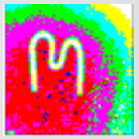


MEDIPIX2 AND TIMEPIX APPLICATIONS AT CERN

MIC-ESE Seminar 28. Sept 2010

Lukas Tlustos

Outline

- Medipix Collaboration ROC's
  - Medipix2 and Timepix, Medipix3
- Applications outside Cern
  - Colour X-ray imaging
  - Materials analysis
- Applications @ Cern
  - Alternative sensor materials and geometries
  - Isolde
  - UA9
  - Background radiation in ATLAS/CNGS/CERF
- Outreach
  - LUCID and Cern@School
- Summary

Two Collaborations

Medipix2

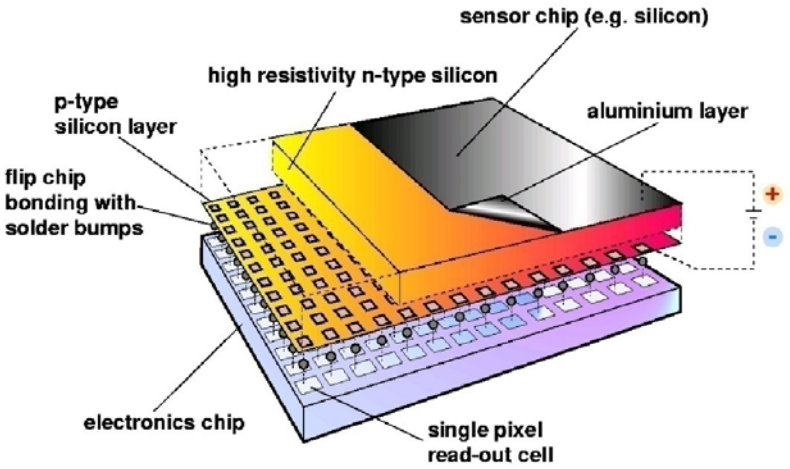
- INFN Cagliari
- CEA-LIST Saclay
- CERN Geneva
- University of Erlangen
- University of Freiburg
- ESRF Grenoble
- University of Glasgow
- University of Houston
- IFAE Barcelona
- Mid Sweden University
- MRC-LMB Cambridge
- INFN Napoli
- NIKHEF Amsterdam
- INFN Pisa
- FZU CAS Prague
- IEAP CTU Prague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

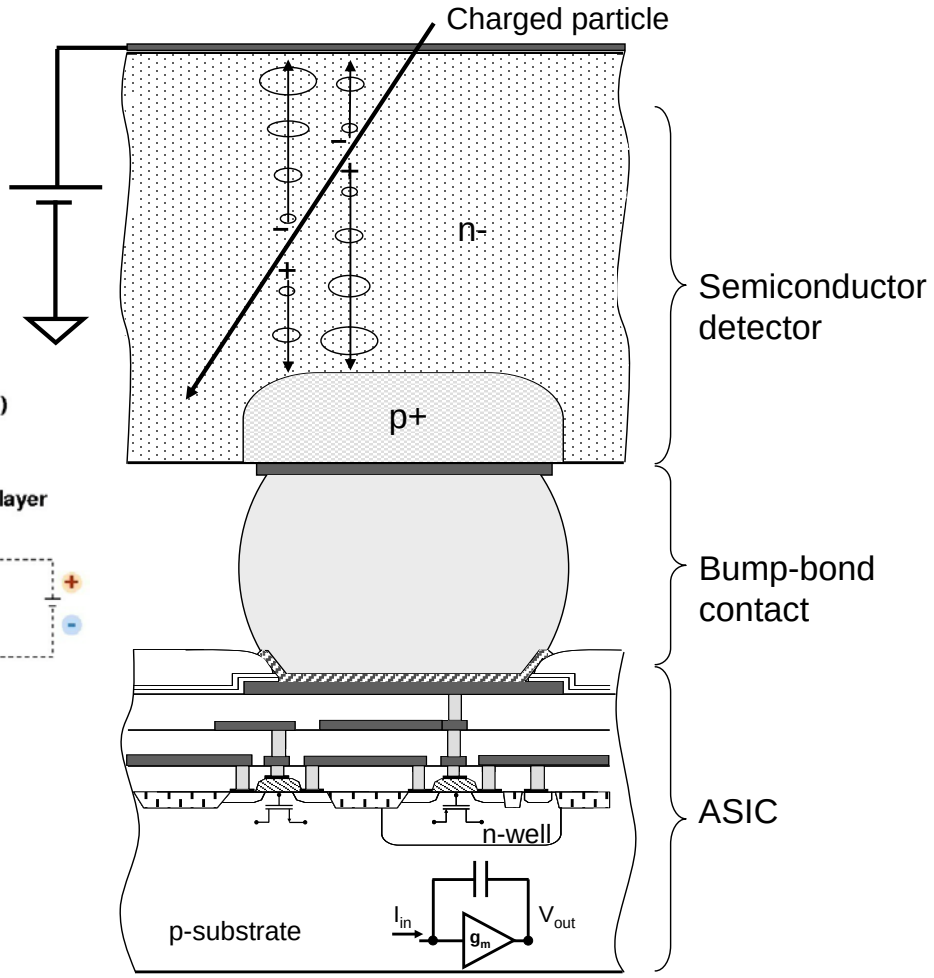
Medipix3

- ALMOF Amsterdam
- University of Bogota
- 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
- University of Karlsruhe
- Leiden University
- Mid Sweden University
- NIKHEF Amsterdam
- IEAP CTU Prague
- SSL Berkeley
- VTT Microsystems

21 collaborating institutes

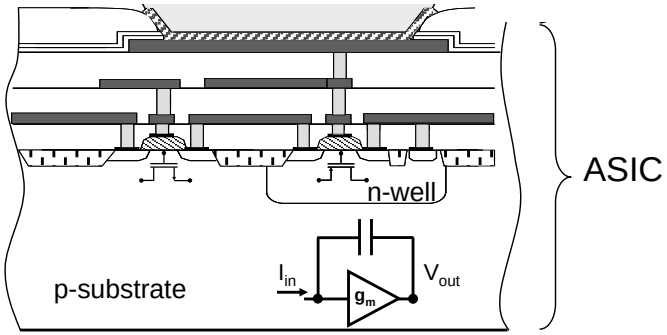
Hybrid-Pixel Detector





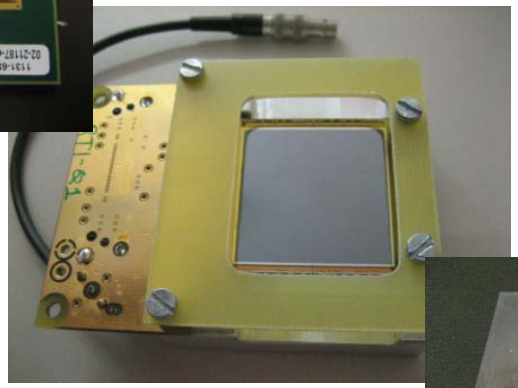
Or Pixel Detector with

- **Gas Amplification Stage in TPC**
  - **GEM**
  - **Micromegas**
- **Microchannel Plate**
  - **Optical photons**
  - **Molecular Imaging**
- **Direct Deposition**
  - **aSi, CdTe, HgI**
- **Bare ASIC**
  - **Mass spectrometry**

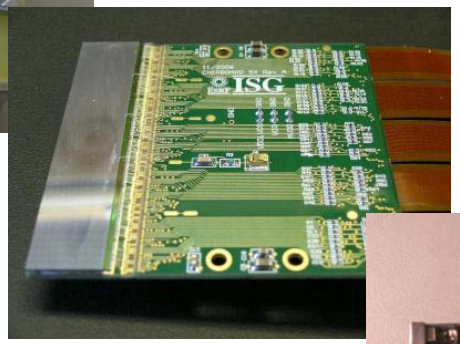


Assemblies & chip cards

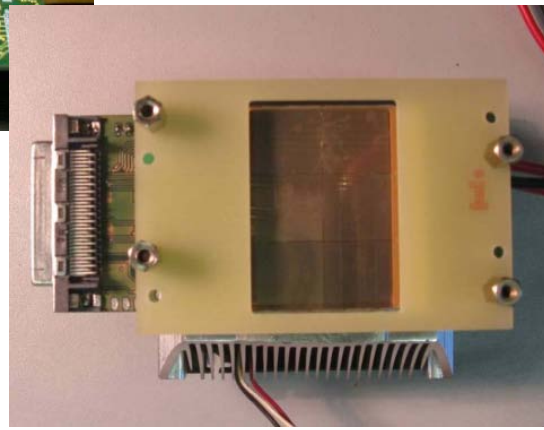
Single



2x2



1x5

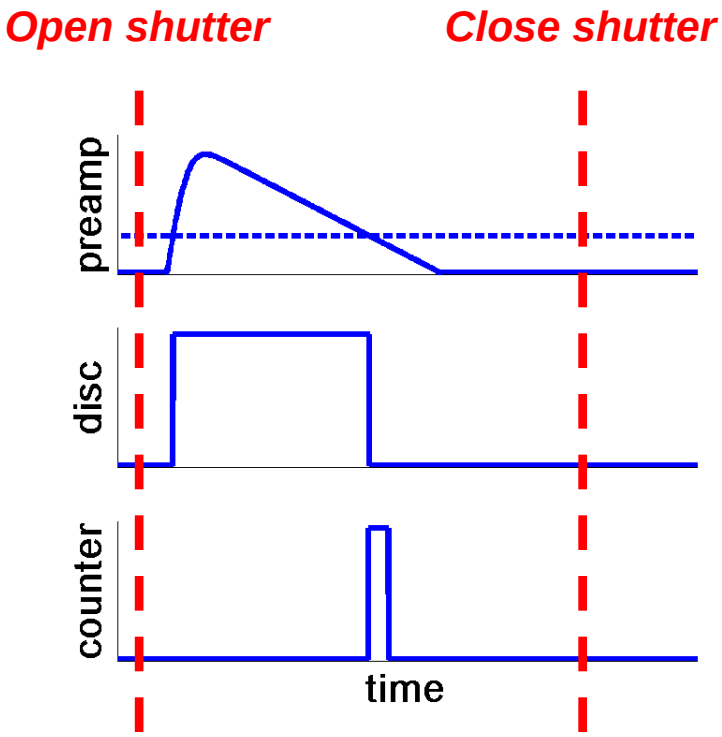


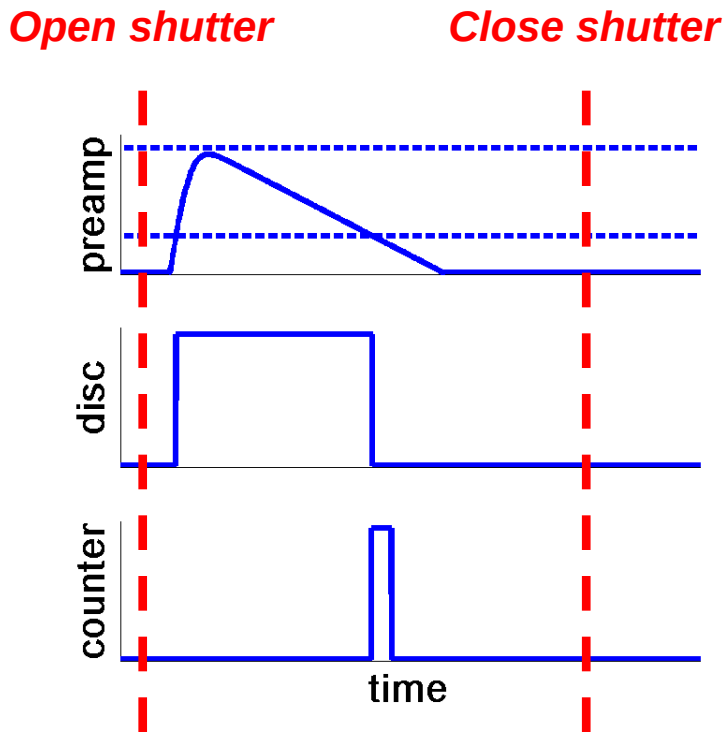
2x3

Medipix2 Modes

- **Single Threshold**
- **Particle Counting**

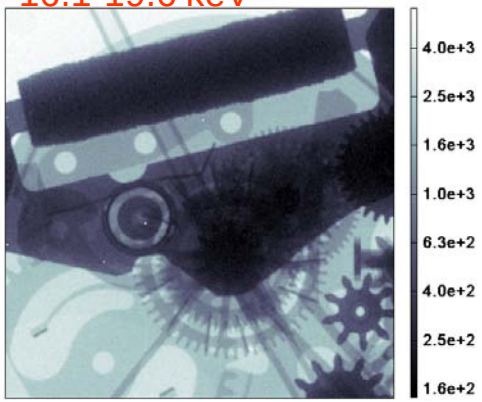
- **Double Threshold**
- **Proof of concept for spectral X-ray imaging**



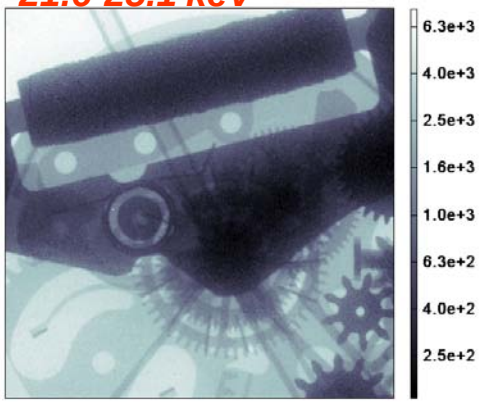


Energy Window Imaging Medipix2

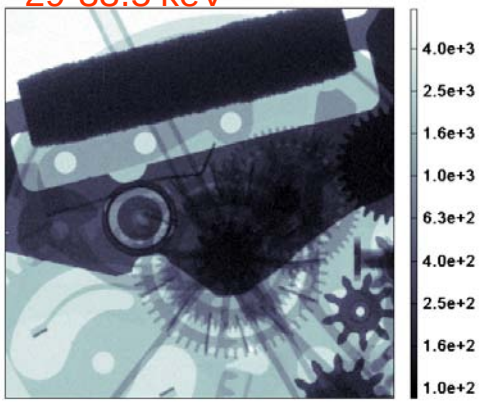
16.1-19.6 keV



21.6-25.1 keV



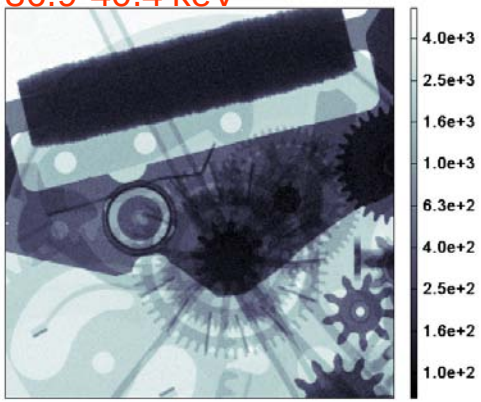
29-33.5 keV



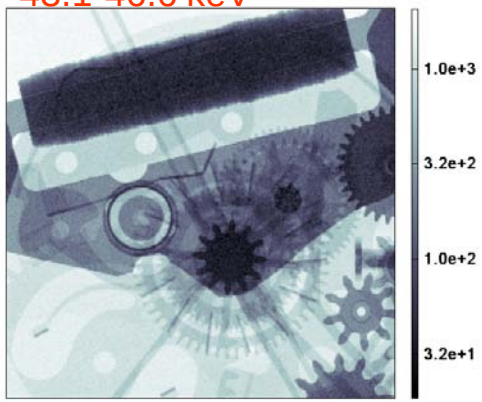
W-Tube 50 kV
2.5 mm Al

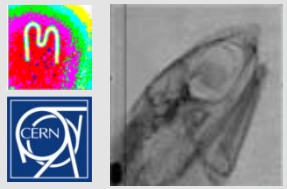
ΔE=3.5 keV

36.9-40.4 keV



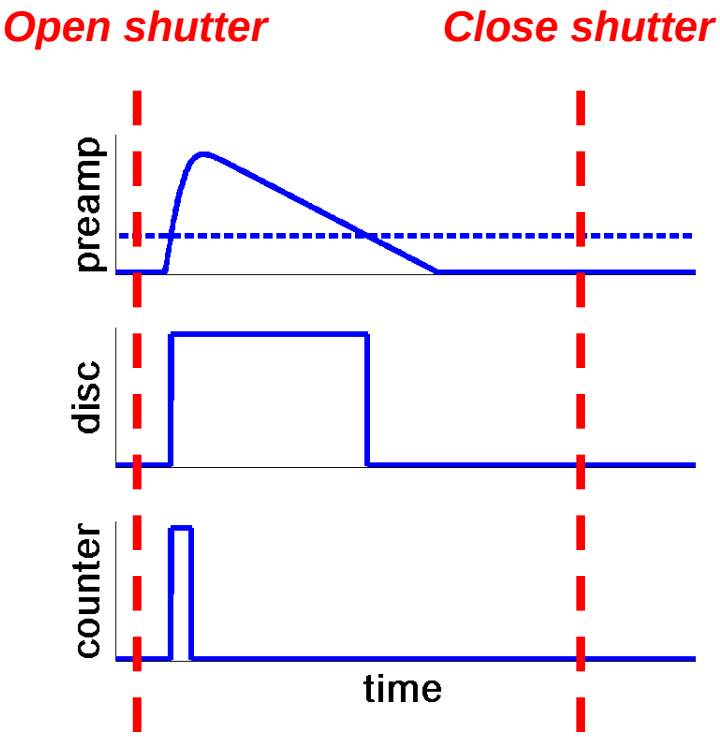
43.1-46.6 keV

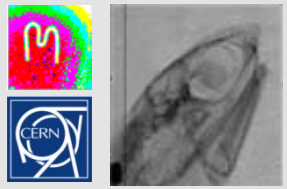




Timepix Modes

- **Single Threshold**
- **Particle Counting**

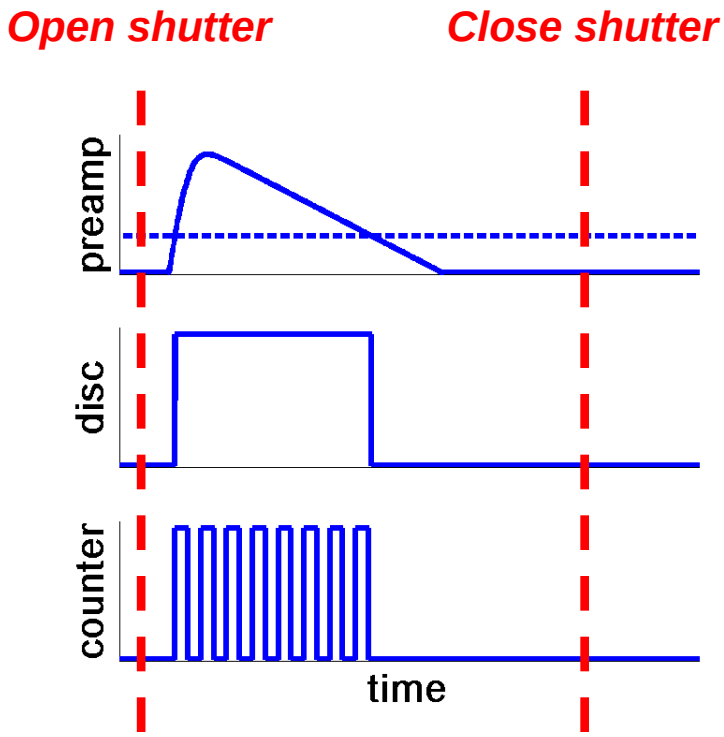


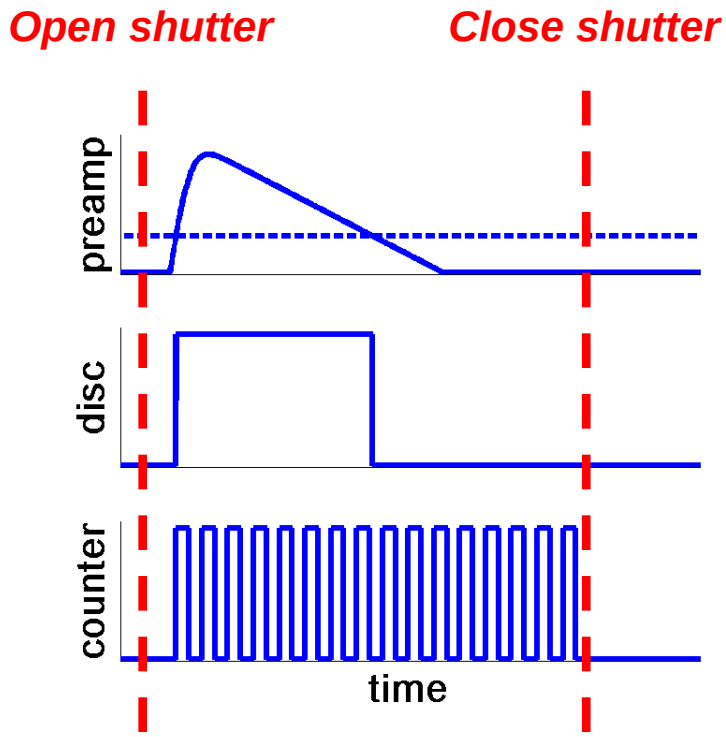


Timepix Modes

- Time over Threshold
- Charge deposition

- Time of Arrival
- TPC readout
  (JRA2/EUDET Collaboration)

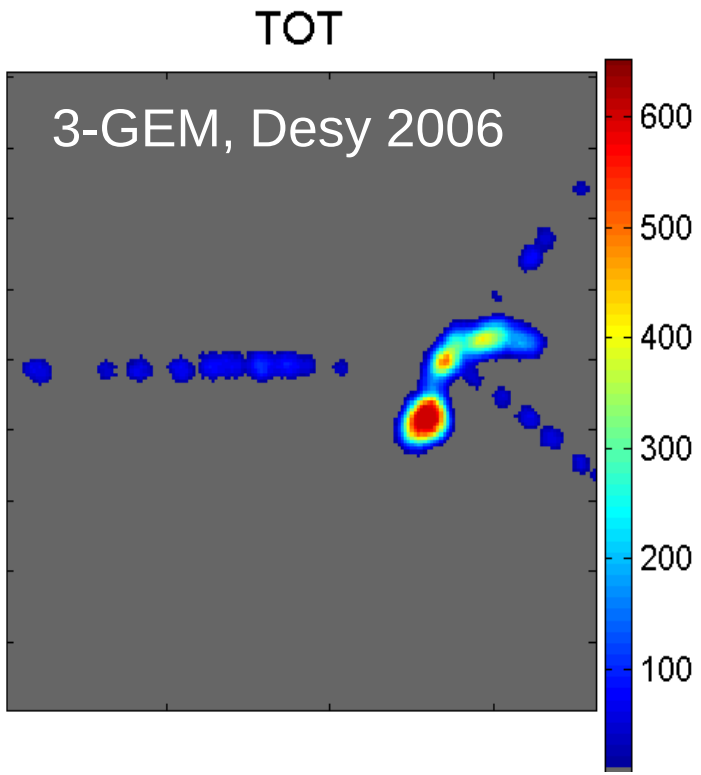


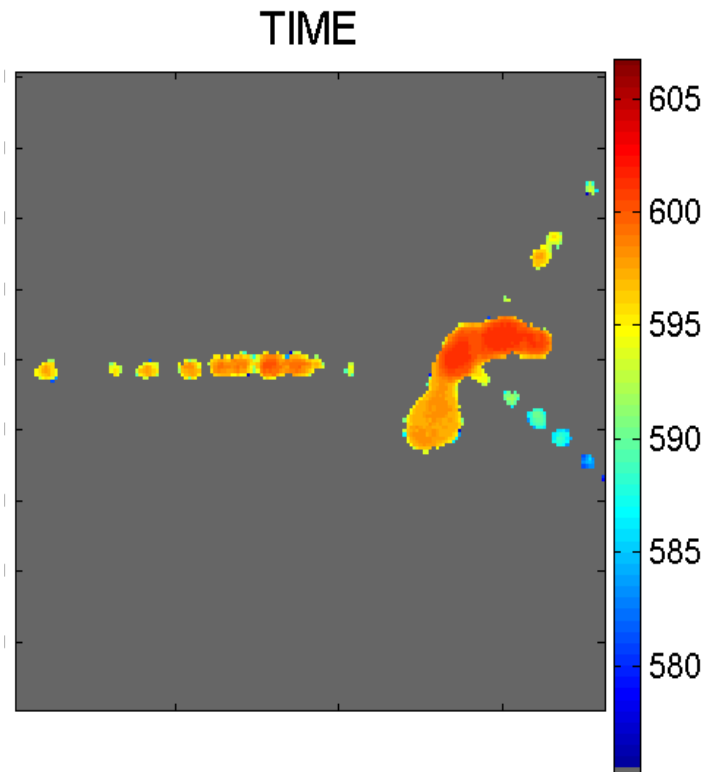


Timepix Modes

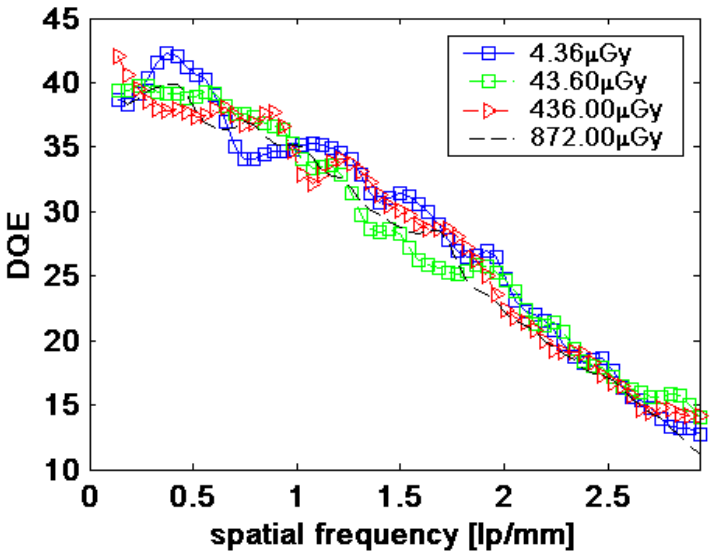
- **Time over Threshold**
- **Charge deposition**

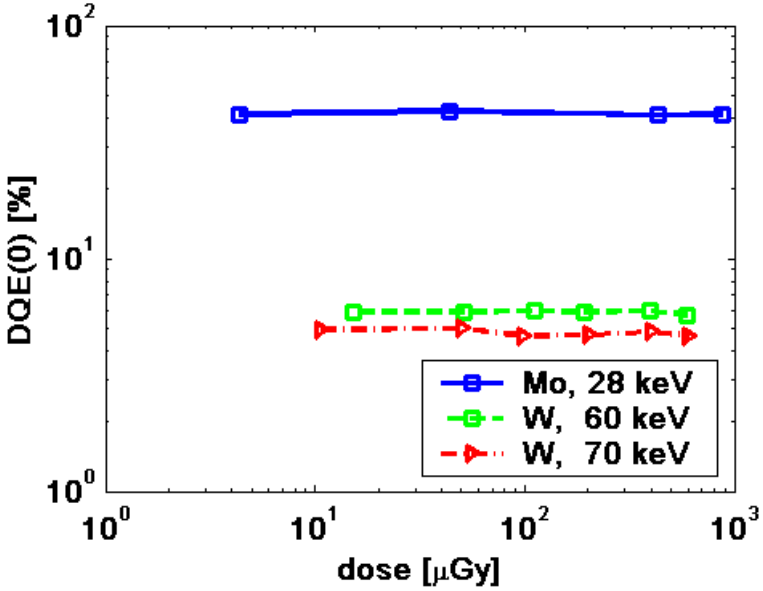
- **Time of Arrival**
- **TPC readout**
  (JRA2/EUDET Collaboration)





Noise free tracking = Noise free imaging





Imaging performance ± dose independent

approaching Poisson limit

High Contrast

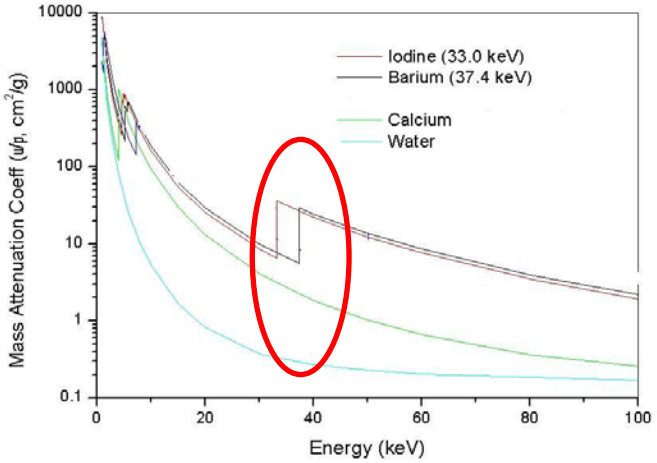
Potential for dose reduction in radiographic applications

Applications

Medical Imaging

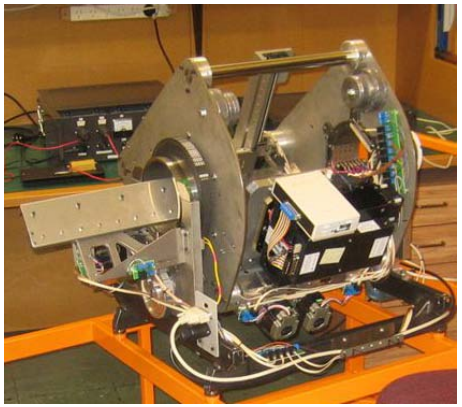
K-edge contrast imaging

- **Used e.g. in angiography**
  - **Technique**
    - **Initial X-ray**
    - **Contrast agent injection**
    - **Delayed contrast X-ray**
    - **Subtraction image shows contrast agent distribution**
  - **Issues**
    - **2 X-rays → noise in datasets is uncorrelated**
    - **Patient motion between two X-rays**
- **Spectral Imaging device**
  - **Single shot K-edge imaging**
    - **1 X-ray acquisition → correlated noise**
    - **No motion artifacts**
  - **Double contrast agent imaging, still one X-ray only**



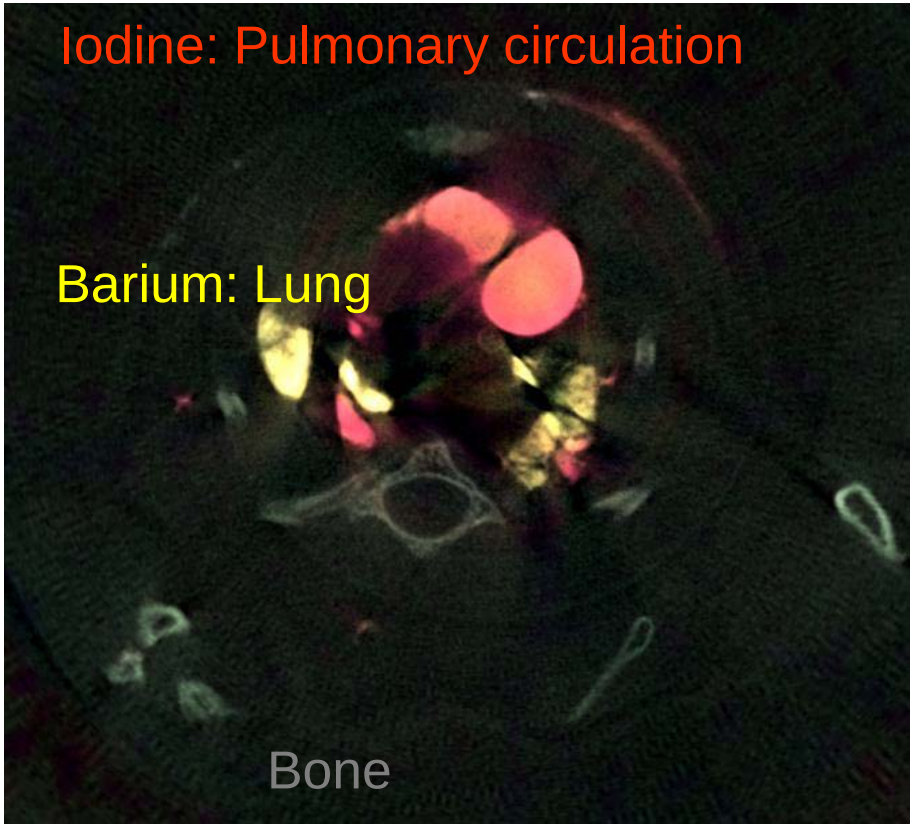
K-edge imaging

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



- **Iodine: Pulmonary circulation**
- **Barium: Lung**
- **Bone: normal structure**

Spectral enhancement



Spectral dataset from 4 energy bins used to compute material composition → Enhanced anatomical information

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

Bone

Why is that relevant?

- **Nano-particle contrast agent**

  - **Contrast agent loaded Lipoproteins(e.g. Au loaded HDL): accumulate in tissue macrophages, for example in coronary plaques. Tested already in pre-clinical stage. Mars CT installed in Mayo clinic.**

  - **Antibody labeled synthetic lipoproteins = targeted contrast agent. CT so far is anatomical imaging modality. Contrast agent loaded labeled lipoproteins turn CT into anatomical AND PET like functional imaging device.**

Applications

Materials analysis

TT to industry- PANalytical

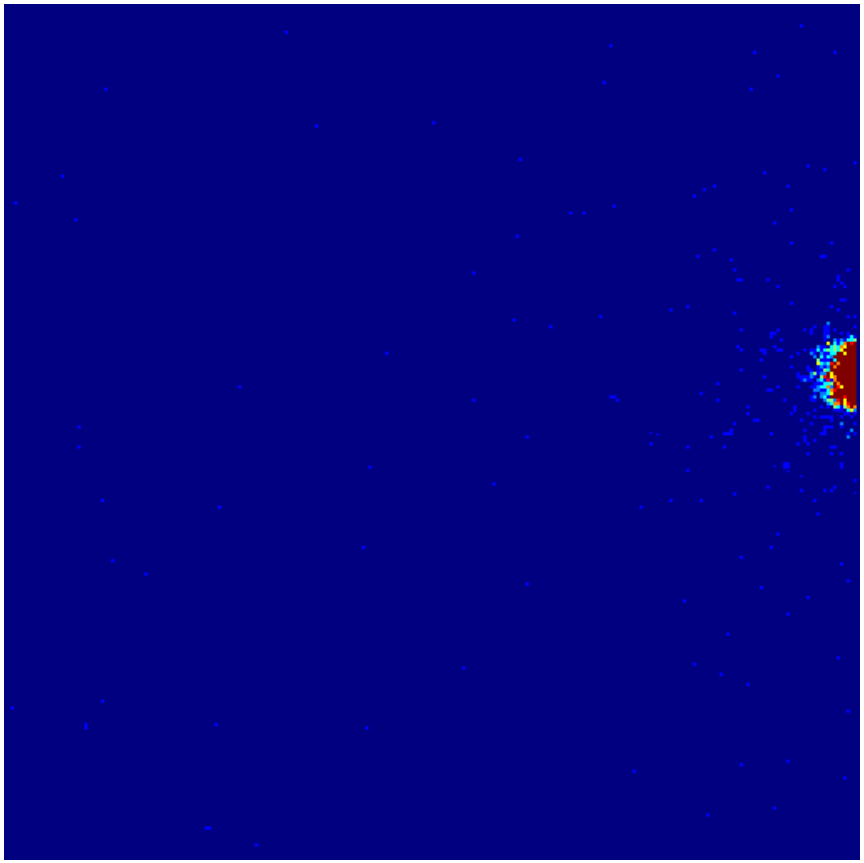
PANalytical

Market introduction 2007
200 installation so far

2D view of recorded data

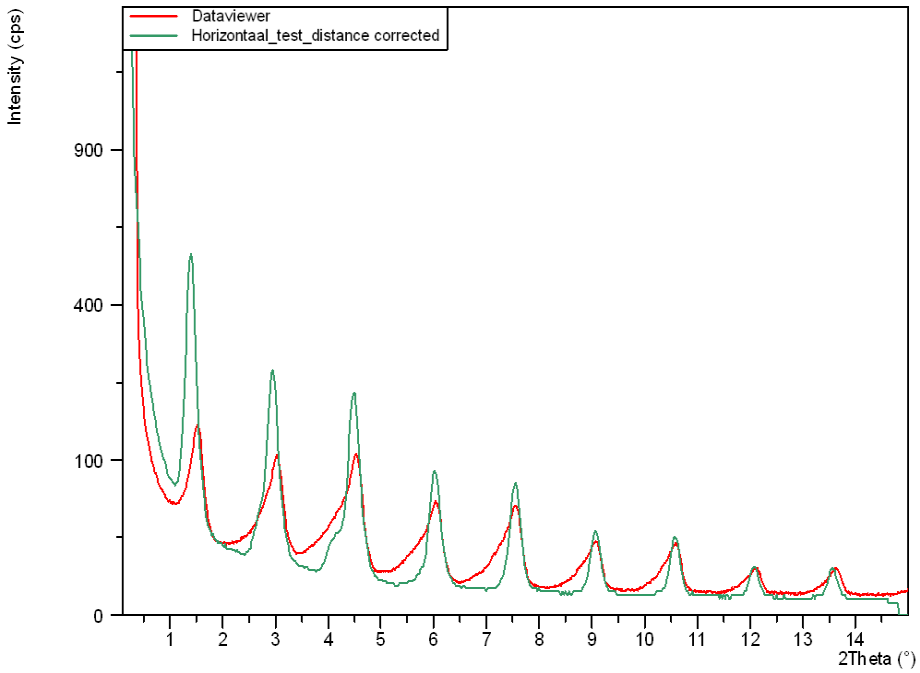
X-ray diffraction off silver reference samples (behenate powder) with PIXcel 3D detector.

- High dynamic range
- No noise
- High resolution
- Linearity:
  - ~500 kCounts/s/pixel



Courtesy PANalytical

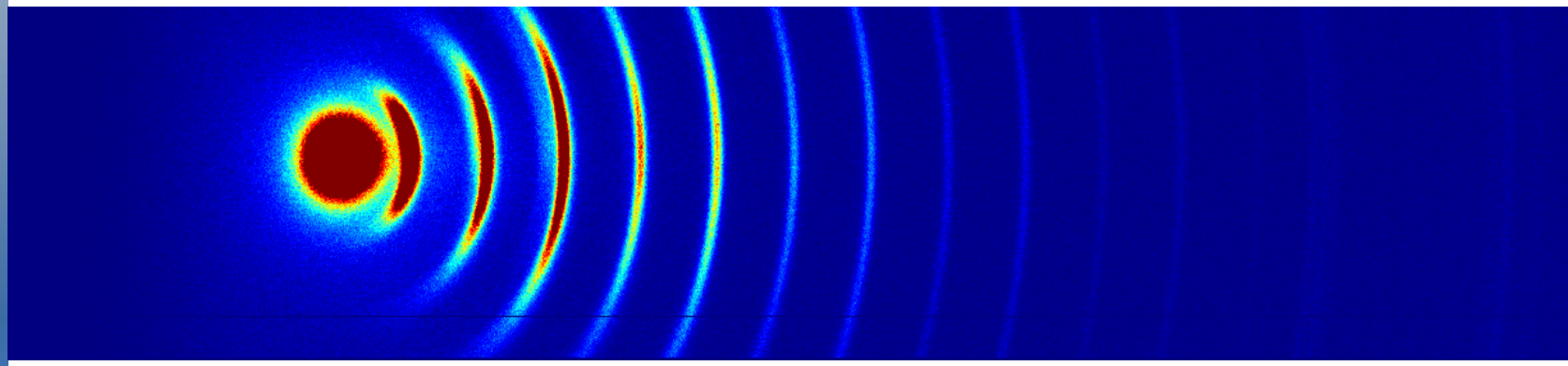
Strip → Pixels



Clear improvement in
- **peak separation**
- **peak to background**

→

separation of more complex spectra



Courtesy PANalytical

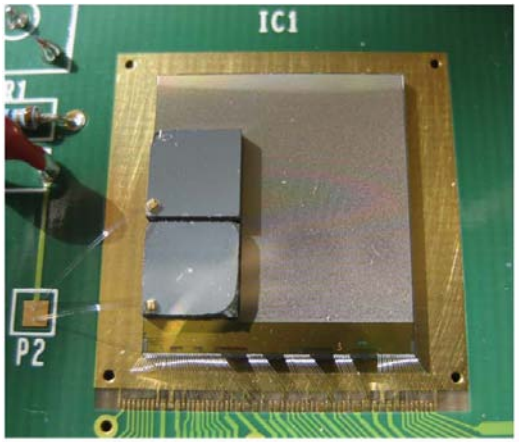
Benefits from collaboration with PANalytical

- **Very early engagement**
- **License agreement contributed to the financing of the chip development**
- **Support contract financed staff at Cern**
- **Royalties per sold detector**

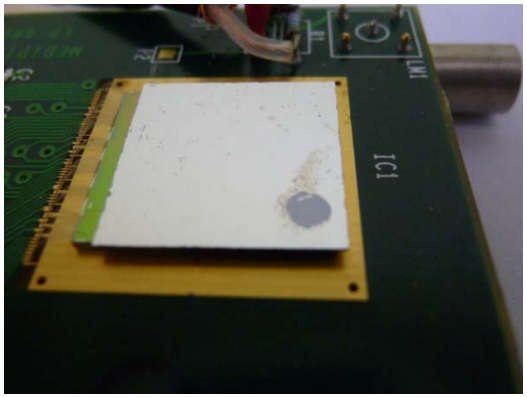
Applications @ CERN

Sensor prototypes

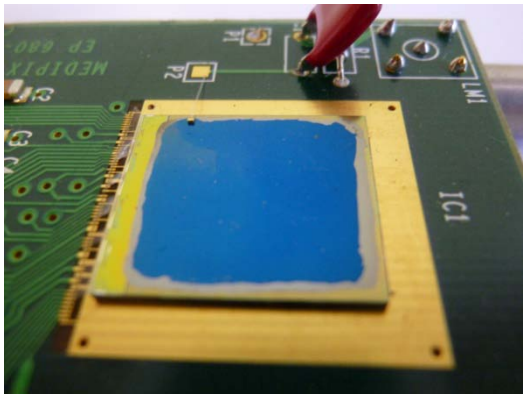
Sensor Prototypes



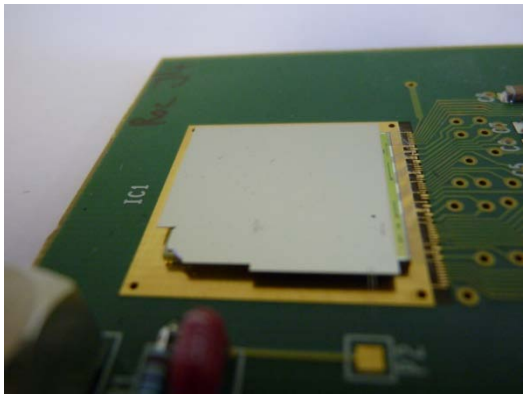
CdTe



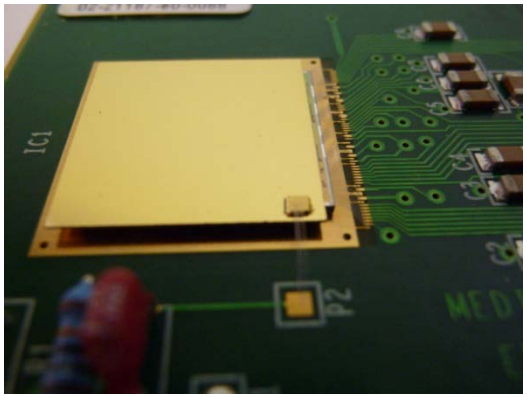
Semi 3D



α Si



Epitaxial GaAs



Si GaAs

High granularity and tuneable threshold used to characterise sensor materials

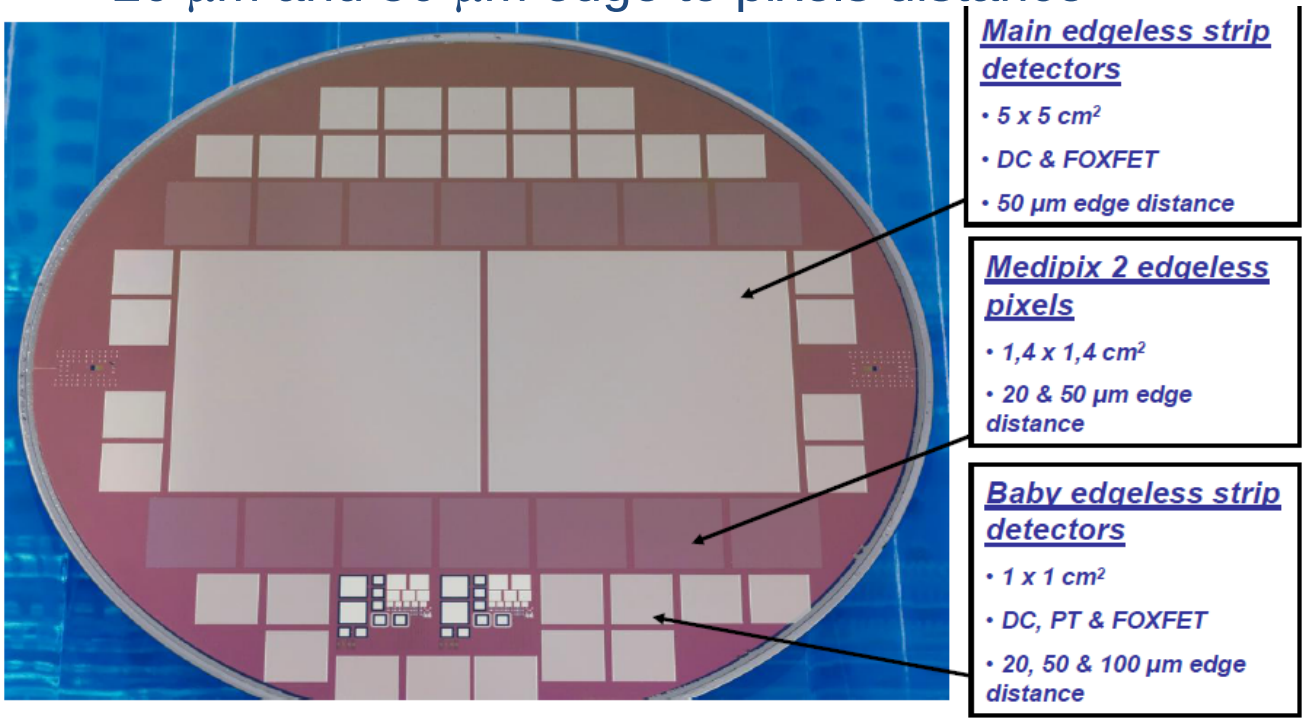
Sensor prototypes

Excellent test vehicle for new sensor materials and sensor geometries

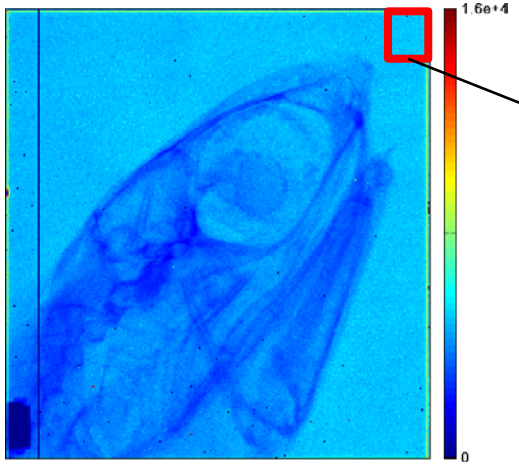
- High leakage current compensation per pixel < 14 nA
- High resolution 55 μm
- High threshold step granularity
  40 e Medipix, 25 e Timepix
- Very well understood standard assembly with 300 μm Si sensor as reference detector
- Availability and ease of use

VTT edgeless Si sensors

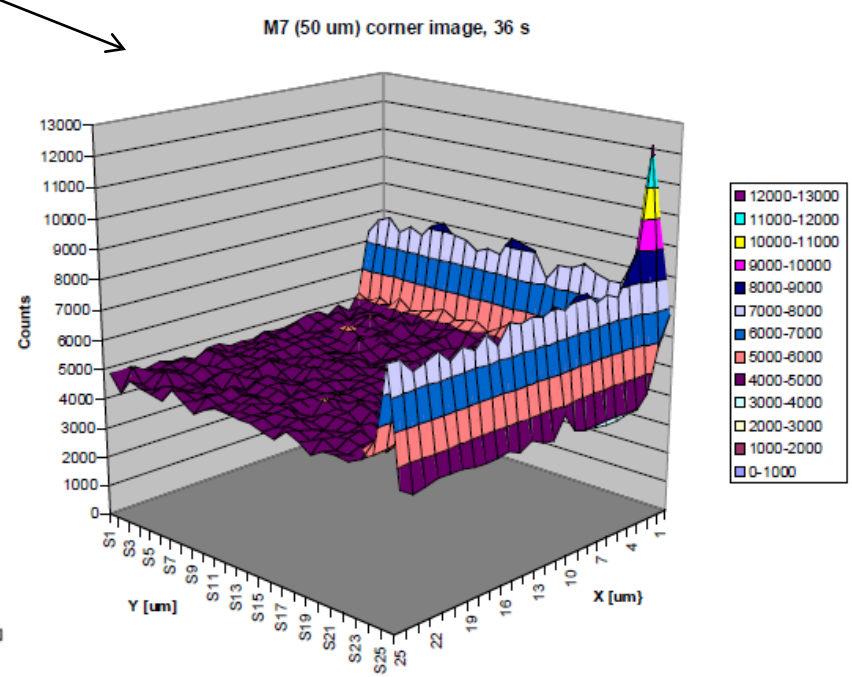
- Advantage of edgeless sensor
  - Minimal distance from beam edge to active area
  - Reduced leakage current, no dicing edge
  - Possibility to tile large areas without yield loss
- Samples
  - 150 μm thick Si n-on-n
  - 20 μm and 50 μm edge to pixels distance



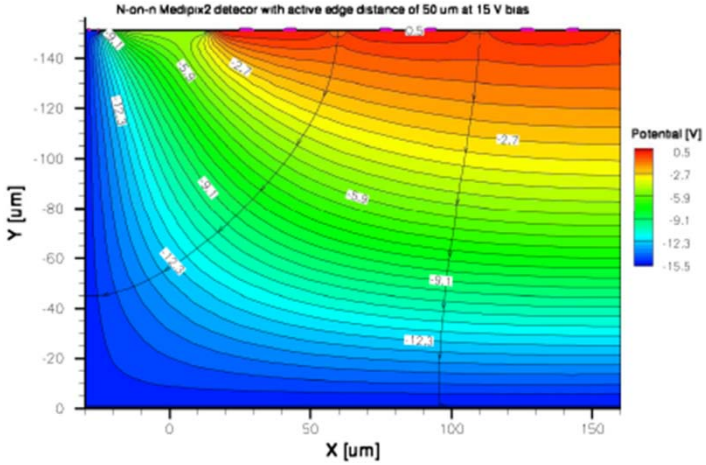
The edge of the edgeless



Cu tube @ 20 kV + 200 μm Cu filter
± quasi monochromatic 8 keV photons

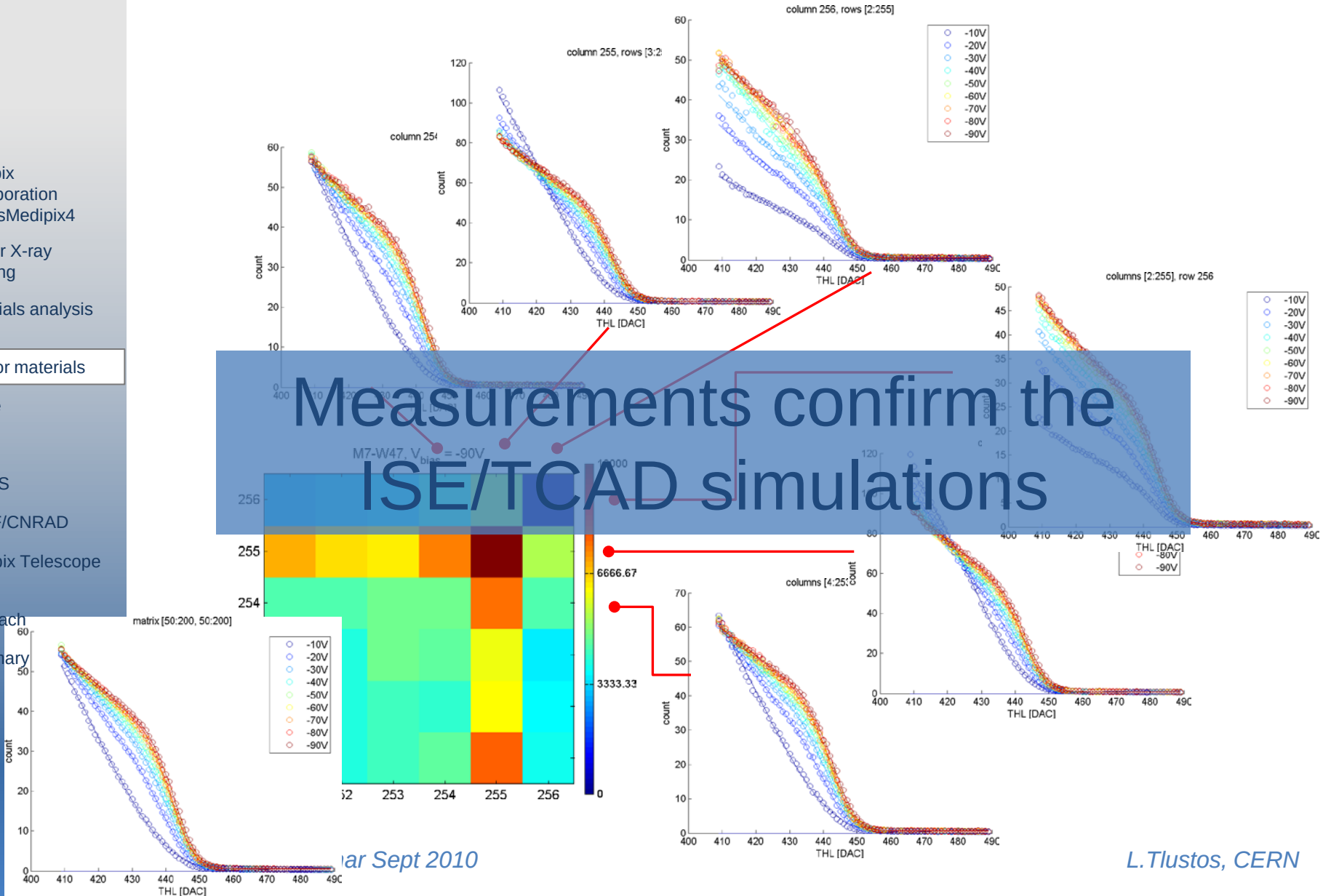


ISE/TCAD simulation



Threshold scans to determine the depletion voltage in edge rows and columns

- Medipix Collaboration ROC'sMedipix4
- Colour X-ray imaging
- Materials analysis
- Sensor materials
- Isolde
- UA9
- ATLAS
- CERF/CNRAD
- Timepix Telescope
- Outreach
- Summary



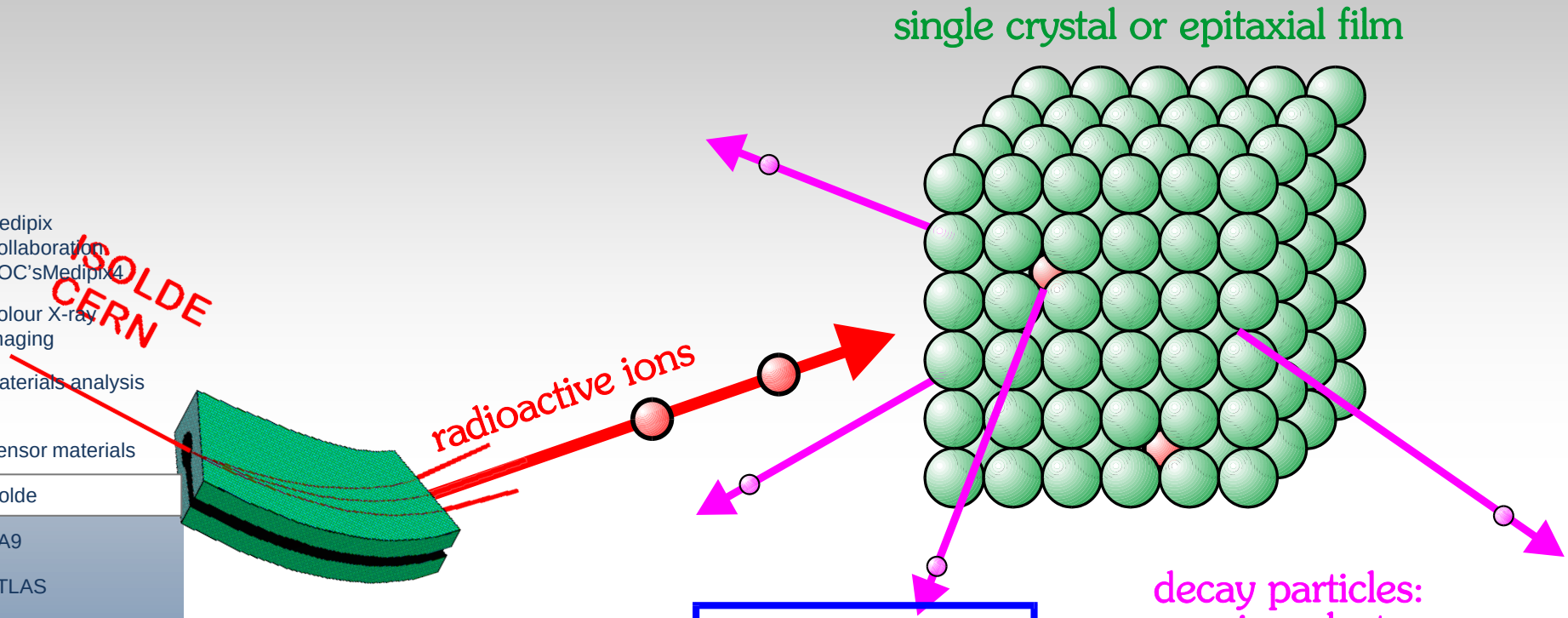
Measurements confirm the ISE/TCAD simulations

L.Tlustos, CERN

Applications @ CERN

Emission channelling, ISOLDE

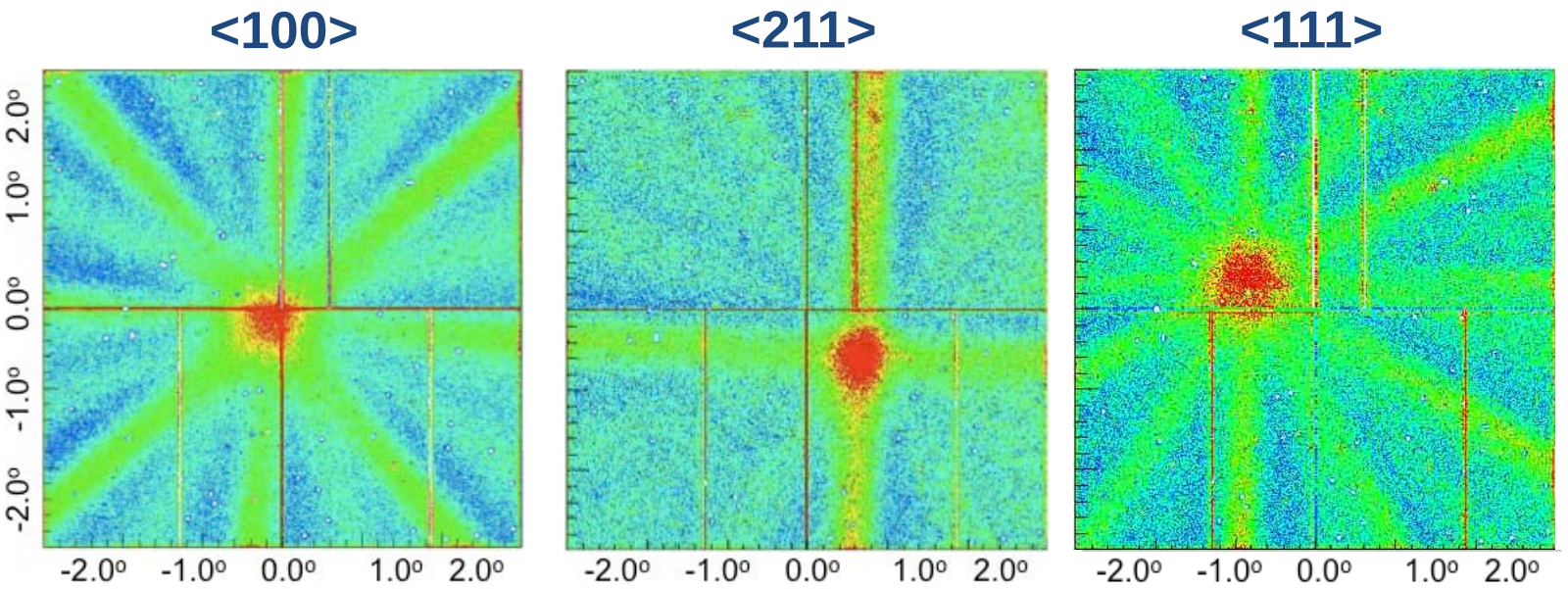
EMISSION CHANNELING: BASIC PRINCIPLES



Courtesy J. Guilherme Correia

TIMEPIX QUAD tests

EC(β^-)→ ^{89}Sr: $SrTiO_3$ (after annealing on air 1050°C)



- **Low detection threshold: Use of low energy electrons 8keV from conversion electrons and Auger sources**
- **High resolution: Resolving fine structure of spectra, particularly when using high energy beta sources**

Pixels between TOCs 165 μm wide are complicating the data analysis

→

Next step: bump bonding of every second pixel, uniform pixels size of 110 μm across matrix

Applications @ CERN

UA9 Experiment

Collimation Requirements for LHC

Super-Conducting Environment

Proton losses into cold aperture

⇩

Local heat deposition

⇩

Magnet can quench

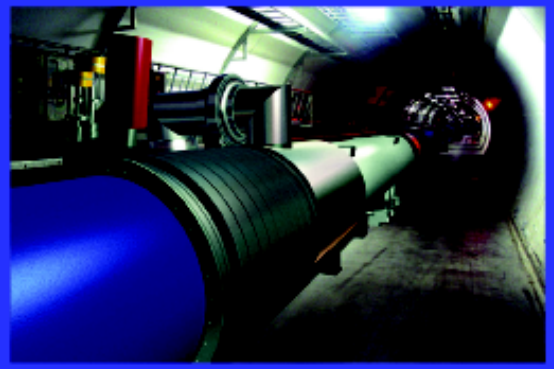


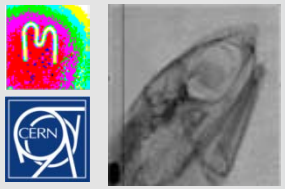
Illustration of LHC dipole in tunnel

Energy [GeV]	Loss rate (10 h lifetime)	Quench limit [p/s/m] (**steady losses**)	Cleaning requirement
450	8.4e9 p/s	7.0e8 p/s/m	92.6 %
7000	**8.4e9 p/s**	**7.6e6 p/s/m**	**99.91 %**

Control **transient losses (10 turns)** to ~1e-9 of nominal intensity (top)!

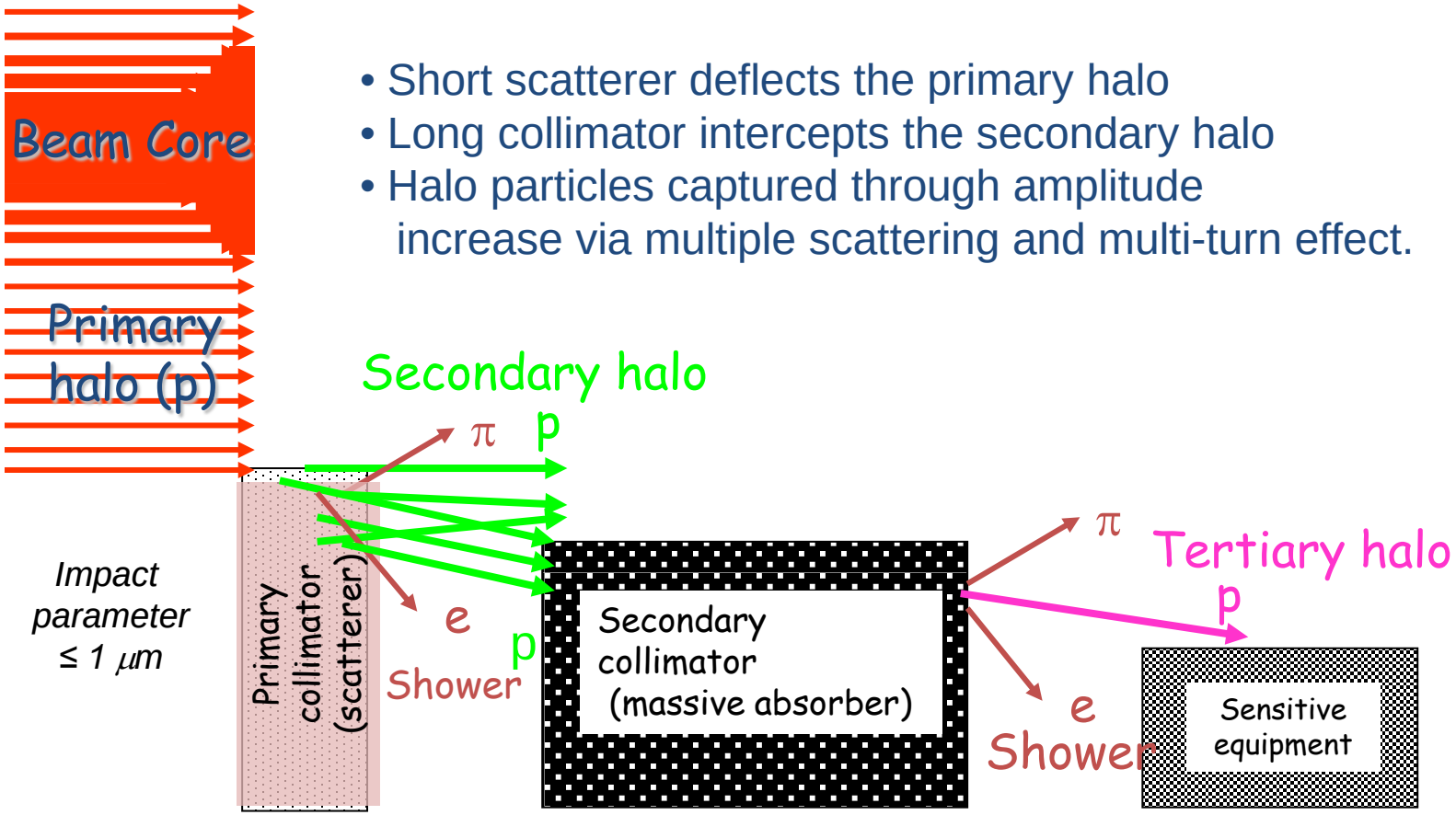
Capture (clean) lost protons before they reach cold aperture!
Required efficiency: **~ 99.9 %** *(assuming losses distribute over 50 m)*

Courtesy R. Assman



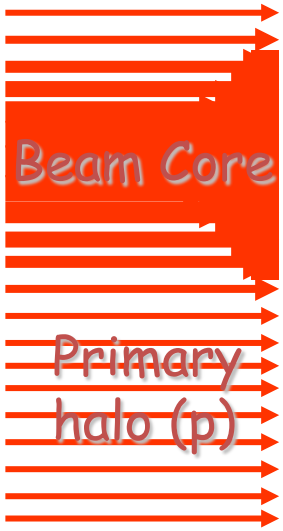
Two stage collimation

- Short scatterer deflects the primary halo
- Long collimator intercepts the secondary halo
- Halo particles captured through amplitude increase via multiple scattering and multi-turn effect.

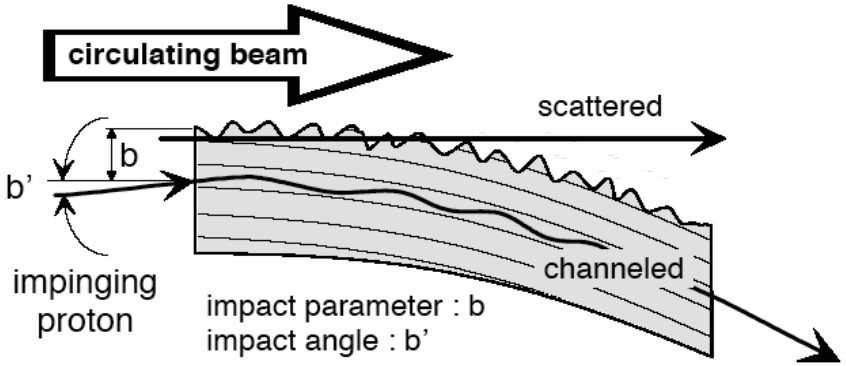


Courtesy Walter Scandale

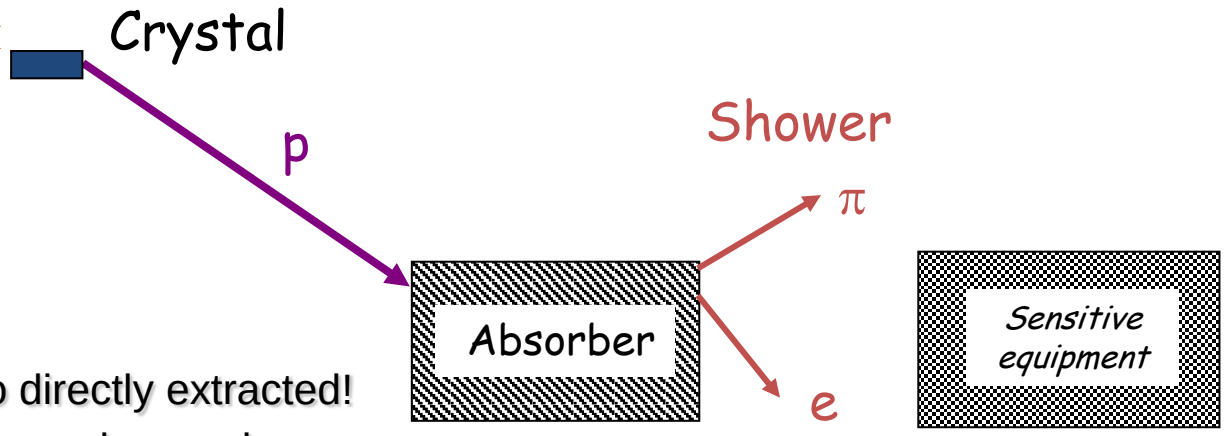
Crystal collimation



Crystal channeling



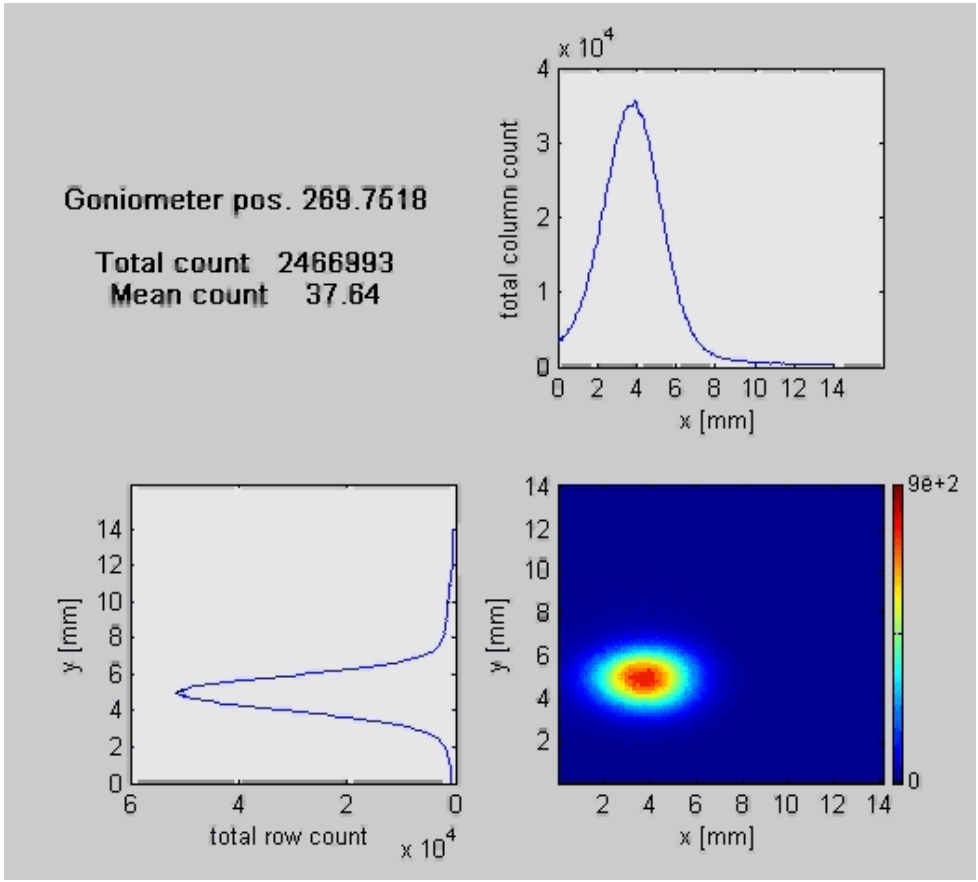
E. Tsyganov & A. Taratin (1991)



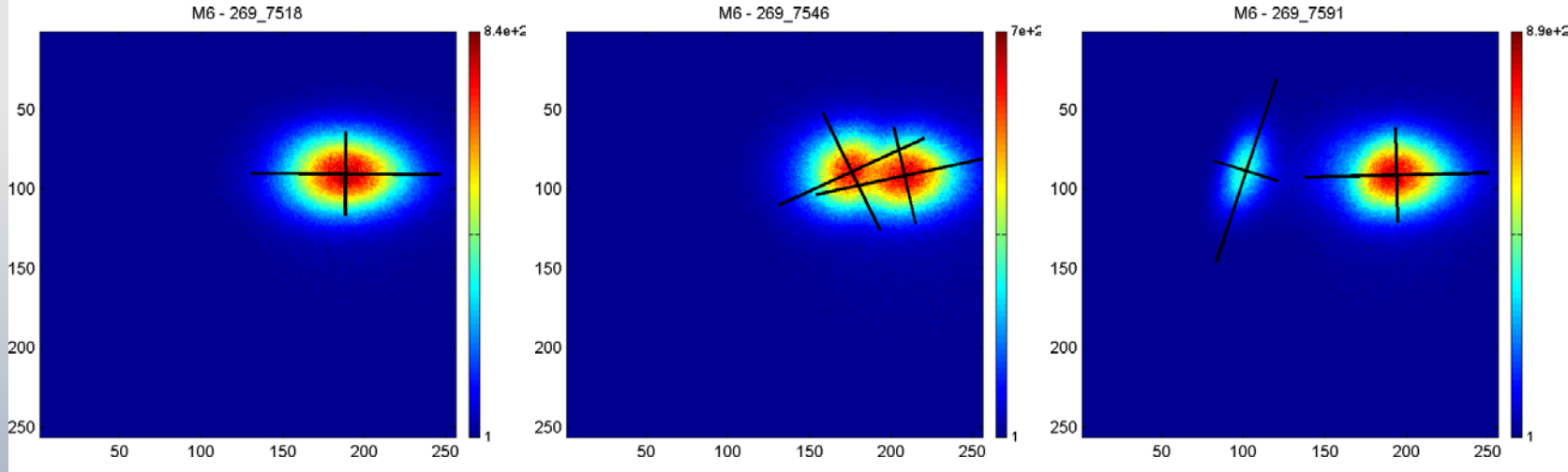
- Primary halo directly extracted!
- Much less secondary and tertiary halos !?

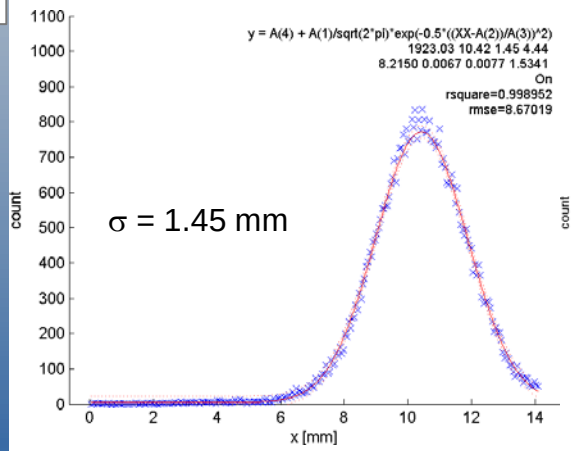
Courtesy Walter Scandale

UA9 – H8 - 5.8.2009
Goniometer Scan, Detector M6

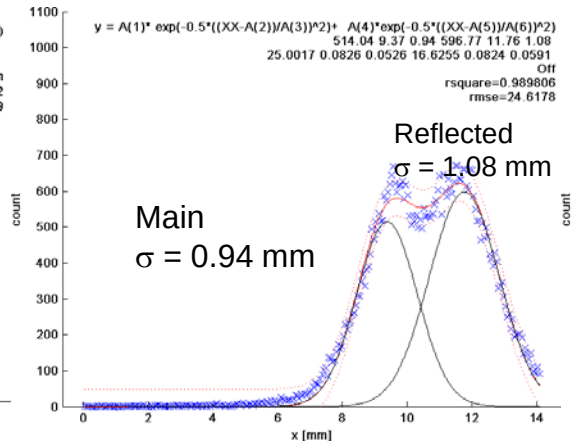


UA9 – H8 - 5.8.2009
Goniometer Scan, Detector M6

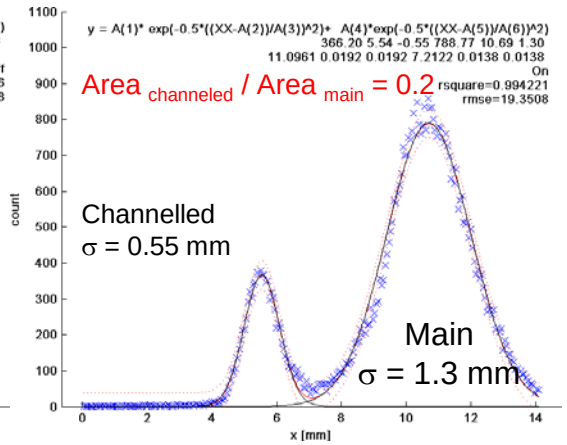




amorphous

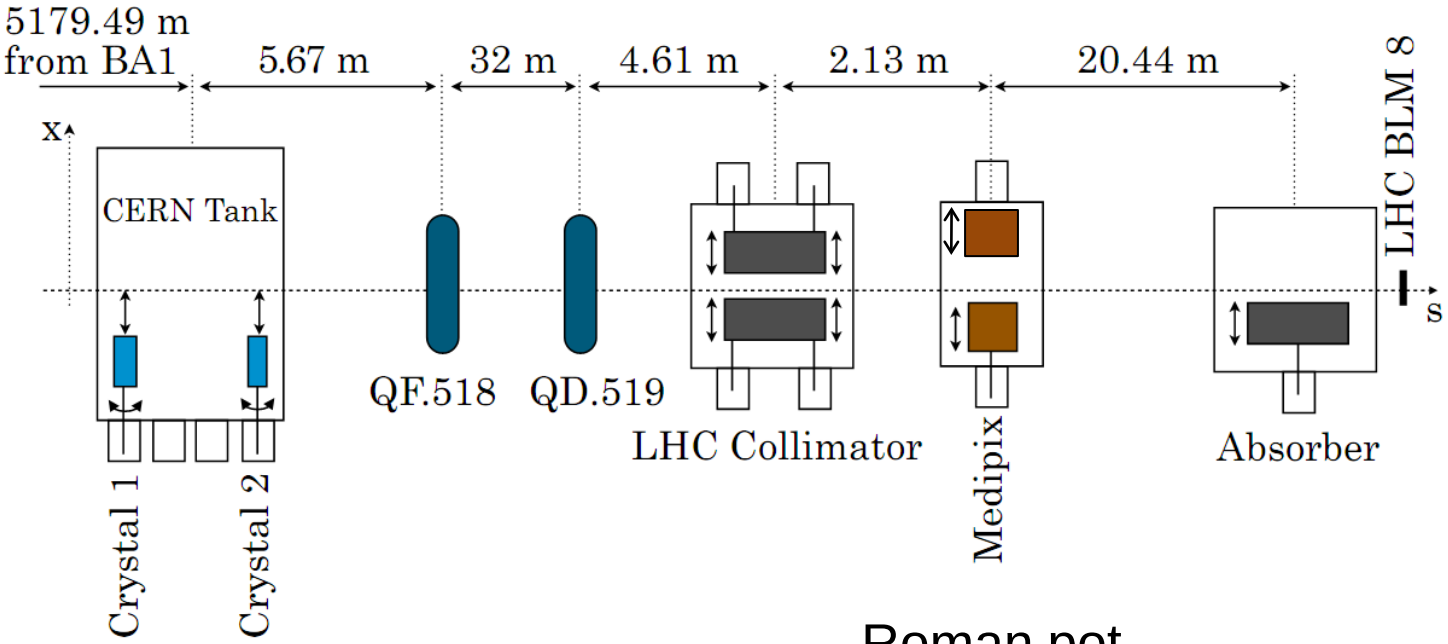


reflection

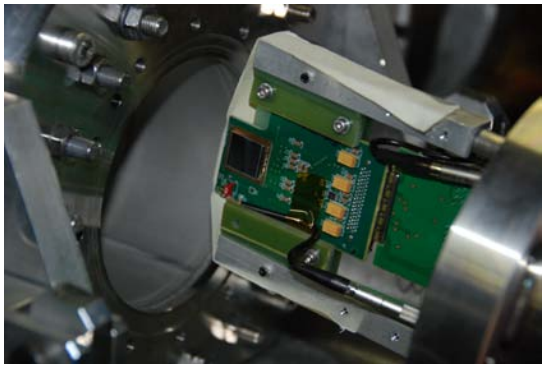


channelling

UA9 – SPS – 10.8.2009
Layout

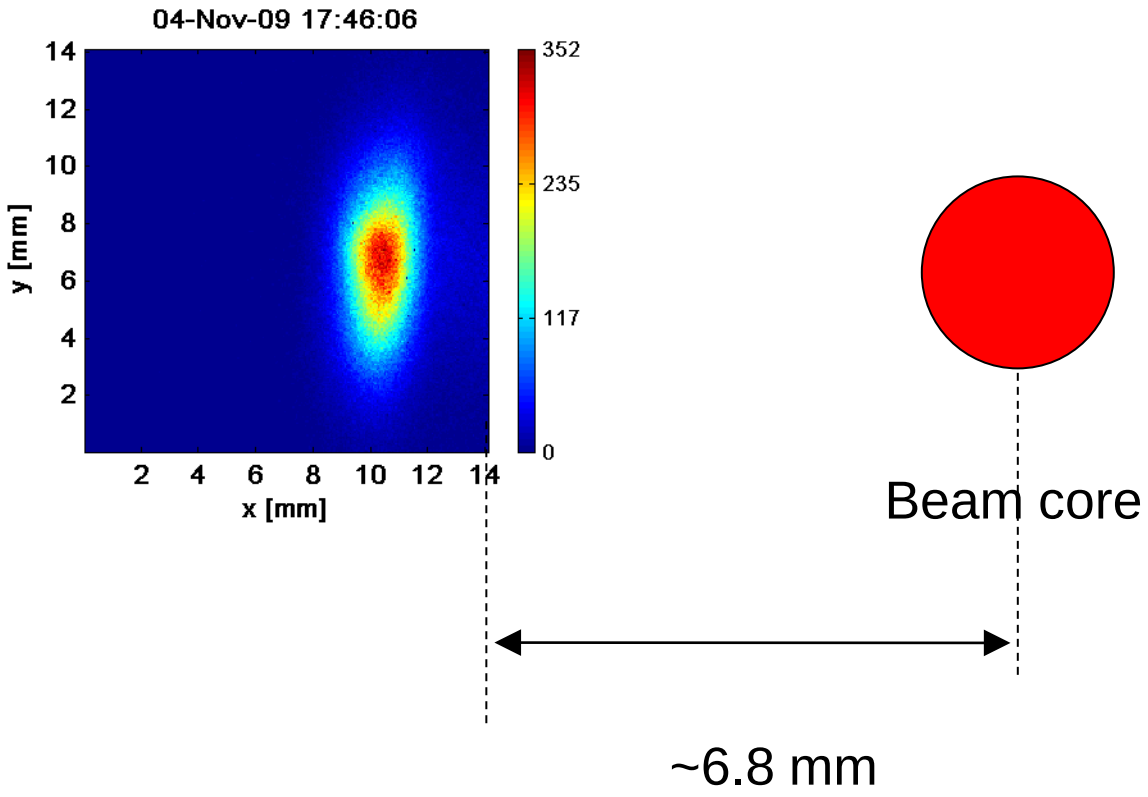


Roman pot



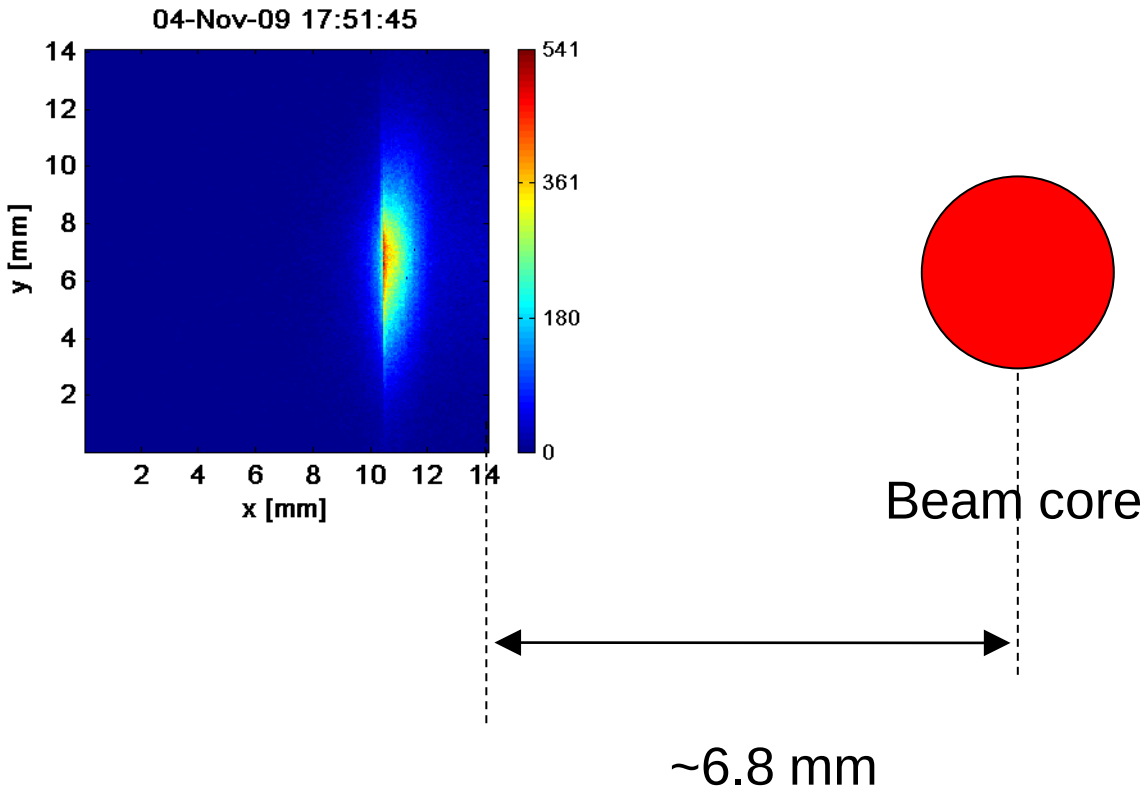
Better edgeless !

Channeling in SPS MD 20091104



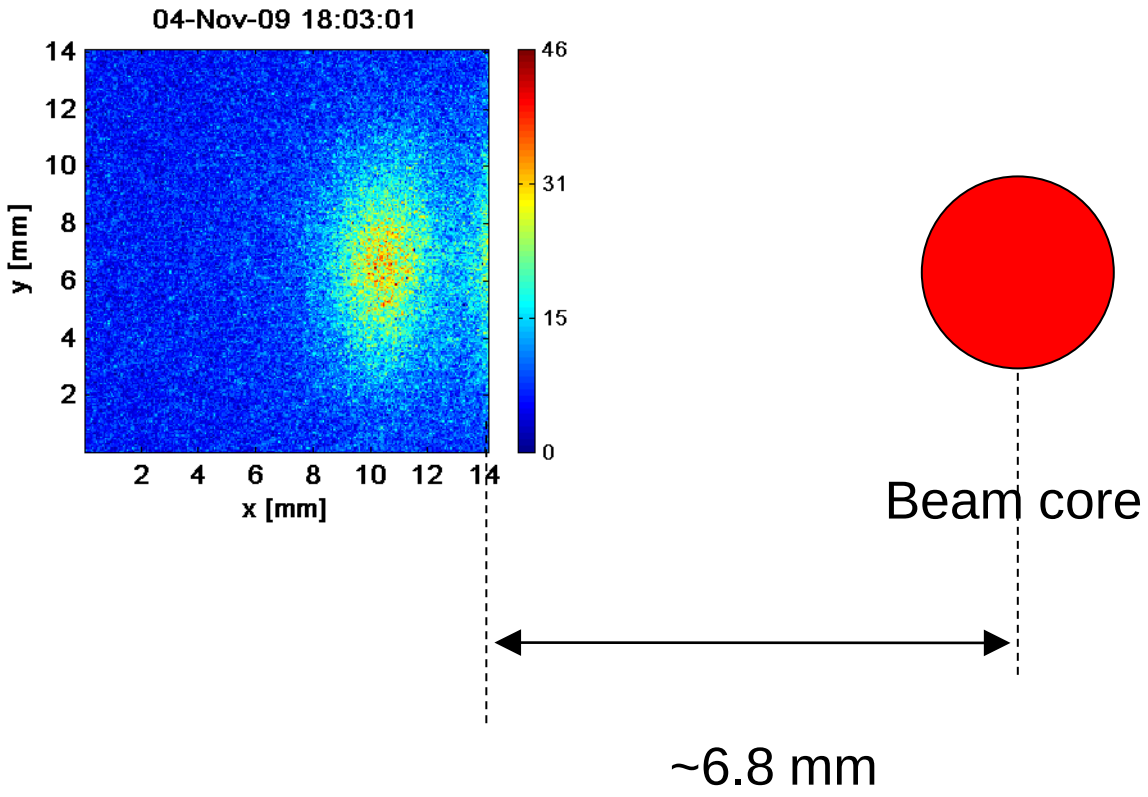
Channeling in SPS MD 20091104

Collimator cutting into the channelled beam



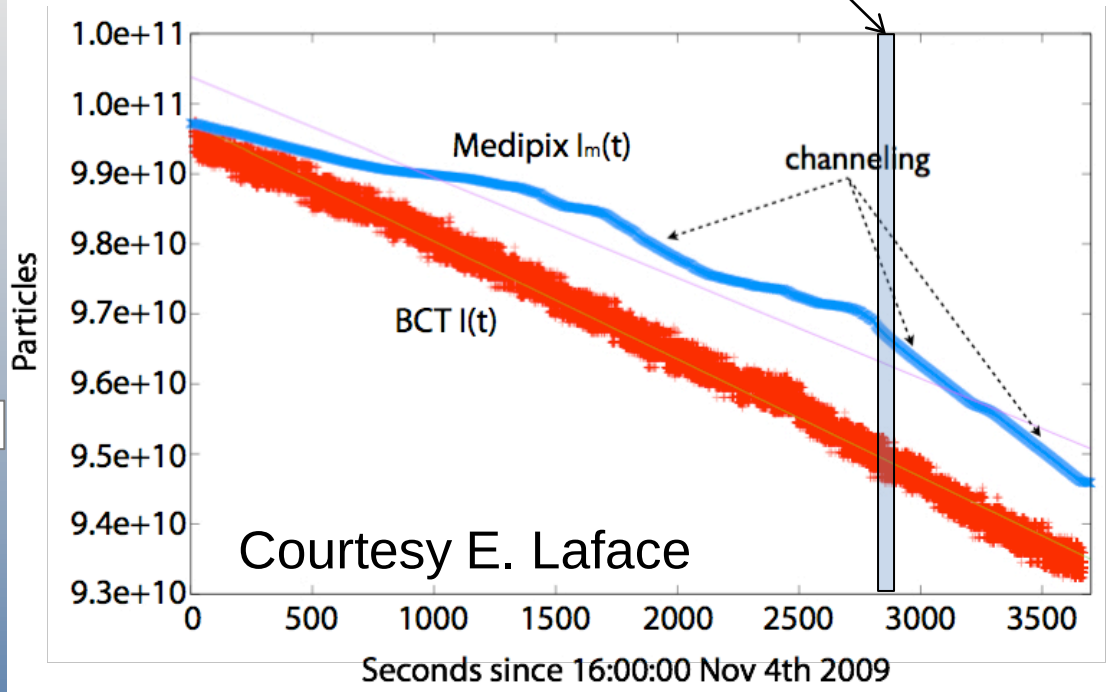
Channeling in SPS MD 20091104

Transmission image of the collimator.



Channelling Efficiency

η = 85% - 97%



Beam current decreases due various loss mechanisms.

Difference between Medipix count and decrease in no particles recorded by BCT gives a measure of de-channelled or scattered particles

100% channelling efficiency: no of particles detected in Medipix = gradient in BTC

Timepix in UA9 Summary

- **2 Timepix (Roman Pot RP.51937) and 1 Medipix (BLM.51900) installed in SPS**
- **Provides a real time monitor of the channelled beam**
- **Estimate of the channelling efficiency**

Next

- **Installing 2 more systems in Roman pot 2 (2nd Nov.)**
- **Upgrade of the RO system. Currently only ~ 1Hz frame rate**

Applications @ CERN

Radiation Monitoring
ATLAS

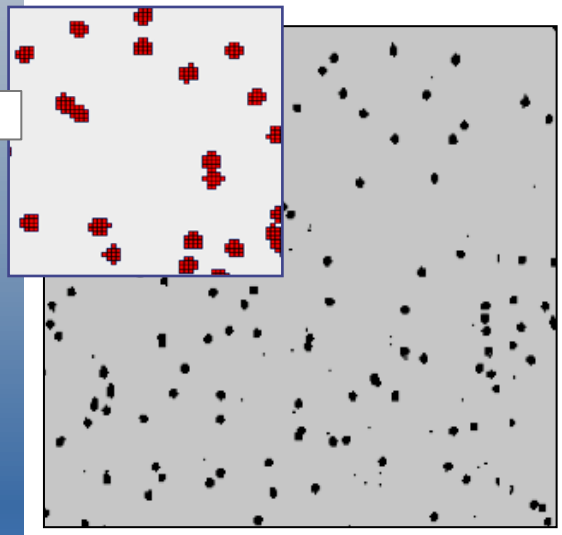
Motivation

- Need for validation of Monte Carlo simulations of the radiation field in and around the experiments
- Real time monitoring of fluxes of the main particle types needed

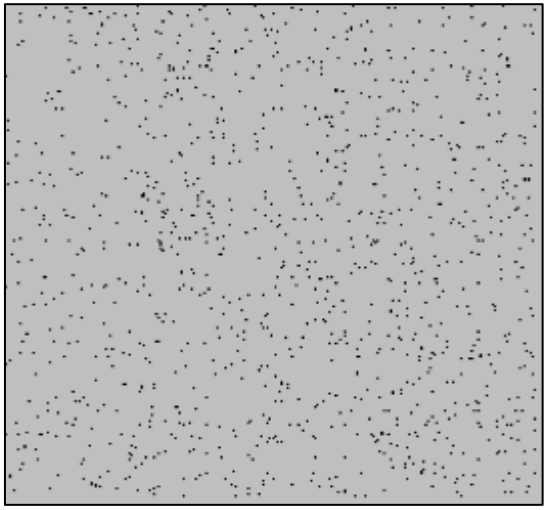
- 15 MPX2 installed in ATLAS
- 4 MPX2 installed in CMS


Principle

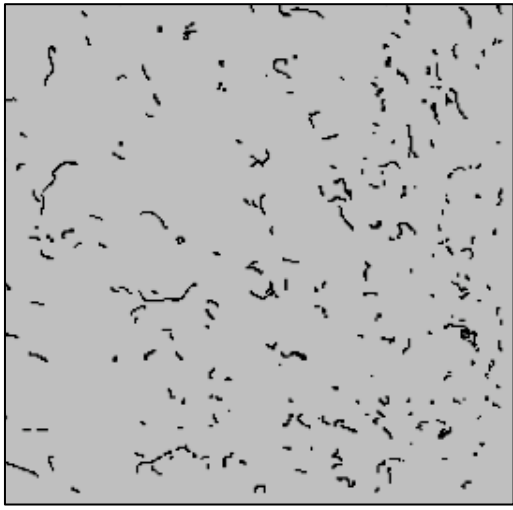
- **Small pixel size allows for particle tracking**
  - **short enough shutter time ⇒ sparse data ⇒ 1 cluster / particle**
- **Different particle types have different event signatures**
  - **use cluster finding algorithms**
  - **decoding of event morphology**
- **Converter layer on top of 300 μm Si sensor add sensibility to neutrons**



^{241}Am alpha source



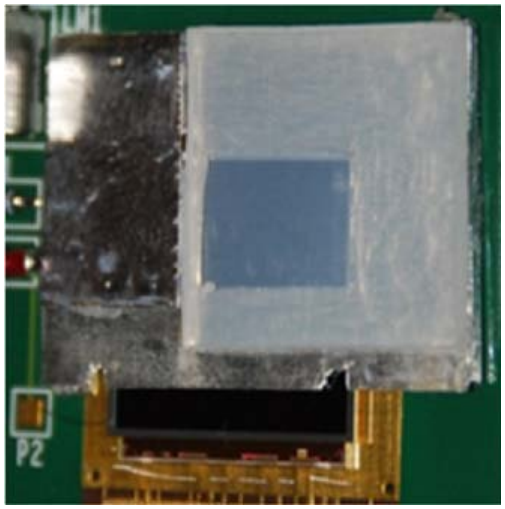
^{55}Fe X-ray source



^{90}Sr beta source

ATLAS-MPX device description

(16 devices installed)

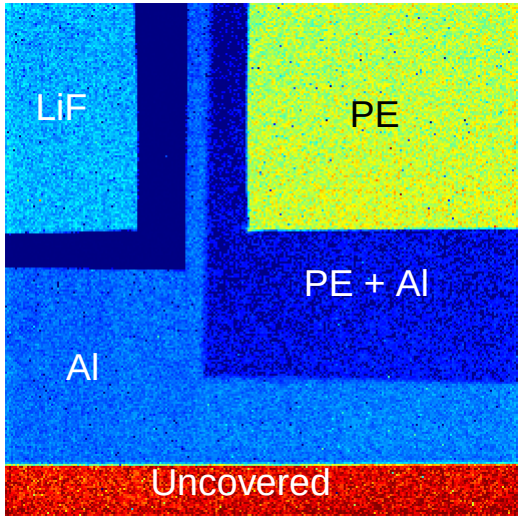


Neutron conversion structures:

- LiF + 50 μm Al foil area
- 100 μm Al foil area
- PE area
- PE + 50 μm Al foil area
- Uncovered area

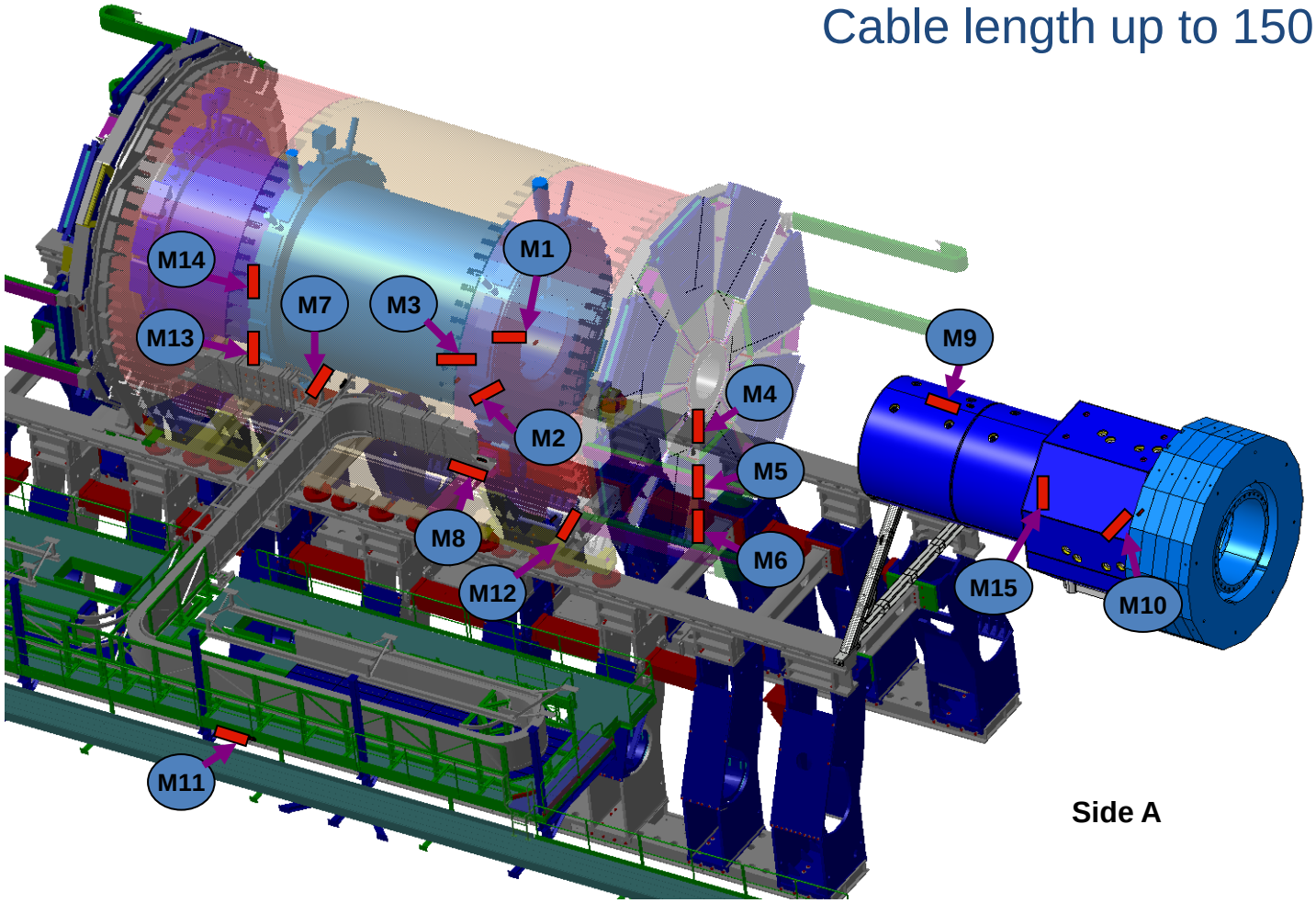
- **Thermal neutrons**
  - ^{6}LiF layer:
    - $^{6}Li + n \rightarrow \alpha + {}^{3}H$
- **Fast neutrons**
  - PE layer: recoil protons
    - $^{2}H + n \rightarrow p + {}^{2}H$
  - Si: direct interaction
    - $^{28}Si + n \rightarrow \alpha + {}^{25}Mg$
    - $^{28}Si + n \rightarrow p + {}^{28}Al$

Conversion layers



ATLAS-MPX position overview

15 n-Medipix2
Cable length up to 150 min



Side A

CMS-Medipix

- 4 Detectors in CMS cavern, cable length <40 m

Cavern (z=15 m, r = 11.5 m)

PC room S1 (behind shielding)

Cluster analysis in tracking mode of operation

Each particle depositing energy above the preset threshold in the sensitive volume of the detector is visualized as it's characteristic track.

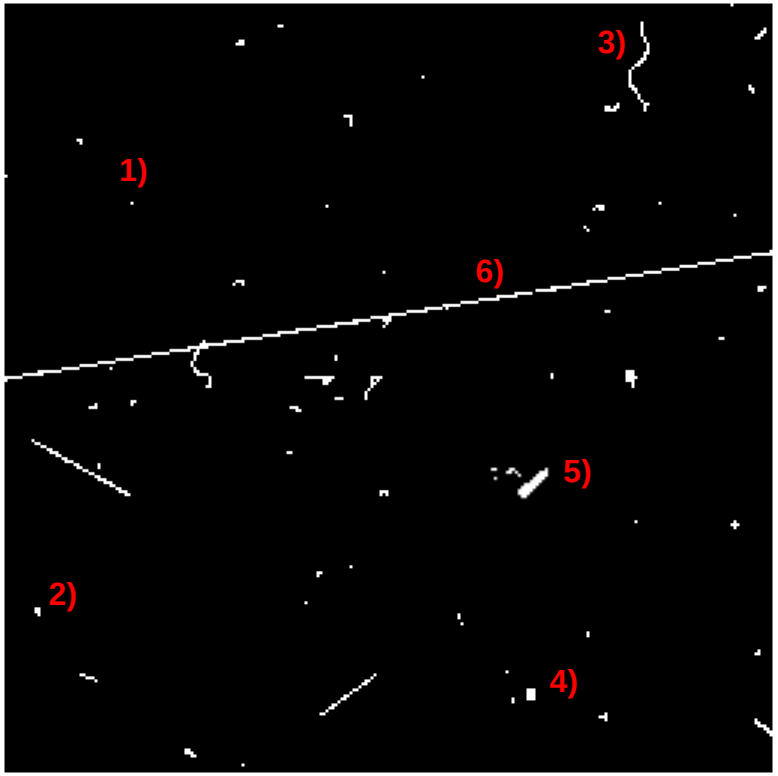
Set of criteria can be established in order to resolve those different shapes:

- **Area (number of pixels) in the cluster**
- **Roundness (surface compared to length of the border)**
- **Linearity (possibility to interleave track with line)**
- **Thickness of the straight track**

Six categories of characteristic patterns were introduced in "tracking mode":

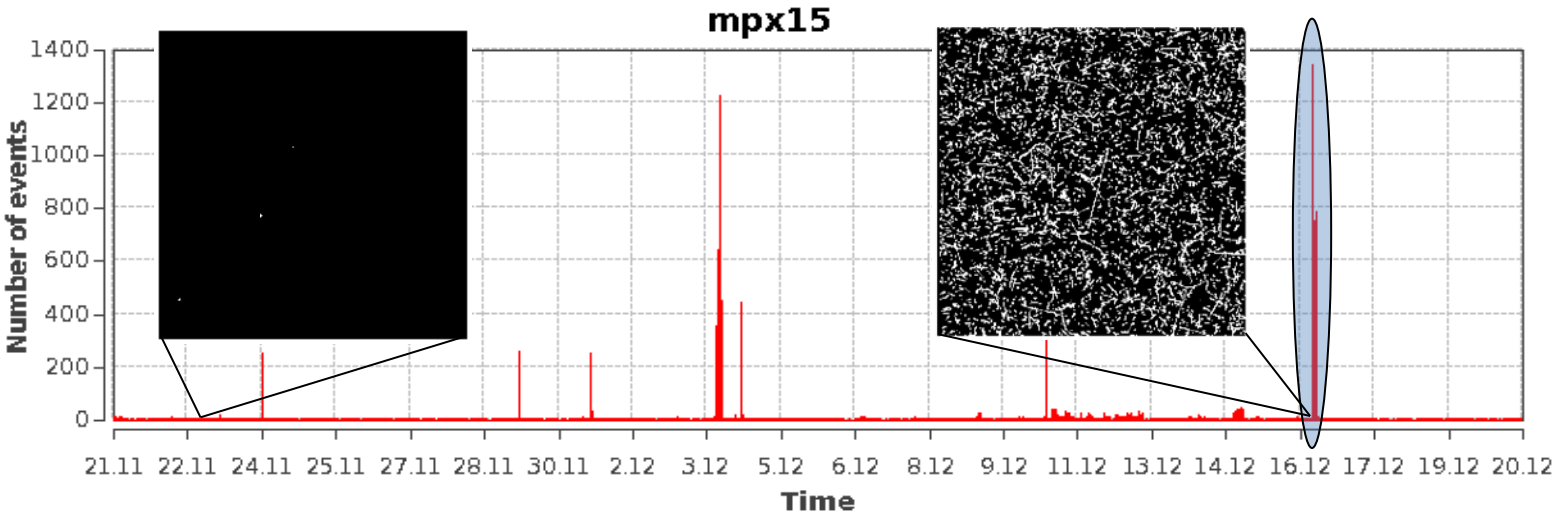
1) Dot – Gamma and X-rays
2) Small blob – Gamma and X-rays, low energy electrons
3) Curly track – electrons (MeV range)
4) Heavy blob - energetic particles with low range (alpha particles,…)
5) Heavy track - energetic heavy charged particles (protons,…)
6) Straight track – energetic light charged particles (MIP, Muons,…)

Background in ATLAS – 100min



Radiation level recorded by MPX15 during LHC run (from 21.11.2009 to 21.12.2009)

Vykydal ,Ringberg 2010



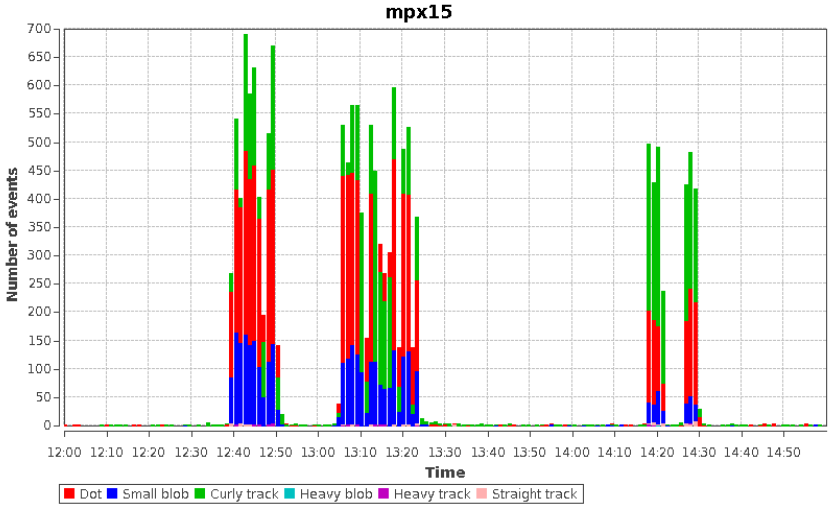
MPX15 device

Time: 21.11.2009 00:00 - 21.12.2009 00:00

Position: Side A, close to LUCID, inside JF shielding, close to beam pipe.

X = 185 mm; Y = -75 mm; Z = 18740 mm;
R = 200 mm

Detail: 16.12.2009 12:00 - 16.12.2009 15:00



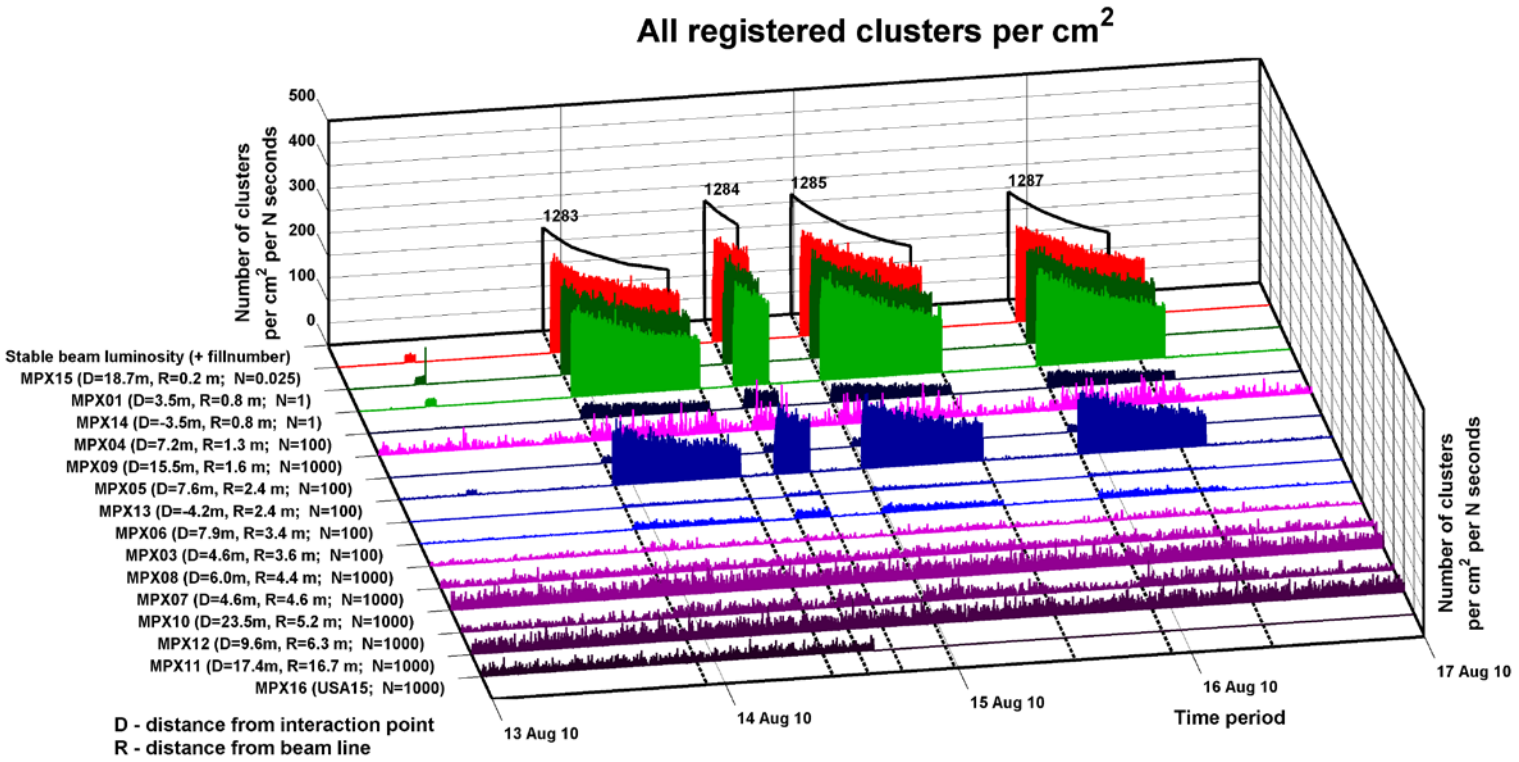
ATLAS-MPX operation

Detail from 13.8 – 17.8.2010

Vykydal ,Ringberg 2010

Periods of stable beam luminosity with corresponding fill numbers. There is a obvious correlation between signal from all devices.

Recorded cluster rates follow beam decay times.



Thermal neutron flux in MPX04

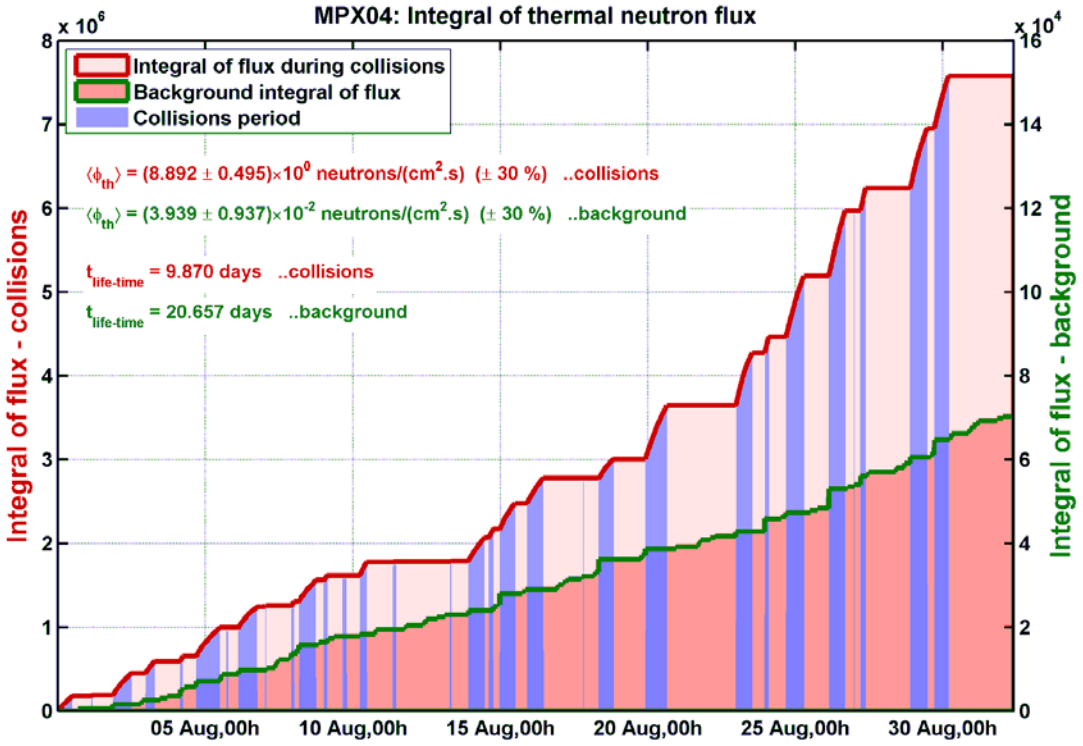
Vykydal,Ringberg 2010

Lifetime integral of thermal neutron flux (~6% dead time because of data readout).
High energy transfer signal generated only in LiF region.

MPX04 device:

Side A, between FCAL and JT wheel.

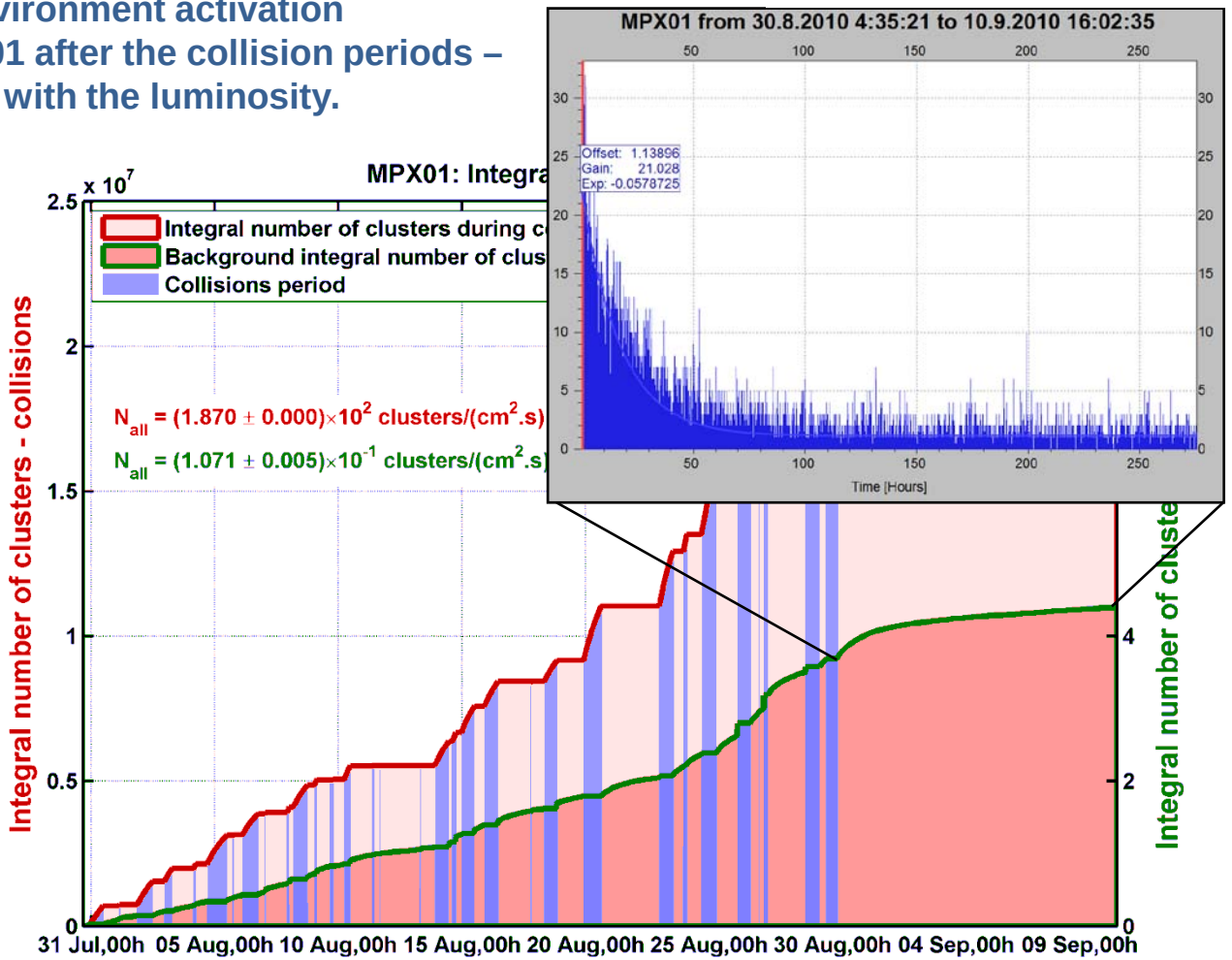
X = -65 mm
Y = -1295 mm
Z = 7120 mm
R = 1295 mm



Activation of the environment

Vykydal ,Ringberg 2010

Examplem of the environment activation observation in MPX01 after the collision periods – activation increases with the luminosity.



MPX01 device:

Side A, between ID and JM plug.

X = -710 mm
Y = 290 mm
Z = 3420 mm
R = 770 mm

Atlas MPX Summary

- **Online measurement of the radiation field across Atlas**
  - **https://atlasop.cern.ch/atlas-point1/operRef.php?subs=../local-server/pc-medipix-01/**
- **Thermal neutron flux**
- **Activation level**

Future

- **Medipix2 → Timepix**
- **Upgrade of rad. hard readout → increased frame rate**

Applications @ CERN

CERF / CNRAD

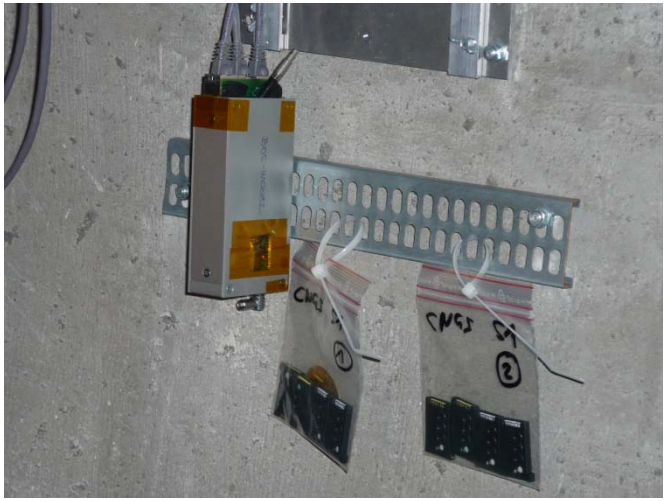
Motivation

- Neutrons may be critical for LHC machine components (SEU and old electrical components containing Boron)
- Evaluate the potential of MPX/TPX as neutron monitor in LHC like environment
- Aim:
  - Estimate neutron spectrum
  - Fluence estimate for
    - Thermal neutron <10eV (SEU in electrical components containing Boron)
    - up to ~10 MeV (SEU nuclear interactions)
    - > 10 MeV (SEU nuclear interactions)
  - Discriminate charged particles signals

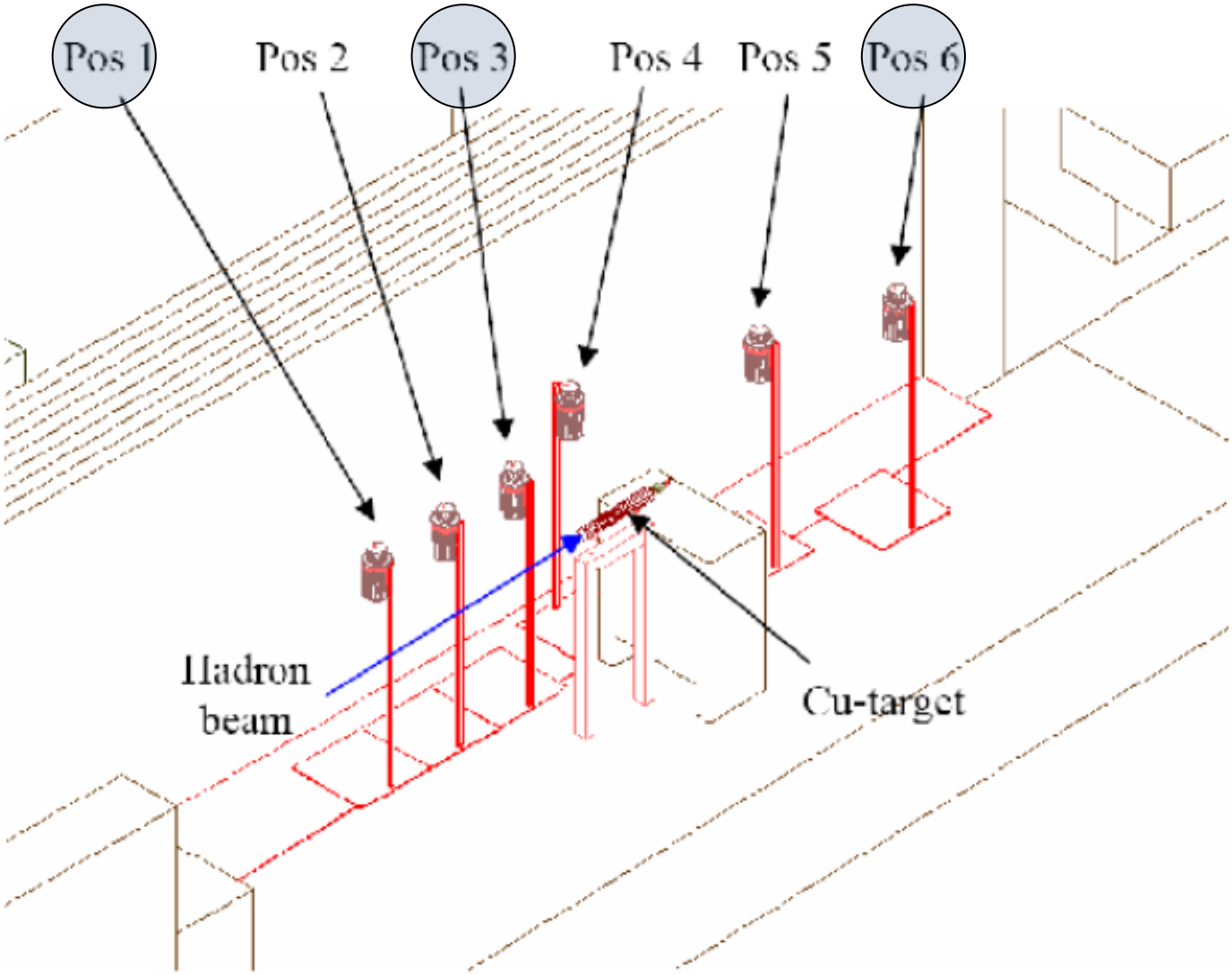
2 installations

- **CERF, July 2010**
  - **Low intensity**
  - **Large hadronic component**
  - **~20 m extension cables**

- **CNGS, still running**
  - **High intensity**
  - **Lower hadronic component**
  - **>100 m extension cables**



CERF Facility Layout (Inside)



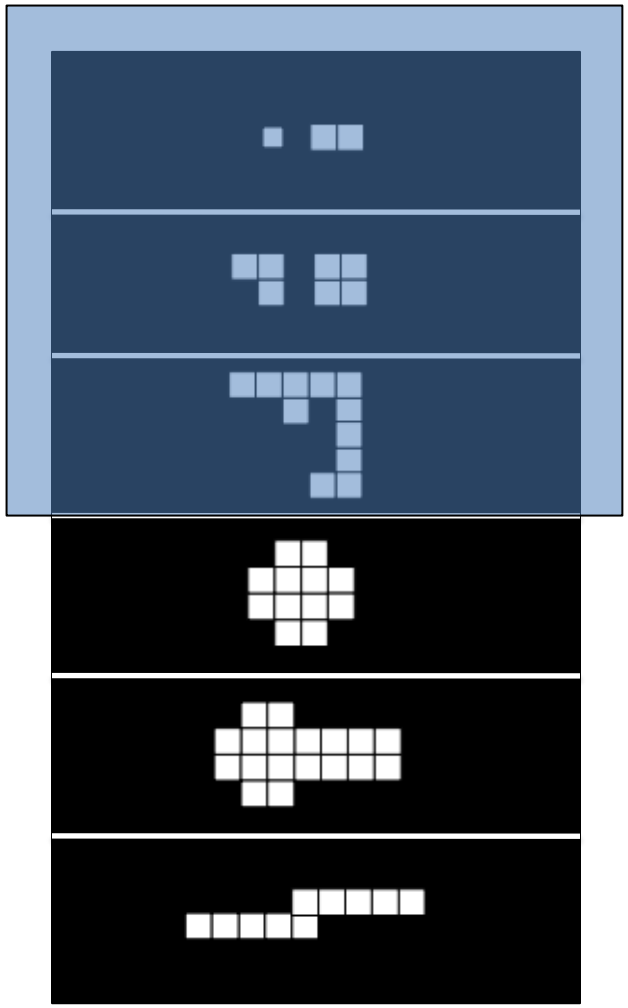
Courtesy M. Brugger

Fluences for Test Locations

Position	Particle fluence per beam particle on target					
	Hadrons (p,n,$\pi^{\pm}$,$K^{\pm}$)		Neutrons			
	>20 MeV	σ_{20MeV} [%]	5-20MeV	σ_{n5-20} [%]	<0.28 eV	σ_T [%]
C250	1.48E-05	0.31	1.70E-05	0.29	2.01E-04	0.23
C150	3.45E-05	0.19	3.96E-05	0.19	3.18E-04	0.17
C2	2.20E-05	1.30	2.53E-05	1.39	3.03E-04	1.18
C1	5.57E-05	0.71	6.39E-05	0.78	4.53E-04	0.87
1	8.75E-05	0.36	9.38E-05	0.35	4.96E-04	0.43
2	2.40E-04	0.20	2.42E-04	0.21	5.85E-04	0.36
3	9.52E-04	0.11	7.72E-04	0.12	6.39E-04	0.35
4	1.01E-03	0.10	3.85E-04	0.16	6.47E-04	0.31
5	1.09E-03	0.09	1.11E-04	0.34	5.39E-04	0.44
6	1.37E-03	0.09	6.56E-05	0.49	4.16E-04	0.48
F1	8.34E-05	0.95	8.97E-05	1.03	4.47E-04	1.31
F2	2.20E-04	0.33	2.36E-04	0.32	5.62E-04	0.64
F3	7.29E-04	0.14	6.60E-04	0.17	7.62E-04	0.53
F4	1.66E-03	0.10	6.59E-04	0.18	7.53E-04	0.53
F5	9.49E-04	0.19	1.74E-04	0.46	5.03E-04	0.77
F6	6.32E-04	0.27	1.01E-04	0.68	3.81E-04	0.86

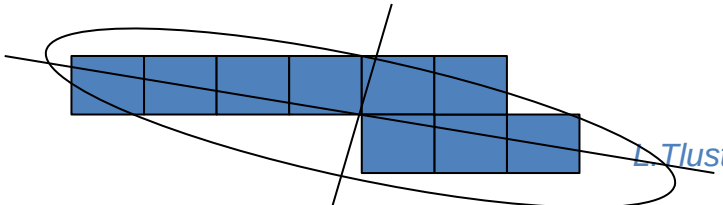
Courtesy M. Brugger

Cluster Analysis

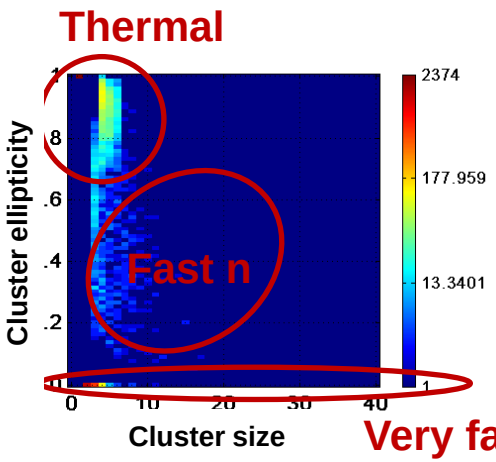


Low energy deposition discriminated
Threshold set to ~ 230 keV

- **Count**
  - **Pixel Count**
  - **Total ToT Count**
- **Principal axes / per cluster**
  - **Tilt α** $\alpha = \text{atan}(v_y/v_x)$
  - **Ellipticity e** $e = |v1|/|v2|$

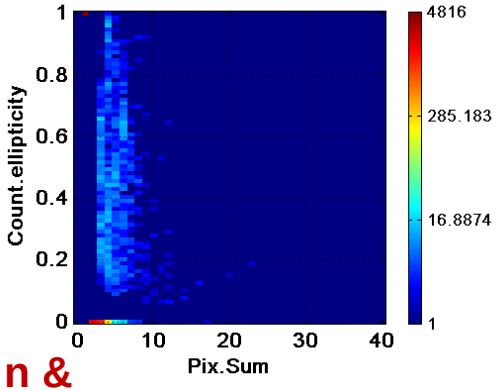


Pos1 ⊥ beam, facing target, HT

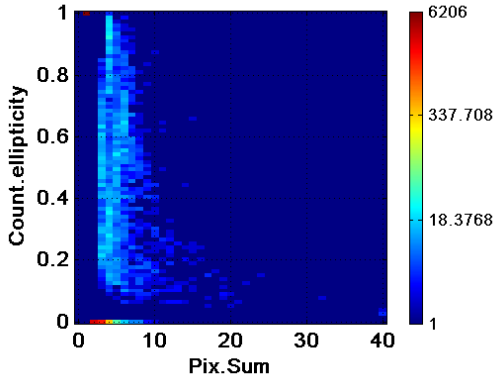


LiF

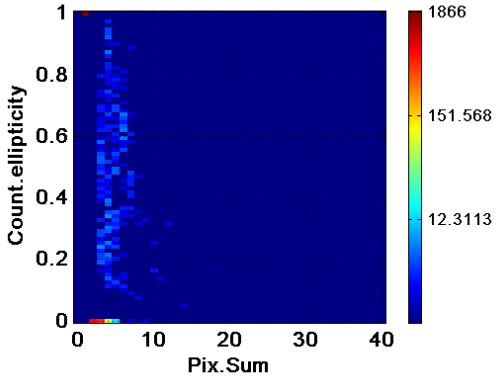
Very fast n & hadrons



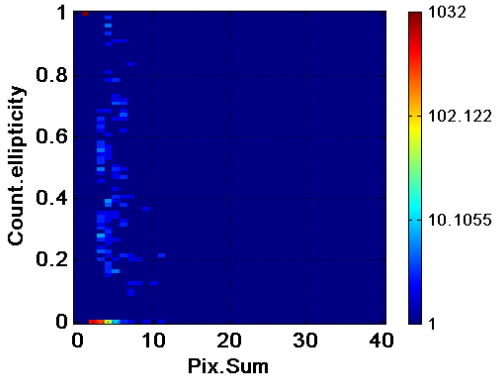
Al1



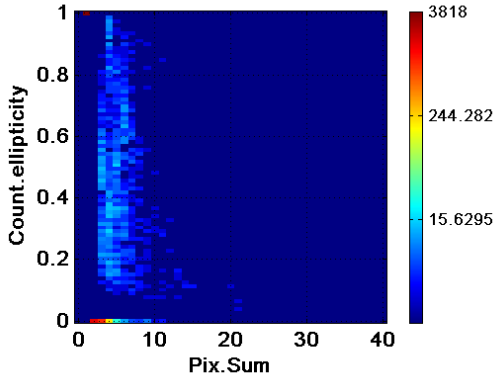
PE



Si

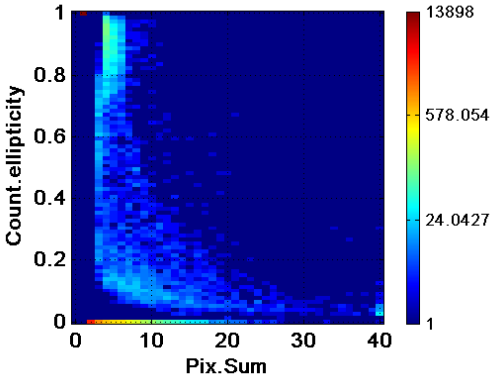


Al2

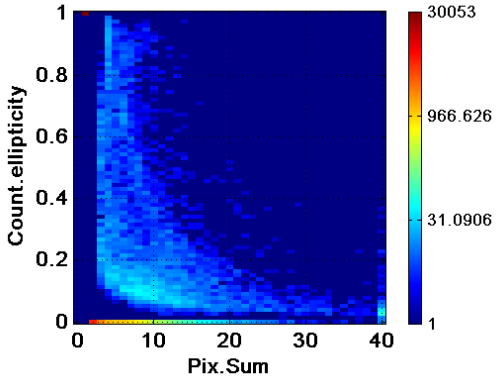


PE+Al

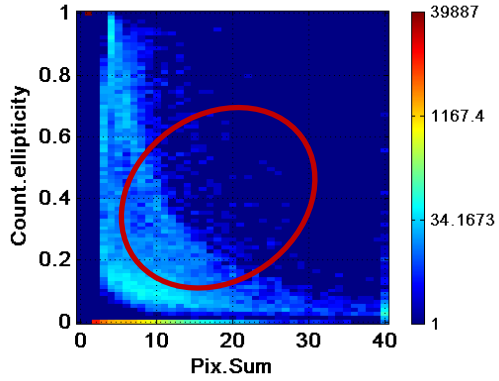
Pos 3 ⊥ beam, facing target



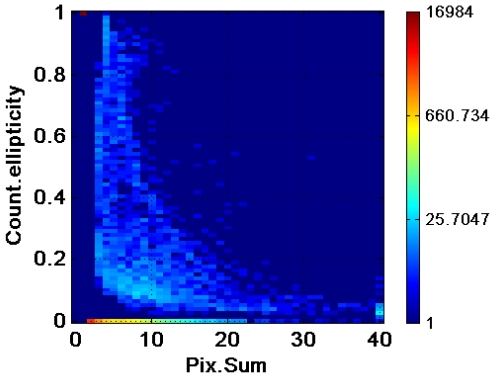
LiF



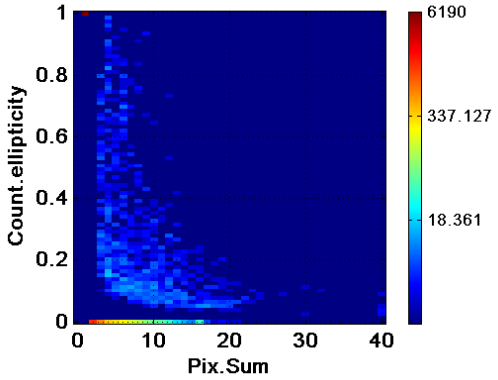
Al1



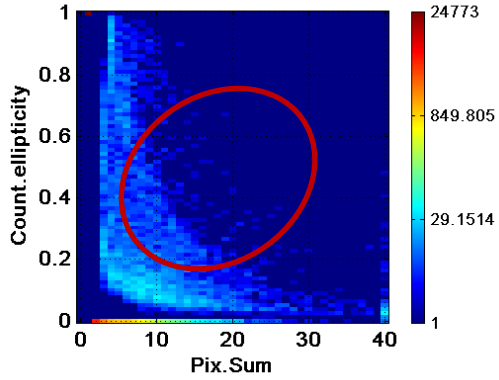
PE



Si

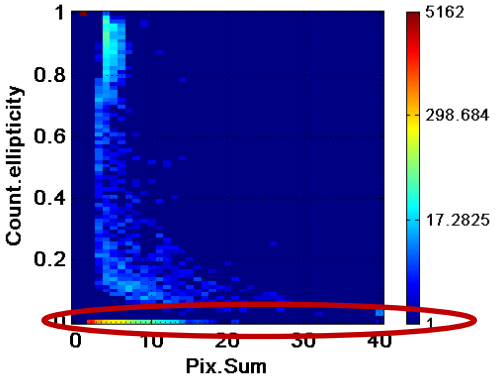


Al2

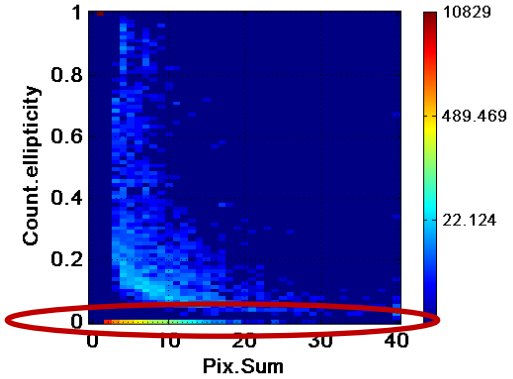


PE+Al

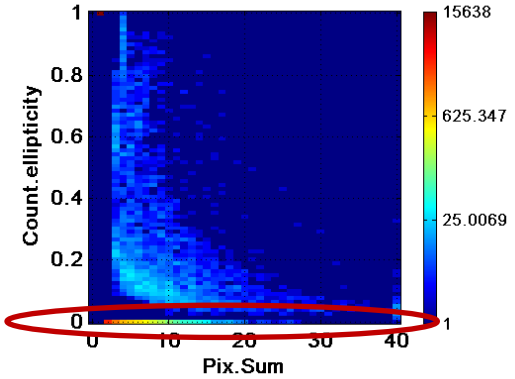
Pos 6 ⊥ beam, facing beam



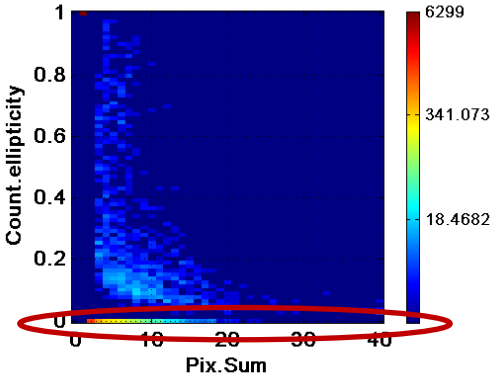
LiF



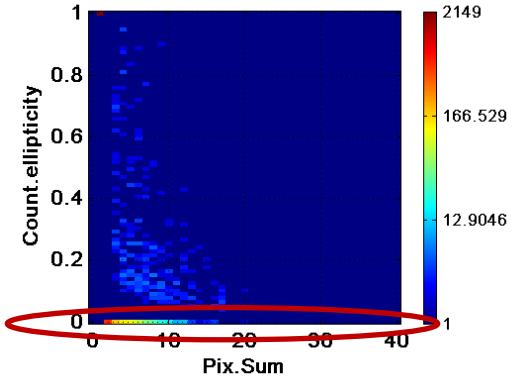
Al1



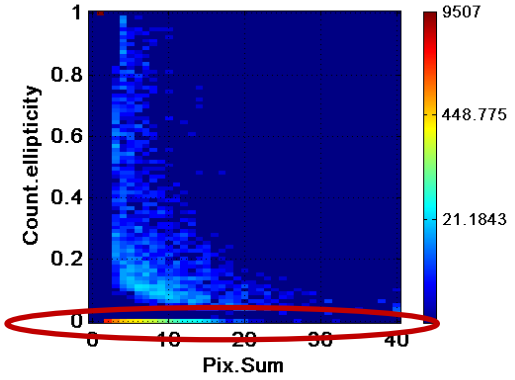
PE



Si

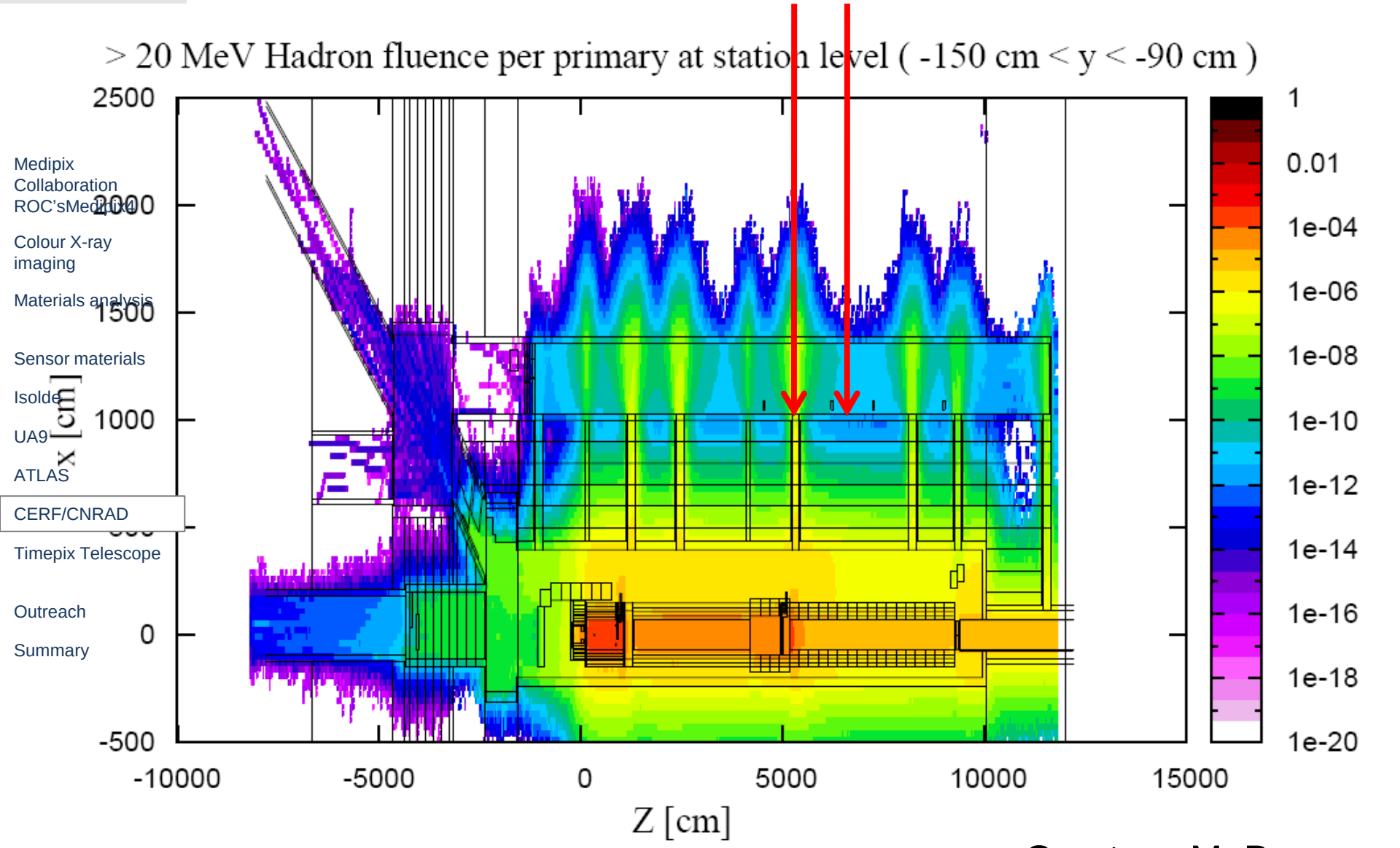


Al2



PE+Al

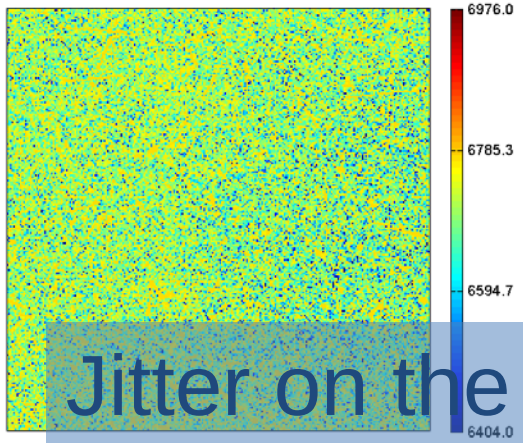
CNGS Radiation Field

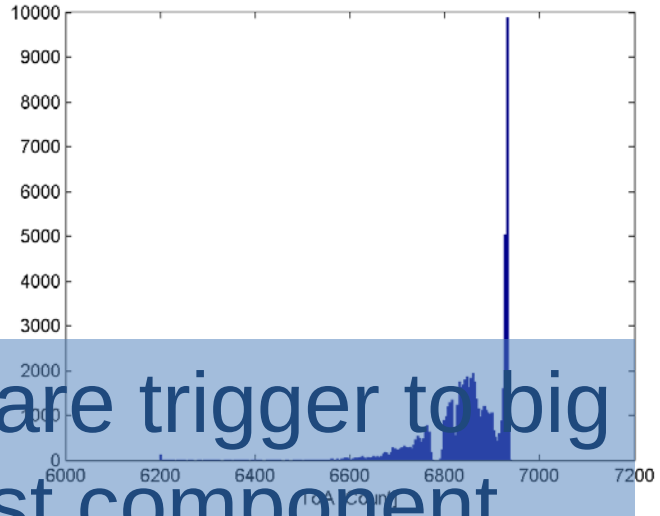


- Medipix Collaboration
- ROC'sMedipix4
- Colour X-ray imaging
- Materials analysis
- Sensor materials
- Isolde
- UA9
- ATLAS
- CERF/CNRAD
- Timepix Telescope
- Outreach
- Summary

Courtesy M. Brugger

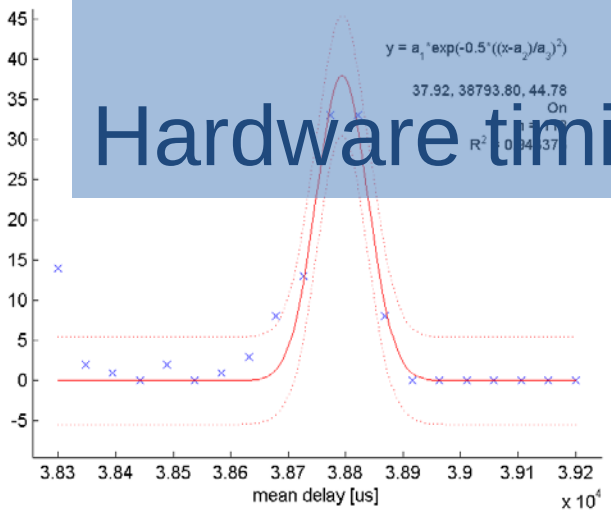
Software Trigger delay measured with ToA

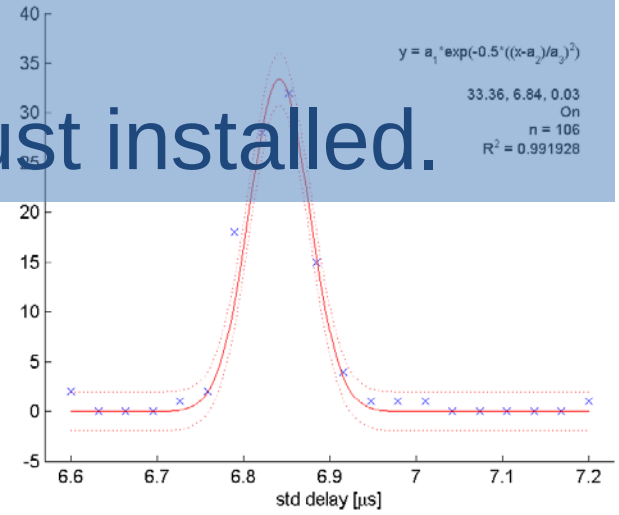




Jitter on the software trigger to big to measure the fast component.

Hardware timing just installed.





Summary CERF / CNRAD

- Positions inside CERF can be distinguished
- Data analysis to compute particle fluences is ongoing

- CNGS data taking up to now difficult due to lack of precise trigger
- Timing unit now installed → sparse data to be taken

Applications @ CERN

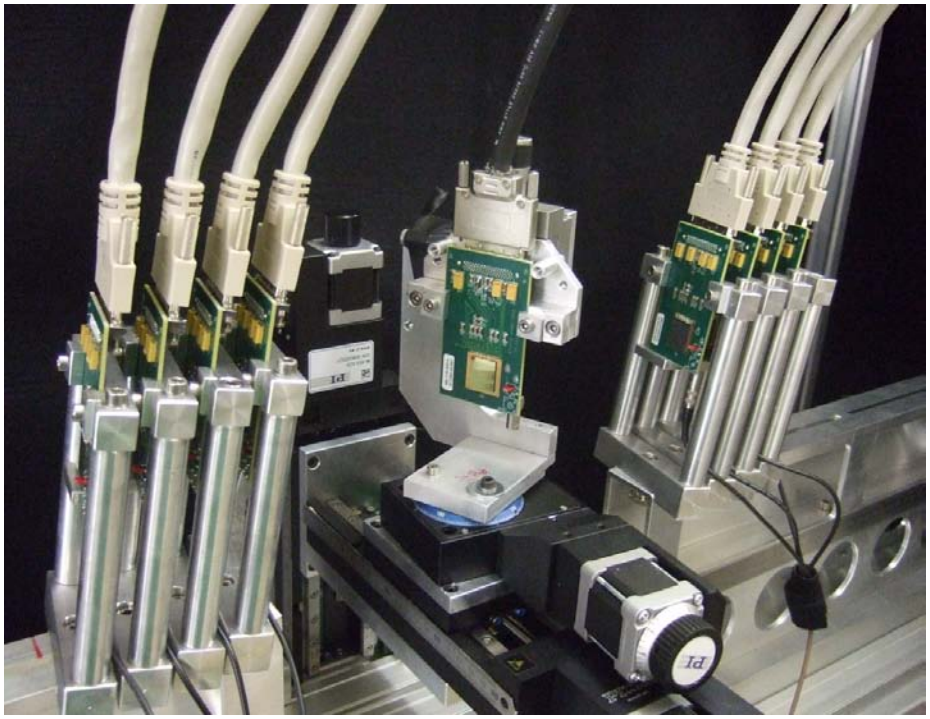
Timepix Telescope

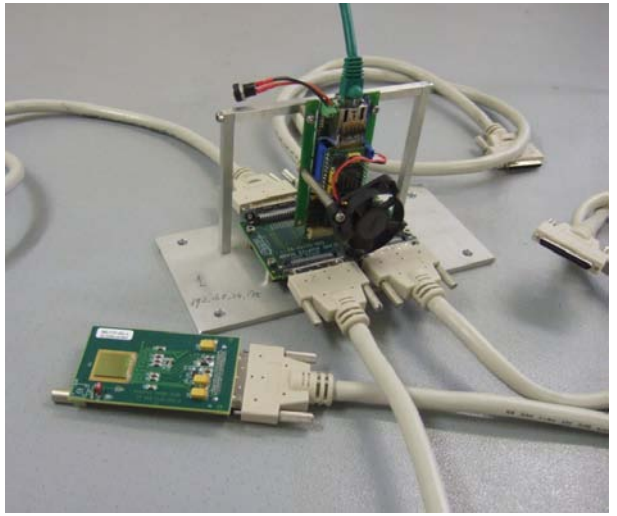
Timepix Telescope

Timepix 2010 August

- Track extrapolation error 1.7um
- Time resolution ~1ns
- Recorded track rate ~2.8kHz

Timepix2 as proof of concept for VELOpix

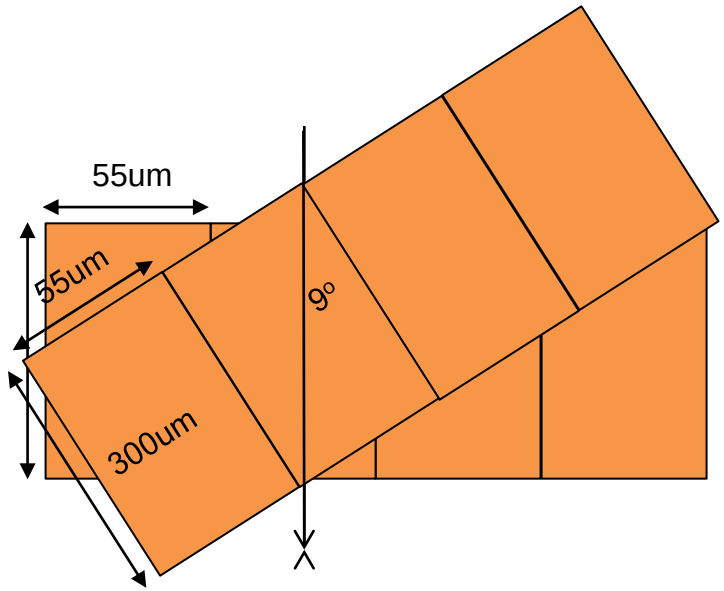


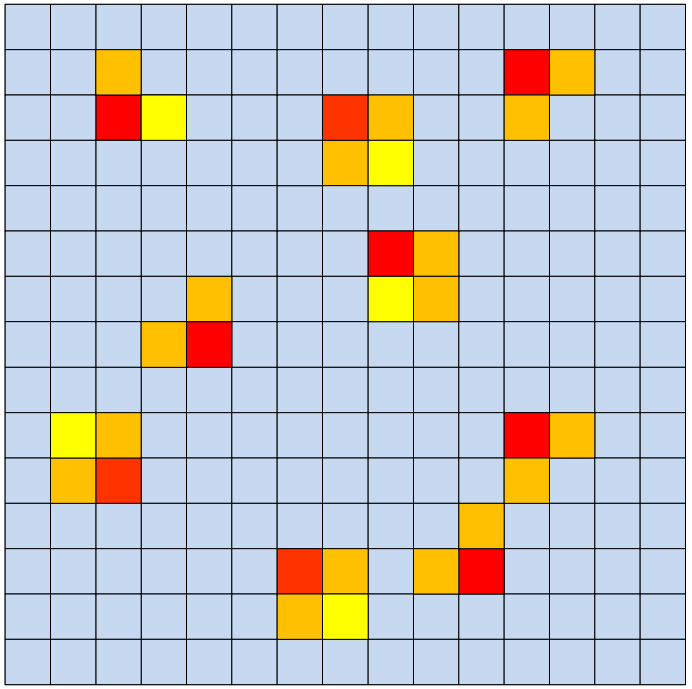


Angled Planes to Boost Resolution

Hits that only affect one pixel have limited resolution (30um region in 55um pixel)

Tilting the sensor means all tracks charge share and use the ToT information in centroid, CoG calculations



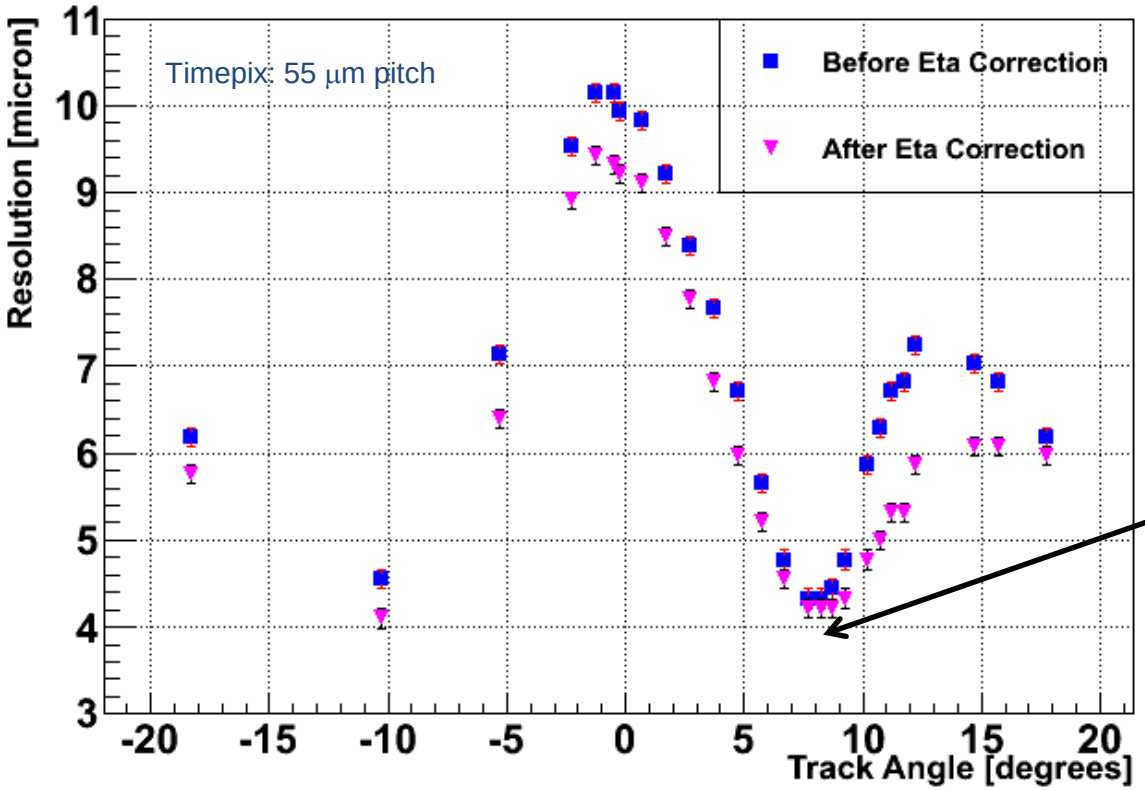


Indicative Timepix events

⊥ **~10 um resolution**

9º **~4.2 um resolution**

2009 Results – Resolution Vs Track Angle



Operating point of Telescope planes

Results from 2009 testbeam demonstrating resolution of a Timepix assembly and the performance of the telescope

Summary Timepix Telescope

- 8 plane telescope operational
- 1 device under test

- Can be borrowed
- Dedicated seminar planned

Outreach

Timepix/USB system used in high schools in

- Classroom experiments using radioactive sources
- Basic X-ray imaging
- Cosmic ray data

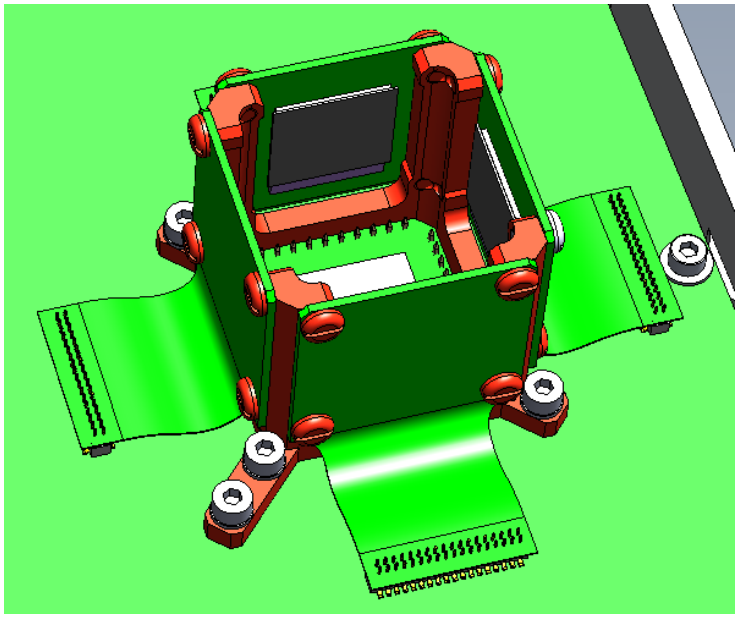
11 Pilot Schools

- Norton Knatchbull - Ashford
- Fort Pitt - Rochester
- Canterbury High – Canterbury
- Simon Langton Boys – Canterbury
- Cranbrook School – Cranbrook
- Dartford Girls - Dartford
- Dover Boys – Dover
- St Edmunds - Canterbury
- Oakwood Park – Maidstone
- Maidstone Girls' – Maidstone
- Bennett Memorial – Tunbridge Wells

LUCID

High school project entered the British National Space Centre, Surrey Satellite Technologies National Competition proposing a Timepix based detector. Result: Satellite launch in 2012

Latest development: Possibly LUCID detector flying round the Moon on the ESA European Student Moon Orbiter.



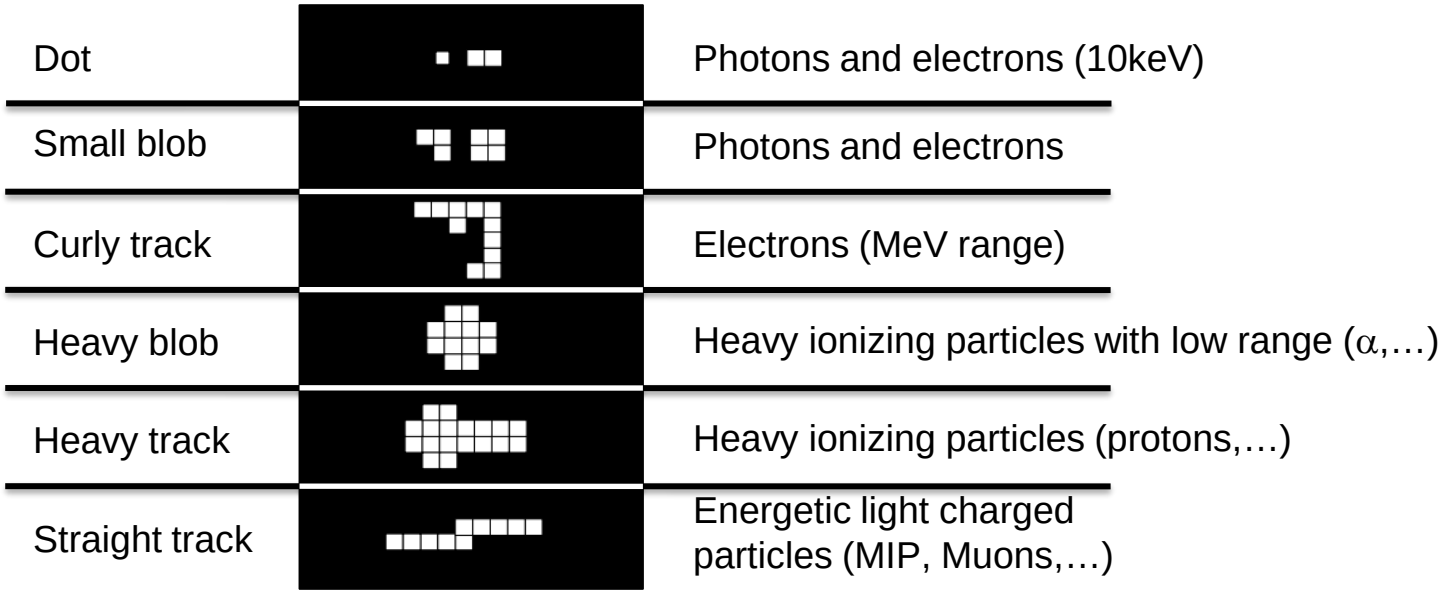
Summary

- Medipix designed for versatility (also due to the large size of the collaborations needed to fund the development)
- Successfully applied in a wide range of applications
- Collaboration with industry. Strong technical feedback. Increased critical mass of effort. Income from royalties.
- From spin off to imaging to spin back to HEP
- Excellent tool to evaluate new sensor materials
- Successfully applied as beam monitor for the channelled beam in UA9
- Monitoring of radiation background in Atlas and CMS
- Under evaluation as possible neutron pseudo spectrometer

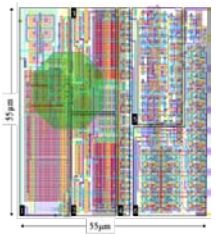
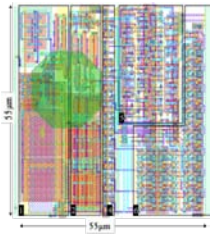
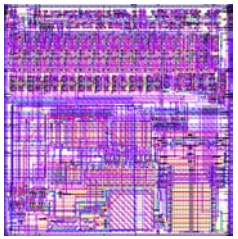
Thanks for your attention!

Detection efficiencies

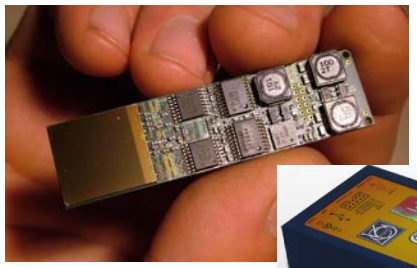
- Minimum threshold safely above noise floor: ~8 keV
- Charged particles (above 8 keV): 100%
- X-rays (10 keV): ~80%
- Gamma-rays (above 1 MeV): ~0.01%
- Thermal neutrons (energy < 1 eV): ~1%
- Fast neutrons (MeV range): ~0.5%



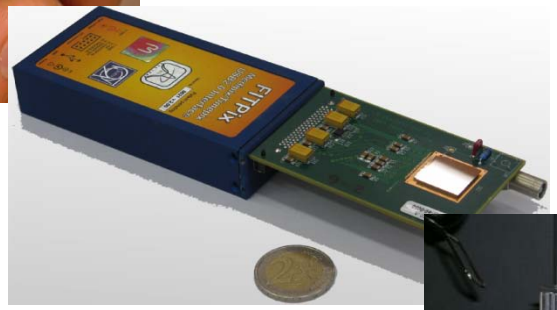
3 ROCs

	MEDIPIX2	Timepix	Medipix3
			
Technology	CMOS 0.25 μm	CMOS 0.25 μm	CMOS 0.13 μm
Matrix	256 x 256		
Pixel no.	65536		
Single chip active area [mm^2]	196		
Pixel density [mm^{-2}]	330		
Operation Mode	Counting	Counting	Counting / Charge Summing
		ToT	
		Timestamp	
Pixel size [um]	55	55	55 or 110
Tiled assembly sizes	1x5, 2x2, 3x2	1x5, 2x2, 3x2	none yet
Pixel noise ENC [e^-]	140	90	75 / 150
Threshold dispersion [e^-]	100	60	55 / 100
Minimum global threshold [e^-]	1000	650	1000
Counter depth	13	13	1, 2, 4, 8, 11, 22
No threshold	2	1	1, 2, 4, 8
Read-out scheme	synchronous	synchronous	synchronous
Read-out mode	full frame	full frame	full frame, ROI, continous RW
Read-out time	10 ms, 300 μs	10 ms, 300 μs	<10 ms
Frame rate [Hz]	100 / 10^3	100 / 10^3	100
Event rate/pixel [Hz]	~ 10^6	~ 10^6	~ 10^6
Poisson event rate [Hz/cm2]	~ 10^9	~ 10^9	~10^9 / ~10^8

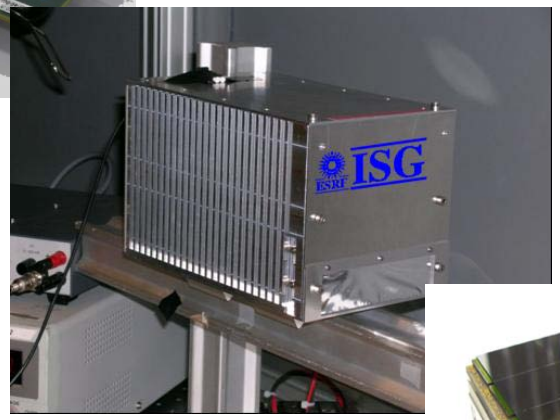
Readouts



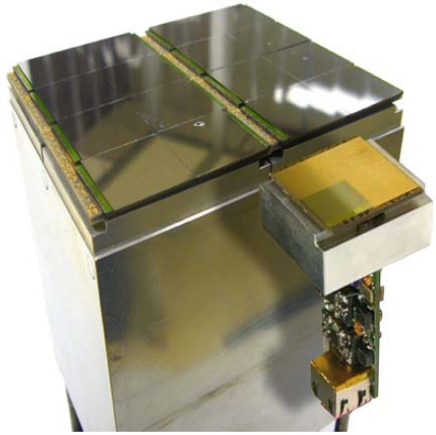
CTU/IEAP
USB1
~3 frames/s



CTU/IEAP
USB2
~100 frames/s



ESRF, 1x5 ladder
Parallel port
~1500 frames/s



NIKHEF RelaxD, tiles of 2x2 assemblies
~100 frames/s