MAPS DETECTORS in non commercial applications - review

- CMOS IMAGE SENSORS
- MAPS - technology for VxDs
  - review of ongoing work, results, architectures …

- MAPS in other fields
  - Direct electron imaging – back-side ill. MAPS
    - beam monitoring
    - β autoradiography $^{3}H(T)$
    - Electron microscopy
- tests in NSLS
- Conclusions

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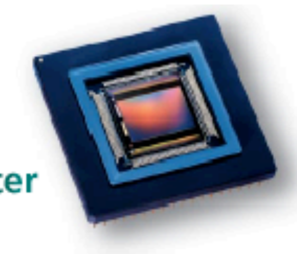
CMOS Image sensors

CMOS Image Sensors industry standard for imaging in visible light?

example:

500-fps, 1.3-Megapixel CMOS Image Sensor

Featuring Micron's TrueSNAP™ Electronic Shutter



Features

- 1,280H x 1,024V image resolution
- TrueSNAP™ freeze-frame electronic shutter
- 500 frames per second (fps)
- Monochrome or color digital output
- <500mW maximum power dissipation @ 500 fps
- On-chip, 10-bit analog-to-digital converters (ADCs)
- Simple digital interface

Description

Micron's MI-MV13 is one of the industry's fastest CMOS image sensors. It features Micron's revolutionary TrueSNAP freeze-frame electronic shutter, which enables simultaneous exposure of the entire pixel array to stop even the fastest motion with crystal clear images. It delivers 10-bit color or monochrome digital images with a 1.3-megapixel resolution at 500 fps—or 655 million pixels per second—for machine vision and high-speed imaging applications.

Applications

The MI-MV13 CMOS image sensor captures complex high-speed events for traditional machine vision applications as well as various high-speed imaging applications. Its electronic shutter is capable of freezing and capturing near-instantaneous events with a 1.3-megapixel resolution while outputting 500 fps. The sensor can capture an event with a series of images taken at a high repetitive rate, enabling them to be viewed at lower speeds.

Applications include machine vision (production line monitoring and control for industries ranging from semiconductor fabrication to food sorting), automotive testing, microscopy, traffic control, 3D imaging, animation, motion analysis, film special effects, forestry, industrial and military research, and security systems. The MI-MV13's capabilities enable camera performance far beyond current CCD-based systems, creating

continuous growth since early nineties when first CMOS image sensors proposed by JPL.

ex.

CMOS active pixel image sensor
Mendis, S.; Kemeny, S.E.; Fossum, E.R.
Electron Devices, IEEE Transactions on, Vol.41, Iss.3, Mar 1994,Pages:452-453

continuous improvement in:

- **image quality,**
- **image resolution,**
- **frame rate,**
- **integrated processing,**
- **power consumption...**

query in IEEE: ***((cmos image sensor<in>metadata)) <and> (pyr >= 2005 <and> pyr <= 2005)***

gives 80 positions

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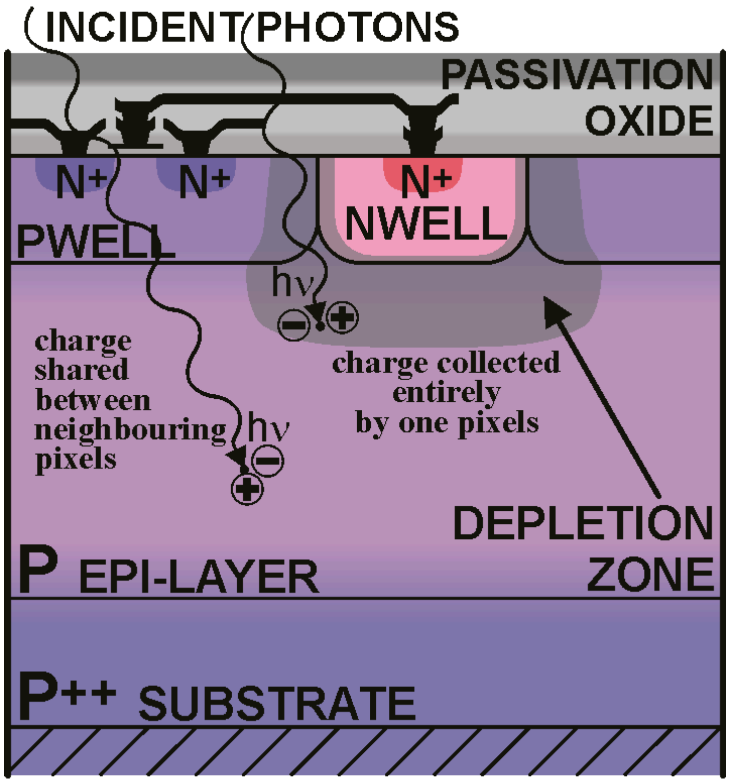
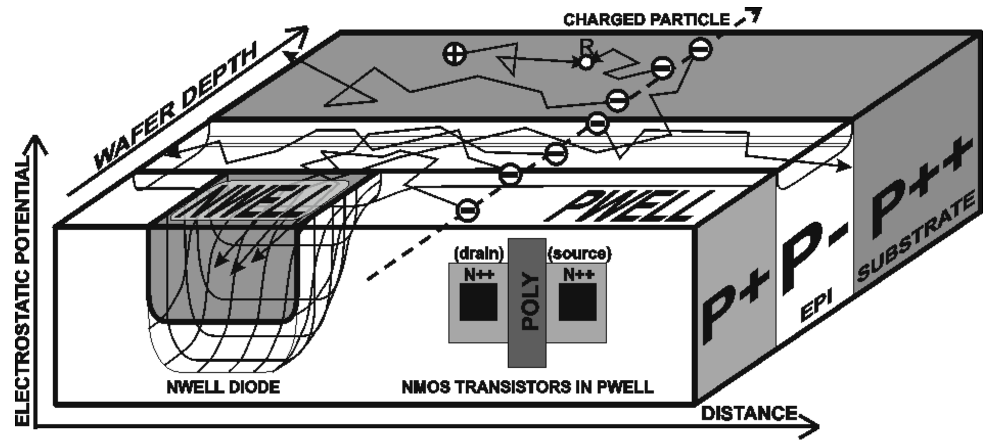
CMOS Image sensors in HEP - MAPS

Operation principle of photodiode MAPS

Monolithic Active Pixel Sensors (MAPS)



structure proposed for visible light allowing 100% detection efficiency (tracking!)



operation:

- signal generated in epitaxial layer (low doping) $Q \approx 80 e^{-} h^{+}/\mu m \Rightarrow \sim 1000 e^{-}$,
- charge collection through thermal diffusion,
- signal sensed as voltage drop on N-WELL anodes,
- reflection bondaries at P-WELL and P-SUB.

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.

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CMOS Image sensors in HEP - MAPS

other MAPS structures

used in visible light applications

photogate

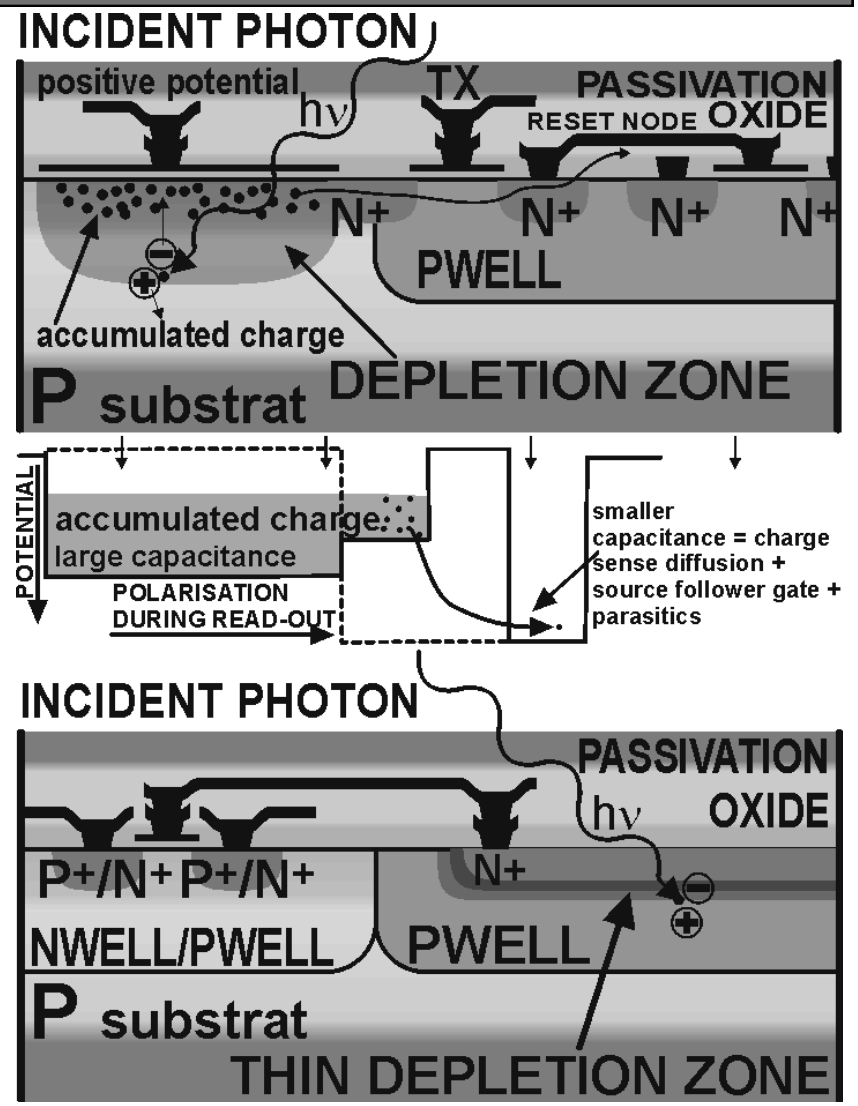
advantages: integrated amplification (collection on big capacitance, conversion to V on small capacitance), faster and more efficient charge collection w.r.t. photodiode,
disadvantages: accumulation of charge close to the interface $Si\text{-}SiO_2$ – sensitivity to trapping – indeed long (ms) time transfer measured

pinned diode – response weaknesses

Eastman Kodak Company (Rochester, NY)
United States Patent 6,320,617
CMOS active pixel sensor using a pinned photo diode

shallow diode

advantages: coexistence of sensing element and both types of transistors in each pixel,
disadvantages: reduced fill-factor, poor sensitivity to deeply penetrating photons and relativistic charged particles



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MAPS – technology for VxDs

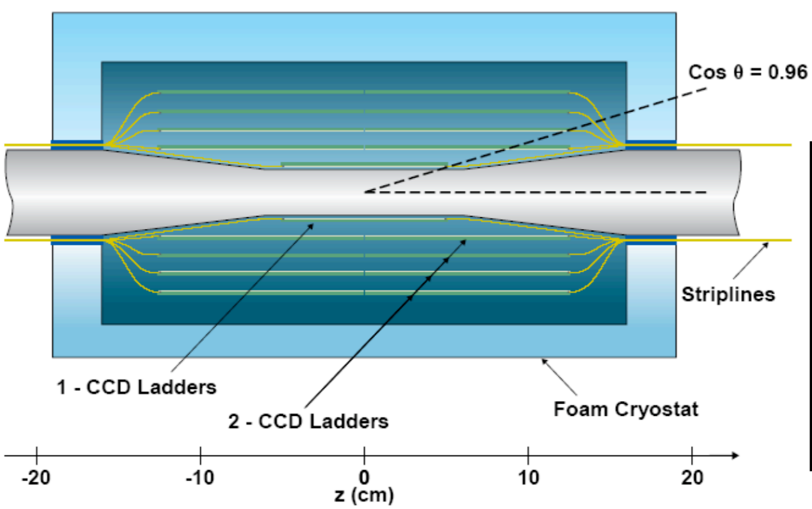
⏩ Idea to use MAPS for applications requiring detection relativistic charged particles tried in IReS-LEPSI,Strasborg, France, collaboration with first prototypes in 1999

ex. **A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology**
Turchetta R.; Berst J. D.; Casadei B.; Claus G.; Colledani C.; Dulinski W.; Hu Y.; Husson D.; Le Normand J. P.; Riester J. L.; Deptuch G.; Goerlach U.; Higueret S.; Winter M., Nucl.Instrum.Meth. A458, 2001, Pages: 677-689

Design and testing of monolithic active pixel sensors for charged particle tracking
Deptuch, G.; Berst, J.-D.; Claus, G.; Colledani, C.; Dulinski, W.; Gornushkin, Y.; Husson, D.; Riester, J.-L.; Winter, M.
Nuclear Science, IEEE Transactions on, Vol.49, Iss.2, Apr 2002, Pages:601-610

⏩ R&D driven by construction of the vertex detector in ILC (construction → 2010)

high performance flavor identification requires high precision, highly granular, high readout speed, light, radiation hard vertex detector



Strasbourg version of ILC VxD: 5 cylindrical layers, R=15-60 mm, surface=3000cm^2, sensor thickness=25-50μm, total >300Mpixel system

Layer	Pitch	$t_{r.o.}$	N_{lad}	N_{pix}	P_{inst}^{diss}	P_{diss}^{mean}
L0	20 μm	25 μs	24	30M	< 120 W	< 6 W
L1	25 μm	≤ 100 μs	16	70M	< 80 W	< 4 W
L2	30 μm	200 μs	24	70M	< 100 W	< 5 W
L3	35 μm	200 μs	32	70M	< 110 W	< 5 W
L4	40 μm	200 μs	40	70M	< 125 W	< 6 W

IReS-Strasbourg, DAPNIA-Saclay, LBNL, RAL, DESY, Oregon Univ., Yale Univ. …

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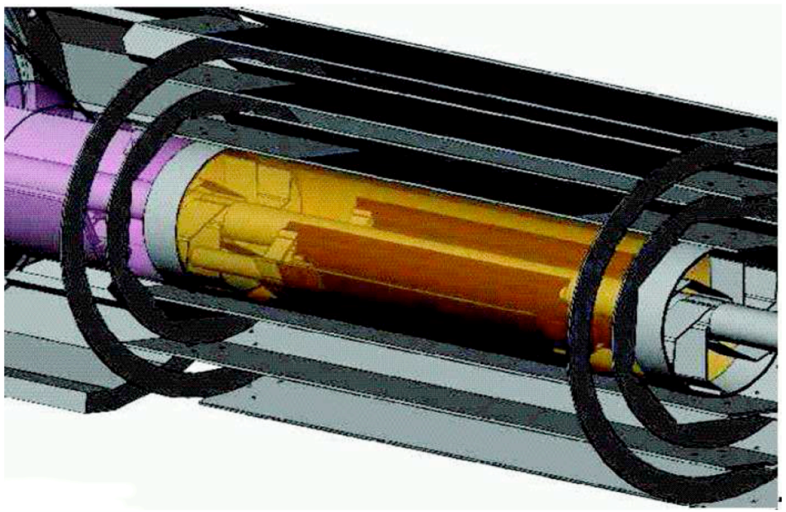
Flagship technology is CCD, however not all requirements can be satisfied

MAPS – technology for VxDs

R&D activities for upcoming VxDs

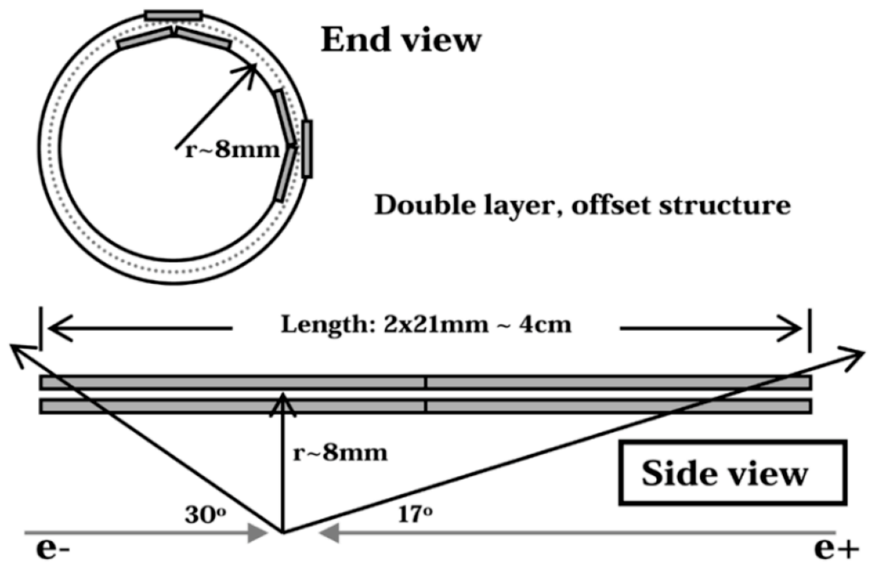
STAR upgrades (LBNL, IReS-Strasbourg, Irvine Univ.)



ex. **Novel integrated CMOS sensor circuits**
Kleinfelder, S.; Bieser, F.; Yandong Chen;
Gareus, R.; Matis, H.S.; Oldenburg, M.; Retiere, F.;
Ritter, H.G.; Wieman, H.H.; Yamamoto, E.
Nuclear Science, IEEE Transactions on,
Vol.51, Iss.5, Oct. 2004, Pages: 2328- 2336

ex. **Development of a B-Factory Monolithic Active Pixel Detector—The Continuous-Acquisition Pixel Prototypes**
Barbero, M.; Varner, G.; Bozek, A.; Browder, T.; Fang, F.; Hazumi, M.; Igarashi, A.; Iwaida, S.; Kennedy, J.; Kent, N.; Olsen, S.; Palka, H.; Rosen, M.; Ruckman, L.; Stanic, S.; Trabelsi, K.; Tsuboyama, T.; Uchida, K.;
Nuclear Science, IEEE Transactions on
Volume 52, Issue 4, Aug. 2005 Page(s):1187 - 1191

BELLE upgrade (SuperBELLE) (Univ.Hawai, KEK, Univ.Tsukuba, INP-Krakow)



MAPS – technology for VxDs

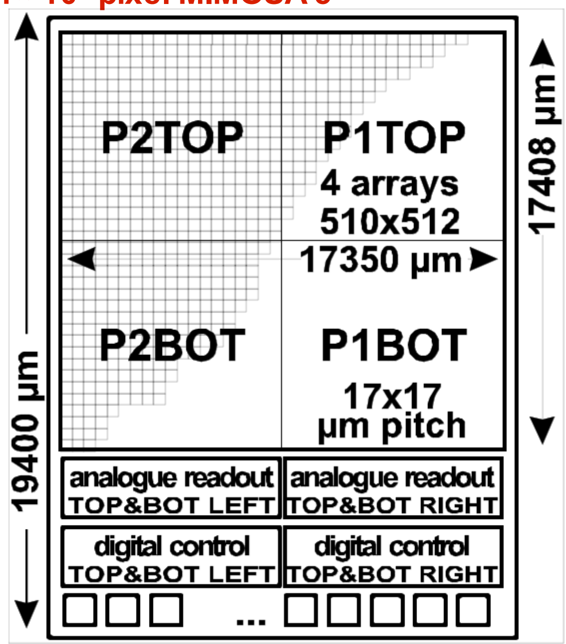
“Field probing” prototypes and results

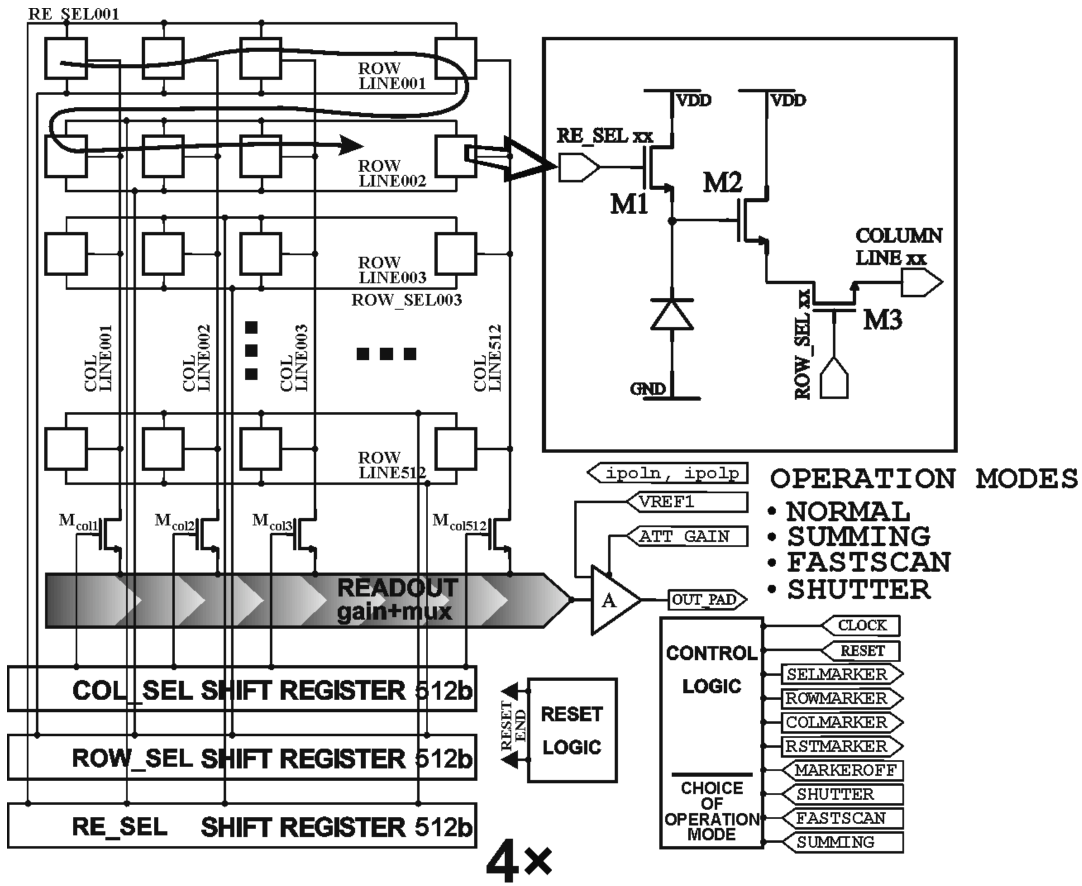
effort allocated to:

- **optimization od charge sensing element and pixel architecture aiming at optimisation of charge collection from ionization process due to single impact and solving radiation hardness problem, etc.**

example of structure developed:

1×10^6 pixel MIMOSA 5



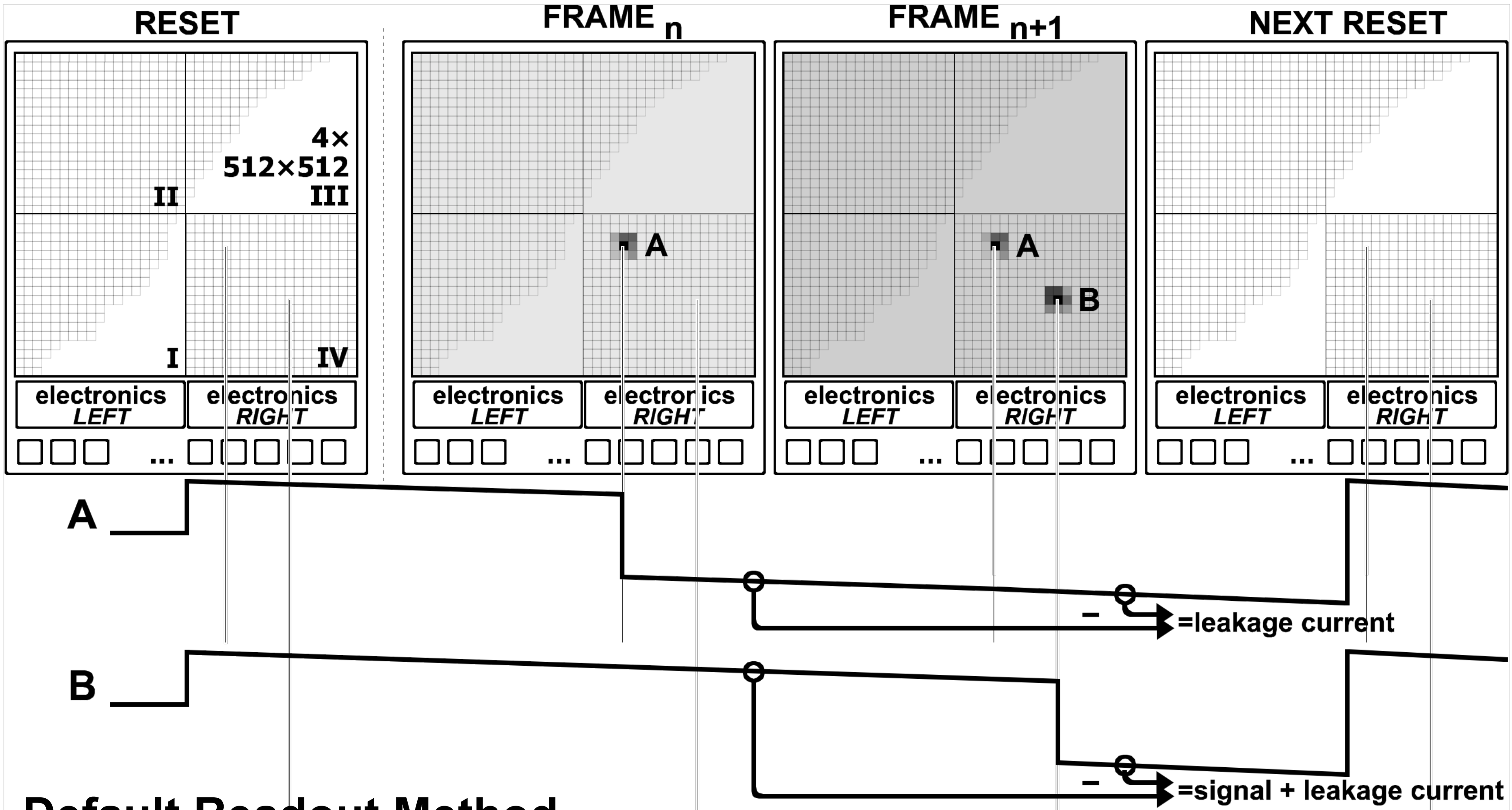


not optimised for any particular application,

- joined IReS-LEPSI effort in 2001

MAPS – technology for VxDs

“Field probing” prototypes and results

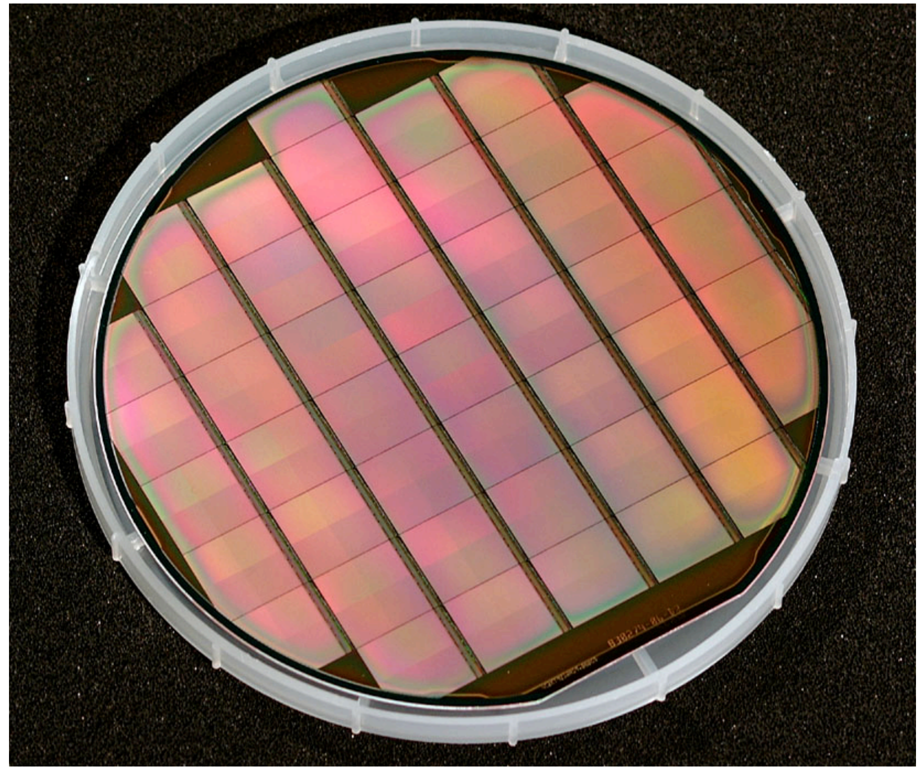


Default Readout Method

- Readout time = Integration time ~8 ms @ 40 MHz f_{clk}.

MAPS – technology for VxDs

MIMOSA V 1_10^6 pixels
micro-photograph



- 0.6 μm CMOS process with 14 μm epitaxial layer,
- 4 matrices of 512 × 512 pixels read-out in parallel; pixel: 17 × 17 μm^2, diodes: P1 - 9.6 pm^2, P2 - 24.0 pm^2, control logic and all pads aligned along one side,

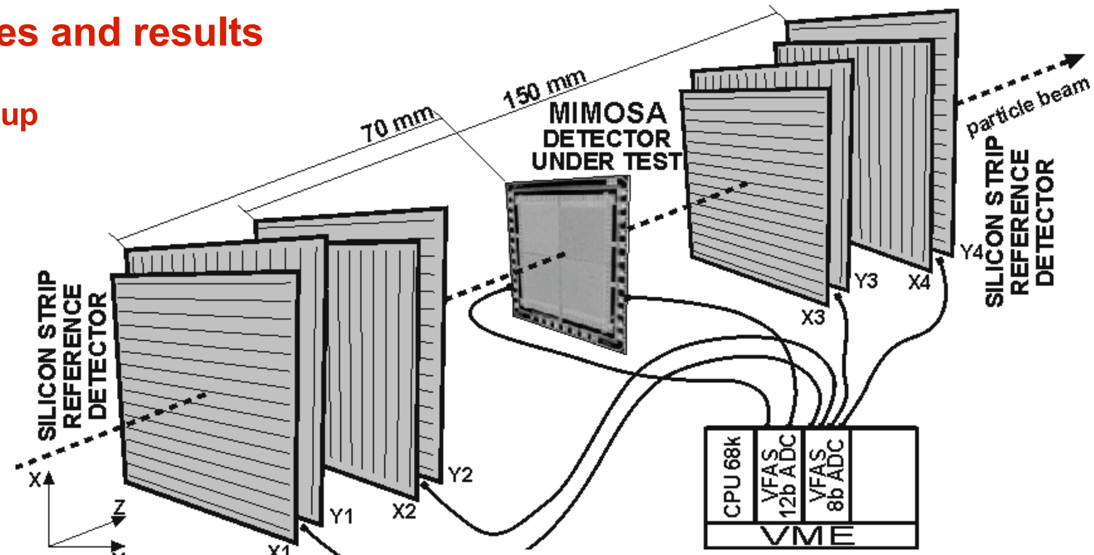
results:

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

MAPS – technology for VxDs

“Field probing” prototypes and results

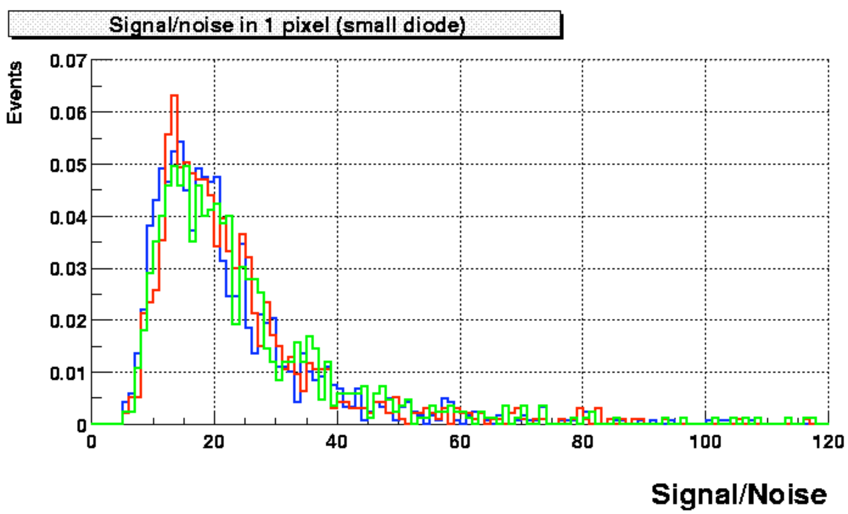
tracking performance test set-up

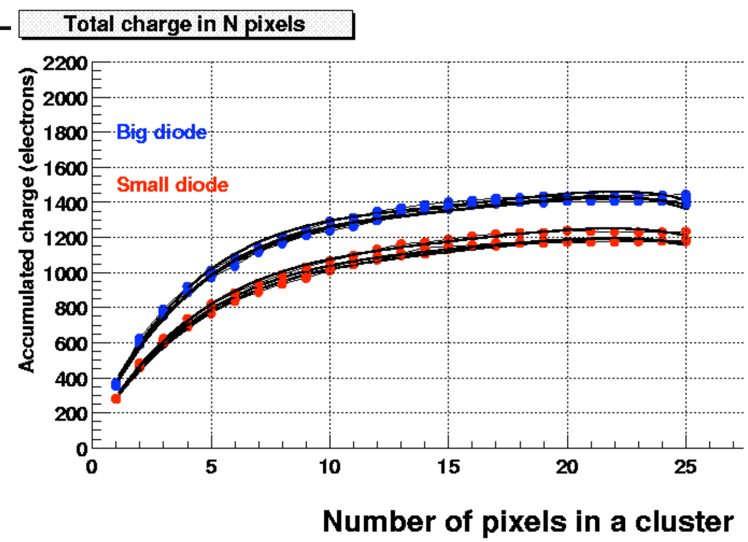


outcame of the initial phase

achievement: obtained satisfactory tracking performances (σ_{sp}, ε_{det})

still investigate: radiation hardness, material budget, and signal processing system/circuitry





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MAPS – technology for VxDs

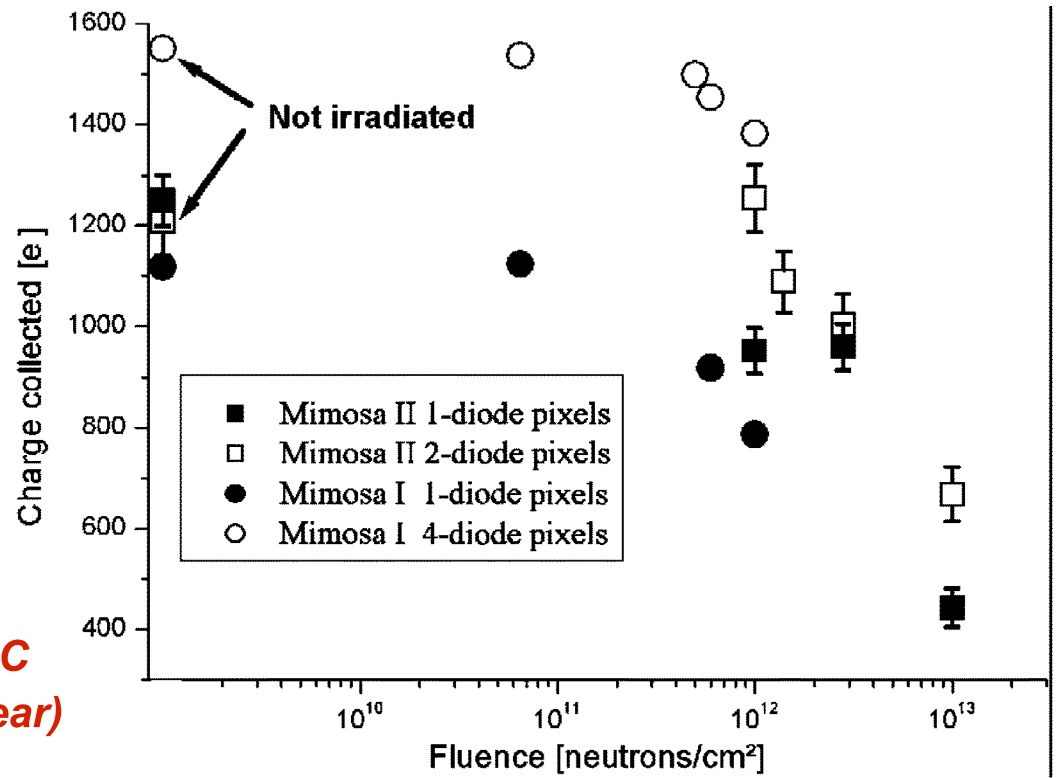
Radiation Hardness – neutron irradiations

interaction of mass particles *(decrease of carrier lifetime in the epitaxial layer - dominant effect)* :

$$\frac{1}{\tau_{R0}} = \frac{1}{\tau} + \kappa_{\tau}\Phi$$

- typical charge collection time = ~100 ns,
- doping dependent electron lifetime = ~10 μs @ 10^{15} atom/cm^3
- carrier lifetime ∝ 1/flux

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

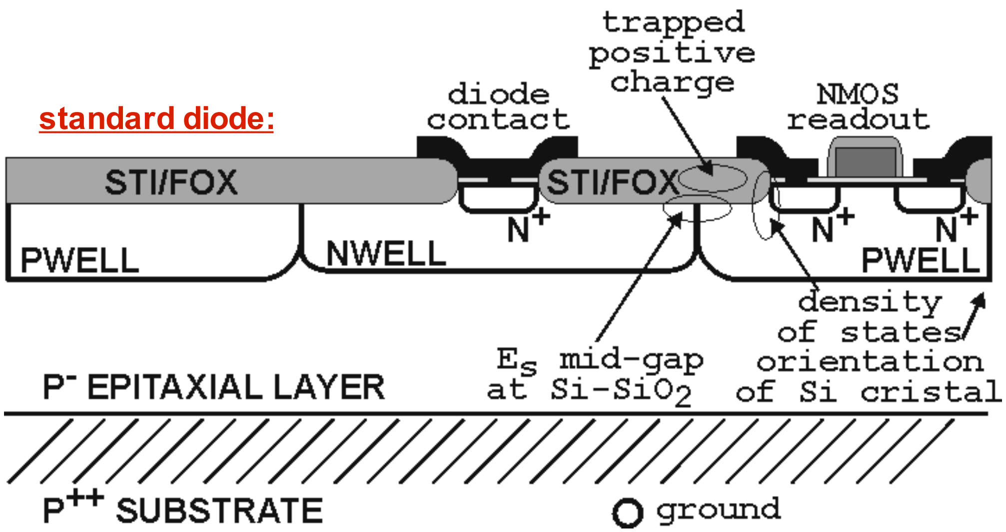


fluences up to 10^{12} n_{1MeVeq}/cm^2 are still acceptable for ILC
(2 orders of magnitude above ILC requirements=10^9 n_{1MeVeq}/cm^2/year)

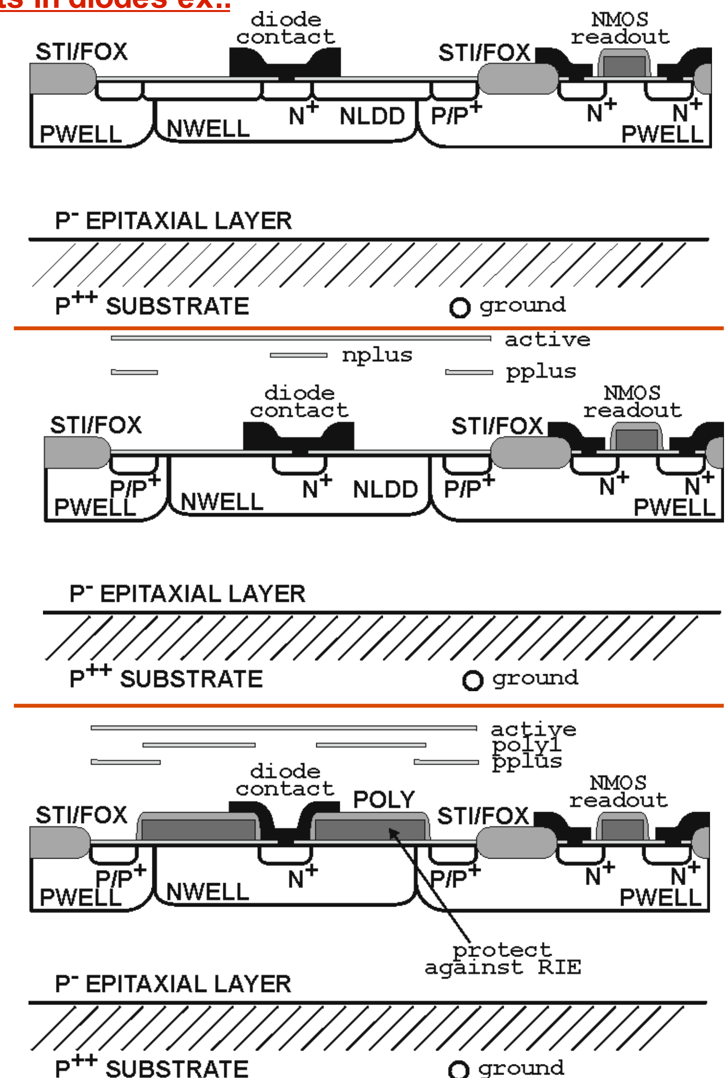
MAPS – technology for VxDs

Radiation Hardness – ionizing doses

standard diode:



improvements in diodes ex.:



ionizing dose damage *(leakage current dominant effect)* :

- accumulation of positive charges in STI/FOX – *inversion of p-type material at the interface and conduction path*,
- high density of trap sites along trench walls (crystal orientation) and at the bottom of the trench (RIE) – *current generation*,
- accumulation of positive charges and charged (+ or -) occupied traps - *distribution of electric field in the device.*

- avoid diode implant span trenches
- protect oxide and interface from RIE

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MAPS – technology for VxDs

Radiation Hardness – ionizing doses

<u>problem studied and addressed in literature:</u>

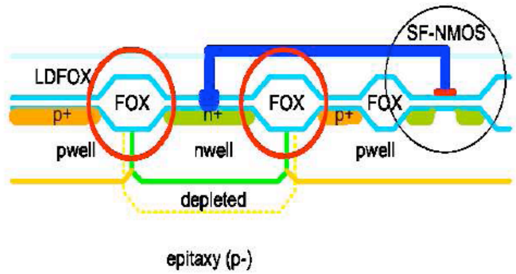
Design and characterization of ionizing radiation-tolerant CMOS APS image sensors up to 30 Mrd (Si) total dose
Eid, E.-S.; Chan, T.Y.; Fossum, E.R.; Tsai, R.H.; Spagnuolo, R.; Deily, J.; Byers, W.B., Jr.; Peden, J.C.; Nuclear Science, IEEE Transactions on Volume 48, Issue 6, Part 1, Dec. 2001 Page(s):1796 - 1806

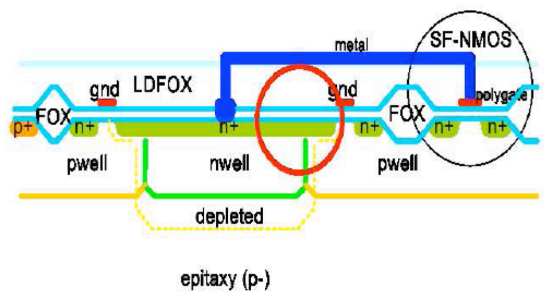
<u>interest for industry and solutions proposed ex.:</u>

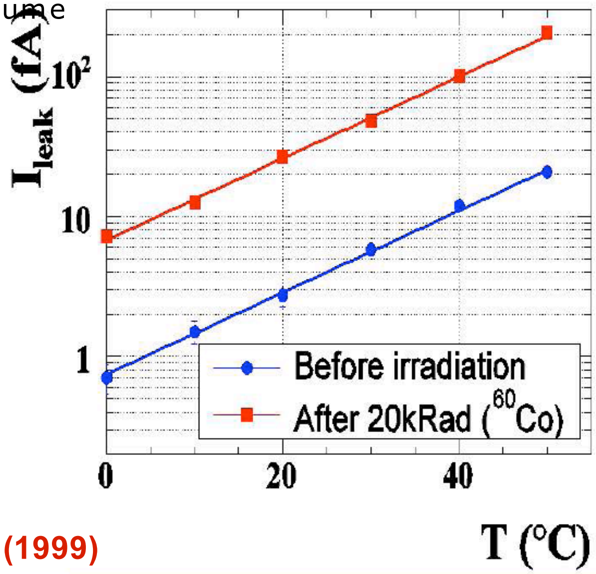
United States Patent: 6,410,359 *(2002) Reduced leakage trench isolation*

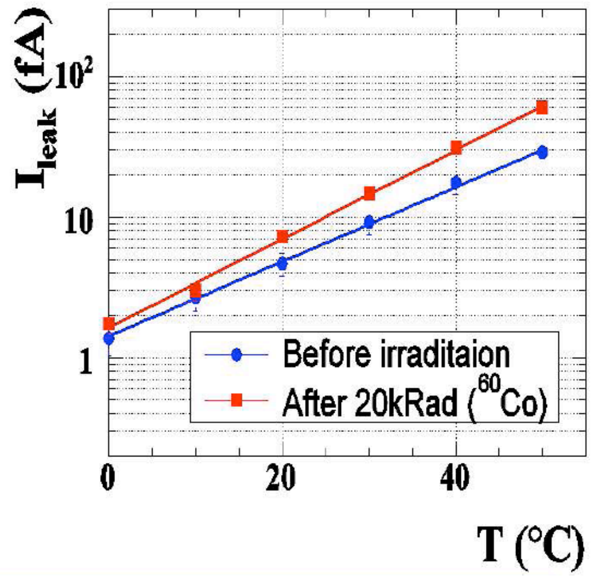
United States Patent: 5,859,450 (1999) *Dark current reducing guard-ring*

United States Patent: 5,970,316 (1999) *Method of making active pixel sensor cell that minimizes leakage current*









improvements in radiation hardness and control of leakage current are significat even for not fully optimised structures (Mimosa 9 from IReS).

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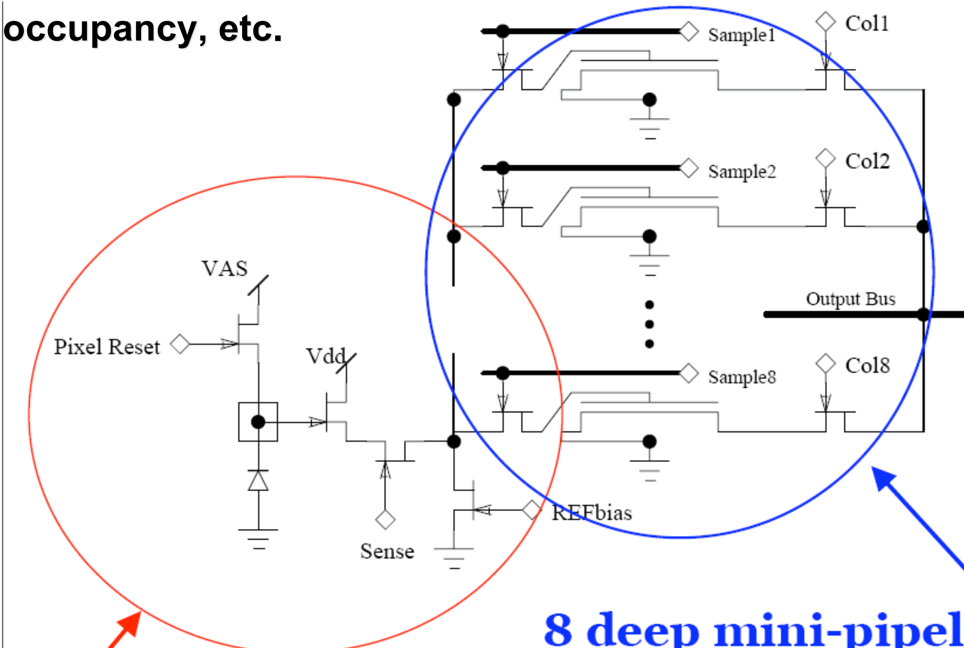
MAPS – Architectures

- choice of the architecture depends application parameters like:

- availability of trigger
- occupancy, etc.

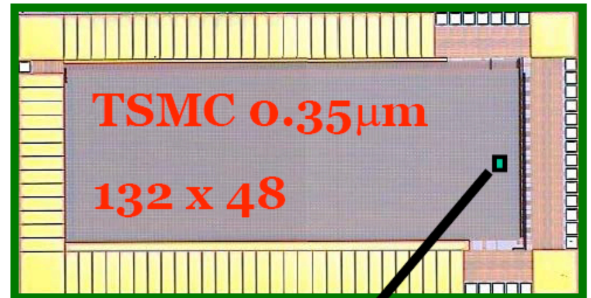


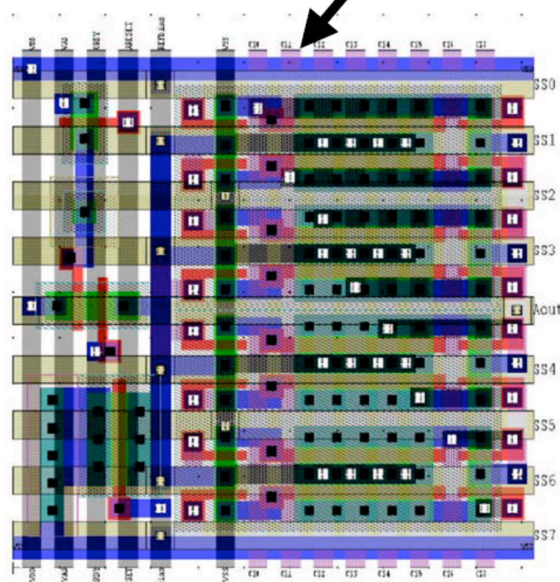
3-transistor cell

8 deep mini-pipeline in each cell

132x48=6336 channels 50688 samples

10μs frame acquisition speed achieved!

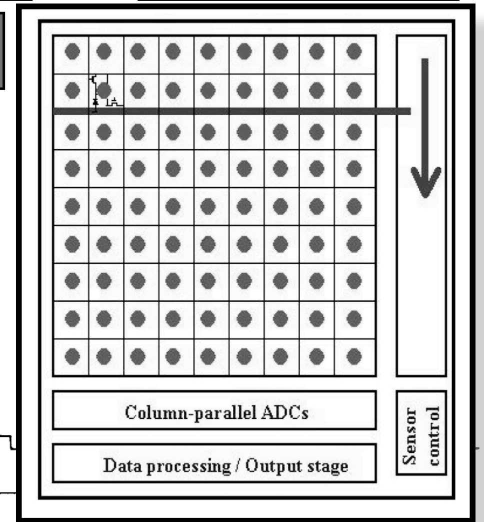




Pixel size 22.5 μm x 22.5 μm

pixel pipeline architecture for Belle upgrade Hawaii Univ. CAP2; progress on DAS: http://www.hll.mpg.de/headline/sds/contributions/stanic.pdf

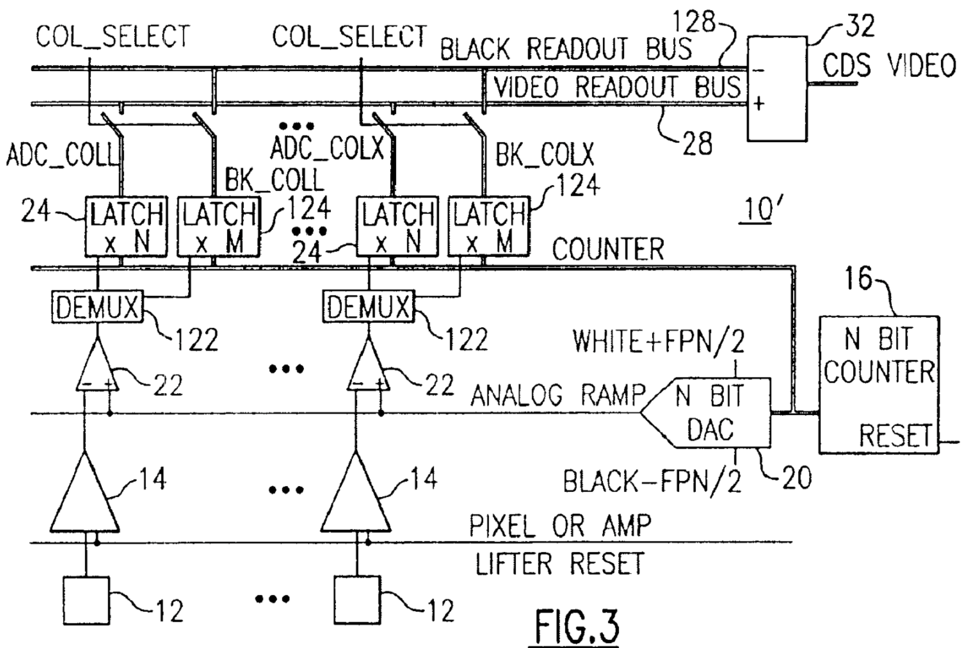
MAPS – Architectures



- advantage of detector + power of mixed mode CMOS on one board ⇒ smart detector sparsification of data on fly!

interest in industry and solutions proposed ex.:

United States Patent: 6,965,407 (2005) Image Sensor ADC and CDS per column



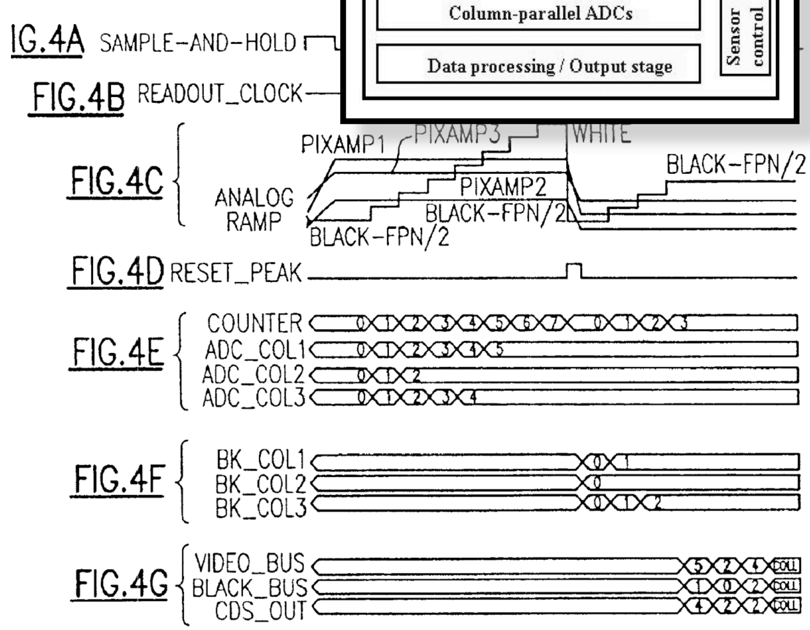
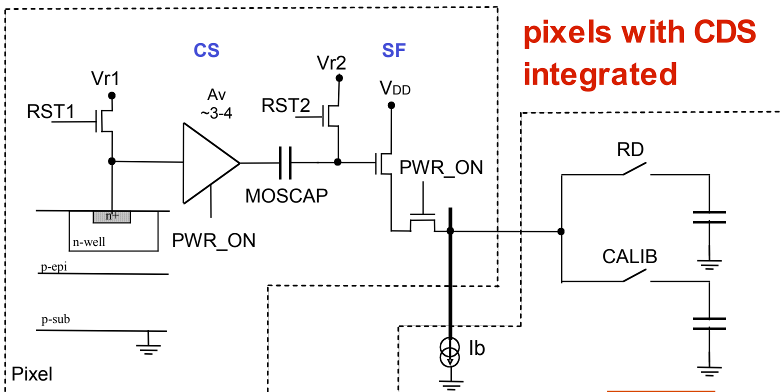


Illustration of direction in which the development of future architecture will go: integrate processing power close to the source of signal (on-chip column bottom), parallel processing of many channels, balance between analog and digital processing, conversion to digital of results

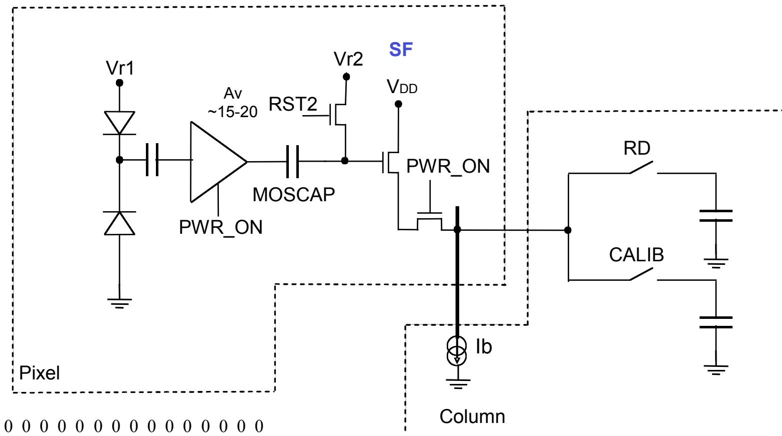
MAPS – Architectures

example of partially operational solution Mimosa 8

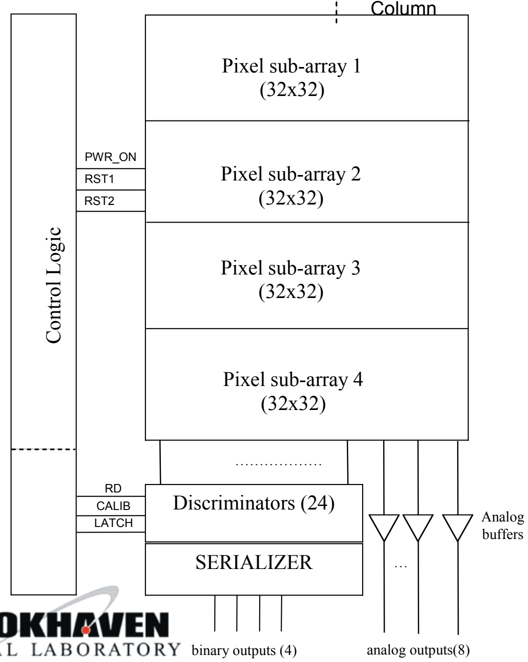
TSMC 0.25μm



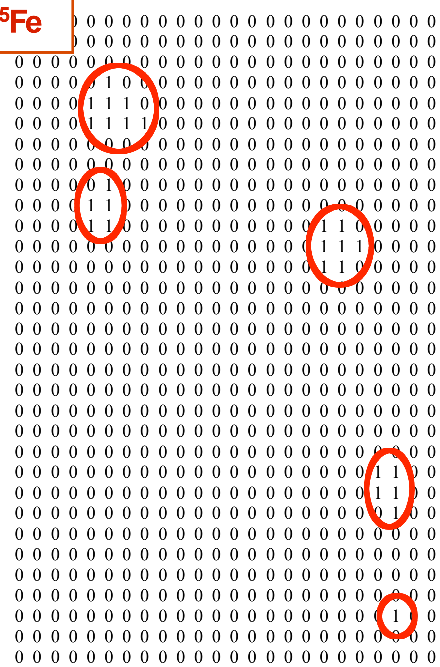
pixels with CDS integrated



pixels with CDS integrated



^{55}Fe



achievements (pixel)

- CVF = ~ 50 – 110 μV/e⁻,
- noise σ = 13 - 20 e⁻ ENC,
- FPN σ = 4 - 10 e⁻ ENC.

(discriminator @40MHz)

- offset = 10 e⁻ ENC,
- noise σ = 8 e⁻ ENC,
- FPN σ = 3 e⁻ ENC

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MAPS in other fields

- development of back-side illuminated sensor

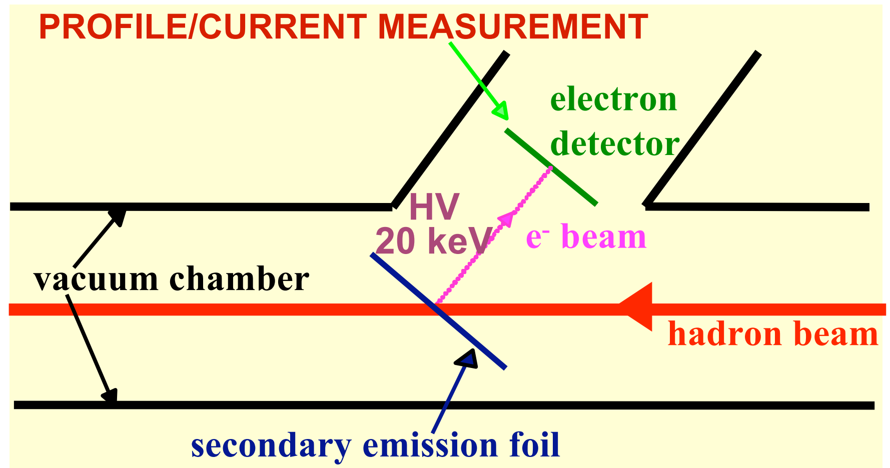
<u>motivation:</u>

Hadrotherapy

- On-line beam monitoring

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

5 ÷ 5000 rad/s (0.05 ÷ 50 Gy/s)



SEM electrons from 0.1 – 0.4 µm thick ($Al-Al_2O_3-Al$) foils

Thinned detector required

- sensitivity to 20 keV e^-,
- active area matrix of minimum 5000 pixels,
- signal range single to 9×10^3 e^-/pixel every 100 µs,
- 10 kHz frame rate (aiming at <2% dose non-uniformity) and no dead time.

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

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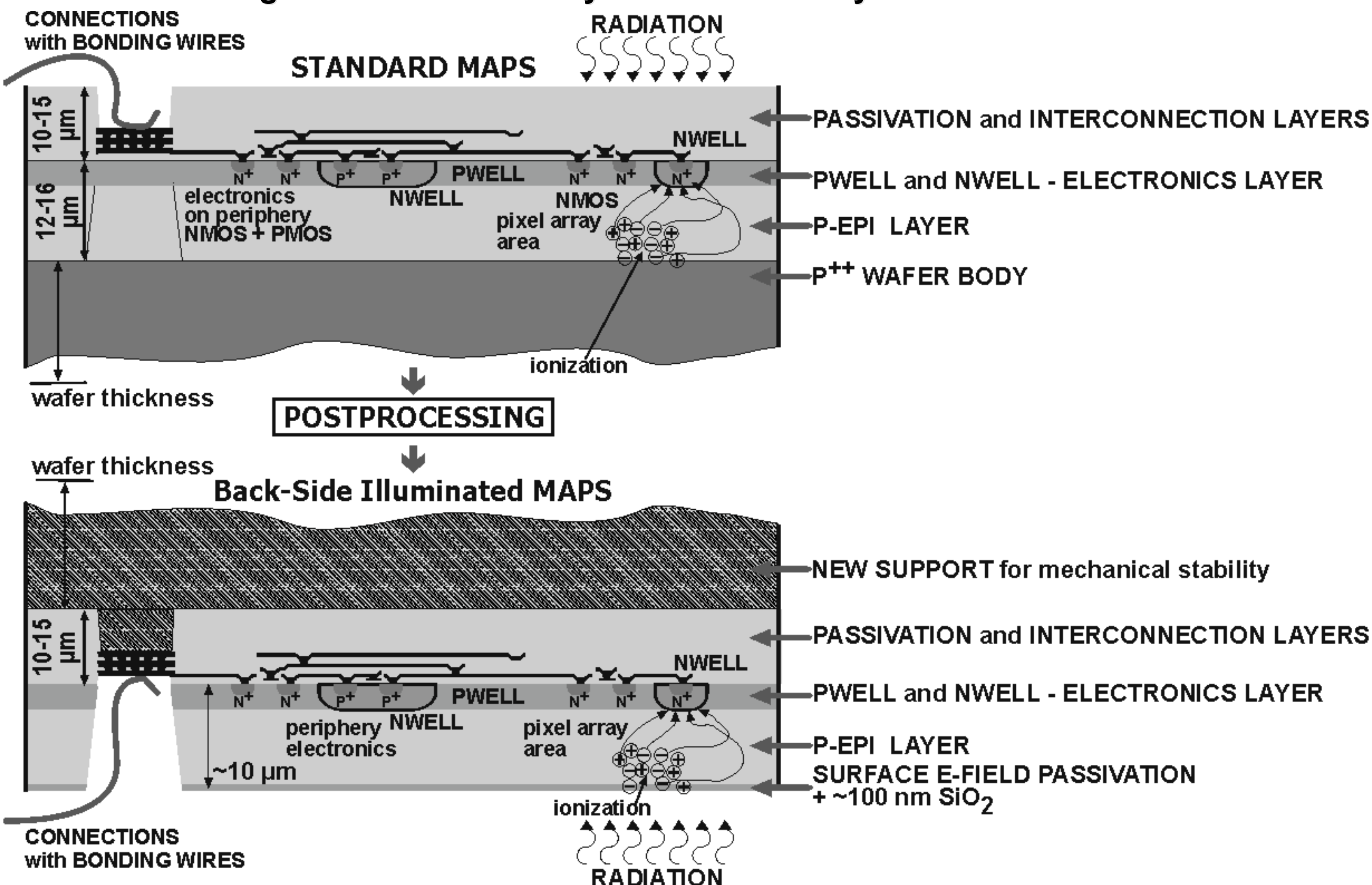
Silicon Ultra fast Cameras for electron and [gamma] sources In Medical Applications: a progress report
Berst, C. Bianchi, J. Bol, M. Caccia, C. Cappellini, G. Claus, C. Colledani, L. Conte et al.,, Nuclear Physics B - Proceedings Supplements, Volume 150, January 2006, Pages 308-312.

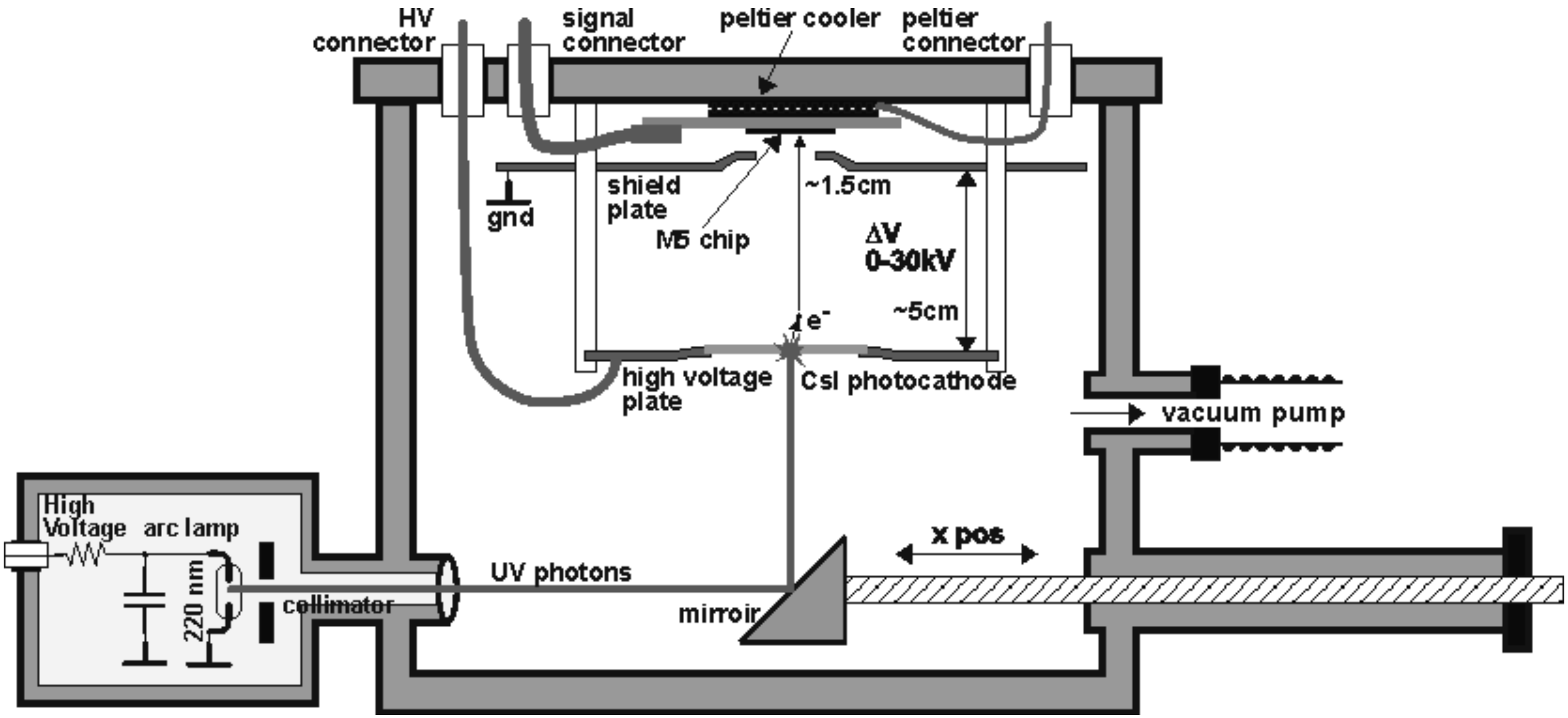
MAPS in other fields

- method for obtaining back-side sensitivity with “0” dead layer



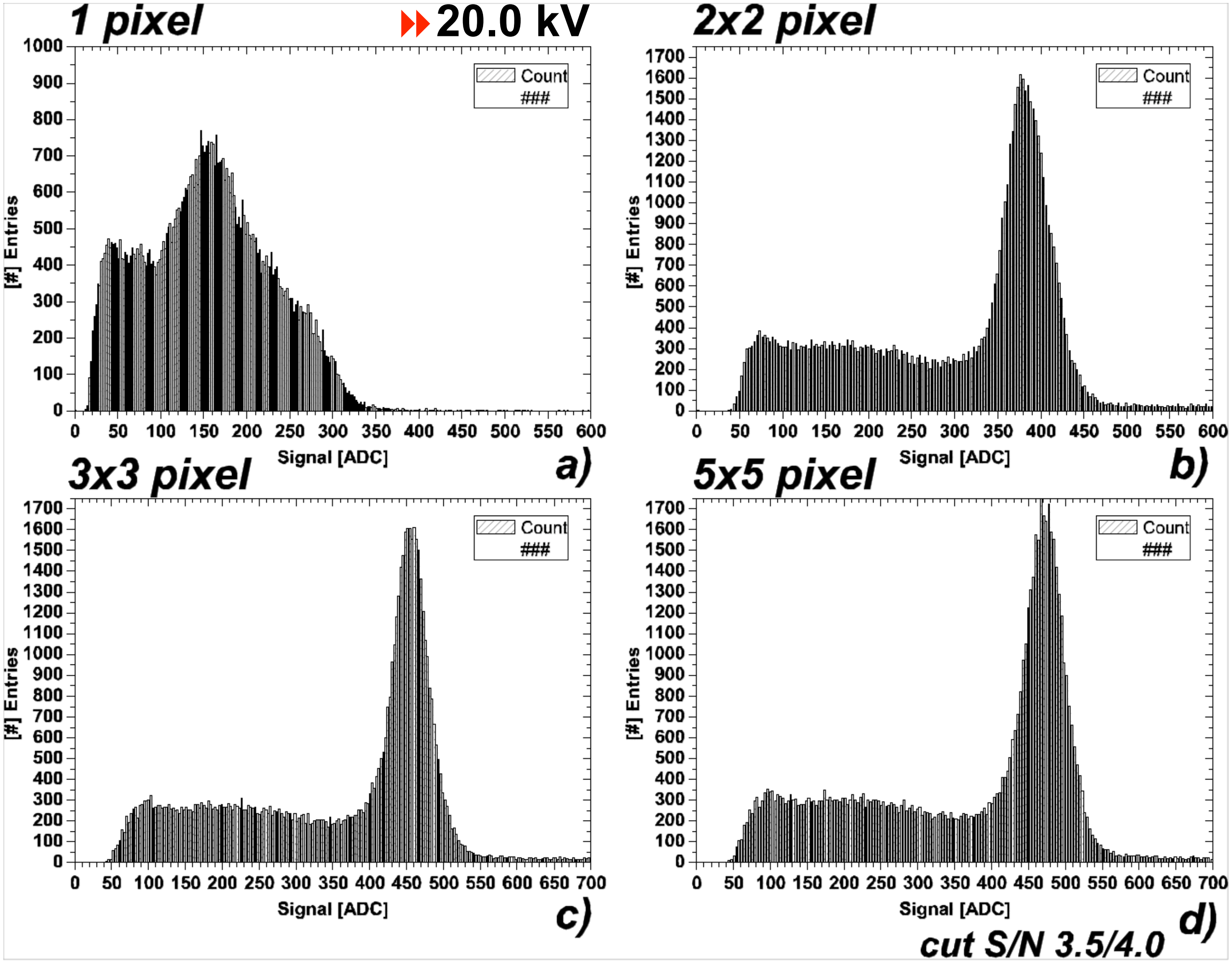
MAPS in other fields

- progenitor of single photon sensitive high resolution imager



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

MAPS in other fields



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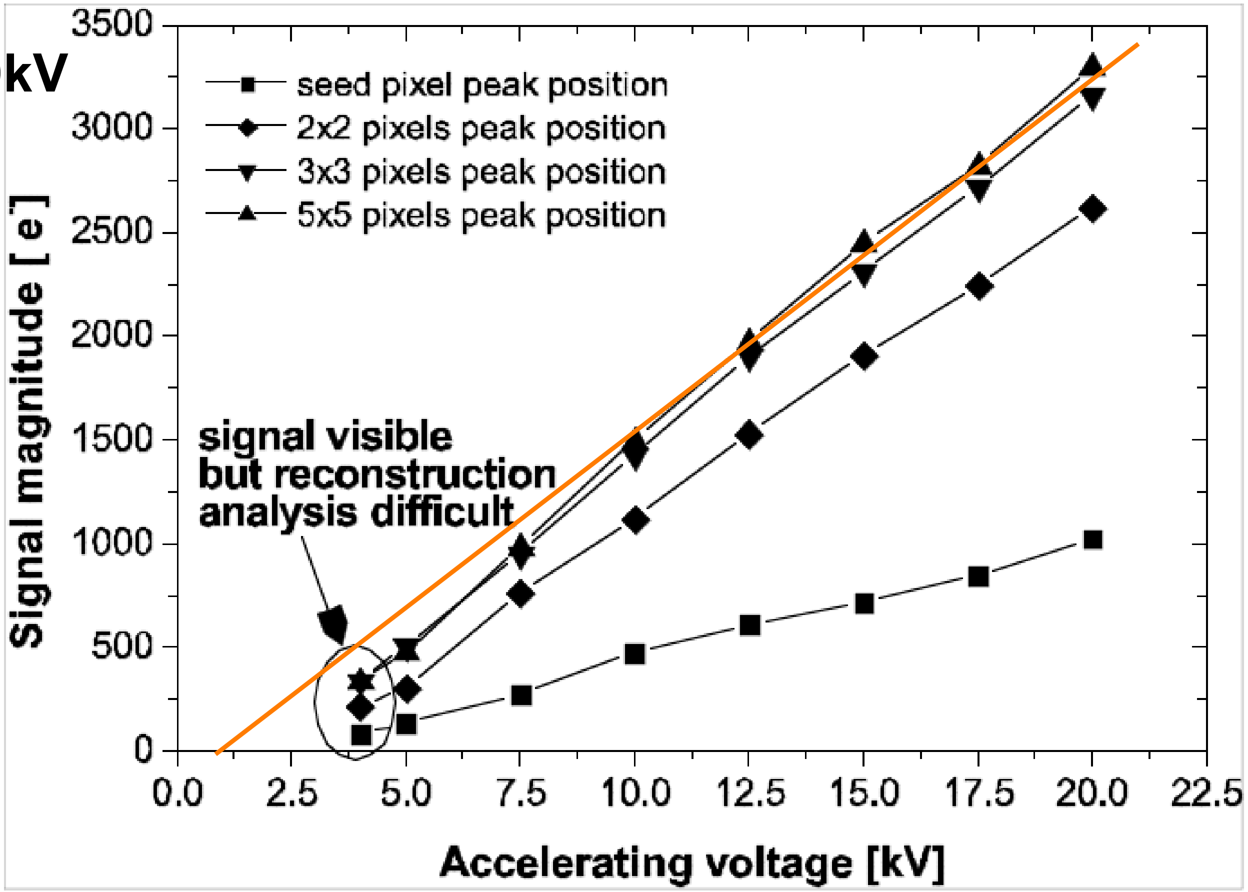
Reconstructed signal clusters

Cooling ~0°C ~60k hits

MAPS in other fields

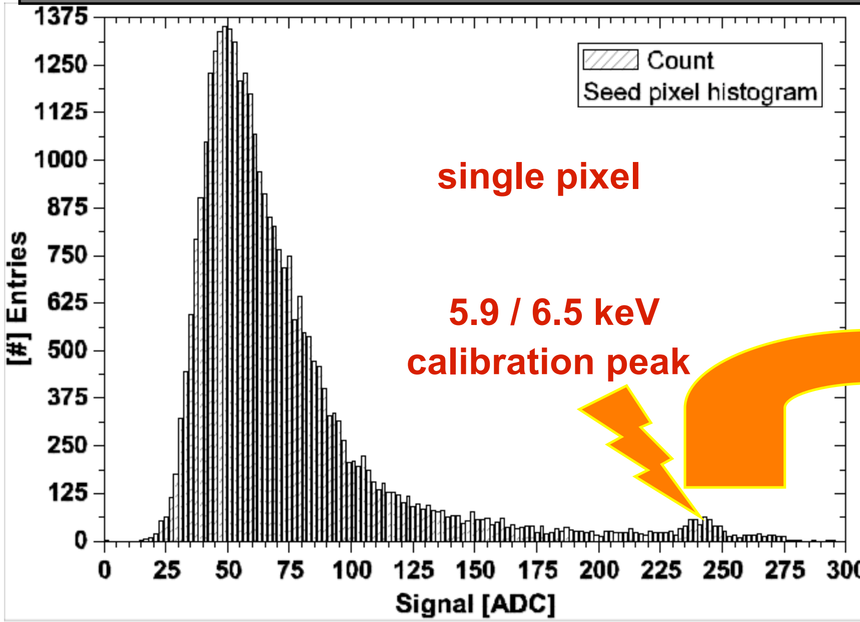
- 4kV – 20kV

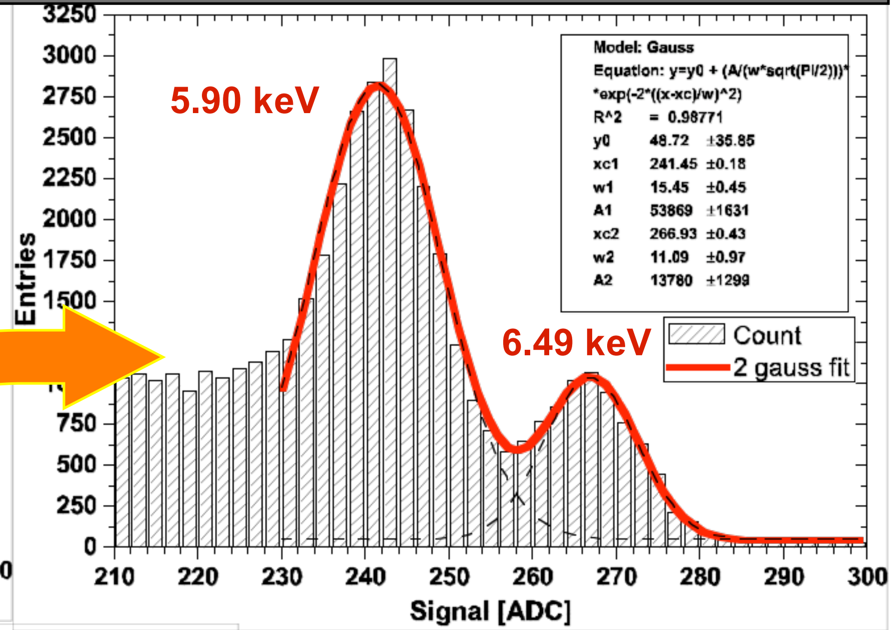


- Close to linear dependence «signal magnitude v.s. accelerating voltage» for ~10 – 20 keV;
- Despite of poor precision, result between 0.5 keV and 1 keV, when the last 4 points are taken, is in a good agreement with simulations of electron interactions in the detector.

Peak positions of signal distributions Cooling ~0°C

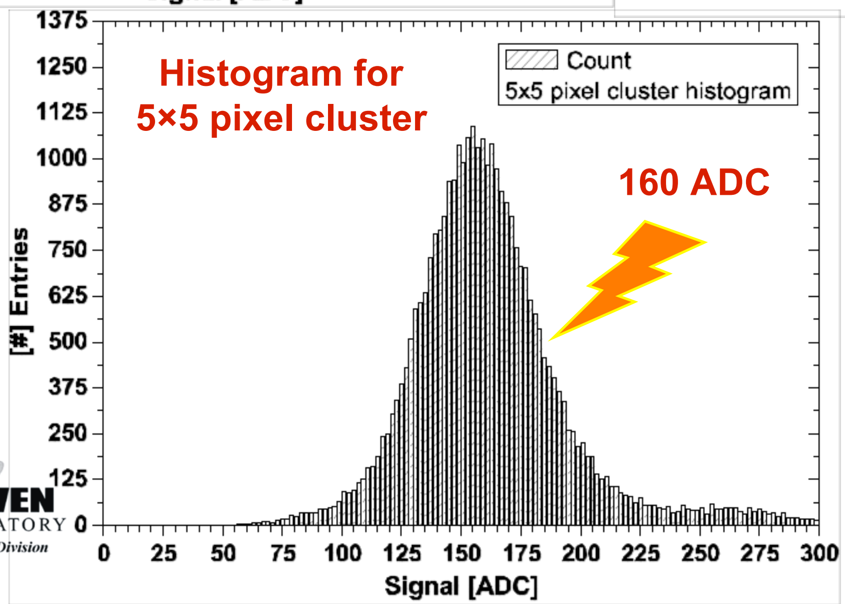
MAPS in other fields





240 ADC

⏩ ^{55}Fe



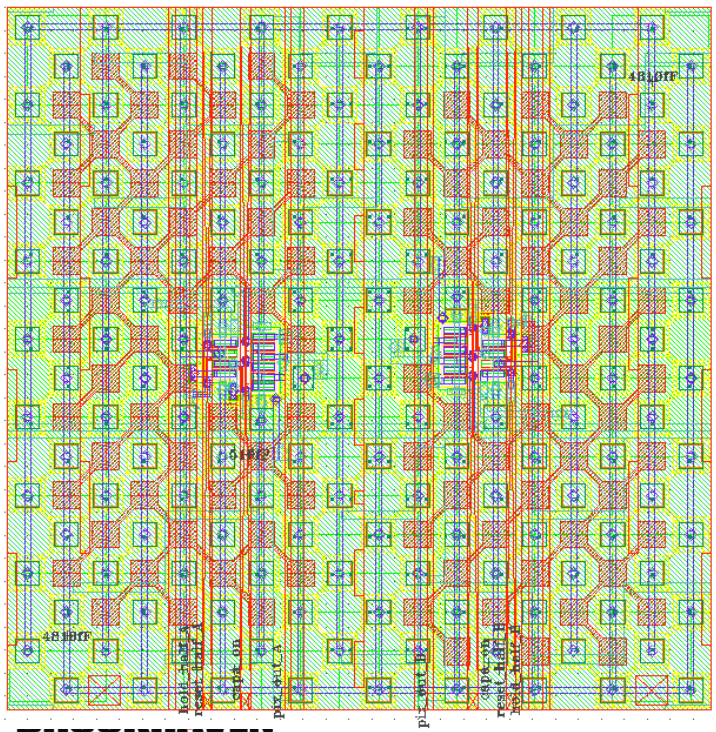
gain calibration with ^{55}Fe

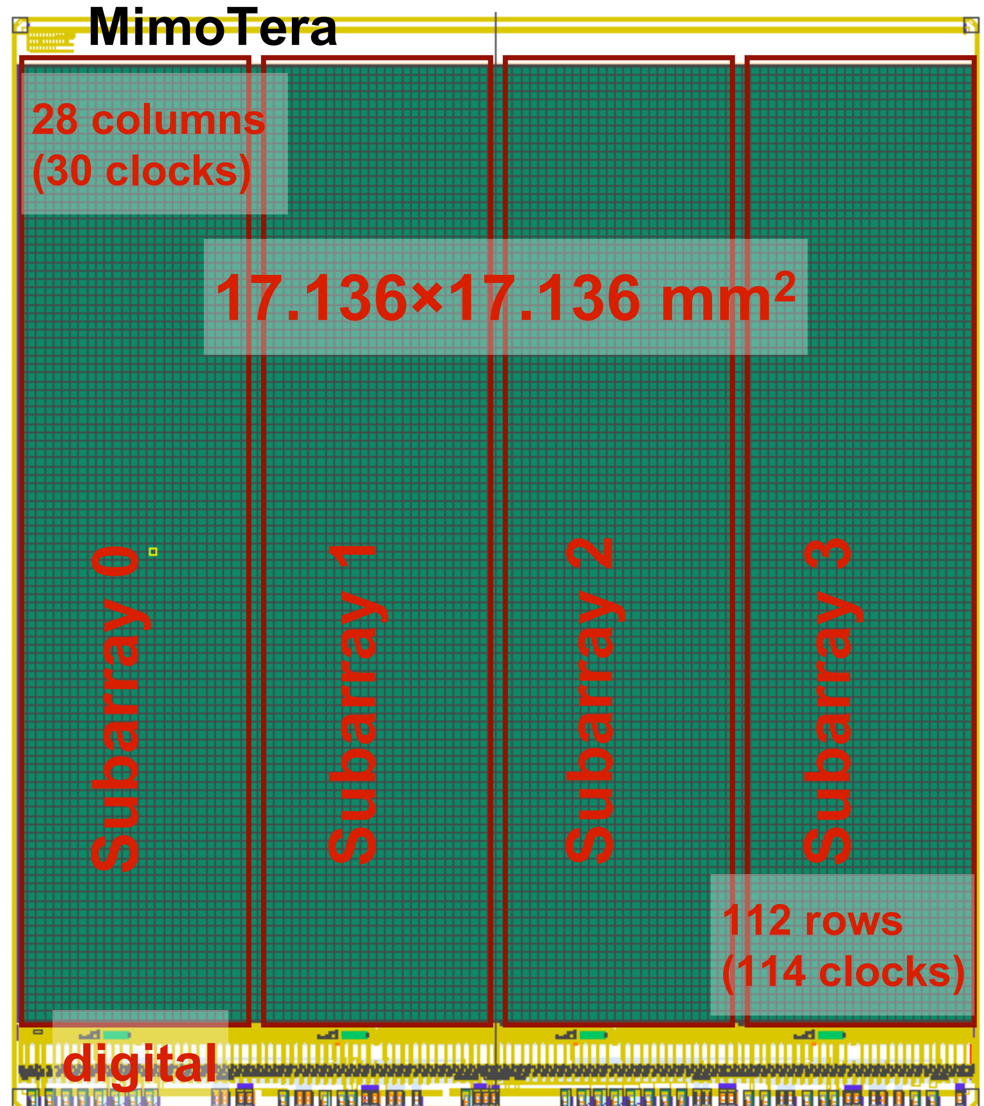
- charge in general spread among adjacent pixels,
- peak of summed signal partially approached calibration peak,

MAPS are not good spectroscopic devices…

MAPS in other fields

- example of the specific design for beam monitoring application
- AMS CUA 0.6 μm CMOS 14 μm epi,
- Chip size: 17350×19607μm^2,
- array 112×112 153×153μm^2 square pixels, each pixel – interdigited array of small n-well/p-epi diodes,





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- CVF=~250nV/e- @ 500fF; noise ~1000 e^- ⊕ 280 e^- kTC (ENC) @ 500fF,
- In-pixel storage capacitors –~0.5pF or ~5pF to cope with signal range.

MAPS in other fields

Autoradiography – Imaging of objects (biological samples or molecules) with radiotracers substituting stable isotope atom positions.

- **Beta autoradiography**
  - 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 – genomics and proteomics studies), etc.
  - X-ray film - the default imaging medium – nonlinearity, low sensitivity and long exposure times (~days to months)
  - ^{3}H betas (endpoint 18.6 keV) weakly penetrating in any detection medium – challenging for solid state detectors.
    - low cost, large surface detector for direct electron detection,
    - discrimination on beta energy (marking with two different radioactive labels at the same time),
    - as low as possible energy detection threshold a few keV e^{-},
    - efficient duty cycle with minimum dead time.

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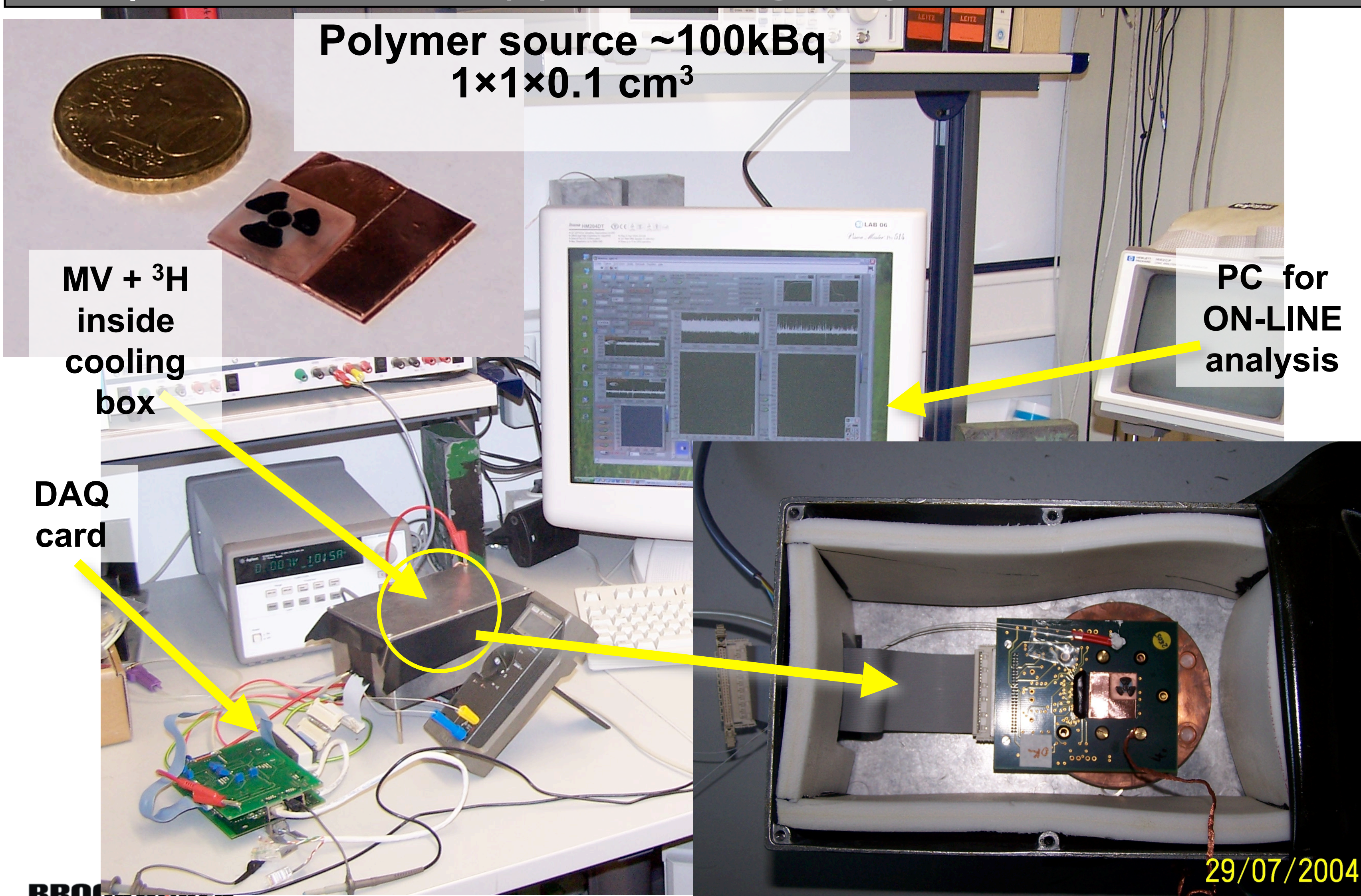
β source tests - ^{3}H(T) Autoradiography

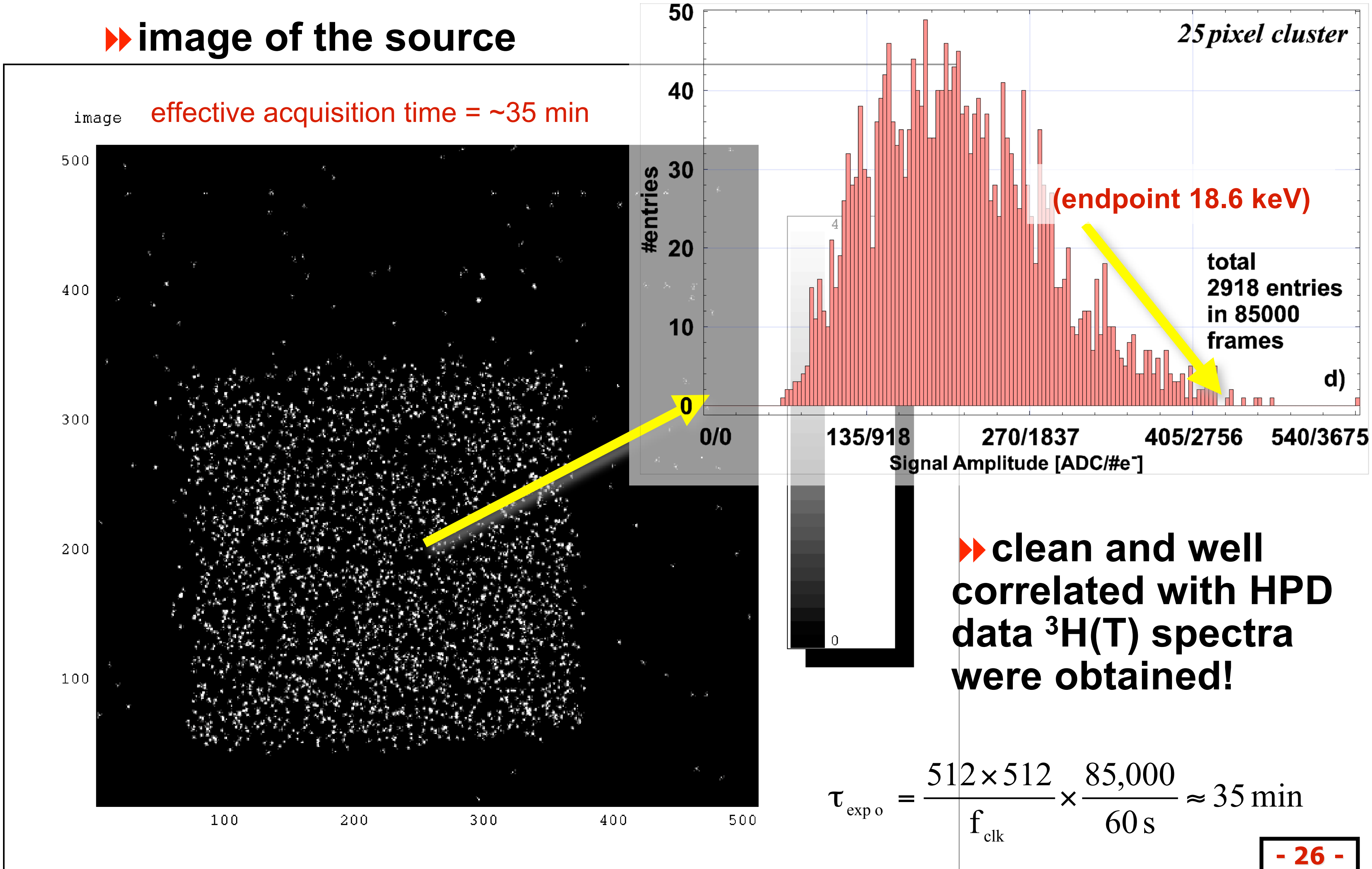


Thanks to N. Wermes and M. Trimpl from Bonn University, Germany

MAPS in other fields

image of the source

effective acquisition time = ~35 min



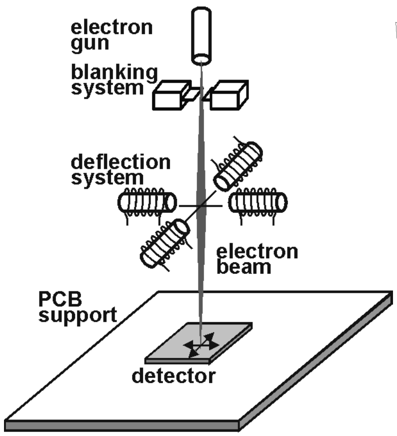
clean and well correlated with HPD data $^3H(T)$ spectra were obtained!

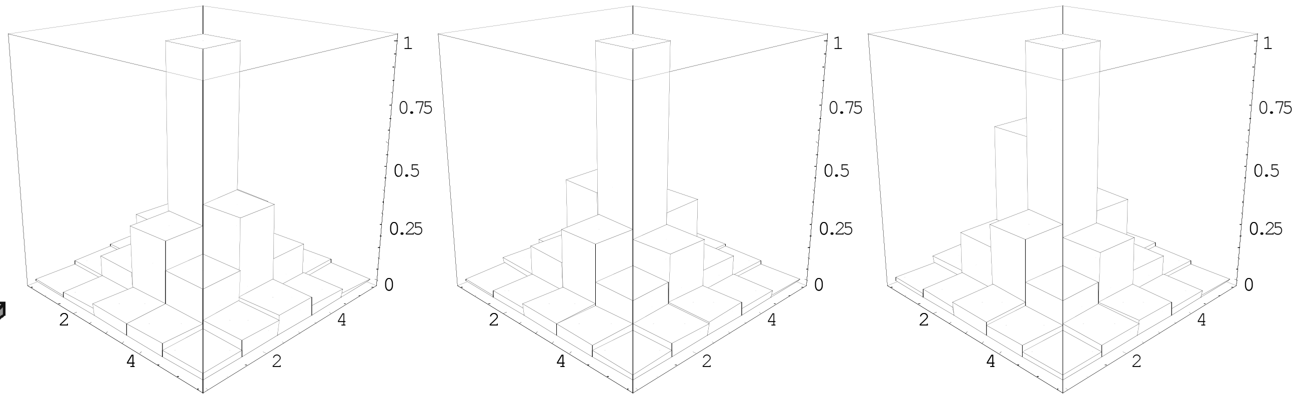
$$\tau_{expo} = \frac{512 \times 512}{f_{clk}} \times \frac{85{,}000}{60\,s} \approx 35\,min$$

MAPS in other fields — Electron microscopy

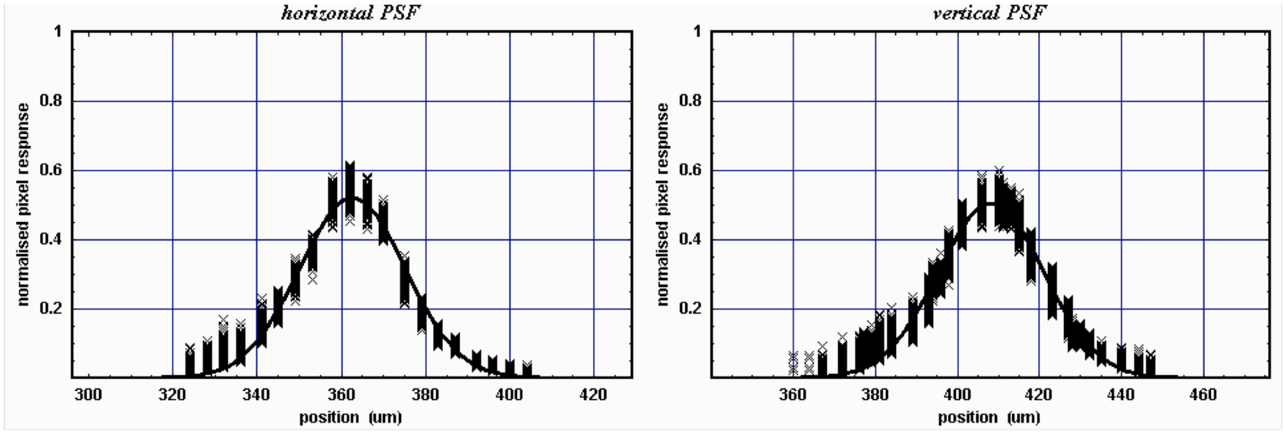
- Asserting usefulness of MAPS for imaging by direct conversion of incident energy of electrons into $e^{-}h^{+}$ pairs in silicon for future STEM and TEM.

Competitive approach to currently used image plates and scintillator coupled cameras





measurements of PSF in SEM set-up (6-30 keV electrons) on back-side illuminated MIMOSAV



Work in collaboration with
IReS, Strasbourg, France: A.Besson and M.Szelezniak

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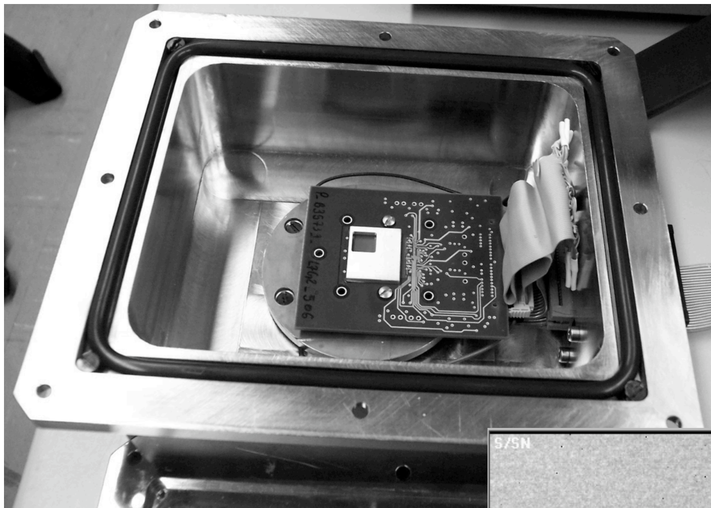
MAPS in other fields — Electron microscopy

Resolution measurements and imaging capabilities:

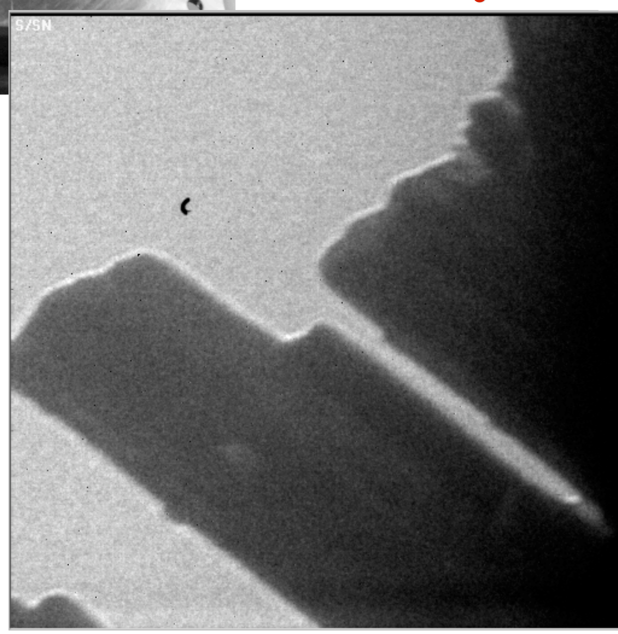


bottom vacuum flange with MAPS detector mounted inside

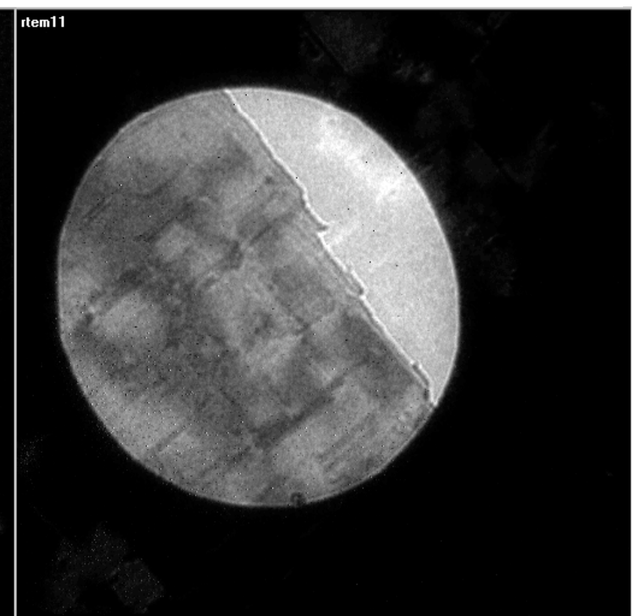
example images of flat plate crystals: good signal to noise ratio and sharp edges.

Low dose (0.1 - a few incident electron per pixel, 100-300 frames averaged).

cristal MoO_3



superconductor YBCO



JEOL 4000EX TEM in BNL Material Science Department

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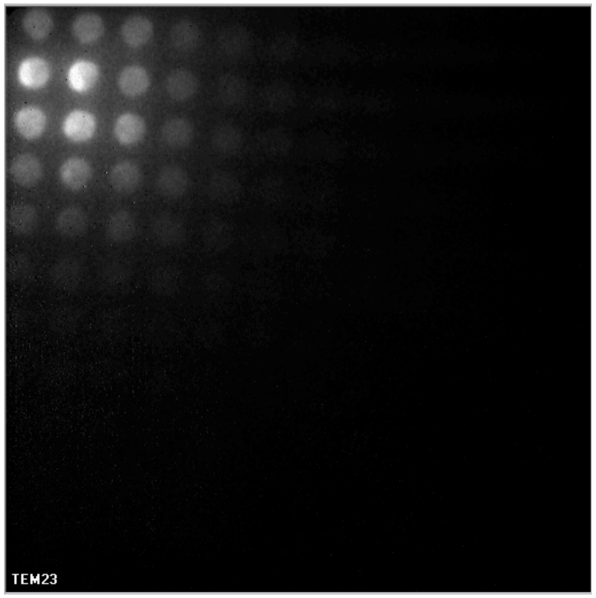
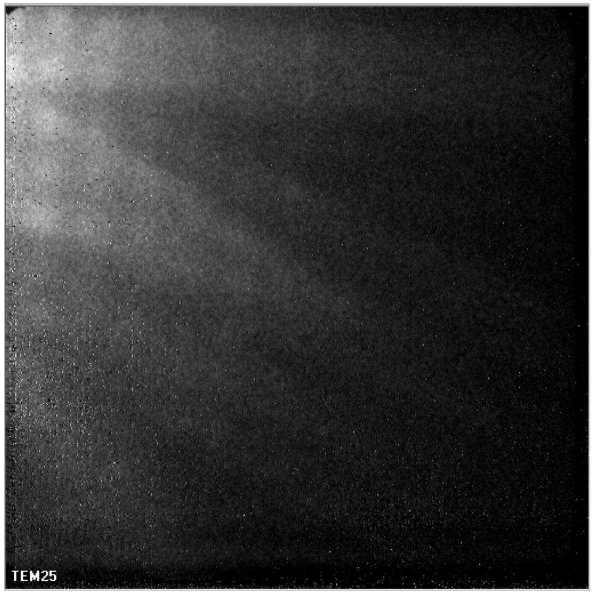
MAPS in other fields — Electron microscopy

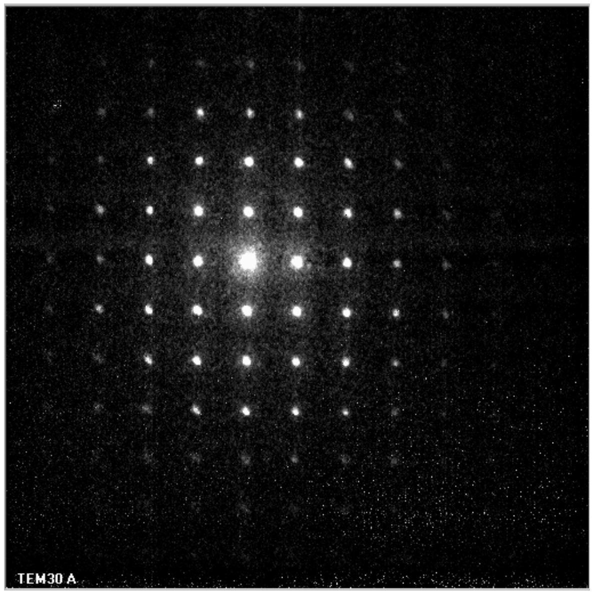
- **Diffraction patterns from JEOL 4000EX**

Low dose (0.1-1.0 incident electron per pixel, 100-300 frames averaged).

superconductor YBCO sample







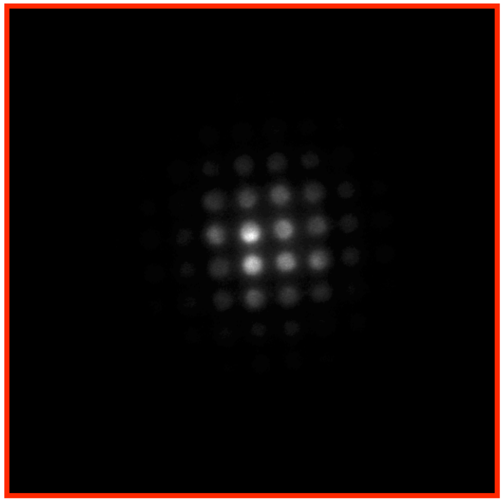


image plate reference

MAPS in other fields — Electron microscopy

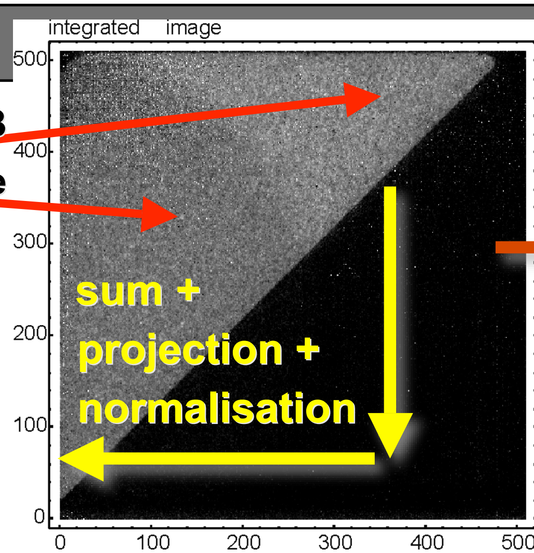
- estimation of imaging performances for front and back side illuminated MAPS

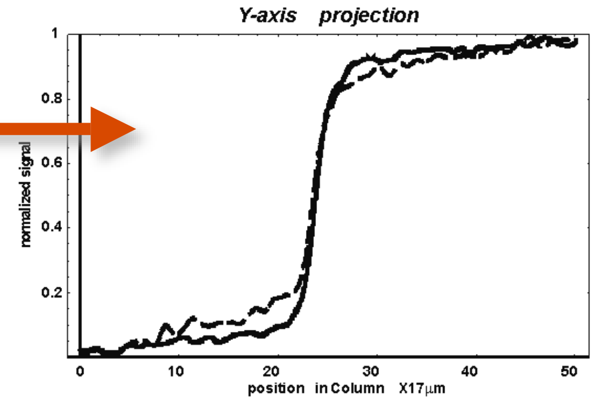
M5F: ~10µm SiO_2,15µm epi, 100 µm substrate + PCB

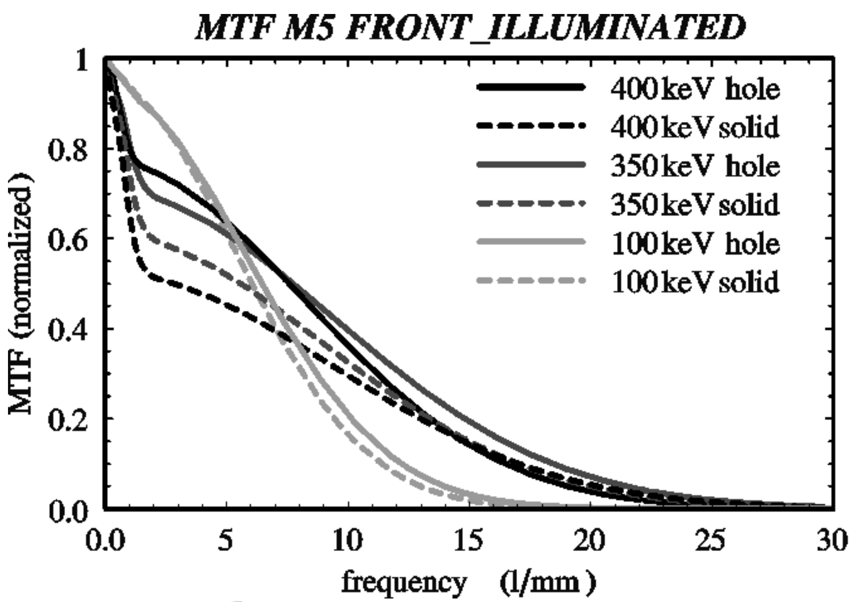
M5B: ~100nm SiO_2,15µm epi, 500µm substrate + PCB

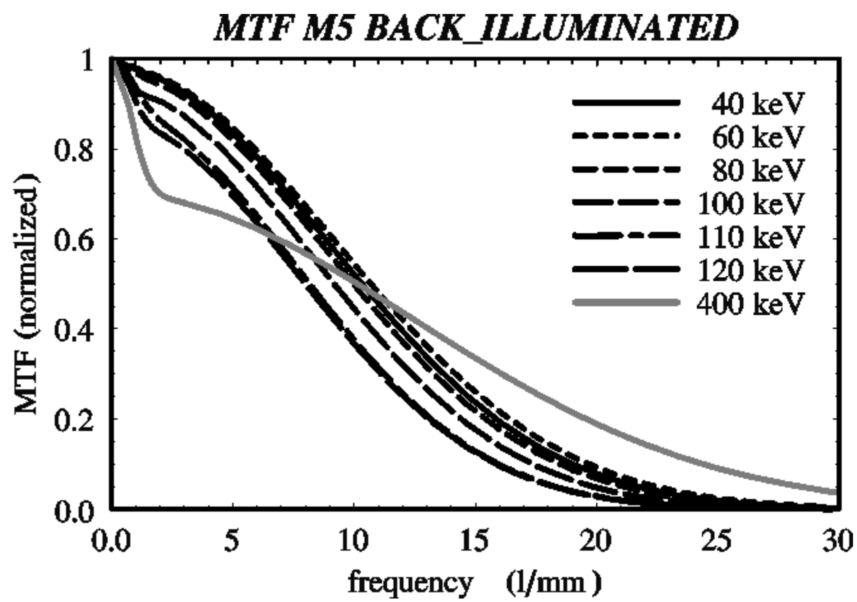
on PCB

on hole









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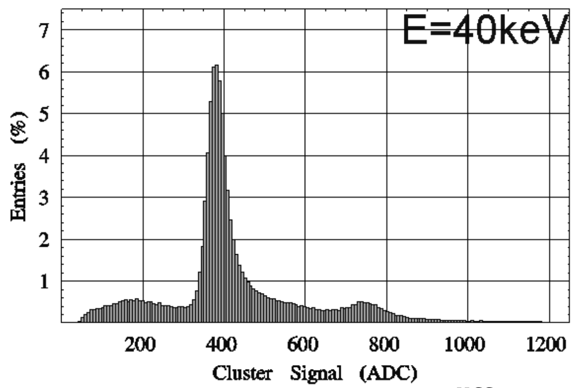
dependence on energy, strong presence of back-scattering

differences between front side and back-side illuminated device

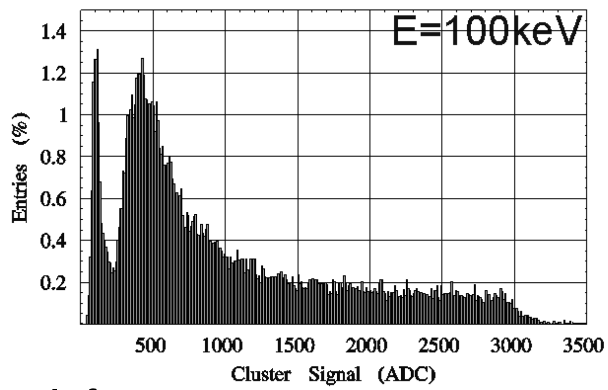
MAPS in other fields — Electron microscopy

example of electron spectra

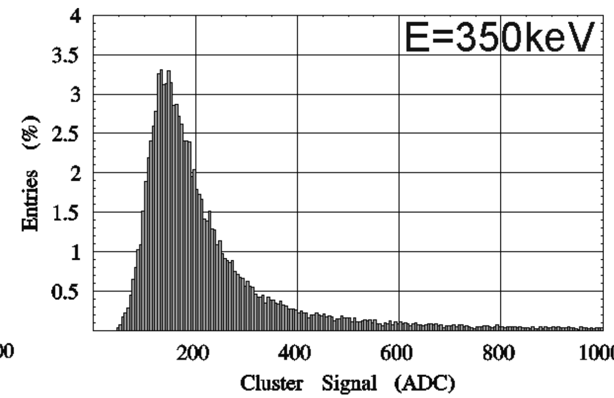


M5B

different scale for M5B and M5F



M5F



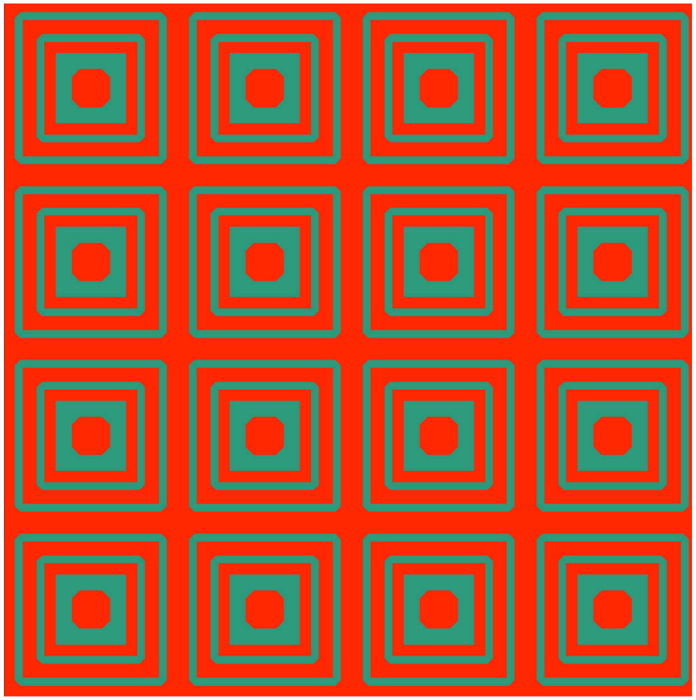
M5F

dependence of dE/dx on E_{e-} and fluctuations of total energy deposited in active layer (multiple scattering, backscattering) = additional source of noise in the images

- **signal integrating detector NOT the best choice,**
- **development of MAPS with counting in each pixel desired,**

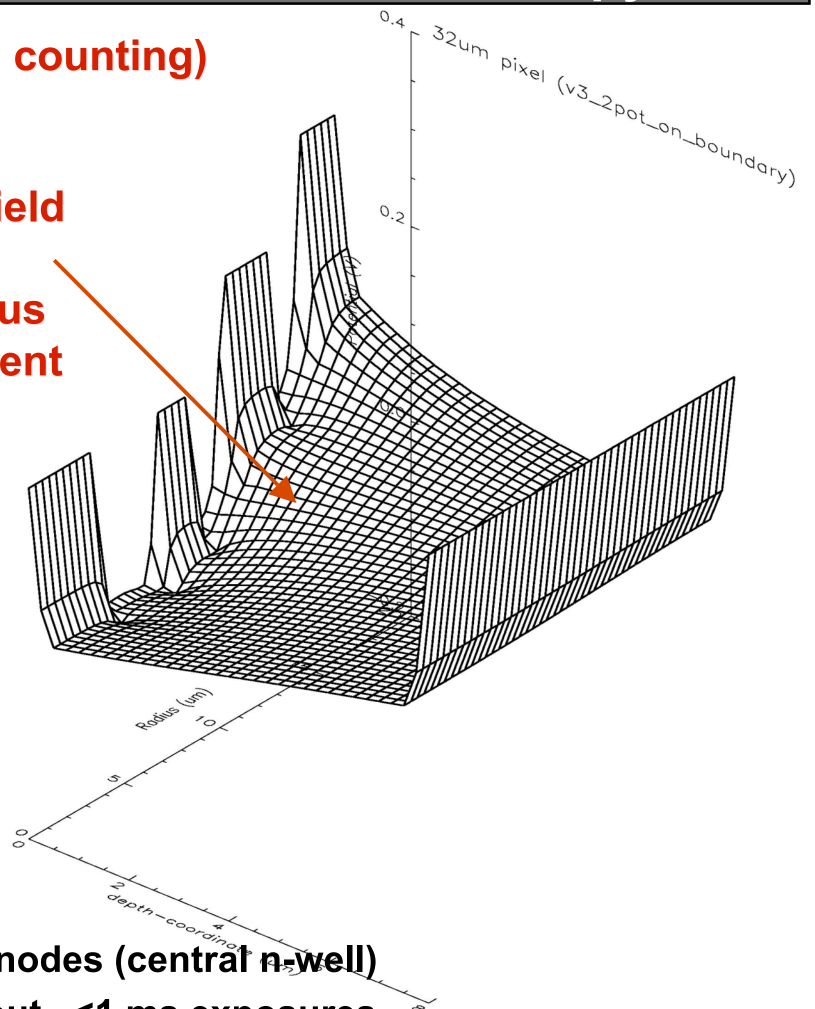
MAPS in other fields — Electron microscopy

MAPS with processing in each pixel (goal counting)



n regions: green, p region : red, ex. 16 pixels

electric field from continuous hole current



unidepleted detector design P.Rehak BNL

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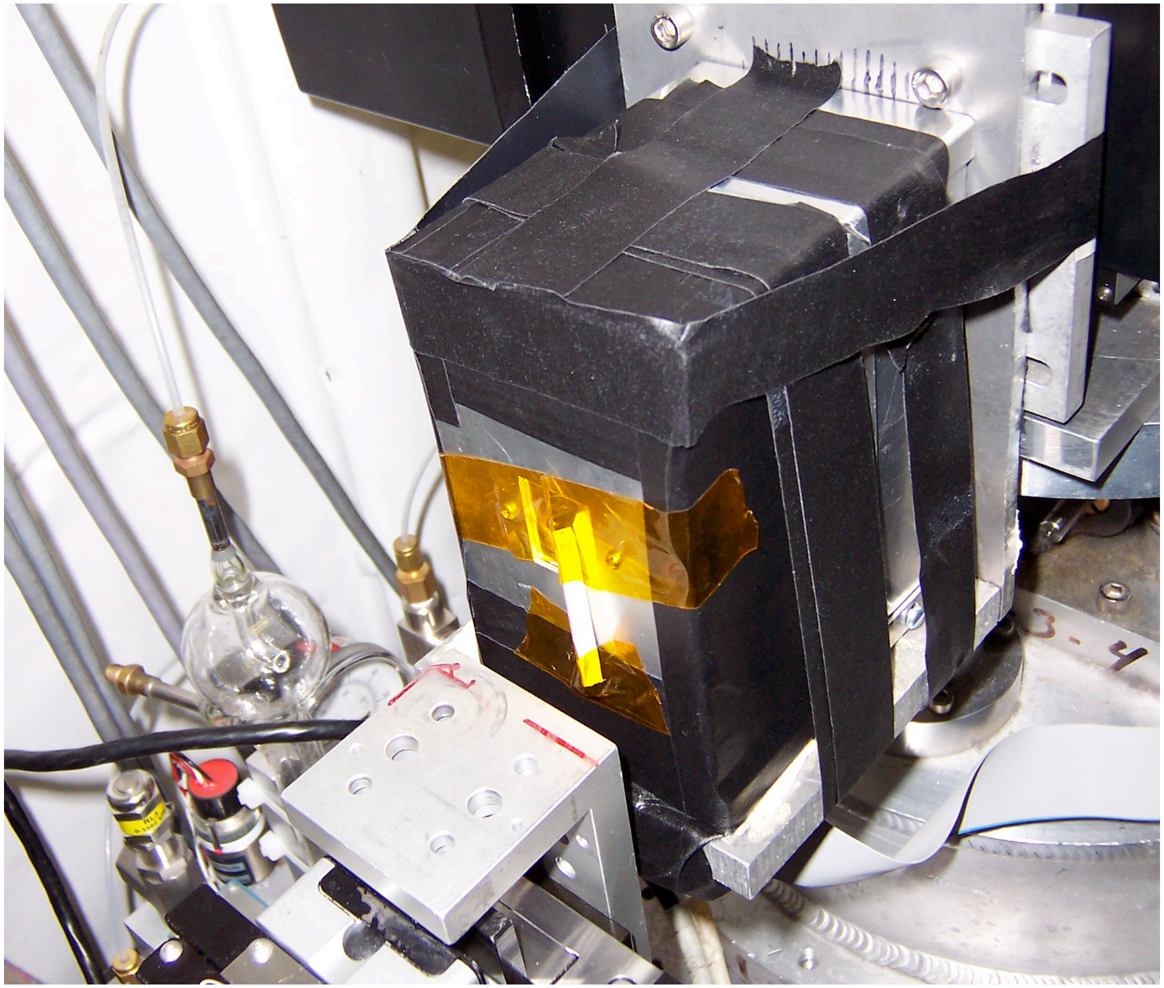
- Full CMOS in each pixel,
- Signal electrons collected by anodes (central n-well)
- Direct exposure, Parallel readout, <1 ms exposures,
- Sensor array : 1k×1k,
- Integration of 16-20 bit counters within each pixel for high dynamic range and virtually noiseless operation,

MAPS in other fields — Tests in NSLS

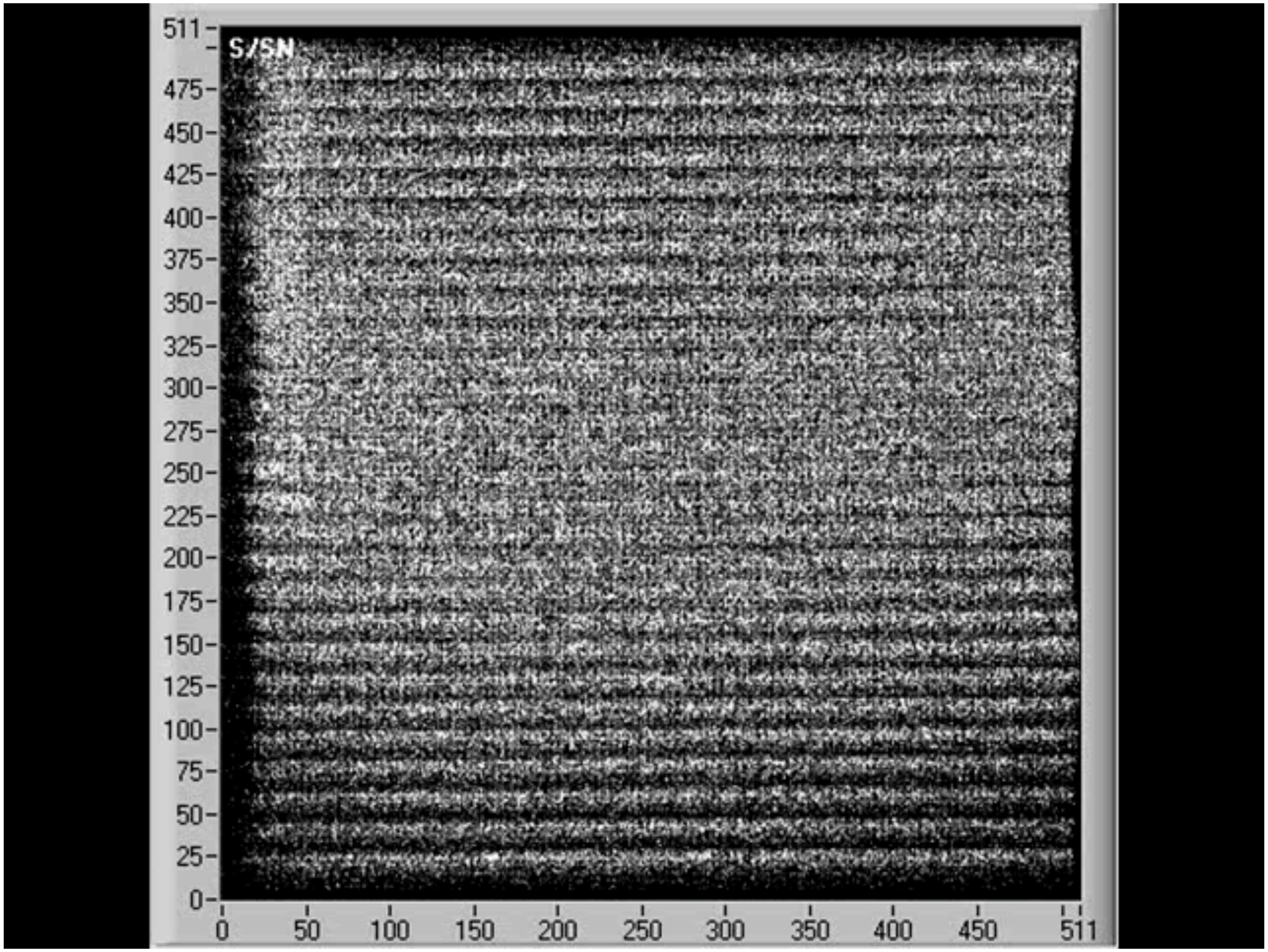
- Back-side illuminated MIMOSA5 MAPS enclosed in aluminum box with mylar window,
- Sample mounted in front of the detector,
- Ensemble mounted on X-Y-Z stage allowing scanning with beam,
- scanning surface ~ 400 µm × 1 cm,
- E= from 5 keV to 12 keV,
- Multiple frames taken due to limited signal swing of pixel



Work in collaboration with IReS, Strasbourg, France: A.Besson and M.Szelezniak

MAPS in other fields — Tests in NSLS

Beam X12A



Example of speciments: bone segment with Ti implant, chityne shell insect,

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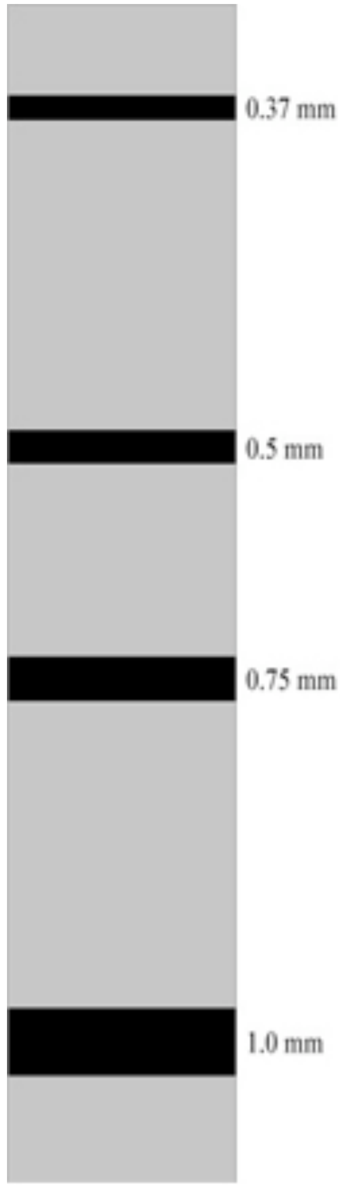
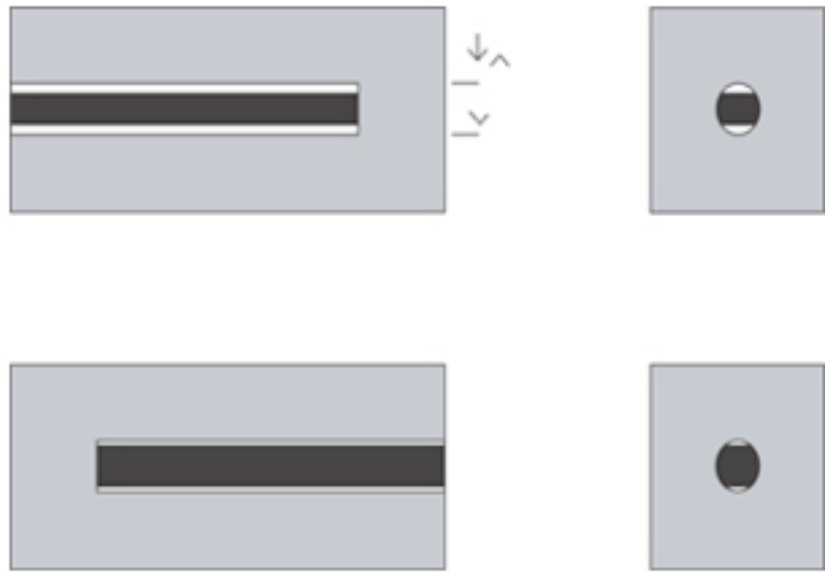
Grzegorz DEPTUCH

MAPS in other fields — Tests in NSLS

- Bone sample with Ti implant





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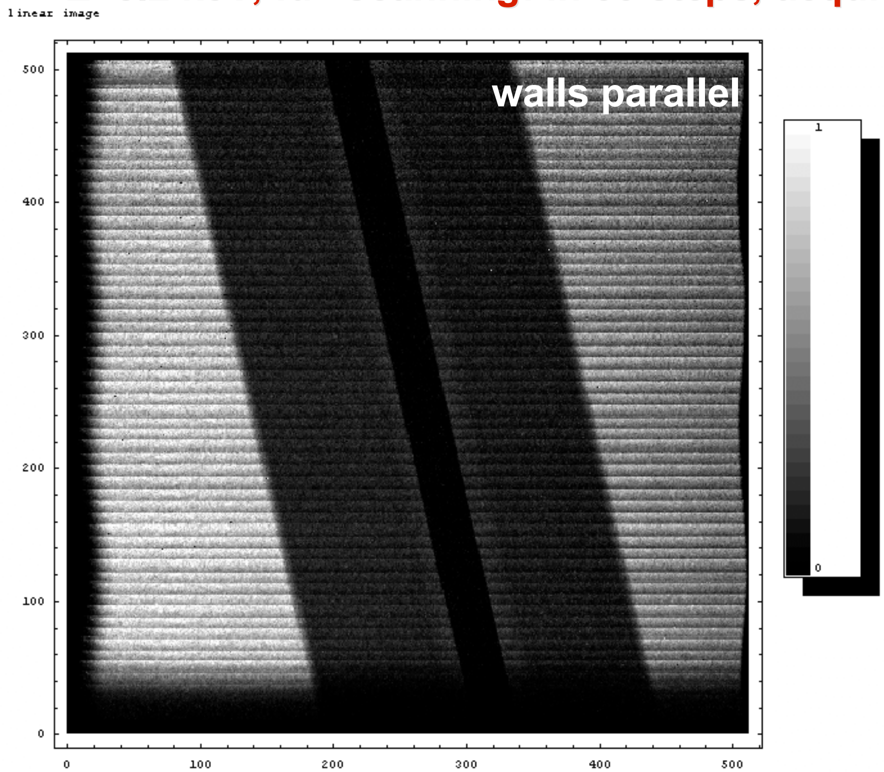
MAPS in other fields — Tests in NSLS

- Bone sample with Ti implant

E=8.2 keV, full scanning: in 55 steps, acquisition: 12 frames / single scan line



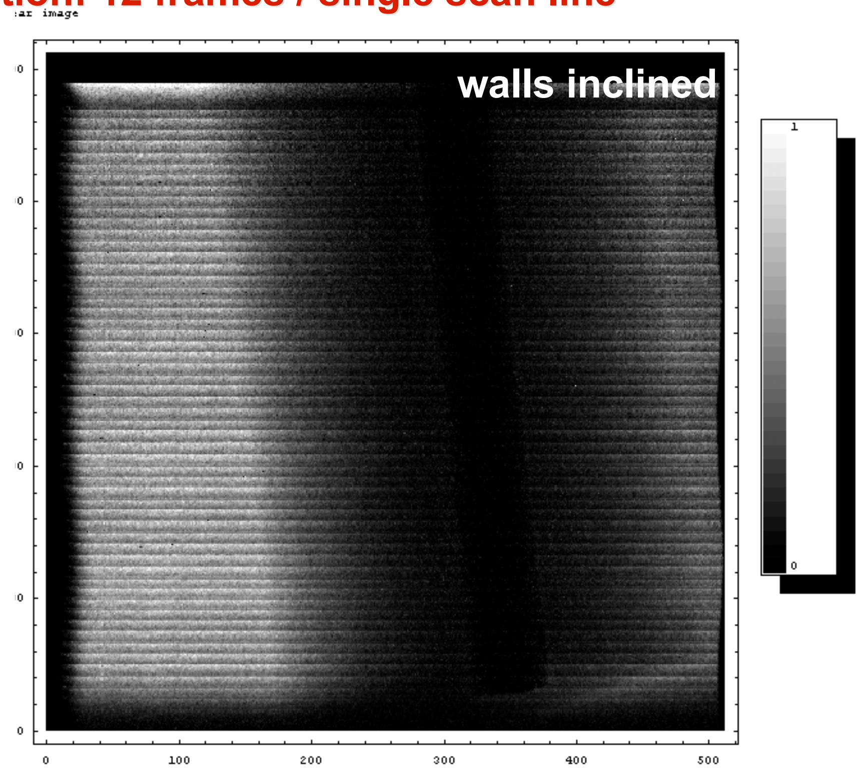


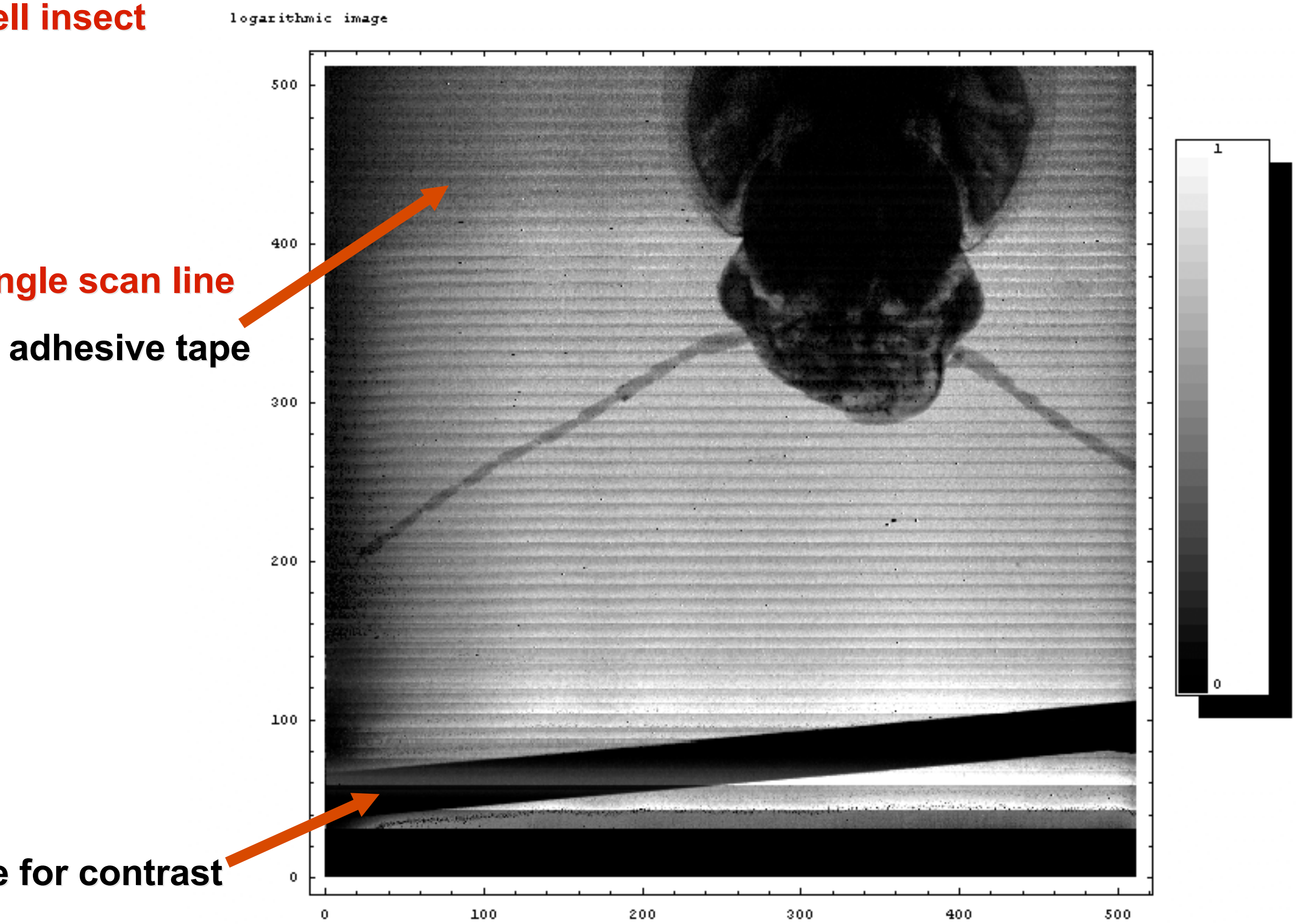
Image distortions:

- non uniform stepping of the Z – coordinate motor, lateral displacement of the table,

MAPS in other fields — Tests in NSLS

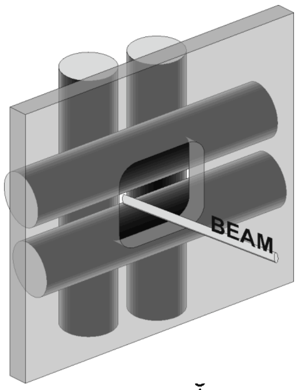
- chityne shell insect

E=5.2 keV,
full scanning:
55 steps,
acquisition:
22 frames / single scan line

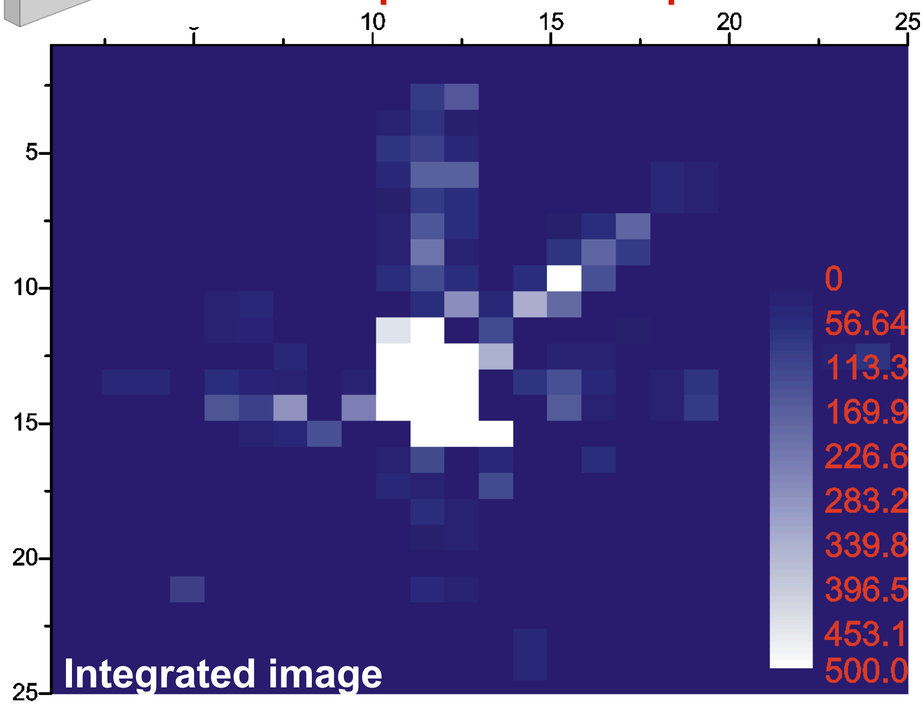


MAPS in other fields

Tests in NSLS

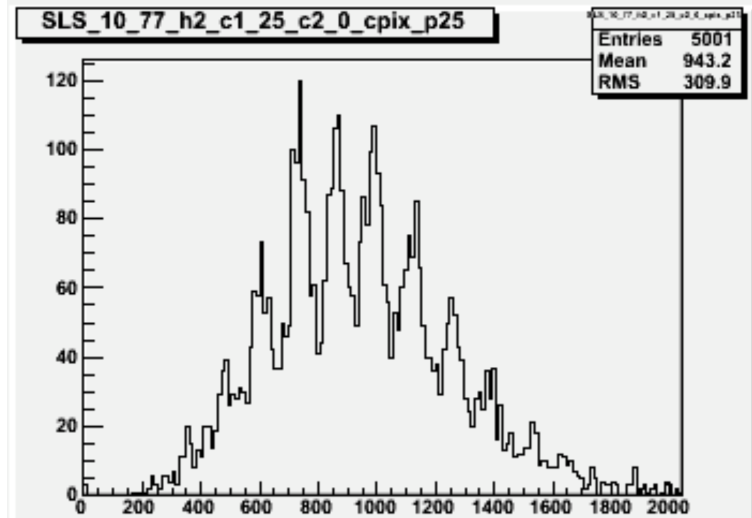


- Spectra of single photons
E=12 keV ,
collimated beam 10 µm,
intensity tuned to yield ~10 photons/frame,
acquisition 25×25 pixels

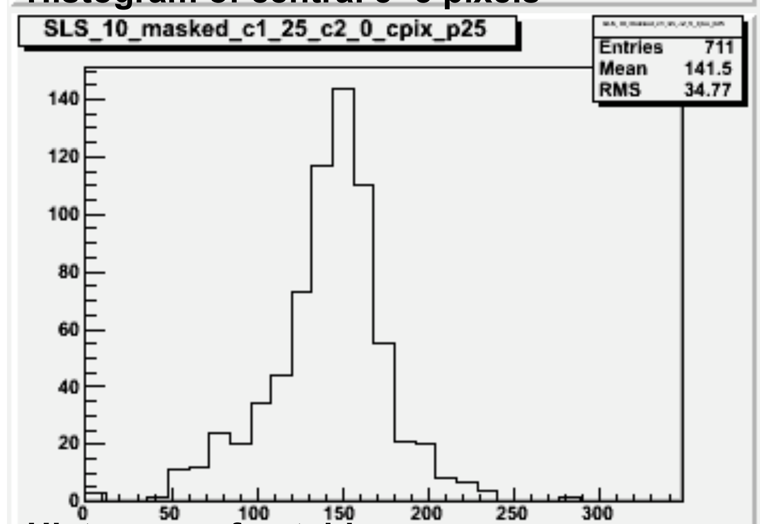


Integrated image

cut1=25



Histogram of central 5×5 pixels



Histogram of outside

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MAPS in other fields

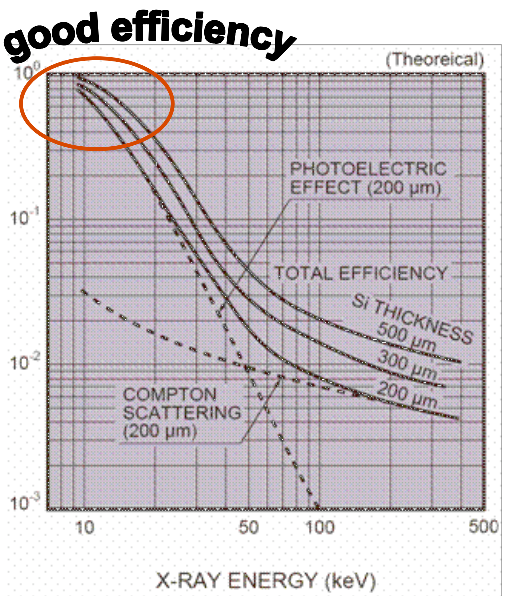
Proposal of novel structure XMAPS

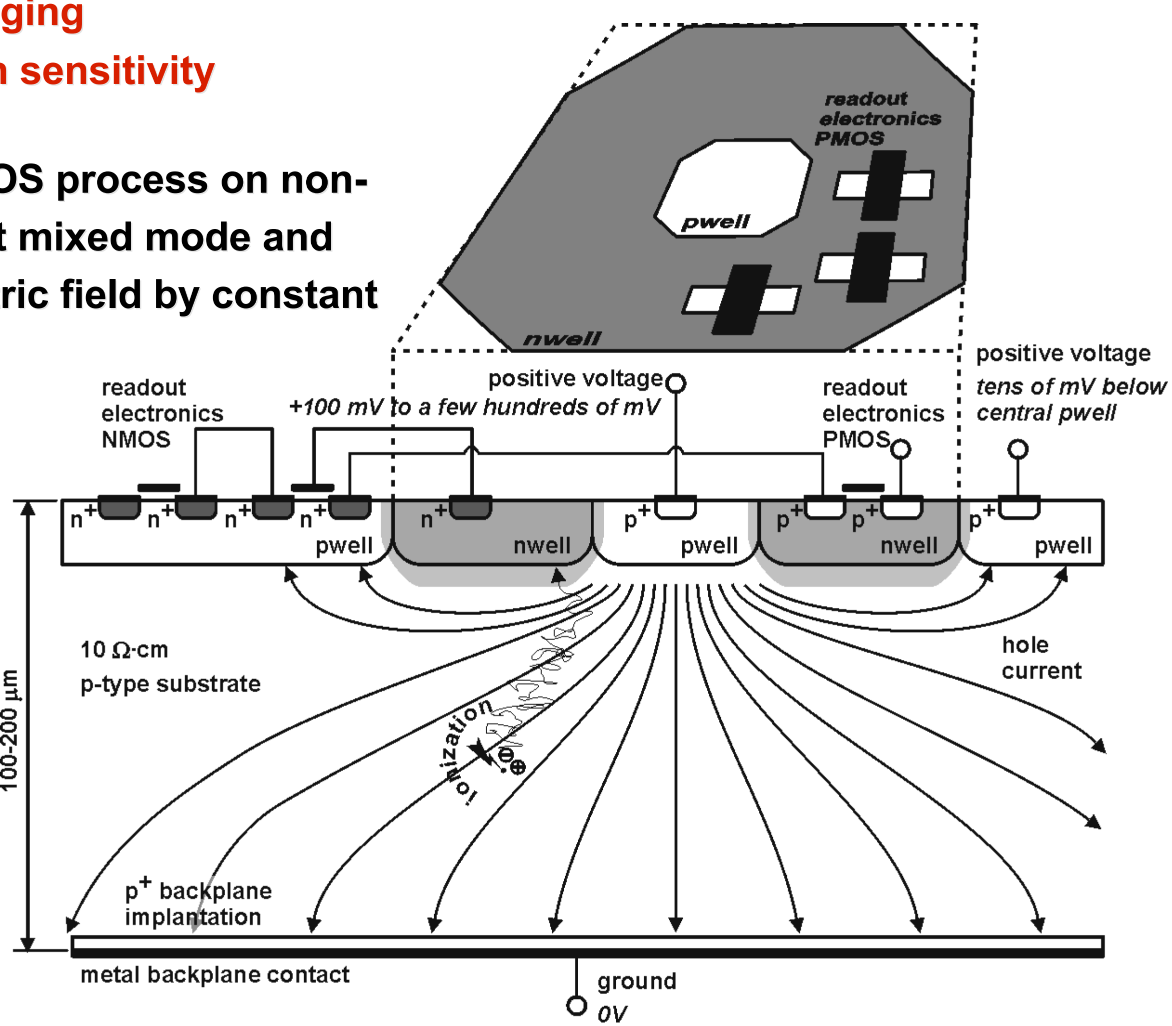
- soft (≤10 keV) X-rays imaging

high spatial resolution, high sensitivity

low cost

Use of standard CMOS process on non-epitaxial wafer (most mixed mode and RF processes), electric field by constant hole current





Proposal of novel structure XMAPS

- **Electric field to: speed up charge collection,**
  increase effective thickness of active volume,
  confine charge in less pixels – improve spatial resolution

electric field, allowing electrons drifting towards N-WELL electrodes, created by constant hole current from substrate to P-WELL electrodes in the middle of NWELL islands

- **brief fordesign *(example):***

classical MAPS: $\tau_{col} = 100\ ns$ and 90% of charge in 3?3 20 µm pixels $\sigma_{charge} \approx 17\ \mu m\,(1.65\sigma)$

planned detector: thickness: $d = 100\ \mu m$; resistivity: $\rho = 10\,\Omega \cdot cm \propto 1/\mu_n$;

e⁻ mob.: $\mu_n = 1100\,cm^2/V \cdot s$ @ 300K; drift vel.: $v_d = \mu_n E$; col. time: $\tau_{col} = d/v_d$

lateral spread during collection time: $\sigma_{lat} = \sqrt{2 \cdot D_n \cdot \tau_{col}} = \sqrt{2\left(\frac{kT}{q}\right)\mu_n \cdot \tau_{col}} = \sqrt{2(\frac{kT}{q}) \cdot \frac{d}{E}}$

1) **assuming** $\sigma_{lat} = 17\ \mu m$ @ 300 K $\Rightarrow \tau_{col} \approx 50\,ns$;

$v_d = 190 \times 10^3\ cm/s$; $E = 172\,V/cm \Rightarrow V = 1.72\,V$ & $I = V / \left(\rho \frac{d}{S = 1\,cm^2}\right) = 11.7\ A/cm^2$

2) **allowing** σ_{lat} 2.5 times wider, $\tau_{col} \approx 330\,ns \Rightarrow V = 0.27\,V$ & $I = V / \left(\rho \frac{d}{S = 1\,cm^2}\right) = 2.7\ A/cm^2$

and power density drops to **0.73 W/cm²** for 100 µm thick detector

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- **is it doable? discuss with foundy on higher ρ wafers!**

What to do?

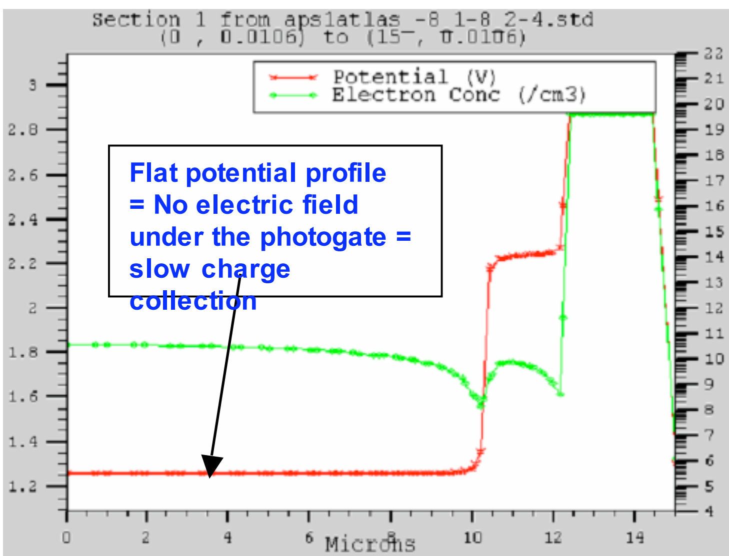
Work on readout and processing circuitry

tailor readout circuitry to the application, analog vs digital processing, sparsification, ability of counting single impacts, optimise data transfer (bottle neck - can be GB/s if big number of pixels)...

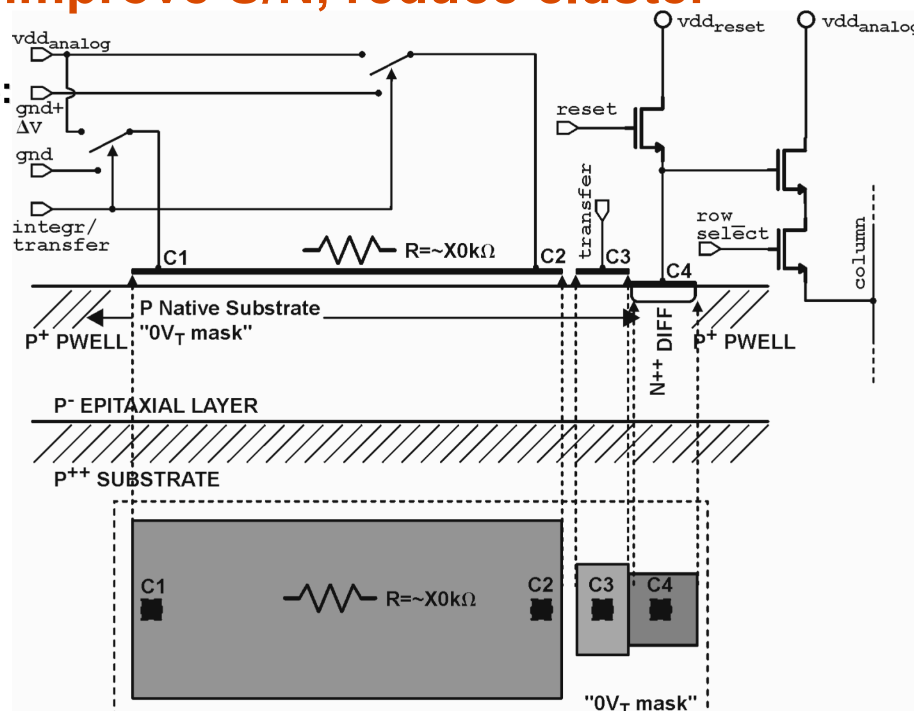
a lot of opprtunities given by CMOS power... but also a lot of work if working with single impacts (S/N)

Work on pixel architecture to improve S/N, reduce cluster extension…

original photogate:



new photogate:



Conclusions

- **MAPS offer a flexible solution for some applications aiming at detection of ionizing radiation:**
  - direct charged particle tracking (oustanding spatial precision),
  - direct imaging by signal integration (ionizing radiation – limitation to soft X-rays),
  - indirect imaging by coupling to scintillators (X-rays) or converters (neutrons),
  - single photon detection (electron-bombarded CMOS),

- **MAPS offer radiation hard solution**
  (harder for example CCDs)
  (moderate doses: X Mrads and 10^{12}n/cm^2),
  highly granular <10μm pixel
  (more granular than hybrid pixels)

- **MAPS do not have to be read in a raster mode – random access available**

- **MAPS offer a cost effective solution for SoC detector systems**

- **MAPS R&D in the world for non commercial applications - dozen of labs involved**