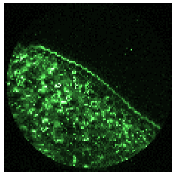
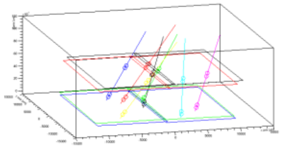
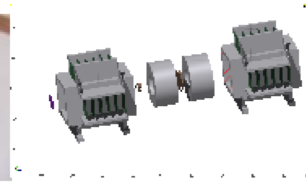
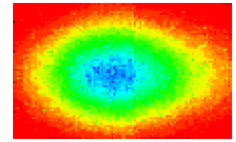
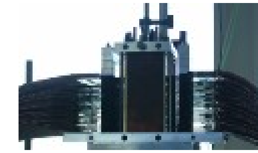









Spin-off activities in the PICSEL & Microelectronic groups

Jerome Baudot

Scientific Council of IPHC
2019 March 8th

IPHC
Institut Pluridisciplinaire
Hubert CURIEN
STRASBOURG

- → Motivations & Limits
- → Overview on all projects
- → Focus on β+, X, hadrontherapy
- → Tentative roadmap of developments

- → Questions addressed to committee

Landscape of CMOS pixel sensors

Public market

- Visible spectrum
- Video rates
- Small pixels

Scientific-CMOS

built on public-CMOS but…

- Wider spectrum: IR, X
- Single photon sensitivity
- Higher dynamic / speed

Subatomic-CPS

- Various radiation types

↓

e-, β+, p, α, ions, X, γ

- Single particle detection

↓

Position, Time, Energy, Type

- Frame rate beyond imaging

↓

kHz - MHz

⇨ Smart customized sensors

Motivations for spin-offs

- Subatomic-flavoured CPS are unique
  - Target niche applications hardly matched by COTS or other scientific sensors
    - Sensitivity: lower energy (≤ 1 keV) / hybrid-pixels
    - Frame speed: orders of magnitude higher than CCDs or sCMOS
    - Advanced analysis: embedded (e.g. histogramming) contrary to CCDs
    - Radiation-tolerance: orders of magnitude higher than CCDs

- There is a demand
  - Inside IPHC / IN2P3 / Unistra and outside
  - Sometimes match existing sensors / sometimes not
  - Potential contribution to group budget

- Progressing on the technology
  - New applications → new requirements → new abilities
  - Potential source of new performances for vertexing / tracking
  - Remark
    - Consumer market applications drives CMOS sensor technology evolution

      ⇨ adapting CPS to subatomic physics is actually the spin-off …

Limits

- Scientific management
  - PICSEL scientists cannot drive / be-user-of the applications
    - Missing expertise & time
- Budget
  - PICSEL budget is not requested for spin-offs

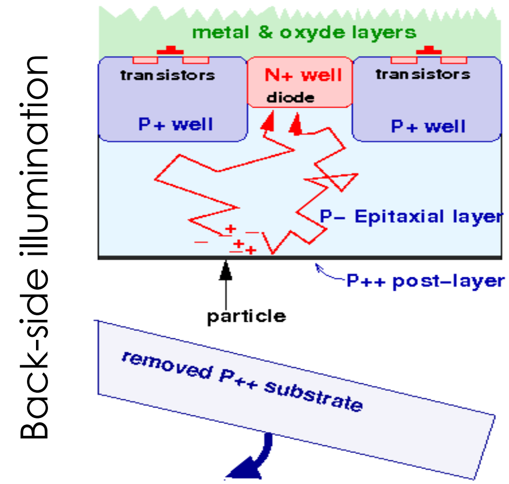
Need partners

- Competitors
  - Cannot compete on manpower against mainstream dvpmt companies
    - Exclude detection of photon close to visible spectrum: sCMOS, CCD
  - Cannot (currently) compete on counting rate against hybrid-type system
    - XPAD, Medipix/Timepix, PILATUS
  - Cannot (currently) compete on time resolution againt Silicon PhotoMultiplier

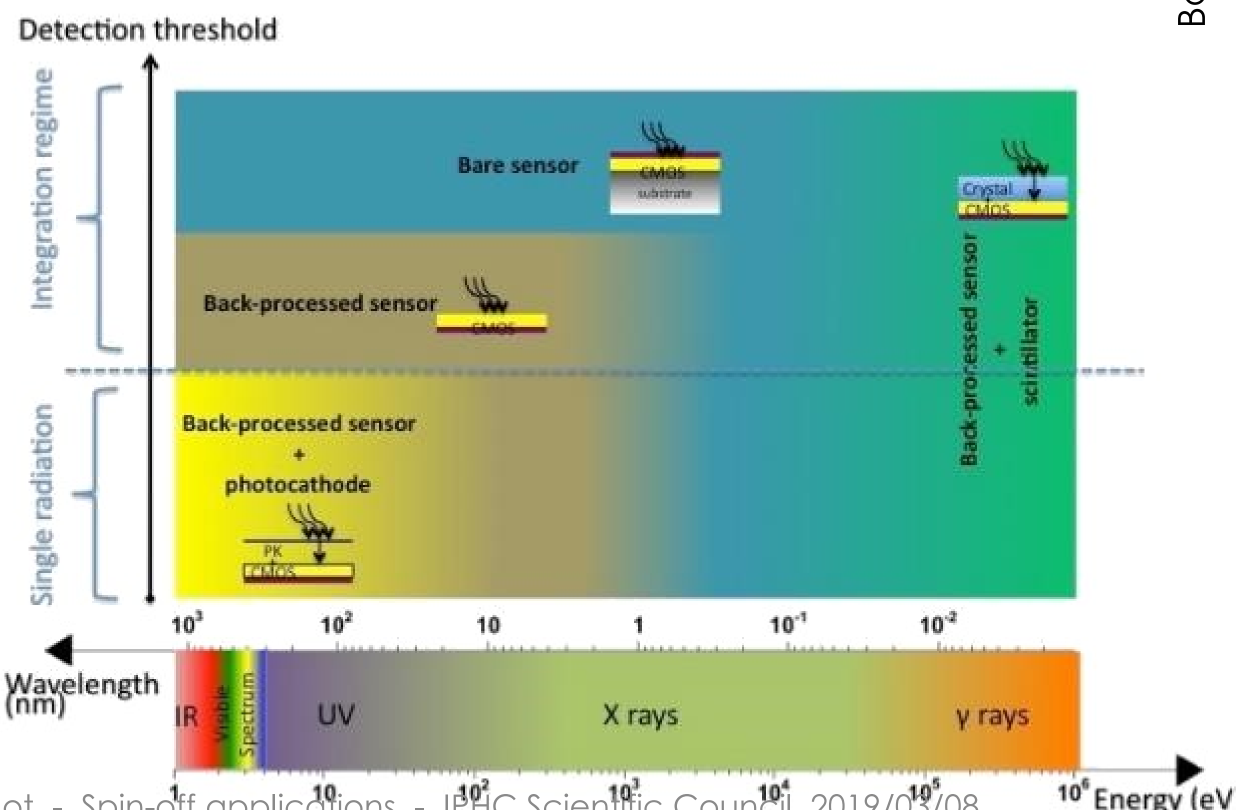
⇨ Selecting the proper niche is crucial

Sensitivity to radiations

- [All charged particles]
  - Equivalent Noise Charge ≤ 20 e-
    → easy detection for E_{loss} ~ keV
  - Limitation for low penetrating part. (e- of few keV, α) ⇨



- Photons



List of activities

Title	Date	Partners	Support	Domain	Work
SUCIMA	01-04	INFN	EU-FP5	Hadrontherapy	New sensor
LUSIPHER	06-10	IPNL, SAGEM, PHOTONIS	contract	Biology	New sensor
QAPIVI	11-13	IPHC/DRS	ANR-Cancer	Hadrontherapy	Existing sensor
FIRST	10-12	IPHC/DRS, LNF	INFN	Hadrontherapy	Existing sensor
FOCAL	10…	Utrecht, Bergen	Utrecht, Bergen	HEP (calorimetry)	Existing sensor
COMETH	10-14			Space tech.	New sensor
PIPPER	13→	(SOLEIL), Tü.Berlin	SOLEIL +	X-analysis	New sensor
MIMOSA-22SX	14-17	SOLEIL	SOLEIL	X-analysis	New sensor
MAPSSIC	16→	IMNC, CPPM, CERMEP, NeuroPsi	IN2P3, CNRS-MI	Pharmacy	New sensor
FOOT	17-20	IPHC/DRHIM, INFN/LNF	INFN	Hadrontherapy	Existing sensor
SITRINEO	17→	KNU (Korea)	FKPPL, PHC, EUR	Education	Existing sensor
SOI	17→	KEK	FJPPL +	HEP + X-analysis	New sensor
µBeam/autorad.	17…	IPHC/DRHIM		Therapy / Biology	Existing sensor
TIIM	19-23	IPHC/DRHIM, GSI, INFN/LNF	EU-H2020	HEP (track+PID)	New sensor
ATTRACT	19-20	IPHC/DRS, Frankfort, INFN/LNF	CERN (EU-H2020)		Request…

Timeline

■■ Tracking dvpmts ■■ Spin-offs ■■ technologies

2005 | 2010 | 2012 | 2014 | 2016 | 2018 | 2020

electrons

MIMOSA-5
1 Mpixels

LUSIPHER
hybrid photo-det.

SUCIMA
Beam monitoring
back-thinning

COMETH
space

ALICE
ALPIDE
$P < 100$ mW/cm^2

MAPSSIC ----------------→
in-vivo imaging

Autoradio
graphy

?ATTRACT?

SITRINEO
education

X-rays

MIMOSA-18
10 µm pitch

←------ PIPPER-1,2,3 -----------→
depletion depth

BIG-PIPPER
spectroscopy

?ATTRACT?

SOI

MIMOSA-22SX
beam/dose-counting

QUARTET
< ns

---

ions

MIMOSA-26
MIMOSA-28
fast & precise
50 µm thin

←------- **PLUME** --→
Large surface, double-sided layer

QAPIVI
FIRST
hadrontherapy

FOOT
hadrontherapy

TIIM
analogue
sparse read-out

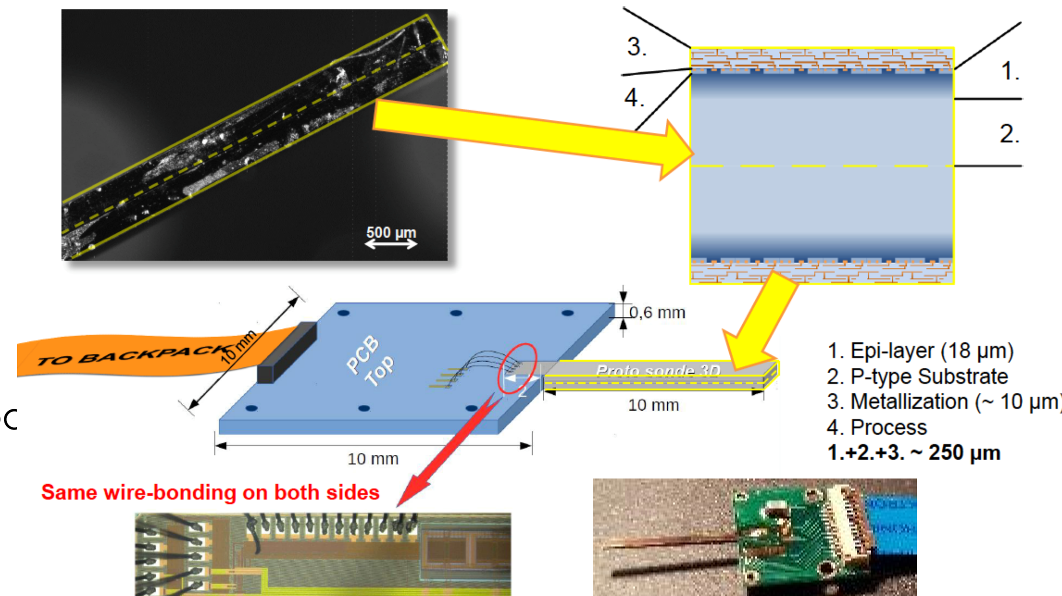
In-vivo molecular imaging

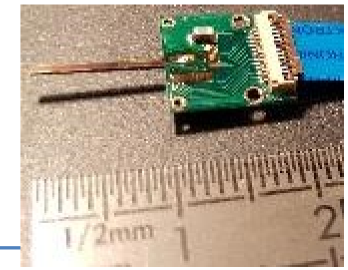
- probe in the
-500
volu

- Scientific case
  - Coupling in-brain imaging with behavioural studies
    - locating **β**+ emitters in brain of freely moving rodent

- Key requirements
  - Positron sensitivity over the largest possible energy range
  - Immunity to γ from positron annihilation
  - Extremely low power dissipation
  - Robustness / implantation

- Project MAPSSIC
  - Partners: IN2P3/IMNC+CPPM,
    CERNMEP, NeuroPsi
  - Exploit front-end derived from ALPIDE
    - One active probe = 160 μW
  - sensitive volume only 18 μm
  - Wireless connection in rodent back-pc



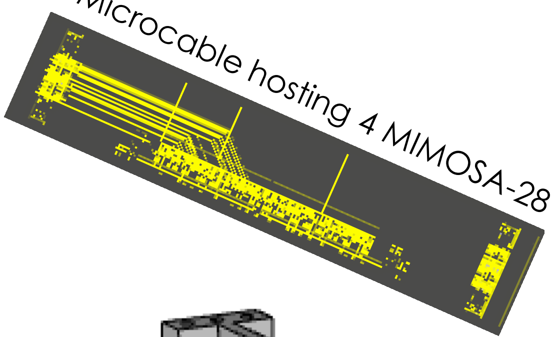


- First probe prototype under test
- New (improved) sensor to be submitted in 2019

Hadrontherapy: X-section

- Scientific case
  - better knowledge of fragmentation cross-section(E,θ) relevant for C path in tissues
    - Some dose deposited outside targeted volume

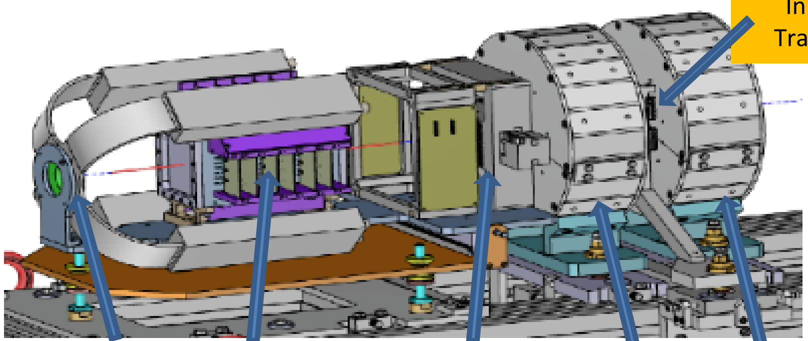
  ⇨Impact on Treatment Planning System



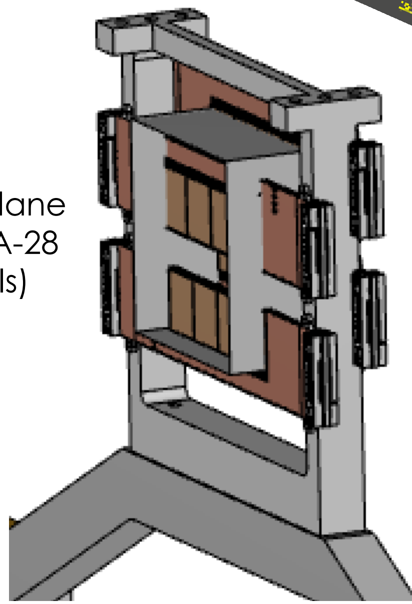
- Key requirements for vertexing/tracking
  - Sensor transparency to ions thickness

  ⇨Usage of 50 µm thin MIMOSA-26 & 28 + integration a la PLUME

- Projects
  - FIRST (2011) → FOOT (2019…)
  - Collaboration with IPHC/DRHIM & INFN/LNF
  - Outsourcing (industry) of PLUME-like module

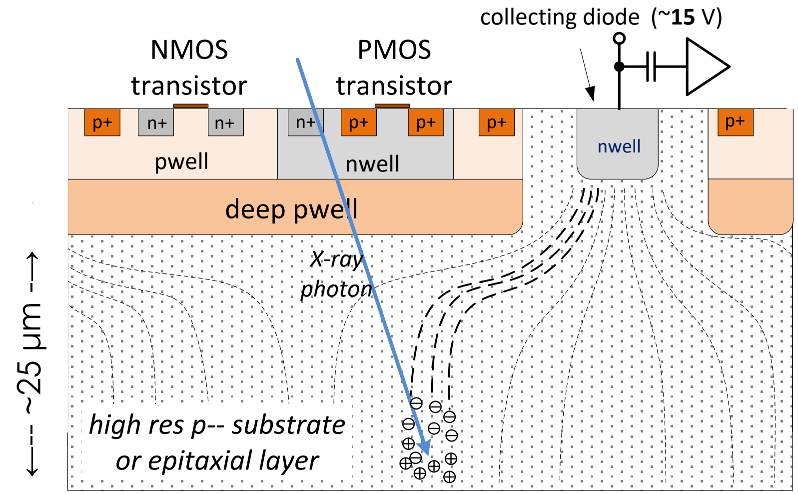


= Two-sided plane 4x4 MIMOSA-28 (29 Mpixels)

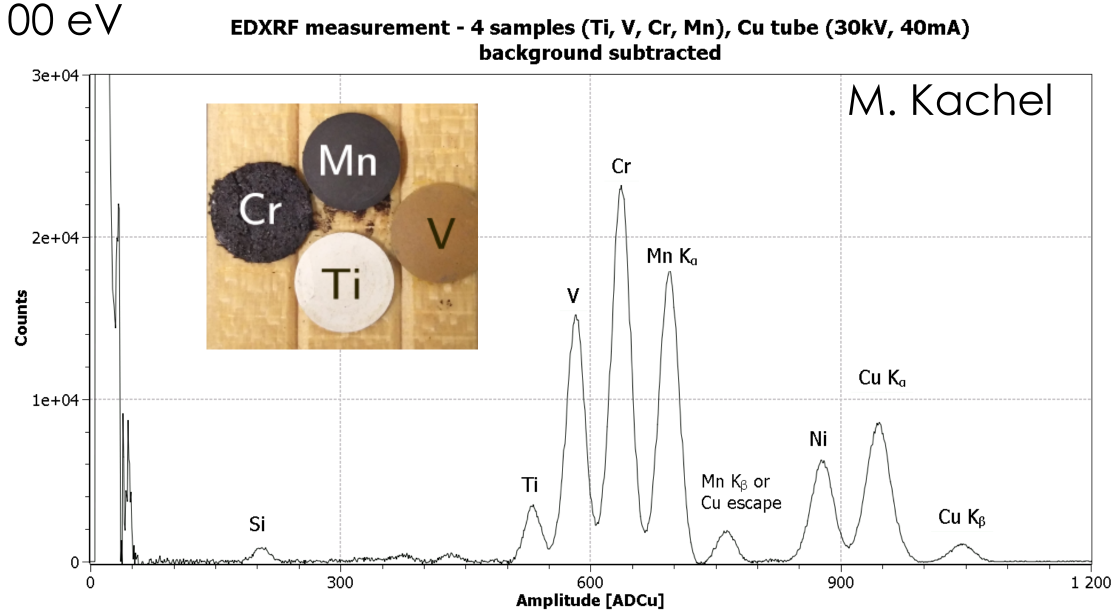


X-ray spectrometry

- Scientific case
  - Instruments for X-ray characterization: cheaper / easier / more performant
  - Partners: SOLEIL, Tech. Uni. Berlin, Uni. Frankfort



- Key requirements
  - Full depletion of sensitive volume
  - Pixel size < hybrid-det case
  - Noise, gain fluctuation < few 100 eV
  - Room T operation



- Project
  - New pixel type: PIPPER
    - AC-coupling
    - **Useful / radio-tolerance in HEP**
  - Prototypes 2013-17
  - Application size: BIG-PIPPER
    - subimission Spring 2019

ATTRACT proposals

- CERN-driven initiative to connect detection-labs with industry
  - 2 Phases: many 1 year projects → few long-term projects
    - 2019-2020: initial "proof of concept" period
  - CMOS pixel sensors @ IPHC involved in 4 projects

- Fast pixelated X-ray spectrometer
  - Based on CMOS pixel sensors measuring energy
  - Partner: Uni. Frankfort, IPHC (microelectronics)
- γ-spectrometry for flux > GHz/cm^2
  - Based on tracking electrons in Coulomb-scattering with a dense sensor stack
  - Partners: IPHC, INFN/LNF, AERIAL
- Contamination (tritium) detector
  - Based on back-illuminated CMOS pixel sensor to locate source
  - Partners: Uni. Frankfort, IPHC
- Flying drone landmine detection
  - Based on light CMOS sensor coupled with neutron converter
  - Partners: IPHC (DeSIs), Lebanese Uni., Uni. S^t. Joseph

Developments related to spin-offs

Sensors

- Sensitive volume
  - Depletion (PIPPER)
- Architecture
  - Sparse analogue read-out (TIIM)
  - Short integration time << µs or ns (QUARTET)
- Technologies
  - SOI

Integration

- Post-processing
  - Back-thinning (SUCIMA, PIPPER)
- System
  - Ultra low power (MAPSSIC)
  - Wireless com. (MAPSSIC)
- Assembling
  - Sensor stack (FIRST, FOOT, ATTRACT)

Conclusion on spin-offs

- A long-standing commitment
  - Started in the first years of the group
  - Various projects going-on & foreseen (ATTRACT)

- A number of successes
  - Boosted usage of sensors designed in the group (MIMOSA-26/28)
  - Enlarged expertise (depletion, integration)

- Strong points
  - Ability to provide custom solution (ex. MAPSSIC)
  - Variety of performances useful to several applications (ex. PIPPER, QUARTET)

    Spatial resolution (done) / Spectrometry (almost done) / Time resolution (to be dvp^{ed})

- Notes
  - No application yet in nuclear physics
  - (almost) budget-less activity from IN2P3 side
  - Difficult balance between
    - number of projects needed to maintain the activity
    - local team commitments

Questions addressed to committee

- The development of CPS is the main motivation of the PICSEL team existence:

  ⇨ **Is the potential of the technology justifying such an investment ?**

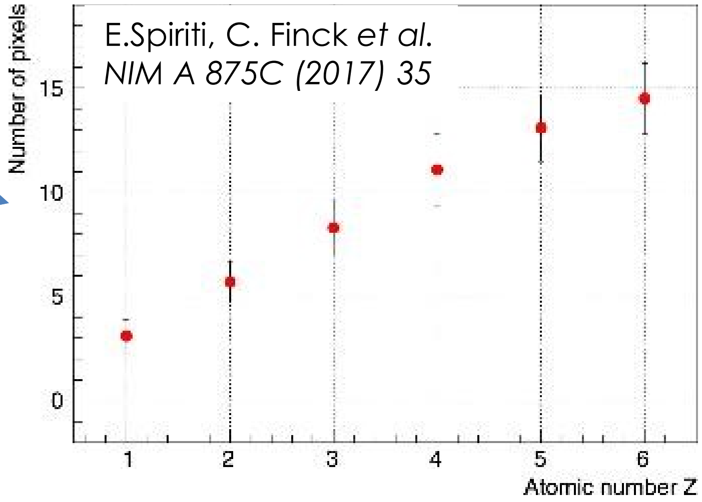
- The operation of the PICSEL team is specifically oriented towards exploiting the potential of the expertise and means available at IPHC for CPS development :

  ⇨ **Is this operation mode justified and appropriate ?**

Additional slides

Particle Identification + Tracking

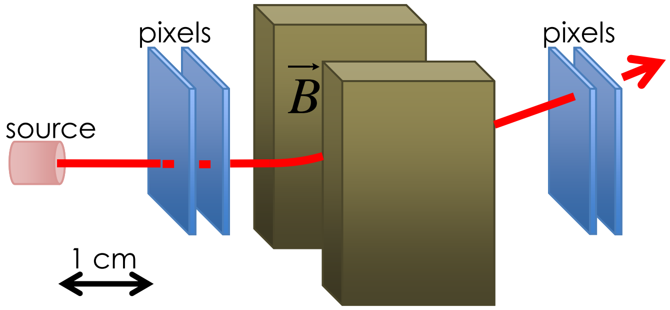
- Scientific case
  - Current CMOS pixel sensors in HEP not used for PID
    - Very thin sensitive layer → large dE/dx fluctuation
  - However:
    - Demonstrated possibilities for ions with large energy loss
    - Many silicon layer systems (ex. ALICE-ITS) mitigate fluctuations



- Project: TIIM
  - Within EU-infra STRONG project, 2019-2023
  - Elaborate pixel architecture combining
    - depletion (for excellent signal collection)
    - analogue or few bits digital output
    - sparse read-out
  - Only prototypes
  - Partners: IPHC/DRHIM, INFN

Education on tracking

- Scientific case
  - Provide a tool for teaching tracking (detectors + algorithms) to student
    - Need multi-layer system: pattern recognition & momentum estimate
    - Propose hands-on experience on an open system: simulation, acquisition, control,
  - Only available source (beyond cosmic rays) = low energy β radionuclides



- Key requirements
  - Miniaturisation !
  - Super thin sensors to minimize material budget
- Project
  - SITRINEO partners: IPHC/DRS, Unistra, KNU (Daegu), INFN/LNF (potentially many others…)
  - Tracker with 4-6 planes of CMOS pixel sensors
  - Permanent magnetic field (< 1T)
  - Hardware almost there
  - First "beam" late Spring 2019
  - Then start "dissemination"

2 out of 4 sensors available

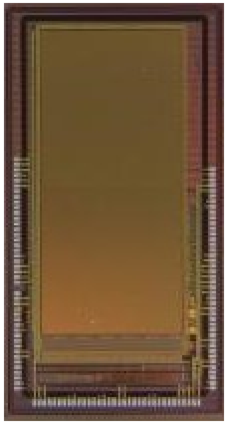
magnet

X-ray counting with MIMOSA-22SX

2014-2017

- Scientific case
  - Provide X-ray counter with
    - small pixels << 50 µm
    - Sensitivity to soft X-rays down to 100 eV

Mimosa 22SX

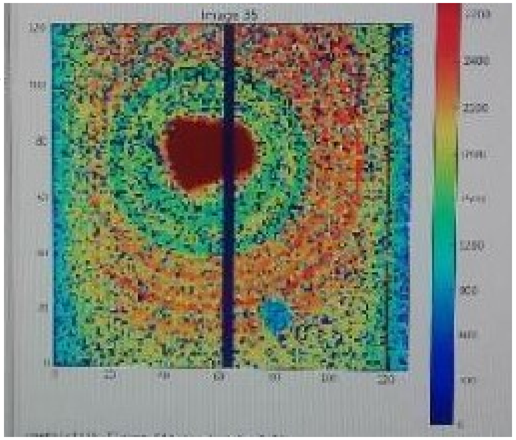


First prototype specs

- Tower Jazz 180 nm CIS
- Depleted substrate, back-thinned
- 128 x 256 pixels with 22µm pixel pitch
- Discriminator with 2 thresholds
  → energy window
- Binary outputs
- 16 mm² of active area

- Project
  - Dedicated proto MIMOSA-22SX combining
    - depletion in PIPPER
    - Fast binary read-out in MIMOSA-22
  - Partner: SOLEIL

Diffraction image obtained at SOLEIL with 1.5 keV X-rays



- Other potential applications:
  - Electron microscopy with single-electron detection
  - Beam monitoring

µBeam with M22SX

- Dose Monitoring by counting

CYRCé Cyclotron at IPHC:
- 24 MeV protons
- Millimetre beam size for small animal proton therapy

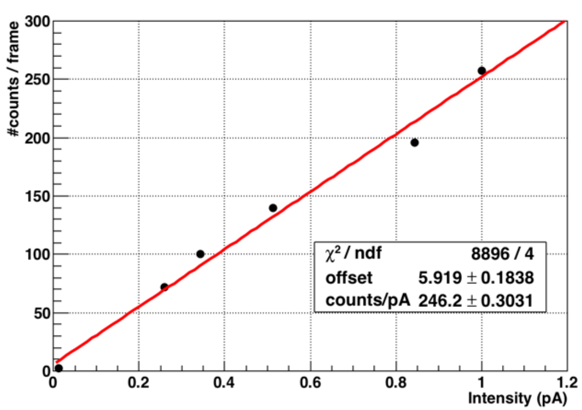
CYRCé
Cyclotron pour l'enseignement et la recherche

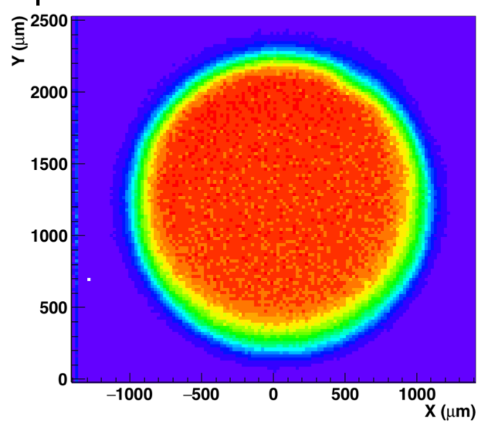
Motivation:
Monitor dose for small beam size (problematic with current detector)

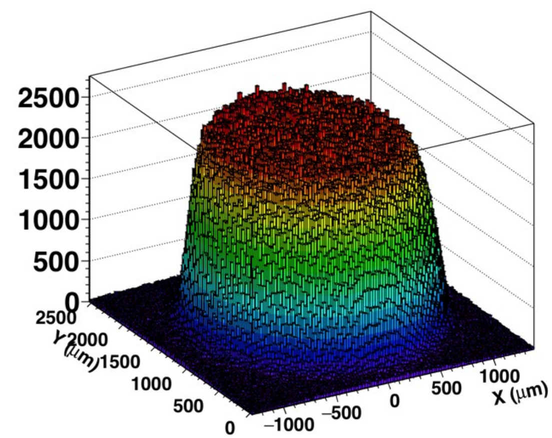
First tests with Mimosa 22SX (with IPHC/DRHIM)

2017

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



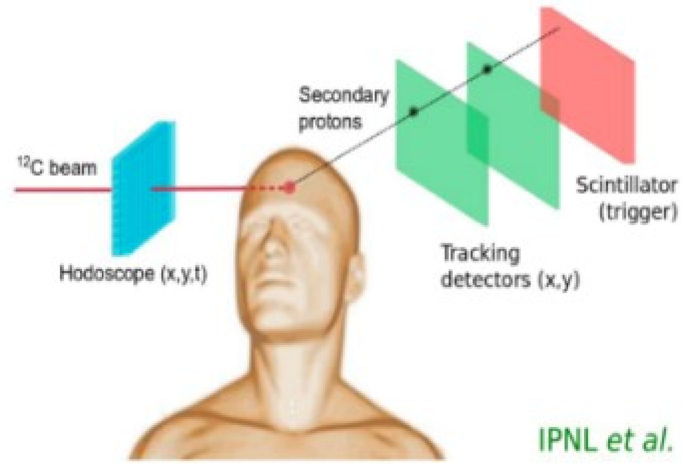




Hadrontherapy: monitoring

2011-2013

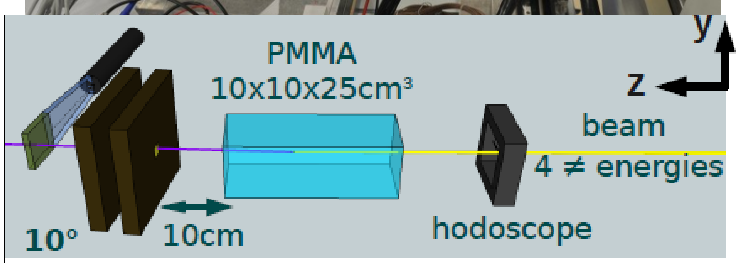
- Scientific case
  - Dose delivery driven by Bragg peak position = fc
  - Real-time monitoring of fragmentation vertices = dose location monitoring



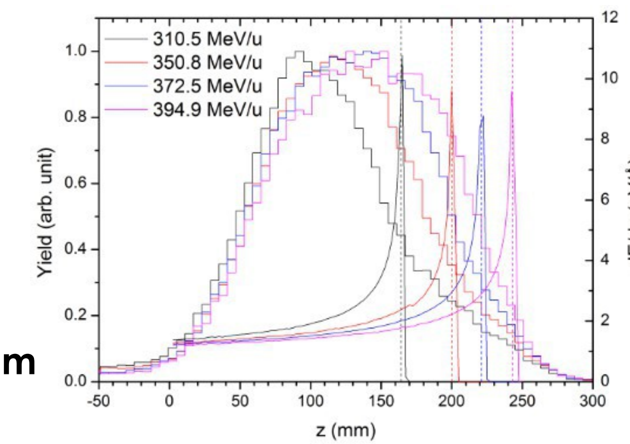
- Key requirements for vertexing
  - Sensor transparency to ions thickness

  ⇨ Usage of 50 µm thin MIMOSA-26 & 28 + integration a l

- Projects
  - QAPIVI = Quality Assurance with Proton Interaction Vertex Imaging
  - Partners: IPHC/DRS-DRHIM, IN2P3/IPNL →GSI



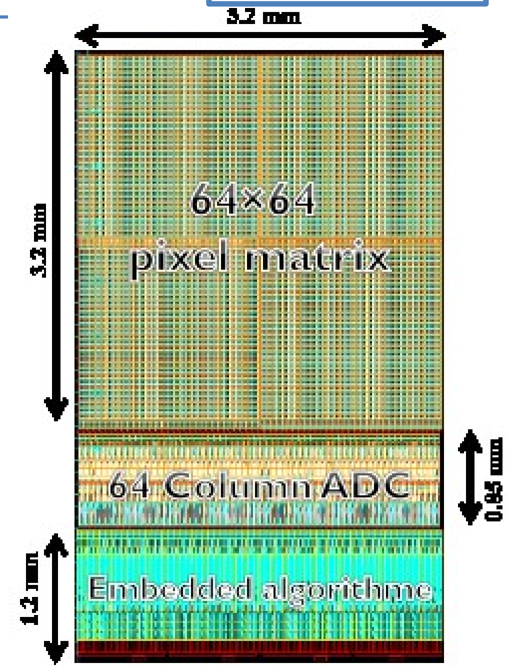
HIT 2011
^{12}C beam



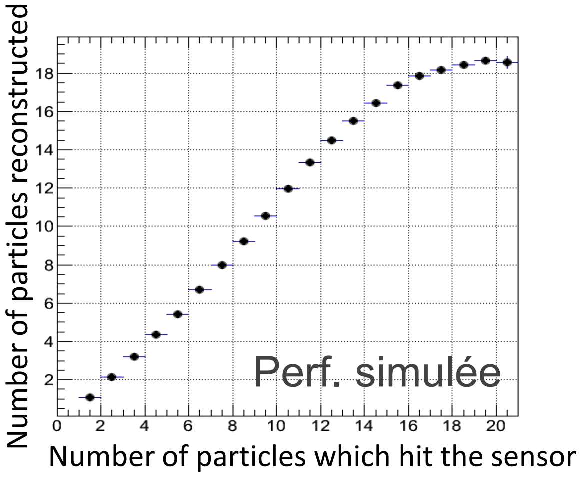
COMETH

2010-2014

- [Real-time dose estimation in space]
  - Satellites on Medium Earth Orbit »
  - Particle counter & rough spectrometry
  - **Electrons:** 100 keV–7 MeV; $10^4 \rightarrow 10^7$ particles/cm²/s
  - **Protons:** 100 keV– 400 MeV; $10^3 \rightarrow 10^4$ particles/cm²/s



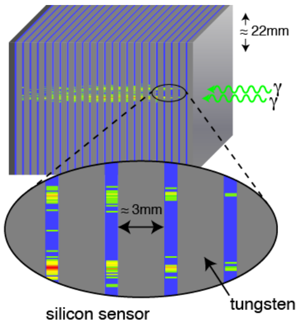
- Key aspects
  - Electron / proton separation
  - Weight, Size, Power
- Project
  - PhD thesis, Yang ZHOU
  - Analogue part fabricated & tested
  - Digital algorithm (histrogramming) designed



DIGITAL Calorimetry: FOCAL

Project targeting ALICE

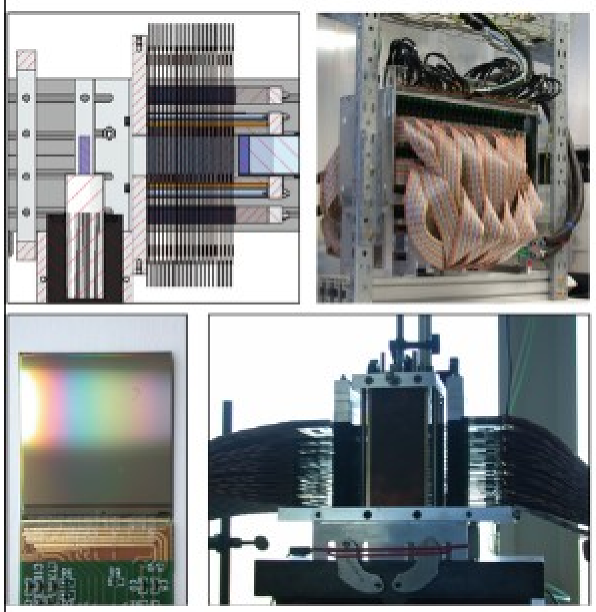
- Utrecht-NIKHEF + Bergen
- Direct γ measurement in p+p, p+A, A+A
- Granularity ≪ Molière radius
- Energy measurement = counting particles



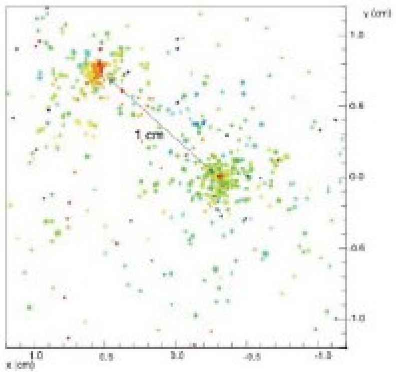
two-particle separation better by orders of magnitude

superior particle identification from extreme transverse and longitudinal granularity

unique measurement capabilities for high particle densities



- activity at Utrecht/Nikhef:
  - full prototype, CMOS (MIMOSA)
  - 39Mpixels, 30μm pitch
- performed systematic tests:
  - test beam data from 2 to 250 GeV (DESY, PS, SPS)
  - cosmic muons



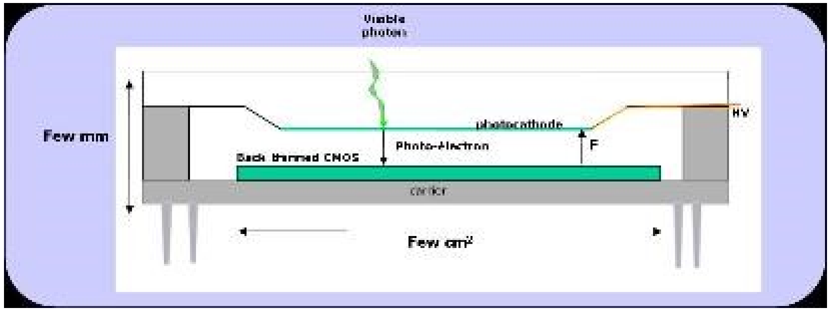
Proto tested in beam 2014 exploits MIMOSA-23 (2008) with tint = 640 µs

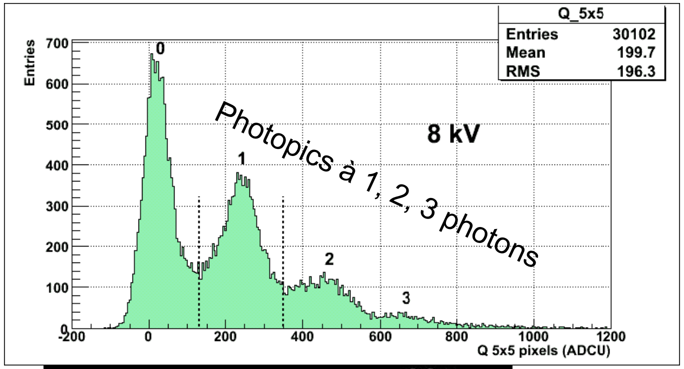
Possible improvement with sensor offering fast analogue read-out ~ TIIM project

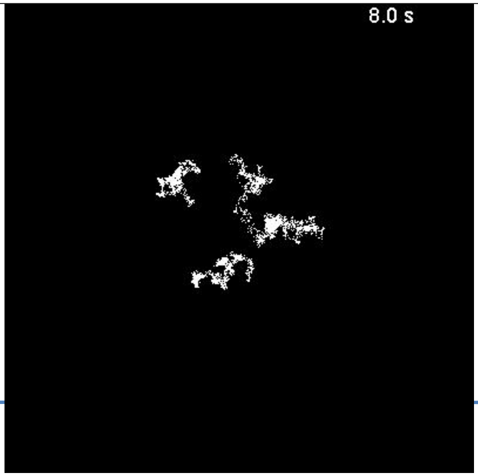
Hybrid-photodetector

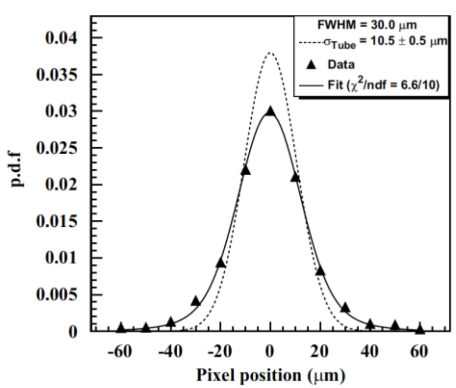
2006-2011

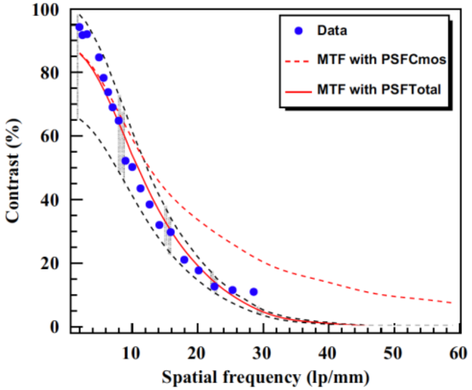
- Electron Bombarded CMOS (ebCMOS)
  - Single photon detector with spatial resolution
  - Collaboration IPN-Lyon (Rémi Barbier), PHOTONIS, SAGEM
- LUSIPHER project
  - Sensor LUCY, 400x800 pixel 10 µm, 600 fps
  - Photocathodes QE~15-25 % @ 480 nm
  - Dark count ~ 15 Hz/mm^2
- Applications
  - Tracking low-intensity light sources
  - Underwater bioluminescence (ANTARES)









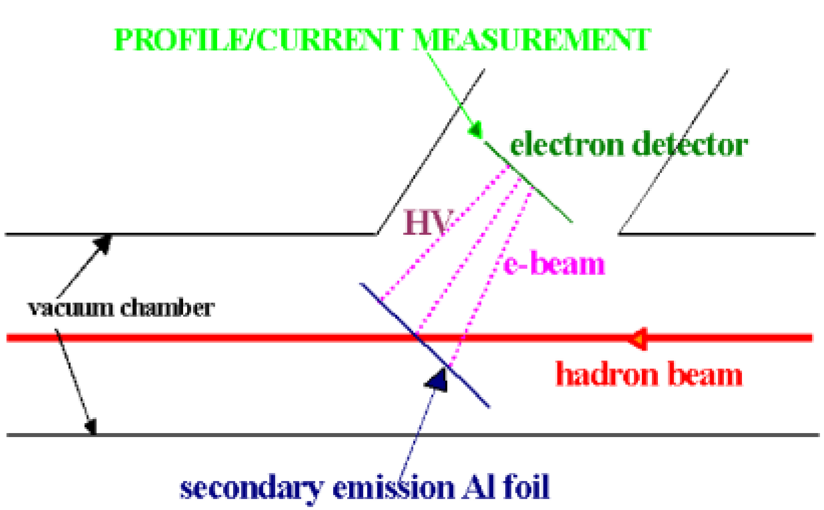


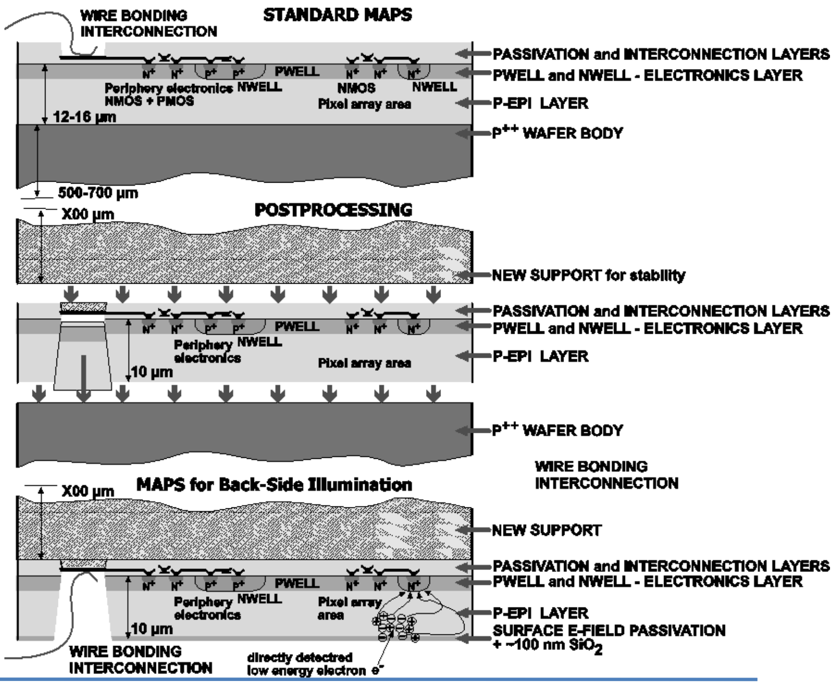
Résultats obtenus par R.Barbier et al. @ IPNL

SUCIMA

2001-2004

- Scientific case
  - Quality Control of beam for hadrontherapy
    - Imaging secondary electrons emitted by a target hit by primary beam
- Project
  - Silicon Ultra fast Camera for electron and gamma sources In Medical Applications
  - Partners: Uni. dell'Insubria, Karlsruhe, Berlin, Krakow, Warsaw, Geneva
  - New sensor MIMOTERA with 10000 frame/sec
    - First back-thinned sensor

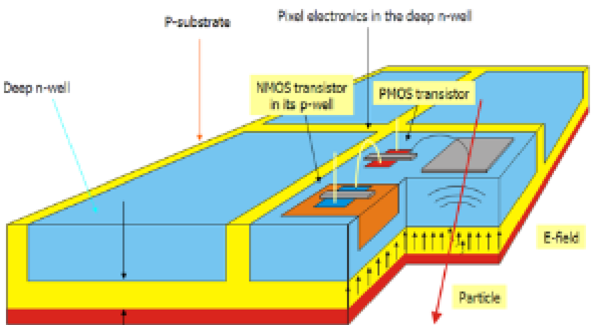




Three ways to deplete MAPS

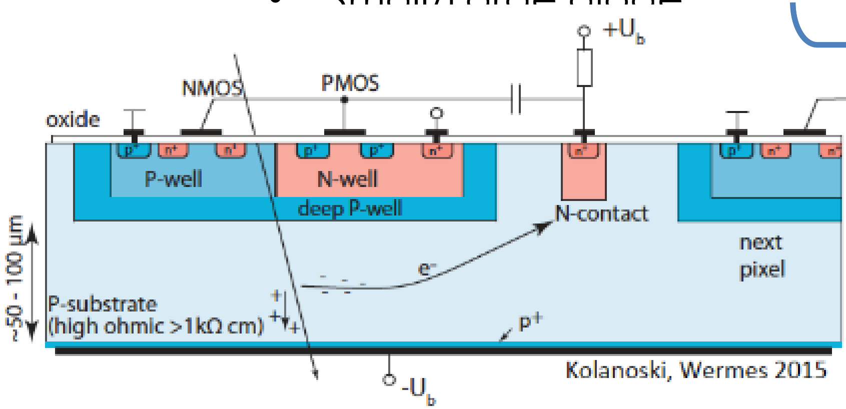
Depletion depth $\propto (V_{bias} \times \rho)^{\alpha}$ with $\alpha \lesssim 1/2$

- **High Voltage**
  - Large diode



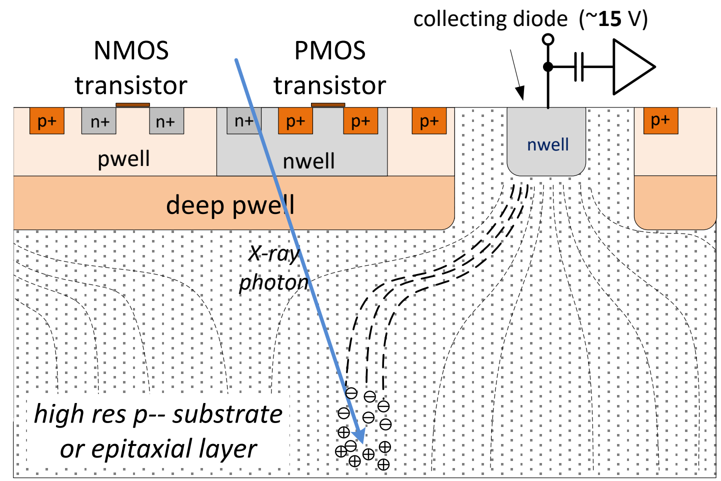
I.Pieric 2010

- **High Resistivity**
  - Back biasing
  - Small/Large diode



Target fast timing

- **High Resistivity**
  - Top biasing
  - Small diode



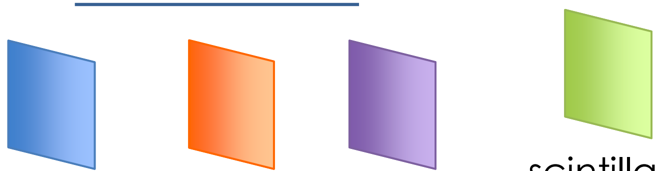
M.Kachel 2013

Target small pixels

✷ All with multiple wells CMOS process:
Remember hybrid tech. offers natural shielding

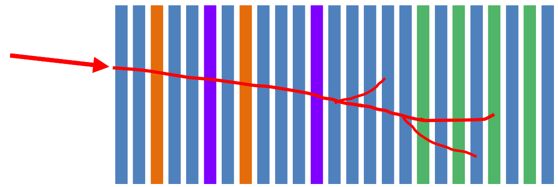
DREAM of electronic emulsion

- Let's stack!

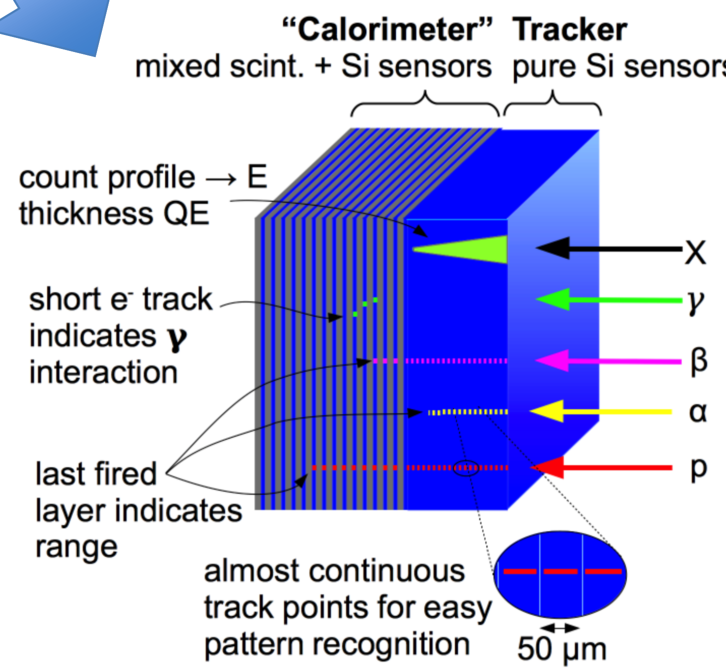


σ_{space} σ_{energy} σ_{time}

scintillator /converter



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~~)