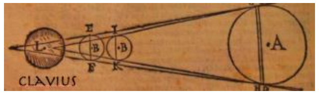
The MIMOTERA: a monolithic pixel detector for real-time beam imaging and profilometry

[U.S. patent no. 7,582,875]



Featuring:

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- ❖ DAQ:
  - ➢ A. Czermak [INP-KraKow]
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&

INFN- Sezione di Milano

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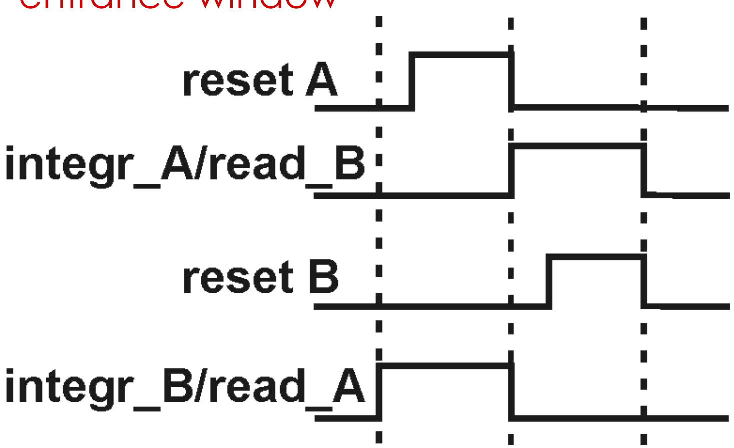
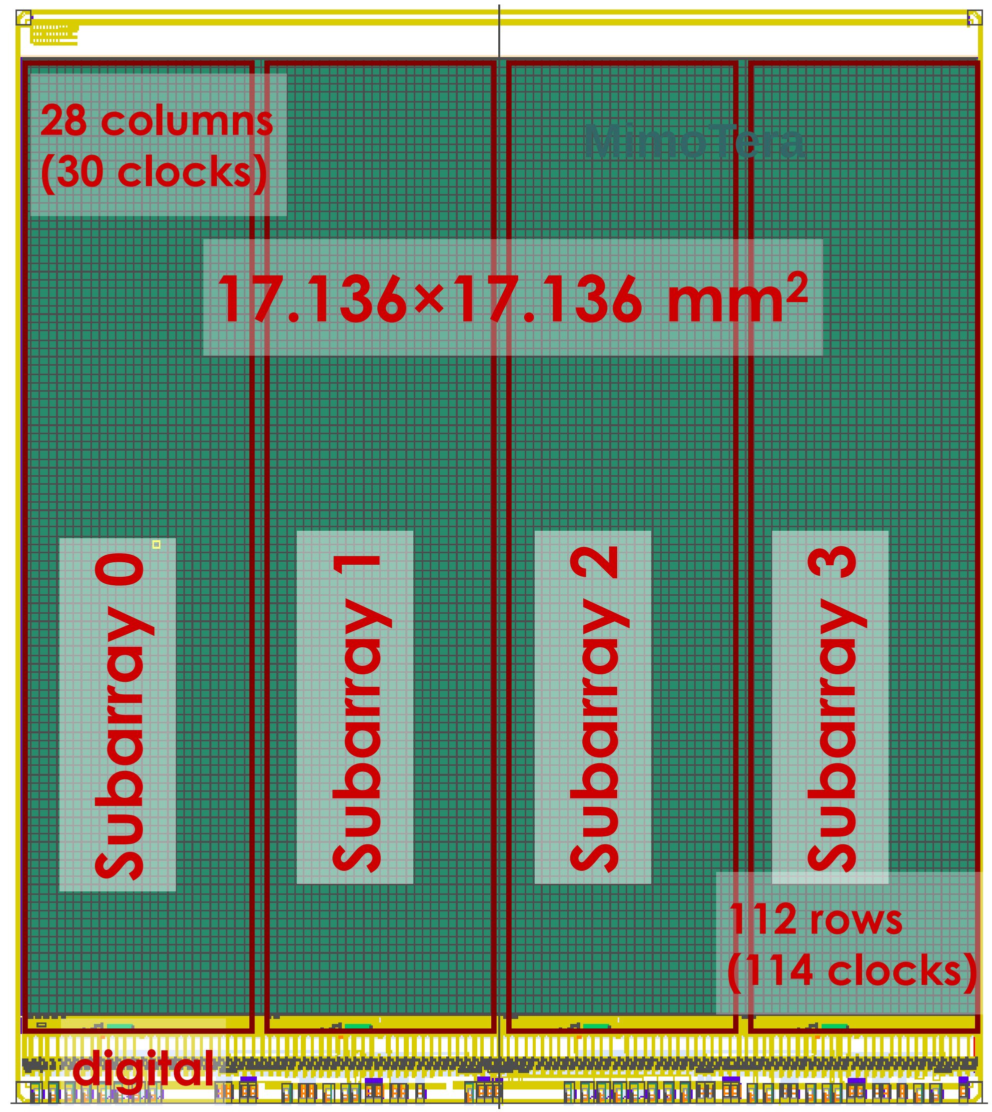
  - ➢ A.C. Wera [LARN]
  - ➢ S. Lucas [LARN]

the MIMOTERA: a monolithic pixel detector for real-time beam imaging and profilometry

- 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

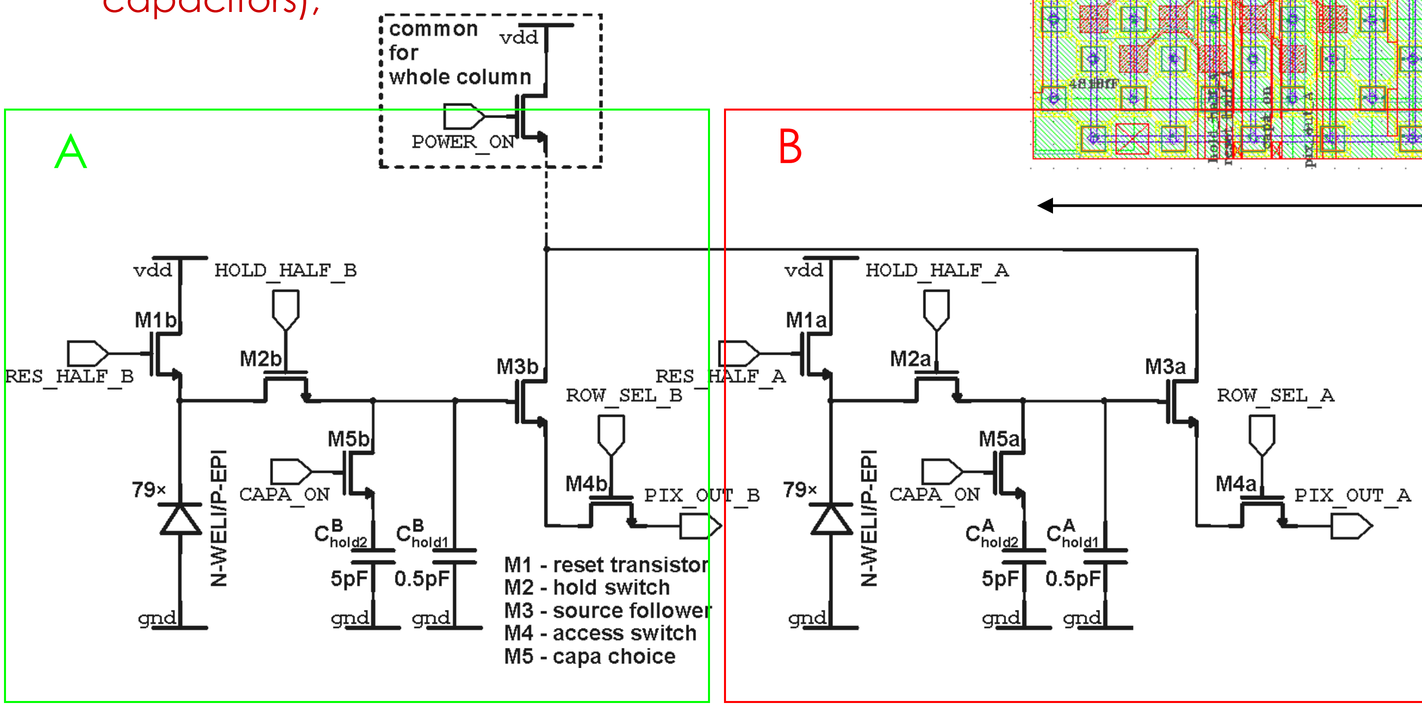


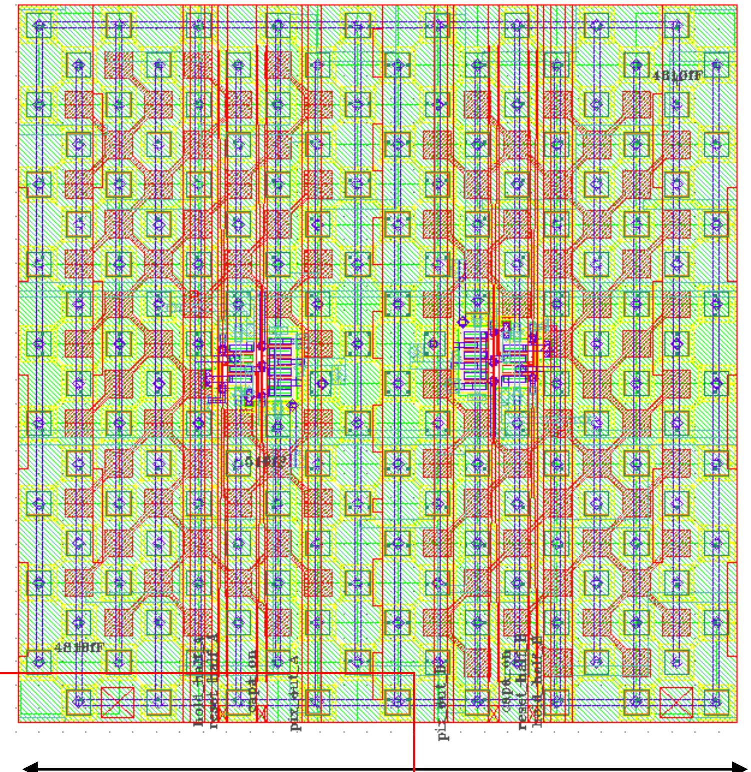
- **no dead time**



Essentials on the MIMOTERA [continued]:

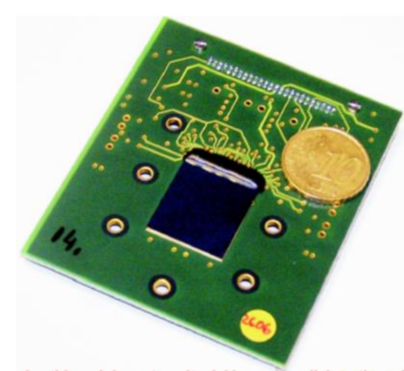
- pixel 153 × 153 µm² square pixels,
- two 9 × 9 interdigited arrays (**A** and **B**) of n-well/p-epi collecting diodes (5 × 5 µm²) + two independent electronics – avoiding dead area,
- In-pixel storage capacitors – choice ~0.5 pF or ~5 pF to cope with signal range (poly1 over tox capacitors),





153 µm

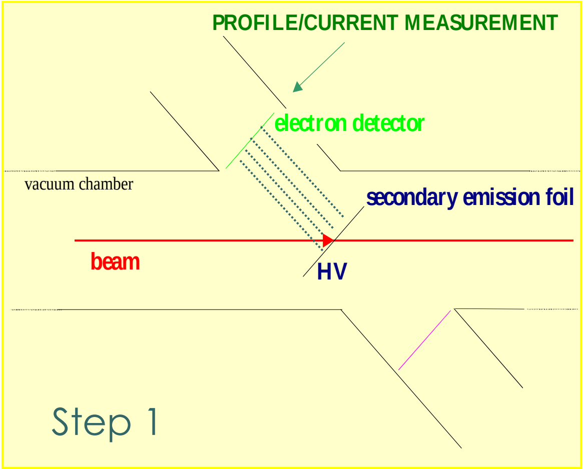
Layout of one pixel

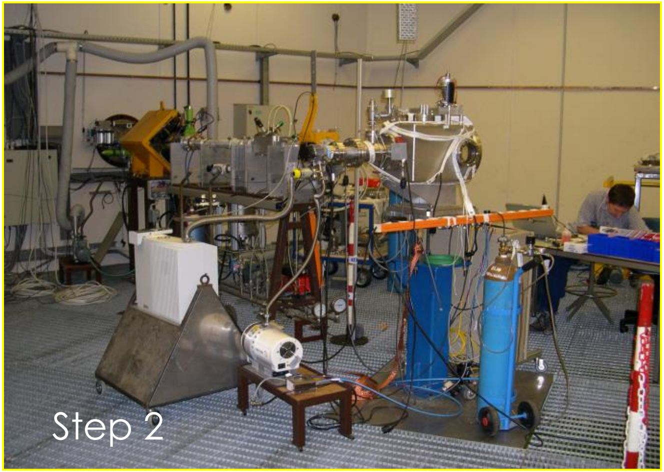


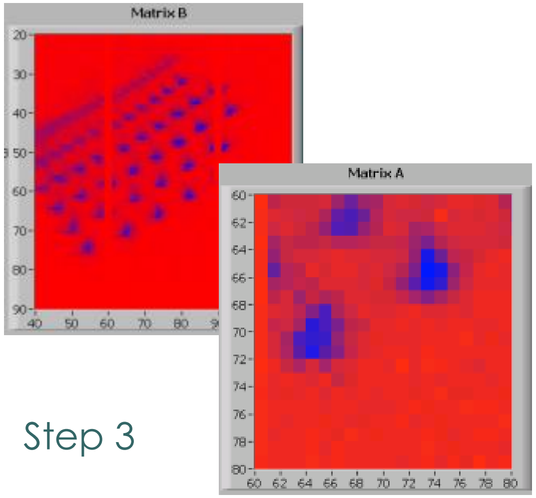
- Charge To Voltage Factor = ~250nV/e⁻ @ 500fF ⇒ well capacity of ~ 36 MeV
- Noise ~1000 e⁻ Å 280 e⁻ kTC (ENC) @ 500fF

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))]







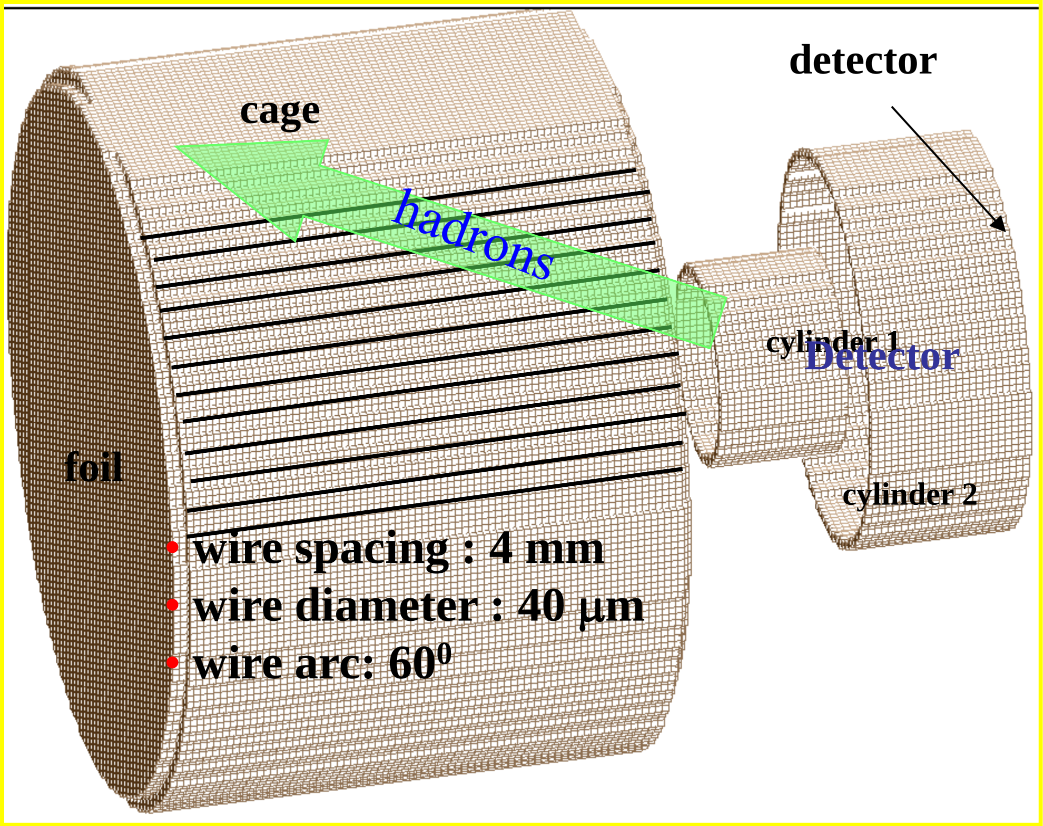
Basic principle:
collection and imaging of secondary 20 keV electrons emitted by sub- µm thin Aluminum foils

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

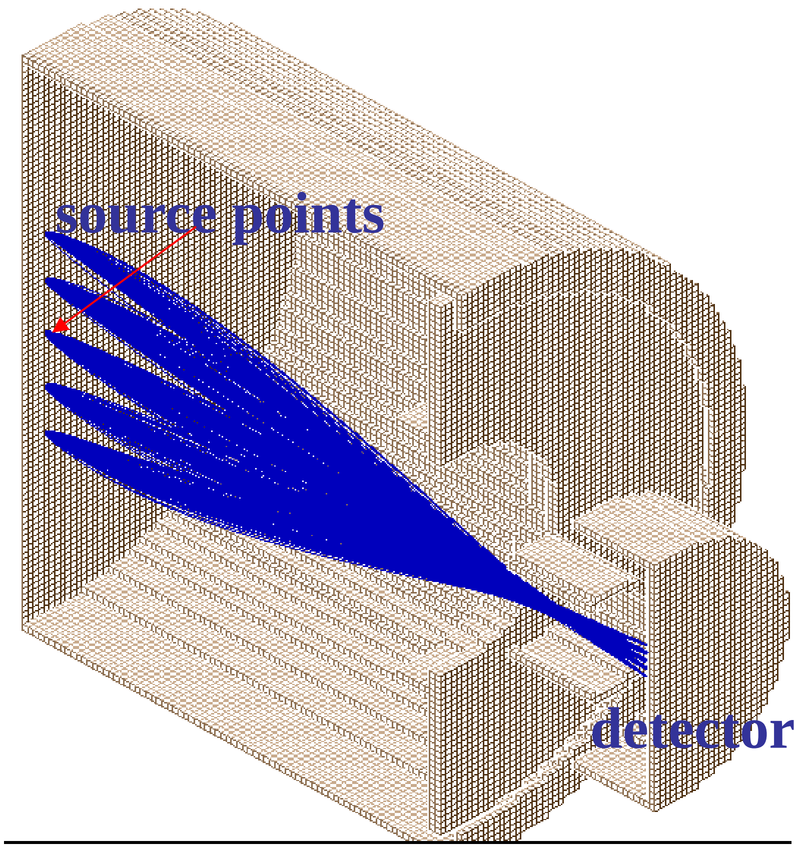
Secondary electrons emitted by a proton beam through a multi-pin hole collimator (Ø = 1mm, pitch = 1.5-6.5 mm)

Complemented by results on beam imaging by DIRECT IMPACT on the sensor

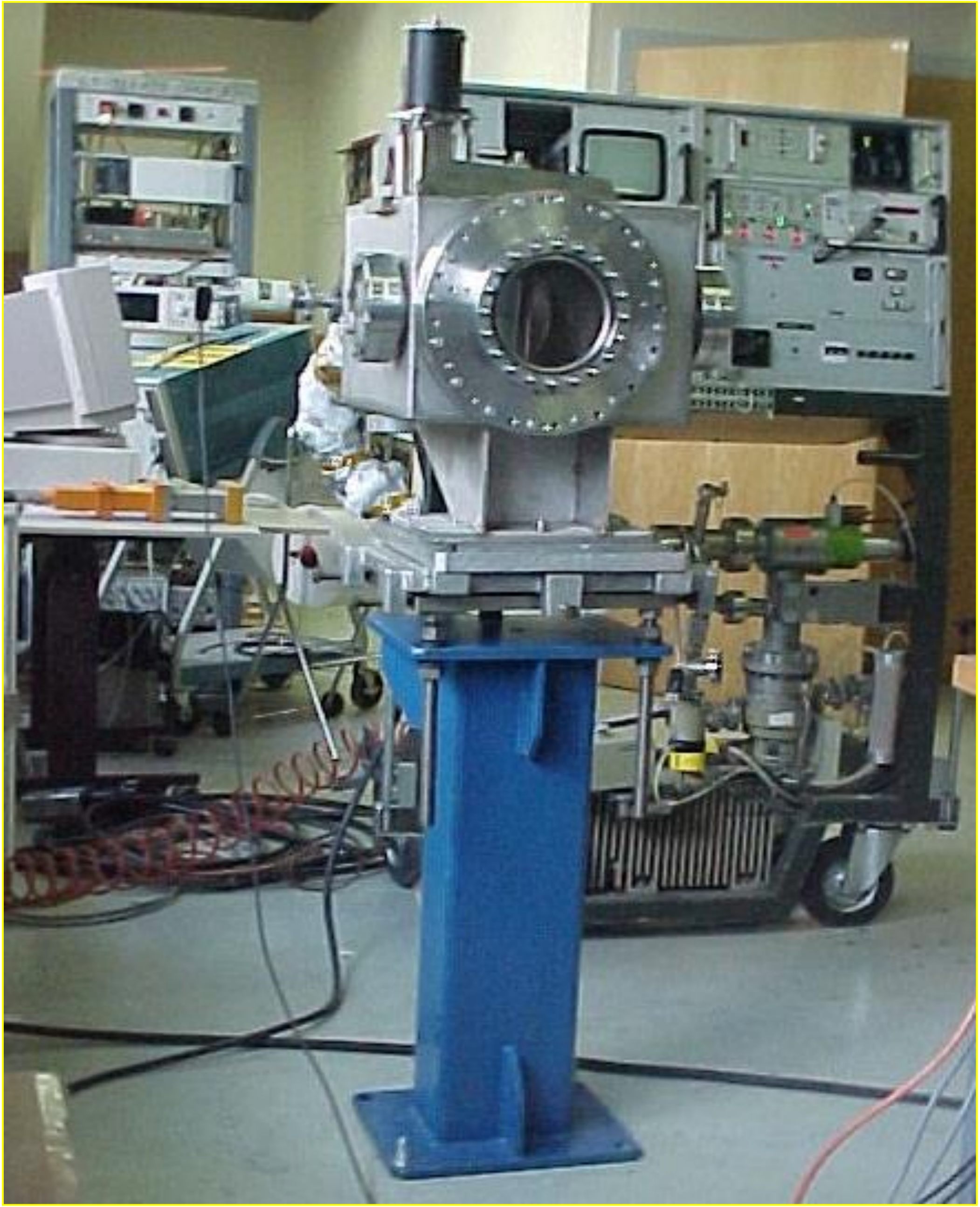
A closer look at the FOCUSING SYSTEM:



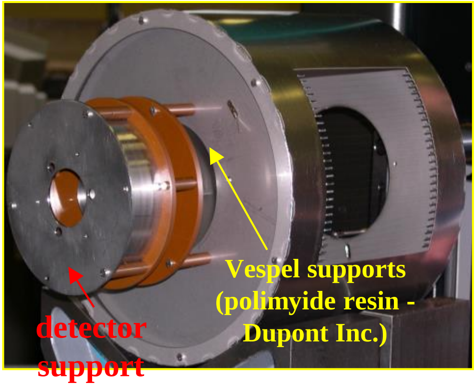
Secondary emission electrons drifted and focalized through a 20 kV field



Demagnifying factor ~ 5

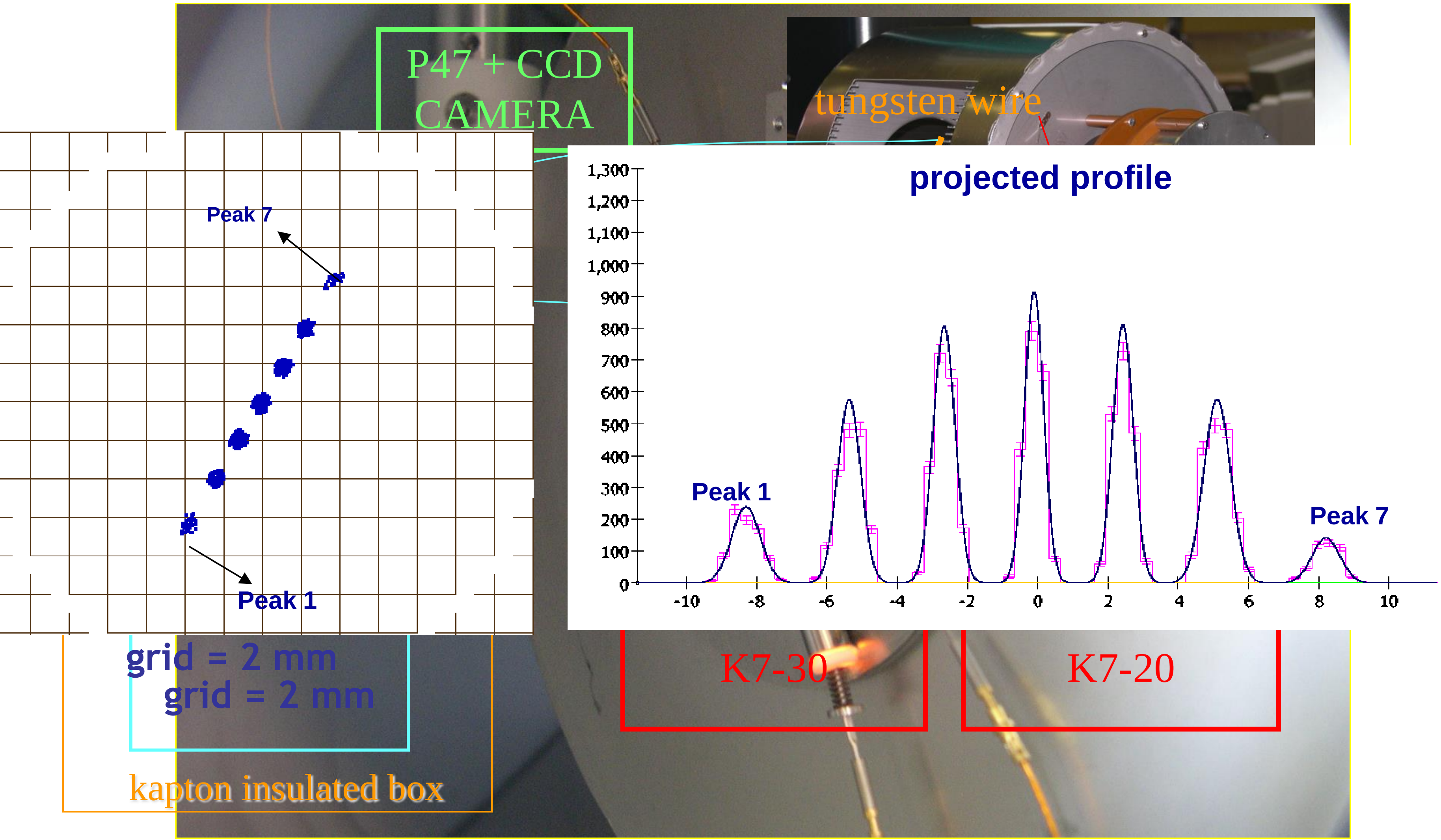


The integrated system at CERN

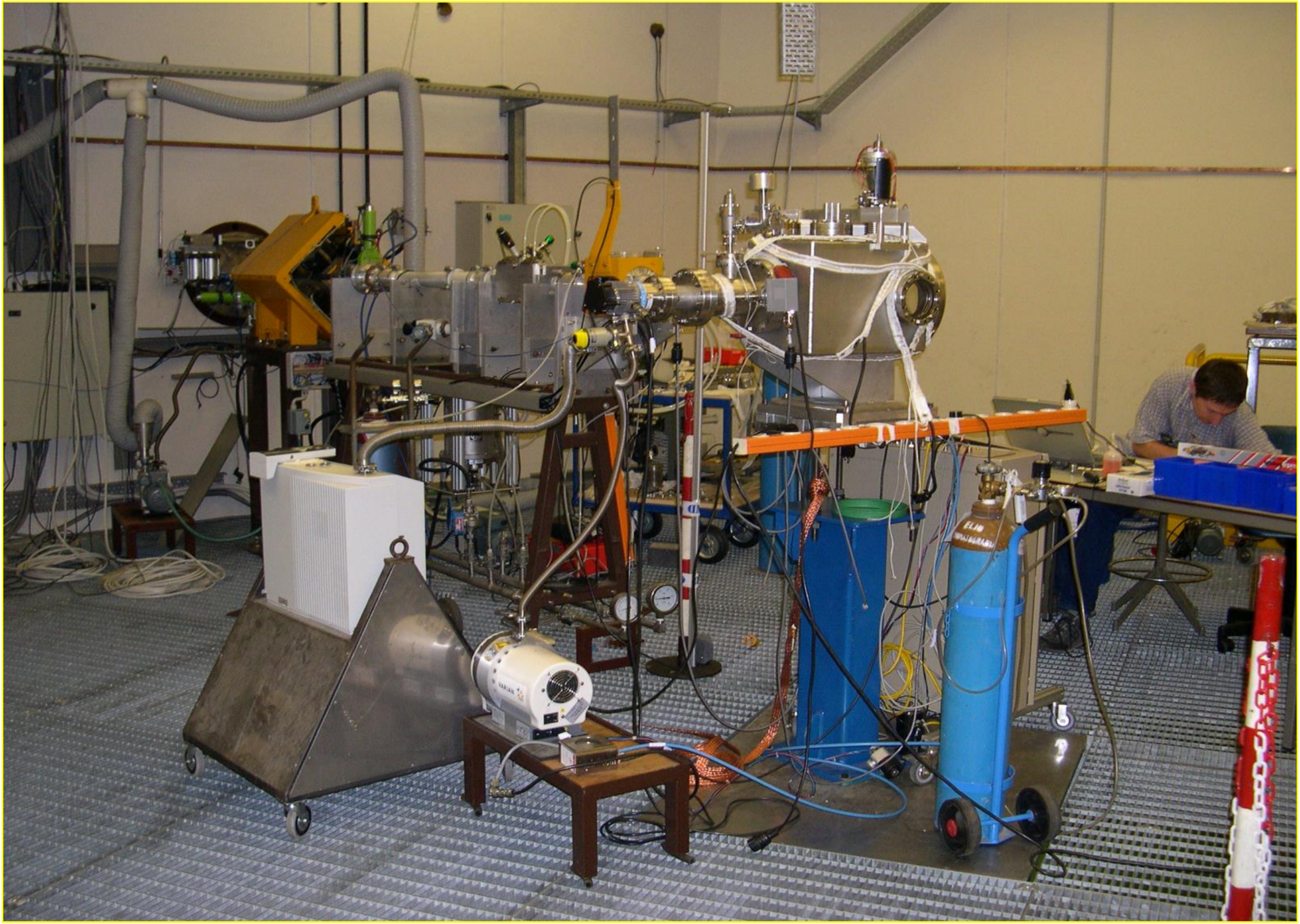


A detail of the focalization system

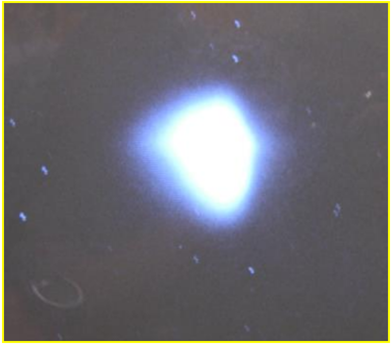
Preliminary tests of the Focalization System using thermo-ionic emission by a hot tungsten wire:

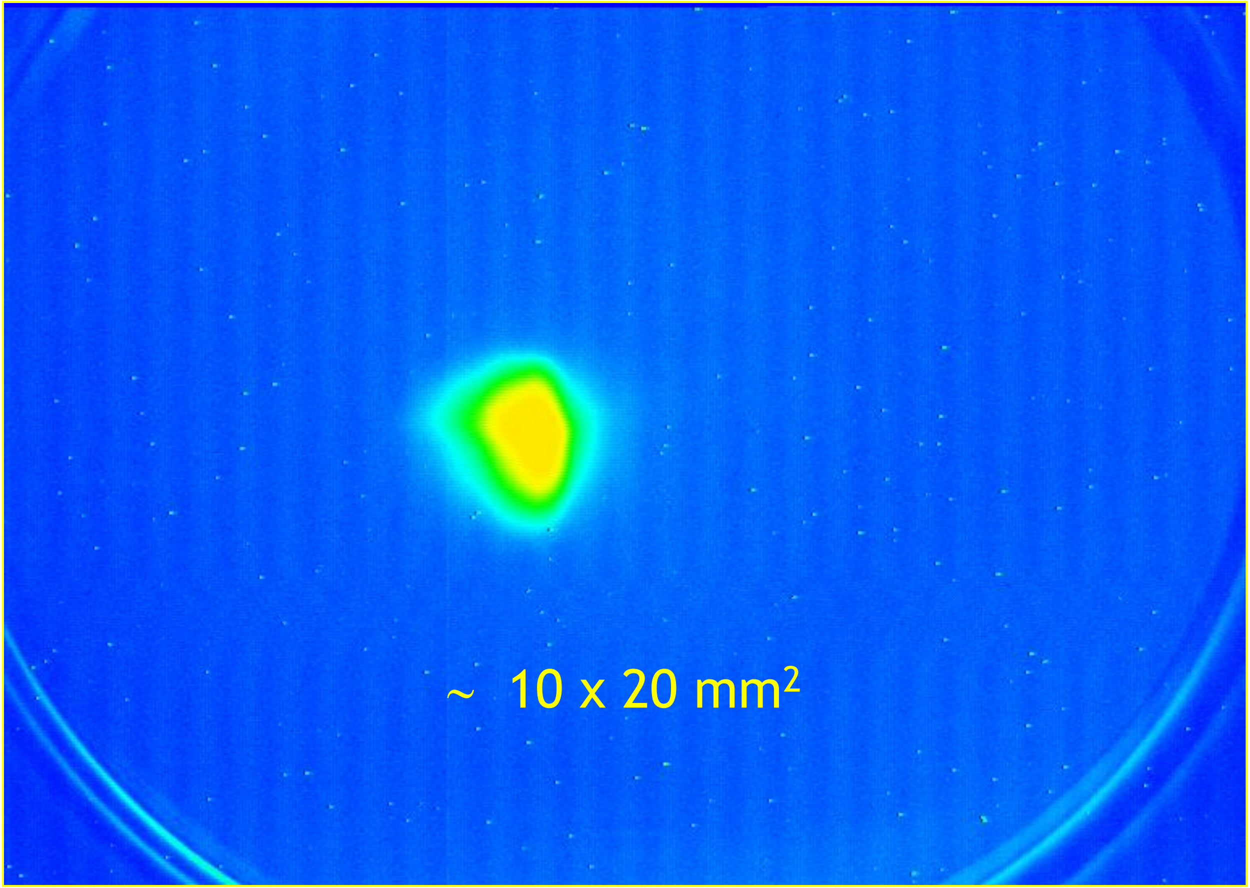


The SLIM installed on an extraction line at the Ispra JRC-Cyclotron
(p, 2H, 4H at energies 8-38 MeV, 100 nA- 100uA)



First images of a beam, imaging the focalized Secondary Electrons by a Multichannel-plate+Phosphor screen+CCD camera system

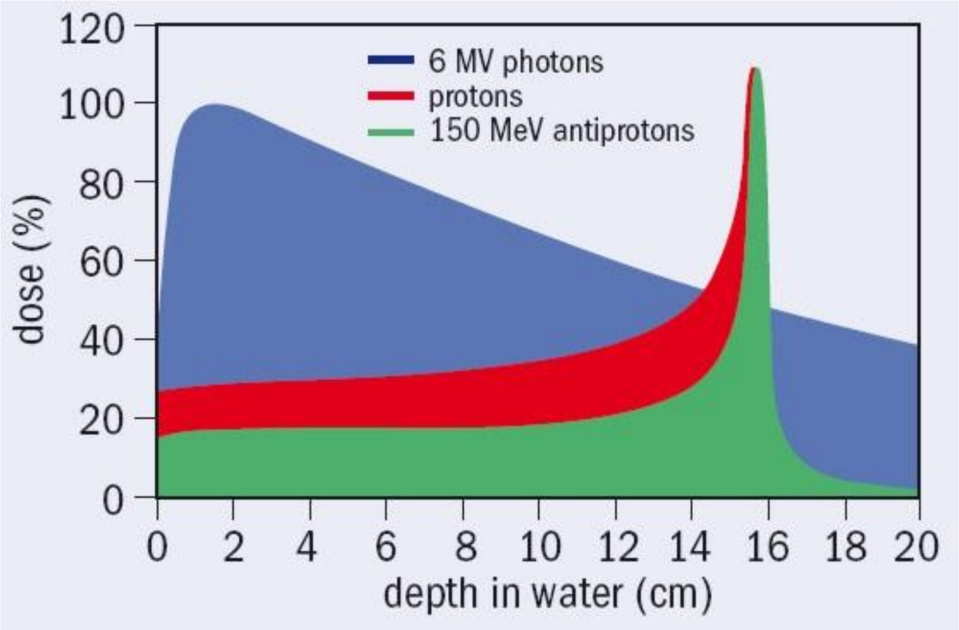




1. Assisting the AD-4 [ACE] collaboration

[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]

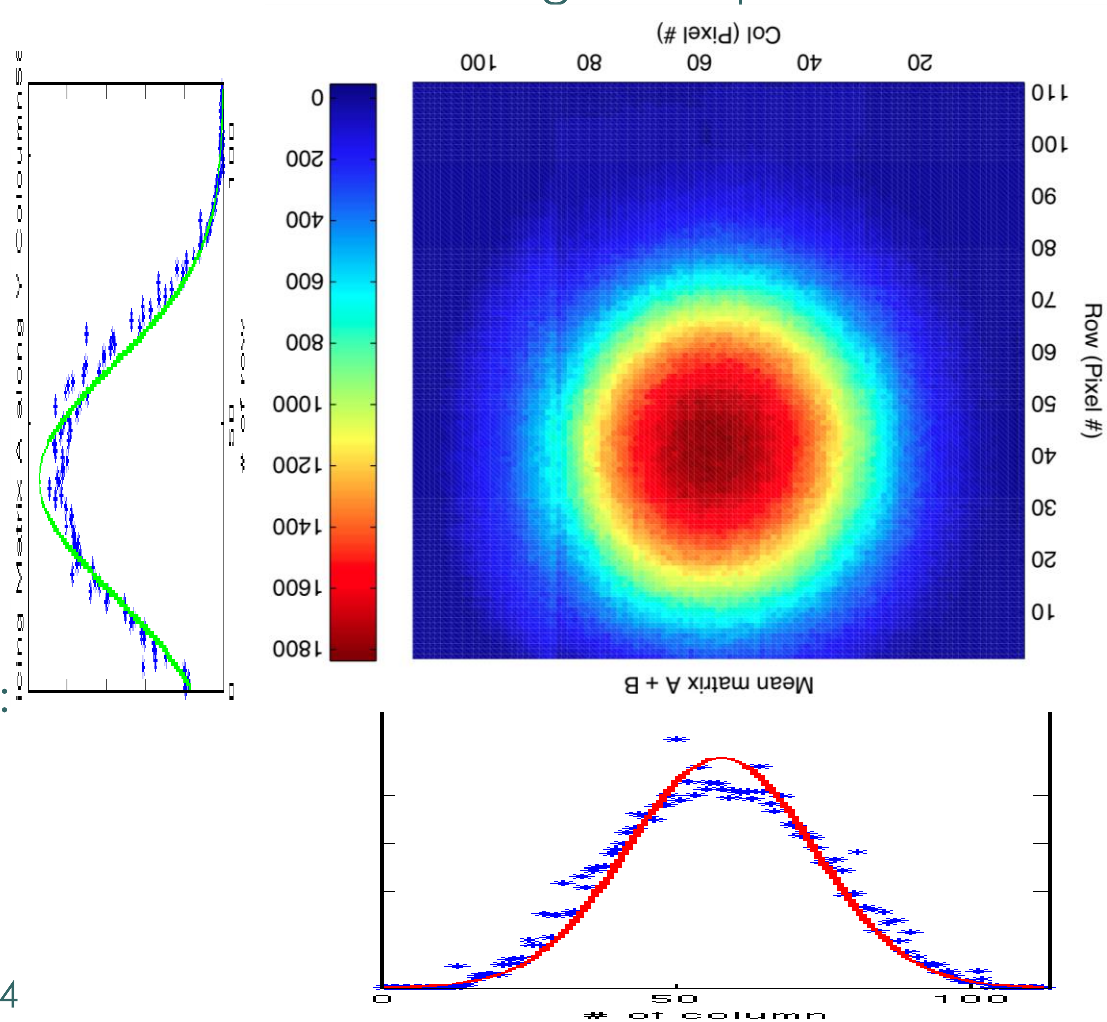
Michael Holzscheiter, ACE spokesperson (left), retrieves an experimental sample after irradiation with antiprotons, while Niels Bassler (centre) and Helge Knudsen from the University of Aarhus look on [courtesy of ACE]

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

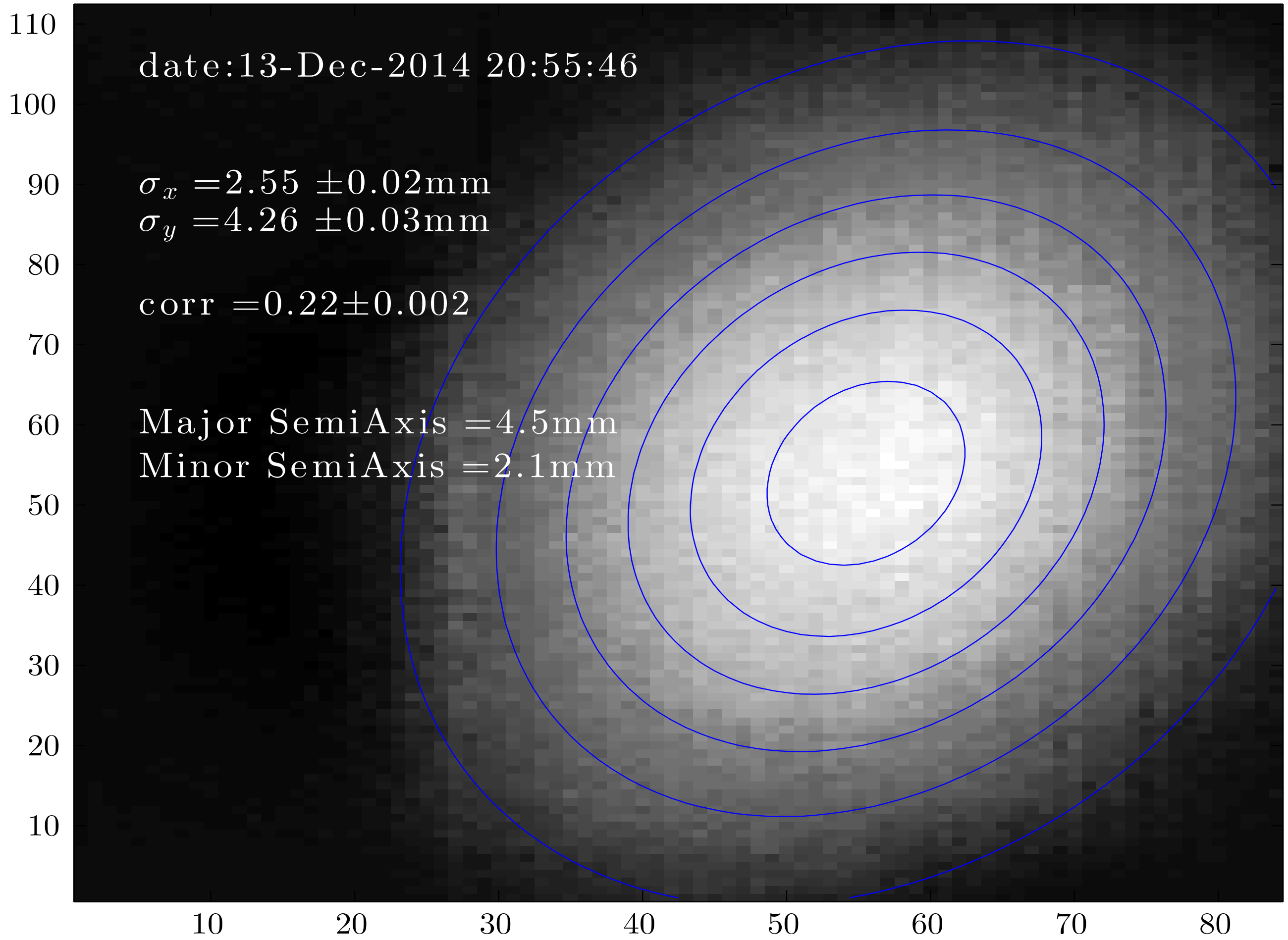
- **beam characteristics:**
  - -120 MeV energy
  - - $3x10^7$ particles/spill
  - - 1 spill every 90”
  - - FWHM ~ 8 mm
- **acquisition modality:**
  - - triggered
- **imaging modality:**
  - - differential
- **radiation damage:**
  - - irrelevant so far

  [max no. of spills on a detector: 1436]
- **data taking runs:**
  - - September 2009
  - - June 2010
  - - October 2010
  - - June 2011, fall 2012, Dec. 2014

Single shot picture



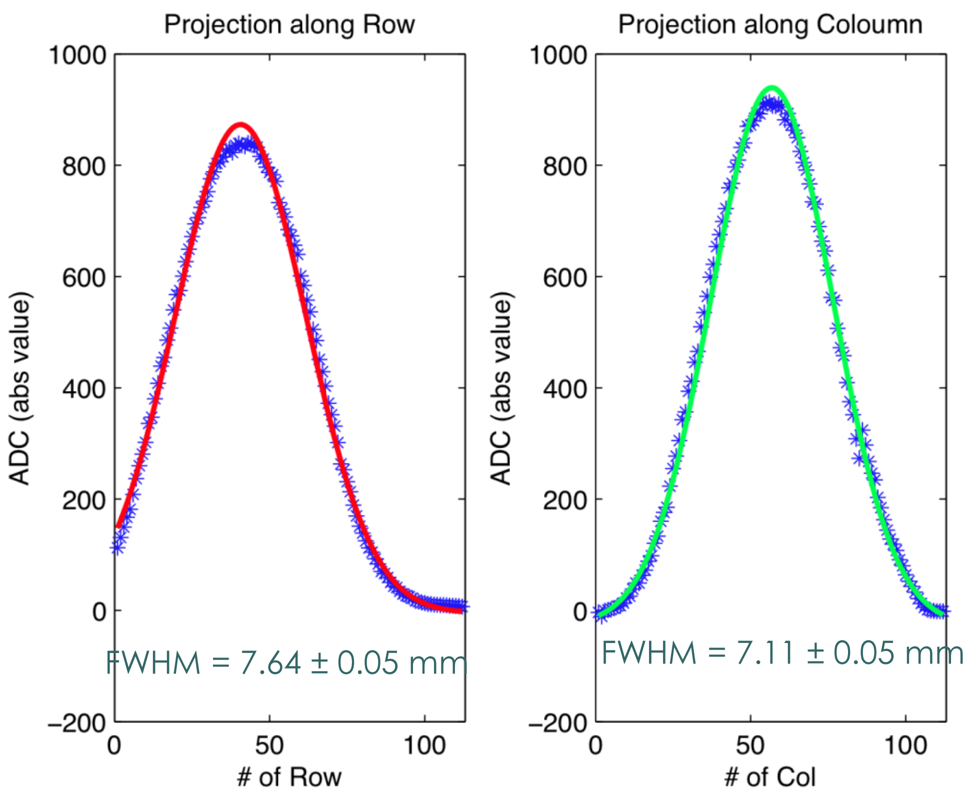
A nice image from the December 2014 vintage

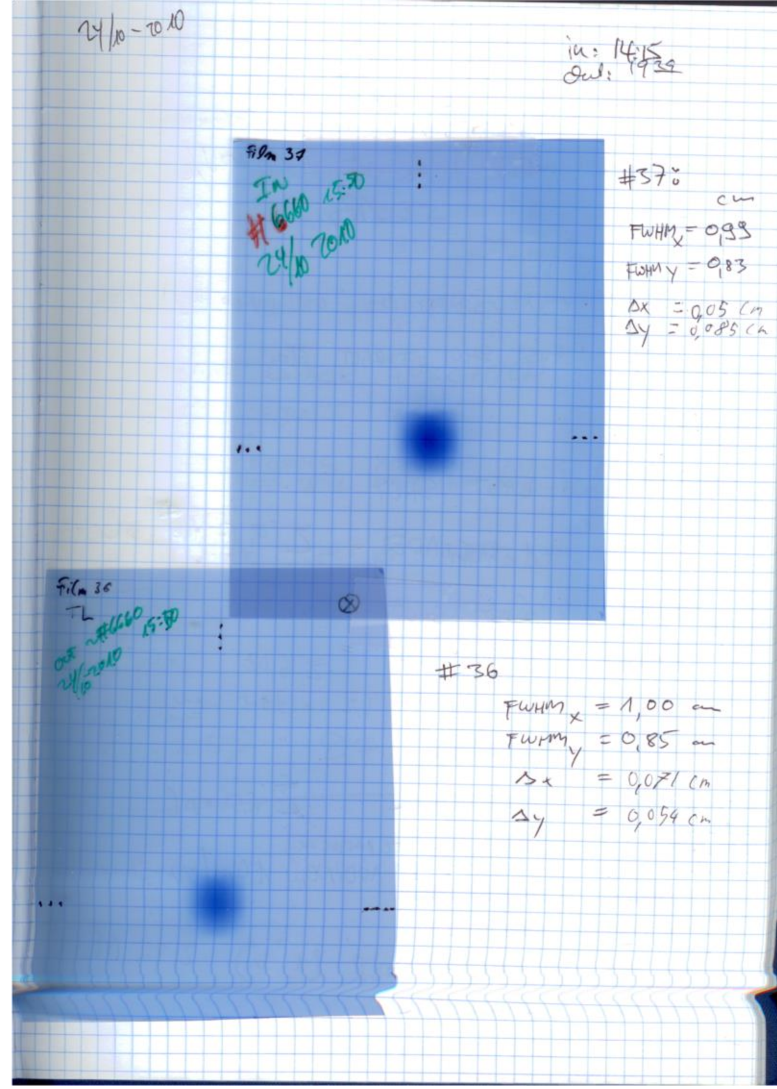


Profiling the beam

[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

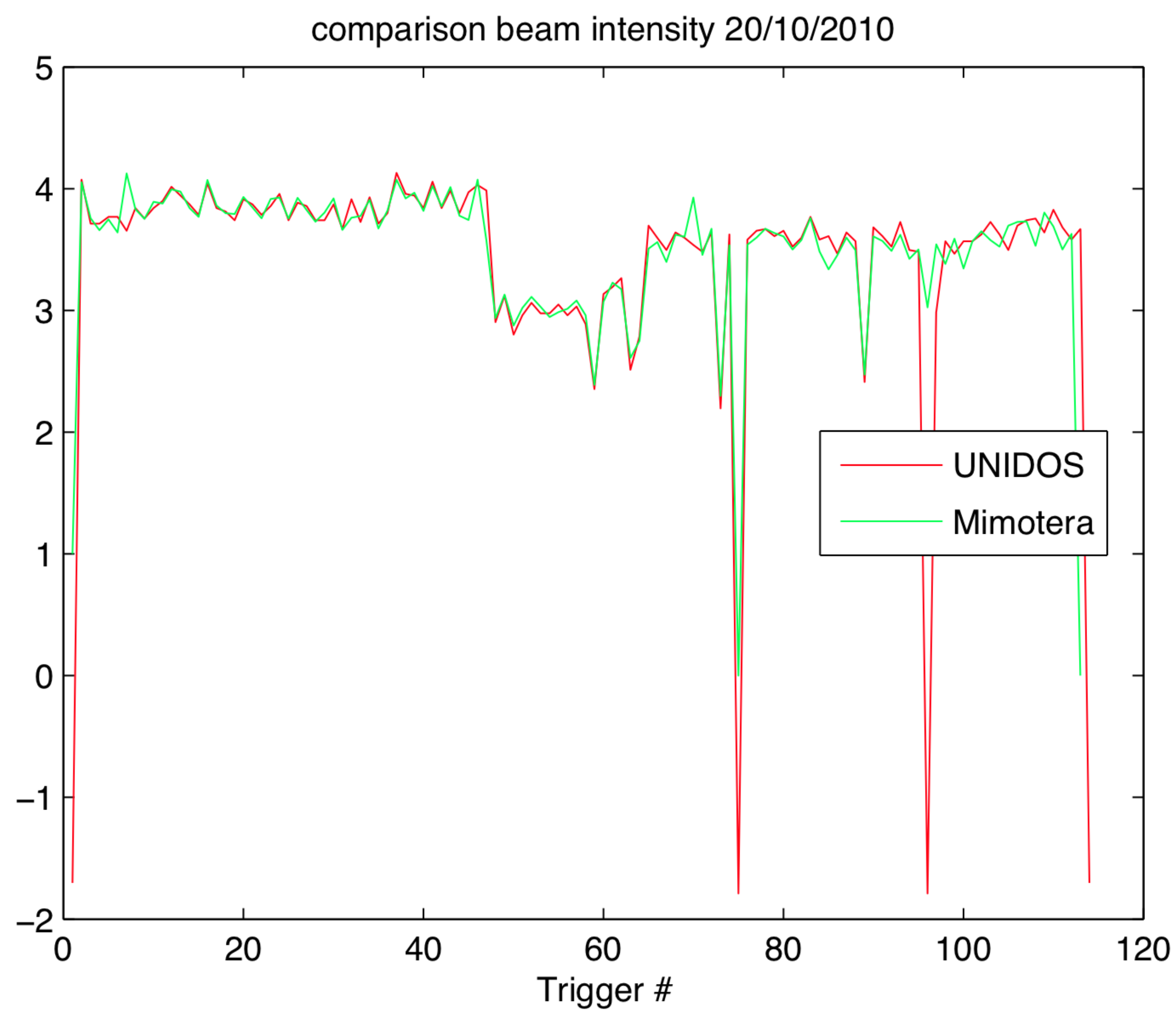




With a GafChromic Film, integrating the spills over a full run …and PROJECTING

Monitoring the intensity fluctuations

MIMO
Vs
UNIDOS*



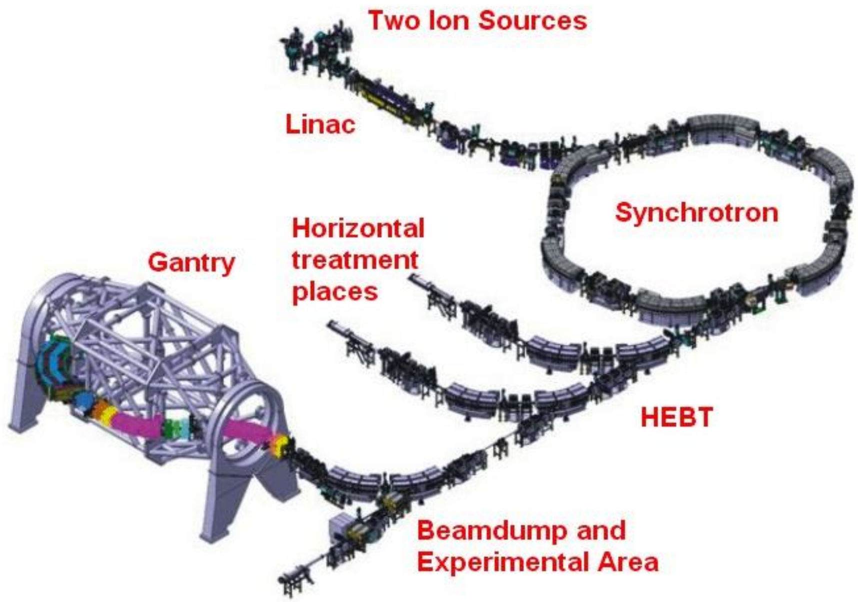
*The PTW UNIDOS is a high performance secondary standard and reference class dosemeter / electrometer

2. 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}]	2.0x10^8	5.0x10^6
I_{max} [s^{-1}]	3.2x10^9	8.0x10^7
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

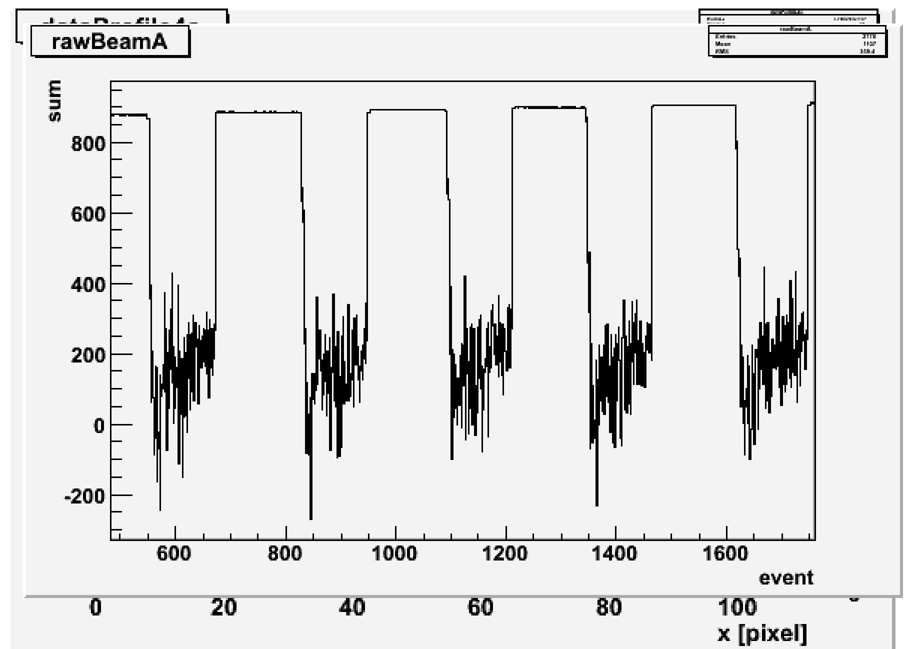
- **beam time characteristics:**
  - duty cycle 50%
  - spill duration 5 s
  - FWHM ~f(particle, intensity, energy)
- **acquisition modality:**
  - free run
- **imaging modality:**

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

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

[Total exposure time so far ~ 3h; about 1'-2' per run at a specified nrj, intensity]

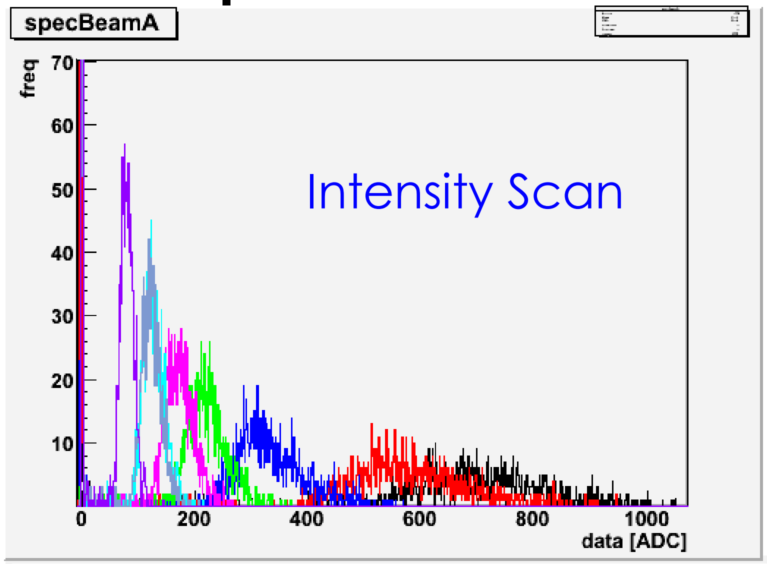
- **data taking runs:**
  - May 2010
  - October 2010

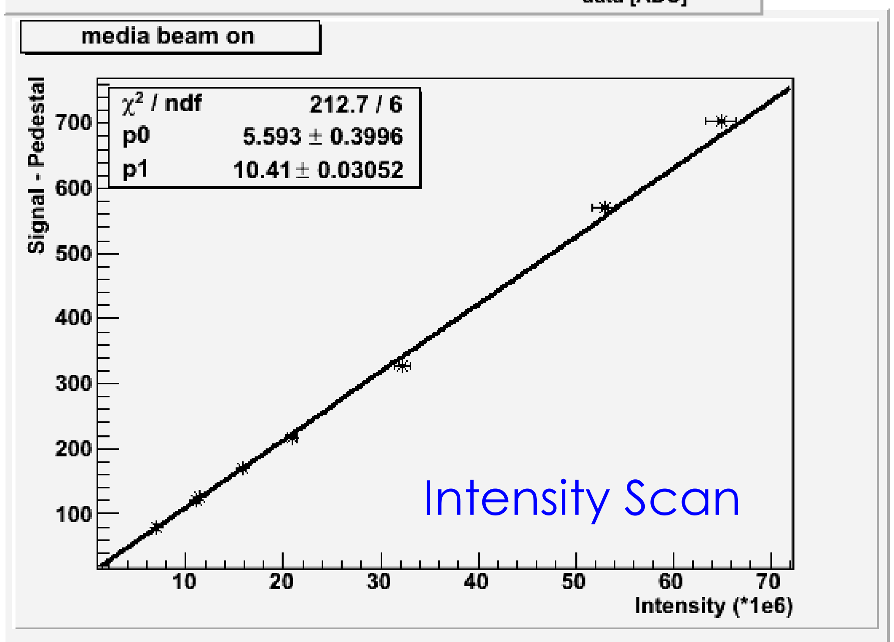


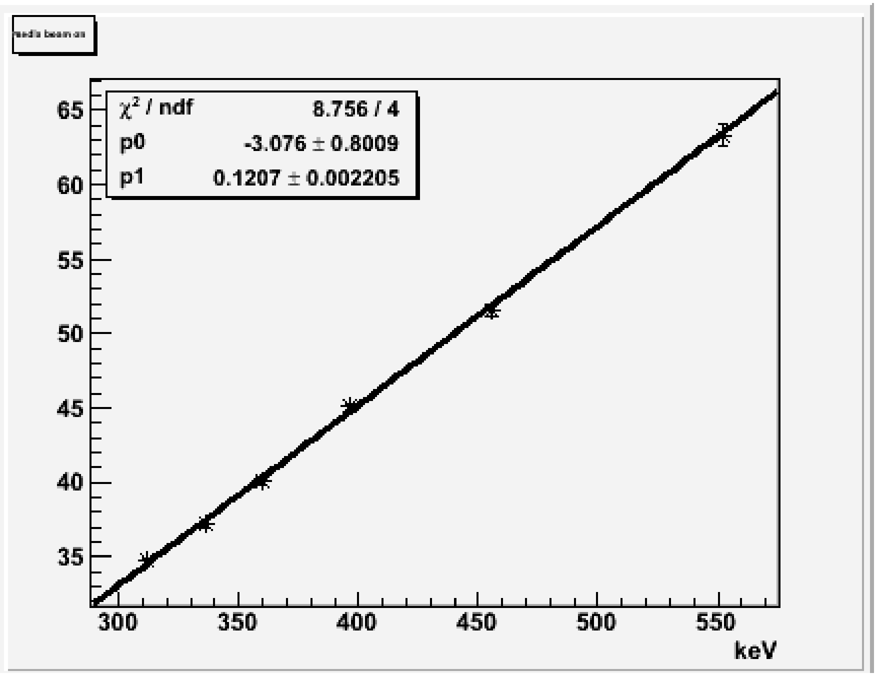
Time development of the beam

$I = 7x10^7$ particles/s, C ions

Quantitative information (C ions)







Energy Scan

3. 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, He, C ion beams]

❖ imaging modality:

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

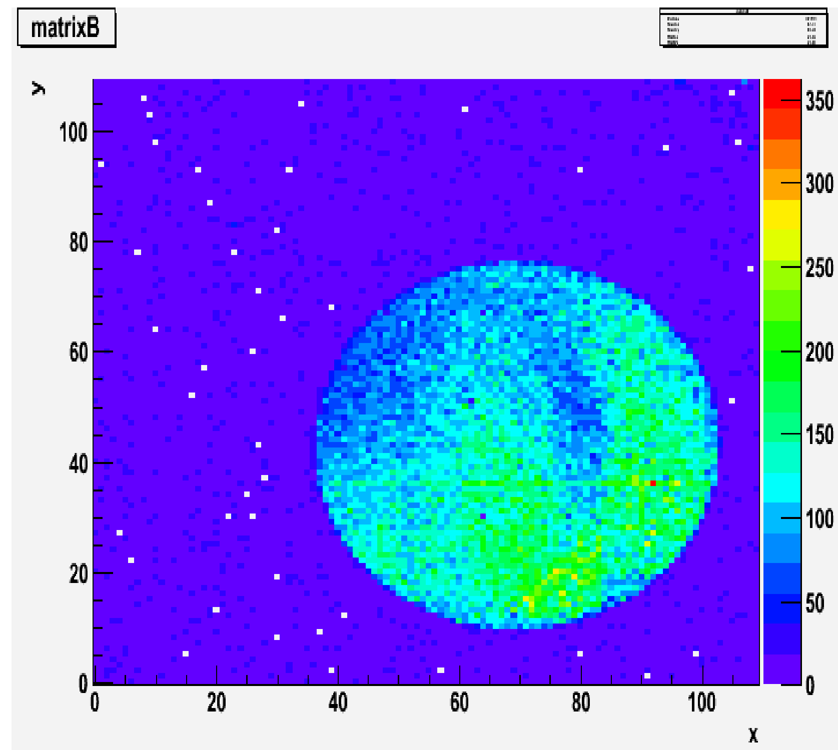


Image obtained by counting with pixel dependent thresholds

❖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] + February 2012 [full system qualification]

Four 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
- February 2012: full system commissioning and qualification

❖ The MIMOTERA run in vacuum

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

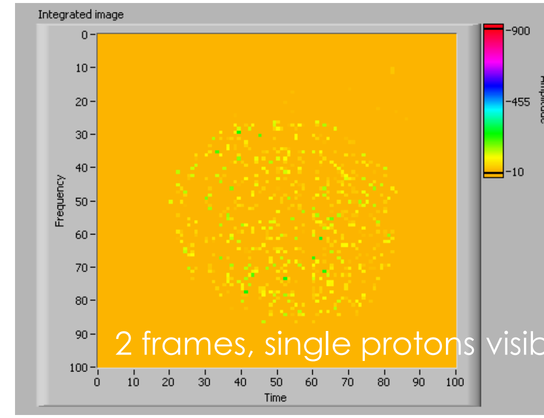
❖ Robust algorithms against radiation related effects tested

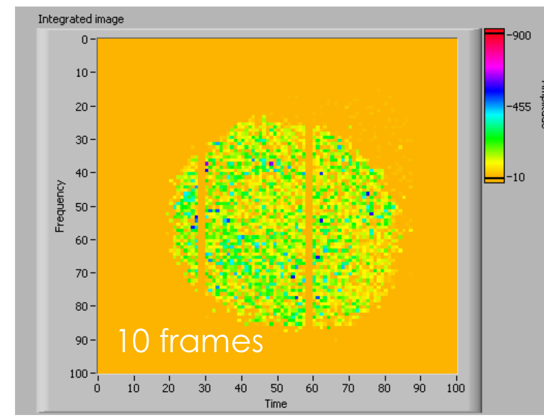
❖ exhaustive data set recorded:

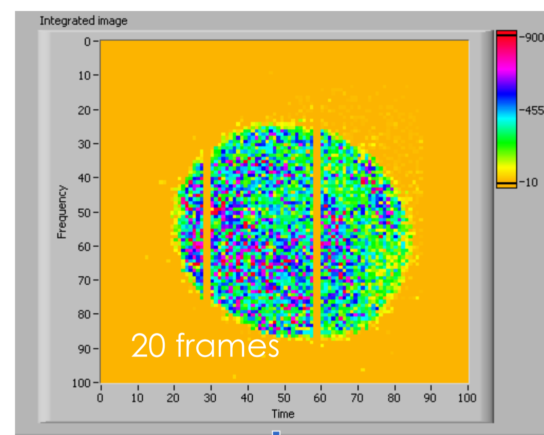
- Scan over 3 orders of magnitude in intensity (p, I = [$10^4 \div 10^7$] p/cm^2/s, 1.2 MeV & 3 MeV energy)
- Energy scan with protons (3.5 to 1 MeV)
- Tested with C ions (Z = +3, 10^6 particles/cm^2/s, 7 MeV)
- Tested with different readout frequencies (2.5 to 20 MHz)

Real-time profiling
(2009 run)

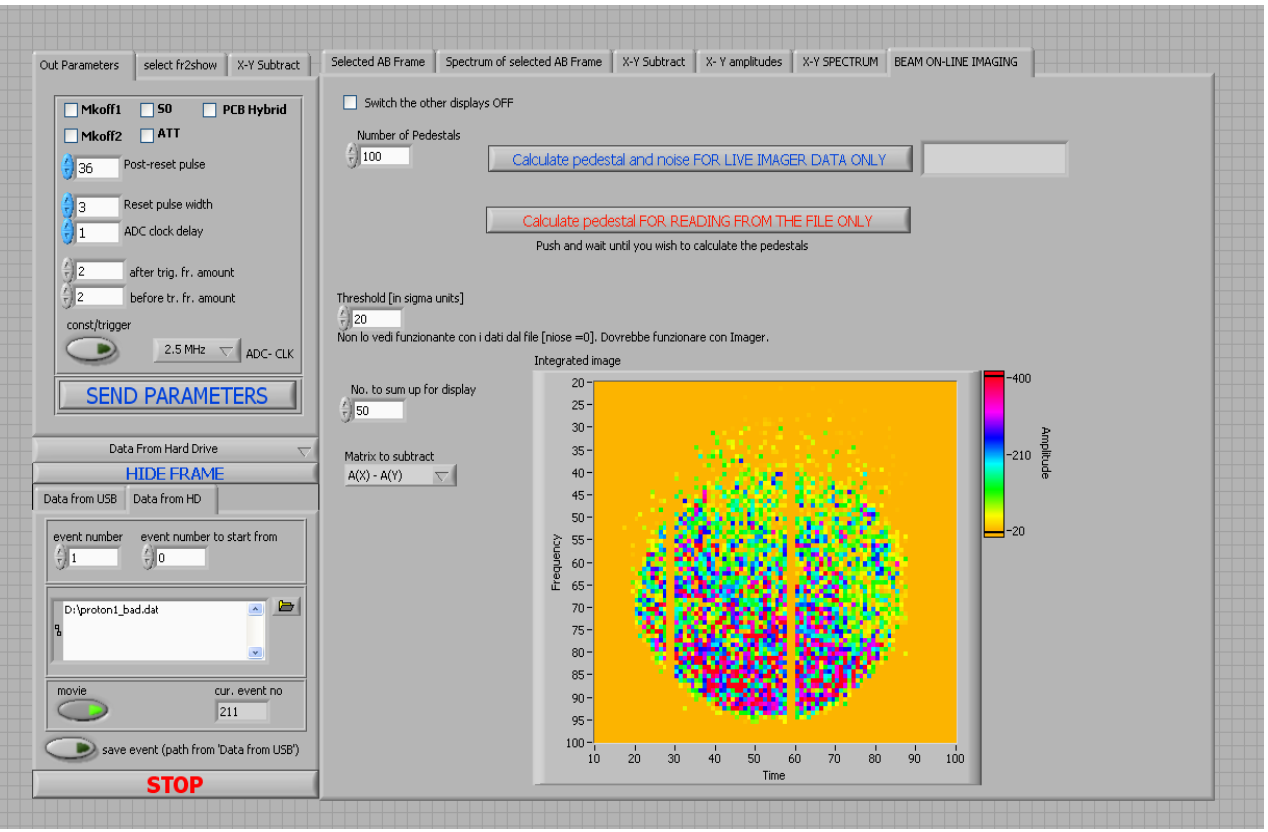
Costruction of a flat beam image overlapping different number of frames





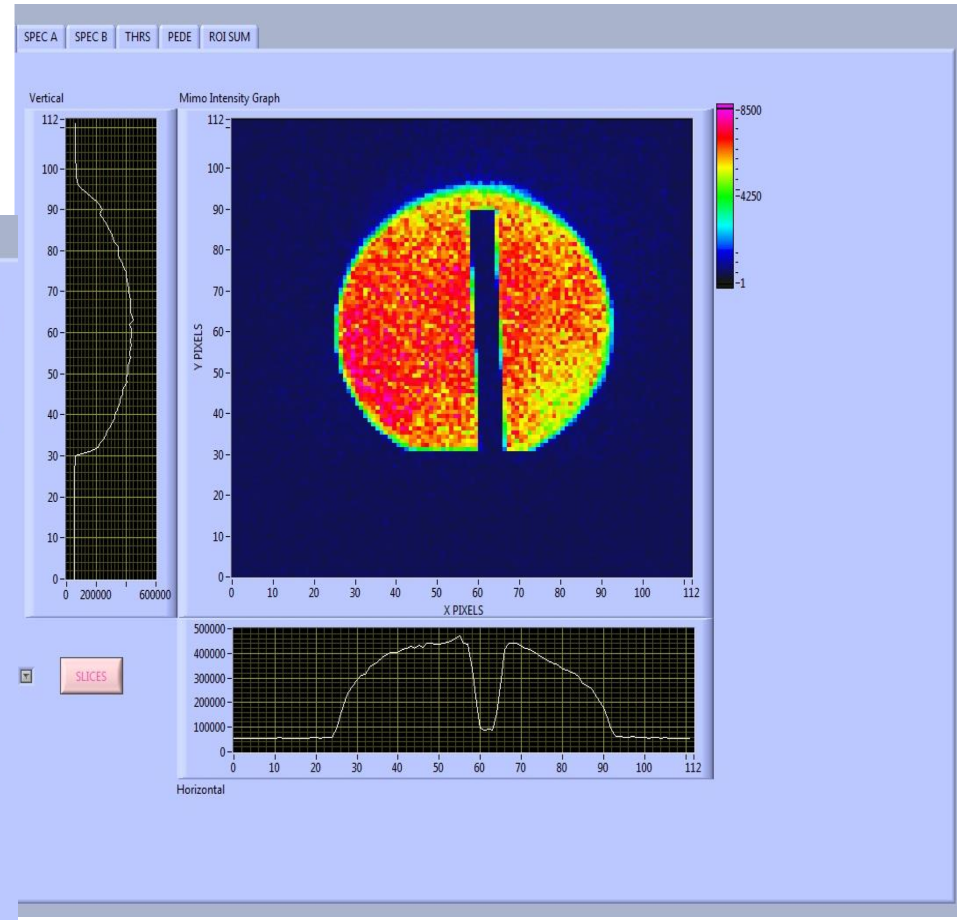


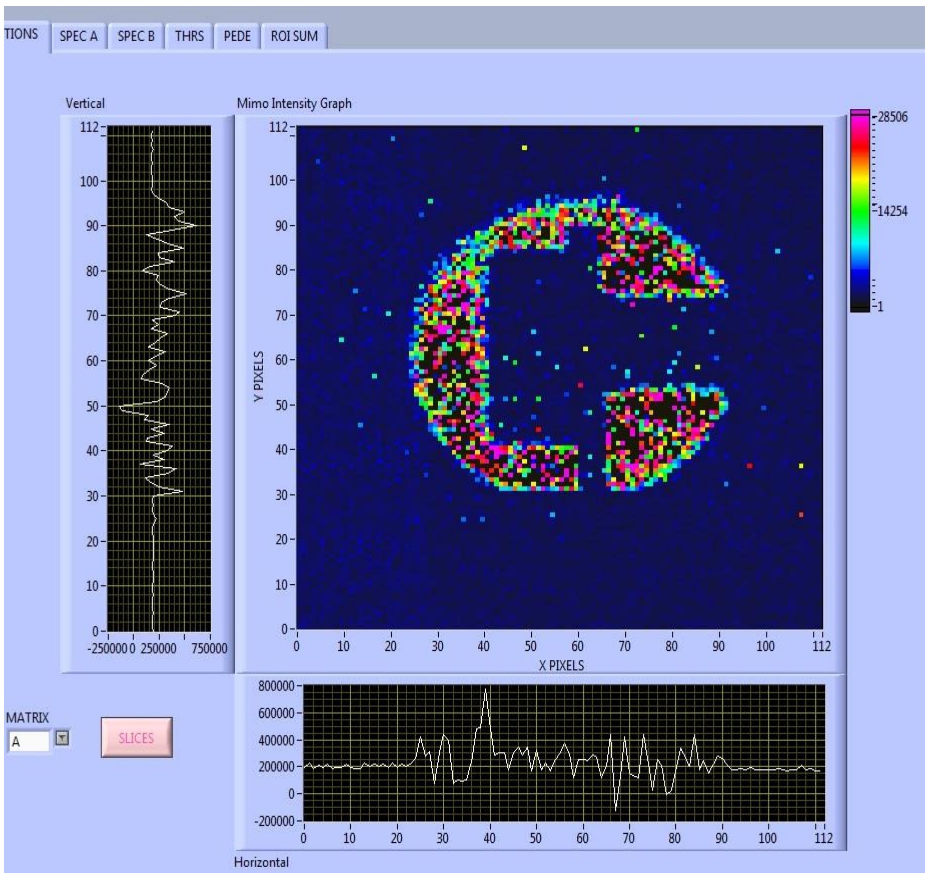
Bottom: image of a tilted beam, obtained overlapping a user defined number of frames



Real-time profiling
(2011 run)

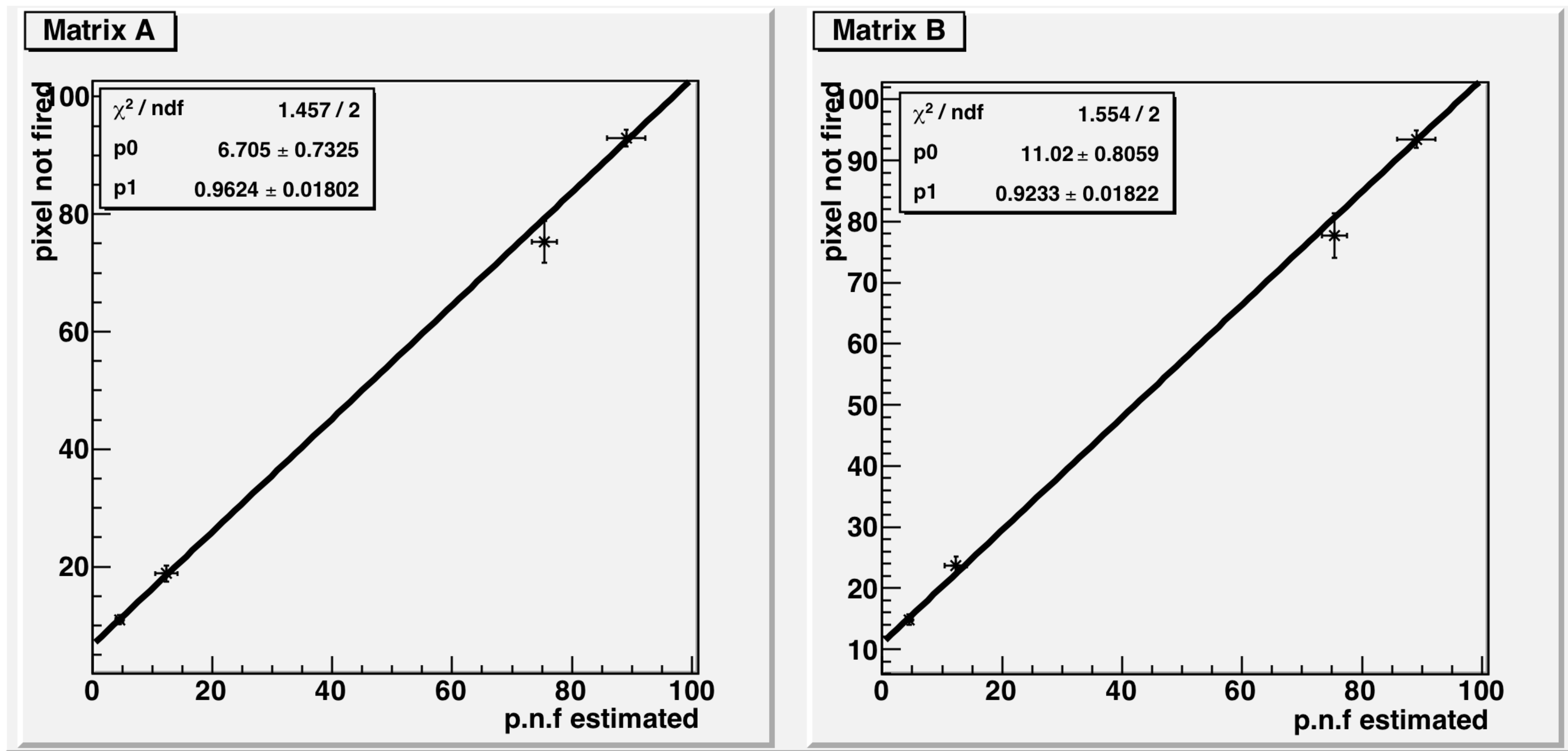
Two images of a proton beam showing the footprint of a fiber (right) and the fiber + the LARN reference detector in the beam area (bottom)





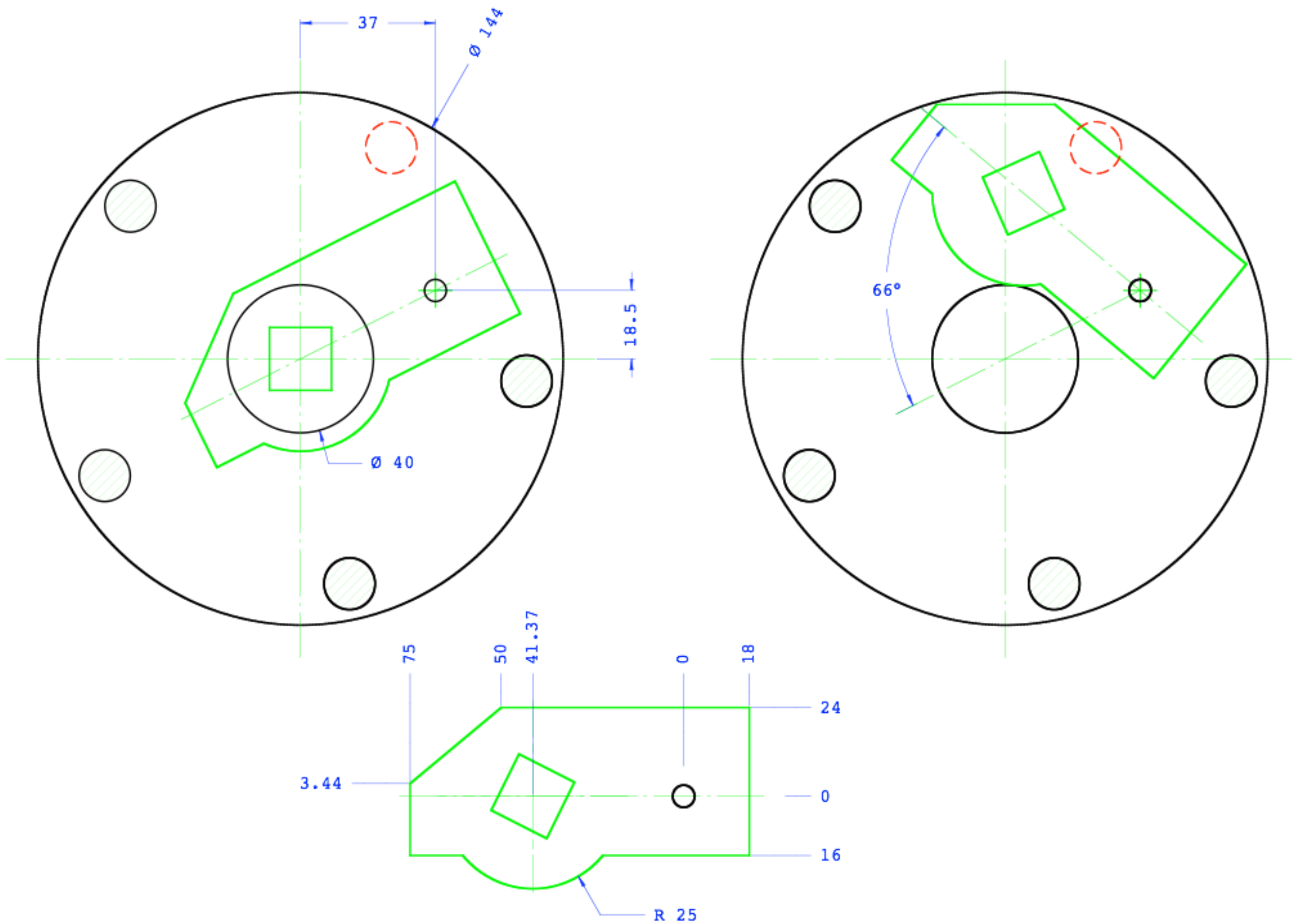
Exemplary Linearity plots, up to 8.8 x 10^6 particles/cm^2/s [limited by the reference instrument in use at Namur]

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

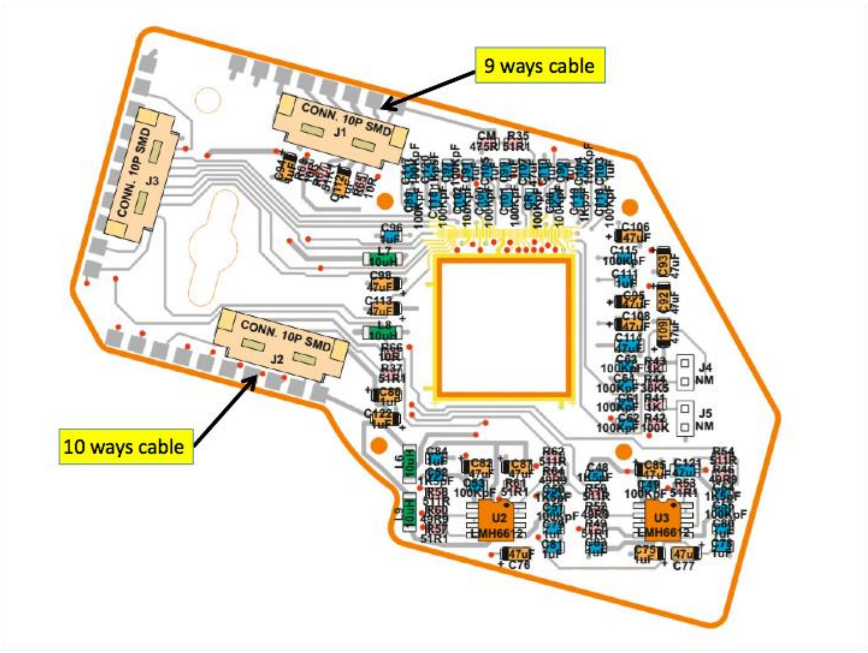


- Y axis: MIMO response; X axis: LARN reference instrument. The observable corresponds to the mean number of pixels NOT fired in a user specified region of interest in the beam core
- clocking at 25 MHz, we can use the MIMO in counting mode till ~ 10^8 particles/cm^2/s

4. The MIMITO: a thin MIMOTERA for the AEGIS experiment (2015)

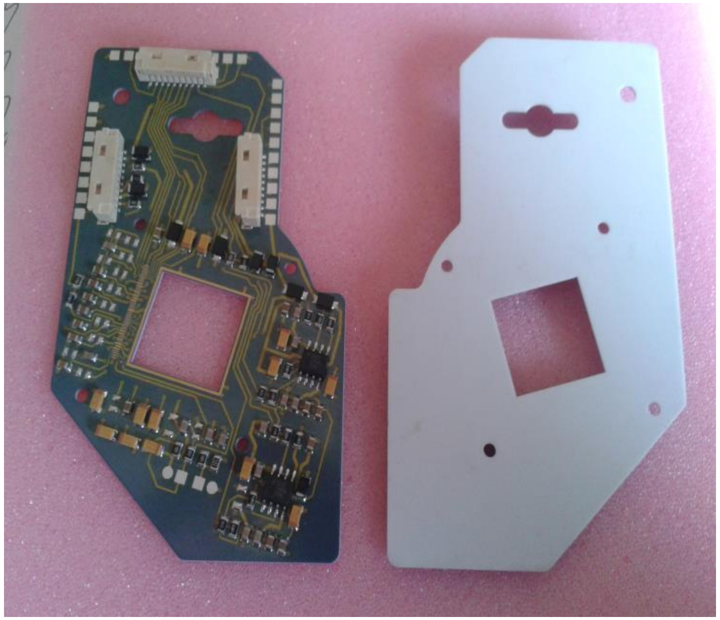


Hybrid Design

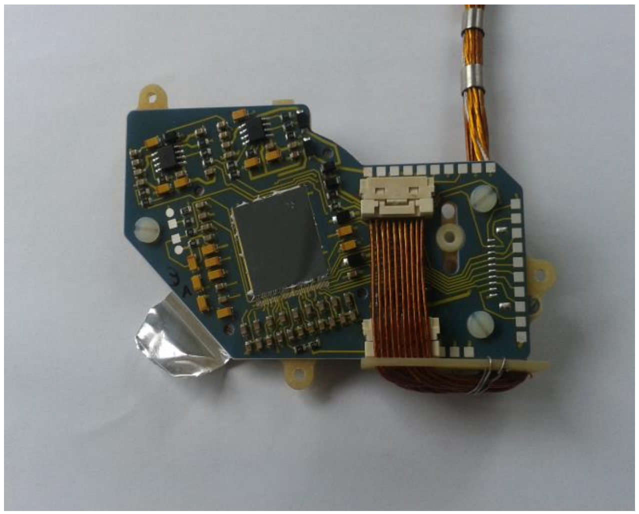


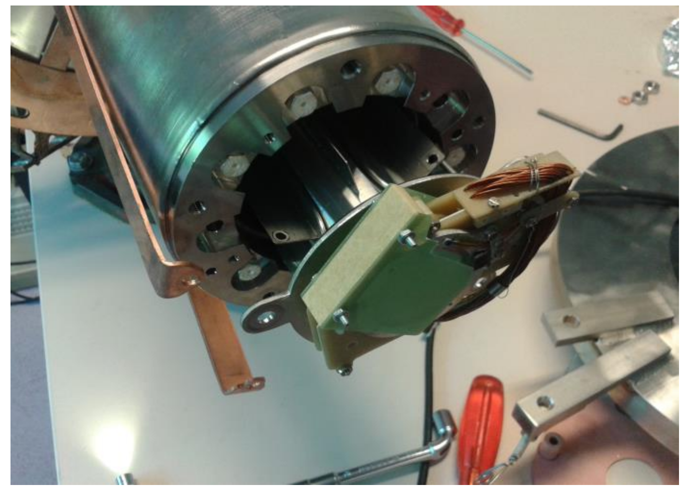
The design…

… and the real thing



The MIMO in the SUN





- cabled, tested on a table, across the same “patching” way
- mounted in the SUN, in the control room, tested
- SUN mounted in AEGIS, tested
- NEXT:
  - have the MIMO on the net, address & readout remotely
  - include the MIMO in the AEGIS DAQ (F. Prelz, INFN-Mi, code ready and tested)
  - wait for the early July beam and commission it!