Direct detection of electrons in back-side illuminated CMOS imagers

- Introduction of MAPS technology
- Applications driving development and delineated
- MIMOSA V 1×10^6 pixel device
- Postprocessing for back-side illumination
- HPD facility @CERN
- ^{3}H(T) autoradiography with MIMOSA V ...
- MIMOSA V – 1st tests in SEM & TEM e-microscope
- Final prototype for Beam Monitor
- Radiation hardness
- Conclusions

Grzegorz Deptuch

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IReS-LEPSI collaboration: **group of over a dozen people - M.Winter (project co-ordinator)**

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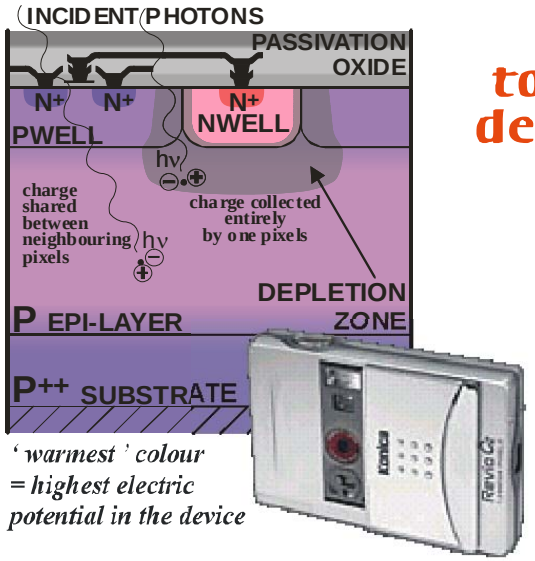
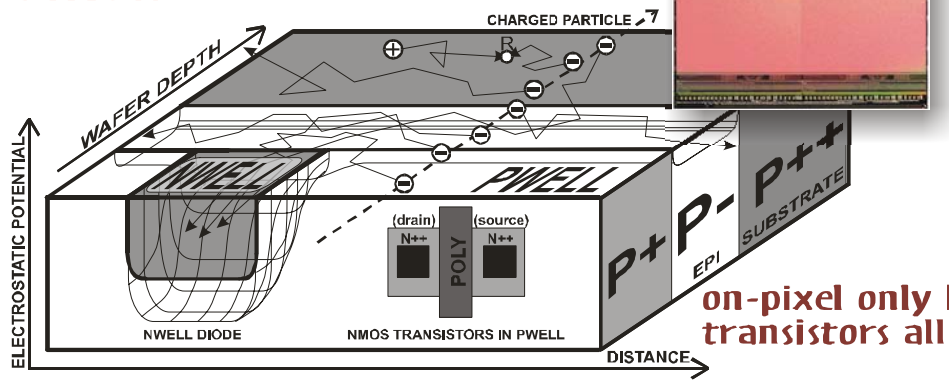
Introduction of MAPS technology

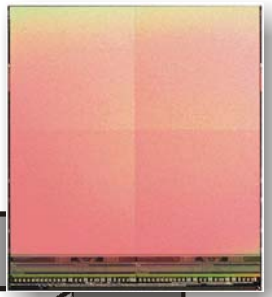
From digital photography



'warmest' colour = highest electric potential in the device

to charged particle detection





MIMOSA V 1×10^6 pixels micro-photograph

on-pixel only NMOS transistors allowed

Monolithic Active Pixel Sensors (MAPS)

The detector is a standard VLSI chip. The active element is a thin moderately doped silicon layer, operated undepleted . The readout electronics is seated on top of this layer. The built-in potential, resulting from differences in doping, screens the detector from the electronics parts and confines the charge diffusing to the readout electrodes. The charge collectors are n-well/p-epi (substrate) diodes. Only NMOS transistors are used for in-pixel readout electronics, but full CMOS electronics is used on the detector periphery.

MAPS advantages:

decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.), small pitch (high tracking precision), low amount of material, fast readout, moderate price, SoC, etc.

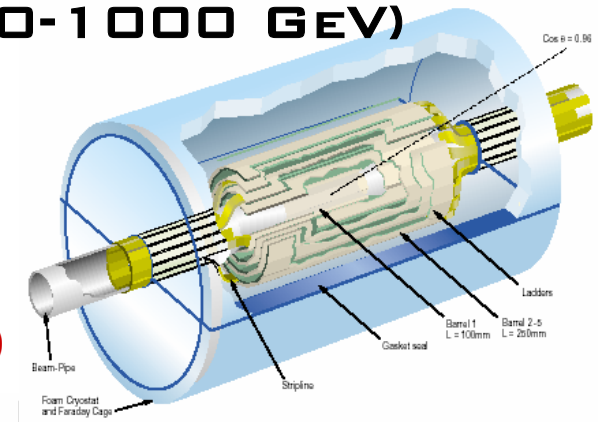
Applications driving MAPS development

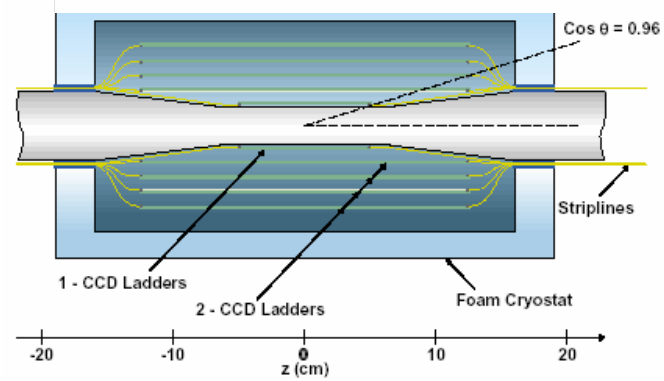
- **High Energy Physics (FLC~ 500-1000 GeV)**
  - **High resolution of IP**
    - Detection efficiency = ~99%
    - $\delta IP < 5\ \mu m \oplus 10\ \mu m GeV / (p \sin^{3/2}\theta)$

      Multiple scattering < 0.1% X_0 / layer

      Thin layers ~50 µm of Si (5 layers: R_1=1.5 cm; R_5=6 cm)
  - **High granularity**
    - Pixel pitch 20×20 µm²
  - **High occupancy**
    - Fast readout (25 µs – 50 µs) - background
    - On-line sparsification
  - **Radiations** *$\Phi_n \approx 5 \cdot 10^9$ n(1 MeV)/cm²/5 y*

    Ionising dose= 500 kRad/5 y





Chosen technology has to combine: granularity, small thickness, high readout speed, radiation hardness

		TESLA	CMS
Granularity	vertex:	~800M pix.	39M pix.
	ecal:	32×10^6	76×10^3
Material budget	tracker:	0.05 X_0	0.30 X_0
	vertex /layer:	<0.1% X_0	1.7% X_0

Applications driving MAPS develoment

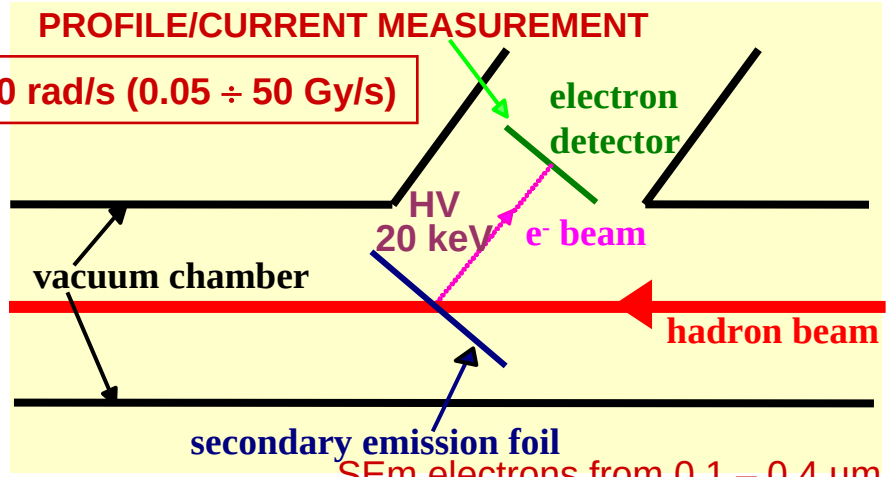
SUCIMA–Silicon Ultra Fast Camera for Electron and Gamma Sources in Medical Applications

Hadrotherapy

On-line beam monitoring

SLIM – SEm *(secondary emission)* for Low Interception Monitoring

Innovative Non-Destructive Beam Monitor for the Extraction Lines of a Hadrontherapy Centre



SEm electrons from 0.1 – 0.4 µm (Al-Al_2O_3-Al) foils

Brachytheraphy

Intravascular Brachytherapy: local radiotherapy

Brachytherapy reduces the restenosis rate, also in the case of a use of STENTS.

Dose (15-30 Gy) delivered by temporary (few minutes) implant of radioactive seeds or wires.

HIGH DOSE and HIGH DOSE RATE: dose evaluation is crucial

^{90}Sr or ^{144}Ce

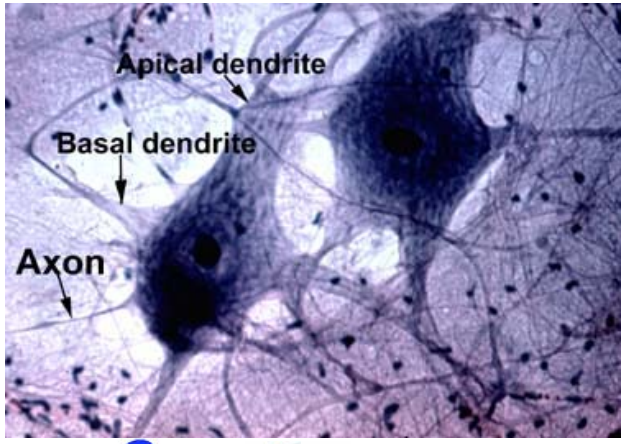
5 ÷ 5000 rad/s (0.05 ÷ 50 Gy/s)

Applications delineated

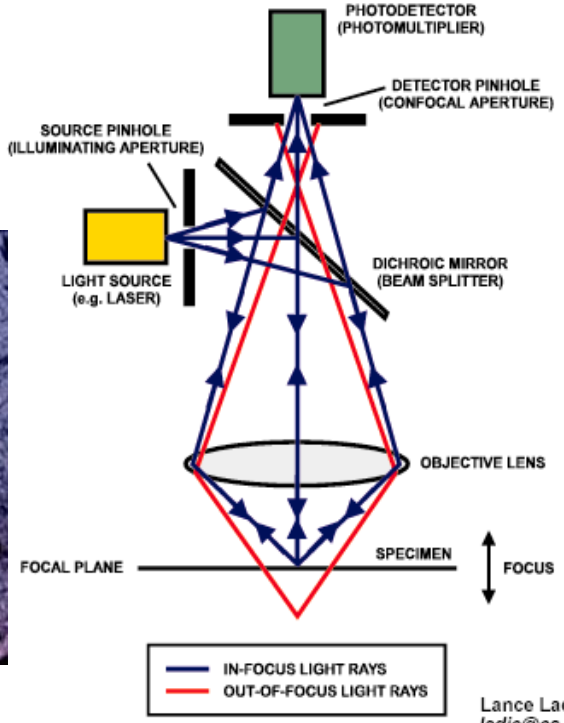
Hybride Photodiode Detector (HPD) for Microscopy of the cellular dynamics

- Detection and tracking of interactions of single biological molecules in their natural environment
- Measurements of single molecules - low concentration of fluorescent markers and microscopy of intracellular ionic exchanges (flux Ca^+),

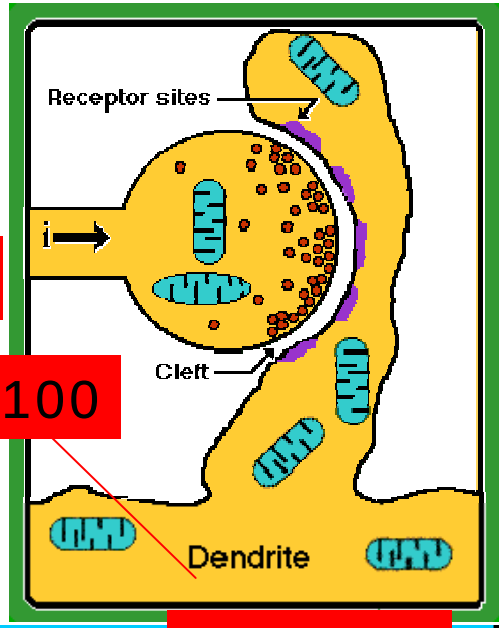
Single photon detection sensitivity and high speed of acquisition (1000 fps)



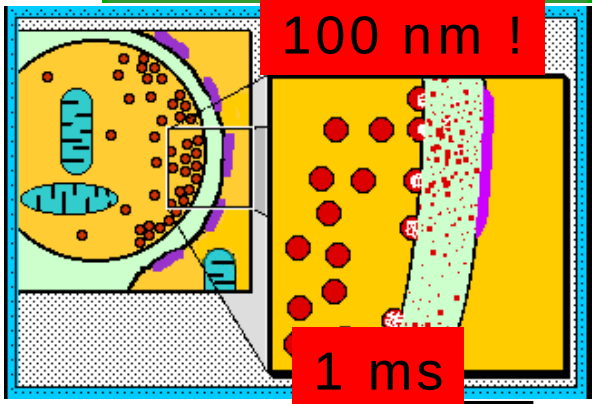
1 photon / ms /pixel



X100



100 nm !



1 ms

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Applications delineated

Transmission Electron Microscope

- TEM - imaging technique whereby electrons focused onto a specimen are causing an enlarged version to appear on a fluorescent screen or photographic film or can be detected by a CCD camera (directly or scintillator-coupled)

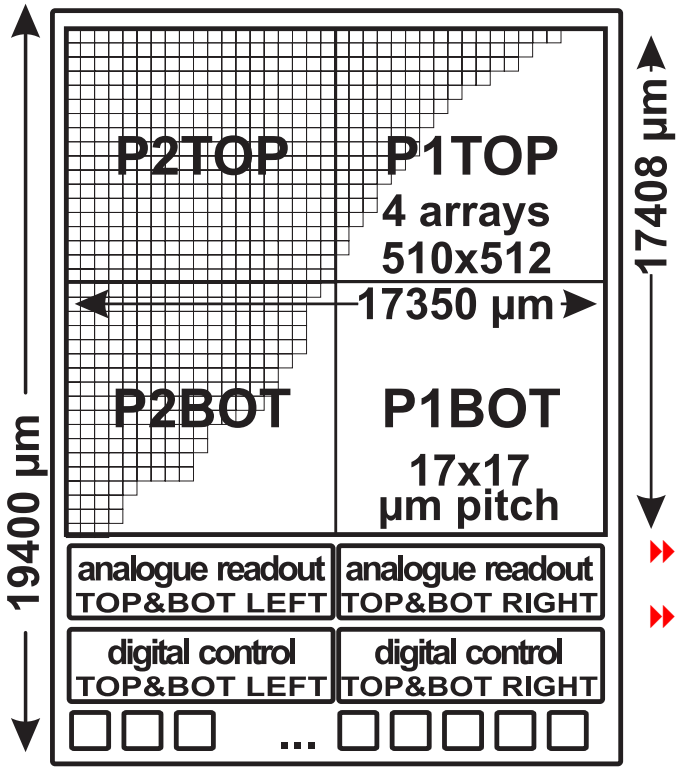
Advantages of MAPS and how one can gain w.r.t. existing Techniques (fluorescent screens, negatives or CCDs):

- High efficiency - thanks to direct detection,
- On-line image – some processing possibly integrated on a detector chip,
- High sensitivity (single electron sensitivity),
- No bluring due to charge transfer,
- High speed by use of multiple readout channels,
- Radiation hardness – conversion to voltage in place where collection.

Idea of P.Rehak, J.Wall … and goal of my 1-mont stay @ BNL

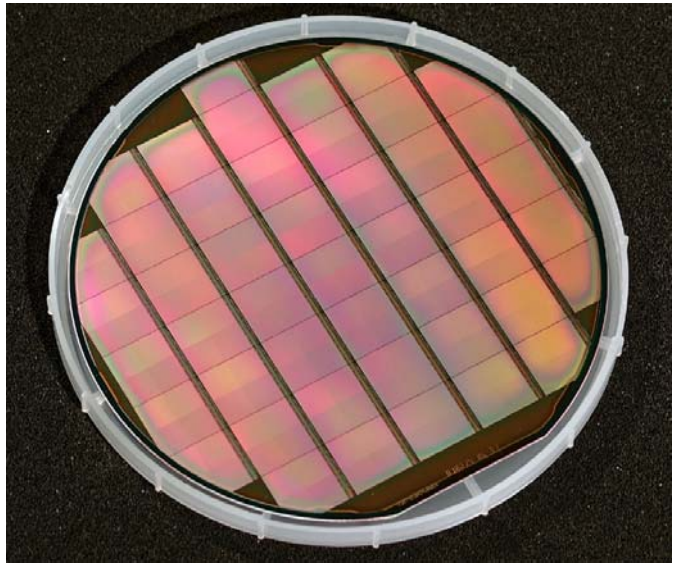
MIMOSA V 1×10⁶ PIXEL DEVICE

CHIP-DETECTOR DESIGN



MIMOSA V

classical
3T
pixel schematics



- 0.6 µm CMOS process with 14 µm epitaxial layer,
- 4 matrices of 512 × 512 pixels read-out in parallel; pixel: 17 × 17 µm², diodes: P1 - 9.6 pm², P2 - 24.0 pm², control logic and all pads aligned along one side,

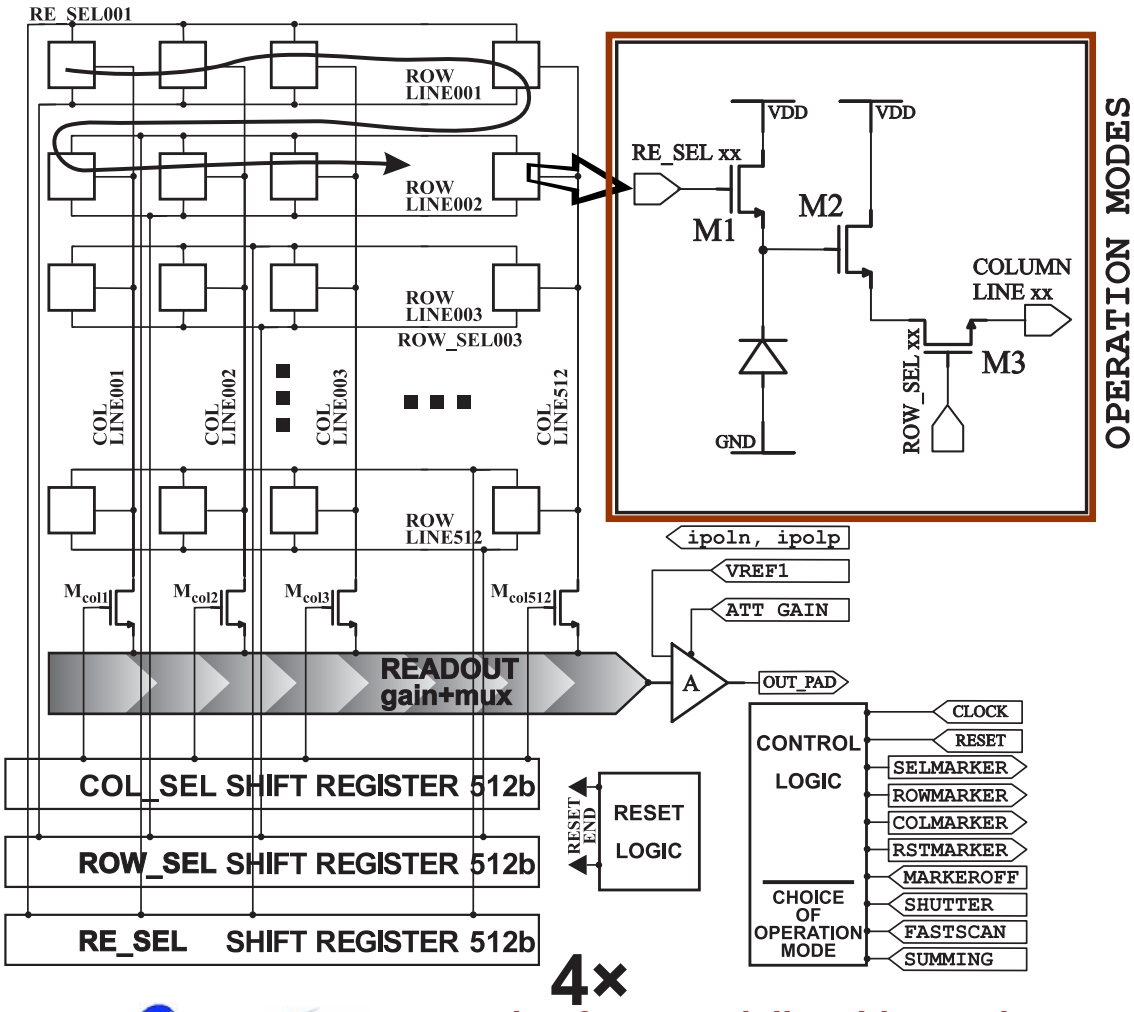
RESULTS:

Noise mean ENC:	20.74 e^-
detection efficiency MIPs (ε):	99.3%
spatial resolution MIPs (σ):	1.7 µm
pixel-pixel gain nonuiformity	~3%

MIMOSA = Minimum Ionising Particle MOS APS

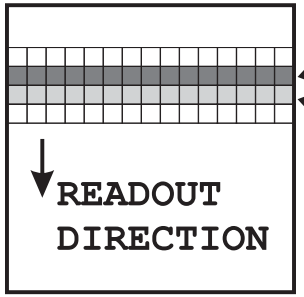
MIMOSA V 1×10⁶ PIXEL DEVICE

Architecture of the prototype



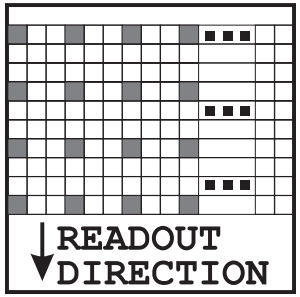
OPERATION MODES

SHUTTER



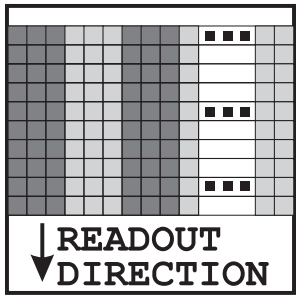
SELECTED for RESET
SELECTED for READOUT

FASTSCAN



EVERY 3rd PIXEL READ IN BOTH DIRECTIONS

SUMMING

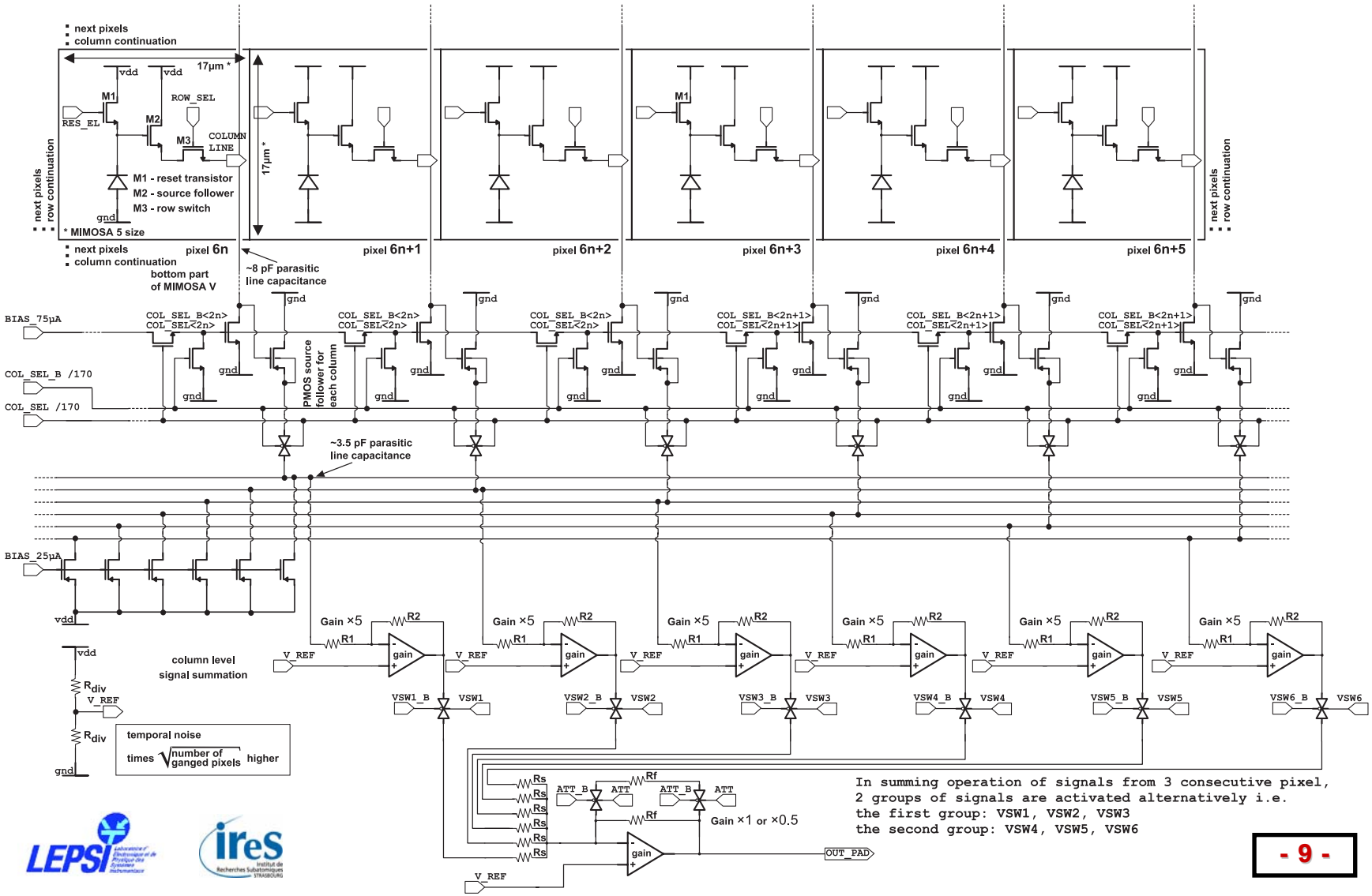


EFFECTIVE PITCH REDUCED to 3x17µm in 1 direction summing 3 consecutive pixels

- Matrix of sequentially addressed pixels, multiplexed on single output buffer.

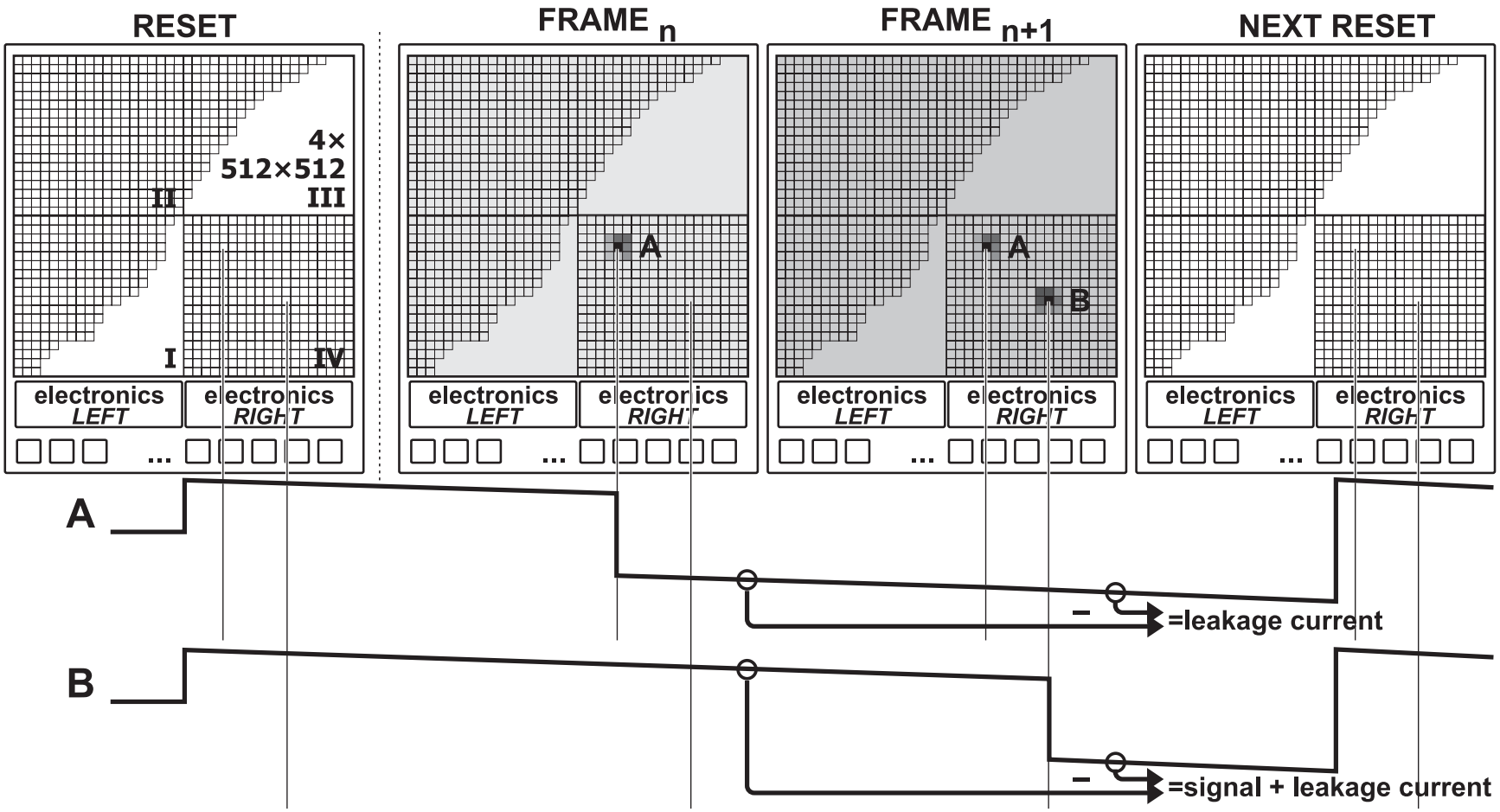
MIMOSA V 1×10⁶ PIXEL DEVICE

ARCHITECTURE OF THE PROTOTYPE

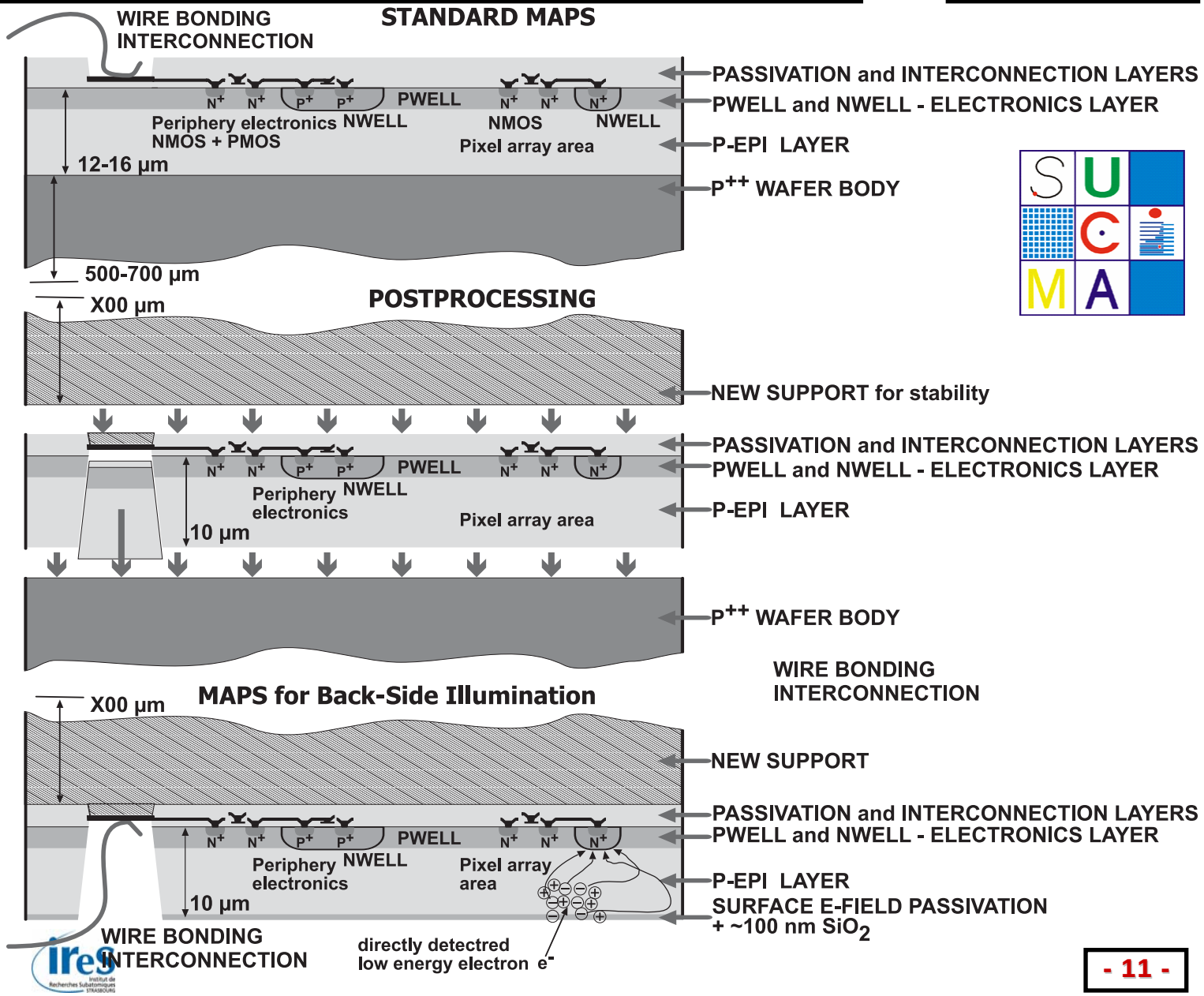


MIMOSA V 1×10⁶ PIXEL DEVICE

Default Readout Method



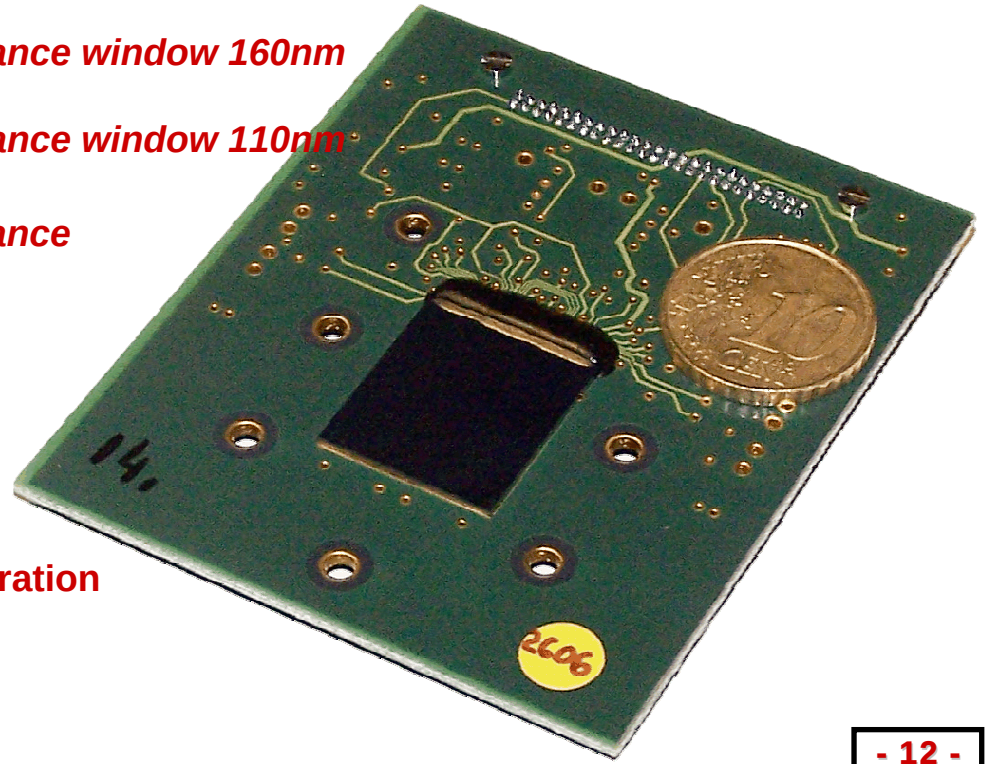
POSTPROCESSING FOR BACK-SIDE ILLUMINATION



Back-side illuminated MIMOSA V device

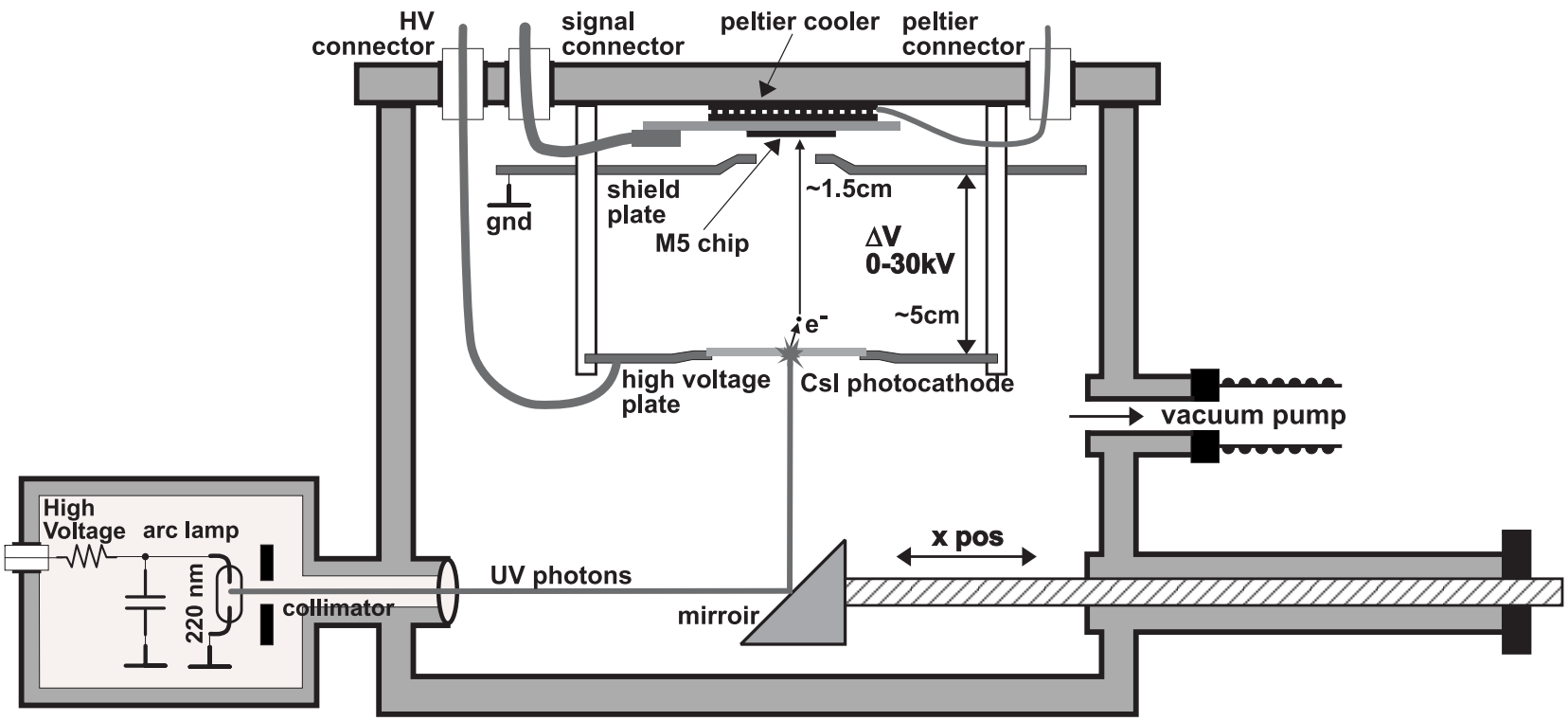
Back-side illuminated thinned M5 device – as a test vehicle for demonstration of 20keV E^- detection capability for Beam Monitoring system and other affined applications

- *Back-side passivation « A » + entrance window 160nm*
- *Back-side passivation « A » + entrance window 110nm*
- *Back-side passivation « B » + entrance window 75nm, 110nm and 160nm*



- Bonding with 17 µm Al wire
- Device thinned down to epitaxial layer to ~10 µm in collaboration with industrial partner

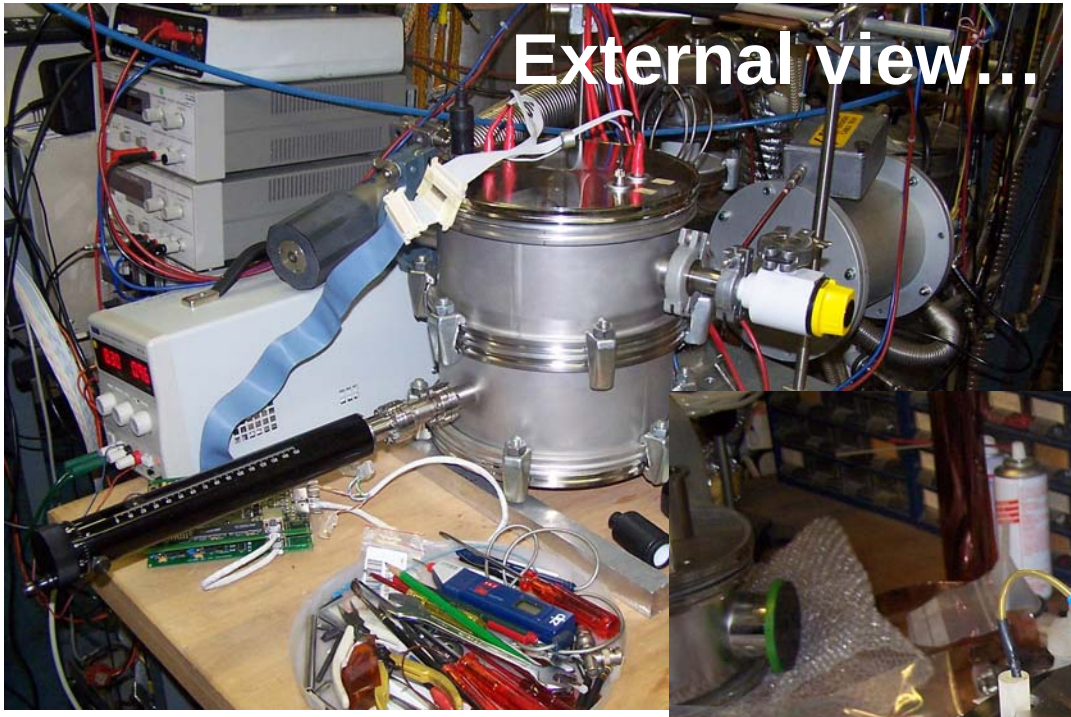
HPD facility @CERN



Simplified view of vacuum pot with proximity focusing optics HPD using CsI photocathode

With invaluable help of J.Seguinot, A.Braems and C.Joram from CERN

HPD facility @CERN

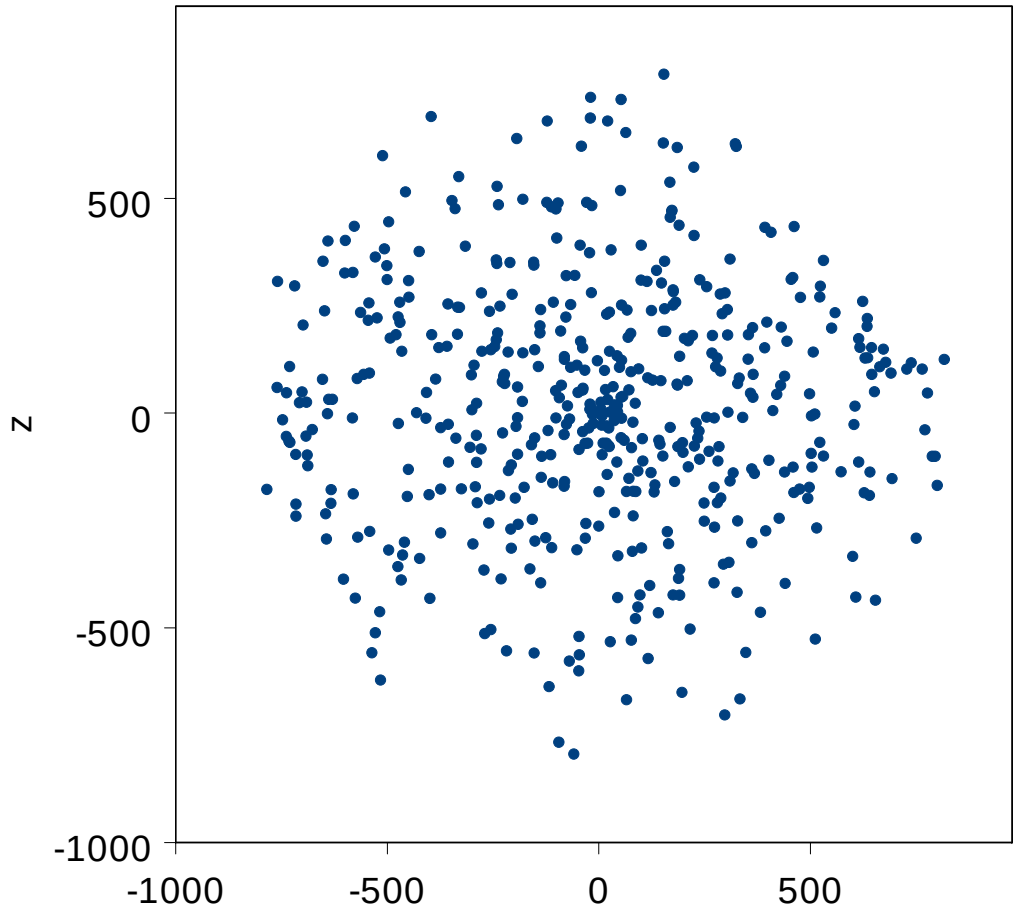


2nd step (electrons emitted from CsI photocathode Excited by photons (220nm edge) from arc lamp

1st step (electrons from photocathode: bombarded by residual ions, or from photons from micro-discharges (2×10^{-5} mbar) (?)

HPD facility @CERN - Simulation

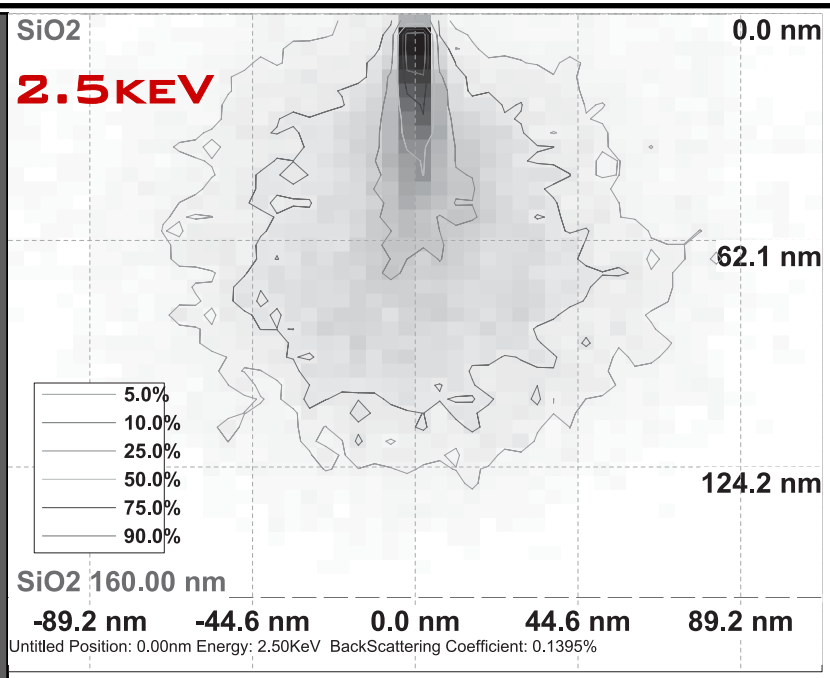
Hit distrib. (500 e-) on MIMOSA V for point source

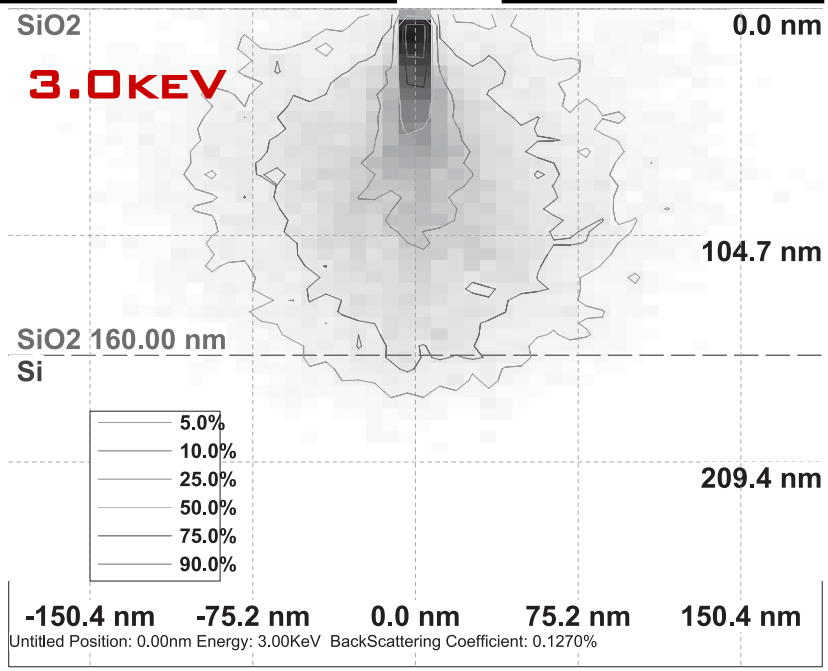


PSF $RMS_x = 360\ \mu m$, $RMS_z = 280\ \mu m$

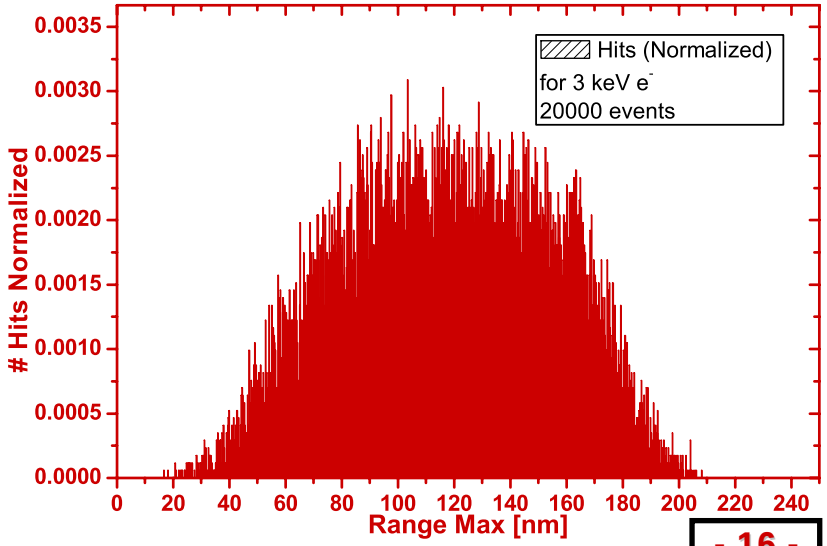
SIMION 3D 7.0, C. Joram, 15 June 2004

HPD FACILITY @CERN - SIMULATION

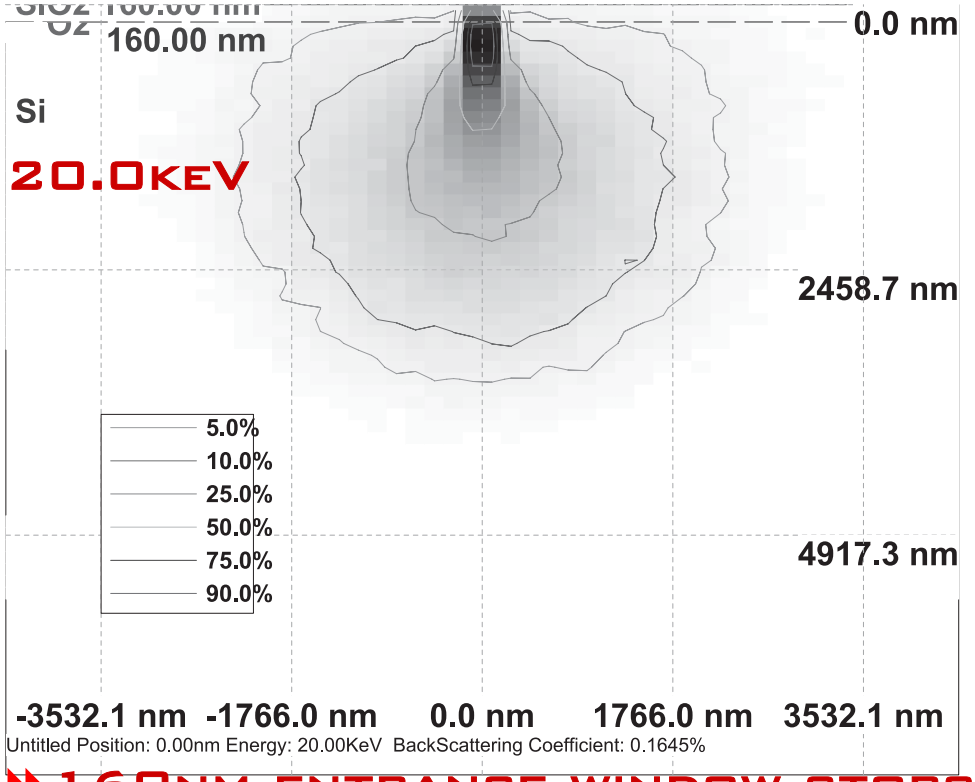


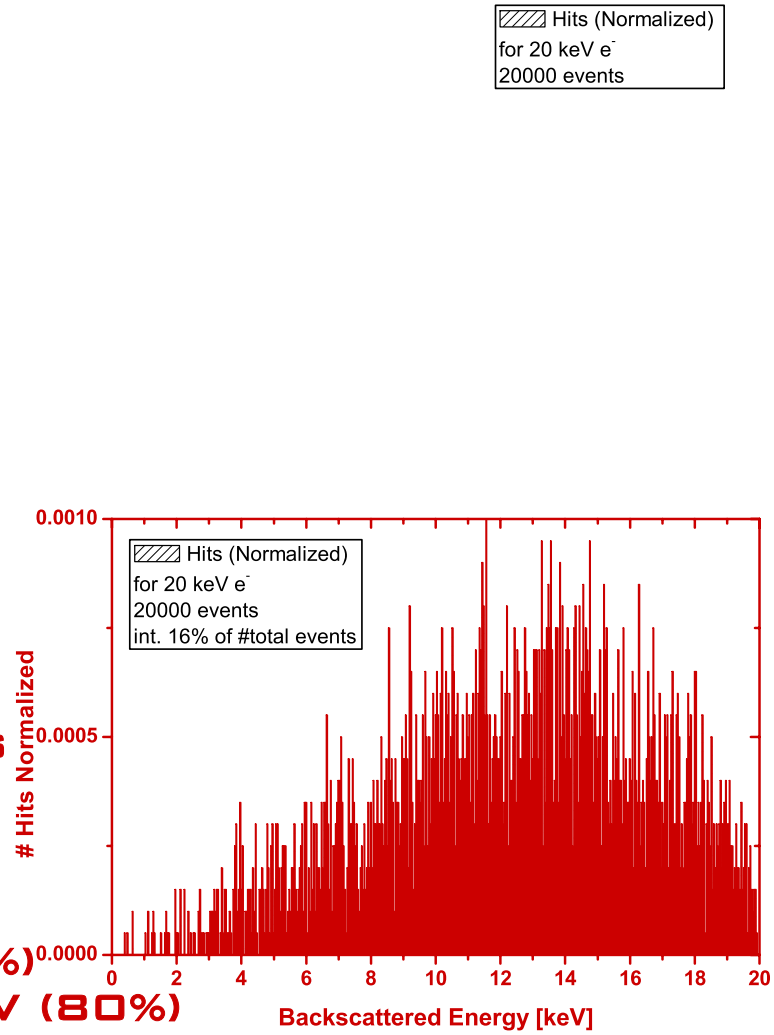


Hits (Normalized)
for 2.5 keV e⁻
20000 events



HPD facility @CERN - Simulation





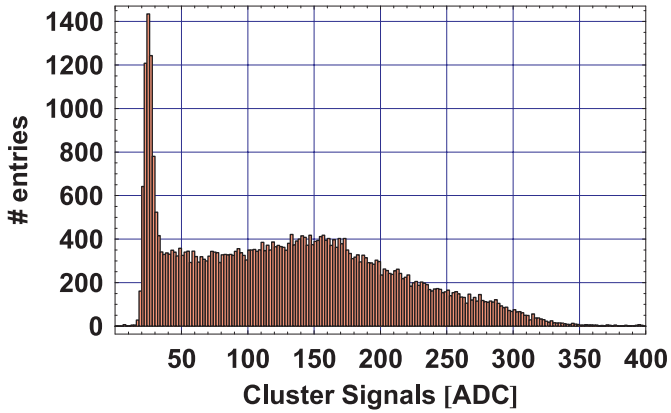
- 160nm entrance window stops completely e- < 2.5keV
- Backscattering will <pollute> recorded spectras
- 19.6keV transmitted @20keV (95%) 9.35keV @ 10keV (90%), 5keV @6keV (80%) for 160nm entr. window

HPD facility @CERN MIMOSA V - results

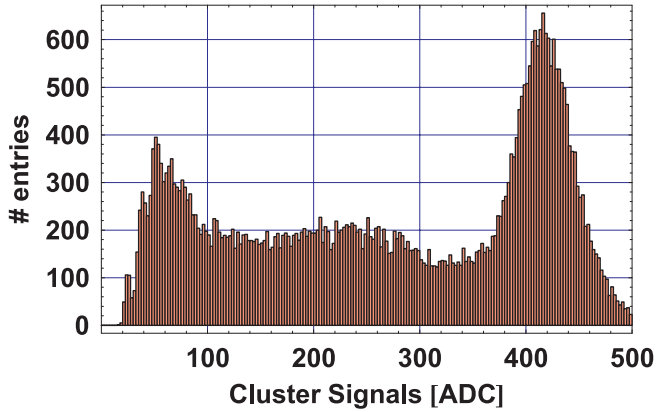
20kV

No cooling

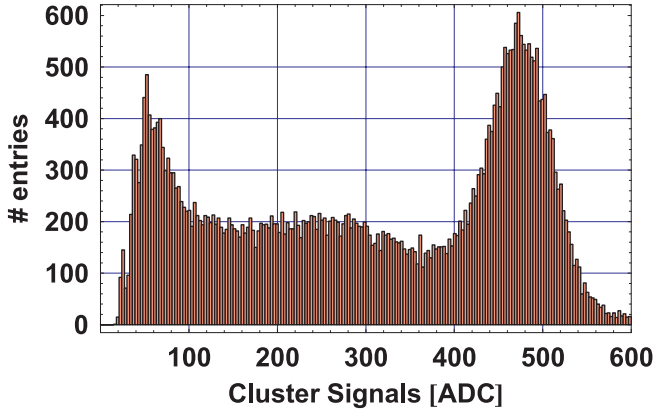
1 Pixel – Cluster Signal Distribution



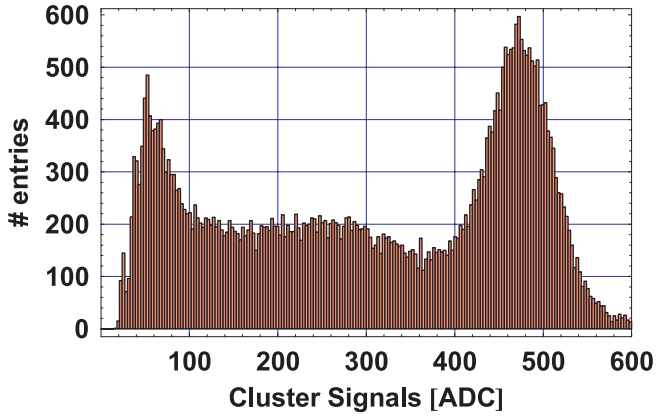
4 Pixel – Cluster Signal Distribution



9 Pixel – Cluster Signal Distribution



25 Pixel – Cluster Signal Distribution



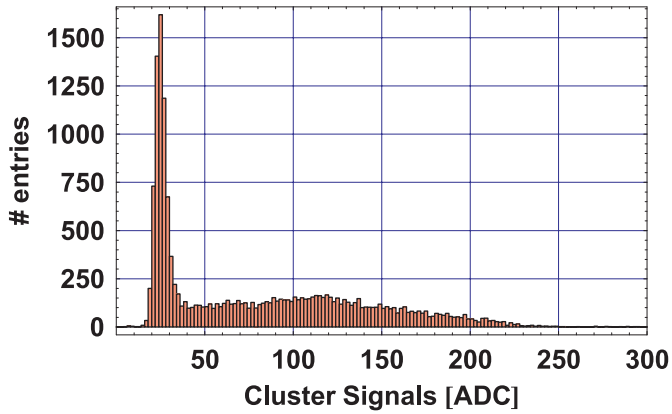
Histograms for reconstructed signal clusters

44623 hits

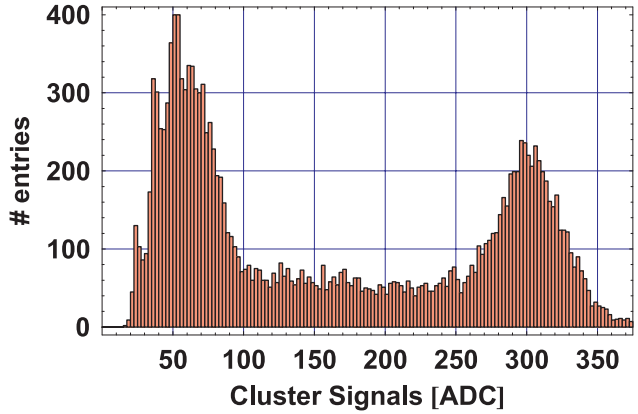
HPD facility @CERN MIMOSA V - results

15kV Data for 1st step – no cooling

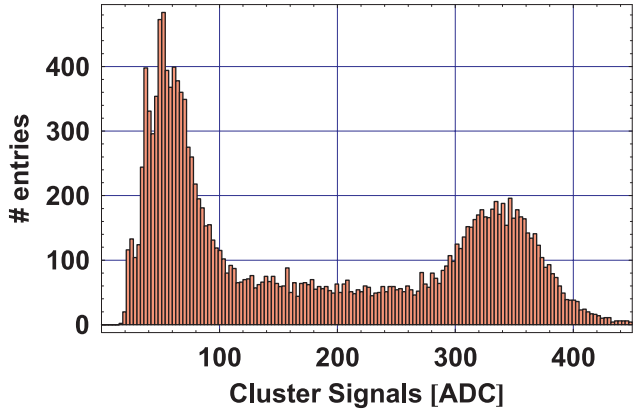
1 Pixel – Cluster Signal Distribution



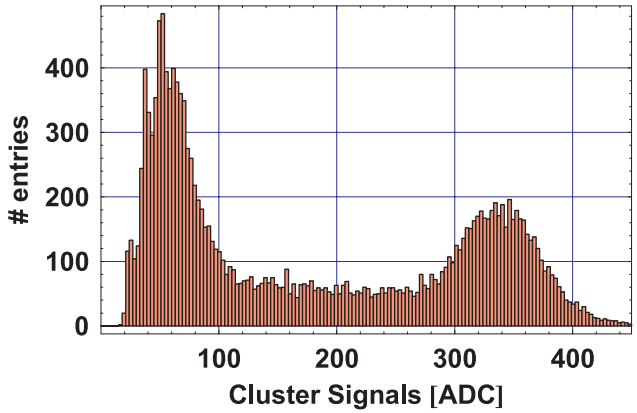
4 Pixel – Cluster Signal Distribution



9 Pixel – Cluster Signal Distribution



25 Pixel – Cluster Signal Distribution

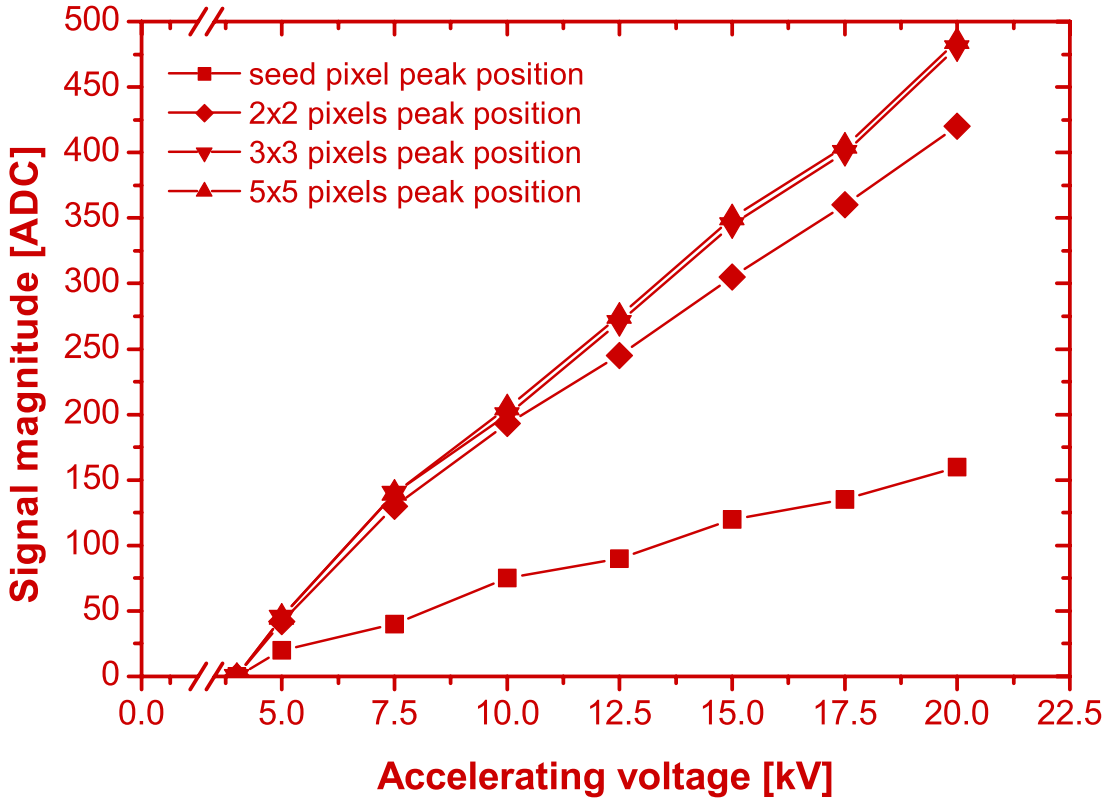


Histograms for reconstructed signal clusters

16254 hits

HPD facility @CERN MIMOSA V - results

4kV – 20kV



- Close to linear dependence « signal magnitude v.s. accelerating voltage » for 7.5 – 20 keV; x-axis intercept at 2.48kV, dependence broaken for 4 keV no detectable signal observed

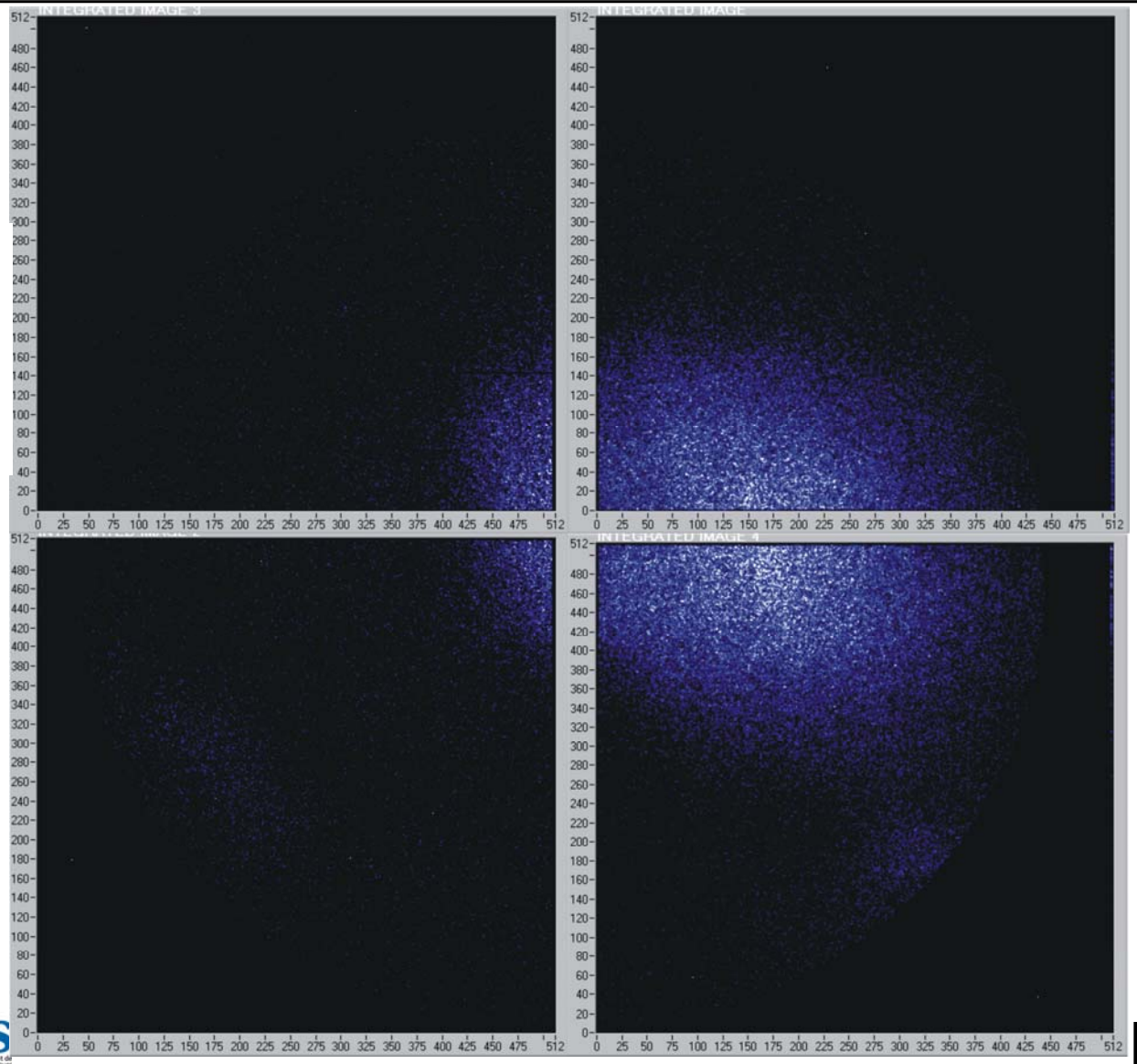
Preliminary plot to be completed with lacking points

HPD facility @CERN MIMOSA V - results

- 17.5kV arc lamp ON

~200k hits

Full 1×10^6 image



HPD facility @CERN MIMOSA V - calibration

- ^{55}Fe

Count
Seed pixel histogram

5.9 / 6.5 keV
calibration peak

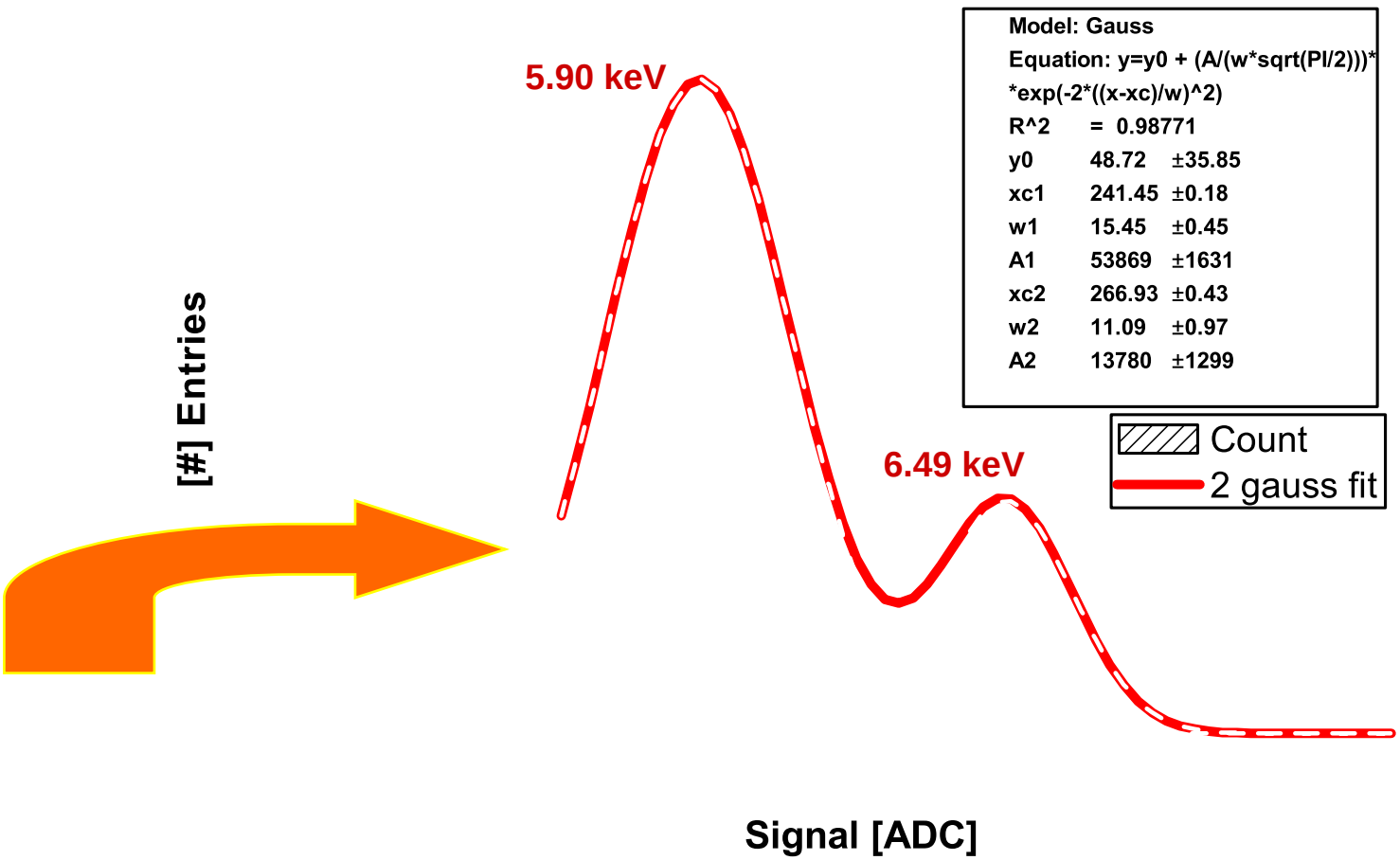
let's look closer

- Histogram for seed pixel S/N=3.5 cut

32716 hits

HPD FACILITY @CERN MIMOSA V - CALIBRATION

- ^{55}Fe



- Histogram for seed pixel S=210 cut

46552 (29000) HITS

HPD facility @CERN MIMOSA V - calibration

- ^{55}Fe

Count
5x5 pixel cluster histogram

160 ADC

- Histogram for 5×5 pixel
- Peak for summed signal partially approaches to the calibration peak

32716 () hits

HPD FACILITY @CERN MIMOSA V - CALIBRATION

Number of entries in calibration peak after subtraction of the left side tail [redacted]000 [redacted] frames [redacted]

N_{ent} = ~ 290[redacted]

Extrapolated [redacted]01 frames [redacted]er of hits for seed pixel :

N_{tot} = ~ 1.6´ 10^6;

N_{tot}, N_{ent}´ 100 %= 1.8[redacted]

Volume of full charge [redacted]ction :

V_f = 3.3^2´ 2.5 + [redacted].3 + [redacted].8 [redacted]8 mm^3 = ~ 74 mm^3

Volume of pixel :

V_p = 17^2´ 10.4 = 3005 mm^3

V_f V_p´ 100 %= ~ 2.5 %

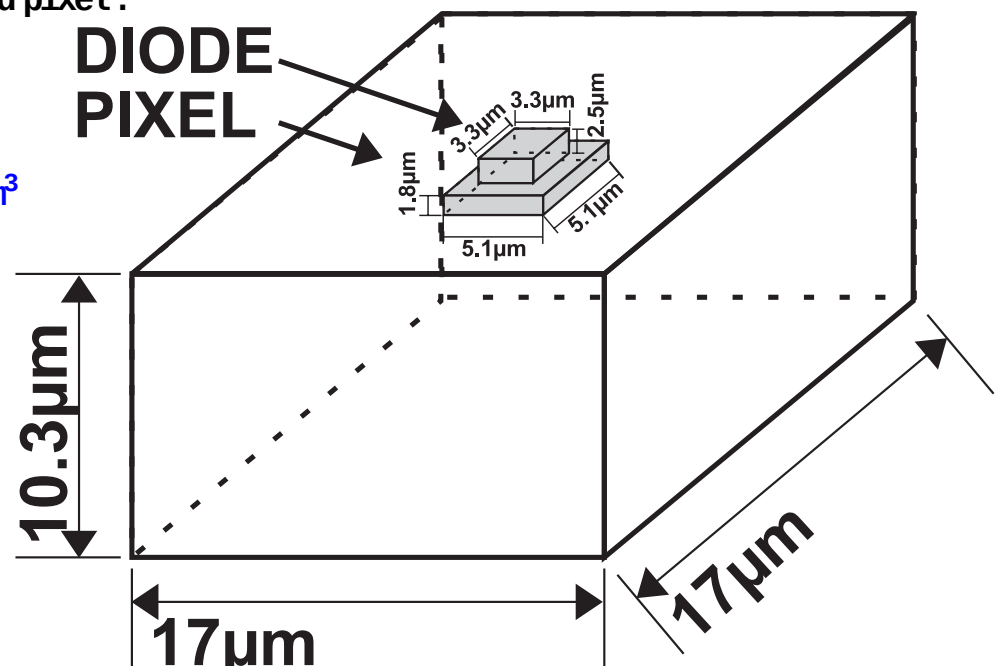
Mean depth of diode from backside :

S_d = 8.[redacted] µm [redacted] = 74 % of photons

Percentage o[redacted] conversion i[redacted] seed [redacted]ixel :

N_{ent}, [redacted]* [redacted] [redacted]%=

= 29000, [redacted].74´ 1.6´ 10^6 [redacted] 1[redacted]0 %= 2.4 %



Veryfying CCE for 5.9 [redacted] photons and b ' s :

for photons : [redacted] 160 AD C, 241 ADC´ 100 %= 66 % and 241 ADC ® 1640 e^- h^+,

thus for b ' s [redacted]0 ke[redacted] 75 A[redacted]C ® 3232 e^- h^+

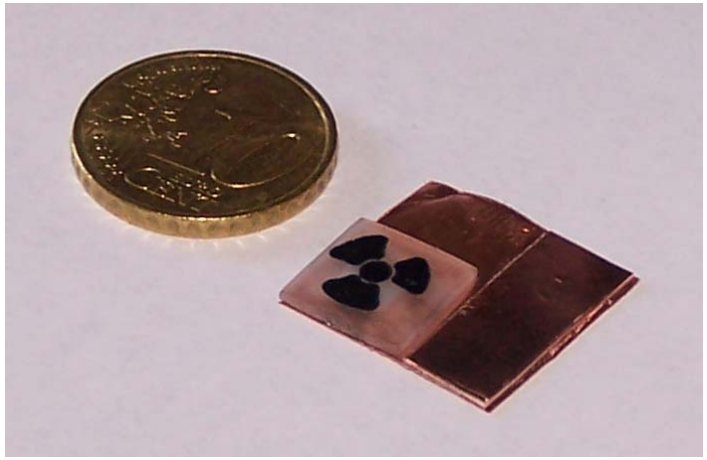
but : 20 keV 3.6 eV = 5555 [redacted] and 0.5 keV lo[redacted]t on entrance = 138 e^- h^+,

thus : $CCE_{b'}$ = 3232 e^- h^+, [redacted]555[redacted] h^+ - 138 e^- h^+ [redacted]%= 59 %

Simply "edgy" model of n-well/p-epi diode (1.8µm @ 3V)

^{3}H(T) Autoradiography with MIMOSA V ...

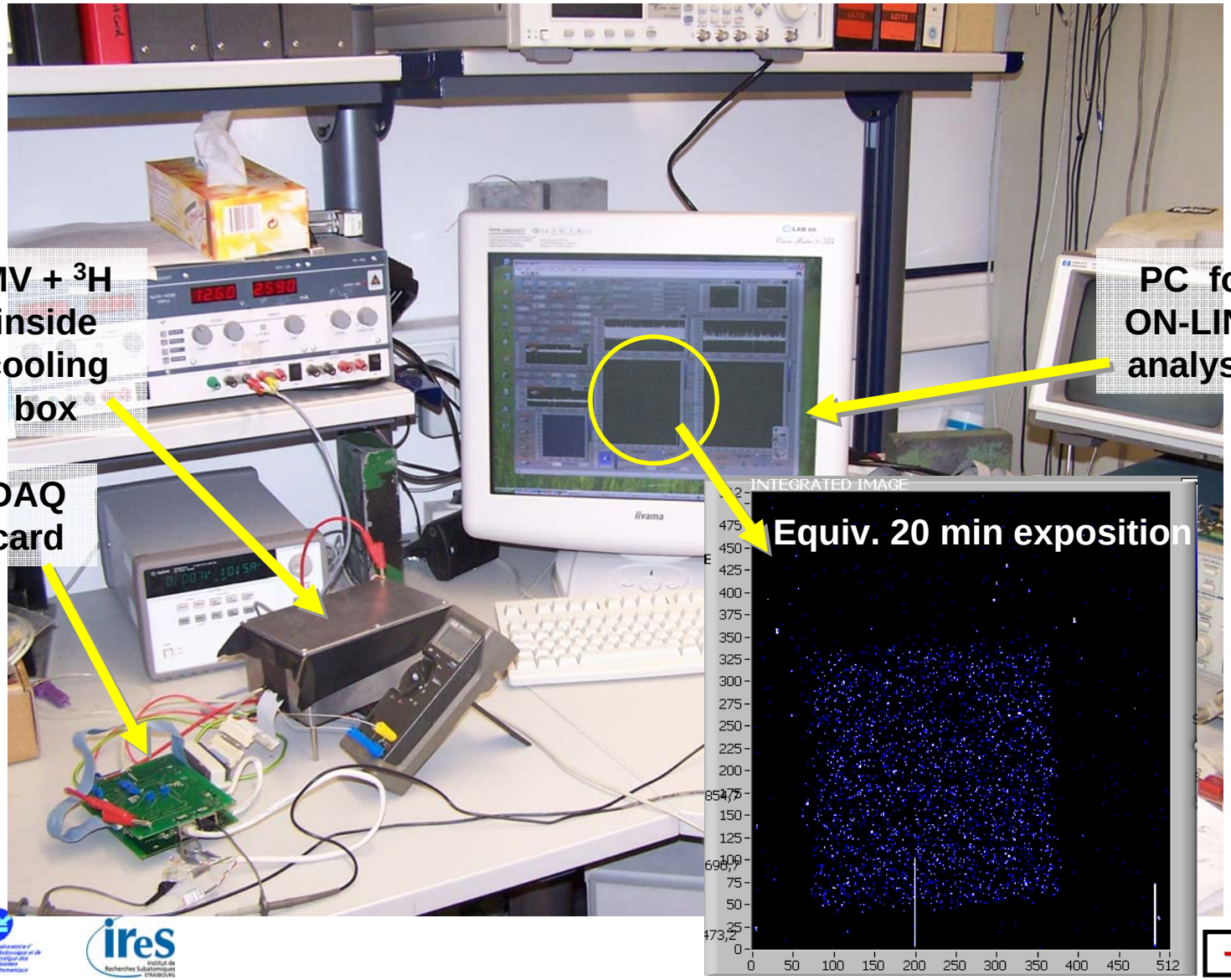
- Common requirement in biology: to map radioactive labels - ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{125}I... in thin tissue sections, electrophoresis gels (of DNA or proteins), etc. X-ray film (the default imaging medium) and exposure times (~days to months) - ^{3}H. ^{3}H betas (endpoint 18.6 keV) weakly penetrating in any detection medium.



Polymer source
281 kBq (20/05/1999)
1×1×0.1 cm^{3}

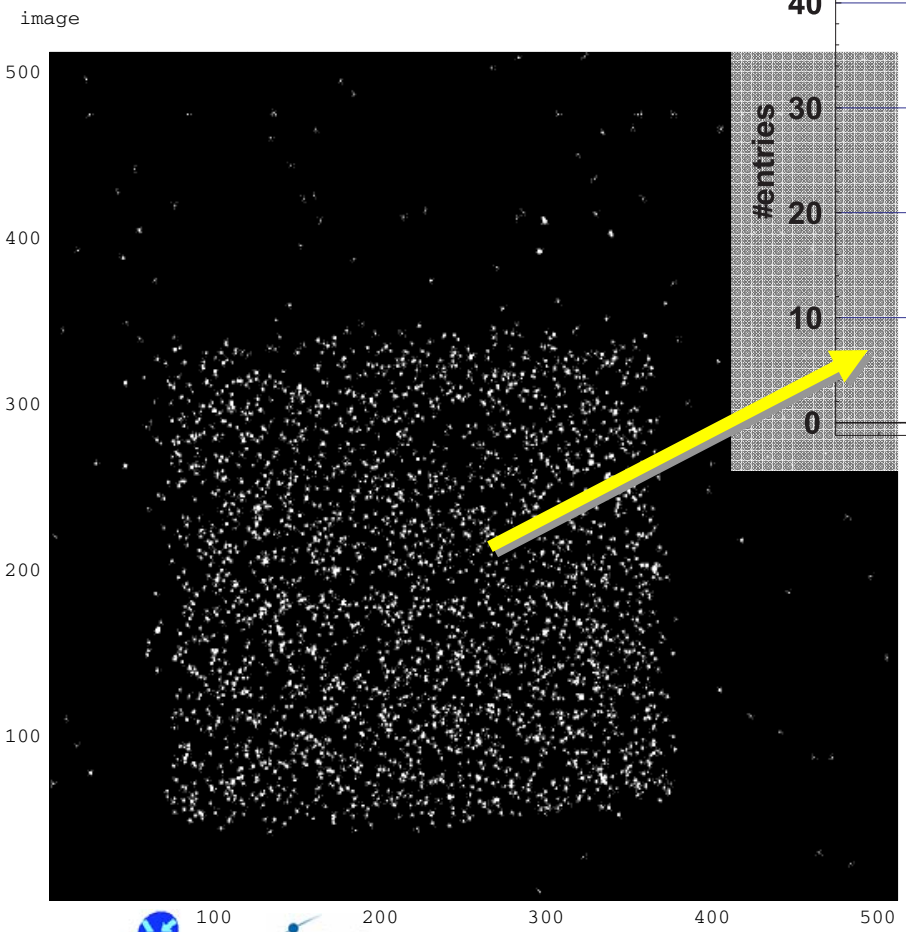
3H-polybutyl methacrylate source

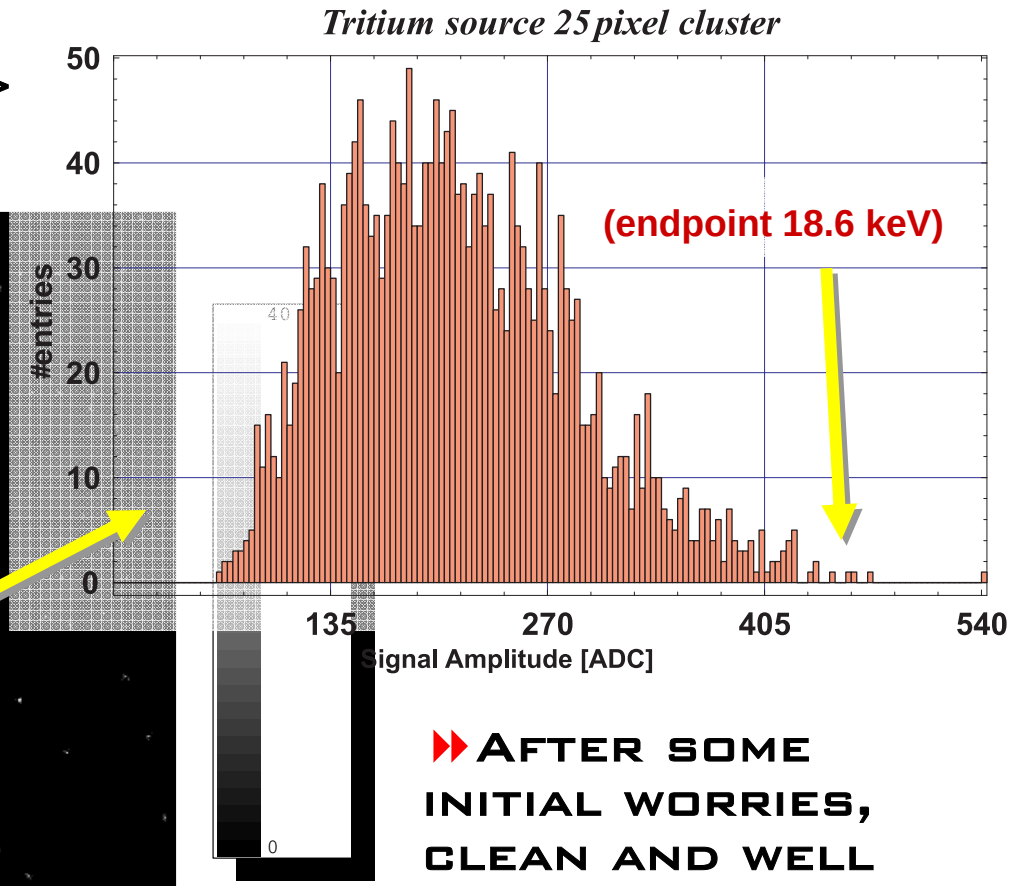
^{3}H(T) Autoradiography with MIMOSA V ...



^{3}H(T) AUTORADIOGRAPHY WITH MIMOSA V ...

- <CLEANED FROM DETECTOR ARTEFACTS> IMAGE OF THE SOURCE

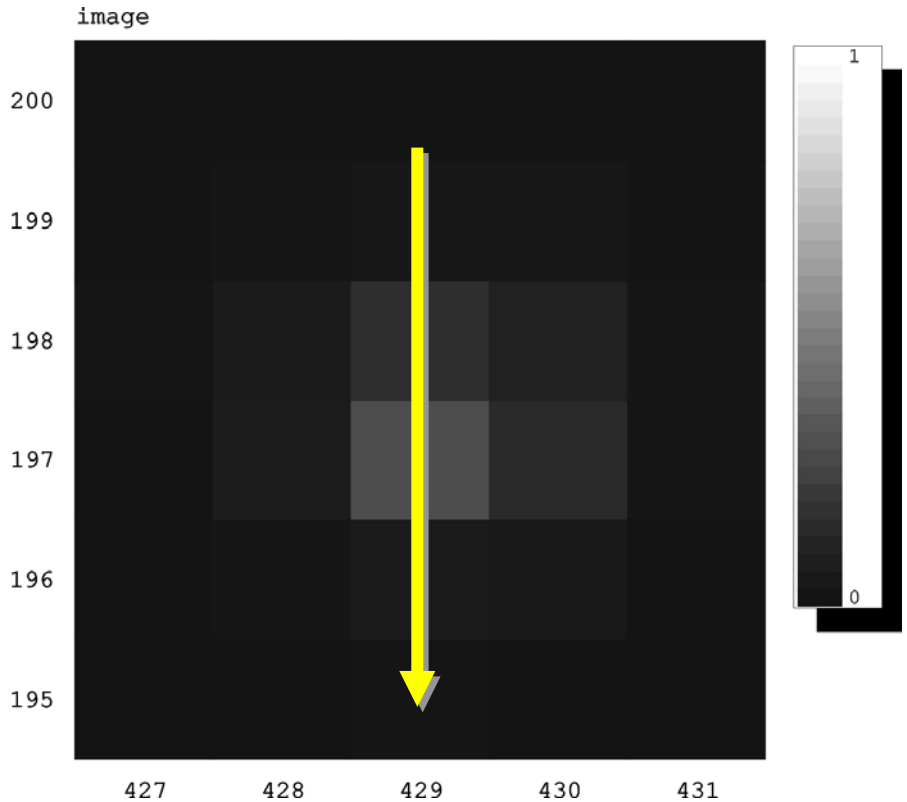




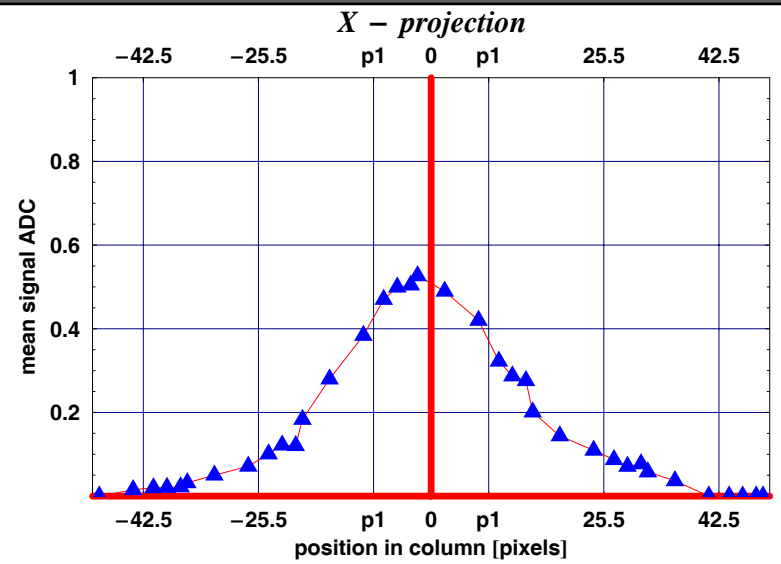
- AFTER SOME INITIAL WORRIES, CLEAN AND WELL CORRELATED WITH HPD DATA ^{3}H(T) SPECTRA WERE OBTAINED!

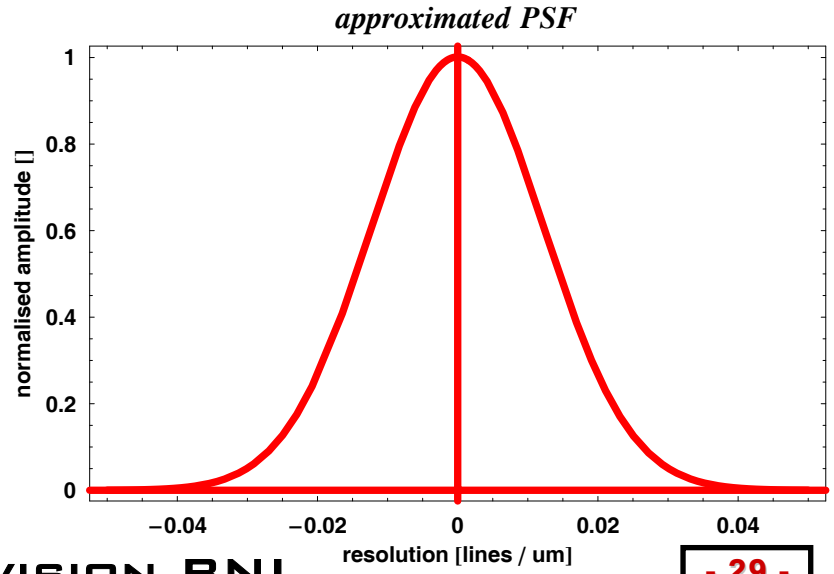
MIMOSA V – 1ST TESTS IN SEM AND TEM E-MICROSCOPE

- SCANNING OF SINGLE PIXEL WITH E- BEAM (25KEV SEM HIT MULTIPLICITY ~5-10 E-)



BEAM SCANNING



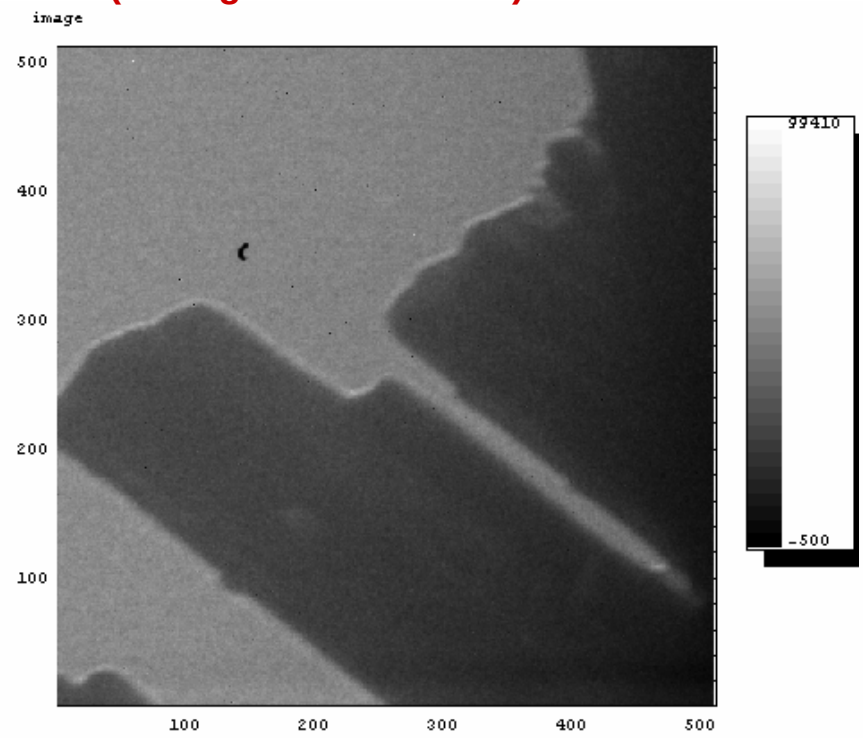


SEM @ INSTR. DIVISION BNL

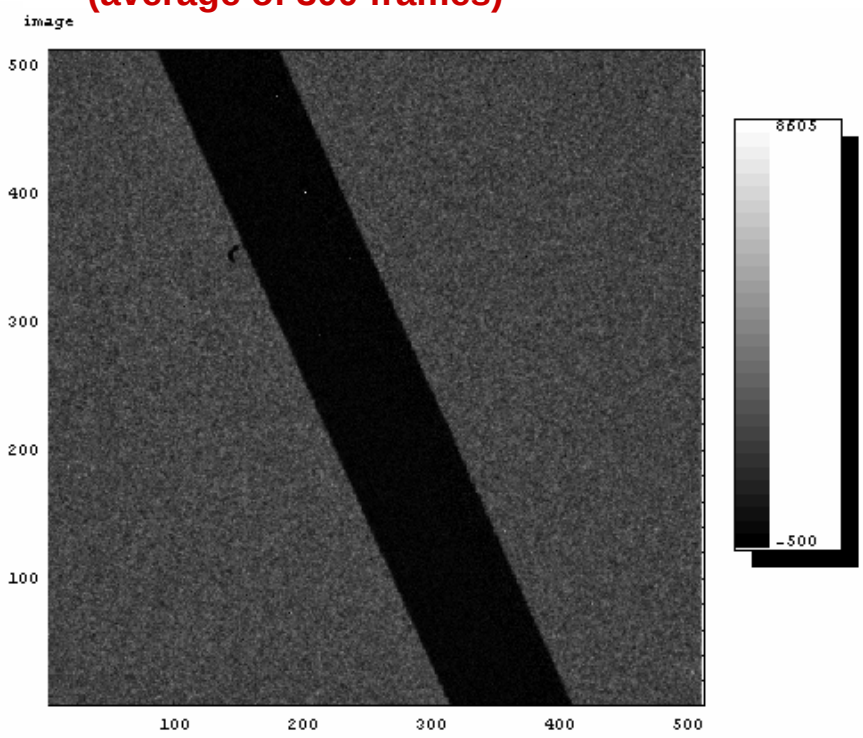
MIMOSA V – 1ST TESTS IN SEM AND TEM E-MICROSCOPE

Scanning of whole array surface with e- beam (40keV TEM hit multiplicity in single image~1e-)

- Image of a cristal specimen obtained with high dose exposure (average of 200 frames)

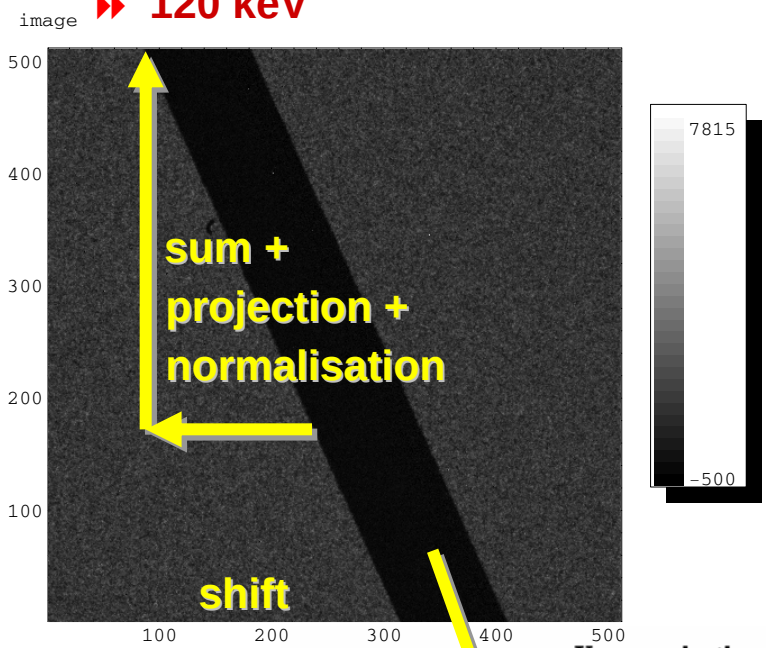


- Image of a metal needle obtained with low dose exposure (average of 300 frames)

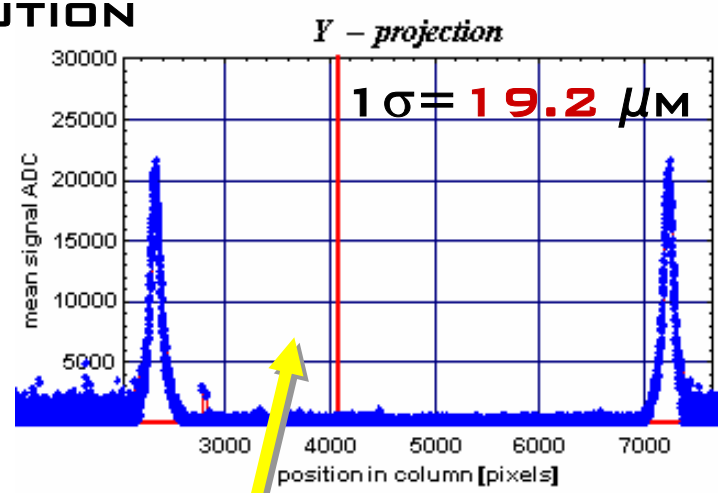


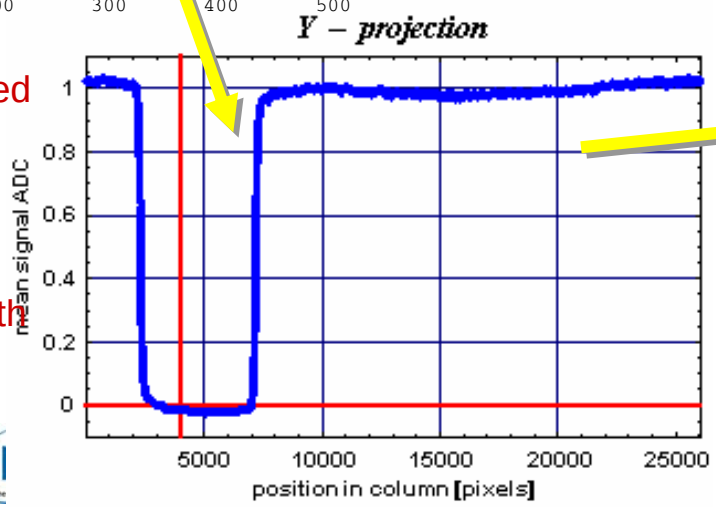
MIMOSA V – 1ST TESTS IN SEM AND TEM E-MICROSCOPE

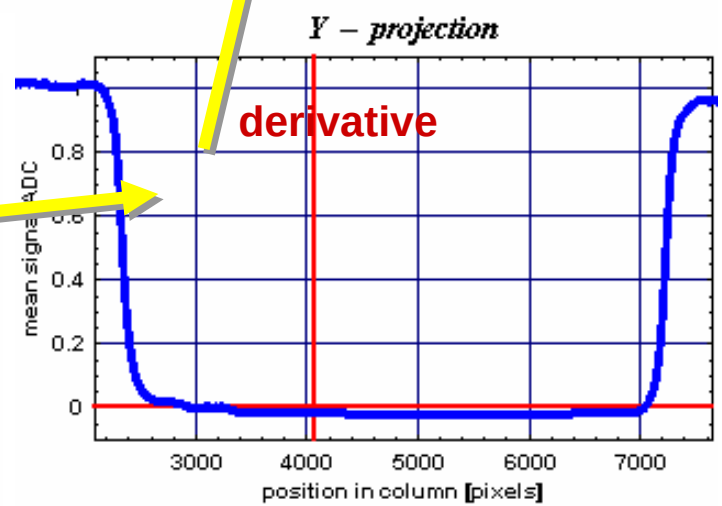
120 keV



Estimation of resolution from basic images



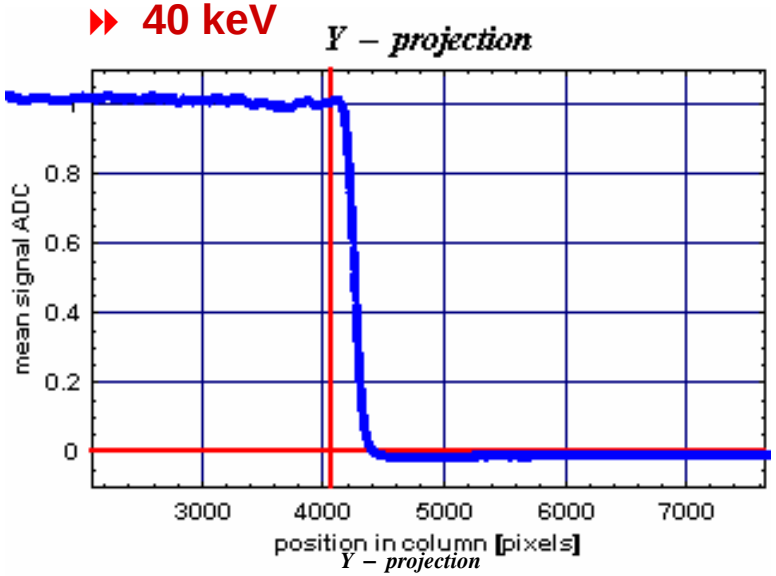




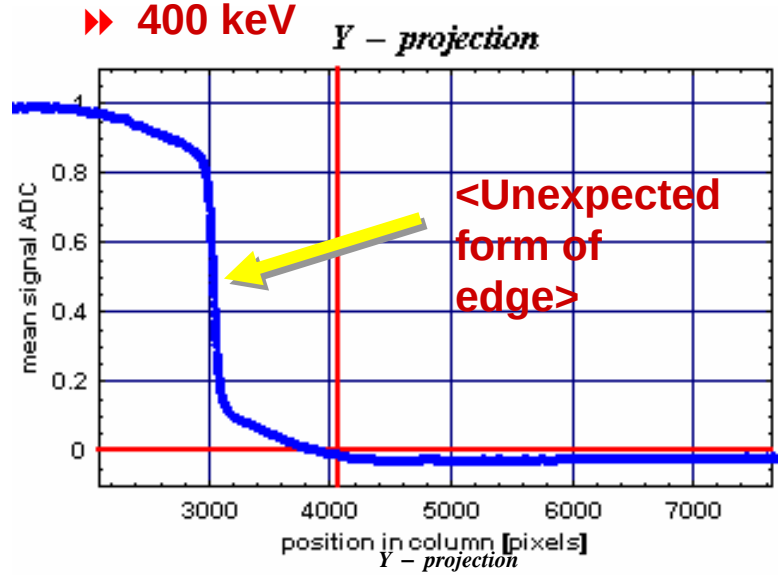
pixel sub-divided in 51 units, projection and sum for 512 lines, slope minimising width after derivation

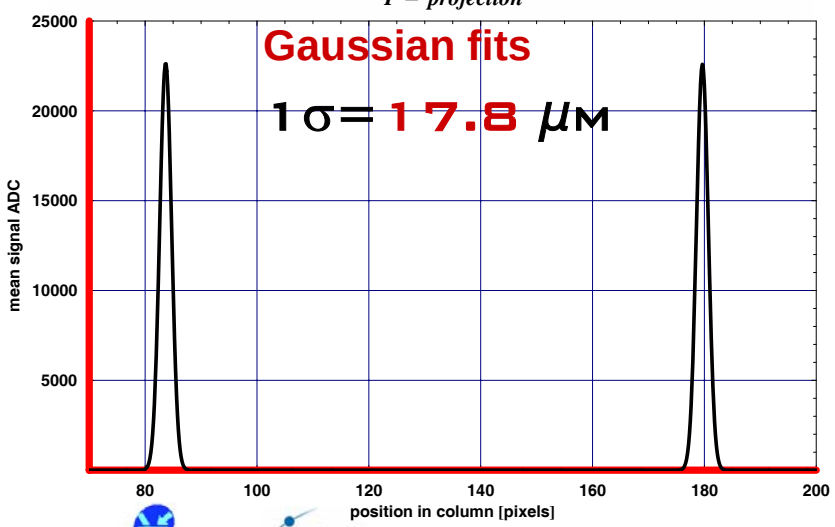
MIMOSA V – 1ST TESTS IN SEM AND TEM E-MICROSCOPE

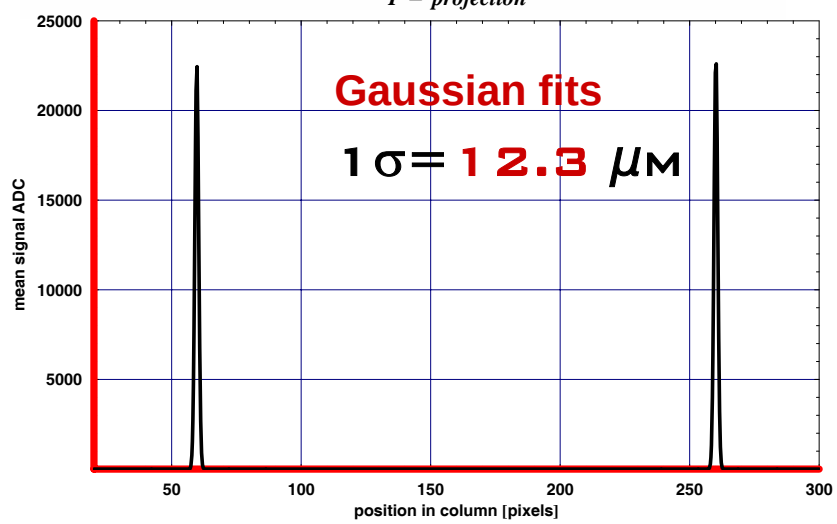
- 40 keV



- 400 keV



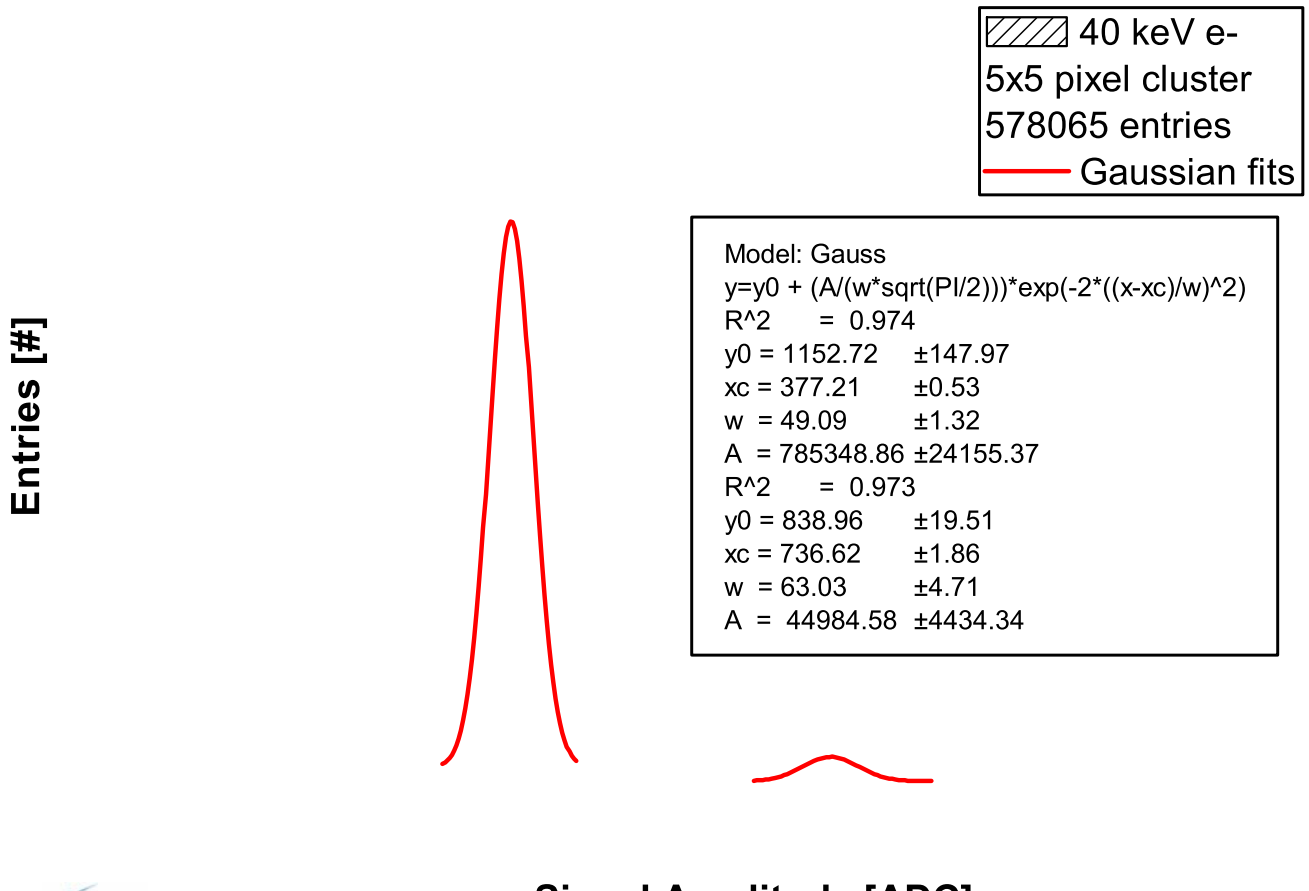




MIMOSA V – 1ST TESTS IN SEM AND TEM E-MICROSCOPE

Electron spectrum for 40 keV

5×5 pixel cluster

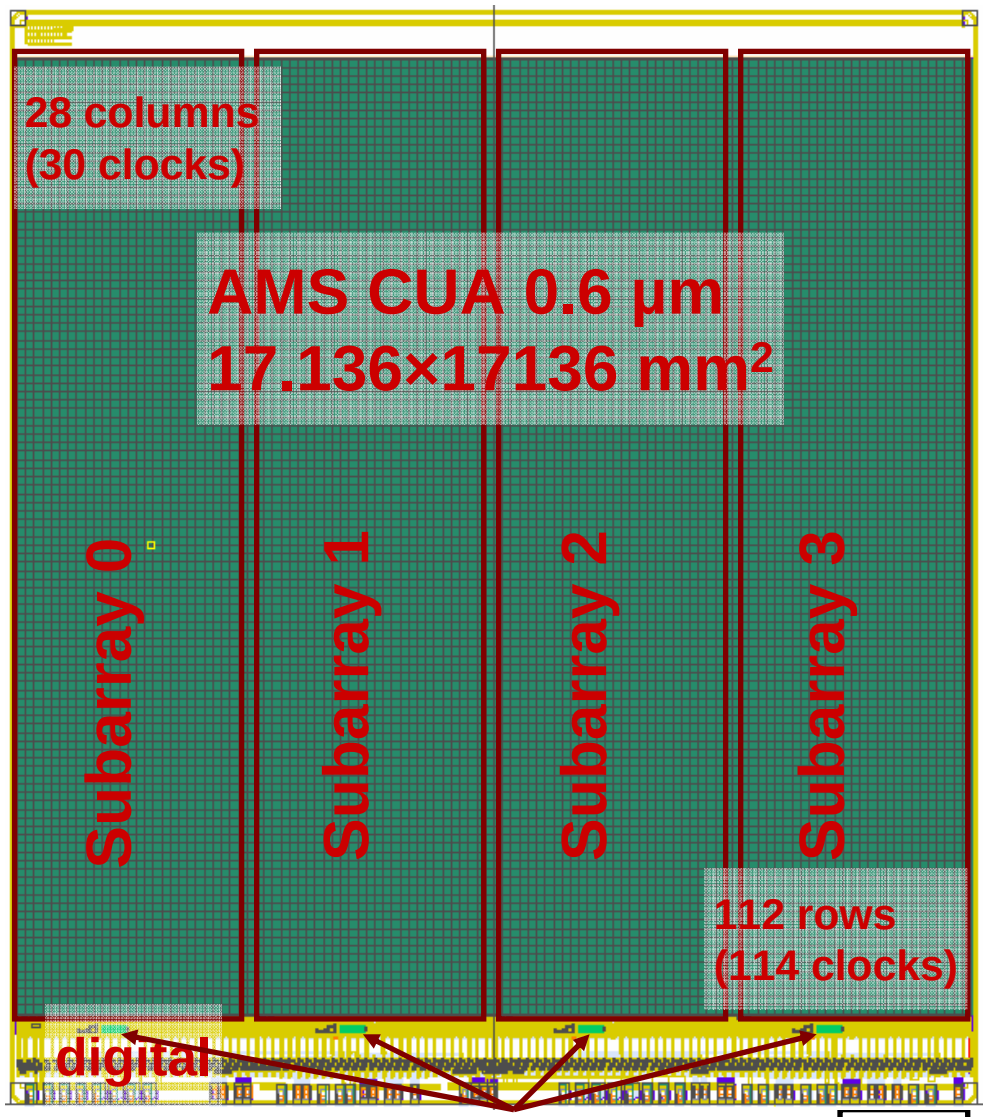


Final prototype for Beam Monitor

electron imager

- sensitivity to 20keV e^-
- image ∅ *after demag.* =~16 mm,
- signal range: $10^4 \div 10^8$ $e^-/mm^2/s$ @ 20 keV energy ➡ p beam: 3 (0.3 @ 2σ) - 9×10^3 of 20 keV electrons @ 200×200 μm^2 pixels / 100 μs,
- time resolution = 100 μs (signal integration and 10 kHz readout),
- spatial res.: 5000 cells or more...,
- no dead time (missing beam fluctuations is not an option).

- Four sub-arrays of 28×112 pixels read out in parallel $\blacklozenge_{read/integr}$<100μs, no dead time – alternate integration and readout in halves of pixels,
- Total array of 112×112 153×153μm^2 square pixels, each pixel – interdigited array of small n-well/p-epi diodes.

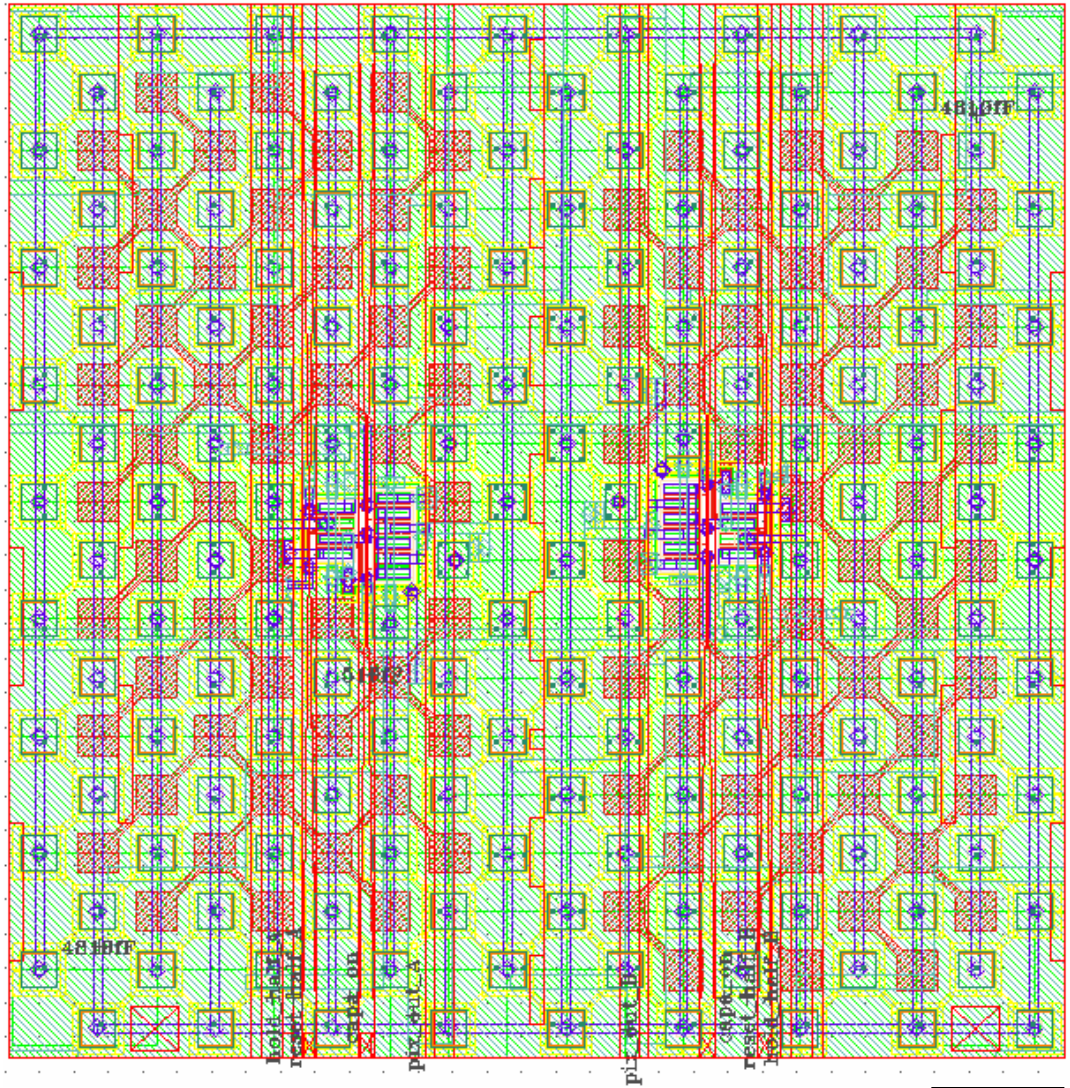


- delivered ~15th of July, tests!

Final prototype for Beam Monitor

MimoTera:

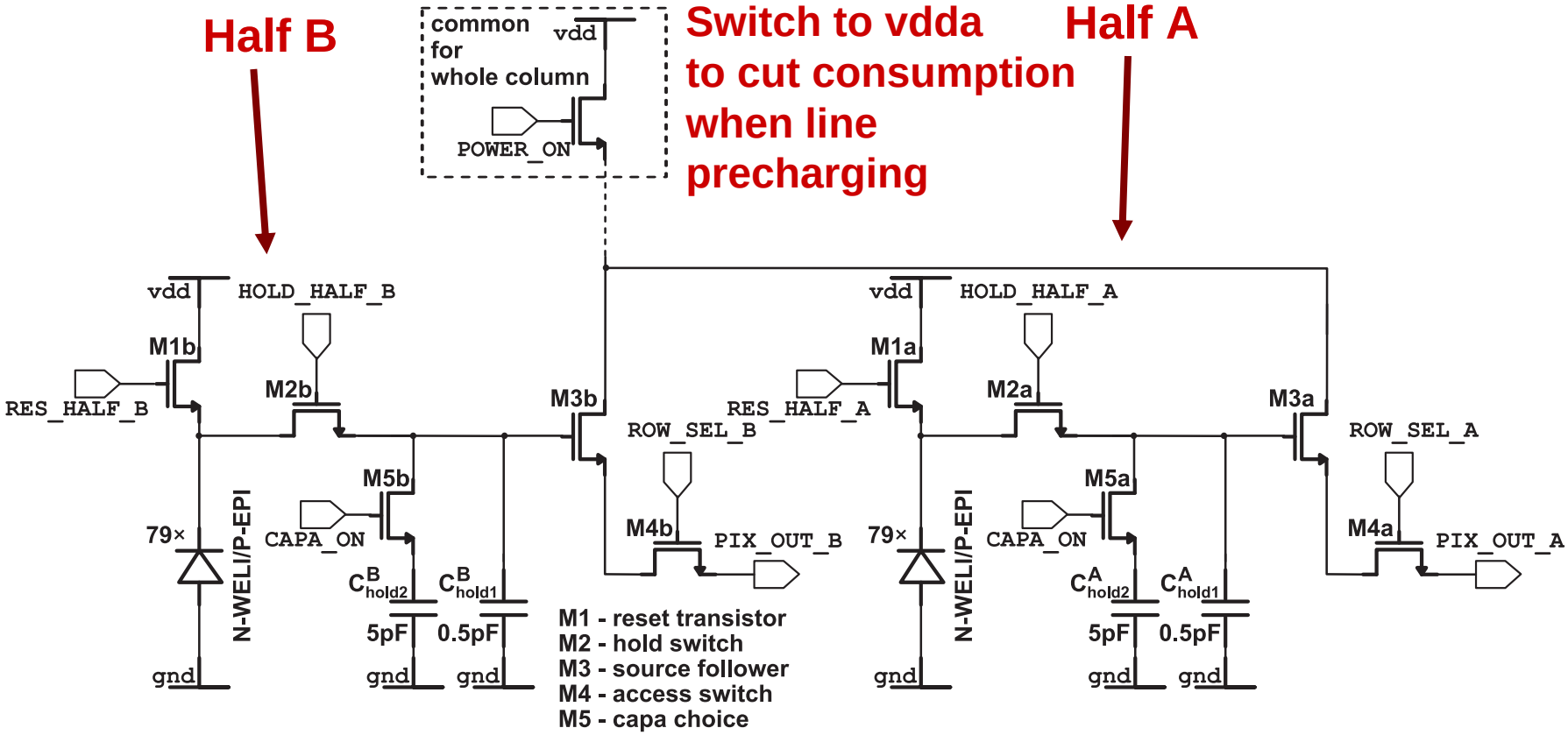
- Two 9×9 interdigited arrays of n-well/p-epi diodes (5×5 μm²) with two independent FE electronics – avoiding dead area,
- No dead time in pixel operation – alternate reset and integration in both arrays,
- In-pixel storage capacitors – choice ~0.5pF or ~5pF to cope with signal range (poly1 over tox capacitors),
- Readout without CDS – kTC noise,
- Signal swing ~2 V (pixel and chip output) @ 40Mpixel/s,
- Design risks:
  tox over whole pixel – no DIFF type defined,



- CVF=~250nV/e- @ 500fF; noise ~1000 e⁻ ⇒ 280 e⁻ kTC (ENC) @ 500fF

Final prototype for Beam Monitor

Pixel schematic diagram



Radiation Hardness

Radiation Hardness

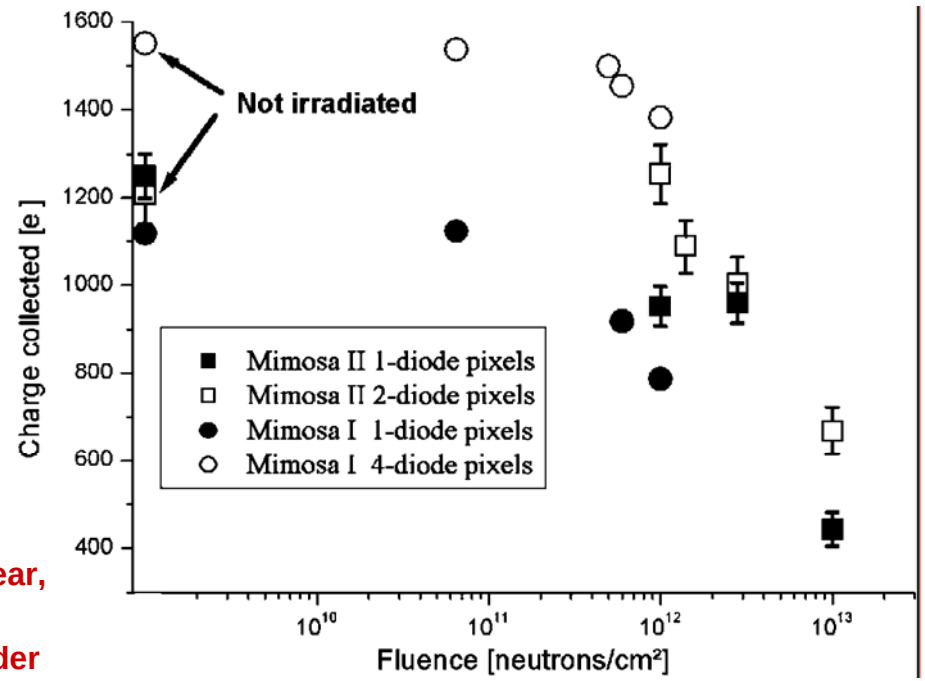
Neutron irradiations

tests up to 10^{13} n_{1MeVeq}/cm^2

$$\frac{1}{\tau_R} = \frac{1}{\tau_0} + \kappa_\tau \Phi$$

carrier lifetime altered

fluences up to 10^{12} n_{1MeVeq}/cm^2 are still acceptable *(2 orders of magnitude above FLC requirements= 10^9 n_{1MeVeq}/cm^2/year)*



Ionising irradiations

tests up to a few 100 krads

doses up to this level acceptable above FLC requirements 50 krad/year, exact sources of performance losses under investigation (diode size and placements of transistors are important parameters)

Conclusions, plans ...

- Ability of back-side illuminated thinned MAPS detectors for low/medium energy e- imaging – shown!,
- 1) Low-intercepting Beam Monitoring: principle shown, final device, tests !,
  2) HPD for biology: principle shown, work on position resolution + speed + duty cycle, tests !,
  3) Autoradiography (^{3}H etc.): principle shown, spatial resolution fine, work on duty cycle!,
  4) E^- microscope: first results quite promising, work on data, propose device adapted to this application,
- Still good understanding of the detector needed; How many blind pixels? Uniformity of signal from different pixels?, etc...

- Finish with analysing of disponible data a.s.a.p.,
- Prepare new PCBs + test chips with different entrance windows and back-side implantations @ HPD – 1 week in sept./Oct. (?), new tests with microscope (?),