Development of Silicon Drift Detectors and recent applications*

*a personal view

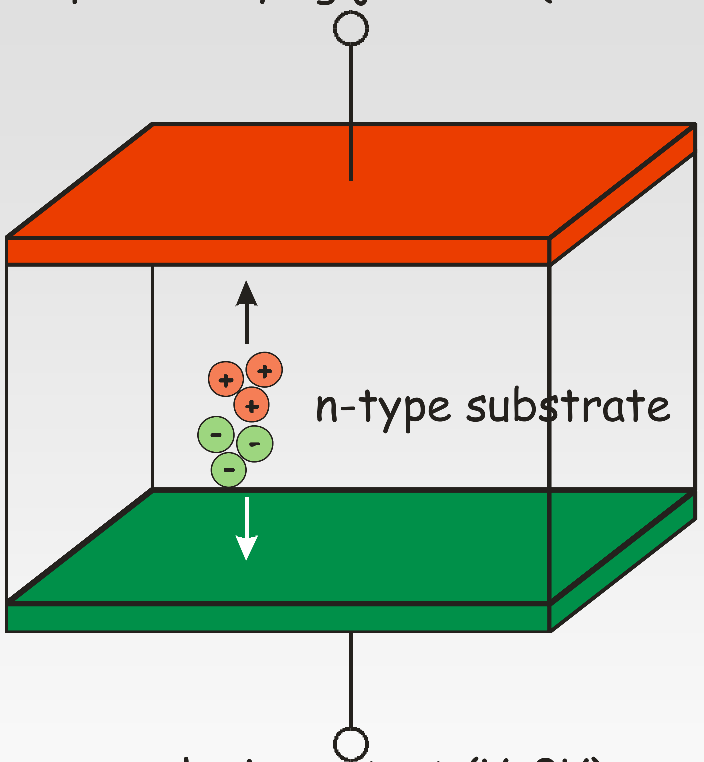
(dedicated to Pavel Rehak – 1945-2009)

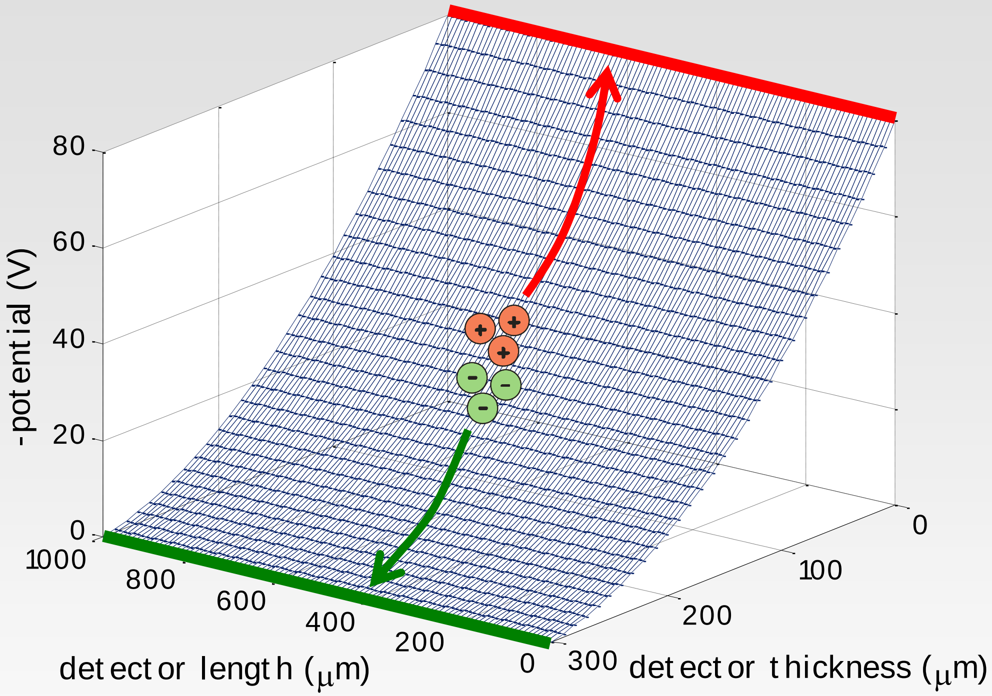
Chiara Guazzoni
Politecnico di Milano and INFN Sezione di Milano
e-mail: Chiara.Guazzoni@mi.infn.it
home.deib.polimi.it/guazzoni

Outline

- The idea of sidewards depletion
- Optimized SDD Topologies
  - spectroscopy
  - 2D position sensing
- Evolution towards spectroscopic imaging: MLSDD and CDD
- Outlook to applications:
  - X-Ray Fluorescence and Proton Induced X-Ray Emission
  - Gamma-ray imaging
  - Advanced X-ray imaging modalities
  - Macro-pixel arrays with DEPFET readout for XFEL
- Conclusions

Planar pn diodes

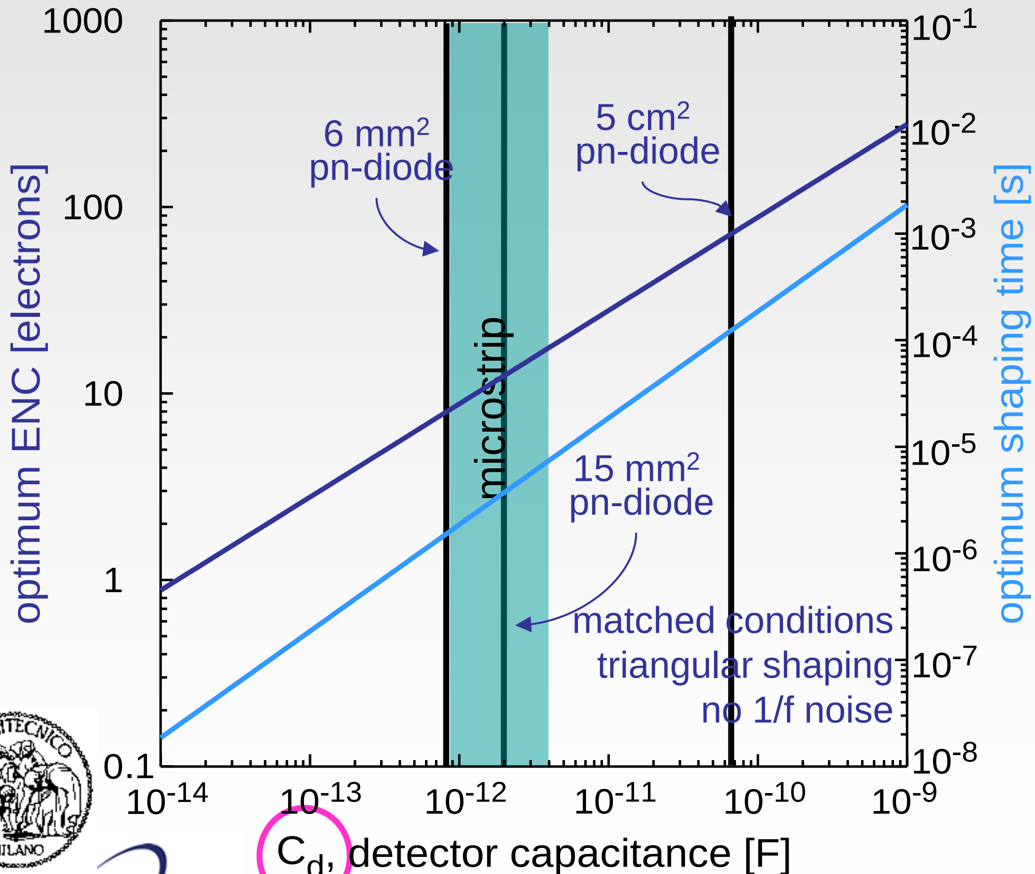




- Detector capacitance increases with diode active area
- Detector capacitance decreases if diode thickness is increased

Planar pn diodes

$$ENC_{opt}^{2} = \sqrt{A_1 A_3}\sqrt{2kTq}\underbrace{\sqrt{\frac{\alpha}{\omega_T}}}_{FET}\underbrace{\sqrt{C_d I_L}}_{detector}\underbrace{\left(\sqrt{\frac{C_G}{C_d}}+\sqrt{\frac{C_d}{C_G}}\right)}_{matching} + ENC_{1/f}^{2}\left(C_T^{2}\right)$$



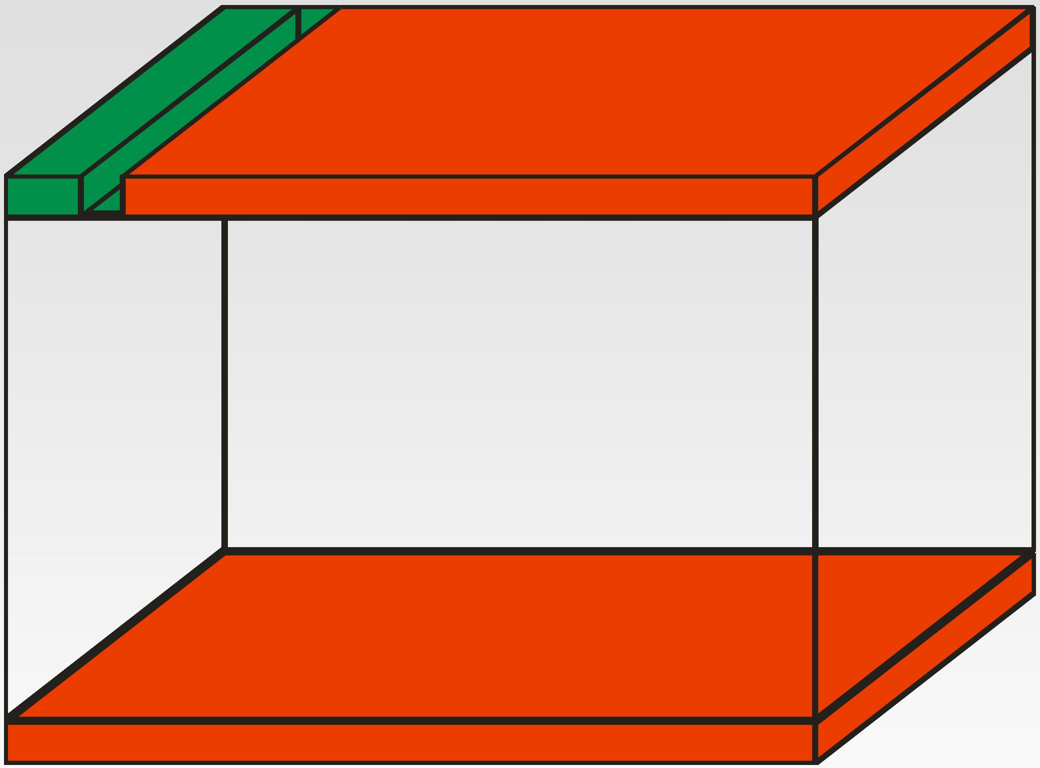
$$\tau_{opt} = \sqrt{\frac{A_1}{A_3}}\sqrt{2V_{th}}\underbrace{\sqrt{\frac{\alpha}{\omega_T}}}_{FET}\underbrace{\sqrt{\frac{C_d}{I_L}}}_{detector}$$

$$\underbrace{\left(\sqrt{\frac{C_G}{C_d}}+\sqrt{\frac{C_d}{C_G}}\right)}_{matching} = \sqrt{\frac{A_1}{A_3}}\tau_c$$

Energy resolution
&
Count rate capability
require
capacitance minimization

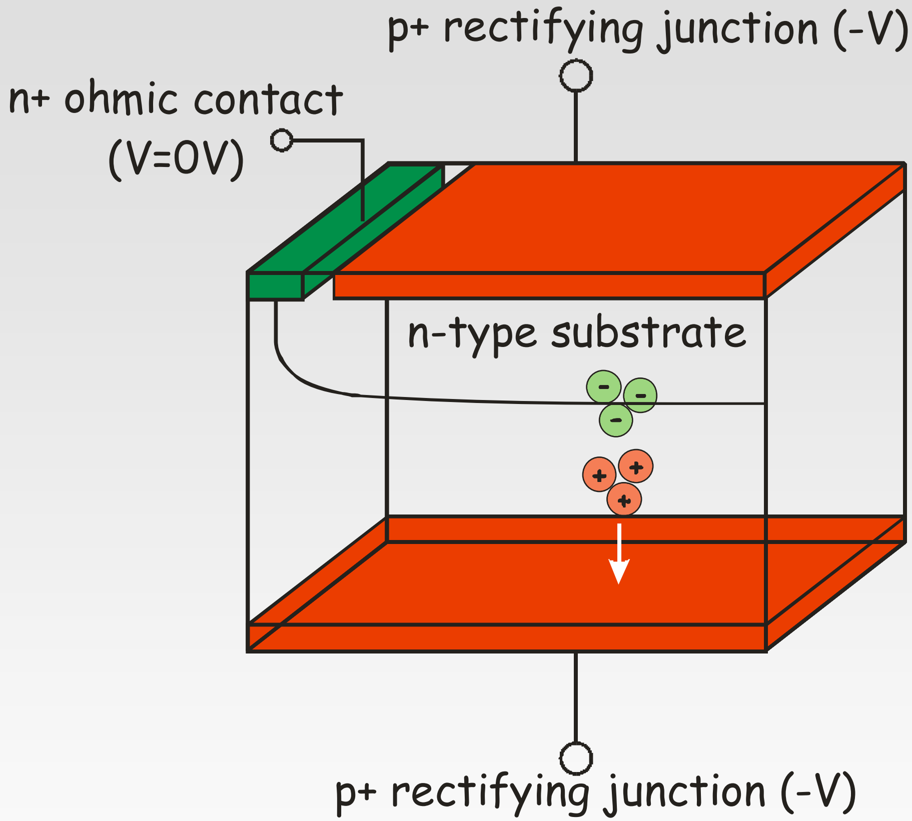
The sideward depletion

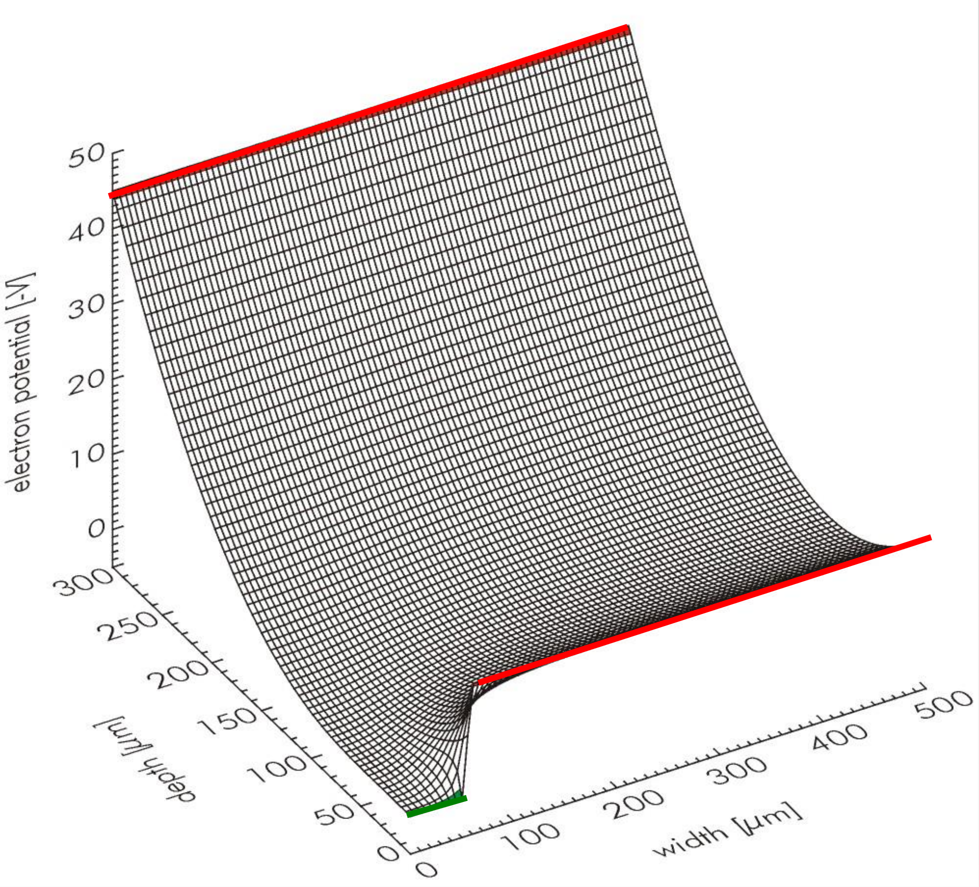
Emilio Gatti & Pavel Rehak, Autumn 1982



basic idea of sideward depletion — the revolutionary concept at the heart of the Silicon Drift Detector — is to fully deplete the semiconductor substrate through a pointlike "virtual contact," as it is called in Gatti and Rehak's original paper.

The sideward depletion

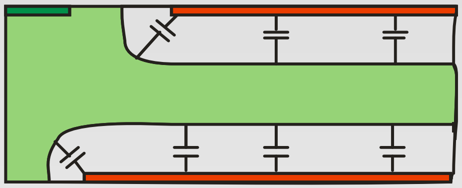




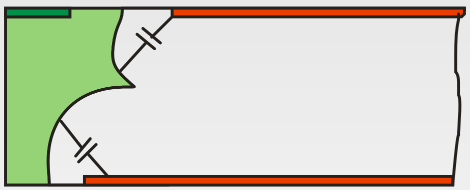
- Detector volume fully depleted by “virtual contact” (point-like)
- Full depletion achieved with only a quarter of the bias necessary for standard p-n diodes

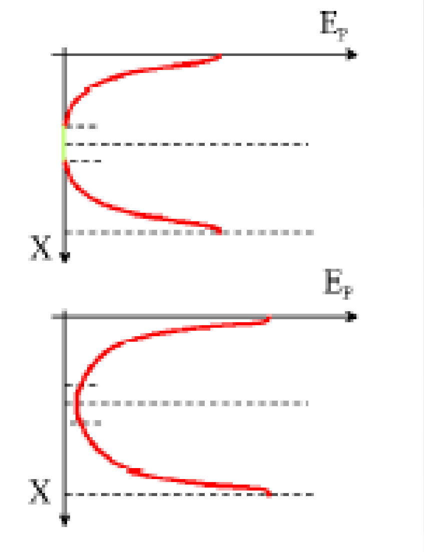
The sideward depletion

Below depletion



At full depletion





Impact on anode capacitance

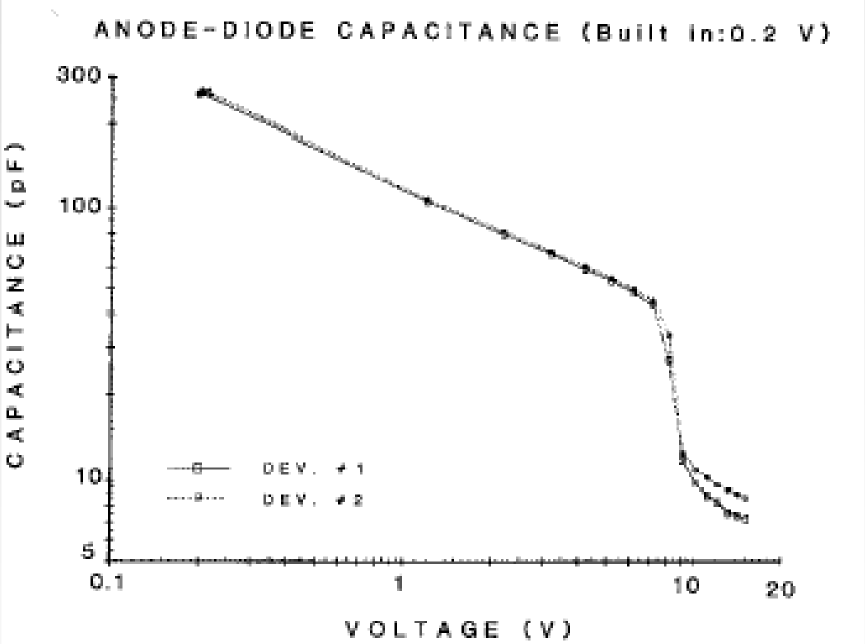
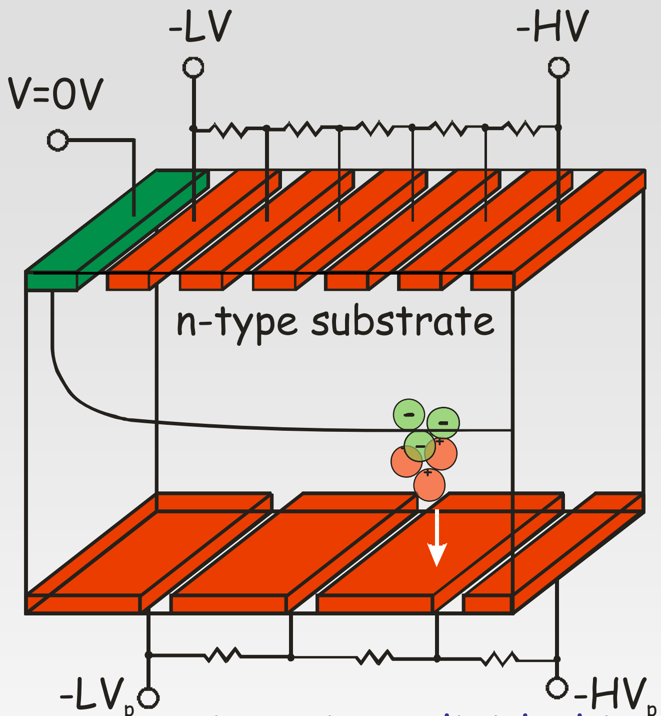


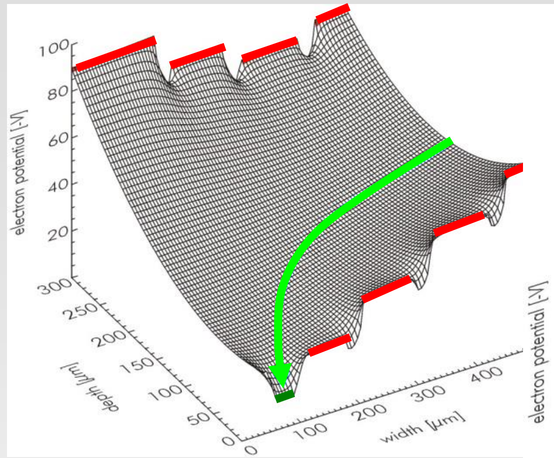
Fig. 12. Capacitance versus voltage plots of two of the test devices provided on the wafer for monitoring its doping uniformity.

- At nearly full depletion the conductive channel at the middle of the detector retracts causing the capacitance to drop abruptly.

- At higher bias voltages the remaining capacitance is the lowest capacitance between the n+ contact and the p+ electrodes.

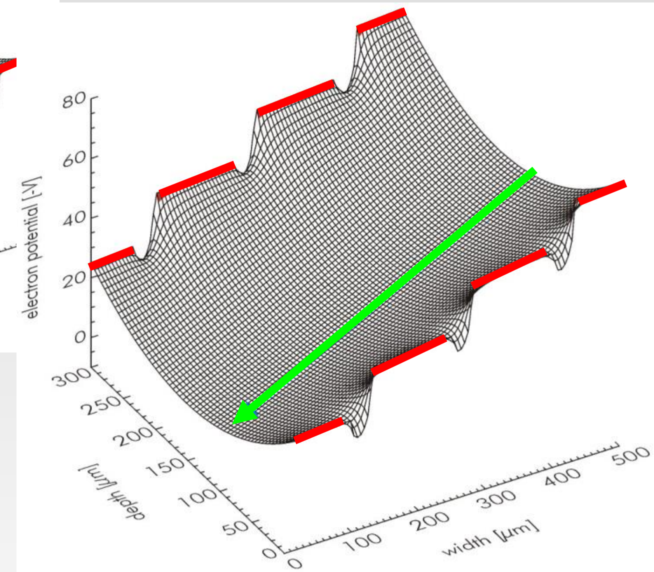
Silicon Drift Detector





Near the anode…

Central drift region…



- p+ junctions divided in strips with increasing potential on both sides → nearly uniform drift field parallel to the surface
- signal electrons focused in the center of the wafer transported at constant velocity towards the readout anode
- 1-D position sensing with only 1 readout channel through drift time
- small anode capacitance → low-noise measurement of time and amplitude

1984: Patent filed…

United States Patent [19] | [11] **Patent Number: 4,688,067**

Rehak et al. | [45] **Date of Patent: Aug. 18, 1987**

[54] **CARRIER TRANSPORT AND COLLECTION IN FULLY DEPLETED SEMICONDUCTORS BY A COMBINED ACTION OF THE SPACE CHARGE FIELD AND THE FIELD DUE TO ELECTRODE VOLTAGES**

[75] Inventors: **Pavel Rehak,** Patchogue, N.Y.; **Emilio Gatti,** Lesmo, Italy

[73] Assignee: **The United States of America as represented by the Department of Energy,** Washington, D.C.

[21] Appl. No.: **583,553**

[22] Filed: **Feb. 24, 1984**

FOREIGN PATENT DOCUMENTS

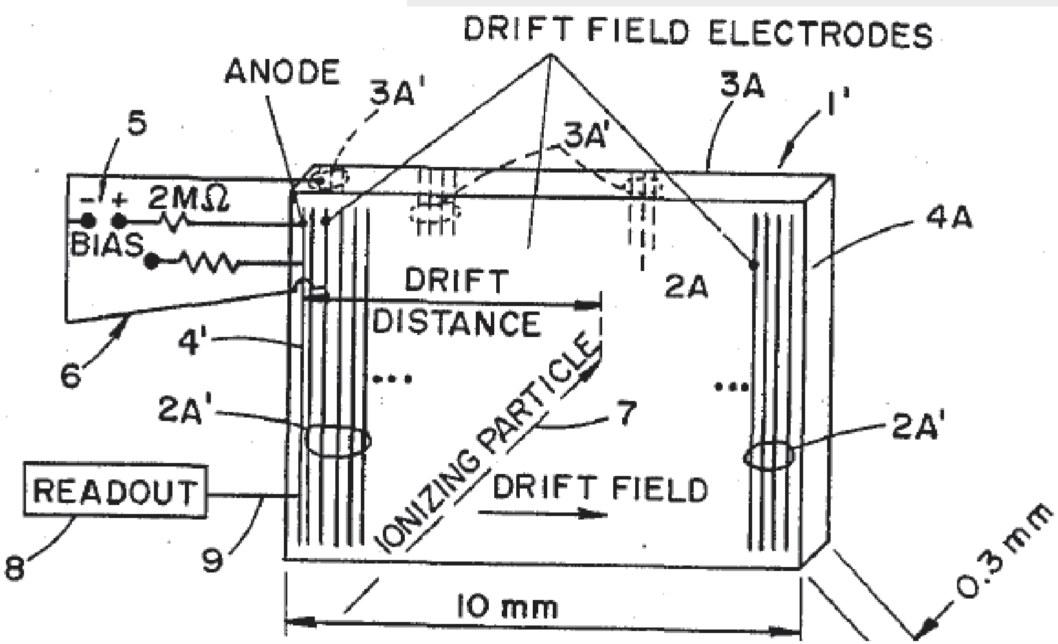
974659 9/1975 Canada .... 357/24 M

OTHER PUBLICATIONS

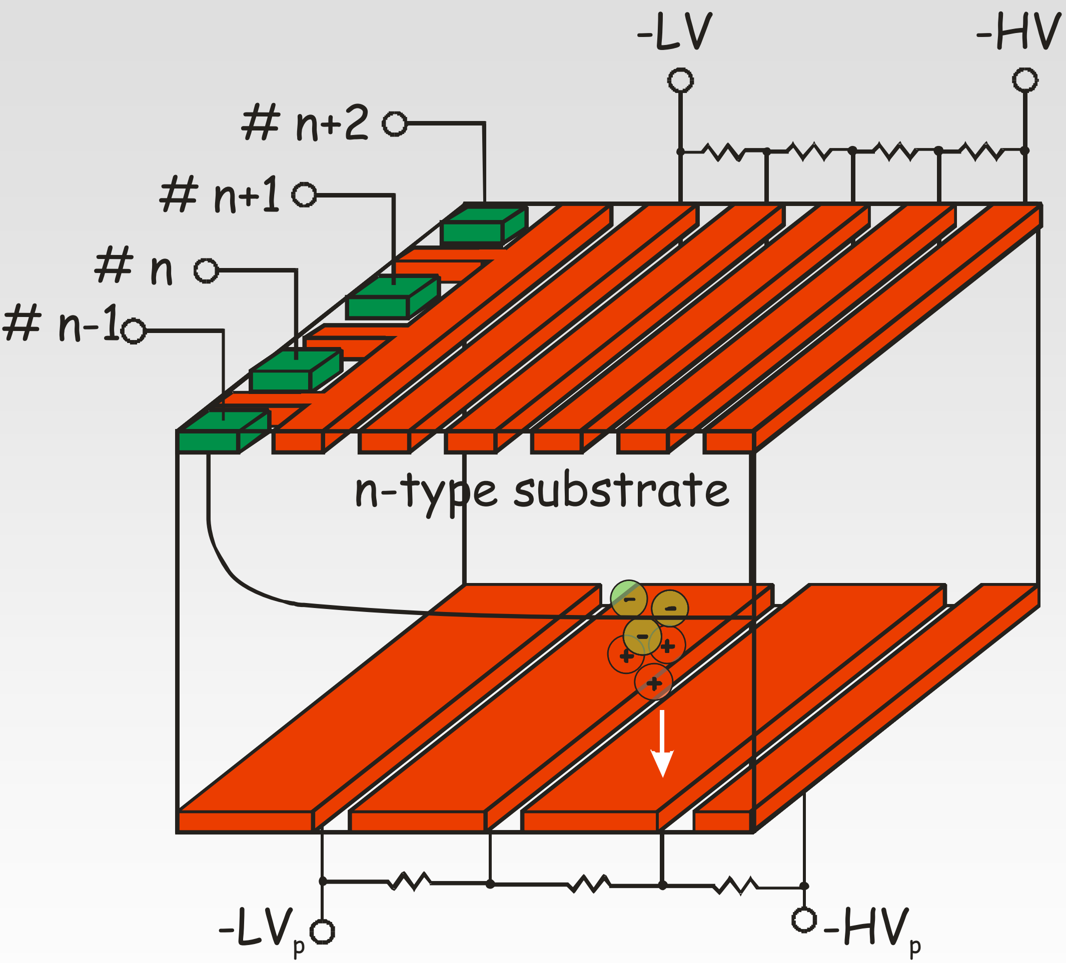
Gatti et al, "The Concept of a Solid State Drift Chamber" DPF Workshop Collider Detectors, Lawrence Berkeley Lab., Feb. 28–Mar. 4, 1983.
Gatti et al, "Semiconductor Drift Chamber . . . " 2nd Pisa Meeting on Advanced Detectors, Grosetto, Italy, Jun. 3–7, 1983.

Primary Examin
Attorney, Agent,
Gottlieb; Judsor

[57]

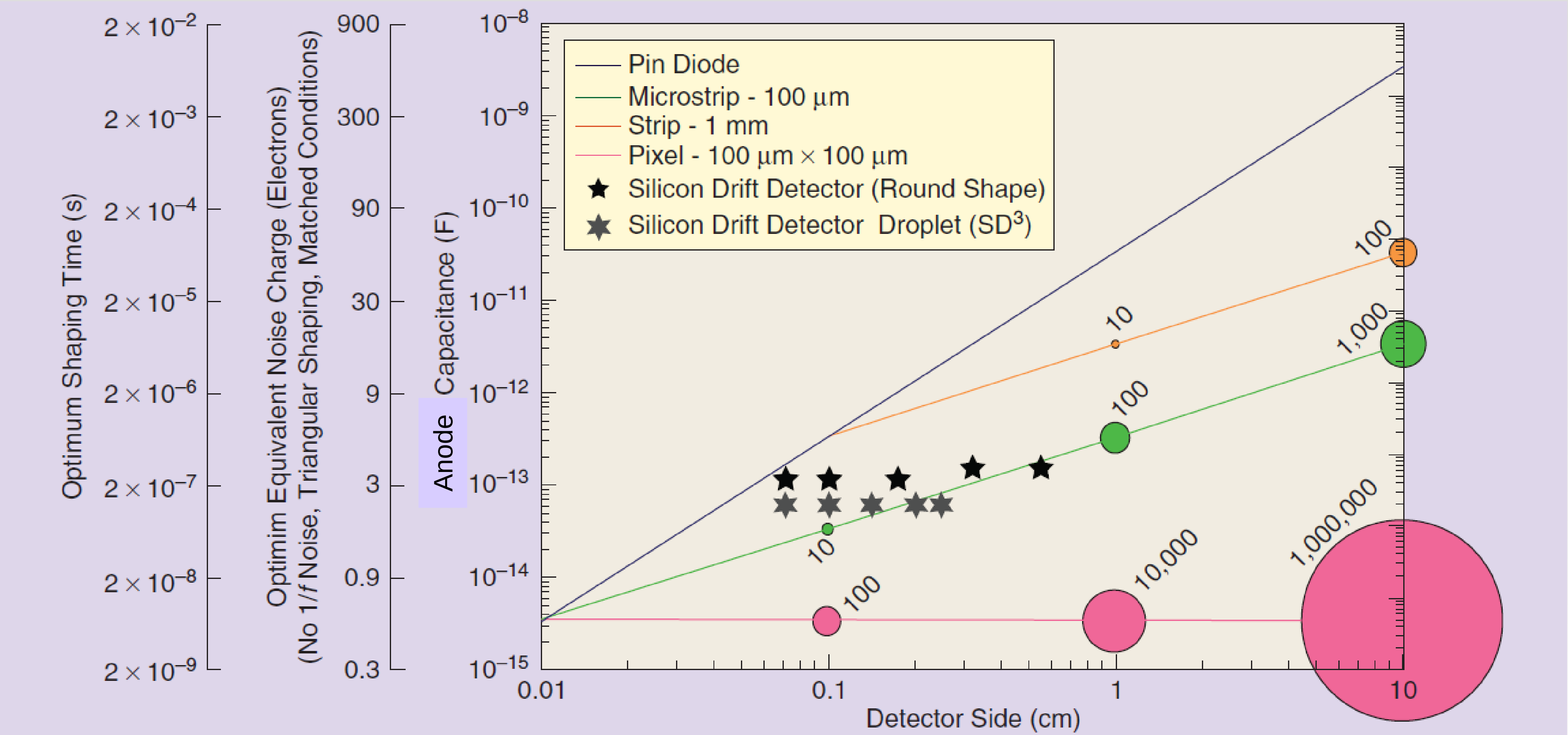


Multianode Silicon Drift Detectors



- granularity of the anodes provides lateral interaction coordinate
- drift time measurement gives position along drift coordinate with high resolution:
  - ~2μm in lab,
  - ~10 μm in test beam
  - ~20 μm in experiments
- external trigger required for 2D position sensing

The Silicon Drift Detector break-through



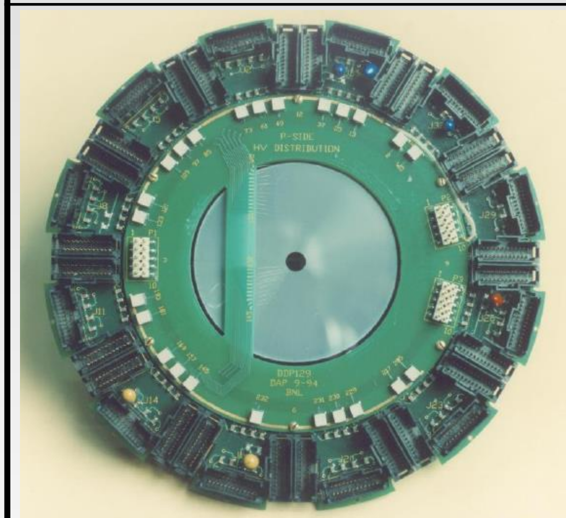
Anode capacitance (of a 300-μm-thick silicon detector), achievable optimal ENC, and optimal shaping time, in the case of no 1/f noise and of triangular shaping for matched conditions between the detector capacitance and the front-end electronics input capacitance, as a function of detector side length for different detector families. The stars report the corresponding values for silicon drift detectors (SDDs) for X-ray spectroscopy. Due to their circular shape, as side length we considered the radius of the active area. This shows how detectors based on the sideward depletion principle broke the tie between active area and output capacitance. The bubble chart represents the number of detector channels needed for a given active area.

A. Castoldi, C. Guazzoni, "IEEE Solid-State Circuits Magazine, Vol. 4 , No. 3, 2012, pp. 46-54

SDDs in High Energy Physics

NA45 - CERES

@ CERN's LEP (1992-2000)



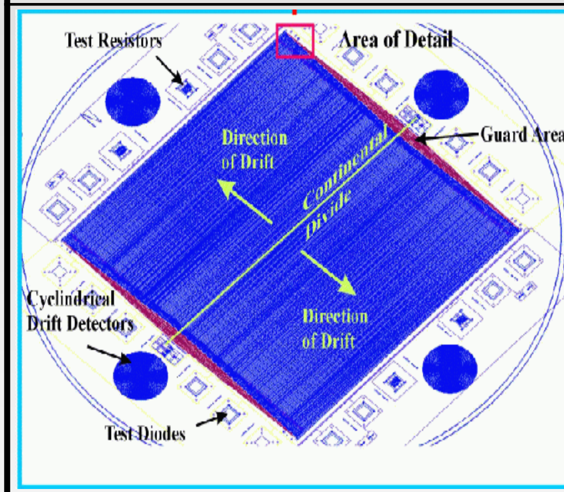
Wafer: 1st ver.: 3" Silicon,
280 μm thick
2nd ver.: 4" Silicon

Active area: 32 cm^2/55 cm^2
360 collecting anodes

Foundry: BNL/Sintef

STAR

@ BNL RHIC (install Feb.01)



Wafer: 4" (NTD) Silicon,
3 kΩcm resistivity,
280 μm thick

Active area: 6.3 × 6.3 cm^2
2 × 240 collecting anodes

Foundry: Sintef

ALICE

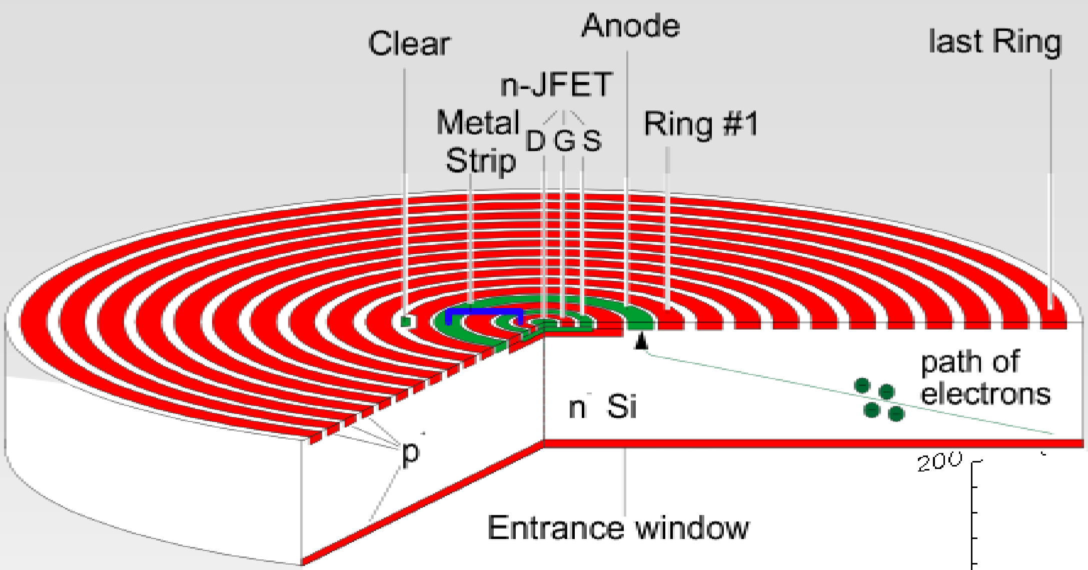
@ CERN's LHC

Wafer: 5" (NTD) Silicon,
3 kΩcm resistivity,
300 μm thick

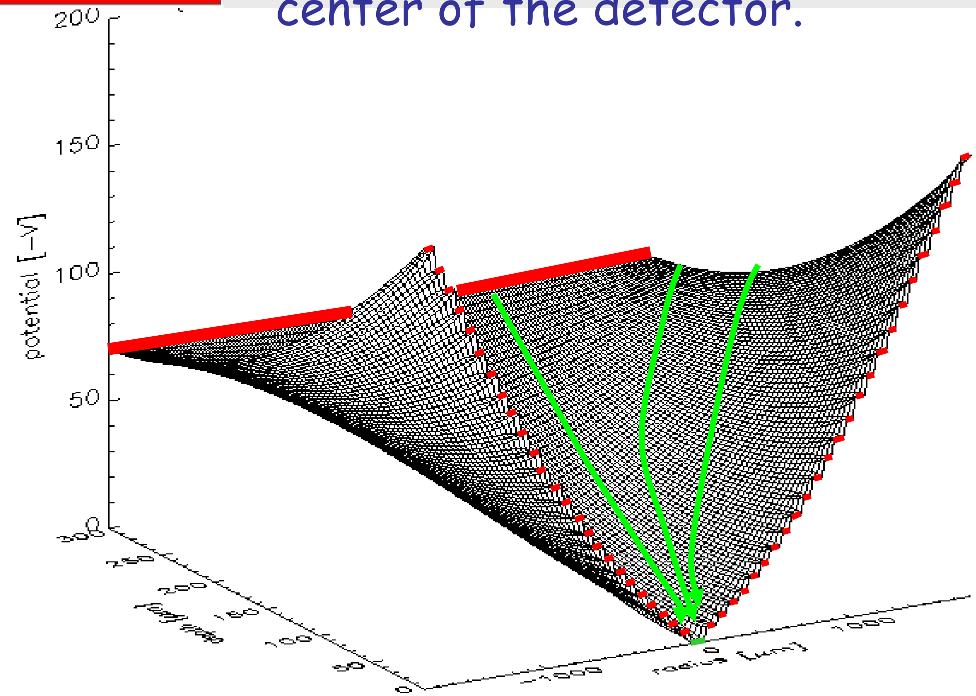
Active area: 7.02 × 7.53 cm^2
512 collecting anodes

Foundry: Canberra

SDD for high resolution X-ray spectroscopy



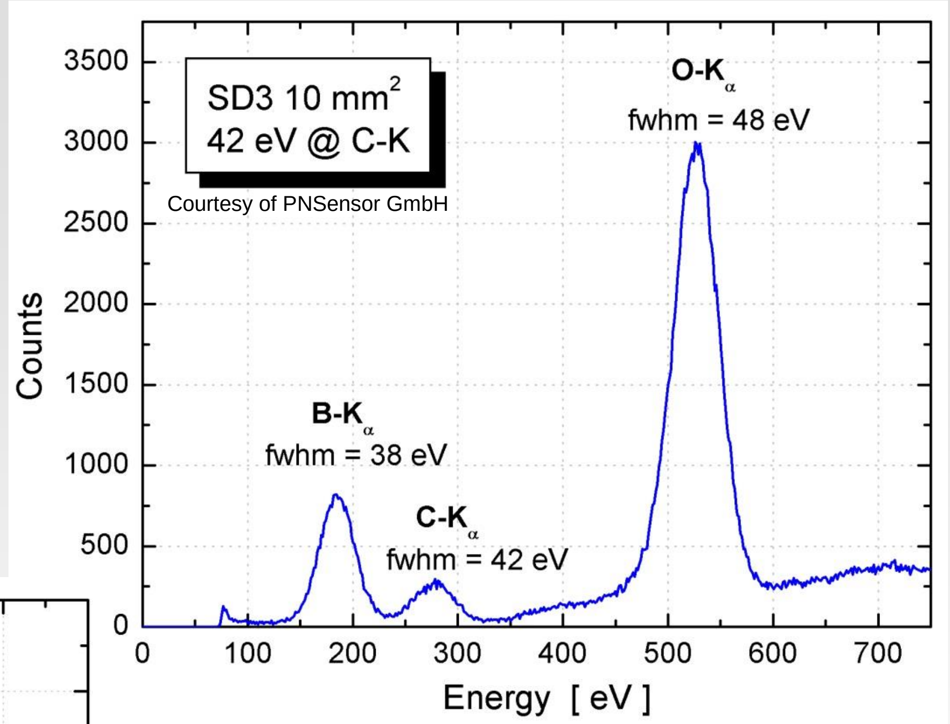
- continuous p+ back contact acting as entrance window
- cylindrical geometry with anode in the center
- transistor located in the center of the detector.

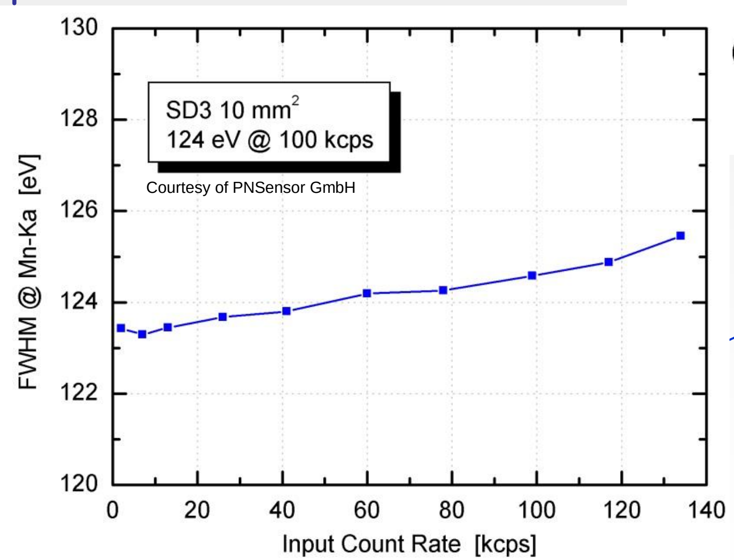


- drift field azimuthally symmetric
- electrons produced anywhere within detector active area are collected at the central anode
- detector capacitance ≅ 100 fF

SDDs for high res. spectroscopy

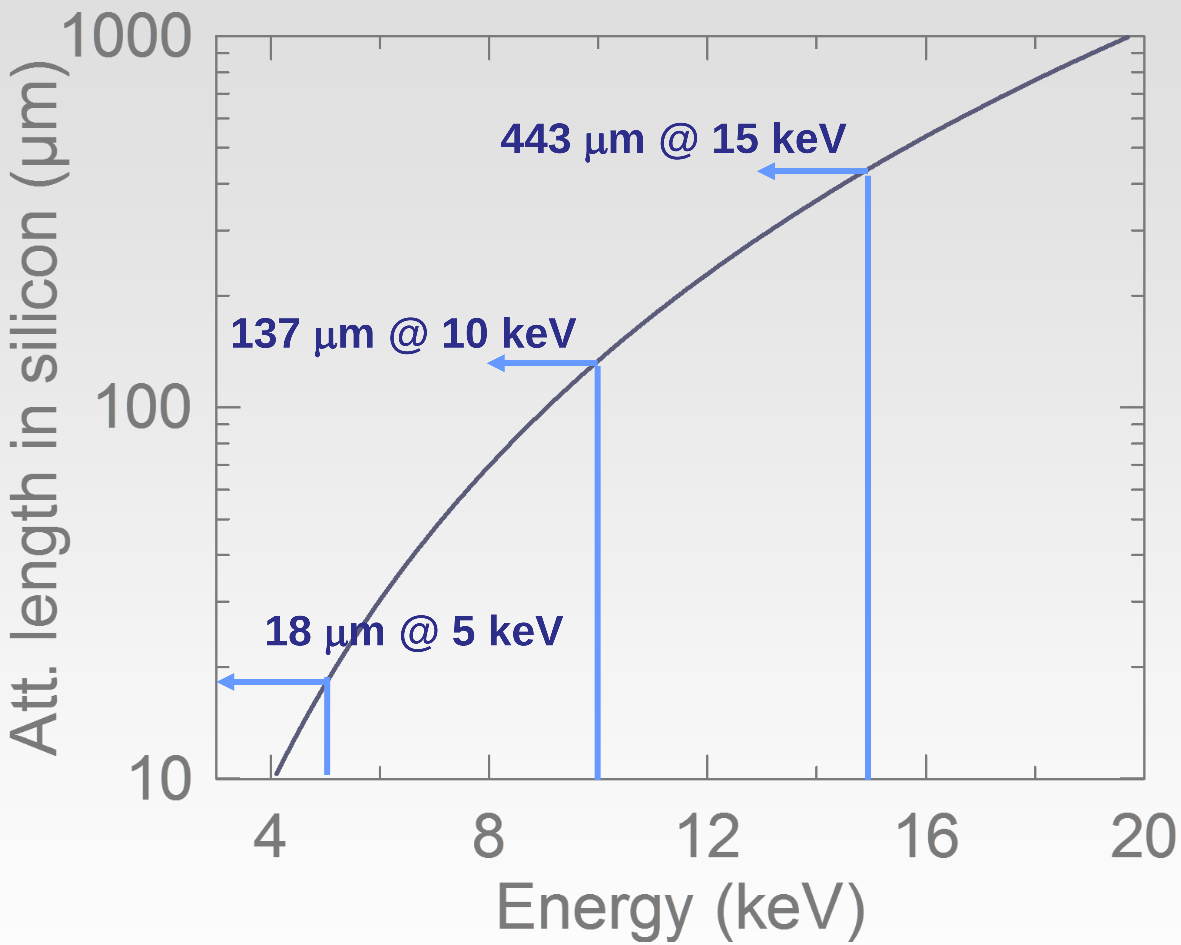
- Anode capacitance: ~200 fF
- Energy resolution: ΔE_{FWHM} = 125 eV (equivalent to ENC=4 el. r.m.s.) @ 200kcps
- Count rate capability: up to 10^6 cps
- Peak/Background ≈ 10.000 : 1
- Quantum efficiency: > 90% @ 0.3-10 keV (Boron line detection)
- Rad. hardness: > 10^{14} Mo_K photons
- Operating temperature: T ≈ - 10° C



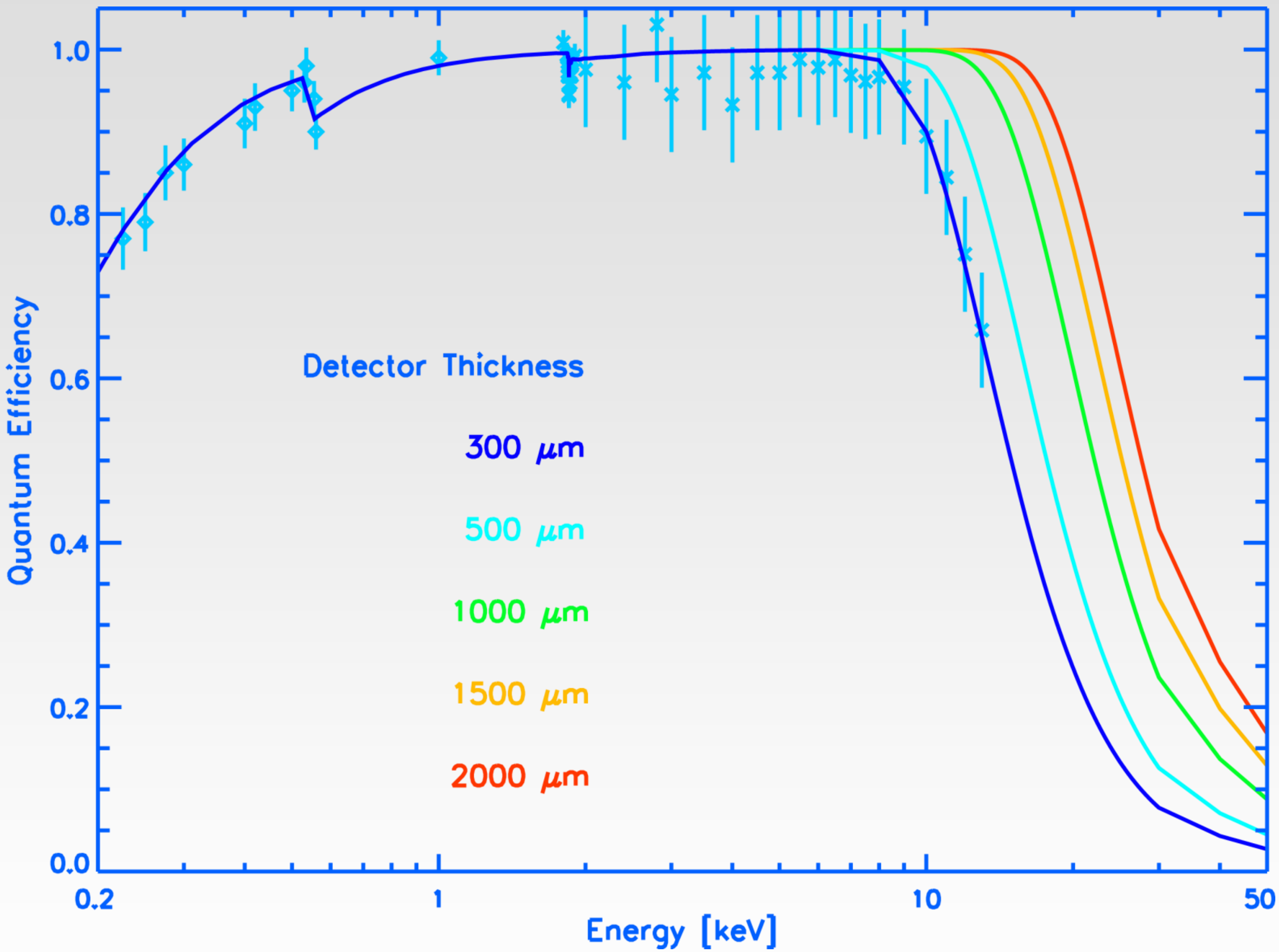


with pulset reset PA thanks to on-chip reset diode

Silicon quantum efficiency

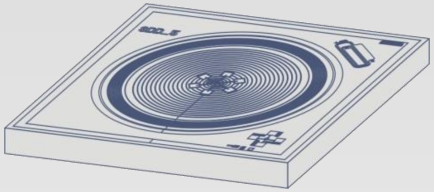


Silicon quantum efficiency



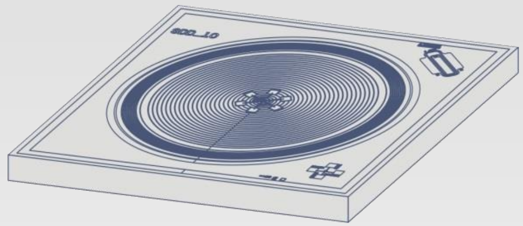
SDDs for high res. spectroscopy

Commercially available classic cylindrical SDDs with sensitive area of 5, 10 and 20 and 30 mm2 up to 1cm^2



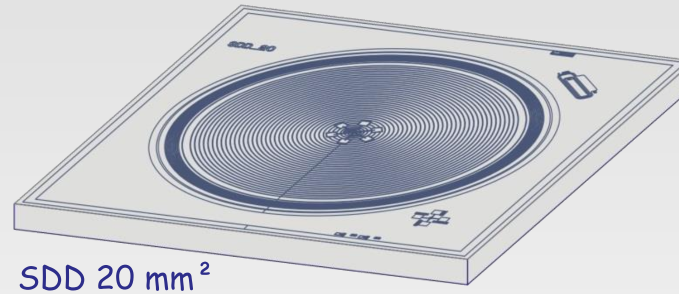
SDD 5 mm^2

chip 5 x 5 x 0.45 mm^3



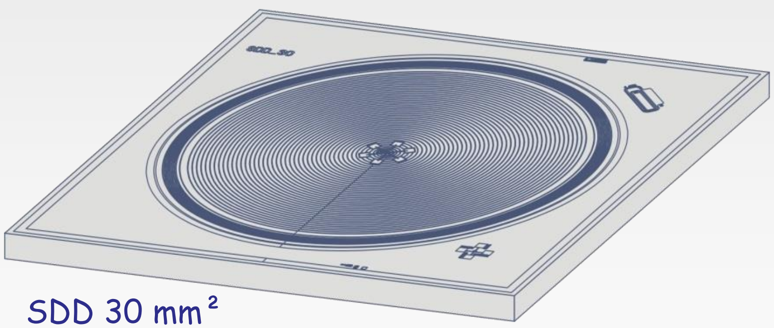
SDD 10 mm^2

chip 6 x 6 x 0.45 mm^3



SDD 20 mm^2

chip 8 x 8 x 0.45 mm^3



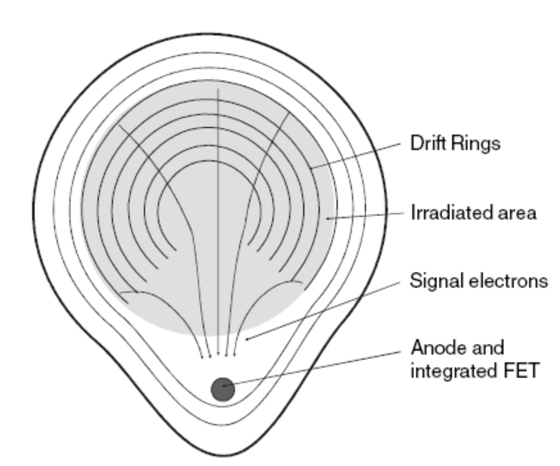
SDD 30 mm^2

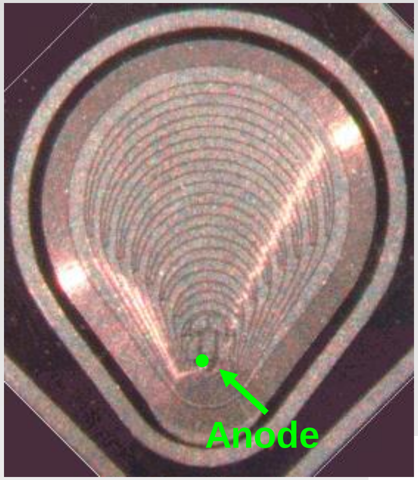
chip 9 x 9 x 0.45 mm^3

SDD 100 mm^2

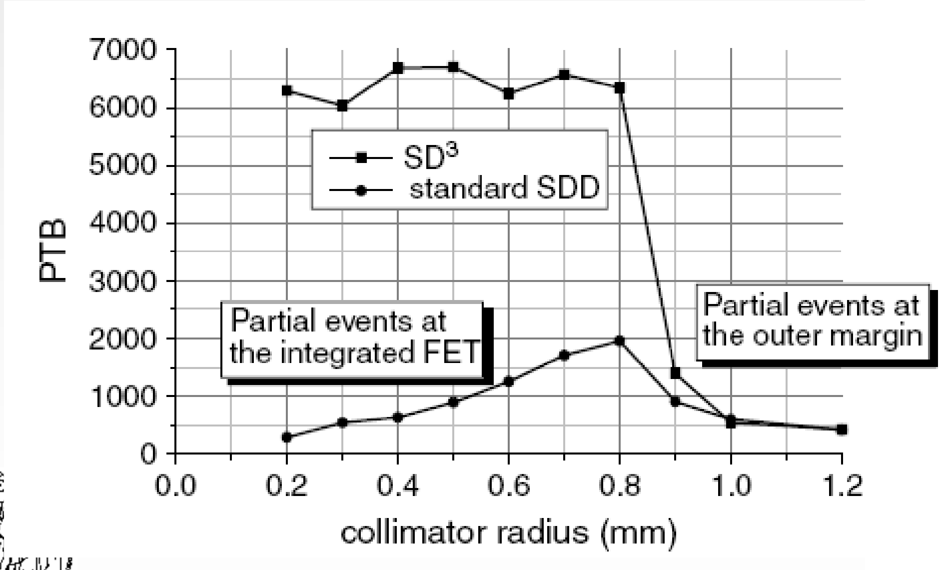
chip 14 x 14 x 0.45 mm^3

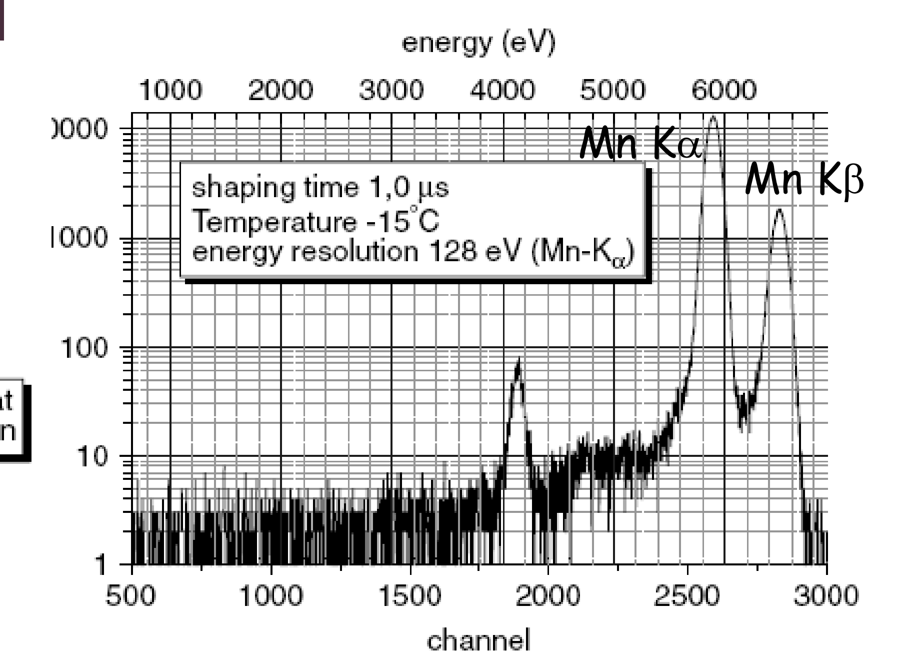
Droplet SDDs: novel evolution



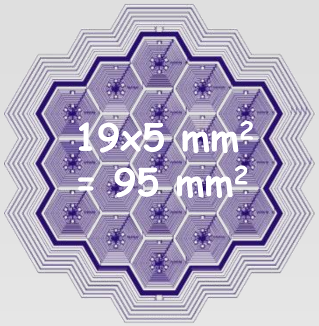


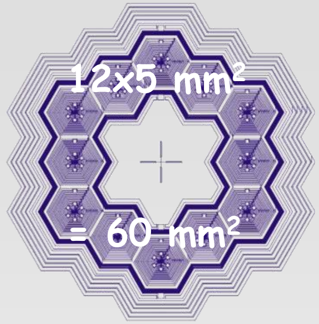
- Anode + on-chip JFET outside detector active area → improvement of the peak-to-background ratio.
- Very small collecting anode → output capacitance about 120 fF much lower than conventional SDDs (larger than 200 fF)

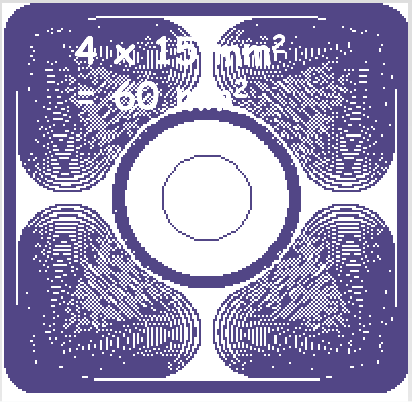


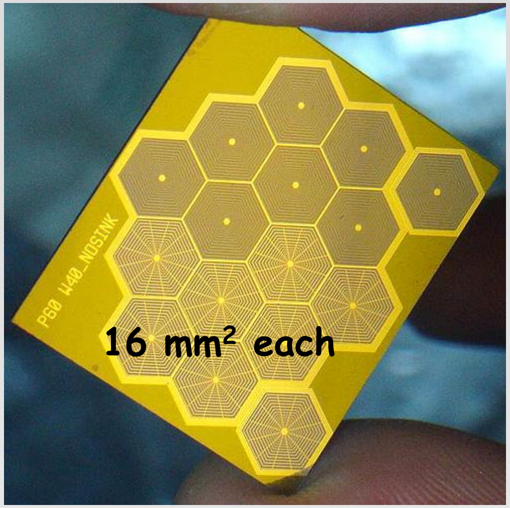


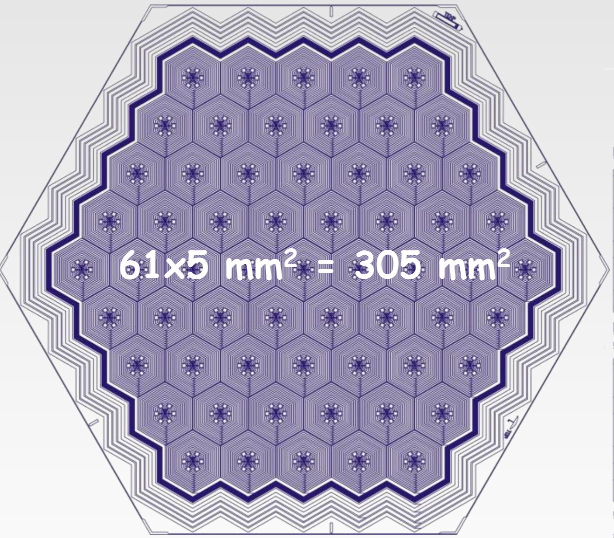
Multichannel SDDs

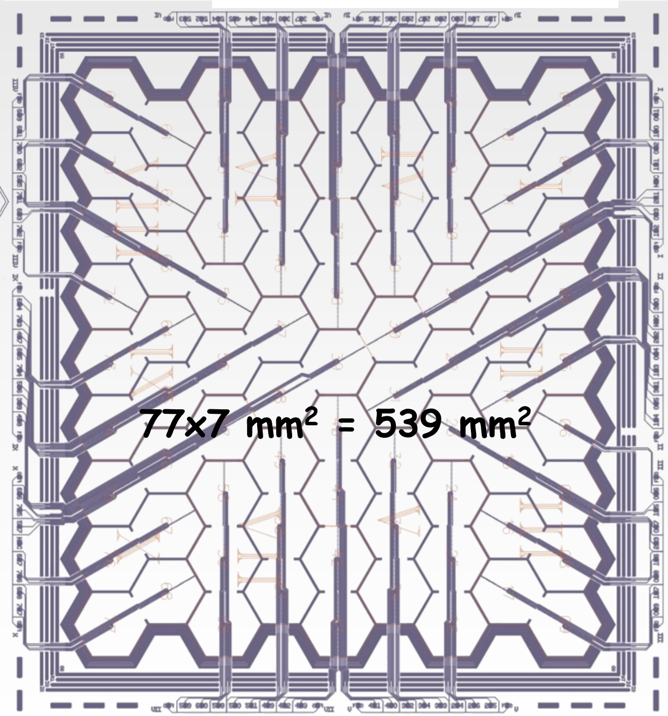


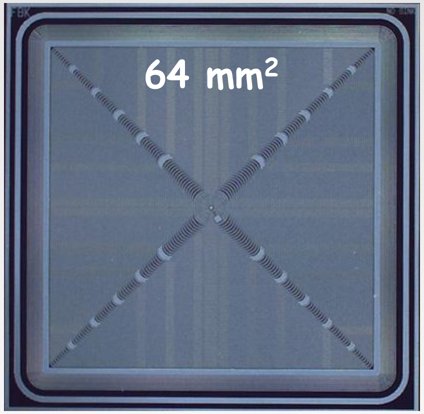


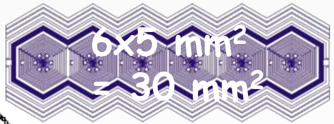


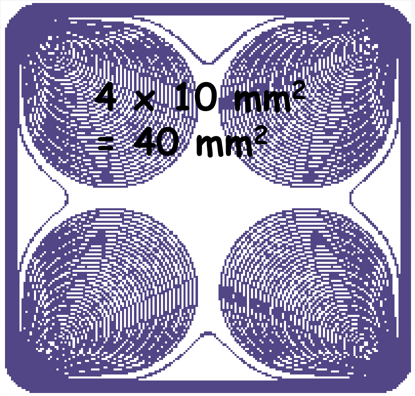






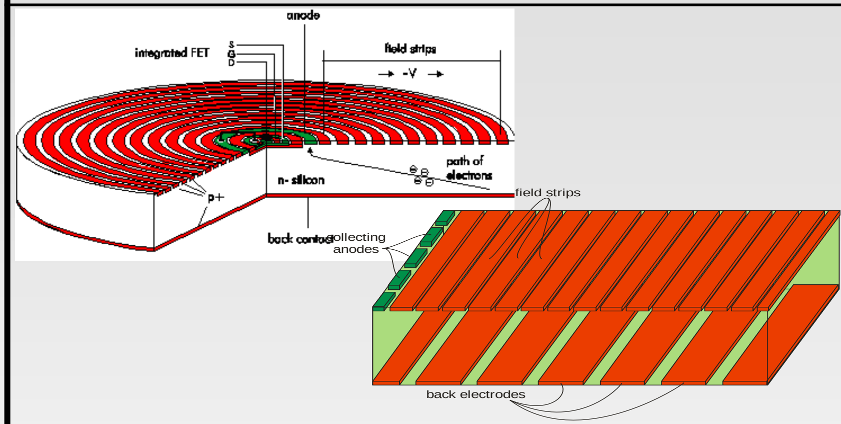




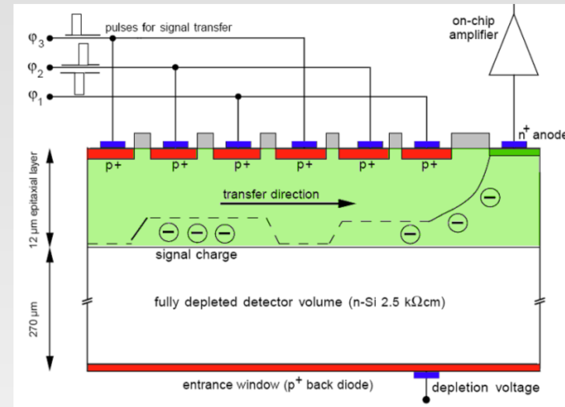


Sideward Depletion Family Tree

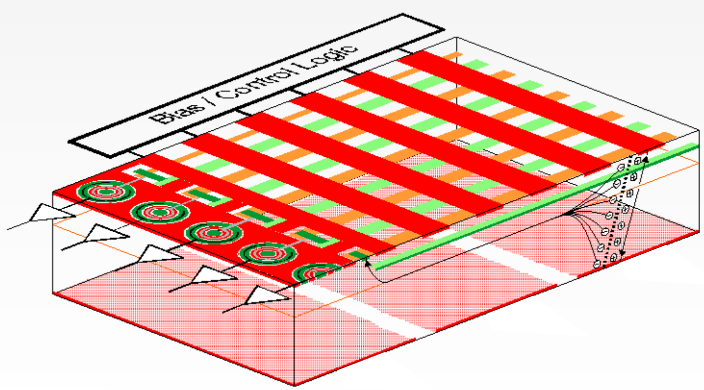
Silicon Drift Detector



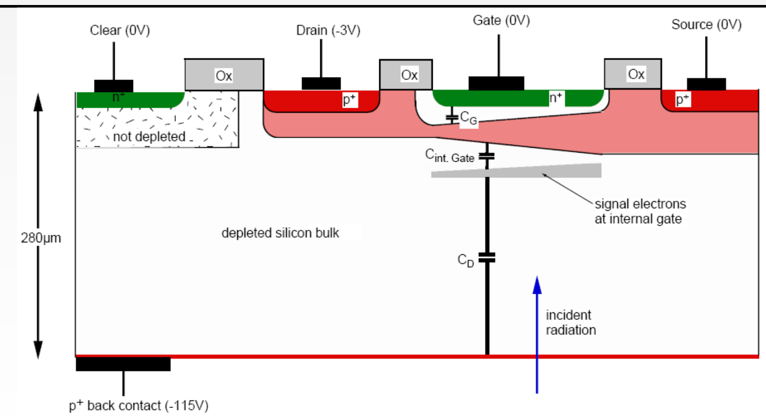
Fully Depleted pnCCD



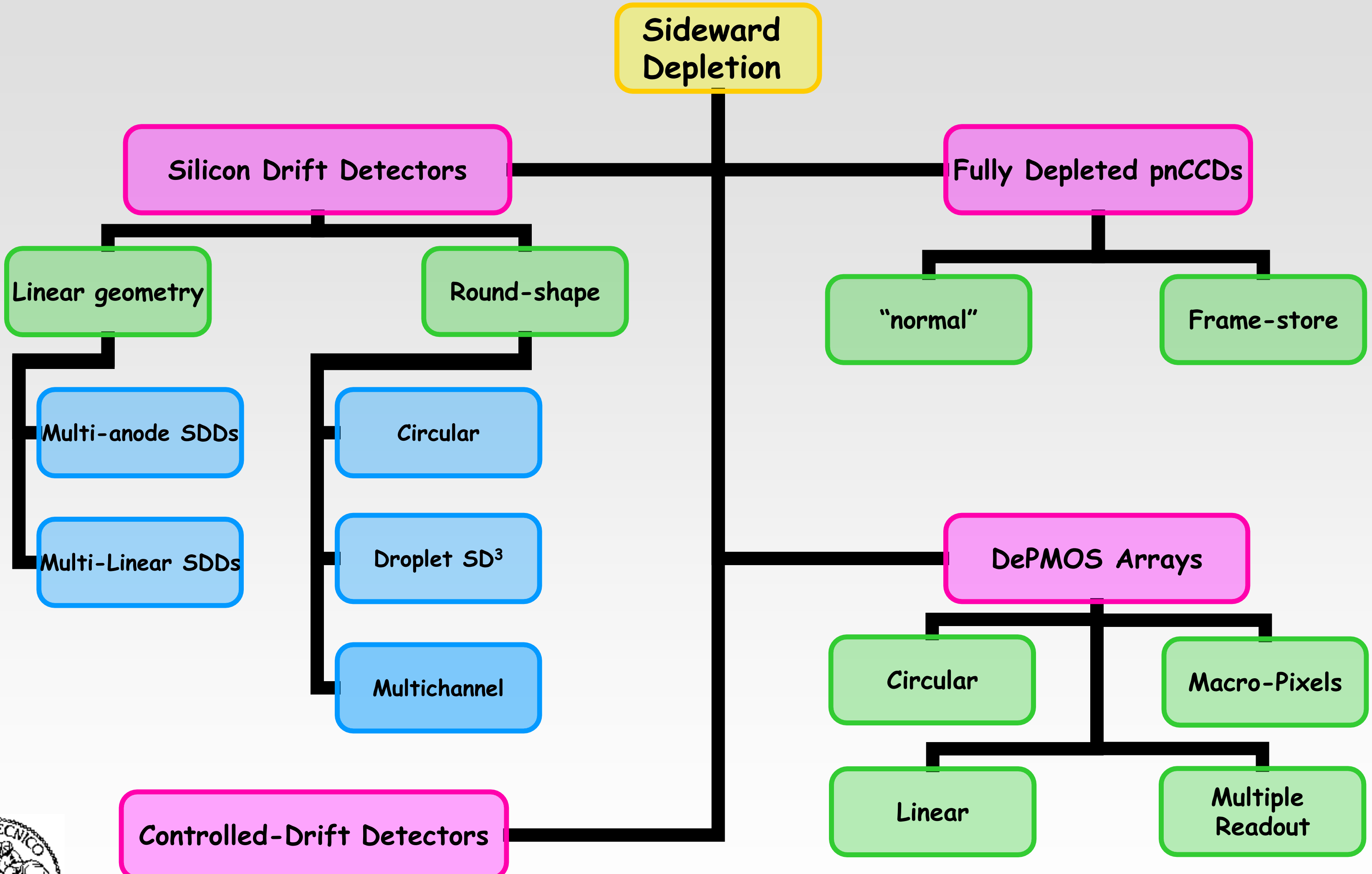
Controlled-Drift Detector



DePMOS



Sideward Depletion Family Tree



Limitations of SDD for 2D position sensing

➢ START TRIGGER NEEDED !

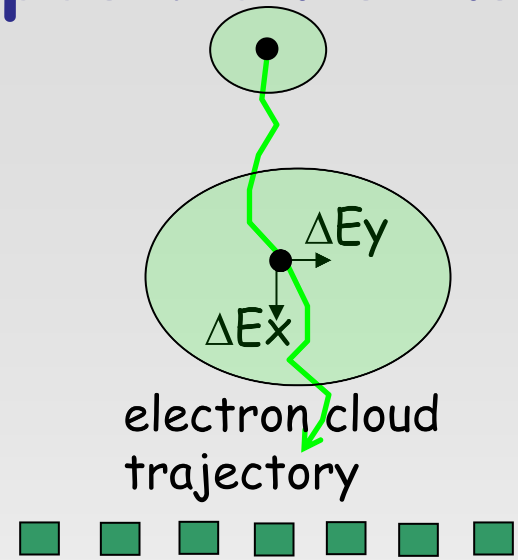
no imaging of random sources (x/γ/…) !

➢ FREE LATERAL BROADENING

☺ position resolution along anodes improved by interpolation

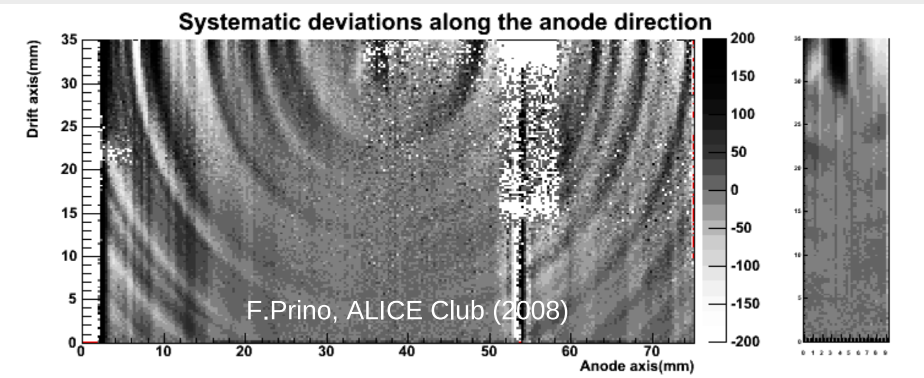
☹ centroid algorithm not optimal for all incident positions

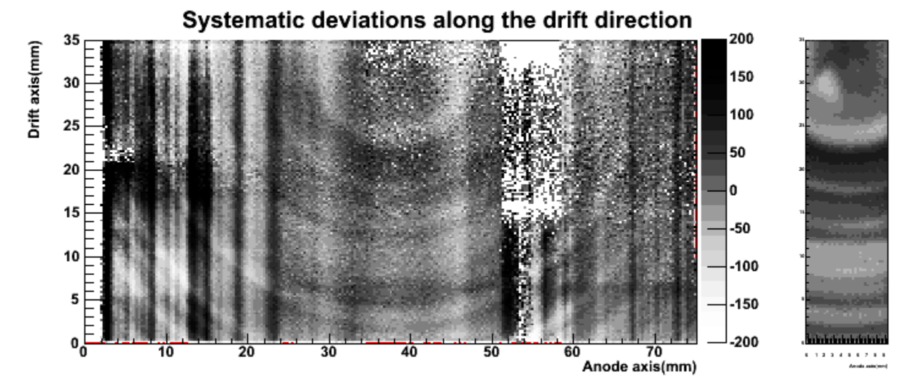
☹ charge sharing limits spectroscopic performance and reduces event rate



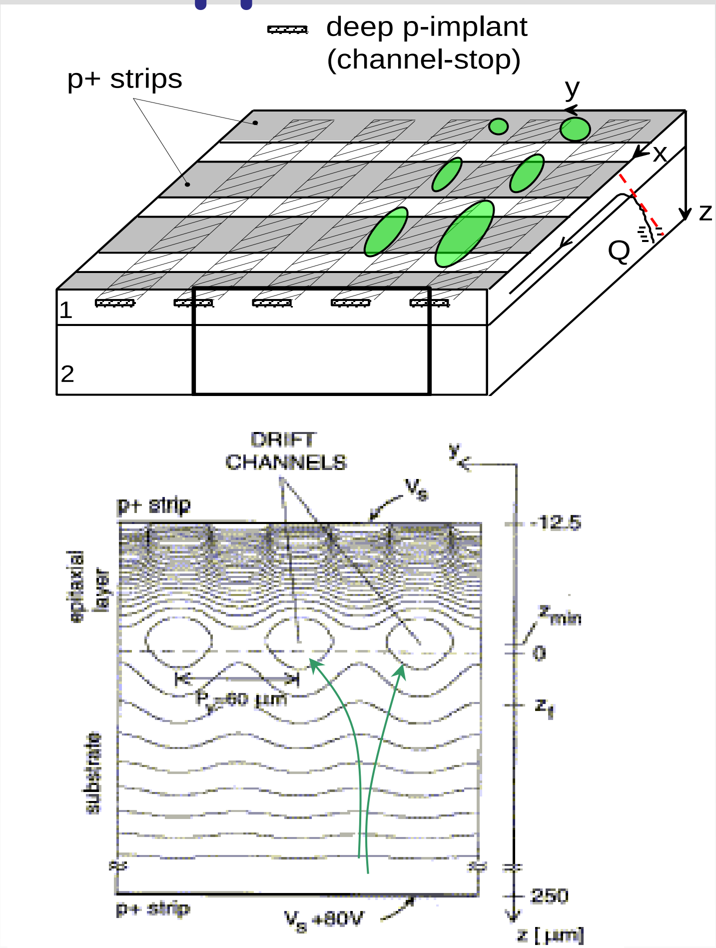
➢ DOPING INHOMOGENEITIES

☹ systematic deviations (up to +/- 200μm) along anode direction

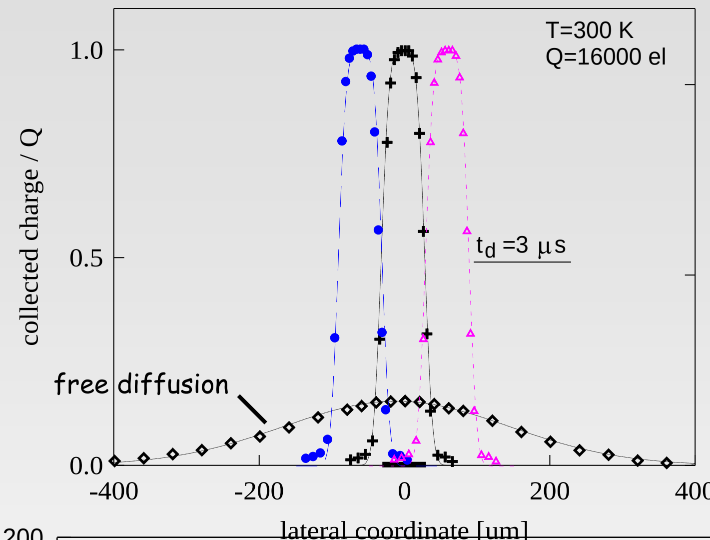


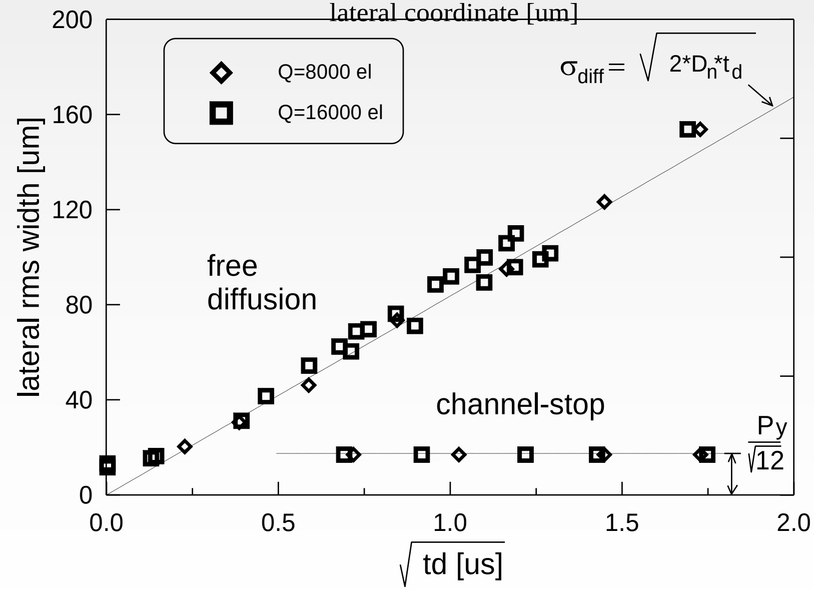


Suppression of lateral broadening



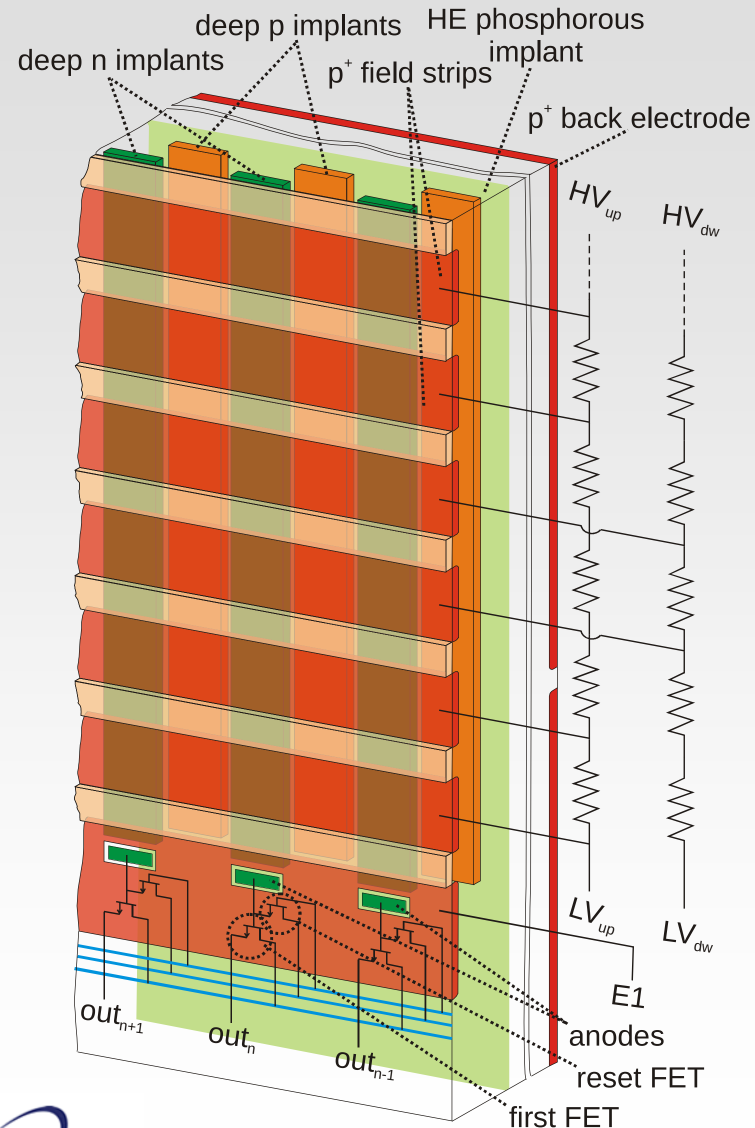
A.Castoldi, P.Rehak, P.Holl, "A New Silicon Drift Detector With Reduced Lateral Diffusion" Nucl. Instr. and Meth., A377 (1996) 375-380.





→ cloud size independent of interaction point
→ compensation of doping inhomogeneities
→ high count rate applications
→ event timing via signal induction

Multi-Linear SDD architecture



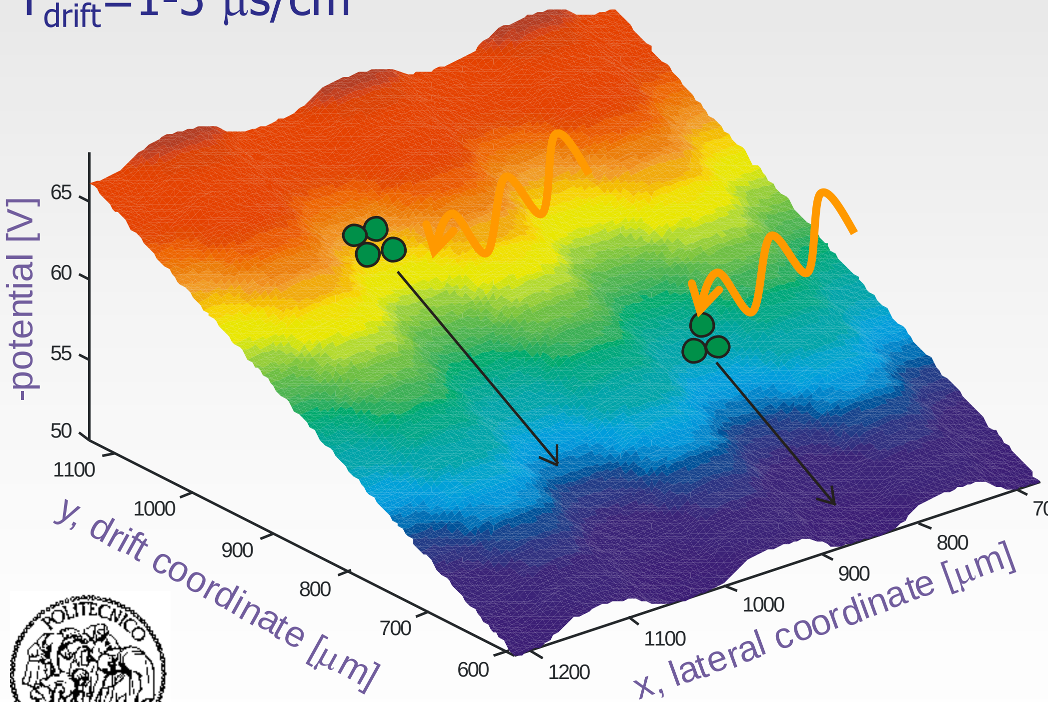
- fully depleted n-type bulk
- p+ entrance window implanted on the back side
- array of p+ strips implanted on the front side
- channel-stops (deep p-implants) for lateral confinement
- channel-guides (deep n-implants) for lateral confinement and drift enhancement
- HE n implant locates the drift channel close to the finely structured surface
- on-chip electronics (JFET in source follower configuration)

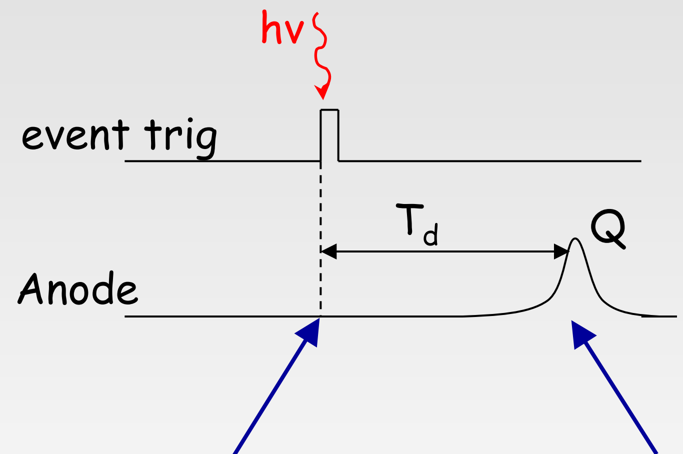
C. Guazzoni – Development of Silicon Drift Detectors and recent applications – Nov. 12, 2013
2013 Workshop of the Technology and Innovation Group of the European Physical Society
"Advanced Radiation Detectors for Industrial Use"

MLSDD operating modalities - I

- free-running mode (external trigger)
- free-running mode (self-trigger from back side)

T_{drift}=1-3 μs/cm



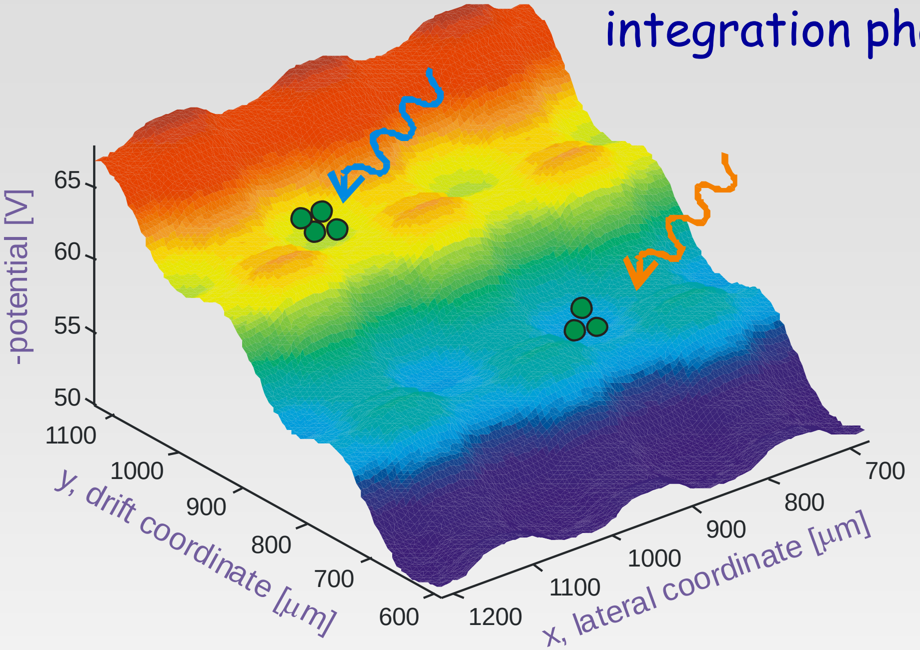


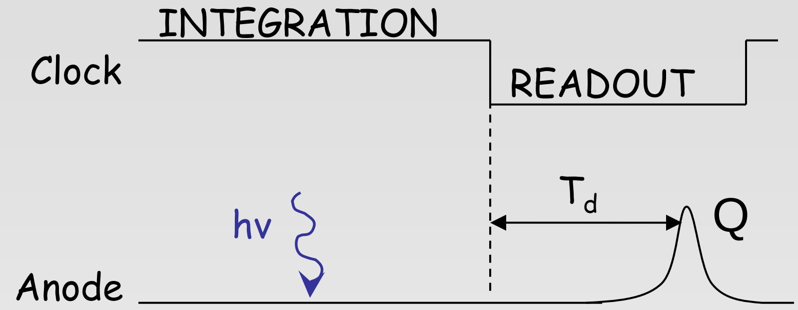
start-time and event-trigger (back side induction or ext. trigger)

stop-time and charge from anode signal

MLSDD operating modalities - II

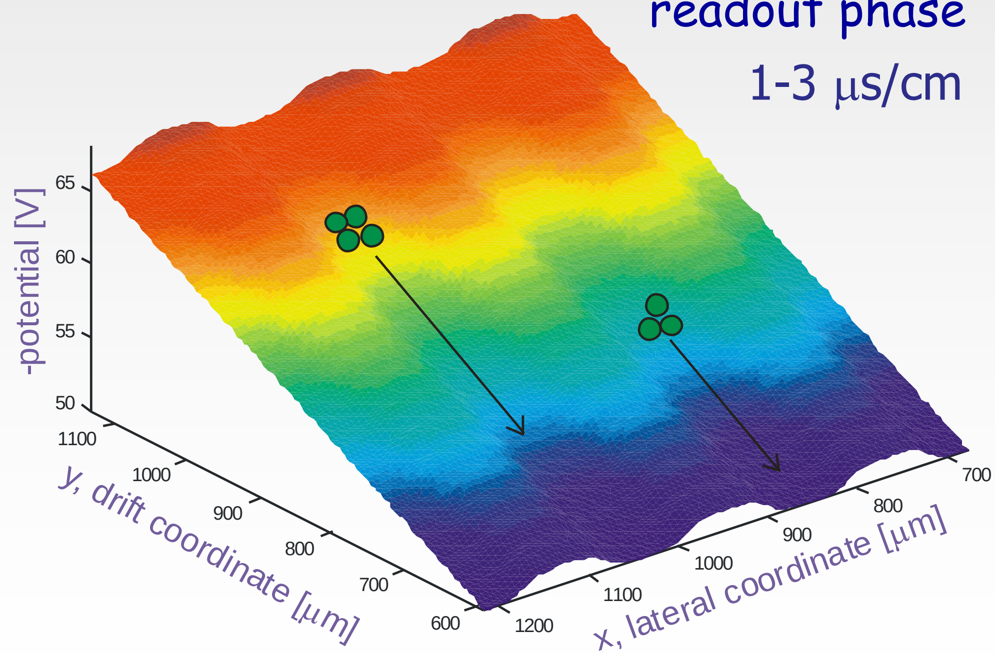
integration phase





readout phase

1-3 μs/cm

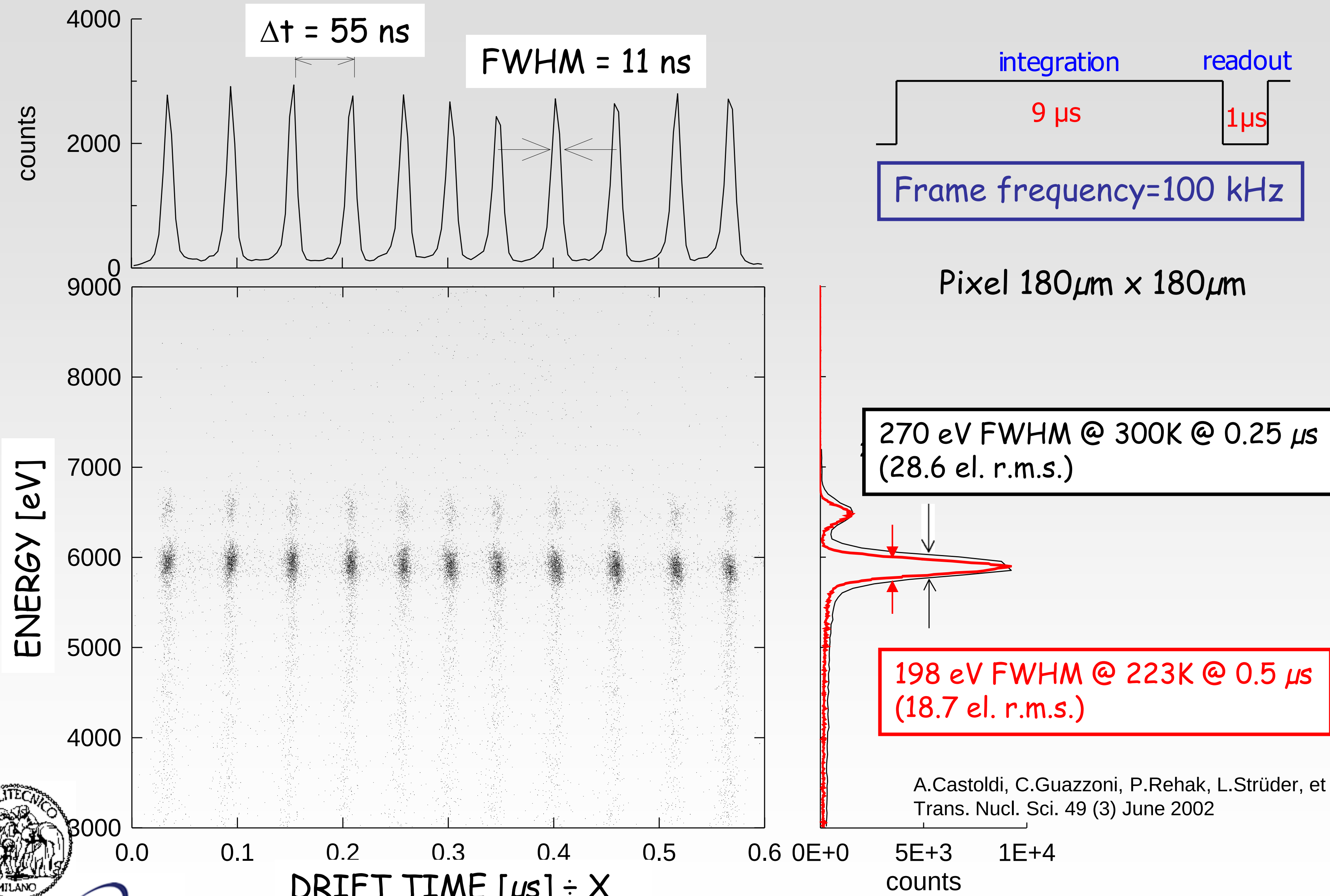


A. Castoldi, C. Guazzoni, C.Ozkan, G.Vedani, R. Hartmann and A.Bjeoumikhov, “Spectroscopic Imaging Applications”, Microsc. Microanal. 15, 231–236, 2009

integrate-readout mode

Controlled-Drift Detector (1997)

1-D imaging & spectroscopy @100 kHz

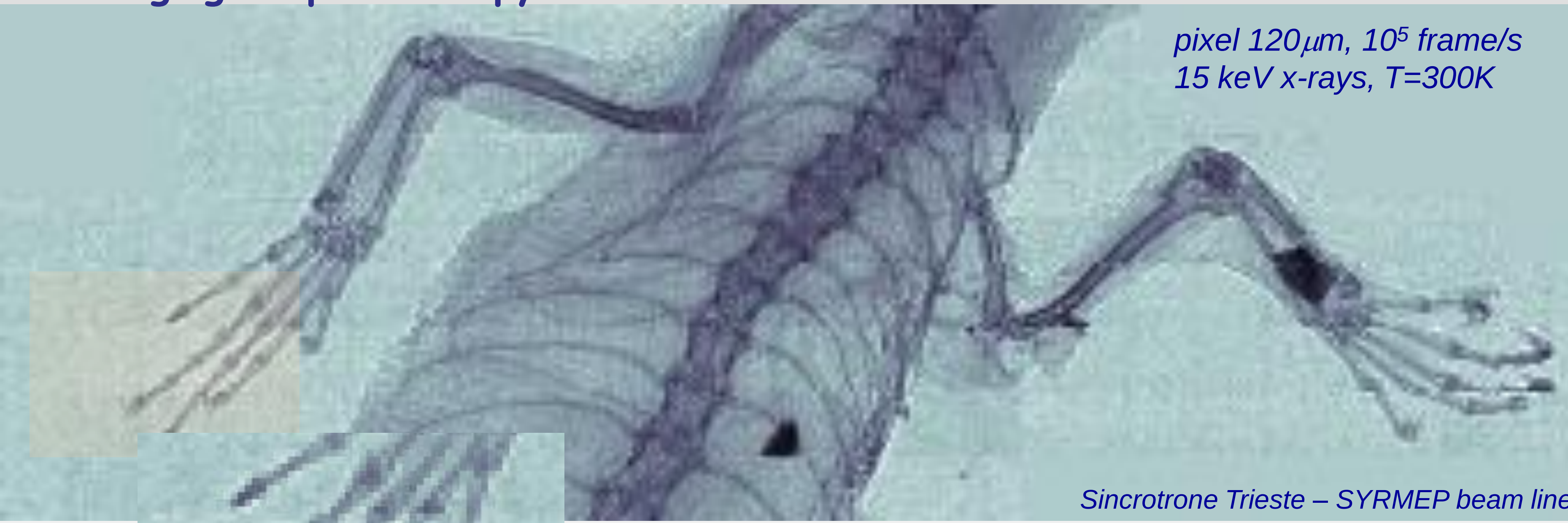


A.Castoldi, C.Guazzoni, P.Rehak, L.Strüder, et al,
Trans. Nucl. Sci. 49 (3) June 2002

2-D spectroscopic X-ray imaging with CDDs

2D imaging & spectroscopy

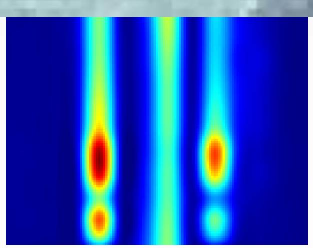
Exp. CODERA (2003)
INFN – Sez. di Milano



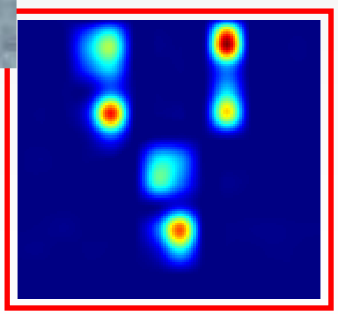
A.Castoldi, G. Cattaneo, A.Galimberti, C.Guazzoni, P.Rehak, L.Strüder, IEEE TNS 49, 3 (2002)
A.Castoldi, A.Galimberti, C.Guazzoni, P.Rehak, L.Strüder, NIM A512 (2003)

219 Hz sine wave
Mask displacement:
2.3 mm p-p

Time-s
X-ray images

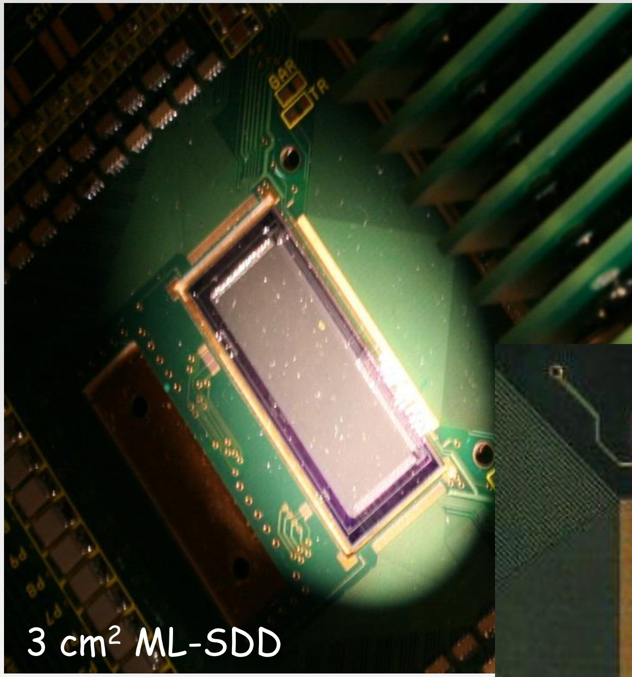


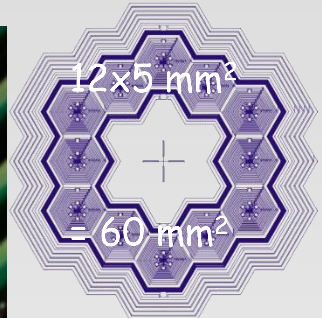
∞

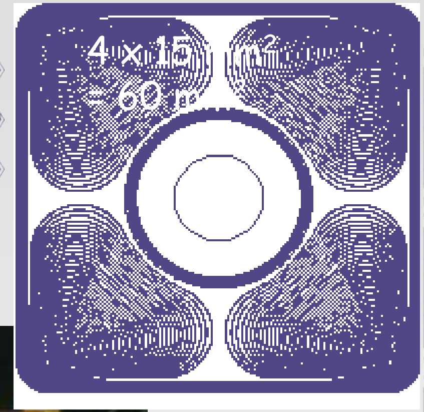


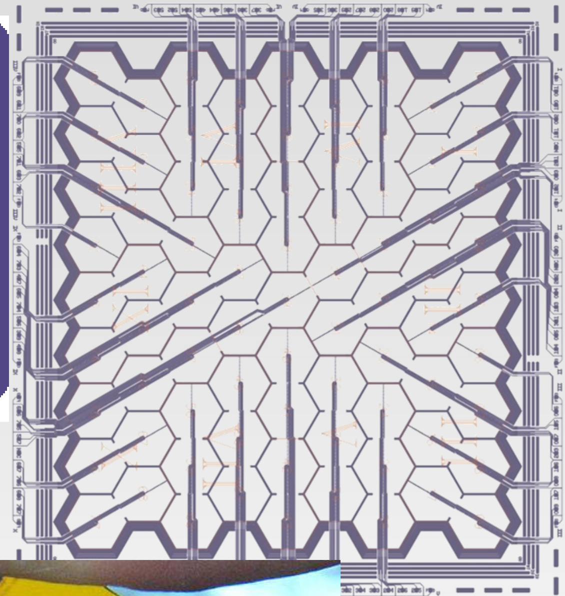
20 µs

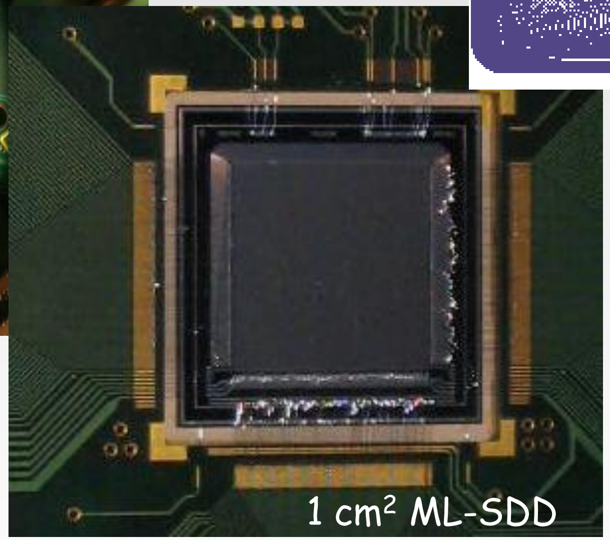
Outlook to applications…

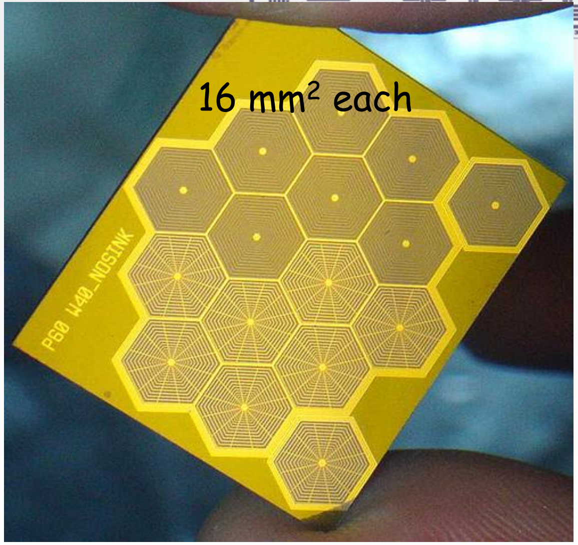


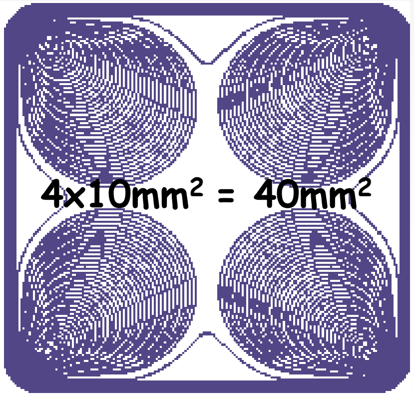


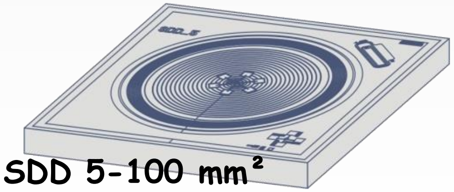










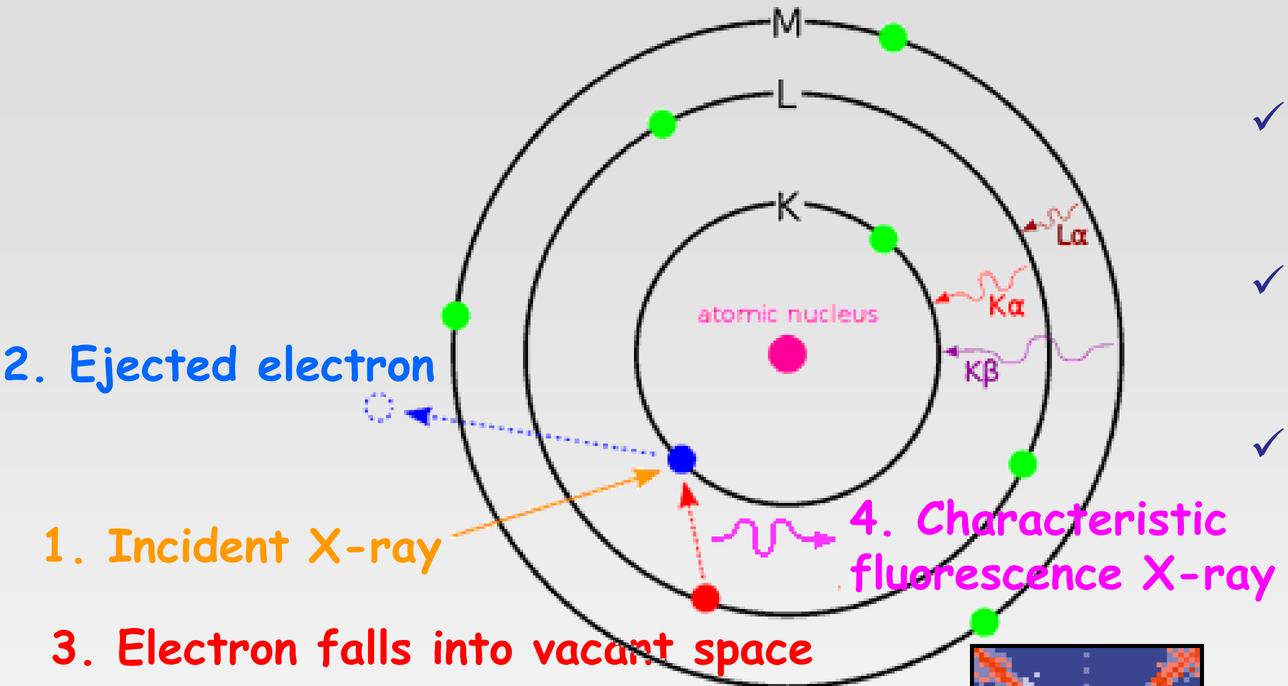


SDD 5-100 mm²
(0.45 mm thick)

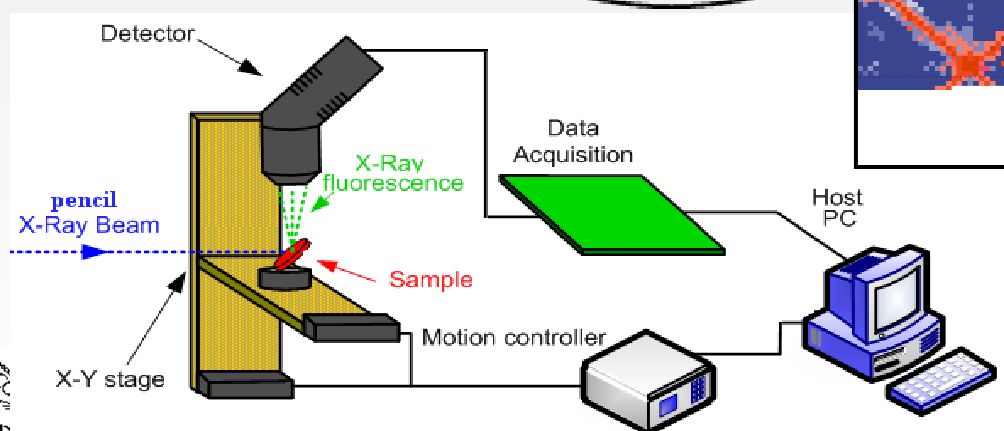
Outlook to applications…

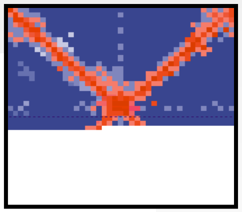
- X-Ray Fluorescence and Proton Induced X-Ray Emission
- Gamma-ray imaging
- Advanced X-ray imaging modalities
- Macro-pixel arrays with DEPFET readout for XFEL

X-ray fluorescence imaging



- ✓ Energy of XRF X-ray is characteristic of element present in sample.
- ✓ Intensity of XRF signal is related to concentration of element in sample
- ✓ XRF is non-destructive.

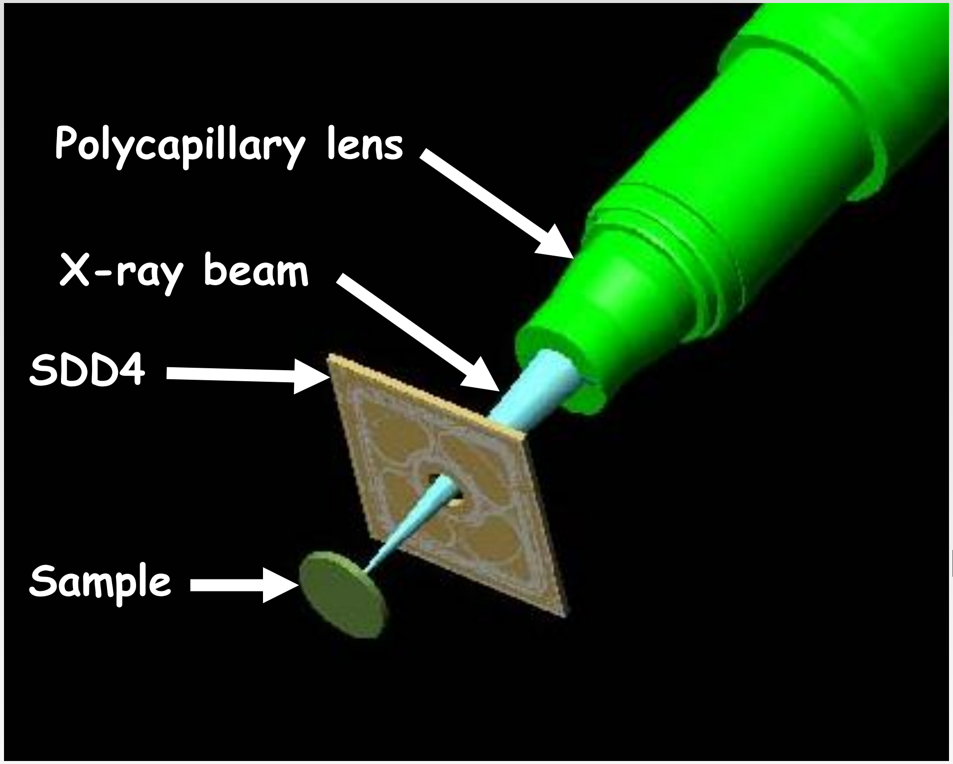


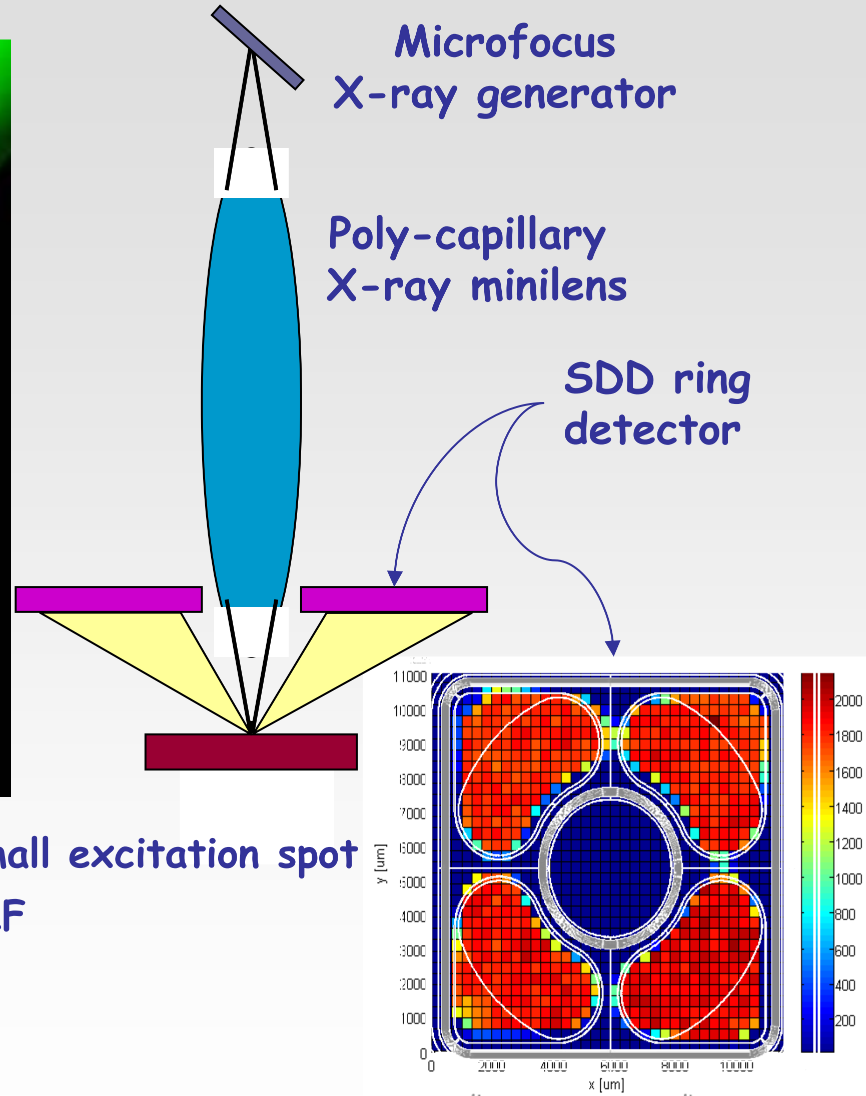


Usually technique performed by a 2D positional scan of a sample against a collimated beam with an energy dispersive detector.

XRF elemental mapping with multi-cell SDDs

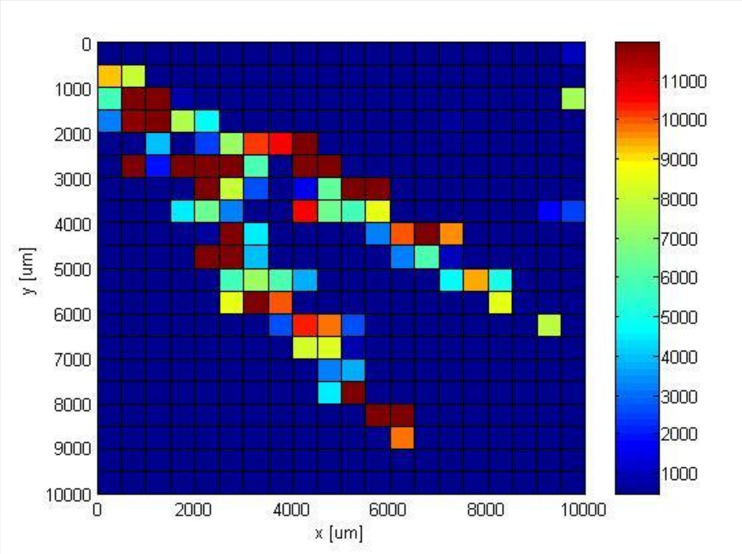
Experiment FELIX INFN Gr.5 2002-05

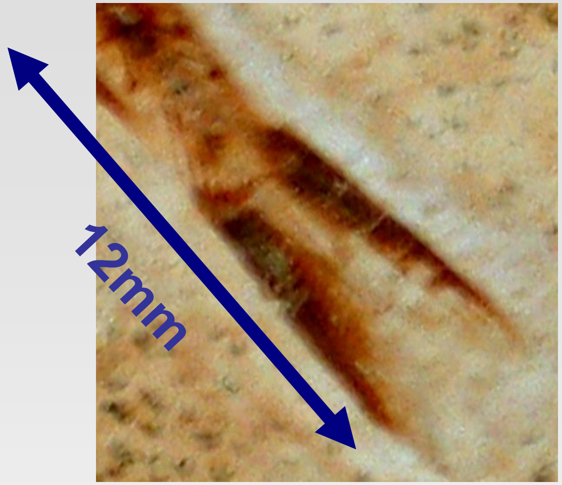


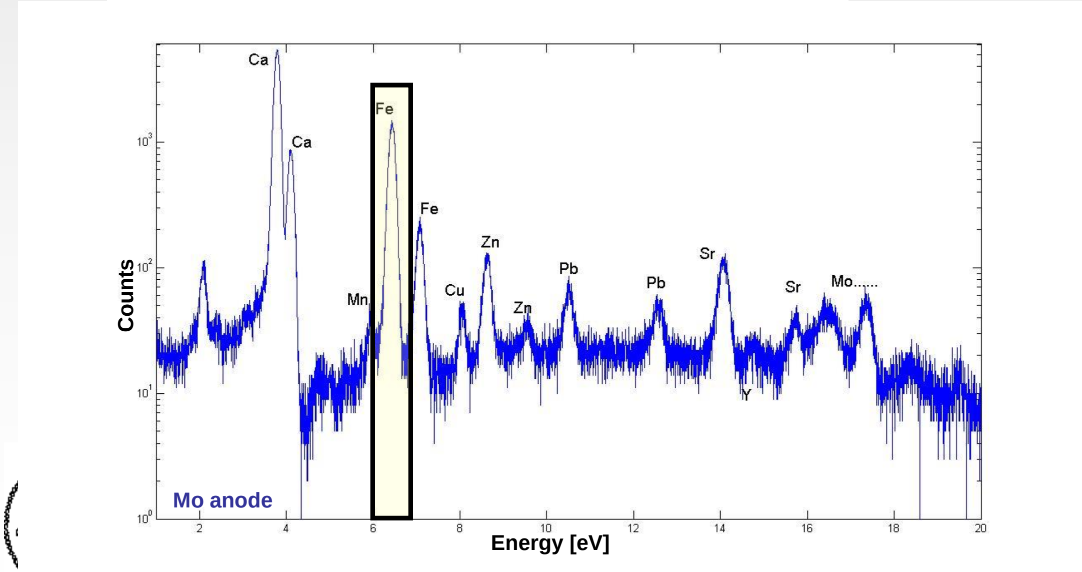


- polycapillary X-ray lens → high photon flux in small excitation spot
- ring-shaped SDD → larger collection angle of XRF

Geological analyses: fossil fish





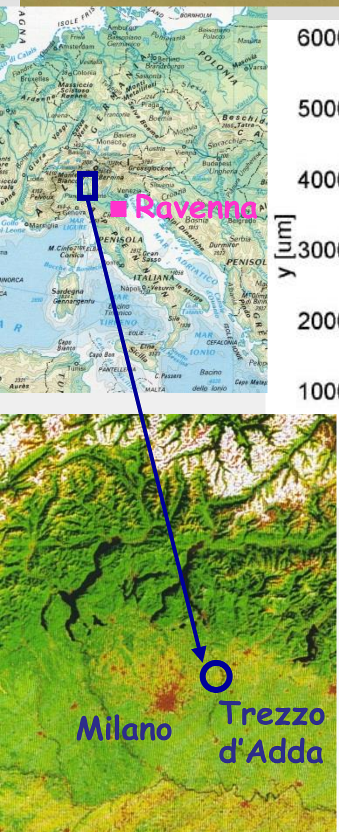


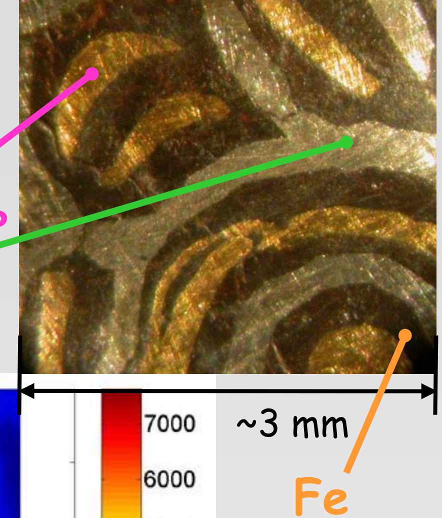
Map of Fe Kα line @ 6.4keV
10x10mm with 500μm step
2 sec per point
Total meas. time 900sec

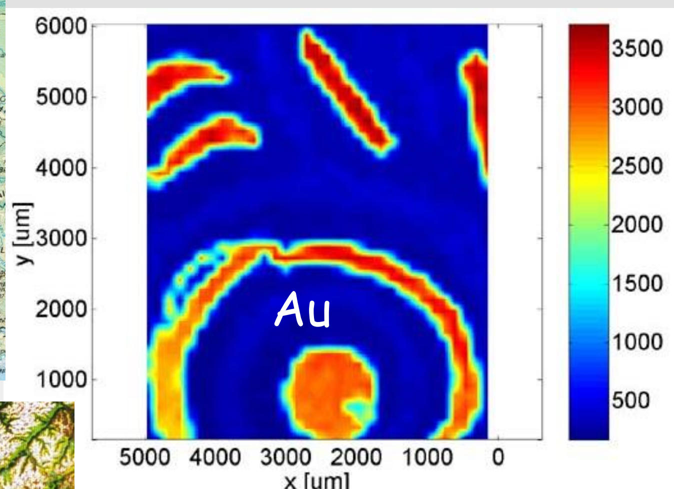
A. Longoni, C. Fiorini, C. Guazzoni, et al., Proc. of the IEEE 2005 NSS, Puerto Rico

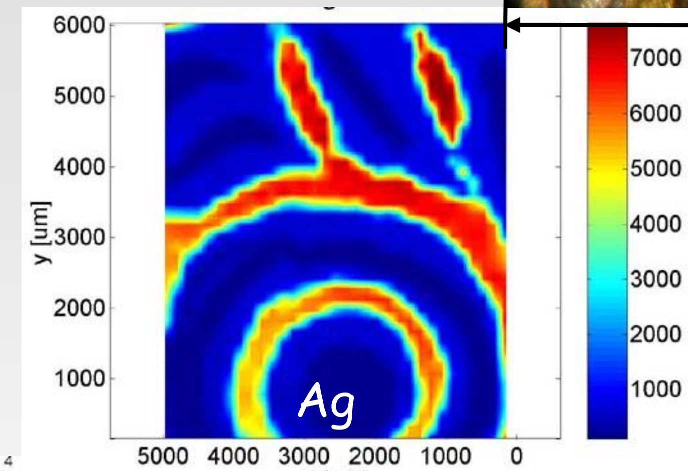
Works of art

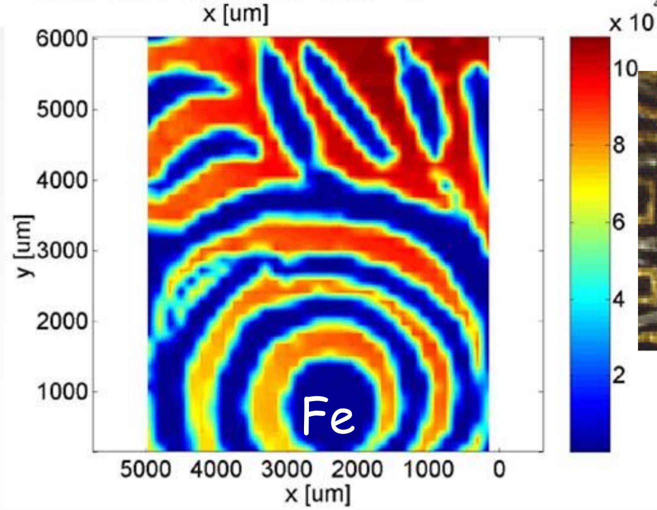
Lombard buckle – inlaid work (agemina) - beginning of VII century A.C. - Trezzo d'Adda, Italy

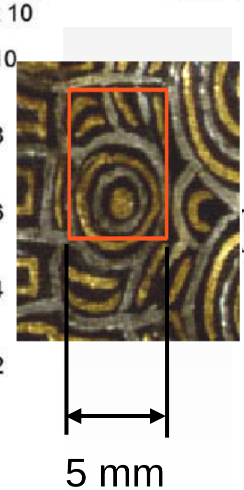


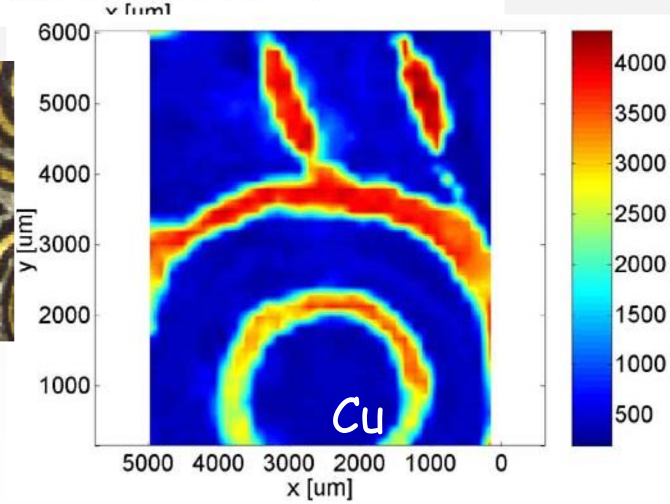












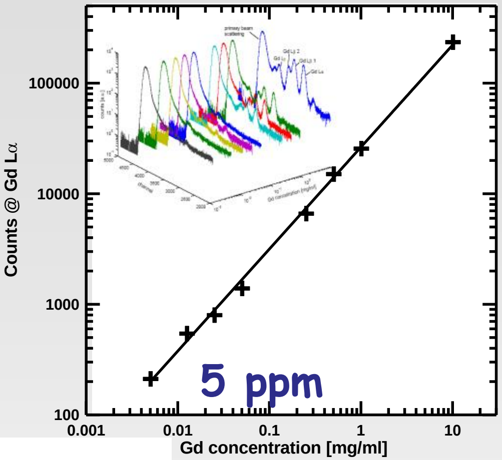
XRF biomedical applications with SDDs

- study of the distribution of drugs and diagnostic agents in biological samples
  - in collaboration with Centro Studi Fegato, University of Trieste, Bracco Centro Ricerche Milano, Center of Molecular Biomedicine (Ts)
  - measurements @ SYRMEP beamline – ELETTRA SINCROTRONE Trieste, Italy

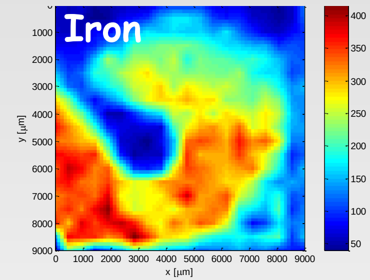
- theranostic imaging of tumours labelled with gold nanoparticles
  - in collaboration with Dept. of Medical Physics and Bioengineering, UCL, Division of Surgery and Interventional Science, UCL Medical School, IfG GmbH)
  - measurements @ DIAMOND Beamline B16, Didcot, UK and in our lab – Polimi&INFN, Milano, Italy

Drugs and diagnostic agents distribution in biological samples

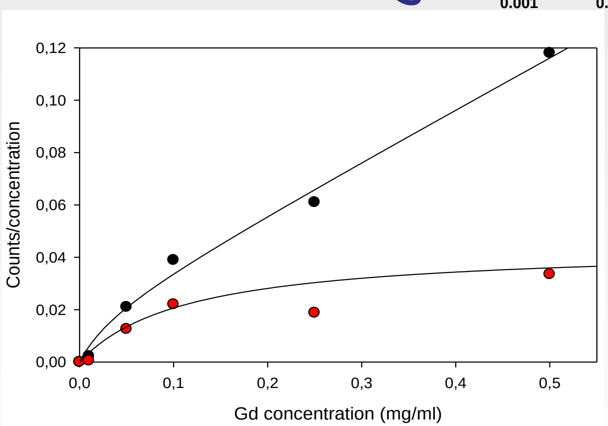
Gadolinium calibr. curve



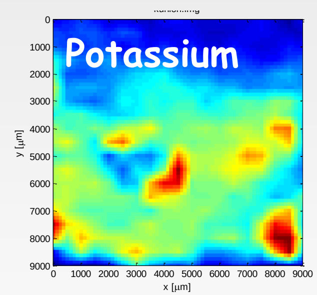
hepatic uptake of Gadocoletic acid trisodium salt (B22956) agent

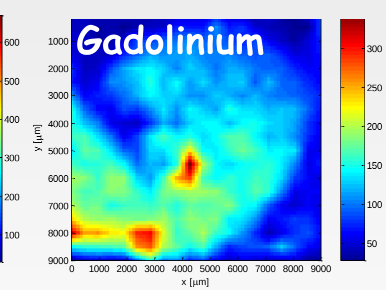


Michaelis-Menten kinetics



Scanned area: 9mm x 9mm
Step: 500µm x 500µm.
Measurement time: 60 s/point





no Gadolinium is detected in spleen, kidney and lung

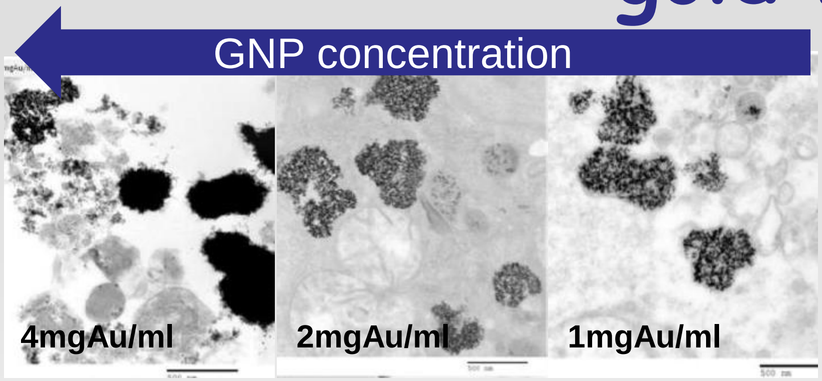
$y = Ns \cdot x + (V_{max} \cdot x)/(k_m + x)$ $k_m = 0.0960 \pm 0.0339$ mg/ml

of the same order of magnitude of the value assessed with radioactive markers

Ns = nonspecific binding
Vmax= max velocity
Km = enzyme/substrate affinity

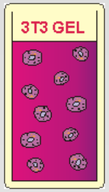
R. Alberti, C. Fiorini, C. Guazzoni, T. Klatka, A. Longoni, R. Delfino, V. Lorusso, L. Pascolo, L. Vaccari, F. Arfelli, L. Mancini, R. H. Menk, L. Rigon, G. Tromba, IEEE Nuclear Science Symposium Conference Records, 2006 IEEE, San Diego, California, Oct. 29 - Nov. 4, 2006 – Vol. 3, pp. 1528-1532

Theranostic imaging of tumours labelled with gold nanoparticles

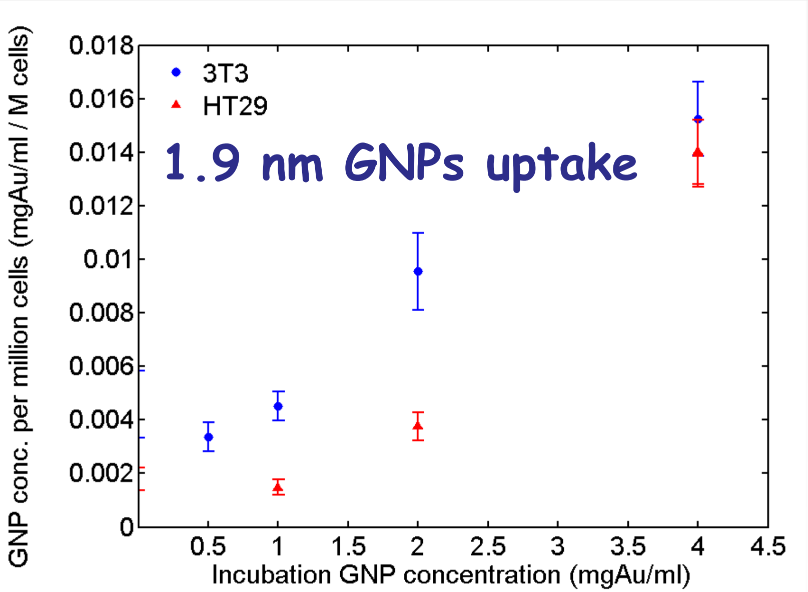


TEM images of GNP-filled vesicles in HT29 cells incubated at different GNP concentrations

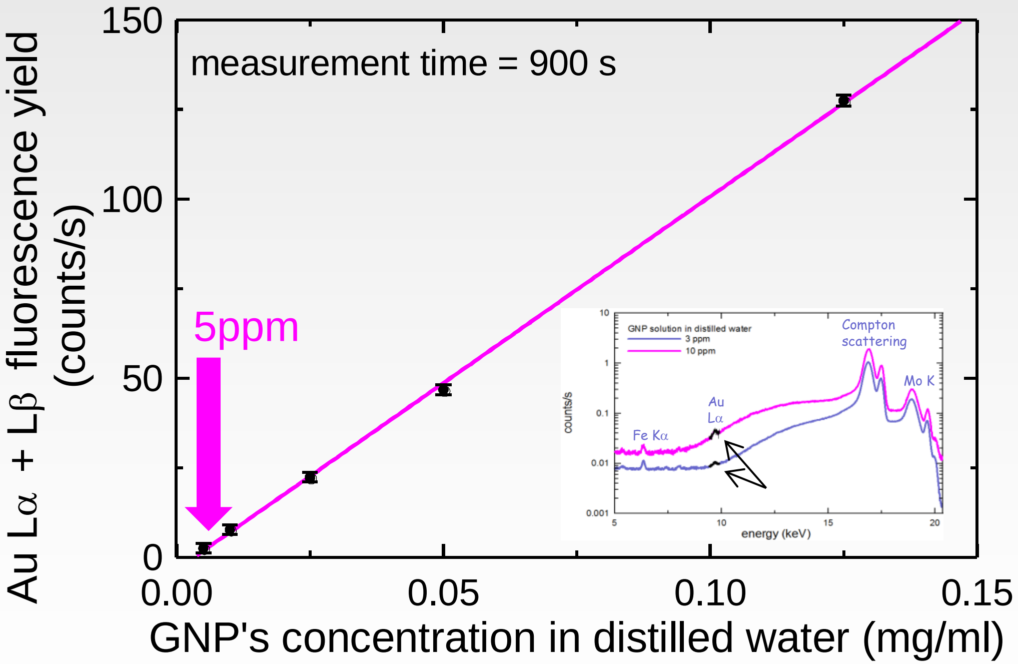
artificial cancer mass of HT29 cells with GNP inclusions



non-dense collagen gel populated by 3T3 fibroblasts



GNP calibration curve



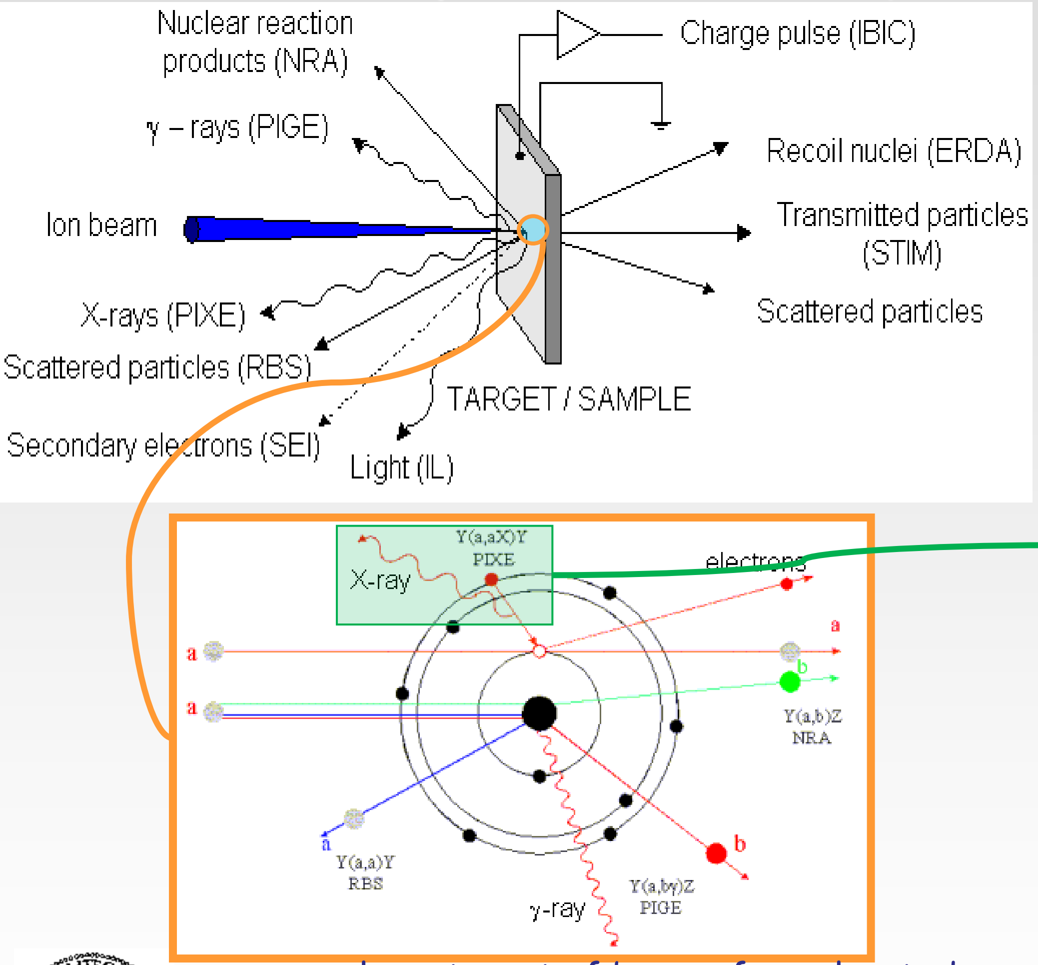
minimum detection limit: 3 ppm

K. Ricketts, C. Guazzoni, A. Castoldi, A. P. Gibson and G. J. Royle, Phys. Med. Biol., vol. 58, 2013, pp. 7841-7856,

INFN Istituto Nazionale di Fisica Nucleare

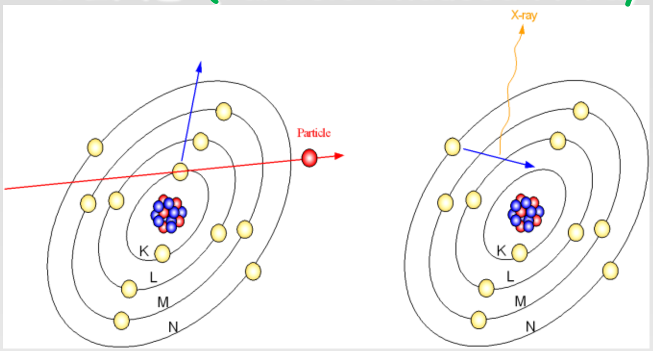
IBA techniques and PIXE

Ion Beam Analysis (IBA) techniques



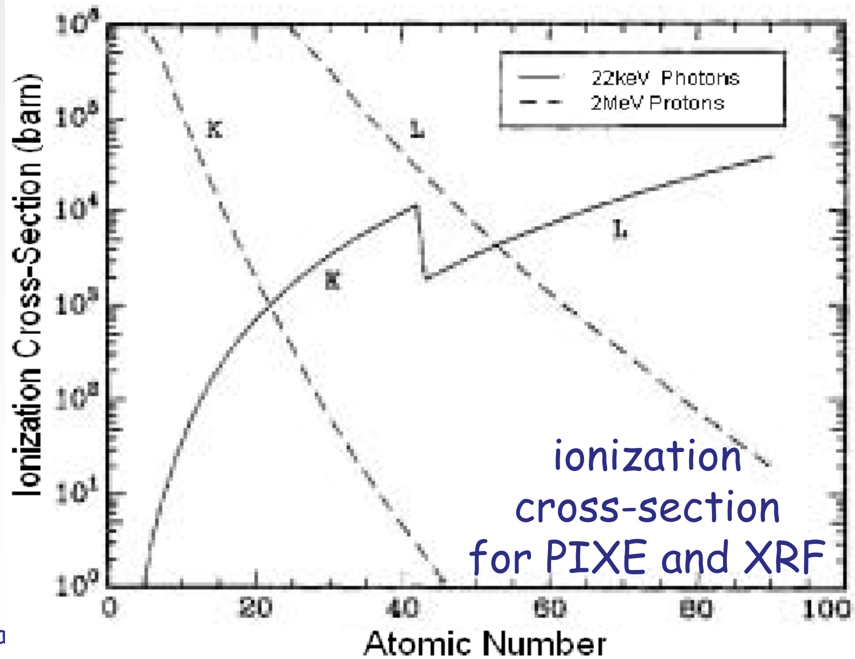
- sample as target of beam of accelerated particles with energy of the order of few MeV.
- secondary radiation energy is characteristic of the emitting atom or nucleus.

PIXE (Particle Induced X-ray Emission)



ionization process

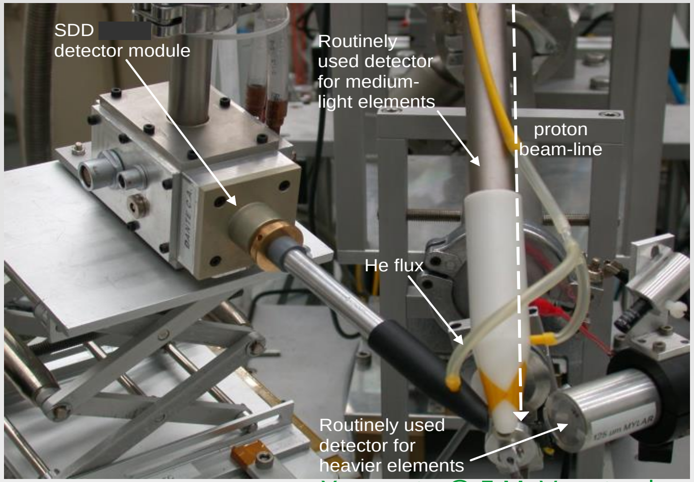
- Multi-elemental
- Quantitative
- Non-destructive



ionization cross-section for PIXE and XRF

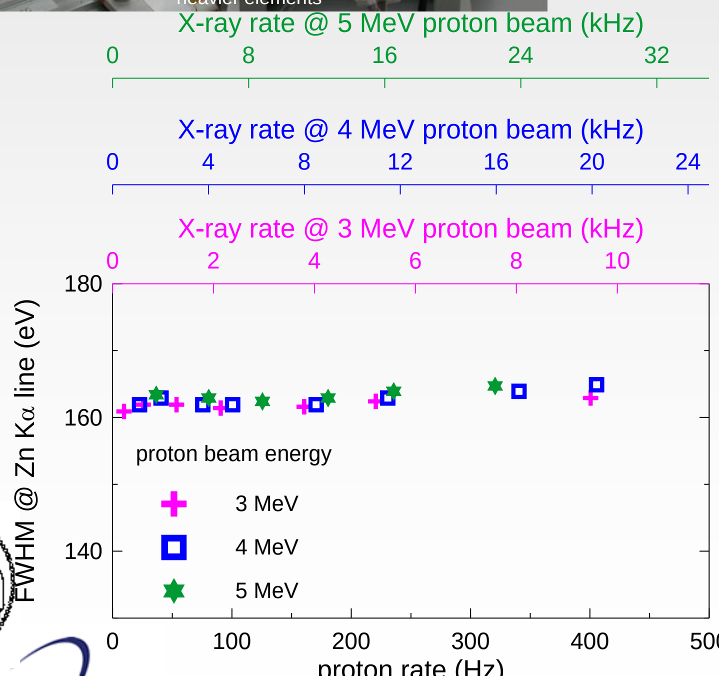
Esp. DANTE
INFN Gr.5 2006-08
Labec, INFN Firenze

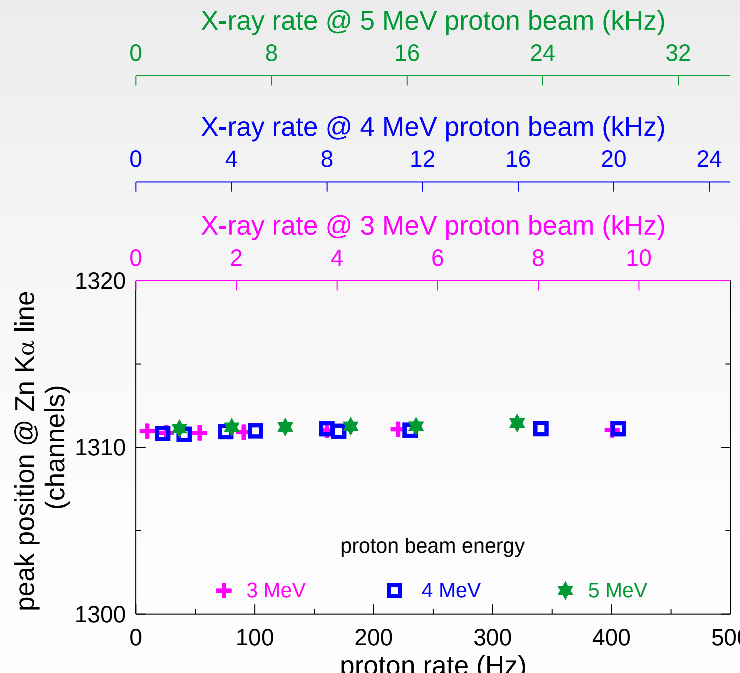
SDD-based PIXE setup - 1



- advantages of SDDs in count rate and energy resolution
- problem: at low X energies (medium-light elements) back-scattered particles degrade energy spectra even at low particle rates

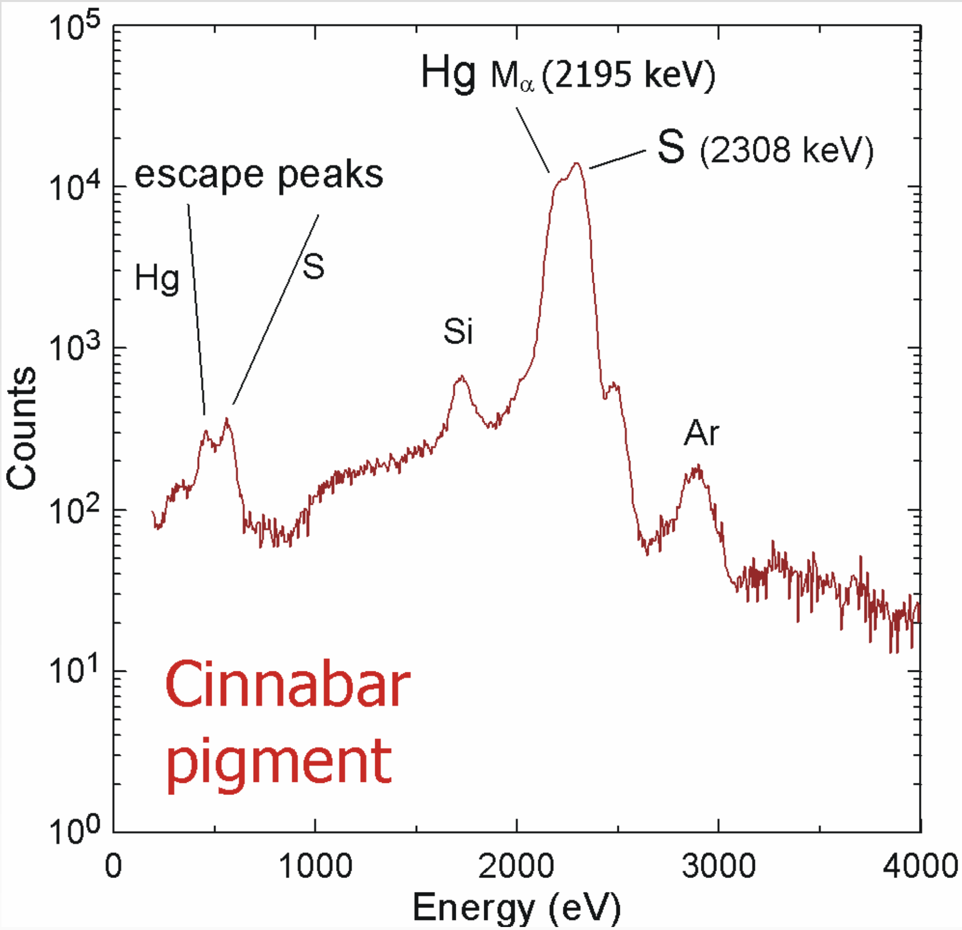
→ **SDD+customized front-end electronics with optimized pulsed reset able to manage the large-signal of particle events without degradation**

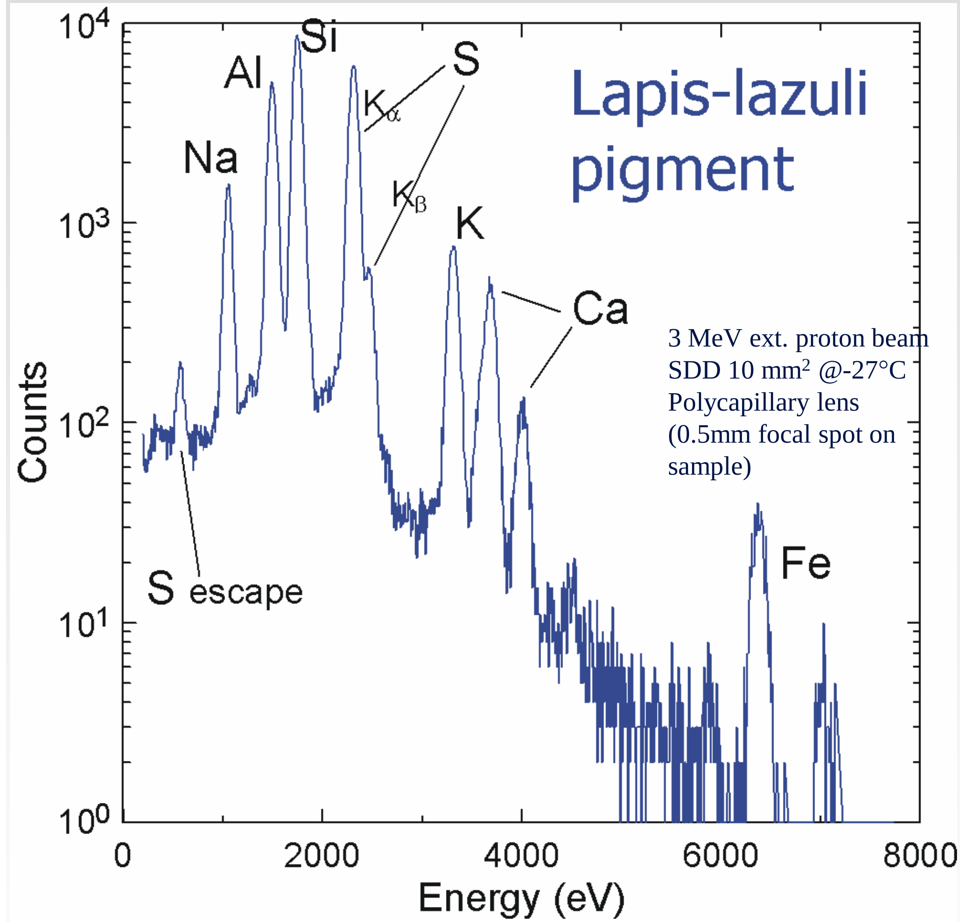




R. Alberti, N.Grassi, C.Guazzoni, T.Klatka, NIM A 607 (2009) 458–462

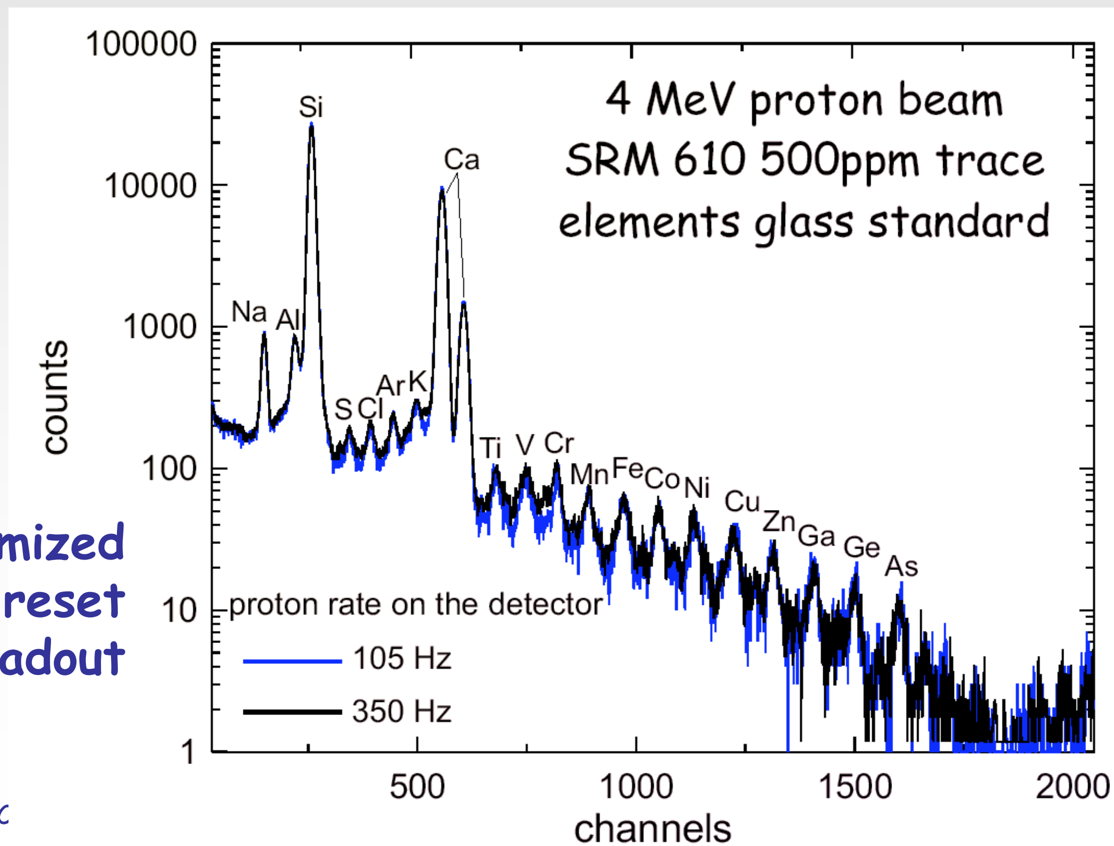
SDD-based PIXE setup - 2





R. Alberti, N.Grassi, C.Guazzoni, T.Klatka, "Optimized readout configuration for PIXE spectrometers based on Silicon Drift Detectors: Architecture and performance", NIM A 607 (2009) 458–462

SDD-based PIXE setup - 2



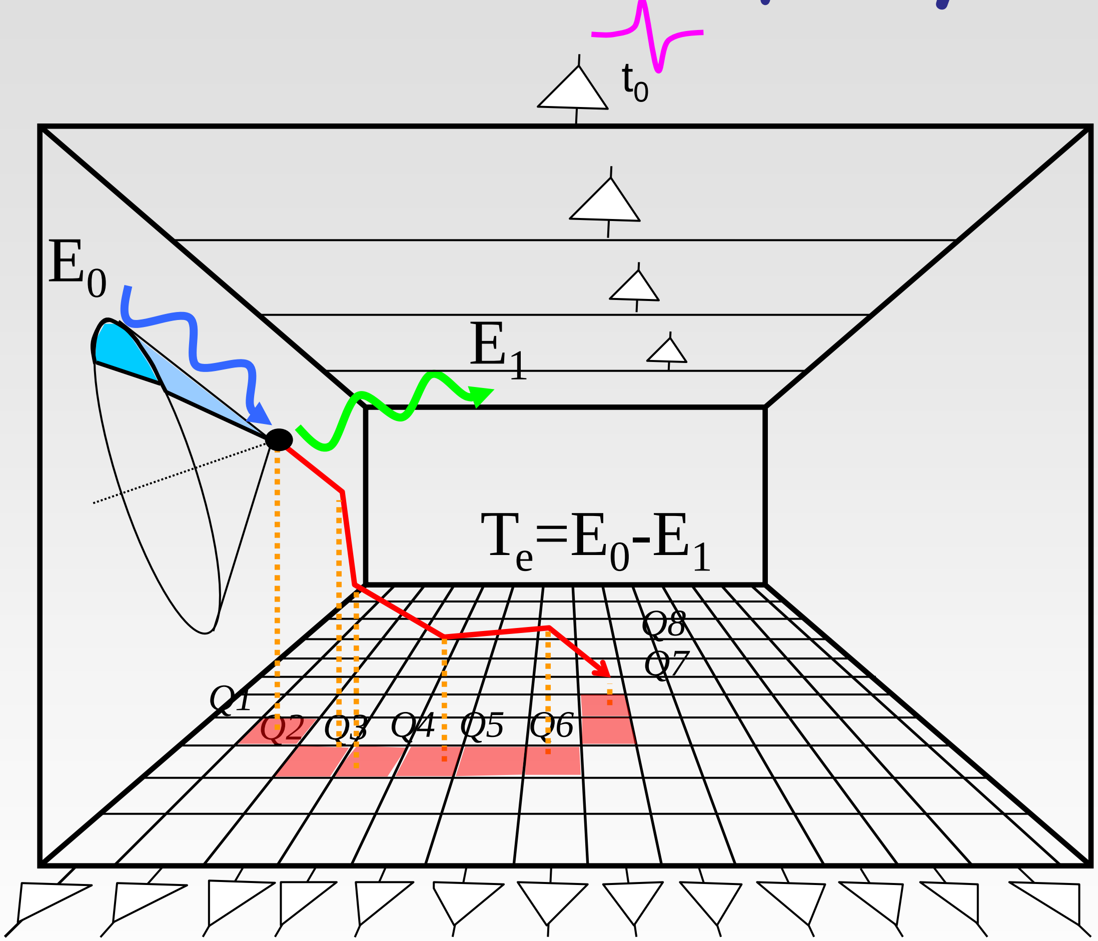
with optimized pulsed reset readout

R. Alberti, N.Grassi, C.Guazzoni, T.Klatka, "Optimized readout configuration for PIXE spectrometers based on Silicon Drift Detectors: Architecture and performance", NIM A 607 (2009) 458–462

Outlook to applications…

- X-Ray Fluorescence and Proton Induced X-Ray Emission
- **Gamma-ray imaging**
- Advanced X-ray imaging modalities
- Macro-pixel arrays with DEPFET readout for XFEL

High-resolution Compton scatter detector for γ-ray imaging



interaction time given from fast induction signal on back strips

→ *fast coincidence imaging in Compton telescope arrangement*

electron tracking with high spatial and energy resolution

→ *vertex of the interaction*

→ *initial direction of recoil electron*

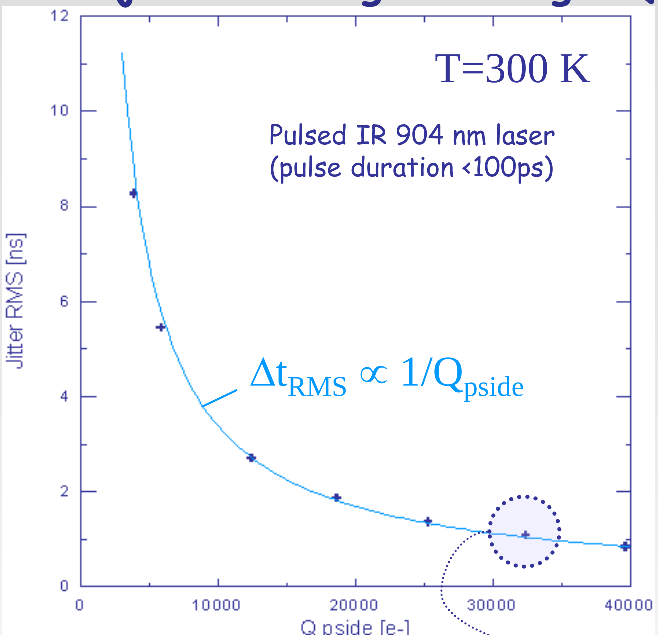
(reduction multiple Coulomb scattering issue)

→ *estimate of dE/dx*

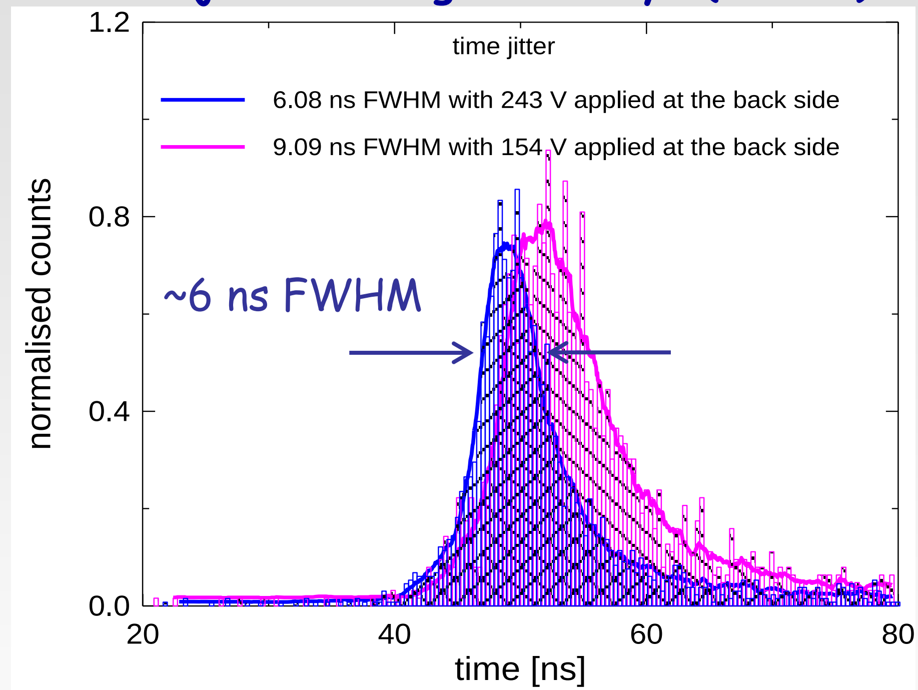
Silicon MLSDD scatter detector with readout of backside strips

Timing resolution

Time jitter vs. signal charge Q

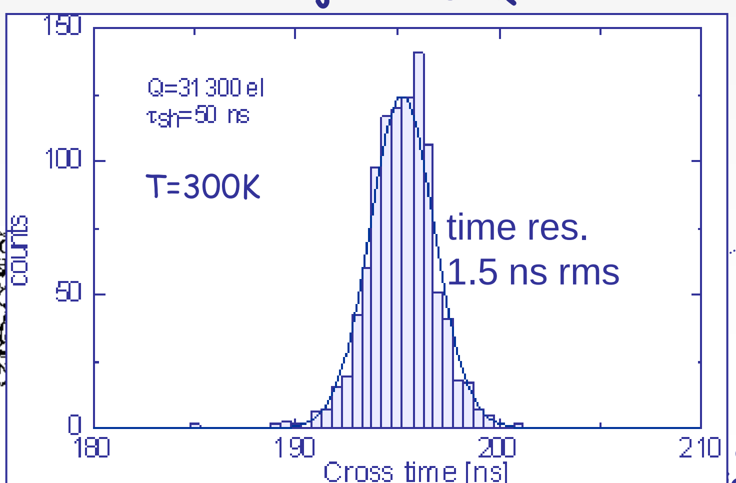


Time jitter with gamma-rays (Na-22)



A.Castoldi, E.Gatti, C.Guazzoni, Nucl. Instr. and Meth. A518 (2004) 429-432

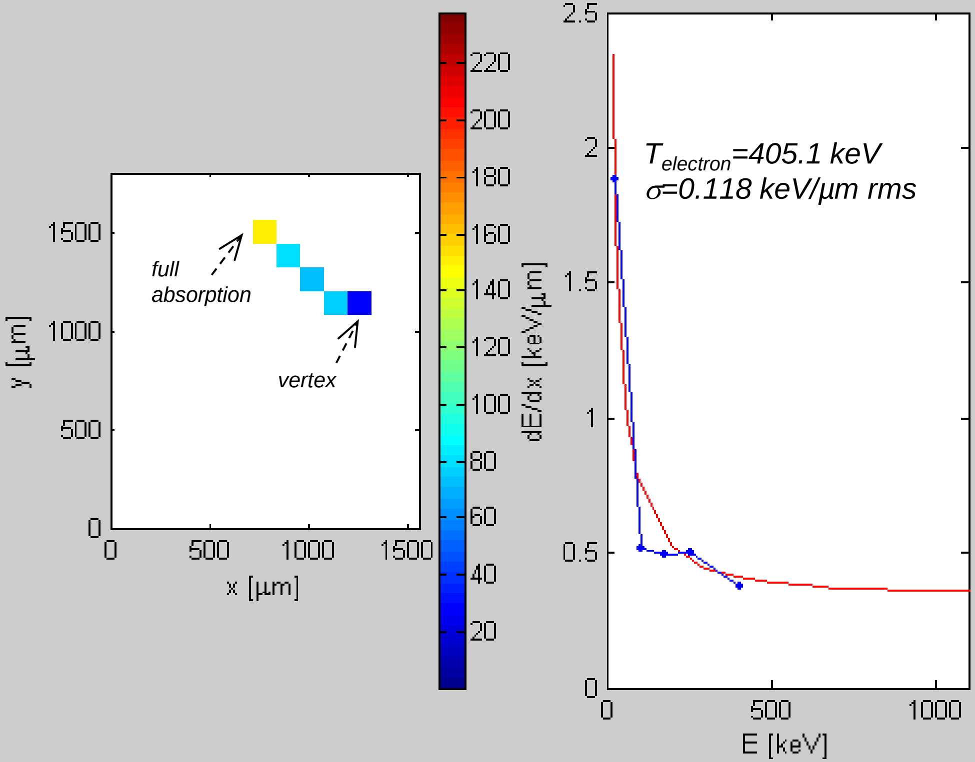
Measured time jitter @ Q=31300 el



Opens to coincidence imaging with ~10ns rms time resolution

Electron tracks

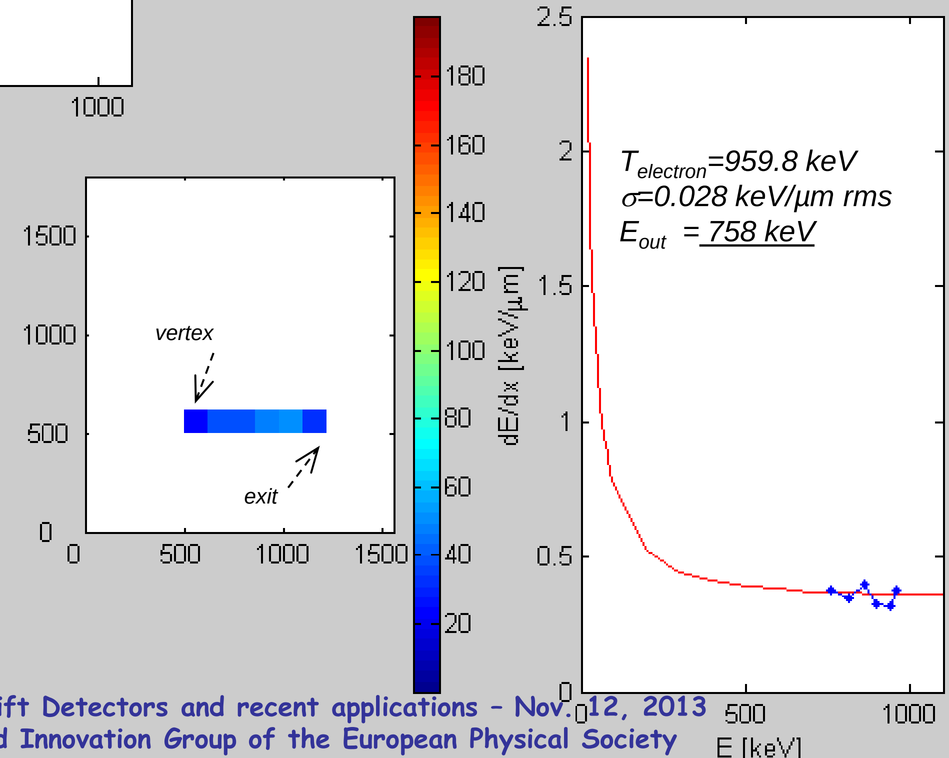
Na-22 source, T=300K



internal absorption

1-st experimental evidence of electron tracks resolved in space and energy in a single silicon layer

Z-exit



A. Castoldi, A. Galimberti, C. Guazzoni, P.Rehak, R.Hartmann, L.Strüder, Nucl. Instr. and Meth. A 568 (2006) 89-95

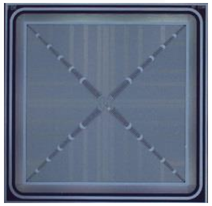
- Started in 2011 within a project supported by ESA for LaBr3 scintillator readout with SDD arrays.
- Back entrance window optimized to achieve QE > 80 % at 380 nm (→ suitable also for soft X-rays).
- Considered suitable for the upgrade of the Siddharta-2 apparatus, with preliminary evaluation on prototypes in 2012/2013

FBK production:

- 4'' wafer
- 6'' wafer upgrade now operative

- 8 mm x 8 mm
- 12 mm x 12 mm
- 9 SDDs array (8 mm x 8 mm each)

thin entrance window suitable for both soft X-ray detection (>200eV) and scintillator readout →



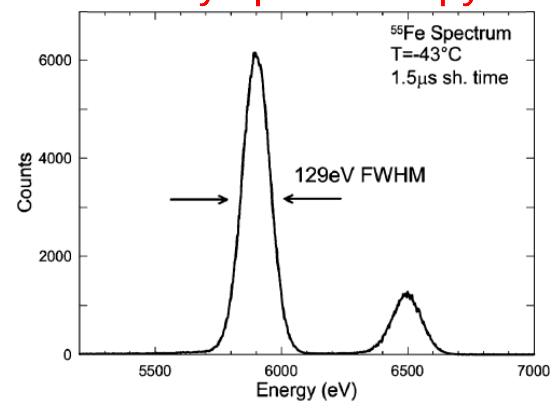
area = 64mm^2

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 60, NO. 4, AUGUST 2013 2923

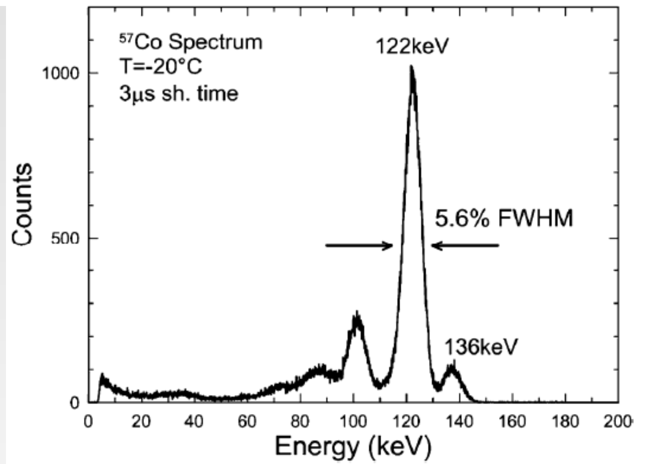
Silicon Drift Detectors for Readout of Scintillators in Gamma-Ray Spectroscopy

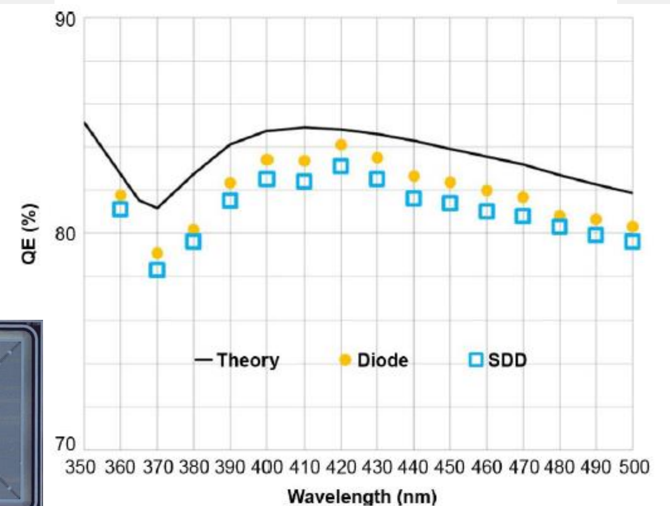
Carlo Fiorini, Luca Bombelli, Paolo Busca, Alessandro Marone, Roberta Peloso, Riccardo Quaglia, Pierluigi Bellutti, Maurizio Boscardin, Francesco Ficorella, Gabriele Giacomini, Antonino Picciotto, Claudio Piemonte, Nicola Zorzi, Nick Nelms, and Brian Shortt

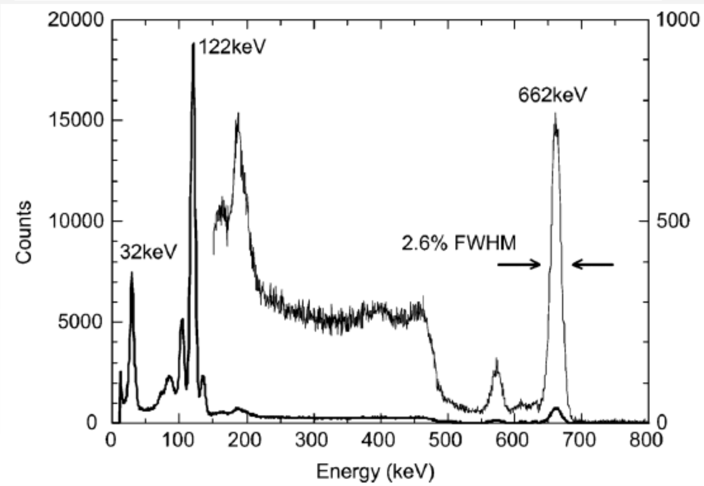
X-ray spectroscopy



γ-ray spectroscopy with $LaBr_3$







carlo.fiorini@polimi.it
Politecnico di Milano, Italy

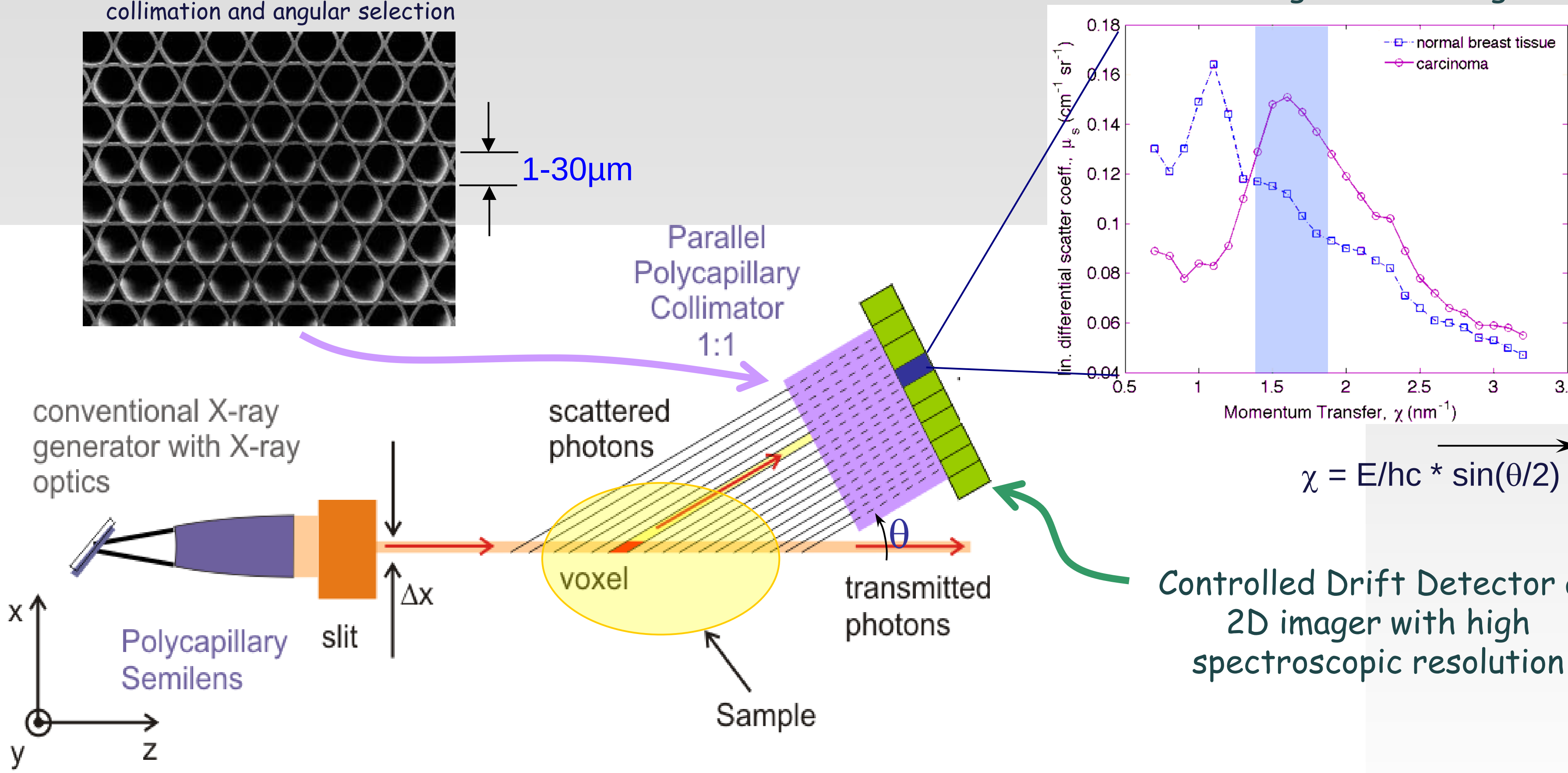
Outlook to applications…

- X-Ray Fluorescence and Proton Induced X-Ray Emission
- Gamma-ray imaging
- **Advanced X-ray imaging modalities**
- Macro-pixel arrays with DEPFET readout for XFEL

X-ray Scatter Imaging (XSI)

Polycapillary technology for beam collimation and angular selection

materials scatter X-rays at distinctive angles and energies

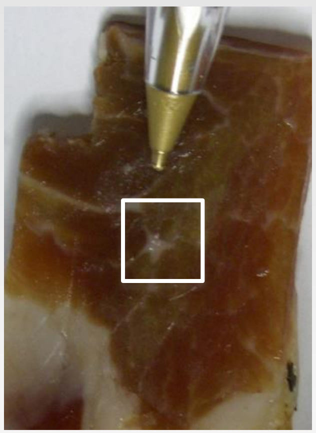


✧ Polycapillary technology allows full exploitation of detector pixel resolution

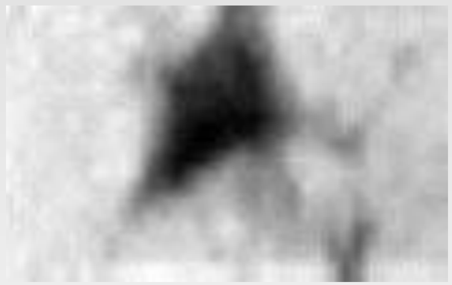
✧ 2D spectroscopic imager (Controlled Drift Detector) allows imaging at multi-momentum transfer values

Scatter images vs TX images with standard collimation @ Synchrotron ELETTRA

pork sample with 2mm detail

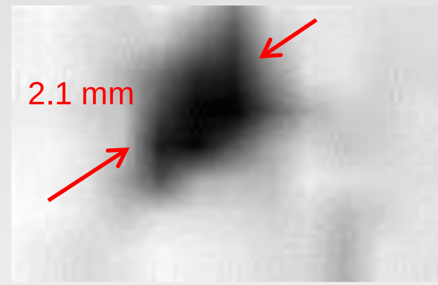


Transmission image
(pixel 180μm)

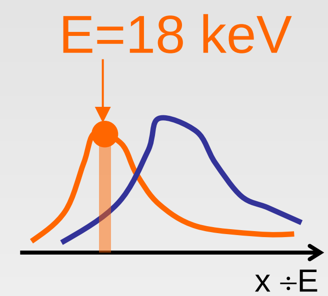


contrast=33%

Scatter image
(pixel 500μm)

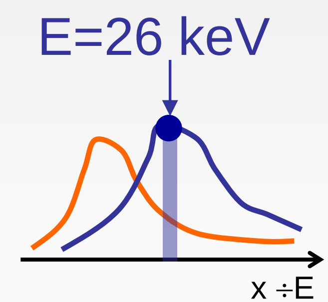


contrast=46%



contrast=11%

contrast=29%



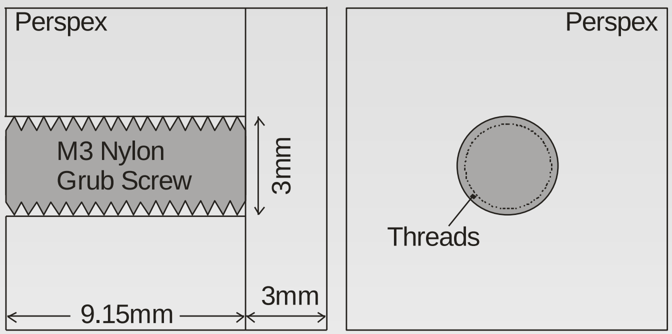
A. Castoldi, C. Guazzoni, A. Galimberti, R. Hartmann, S. Pani, G. Royle, and L. Strüder, IEEE Trans. Nucl. Sci. 54 (2007) pp. 1474-1480

- contrast optimization with energy selection
- conventional mechanical collimation limits spatial resolution

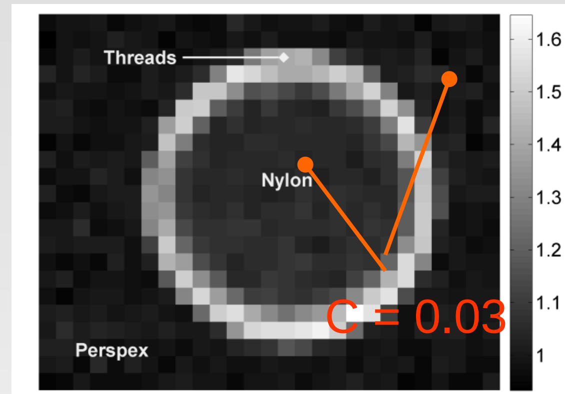
X-ray Scatter imaging with X-ray tube and high-resolution polycapillary collimation

Perspex / Nylon6,6 Phantom

A. Bjeoumikhov, et al.
IEEE Nuclear Science Symposium Conference Record, 2008 IEEE NSS Records, 19-25 oct., pp.1-7.

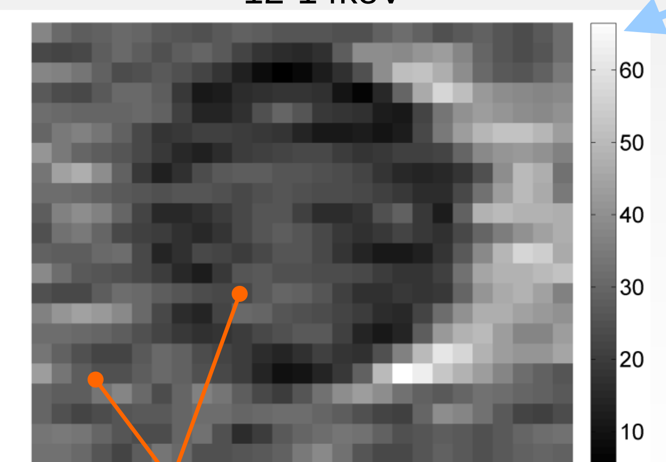


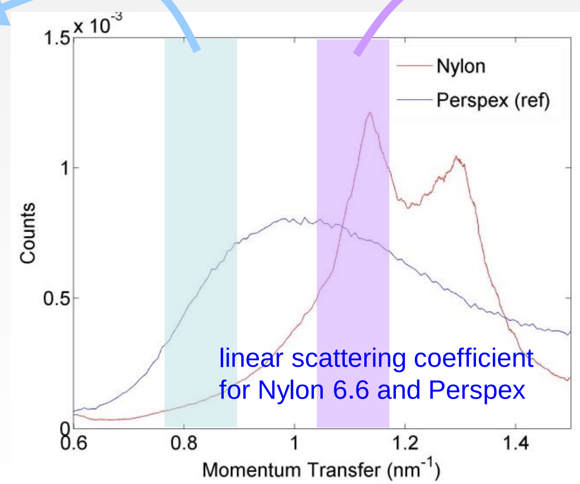
Transmission



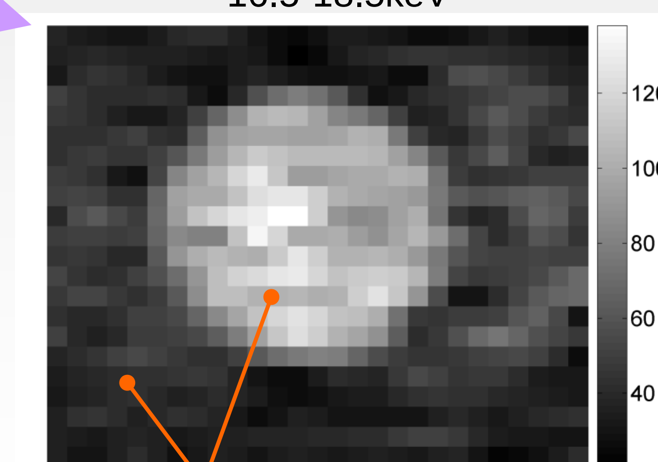
Multi-momentum imaging (energy selection)

12-14keV





16.5-18.5keV



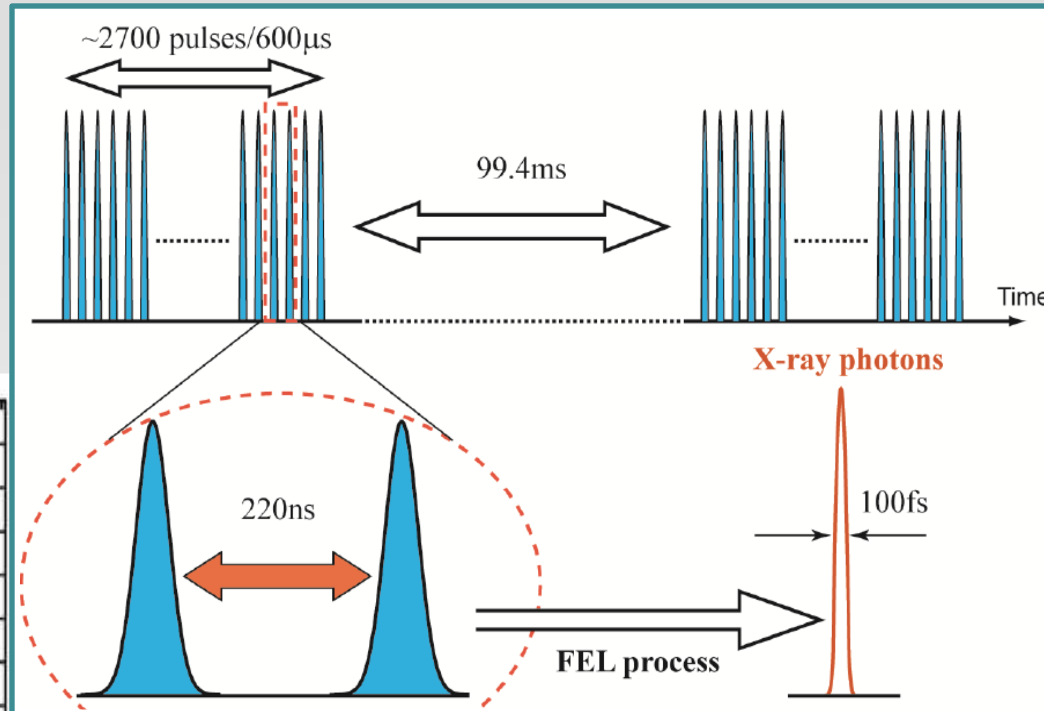
INFN Istituto Nazionale di Fisica Nucleare

Outlook to applications…

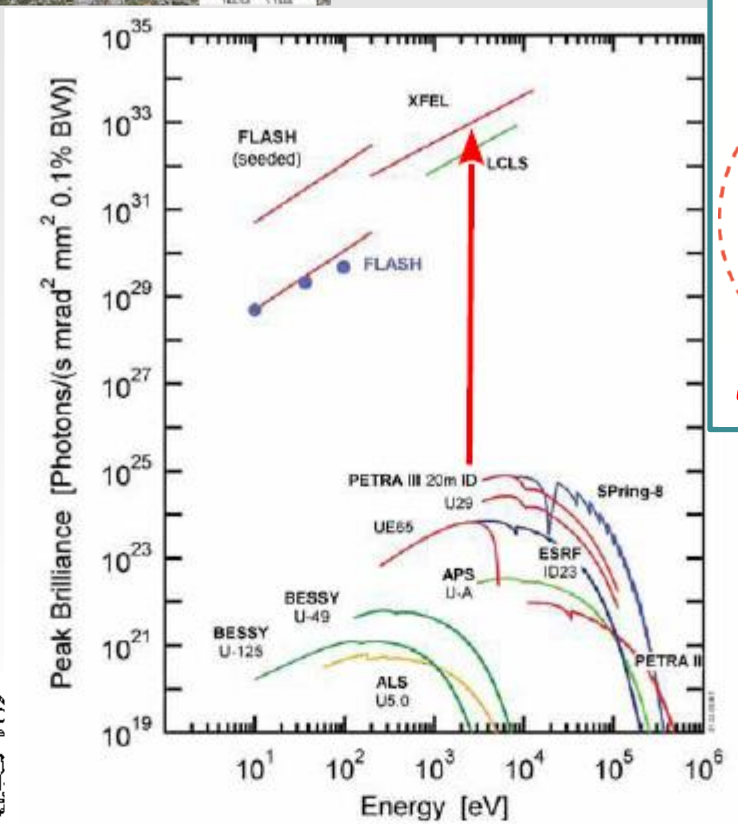
- ❑X-Ray Fluorescence and Proton Induced X-Ray Emission
- ❑Gamma-ray imaging
- ❑Advanced X-ray imaging modalities
- ❑**Macro-pixel arrays with DEPFET readout for XFEL**

2D area detectors for XFEL beams

scheduled for operation end 2015



Max bunch rate: 4.5 MHz

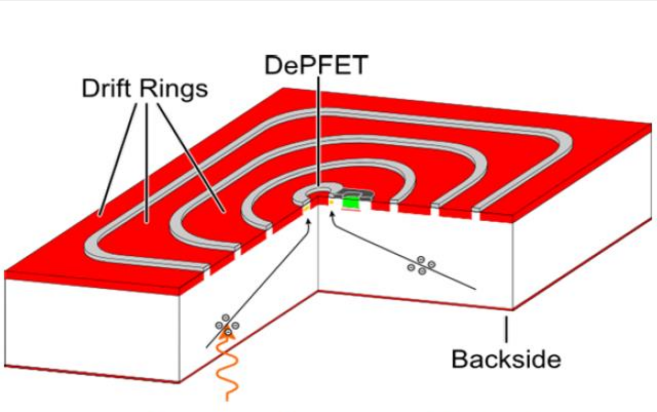


- ✓ high dynamic range ($<10^4$ X-rays/pixel)
- ✓ high speed (~5 Mframes/s)
- ✓ low noise (E=2-15 keV)

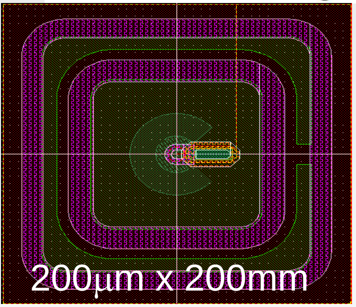
Experiment RIXFEL
INFN Gr.5 2008-2010

DePMOS Sensor w/ Signal Compression

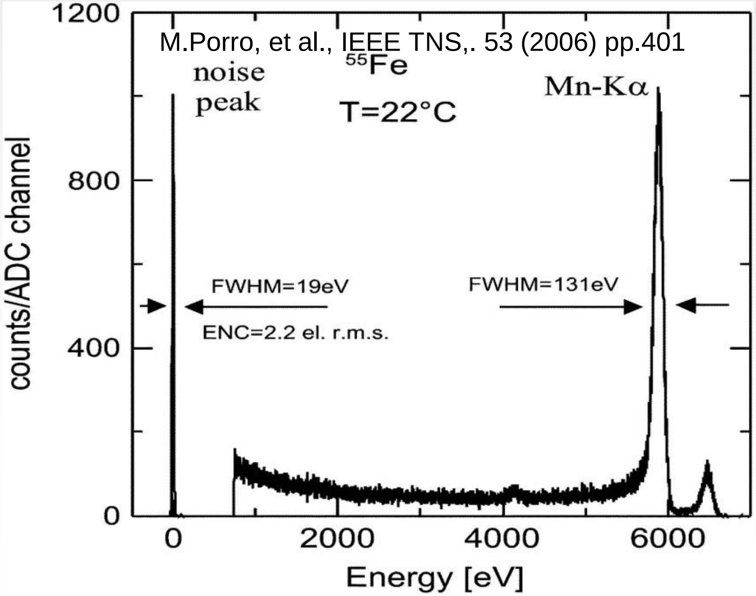
DSSC consortium

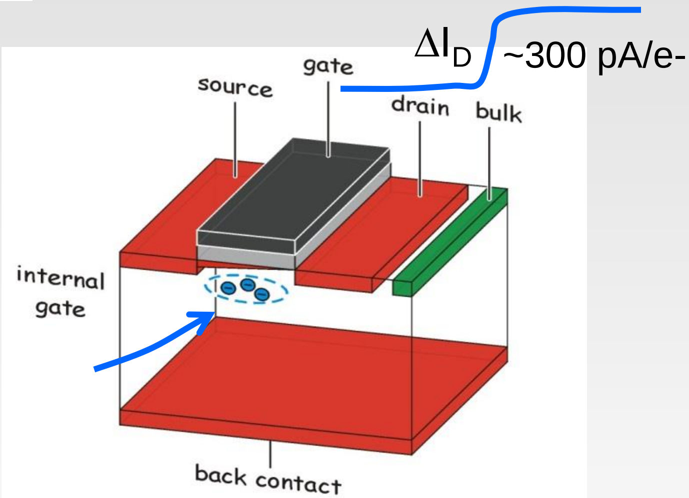


Cut through a macropixel cell



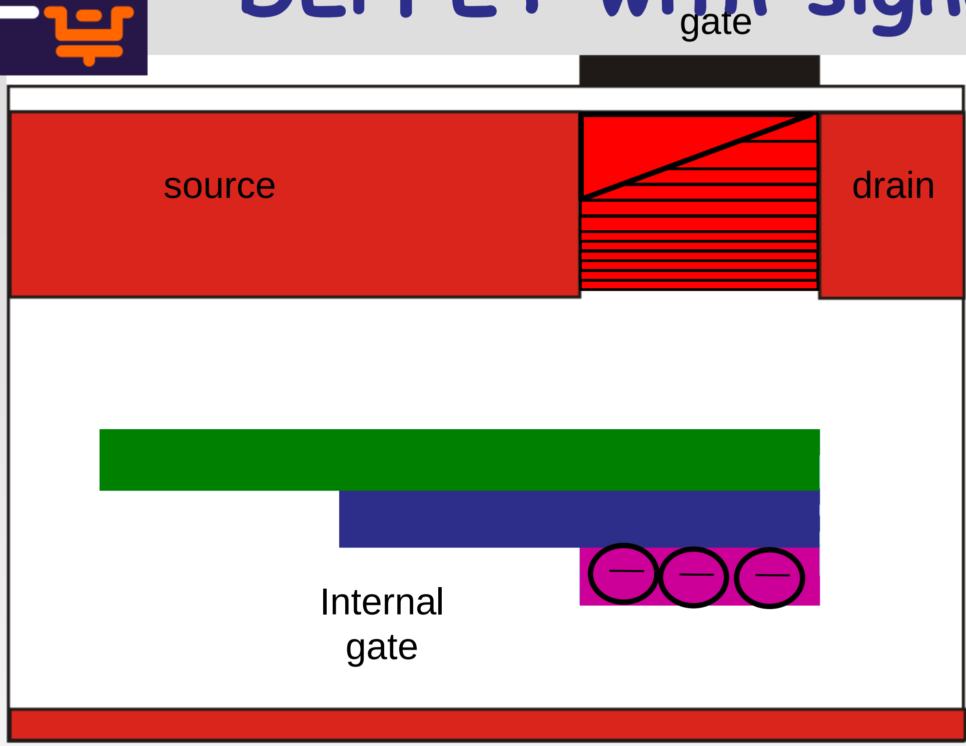
M.Porro, et al. IEEE Trans. Nucl. Sci., Vol. 59, 2012, pp. 3339 - 3351

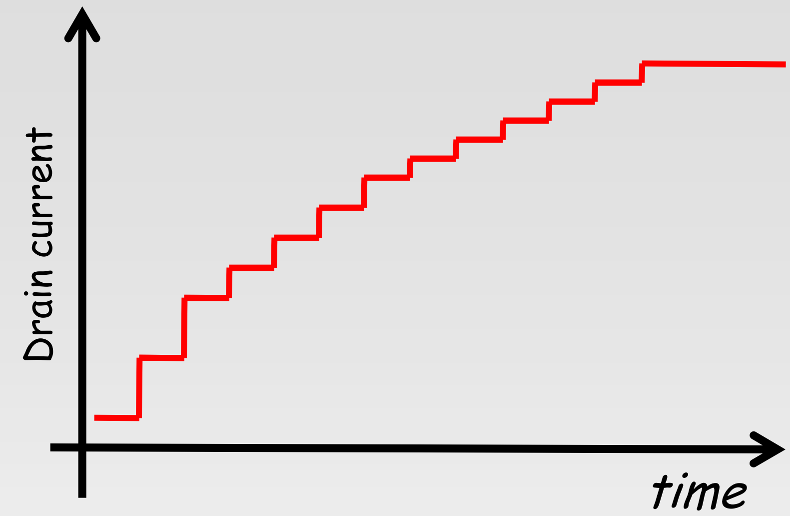


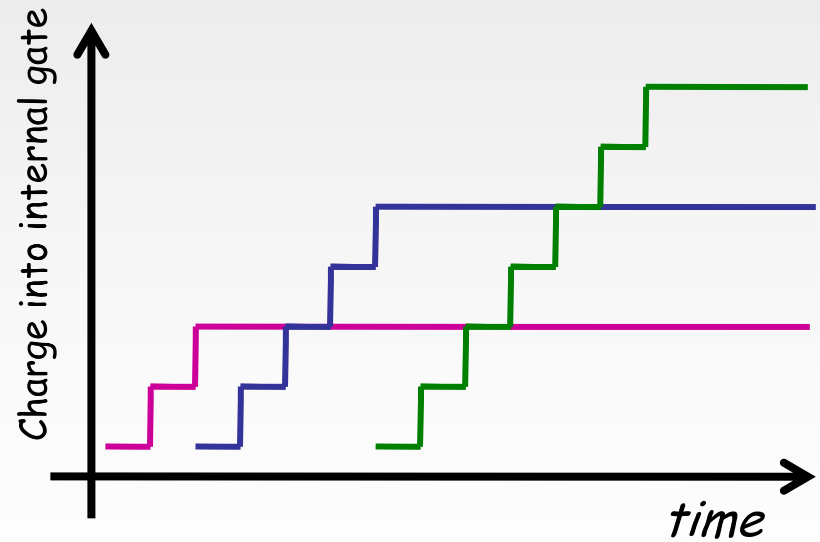


- Drift structure to allow fast and complete collection at buried gate
- DEPFET readout
  - ✓ collecting anode=internal gate
  - ✓ high energy resolution (2 keV photon counting)
  - ✓ analog compression

DEPFET with signal compression



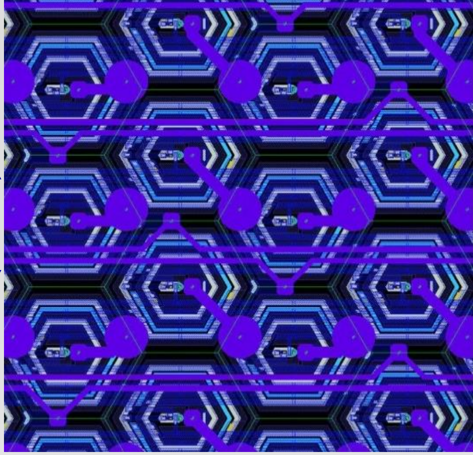




- ✓ The internal gate extends into the region below the source
- ✓ Small signals assemble below the channel, being fully effective in steering the transistor current
- ✓ Large signals spill over into the region below the source. They are less effective in steering the transistor current.

M.Porro, et al.
IEEE Trans. Nucl. Sci., Vol. 59, 2012, pp. 3339 - 3351

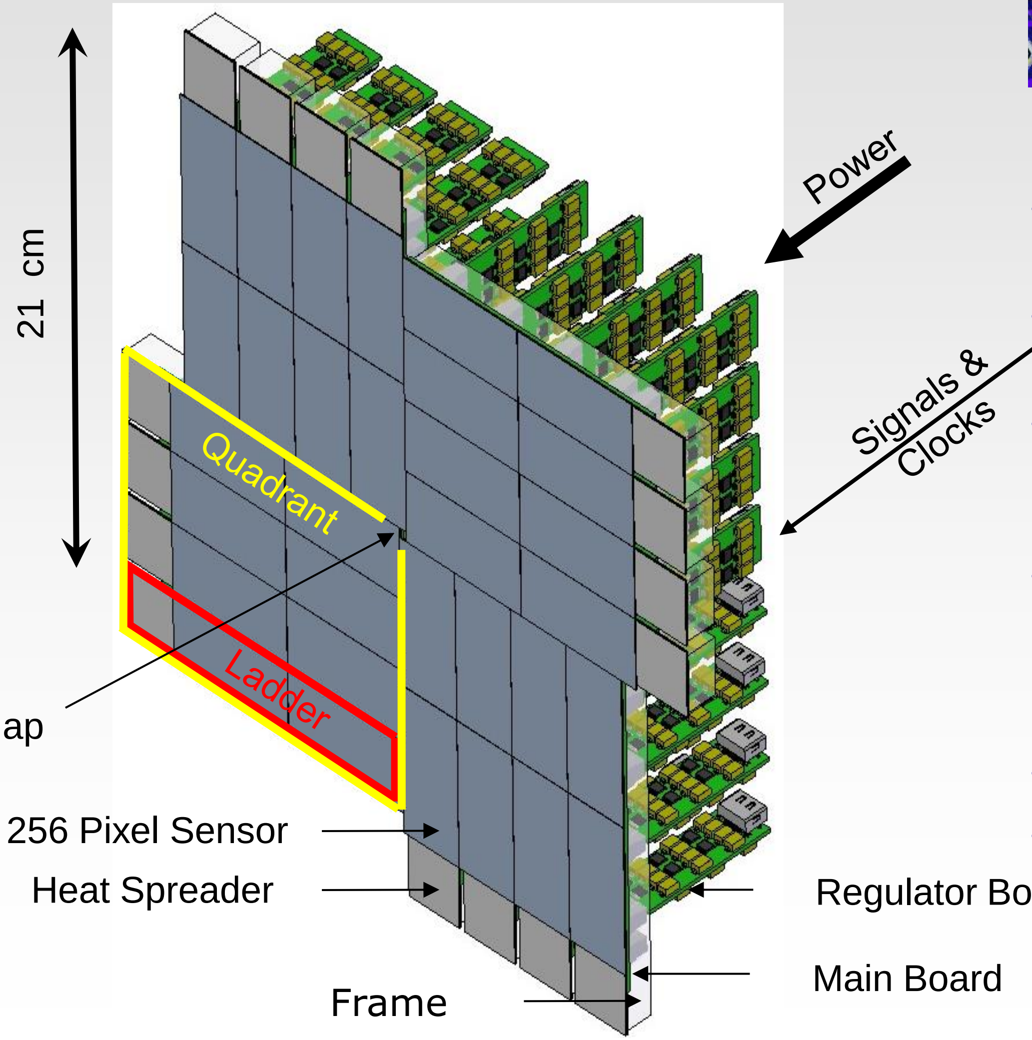
Focal plane overview



Developed by DSSC consortium (Italy-Germany) under contract with DESY/XFEL GmbH

M.Porro et al., “Expected Performance of the DEPFET Sensor with Signal compression: a Large Format X-ray Imager with Mega-Frame Readout Capability for the European XFEL”, NIM A624 (2010) 509

M. Porro et al., “Development of the DEPFET Sensor with Signal Compression: a Large Format X-Ray Imager With Mega-Frame Readout Capability for the European XFEL”, IEEE Trans. Nucl. Sci. 59 (2012) 3339



- 1024x 1024 pixels
- 16 ladders/hybrid boards
- 32 monolithic sensors 128x256 6.3x3 cm^2
- DEPFET Sensor bump bonded to 8 Readout ASICs (64x64 pixels)
- 2 DEPFET sensors wire bonded to a hybrid board connected to regulator modules
- Heat spreader
- Dead area: ~15%

Conclusions

- **Silicon Drift Detectors** were **invented** by E. Gatti and P. Rehak **almost 30 years ago** as particle-tracking detectors in physics experiment.
- Nowadays **widely spread in X-ray spectroscopy**, and **commercially available** in different shapes and sizes
- **Conventional and non-conventional applications** have been **shown** (e.g., nondestructive analysis of cultural heritage, environmental monitoring, industrial control based on XRF and XRD, novel diagnostic tools for biomedical imaging with X and gamma-rays, etc.).
- As Gatti and Rehak stated in their first patent, "**additional objects and advantages of the invention** will become **apparent to those skilled in the art**"

Let us hope to be skilled enough in the art to reach new milestones in this fascinating field and keep "drifting" on towards new horizons…

Thank you for your attention…

…and a special thank to everyone who actively contributed in this exciting development