HYBRID PIXEL DETECTORS
STATUS AND FUTURE CHALLENGES

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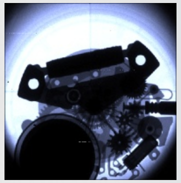
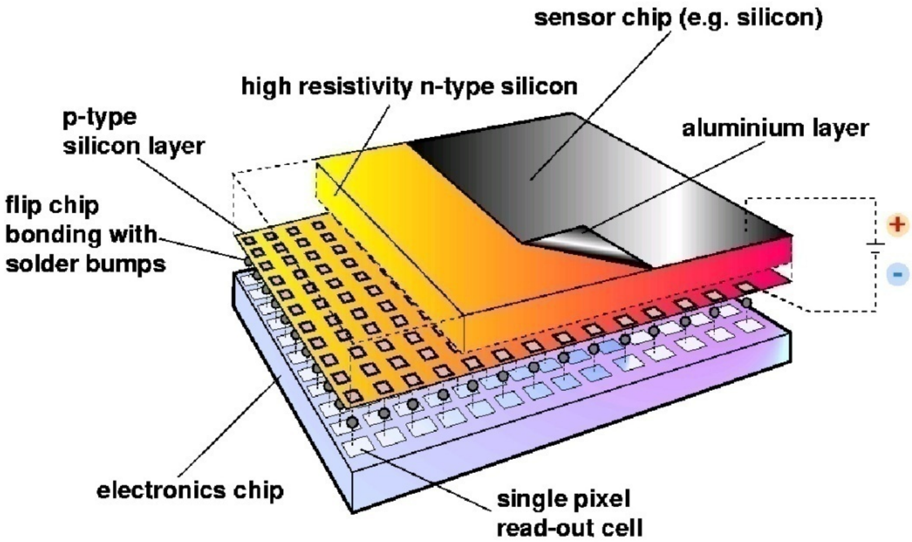
CERN
Geneva, Switzerland
7-9 February 2010

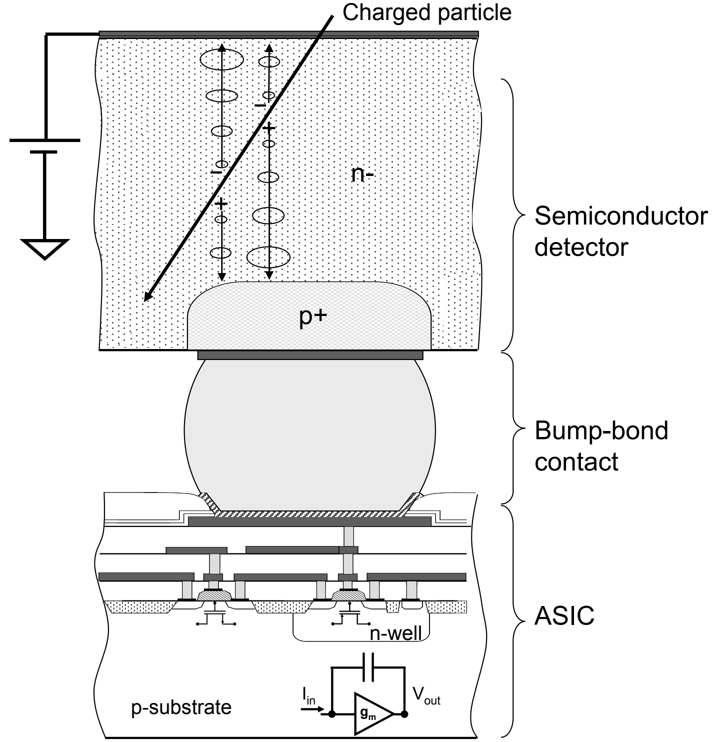


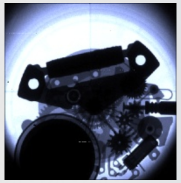
Outline

- Why hybrid pixels?
- Hybrid pixel detectors at LHC
- The Medipix2 chip
- The Timepix chip
- Imaging with the Timepix chip
- Spectroscopic X-ray imaging with Medipix2
- Limitations of Medipix2/Timepix
- Medipix3
- Future challenges for HEP and other fields
- Conclusions and future work

Hybrid-Pixel Detectors





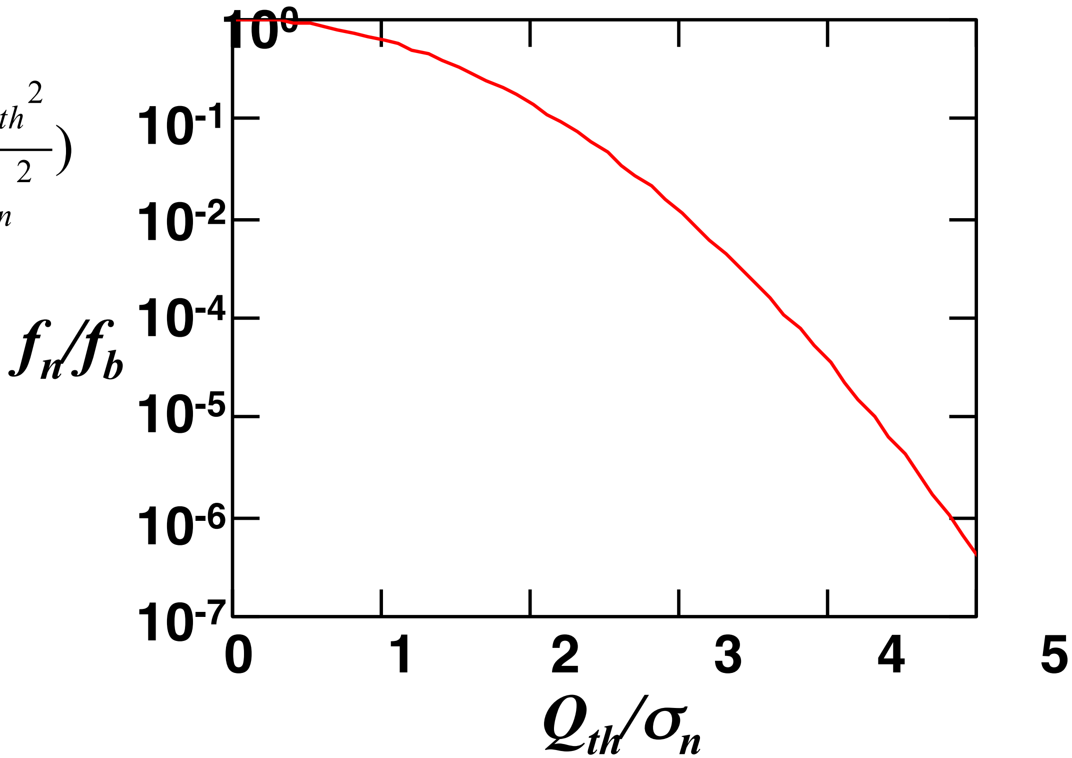


Why use hybrid pixels?

- Any CMOS commercial process can be used
- The detector can be optimised for application
  - Si, thin EPI or 3D Si
  - GaAs, CdTe for mammography etc..
- Sometimes no sensor is used
  - Gas gain grid for gas detector readout
  - Micro channel plate
- Optimal signal to noise at high rates – essential for clean pattern recognition in complicated high energy physics events

Noise hit rate for a discriminator

$$f_n = \frac{1}{\sqrt{3}} f_b \exp\left(\frac{-Q_{th}^2}{2\sigma_n^2}\right)$$



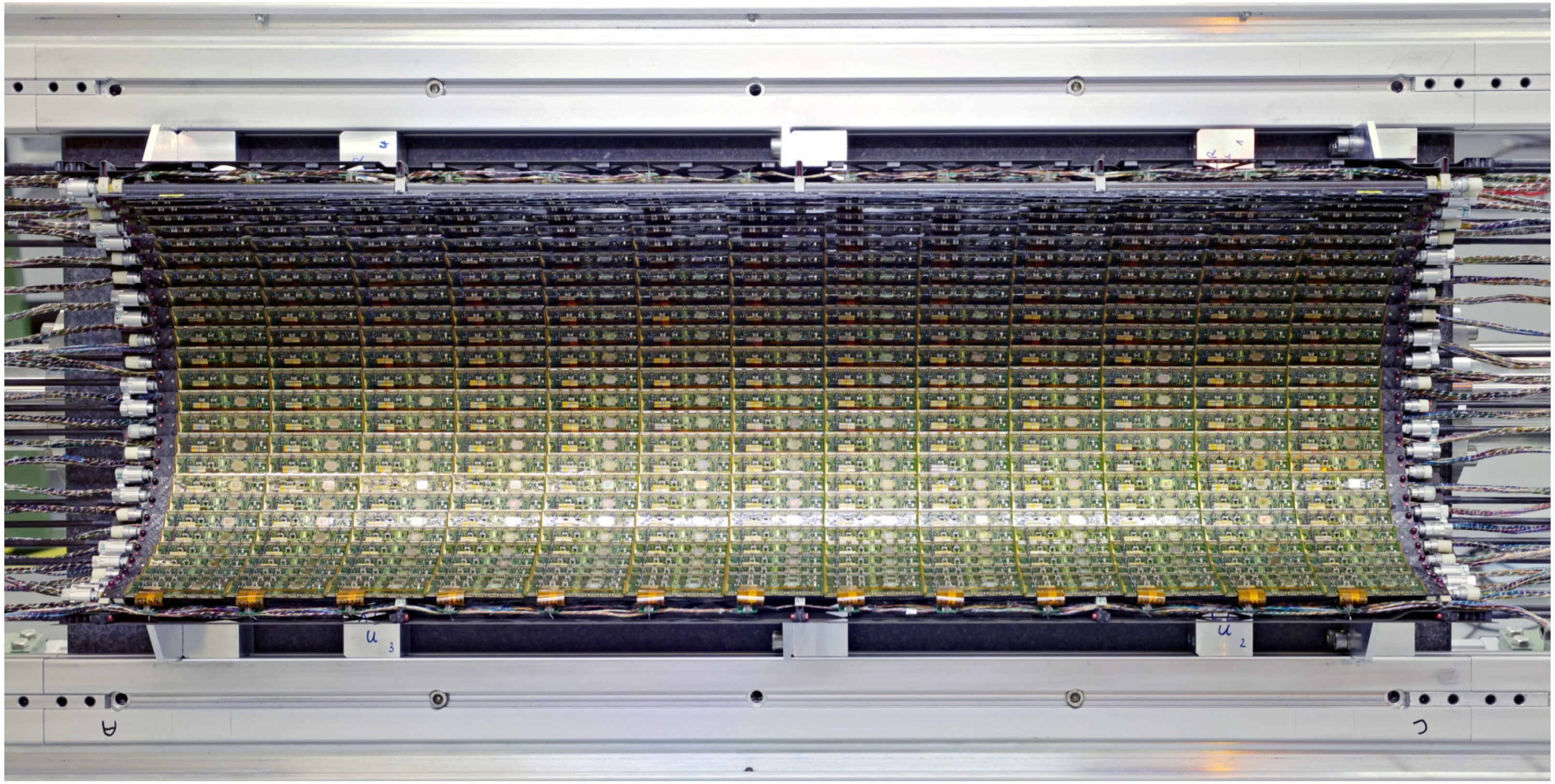
f_n = noise hit rate
f_b = system bandwidth
Q_{th} = threshold
s_n = noise

In a large bandwidth system (such as an HEP experiment) noise and threshold variation must be kept very far from the threshold to produce clean event information.

Hybrid pixels @ LHC - ATLAS

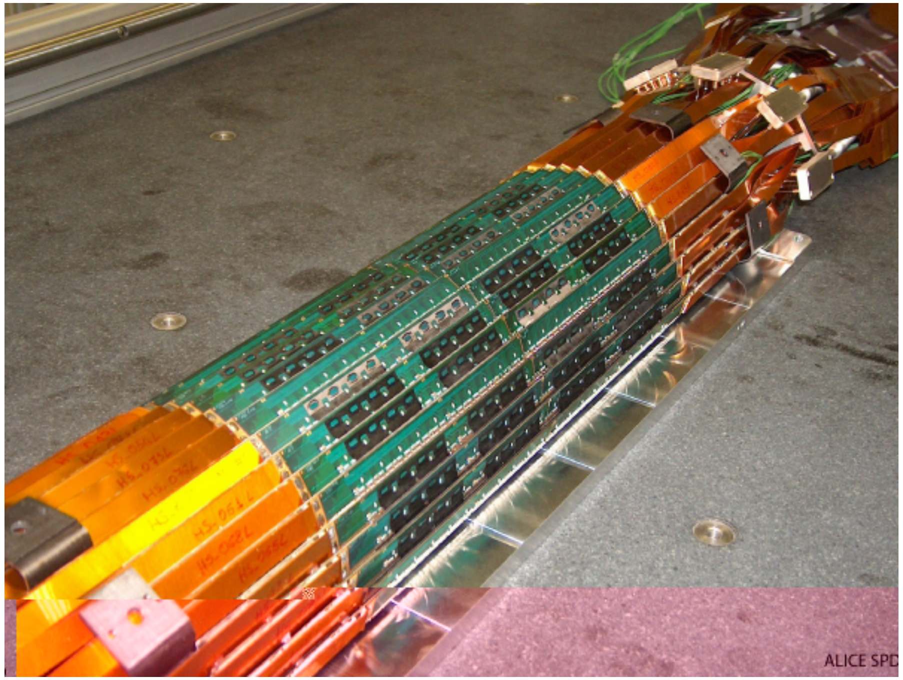
ATLAS Pixel Detector ~ 100M channels

Half-shell of pixel layer 2 (interior):



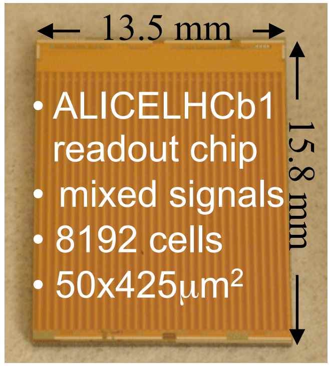
The Alice Silicon Pixel Detector

2 layer barrel
10M pixels
Total surface: ~$0.24m^2$
Power consumption ~1.5kW
Evaporative cooling C_4F_{10}
Room temperature
Material budget per layer ~1% X_0

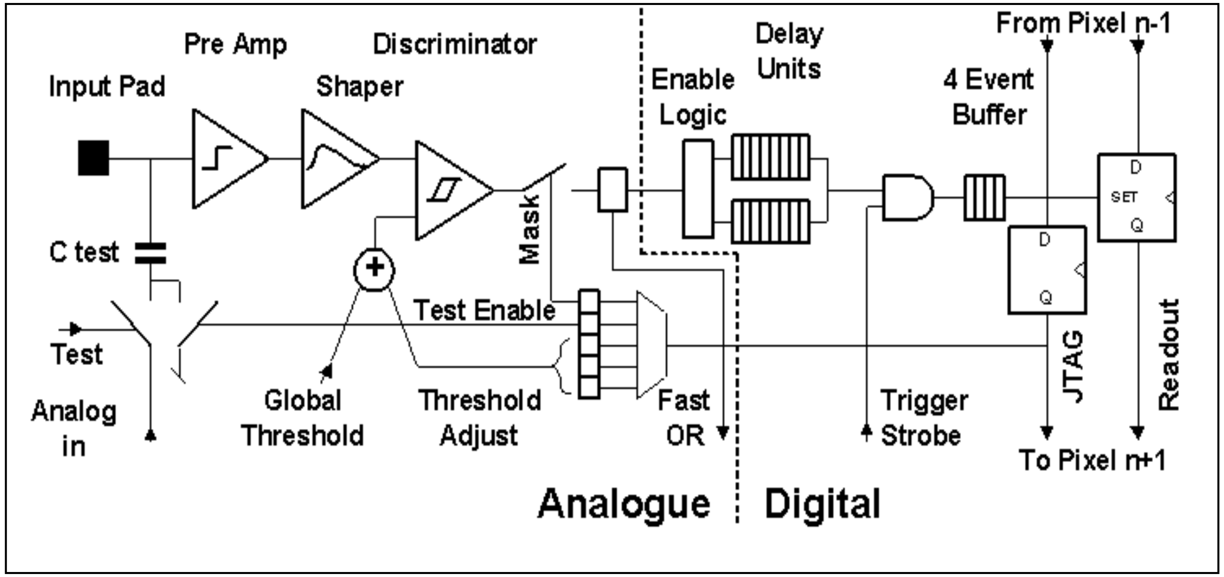


Slide courtesy of V. Manzari

The Alice Silicon Pixel Detector



- ALICELHCb1 readout chip
- mixed signals
- 8192 cells
- 50x425μm^2



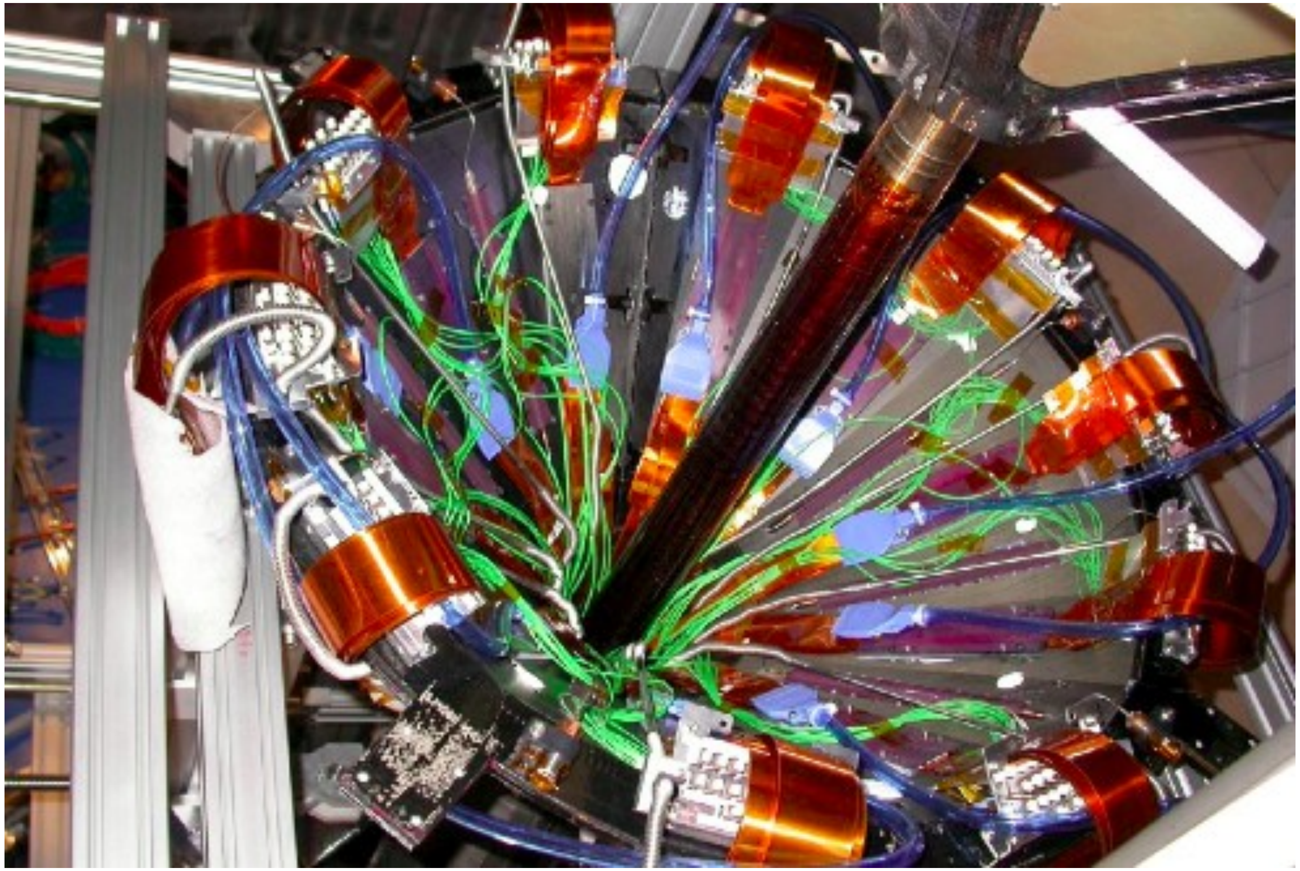
Pixel block diagram

Slide courtesy of V. Manzari

The Alice Silicon Pixel Detector- final checks of top half

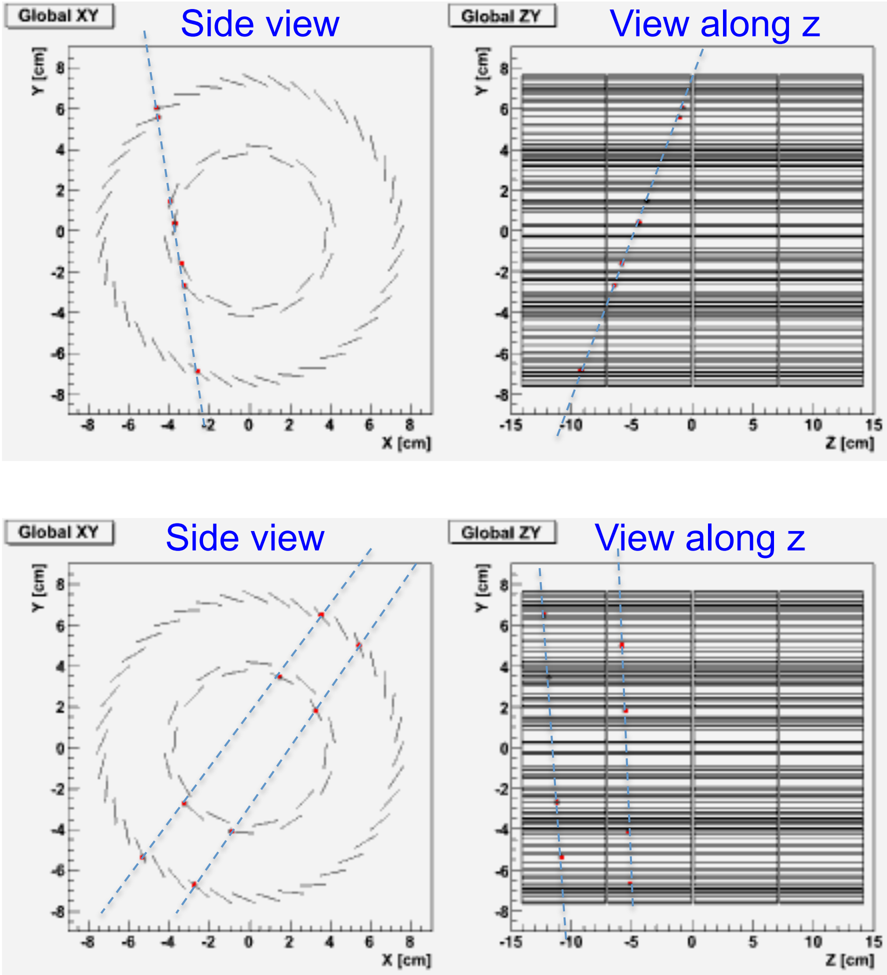
Slide courtesy of V. Manzari

The Alice Silicon Pixel Detector - final installation



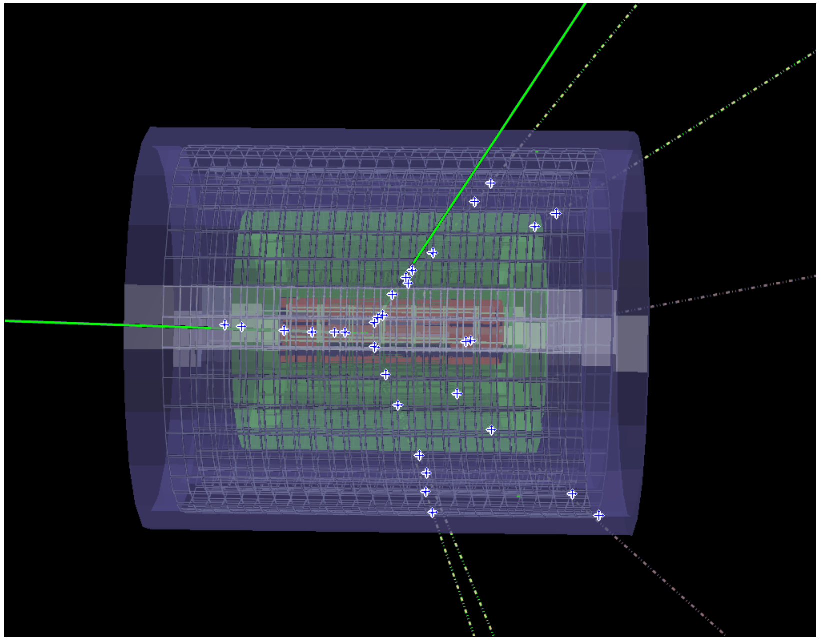
Slide courtesy of V. Manzari

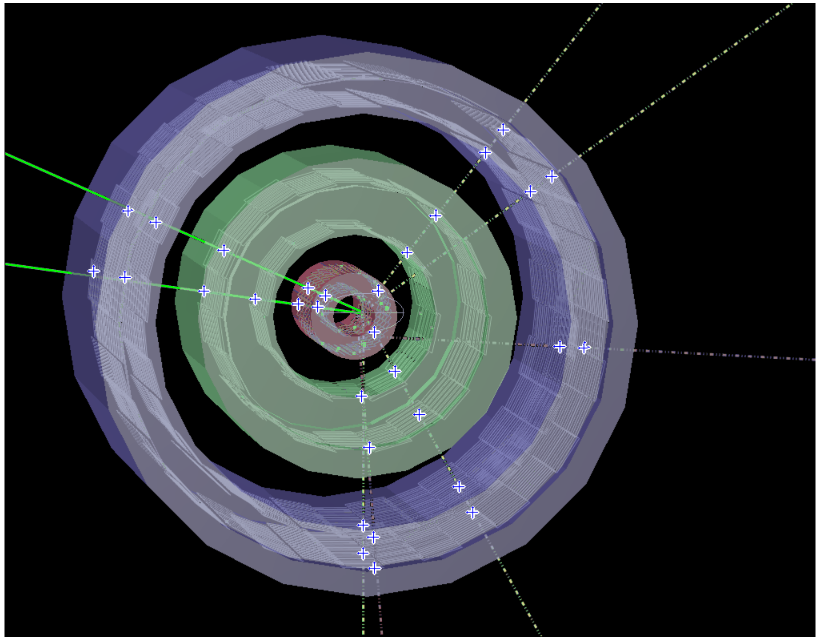
The Alice Silicon Pixel Detector – Detector Commissioning



SPD Online Event Display - Cosmic Run
Self-triggered (FastOr) coincidence of top outer and bottom outer layer

ALICE Silicon Pixel Detector – first collisions



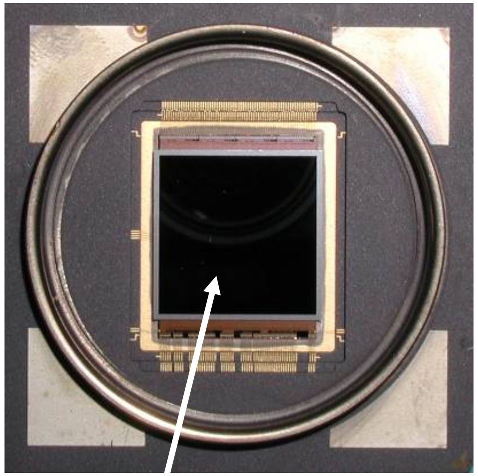


Detector triggered by pixel FAST-OR
>=One hit per layer

Slide courtesy of V. Manzari

Photon detector @ LHCb

- **Hybrid Photon Detectors (HPD) developed in collaboration with industry**
  Principal partner: DEP-Photonis for encapsulation of pixel anode in tube

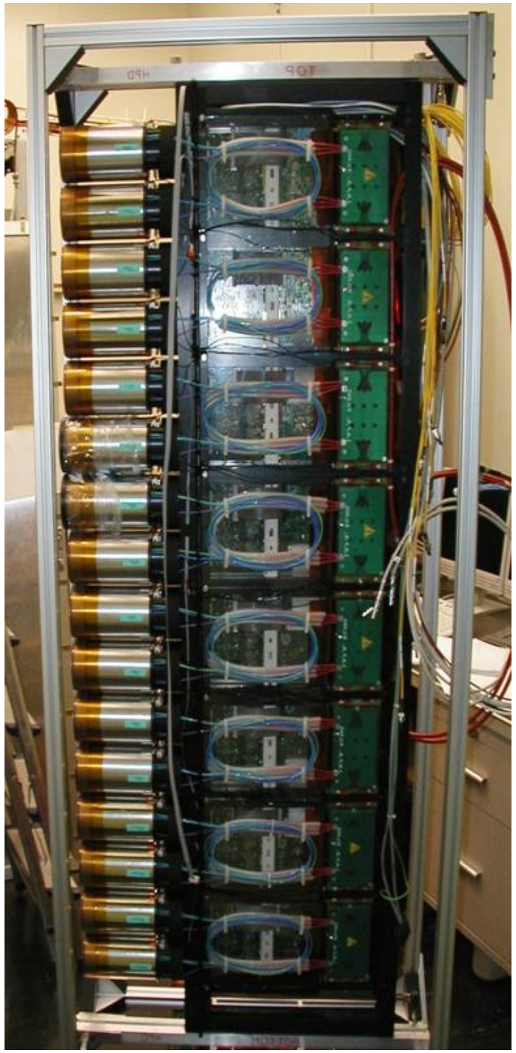


8192-channel pixel chip
8× OR → 1024 pixels
(500 × 500 μm square)

5× demagnification from electron optics -> 2.5 mm at photocathode, as required

Slide courtesy of R. Forty, T. Gys, K. Wyllie

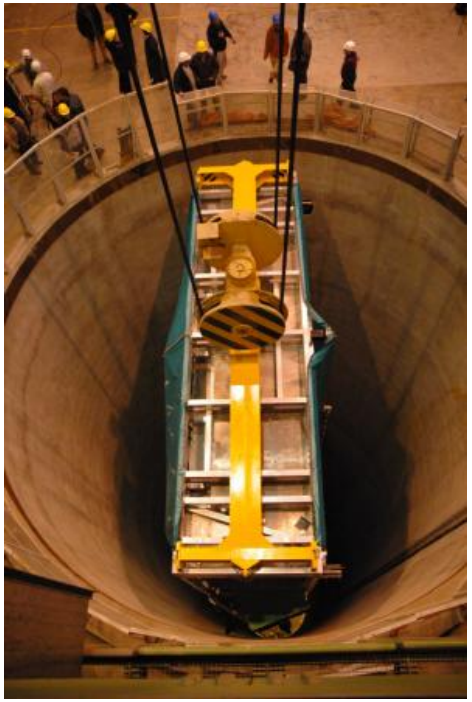
Fully equipped plane



Slide courtesy of R. Forty, T. Gys, K. Wyllie

LHCb RICH2 installation

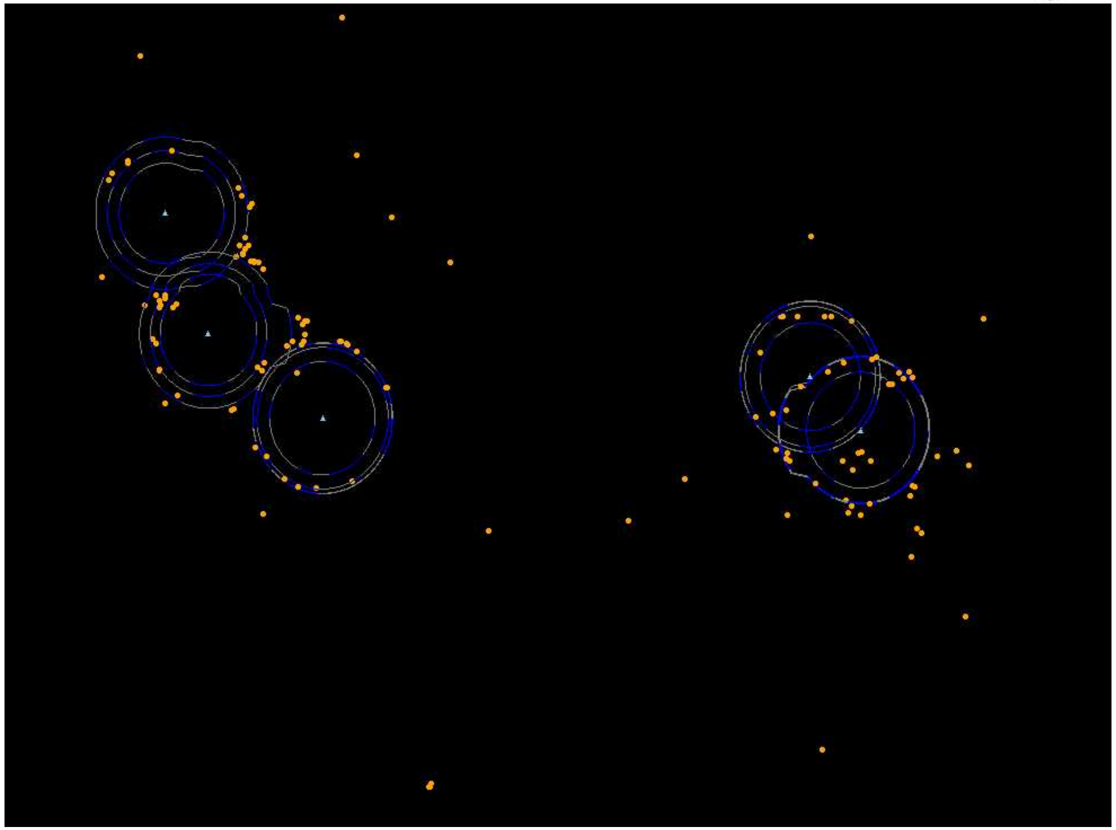
- RICH2 constructed on surface, including alignment of optical elements
  Delicate transport (~ 1 km/h) to the LHCb cavern, 100 m underground



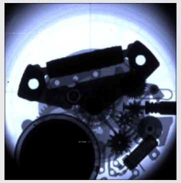
Slide courtesy of R. Forty, T. Gys, K. Wyllie

LHCb RICH – First rings

RICH2 HPD Panels with Pixels and CK Rings

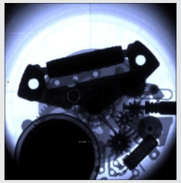


Slide courtesy of R. Forty, T. Gys, K. Wyllie



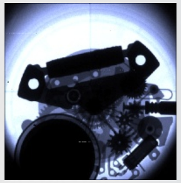
Hybrid Pixels in High Energy Physics - Summary

- Hybrid pixels offer simultaneously:
  - Practically noise free images
  - Fast ‘shutter’ times
  - On pixel event selection
- Hybrid pixels have been used as vertex tracking detectors
  - Extremely good pattern recognition performance
  - Modest material budget
- Hybrid pixels have been used as photon RICH detectors
  - Very high pattern recognition performance



Medipix2 chip developments

- Chip designed in same CMOS technology as Alice and LHCb
- Pixel shape now square - 55μm pitch
- Matrix of 256 x 256 pixels
- In-pixel counter with ‘camera’ logic
  - Externally applied shutter
  - Window discriminator
  - 14-bit counter with stop at 12000
- Very high flux capability
  - $\geq$ 3 GHits/cm^2
- Frame-based readout



Two Collaborations

Medipix2

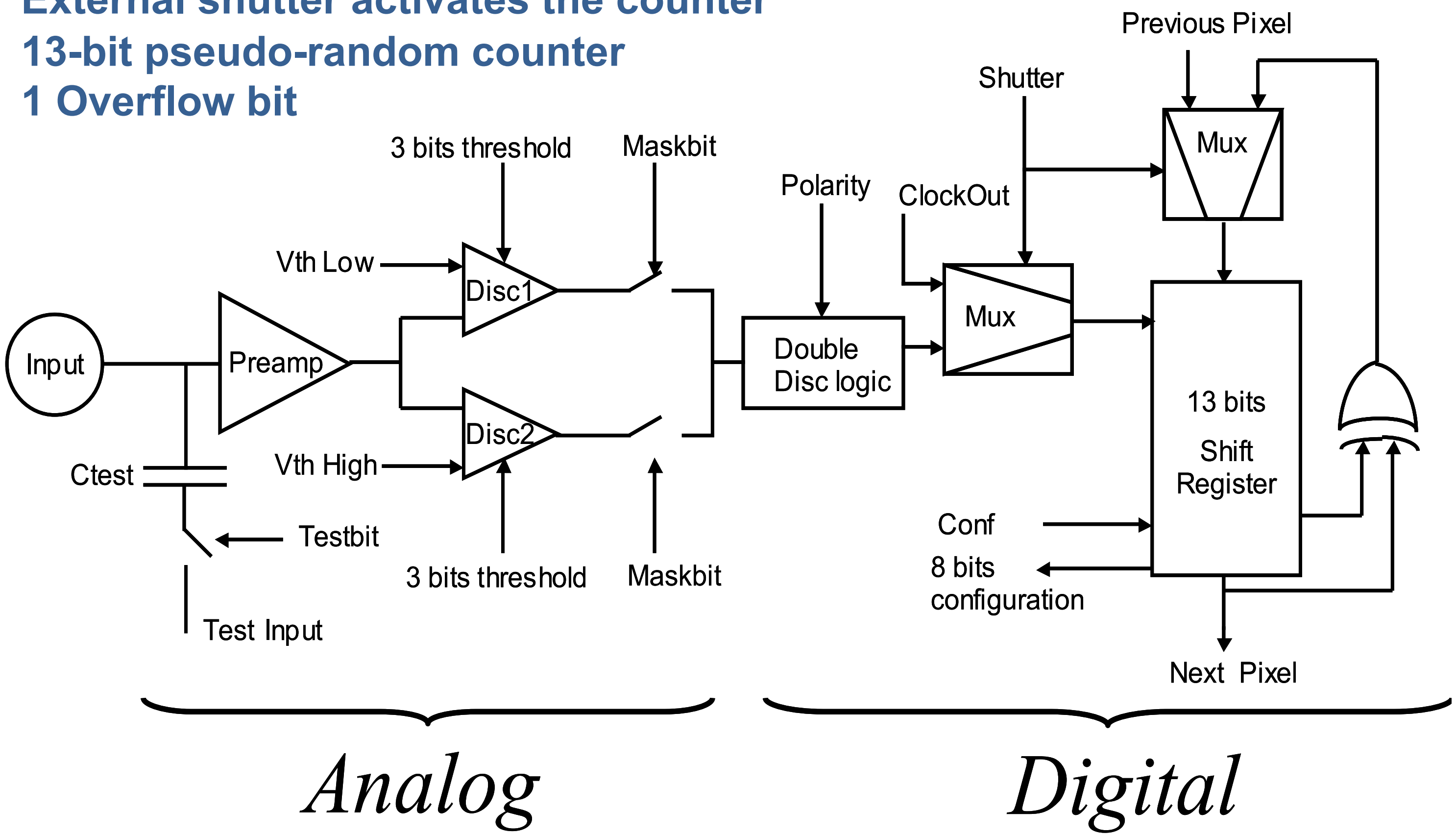
INFN and University of Cagliari
CEA-LIST Saclay
CERN Genève
University of Erlangen
ESRF Grenoble
University of Freiburg
University of Glasgow
IFAE Barcelona
Mid Sweden University
MRC-LMB Cambridge
INFN and University of Napoli
NIKHEF Amsterdam
INFN and University of Pisa
FZU CAS Prague
IEAP CTU Prague
SSL UC Berkeley
University of Houston

Medipix3

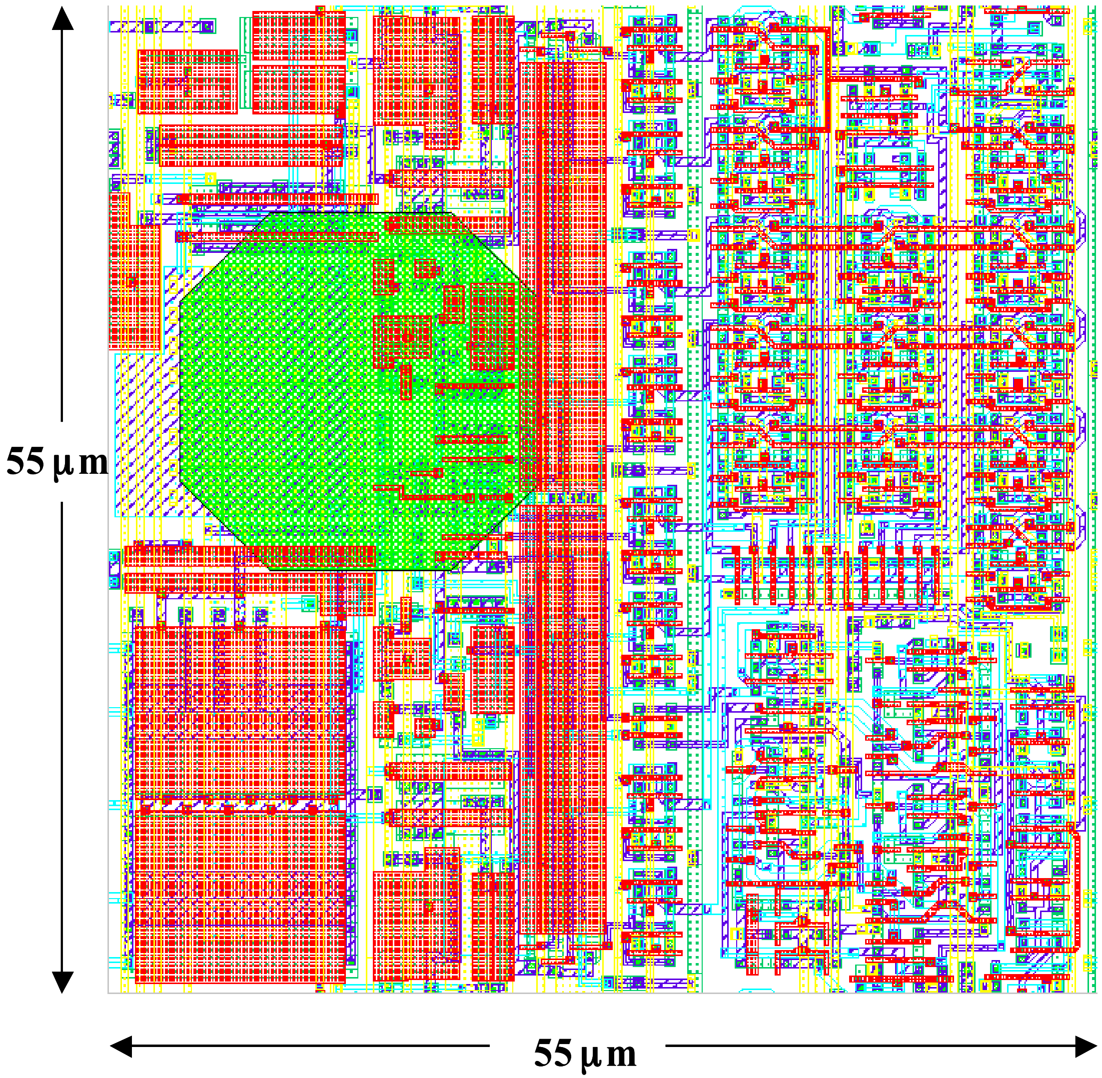
AMOLF Amsterdam
Universidad de los Andes, Bogota
University of Bonn, Germany
University of Canterbury NZ
CEA-LIST Saclay
CERN Geneva
DESY Hamburg
Diamond Light Source
University of Erlangen
ESRF Grenoble
University of Freiburg
University of Glasgow
ITER Cadarache
ISS University of Karlsruhe
Leiden University
Mid Sweden University
NIKHEF Amsterdam
IEAP CTU Prague
SSL Berkeley
VTT Microsystems

Medipix2 Pixel Cell Schematic

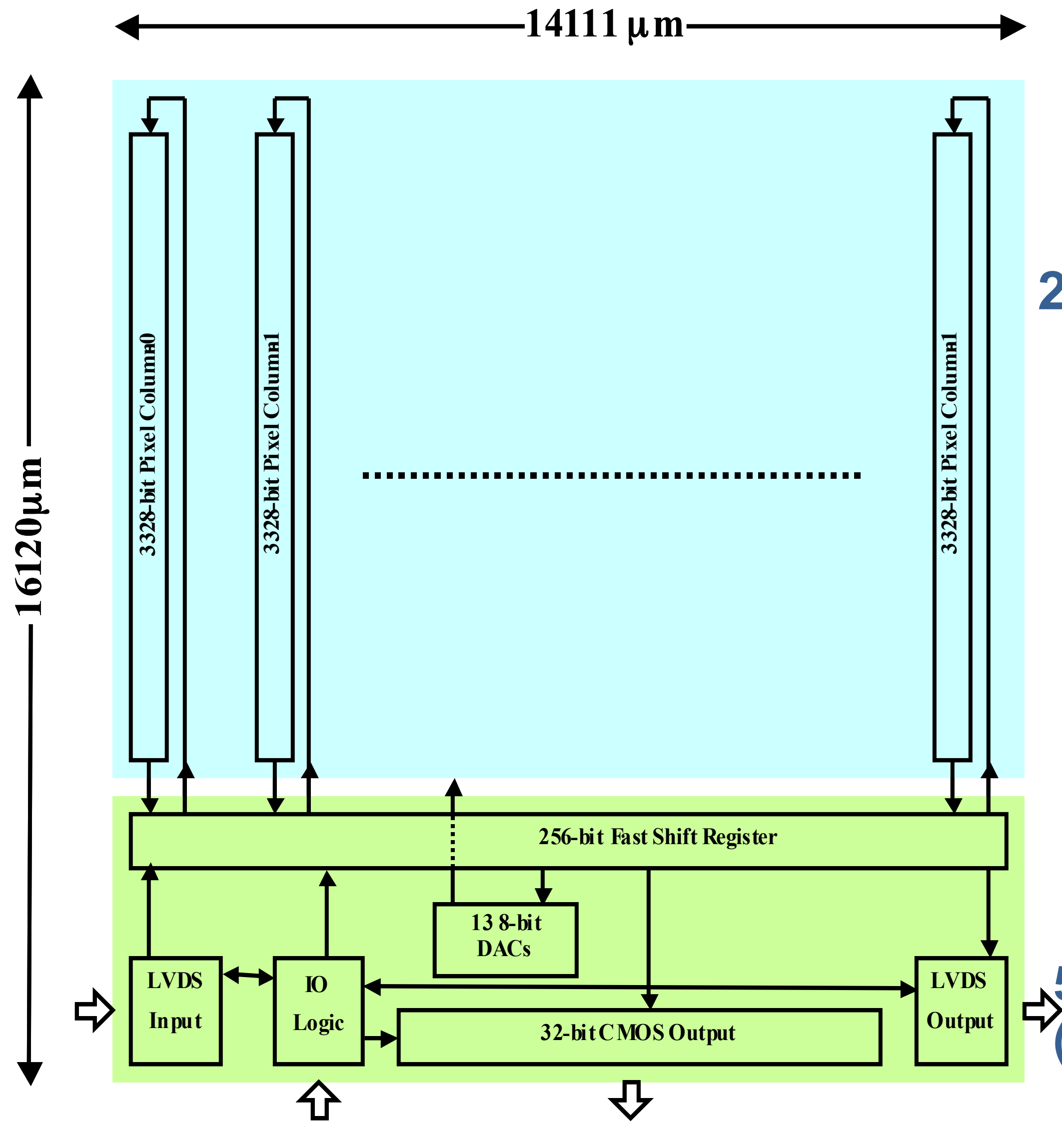
Charge sensitive preamplifier with individual leakage current compensation
2 discriminators with globally adjustable threshold
3-bit local fine tuning of the threshold per discriminator
1 test and1 mask bit
External shutter activates the counter
13-bit pseudo-random counter
1 Overflow bit



Medipix2 Cell Layout



Medipix2 Chip Architecture

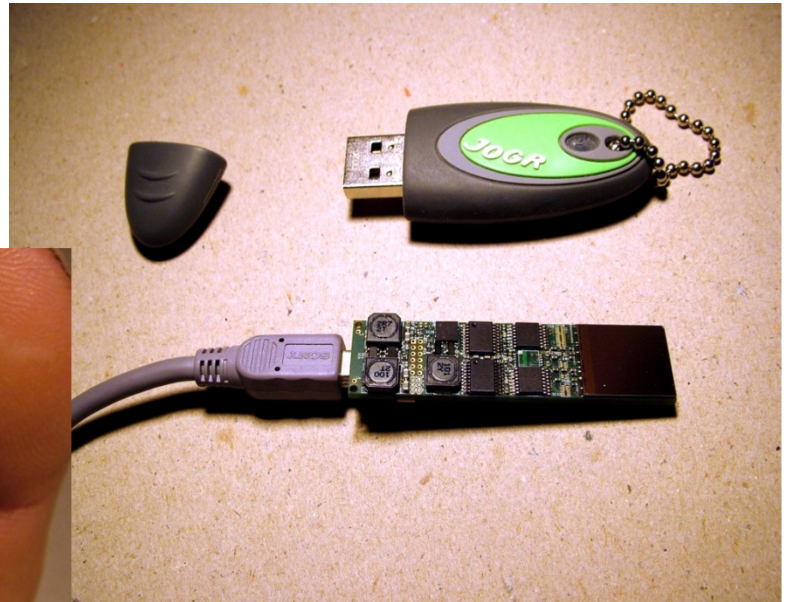


256 x 256 pixels

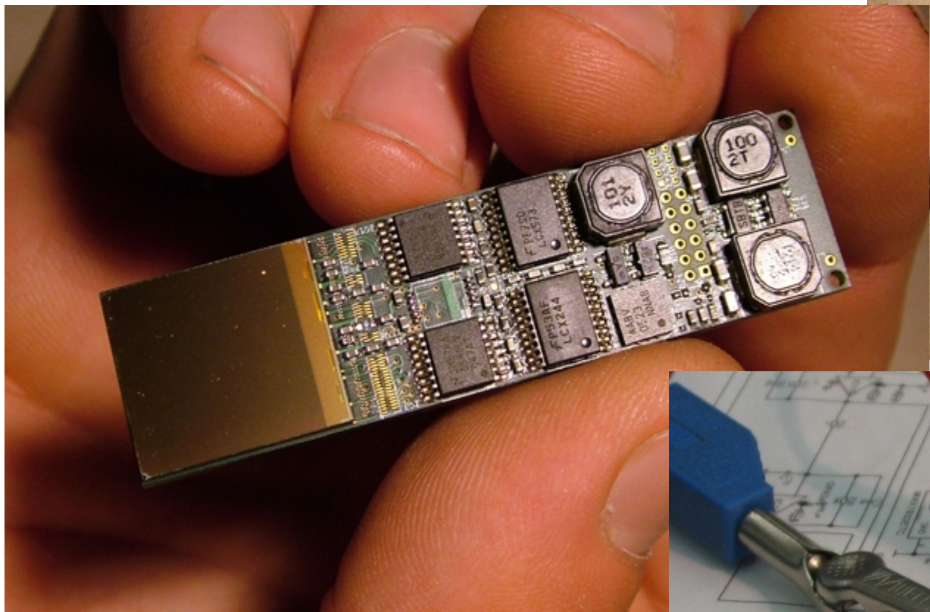
5ms readout time (serial @ 200MHz)

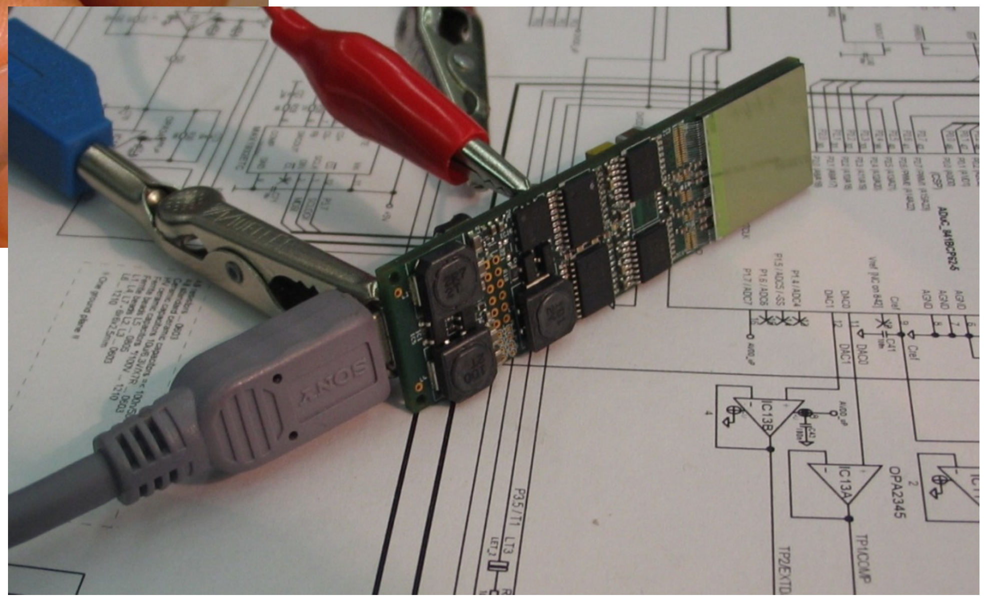
300µs readout time (parallel @ 100MHz)

USB Lite

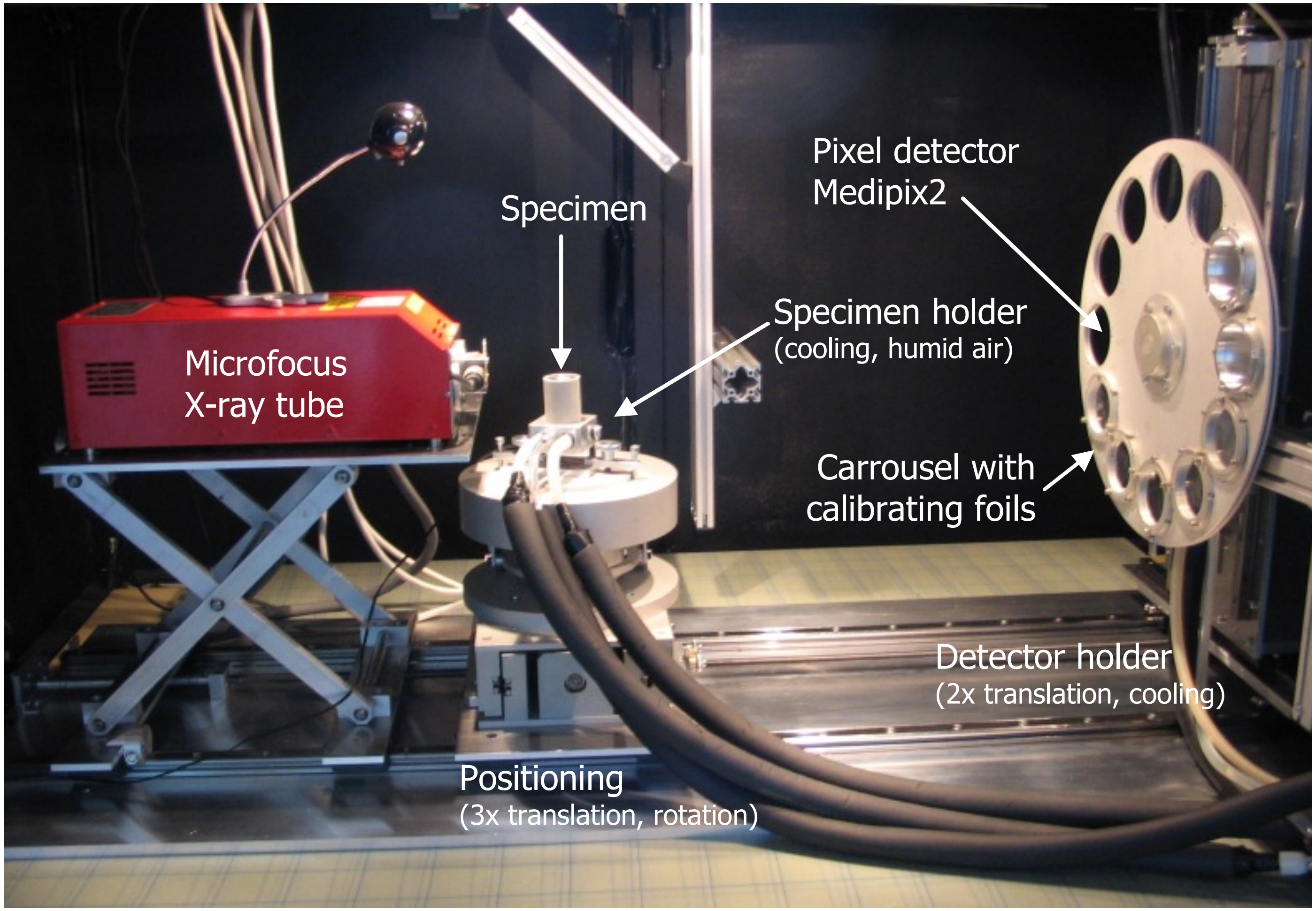


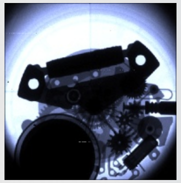
with bonded bare chip



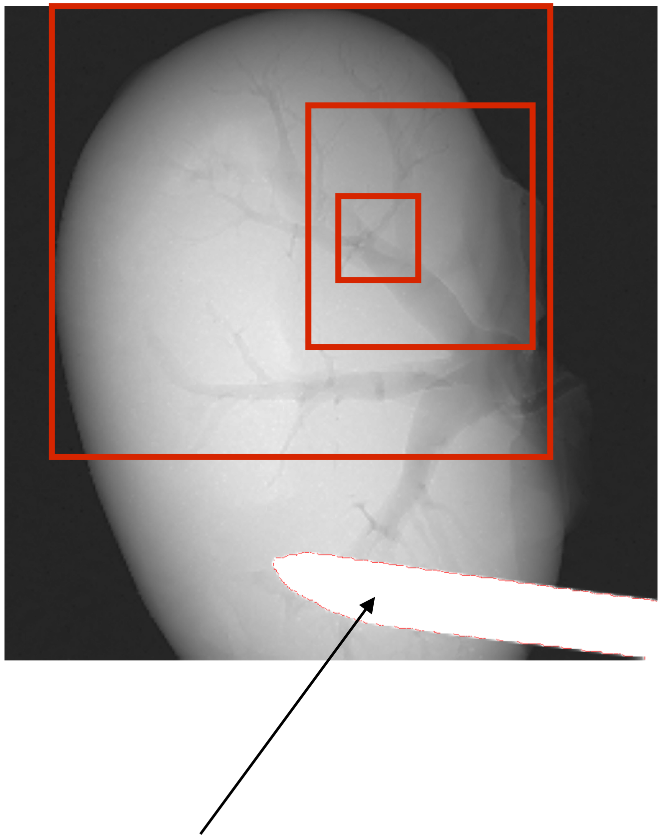


High resolution X-ray imaging using a micro-focus X-ray source(1)

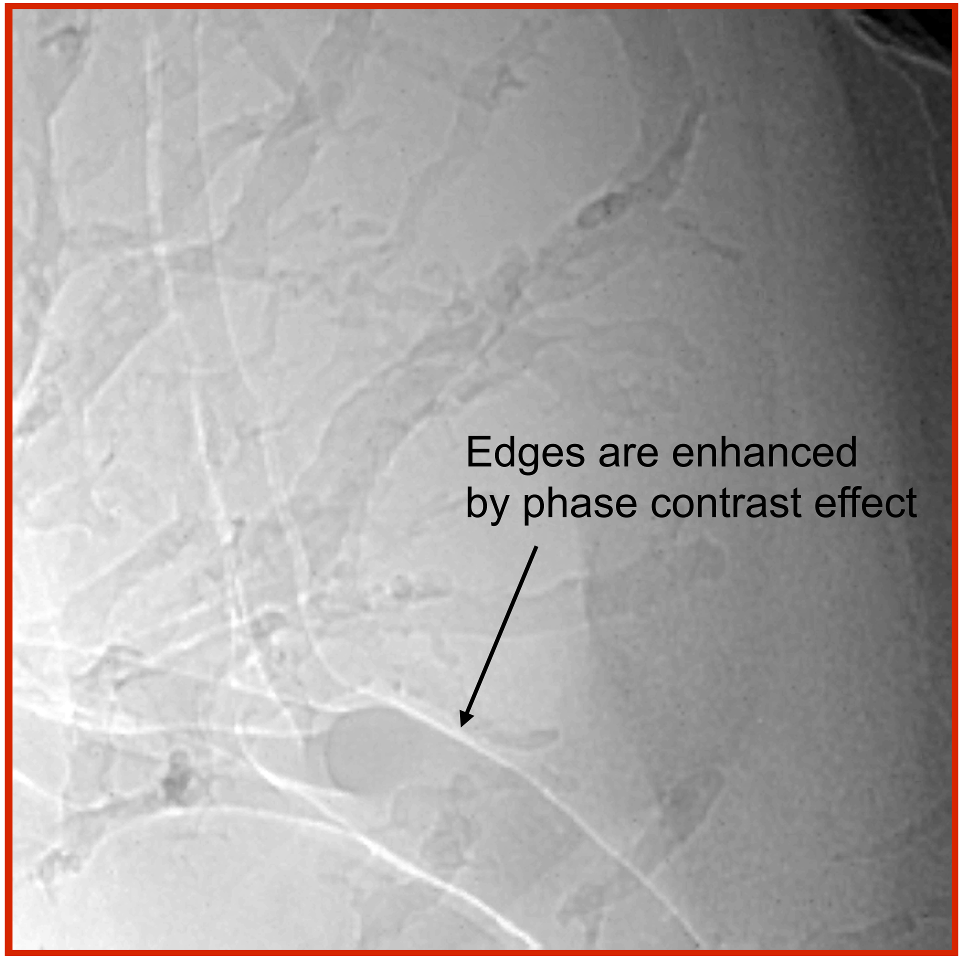


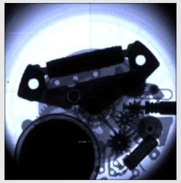


High resolution X-ray imaging using a micro-focus X-ray source(2)

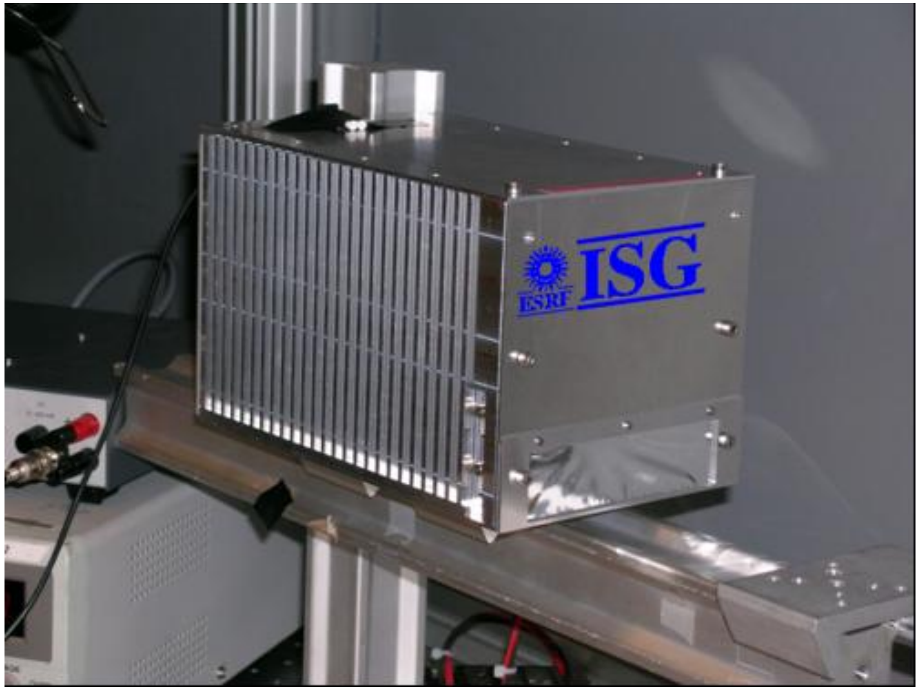


Needle holding the sample





MAXIPIX : a high frame rate pixel detector for SR experiments



Based on MEDIPIX2* photon-counting readout chip

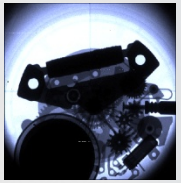
- 1280 x 256 pixels (5 readout chips)
- Pixel size 55 x 55 μm^2
- 6-20 keV range (500 µm Si sensor)
- > 10^5 counts/pixel/s
- low and high energy thresholds
- 0.20 ms readout dead time
- 300 Hz frame rate (full frame)
- 1500 Hz frame rate (256x256 pixels)

- noiseless (photon-counting)
- high temporal resolution (fast readout)
- high spatial resolution (small pixels)

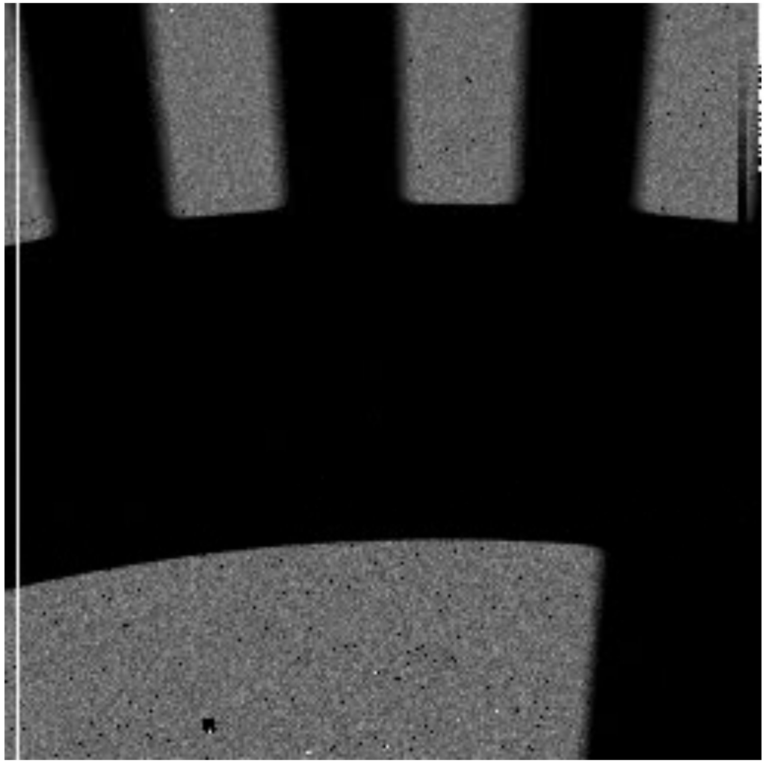
Main applications :

- inelastic scattering
- time-resolved XPCS
- time-resolved SAXS, GISAXS
- surface diffraction and scattering

Slide courtesy of C. Ponchut



Real high rate images

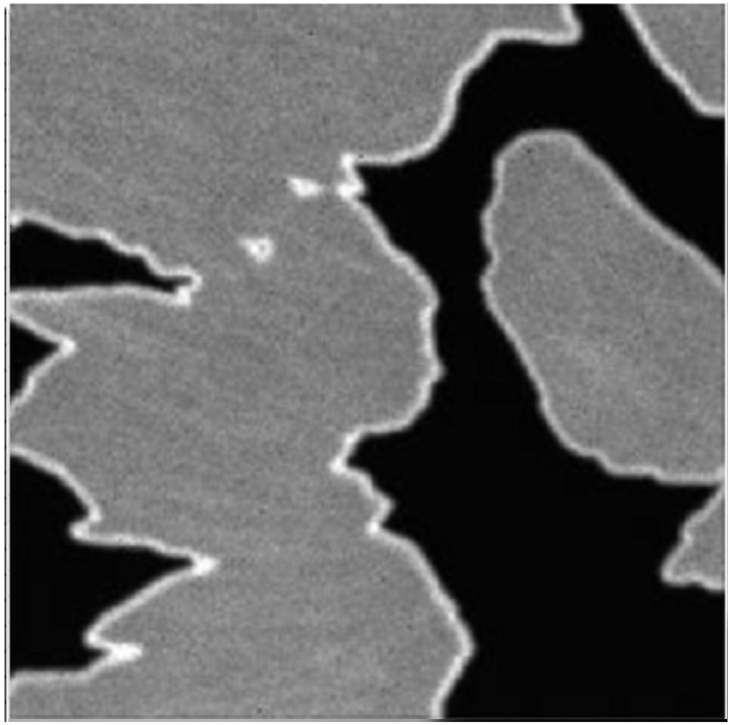


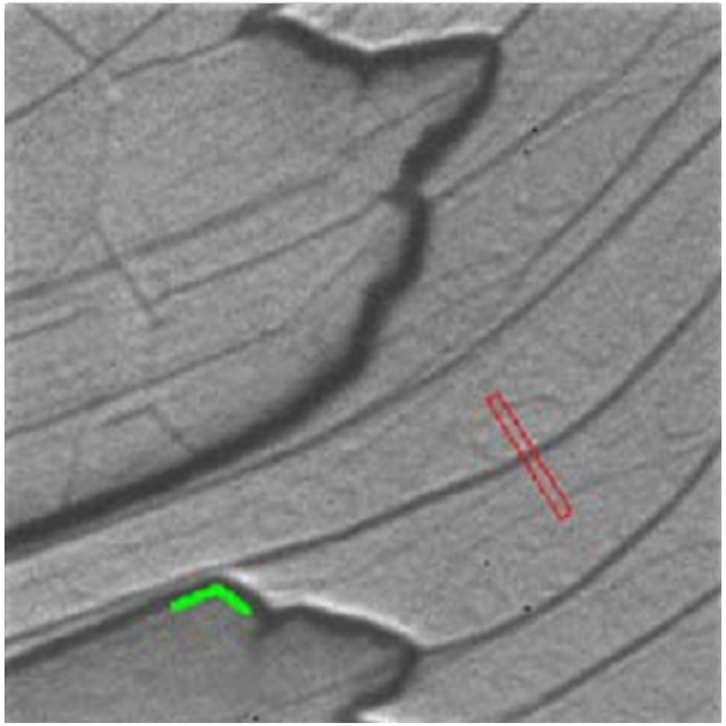
Application required development of a new fast readout system (ESRF Grenoble)

1 kHz frame rate imaging could be achieved turning chopper wheel

Slide courtesy of C. Ponchut

Low Energy Electron Microscopy



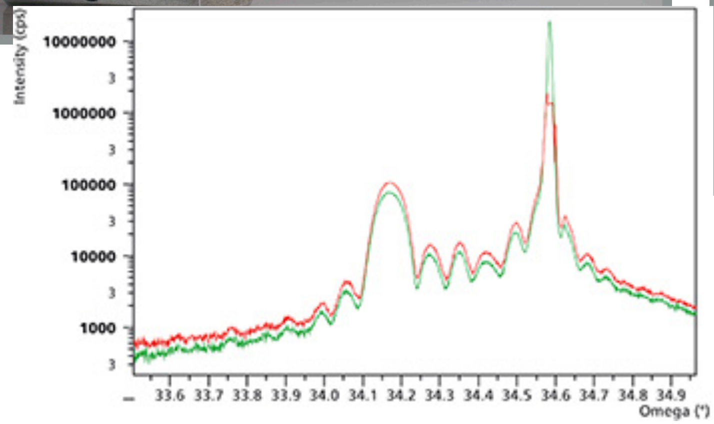


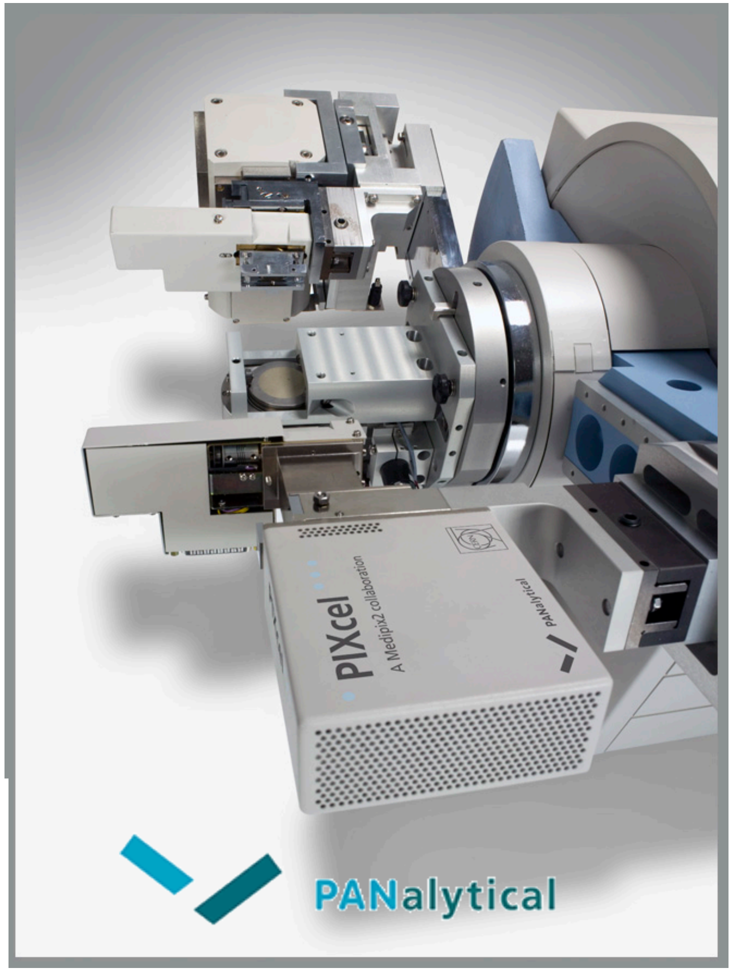
Medipix2 Images
images

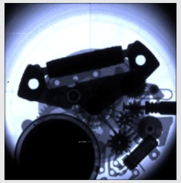
Graphene flakes

I. Sikharulidze, J-P Abrahams and co-workers
'Medipix2 applied to low energy electron microscopy',
Ultramicroscopy 110 (2009) 33 - 35

TT to industry- PANalytical



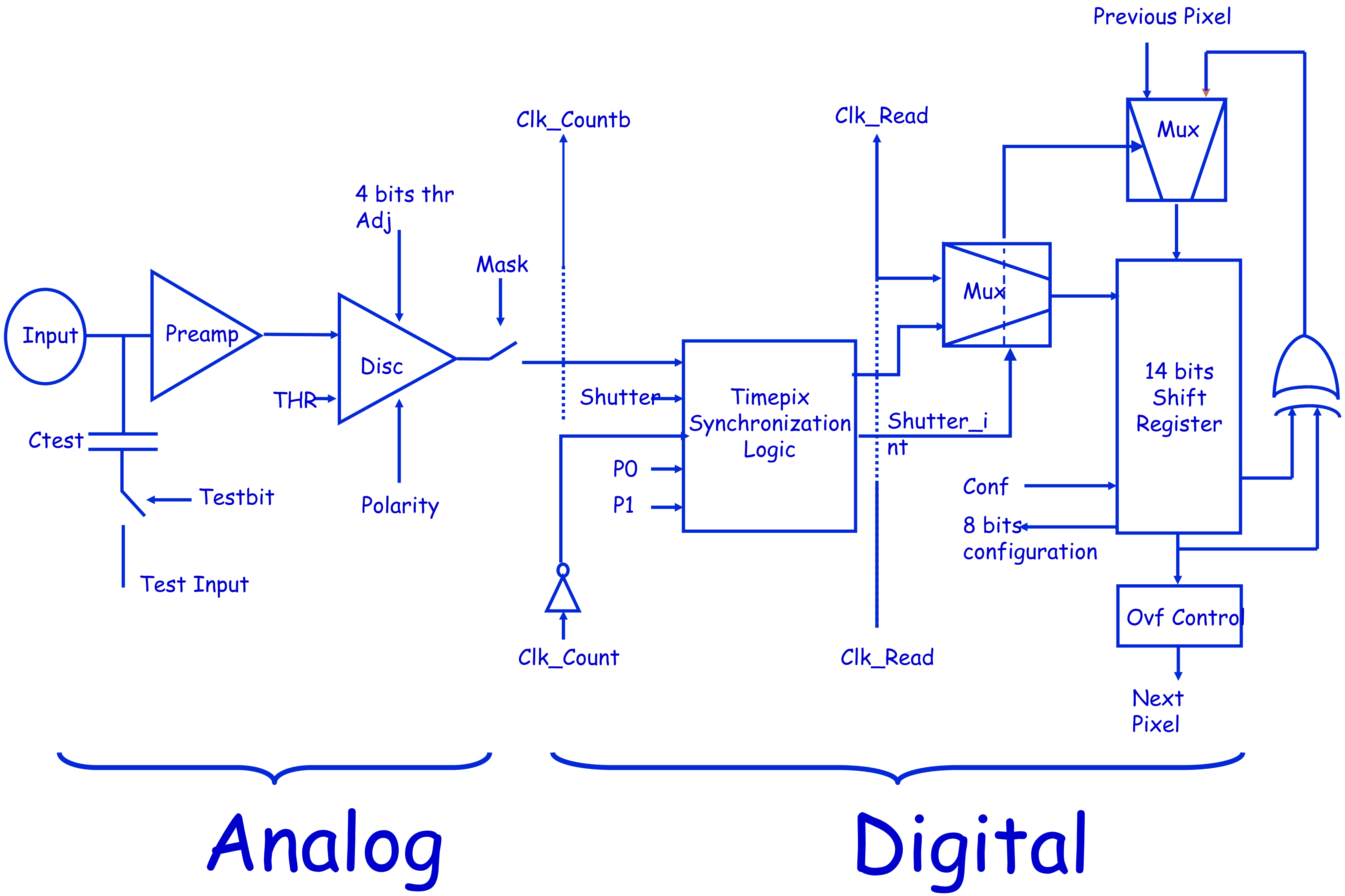




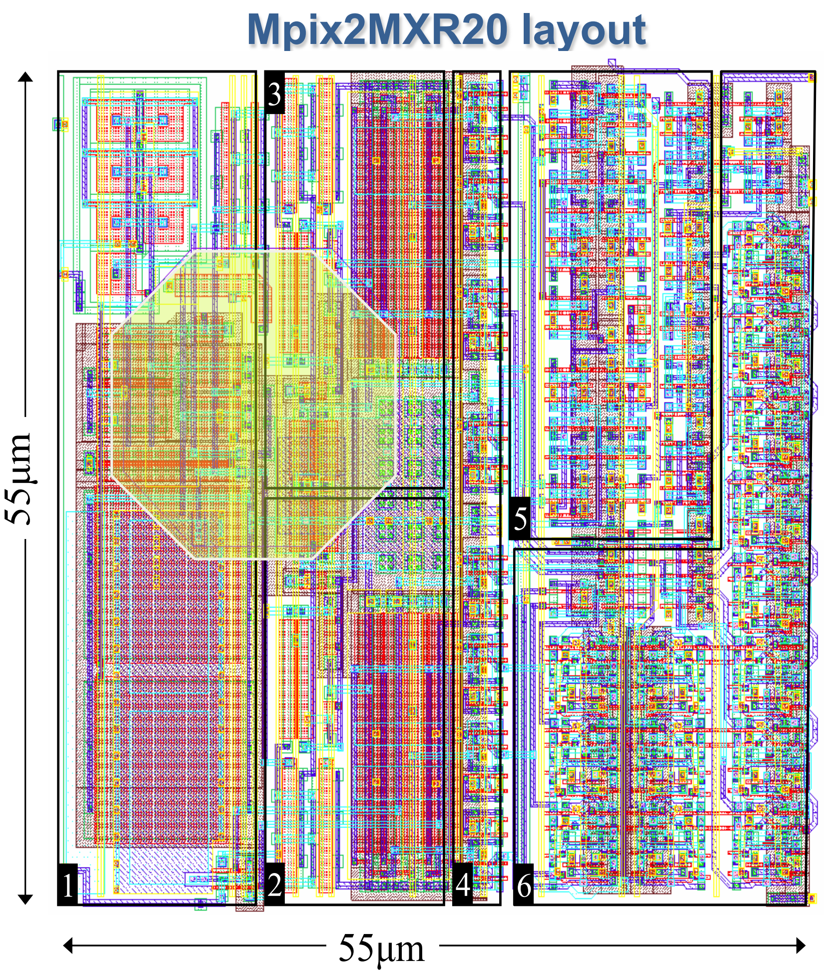
Timepix chip

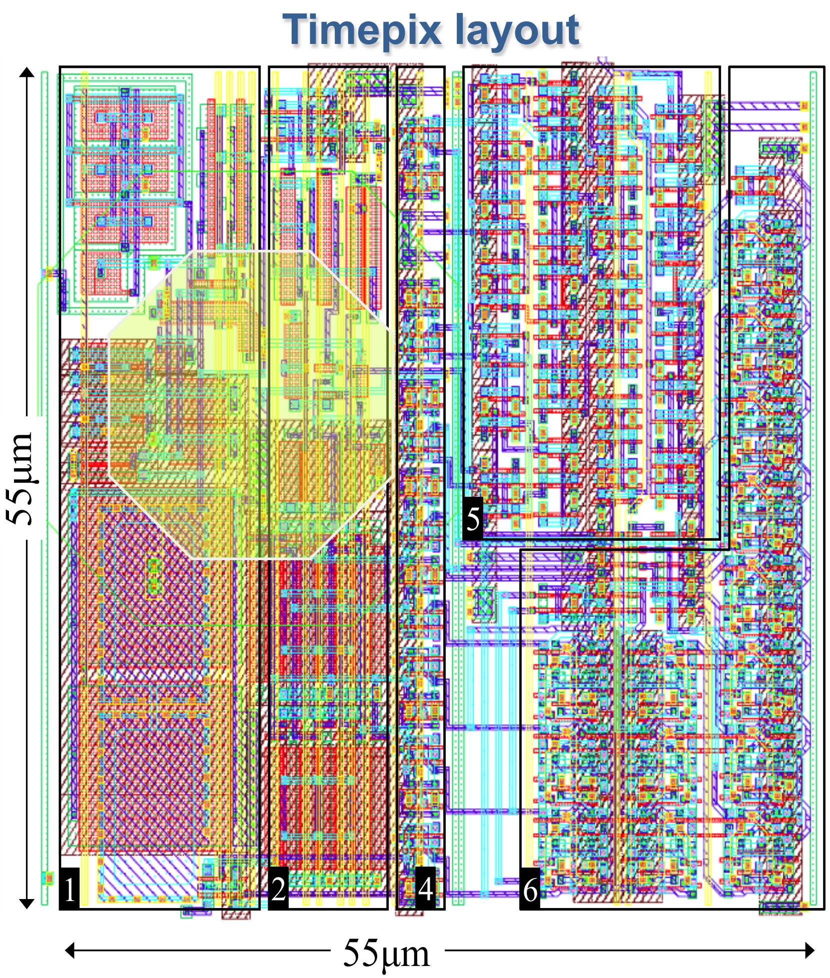
- Conserve dimensions and readout philosophy of Medipix2 (same CMOS technology)
- Requested by EUDet gas detector community
  - Add running clock during DAQ to obtain arrival time information wrt end of shutter
  - Added Time-over-Threshold capability

Timepix Schematic

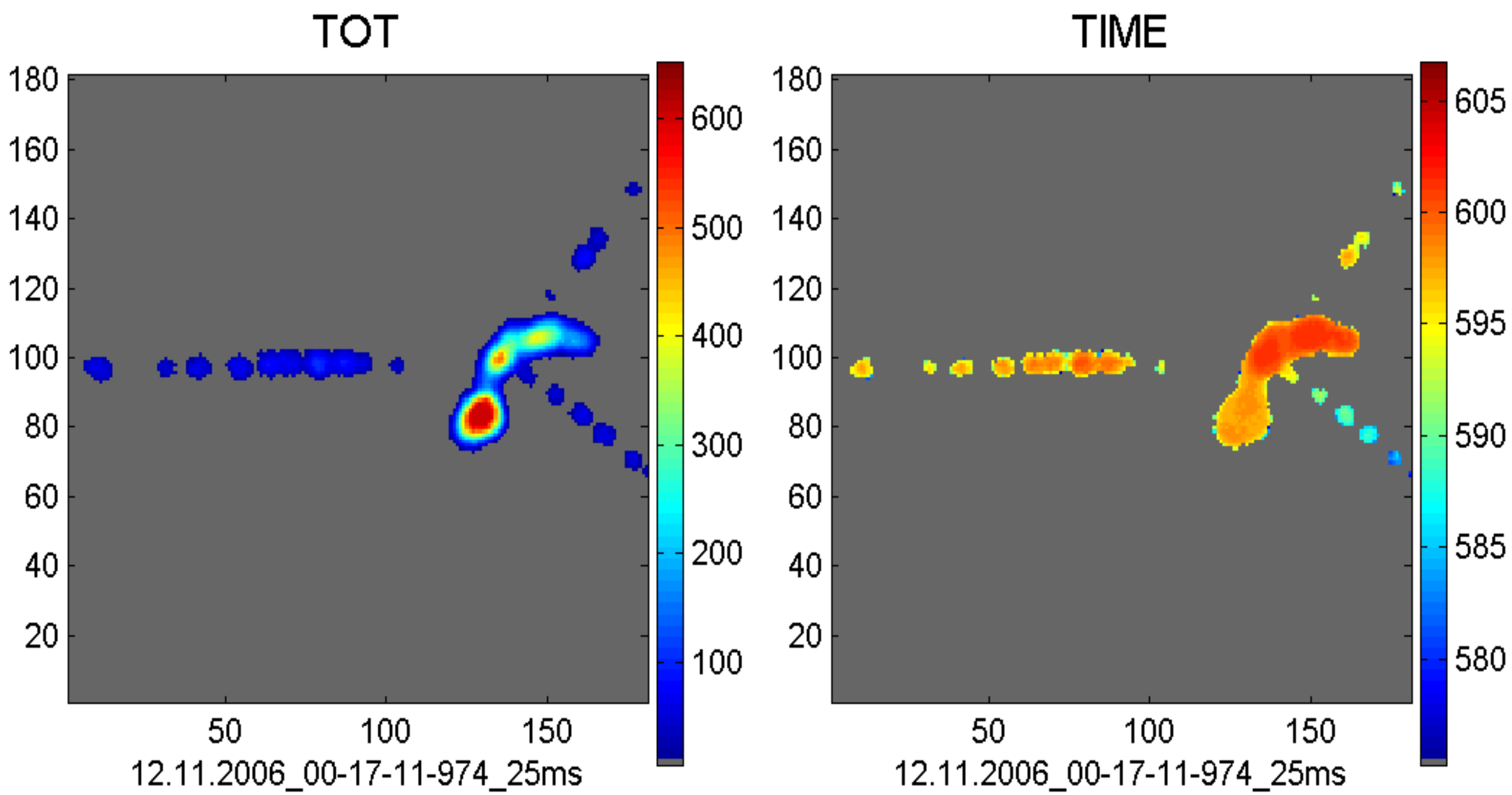


Medipix2 vs Timepix Layout



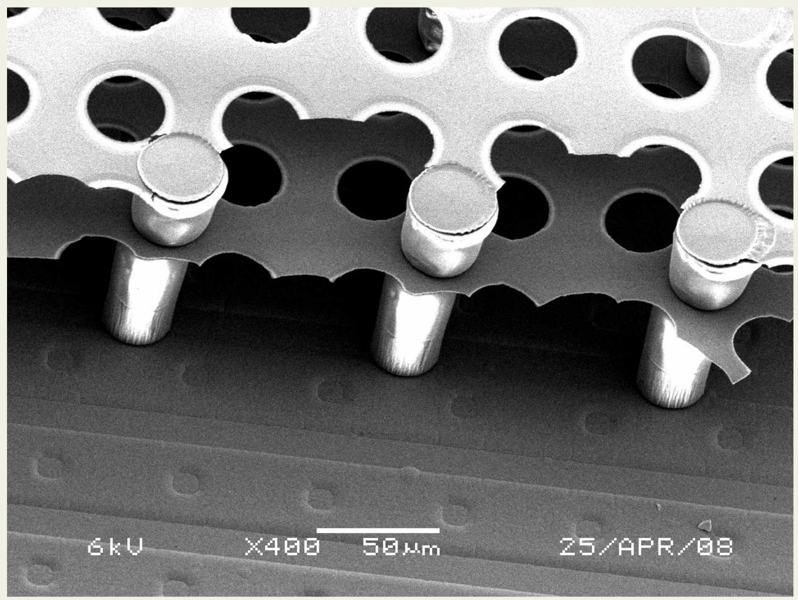


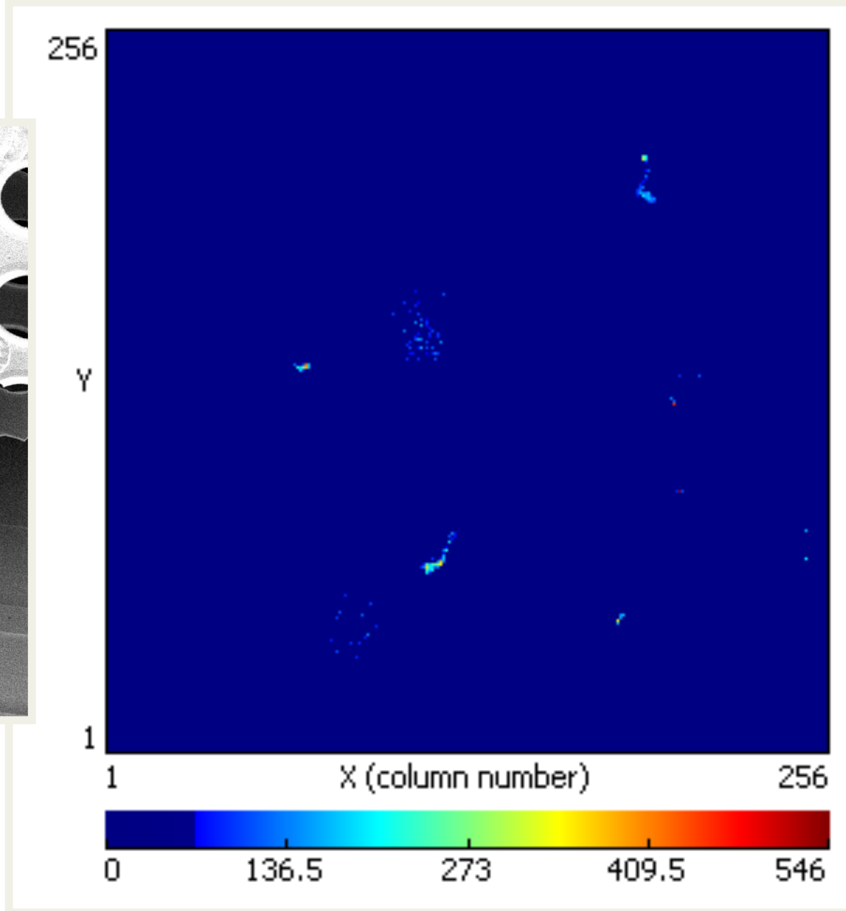
Timepix with 3-GEM detector



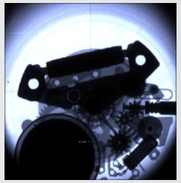
DESY testbeam in November 2006 (A.Bamberger, U. Renz, M.Titov)

Twin grid on Timepix

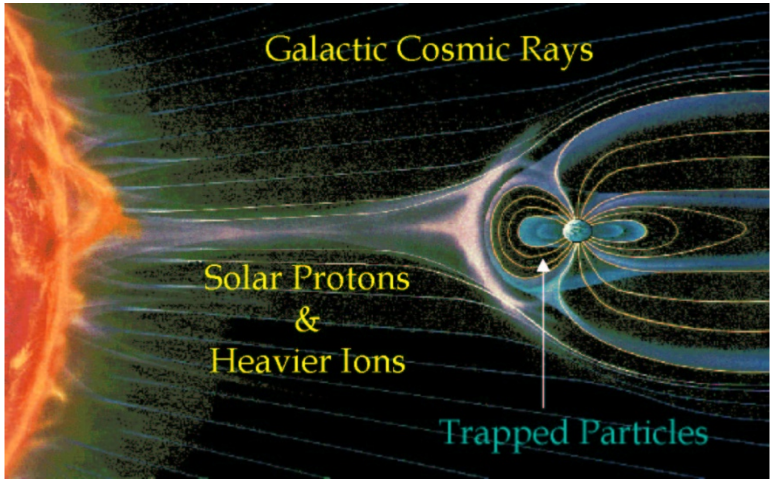




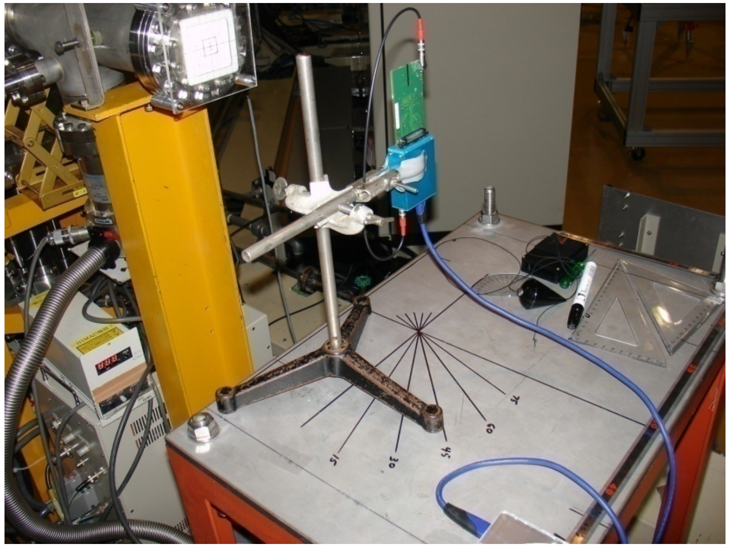
Developed by H. Van Der Graaf and co-workers



Developing a TimePix-Based Dosimeter for Space Radiation



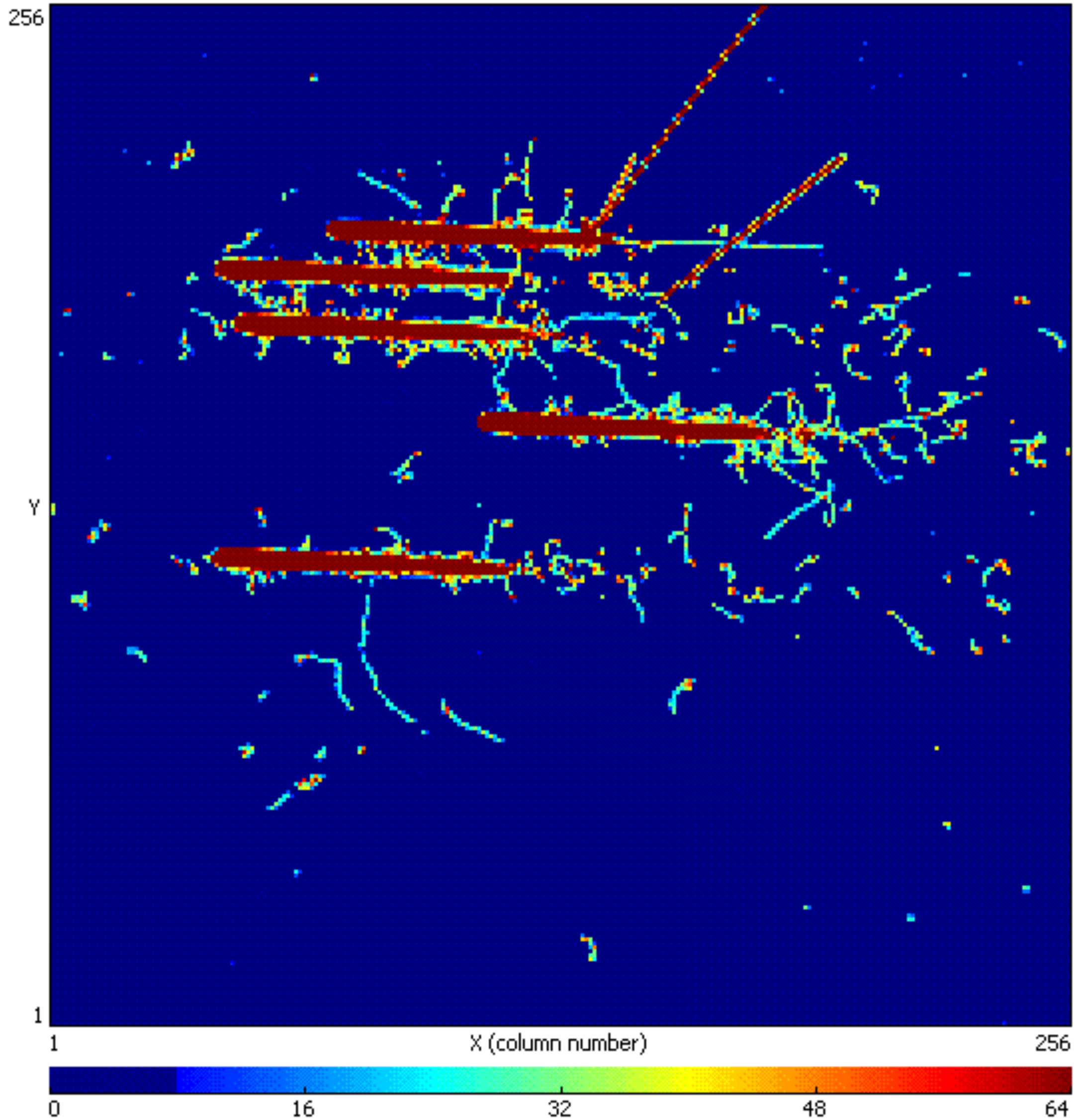
- **The University of Houston Medipix Group is working with NASA to develop a TimePix-based dosimeter for Space Radiation Applications…**
- **Such a device must be able to detect and measure all of the components of the Space Radiation Environment, which includes Energetic Heavy Ions…**
- **Data have been taken with Heavy Ion beams at the HIMAC Facility in Japan…**



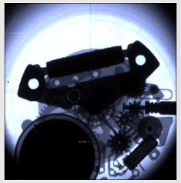
Penetrating Heavy Ion Charge and Velocity Discrimination with a TimePix-based Si Detector

L. Pinsky and co-workers, Univ. Houston, USA

Tracks of 85 degree incident Si at 800 MeV/nuc moving from left to right

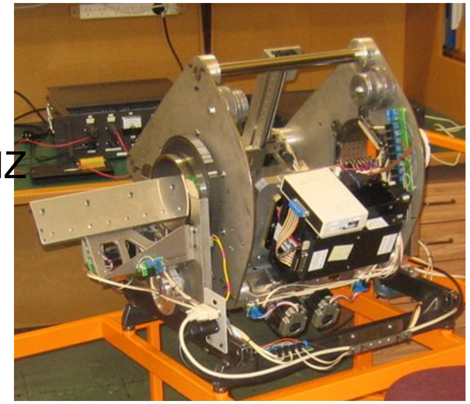


L. Pinsky and co-workers, Univ. Houston, USA

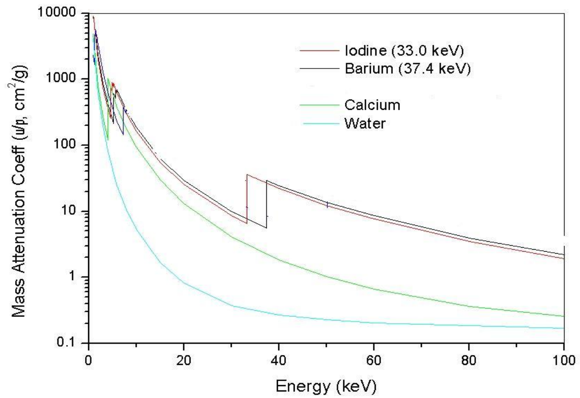


K-edge imaging

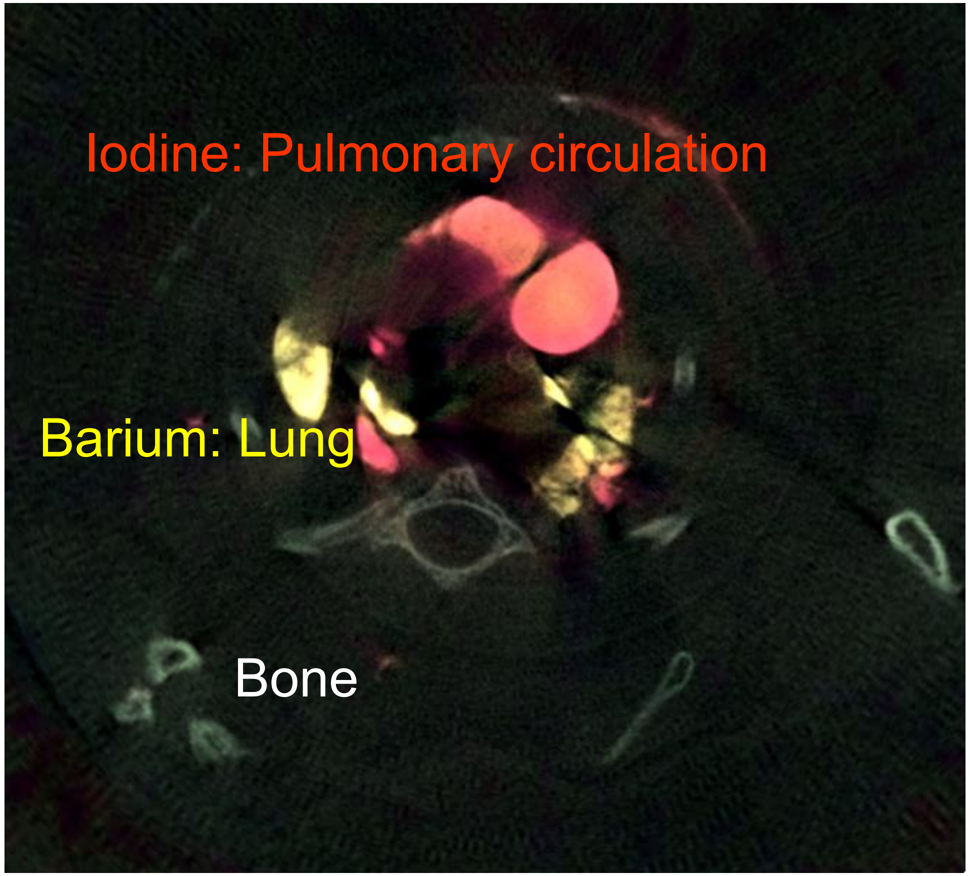
Univ. Canterbury, NZ
Mars bio-imaging
Small animal CT



- Iodine: Pulmonary circulation
- Barium: Lung
- Bone: normal structure
- 4 energy CT and PCA



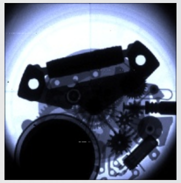
Spectral enhancement



Butler, A., et al., *Processing of spectral X-ray data with principal components Analysis*, IWORID 2009, Prague

CERN@school

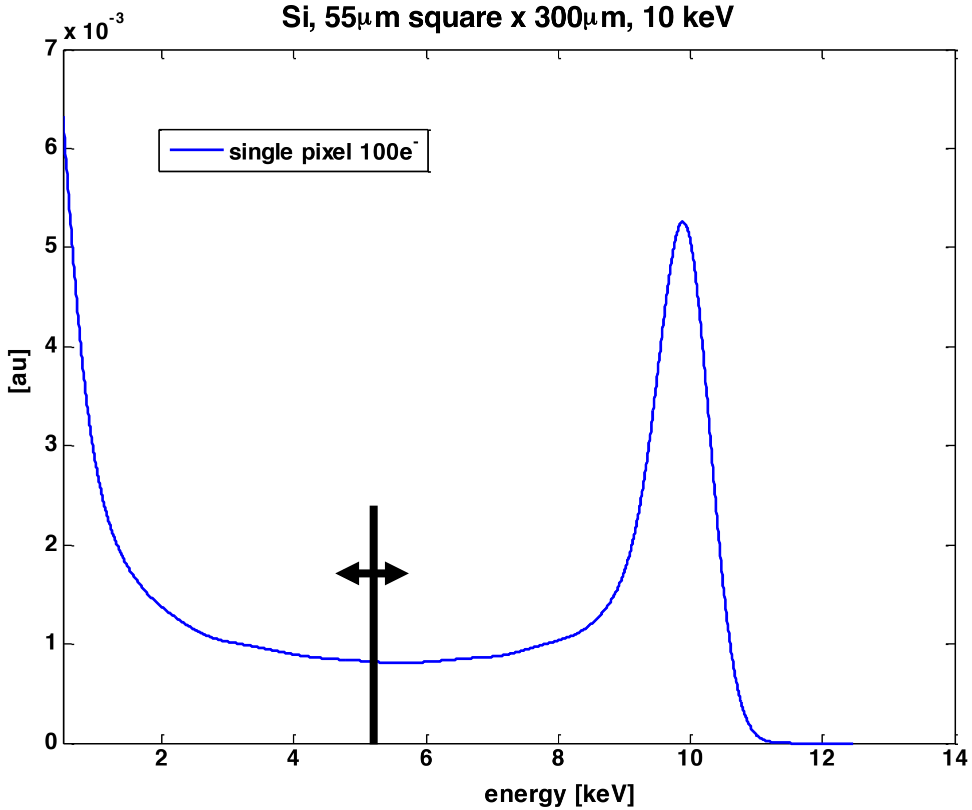
Simon Langton School, Canterbury, England



Performance of Medipix2/Timepix

- **Single photon counting provides excellent noise free images**
- **Ideal in photon starved situations**
- **Spectroscopic X-ray imaging possible**
- **Many different application both foreseen and otherwise!**
  - Electron microscopy (TEM and LEEM/PEEM)
  - Neutron imaging
  - Nuclear power plant decommissioning
  - Mass spectrometry
  - Adaptive optics
  - Dosimetry in space
  - Gas detectors
  - Teaching science

Medipix2 – charge sharing



Simulated Data

Si 300mm, 55mm pixel

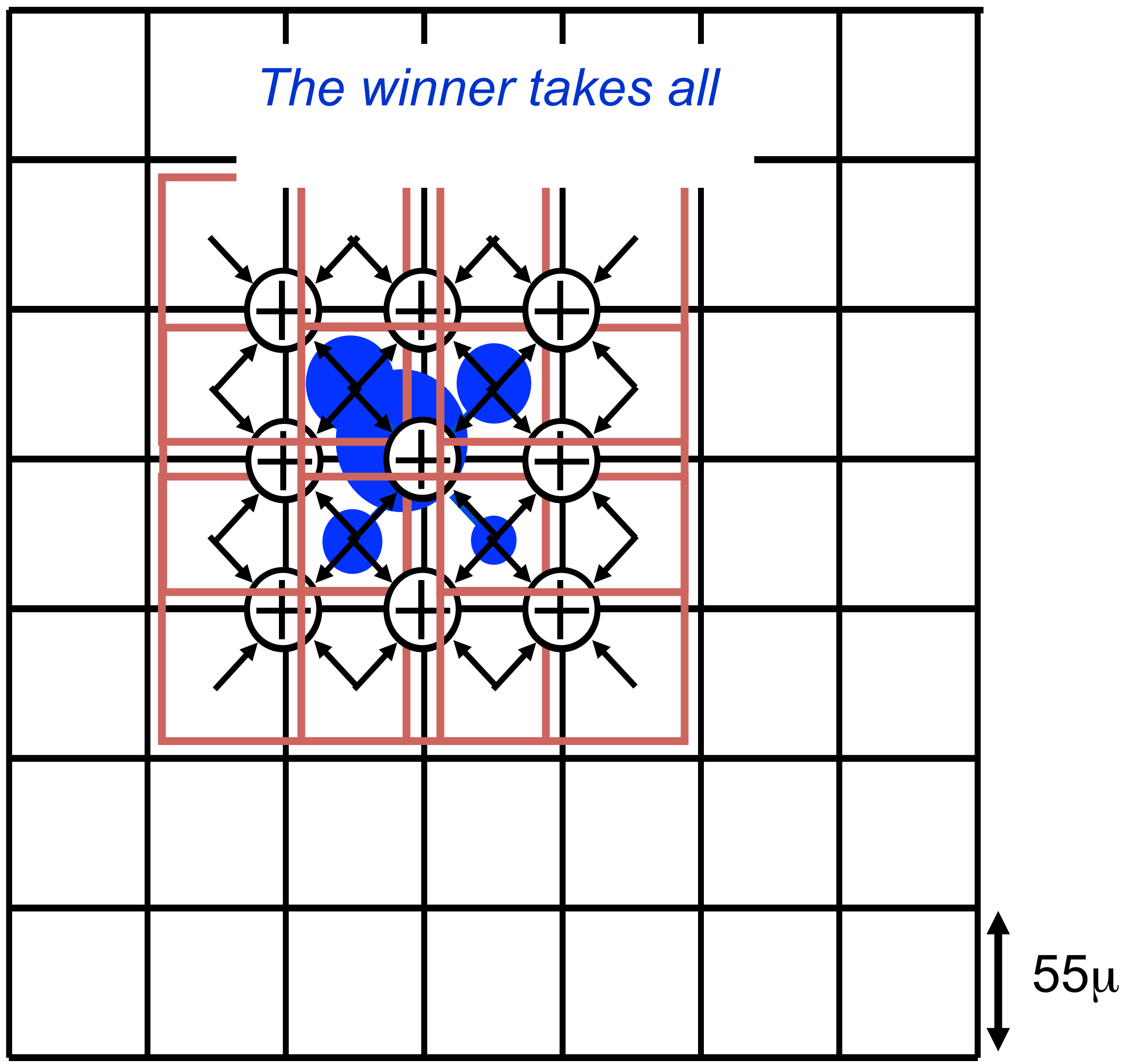
10keV monochromatic photon beam

Charge diffusion produces "charge sharing" tail

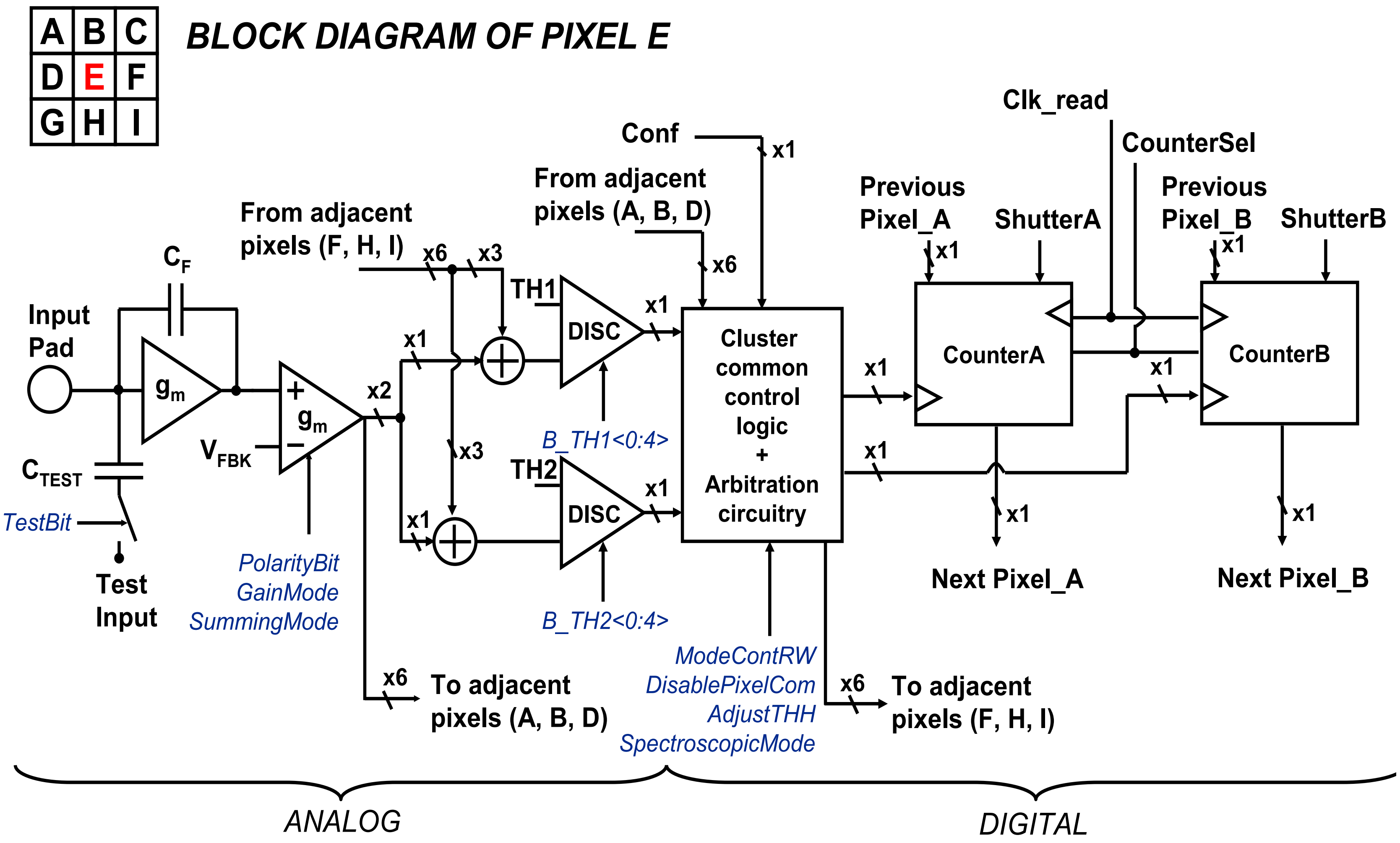
Threshold variations produce noise in image

L. Tlustos

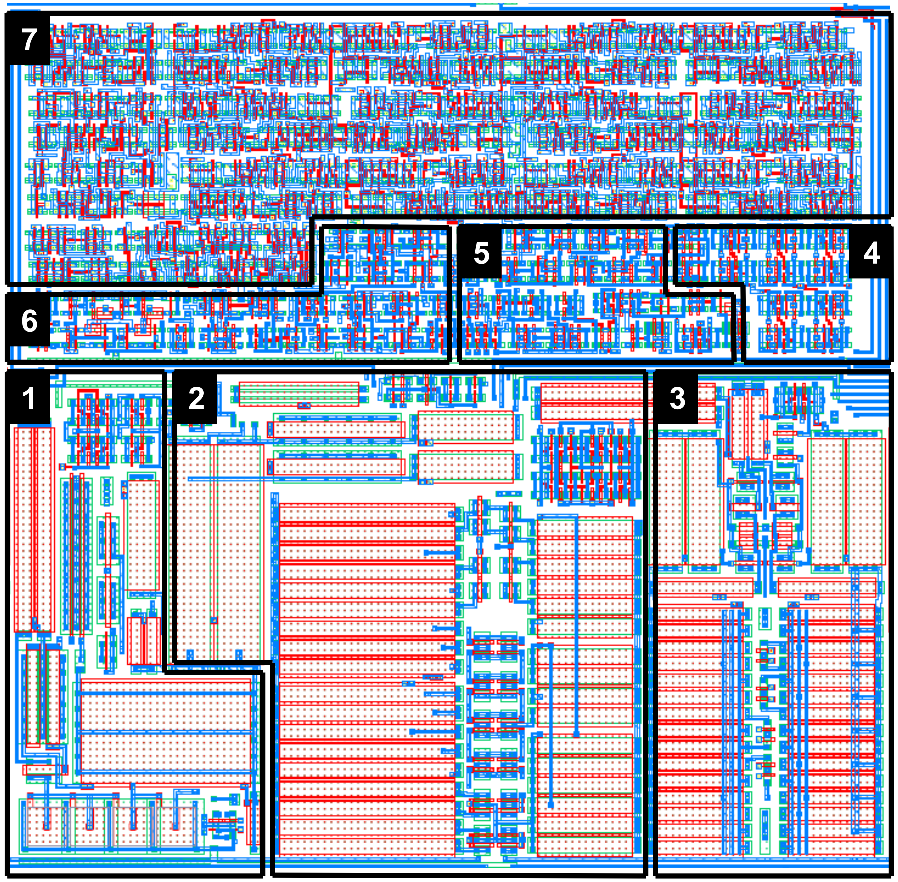
Medipix3 – charge summing concept



Medipix3 Cell Schematic

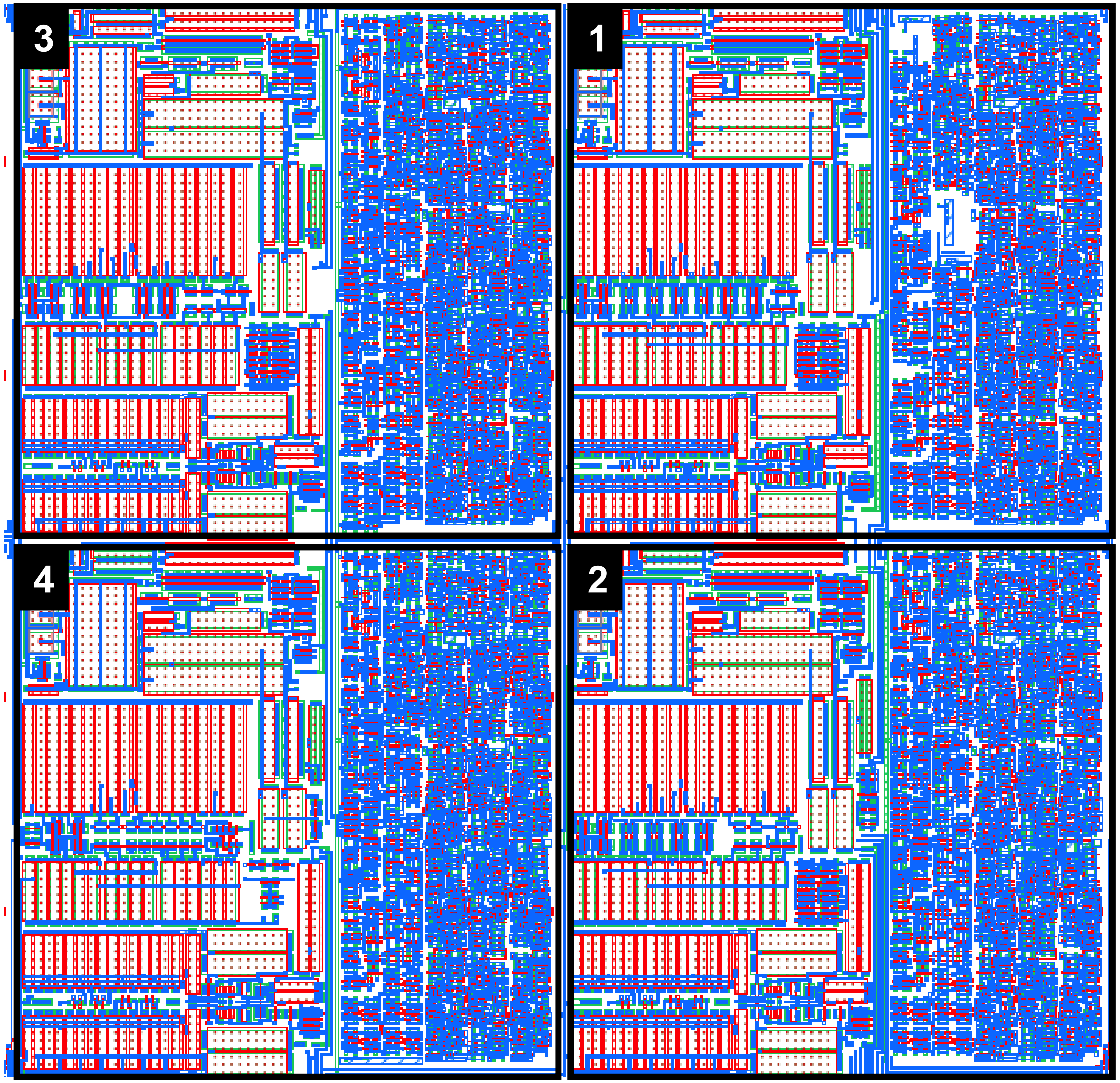


Medipix3 Cell Layout

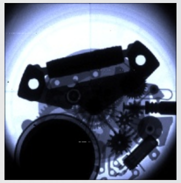


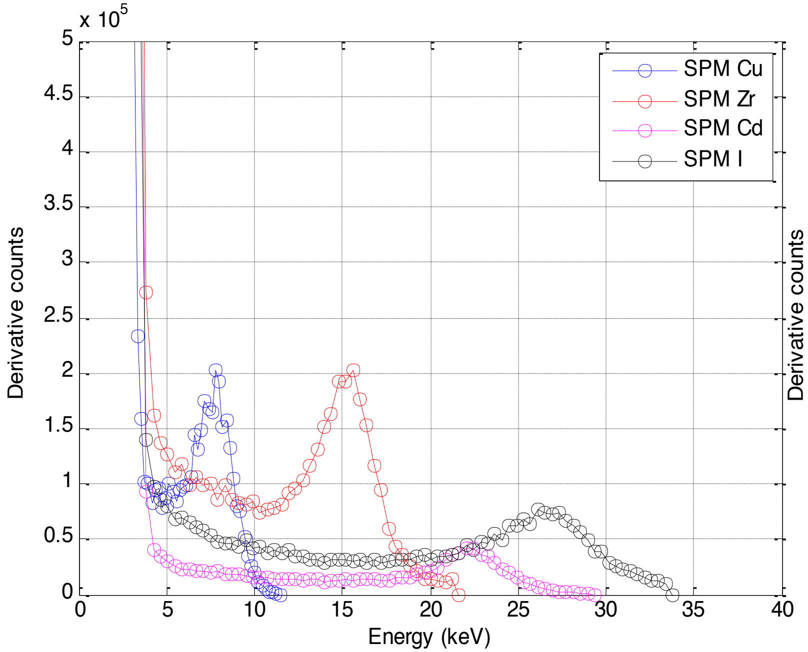
1. Preamplifier
2. Shaper
3. Two discriminators with 4-bit threshold adjustment
4. Configuration bits
5. Arbitration logic for charge allocation
6. Control logic
7. Configurable counter.

Medipix3 - regular pixel structure

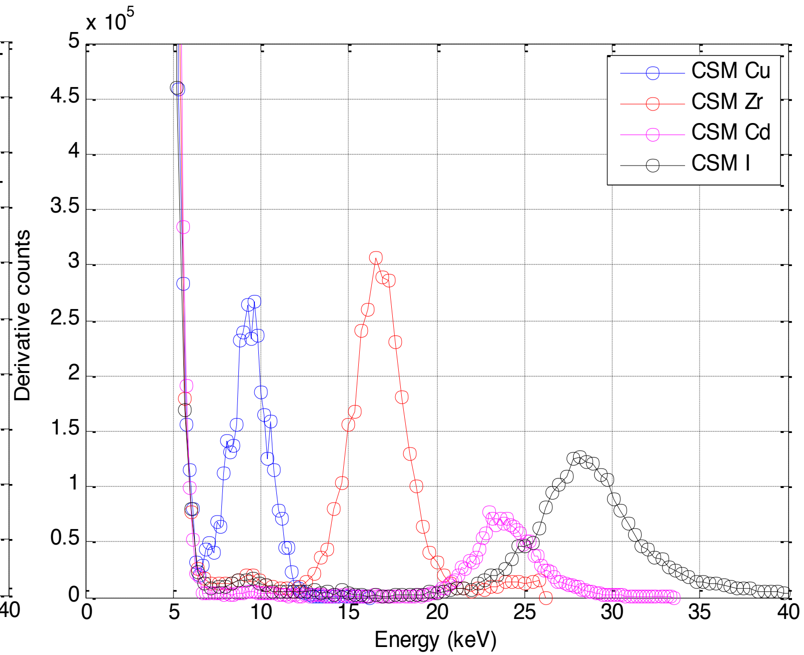


Medipix3 – spectroscopic performance





Single pixel mode



Charge summing mode

Fluorescence photons from various elements

Spectra taken by summing all counts in the chip at different thresholds and then differentiating wrt energy

Suppression of charge sharing tale is evident

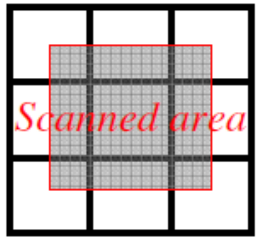
R. Ballabriga, L. Tlustos

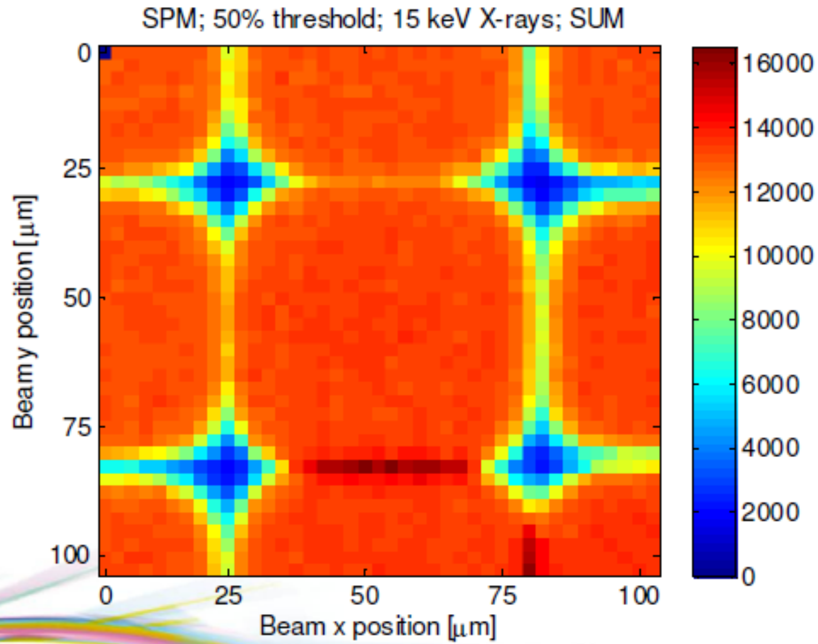
Pixel scan with microfocused beam

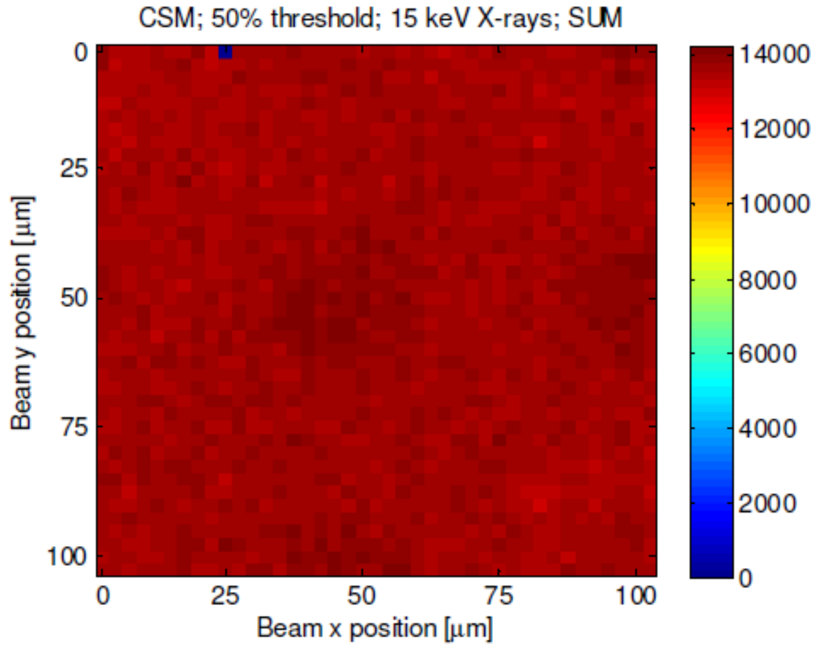
SPM and CSM

Sum of counts recorded in all neighboring pixels as a function of beam position in x and y

X-ray: 15keV; Threshlold: 7.5 keV





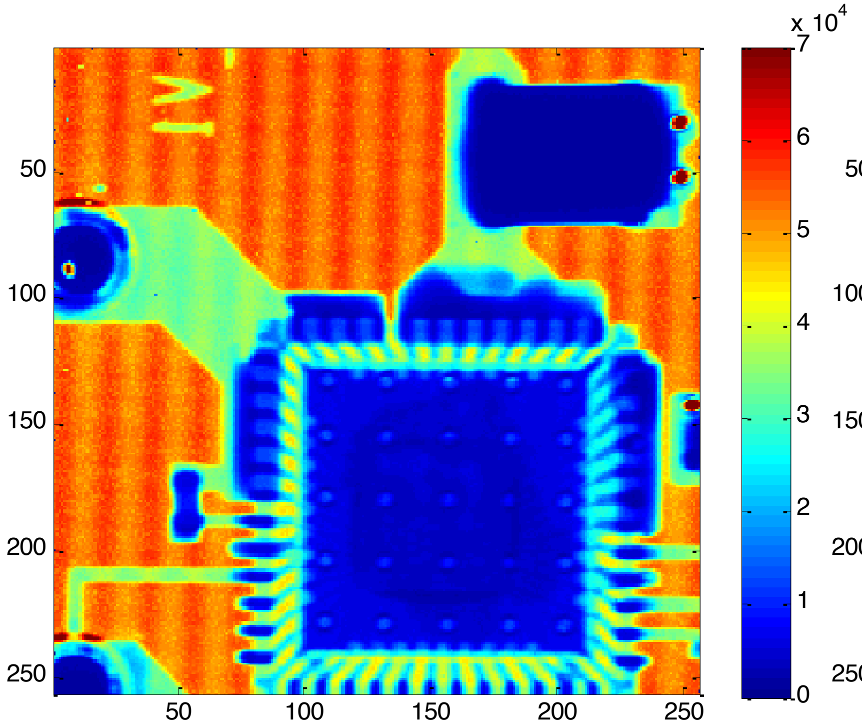


In CSM every photon is counted

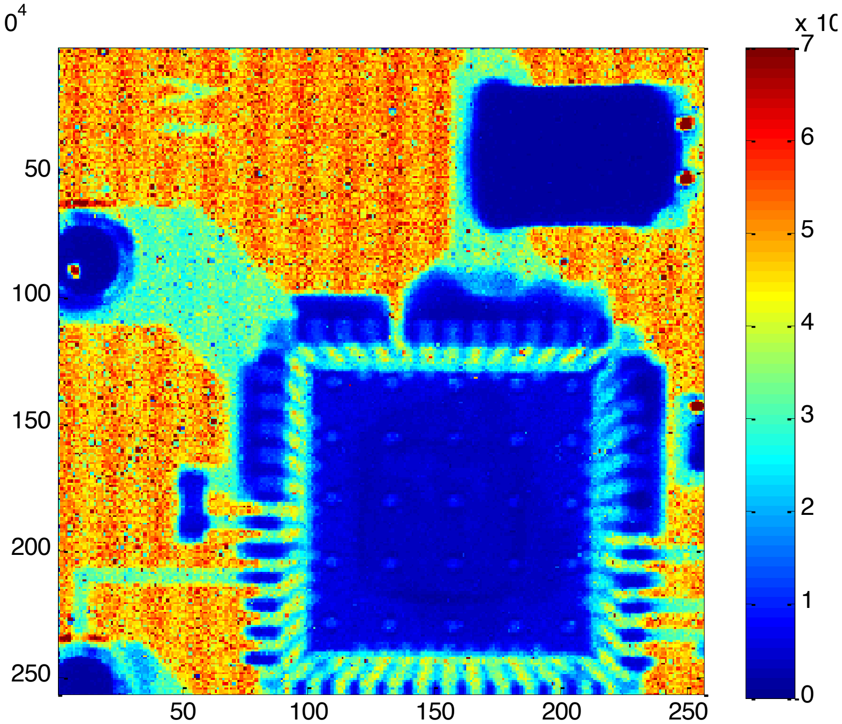
Courtesy Eva Gimenez-Navarro

diamond

Imaging with Medipix3



Single pixel mode



Charge summing mode

X-ray tube at 40kV, 40mA

0.5% pixels masked in equalization algorithm (~320)

Flat field corrected

Unexpectedly high pixel-to-pixel mismatch degrades hit allocation logic in CSM

Effect being studies by design team

R. Ballabriga

Imaging with Medipix3

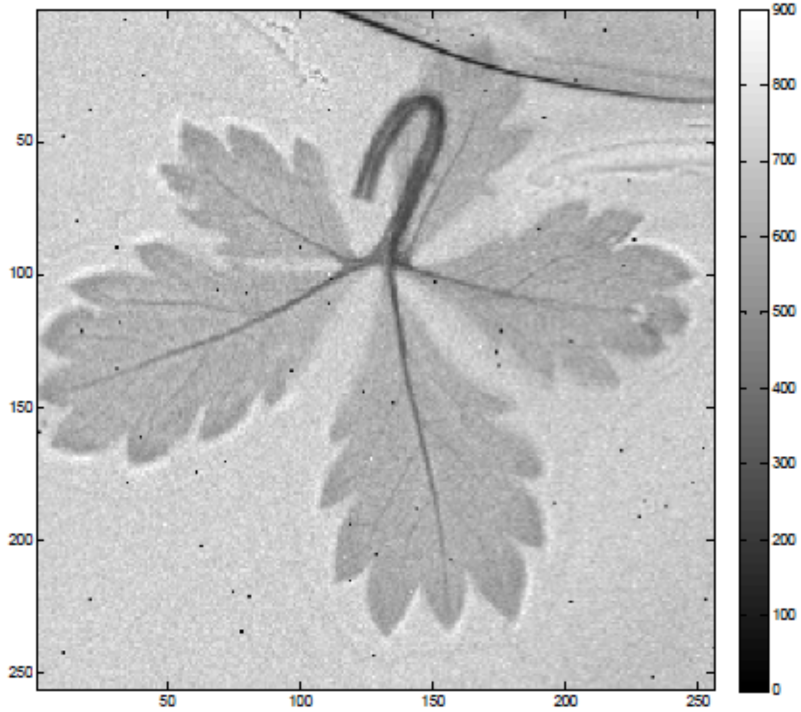
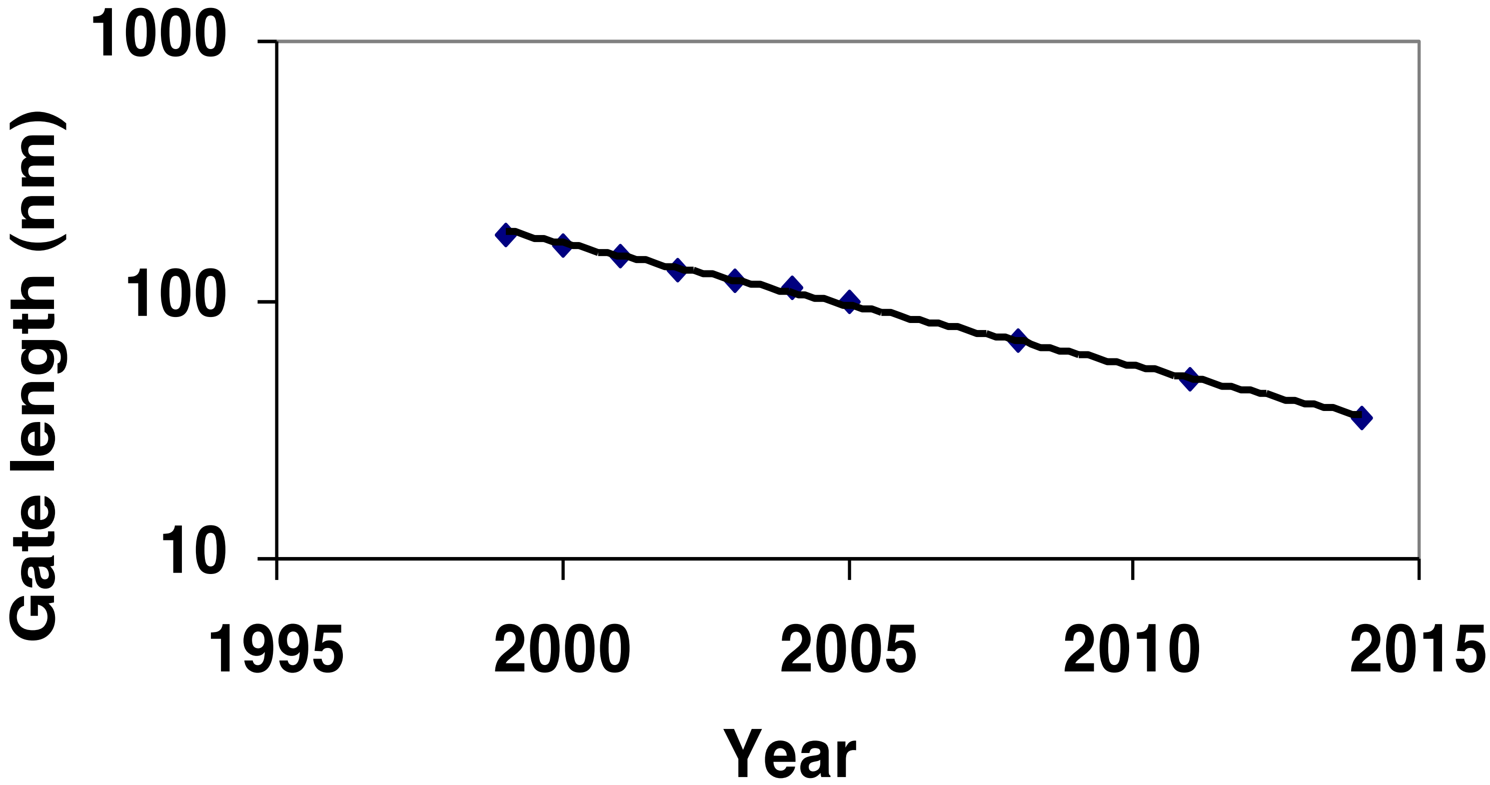


Image of a leaf with Fe^{55} source
930 e^- minimum threshold in SPM
Very long exposure time

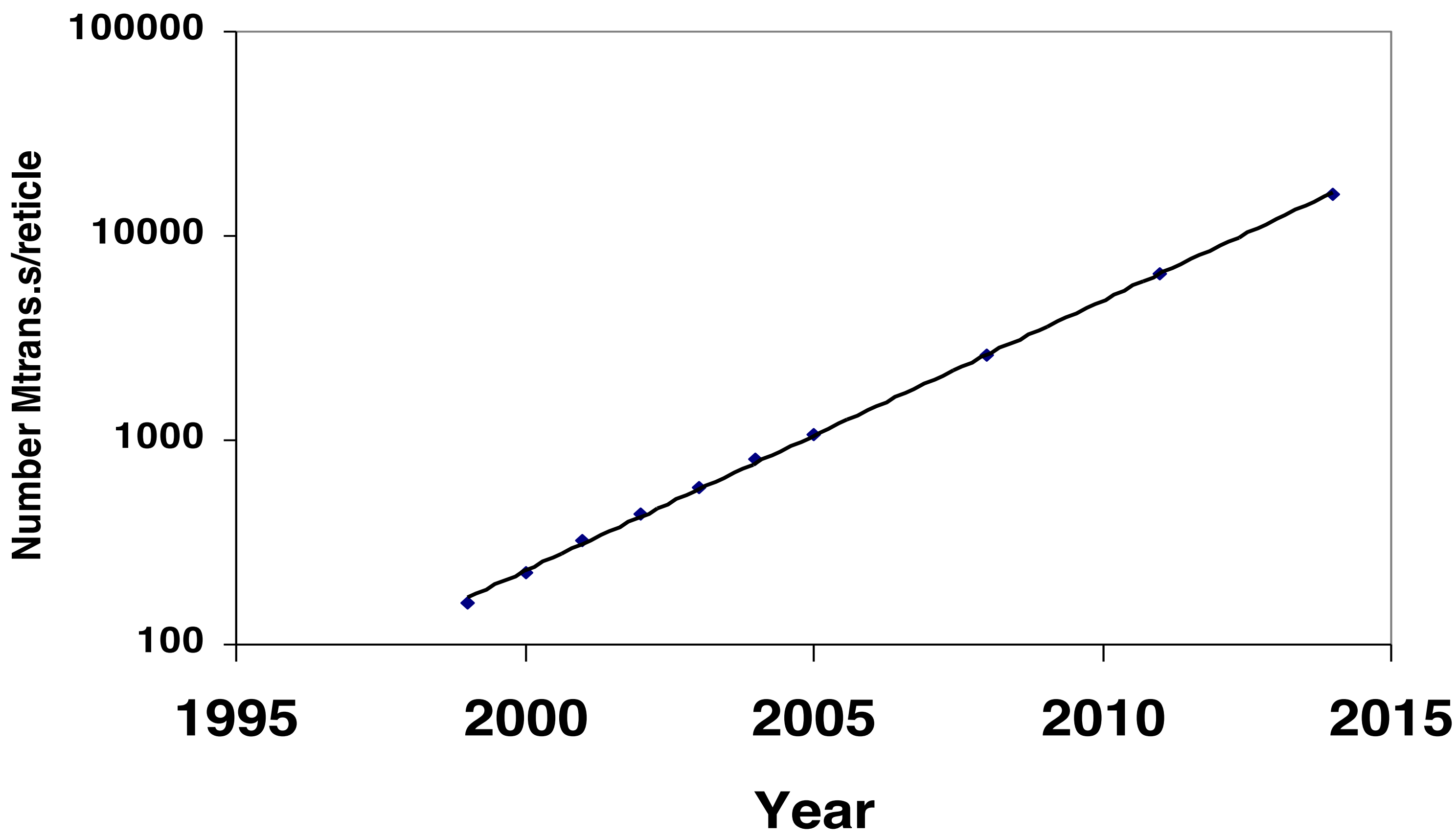
R. Ballabriga

Moore's law - transistor feature size

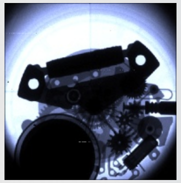


SIA Roadmap 1999

Moore’s Law - components per chip

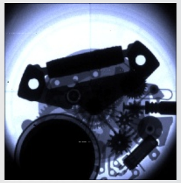


SIA Roadmap 1999



Implications of progress in CMOS processing for pixel detector development

- More and more functionality can be packed into a pixel
- Transistor matching for a fixed area and therefore pixel-to-pixel matching improves
- The cost/unit area of Si is more-or-less constant
- However, prototyping costs are increasing
- Power management becomes an issue



Future Challenges

<u>In HEP :</u>

Reduce material budget for inner layers

Tracking input to trigger

Data driven architectures - LHCb VELO upgrade

<u>X-rays and other particle imaging :</u>

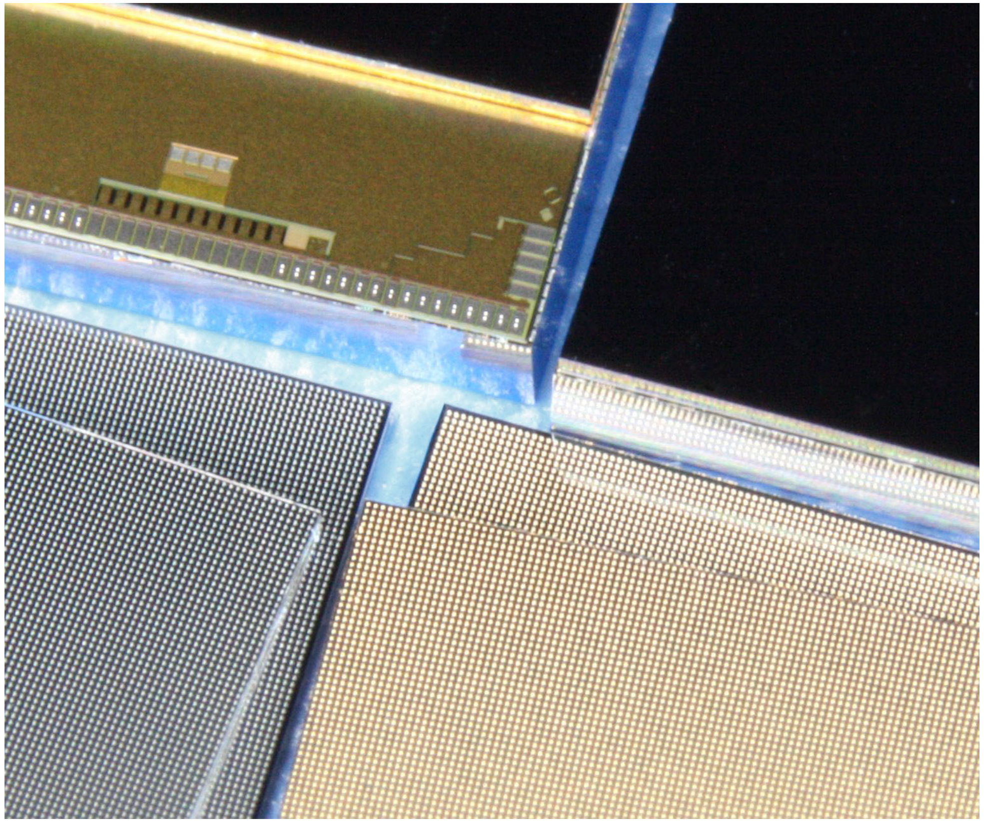
Improve sensor material uniformity/availability

<u>In General :</u>

Reduce cost per unit area – bump bonding

Improve yield – single 4-side buttable tiles - TSV

Future Challenges – edgeless sensors 1

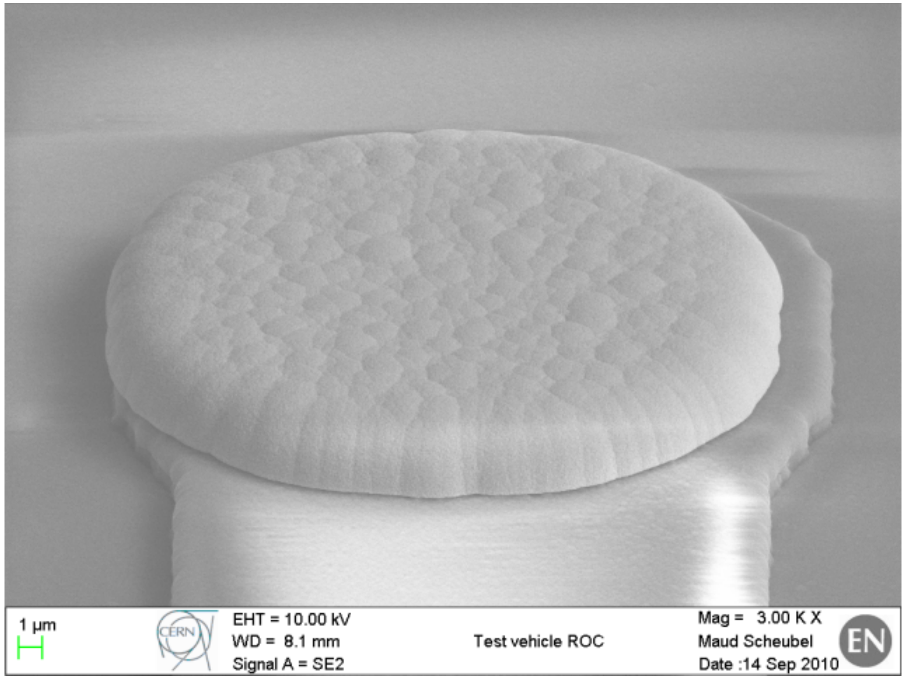


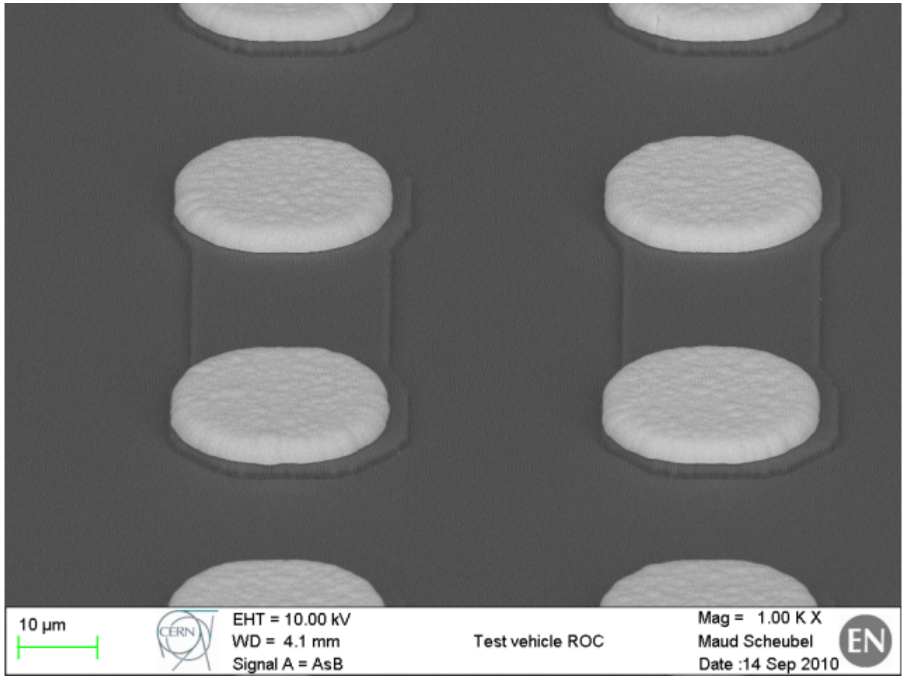
150 μm Si
50 μm edge

J. Kaliopuska, VTT, Finland

ENIG UBM on Test Vehicle Chips

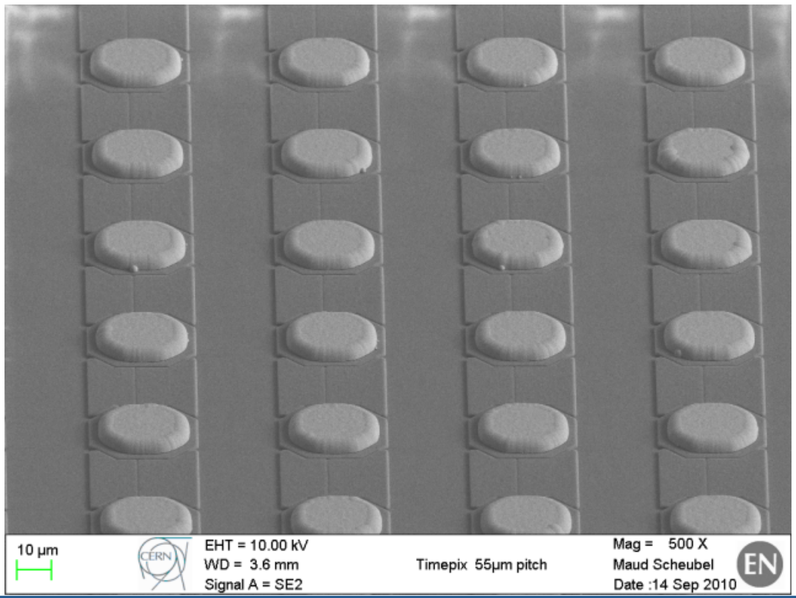
- SEM pictures of ENIG UBM pads on test vehicle chips are presented below.
  - UBM diameter ~ 27 µm, height 4 µm
- Picture on the left, a single ENIG UBM pad.
- Picture on the right taken with Angle-Selected Backscattered (AsB) mode.
  - Heavy elements (Ni UBM pads) are shown as brighter colours



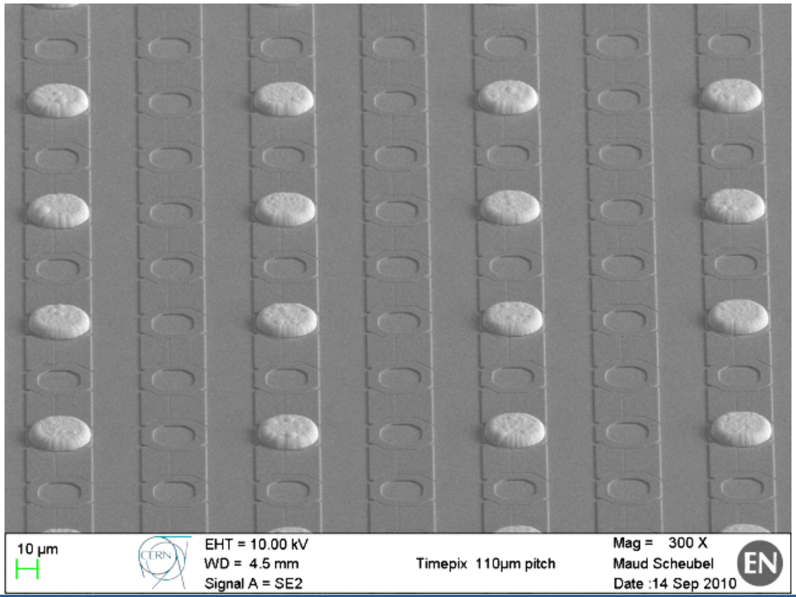


ENEPIG UBM Tests with Timepix Wafers

- Test vehicle wafers were used for gathering statistics from FC assemblies.
- Real CMOS wafers processed with ENEPIG was feasibility test.
- ENEPIG UBM was grown on Timepix wafers with two different pitches
  - 55 µm – without photoresist mask
  - 110 µm – with photoresist masking. Chips were electrically measured after EN process – no degradation in electrical performance.
- Electrical testing is not completed yet. Flip chip test are still needed!



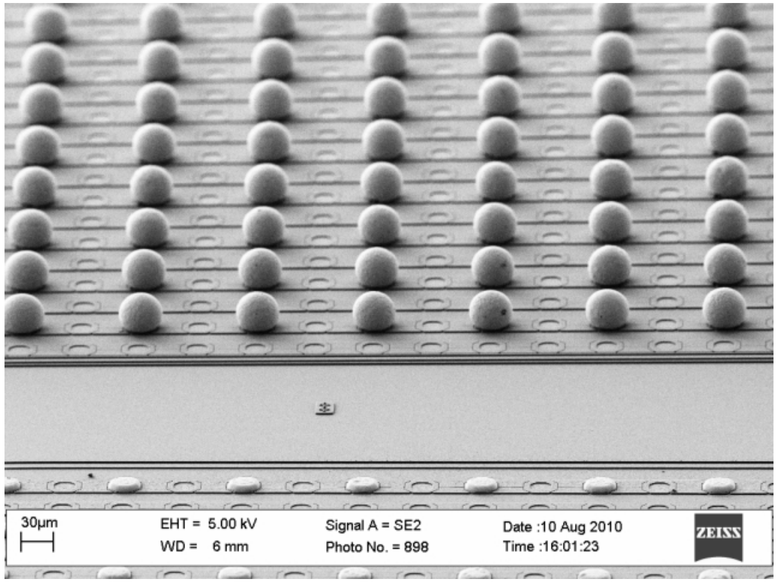
ENEPIG UBM pads on Timepix chip (55 µm pitch)

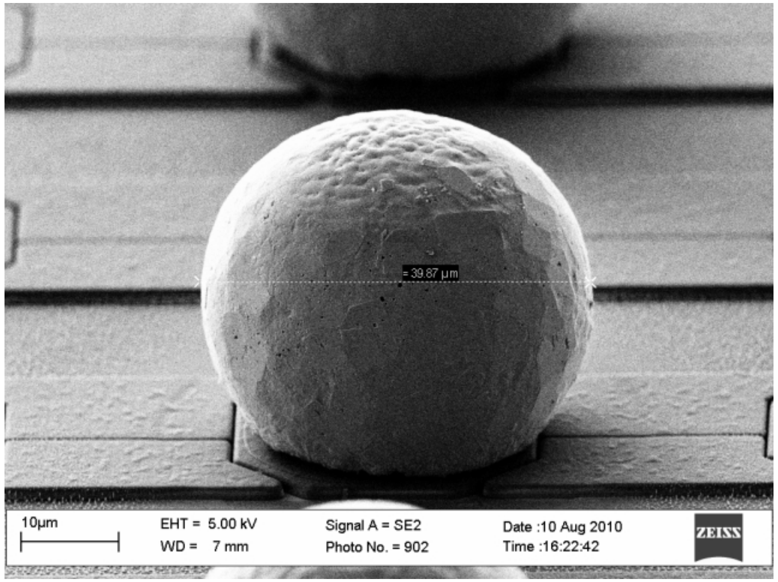


ENEPIG UBM pads on Timepix chip (110 µm pitch)

PacTech Movie

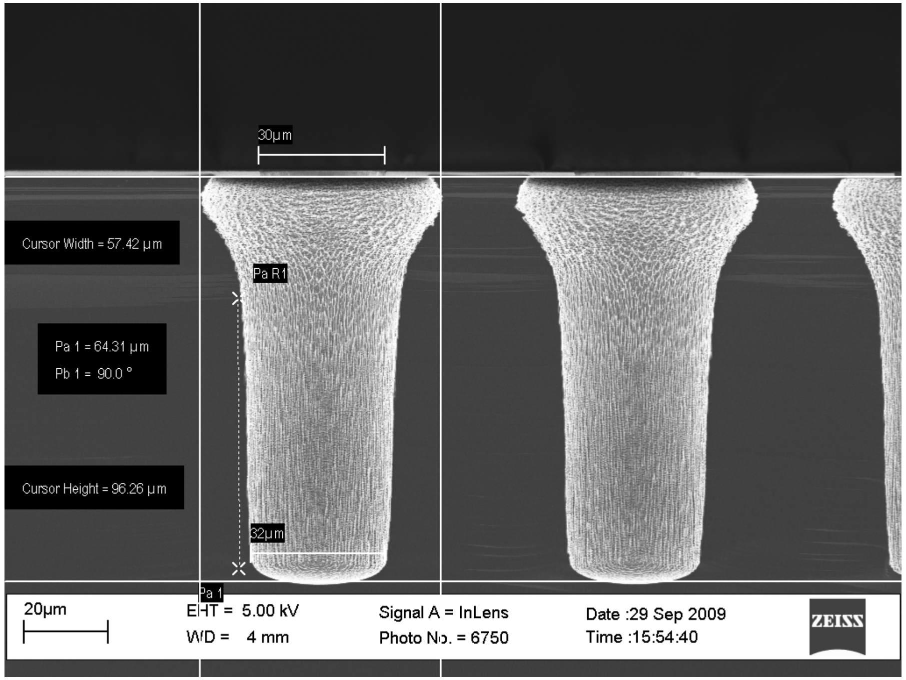
Solder Ball Placement Test





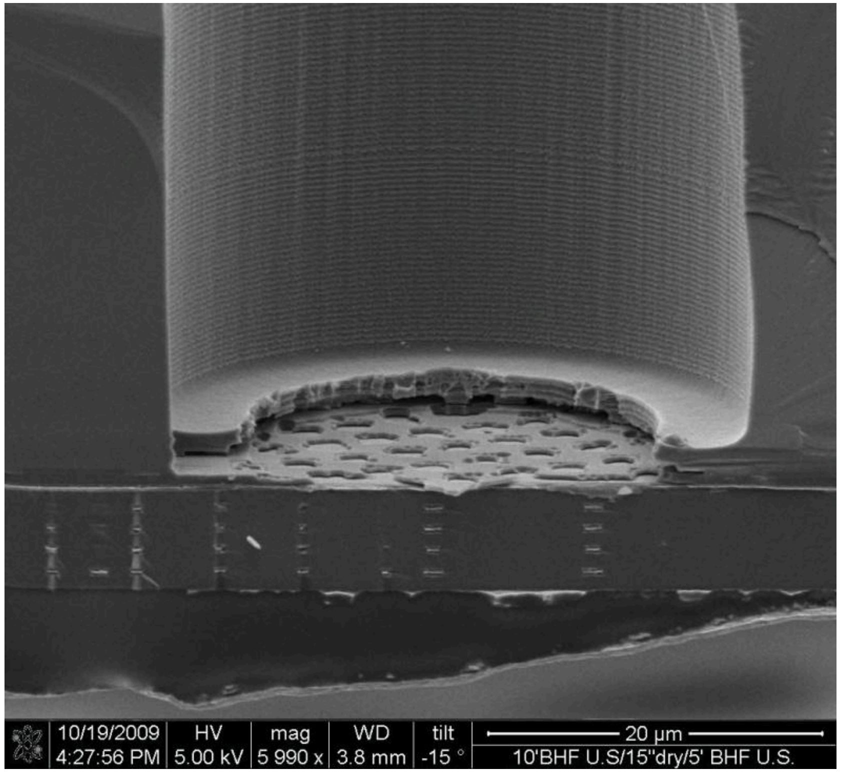
First solder ball placement test on a Timepix chips

TSV development with VTT, Finland



TSVs etched by VTT on dummy wafer with 100 µm pitch

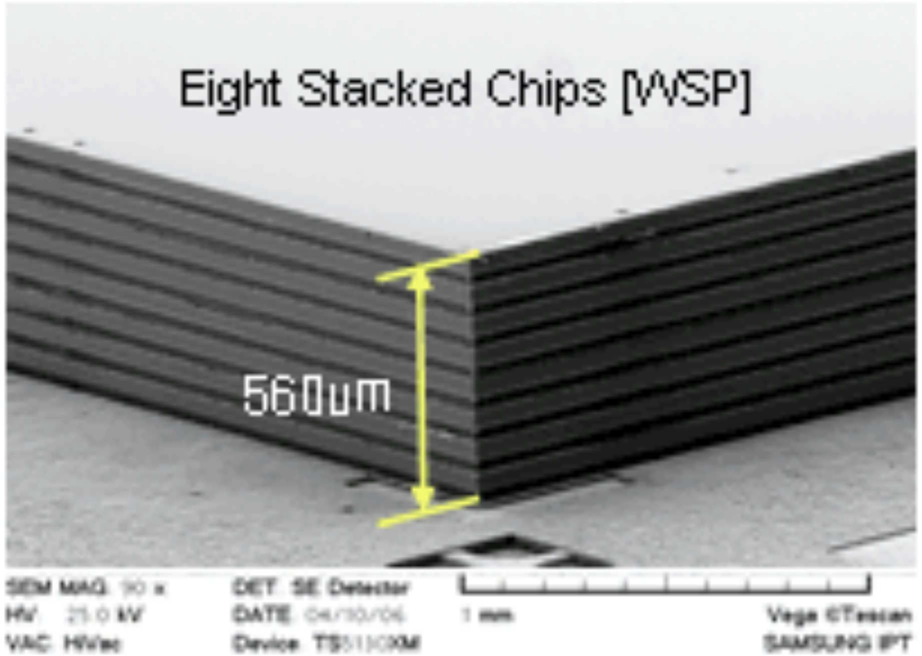
TSV development IMEC



TSVs etched IMEC in context of RelaxD project

Example of stacked chips

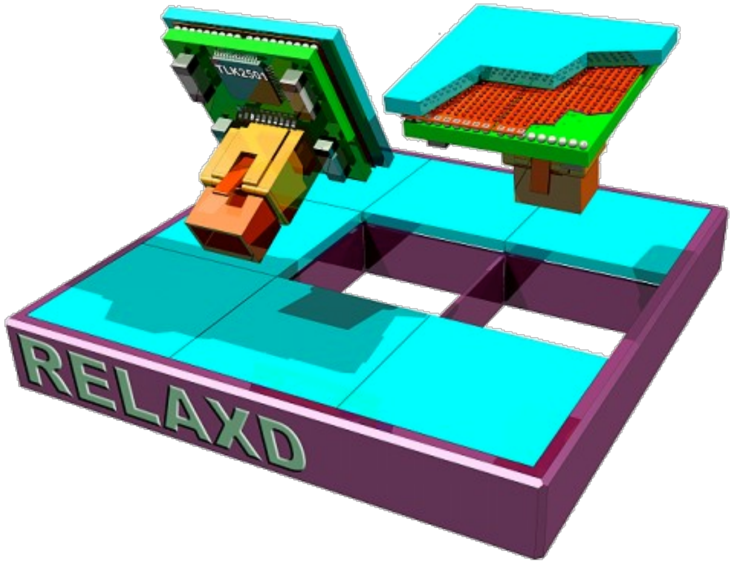
Samsung



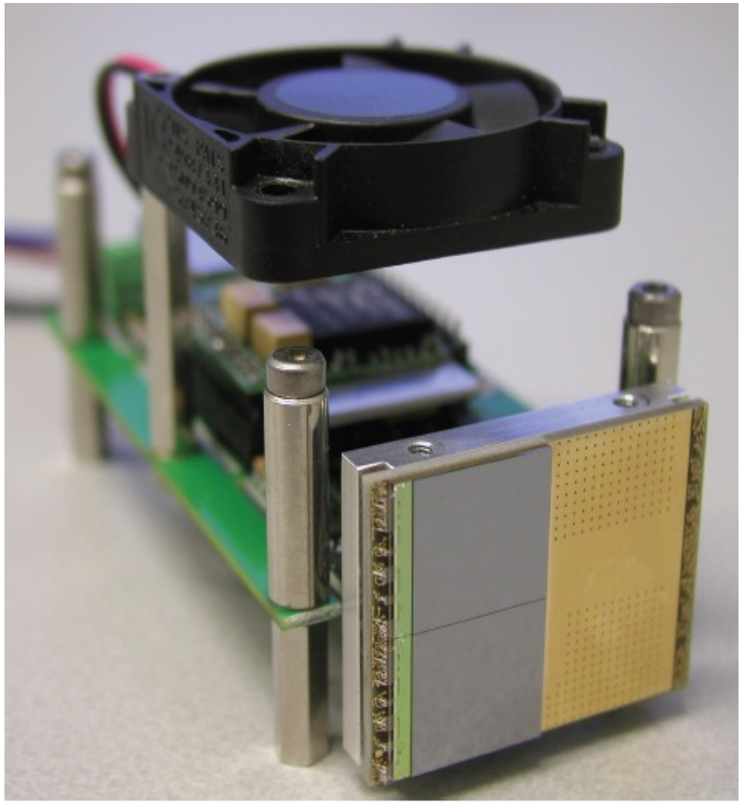
<u>Eight-Chip WSP</u>

Flat panel X-ray

- Relaxd
- To develop a 4-side buttable tile for flat panel X-ray detectors
- Partners: PANalytical, Canberrra, IMEC, Nikhef

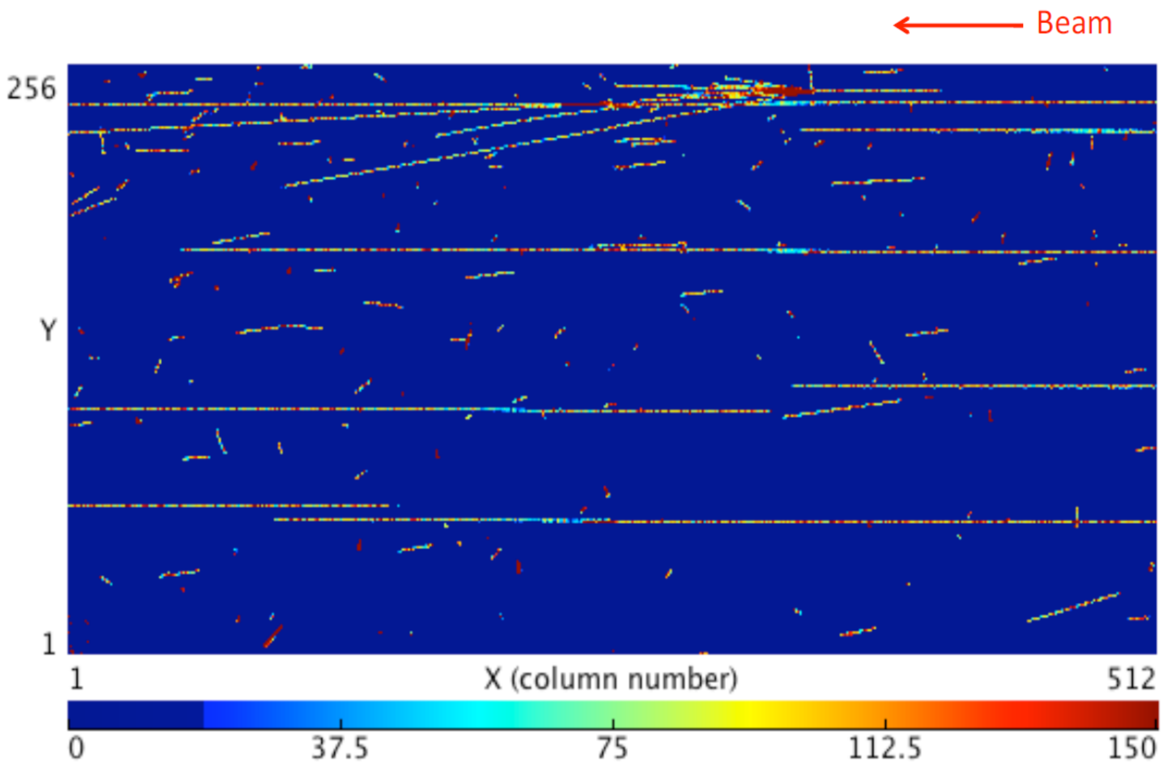


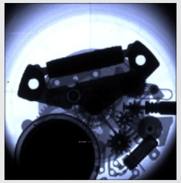
Future Challenges – edgeless sensors 2



J. Visser et al, Nikhef

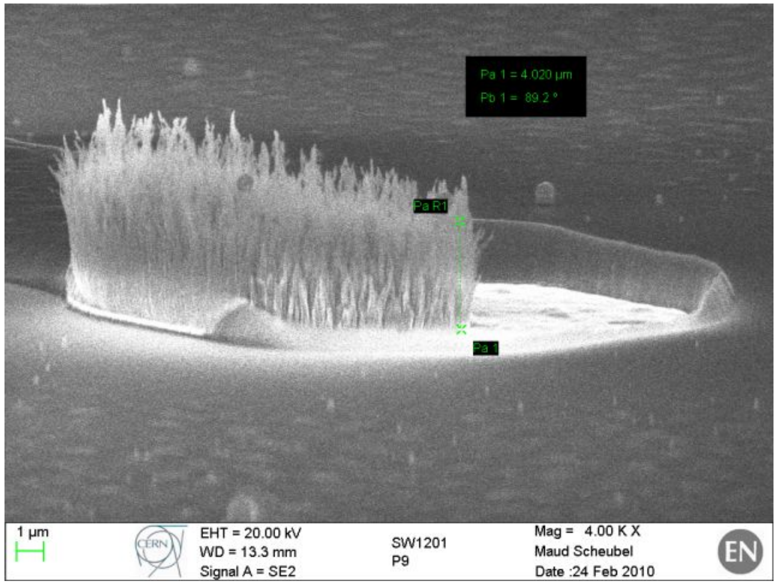
Future Challenges – edgeless sensors 2

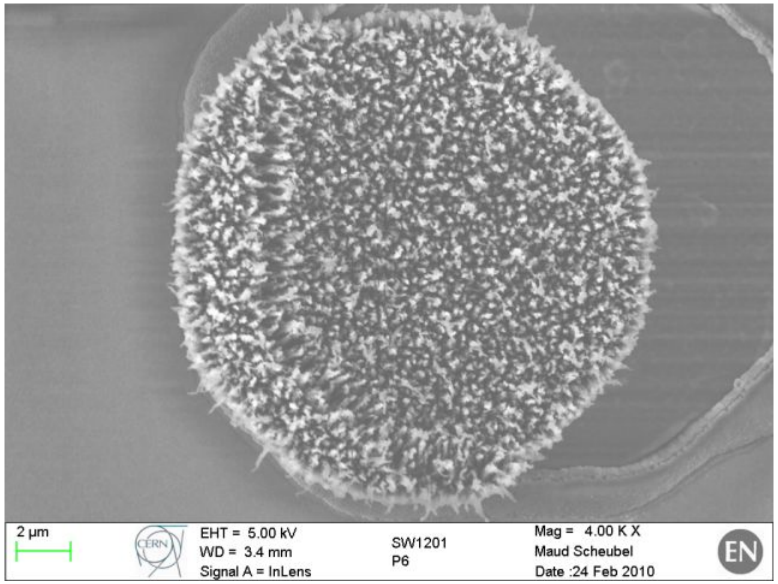




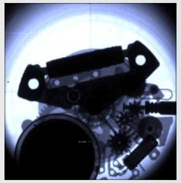
Carbon nano-fiber (CNF)

- **Smoltek has delivered the first CERN test vehicle chips with CNF’s**
- **We are looking into a common project for developing ultra-high-density (ultra low mass) flip chip process with CNF’s.**
- **CNF’s were deposited at 400 ˚C (a relatively low-temperature process)**
- **Test samples were analyzed and process issues were identified**
  - → **new process tests with improved cycle coming in early summer**
- **Smoltek will make offer for work on test vehicle and real devices.**





CNF forests on CERN test



Conclusions and Future Work

- Hybrid pixel detectors were developed to answer specific ‘imaging’ needs in HEP experiments:
  - Provide clean fast ‘images’ at LHC
- The Medipix Consortia have broken new ground in terms of pixel size and sophistication
- The device has been applied to many varied imaging applications
- Future challenges include:
  - Reduced material in HEP (sensor thickness, ASIC threshold
  - Reducing cost of bump bonding covering
  - Improving yield with 4 side buttable tiles
  - 3D stacking?large