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Sensor developments for tracker detectors after LHC

G. Casse – University of Liverpool

OUTLINE:

- Requirements for detectors for hadron machines (Super LHC)
    - Present baseline detectors
    - Possible alternatives
- Developments for Linear Colliders (LC)

Requirements for Super-LHC (SLHC)

Luminosity upgrade: several phases, but target luminosity of ~ 10^{35} cm^{-2} s^{-1}, with possible E=28 TeV and bunch crossing 25 ns. This implies a change in the detector environment. What are the predictable changes? They are driven by several issues: physics, electronics, sensors, mechanical and cooling. Physics will require tracking, even at low radius. Jets will be more energetic, with higher track density. Higher granularity required, but trade of with power dissipation and material budget. Sensors and electronics are linked in term of requirements. The cell size (total number of channels) depends on the ability of cooling down the electronics and to realise data suppression at early stages. The feature size of the rad-hard electronics will be much smaller, and possibly need less power (…but many issues on the electronics are open: we'll be obliged to follow the main trends, can be costly, more complex design tools, and, if power reduction will be achieved by lower supply voltage, dynamic range can be affected, and driving signals over long cables more difficult…).

Sensor issues:

Reduced cell size at corresponding radius

~10 times more radiation at same radius

Target: good tracking performances at the end of experiment: S/N ~ 10

Geometrical parameters to play with: cell size (reduced occupancy and input noise to electronics) and thickness (benefit material budget, but penalises signal)

Future trackers: silicon or other semiconductor materials?

The most studied alternative materials, that show possible benefits in term of radiation hardness, are diamond, SiC and, now, GaN.

Property	Diamond	4H SiC	Si
E_g [eV]	5.5	3.3	1.12
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	800	1450
μ_h [cm^2/Vs]	1200	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	$2 \cdot 10^7$	$0.8 \cdot 10^7$
Z	6	14/6	14
ε_r	5.7	9.7	11.9
e-h energy [eV]	13	8.4	3.6
τ_h [s]	10^{-9}	$5 \cdot 10^{-7}$	$2.5 \cdot 10^{-3}$
Wigner En.[eV]	43	25	13-20

Bandgap higher than silicon: lower leakage current

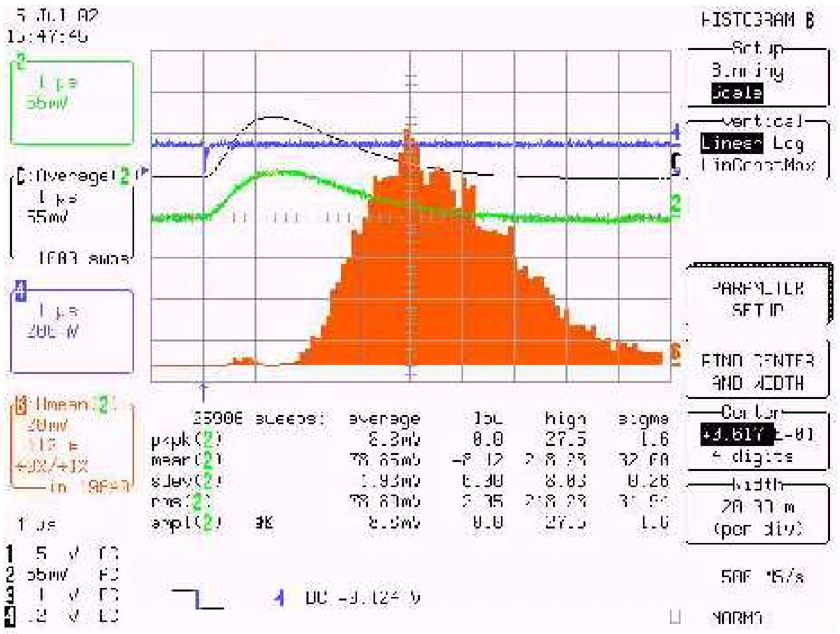
Signal:
Si $\Rightarrow$ 80 e/μm
SiC $\Rightarrow$ 51 e/μm
Diamond $\Rightarrow$ 36 e/μm

Displacement threshold

Higher than Si $\Rightarrow$ better Radiation tolerance?

Diamond: RD42 results

Latest Diamonds Measured with a ^{90}Sr Source:



- System Gain $= 124\ e/$mV
- $Q_{MP} =$ 62mV $=$ 7600e
- Mean Charge $=$ 79mV $=$ 9800e

- Source data well separated from 0
- Collection Distance now 275μm
- Most Probable Charge now $\approx$ 8000e
- 99% of PH distribution now above 3000e
- FWHM/MP $\approx$ 0.95 — Si has $\approx$ 0.5
- This diamond available in large sizes

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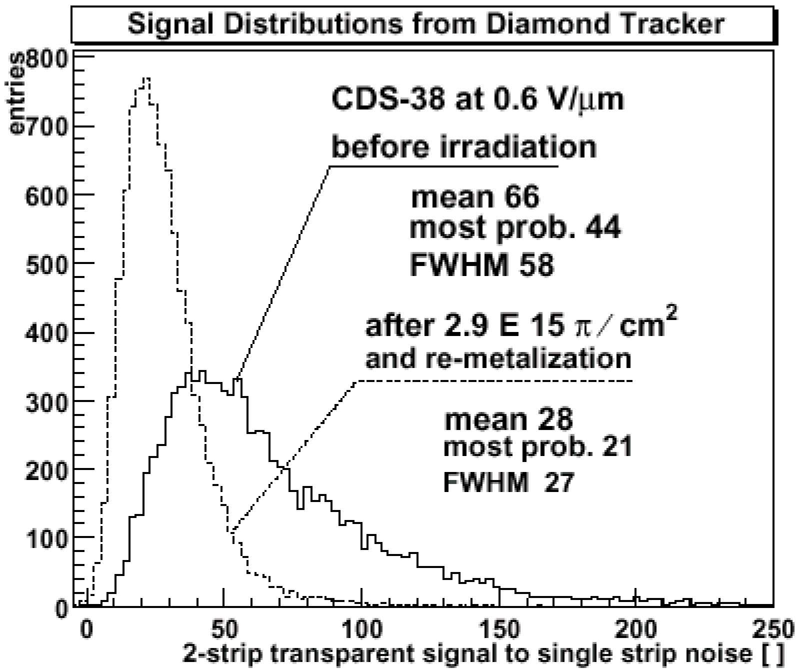
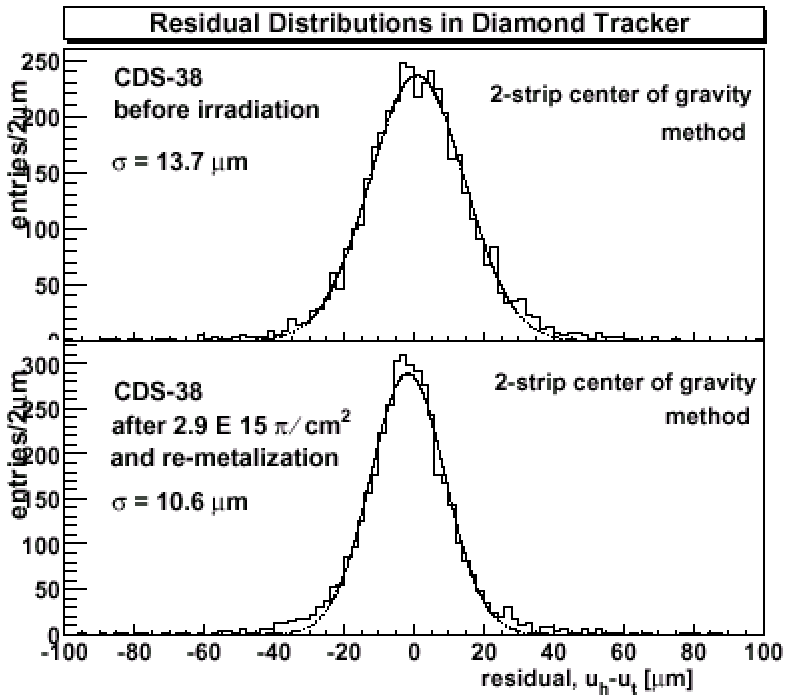
Diamond radiation resistance

Pion irradiation studies from RD42





- Dark current decreases with fluence
- 50% loss of S/N at 2.9×10^{15}/cm^2
- Resolution improves 25% at 2.9×10^{15}/cm^2

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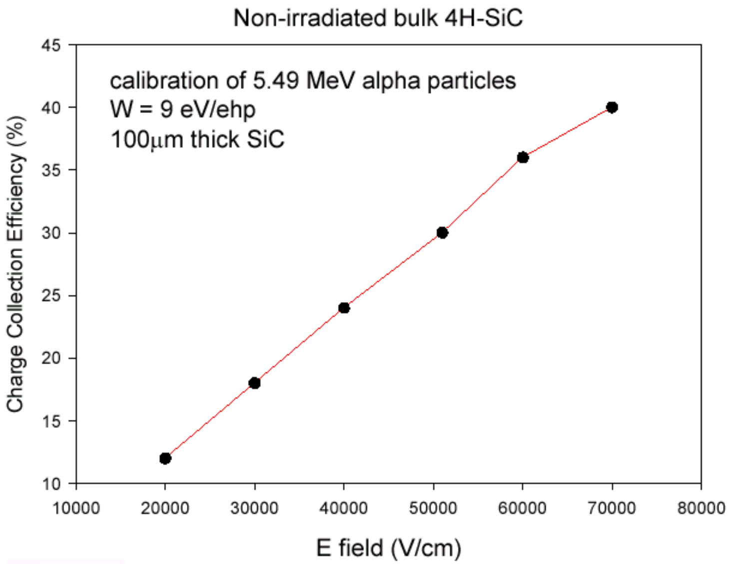
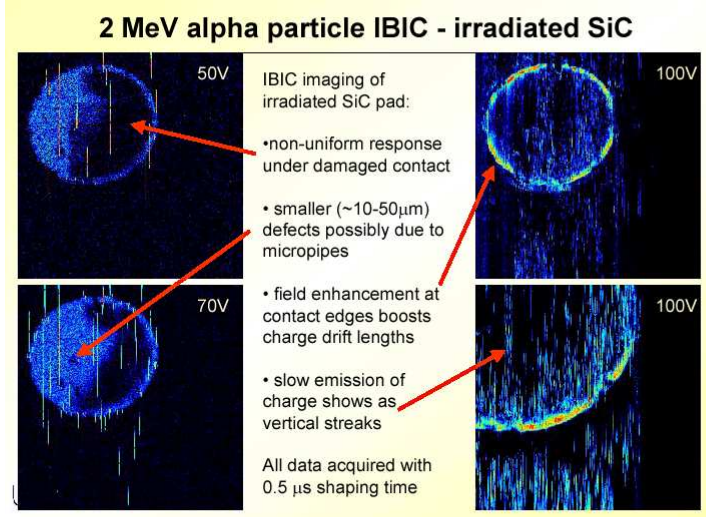
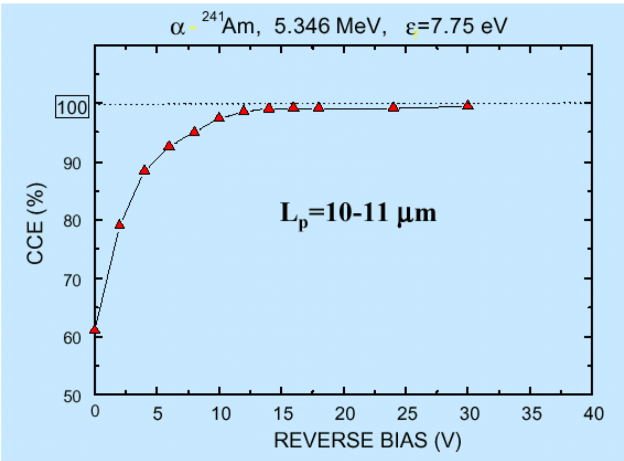
Bulk SiC has incomplete charge collection (no e transport) and suffers for polarisation effects (traps/micropipes) Data: P. Sellin

SiC



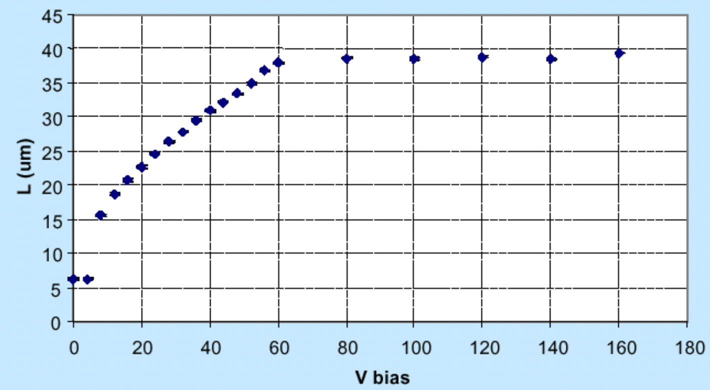


Epitaxial SiC: good homogeneity and charge collection, negligible polarisation – Thin layers (up to 50µm), very high cost: 9000 $ for 2” wafers



M. Bruzzi et al. 2nd RD50 Workshop, CERN May 18-20 2003

 # electrons/55 per µm
The cce MIP meaurements are consistent with the other characterization: Vsat =60V N_{eff}= 4 10^{13}/cm^3
100% efficency



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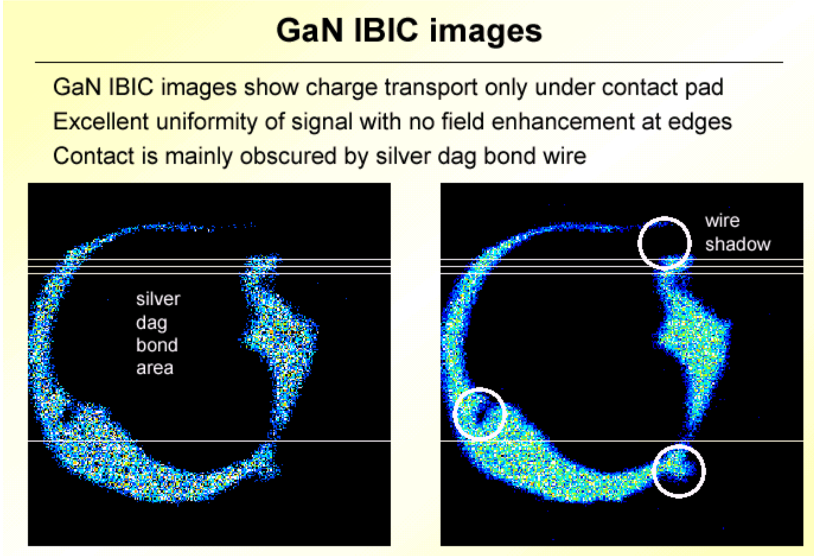
GaN

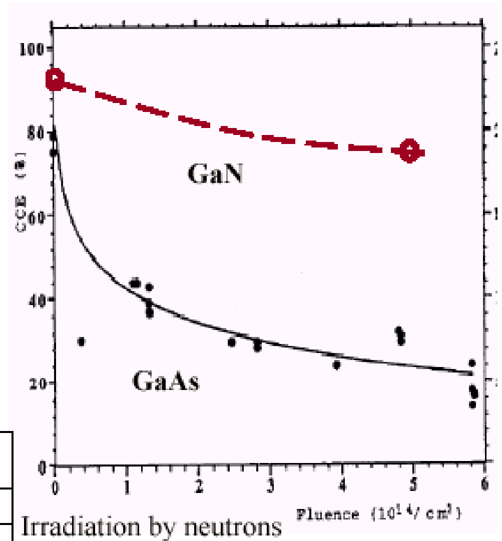
See P. Sellin and J. Vaitkus talks at 2nd RD50 workshop



Conclusions for GaN

1.

SI- GaN	Energy /fluence	c.c.e.
nonirradiated		92 %
Irradiated by X-rays	10 keV / 600 Mrad	100 %
Irradiated by neutrons	> 100 keV / 5 10^{14} cm^{-2}	77 %



2. A main actuality: to grow a thick SI-GaN !!!

Exotic silicon

Nonetheless, the present performances of materials alternative to silicon are no such to justify their use for detector manufacturing. Moreover the cost and size issue are unapproachable at present, and probably also for the time scale of SLHC. What is the present situation with *exotic* silicon materials? Impurity doped silicon must fulfil a few requirements: increasing the radiation hardness of the detectors without harming the electrical performances and being acceptable for processing by the main device manufacturers. The size of the project will not allow *niche* producer to bid for construction, so the *new silicon* materials will need to be accepted by the long established manufacturers. This will limit the type of impurities acceptable in the silicon crystal.

Exotic silicon: what impurities?

The impurities that will probably b accepted by manufacturers, without special precaution, are the ones already present in the silicon crystal: mainly H, O, C, N. Also Si-Ge is processed by a few manufacturers. The effect of these impurities, with the exception of H (usually the content of H in the Si crystal is unknown), on the properties of the detectors after irradiation have been tested.

Facts about the radiation hardness of silicon sensors.

A few materials have been claimed as having improved radiation hardness with respect to the standard high purity FZ silicon

HT Oxygen enriched silicon

CZ silicon

EPI silicon

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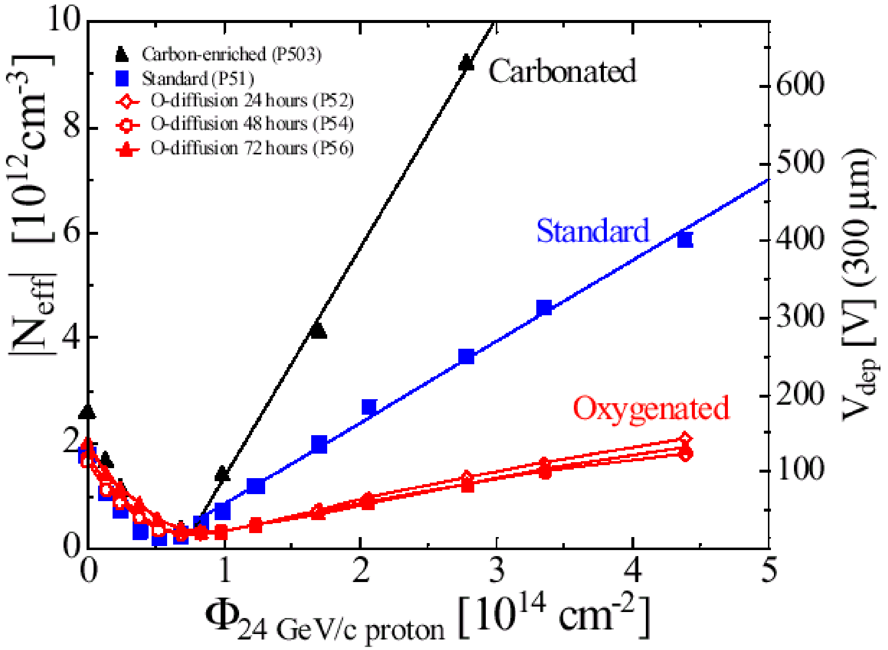
HT Oxygen enriched (~1-2 10^{17} a cm^{-3}) silicon

No changes in the increase of the reverse current, but

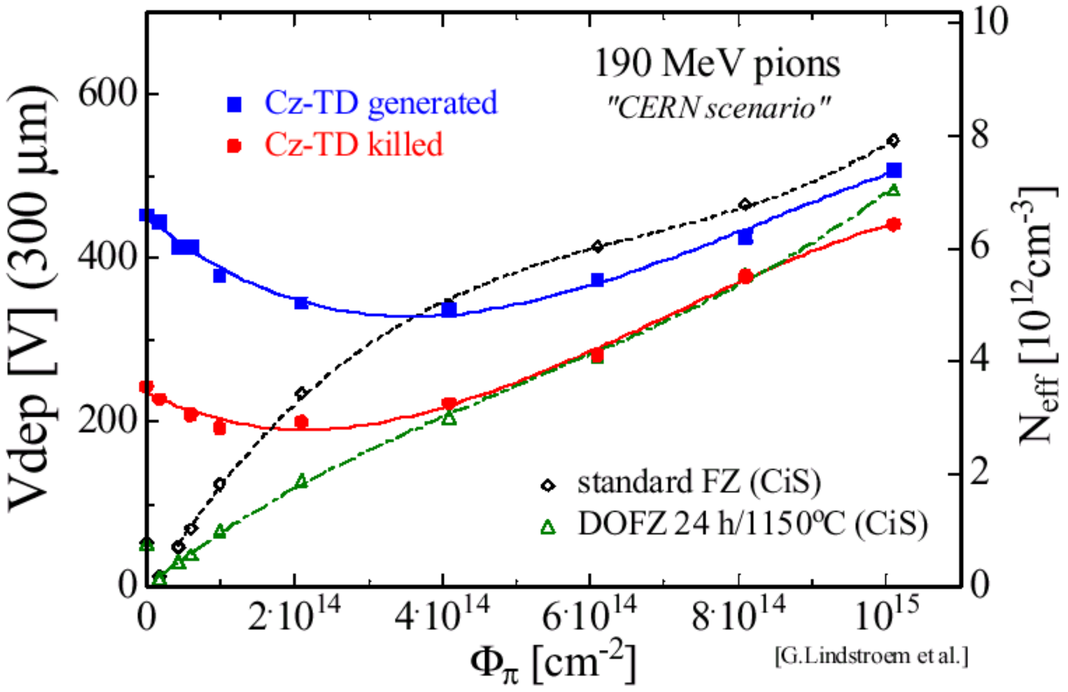


[RD48-NIMA 465(2001) 60]

Benefit of the O enriched Si with 24 GeV/c protons in term of β. No benefit with neutrons. Elimination of degradation of V_{fd} with gamma irradiation. Deterioration of the radiation hardness in C enriched material.

Czochralski (CZ) silicon from Sumitomo

High resistivity CZ (>1 kOhm cm), high O content (~10^{18} a cm^{-3})



No type inversion for this material. Long term behaviours to be proven better than HT oxygenated silicon

Reverse current and charge trapping comparable to FZ silicon

Magnetic Czochralski (MCZ) silicon from Okmetic

High resistivity CZ (>1 kOhm cm), high O content (5-6 10^{17} a cm^{-3})

Summary of the β parameter:

	Fz	n-Cz
10 MeV	5.14E-3	3.77E-3
50 MeV	1.79E-2	1.24E-2
24 GeV/c	8.40E-3	4.76E-3

	p-Cz
10 MeV TD	5.85E-3
10 MeV std	3.80E-3
50 MeV TD	9.44E-3
50 MeV std	6.24E-3

Esa Tuovinen, 4th RD50 Workshop, CERN May 2004

Epitaxial material

Epi-Si: low resistivity (50 Ohm cm), [O] ~ 5 10^{17}

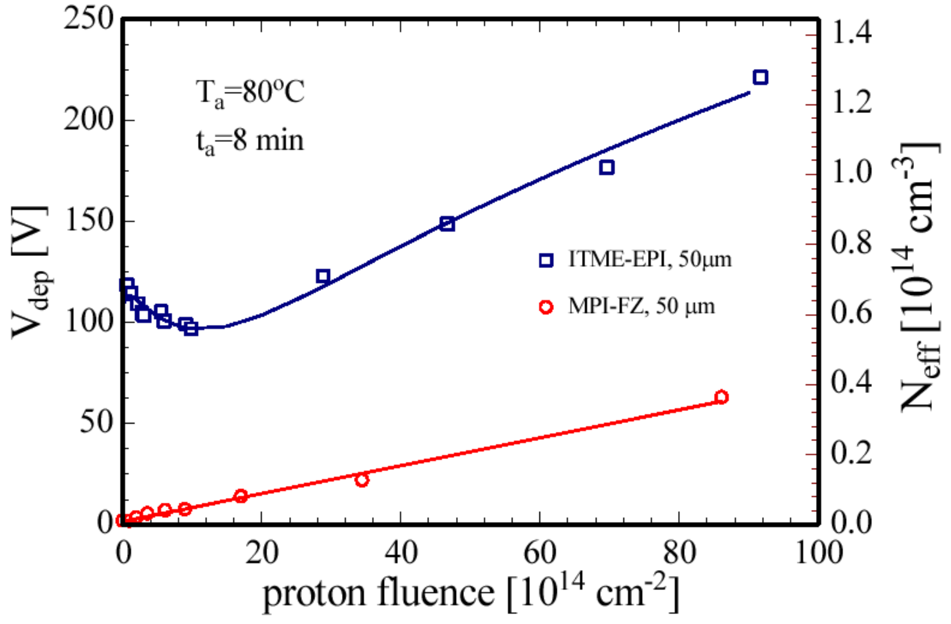
Thin epi layer (50 µm)

Compared with thinned (to 50 µm) standard high resistivity FZ

The degradation of the V_{fd} is measured by the parameter β. Here:

$\beta = 0.0036\ cm^{-1}$ for FZ

$\beta = 0.0084\ cm^{-1}$ for EPI



No type inversion for EPI-Si. Long term behaviours worse than HT oxygenated silicon. Reverse current and charge trapping comparable to FZ silicon.

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Important parameter of degradation: S/N

The degradation of the signal to noise with fluence is limiting the lifetime of the present sensors.

What is the final limit to the lifetime of the detector in the high radiation environment? The tracking capability of the detectors will be badly affected when the S/N will fall below 10.

The degradation is mainly due to the reduction of the signal, while the noise can be assumed to be almost constant. In fact, it is now well proved that, with 20ns shaping time electronics, the noise is not much affected by the reverse current (shot noise). With small cell size and low temperature, the amount of reverse current can be kept under control also at very high doses. So it is reasonable to expect a noise level unchanged by irradiation.

The noise is therefore determined almost uniquely by the geometry of the segmented detector (and fan-ins) ⇒ input capacitance to the read-out electronics

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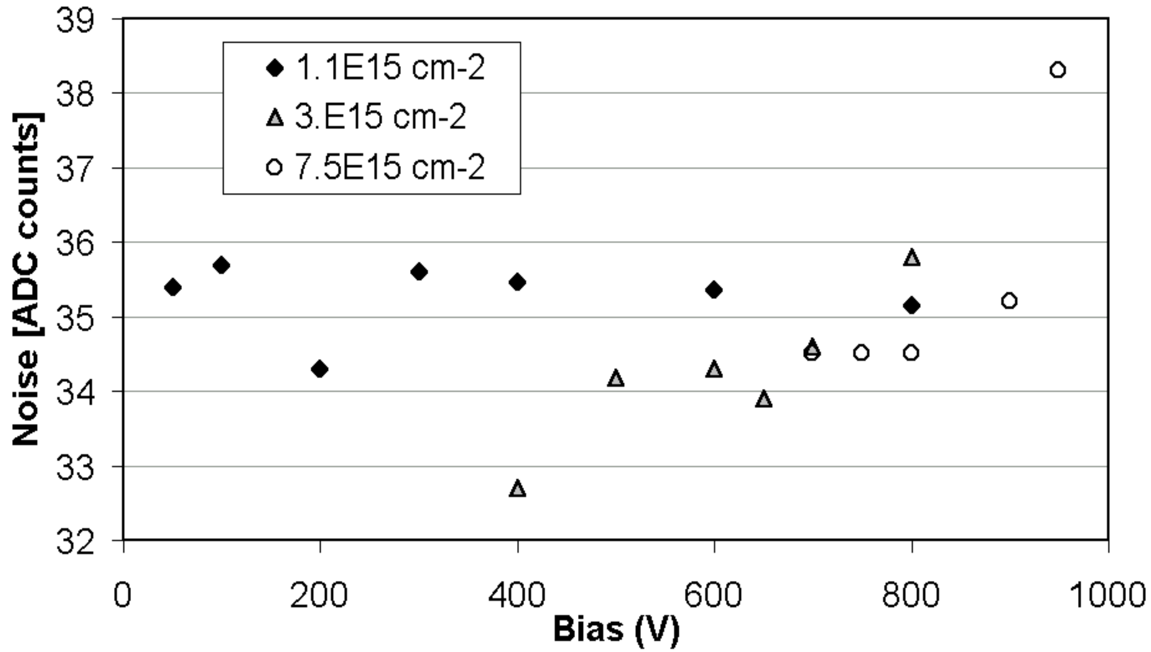
Studies in LHC configuration: dependence of the noise on bias and irradiation fluence

Noise as a function of the applied voltage for three different irradiation doses. The pre-irradiation value is about 35 ADC counts, similar to the value found after irradiation.



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Degradation of S/N

Degradation of the signal due to charge trapping at radiation induced defect centres. Importance of the fast signal formation.

Irrespectively on the oxygen content of the starting material, the largest beneficial impact on the charge collection properties of the segmented devices is given by the choice of the read out geometry. Keeping the high electric field on the read out side gives significant benefit in charge collection at low bias voltages with segmented detectors. After a few 10^{13} particle cm^{-2}, n-type silicon inverts to p-type, than the high electric field is always on the n-in-p junction in heavily irradiated devices.

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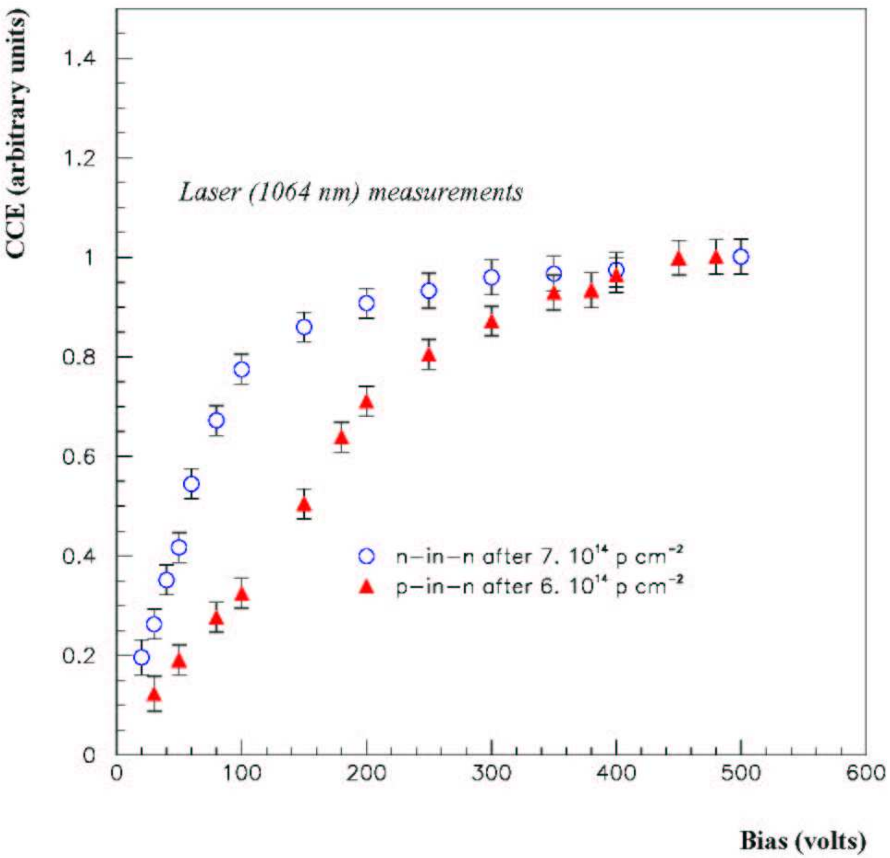
N-side read out: n-in-n devices

Example: comparison between a traditional p-in-n geometry (with high electric field on the backplane after type inversion) and n-in-n geometry (high electric field on the read-out side after type inversion)

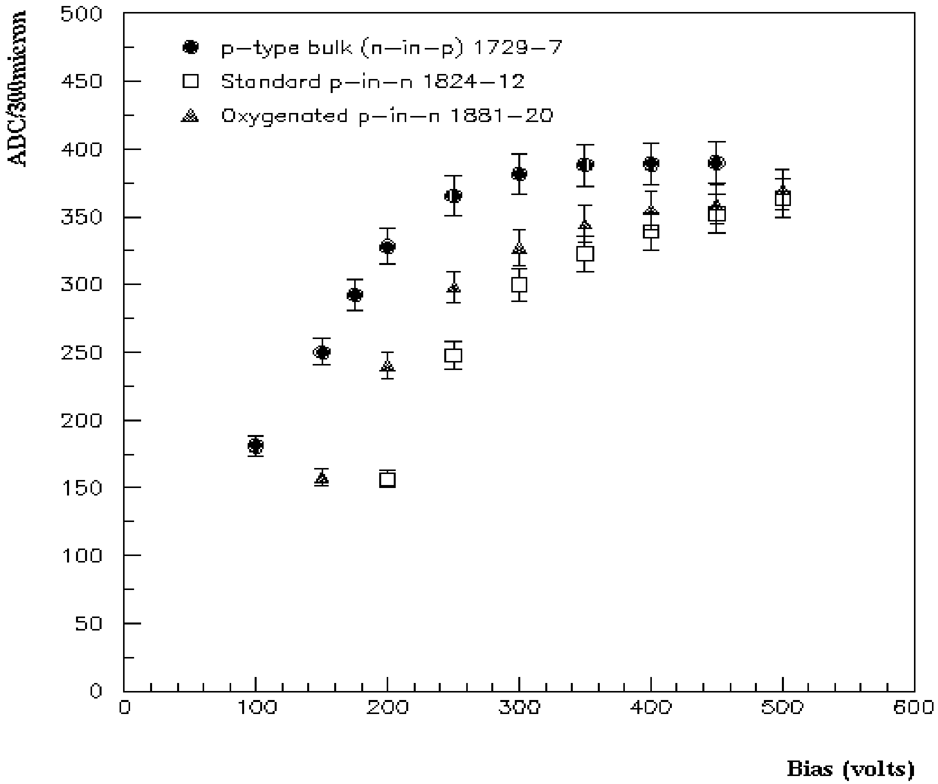
n-side read-out detector after 7.10^{14} p cm^{-2}, p-side read-out detector after 6.10^{14} p cm^{-2}.



This result has determine the choice for the LHCb VELO microstrip (the closest to the beam pipe in the LHC experiments)

N-side read out: n-in-p devices

Full size (6x6 cm^2) segmented (microstrip) detectors have been made and successfully tested on standard p-type substrate (n-in-p) after 4.10^{14} p cm^{-2}



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Keeping the high field on the read-out side of single side segmented devices:

1. N-in-n diode geometry (now used for the highest radiation hard performances): double sided process is necessary
2. N-in-p diode geometry (full size segmented detector have been manufactured on p-type substrates): double sided process is not required
3. P-in-n geometry with non-inverting n-type silicon

What's the best solution?

1. Is the best proven technology, very good radiation hardness results with oxygen enriched silicon, the mandatory double sided process is more expensive. Fast signal formation (e^- read out). Possible on High Res. CZ.
2. This can be cheaper, but high resistivity p-type wafers are less common. Oxygen enrichment available. Fast signal formation (e^- read out). Possible on High Res. CZ.
3. Cheap processing. Slower signal formation (h read out). Non-inverting materials are Sumitomo CZ (not available) and Epi-Si (low resistivity, thin material, not really impressive performances predicted for thicker devices)

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N-in-P devices

Excellent results have been obtained using miniature detectors (ATLAS-like pitch) designed by the University of Liverpool and processed by CNM-Barcelona. The devices were 1X1 cm^2, ~100 strips, 280 μm thick.

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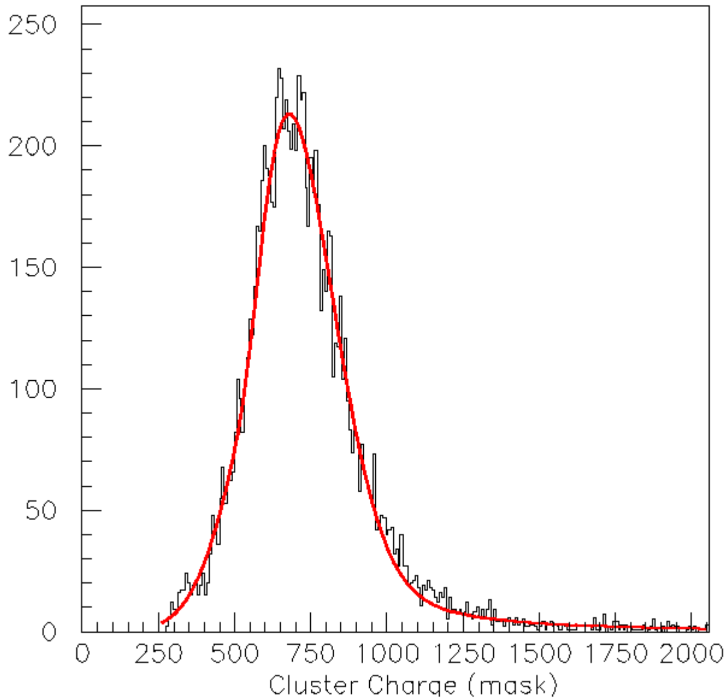
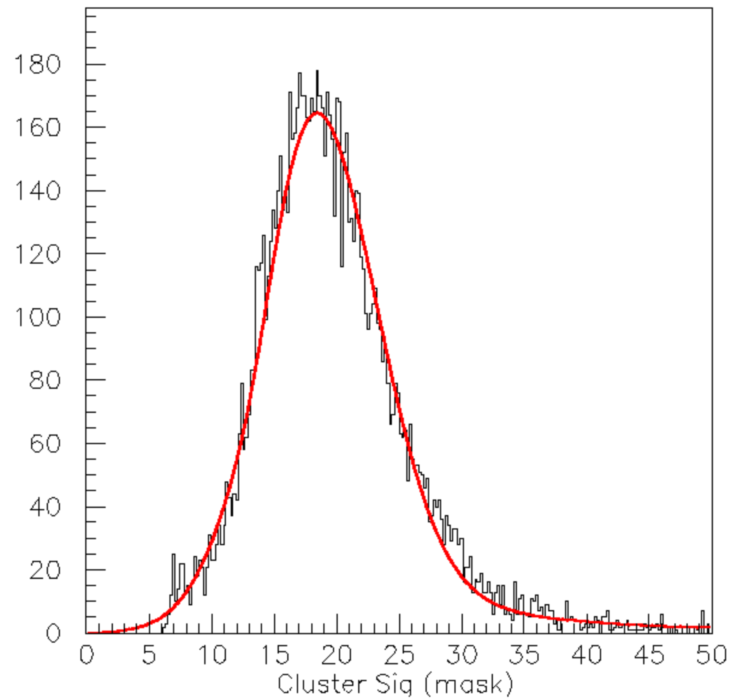
Signal and cluster significance after 1.1 10^{15} p cm^{-2} (800 V)





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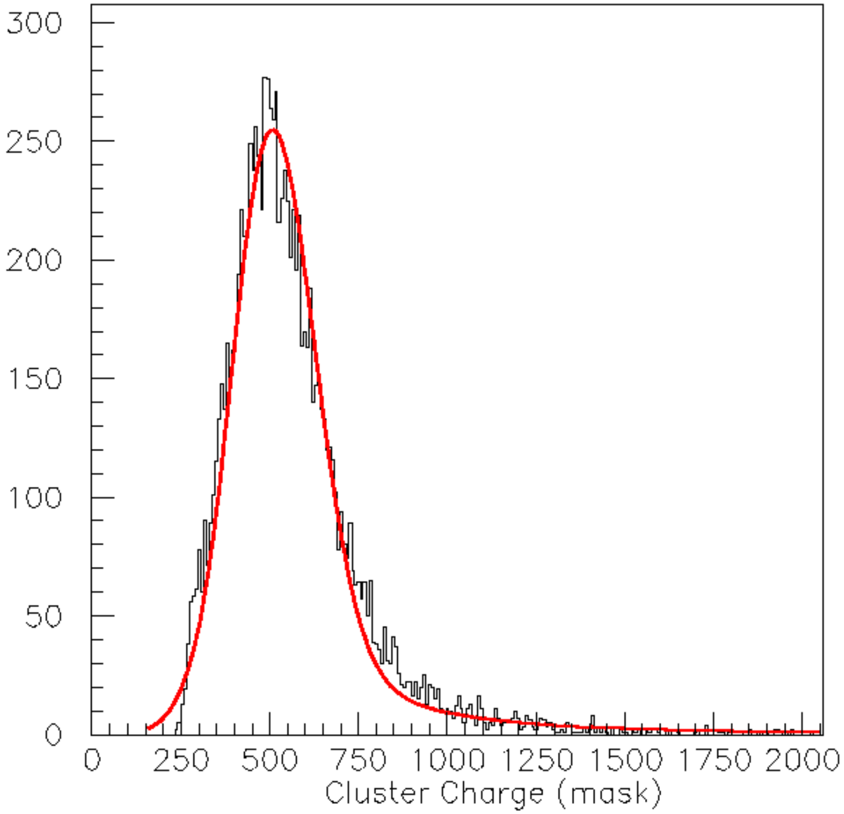
Signal after 3. 10^{15} p cm^{-2} (700 V)



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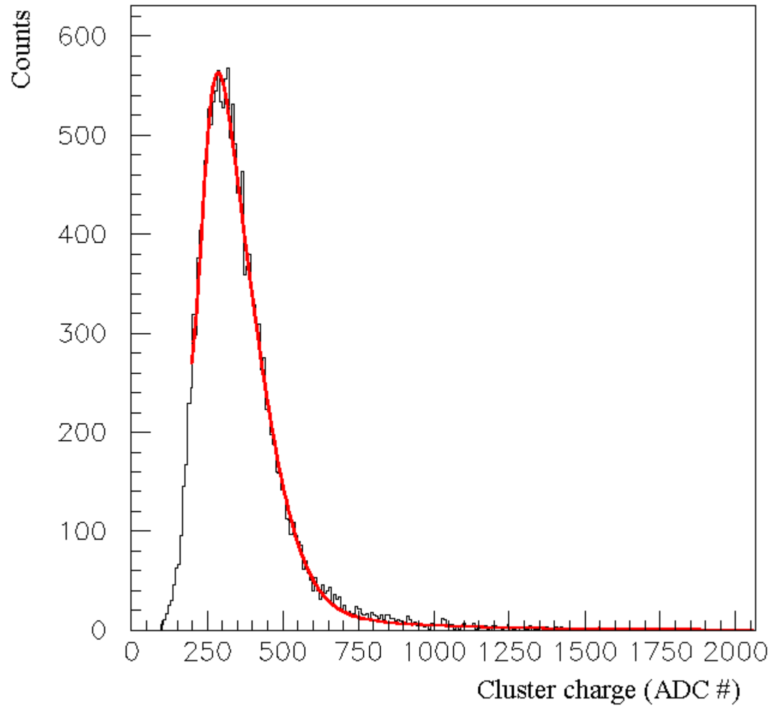
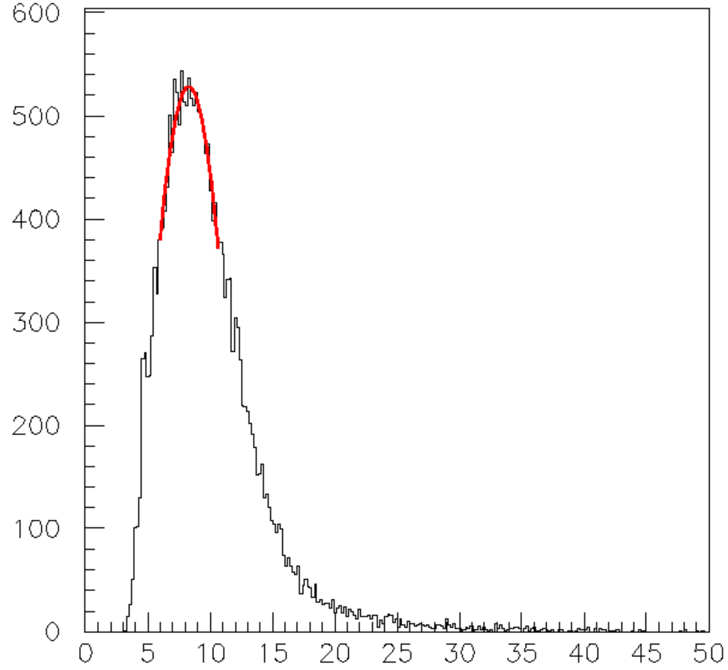
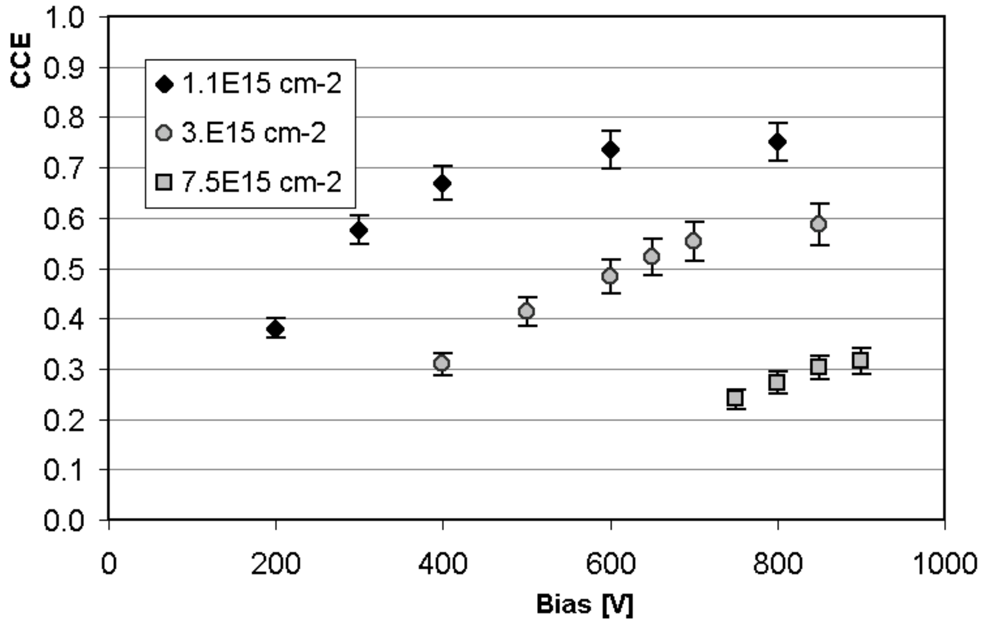
Signal and cluster significance after 7.5 10^{15} p cm^{-2} (900 V)





CCE(V) vs applied bias voltage, normalised to the pre-irradiation value, of n-in-p detectors after 1.1, 3 and 7.5 10^{15} p cm^{-2}. The detector irradiated to 3. 10^{15} cm^{-2} is standard p-type substrate, while the other devices are oxygen-enriched.



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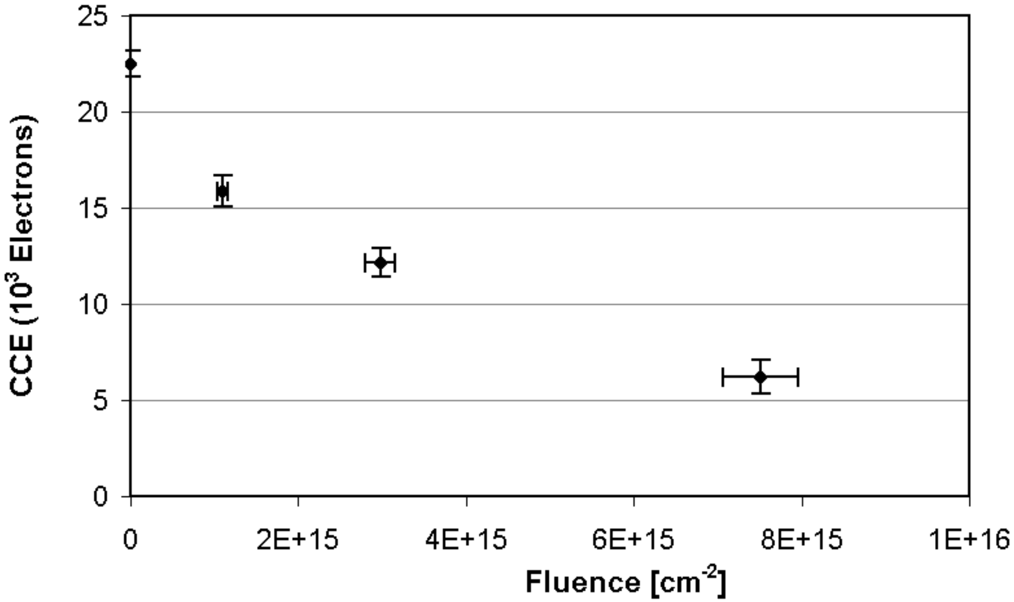
Degradation of the collected charge as a function of the irradiation fluence for n-in-p microstrip detectors. The applied voltages are 800, 800 and 900 volts for the three different irradiation fluences, respectively.



N-in-P devices

PERPECTIVES:

As long as the input noise (input capacitance) is kept relatively small (<10pF), microstrip (ministrip, strixels….) detectors with n-side read-out, and in particular p-type bulk, appear to be well usable for future SuperColliders. This read-out geometry also overcome the necessity of reduced thickness of the devices, which can be decided on the basis of other considerations (low mass vertex detectors…).

After **$7.5\ 10^{15}$ p cm^{-2}** the n-in-p devices were still able to collect **>6500 e^{-}**, corresponding to a ionisation depth of 90 μm of a non-irradiated device. Stripsel, or ministrip detectors with input capacitance such to produce a noise of ~700 e will fulfill the requirement of S/N ~ 10 after irradiation!

More systematic studies are needed in this very promising direction: role of oxygen, CZ materials, how much over-bias is useful (CCE(V) saturation due to trapping….)

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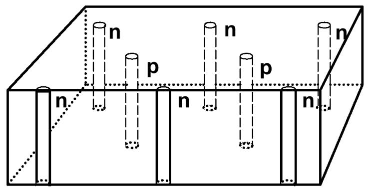
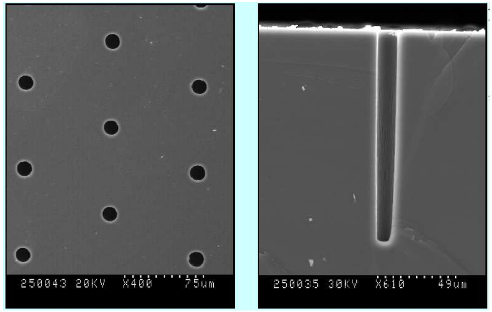
New structures

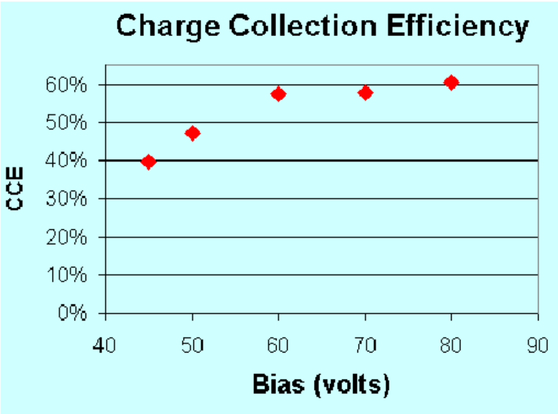
3-d devices, proposed by S. Parker.

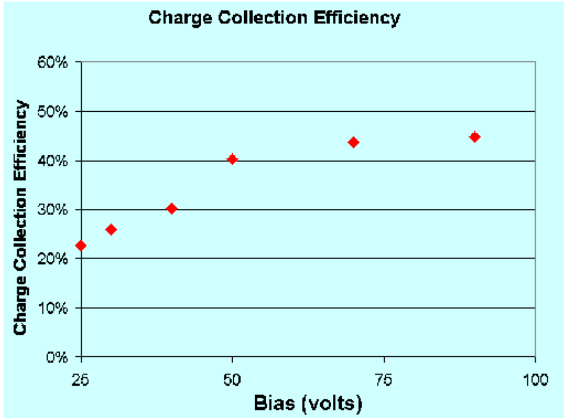
Holes processing: dry etching, Laser drilling, Photo electrochemical. Present aspect ratio (within RD50) 13:1, target > 30:1





Some result (α spectroscopy) before and after 10^{14} 300 MeV/c π cm^{-2}





Very promising silicon devices for speed and radiation hardness. Will the technology be mature enough in a few years to cover the system aspects, cost …….?

Data from P. Roy, 2nd RD50 workshop

Linear Collider (LC) Vertex Detectors

Three different projects (0.5-1 TeV): 1 cold (TESLA), 2 warm (NLC. JLC)

Requirements: fast (up to 50MHz clocking speed for TESLA, for a read-out time of 50µs), very high resolution and low mass (0.1% X_0).

Possible detectors: Column parallel read-out CCD (CP CCD), Hybrid pixels, Active pixels (MAPS, FAPS, Radfet, RAPS)

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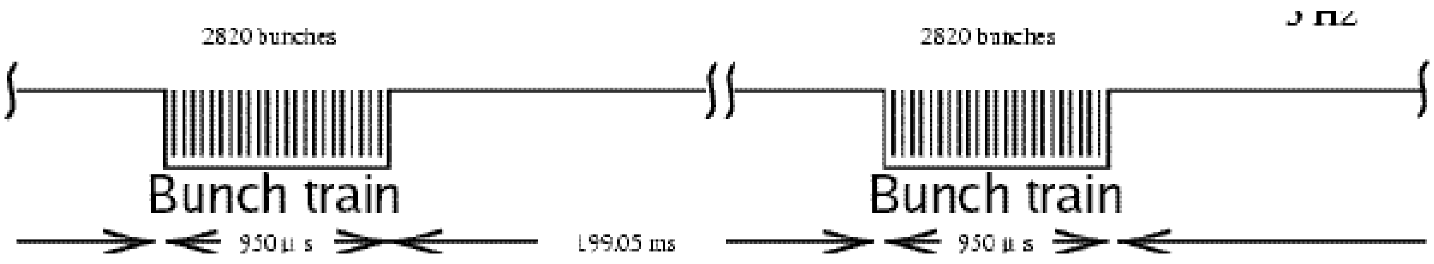
Example: TESLA beam structure



- Train length ~1ms
- 2820 bunches / train
- 337 ns between bunches
- 200 ms between trains
  - Data are store in the Front-end
  - Read out during the 200ms

No trigger nor dead time!

The TESLA detector: high precision

Granularity	Vertex	800 Mpixels
	Ecal	32x106
Material budget	Tracker	0.05 X_0
	Vertex	0.01 X_0

Required: 99% efficiency, High resolution $\delta IP \leq 5$ μm, 5 layers ~ 50μm/layer

Pixel size ~ 20x20μm

Quick read-out 25-50 μs

On line sparsification

Radiation resistance

What technology for the LC?

- CP-CCD (SLD)
  - ⇧Thin detectors proven, high granularity
  - ⇩Speed is still an issue, poor radiation hardness?
- Hybrid pixels
  - ⇧Fast and very rad-hard
  - ⇩ Thickness, granularity (bump bonding at the 20μm level)?
- MAPS (CMOS detectors)
  - ⇧Granularity, thickness
  - ⇧Speed (faster than CCD's)
  - ⇧Good rad-hardness, possible to improve?
  - ⇧Cost (standard CMOS processing)
  - ⇧On-chip electronics: logic, ADC, pre-amplification etc.
  - ⇩ Technology is fast improving, but yet not mature
- DEPFET, SOI, etc. Early stages, probably longer term technologies

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Status and first results of the UK active pixel collaboration

- APS1
  - Laser test
  - Simulation program
  - Radiation test
- APS2
  - Source measurements
  - FAPS
- Summary & Outlook

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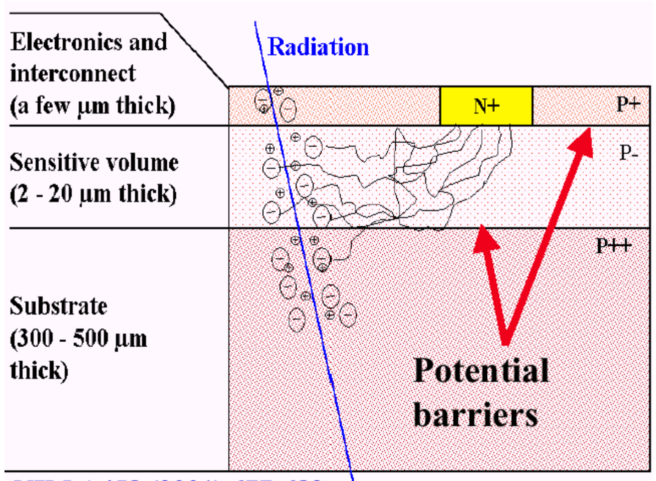
Operation principle of CMOS sensors

- Eight 8*8 arrays (15 µm pitch)
  - Baseline 3MOS pixel
  - 4 diode
  - TX (CDS)
  - Baseline with cal
  - (4 Photogate pixels)
- 2 µm epi-layer
- 0.25 CMOS IBM

APS1



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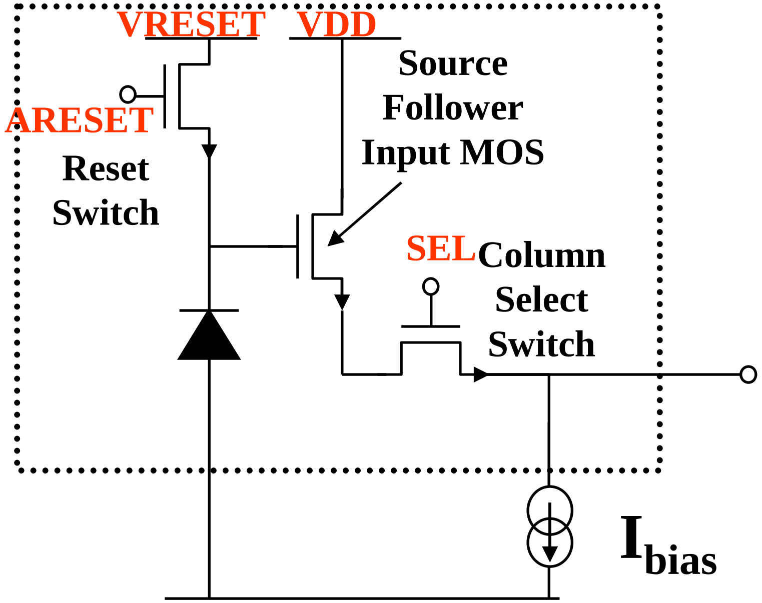

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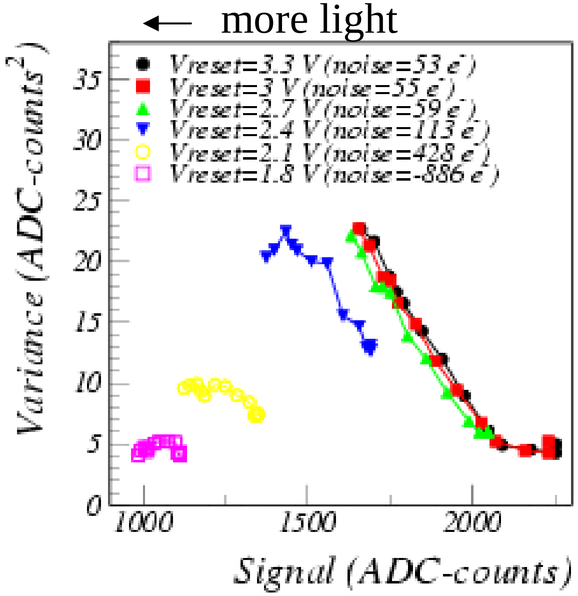
Noise: Photon-transfer curve

- Get noise using Photon-transfer curve
  - Assume: variation in signal dominated by variation in number of absorbed photons:

$$\sigma = G\sqrt{n_{photo-electrons}}$$

$$S = Gn_{photo-electrons}$$

  - Plot Variance vs Signal
  - Fit straight line ⇒ gain in ADC/e$^-$
  - Convert dark noise in ADC to noise in e$^-$



Pixel type	Noise (e$^-$)
Std 3MOS	52±1
4 diode	184±6
TX (diode conn)	52±2
3MOS+cal	54±1

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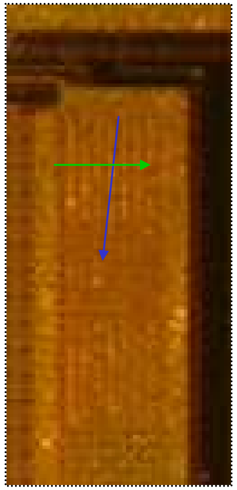
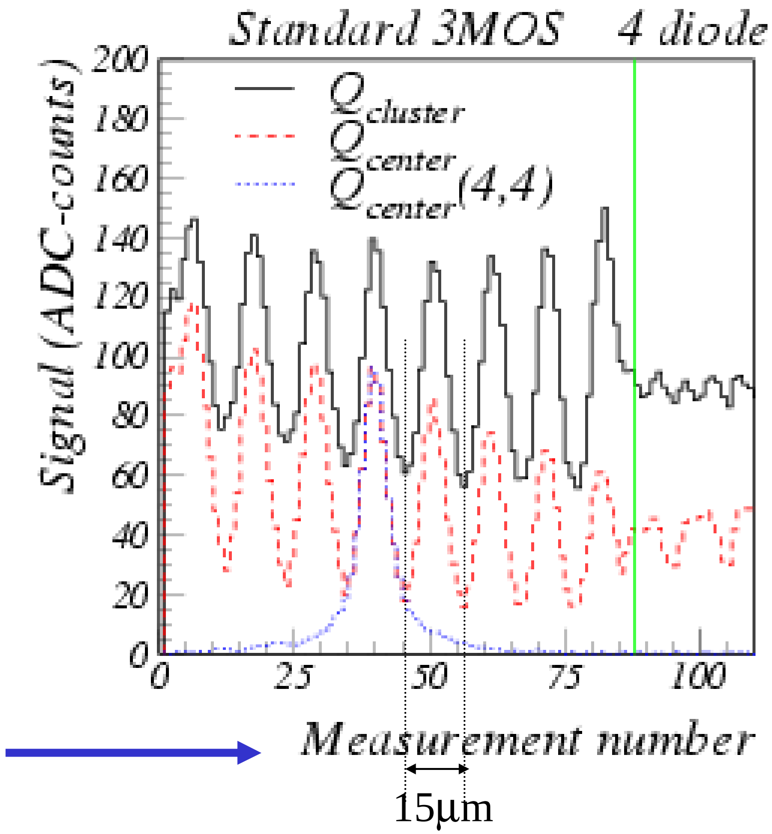
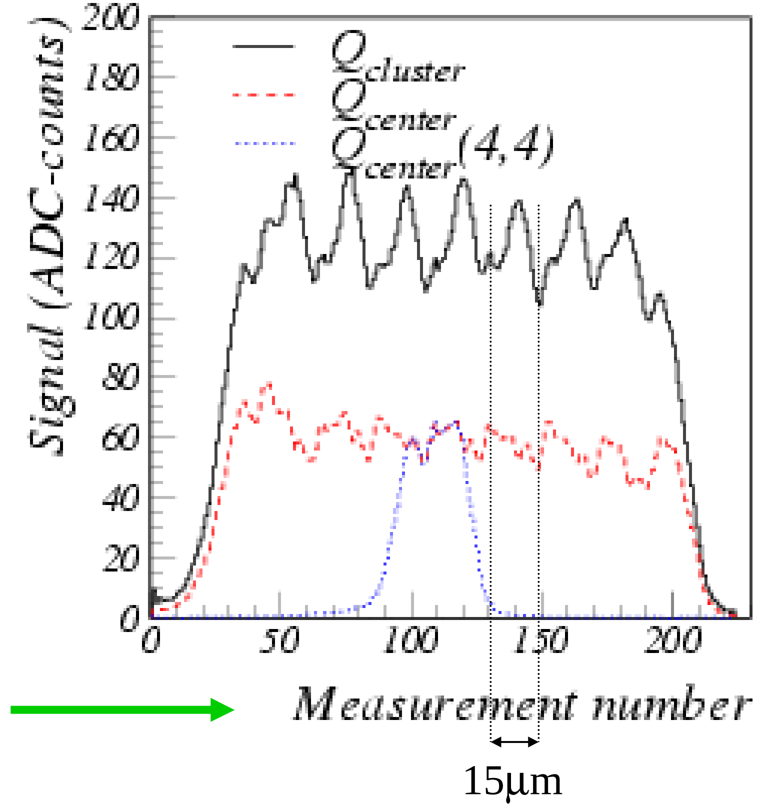
APS1: Laser test







- Scan using laser along arrows
- Laser spot: σ=7µm
- Effects of metal structure clearly visible

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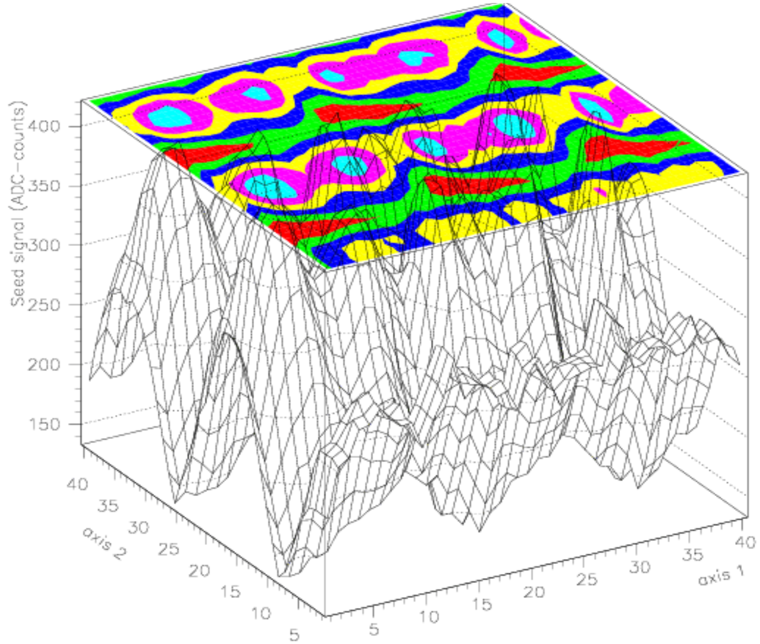
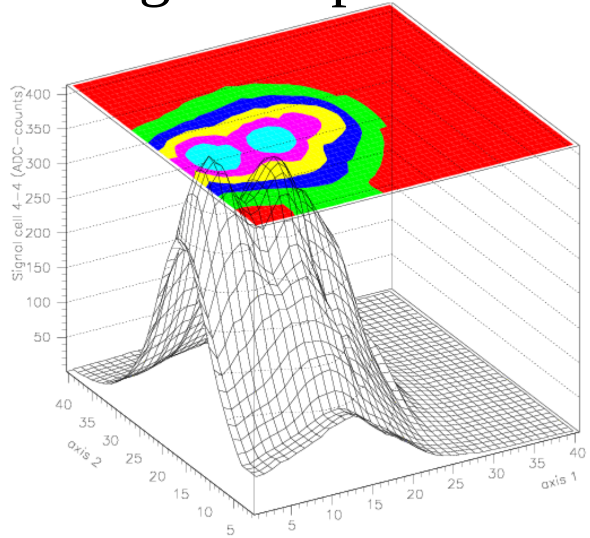
APS1: Laser test (II)

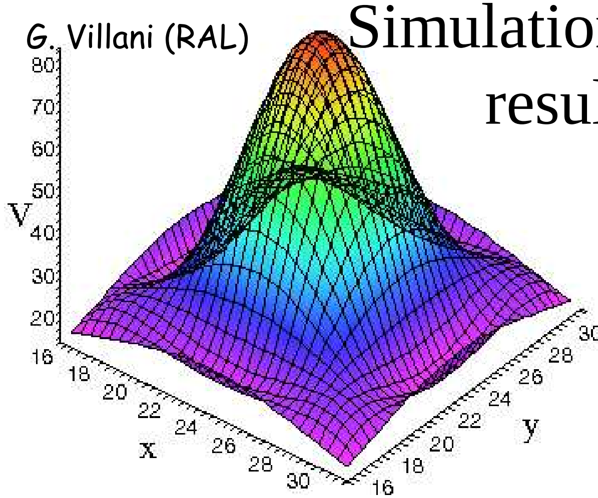
Largest signal of 1 pixel



Signal in pixel 4-4



Simulation result



- Simulation agrees reasonably well (no metal in simulation)

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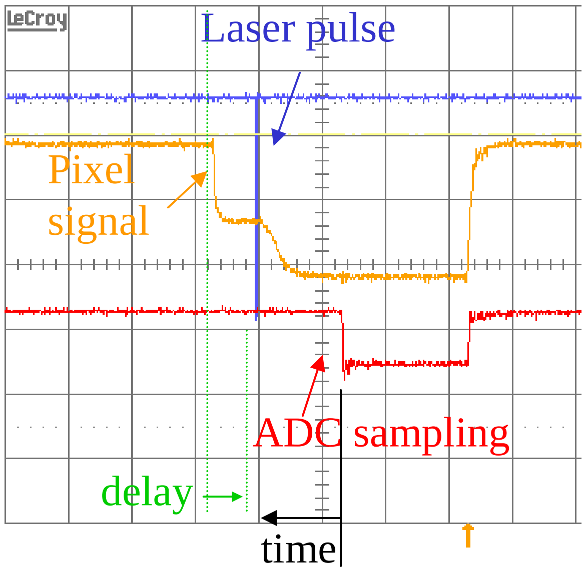
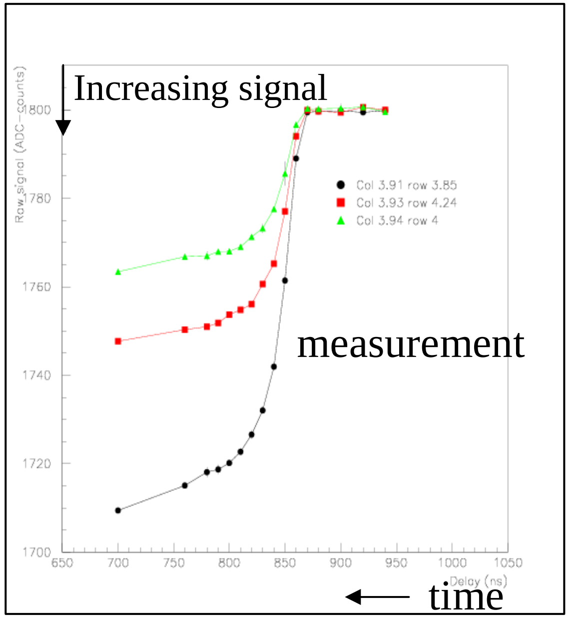
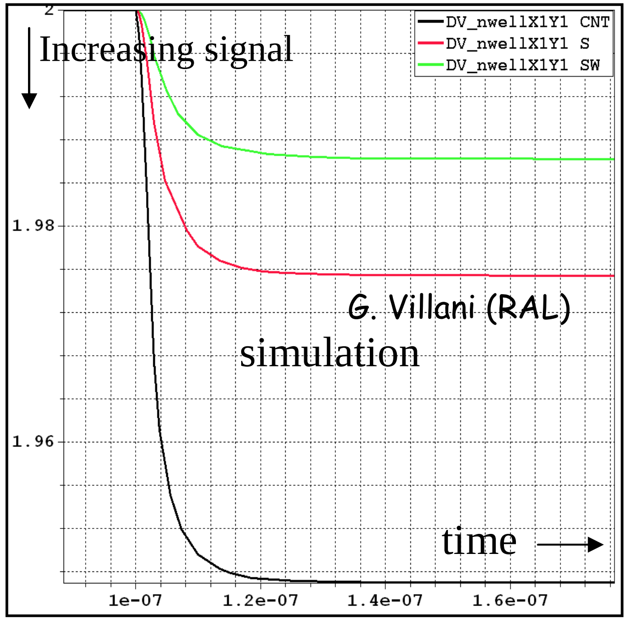
APS1: Laser test







- Simulation reproduces unirradiated signal rise time.
- Measured APS1 at 10^{11} and 10^{12} p/cm^2. No noise increase measured. Agrees with simulation; expect deterioration around 10^{14} p/cm^2

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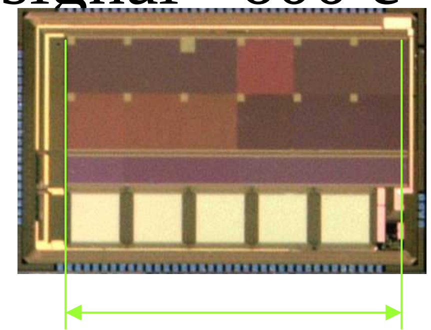
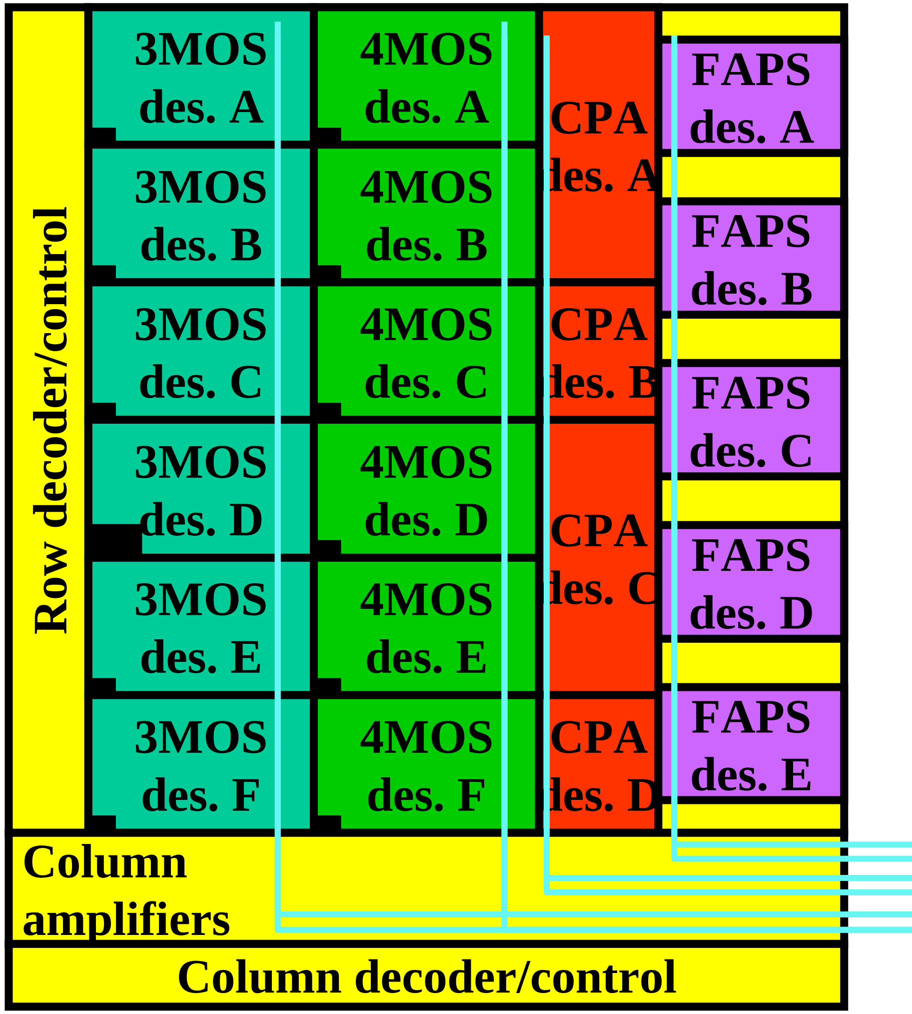
APS2

- 4 pixel types, various flavours
  - – Std 3MOS
  - – 4MOS (CDS)
  - – CPA (charge amp)
  - – FAPS (10 deep pipeline)
- 3MOS & 4MOS: 64x64, 15μm pitch, 8μm epi-layer ⇒ MIP signal ~600 e-



Design: R. Turchetta (RAL)



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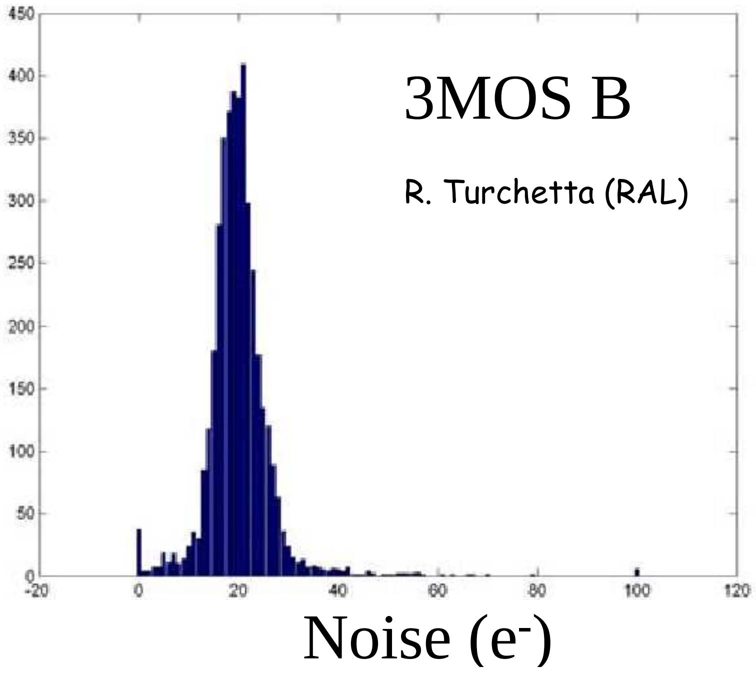
APS2: noise PTC

- Measured noise using PTC

Type	Noise (e^-)
3MOS B	45.7±0.2
3MOS A	54.0±0.2
4MOS C	55.7±0.2
4MOS B	51.8±0.2
4MOS A	46.3±0.2



- Noise measured in Liverpool ~2x noise at RAL. Have identified problem in Liverpool. No results yet.

APS2: Source test

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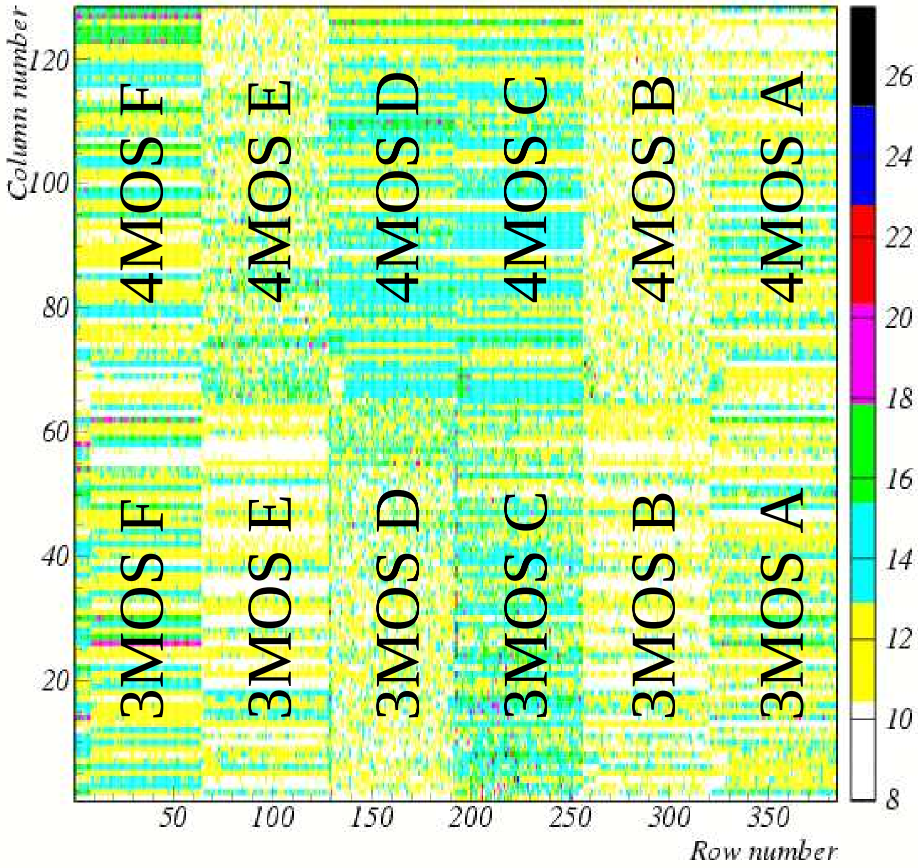
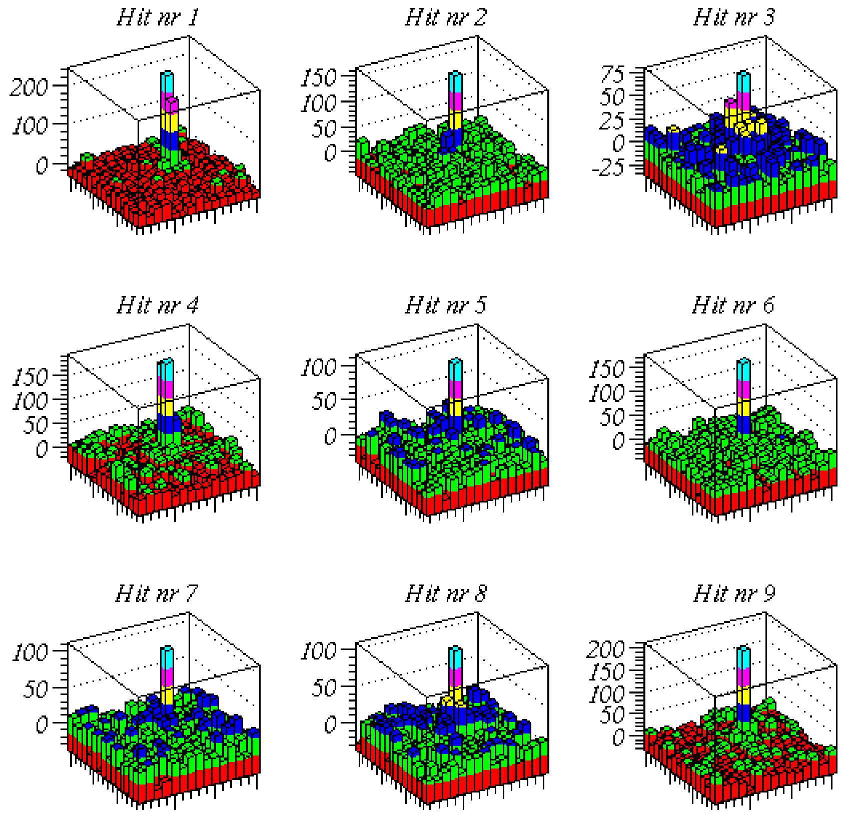
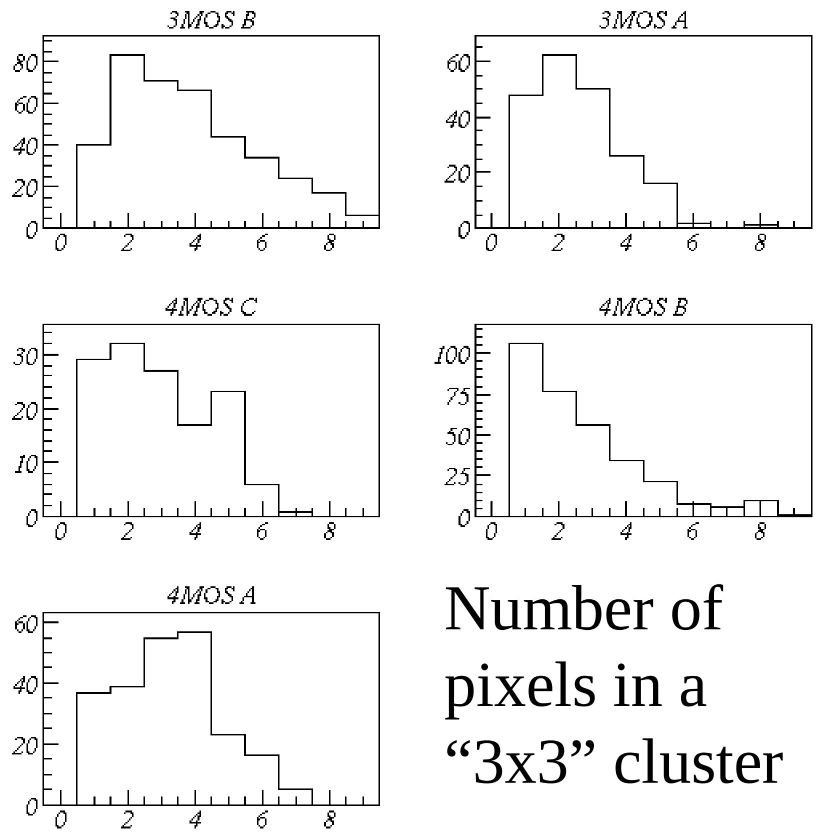
- Here only use 3MOS and 4MOS with TX high (no CDS)
- Calculate pedestals
  - Average output after removing hits
- Calculate common mode noise
  - Average pixel type output after pedestal subtraction
- Calculate random noise
  - Sigma of pedestal and common mode corrected output
- Cluster definition
  - Signal >6σ seed
  - Signal >2σ next

Noise in ADC counts



APS2: Some Clusters





Number of pixels in a "3x3" cluster

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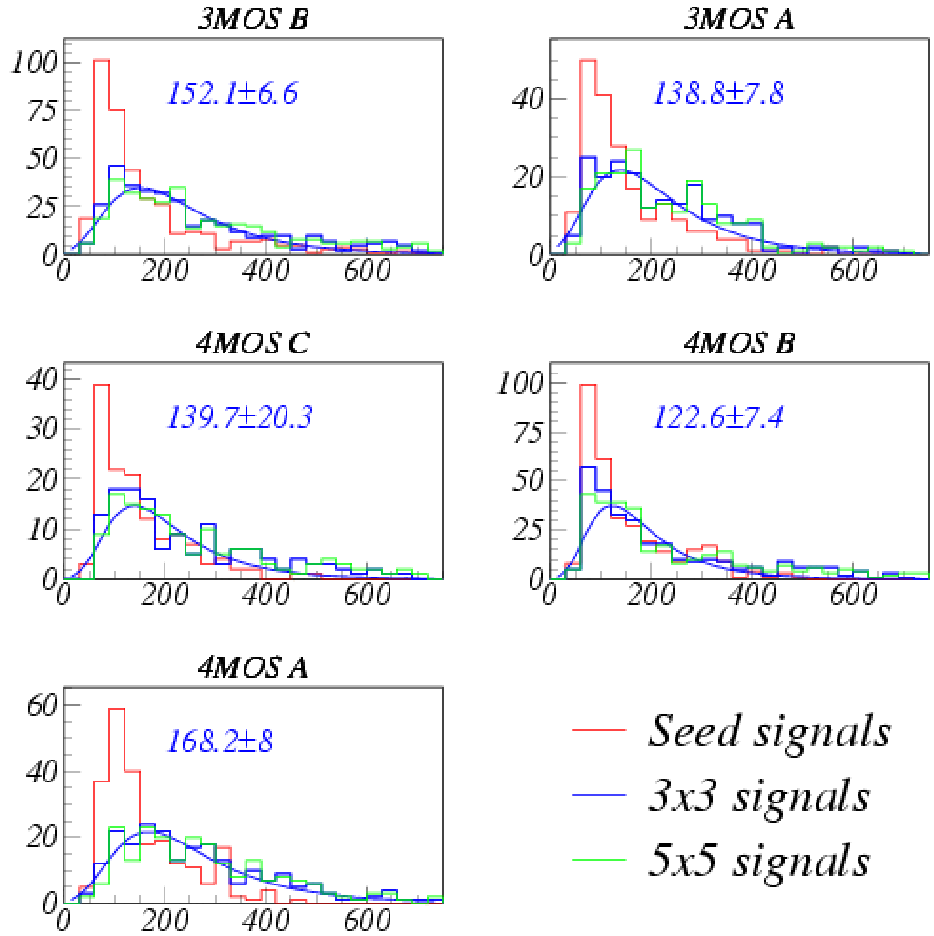
APS2: Cluster signals

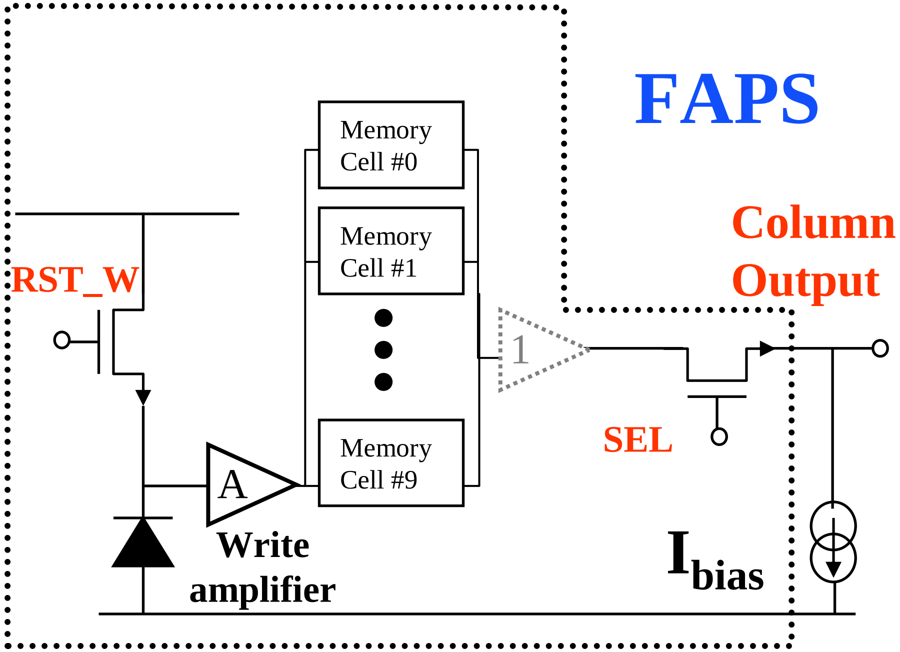
- From PTC hand waving S/N estimate

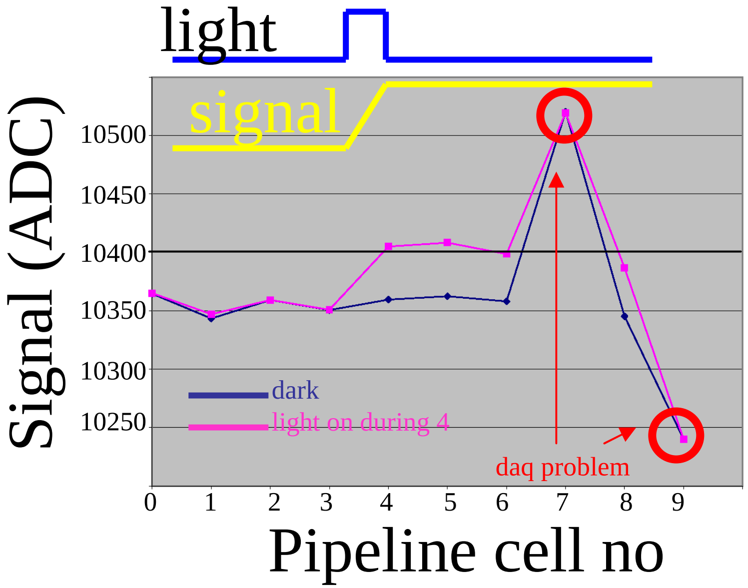
type	S/N exp	S/N
3MOS B	15	13.1±0.6
3MOS A	10	11.5 ±0.7
4MOS C	12	11.6 ±1.7
4MOS B	12	10.3 ±0.6
4MOS A	13	13.8 ±0.7

- Noise measured at RAL 2x smaller. Have identified problem in Liverpool. No results yet.



APS2: FAPS





- FAPS=Flexible APS
  - –Every pixel has 10 deep pipeline

Data example using pulsed diode

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Conclusions…

For very large hadron colliders:

The present detector technology is not dead! Stripsel, ministrip or hybrid pixel detectors can be used also in the radiation environment predicted within the future hadron machines: a lot of effort in the system aspects is though required…..

For linear colliders:

Various alternative routes to the optimal sensors for LC are being pursued. Very promising in this respect are the results obtained with CMOS sensors.