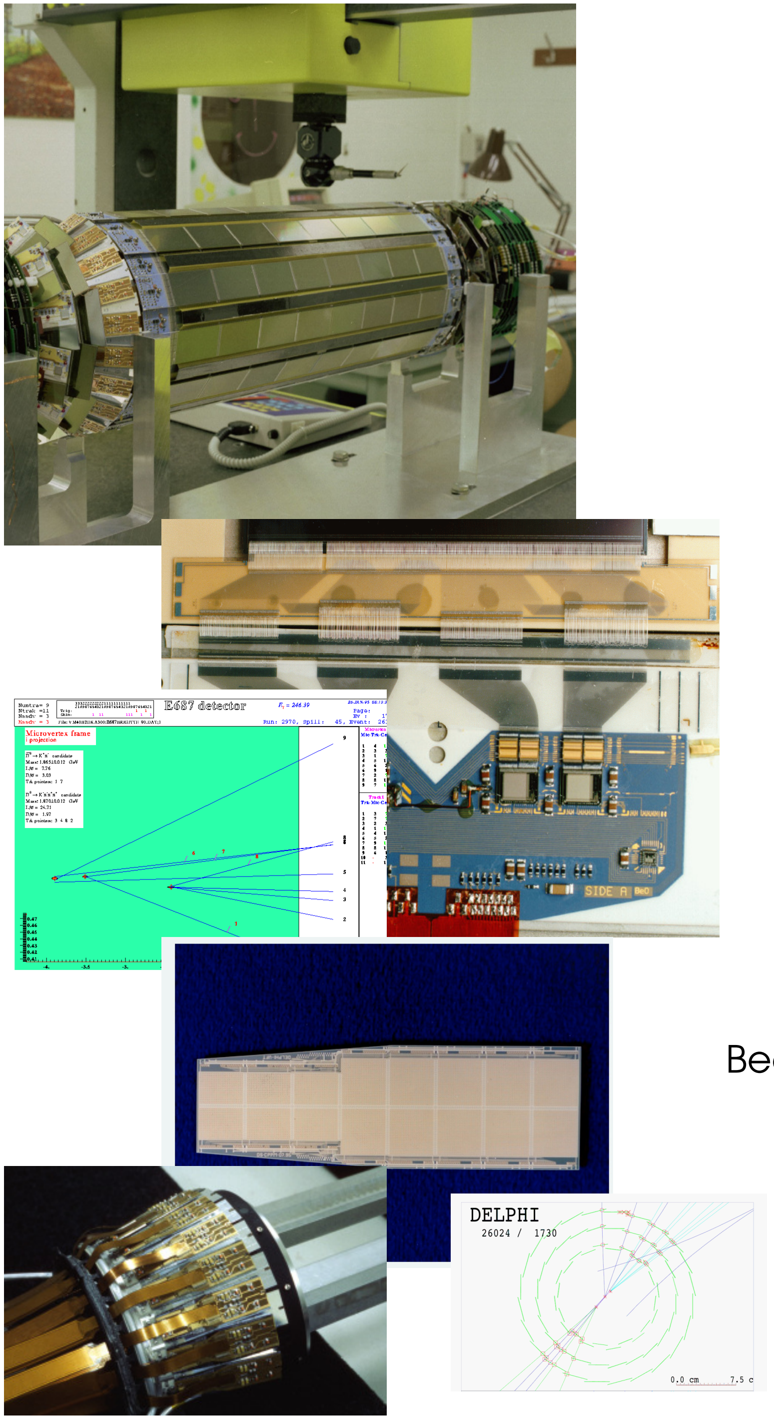


Beam Imaging With Position Sensitive Silicon detectors

GSI - November 10, 2011

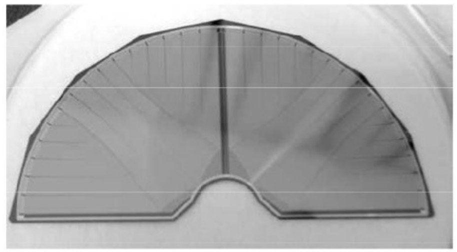
Beam Monitoring Instrumentation and Quality Assurance
industry-academia matching event

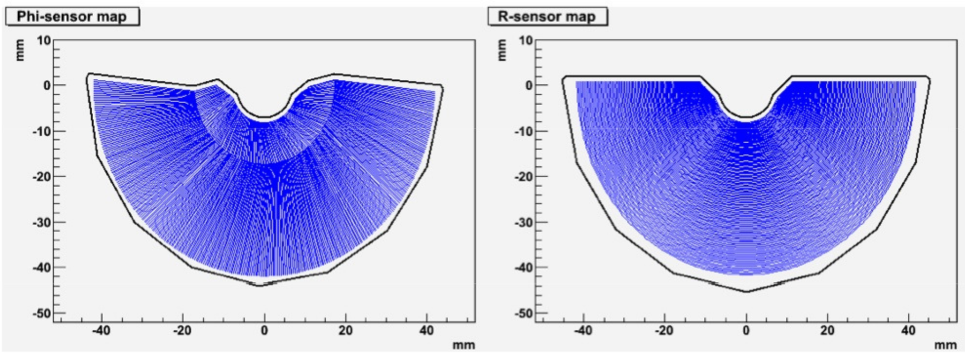
Massimo Caccia
Uni. Insubria & INFN

Exemplary illustration 1:

Beam Imaging with micro-strip detectors at the Clatterbridge Cyclotron for Proton Therapy*

(reference & ackn.: Phil Allport & G.L.Casse, Liverpool)



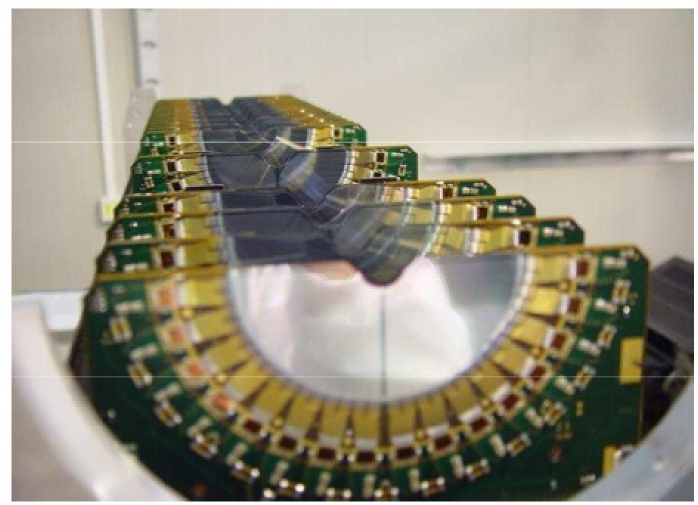


Radial strips, measuring the azimuthal coordinate

Semi-circular strips, measuring the radial coordinate

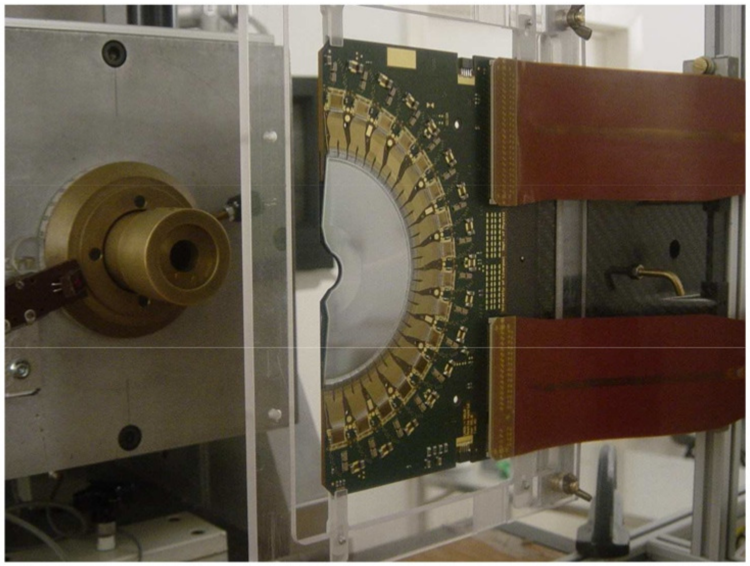
Based on the LHCb-VELO Microstrip half-moons,

withstanding up to 10^{16} 1MeV neutron equivalent cm^{-2}



(*Scanditronix MC-60 cyclotron, delivering 62 MeV protons with intensity to 10 nA, with a flat beam spot width of 34 mm, suitably collimated)

Measuring the beam divergence by the halo particles



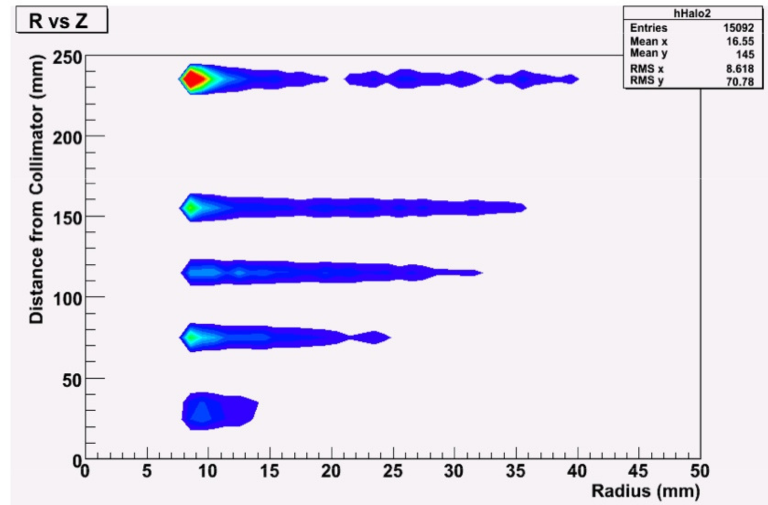
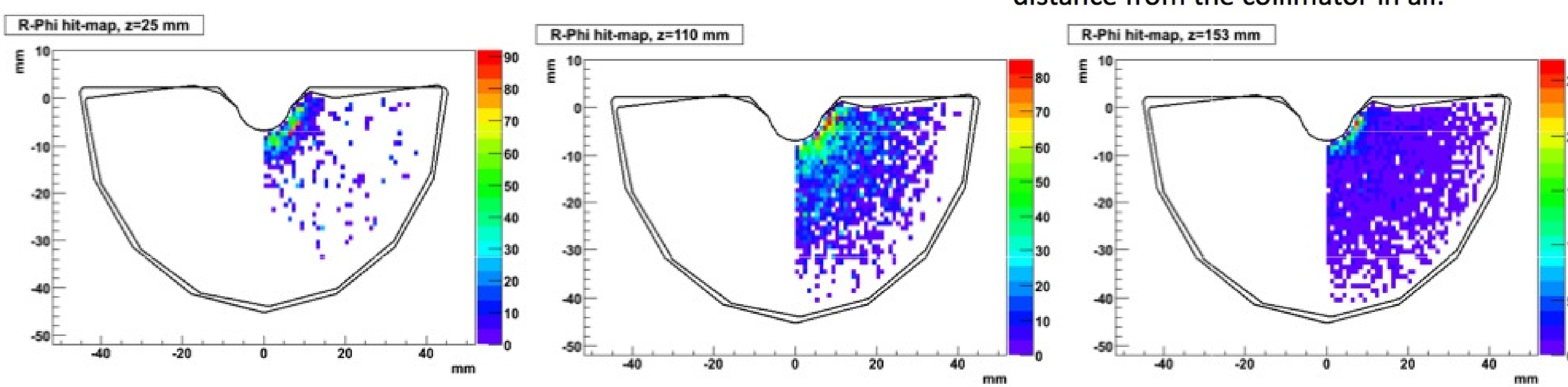


Figure 7. Divergence of the beam spot halo with distance from the collimator in air.



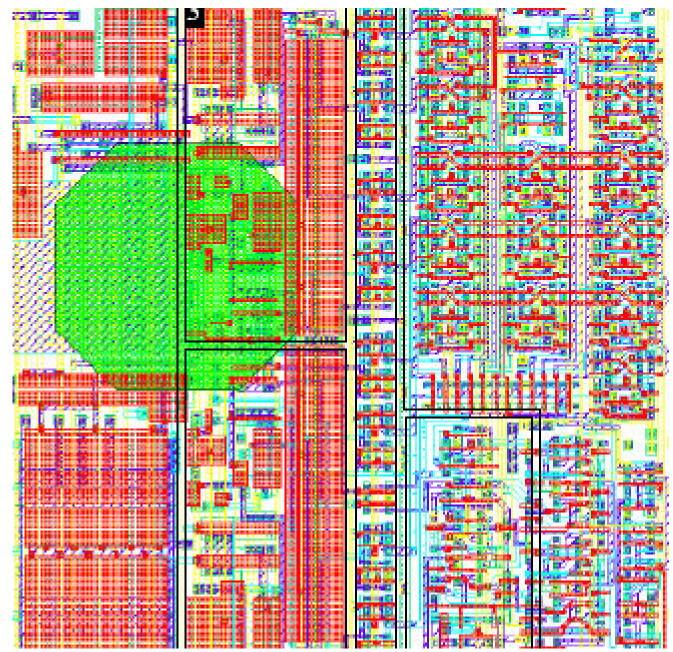
Exemplary illustration 2:

LET measurement and scattered radiation at the HIT beam with a hybrid pixel detector based on the MEDIPIX/TIMEPIX chip

(ref. & ackn: Jan Jakubec, IEAP-CTU Prague)

Highlights of the MEDIPIX 2, the MEDIPIX family block-buster:

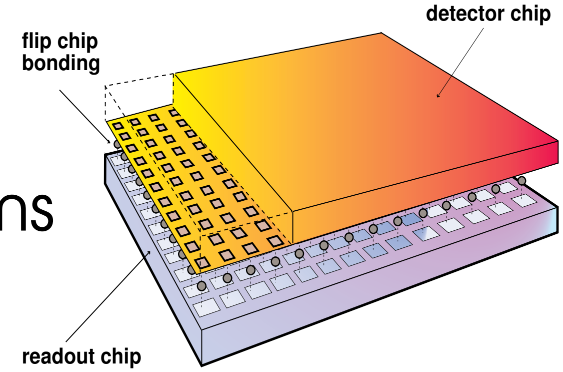
- squared pixels, 55 µm pitch
- 256 x 256 pixel matrix
- energy windowing with lower and upper thresholds, tunable on each pixel
- 13 bit counter, integrated in each pixel cell
- maximum counting frequency ~ 1 MHz
- maximum readout frequency ~ 100 MHz
- designed in 0.25 µm technology
- 500 transistors/cell (33 million transistors/chip)



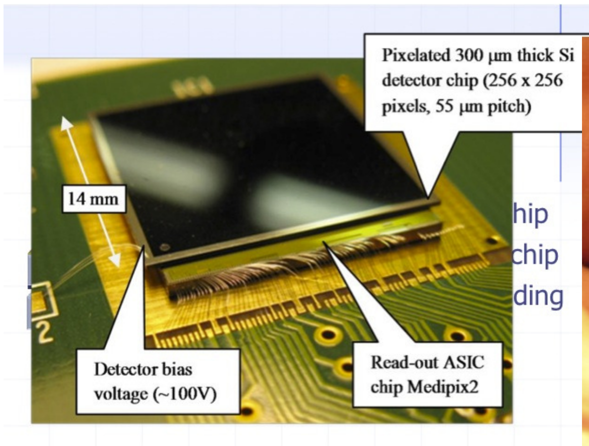
MEDIPIX 2 => MEDIPIX 3 & TIMEPIX (measuring as well the deposited energy by TimeOverThreshold or the TimeOfArrival)

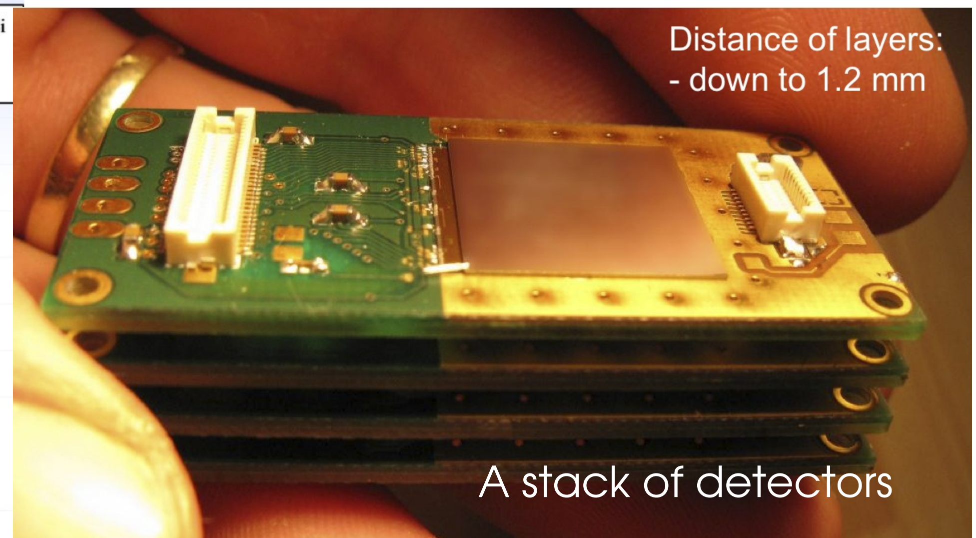
http://www.cern.ch/MEDIPIX

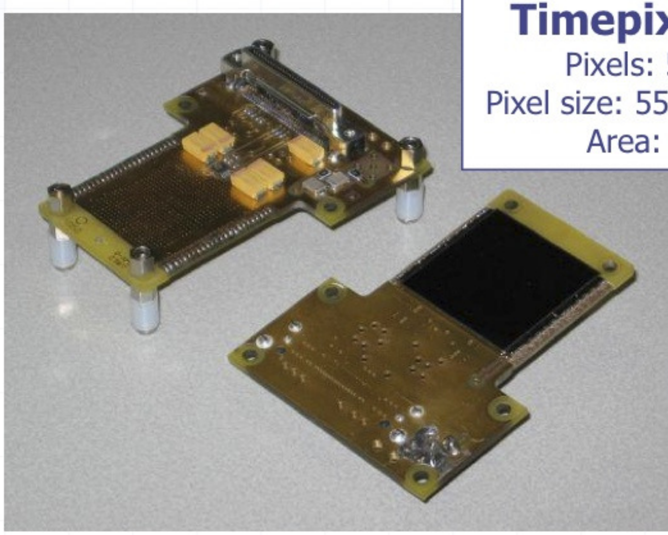
MEDIPIX based large area systems



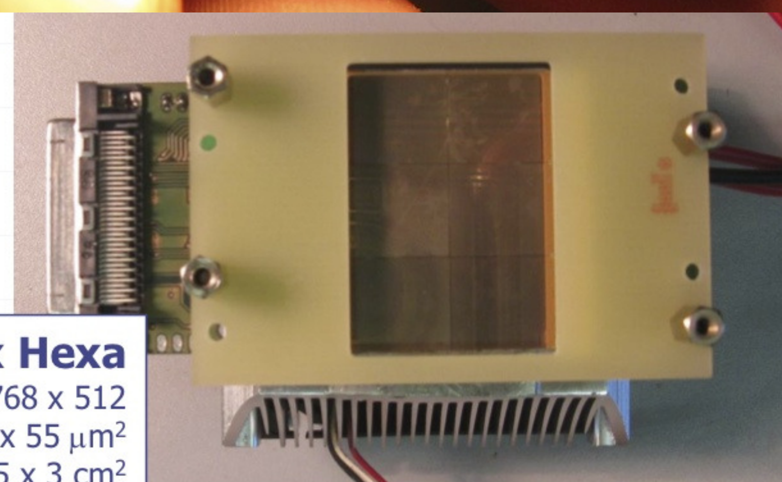
The building block







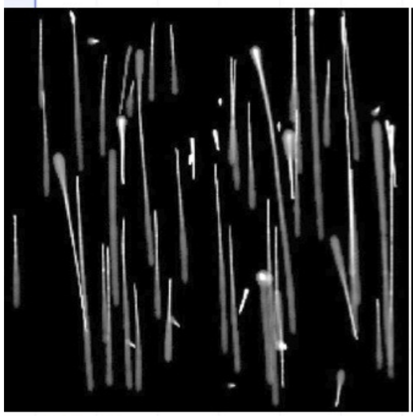
Timepix Quad
Pixels: 512 x 512
Pixel size: 55 x 55 μm^2
Area: 3 x 3 cm^2



Timepix Hexa
Pixels: 768 x 512
Pixel size: 55 x 55 μm^2
Area: 4.5 x 3 cm^2

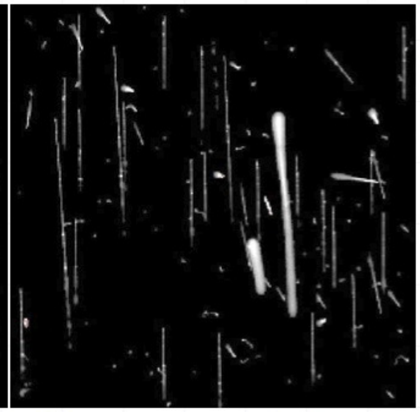
Measurement of the LET curve (TIMEPIX, TOT)

Protons 48 MeV



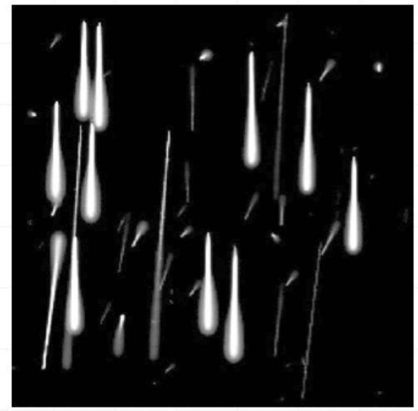
Only protons and their scattering, no secondaries.

Protons 221 MeV



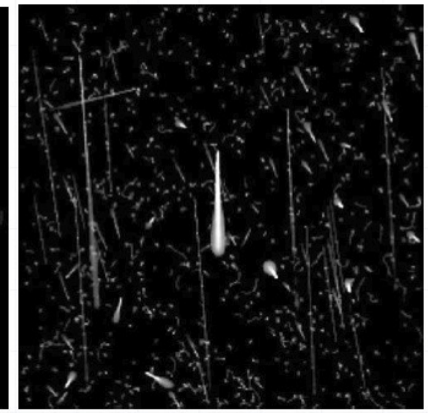
Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u

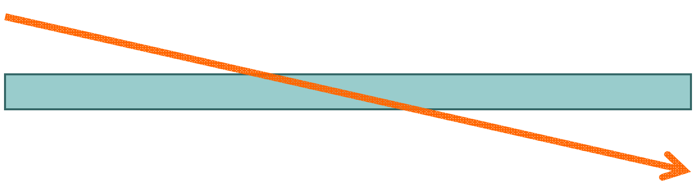


Carbons and protons and their scattering, no secondaries.

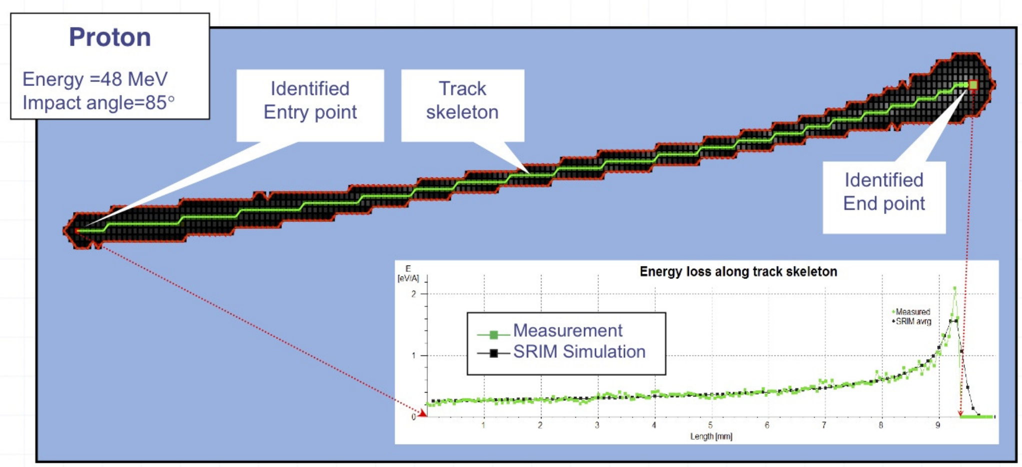
Carbons 430 MeV/u



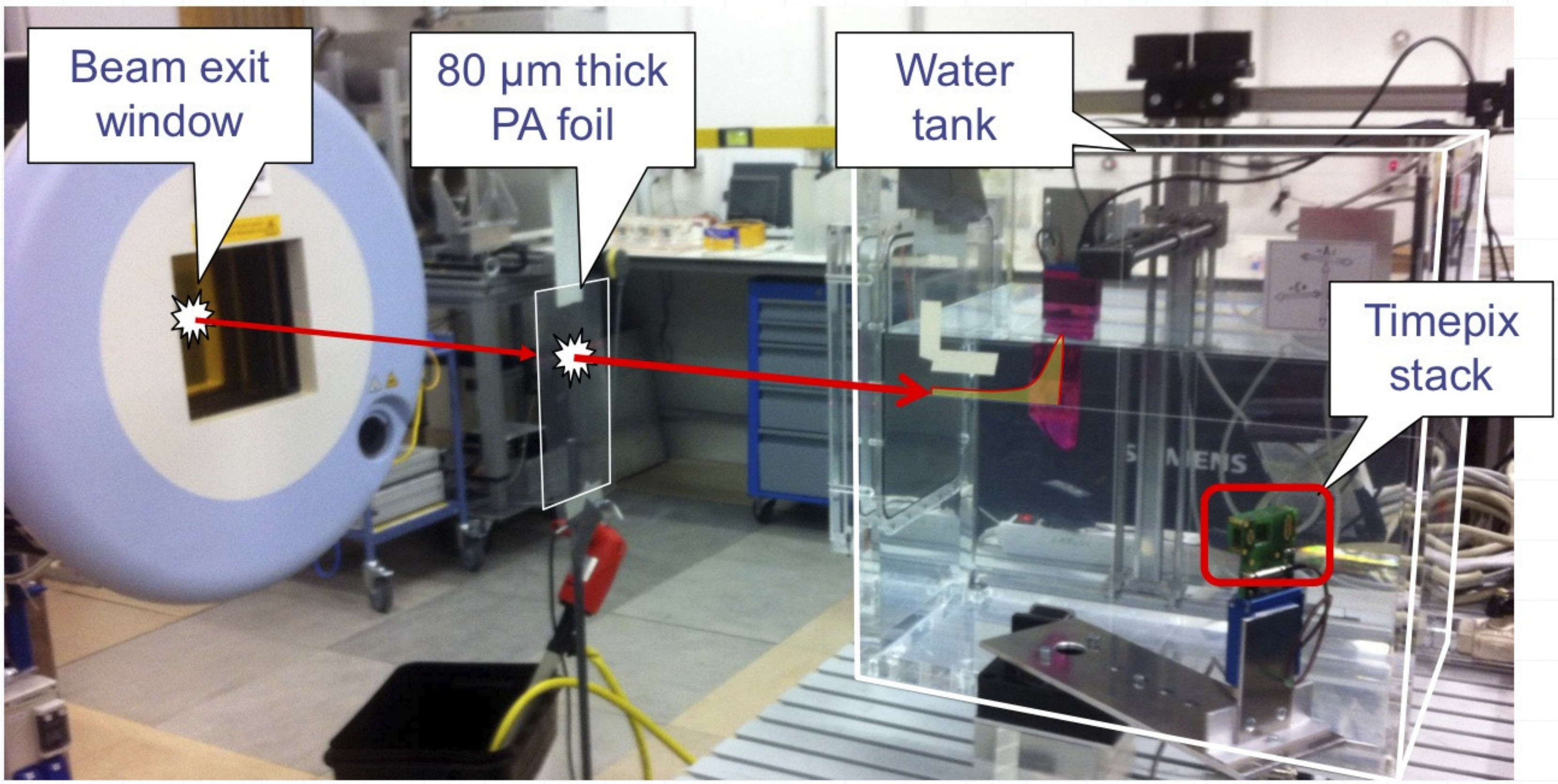
Carbons and many secondaries.



Characterizing particles by their track while crossing at shallow angle the detector



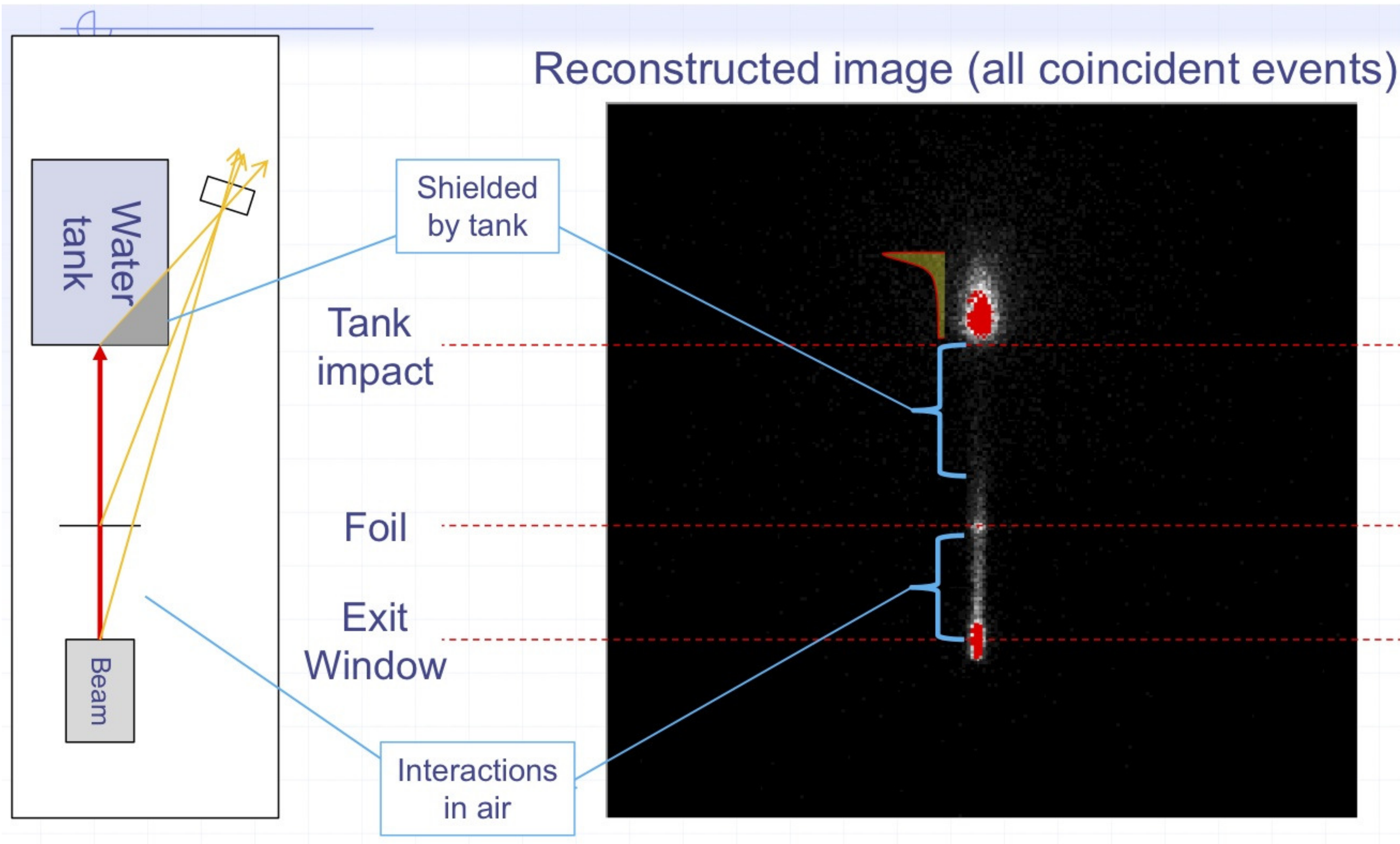
Imaging scattered radiation along the HIT beam (1/3)



Experimental set-up (Sensor=2 cm^2, distance=140 cm)

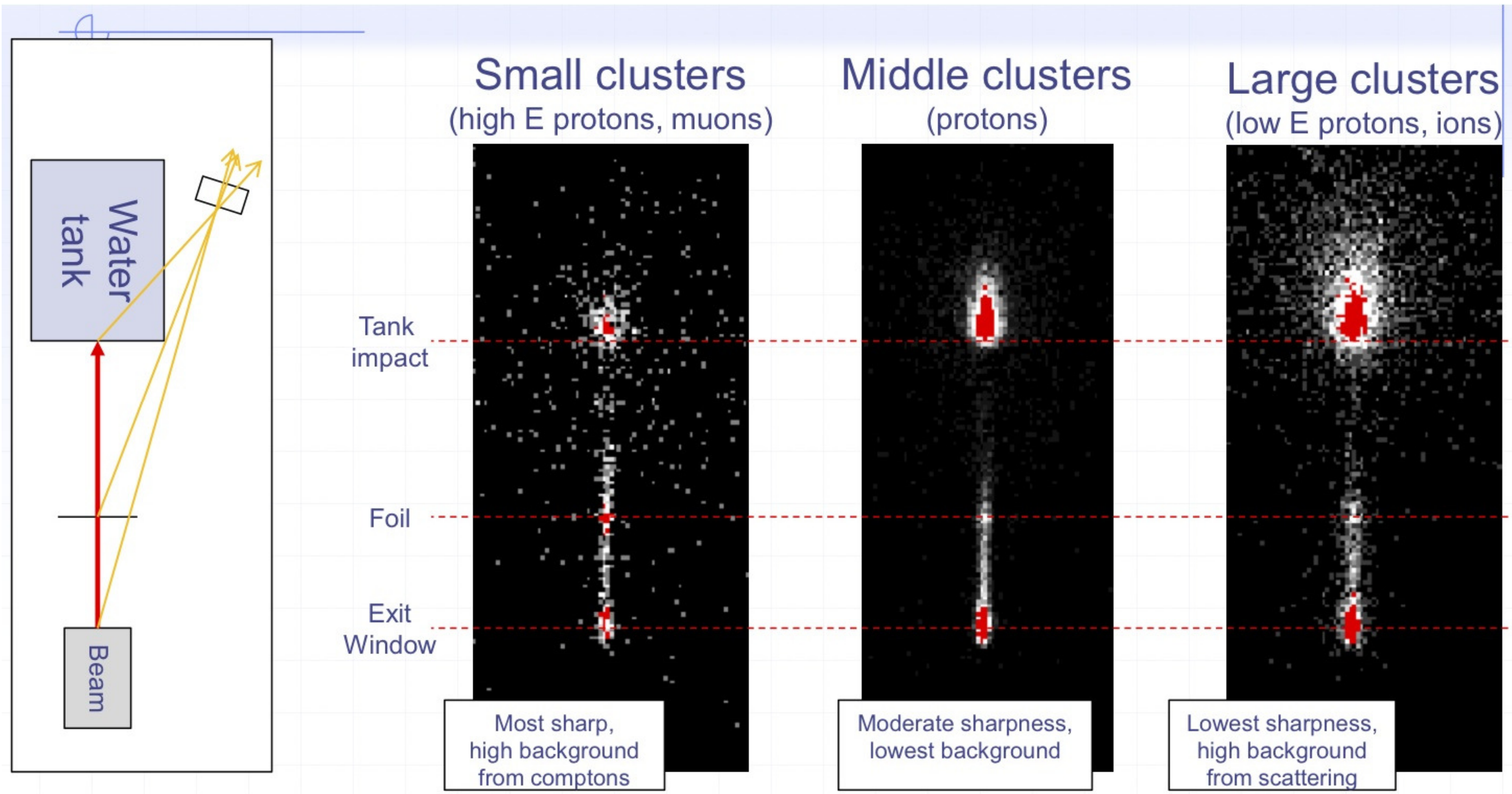
Imaging scattered radiation along the HIT beam (2/3)

(^{12}C at 250 MeV/u, 8 min at beam intensity of 5×10^6 ions/sec)

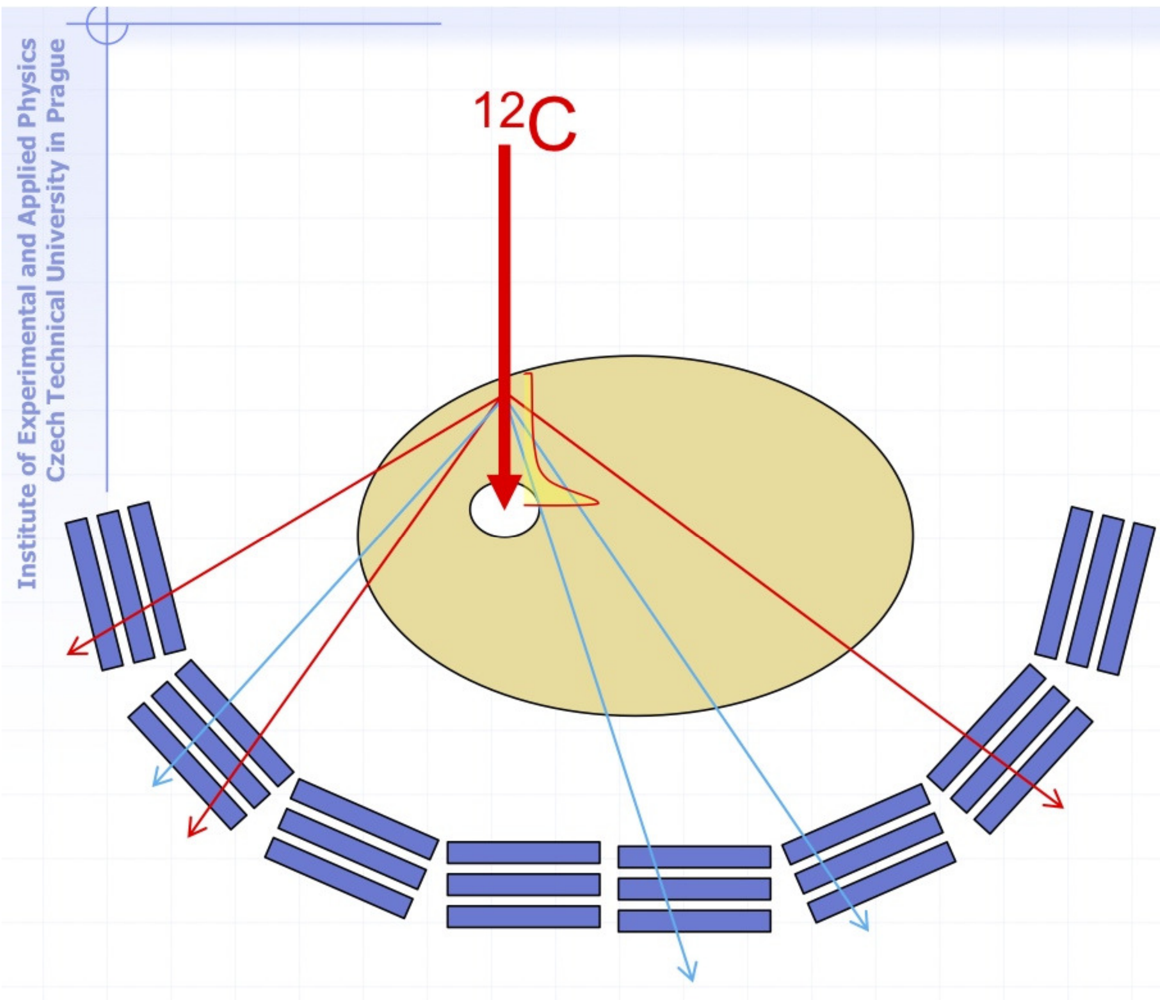


Imaging scattered radiation along the HIT beam (3/3)

(telling a particle by its cluster shape)



The final goal: improve the treatment plan by measuring scattered and secondary radiation

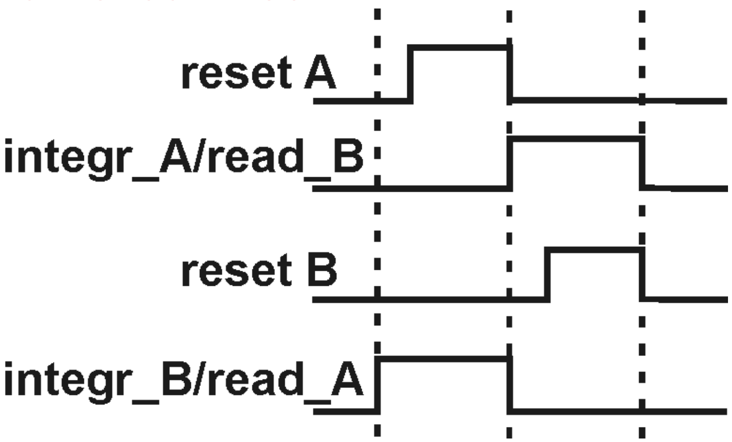


- The tracker would optimally surround the irradiated body.
- Tracker data can be back-projected to form an image of the beam path.
- Possibility to select particles with higher penetration power would improve quality.

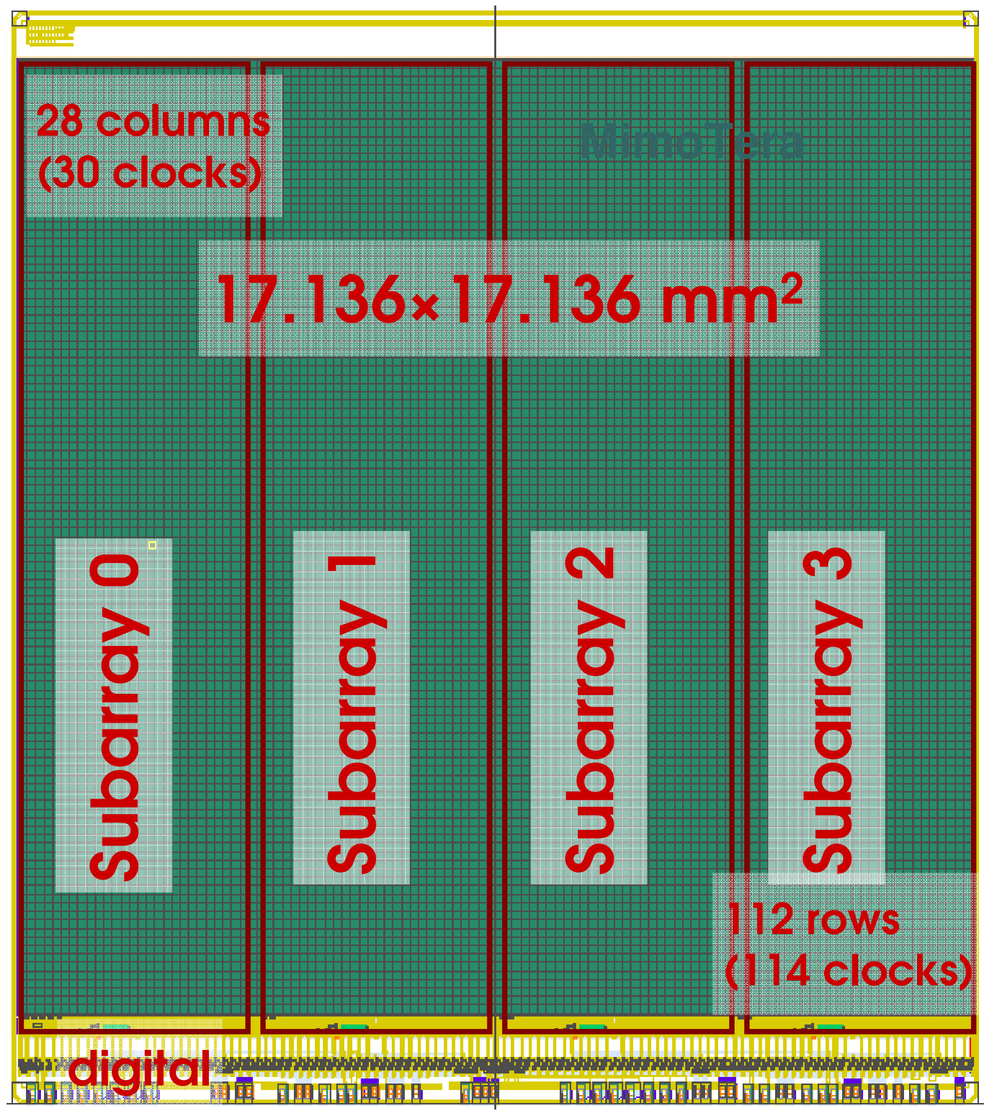
Exemplary illustration 3:

the MIMOTERA: a monolithic pixel detector for real-time beam imaging and profilometry
(U.S. patent no. 7,582,875
contact: massimo.caccia@uninsubria.it)

- AMS CUA 0.6 μm CMOS 15 μm epi,
- chip size: 17350×19607μm^2
- array 112×112 square pixels,
- four sub-arrays of 28×112 pixels read out in parallel $t_{read/integr}$<100μs **(i.e. 10 000 frames/second)**
- **Backthinned** to the epi-layer (~ 15 μm), back illuminated through an ~80 nm entrance window

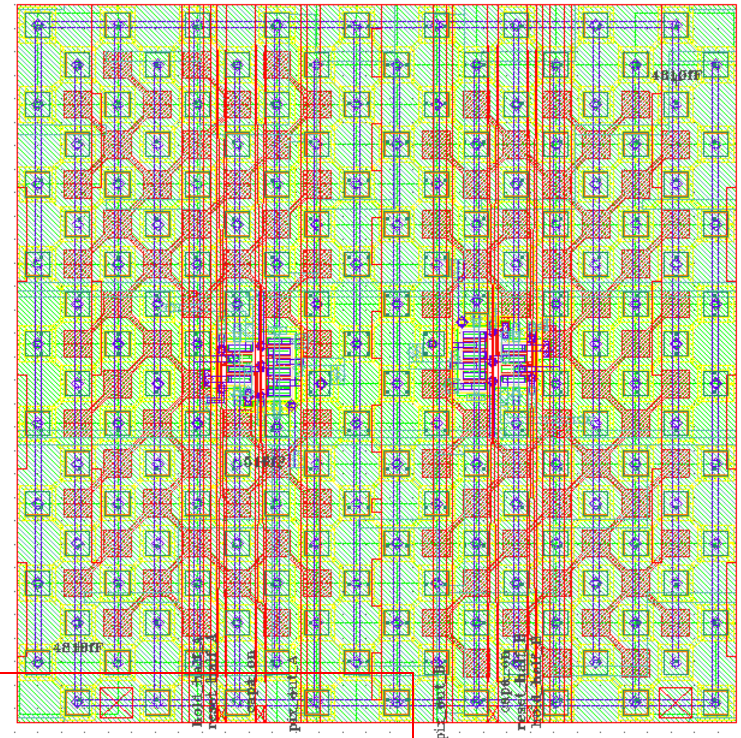


- **no dead time**

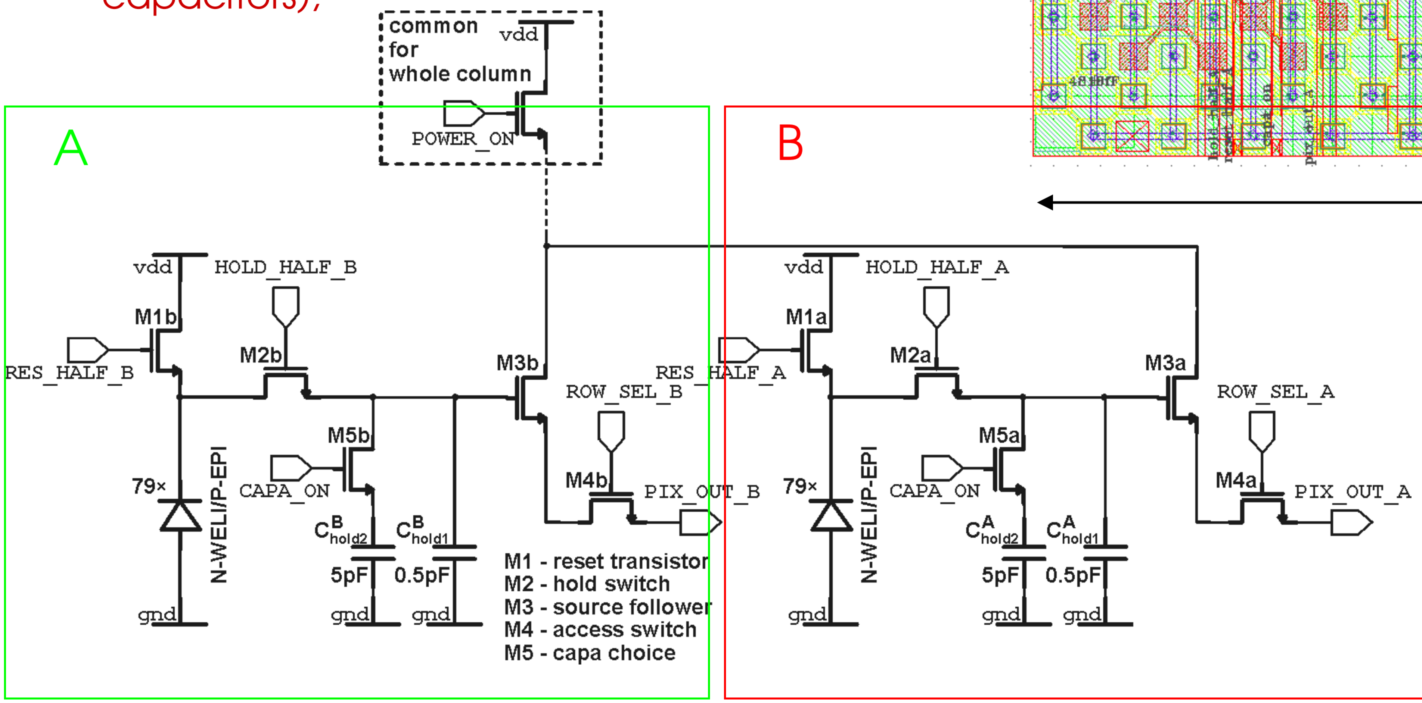


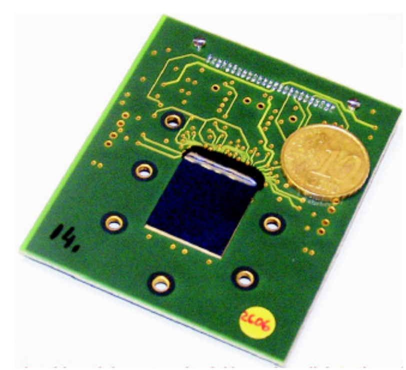
Essentials on the MIMOTERA (continued):

- pixel 153×153 µm^2 square pixels,
- two 9×9 interdigited arrays (**A** and **B**) of n-well/p-epi collecting diodes (5×5 µm^2) + two independent electronics – avoiding dead area,
- In-pixel storage capacitors – choice ~0.5 pF or ~5 pF to cope with signal range (poly1 over tox capacitors),



153 µm

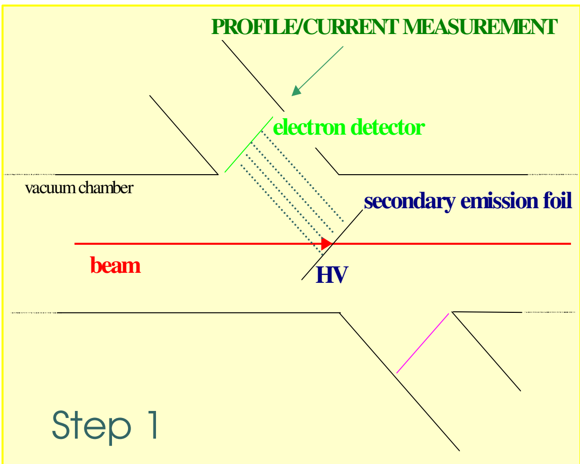


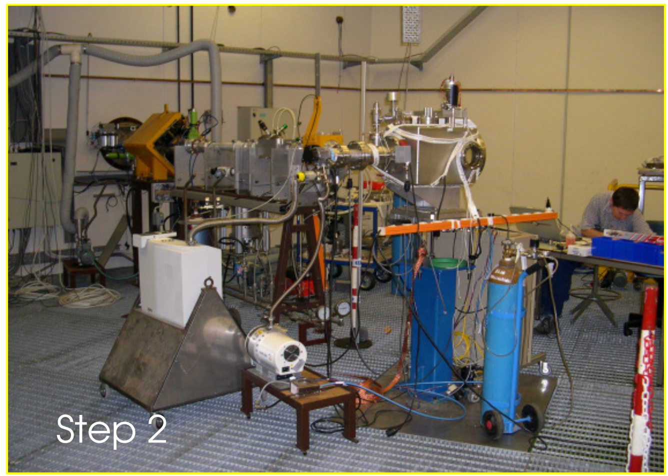


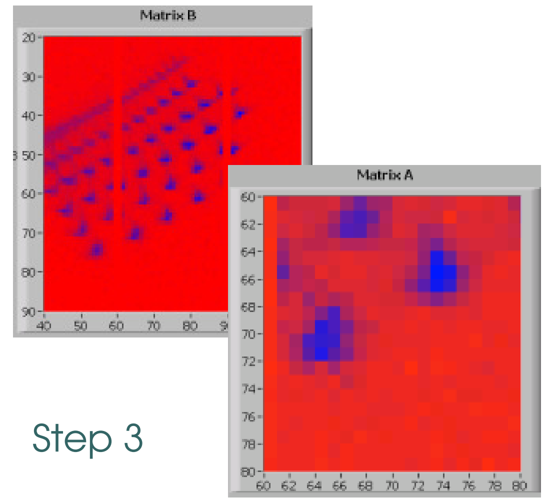
- Charge To Voltage Factor = ~250nV/e$^-$ @ 500fF ⇒ well capacity of ~ 36 MeV
- Noise ~1000 e$^-$ Å 280 e$^-$ kTC (ENC) @ 500fF

Original push for the MIMOTERA development: minimally invasive real-time profilometry of hadrontherapy beams by secondary electron imaging

(IEEE Trans.Nucl.Sci. 51, 133 (2004) and 52, 830 (2005)))







Basic principle:
collection and imaging of secondary 20 keV electrons emitted by sub- mm thin Aluminum foils

The SLIM installed on an extraction line at the Ispra JRC-Cyclotron
(p, 2H, 4H at energies 8-38 MeV, 100 nA- 100uA)

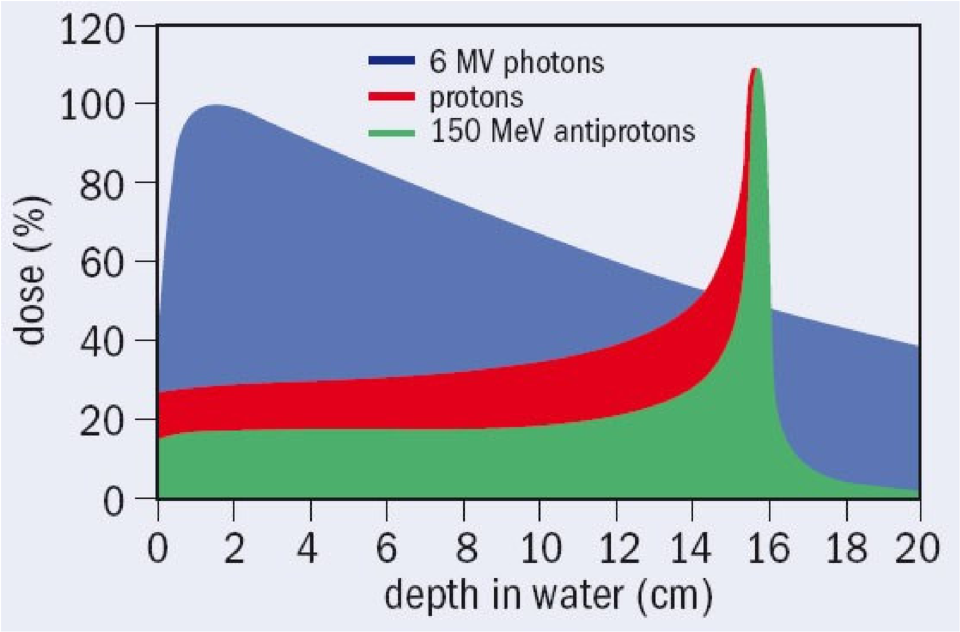
Secondary electrons emitted by a proton beam through a multi-pin hole collimator (Ø = 1mm, pitch = 1.5-6.5 mm)

Today: results on beam imaging by DIRECT IMPACT on the sensor

Assisting the AD-4 (ACE) collaboration

(ACE, http://www.phys.au.dk/~hknudsen/introduction.html)

"Cancer therapy is about collateral damage"
⇒ compared to a proton beam, an antiproton beam causes four times less cell death in the healthy tissue for the same amount of cell deactivation in the cancer.



(courtesy of ACE)

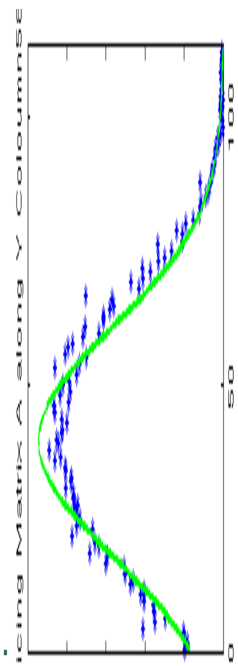
Michael Holzscheiter, ACE spokesperson (left), retrieves an experimental sample after irradiation with antiprotons, while Niels Bassler (centre) and Helge Knudsen from the University of Aarhus look on (courtesy of ACE)

Shot-by-shot beam recording at the CERN anti-proton decelerator tests

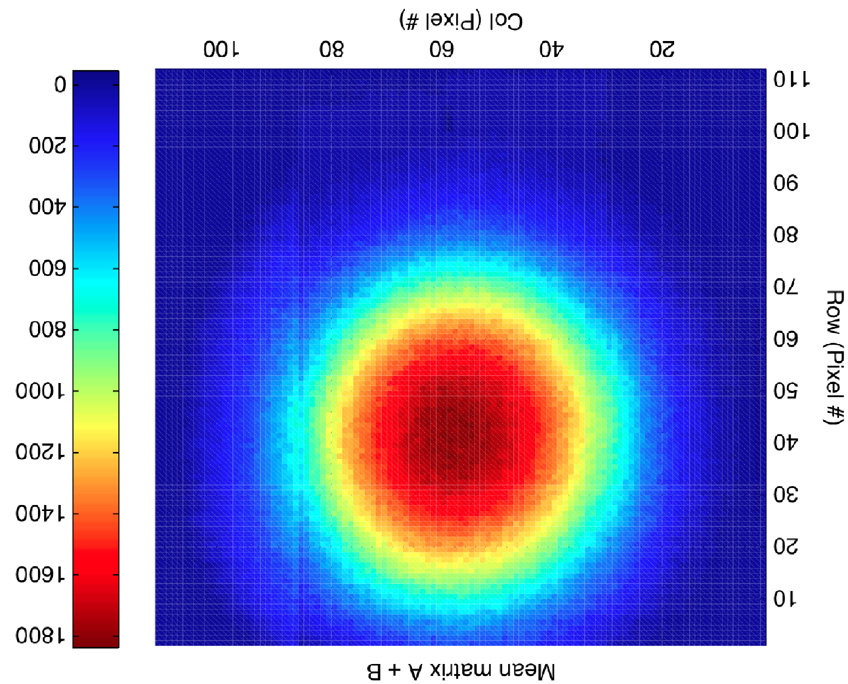
- beam characteristics:
  - -120 MeV energy
  - - $3x10^7$ particles/spill
  - - 1 spill every 90”
  - - FWHM ~ 8 mm
- acquisition modality:
  - - triggered
- imaging modality:
  - - differential
- radiation damage:
  - - irrelevant so far

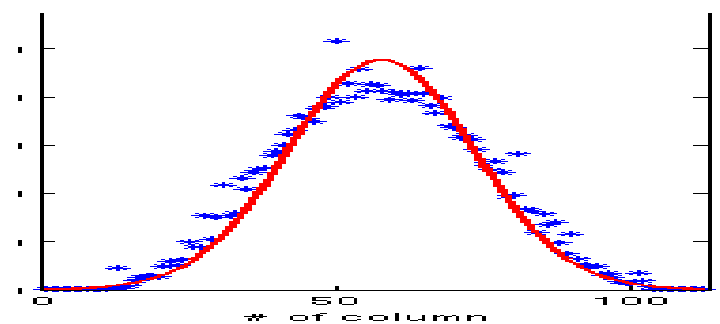
(max no. of spills on a detector: 1436)

- data taking runs:
  - - September 2009
  - - June 2010
  - - October 2010



Single shot picture

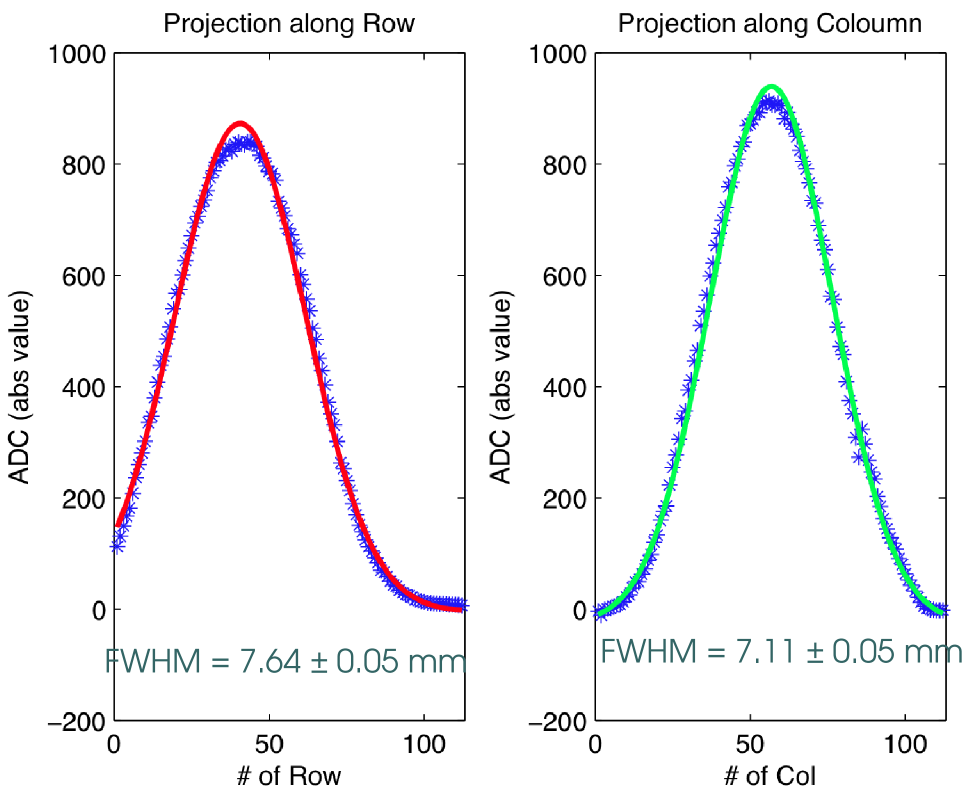


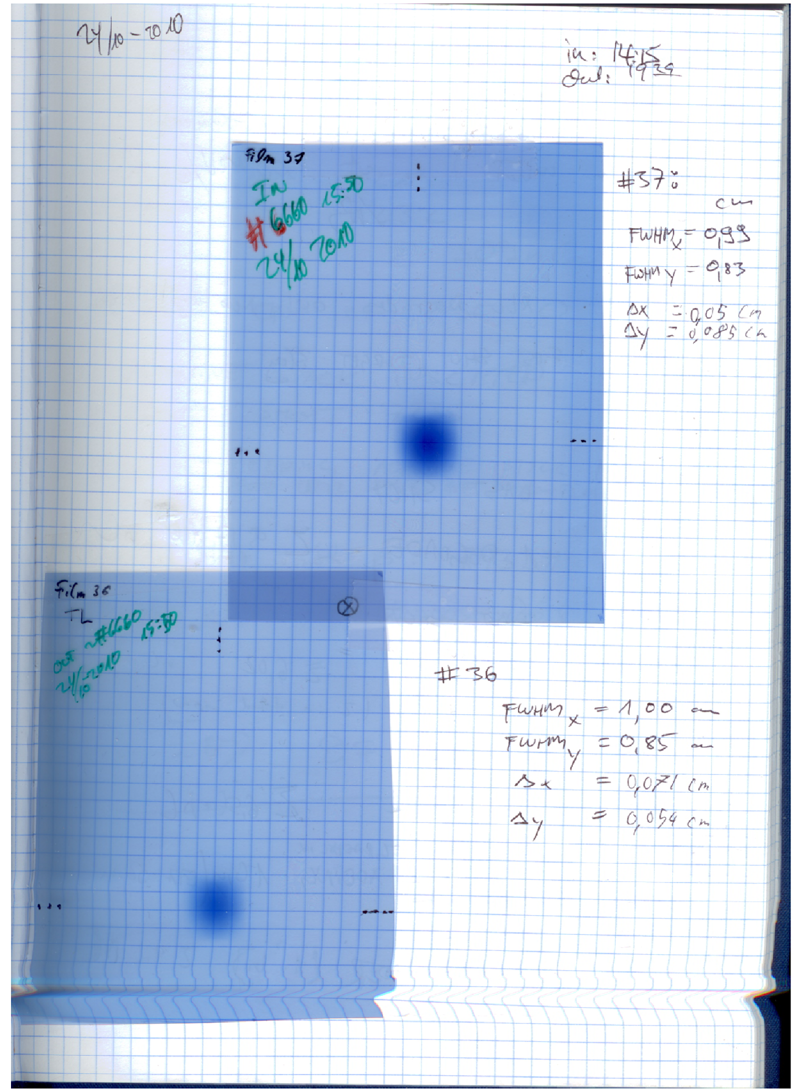


Profiling the beam

(PRELIMINARY RESULTS:
- FWHM calculation checked,
- errors on the GAF still being evaluated)

With the MIMO, overlaying the 120 events in run #37 events to mimic the Gaf

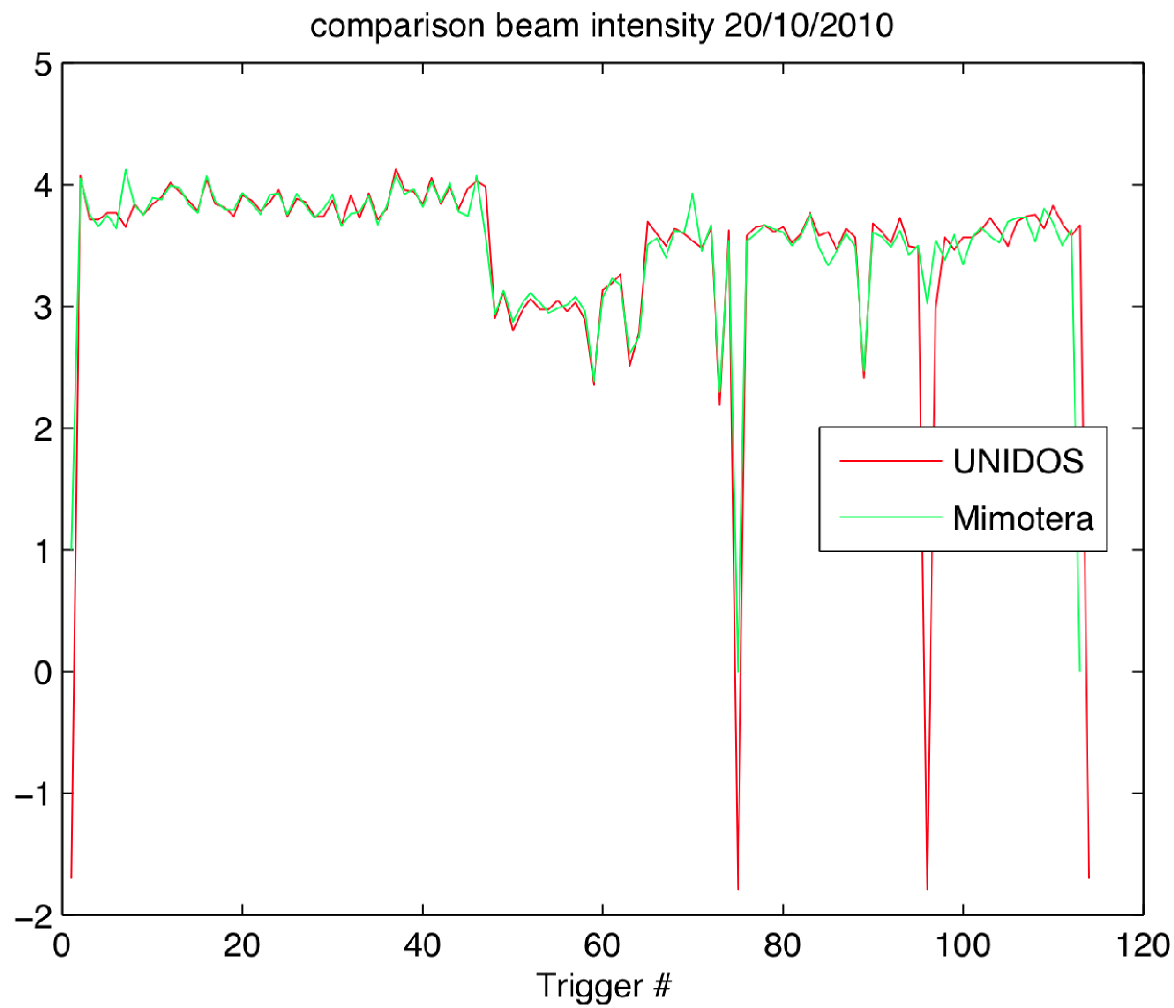




With a GafChromic Film, integrating the spills over a full run …and PROJECTING

Monitoring the intensity fluctuations

MIMO
Vs
UNIDOS*



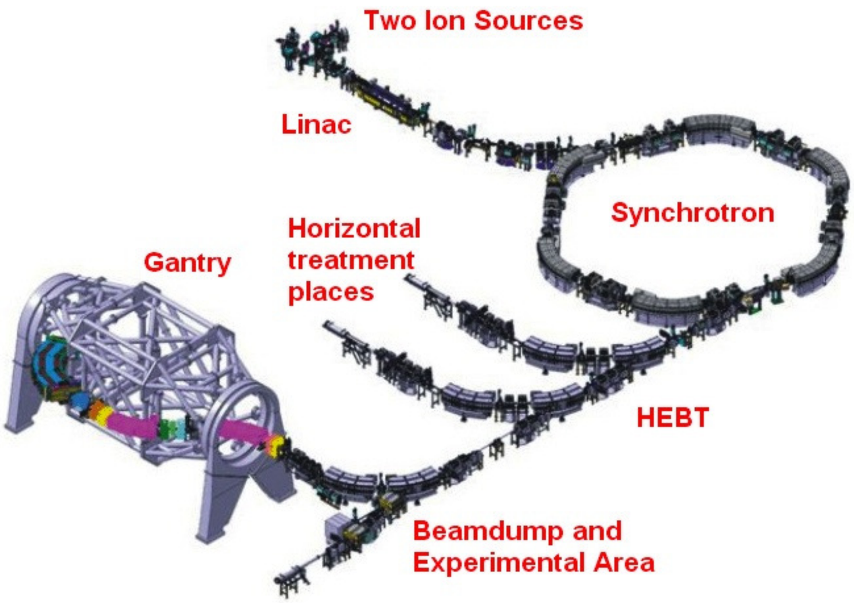
*The PTW UNIDOS is a high performance secondary standard and reference class dosemeter / electrometer

HIT (Heidelberg Ion-Beam Therapy Center): Quality control of pencil Carbon Ions & proton beams

http://www.klinikum.uni-heidelberg.de/index.php?id=113005&L=en

The facility building

The accelerator complex
(patients treated since 2008)



The beam parameters

Properties	Protons	Carbon Ions
X_{min}		
X_{max}		
E_{min} [MeV/u]	48.12	88.83
E_{max} [MeV/u]	221.06	430.1
Energy steps	255 steps, 1mm in depth each	
$FWHM_{min}$ [mm]	8.1-12.6*	3.4-9.8*
$FWHM_{max}$: [mm]	32.4-32.7*	9.8 – 13.4*
Focus steps	4 steps	
I_{min} [s^{-1}]	2.0×10^{8}	5.0×10^{6}
I_{max} [s^{-1}]	3.2×10^{9}	8.0×10^{7}
Intensity steps	8 steps	

* small values for high energies

Interested in high granularity (in time & space) and linearity against the deposited energy

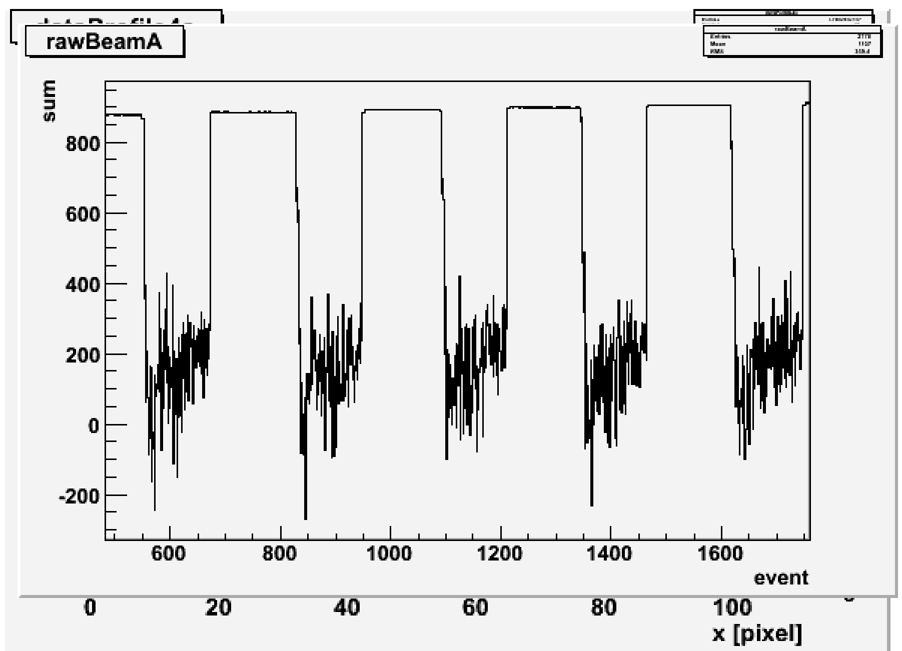
Data taking conditions & qualitative information

- **beam time characteristics:**
  - duty cycle 50%
  - spill duration 5 s
  - FWHM ~f(particle, intensity, energy)
- **acquisition modality:**
  - free run
- **imaging modality:**

$$\sum_i [Signal - Pedestal]_i \,, i \in ROI$$

- **radiation damage:**
  - relevant but not dramatic

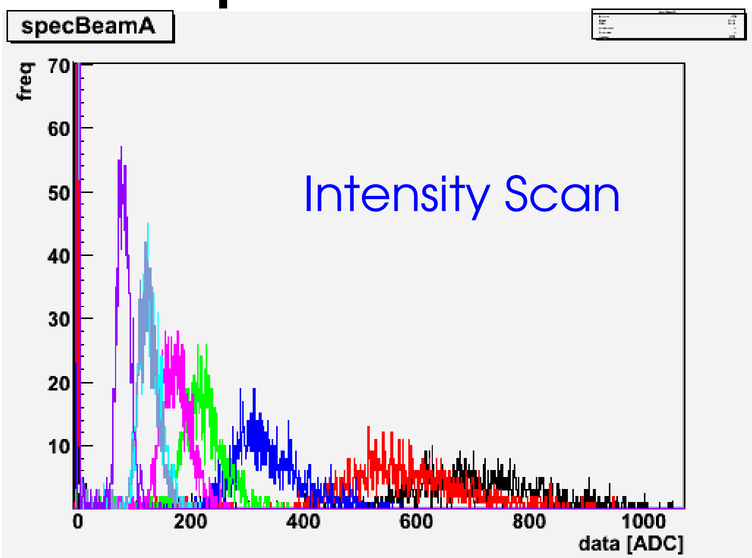
  (Total exposure time so far ~ 3h; about 1′-2′ per run at a specified nrj, intensity)
- **data taking runs:**
  - May 2010
  - October 2010

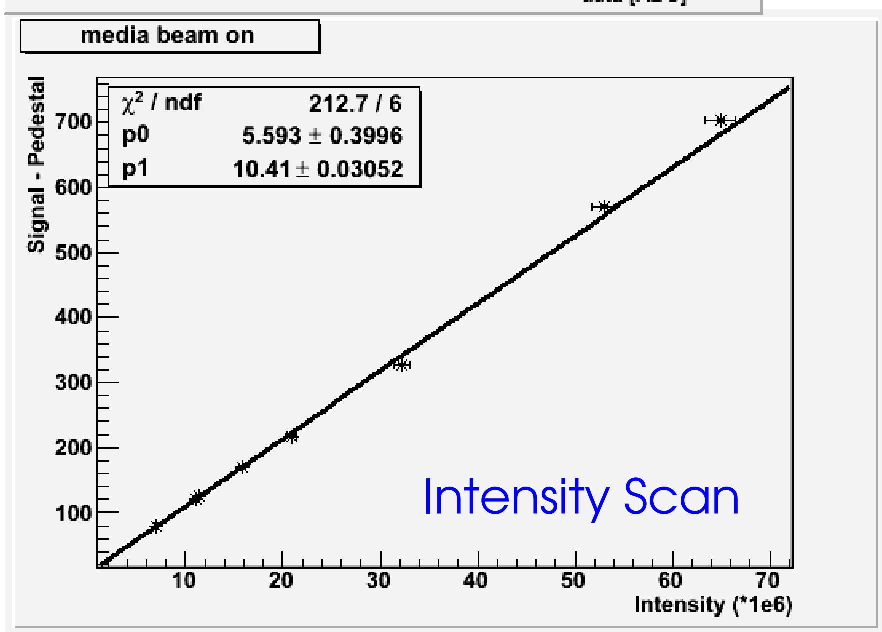


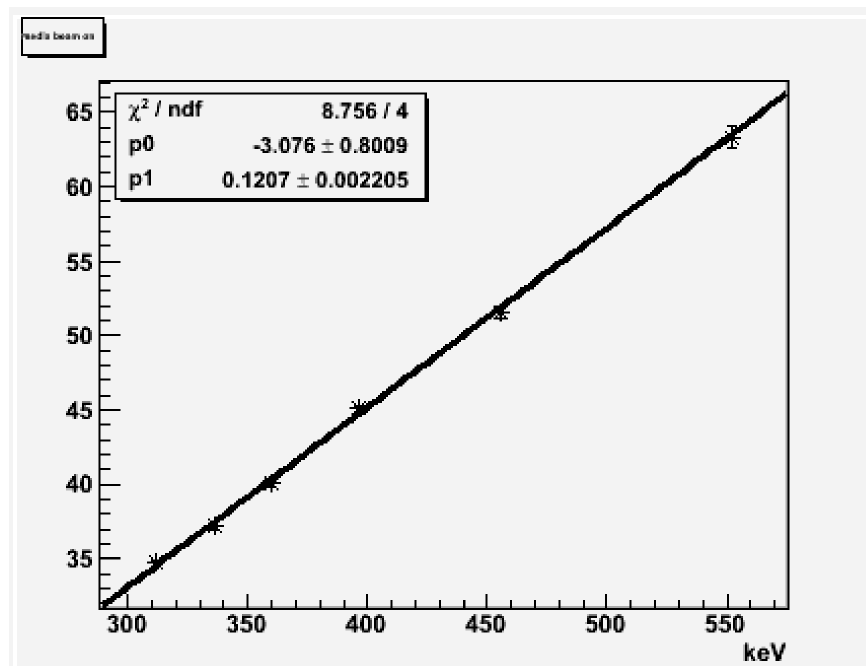
Time development of the beam

I = 7×10^7 particles/s, C ions

Quantitative information (C ions)







Energy Scan

Imaging the LARN Tandem beams at Namur (B)

Main interests:

- The MIMO as a real-time, high granularity "digital" alumina screen, to optimize the set-up

- QC of the beam in terms of homogeneity

- quick measurement of the absolute intensity (particle counting!)

Data taking conditions & qualitative information

❖ **beam time characteristics:**

- continuous beams!
- any ion (!) with an energy in MeV/amu range
- intensities ∈ $(10^3;10^8)$ p/cm^2/s range

❖ **acquisition modality:**

- free run; MIMOin vacuum

❖ **radiation damage:**

- may really be dramatic!

(Total exposure time so far ~ 60h; p, α, C ion beams)

❖ **imaging modality:**

- standard: signal - pede
- differential: $\Delta(i,j,n)$ = signal (i,j,n) - signal$(i,j,n-1)$
- based on $< \Delta^2(i,j,N) >$
- digital with a pixel dependent threshold

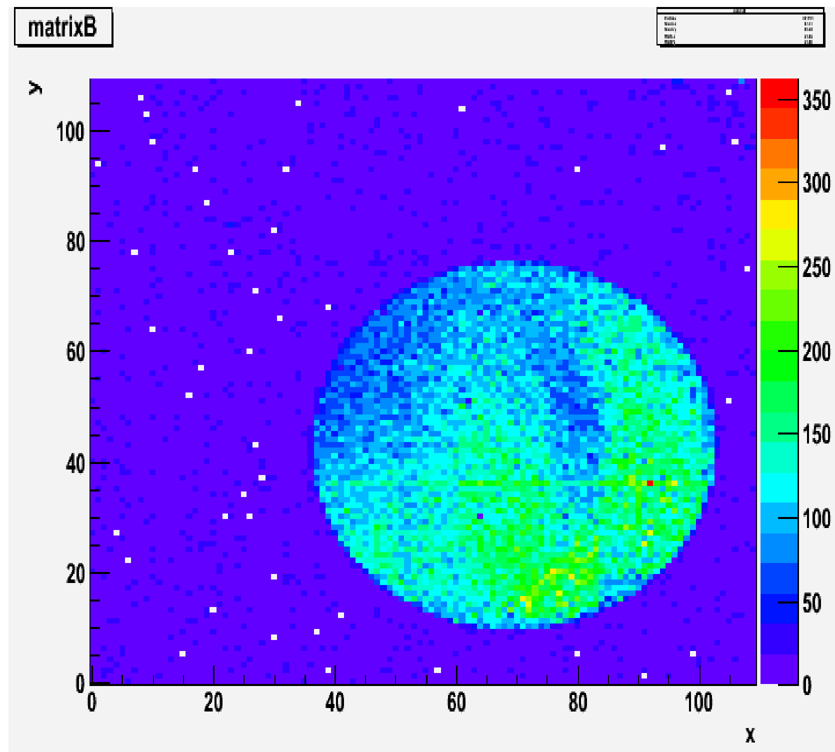


Image obtained by counting with pixel dependent thresholds

❖ **data taking runs:**

- July 2008, April 2009 + series of short runs since April 2010 performed by the people at LARN
- June 2011 (new DAQ commissioning)

Three runs:

- July 2008: proof of principle
- April 2009: improved set-up + extensive data set
- June 2011: commissioning new Data Acquisition System/extensive tests on different imaging modalities

❖ The MIMOTERA run in vacuum

❖ Real-time data handling (e.g. sum of a user specified number of frames) implemented

❖ Robust algorithms against radiation related effects tested

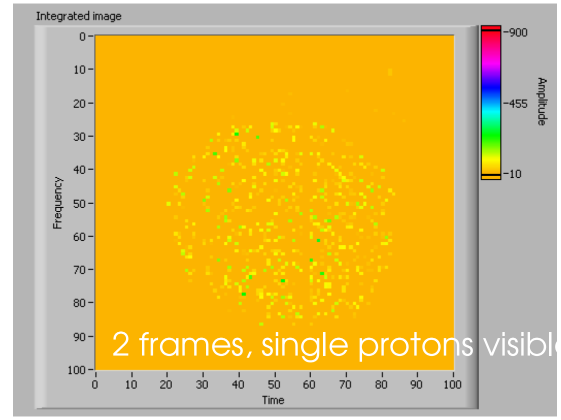
❖ exhaustive data set recorded:

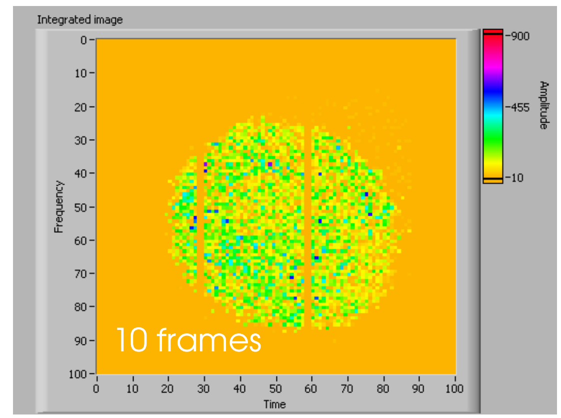
- v Scan over 3 orders of magnitude in intensity (p, I $\in$ (10^4 ; 10^7) p/cm^2/s, 1.2 MeV & 3 MeV energy)
- v Energy scan with protons (3.5 to 1 MeV)
- v Tested with C ions (Z = +3, 10^6 particles/cm^2/s, 7 MeV)
- v Tested with different readout frequencies (2.5 to 20 MHz)

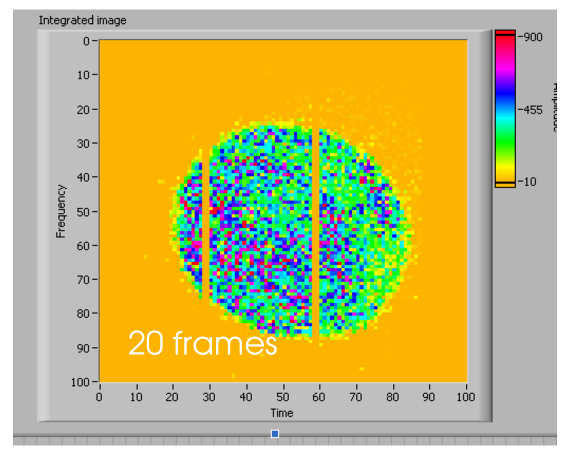
Real-time profiling

(2009 run)

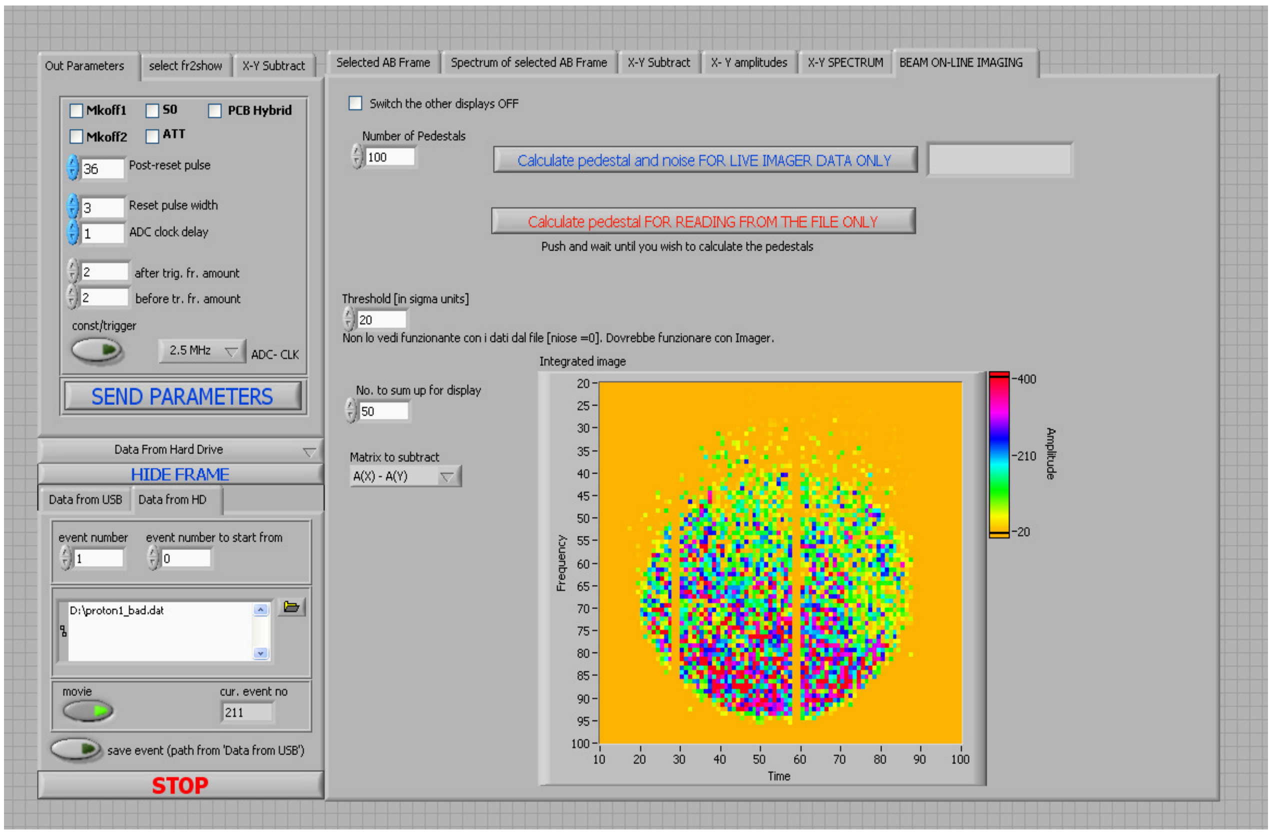
Costruction of a flat beam image overlapping different number of frames





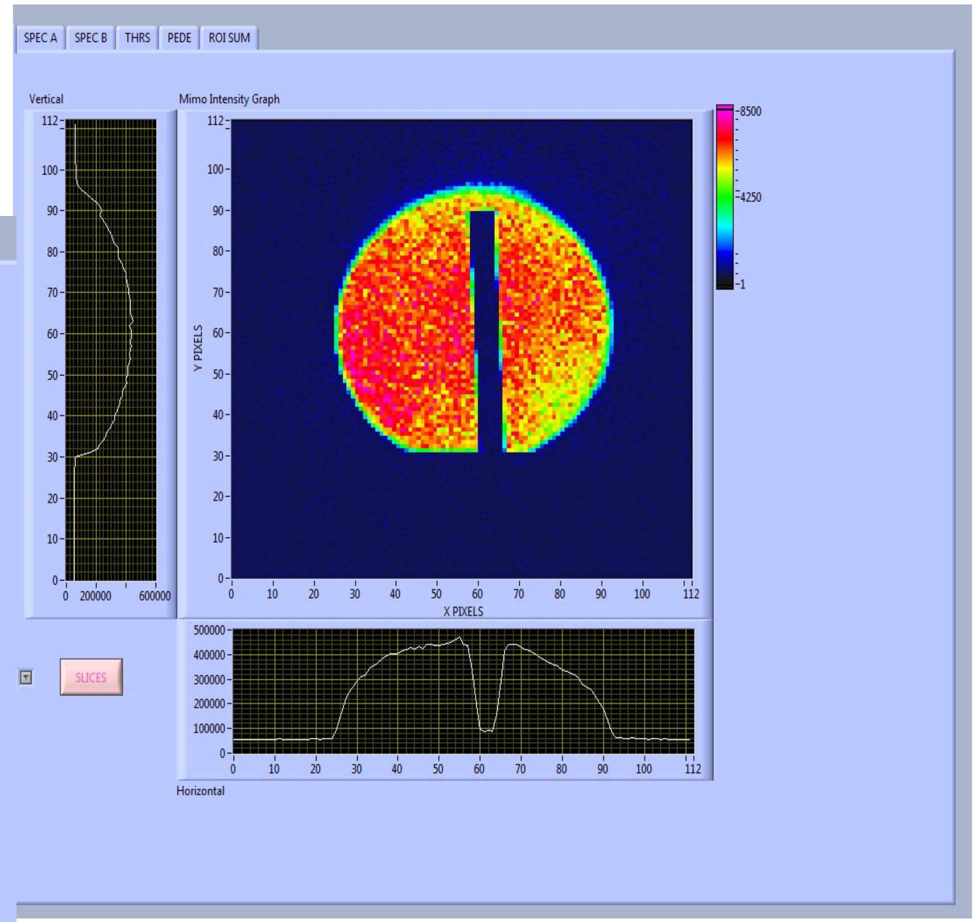


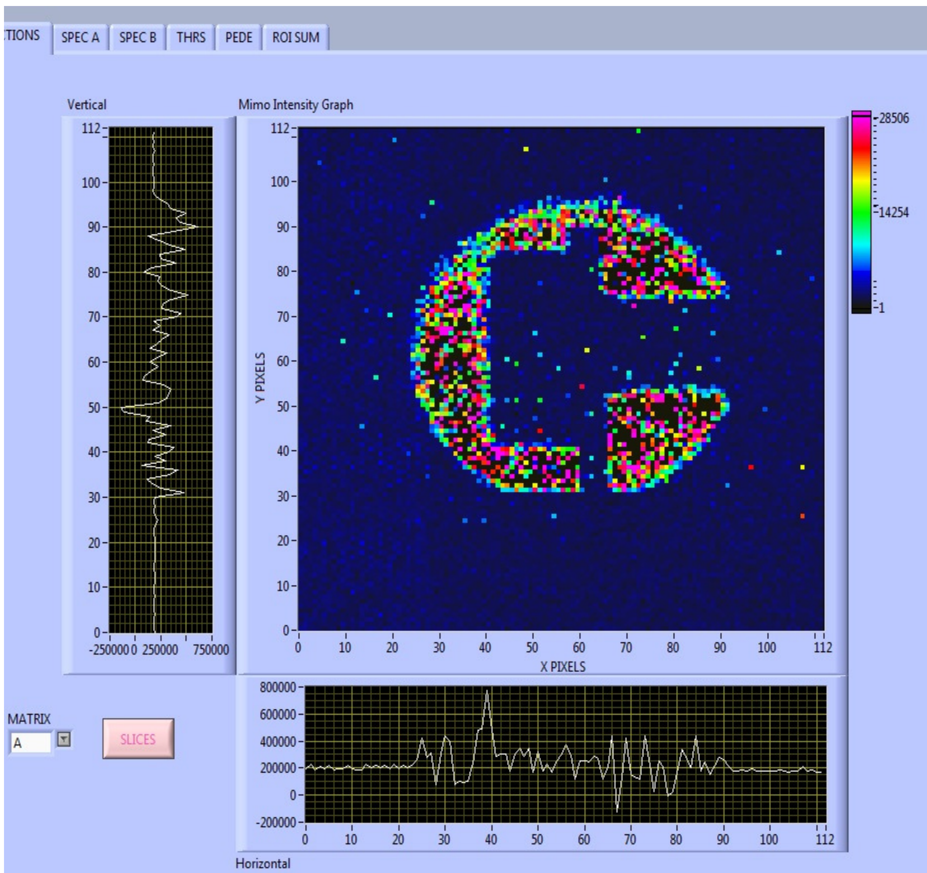
Bottom: image of a tilted beam, obtained overlapping a user defined number of frames



Real-time profiling
(2011 run)

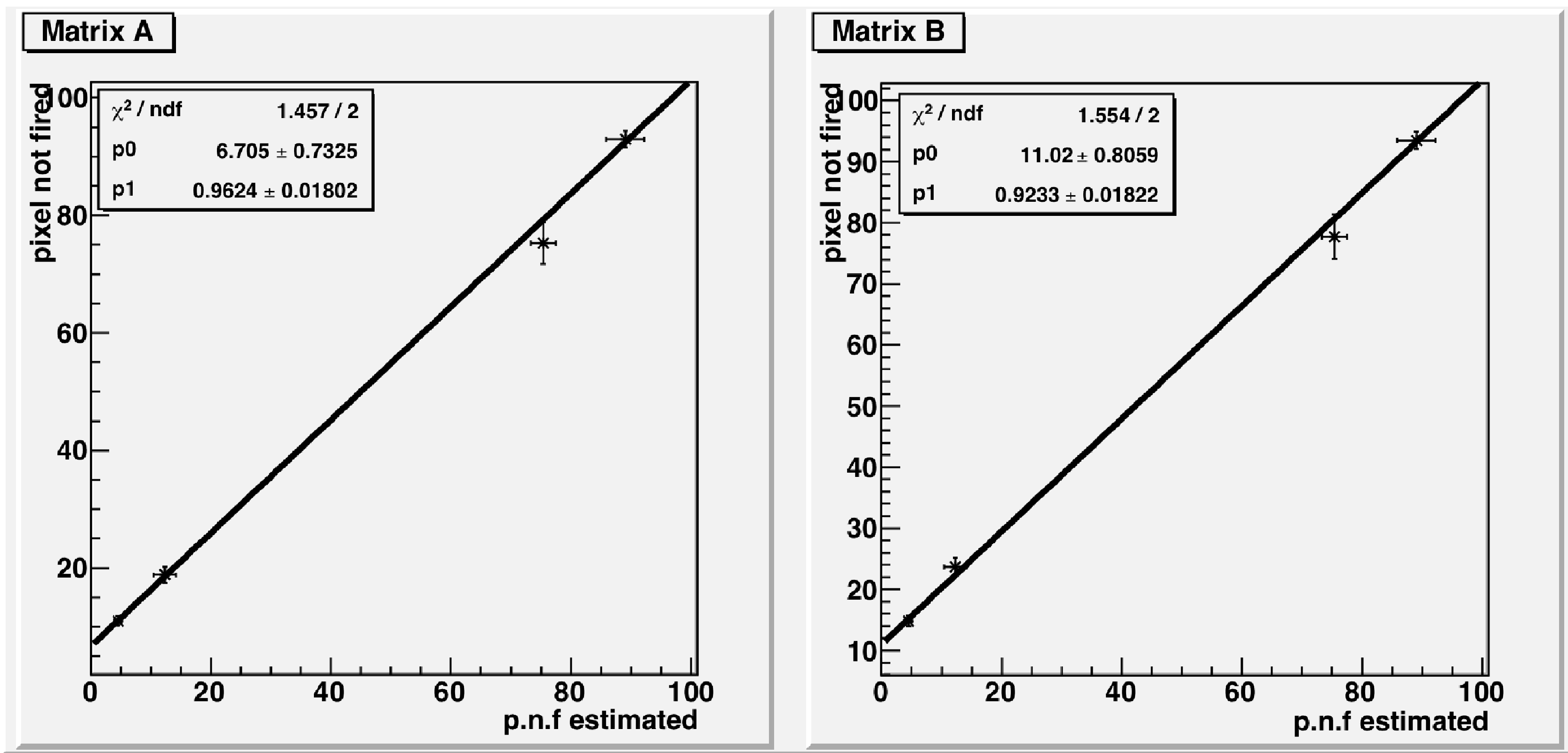
Two images of a proton beam showing the footprint of a fiber (right) and the fiber + the LARN reference detector in the beam area (bottom)





Exemplary Linearity plots, up to 8.8 x 10^6 particles/cm^2/s (limited by the reference instrument in use at Namur)

- protons, 1.2 MeV energy;
- MIMO clocked at 2.5 MHz
- differential mode



- Y axis: MIMO response; X axis: LARN reference instrument. The observable corresponds to the mean number of pixels NOT fired in a user specified region of interest in the beam core
- clocking at 25 MHz, we can use the MIMO in counting mode till ~ 10^8 particles/cm^2/s

Conclusions

❖ Position Sensitive Silicon detectors may certainly be considered a mature technology

❖ "Tools" are ready and several preliminary exercises have been performed

❖ we just need to foster the collaboration with the end-users and I'm sure we will have a lot of fun and more to report by the time of the next "event"!