Development of a New Active Dosimeter for Use in Space Radiation Environment And *For Characterizing Accelerator Beams*

Lawrence Pinsky, Dilan Minthaka & Jeff Chancellor

Physics Department

University of Houston

Important Disclaimers

- **Note that many of the properties regarding the design and performance of the MEDIPIX technology are Propriatary and are to be considered CONFIDENTIAL to the extent that subsequent patent applications may be submitted. However, the information regarding the Medipix2 technology disclosed in this talk and the accompanying paper are not generally confidential.**
- **The University of Houston is presently a member of the Medipix Consortium, and we have been formally invited by that Collaboration to join for the purpose of pursuing the adaptation of this technology to Space Radiation Dosimetry…**
- **This talk is about the potential to adapt and employ this technology as the basis for an active space radiation dosimeter, and is an update on the talk given at the 2007 IEEE Aerospace Conference…**

The Medipix2 Consortium

- Institut de Fisca d'Altes Energies, Barcelona, Spain
- University of Cagliari and INFN Section thereof, Italy
- CEA, Paris, France
- CERN, Geneva, Switzerland,
- Universitat Freiburg, Freiburg, Germany,
- University of Glasgow, Scotland
- Universita' di Napoli and INFN Section thereof, Italy
- NIKHEF, Amsterdam, The Netherlands
- University of Pisa and INFN Section thereof, Italy
- University of Auvergne, Clermont Ferrand, France,
- Laboratory of Molecular Biology, Cambridge England
- Mitthogskolan, Sundsvall, Sweden,
- Czech Technical University, Prague, Czech Republic
- ESRF, Grenoble, France
- Academy of Sciences of the Czech Republic, Prague
- Universität Erlangen-Nurnberg, Erlangen, Germany
- University of California-SSL, Berkeley, USA
- University of Houston, Houston, Texas USA

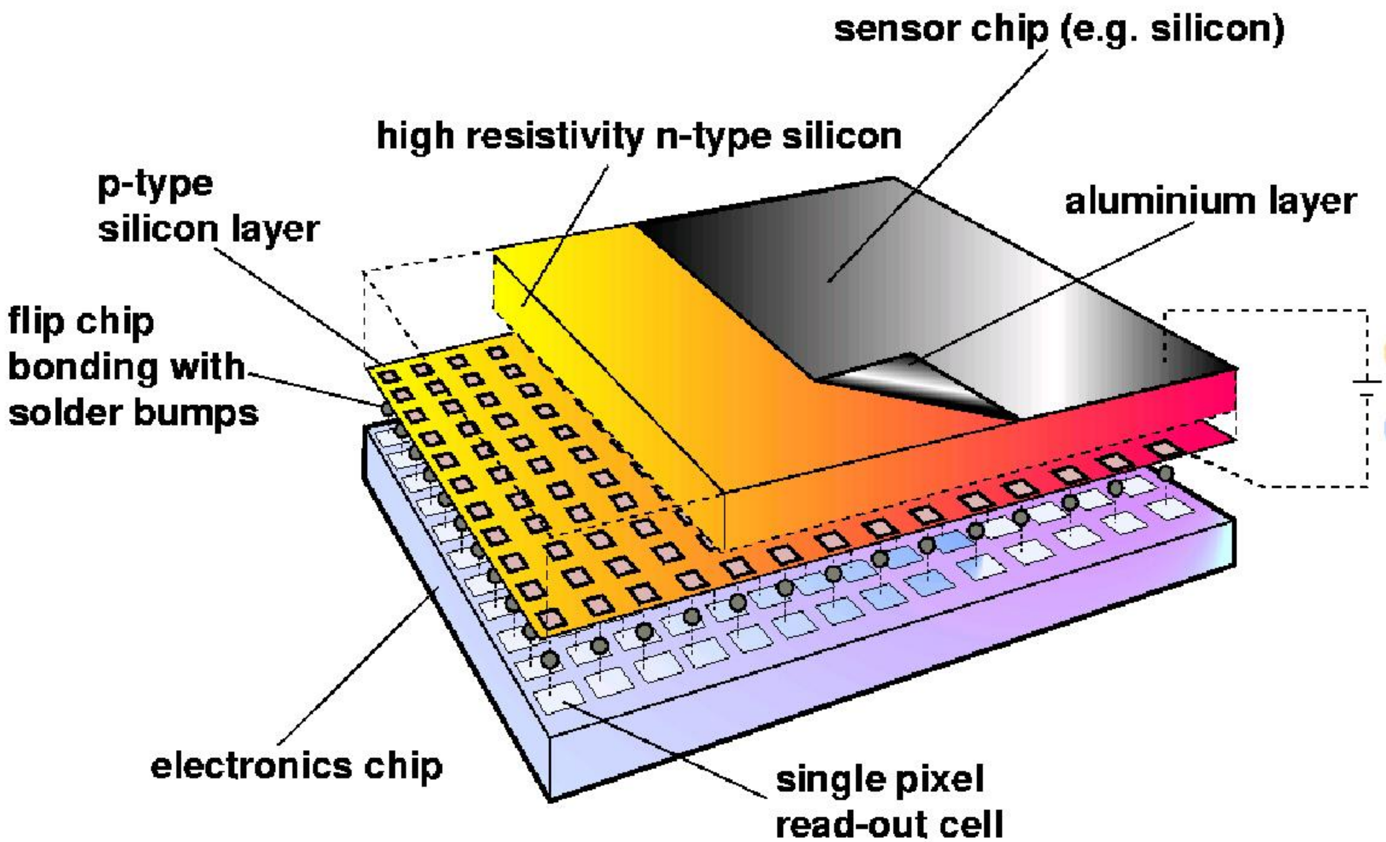
WHAT IS MEDIPIX2 DETECTOR?

Medipix2 is a pixel-based detector technology that can be employed to measure charged particles, photons (IR through gammas), and neutrons. It is based on a read-out chip that embeds the electronics for each pixel within the pixel's footprint!

Outline of This Talk

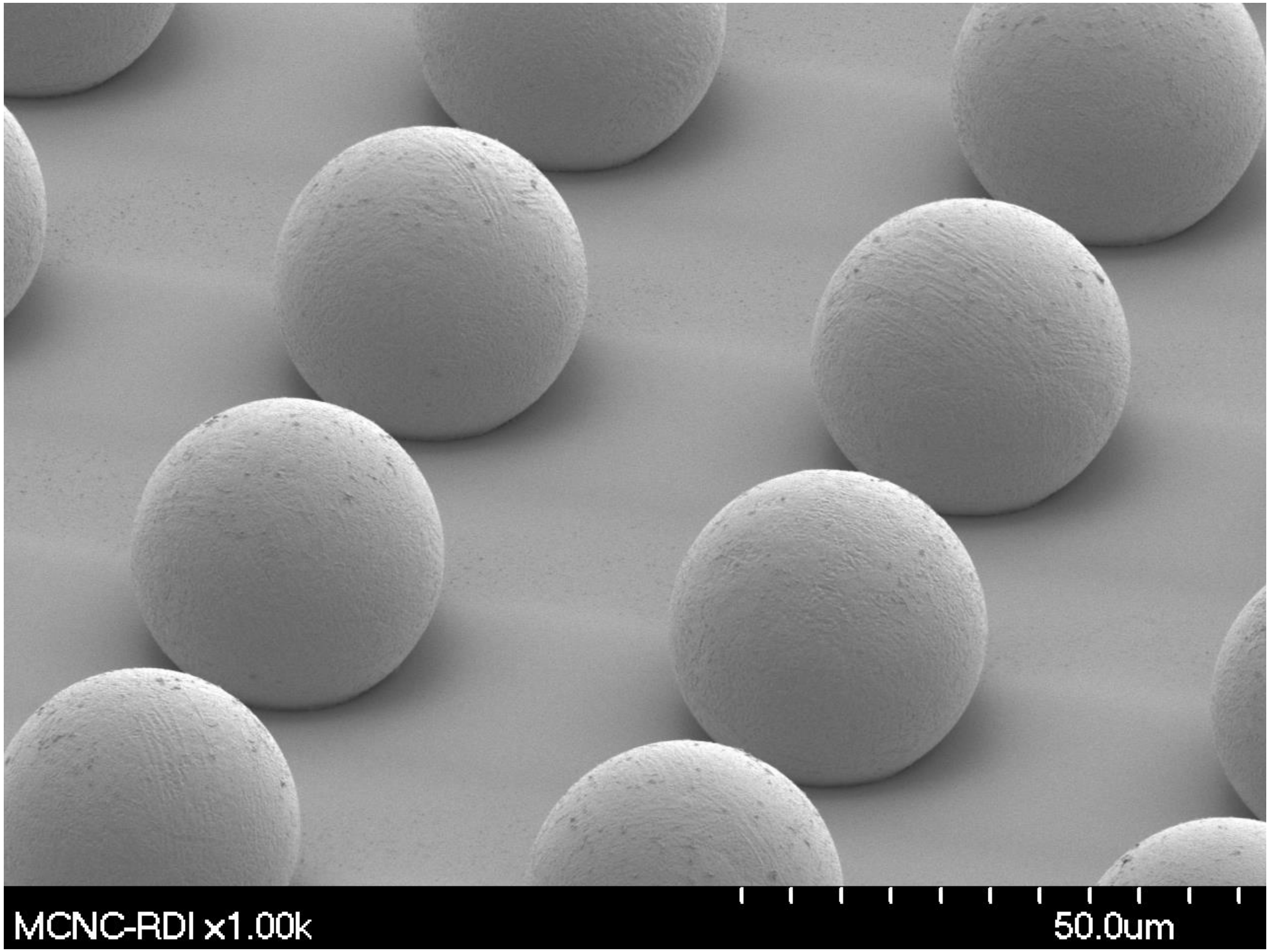
- **The Medipix2 Chip and TimePix Readout System…**
- **Recent Heavy Ion Beam TimePix Exposures…**
- **Recent High Intensity Exposures in Cancer Therapy Beams**
- **Where Do We Go From Here With Medipix…**
- **A Review of Dosimeter Philosophies**
- **Check the Demo…**

Hybrid Pixel Detector

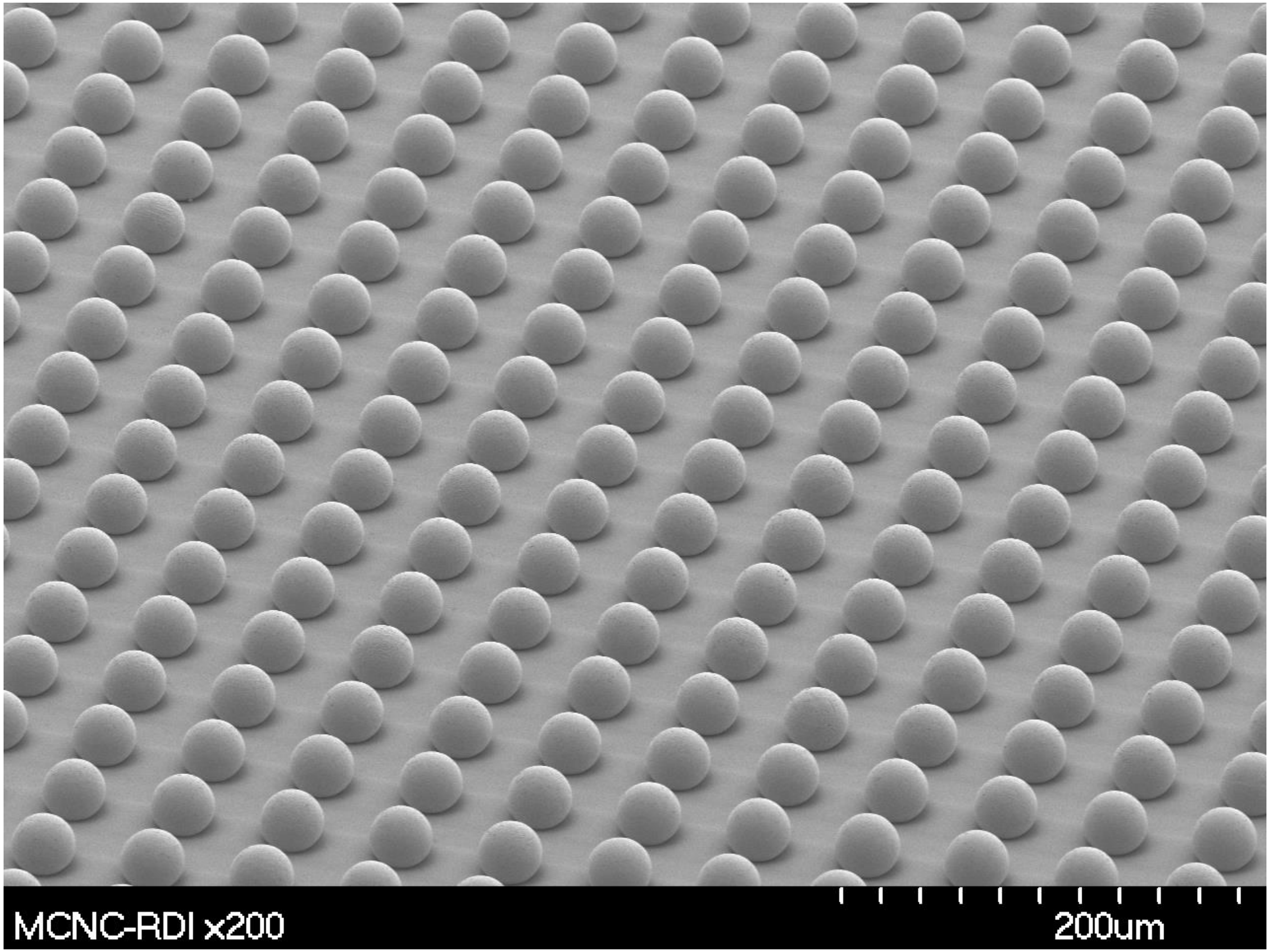


Detector and electronics readout are optimized separately

Bumps on the readout side – close up



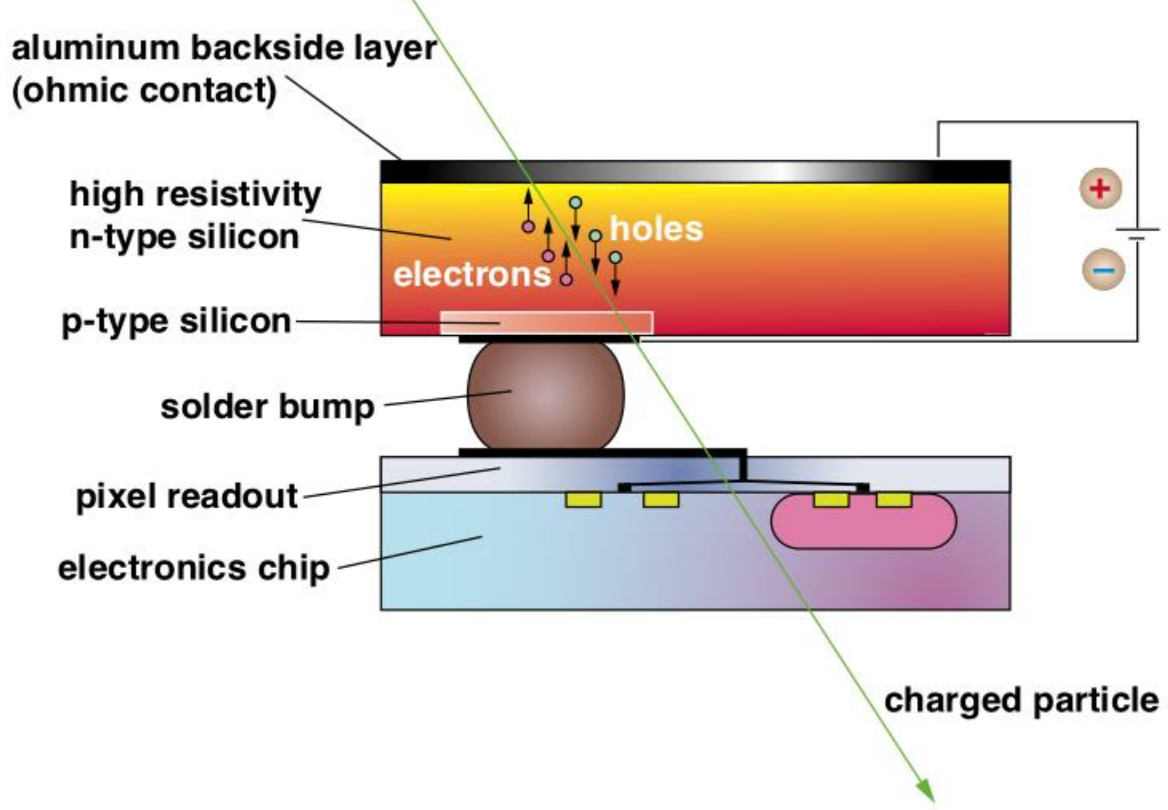
Bumps on the readout side



Hybrid Pixel Detector - Cross Section

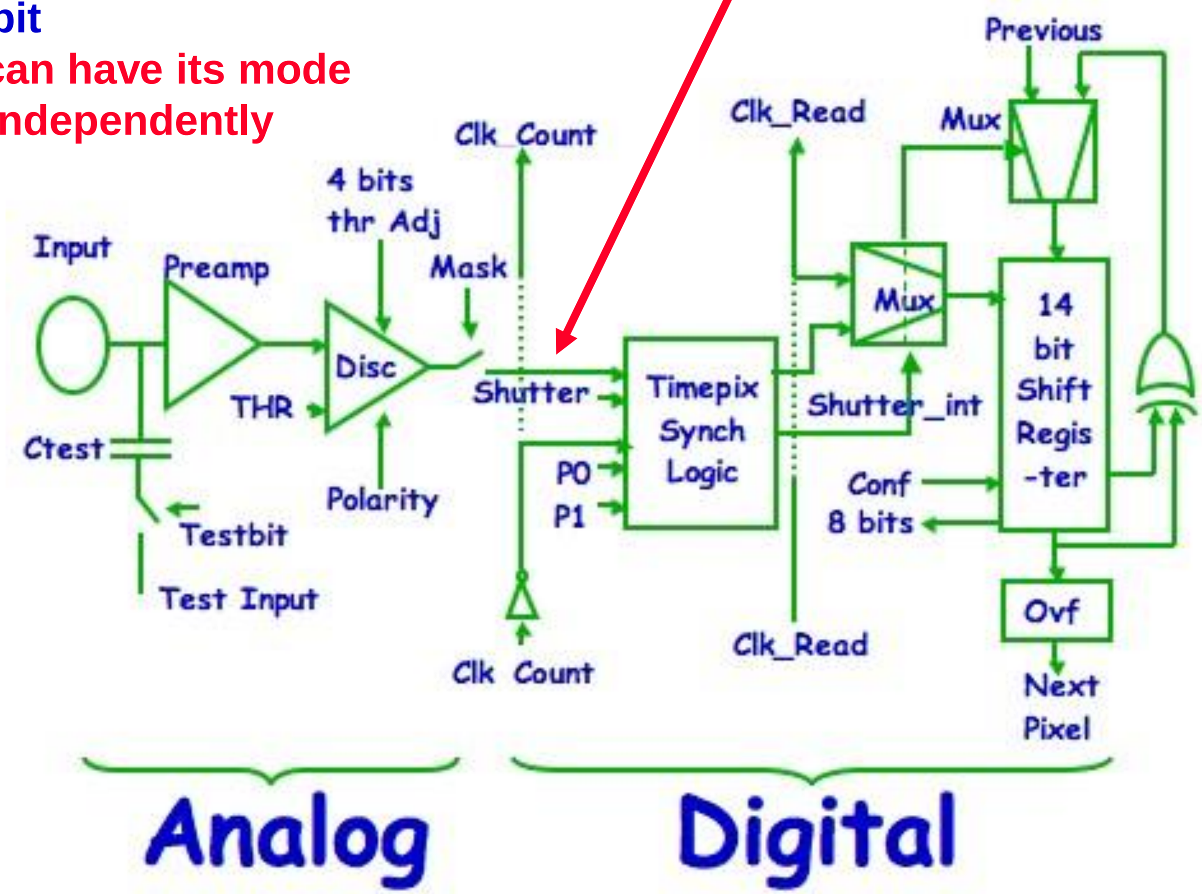
UH is currently working on direct epitaxial deposition techniques that will allow *the direct deposition of the detector layer onto the electronic chip wafer…*

This will allow the facilitate of high efficiency Embedded-Neutron-Converter detectors

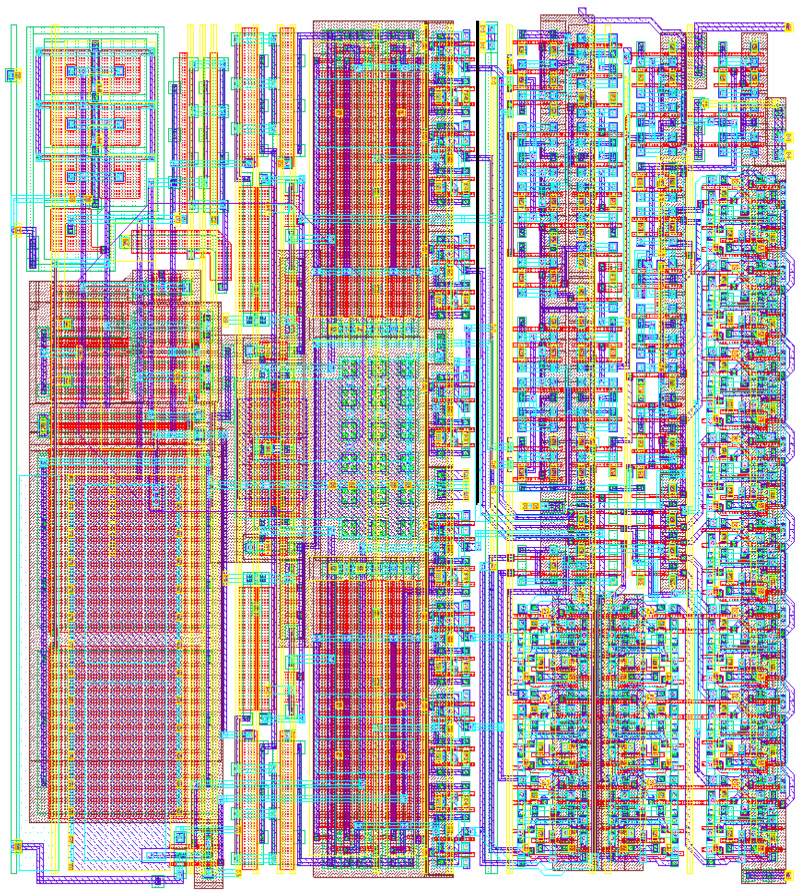


TimePix Cell Schematic

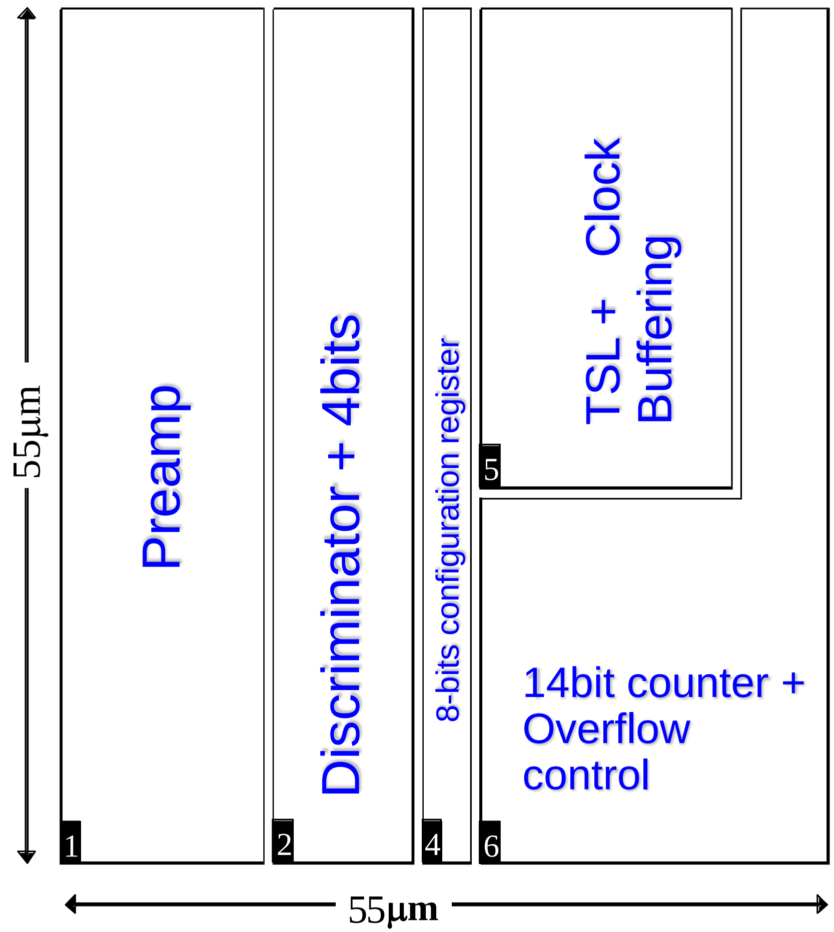
- Charge sensitive Preamp/Shaper w/ individual leakage current compensation
- Discriminator with globally adjustable thresholds & individual 4-bit fine tuning offset
- Individually settable test and mask bits for each pixel
- External shutter activates the counter (can be set as short as 10 ns)
- 14-bit output register (11,810 decimal)
- 1 Overflow bit
- Each pixel can have its mode set independently



Timepix Chip Layout



Mpix2MXR20 “TimePix” layout

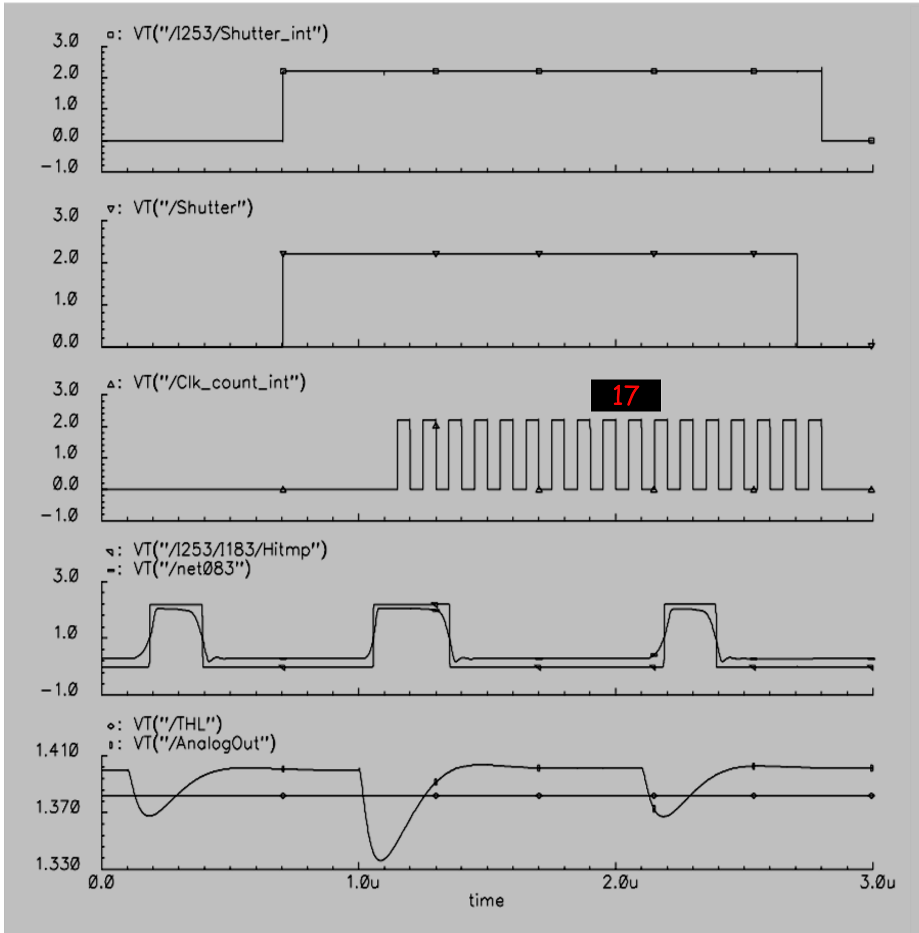


Timepix “Floorplan”

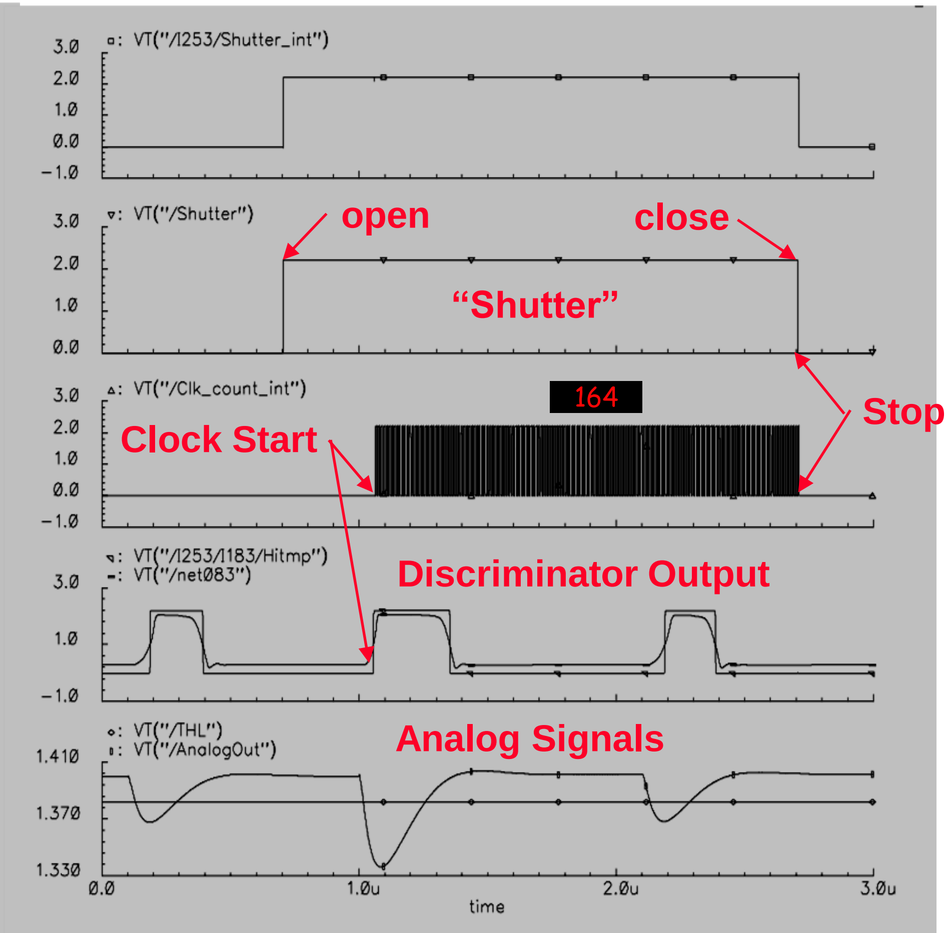
TimePix Modes

- **Time-Over-Threshold (TOT) >>> "ADC" Mode**
  - **During Shutter Open, Counter Clock pulses are added to Output Register while shaped input pulse exceeds Threshold value.**
- **TimePix >>> "TDC" Mode**
  - **During Shutter Open, Counter Clock pulses are added to Output Register starting when shaped input pulse first exceeds Threshold value.**
- **Medipix >>> "Hit" Counter Mode**
  - **While the Shutter is Open, the Output Register is Incremented every time the shaped input pulse leading edge crosses the Threshold value.**

Timepix ("TDC") Mode (P0=1,P1=1)

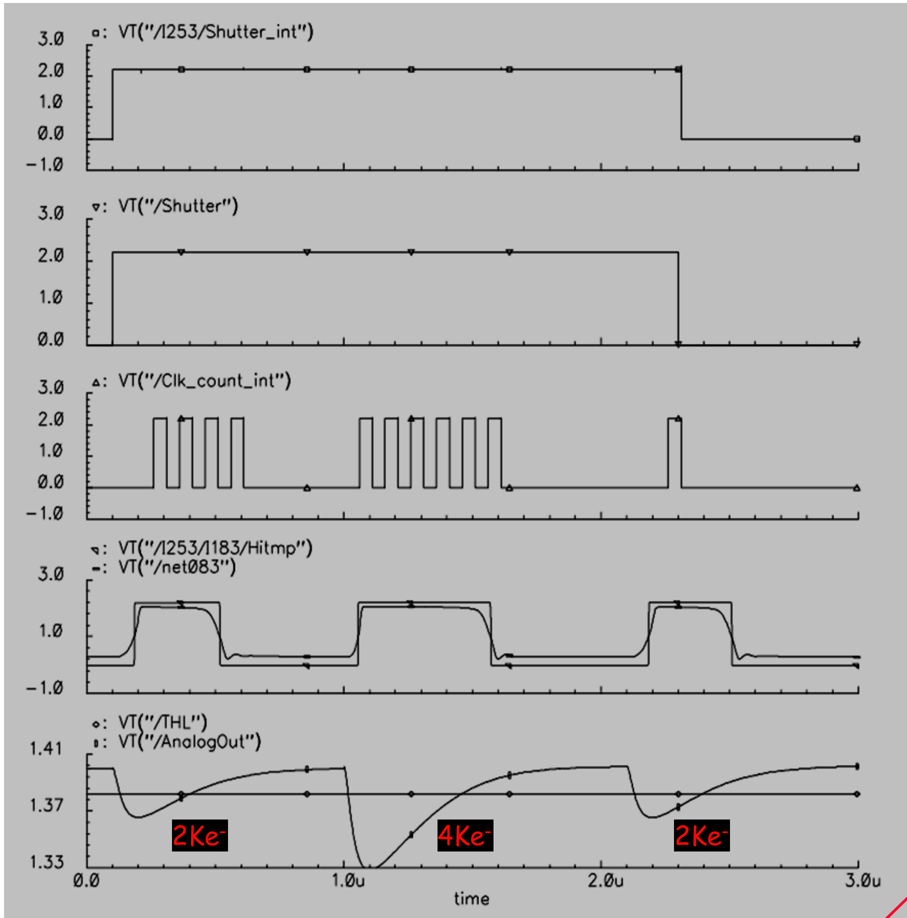


10MHz

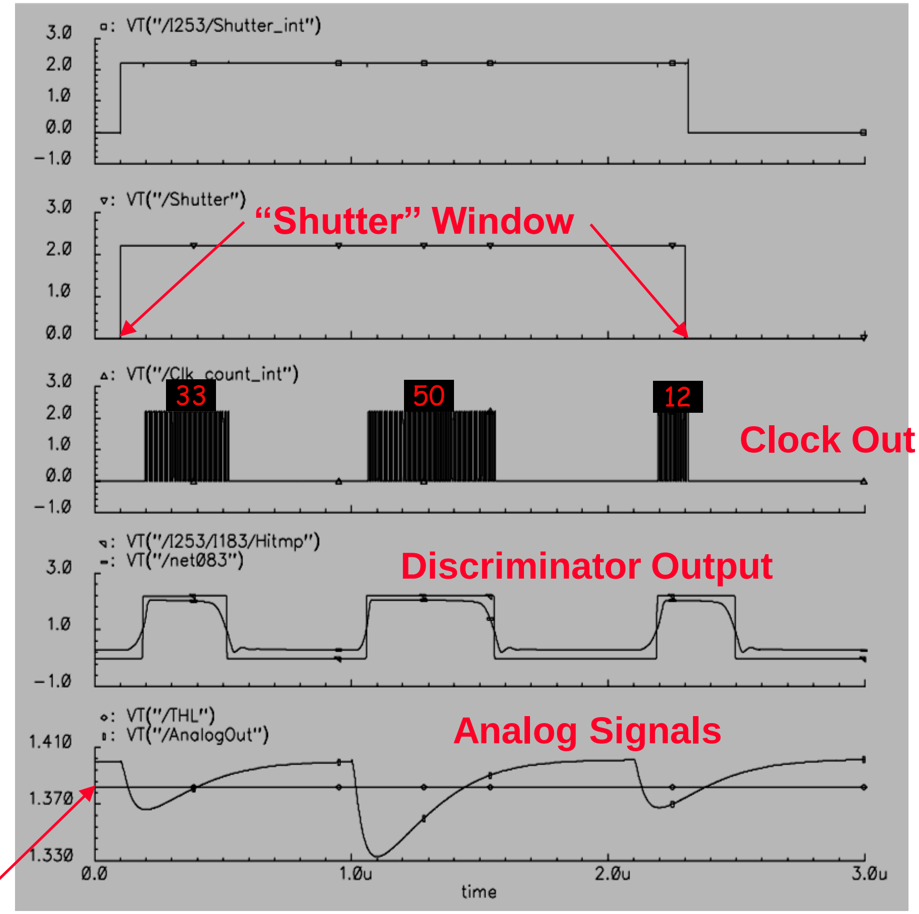


100MHz

Time-Over-Threshold ("ADC") Mode (P0=1,P1=0)



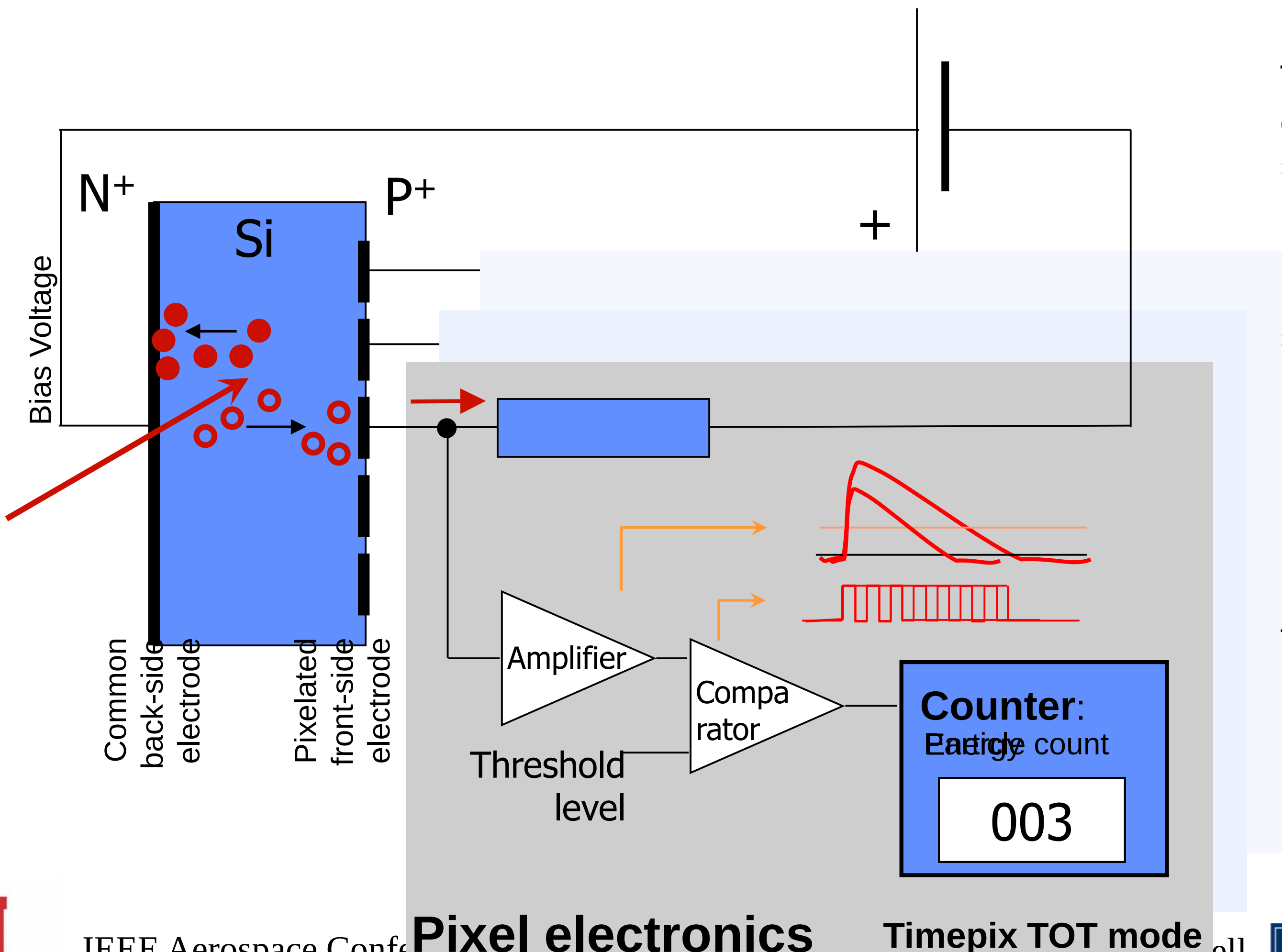
10MHz



Threshold

100MHz

TimePix TOT (ADC) Mode with Silicon Detector Layer



Threshold level above electronic noise
⇒No false counting.

Digital integration (counting)
⇒ No dark current.

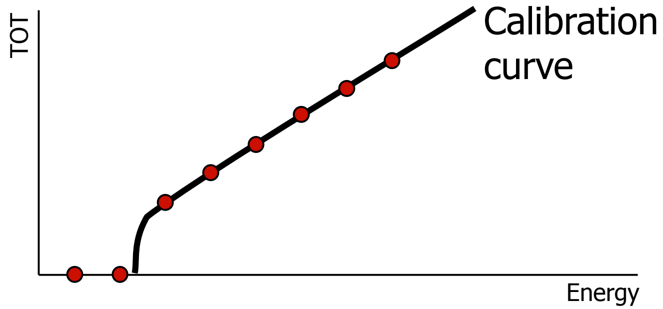
Unlimited dynamic range and exposure time.

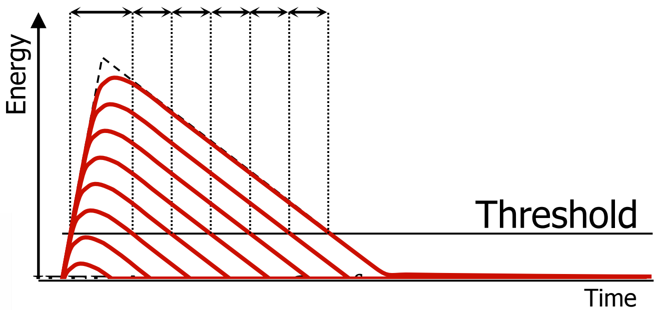
Detected count obeys poissonian distribution

TimePix and its TOT mode

Counter in each pixel can be used as

- **Timer** to measure detection time => TOF experiments, TPC detectors, …
- Wilkinson type **ADC** to measure energy of each particle detected.





- **If the pulse shape is triangular then Time over Threshold is proportional to collected charge i.e. to energy.**
- **Due to limited bandwidth the pulse can be NEVER perfectly triangular.**
- **Non-linear TOT to energy dependence**

Slides Courtesy of Michael Campbell, Stanislav Posposil & Jan Jakubek

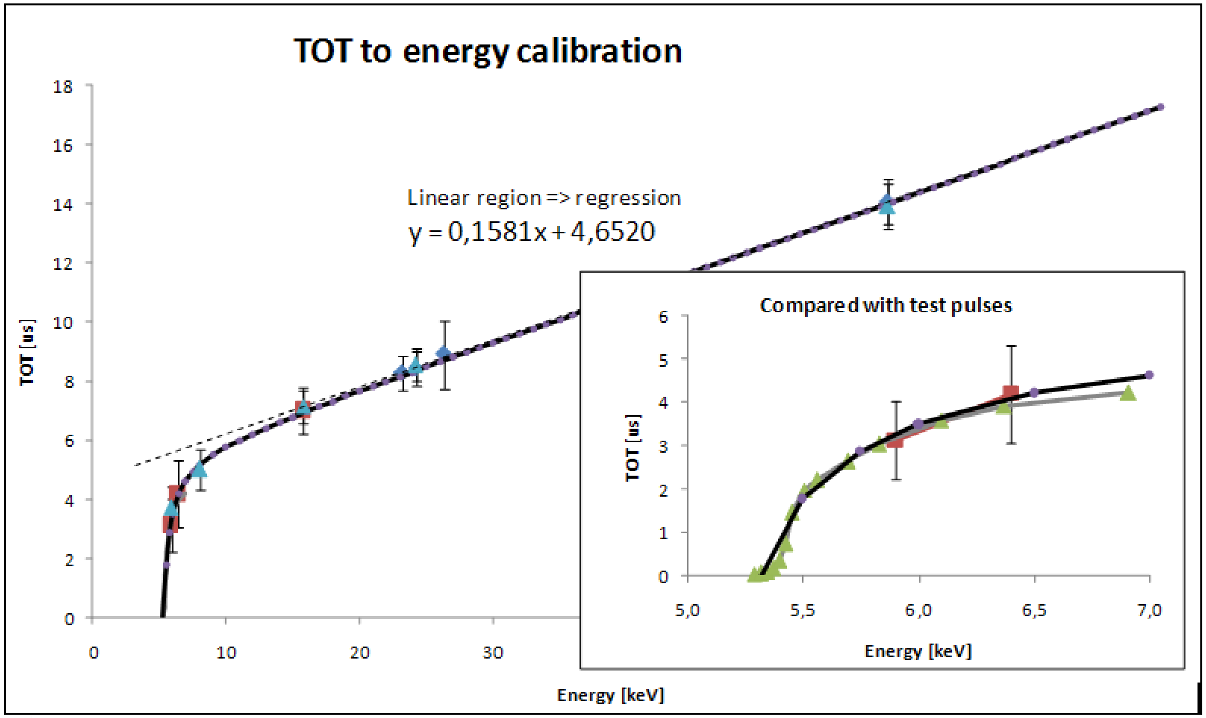
Jan Jakůbek

TOT mode calibration:
Surrogate calibration function

$$f(x) = ax + b - \frac{c}{(x-t)^d}$$

Meaning of parameters:

a,b – linear regression in high energy range
c,d – curvature (extent and symmetry)
t – threshold



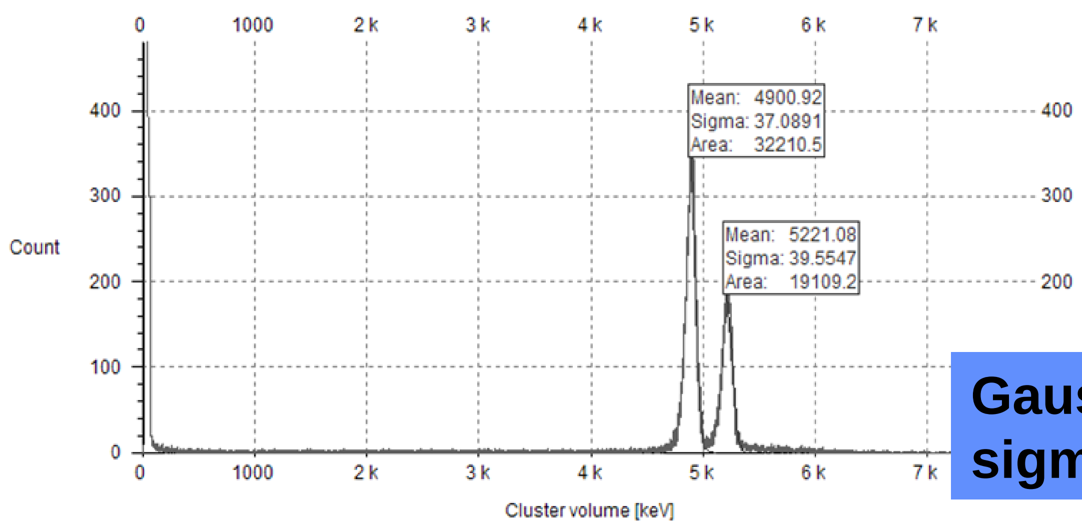
Parameters computed Using global calibration data:

a=0.158
b=4.65
c=2.4
d=1
t=4.86

Stopping Heavy Charged Particles
Total Energy Resolution

- Am241+ Pu239 combined source
- 5.2 and 5.5 MeV alphas
- "Heavy" calibration extrapolation

Cluster volume (energy) spectrum (measured in air)



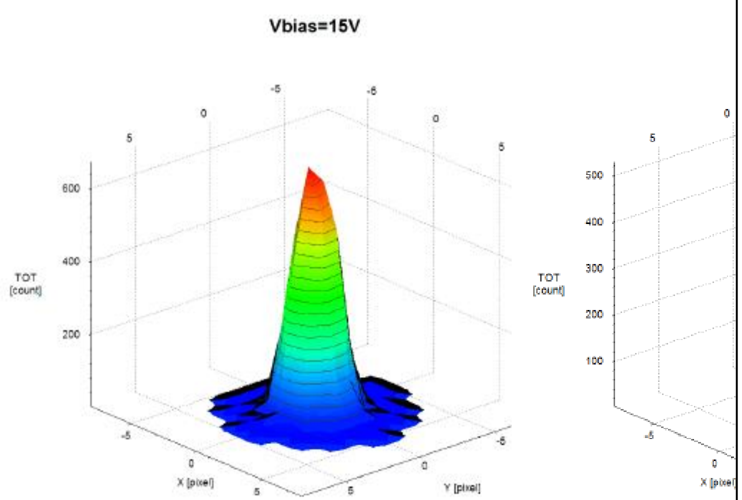
0.67%

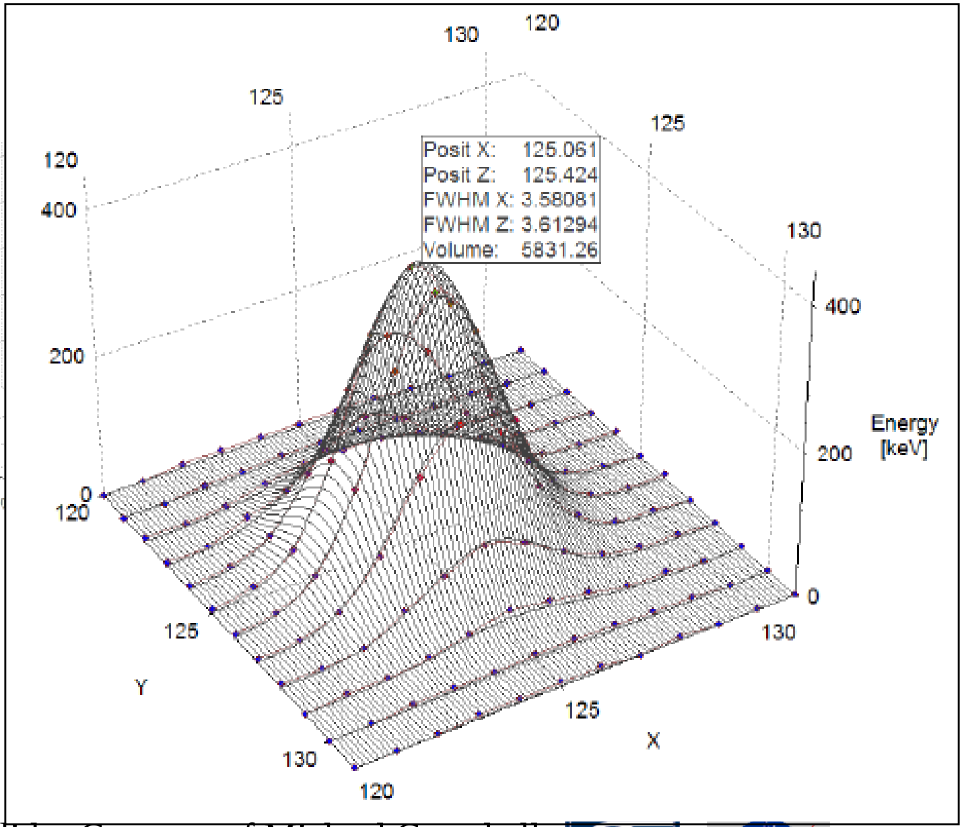
Gaussian fit sigma = 37 keV

First results with TimePix:

Subpixel resolution

- Cluster shape depends on detector bias voltage.
- Gaussian shape for low bias voltages (diffusion dominates)



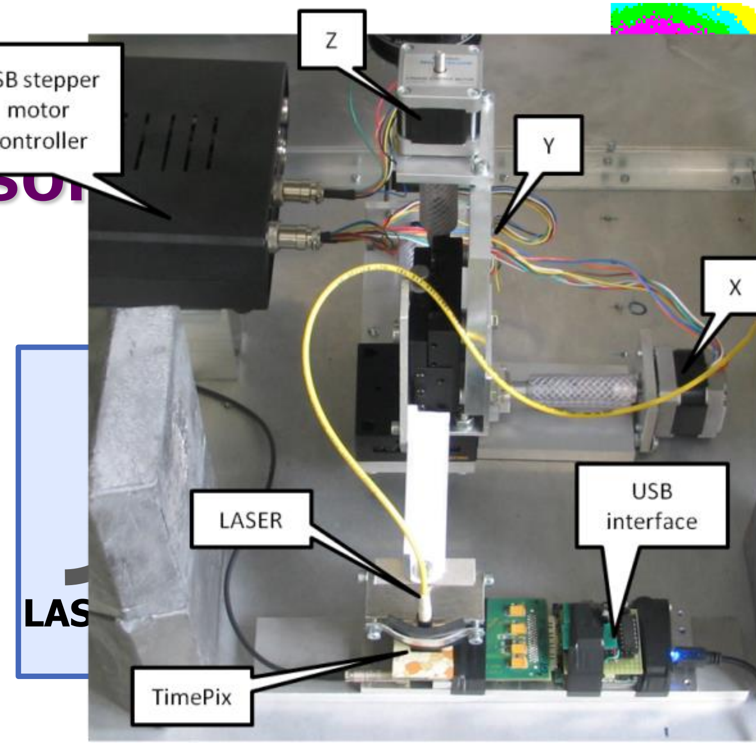


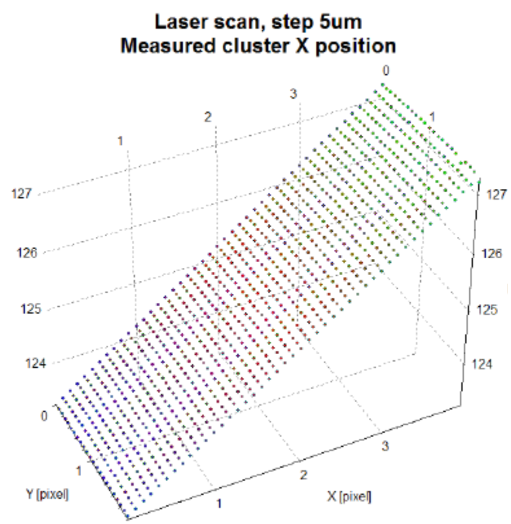
=> Subpixel resolution can be reached by Gaussian fit.

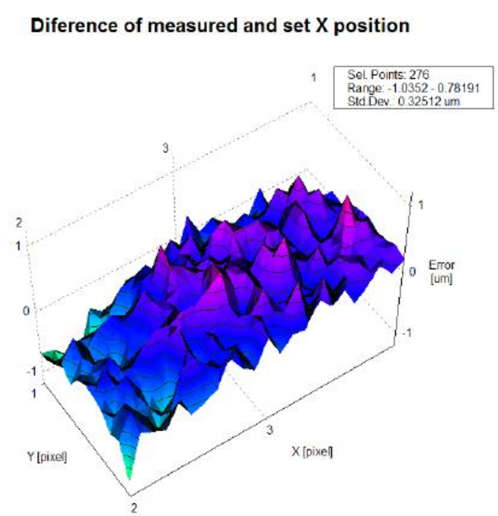
Spatial resolution

Subpixel reso

- Alpha particles simulated by red LASER pulses
- Laser spot positioned with 1um accuracy
- Area of 3 x 2 pixels scanned with step of 1.25 um. Just single shot evaluated in each position.







Standard deviation of position determined by fit is **0.32 μm**

$\Rightarrow$ Each pixel can be divided to 100 x 100 subpixels

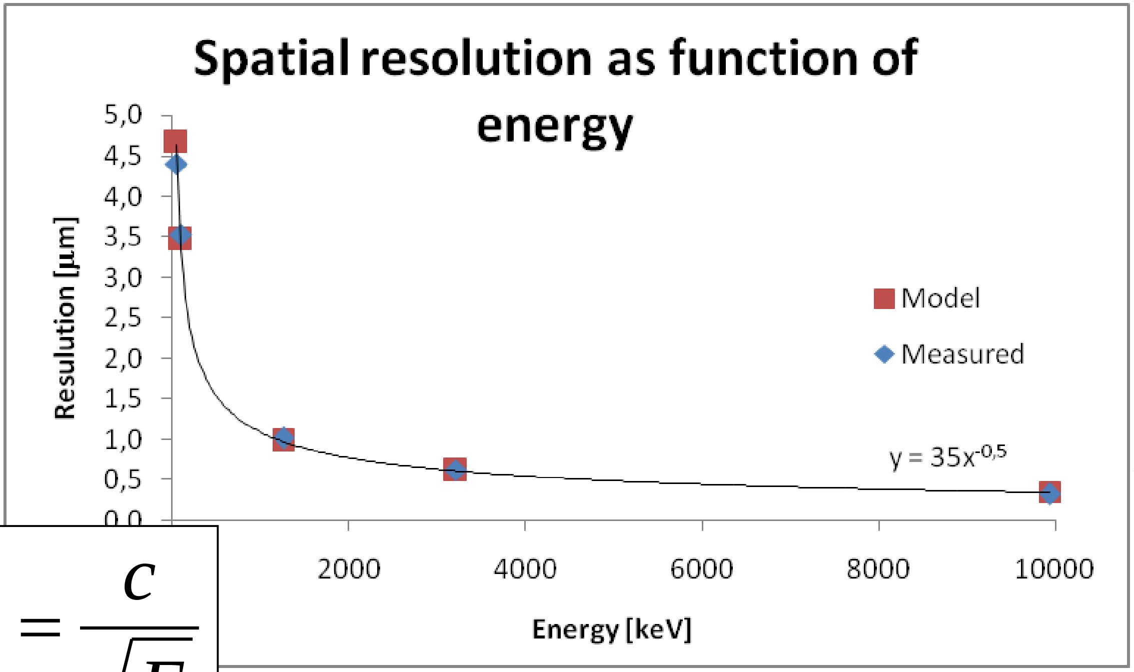
$\Rightarrow$ **655 Megapixels!**

If center of gravity is used then Std.Dev. is **0.63 μm**.

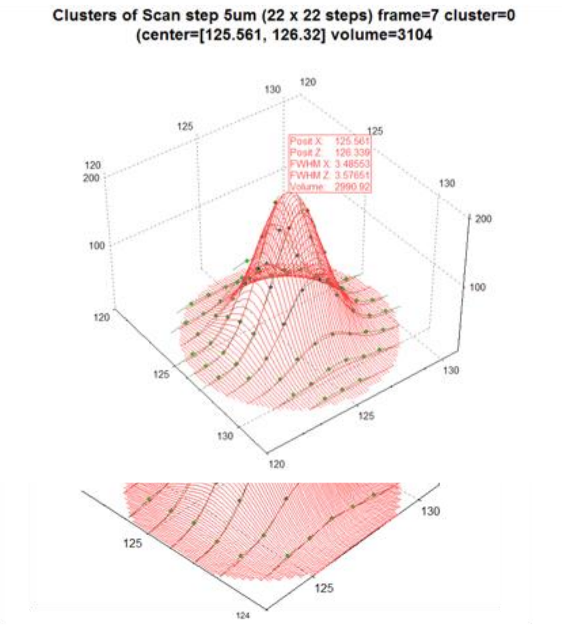
Spatial resolution determination:

Spatial resolution as a function of energy

- LASER test performed for different equivalent energies of 50keV, 120keV, 1.2MeV, 3.2MeV and 9.9MeV

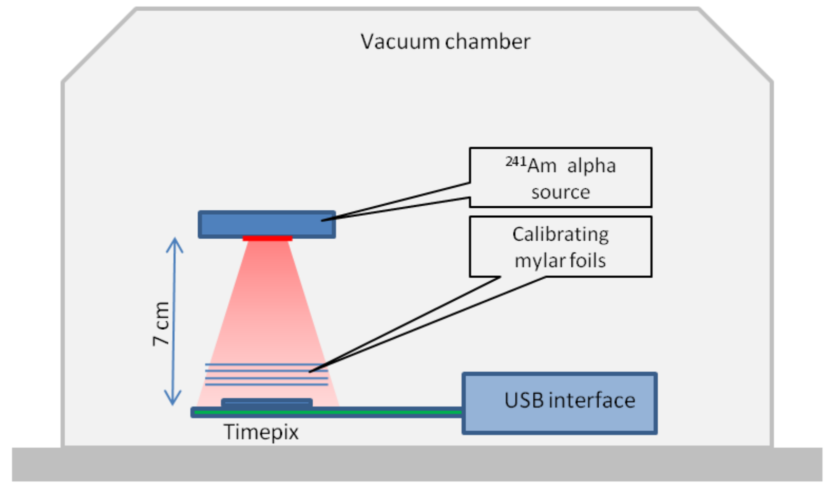


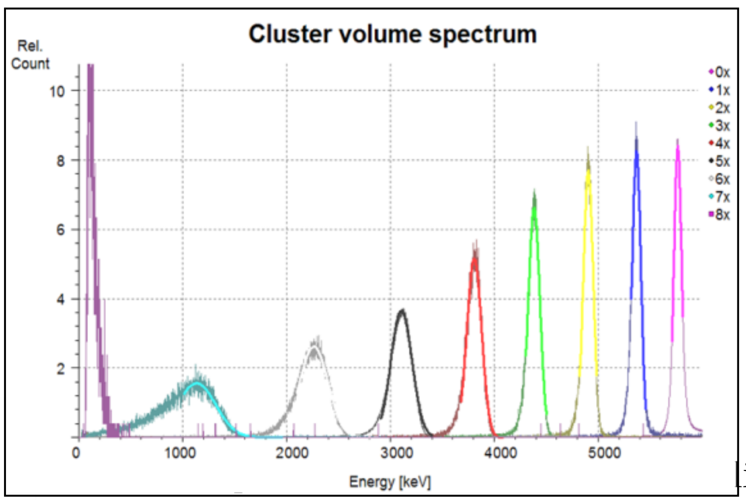
$$r = \frac{c}{\sqrt{E}}$$

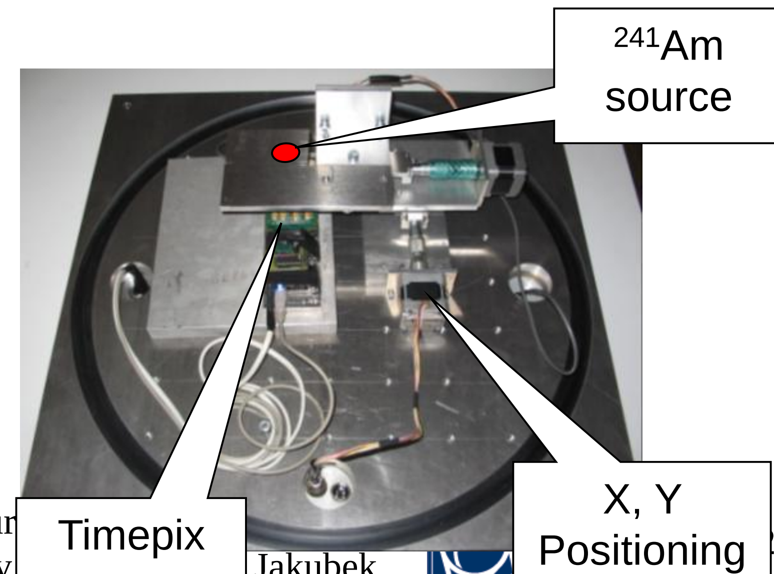


Radiography with heavy charged particles:
Example with TimePix

- ^{241}Am alpha source used
- Set of Mylar foils used to attenuate energy
- Measurement performed in vacuum



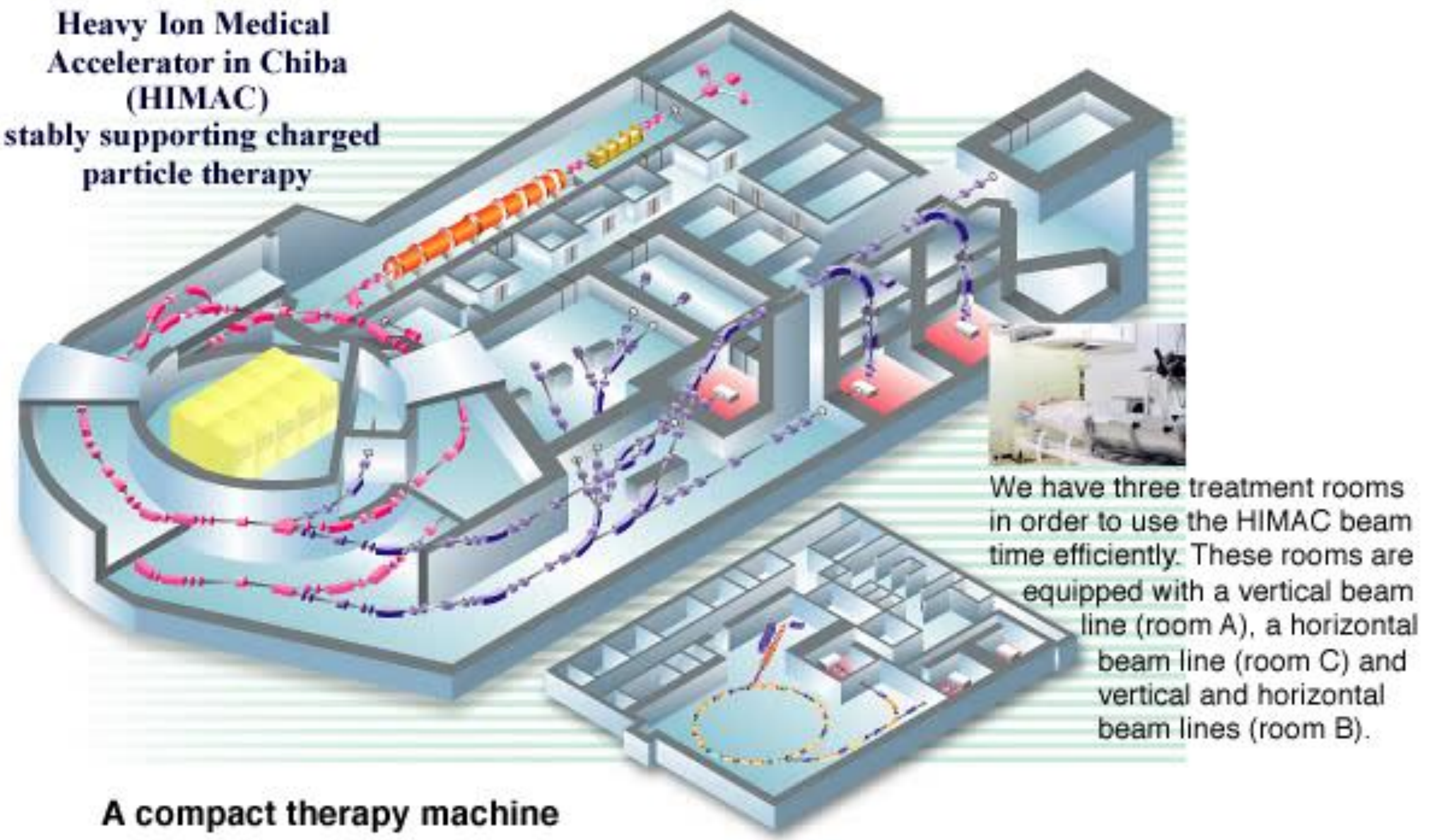




HIMAC @ NIRS in Japan

- HIMAC - (Heavy Ion Medical Accelerator Center) @ NIRS (National Institute for Radiological Sciences) in Chiba, Japan.
- Primarily a Cancer Therapy Center, but they give us free beam time

HIMAC Layout

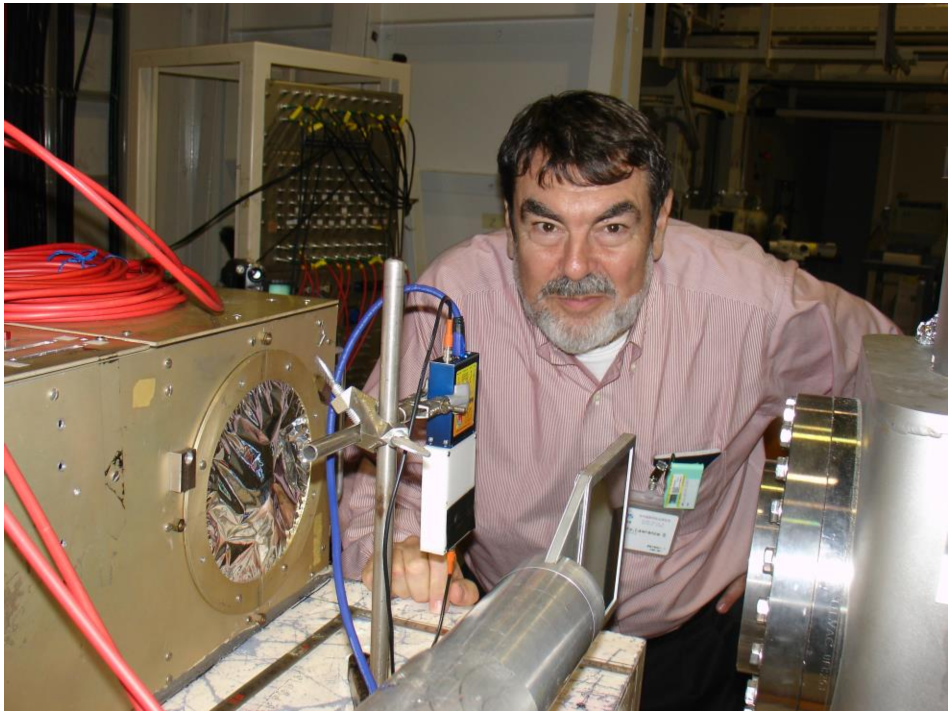


A compact therapy machine

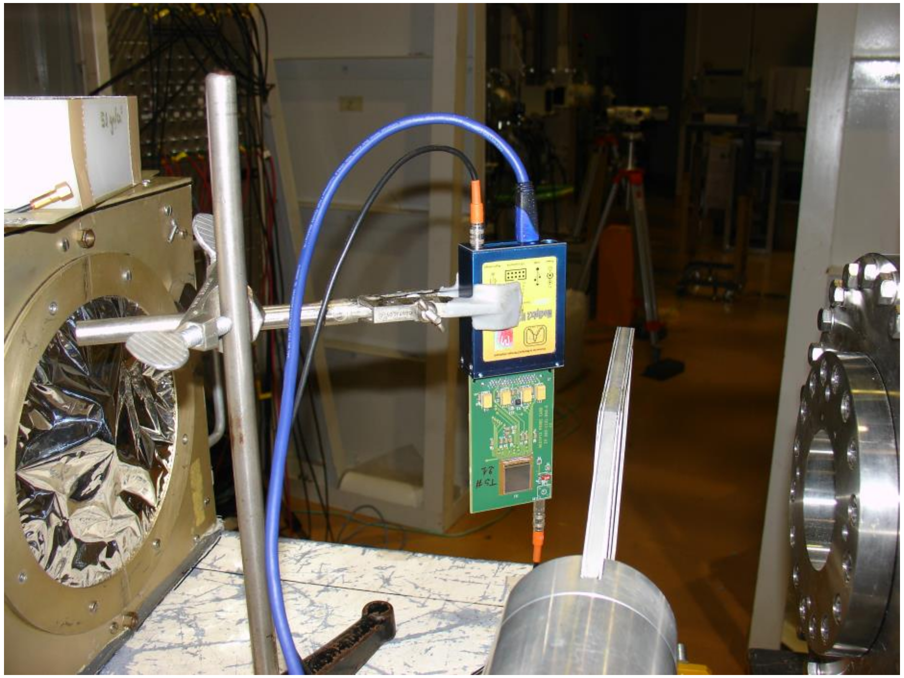
The NIRS completed research and development on a compact carbon therapy machine in FY 2005. Gunma University has adopted our proposal and will start construction of a new therapy facility in FY 2006. The NIRS is giving technical support to this project at Gunma University.

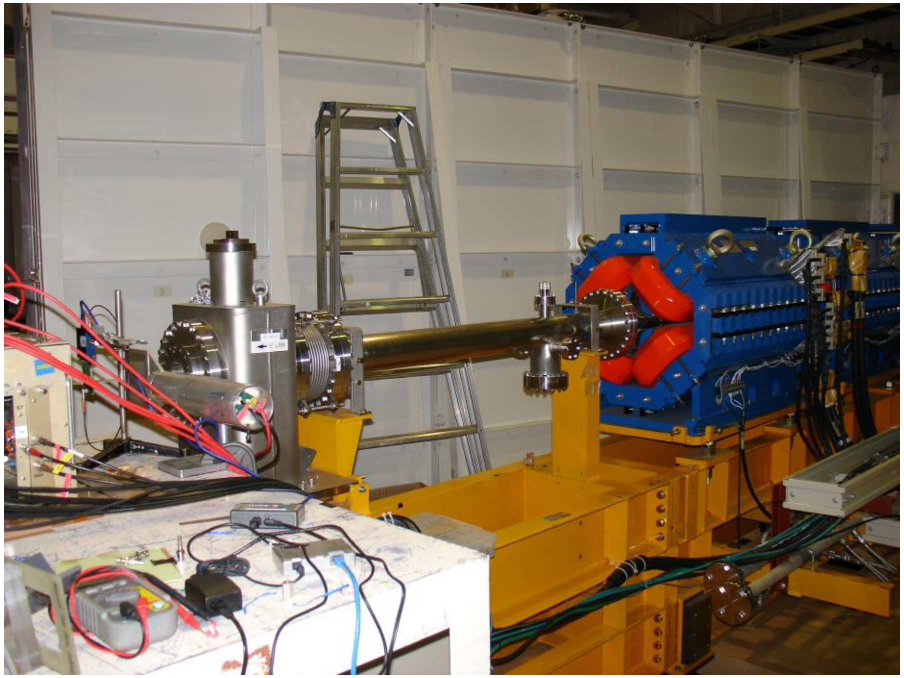
TimePix in the HIMAC ^{10}B & ^{11}B Beams

- Data were taken in both ^{10}B & ^{11}B beams @ 290 MeV/nuc…
- @ Incident angles of 0°, 15°, 30°, 45°, 60°& 90°
- …With TimePix clocks of 20, 40, and 80 MHz.
- …& with IKRUM's of 5, 10, 15 & 20 for Bias Voltages of 50, 75 and 100V…

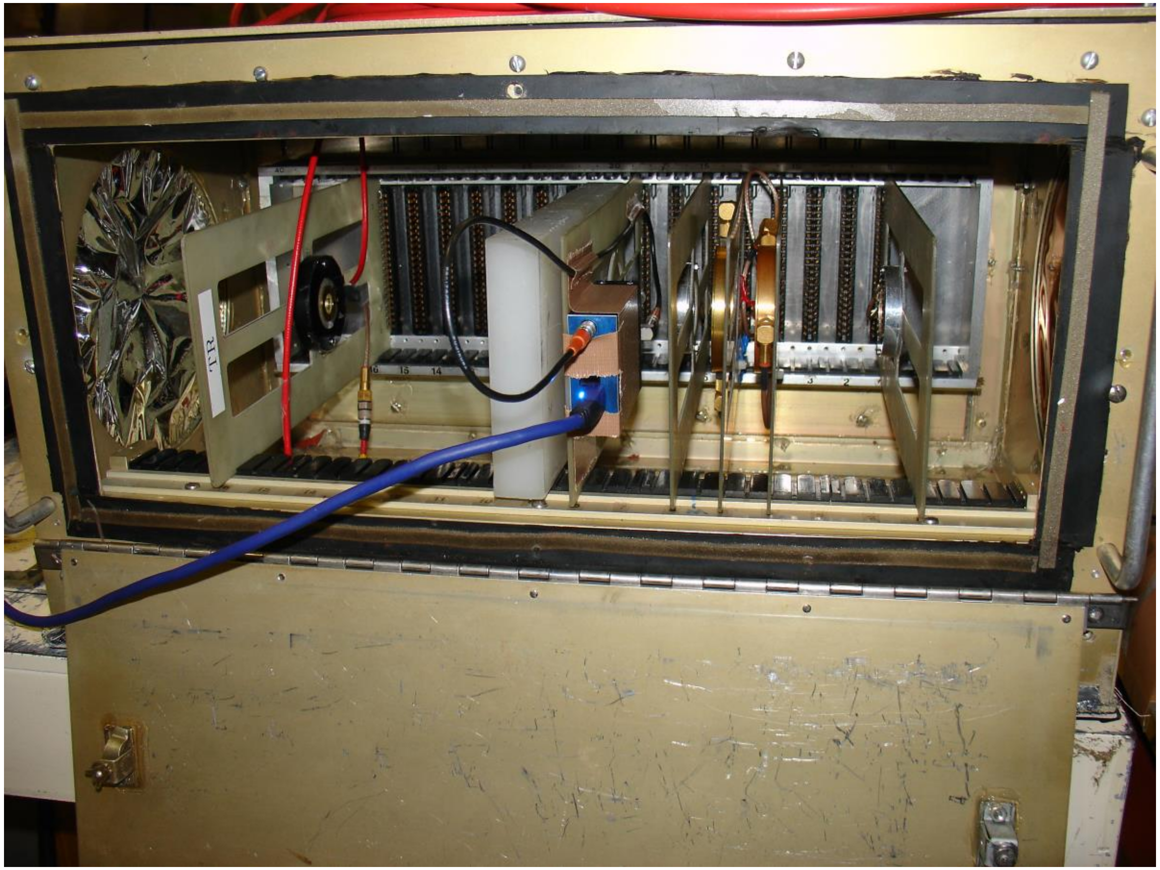


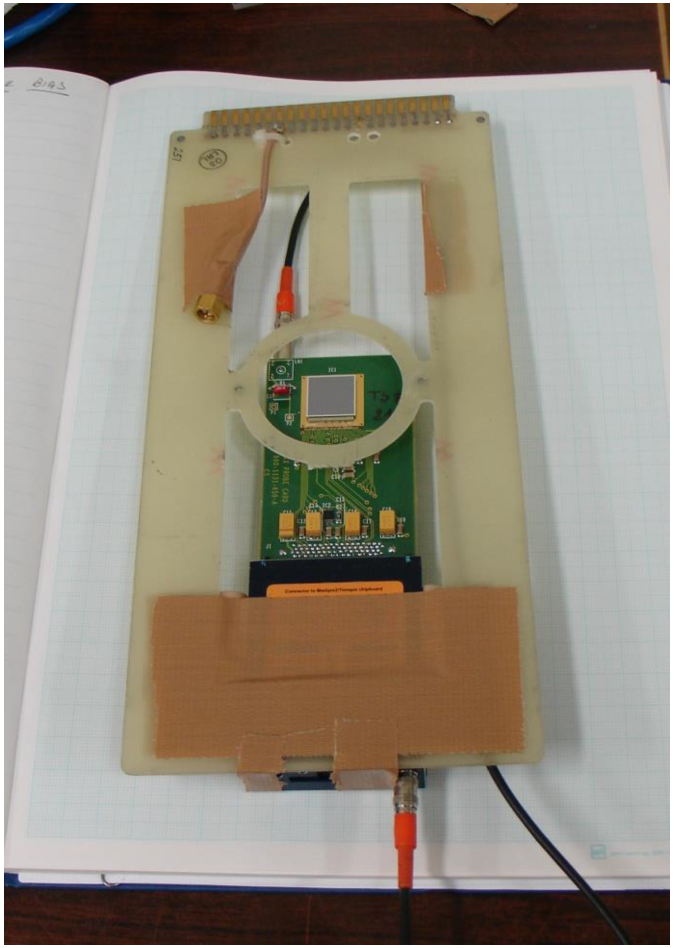
TimePix Directly in the HIMAC Beam



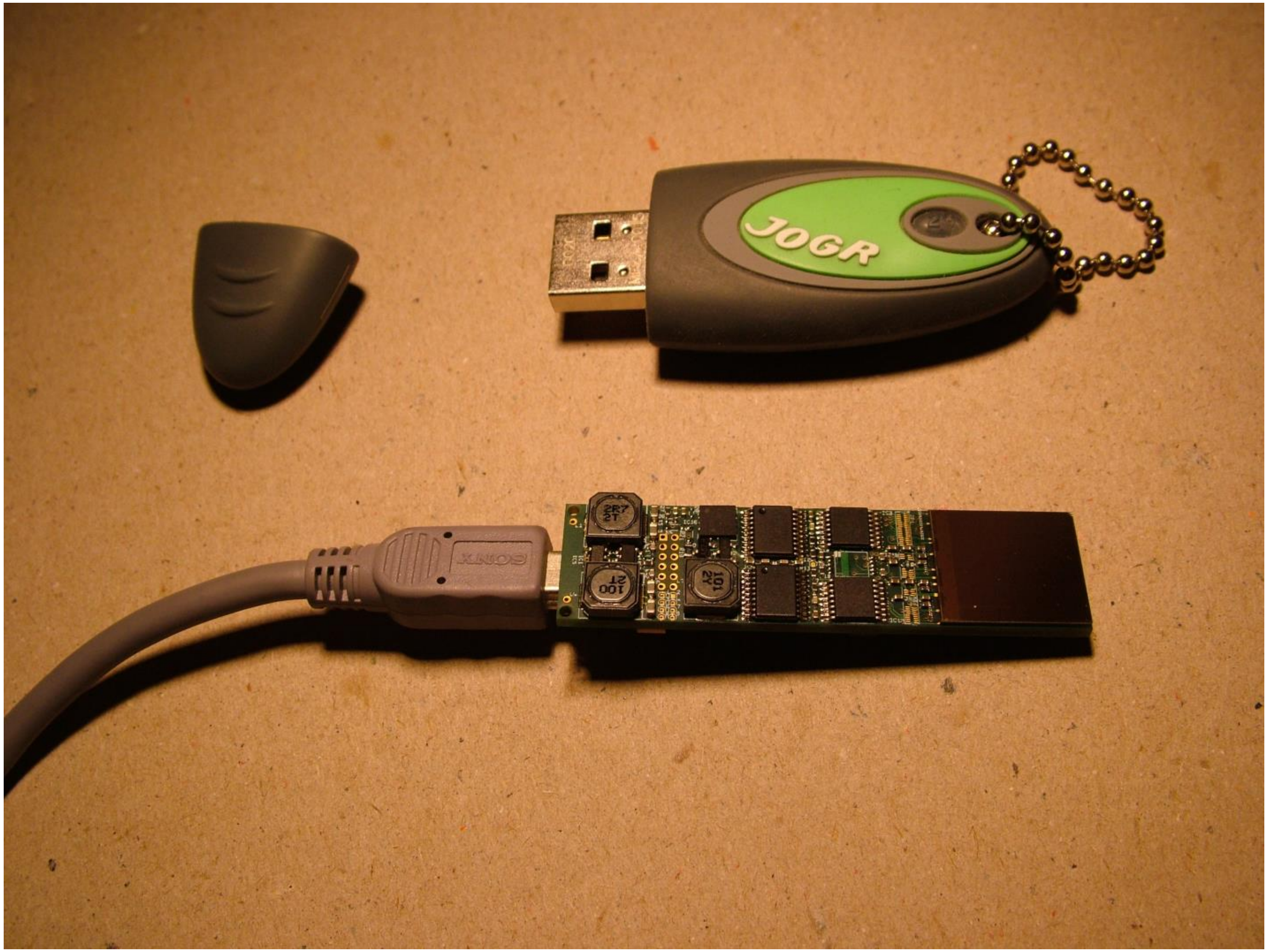


TimePix Behind the NASA Shield Targets



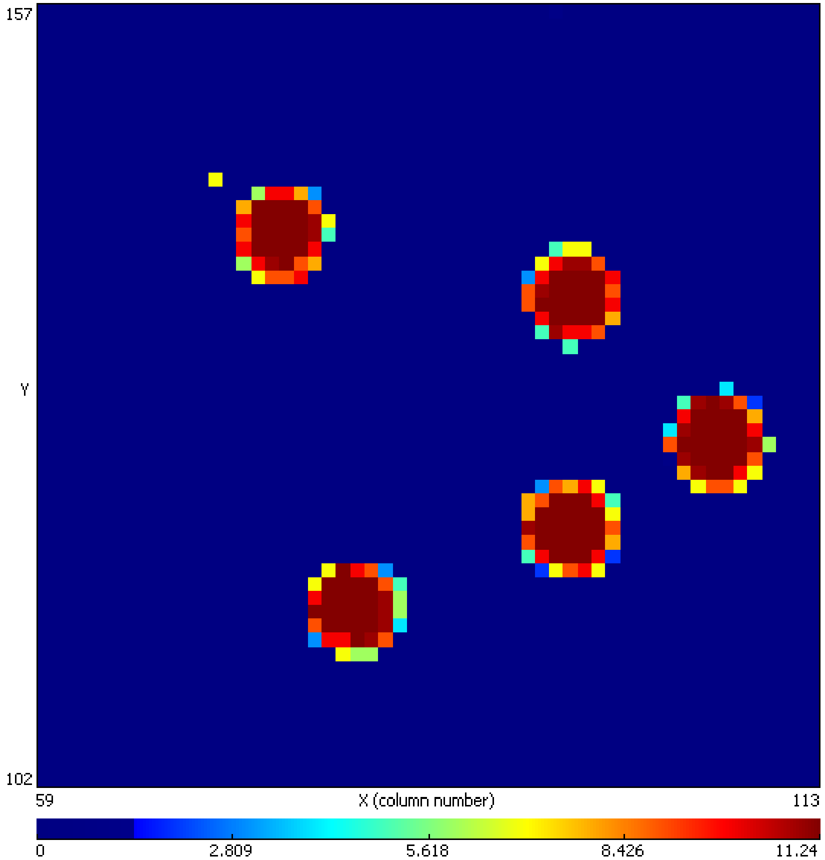


New “USB Lite” Interface

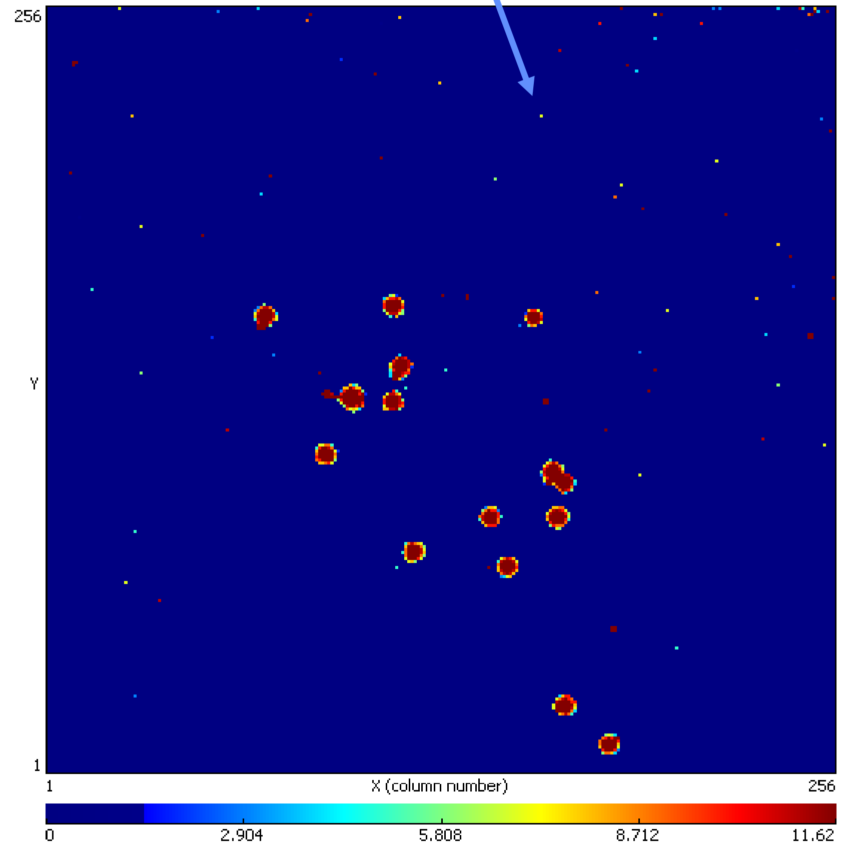


Typical Frames from ^{11}B @ 0°

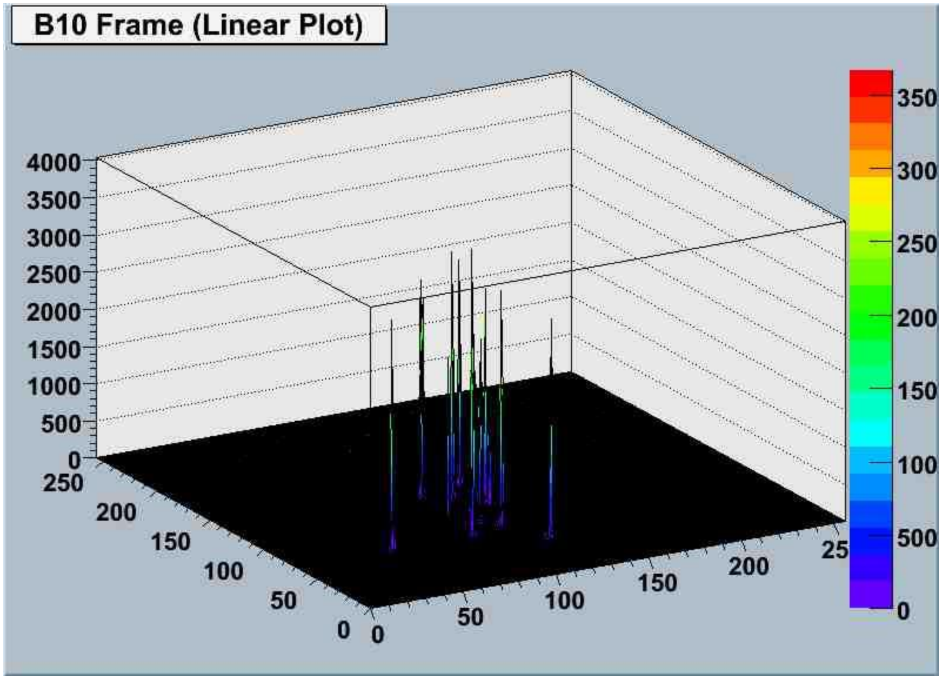
Blow-up of Track images

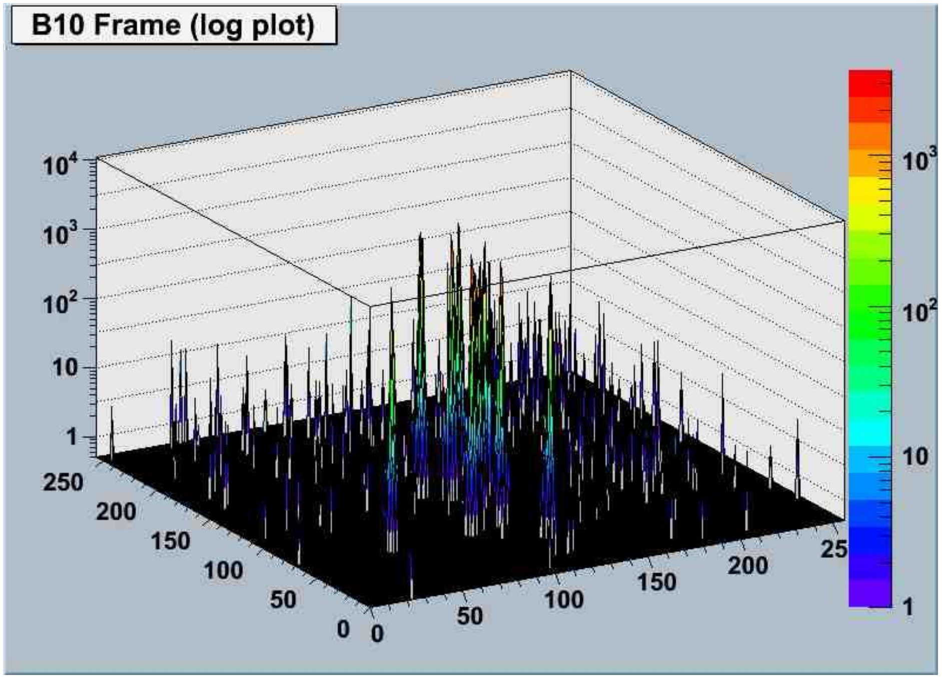


Note the background decay gamma rays



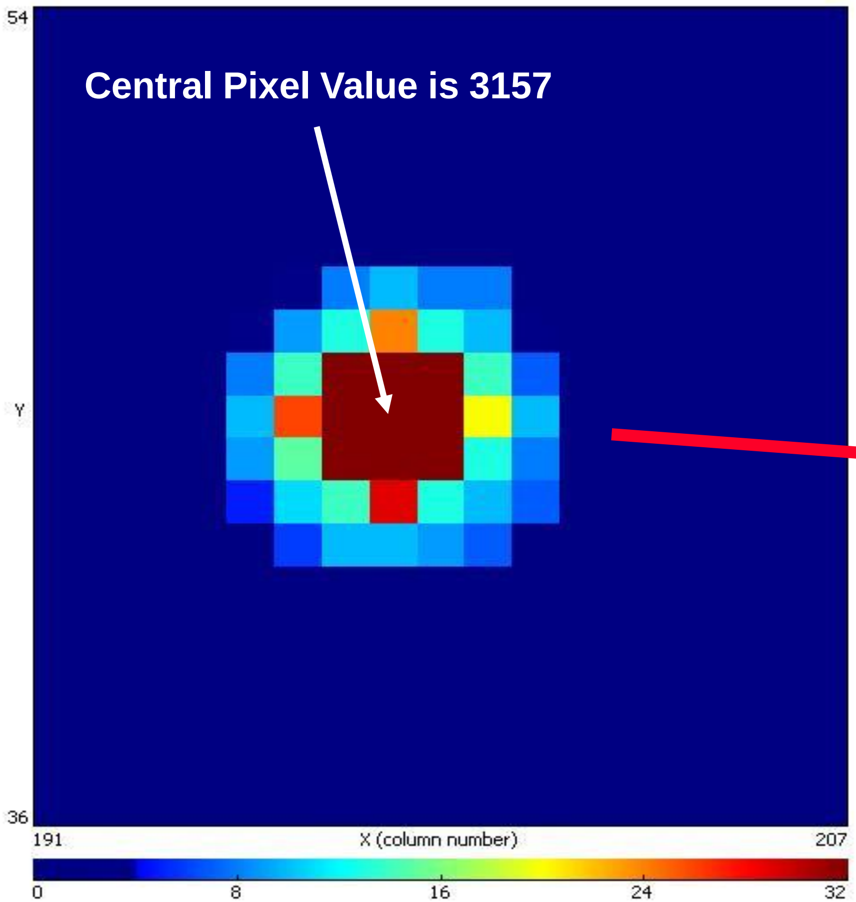
^{10}B Frame "Lego" Plot



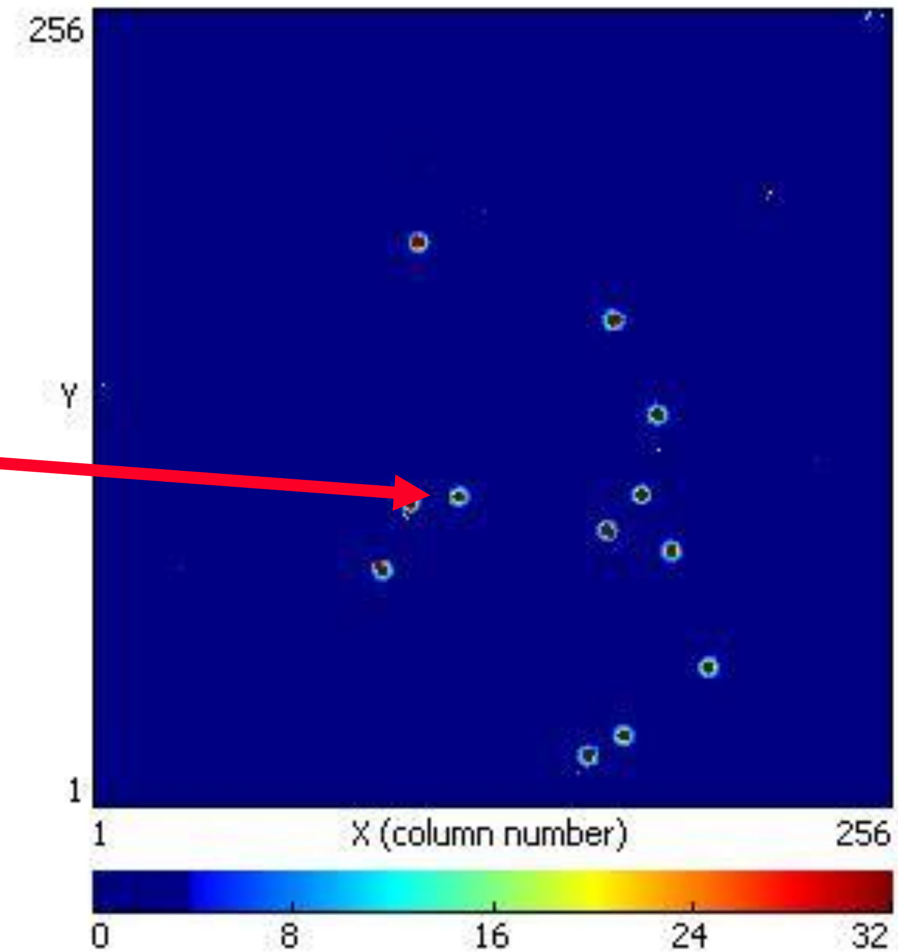


0° Incident ^{11}B Tracks

Blow-Up of a Single Track

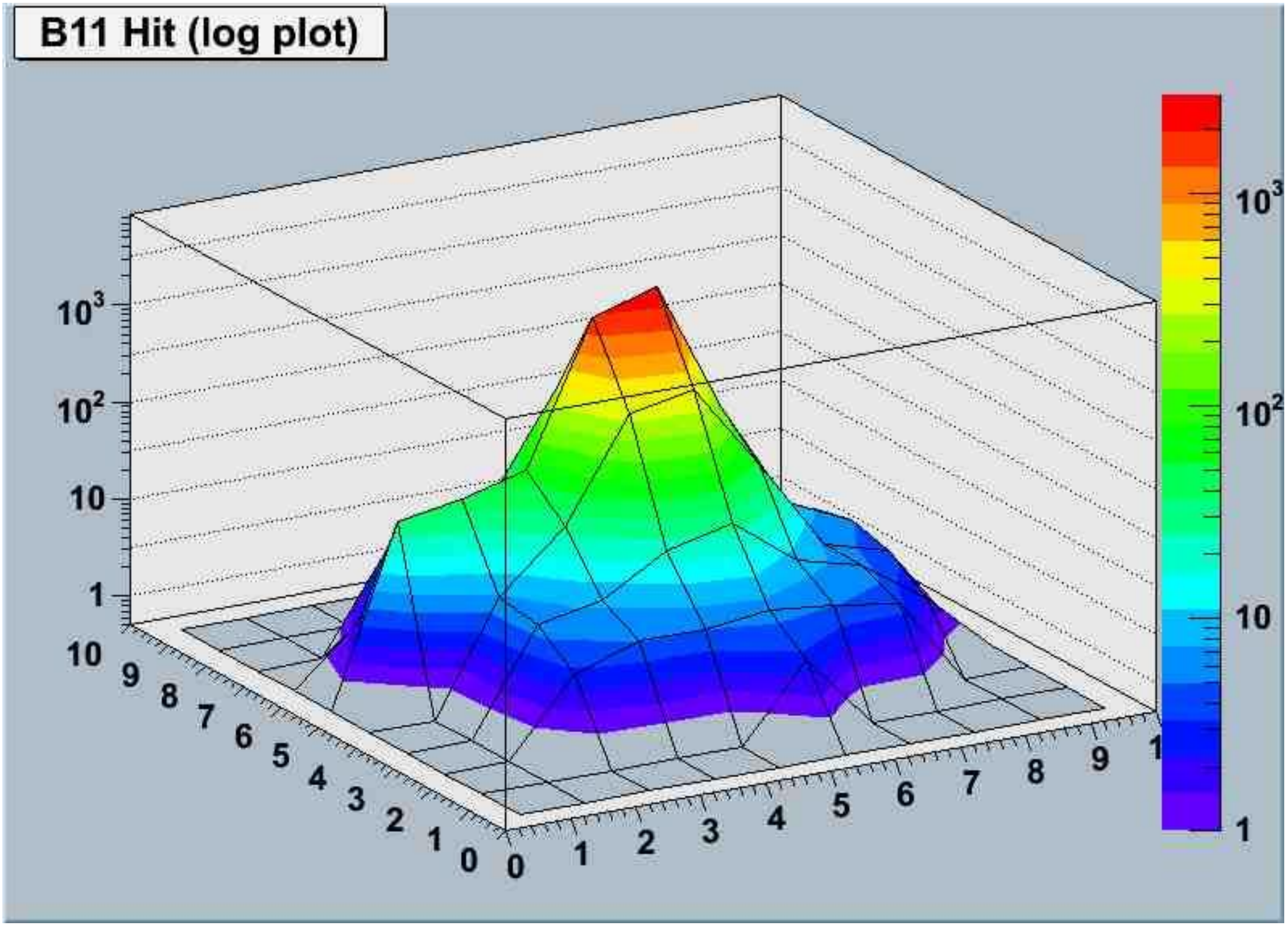


Full Frame of 1 ms Shutter

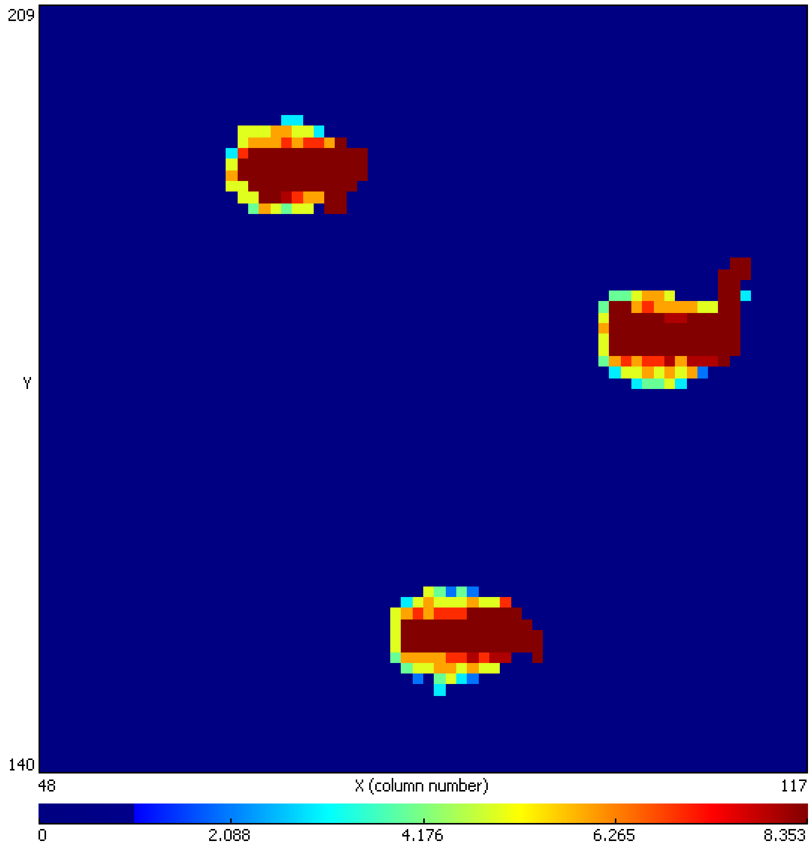


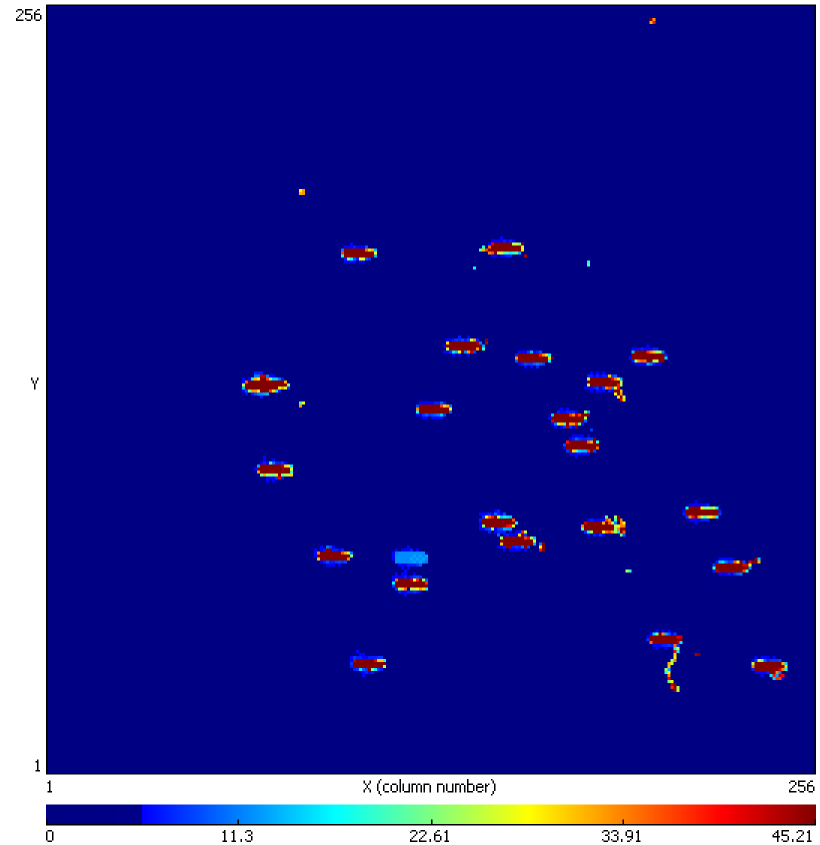
Recorded data has detailed values for each pixel

^{11}B Single "Track" Charge-Drift Footprint Contour Plot (Log Scale)

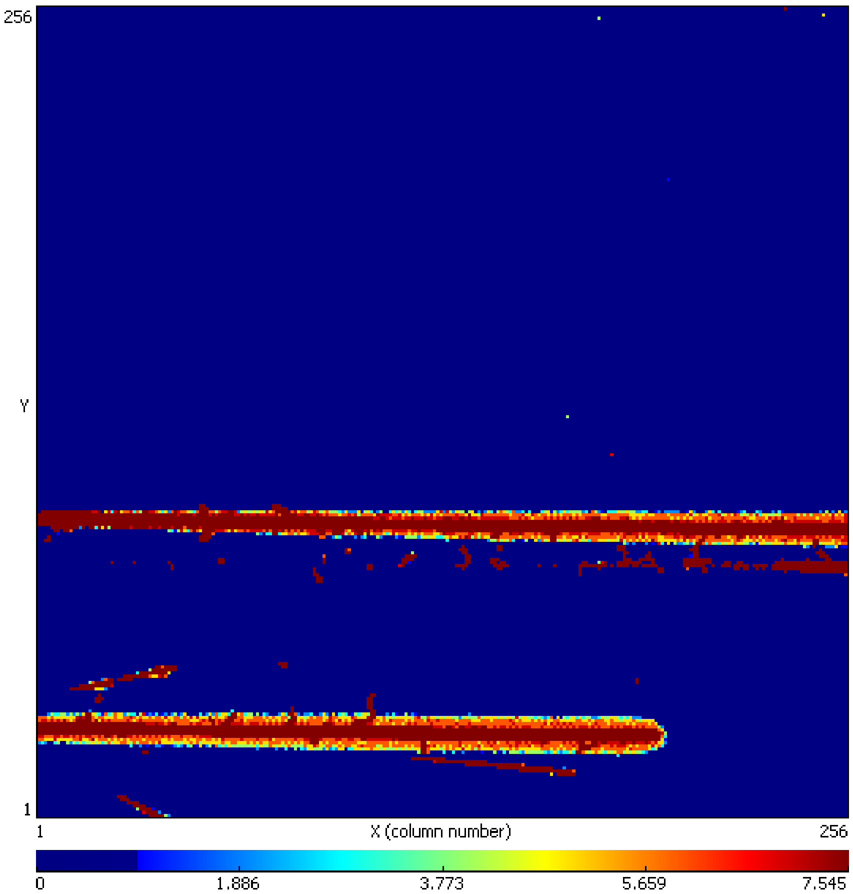


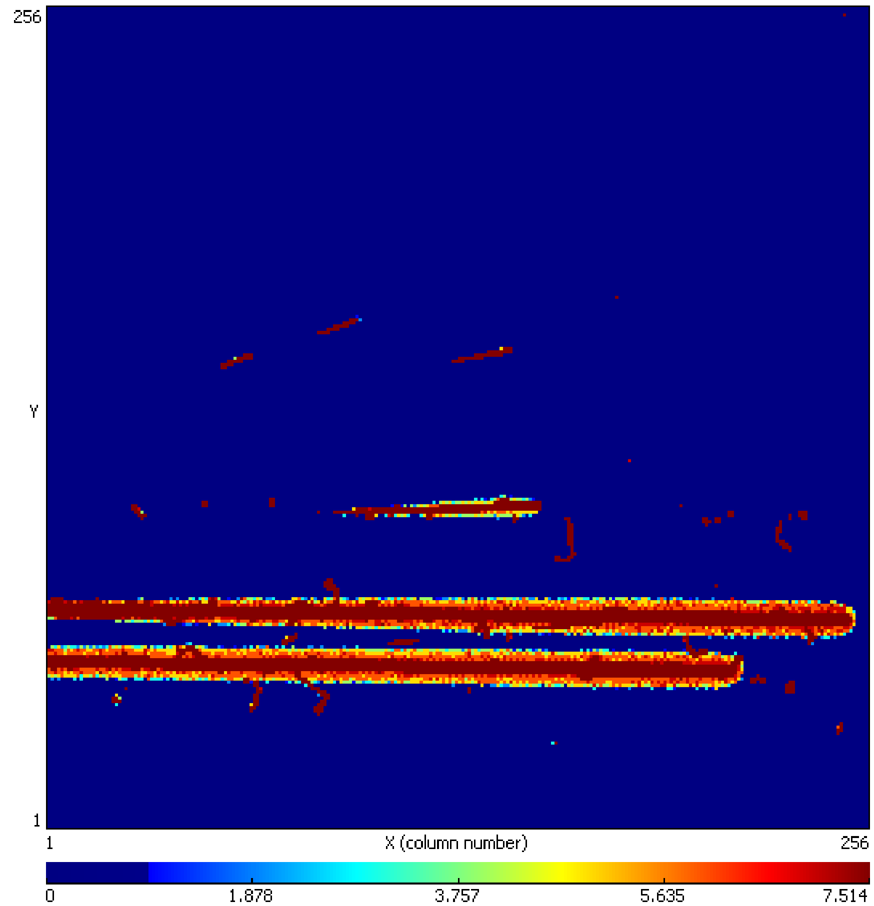
Pixelman Frames from ^{11}B @ 60°



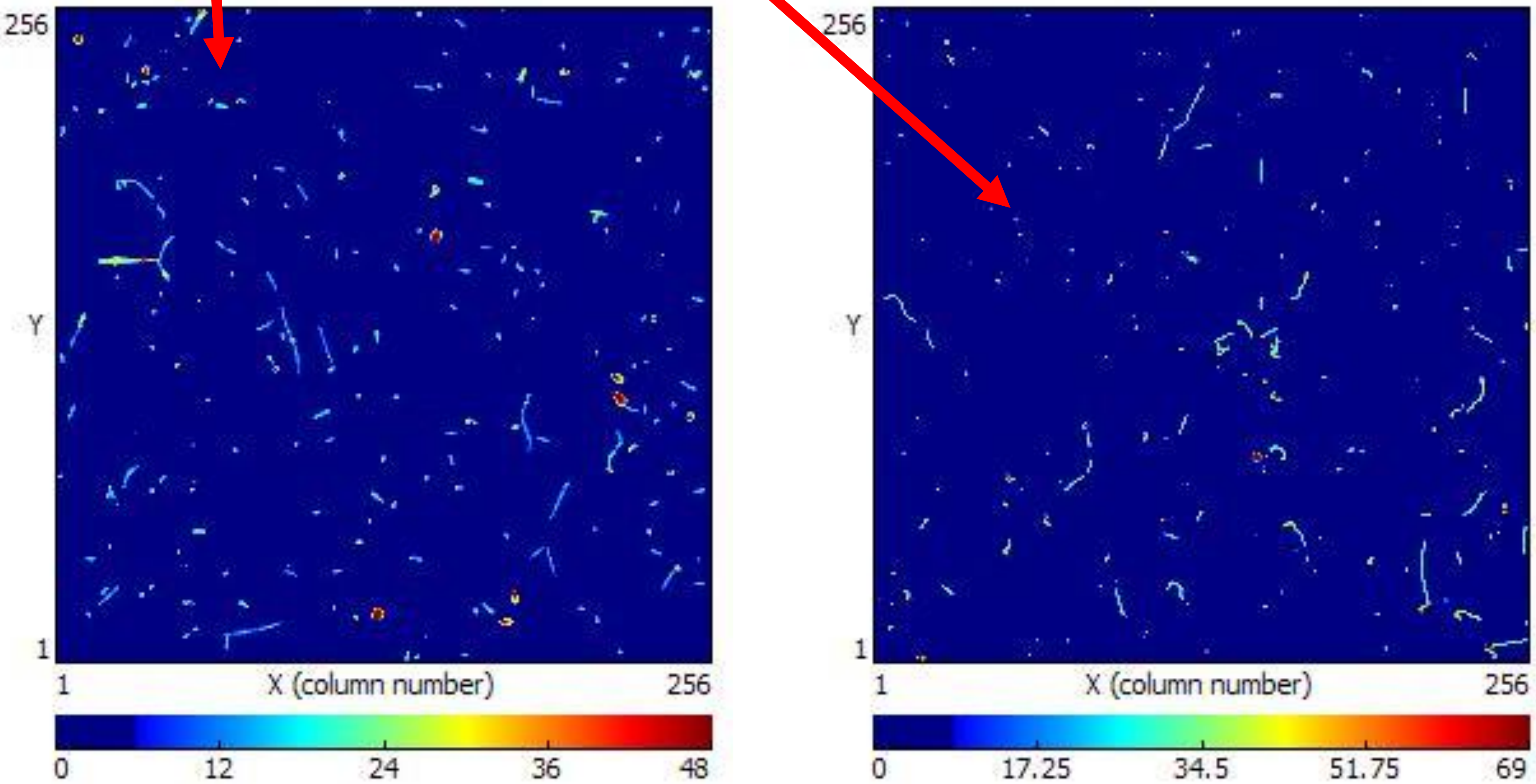


Pixelman Frames from ^{11}B @ ~90°



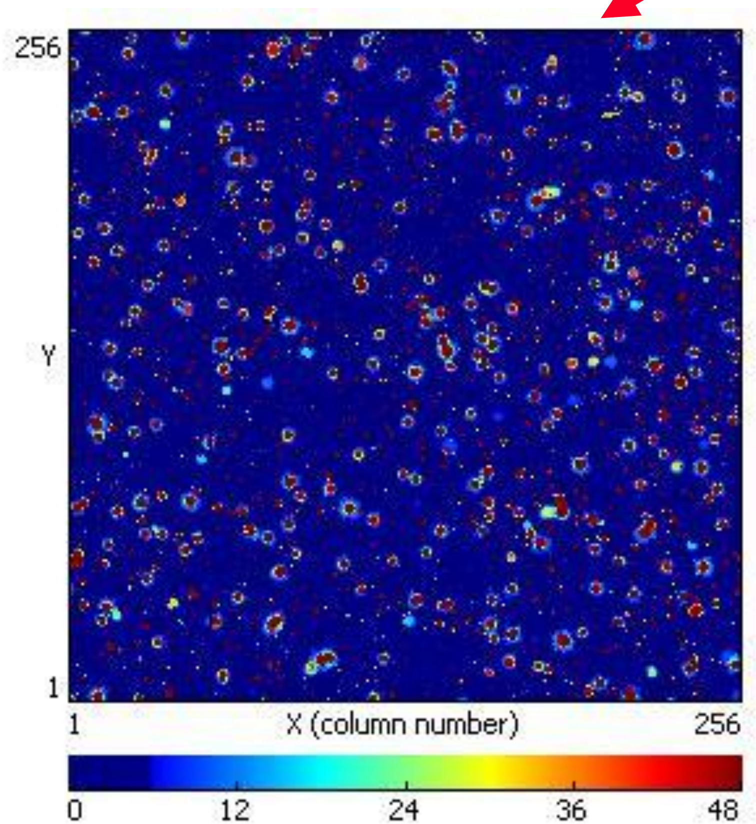


100 Sec @ 34,000 Feet in a 777 over the Bering Sea v. 1000 Sec in my office in Houston



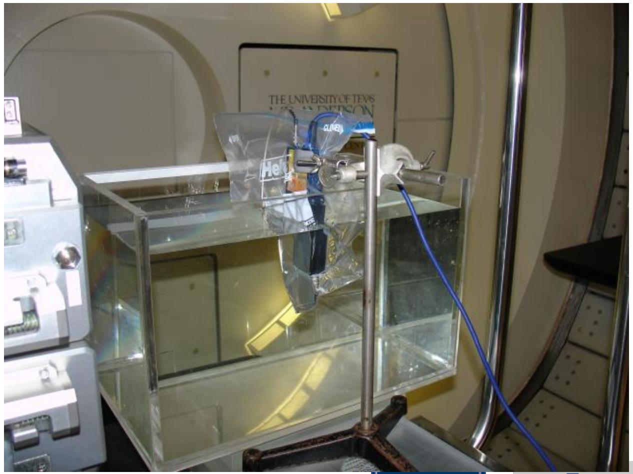
A Recent Exposure at the M.D. Anderson Proton Therapy Center

A 10 μs snapshot of what the tumor cells see…



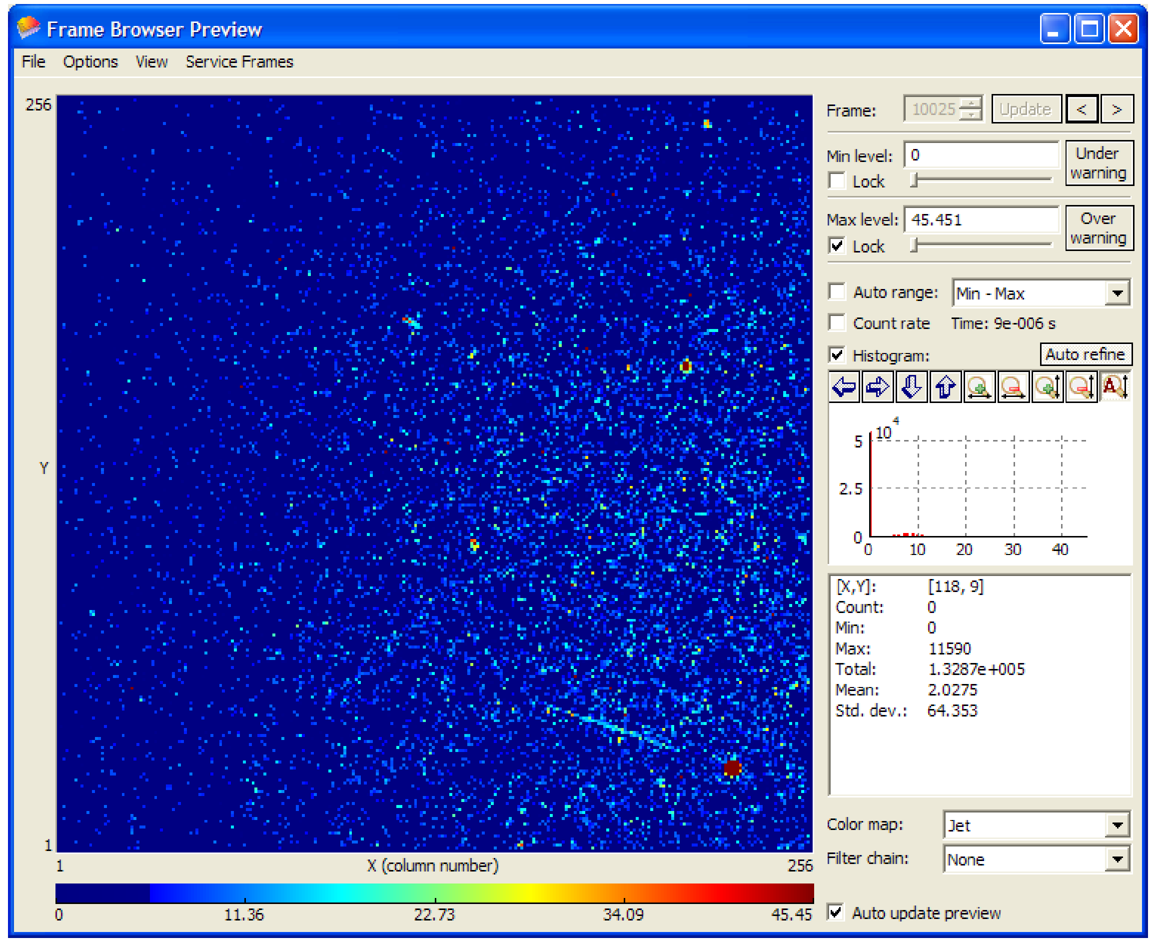
Filling the Water Phantom Tank

Water Phantom W/Timepix inside a plastic bag



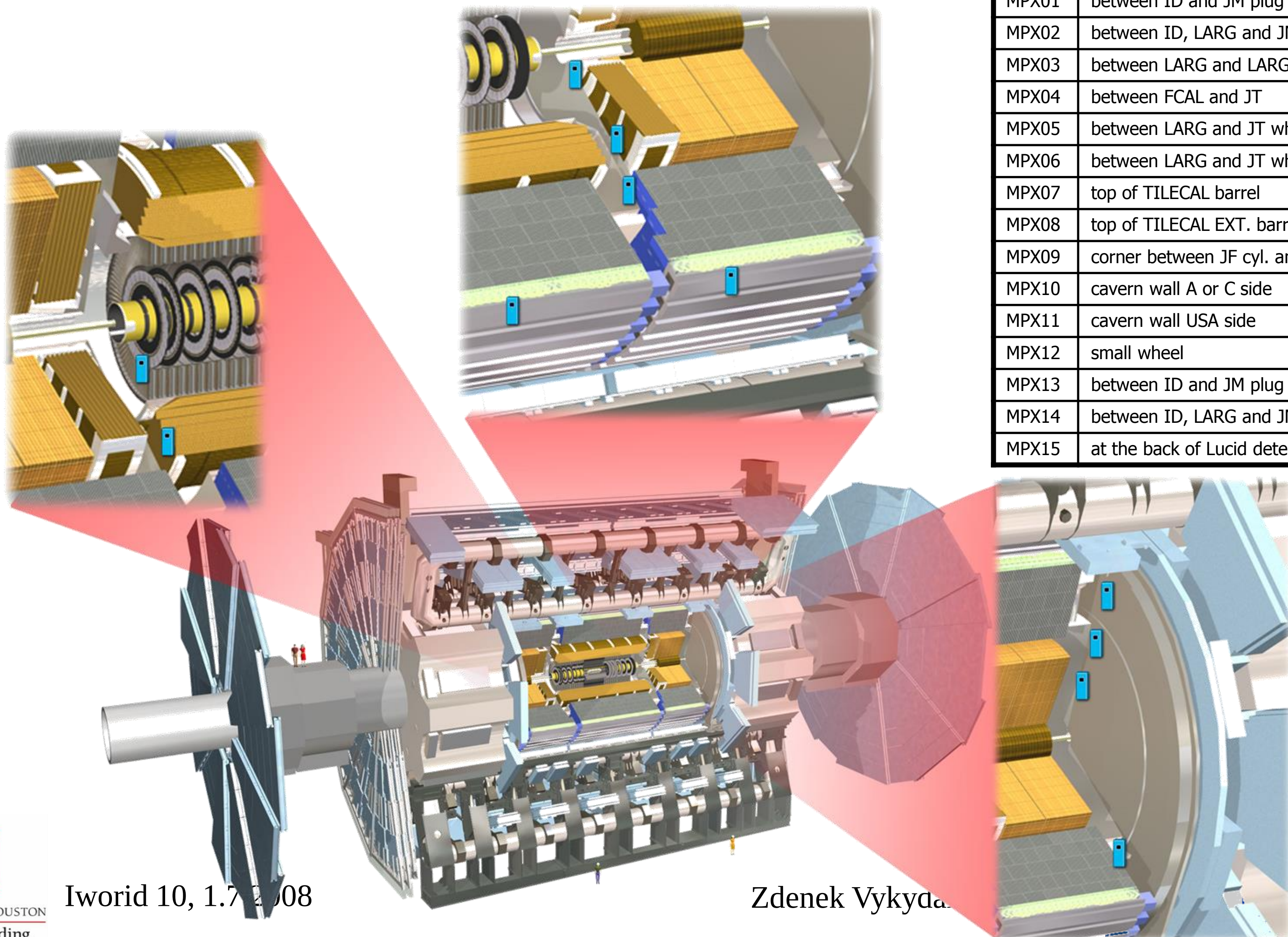
M.D. Anderson Proton Therapy Center Scanning Beam Frame

This 10 µs frame was taken in the high intensity scanning beam at the M.D. Anderson Proton Therapy Center in Houston, Texas. The fluence is > 10^8 protons/cm^{2}s. The beam is centered near the lower right edge of the frame and is nominally 1 cm in diameter. The frame is ~1.4 cm across. At this fluence, the charge sensitive pre-amp shaping return feedback had to be minimized to reduce the total current draw on the Medipix chip to avoid a voltage sag that would have affected the chip's overall functioning. Individual p tracks are visible in the core of the beam and in the beam's halo…



MPX-ATLAS position overview

MPX01	between ID and JM plug
MPX02	between ID, LARG and JM
MPX03	between LARG and LARG EC
MPX04	between FCAL and JT
MPX05	between LARG and JT wheel
MPX06	between LARG and JT wheel
MPX07	top of TILECAL barrel
MPX08	top of TILECAL EXT. barrel
MPX09	corner between JF cyl. and hexagon
MPX10	cavern wall A or C side
MPX11	cavern wall USA side
MPX12	small wheel
MPX13	between ID and JM plug
MPX14	between ID, LARG and JM
MPX15	at the back of Lucid detector



MPX-ATLAS
Detector Description

Description of the detector

Medipix2 ASIC with 300µm Si sensor + USB interface

Neutron conversion structures:

1)LiF+50µm Al foil area

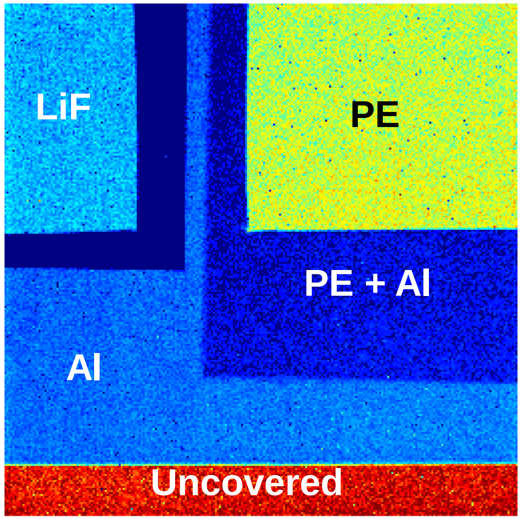
2)100µm Al foil area

3)PE area

4)PE+50µm Al foil area

5)Uncovered area

X-ray image of conversion layers



Detected particle types

Detected particle types:

- All charged particles with energy above 5keV (minimal threshold level)
- Other particle types have to be converted into secondary charged particles

Efficiency of the detection:

Efficiencies for noncharged particles are reduced by the conversion efficiency to detectable charged particles and geometry factors to following:

- Charged particles (above 5keV): 100%
- X-rays (5keV – 10keV): ~100%
- X-rays (from 1MeV): ~0.1%
- Thermal neutrons (energy < 1eV): ~1%
- Fast neutrons (MeV range): ~0.5%

Each detector is calibrated for fast neutrons using ^{252}Cf source , AmBe source and Van de Graaff accelerator and for thermal neutrons from grafit prism.

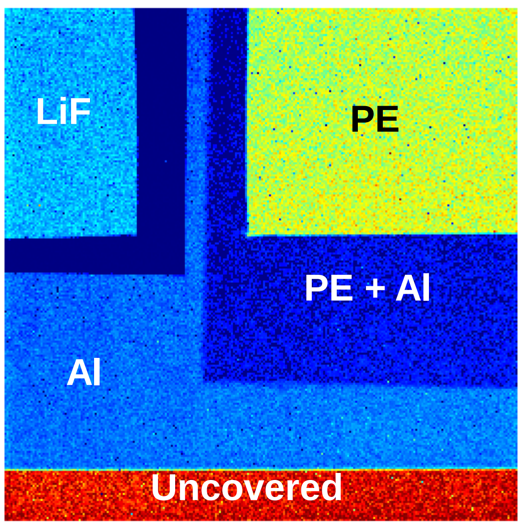
Description of the detector

Medipix2 ASIC with 300µm Si sensor + USB interface

Neutron conversion structures:

1) LiF+50µm Al foil area
2) 100µm Al foil area
3) PE area
4) PE+50µm Al foil area
5) Uncovered area

X-ray image of conversion layers



Detected particle types

Detected particle types:

- All charged particles with energy above 5keV (minimal threshold level)
- Other particle types have to be converted into secondary charged particles

Efficiency of the detection:

Efficiencies for noncharged particles are reduced by the conversion efficiency to detectable charged particles and geometry factors to following:

- Charged particles (above 5keV): 100%
- X-rays (5keV – 10keV): ~100%
- X-rays (from 1MeV): ~0.1%
- Thermal neutrons (energy < 1eV): ~1%
- Fast neutrons (MeV range): ~0.5%

Each detector is calibrated for fast neutrons using ^{252}Cf source , AmBe source and Van de Graaff accelerator and for thermal neutrons from grafit prism.

Counting x Tracking mode of operation

The MPX-ATLAS device can operate in two "modes" chosen by selecting appropriate acquisition time for given particle flux.

Counting mode:

a)Acquisition time is relatively long, so the signal from the individual particles is overlaped.

b)Overlaping limit is given by the depth of the Medipix2 pixel counter to 11810.

c)Negligible dead time.

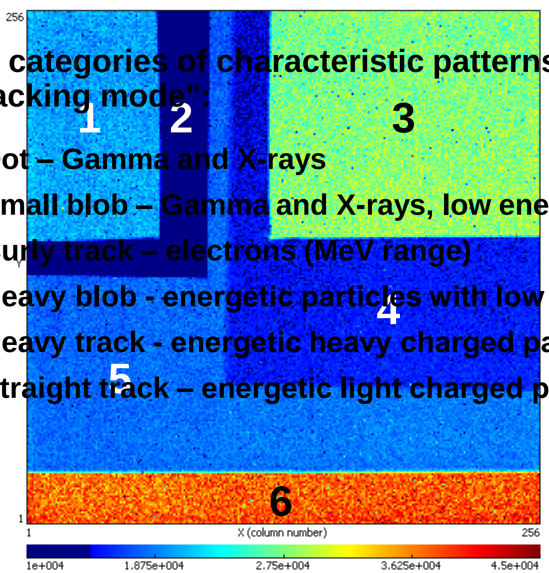
Tracking mode:

a)In the same field conditions the acquisiton time has to be ~1E6 times lower than in counting mode.

b)Identification of the particle type and energy from it‘s characteristic track.

c)Dead time can significantly increase because of data transmission.

X-ray image of conversion layers



Six categories of characteristic patterns can be recognized in "tracking mode":

1)Dot – Gamma and X-rays

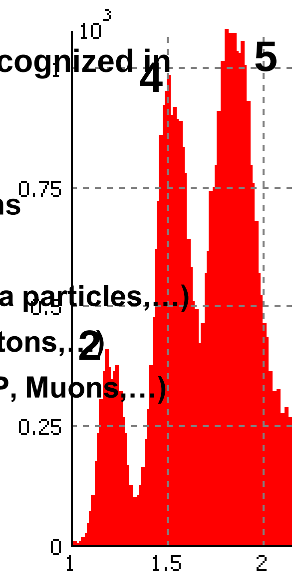
2)Small blob – Gamma and X-rays, low energy electrons

3)Curly track – electrons (MeV range)

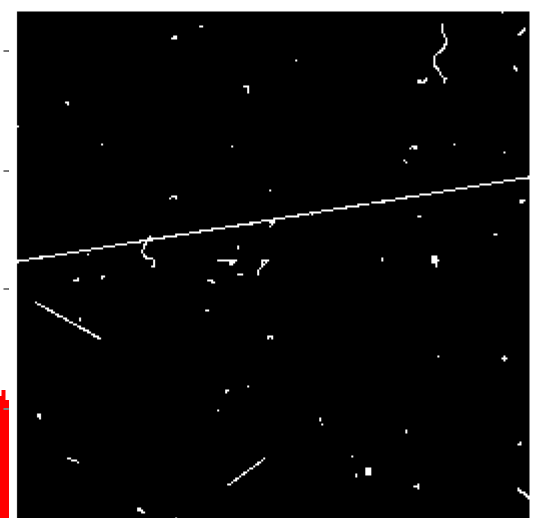
4)Heavy blob - energetic particles with low range (alpha particles,...)

5)Heavy track - energetic heavy charged particles (protons,...)

6)Straight track – energetic light charged particles (MIP, Muons,...)



Atlas background – 100min



Low x High Threshold

Two basic threshold levels are used with respect to the kind of radiation we want to study:

Low threshold: energy of 10 keV

a)Necessary for measurement of gamma radiation and electrons.

b)Shorter acquisition times are needed for cluster recognition.

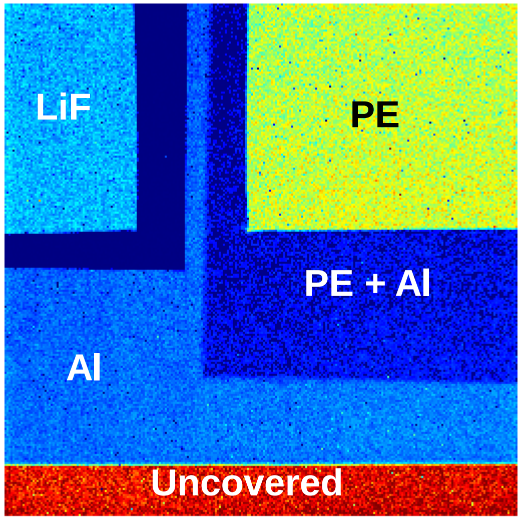
High threshold: energy of 230keV

a)Needed for neutron measurements because of low detection efficiency compared to the signal from primary or secondary electrons.

b)Signal from electrons is cut out (threshold level was found using ^{90}Sr source - 195keV electrons)

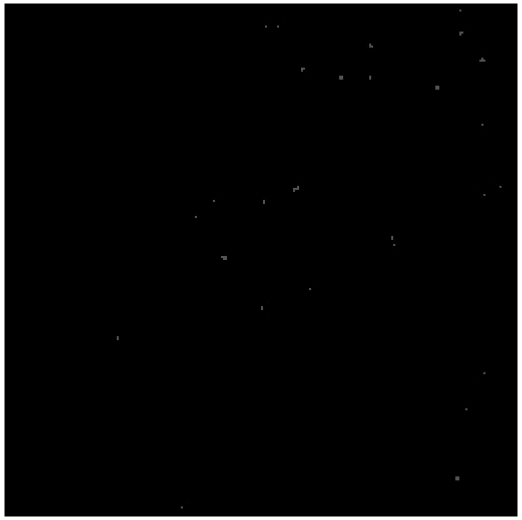
c)Allows using of longer acquisition times

X-ray image of conversion layers



Low Threshold 252Cf – 1s

High Threshold 252Cf – 2000s



Neutron efficiency calibration

(see also poster 3.2.4 of Dominic Greiffenberg)

Calibrated efficiency:

Thermal: 1.41E-2 ± 7.11E-4 $cm^{-2}s^{-1}$

252Cf: 1.19E-3 ± 1.89E-5 $cm^{-2}s^{-1}$

AmBe: 2.86E-3 ± 5.46E-5 $cm^{-2}s^{-1}$

VDG: 7.23E-3 ± 5.81E-4 $cm^{-2}s^{-1}$

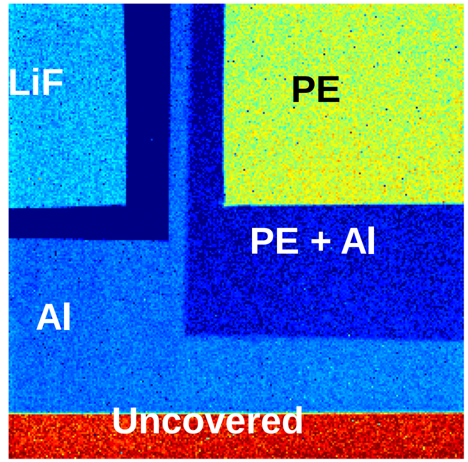
PE / PE+Al cluster count ratio:

252Cf: 10.70 ± 0.04

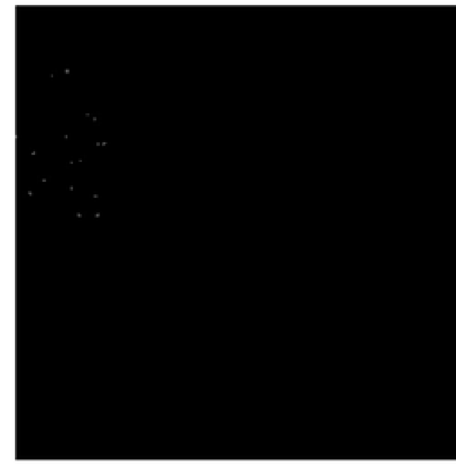
AmBe: 5.18 ± 0.03

VDG: 2.51 ± 0.03

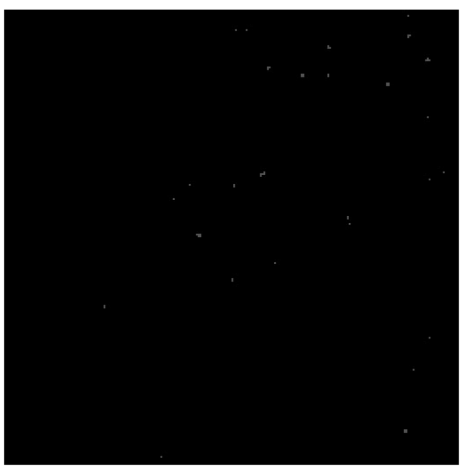
X-ray image of conversion layers



Thermal neutrons – 500s, 25meV



252Cf – 2000s, 2MeV (mean)



AmBe – 2000s, 4MeV (mean)

Van de Graaff – 1000s, 14MeV

The 2 Basic Dosimeter Philosophies

- **Measure the actual energy deposited in a Tissue-Equivalent medium…**
  - **Pros--You actually measure the DOSE by definition.**
  - **Cons--It is not easy to take "Quality Factors" into account…**
- **Determine the detailed nature of the Radiation Field…**
  - **Pros--You can easily calculate any dosimetric endpoint…**
  - **Cons--The detectors and analysis are more complex…**

Where Do We Go From Here?

- With Medipix we clearly choose the latter approach, namely to accurately determine the full nature of the radiation field that is present.
- To do that, we need to develop algorithms that can parse the pixel field and identify the source of each energy deposition.
- So, we will take data in each kind of radiation field independently, and model the detector response using the FLUKA Monte Carlo code.
- Then we will simulate the mixed space radiation fields as a source for the algorithm development.
- Ultimately, we will install a signal processor on the device itself and calculate the dosimetric endpoints directly…

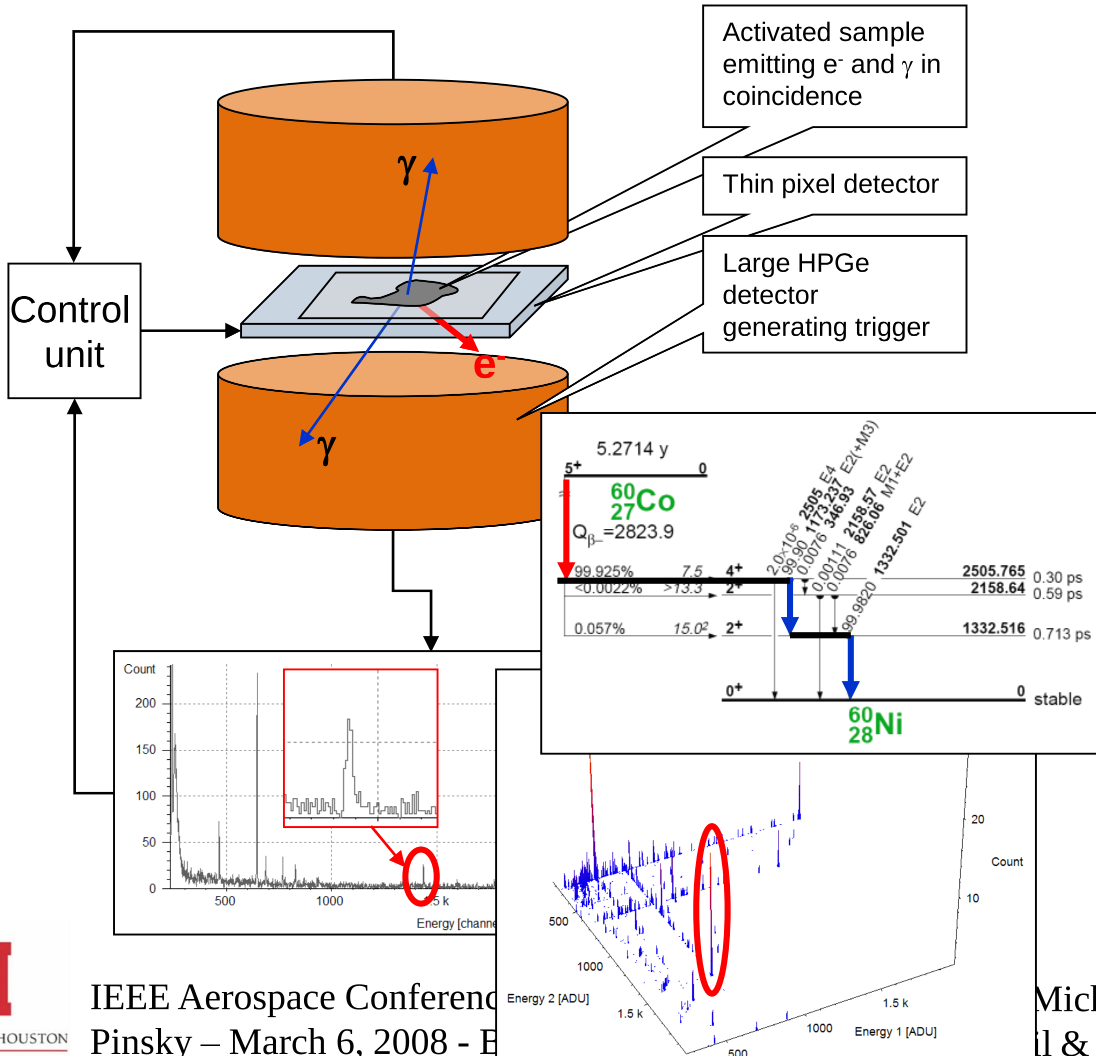
Future Evolution of Medipix Neutron Sensitivity

- We are collaborating with the Medipix Group in Prague (Stanislav Posposil).
- Considerable monoenergetic neutron response data are available and will be taken…
- CERF Run, Data taken Oct. 29, 2007
- Future PROPRITARY Techniques may be applicable to raise the neutron efficiency in the 1-100 MeV range to over 35%
- Simulations confirm the potential…
- May be tested soon…
- Unable to say more at present…

Thank You For Your Attention..

…And, Now
Let's Check the Demo…

Coincident imaging:



Application field:

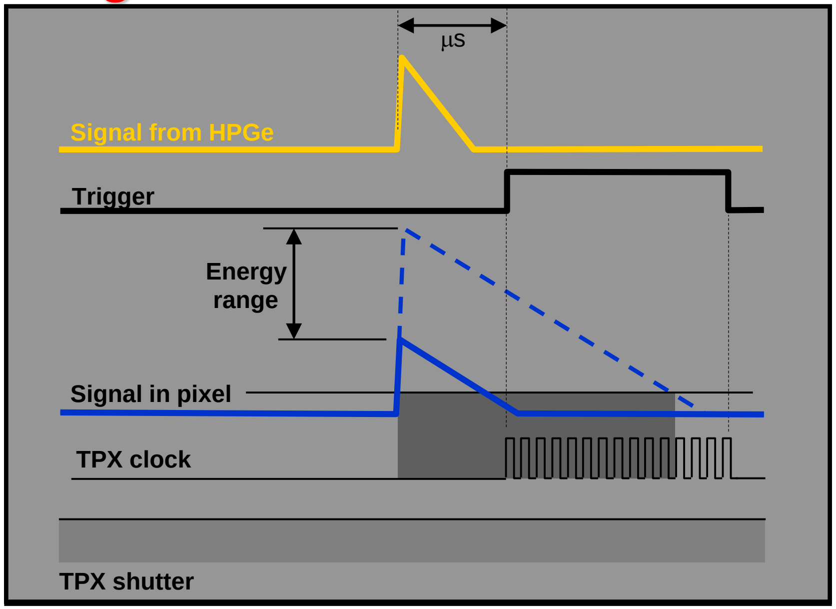
- Imaging in Activation Analysis
- Prompt gamma imaging
- …

Activation analysis:

- Excited nucleus emits radiation
- Energy of emitted gamma is typical for each element => direct measurement of element concentration
- Very sensitive method (<ppm)
- To improve selectivity several detectors can be used in coincidence
- Electrons are often present de-excitation in cascades

=> Chance for thin Si pixel detector

Coincident imaging:
Triggered image integration with TimePix



Situation:

- Just electrons emitted in coincidence with right gamma photon have to be counted.
- Detection of electron in the pixel detector and detection of gamma in HPGe is simultaneous.

=> When trigger from HPGe comes the detection in pixels is already finished.

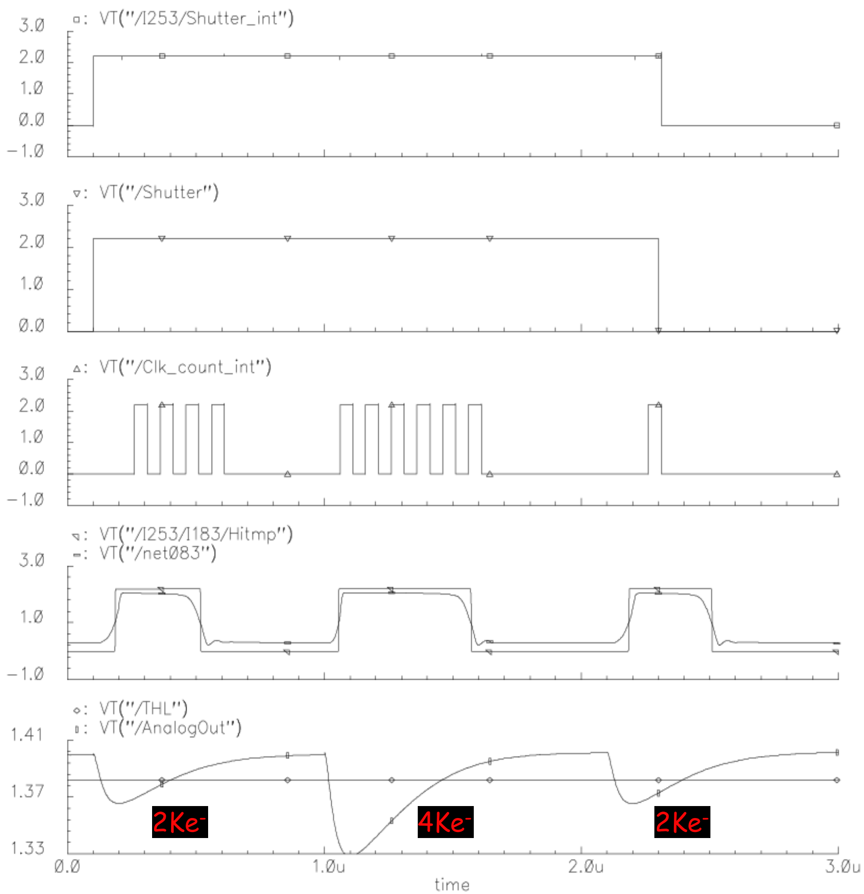
Solution 1 (not elegant):

- Shutter is opened for certain (very short) time period
- If trigger from HPGe comes then frame is read, otherwise it is erased.
- Integration is performed in a computer
- Image has to be transferred for each trigger => **Very long dead time**

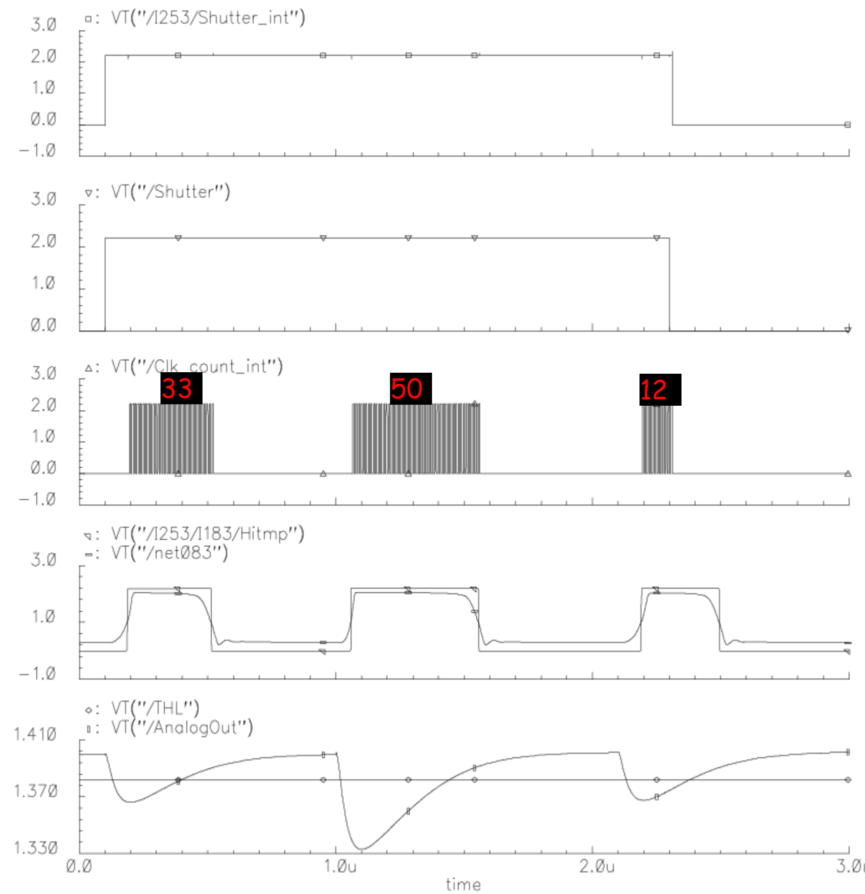
Solution 2 (“smarter”):

- Shutter is opened all the time, TPX is set to TOT mode. Shaping is set to be very long.
- Clock is generated just if trigger appears.
- In non-coincident case there is no clock => pulses are not counted.
- Integration is performed directly in the chip => **negligible dead time**

TOT Mode (P0=1,P1=0)

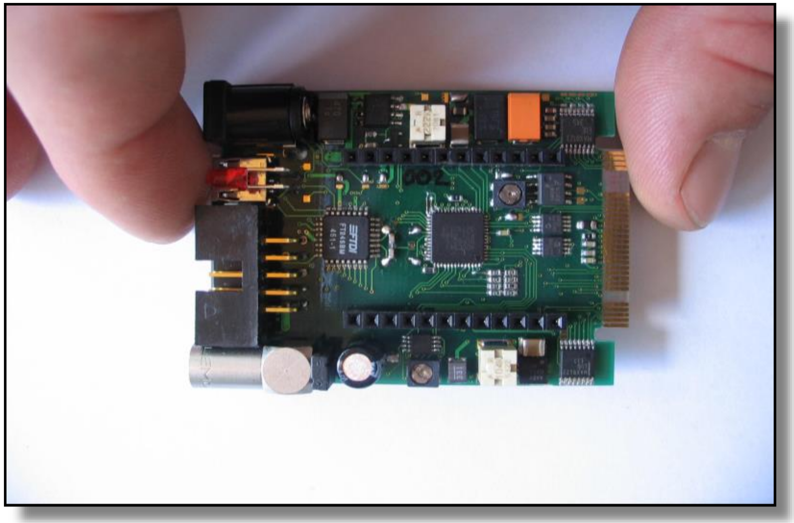


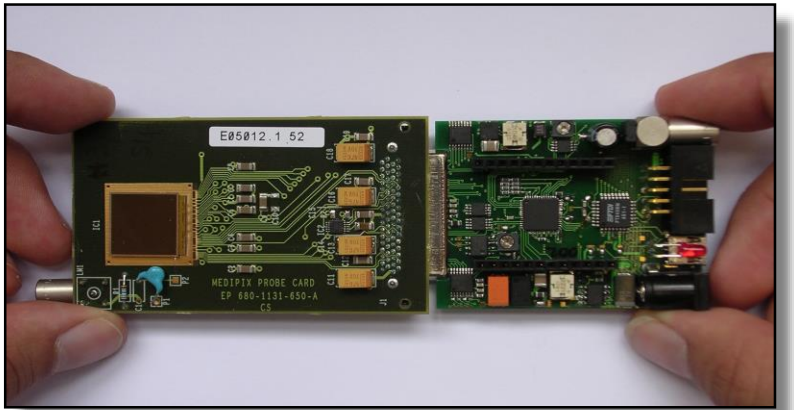
10MHz



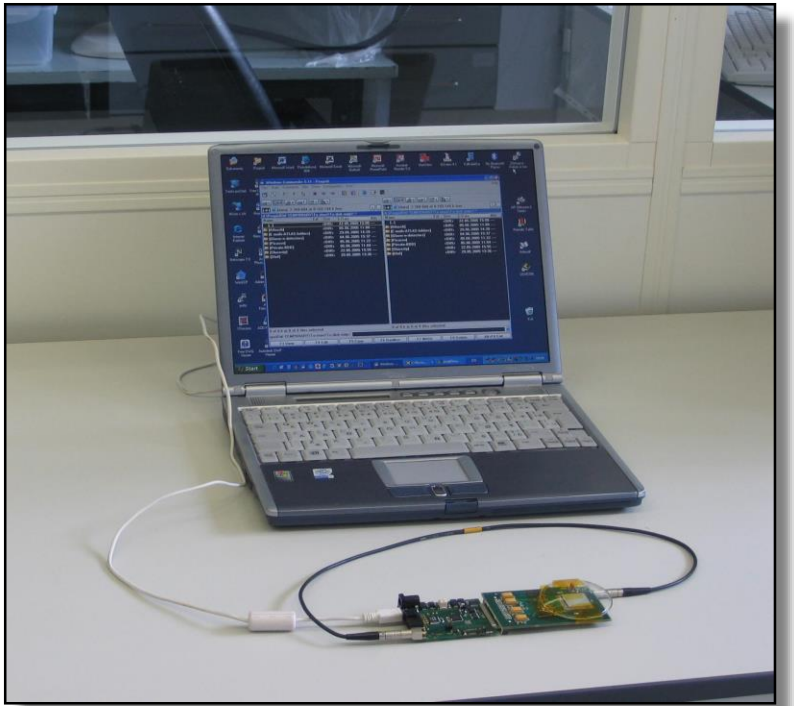
100MHz

A new USB based Medipix2 Readout System





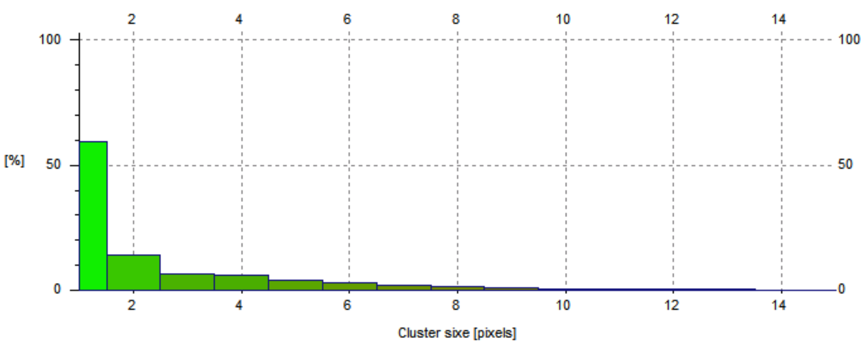
USB1 compatible
Developed by S. Pospisil et al.
CTU, Prague



Amorphous ^{10}B converter (Cluster Sizes)

- Energy of heavy charged particles is lower than in case of ^{6}Li converter => smaller clusters are produced.
- From γ interactions electrons are generated => electron tracks are present. Spatial resolution is deteriorated by electron tracks.
- Energy of electrons is lower then energy of heavy particles => electron tracks can be suppressed by suitable threshold selection.

Cluster size distribution for 10B converter
Exposition= 50 x 0.001s, Vfbk=250, Vthl=200



Clusters of 10B converter
(Exposition=0.001s, Vfbk=250, Vthl=200)