

Change of Vb (breakdown voltage) :	> 5 V
Id (dark current):	anomalously large
Id/M (Id divided by gain, M):	rises in range M = 50 - 400
Noise:	anomalously large at M = 1, 50, 150, 300

Also:

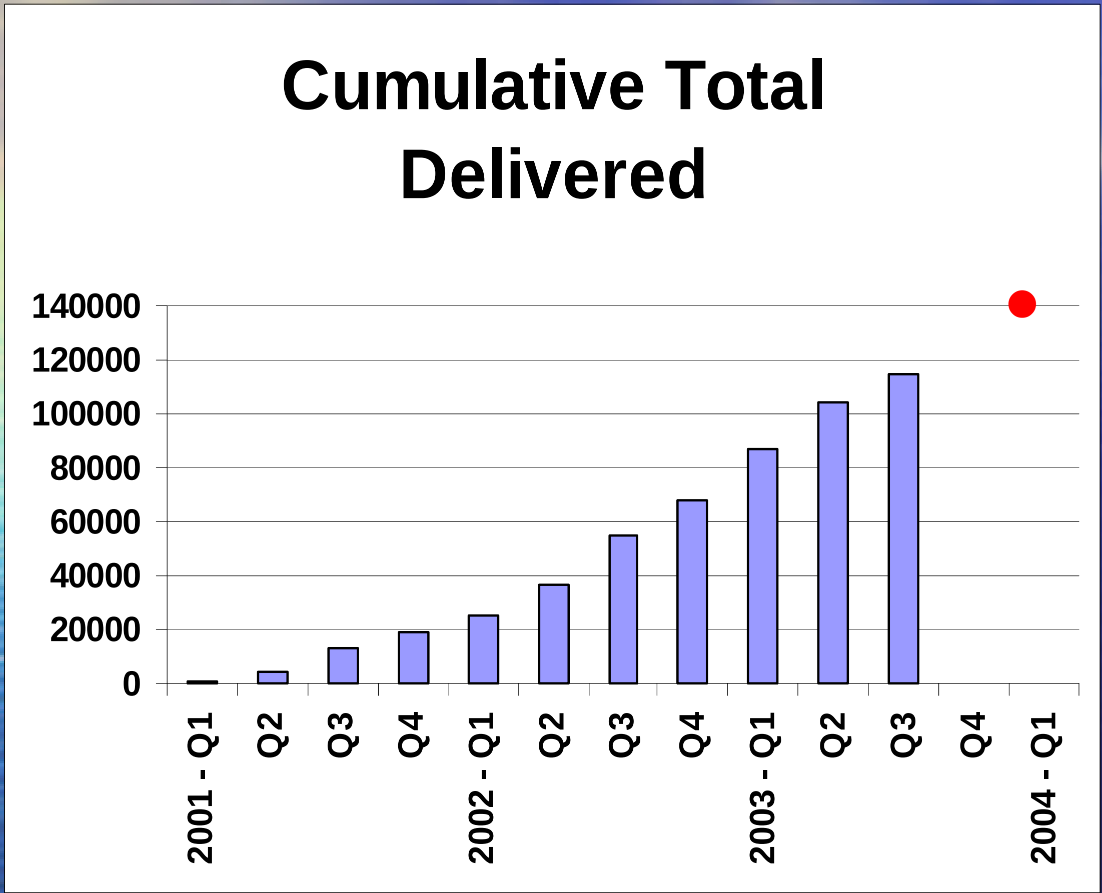
Bad Positions: All APDs in a Lot from a position on wafer where > 30% fail screening

Efficiency of the screening method



834 APD`s which passed 1st irradiation and annealing were irradiated the 2nd time. Only 1 APD failed the second irradiation.

Production Status (to end 8/03)



115,000 delivered

On schedule to complete ● by January 2004 (140,000 APDs)

90,000 screened

On schedule to complete by May 2004

Summary on CMS APD's

The Hamamatsu APD for CMS

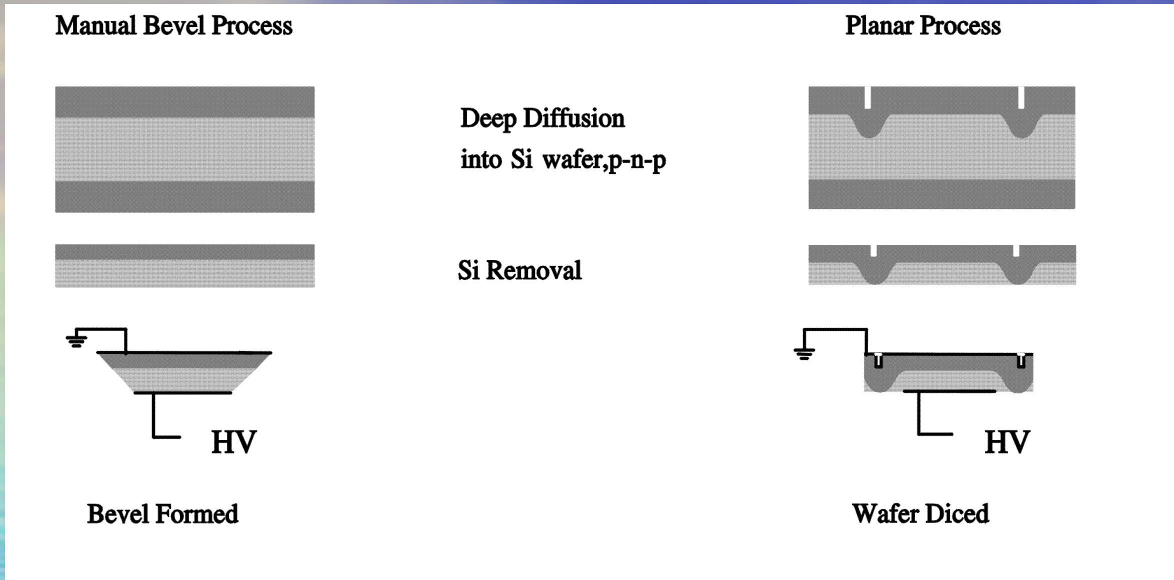
- is very robust
- is radiation "hard"
- will have Id after 10 years of LHC ~ 50 MeV noise per crystal

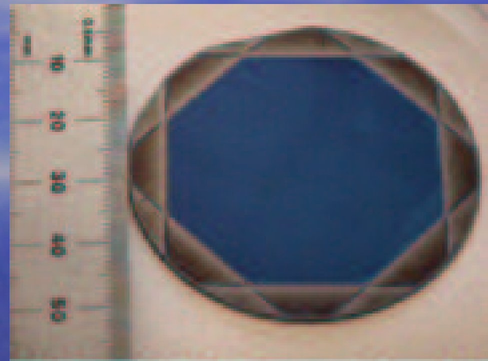
By screening out ca 5% of APDs, anticipate 99.9% reliability in CMS

Production and screening on schedule

New APD developments

Planar APDs from RMD





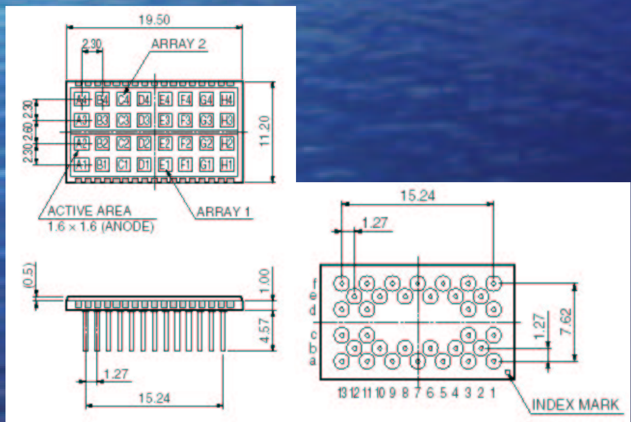
$13\ cm^2$ APD on a 2 inch diameter silicon wafer

This APD is really large!

64-pixel APD array
$0.9x0.9\ mm^2$ pixel size

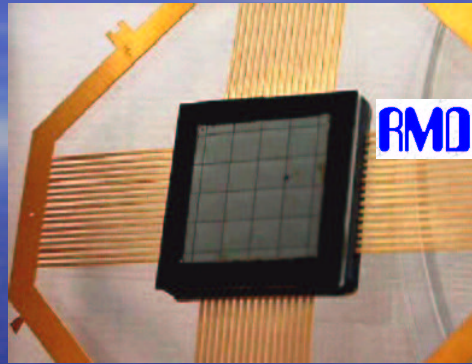
Avalanche photodiodes: Arrays

S8550 4x8 pixel array,
1.6x1.6 mm^2 pixel size,
2.3 mm element pitch,
low noise and enhanced UV sensitivity

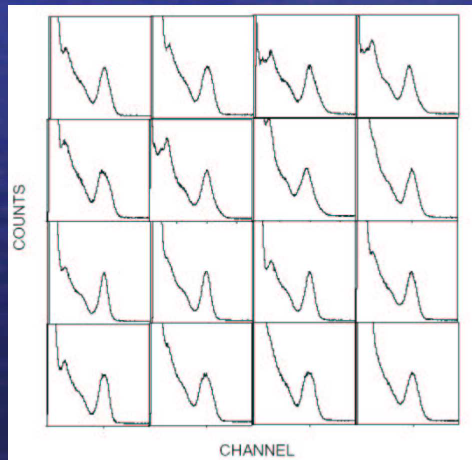


Arrays of APDs can be produced with a very good fill factor.

The biggest problem is the connection to the readout electronics.



2.1x2.1mm^2 pixel size

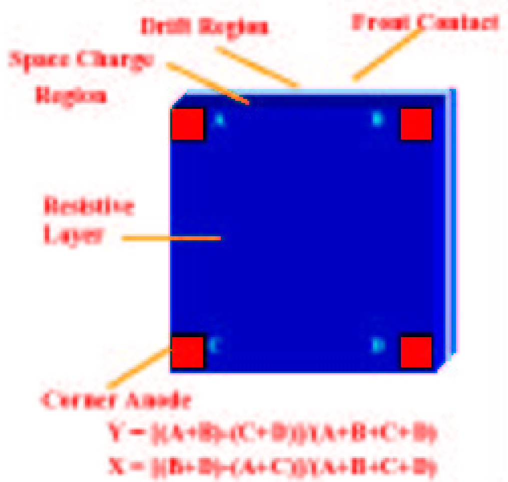


16 CsI(Tl) crystal coupled to the array and illuminated by a ^{22}Na source

R. Farrell et al., NIM A442 (2000) 171

Position Sensitive APDs (RMD)

PSAPDs: Simple Design

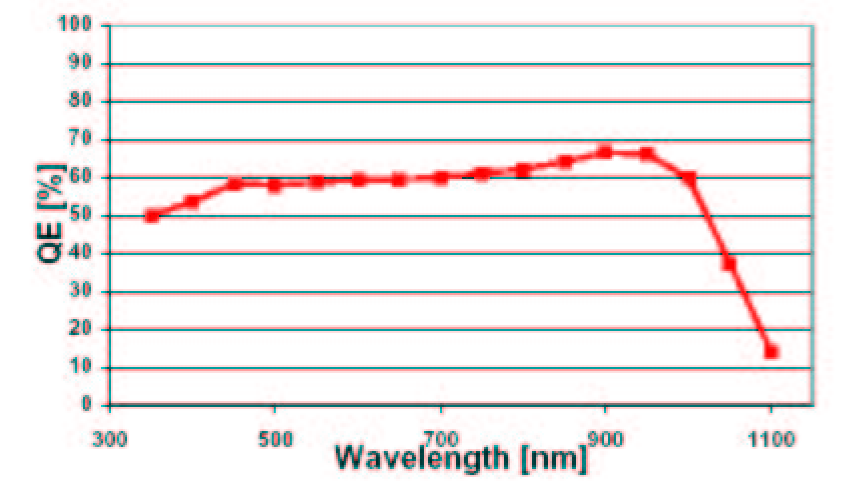


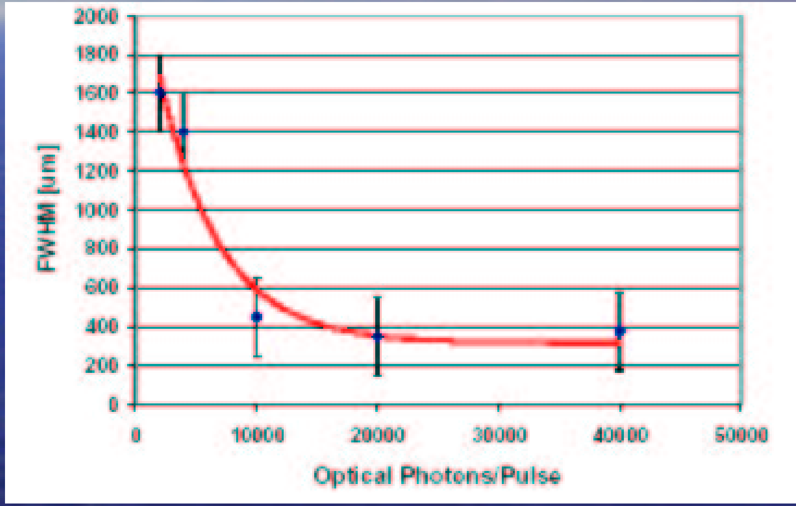
- Planar processing used for PSAPD fabrication.
- Charge sharing amongst anodes used to obtain position information.
- High gain and QE of APDs allows good spatial resolution even with large devices (28 x 28 mm^2)
- Only five contacts needed.

- High Gain: >1000
- Low Noise: 200-300 e$^-$ fwhm (14 x 14 mm^2)
- High Quantum Efficiency: ≥ 60%
- High Spatial Resolution: 0.3 mmfwhm
- Larger PSAPDs (28 x 28 mm^2) show noise of 700 e- fwhm and spatial resolution of < 1 mm fwhm

(From talk given by K.S. Shah at "New developments in photodetection", Beaune, 2002)

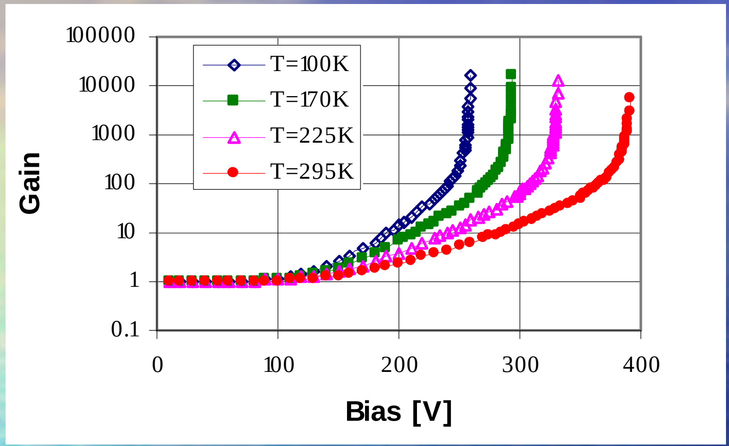
Quantum efficiency and spatial resolution (14x14 mm^2 APD, 25 C)

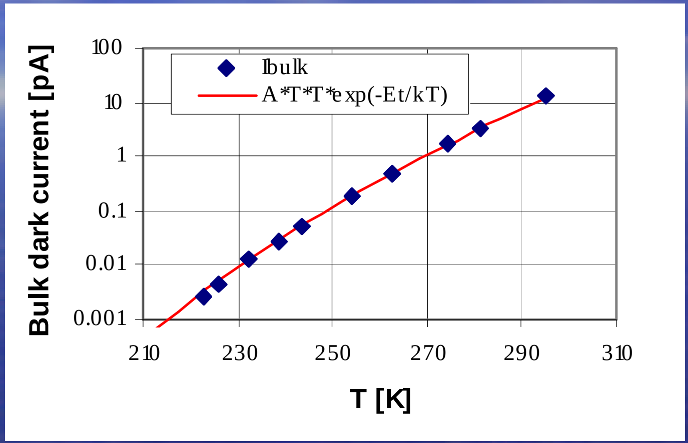


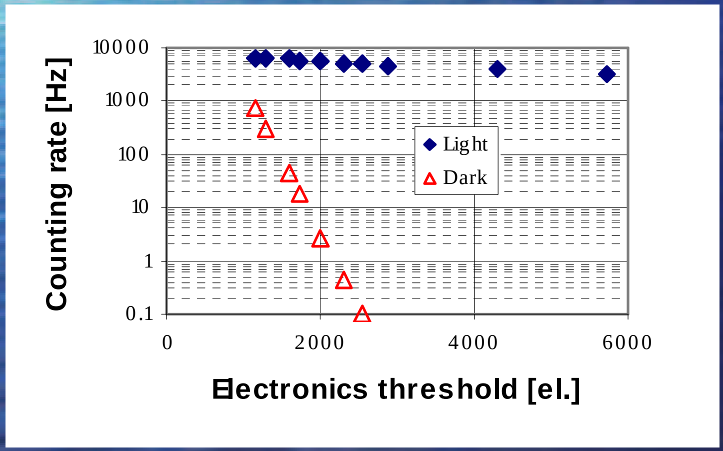


(From talk given by K.S. Shah at "New developments in photodetection", Beaune, 2002)

Photon counting at low temperatures







Hamamatsu 5x5 mm² APD successfully operated at T=100K. For 470 nm light ~16 % photon detection efficiency was measured with an APD operated at M~8000 and 2550 el. electronics threshold, while noise count was extremely low (0.1 Hz)

A. Dorokhov et al., NIM A504 (2003) 58

APD’s operated in Geiger mode

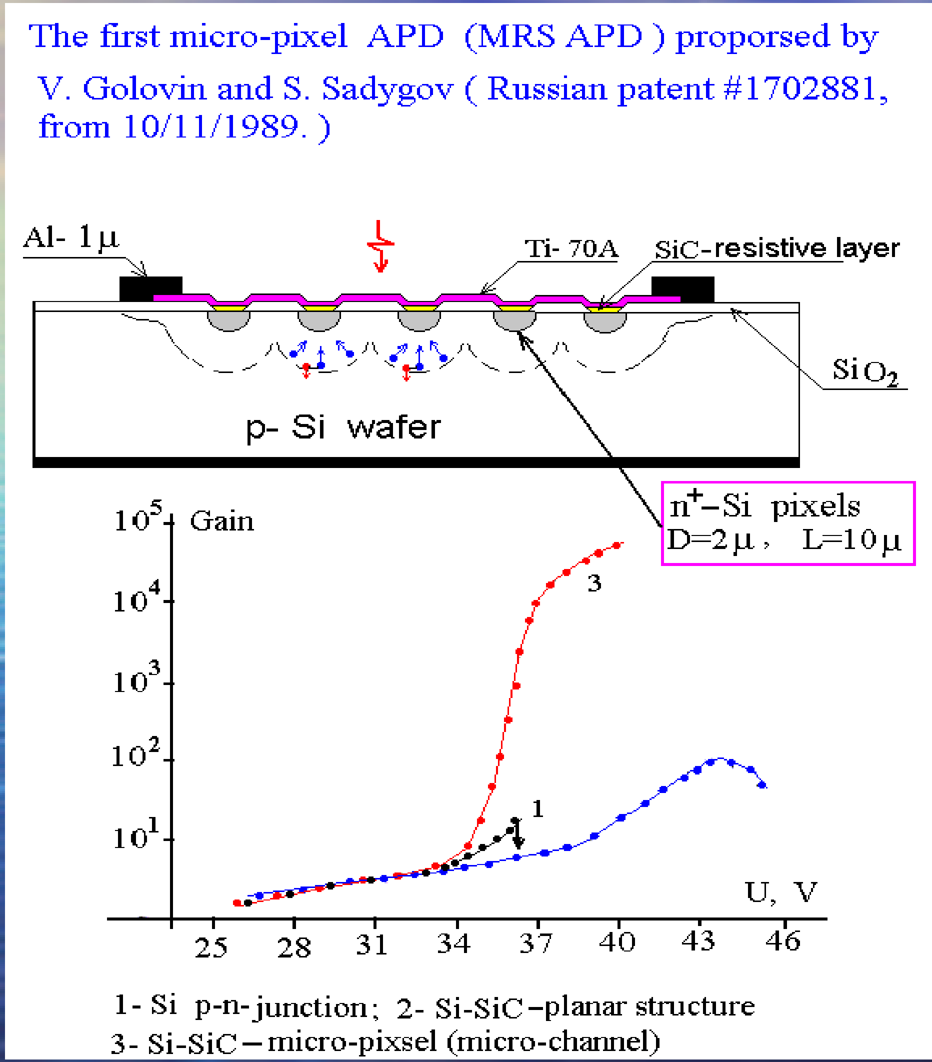
- Single pixel Geiger mode APD’s developed long time ago
  (see for example: *R.Haitz et al, J.Appl.Phys. (1963-1965))*
- Commercially available from single producer: Perkin Elmer Optoelectronics (up to Ø500 μm active size)

A prototype of sci. fiber hodoscope (Ø1mm fibers) was built and efficiencies up to 90% for 20 GeV electrons were reached. High sensitivity to radiation damage by neutrons was found (W. Bruckner et al., NIM A313 (1992) 429)

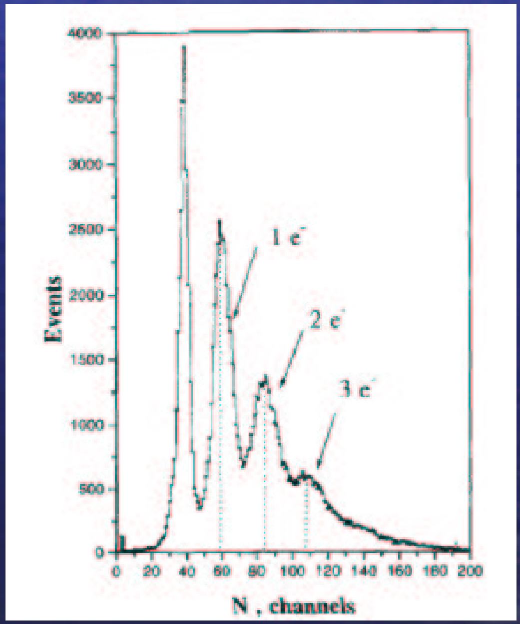
- Single pixel devices are not capable of operating in multi-photon mode
- Sensitive area is limited by dark count and dead time (few mm^2 Geiger mode APD can operate only at low temperature, needs “active quenching”)

Solution: multipixel Geiger mode APD

MRS APDs (old design)



Few % photon detection efficiency for red light was measured with 0.5x0.5 mm^2 APD. Good pixel-to-pixel uniformity. Small geometrical efficiency.



LED pulse hight spectrum (A. Akindinov et al., NIM387 (1997) 231)

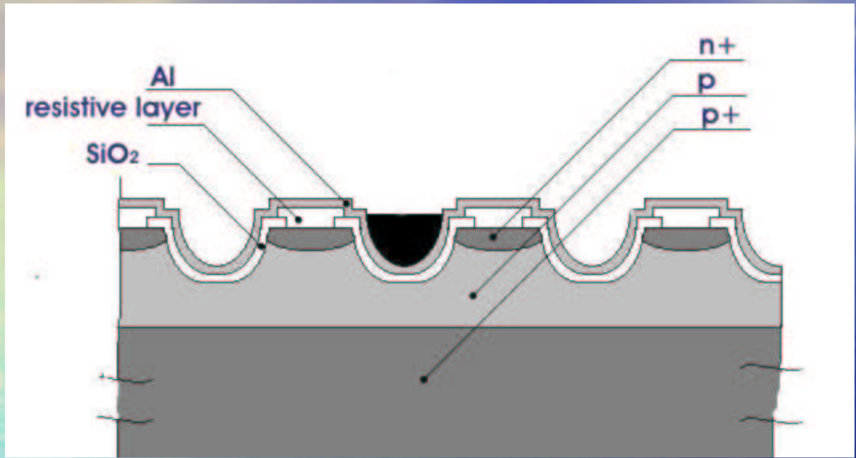
New APD designs

Today there are at least - 3 producers:

- Pulsar/MEPhI (see presentation of B. Dolgoshein)
- CPTA (V.Golovin)
- Dubna (INR/JINR, Z.Sadygov)

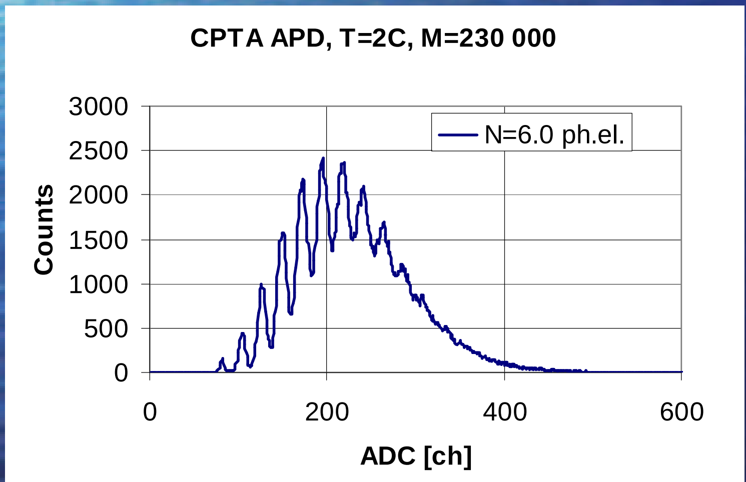
I will briefly describe structure and performances of CPTA and Dubna APDs

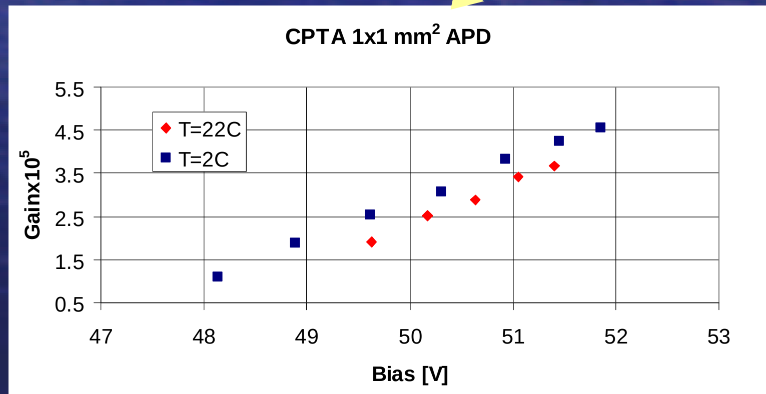
CPTA APD



Schematic APD structure

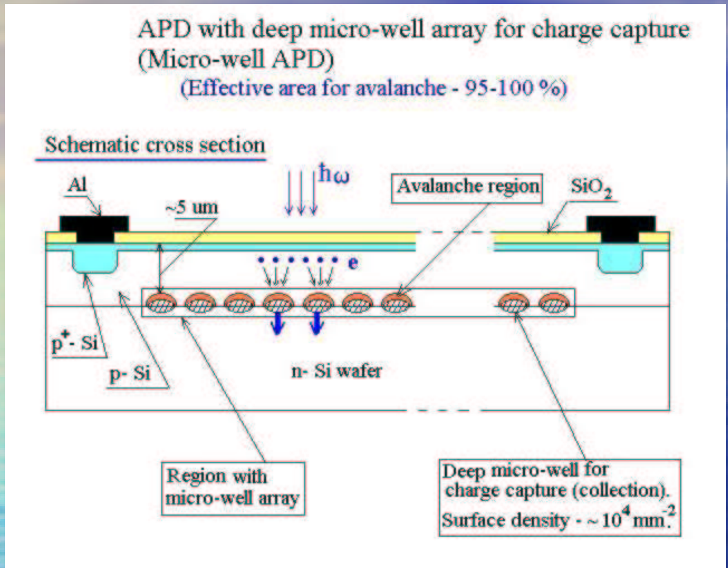
~1440 pixels/mm^2, geometric factor ~60% gain= 2÷4$\cdot$10^5, excellent temperature stability – 15% change of the gain for ΔT=20C and gain= 4$\cdot$10^5, 1x1 mm^2 and 3x3 mm^2 APD have been produced

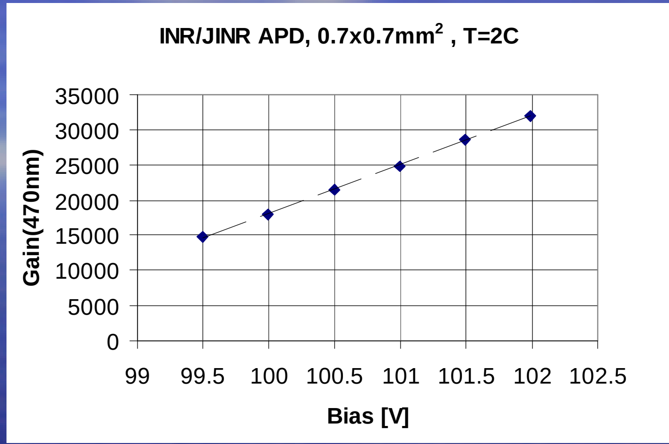


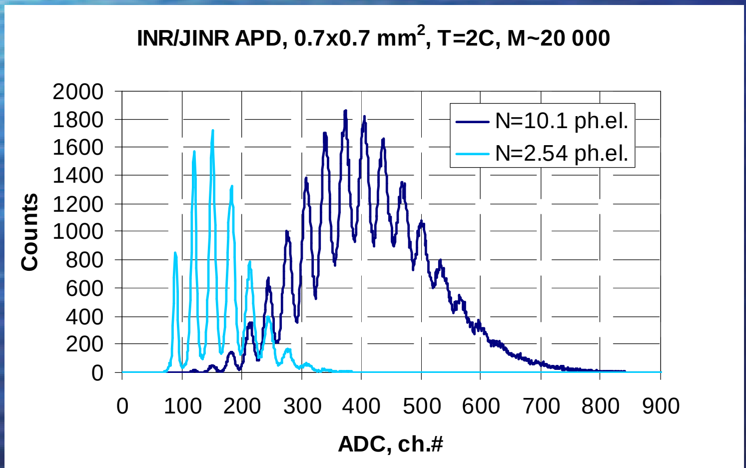


LED pulse hight spectrum

Dubna (INR/JINR) APDs



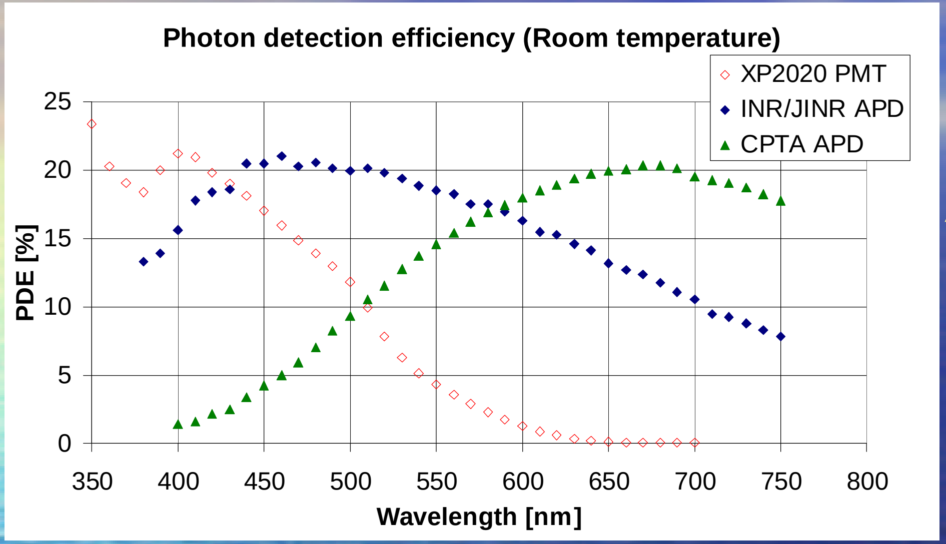




APD designed to be sensitive for blue and UV light. Pixel size is small ~10x10 μm^2 – increased dynamic range (up to 10^4 g/mm^2)

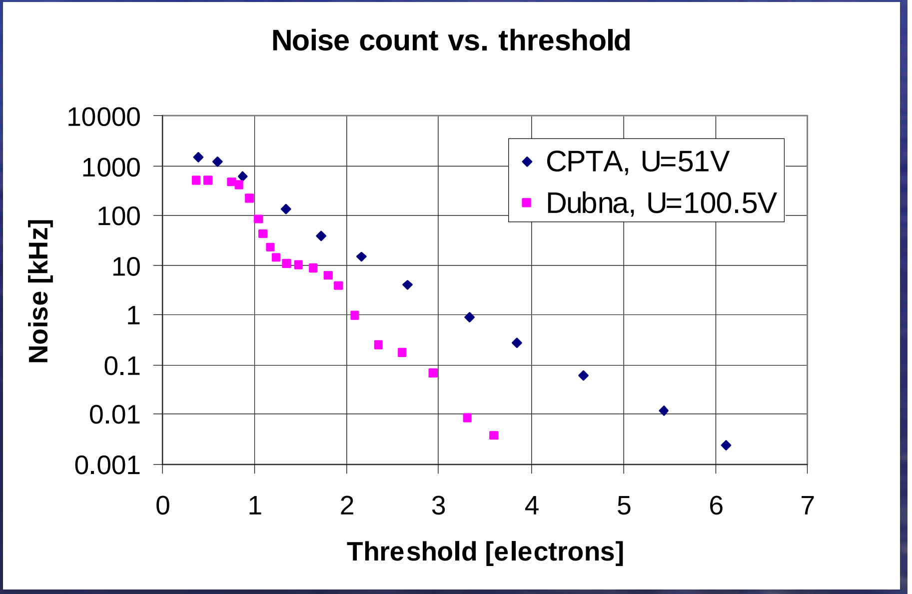
Excellent gain uniformity, 0.7x0.7 mm^2, and 2.7x2.7 mm^2 APD's are produced

Photon Detection Efficiency and Noise Count

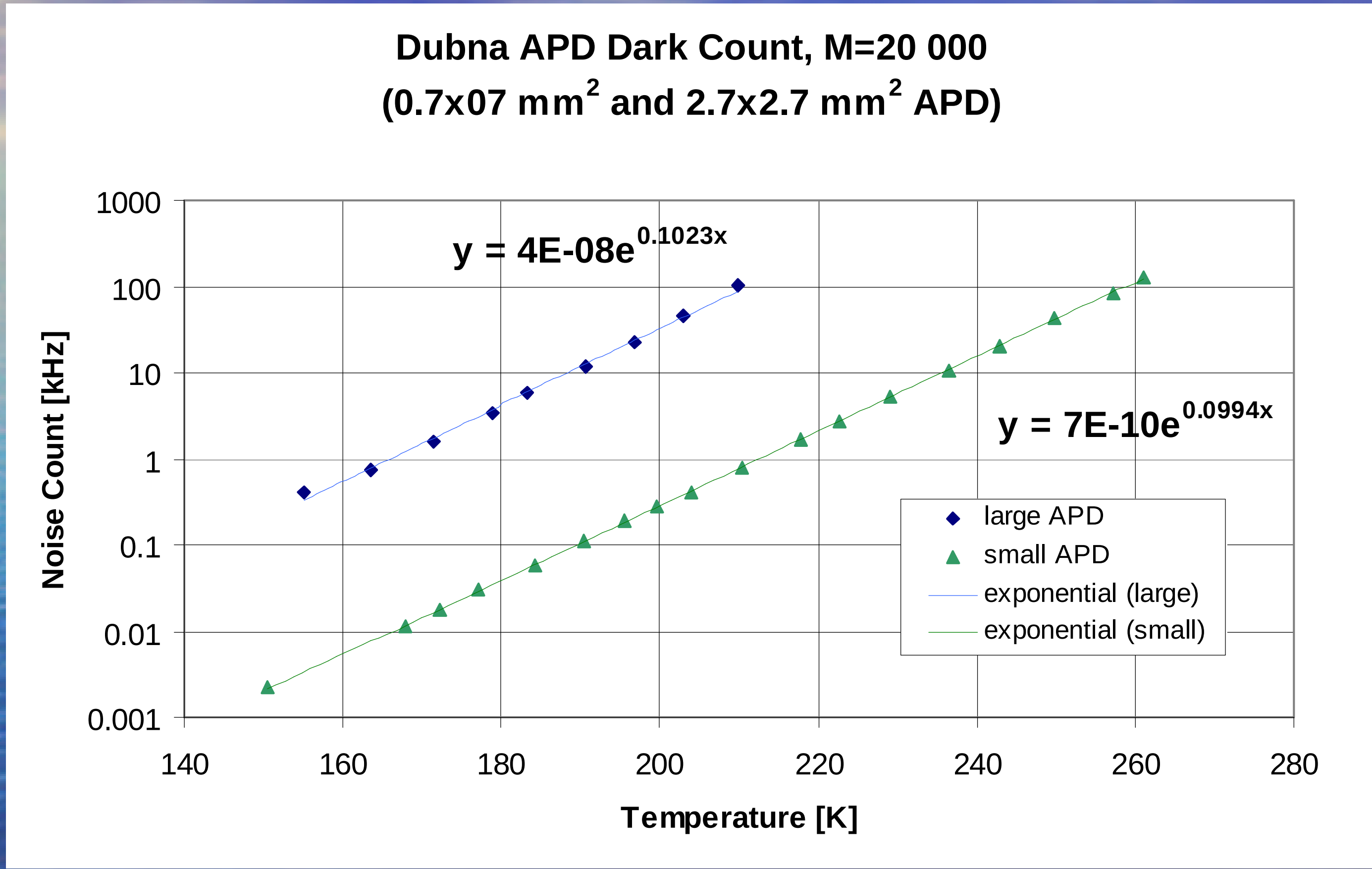


Photon detection efficiency vs. wavelength for CPTA, Dubna APDs and XP2020 photomultiplier

Dark count vs. electronics threshold (calibrated in electrons) For Dubna APD cross-talk between pixels is very small. For CPTA APD it is less than 10%.



Low temperature operation



Dark count reduces exponentially with the reduction of temperature .
Dubna APD proved to be operational at T~20 K

Conclusion

- *Last 5-7 years - enormous progress in APD development*
- *Linear mode APDs (thanks to cooperation between CMS and Hamamatsu) became robust reliable and radiation hard*
- *Excellent APDs from several producers (Hamamatsu, API, RMD, Perkin Elmer) are available on the market – photosensors-candidates for supercolliders*
- *New APD's developments look very promising*

Solid state photomultipliers – dream, becoming a reality ?