Développements de pixels CMOS à l'IPHC : détection alpha, beta, ions & X-rays

Journées thématiques du Réseau Semi-conducteurs - Les détecteurs à pixels
Grenoble, 31 mai – 1er juin 2018

→ Depleted CMOS pixel sensors

→ Application to X-rays

→ Application to charged particles

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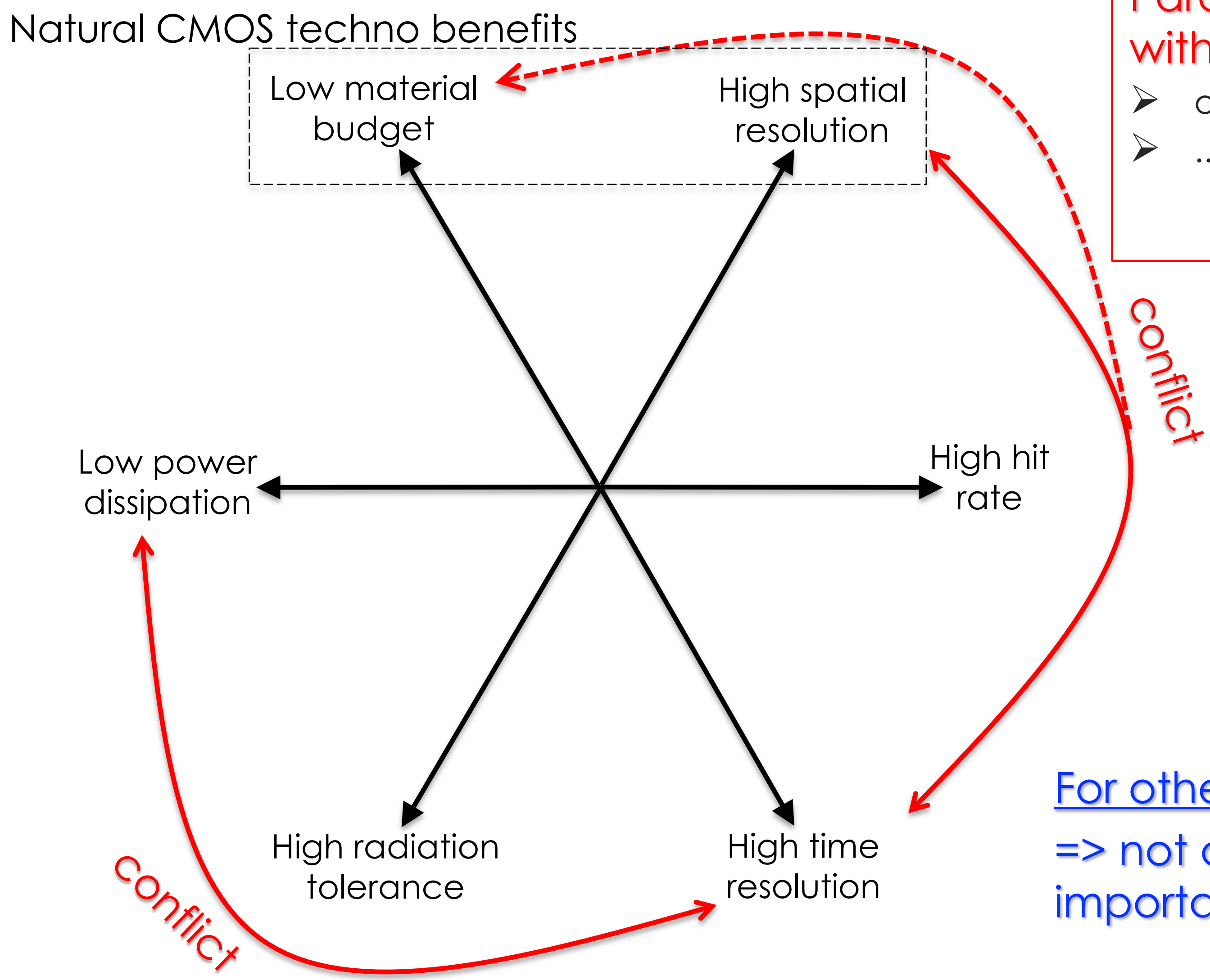
Université de Strasbourg

Requirements from tracking/vertexing



Parameters correlated within one technology

- optimisation required…
- …or going to 3D

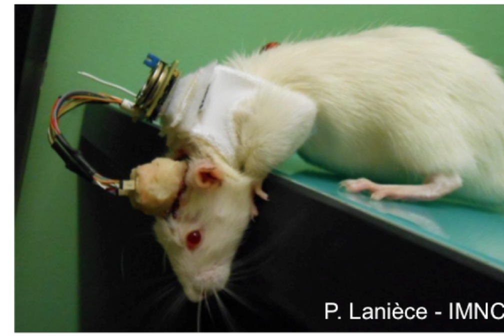
For other applications

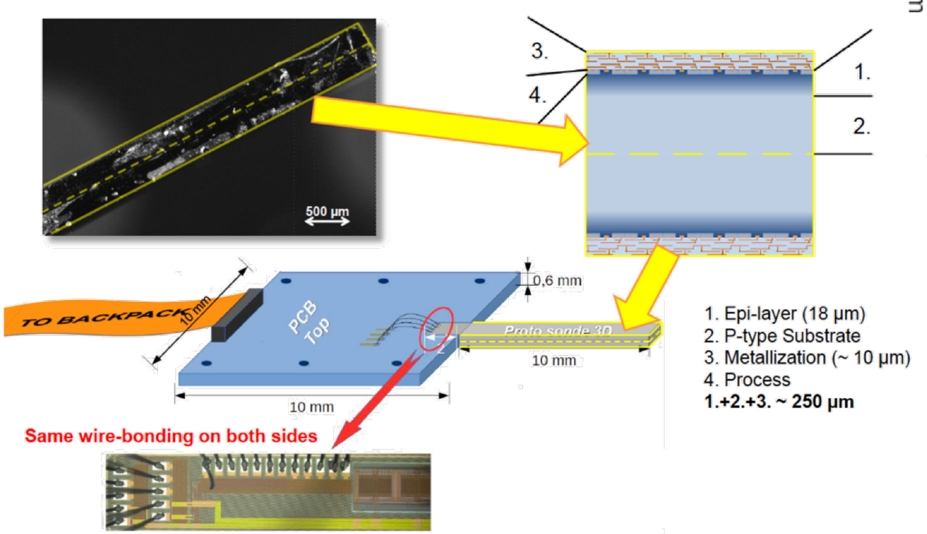
=> not all requirements important

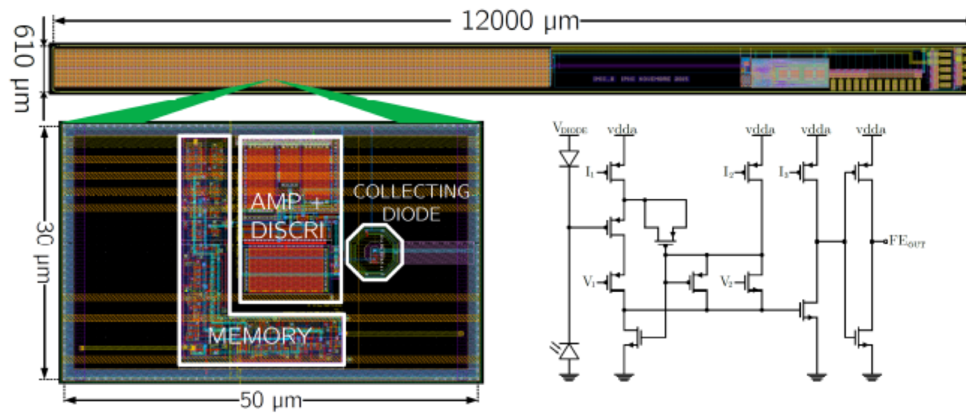
Charged particles dosimetry

Molecular imaging with β+ emitters in moving rodent

- MAPSSIC: extreme integration in specific environment
  - Constraint on size and power dissipation
  - **IMNC, IPHC, CPPM, CERMEP, NeuroPSi**
- Exploit CMOS sensors derived from ALICE
  - One active probe = 160 μW
  - For few counts / s
- Wireless connection from μControler





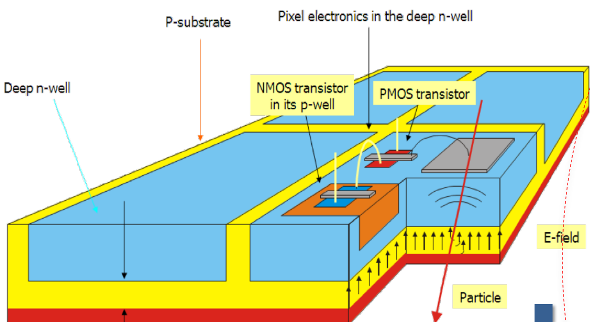


probe in the brain :
- section ~500x500 μm²
- sensitive volume (18 um) immune to γ
- first prototypes under test

Three ways to deplete MAPS

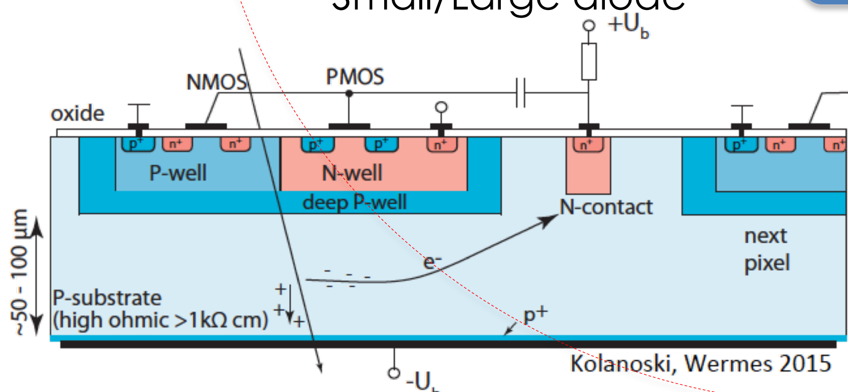
Depletion depth $\propto (V_{bias} \times \rho)^{\alpha}$ with $\alpha \lesssim 1/2$

- <u>High Voltage</u>
  - Large diode



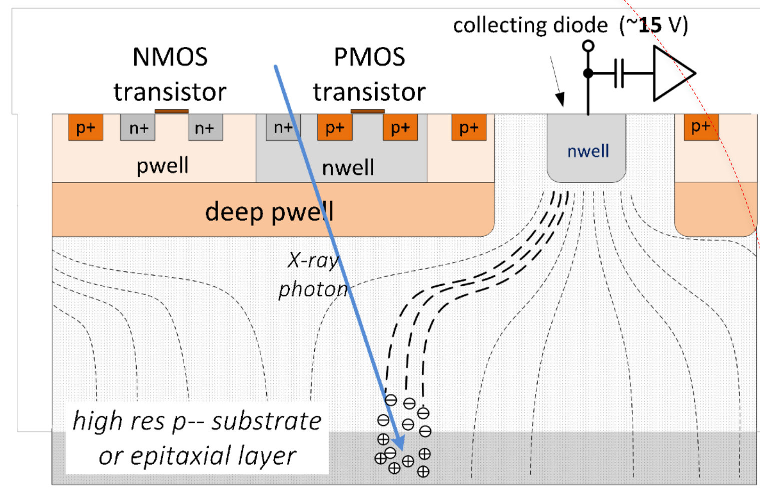
I.Pieric 2010

- <u>High Resistivity</u>
  - Back biasing
  - Small/Large diode



Kolanoski, Wermes 2015

- <u>High Resistivity</u>
  - Top biasing
  - Small diode



M.Kachel 2013

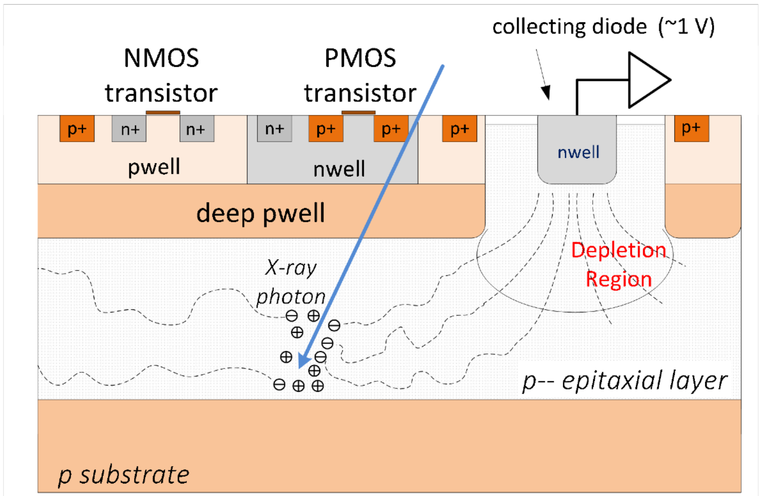
Target small pixels

! All with multiple wells CMOS process

Studied at IPHC

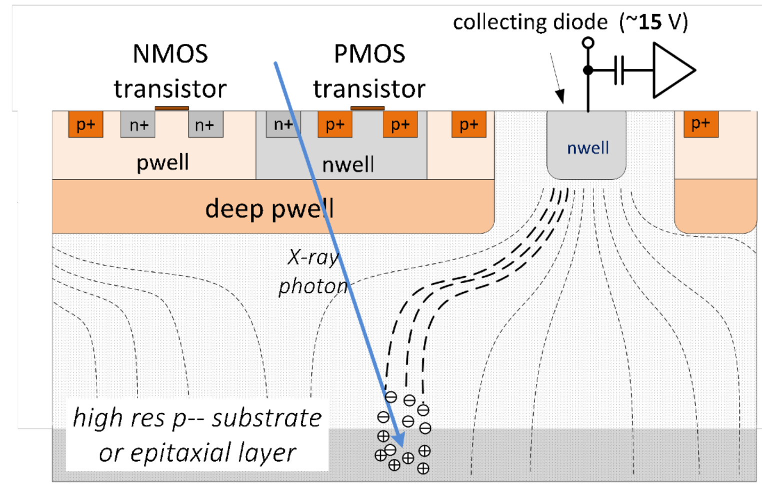
Front-depletion with small diode

Low-resistivity layer
(the std old way)



Charges move MOSTLY from therm. diffusion
- Long (~100 ns) collection time
- Important charge sharing

Depleted MAPS
(the new way)



Charges move MOSTLY from E drift
- Short (< 10 ns) collection time
- Low charge sharing

Back-side illumination
- Substrate removed (50 µm easy in industry)

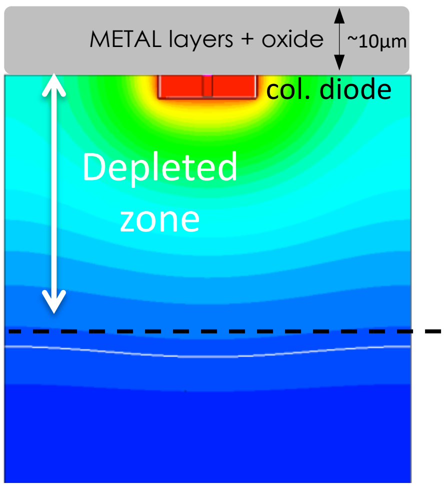
- Sensors too thin (~20 µm) => front support
- Complex connexion (costly)

- Could stay thick => no complexity

Back Side Processing

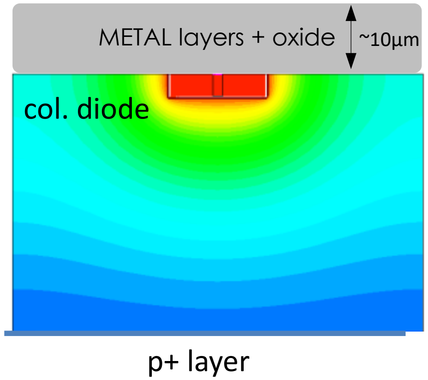
- Goal: « costless » BSI sensor

Based on CZ wafer
with resistivity ≫ 600 Ω.cm



[J. HEYMES]

- **Thinning 50 µm**
- **Ion implant**
- **Annealing**



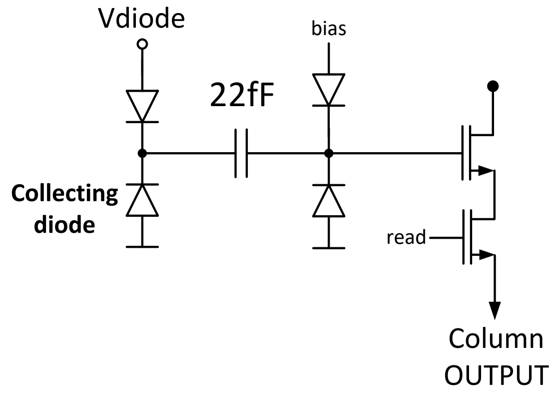
IBS PULSION®

Major benefit expected

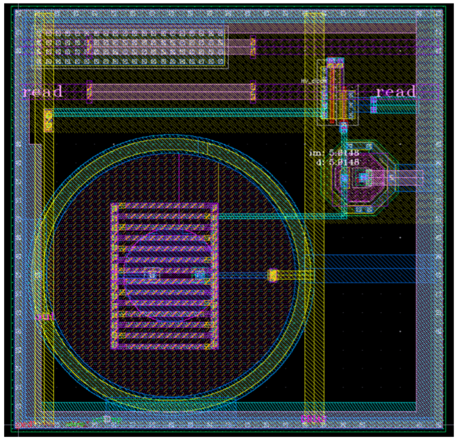
- Sensitivity to low penetrating radiations
- X-rays ≲ 1 keV
- Alpha or slow ions
- Visible photon (needs extra coating)

Depletion on prototype sensors

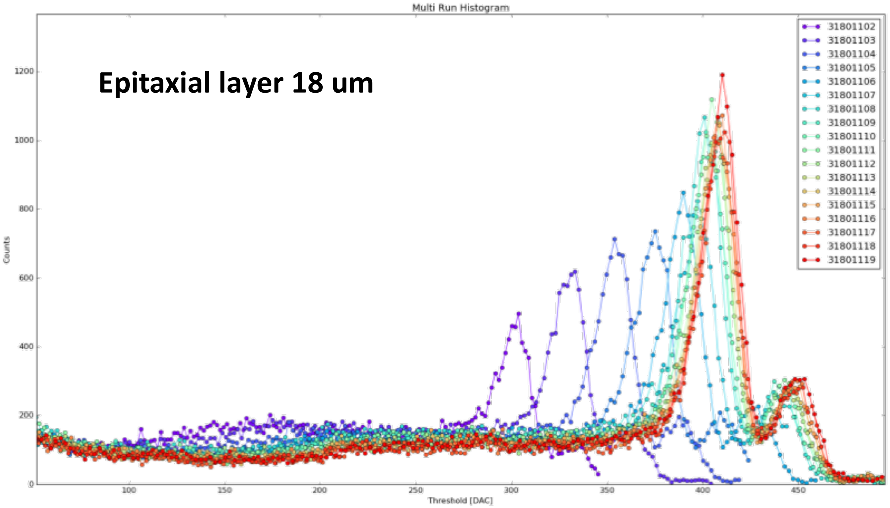
- PIPPER-1 (2014), PIPPER-2 (2016), PIPPER-3 (2017)



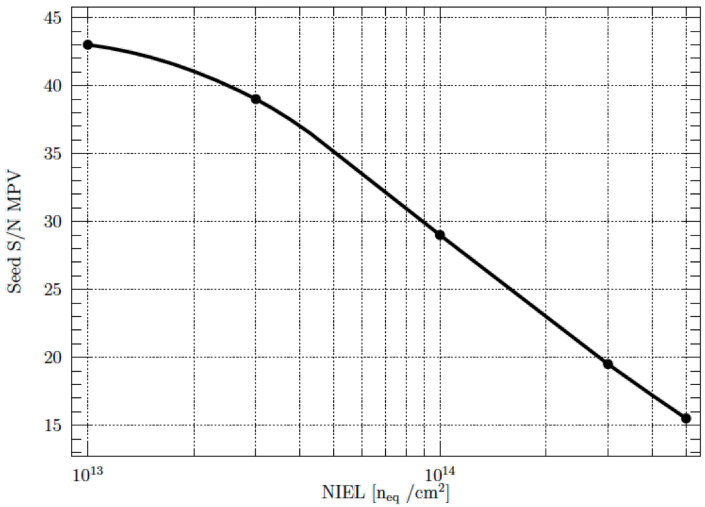
- Prorotype chip 32 x128 pixels
- Analog outputs
- Pixel size 22x22 µm
- AC coupled collecting diode
- Produced on two substrates:
  - Epitaxial layer 18µm
  - Czochralski substrate + PULSION post-process



^{55}Fe irrad. function of diode bias (1-19V)



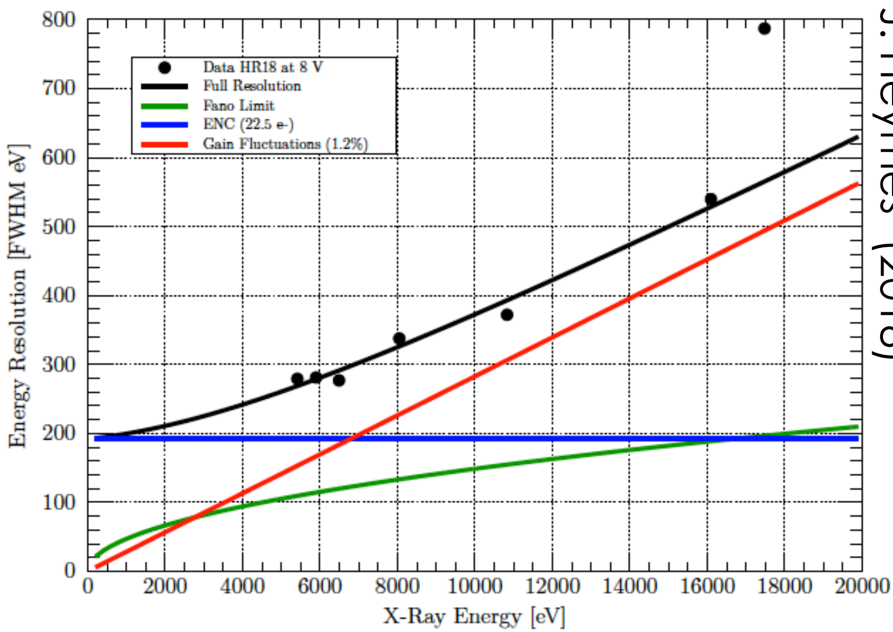
β-source SNR at -20 C, after neutron irradiation



Some PIPPER performances

Energy resolution

- Temperature ~10 °C
- Computed after clustering

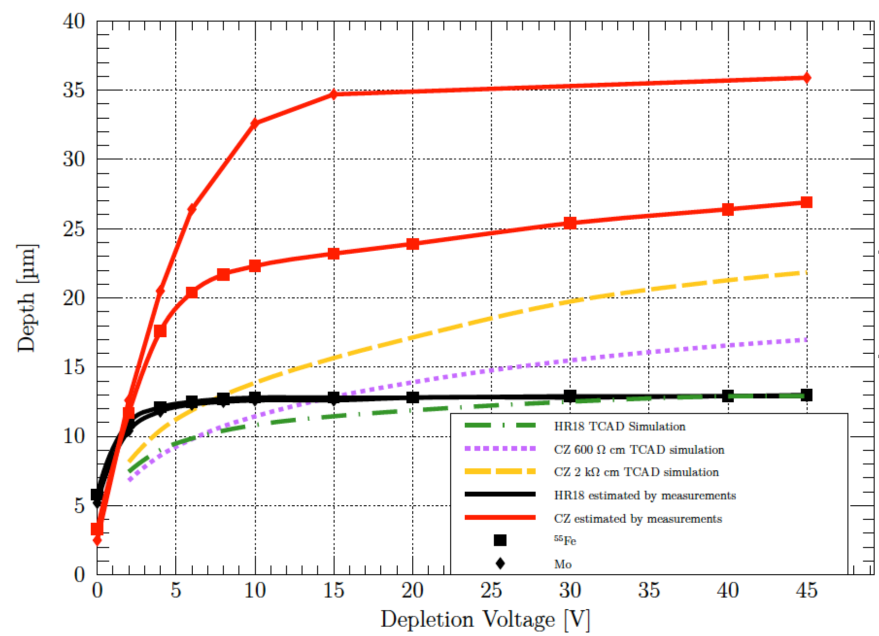


J. Heymes (2018)

- dominated by pixel-gain & charge-collection fluctuations
- Linearity checked up to 15 keV

Collection depth

- Computed from counts in peaks
- Deeper collection exists but at lower energy resolution

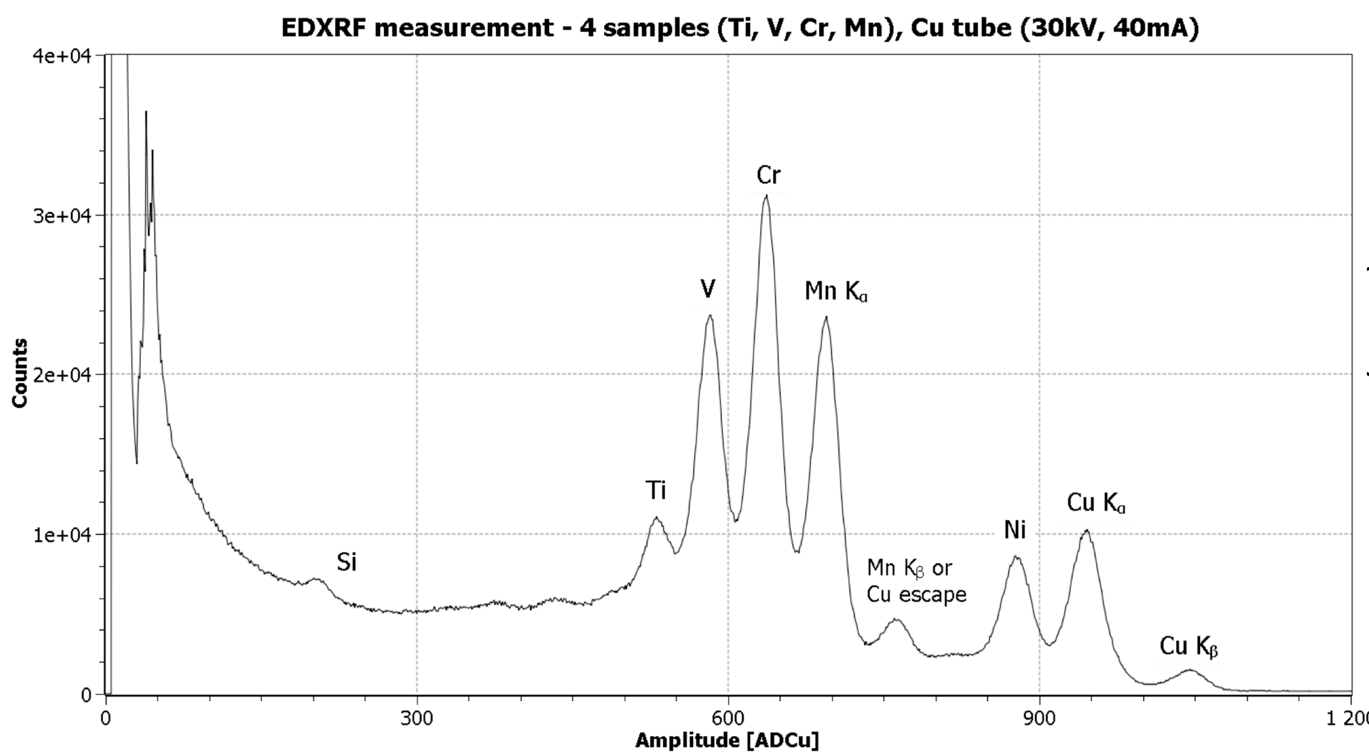


J. Heymes (2018)

- 40 µm not really fully depleted BUT fully collect

Application to X-ray fluorescence

- Irradiation of Ti, V, Cr, Mn samples
  - X-ray lamp with Cu target
  - Ni-shielded
  - Note/ Si-line = internal Fluorescence



M.Kachel (2018)

Prototype small pixel X-ray counter

Counting Low energy X-ray - Mimosa 22SX

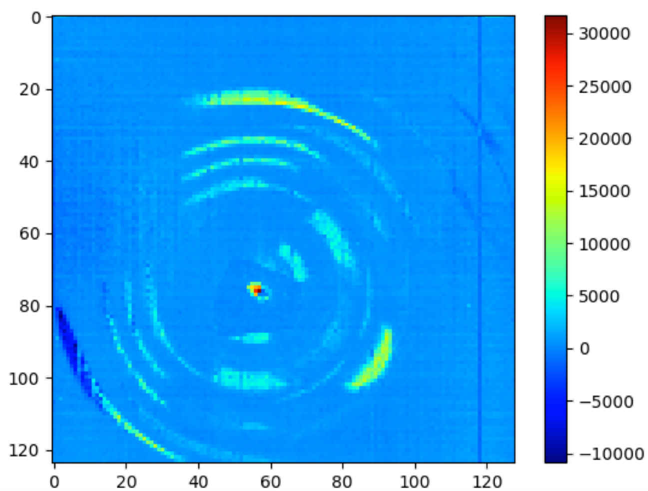
Requirements:

- X-Ray Energy Range [**few 100 eV – 5 keV**] with 100% QE
- Counting Dynamic [1-10^7] ph/pix/s
- High Spatial Resolution (pixel pitch ~ 20 µm)

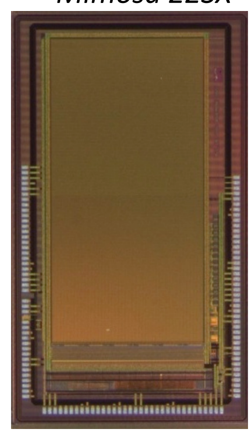
Test at HERMES beam-line

- F.Orsini *et al.*
- Simple pin-hole diffraction
- Low energy, down to 1 keV

PRELIMINARY

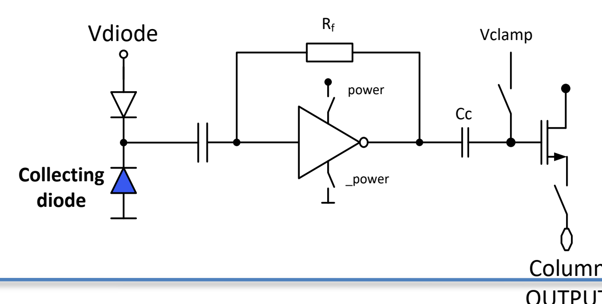


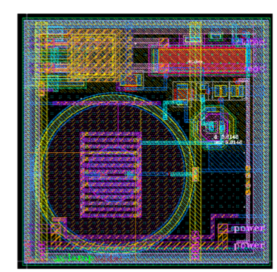
Mimosa 22SX



First 2D prototype specs

- Tower Jazz 180 nm CIS
- 128 x 256 pixels with 22µm pixel pitch
- Collecting diode AC coupled to ampli.
- Discriminator with 2 thresholds → energy windowing
- Binary outputs
- 16 mm² of active area





Application to charged beam

- Dose Monitoring by counting

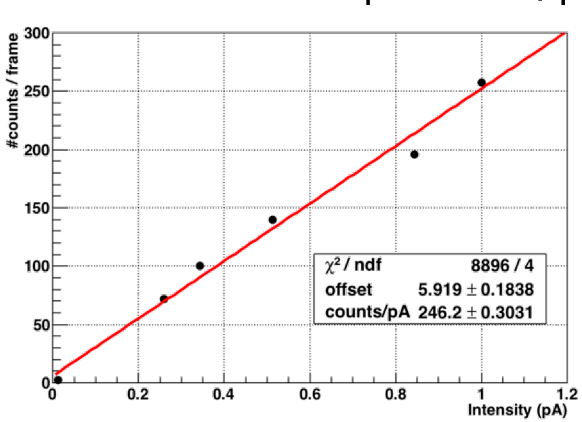
CYRCé Cyclotron at IPHC:

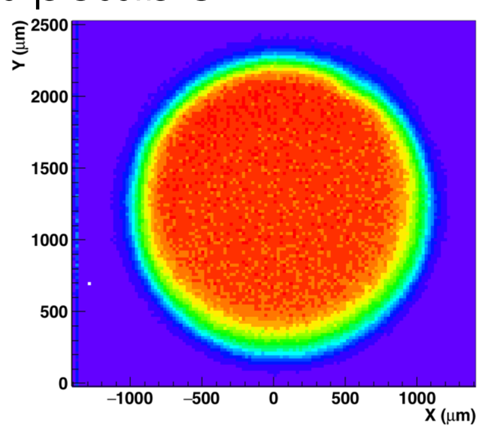
- 24 MeV protons
- Millimetre beam size for small animal proton therapy

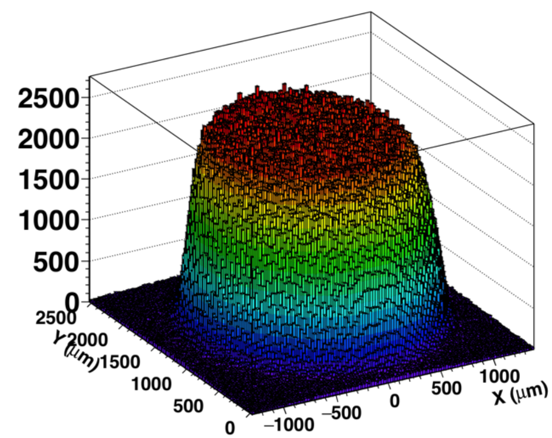
Motivation:
Monitor dose for small beam size (problematic with current detector)

First tests with Mimosa 22SX

- Linear behaviour in the measured fluence range
- At least 1000 protons/pix/s possible

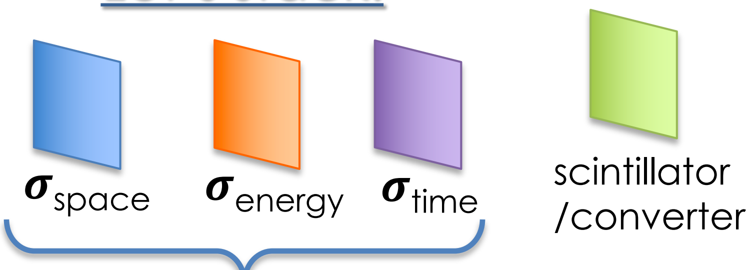


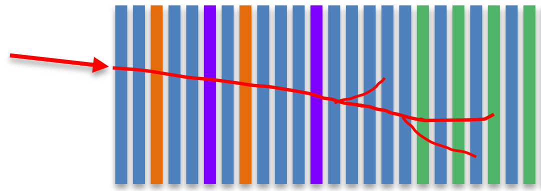




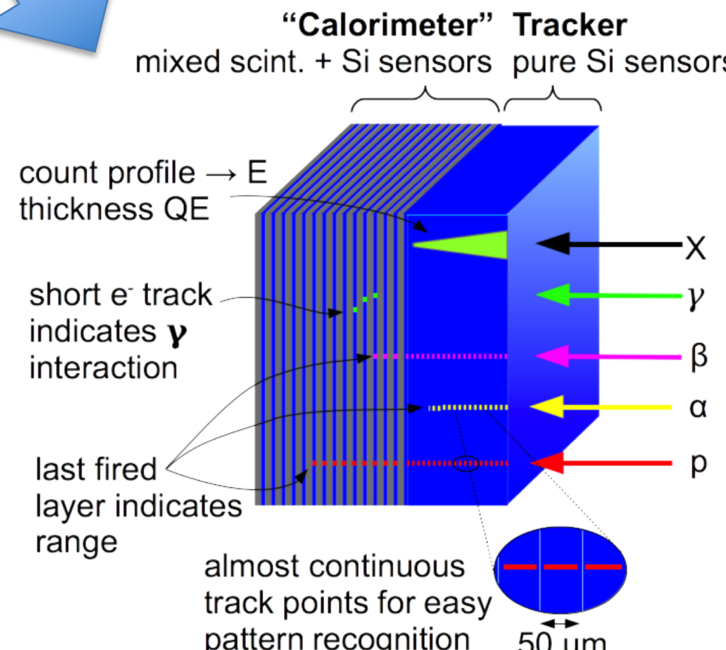
DREAM of electronic emulsion

- Let's stack!





CMOS pixel flavours with sense layer ~ 100 % thickness

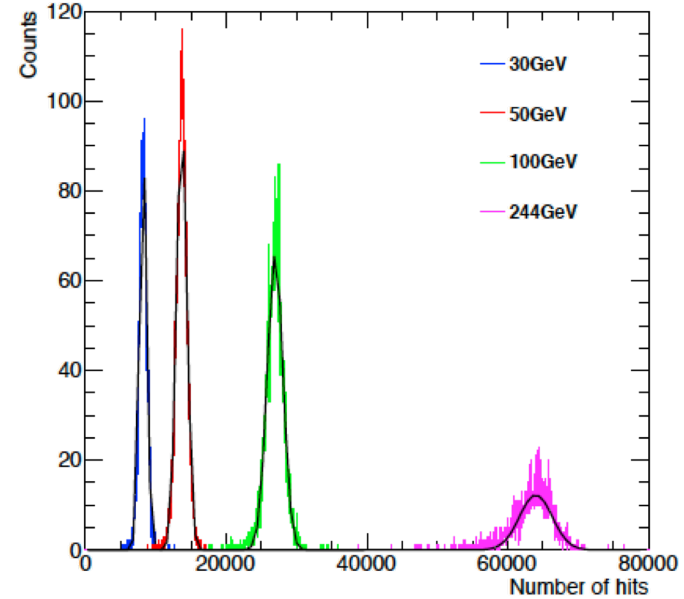


Fast electronic equivalent of a nuclear emulsion

- **8D measurements**
  - 3D position + 3D direction
  - 1D time
  - 1D energy (range / sampling)
- **Adjustable performances**
  - Stack re-shaping (~~sensor redesign~~)

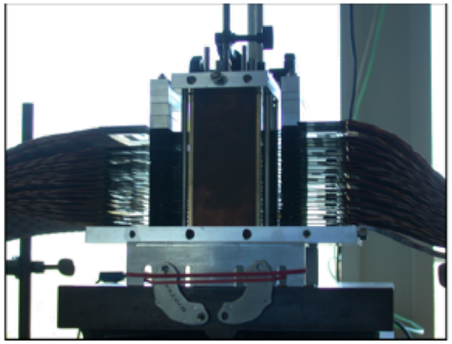
 T.Peitzman et al., arXiv:1708.051

- High-Granularity digital electromagnetic calorimetry
  - Stack of (tungsten + MAPS) layers



- response to electrons from SPS test beam
- calculated from per-event hit density distributions

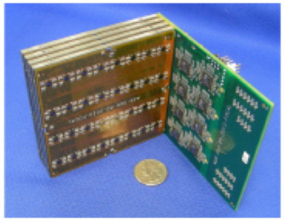
24 layer pixel detector

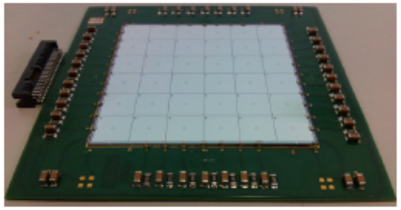


Several groups involved:
Full prototype with pixel detectors CMOS (MIMOSA) 39M pixels, 30μm pitch
use synergy with R&D for ALICE ITS upgrade
Full prototype with pad readout

Performed systematic tests:
Test beam data from 2 to 250 GeV (DESY, PS, SPS)
Cosmic muons

Pad layer integration





Utrecht/Nikhef (Netherlands),
Bergen (Norway),

Tsukuba, Nara, Hiroshima (Japan),
ORNL (US)
VECC Kolkata,
BARC Mumbai (India)

R&D Activities with Si-pad/W Calorimeter Prototypes (Japan/ORNL, India) not covered here

Conclusion & outlooks

- CMOS processes are evolving quickly
  - Followed with related integration technologies
  - Many labs and design companies are pushing various performances
    - Ex: spectrometry, electron multiplying CMOS, …
  - „Full“ depletion of sensitieve volume opened up:
    - Time resolution: today ~10 ns, tomorrow ~100 ps ?
    - Energy resolution: today ~5% for soft X-rays

- 2 depleted architectures emerging @ IPHC:
  1. Fast and/or time-resolved binary outputs (counting & tracking)
  2. Energy deposited measurement outputs

- Projects
  - Soft X-ray spectroscopy & counting (~1cm^2 prototype in design)
  - Ionizing particle spectroscopy
    (to be started with IPHC-DESiS group)
  - High energy particle identification from energy loss
    (to be started with L.N.Frascati & IPHC-DRHIM)

BACKUPs

Energy resolution

After clustering → Seed pixel distribution

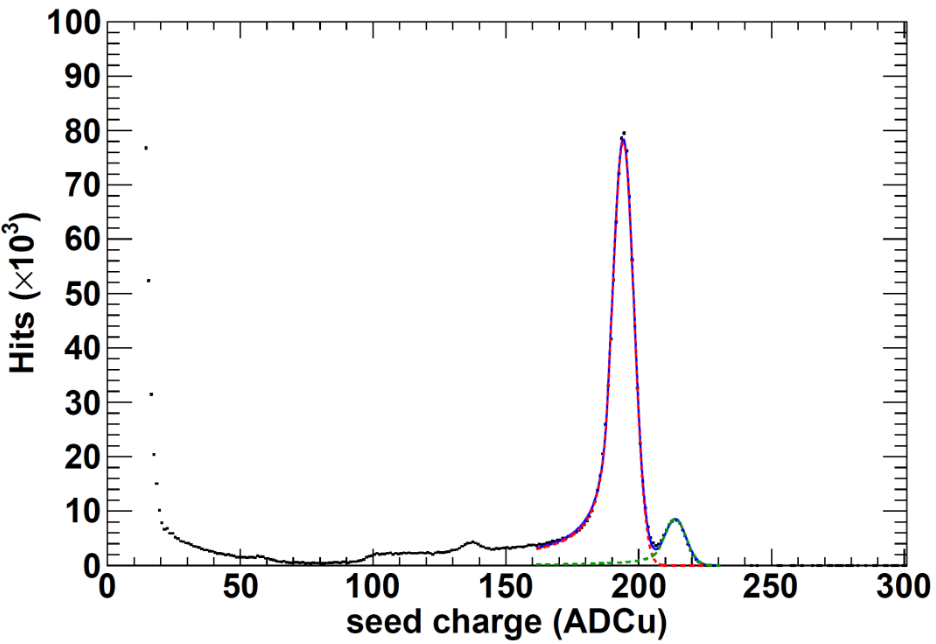
- Energy resolution dominated by pixel-gain & charge-collection fluctuations

○ **HR-18**

- ❑ ENC = 24 e^-
- ❑ FWHM (5.9 keV) = 280 eV
- ❑ 75 % charges collected on the seed pixel

○ **CZ**

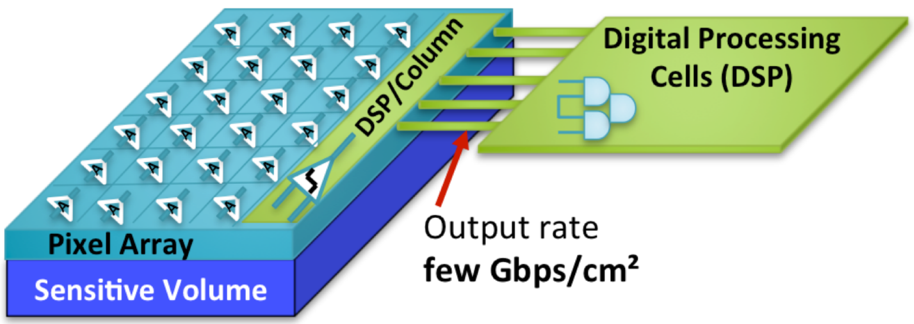
- ❑ ENC = 26 e^-
- ❑ FWHM (5.9 keV) = 288 eV
- ❑ 68 % charges collected on the seed pixel



Pipper-2 measurements (presc. 2, $T°_{cool}$=7 °C, V_{diode}=30V) ^{55}Fe irradiation – 400000 frames

Photon counting?

- <u>2D architecture</u>
  - 1 sensor = **SYNAPS-2D**
  - Rolling shutter with // columns analogue signal readout
    - 100-200 ns readout per row
    - About 512 rows
  - Digitization (binary) at column end with <u>energy window</u>
  - Dynamic range 1-2x10^4 photons/pixel/s



- <u>Mid/Long-term → 3D architecture</u>
  - 1 sensor + 1 DSP chip = **SYNAPS-3D**
  - Local rolling-shutter within submatrix
    - 1 µs readout per submatrix
    - ~10 photons (5 keV) dynamic per pixel
  - Digitization + Memory in DSP
  - Dynamic range 1-10^7 photons/pixel/s