Radiation damage in multipixel Geiger-mode avalanche photodiodes (G-APDs).

Y. Musienko,

Northeastern University, Boston

&

INR, Moscow

Outline

- *Radiation damage in silicon detectors*
- *Specific features of G-APDs radiation damage*
- *G-APD radiation damage studies:*

  - positrons

  - gammas

  - neutrons

  - protons
- *Discussion of the results*

Radiation damage in semiconductors (Si)

Radiation damage in silicon is strongly dependent on the type and energy of the radiation

Two types of radiation damage:

- *Surface damage (ionizing damage in the Si/SiO_2 interface)*
- *Bulk damage (crystal lattice defects: displacement of silicon atoms)*

Surface damage

SiO_2 is a very good insulator (or a semiconductor with a large band gap of 8.8 eV). Electron/hole pairs created by ionizing particles can be trapped into very deep levels associated with the defects in oxide from which the emission back into conduction/valence band is very unlikely at room temperature

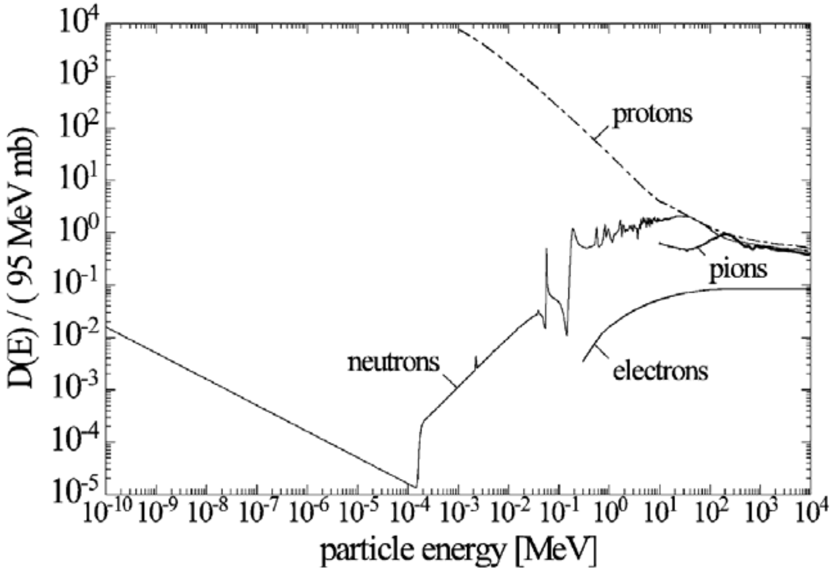
Accumulation of positive charges in the oxide (SiO_2) and the Si/SiO_2 interface leads to a creation of parasitic fields

This may cause:

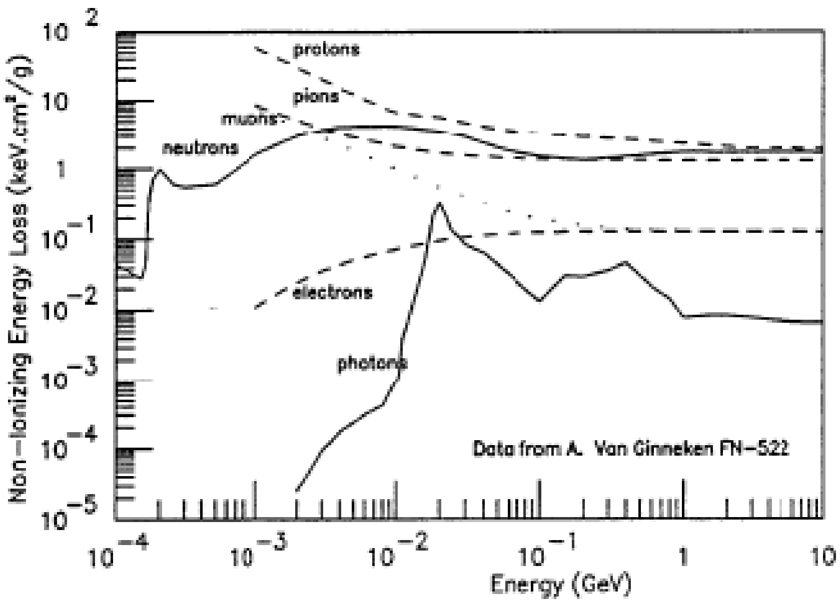
- breakdown voltage shift (early APD breakdown or unrecoverable dielectric damage)
- QE reduction
- surface current increase

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).

NIEL(1 MeV gammas) ~ 10^{-5} * NIEL(1 MeV neutrons)

Bulk damage effects

- Formation of mid-gap states, which facilitate transition of electrons from the valence to the conduction band → increase of the dark current generated in the silicon bulk:

$$I = \alpha \Phi_{eq} V$$

Φ_{eq} – 1 MeV neutron equivalent total flux

V – silicon active volume

α – dark current damage constant (~4*10^{-17} A/cm for 1 MeV neutrons after 80 min annealing at 60 C or ~10^{-16} A/cm few day annealing at room temperature)

- Creation of states close to the band edges → charge trapping (QE readuction)

- Creation of acceptor-like states → changes in the effective doping concentration :

$$\Delta N = N_0(1 - e^{-c\Phi}) + b\Phi$$

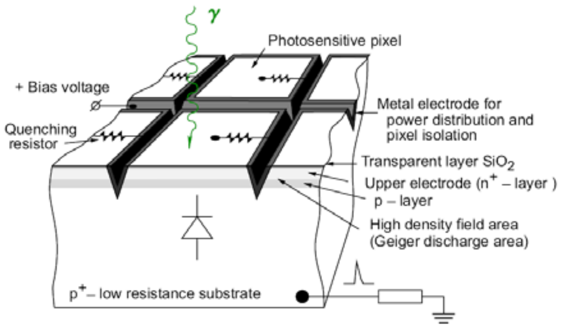
where $N_0 = 3.36(\pm 0.03) \times 10^{11}\,\mathrm{cm}^{-3}$, $c = 3.58 (\pm 0.2) \times 10^{-13}\,\mathrm{cm}^2$, $b = 0.0171(\pm 0.0001)\,\mathrm{cm}^{-1}$, and Φ is the total neutron fluence in neutrons/cm^2.[5]

HERA-B Design Report, DESY–PRC 95/01, 1995.

Changes in the effective doping concentration may cause changes of the electric field distribution → change of the APD gain

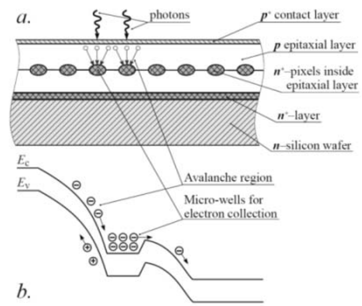
Specific features of G-APDs radiation damage

<u>CPTA/Photonique SSPM (schematic view)</u>



(from O.Mineev et al. NIM A577)

<u>Zecotec MAPD (schematic view)</u>



(from Z. Sadygov et al. NDIP-08 conference)

G-APDs specific features: integrated quenching resistor ~100 kOhm – 100 MOhm, high electric field (close to the device surface), high gain ~5*10^4 – 5*10^6 …

<u>G-APDs possible radiation damage:</u>

- **Dark current and dark count increase:**
  - **- thin epi layer (2-5 μm) → low volume, low thermal generation rate**
  - **- high electric field (>3*10^5 V/cm) → field enhanced generation (?)**
- **Quenching resistor damage/change (made of polysilicon) (?)**
- **Change of the gain and PDE vs. voltage dependence:**
  - **- due to G-APD cell limited recovery time and high dark carrier generation rate**
  - **- breakdown voltage change (due to charge accumulation in SiO_2 layer or/and junction temperature increase)**
- **Fatal G-APD damage (G-APD can't be used after certain absorbed dose)**

G-APD radiation hardness studies

G-APD's radiation hardness was studied with:

200 MeV protons (ITEP)

- *MEPhI/Pulsar SiPMs*

53.3 MeV protons (Osaka Univ.)

- *Hamamatsu MPPCs*

0.1-1 MeV neutrons (reactor (YAYOI))

- *Hamamatsu MPPCs*

290 MeV/nucleon $C6^{+}$ ions (HIMAC)

- *Hamamatsu MPPCs*

Co^{60} ~1 MeV gammas (Tokyo Tech)

- *Hamamatsu MPPCs*

28 MeV positrons (PSI)

- *Hamamatsu MPPCs, CPTA/Photonique SSPMs, Dubna/Micron AMPDs*

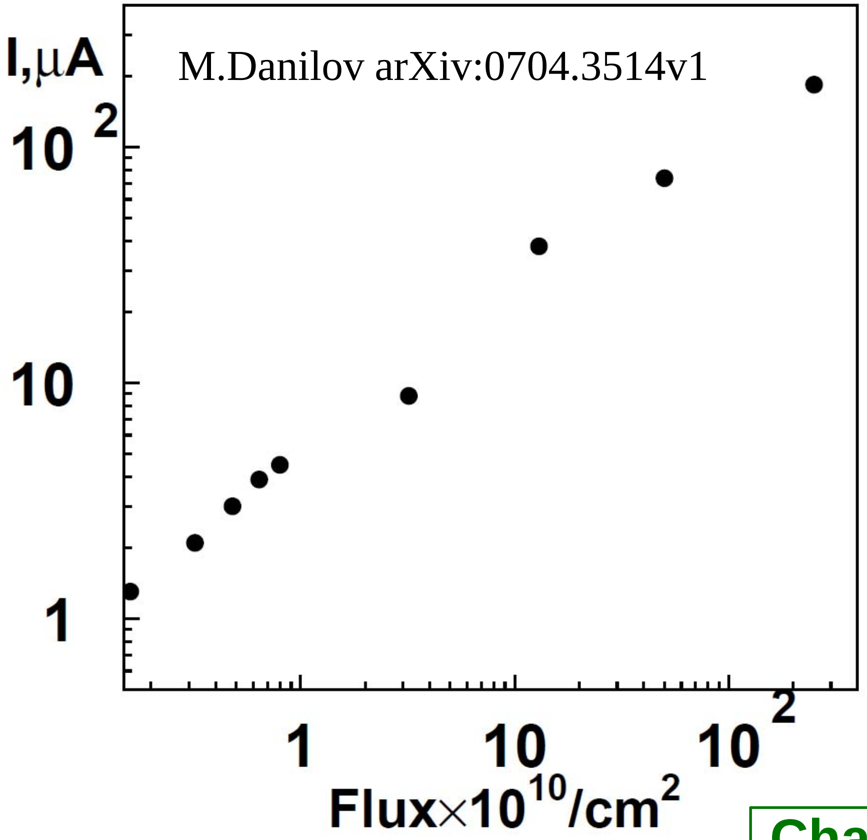
82 MeV protons (PSI)

- *Hamamatsu MPPCs, CPTA/Photonique SSPMs, Zecotec MAPDs, Pulsar SiPMs, FBK-irst SiPMs, SensL SPMs*

212 MeV protons (Massachusetts General Hospital)

- *Hamamatsu MPPCs, CPTA/Photonique SSPMs, Zecotec MAPDs, FBK-irst SiPMs*

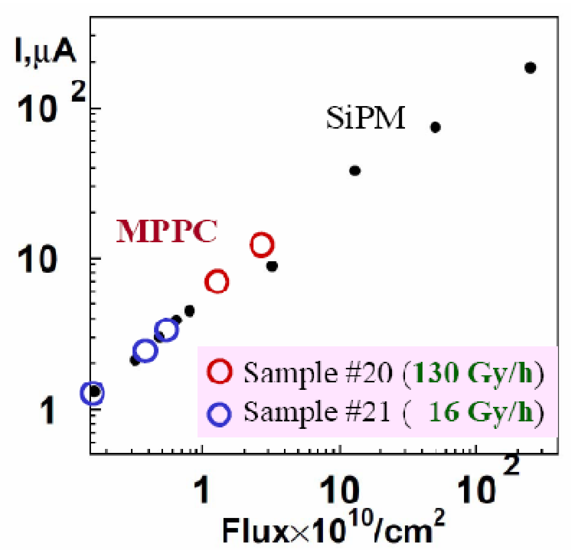
200 MeV protons (MEPHI/Pulsar SiPMs)

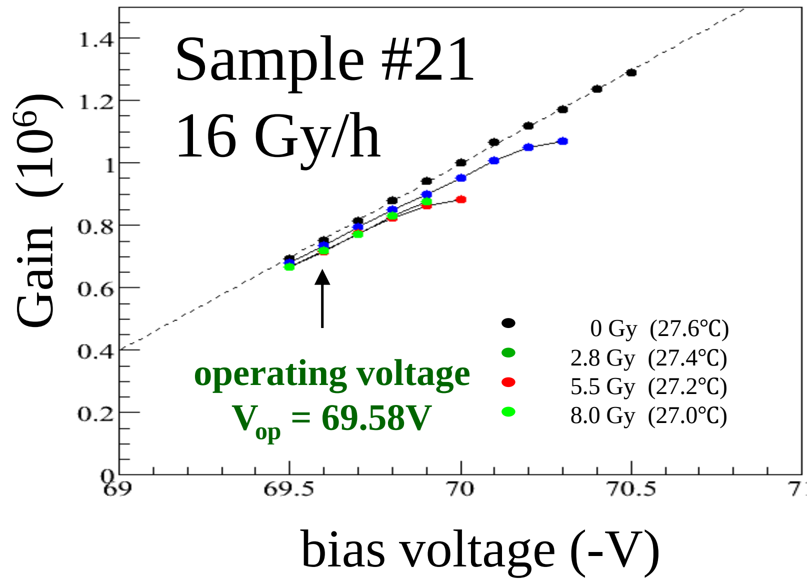


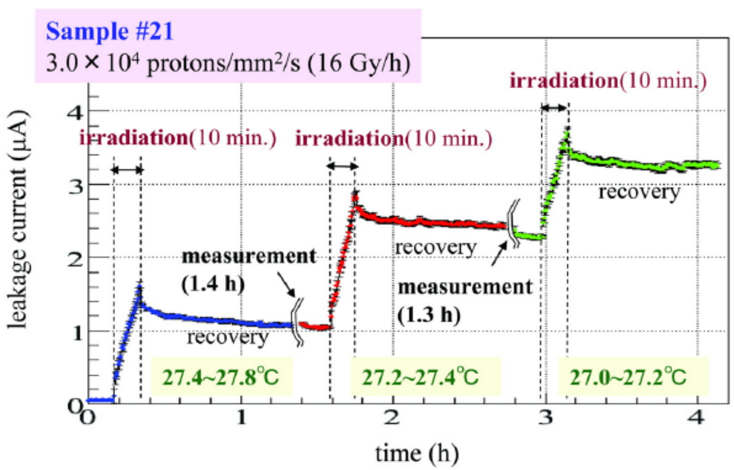
- $\Delta I \cdot M = 4\ \mu A$ after 10^{10} p/cm^2
- M ~10^6 , PDE(515nm) ~15%, S~1.2 mm^2
- NIEL(200 MeV protons)~ NIEL(1 MeV neutrons)

Change of PDE, Gain, dark count increase was not measured

53.3 MeV protons (Hamamatsu MPPC)







ΔI*M~4 µA after 10^{10} p/cm^2
M ~10^6 , PDE(515nm) ~30%, S=1 mm^2
NIEL(53 MeV protons)~ 2*NIEL(1 MeV neutrons)
Change of the gain vs. bias dependence? PDE?

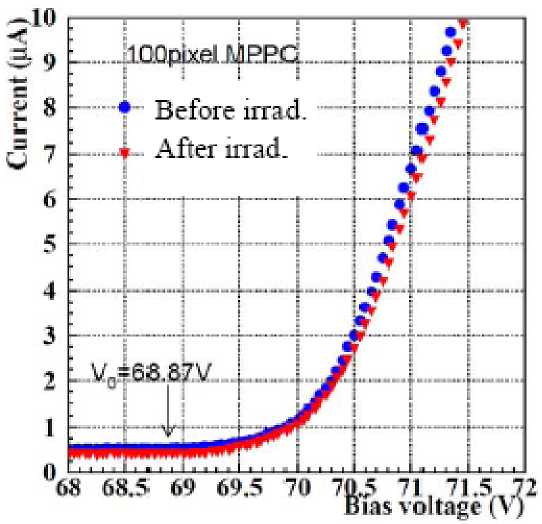
(From talk of T. Matsumura at PD-07)

Reactor neutrons

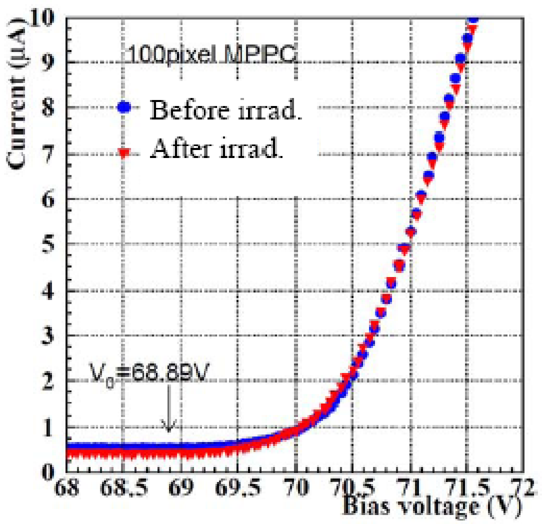
I-V curves (preliminary)

MPPC S10362-11-100CK (100 pixels)

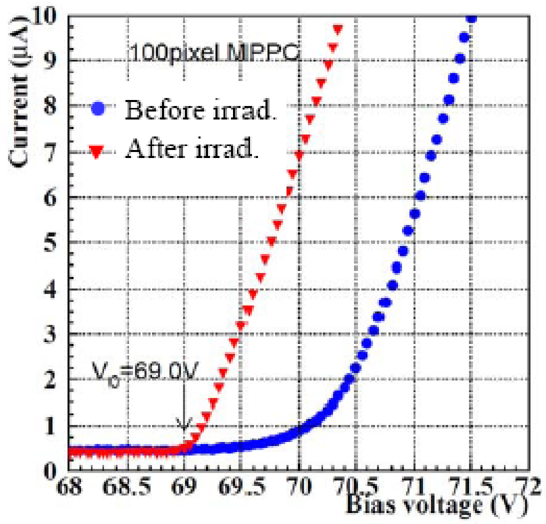
8.3×10^4 neutrons/mm^2



3.3×10^5 neutrons/mm^2



1.0×10^8 neutrons/mm^2

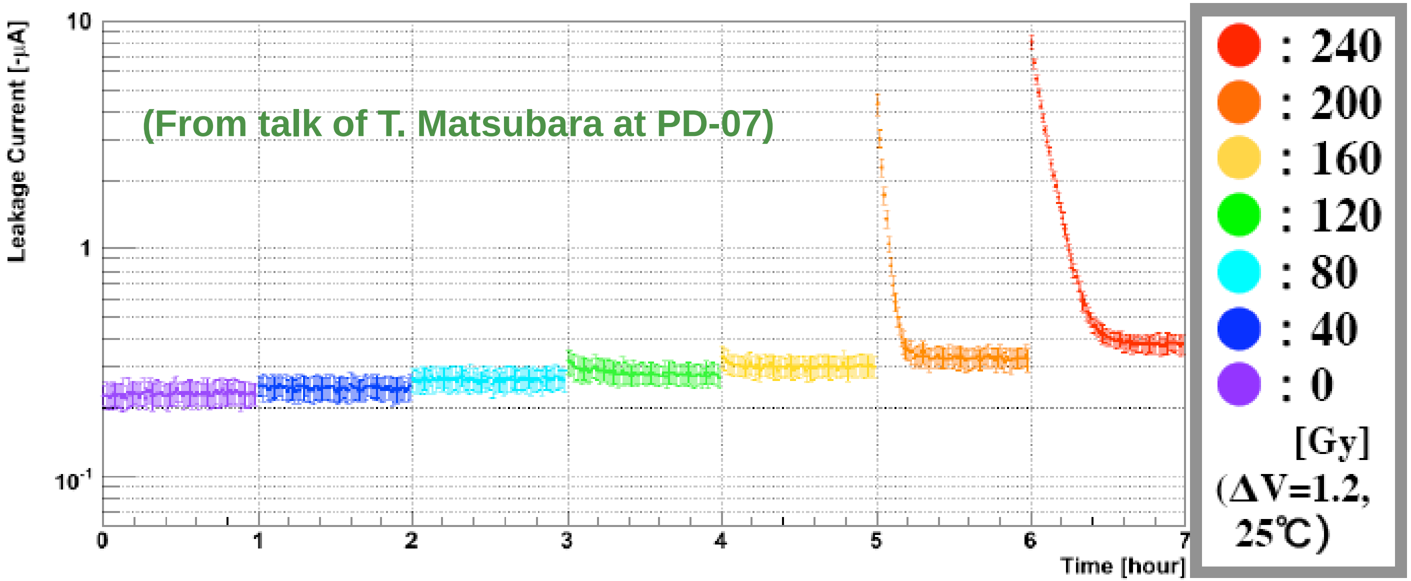


(From talk of T. Matsumura at PD-07)

$\Delta I \cdot M \sim 10$ μA (V-VB~1.4V) after 10^{10} n/cm^2
M ~2.5-3*10^6 , PDE(515nm) ~35%, S=1 mm^2
Gain? PDE?

1 MeV gammas from Co-60 source

Leakage current after each irradiation



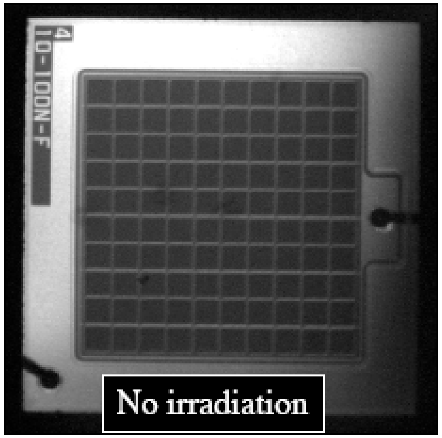
- Leakage current at V_{op} increased ~1.7 times by these irradiations comparing the second half of each data
- Annealing effect were observed from 120Gy irradiation
- Leakage current changed so much just after 200Gy and 240Gy

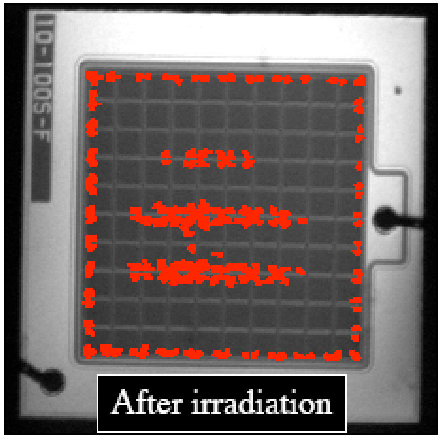
(From talk of T. Matsubara at PD-07)

MPPC damaged by gamma irradiation

Infrared emission

- We took a picture by infrared camera, supplying bias voltage in order to look at where the high dark noise generated
- A large current flows in the red area





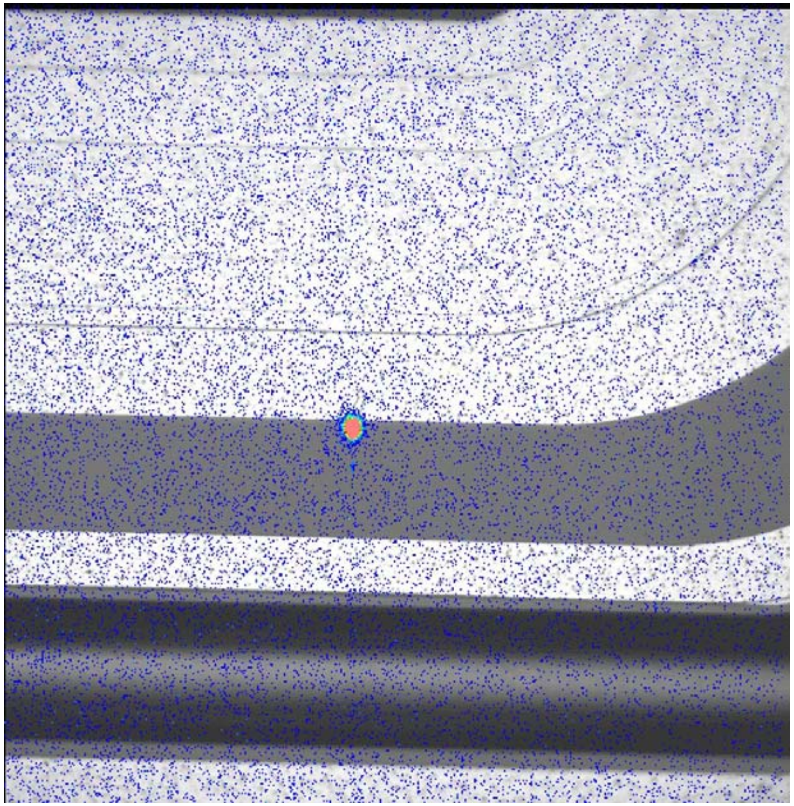
- We find the localized spot where the high dark noise generated
  - Outer edge of device and along the bias lines (to see full device)
  - Edge of a pixel (to see 1 pixel)

(＊)Bias lines exist alternately

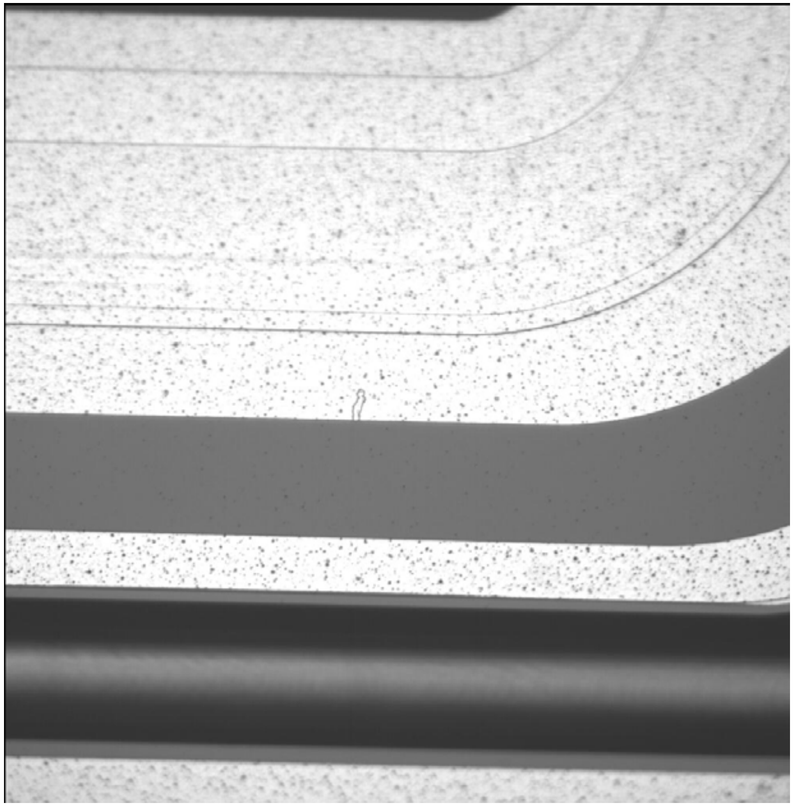
(From talk of T. Matsubara at PD-07)

CMS APD damaged by 1 MeV gammas

Bias "ON"



Bias "OFF"



"Defect" is seen on all APD`s from the same position on the wafer - defect of the mask

28 MeV positrons (PSI)

The reason we used 28 MeV positrons for APD irradiation:

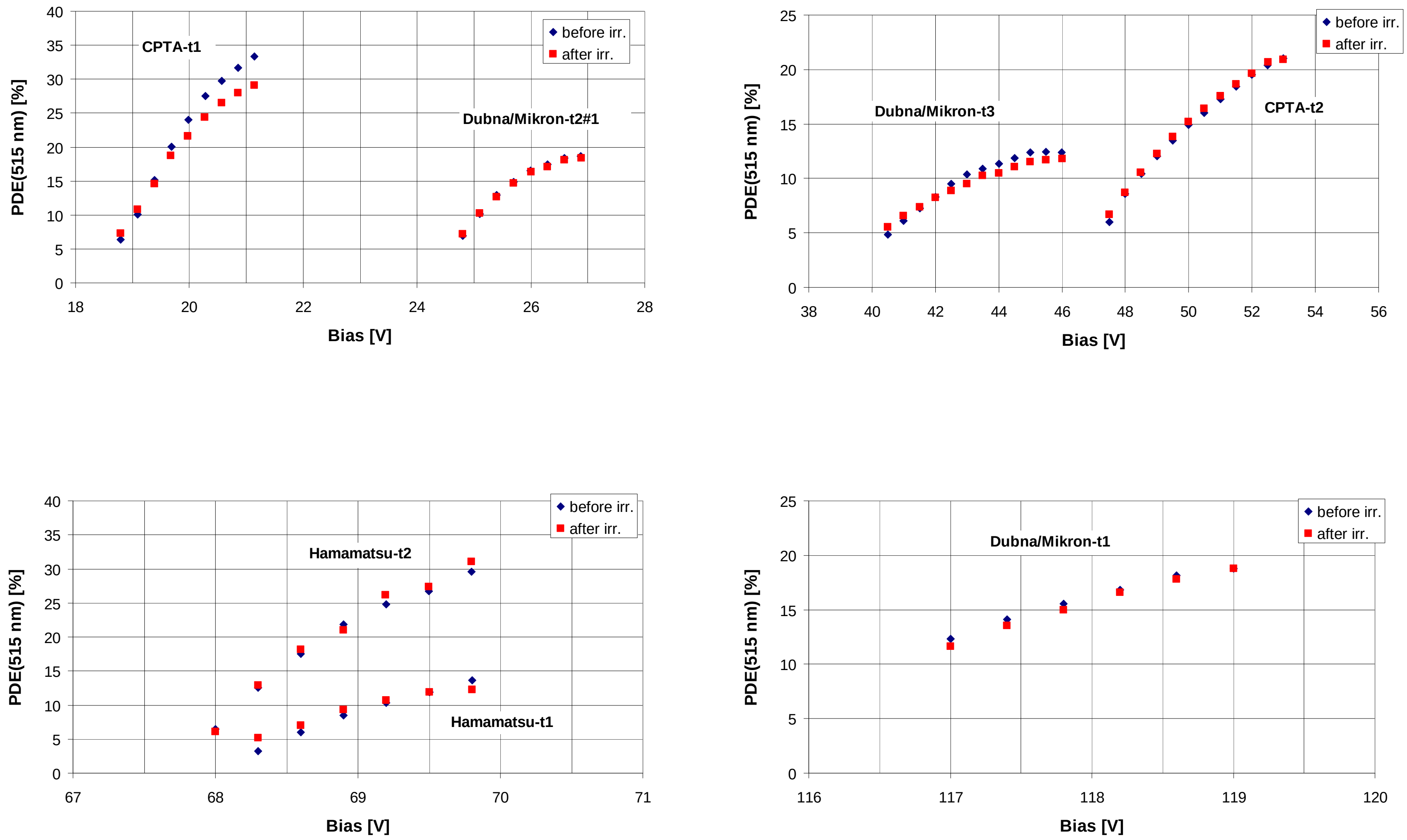
- Excellent positron beam available at Paul Scherrer Institut (Villigen, Switzerland)
- Possibility to monitor and control beam intensity
- APDs are not activated during irradiation and measurements can be performed immediately after irradiation

G-APDs and their parameters before irradiation (T=22 C)

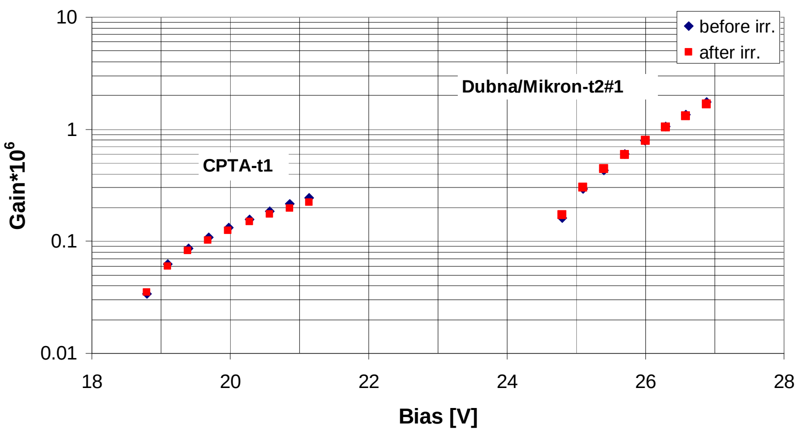
G-APDs	Producer's reference	Substrate	Area [mm²]	# of pixels	Uop [V]	Gain*10⁶ (Gate=60 ns)	PDE(515 nm) [%]	Dark Count [MHz]
CPTA-t1	SSPM-0606BG4MM-PCB*	p-type	4.41	1748	21	0.2	32	20
CPTA-t2	F1707	p-type	1	556	52.5	1.2	20	4
Dubna/Mikron-t1	MW-3	n-type	1	10 000	119	0.05	19	7
Dubna/Mikron-t2#1	p-INT-2	p-type	3.24	2436	26.5	1.5	18	8
Dubna/Mikron-t2#2	p-INT-2	p-type	3.24	2436	26	1.5	18	8
Dubna/Mikron-t3	pMP-3d-11	p-type	1	1024	45.5	0.9	12	5
Hamamatsu-t1	311-31A-001	n-type	1	1600	69.5	0.5	12	0.5
Hamamatsu-t2	311-53-1A-001	n-type	1	400	69.5	3.5	27	1.3

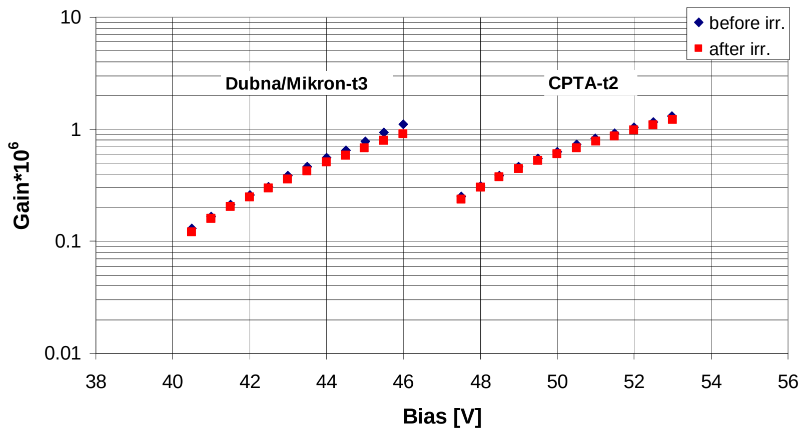
*Photonique SA reference

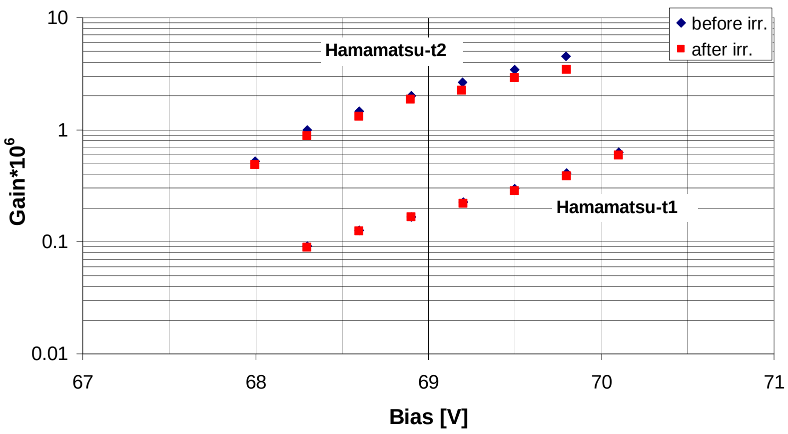
Photon detection efficiency vs. bias voltage dependence (before and after $8 \cdot 10^{10}$ positrons/cm^2) measured at T=22 ºC

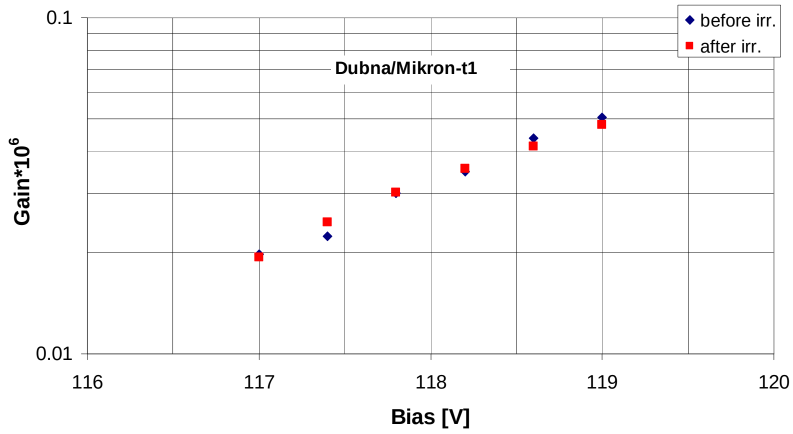


Gain vs. bias voltage dependence (before and after $8*10^{10}$ positrons/cm^2) measured at T=22 ºC

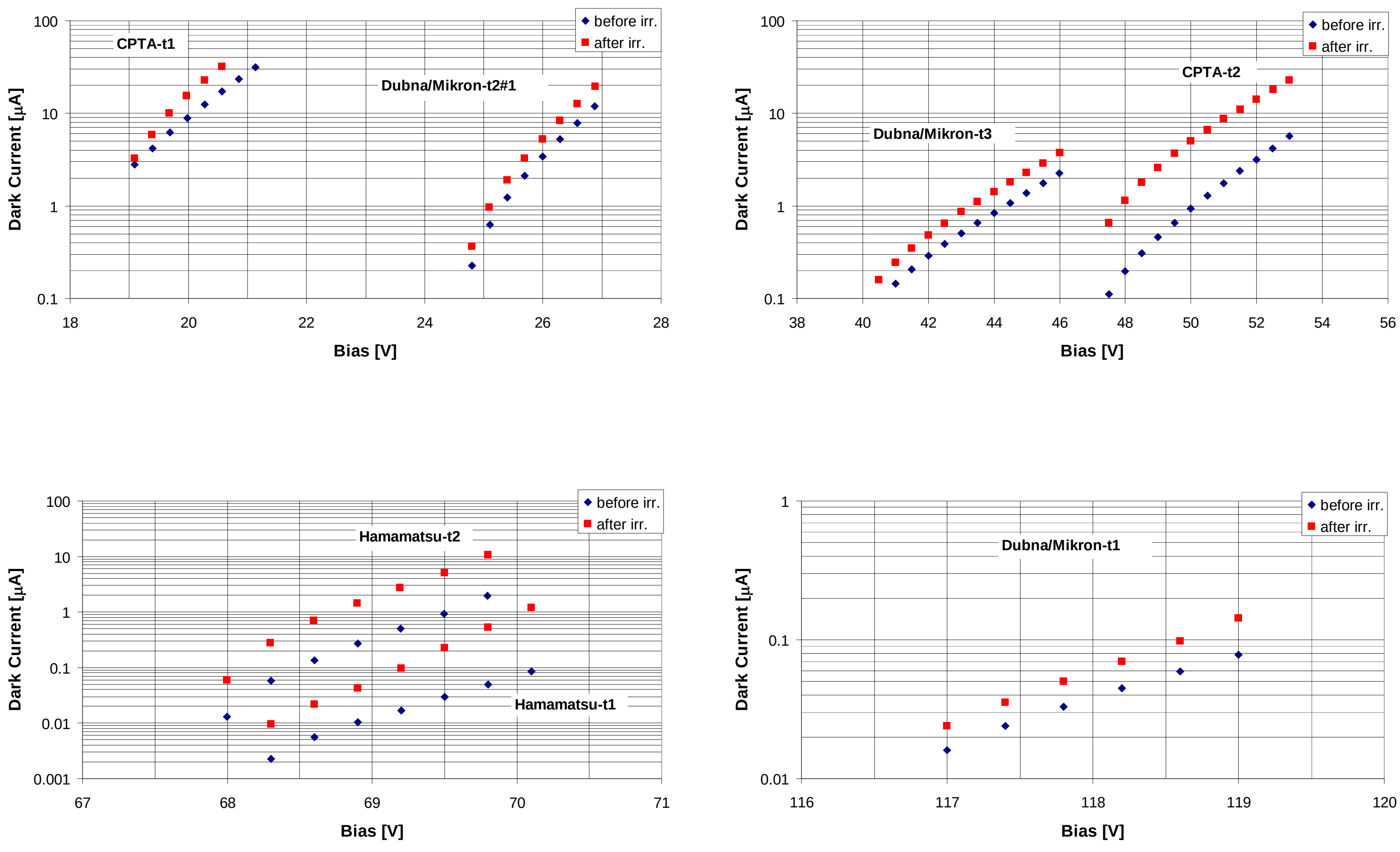




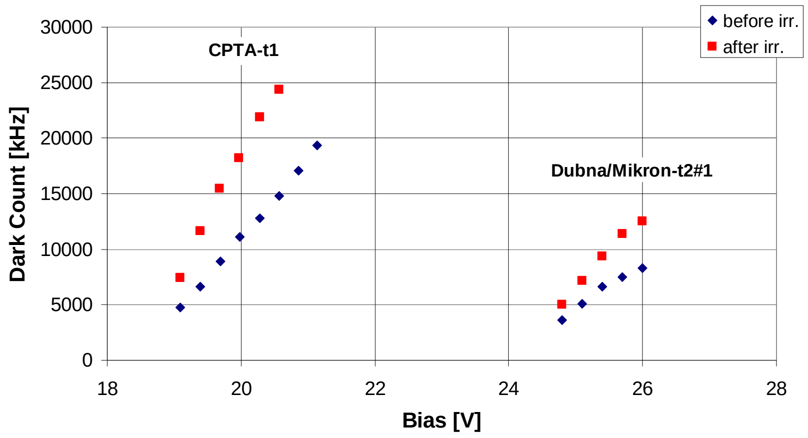


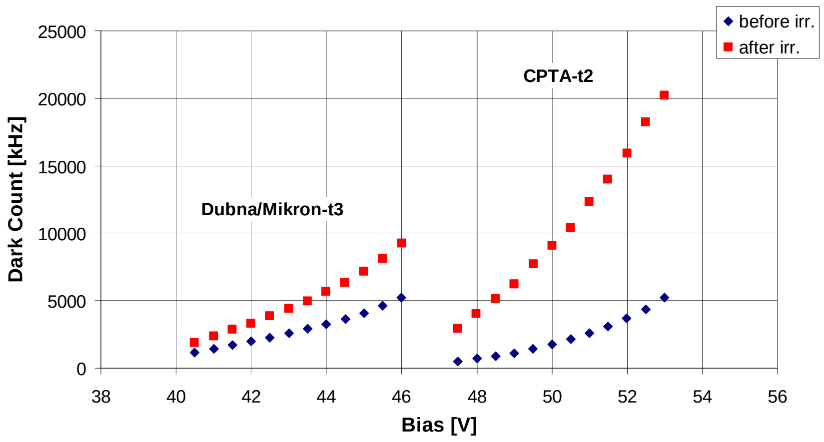


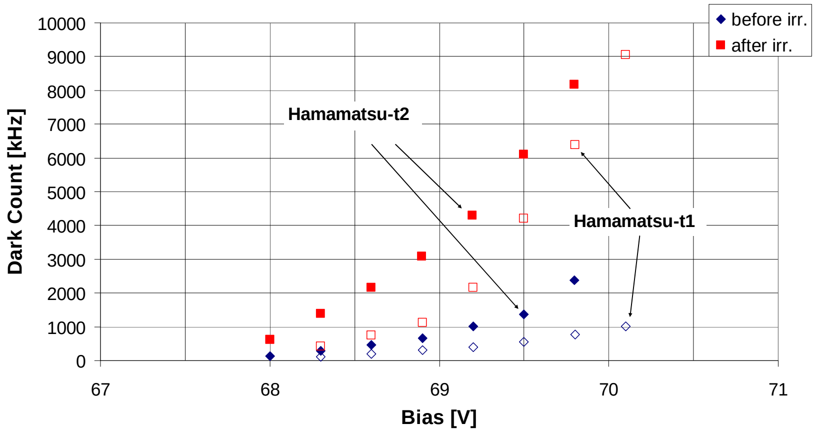
Dark current vs. bias voltage dependence (before and after 8*10^{10} positrons/cm^2) measured at T=22 ºC

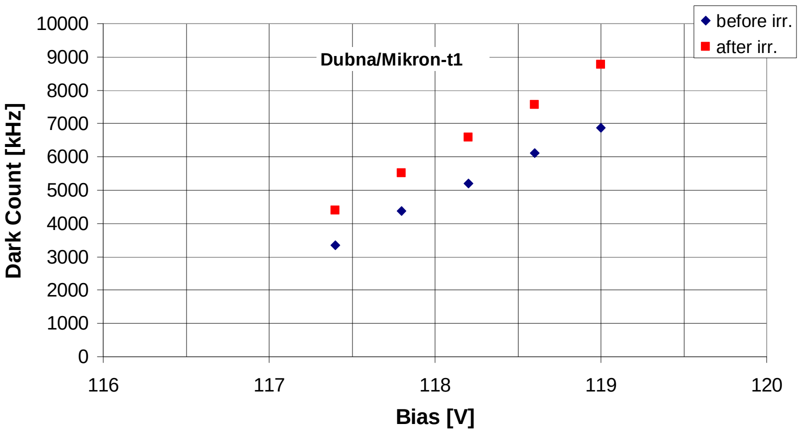


Dark count rate vs. bias voltage dependence (before and after $8*10^{10}$ positrons/cm^2) measured at T=22 ºC









G-APD dark current increase due to radiation

Model (see Y. Musienko et al. NIM A581)

Active G-APD volume:

$V = S*G*L = s*L$

S - total area

s - active area (total area minus non-sensitive area between pixels)

G - geometric factor

L - depletion layer thickness

Expected G-APD dark current increase after irradiation:

$\Delta I = \alpha * M * P_G * \Phi_{eq} * V$

α - dark current damage constant

M – G-APD gain

P_G – Geiger discharge probability (is a f[V-VB])

Φ_{eq} – 1 MeV neutron equivalent total flux

Dark Count Increase/PDE/Area

G-APDs have different area, geometric factor, depletion volume, etc. How to compare the dark count increase produced by radiation in different G-APDs?

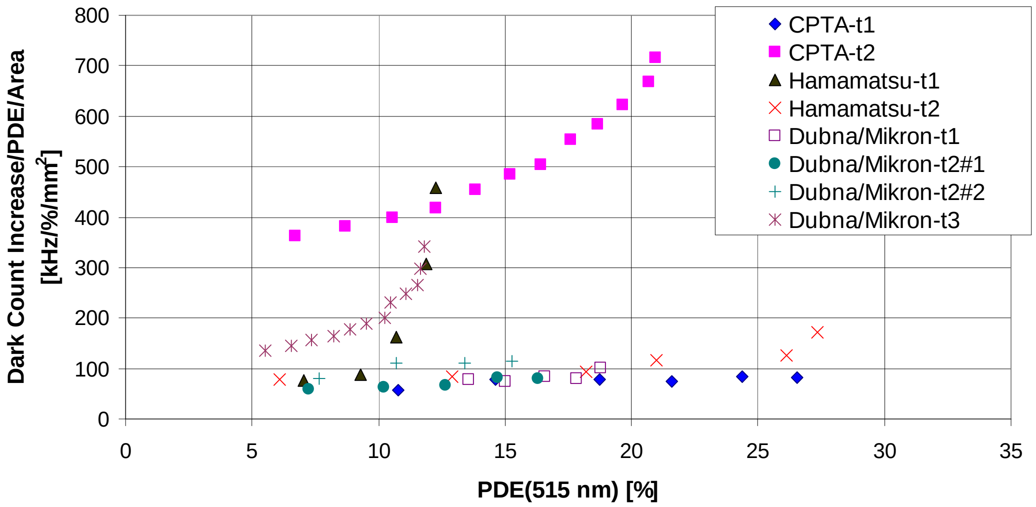
Expected G-APD dark count increase after irradiation:

$\Delta N = \Delta I/q/M = \alpha * M * P_G * \Phi_{eq} * V/q/M = \alpha * P_G * \Phi_{eq} * S * G * L/q$, *q – electron charge*

Assuming that $PDE = QE * P_G * G$:

$\Delta N \sim \alpha * PDE * \Phi_{eq} * S * L/q/QE \rightarrow \Delta N/PDE/S \sim 1.4 * \alpha * \Phi_{eq} * L/q$ **(QE(515nm)~0.7)**

This ratio is expected to have weak dependence on the G-APD PDE, geometric factor and sensitive area. Dependence on the depletion thickness remains.



NIEL factor for 28 MeV positrons is ~30 times smaller than for 1 MeV neutrons → L~3-25 μm

G-APDs irradiation studies at PSI (82 MeV protons)

- 23 G-APDs from 5 different producers irradiated at PSI at the end of last year

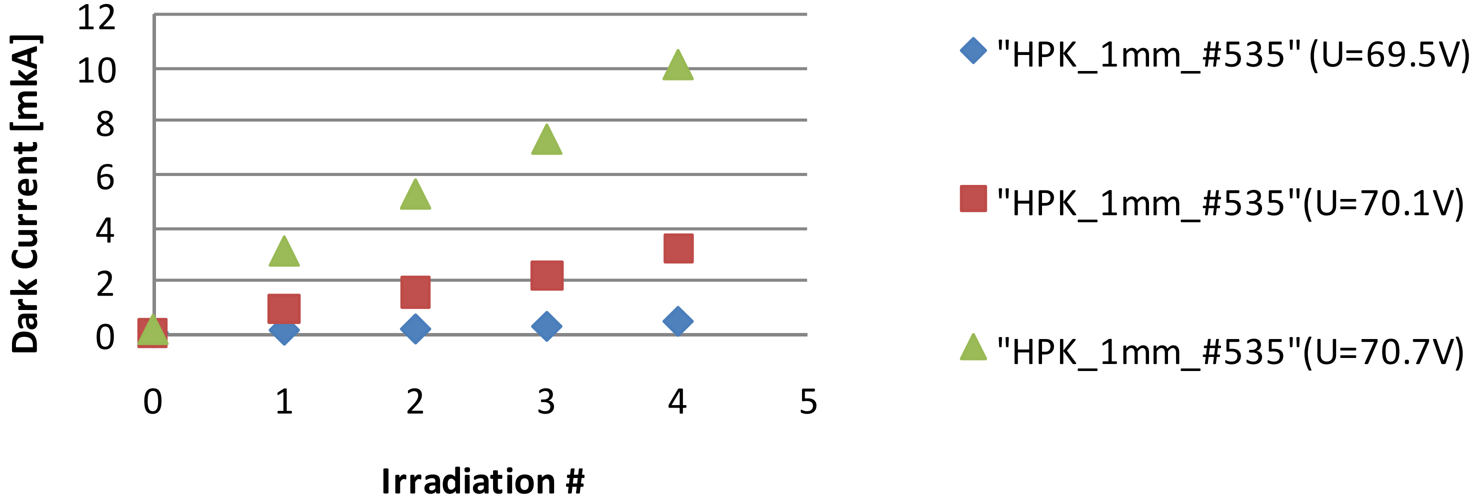
- **CPTA/Photonique**
- **FBK**
- **Hamamatsu (HPK)**
- **MEPhI/Pulsar**
- **Zecotek**

- $1*10^{10}$ 400 MeV/c (82 MeV kinetic energy) protons/cm^2 in 4 steps
- NIEL factor is ~2 times of 1 MeV neutrons, Total flux: $1*10^{10}$ protons/cm^2, equivalent to ~$2*10^{10}$ 1 MeV neutrons/cm^2
- Gain, PDE, Id, Dark count vs. voltage, forward G-APD current were measured before and 4 month after irradiation

G-APDs and some of their geometric and electrical parameters before irradiation (T=22 C)

G-APDs	Substrate	Area [mm²]	# of pixels	VB [V]	R_{pix} [MOhm]
CPTA/Photonique	p-type	1	556	30.1	7.1
MEPhI/PULSAR	p-type	1	1024	56.4	0.4
FBK	p-type	1	400	30.75	0.43
Zecotek (MAPD-2A)	p-type	1.1	576	33.85	0.2÷0.8?
HPK S10362-11-050C	n-type	1	400	69.05	0.11

Dark current increase during irradiation



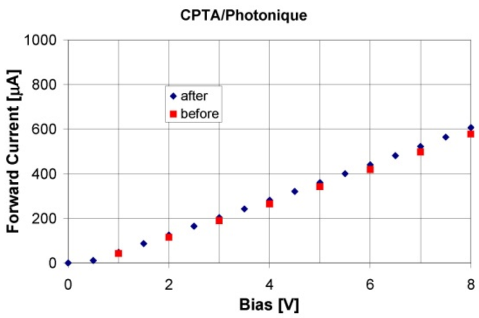
First result: Dark current increased linearly with the integrated flux for all 5 G-APDs

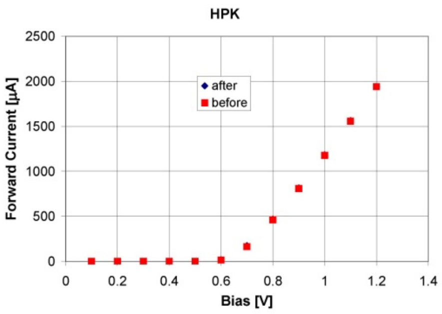
Change of the breakdown voltage after irradiation (T=22 C)

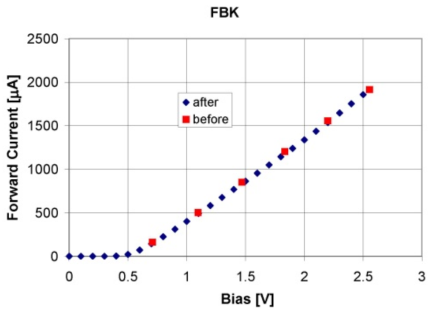
G-APDs	VB [V] – before irr.	VB [V] – after irr.	Estimated measurements error [V]
CPTA/Photonique	30.1	30.06	0.05
MEPhI/PULSAR	56.4	56.44	0.05
FBK	30.75	30.78	0.05
Zecotek (MAPD-2A)	33.84	33.86	0.05
HPK S10362-11-050C	69.05	69.05	0.05

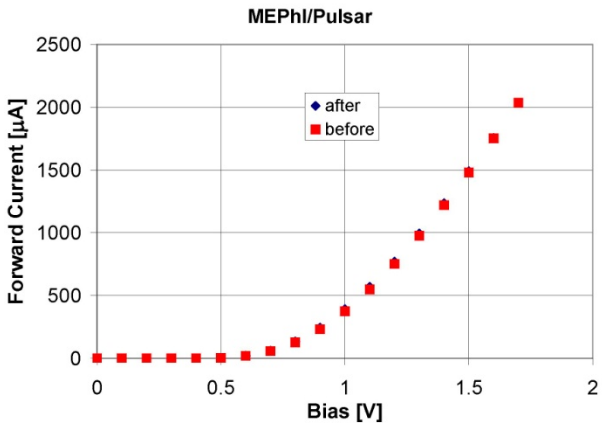
Second result: No VB change within the accuracy of our measurements (~50 mV)

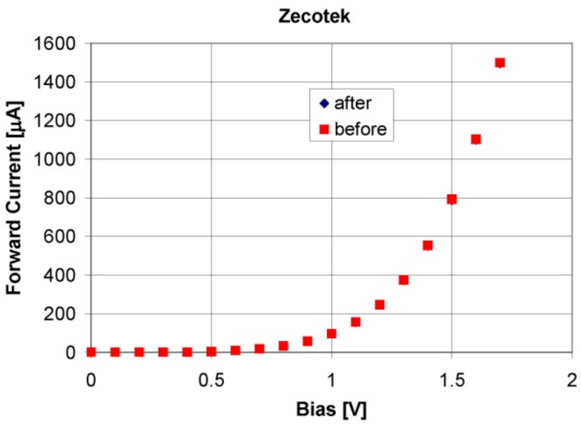
Forward bias measurements before and after irradiation





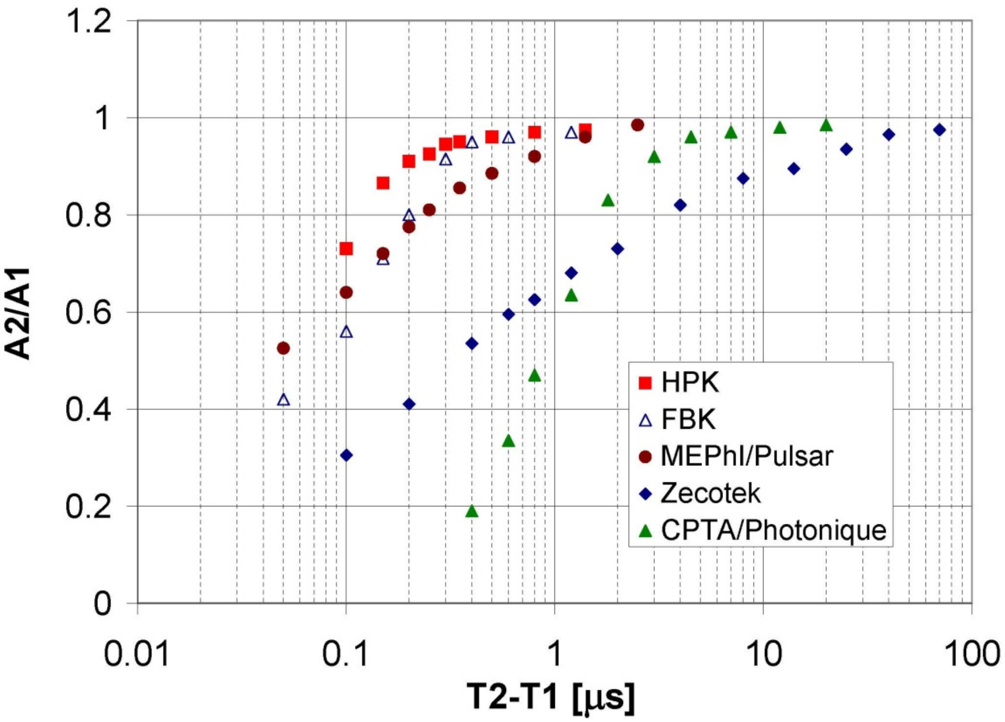






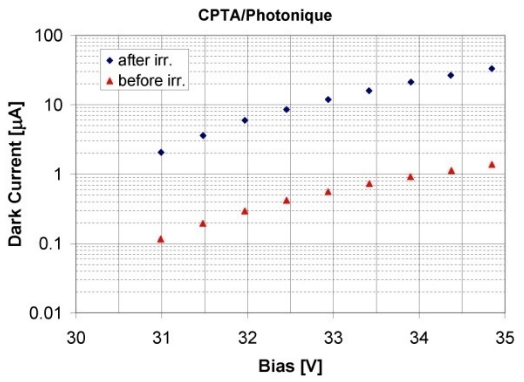
Third result: No cell resistor change within the accuracy of our measurements (~5%)

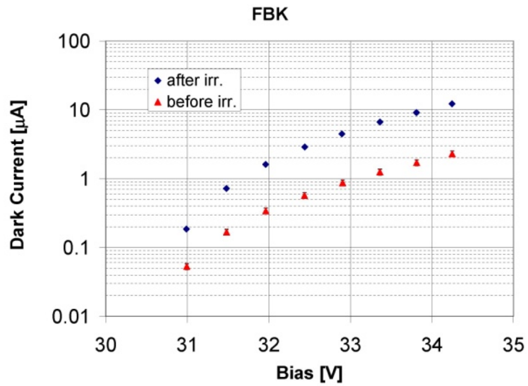
Cell recovery

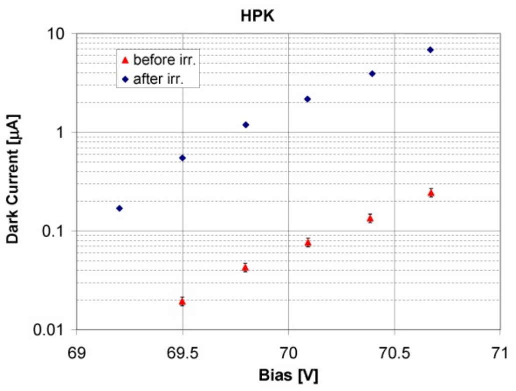


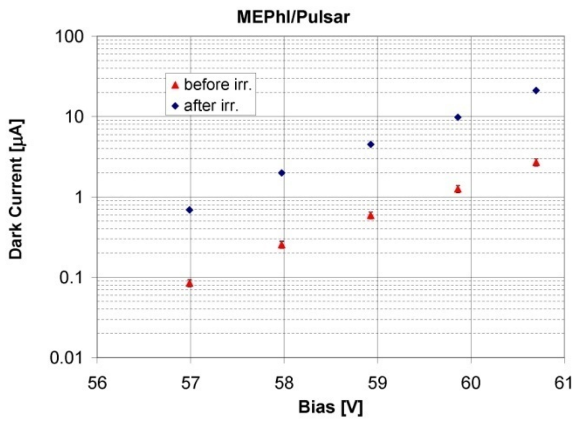
Double LED pulse method was used to measure the cell recovery time. The intensity of the first LED pulse was ~200 000 photons/pulse in order to saturate the response of all G-APDs studied. The second LED pulse was adjusted to a significantly smaller number of photons ~200 photons/pulse. Durations of the LED pulses were 10 ns FWHM. The response of the G-APD to the second LED pulse was measured as a function of the pulse delay.

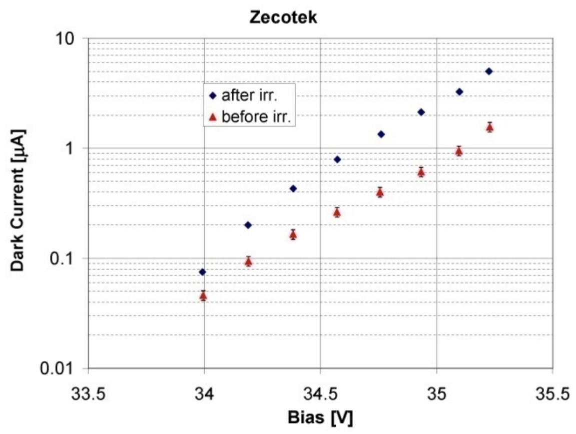
Dark current vs. voltage before and after irradiation



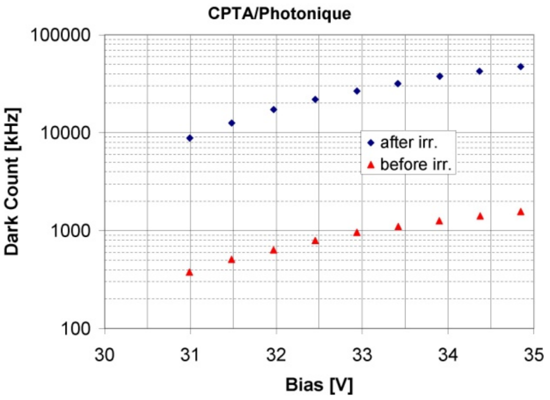


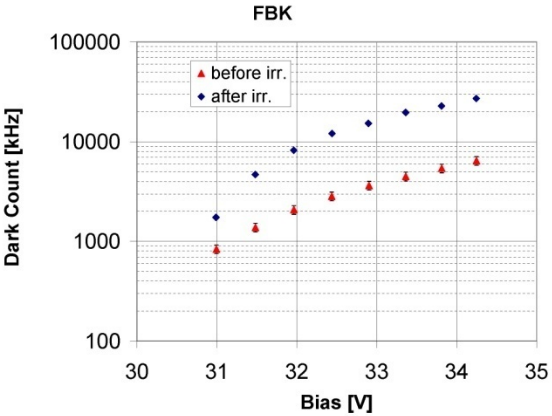


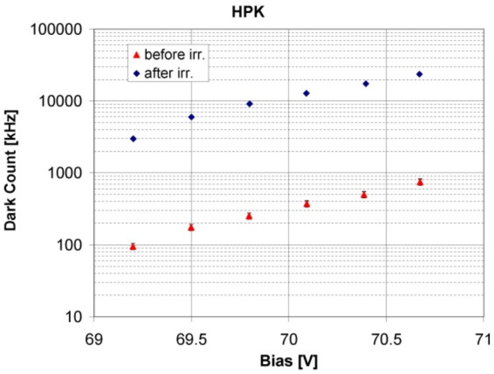


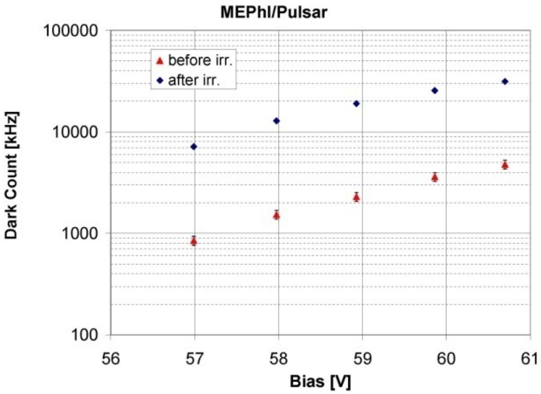


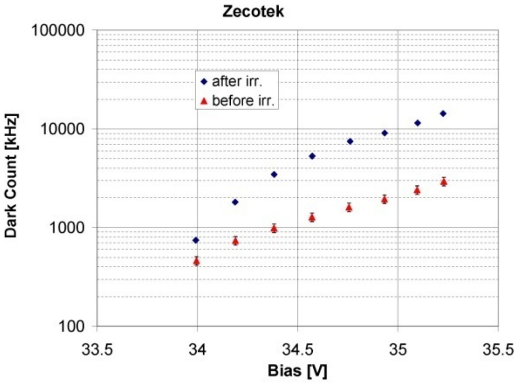
Dark count vs. voltage before and after irradiation



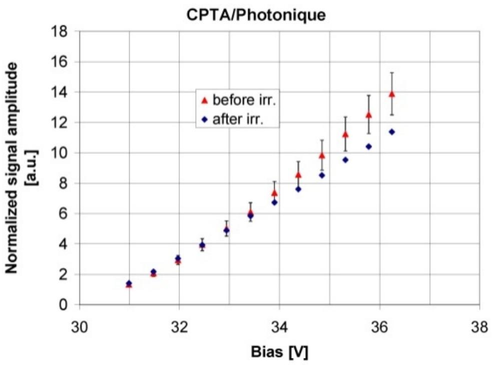


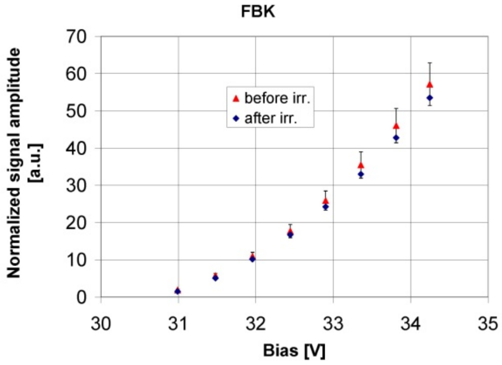


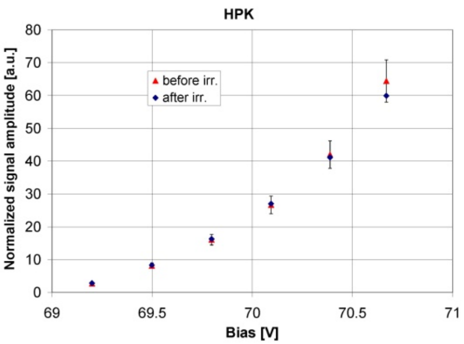


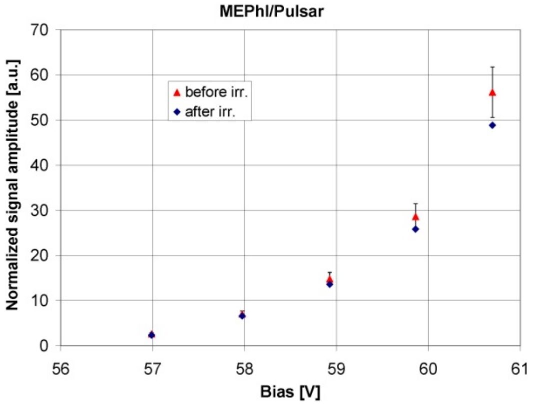


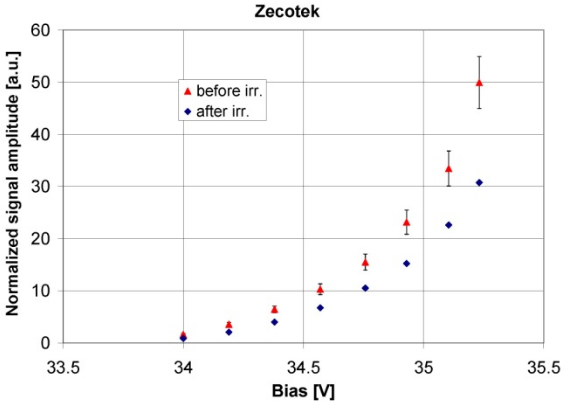
Normalized LED amplitude vs. voltage before and after irradiation





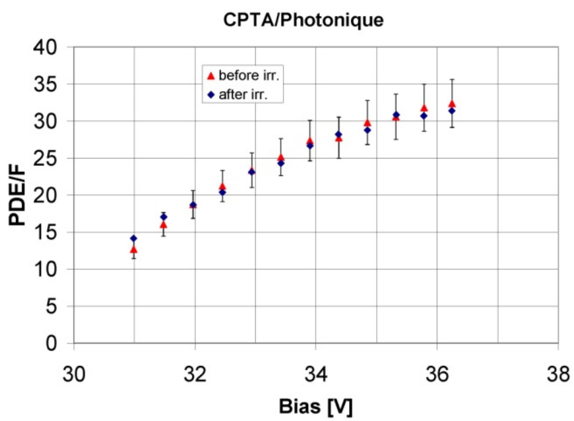


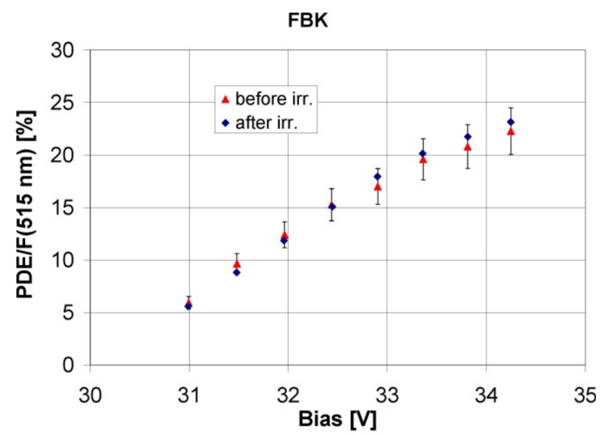


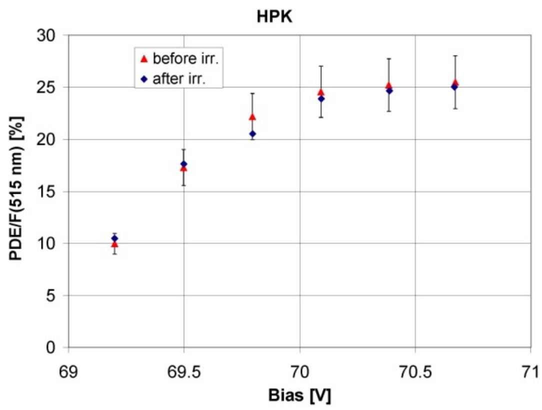


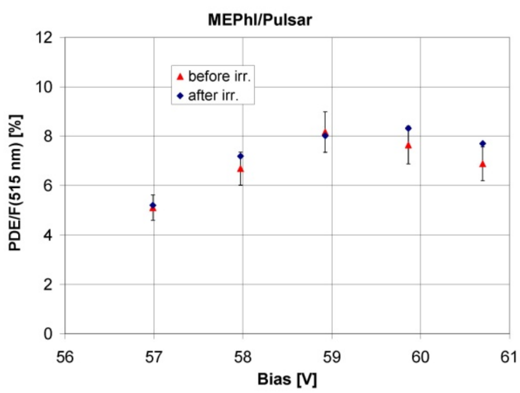
Measured with low intensity, fast (~50 photons, 10 ns) green LED pulse. The LED pulse was normalized using XP2020 PMT.

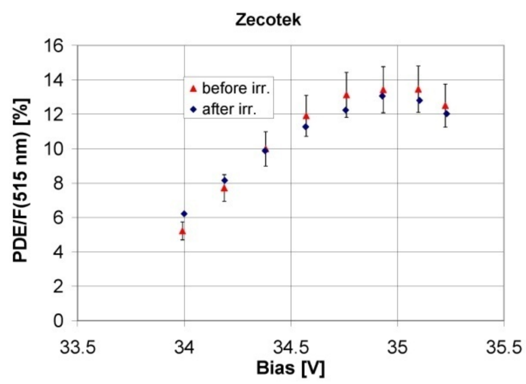
PDE/F vs. voltage before and after irradiation









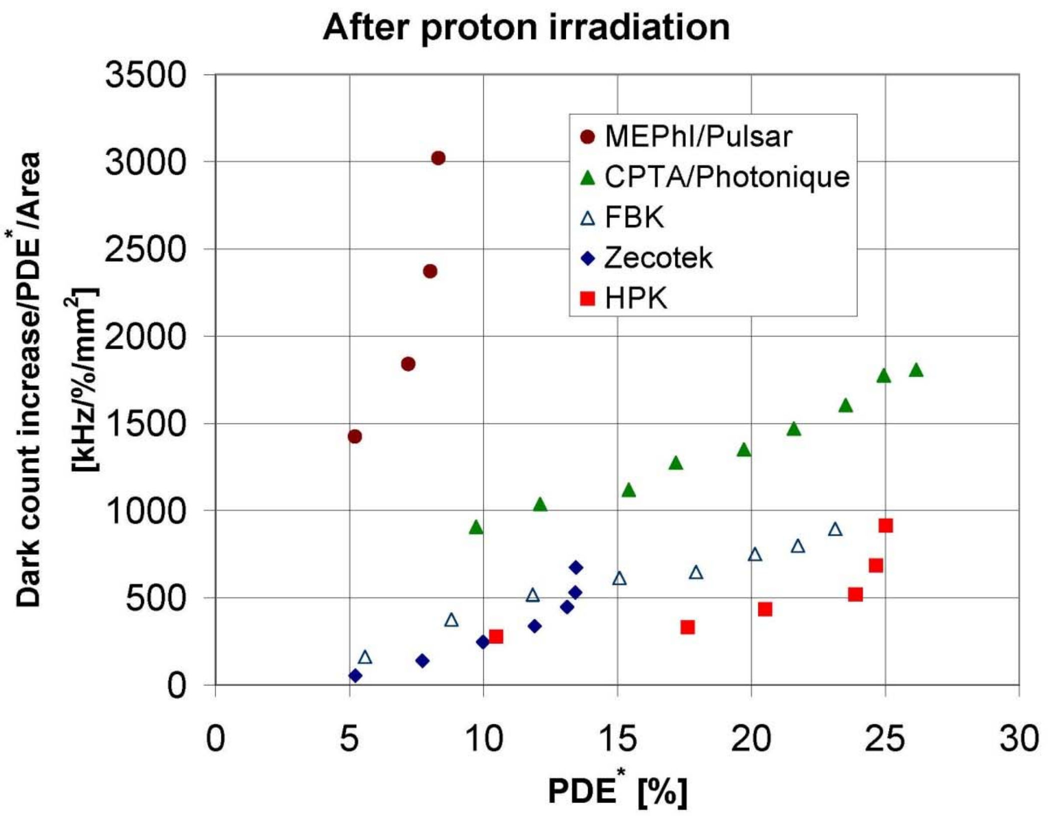


It is difficult to measure PDE after irradiation. We measured:

$PDE^* = PDE/F = (A - Ped)^2 / (RMS_A^2 - RMS_{Ped}^2) / N_{photons}$

$N_{photons}$ – average number of photons in a LED pulse, measured using calibrated XP2020 PMT

Dark Count Increase/PDE/Area-II



The effective thickness

$4 \cdot 10^{-17}$ A/cm/n damage constant → ~250 Hz/cm/n dark count

$2 \cdot 10^{10}$ n/cm^2 → ~5 MHz/µm/mm^2 or 50 kHz/µm/mm^2/%

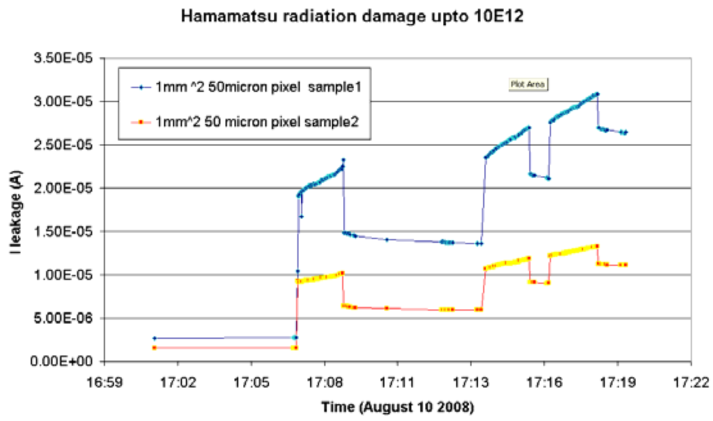
We measured 200 – 1500 kHz/µm/mm^2/%

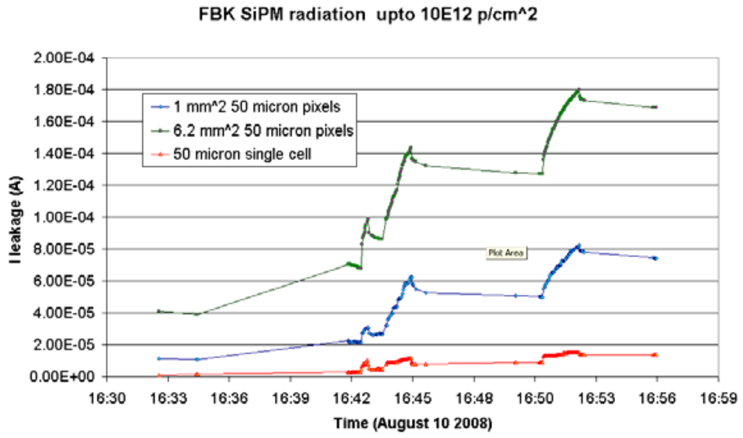
Effective thickness: 4 – 30 µm

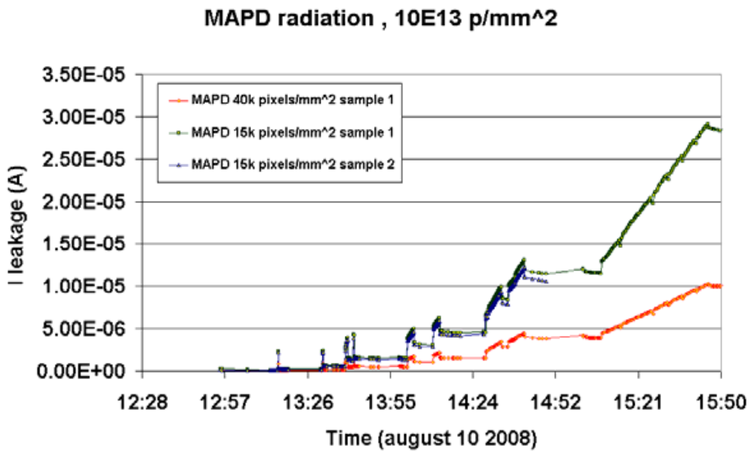
Summary of the results on 82 MeV proton irradiation ($1*10^{10}$ p/cm^2)

- No change of VB (with 50 mV accuracy)
- No change of R_{cell} (with 5% accuracy)
- Dark current and dark count significantly increased for all the devices
- No change of PDE/F ratio (resolution) (with ~15% accuracy)
- The gain of some G-APD decreased by 10-40 % (probably due to cell occupation)
- The G-APDs operate as a Si device with 4 – 30 μm effective thickness

G-APDs irradiated with 212 MeV protons at MG Hospital (Boston)

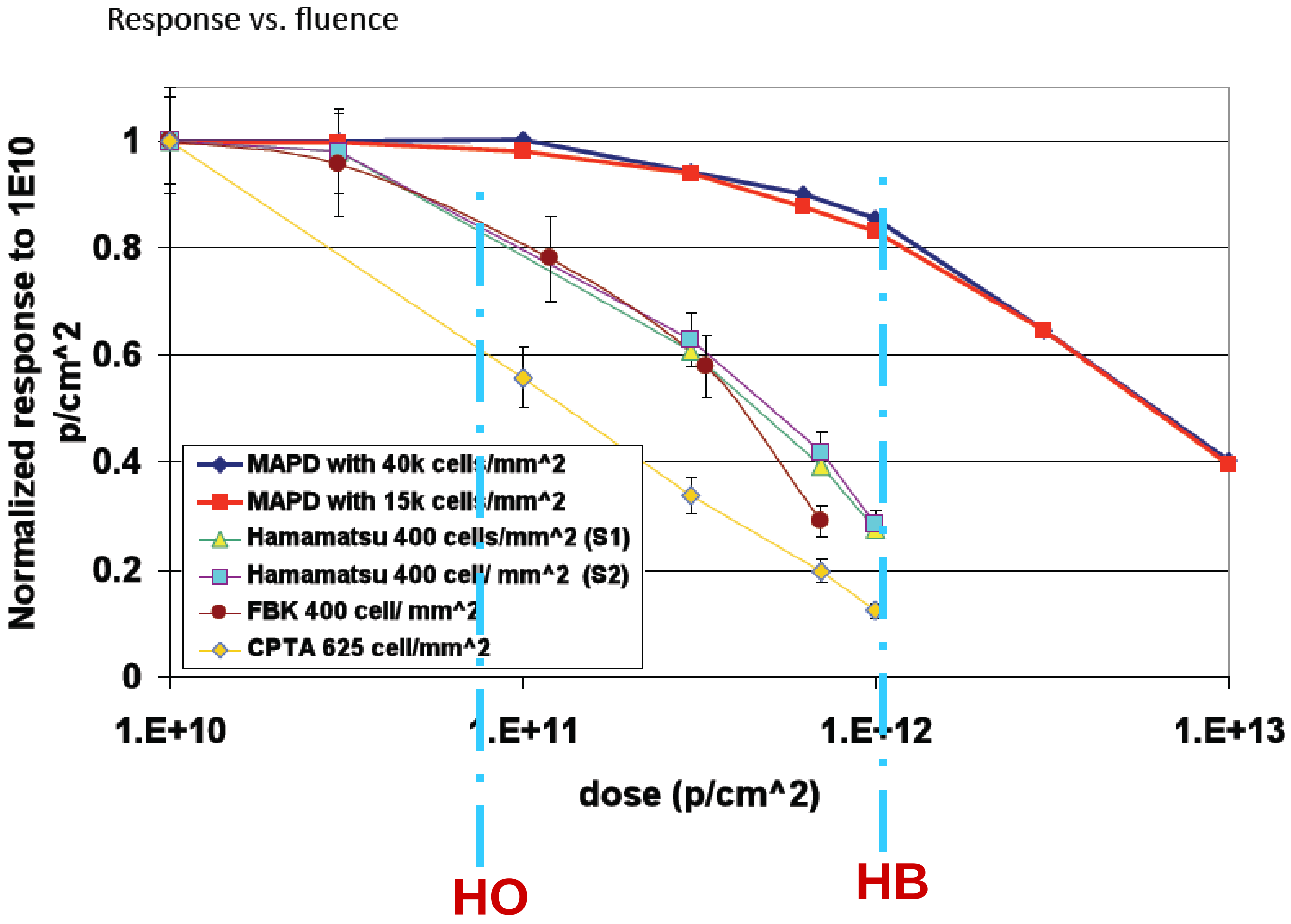






(A.Heering, CMS week, CERN, Sept. 2008)

G-APDs irradiated with 212 MeV protons at Boston Hospital



(J.Freeman, CMS HCAL Upgrade Workshop, FERMILAB, Sept. 2008)

Conclusions

G-APDs radiation hardness was studied by several groups using positrons (28 MeV), protons (53, 82, 200 and 212 MeV), neutrons (1 MeV) and gammas (1 MeV).

From the results of these studies we can conclude:

- G-APDs dark currents and dark counts increase linearly with the dose according to the particles NIEL factor
- Under irradiation GAPDs behave like silicon devices with 4÷30 μm effective thickness
- Gain and PDE of irradiated G-APDs may significantly drop due to high dark count rate and limited cell recovery time
- Ionizing radiation may cause damage of the G-APD dielectric layer and as a consequence - the G-APD fatal damage
- G-APDs made on n-type silicon have smaller dark count increase after irradiation in comparison to the devices produced on p-type silicon
- G-APDs with small cell size and fast cell recovery time are better suitable for applications in high radiation environment

G-APDs spectral responses - measured at T=22 ºC