# Future?

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# The title

The actual title is "Vision for the future"

☞Need some old instrument which I am not able to use…

- ⇨In absence I can still look at the physics as see what it tells me..
- ⇨I will try to point you to a few topics which I think will be important in the years to come for detectors R&D

# Some open questions

At least

- ☞EWK symmetry breaking
- ☞Dark Matter/Dark Energy
- ☞Neutrino masses
  - ⇨CP violation in the lepton sector?
- ☞Quark-Gluon Plasma ?
- ☞Do we have to survive with the SM even it is incomplete? Where do we put gravitation?

# Tools

Colliders provided a convenient source of large energy in center of mass

- ☞You cannot beat Einstein

However we are now at the point to use cosmic rays and cosmological measurement as precision tools to understand Nature

- ☞Unfortunately there is one BIG experiment (the Universe) and many observations

If we want to really understand the processes we should be able to reproduce them under controlled situation

- ☞Laboratories
- ☞Possibly next generation of machines will be different

# New times old machines

During the heyday of the last century research (and detectors) mainly driven by opportunities provided by new accelerators

- ☞Recently a small (but significant) shift
  - ⇨Tevatron heavily upgraded
    - →Challenge for D0 and CDF to study the "energy frontier" at high intensity.
  - ⇨Opportunistic approach to beam exploitation
    - →How to get most of the physics from existing facility (or *easily* obtainable upgrade to existing machine)
      - Easily often means "cheap" (relatively) or "obtainable with limited resources"

  - ⇨One of the Super-B proposal on the ground based on similar assumptions (reciclying)

# Future?

- LHC will start
  - ☞It has to if we want to keep running this field…
    - ⇨It will be upgraded
      - →No doubt: too large an investment
  - ☞Any discovery will pave the way to a new $e^{\pm}$ collider
- Flavour physics can be interesting
  - ☞High intensity frontier in B Physics
    - ⇨New machine or upgrade of KeK-B?
- High Intensity can complement the energy frontier
- New table-top machines?

# Colliders

The requirements for new detectors for collider will not change substantially

- ☞Physics objects are still leptons and photons as the final states of more complicated events
- ☞No room for new detectors?
  - ⇨Wrong!!!
- ☞More luminosity
  - ⇨More radiation damage on detectors and electronics
  - ⇨Higher rates (faster detectors and electronics)
- ☞Often need to reconstruct low energy particles
  - ⇨"massless" yet robust detectors
    - →Some time imbedded in even stronger B

# Frontiers

Particle Physics has always been at the frontier of discoveries

- ☞It is its role, its destiny

Now we have two frontiers

- ☞New particles/processes by increasing energy
- ☞Access via indirect (rare) effects higher energy phenomena
  - →In the '70, for example, observation of neutral currents in neutrino interactions were the first proof of existence of the Z0 particle at a much lower energy
- ⇨ you must have very high rate (*high intensity frontier)*

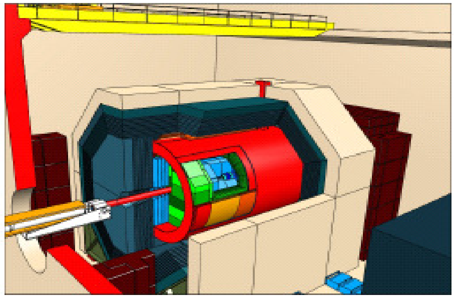
# High Energy

- Super LHC
  - ☞Physics case is not there (yet)
    - ⇨It might even not arise at all
      - →Extend physics reach of LHC
- As long as you have a running machine
  - ☞my prediction is that it will be upgraded (if possible)
- Current wisdom
    - ⇨LHC luminosity (design) $10^{34}$ $cm^{-2}s^{-1}$
    - ⇨SLHC luminosity predicted at $10^{35}$ $cm^{-2}s^{-1}$
      - →A factor 10 in luminosity implies a factor 10 in overlapping events, radiation damage etc
        - Actually the factor is 15 (technicality)
- Timescale of the process still unknown
  - ☞Optimistic: 10 years after startup of LHC (2008?)

# The Big Linear One

## ILC (International Linear Collider)

- 500x2 e+e- collisions
  - Single pass (i.e. beams are lost after crossing)



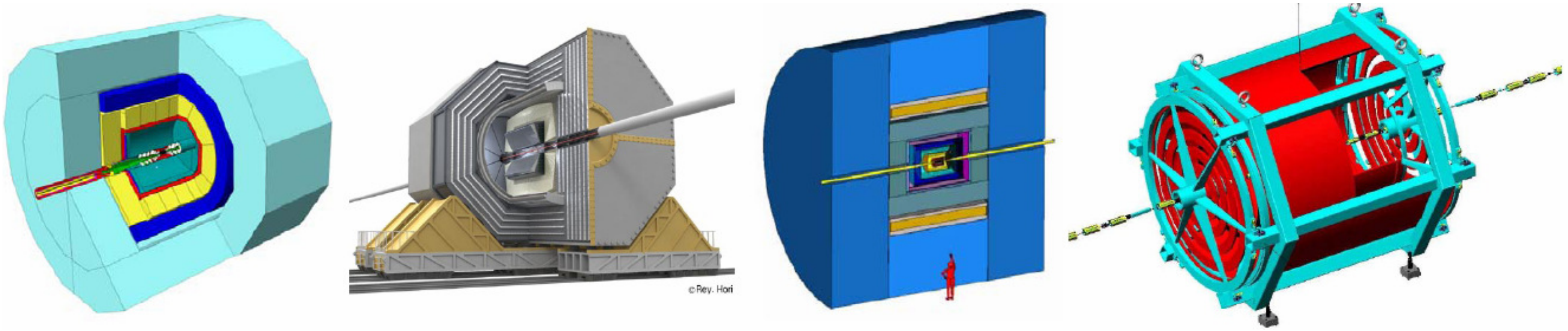
Highest priority new HEP facility
Costs $5-7B
Requires an international effort
Operation by 2015-2020?

  - Able to explore the Higgs sector by itself
- Currently linked to the success of LHC
  - Interesting implications fron the point of view of detectors (and machine)

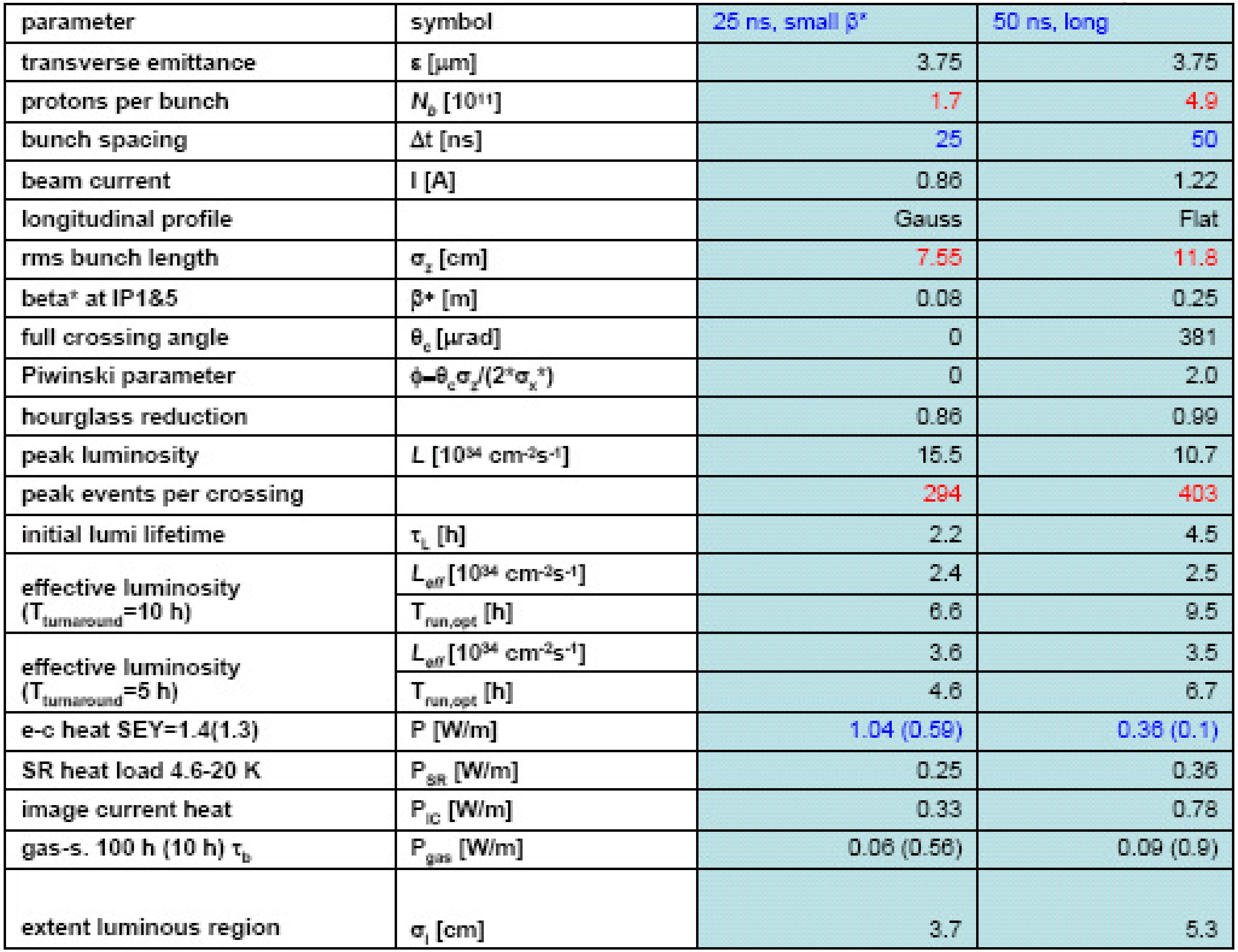
# What do they have in common?

At the moment they both need large detectors with strong B field, and the usual shopping list

- ☞ Many differences:
  - ⇨ pp vs ee environment (clean vs not clean initial state)
  - ⇨ Different radiation damage (lower at the ILC)
  - ⇨ Different interbunch structure
  - ⇨ Trigger-less option for the ILC
  - ⇨ Different requirements on calorimetry

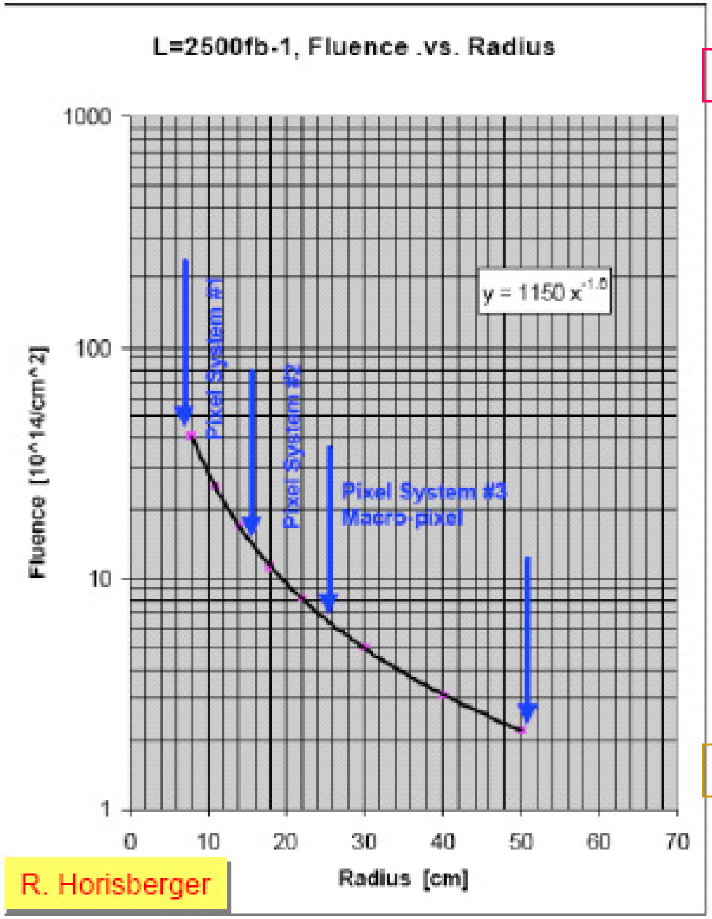


# SLHC parameters

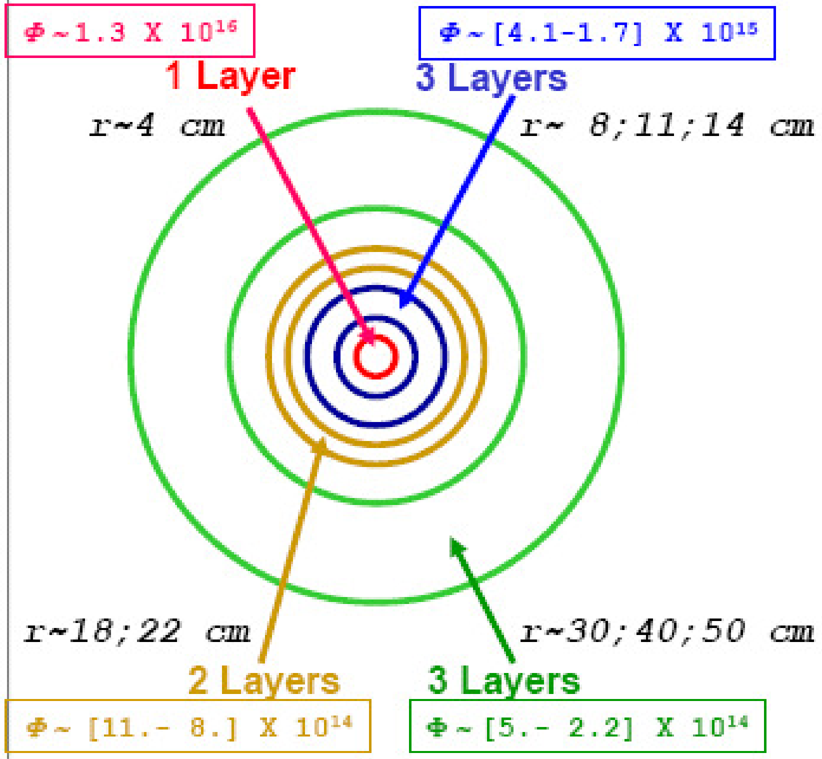


| parameter | symbol | 25 ns, small β* | 50 ns, long |
|---|---|---|---|
| transverse emittance | ε [μm] | 3.75 | 3.75 |
| protons per bunch | $N_b$ [$10^{11}$] | 1.7 | 4.9 |
| bunch spacing | Δt [ns] | 25 | 50 |
| beam current | I [A] | 0.86 | 1.22 |
| longitudinal profile | | Gauss | Flat |
| rms bunch length | $\sigma_z$ [cm] | 7.55 | 11.8 |
| beta* at IP1&5 | β* [m] | 0.08 | 0.25 |
| full crossing angle | $\theta_c$ [μrad] | 0 | 381 |
| Piwinski parameter | $\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$ | 0 | 2.0 |
| hourglass reduction | | 0.86 | 0.99 |
| peak luminosity | L [$10^{34}$ cm$^{-2}$s$^{-1}$] | 15.5 | 10.7 |
| peak events per crossing | | 294 | 403 |
| initial lumi lifetime | $\tau_L$ [h] | 2.2 | 4.5 |
| effective luminosity ($T_{turnaround}$=10 h) | $L_{eff}$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 2.4 | 2.5 |
| | $T_{run,opt}$ [h] | 6.6 | 9.5 |
| effective luminosity ($T_{turnaround}$=5 h) | $L_{eff}$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 3.6 | 3.5 |
| | $T_{run,opt}$ [h] | 4.6 | 6.7 |
| e-c heat SEY=1.4(1.3) | P [W/m] | 1.04 (0.59) | 0.36 (0.1) |
| SR heat load 4.6-20 K | $P_{SR}$ [W/m] | 0.25 | 0.36 |
| image current heat | $P_{IC}$ [W/m] | 0.33 | 0.78 |
| gas-s. 100 h (10 h) $\tau_b$ | $P_{gas}$ [W/m] | 0.06 (0.56) | 0.09 (0.9) |
| extent luminous region | $\sigma_l$ [cm] | 3.7 | 5.3 |

# Radiation damage at SLHC



R. Horisberger



$\Phi \sim 1.3 \times 10^{16}$

1 Layer

r~4 cm

$\Phi \sim [4.1-1.7] \times 10^{15}$

3 Layers

r~ 8;11;14 cm

r~18;22 cm

2 Layers

$\Phi \sim [11.- 8.] \times 10^{14}$

r~30;40;50 cm

3 Layers

$\Phi \sim [5.- 2.2] \times 10^{14}$

Except for the innermost layers current technologies should survive at SLHC

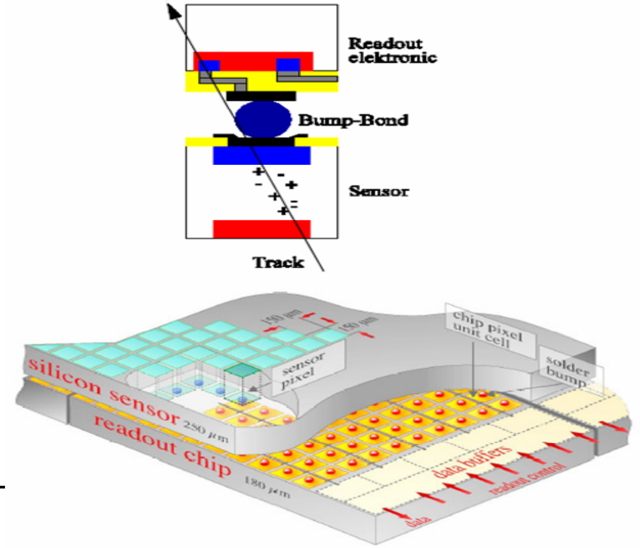
# Tracking

They all need more precision tracking with less material

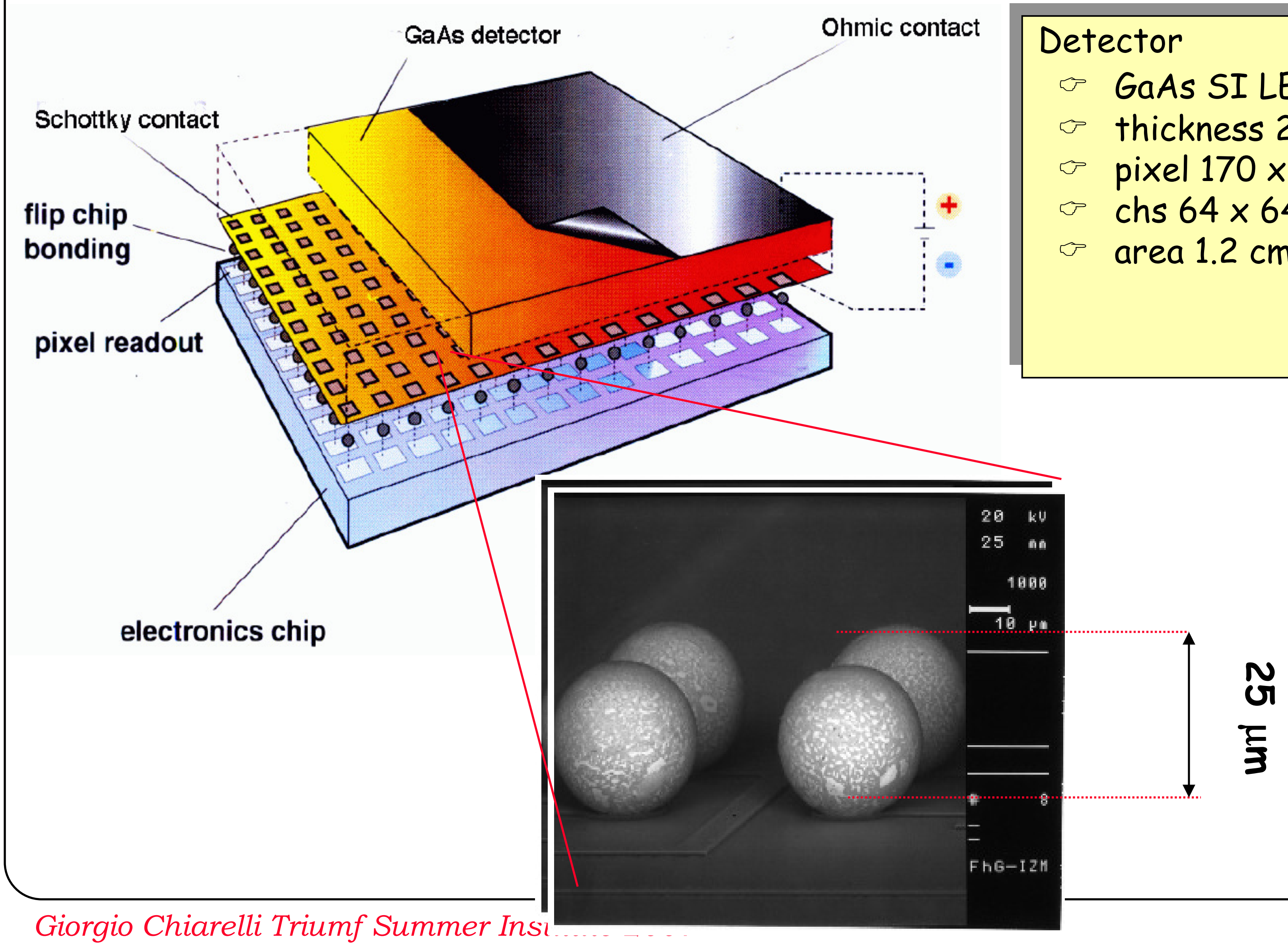
- ☞ For the ILC at large radius you might use a gas-based system (TPC)
- ☞ At small radius in both cases semiconductor (silicon?) sensors
  - ⇨ ILC wants a $\Delta P_T/P_T^2 = 5\times10^{-5}$ and asymptotic impact parameter resolution of 5 µm

Proposed: $10^9$ pixel with $20\times20\ \mu m^2$ dimensions and $<0.1X_0$

Very close to IP: rad.damage



# Medipix 4096 channels



Detector

- GaAs SI LEC <100>
- thickness 200 µm
- pixel 170 x 170 $\mu m^2$
- chs 64 x 64
- area 1.2 $cm^2$

# Possibilities

The trend towards integrating electronics design into the detector design is beneficial

- ☞However the issue of power consumption is becoming more and more relevant
  - ⇨Cooling systems are bulky and does not help reducing material on the sensors/electronics side if then you must run more cooling pipes
- ☞That implies that you cannot increase the number of channels at will

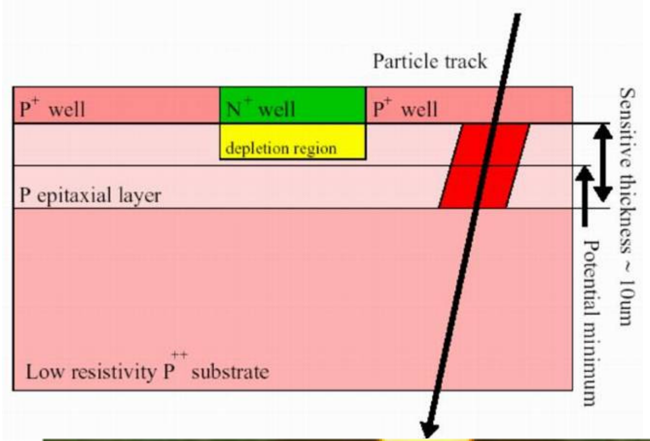
- ☞Resistance to radiation damage has large overlap with space-based application

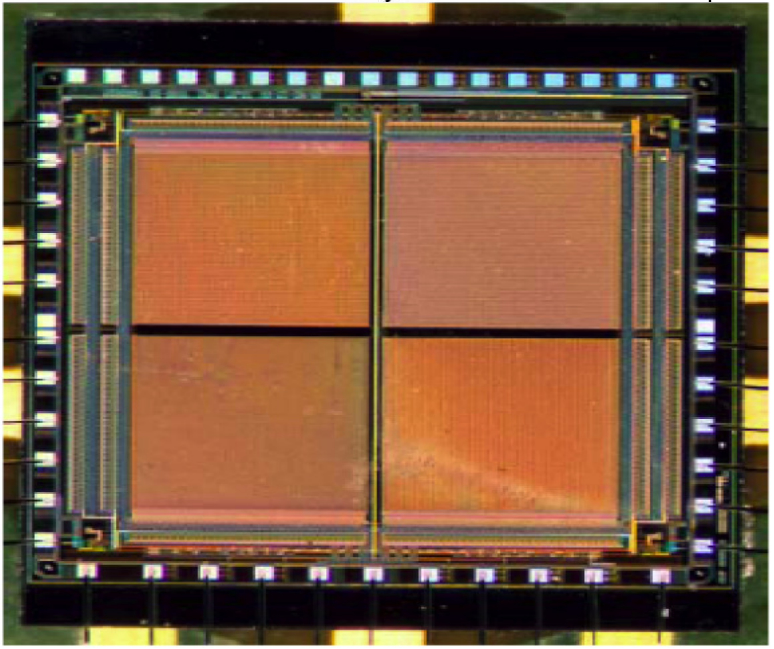
# MAPS

## MAPS

- ☞ Monolithic Active Pixel Sensors
    - ⇨ Electronic is integrated on the detector itself
- ☞ Promising technique but
    - ⇨ low response
    - ⇨ power consumption
    - ⇨ Packing fraction (dead areas)
- ☞ Design can be improved
    - ⇨ More R&D needed

## Schematic:



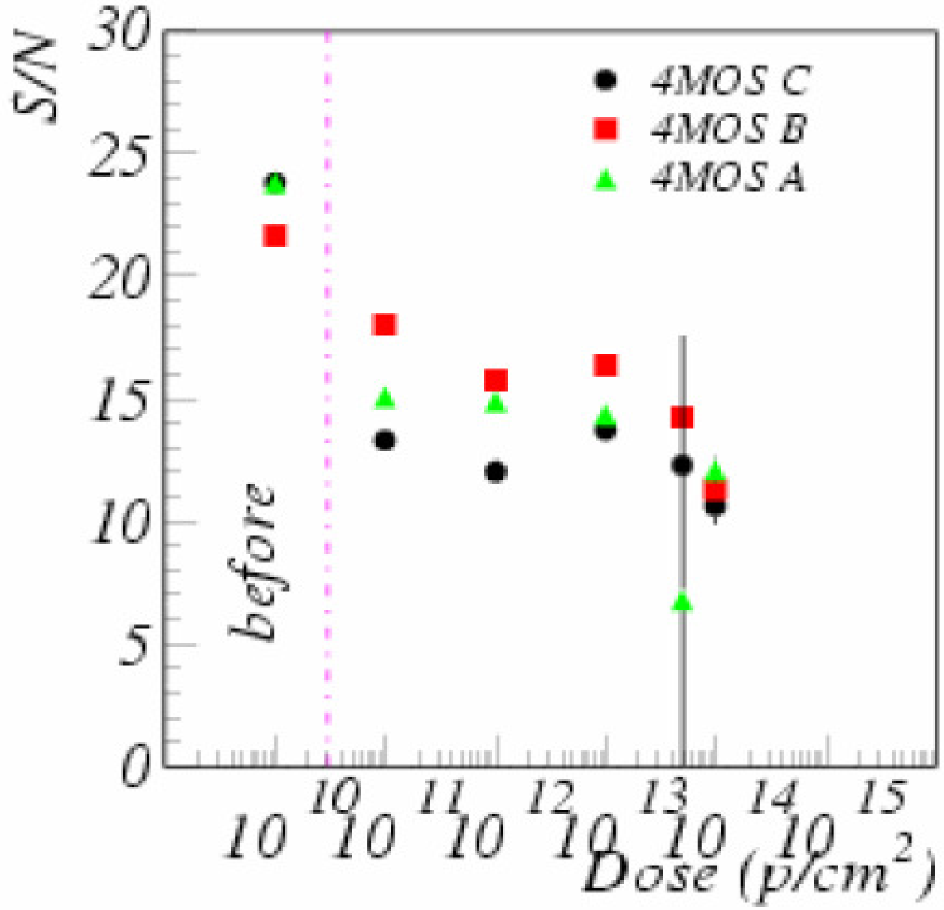


# Radiation tolerance?

## Work in progress

- Limited issue for ILC/Super-B
- More important for SLHC ($10^{15}$ cm-2)
- Room for improvements

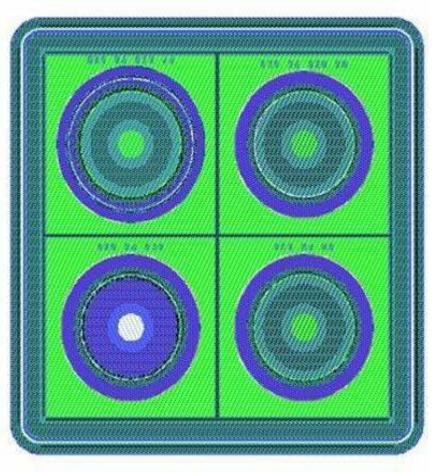
## MIMOSA test

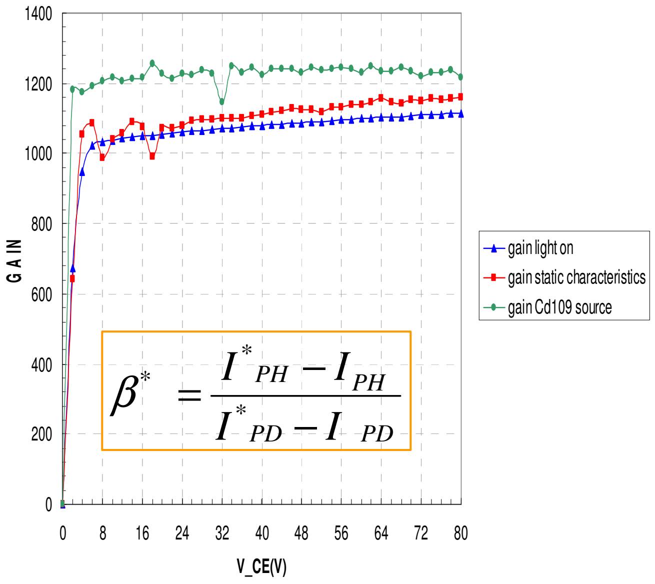


# MAPS

## Recent developments on detectors built with electronics on high resistivity silicon

- ☞NIM A518 (2004), 354-356: phototransistor.
  - ⇨Transistor strcuture is directly built on high resistivity silicon sensible to visible light (on surface) and X-ray in the bulk





$$\beta^{*} = \frac{I^{*}_{PH} - I_{PH}}{I^{*}_{PD} - I_{PD}}$$

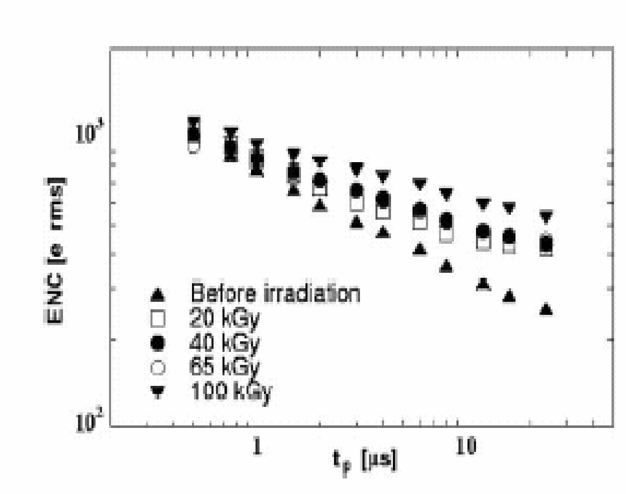
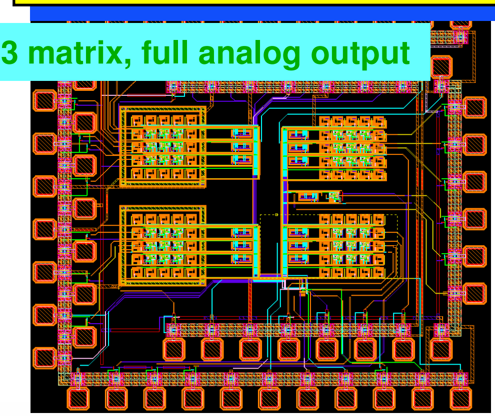
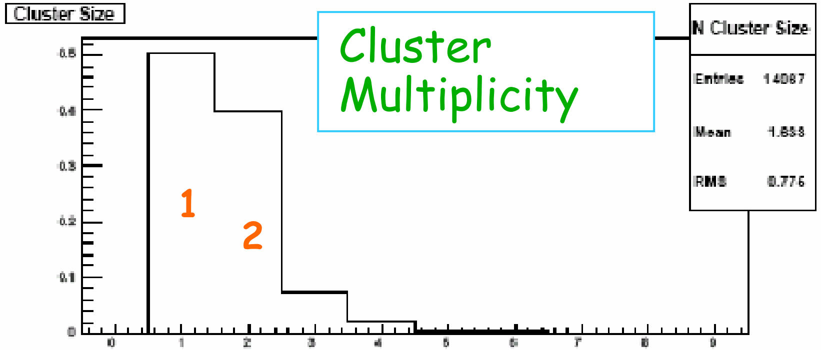


Fig. 1. ENC vs $t_p$ before and after γ irradiation.

# Characterization of CMOS 3x3-analog output

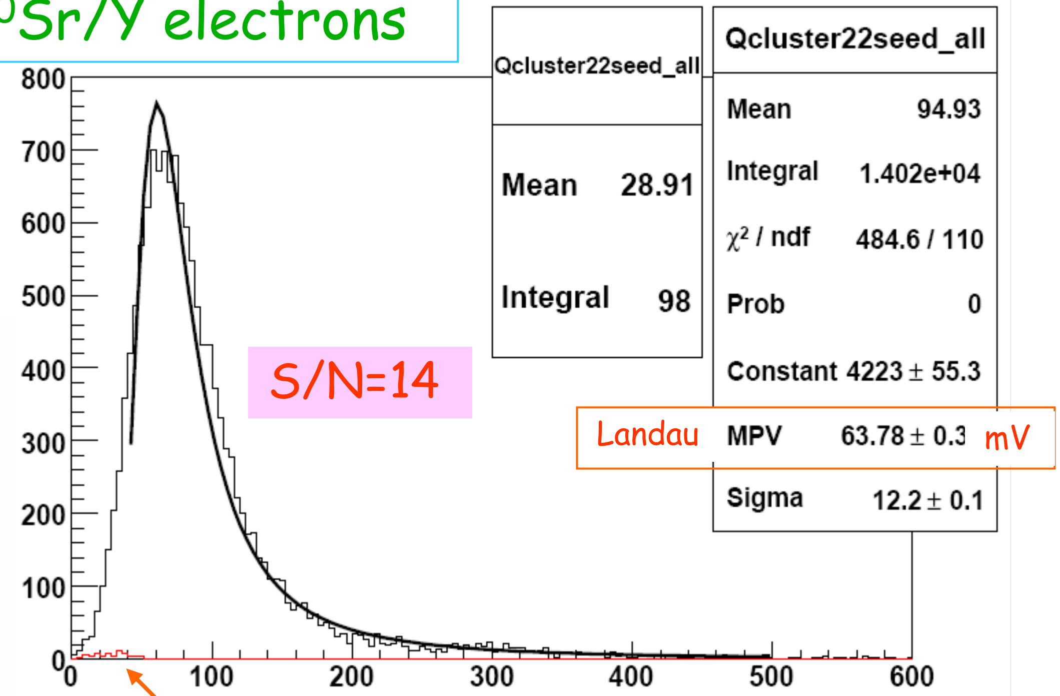
3x3 matrix, full analog output





Cluster Multiplicity

$^{90}$Sr/Y electrons



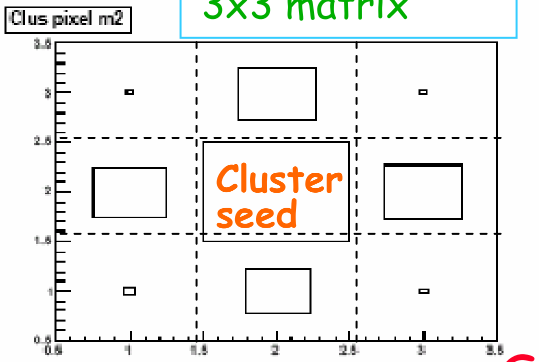
S/N=14

Landau MPV mV

Noise events properly normalized

Cluster signal (mV)

Hit pixels in 3x3 matrix



Cluster seed

- Noise ENC = 50 e-
- Indications of small cluster size (1-2 pixels)
- Cluster Signal for MIP (Landau MPV) 700 e-

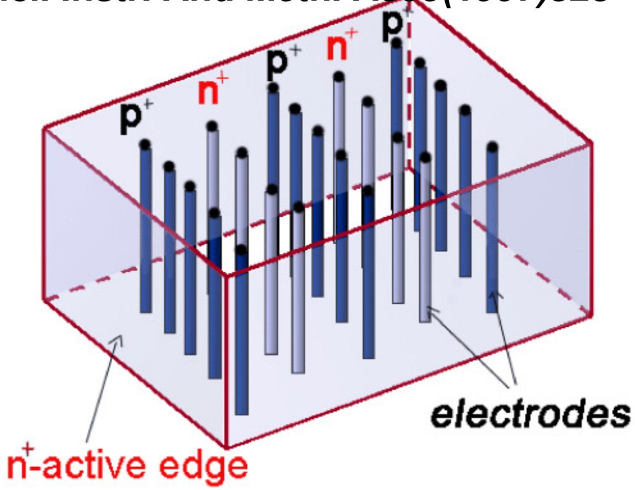
→ S/N = 14

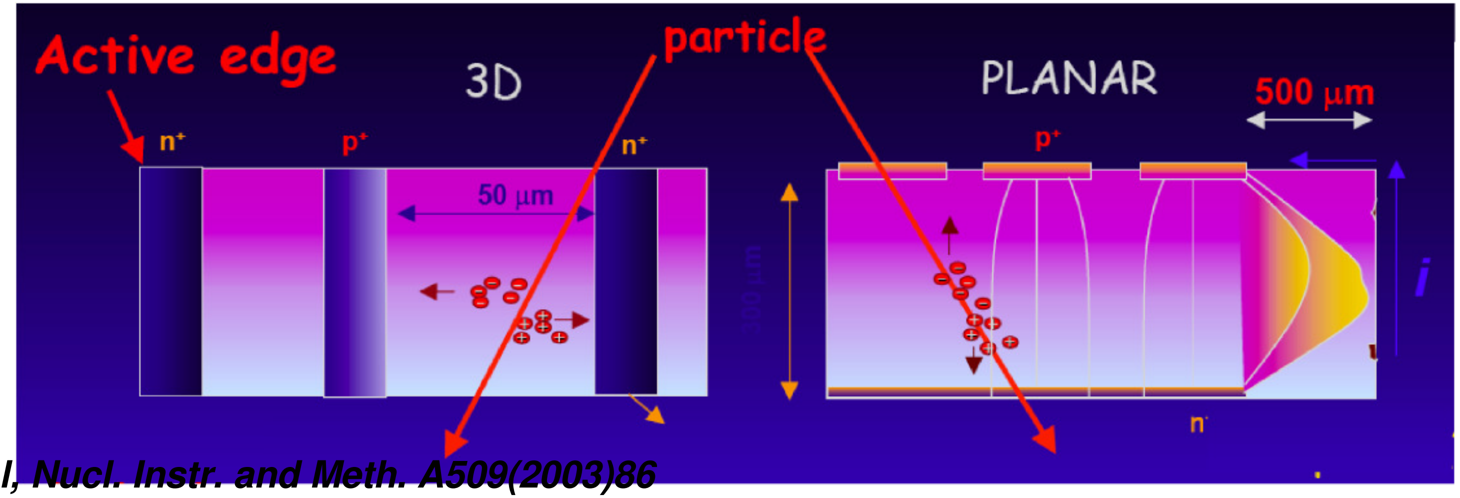
# 3D detectors

From planar to 3D structure:

Reduce dead zone at the edges

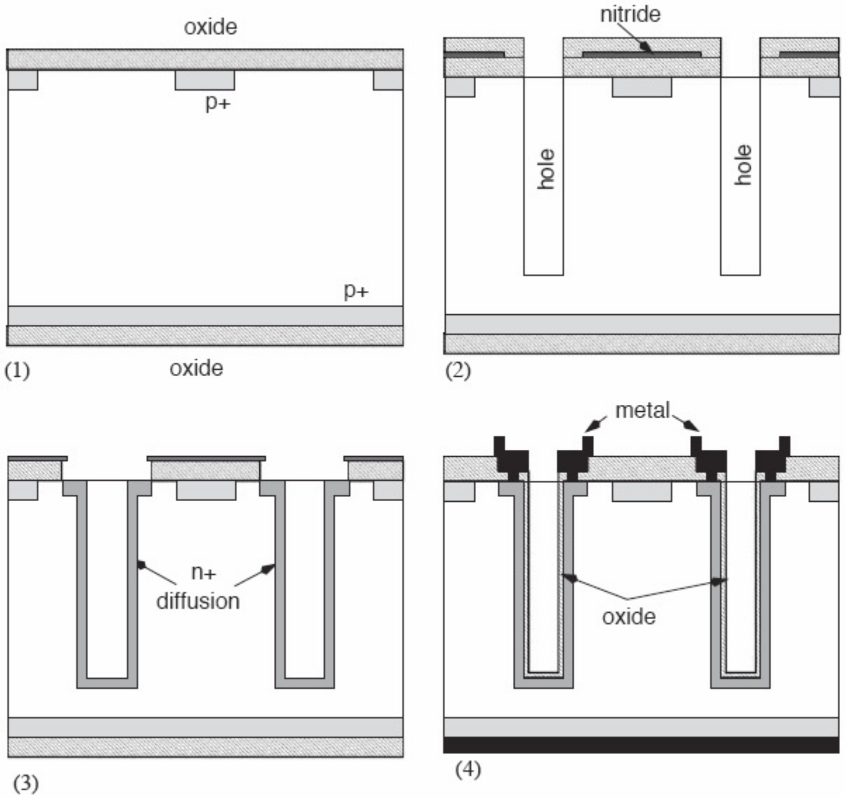
S. Parker, Nucl. Instr. And Meth. A395(1997)328



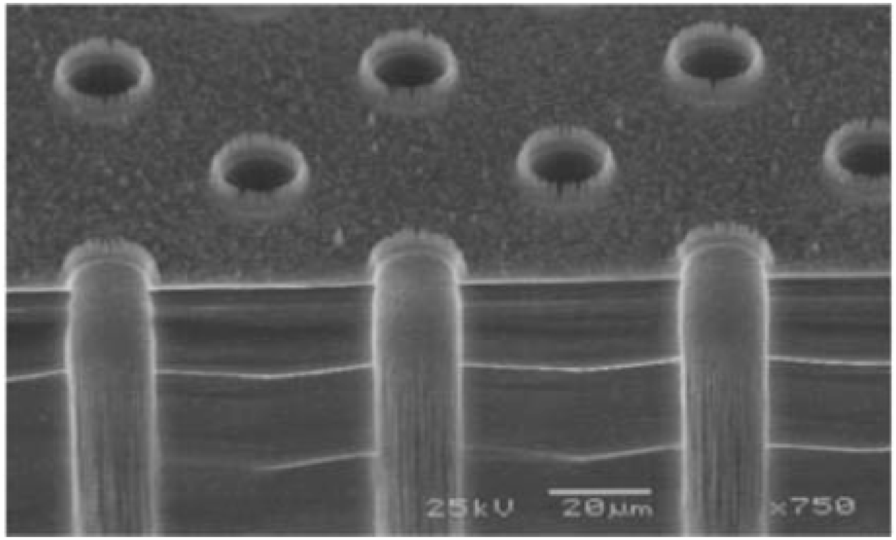


C. Da Via et al, Nucl. Instr. and Meth. A509(2003)86

# 3d detectors manifacturing



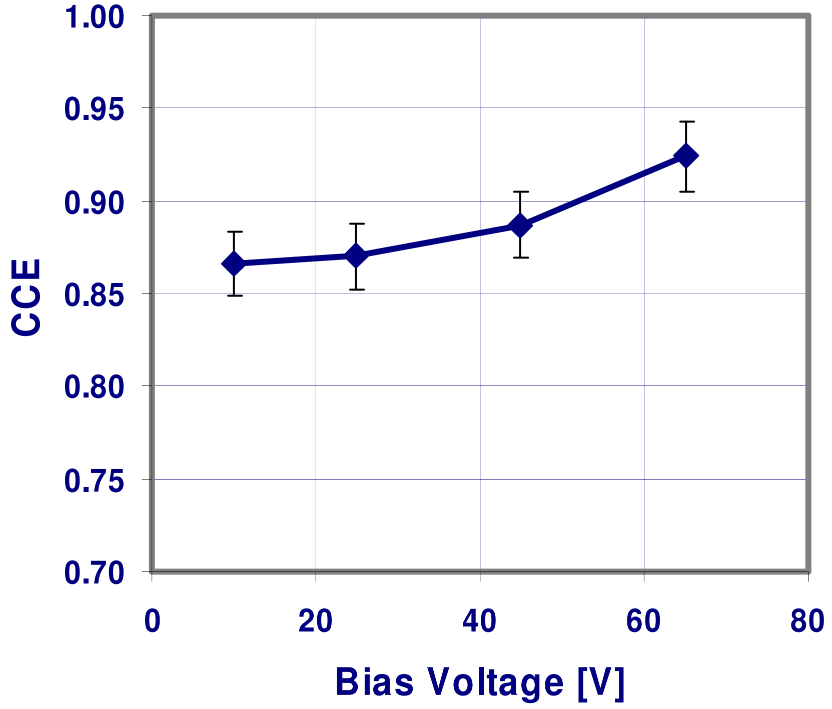
***C. Piemonte et al,***
***Nucl. Instr. and Meth. A541(2005)441***

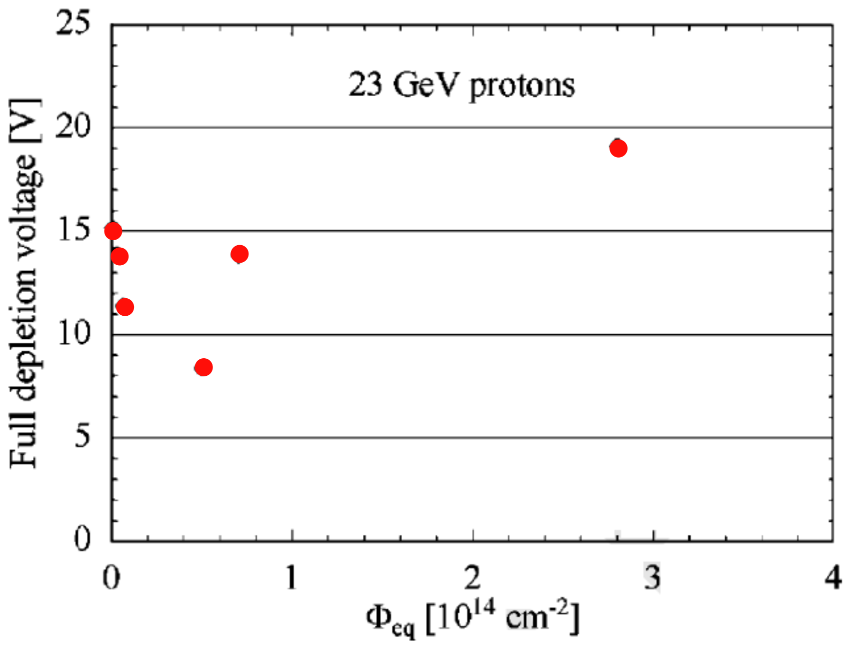


# Radiation resistance

Radiation hardness coming from small depletion region

***CHARGE COLLECTION EFFICIENCY AFTER 1x10$^{15}$p/cm$^{2}$ (5x10$^{14}$n/cm$^{2}$):***





# Photon detectors

Many detectors need to translate light into electric signals

- ☞Traditional mean: Photomultipliers

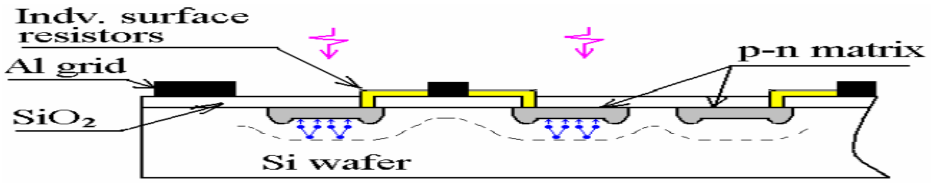
- ☞New means:
  - ⇨Multianode PM
  - ⇨APD
  - ⇨HPD
  - ⇨VLPC
  - ⇨SiPM
- ☞I will spend a few slides about the latter

- ☞Photon detectors have a much wider use than in HEP (medical for example)

# SiPM

Silicon PhotoMultipliers originally developed in former USSR

- ☞ Solid state devices sensitive to IR light with no information on individual photon characteristics
  - ⇨ In the '90 matrix of SiPM proposed
    - → Output signal proportional to the number of SiPM "on"



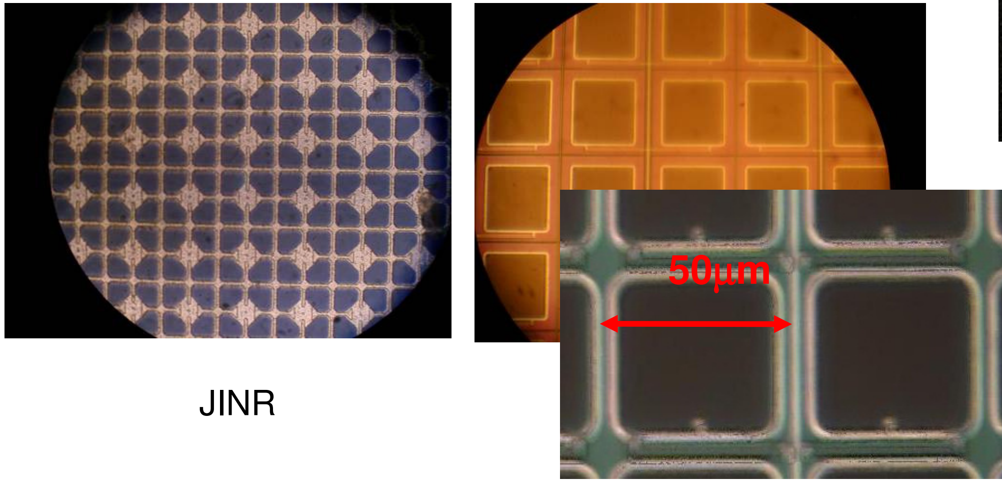
AMPD with individual surface resitors

Sadygov patent No. RU 2102820, 1998

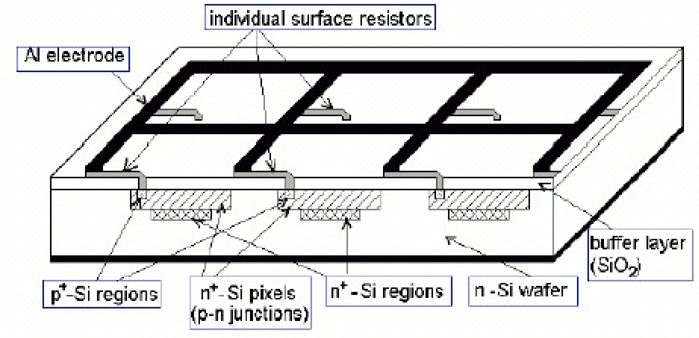
  - ⇨ R&D results presented in 2003 (Pisa Conference and then Vienna) with strong impact on community
  - ⇨ In 2006 the technique had rapidly been exported outside Russia
    - → A lot learned on the physics principles of SiPM

# SiPM structure

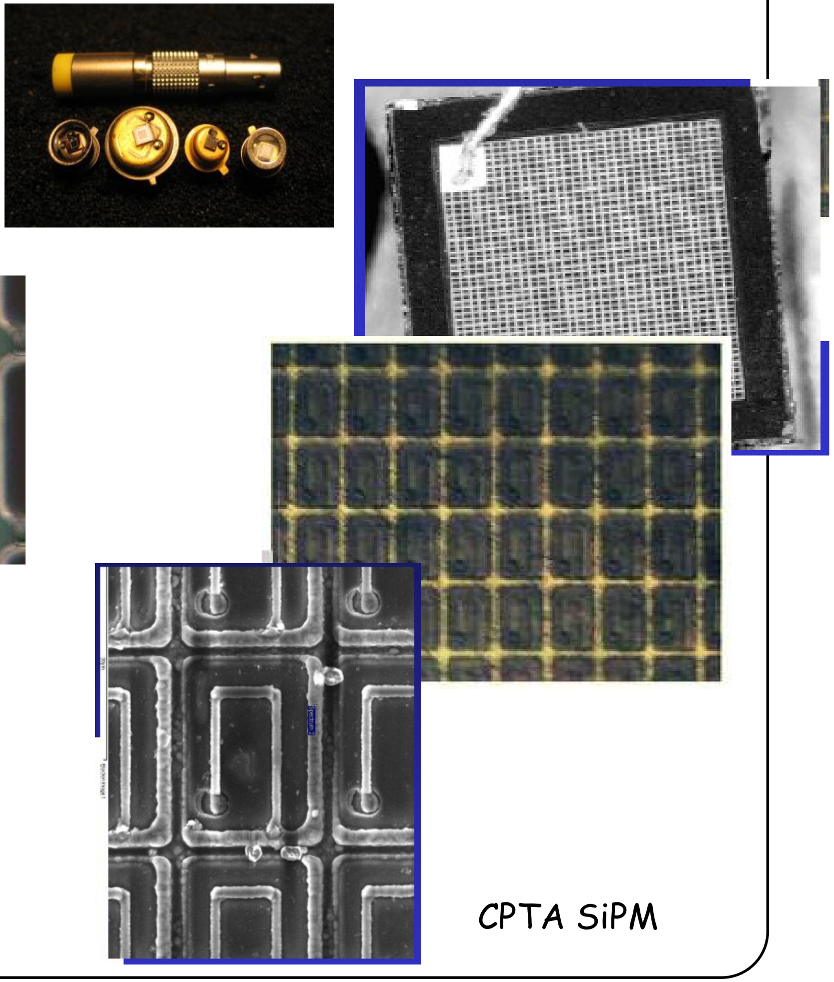
A silicon photo-multiplier consists in
a matrix of Single Photon Avalanche Diodes (SPAD)
i.e. avalanche diodes operated a
few volts above the breakdown
voltage (Geiger Mode APD)



JINR



HAMAMATSU



CPTA SiPM

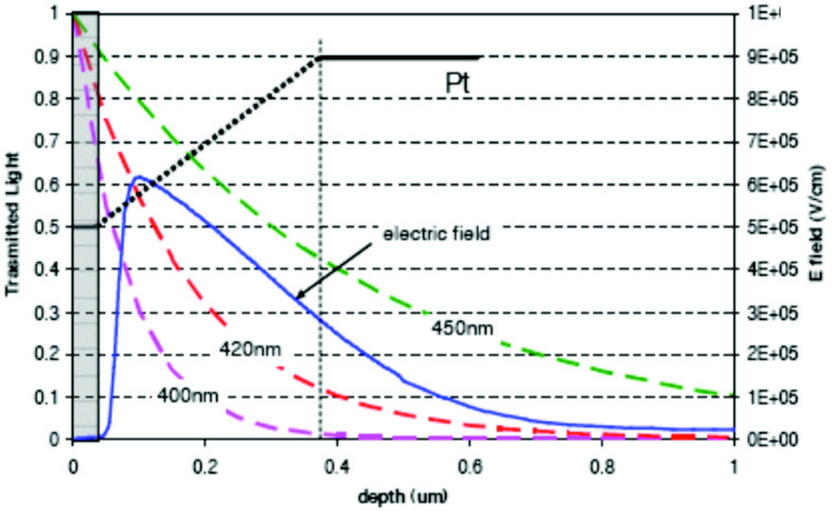
# QE: Efficiency of a single cell

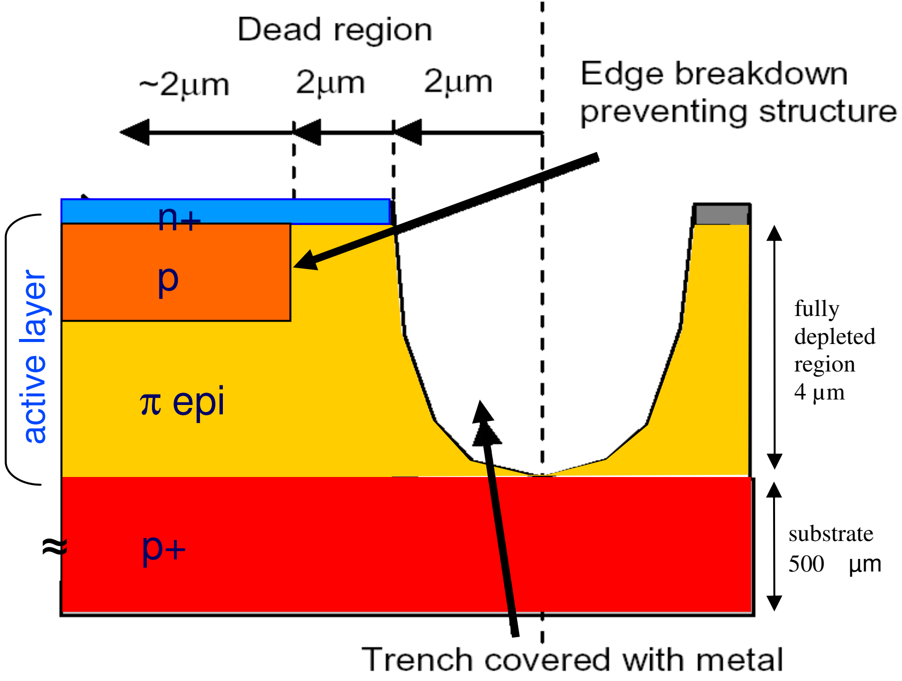
Two factors in QE:

(1) transmittance of the entrance window
(dielectric on top of silicon surface)

(2) probability of a photon inside to
generate an e-h pair in the active layer
(internal quantum efficiency)

Only the depleted region is fully active to efficiently photo-generate because of high recombination probability in the undepleted regions. Only a small layer at the edge of undepleted regions contributes to the photo-generation : $\lambda_{diffusion} \sim \sqrt{D\tau_{recomb}}$
with D (diffusion coefficient cm**2/s)
and $\tau$ (recombination time)

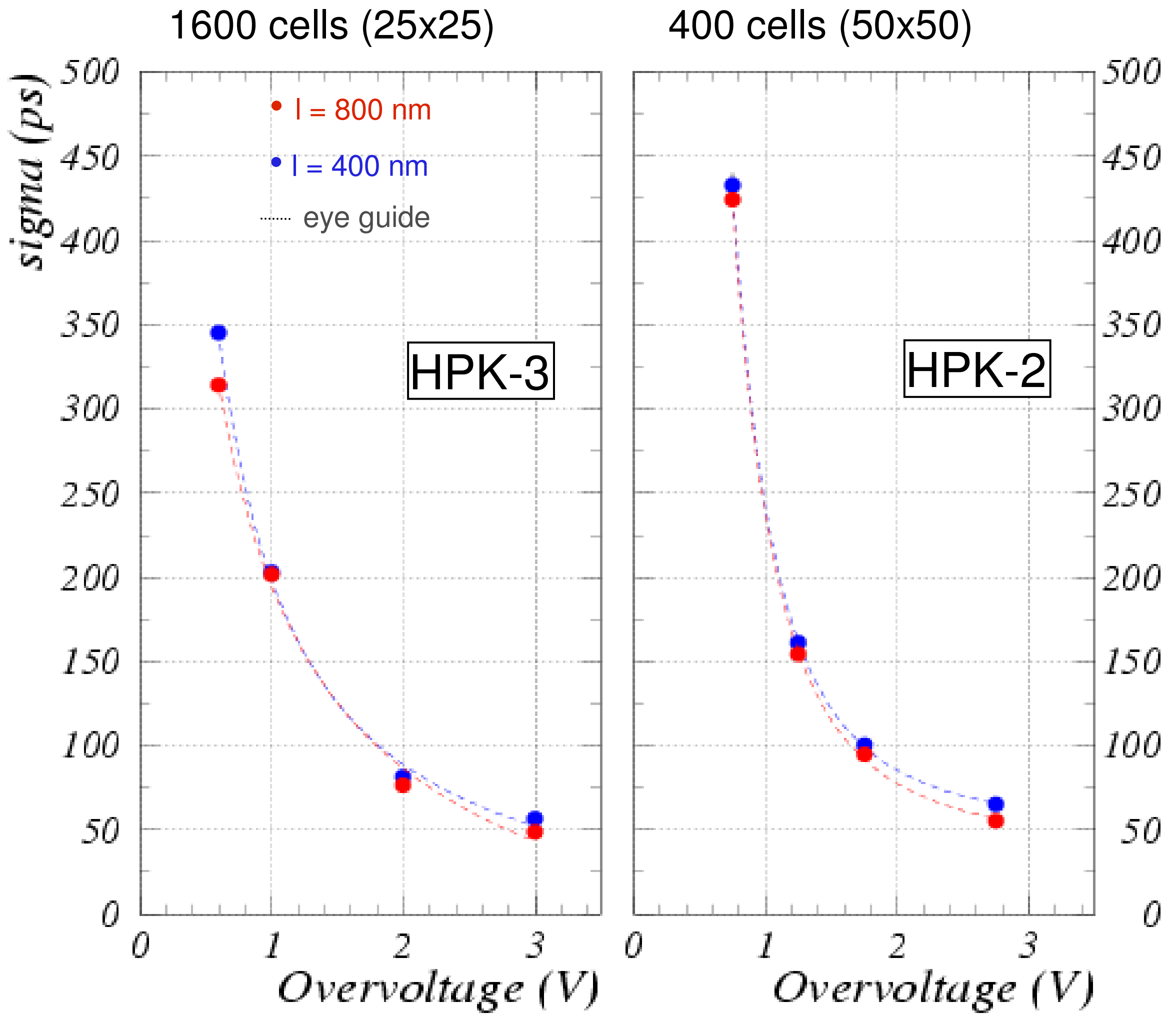




## QE optimization

- Anti-reflective coating (ARC)
- Shallow junctions for short λ
- Thick epi layers for long λ

# Timing- Hamamatsu devices



# Temperature dependence

Variation of $V_{bk}$ and Gain with 1 ℃ $\Delta T$

| | FBK-SiPM | APD |
|---|---|---|
| $\Delta V_{bk} / V_{bk}$(@300K) % | ~0.2 → 0.1 | |
| $\Delta V_{bk}$ [mV] | ~ 60 →30 | 60-200 ** |
| $\Delta G/G$(@300K) % | ~ 3 →1.5 | 3.4* |

** J.P.R. David and G.J.Rees, RAD Hard Workshop 2003

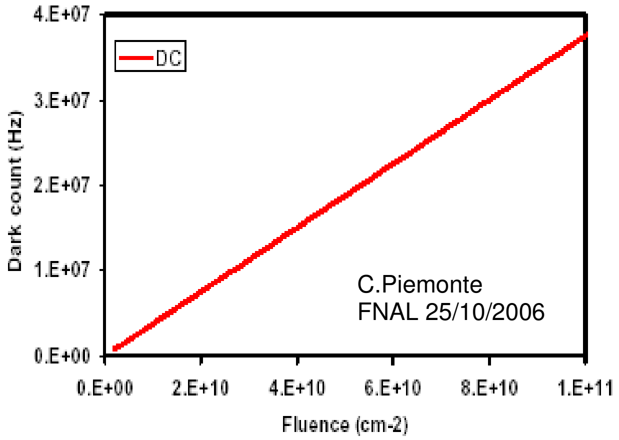
* Spanoudaki et al., IEEE NSS-MIC 2005

# Radiation damage -basics

Expected effects:

**1) Increase of dark count rate** due to introduction of generation centers

The effect is the same as in normal junction diodes:
- independent of the substrate type
- dependent on particle type and energy (NIEL)
- proportional to fluence



C.Piemonte
FNAL 25/10/2006

Dark rate increase
$D_{DC} \sim P_t/q_e \cdot \alpha\, \Phi_{eq} Vol_{eff}$
where $\alpha \sim 3 \times 10^{-17}$ A/cm is a typical value of the radiation damage parameter for low E hadrons
and $Vol_{eff} \sim Area_{SiPM} \times GF \times W_{epi}$

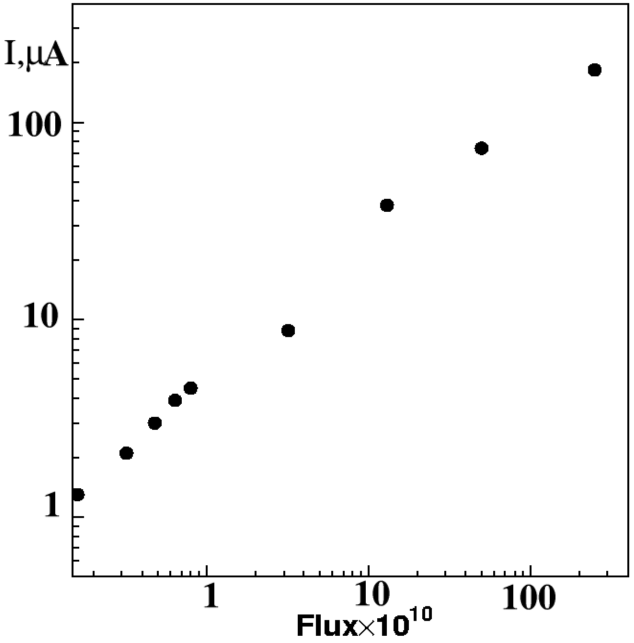
**2) Increase of after-pulse rate** due to introduction of trapping centers

 loss of single cell resolution

The few existing preliminary measurements are in agreement with expectations for the radiation damage parameter a within a factor of 2 (Musienko and Danilov, VCI07)

# Radiation damage

## Dark count rate increase



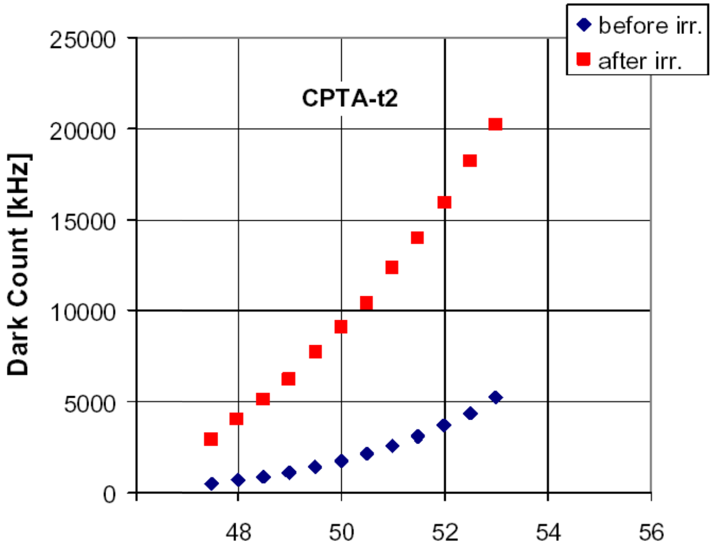
M.Danilov - VCI07

CALICE collaboration

MEPhI/Pulsar SiPM

~ Positron 28 MeV

(8x10$^{10}$ cm$^2$)



Photonique/CPTA device

Y.Musienko – Vienna VCI 2007

# Materials

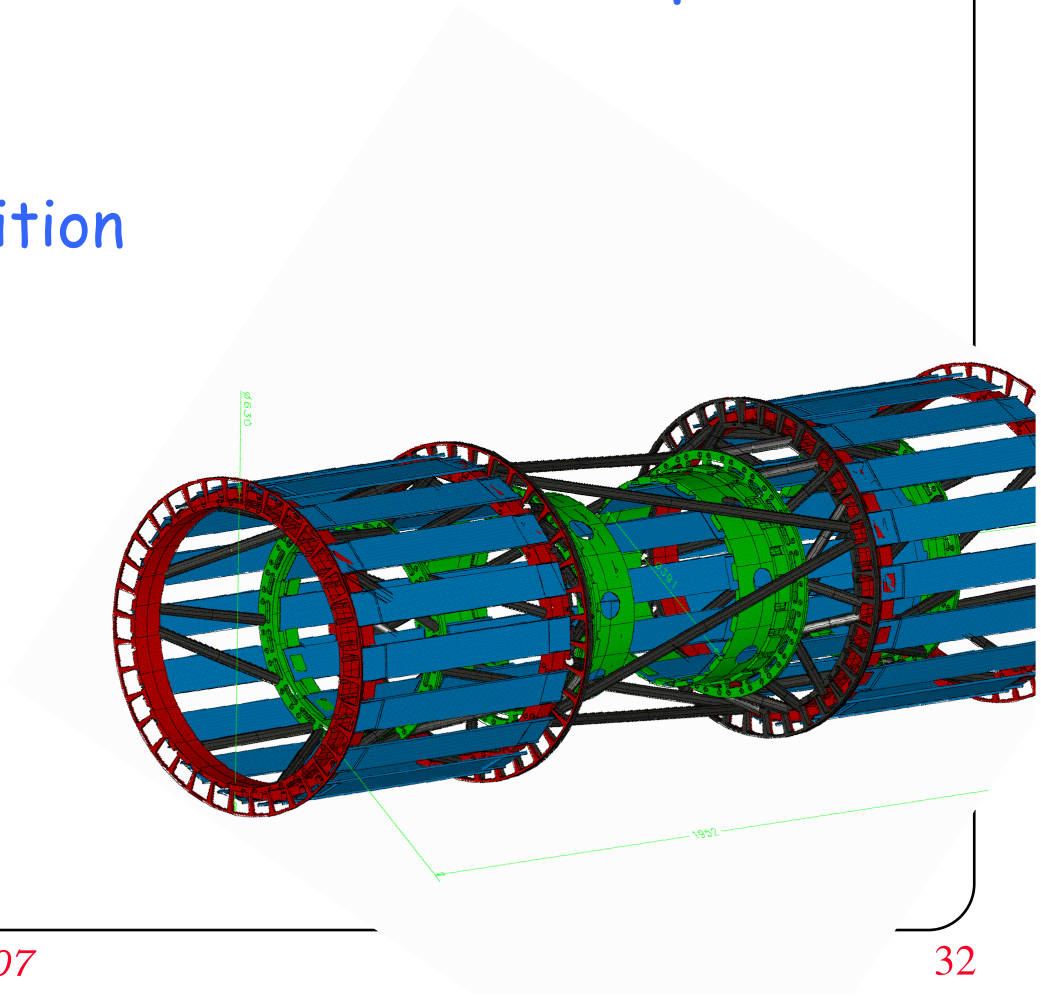
The need for lighter, radiation-resistance, cheap material with very good mechanical properties shifted our interests to composite

- ☞Kevlar
- ☞Carbon fiber
  - ⇨Different composition
- ☞Glass fiber

The CDF Space Frame:

7Kg, holding 100 Kg with max deflection 20 µm

Year: 1997

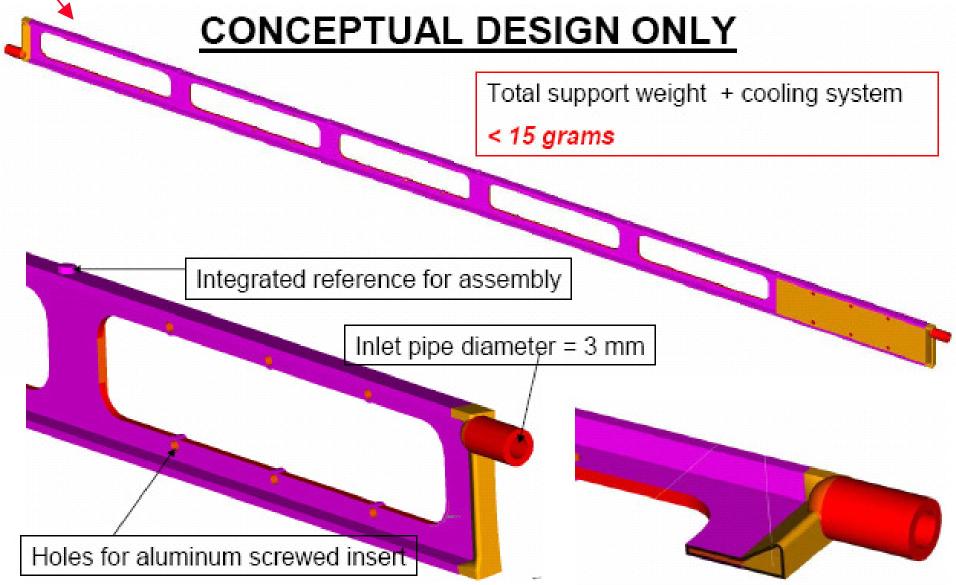


# SLHC?

CDF also developed a L00 where the support integrates the cooling lines inside

- ☞ Time to move on example of a pixel ladder for SLHC
- ☞ Need of new materials
  - ⇨ Selective Laser Sintering on thermoplastic materials with powd of Al, CF, CNT etc
  - ⇨ Multi-Jet-Modeling
    - → Thermoplastic materials used in jewelry for examp

CMS design largely based on that experience



# Nanomaterials

In previous slide I mentioned NanoMaterials

- ☞ Not accidental

Large efforts (outside HEP) in understanding nanomaterials, with large investments

  - ⇨ So far the advance is still scattered but the field is enormous (and growing)

Claim: some improvements on materials due to understanding of nano-behaviour can be used in the (near?) future

- ☞ Example: strengthened structures, x-ray reflecting coating
  - ⇨ Aimed R&D?

# Nanodetectors

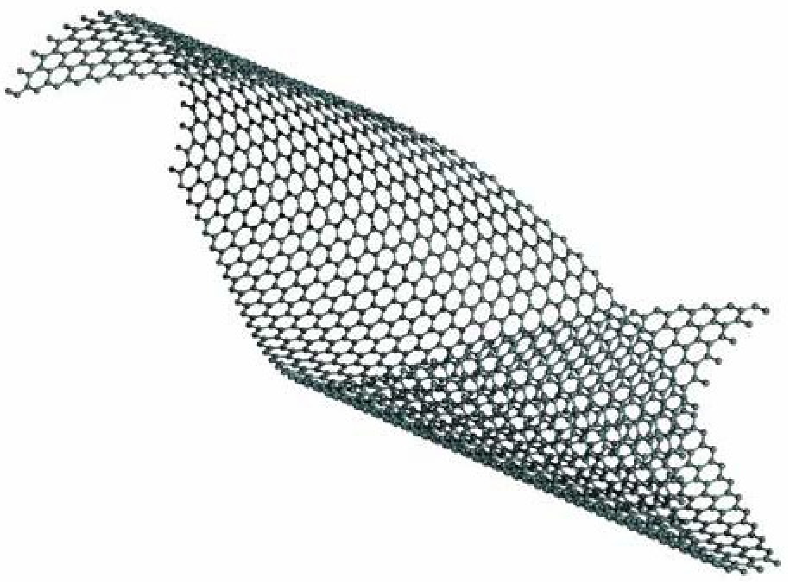
## Until a few years ago it was more of a dream

- ☞ Some progresses were made

Nanotubes have been used as IR detectors.

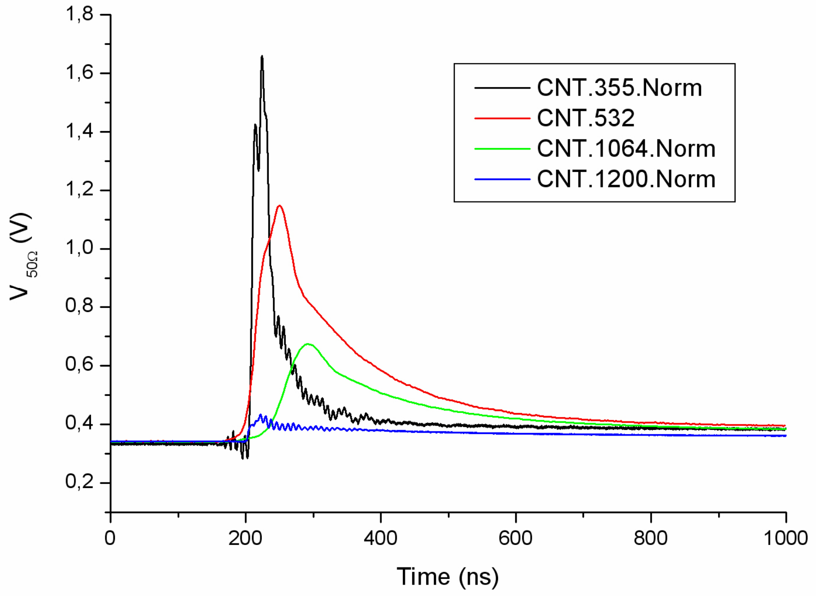
*(I.M.Xu: Highly ordered carbon nanotube arrays and IR detection – Infrared Physics and Technology 42 (2001) 485 – 491)*

*(M.E. Itkis: Bolometric Infrared Photoresponse of suspended Single-Walled Carbon Nanotube Film – SCIENCE Vol. 312 (2006) 413 – 416)*



CNT response to laser

M.Ambrosio, Vienna 2007



# In the future…

I see more collaboration with colleagues working outside our field

- ☞ Medipix a good example:
  - ⇨ Born from an idea of developing a chip for Medical application (Medi…pix)
    - → Two generations,
    - → Now used by LHCb, improved, back to medical appl.
- ☞ SiPM also of wide interest outside our field
  - ⇨ This is generally true for all sturdy, high efficiency devices
    - → Solid state over gas?
- ☞ Electronics:
  - ⇨ Main breakthrough for rad resistance electronics came from sub-micron processing (no input on our side)

# Conclusion

Thank you very much for following me in this short trip

- Many thanks to the Organizers and to TRIUMF for the invitation and the hospitality
- Thank you to your patience in following these lectures

- Posted on my website http://www.pi.infn.it:/~giorgio

# Something to remember

La fantasia abandonada de la razon produce monstruos inposibles: unida con ella es madre de las artes y origen de sus **marabillas**"
**(Francisco Goya, Capricho 43)**

The best asset of an experiment is its people

There are still questions to be answered

- ☞We need your work and ingenuity to find them