Detector development within the ARDENT EU project

Advanced **R**adiation **D**osimetry **E**uropean **N**etwork **T**raining initiative

www.cern.ch/ardent

Marco Silari (CERN)

on behalf of the ARDENT consortium

9th International Workshop on Ionizing Radiation Monitoring, Oarai, 3 Nov-1 Dec 2013

ARDENT

February 2012 – January 2016

Marie Curie Initial Training Network under EU FP7 – 4 M€

8 Full Partners and **6 Associate Partners**

Coordinator: CERN, Scientist-in-Charge: Dr. M. Silari

CERN (coordinator), Geneva, Switzerland	INFN Legnaro National Laboratories, Italy
AIT Vienna, Austria	ST Microelectronics, Italy
CTU - IAEP Prague, Czech Republic	University of Erlangen, Germany
IBA Dosimetry, Schwarzenbruck, Germany	University of Houston, USA
Jablotron, Jablonec nad Nisou, Czech Republic	University of Ontario, Canada
MI.AM, Piacenza, Italy	University of Wollongong, Australia
Politecnico of Milano, Italy	
Seibersdorf Laboratories, Austria	

YEARS/ANS CERN

Sponsorships and partenrships

MARIE CURIE ACTIONS

African School of Physics
Stellenbosch (SA) –August 2010

African School of Physics 2012
Kumasi, Ghana – July 2012

African School of Physics 2014
Dakar, Senegal, August 2014

ARDENT

The ARDENT researchers

Eleni Aza – ESR 1

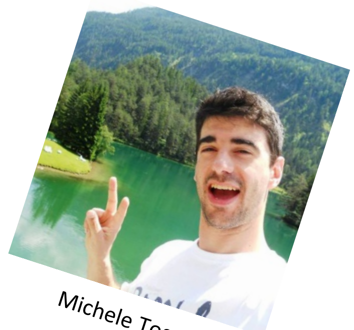
Andrej Sipaj – ESR 6

Alvin Sashala Naik
ESR 13

Elena Sagia – ESR 14

Benedikt Bergmann
ESR 9

Silvia Puddu – ESR 3



Michele Togno
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Jayasimha V. BAGALKOTE
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Vijayaragavan Viswanathan
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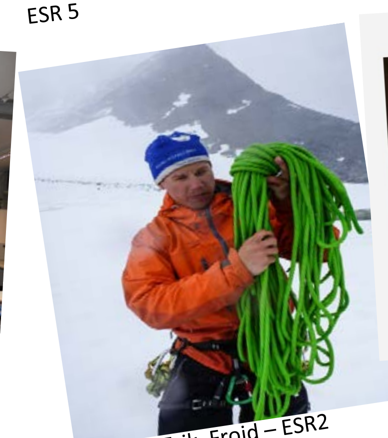
Kevin Loo – ESR 8

Stuart George – ESR 4

Ivan Caicedo – ESR 7

Francesca Bisello – ESR 10



Erik Frojd – ESR2

Chris Cassel – ESR 15

Development of advanced instrumentation for radiation monitoring

Three technologies

- Gas detectors: gas electron multipliers (GEM), tissue equivalent proportional counters (TEPC), ionization chambers
- Solid state detectors: Medipix, silicon micro-dosimeters
- Track detector techniques: CR-39

Development of advanced instrumentation for radiation monitoring

Main objectives

- Radiation dosimetry
- Micro- (and maybe sub-micro-) dosimetry
- Neutron spectrometry

Applications

- Characterization of radiation fields at particle accelerators
- Characterization of radiation fields on-board aircrafts and in space
- Medical applications: diagnostics and therapy

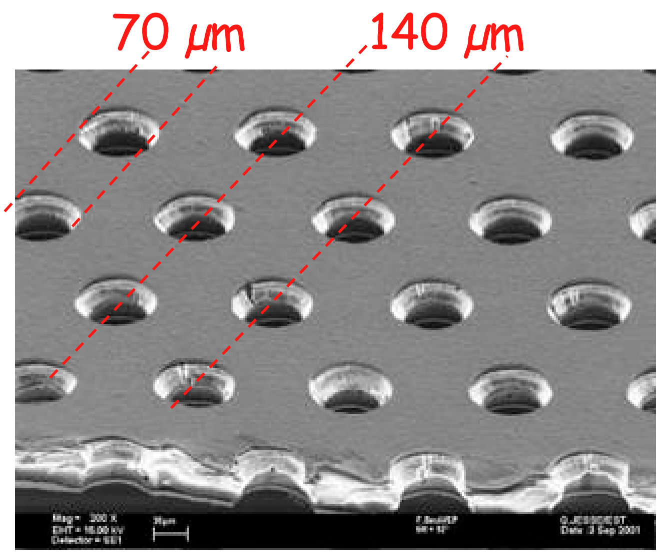
Gas detectors

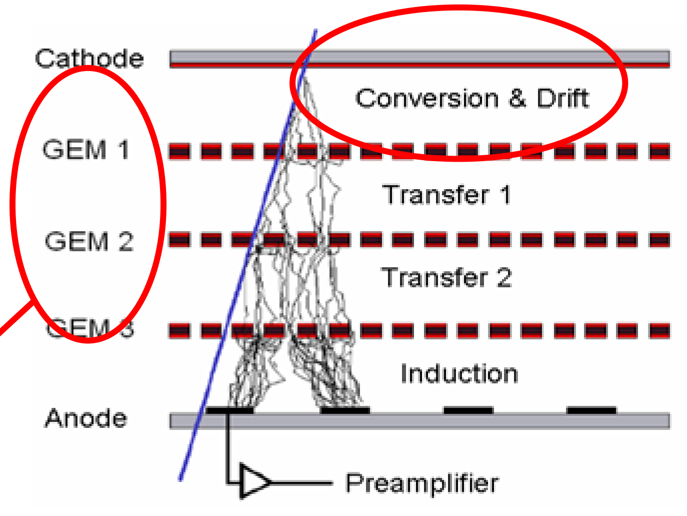
Triple GEM (gas electron multiplier)

Gas Electron Multiplier:

- 50 μm thick kapton foil
- 5 μm of Copper on each side
- high surface-density of bi-conical channels

The three functions
Conversion, Amplification & Readout
are well separated and decoupled



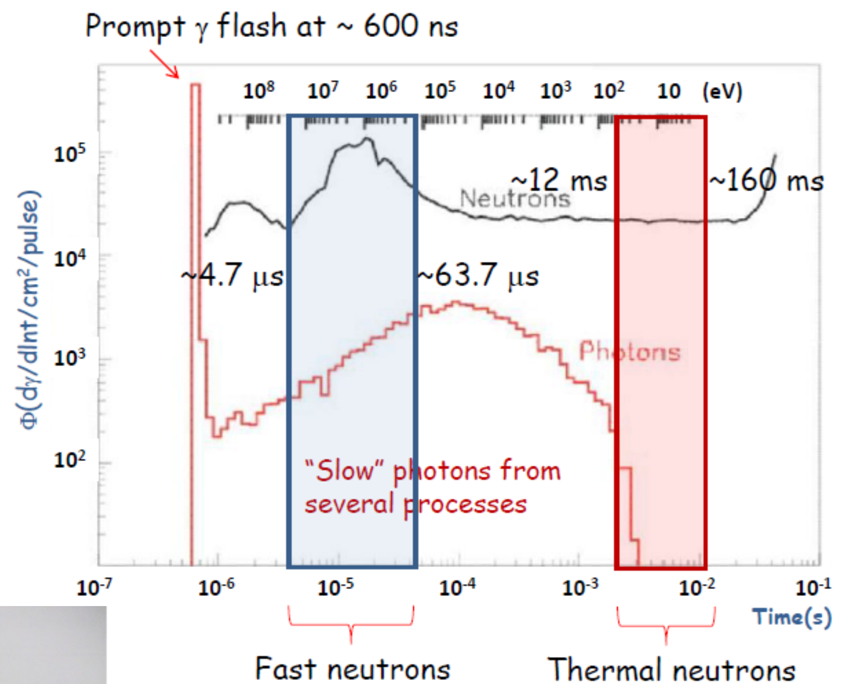


Working with different levels of gain it is possible to obtain a high level of particle discrimination

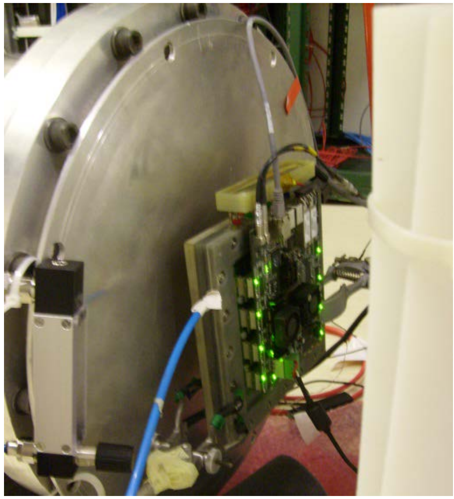
Measurements at CERN n_TOF

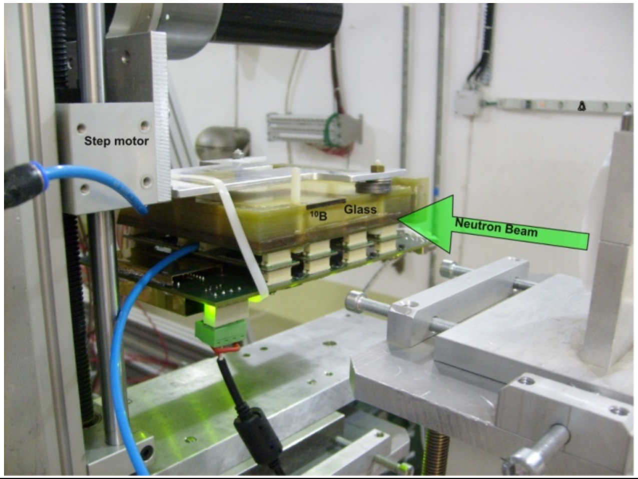
Silvia Puddu, CERN and University of Bern

- n_TOF facility @ CERN: neutron production from spallation reactions; a 183 m path define neutron energy from TOF.
- Two activities with GEM:
  - Beam imaging with fast neutron detector
  - Beam imaging with thermal neutron detector
- Neutrons interact with a converter and the generated charged particles are detected by GEM
- Neutron energy selected by delaying the trigger of the GEM



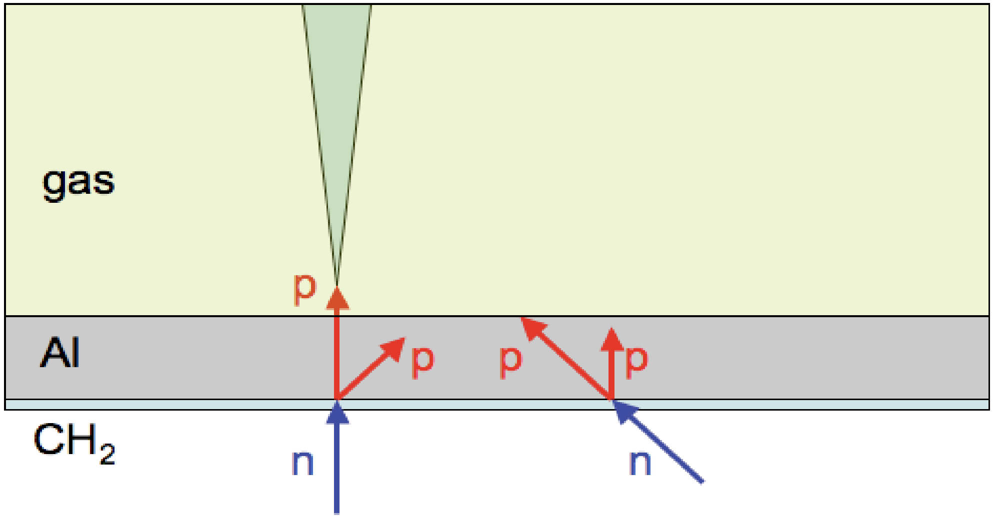
Fast neutrons





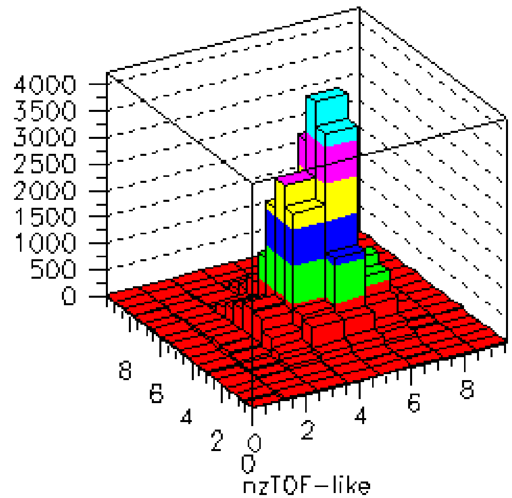
Thermal neutrons

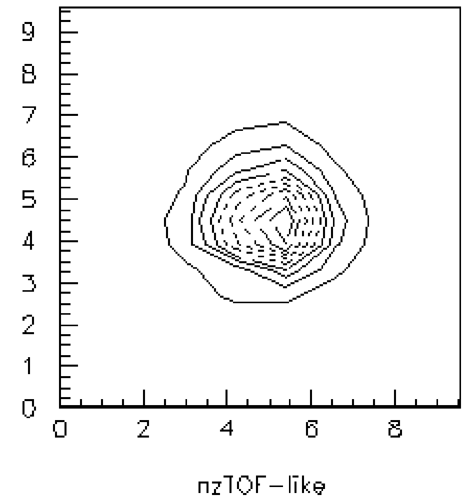
Fast neutron detection with GEM



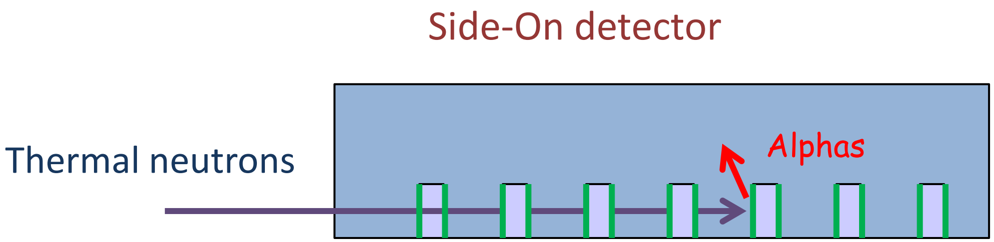
Fast neutrons:

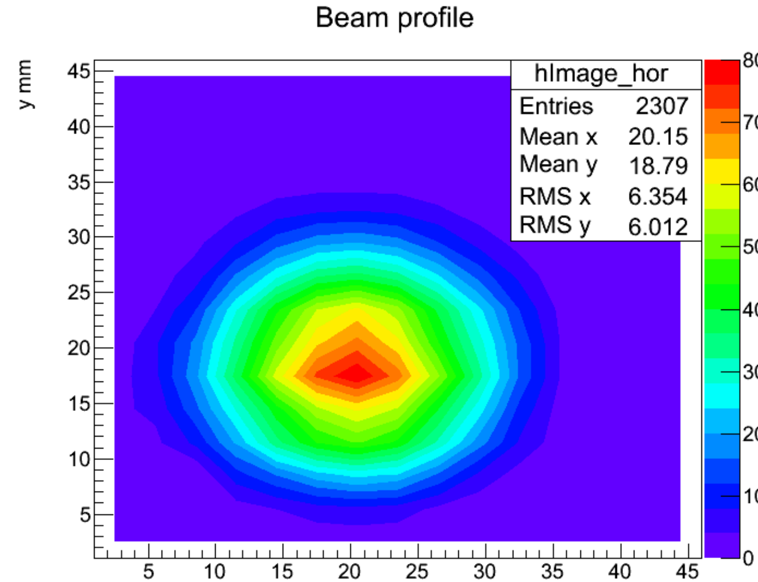
- Head on detector
- Converter: PE + Al
- Low sensitivity to γ background at chosen WP

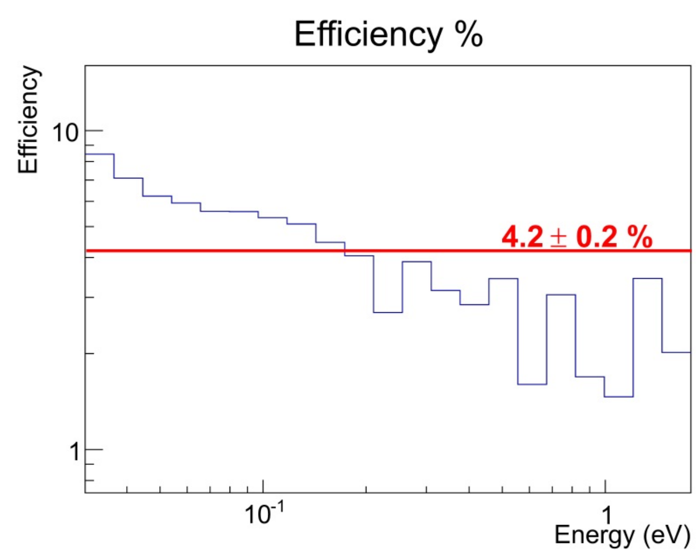




Thermal neutron detection with GEM





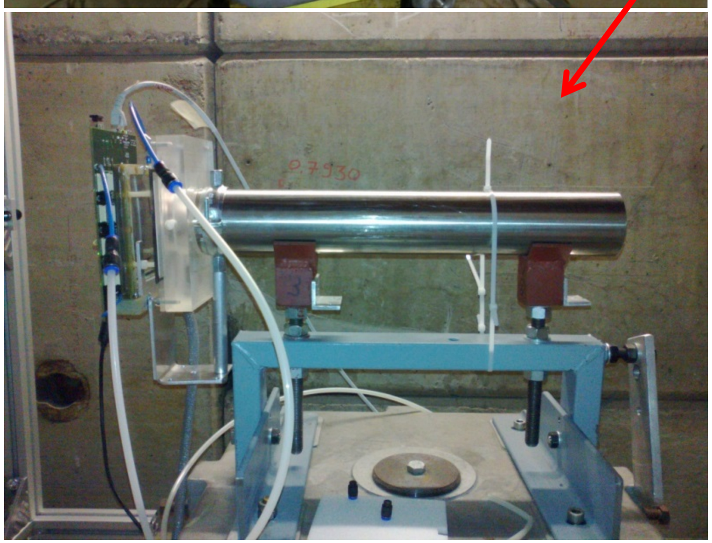


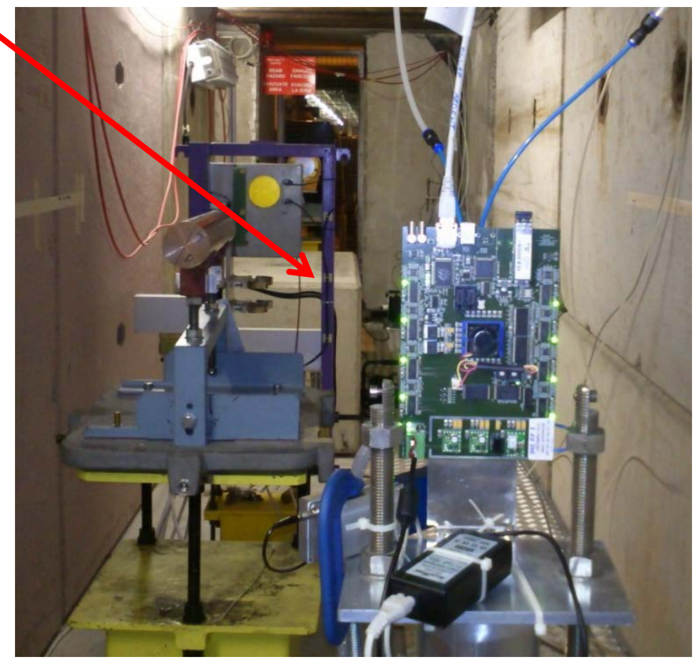
Thermal neutrons:

- Converter: series of thin sheets of ^{10}Bo
- Low sensitivity to γ background at chosen working point
- Beam image reconstructed from scan
- Efficiency of the detector vs neutron energy
- Mean efficiency of 4.2% can be extrapolated

GEM measurements at CERF

- CERF @ CERN: mixed field of secondary particles (p, π, e⁻, γ, n) from spallation reactions
- Measurements with Timepix:
  - – mixed field analysis
- Measurements with GEM:
  - beam monitoring
  - measurements of individual radiation components

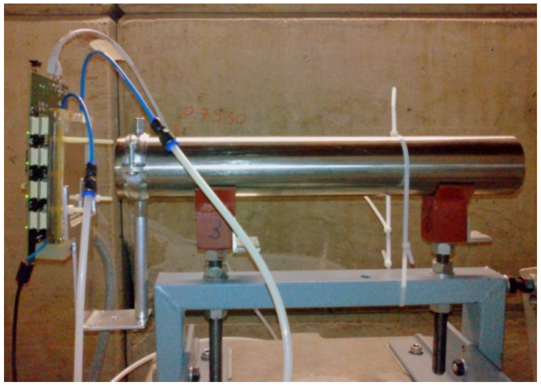


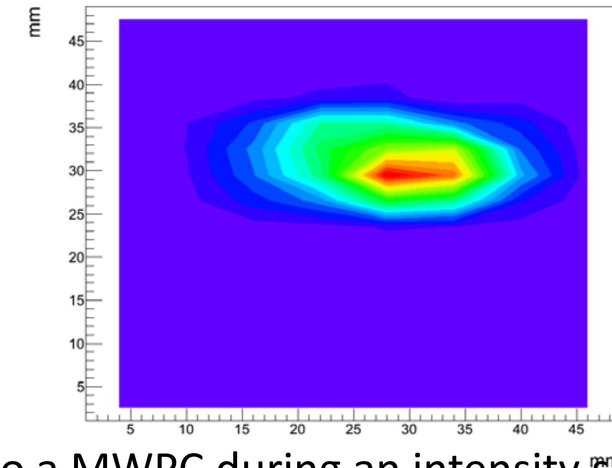


The Triple GEM detector as beam monitor

Eleni Aza, CERN and University of Thessaloniki

Experimental set-up

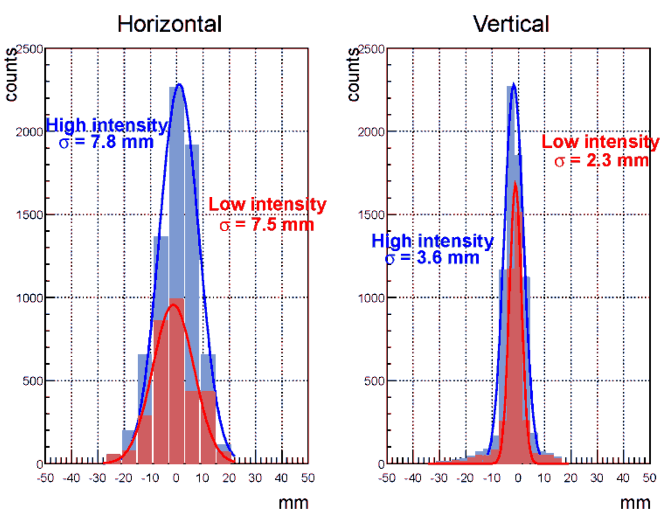




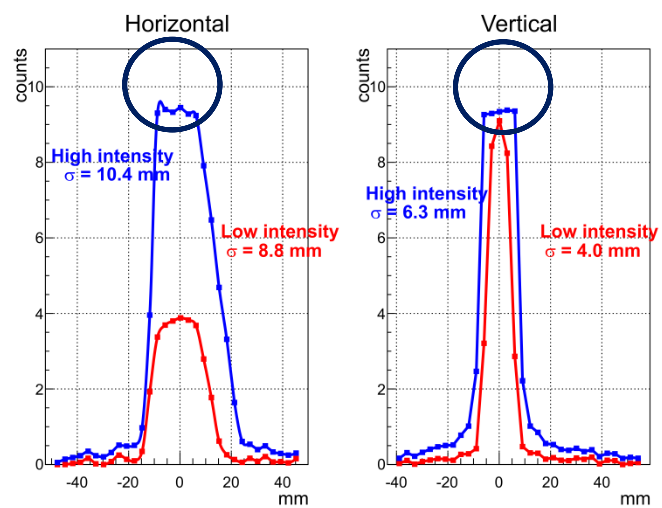
Beam image

$\mathbf{0.6 \pm 0.1\%}$ **efficiency**

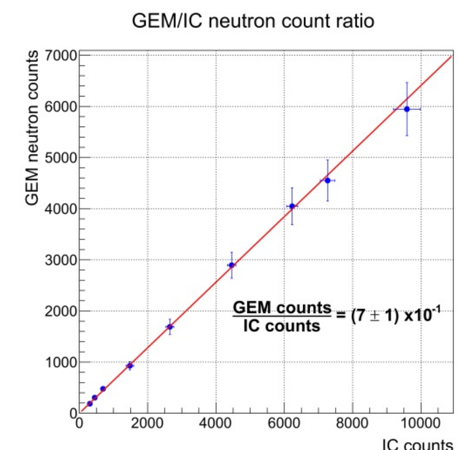
Beam profile comparison to a MWPC during an intensity scan



GEM

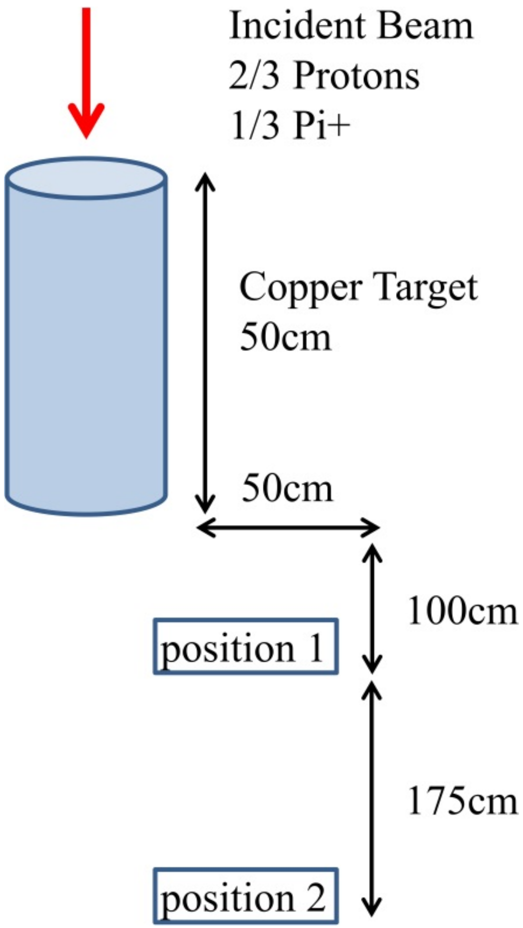


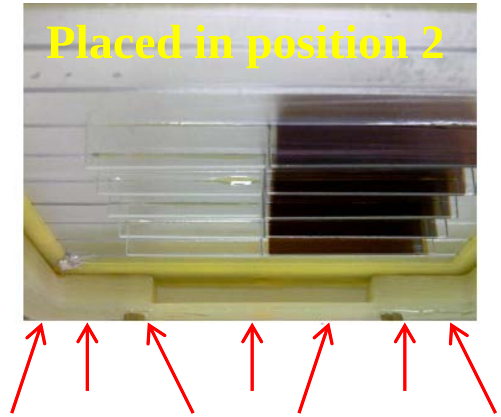
MWPC (saturates)



Good correlation with IC reference monitor

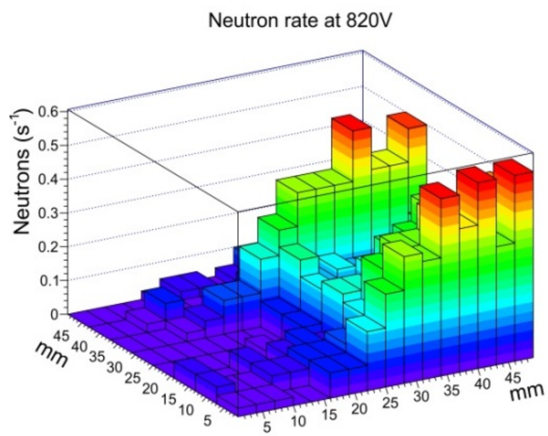
The Triple GEM detector for slow neutron detection at CERF @ CERN



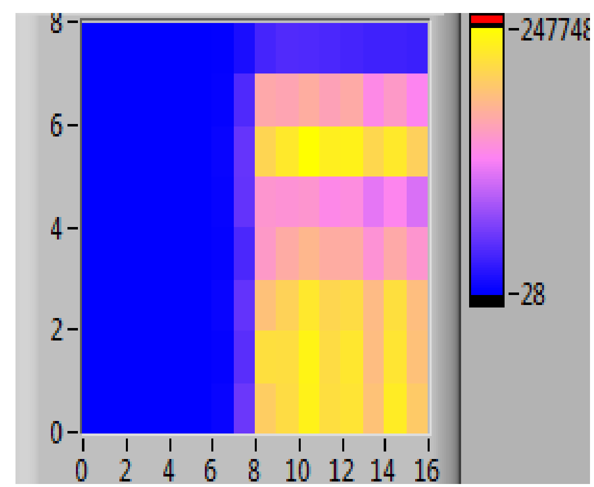


Non-borated and borated glass sheets

Neutrons generated from the target



On-line image



LUPIN

Chris Cassell, POLIMI and University of Wollongong

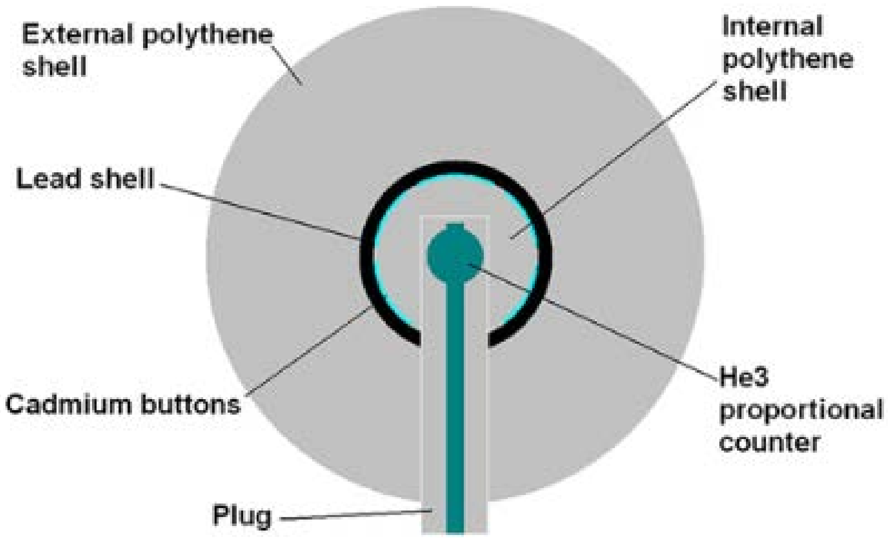
Proportional counter
^{3}He or BF_3

+

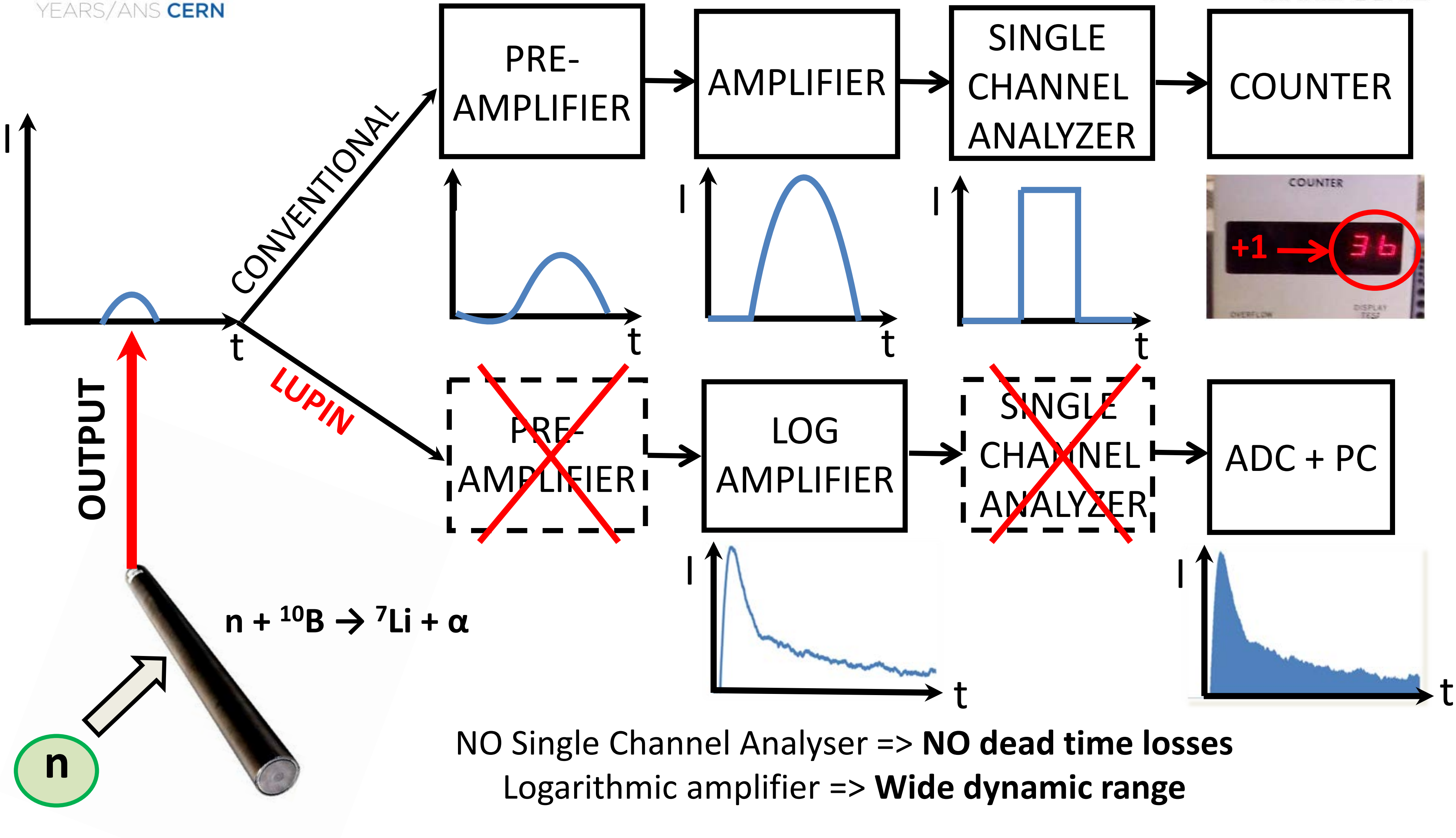
Moderator
(response function reproduces the curve of the **neutron fluence to H*(10)** conversion coefficients)

+

Innovative front end electronics



LUPIN

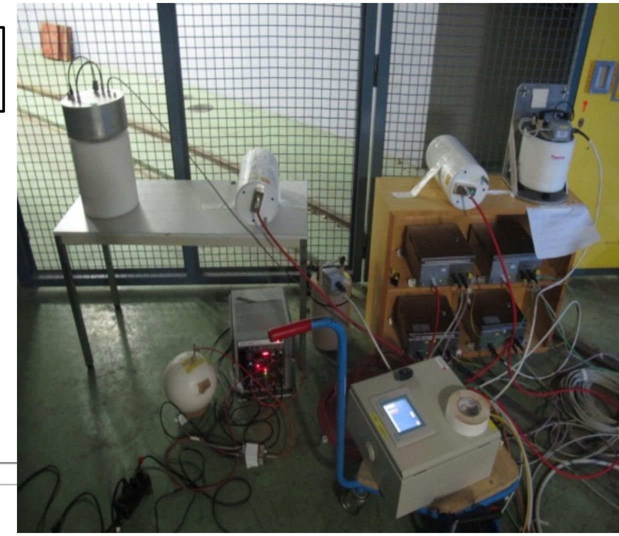


NO Single Channel Analyser => **NO dead time losses**

Logarithmic amplifier => **Wide dynamic range**

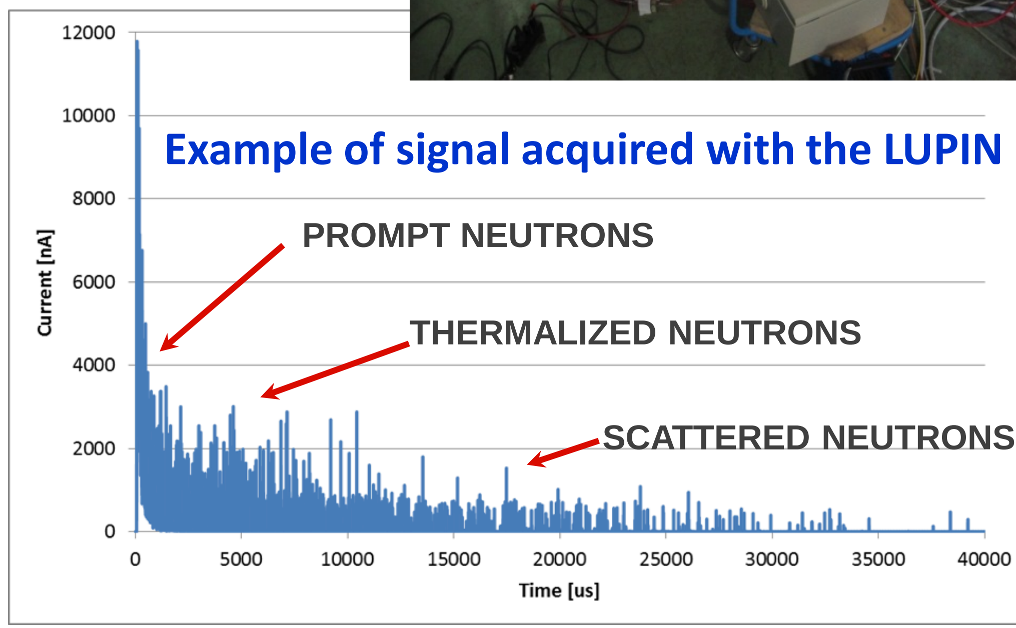
Measurements in pulsed neutron fields at CERN (just two examples)

Access to the PS tunnel



HiRadMat

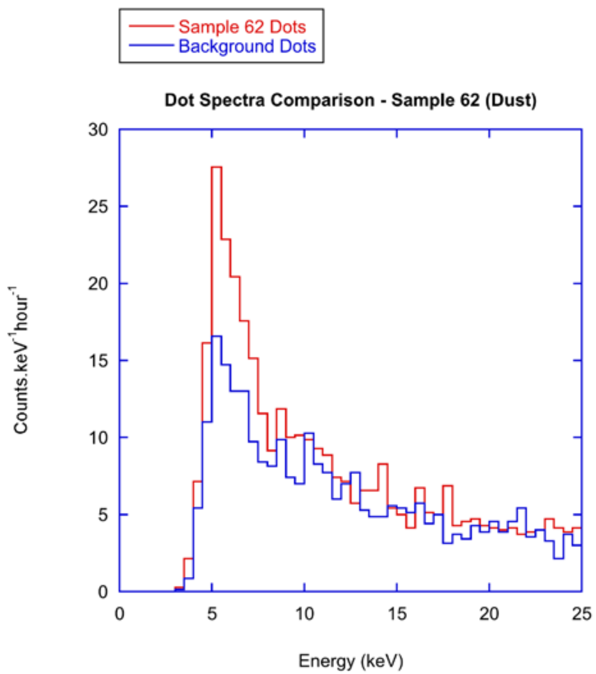
Detectors mounted on carousel

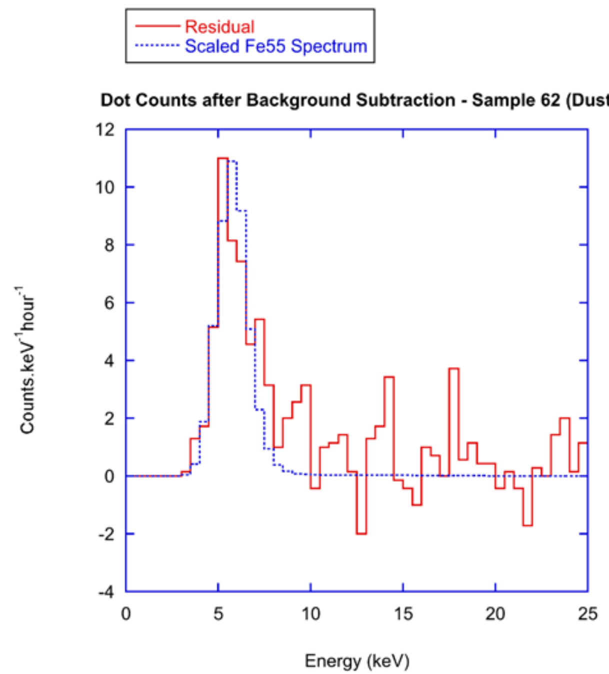


Detection of ^{55}Fe with Timepix

Stuart P. George, CERN and University of Wollongong

Detection of ^{55}Fe in radioactive waste is a major challenge…





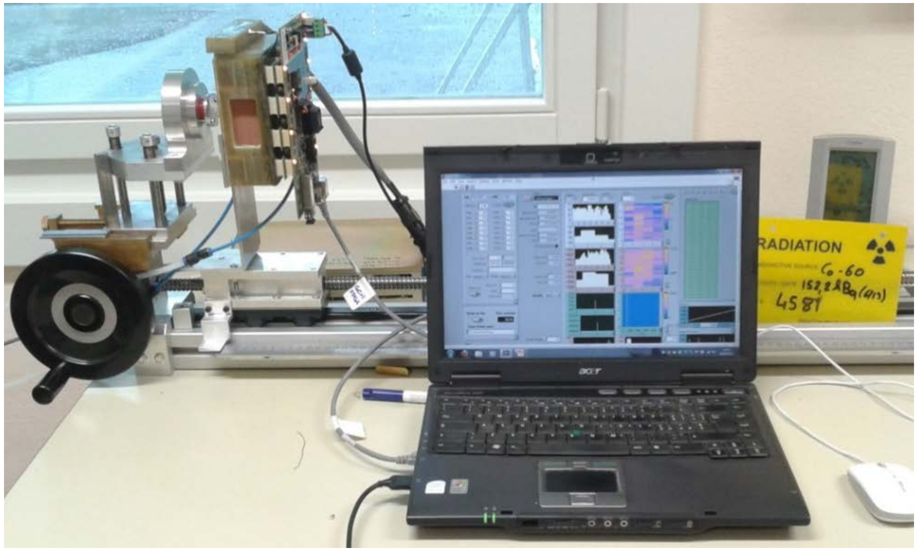
Determination of ^{55}Fe in radioactive waste

Silvia Puddu, CERN and University of Bern

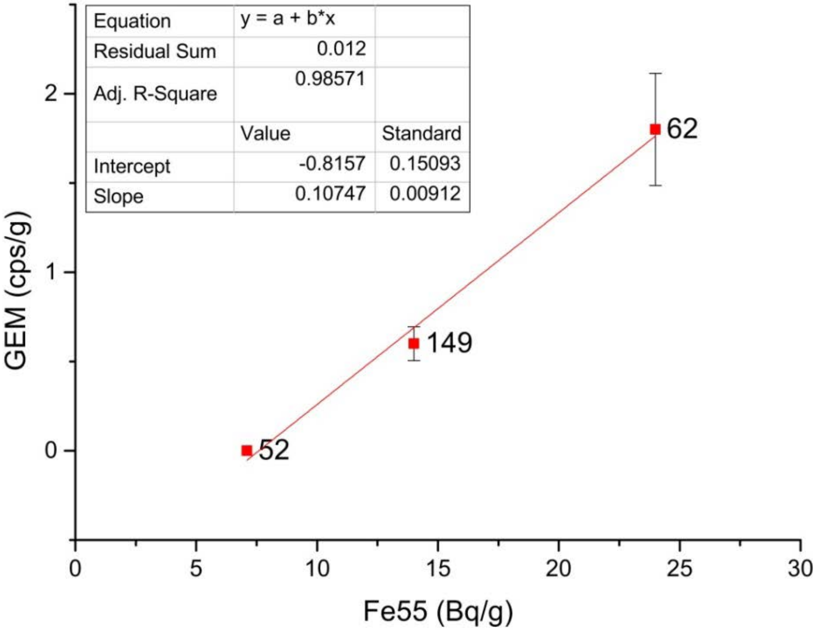
Efficiency to ^{55}Fe X- rays: 39%
Efficiency to ^{60}Co γ-rays: 1.14%
Gamma rejection factor: 34

Sample id	Weight (g)	GEM count rate (cps)	^{55}Fe (Bq/g) RC analysis
52	0.04	0.00±0.00	7.1
149	0.05	0.03±0.02	14.0
62	0.05	0.09±0.03	24.0

Procedure:
Sample reduced into dust and measured for ½ hour

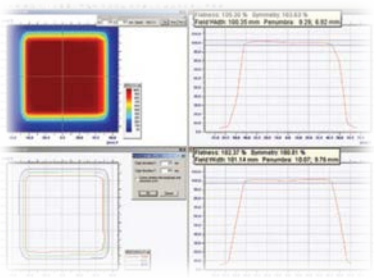


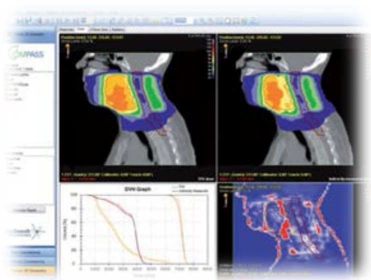
Test bench in laboratory with GEM set-up



New generation of high performances ionization chambers 2D detectors for radiotherapy

Michele Togno, IBA Dosimetry and Technical University Munich





Needs in clinical applications:

- Quality Assurance measurements: check of critical LINAC parameters such as penumbra, symmetry, flatness and field size
- Radiotherapy treatment validation: verification of absorbed dose vs planned dose

The goal is to develop a detector which is suitable to perform:

- Fast and accurate field profiling
- Measurements of absorbed dose in photon, electron and proton beams
- Measurements within a water phantom

2D detectors for radiotherapy

Starting point: IBA experience (MatriXX detector family, developed in collaboration with *INFN Turin*)

Outperform existing devices in terms of:

- improved stability of the detector
- better spatial resolution
- high charge collection efficiency at high dose rates (X-ray and p^+)
- lower production cost, better yield and less security concerns

Experimental activity

Characterization of first detector prototype (1D linear array) under ^{60}Co and MV X-ray:

- investigation of individual pixel dynamic response
- measurement of 1D dose distribution

Microdosimetry with TEPC

Jayasimha V. Bagalkote, Seibersdorf Laboratories and TU Graz

- Radiation quality and dose in complex radiation field in space on the International Space Station (ISS)

- Document astronaut’s exposures and support risk assessment

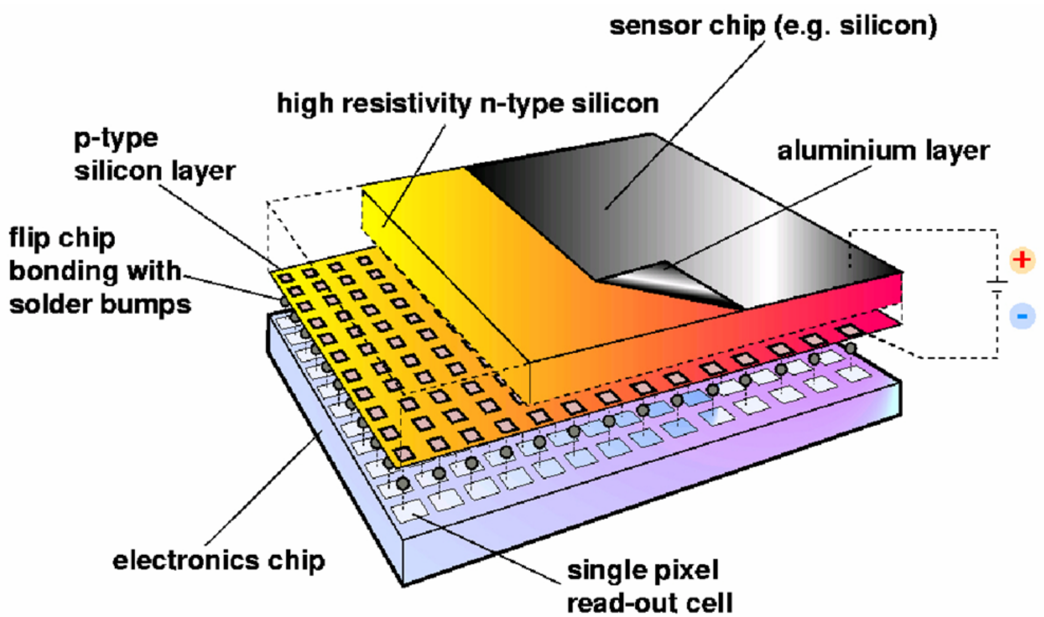
Activities:

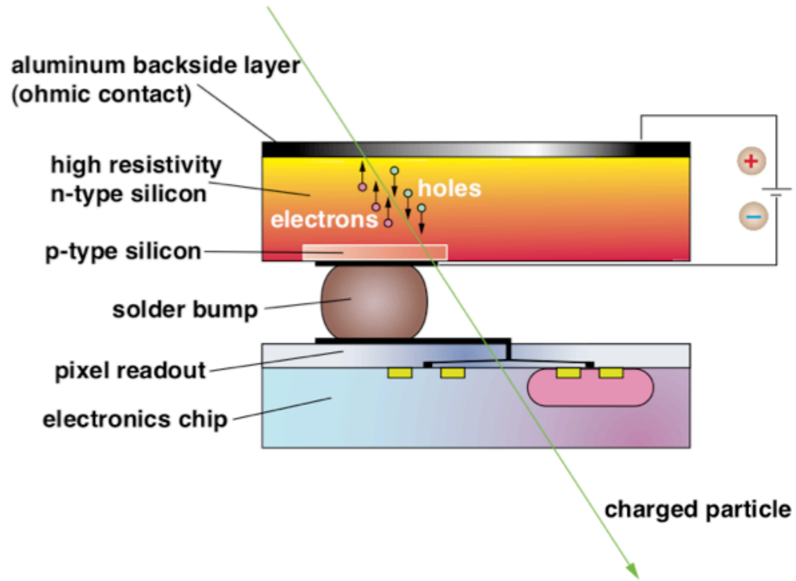
- Measurements with TEPC in irradiation facilities
- Numerical simulation by Monte Carlo methods

Solid state detectors

Medipix and Timepix

- Hybrid pixel detector architecture, where radiation sensor and readout are separated
- Sensor segmented with the same geometry as the readout chip – detector and readout cells connected using standard flip-chip technology
- Separation in processing allows for independent optimization of readout and sensor and different sensor materials can be used with the same readout

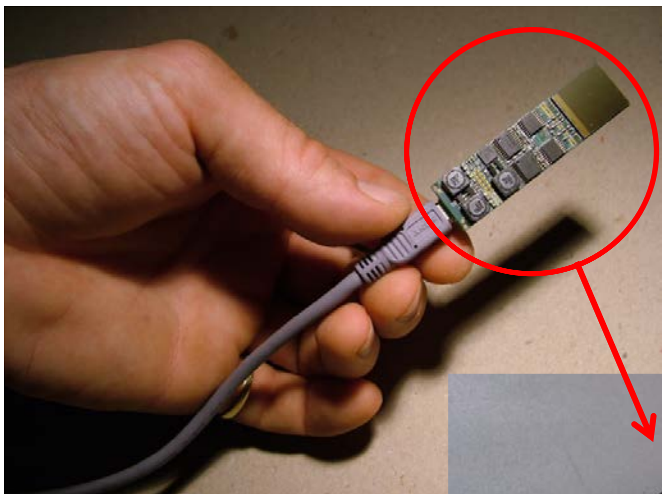




Schematic of a hybrid pixel detector with the sensor chip and the electronics chip connected via bump bonds

Medipix and Timepix

- Use USB standard for detector read-out and data acquisition control
- Plug & Play
- Fully USB powered
- External triggering
- Compact size of interface

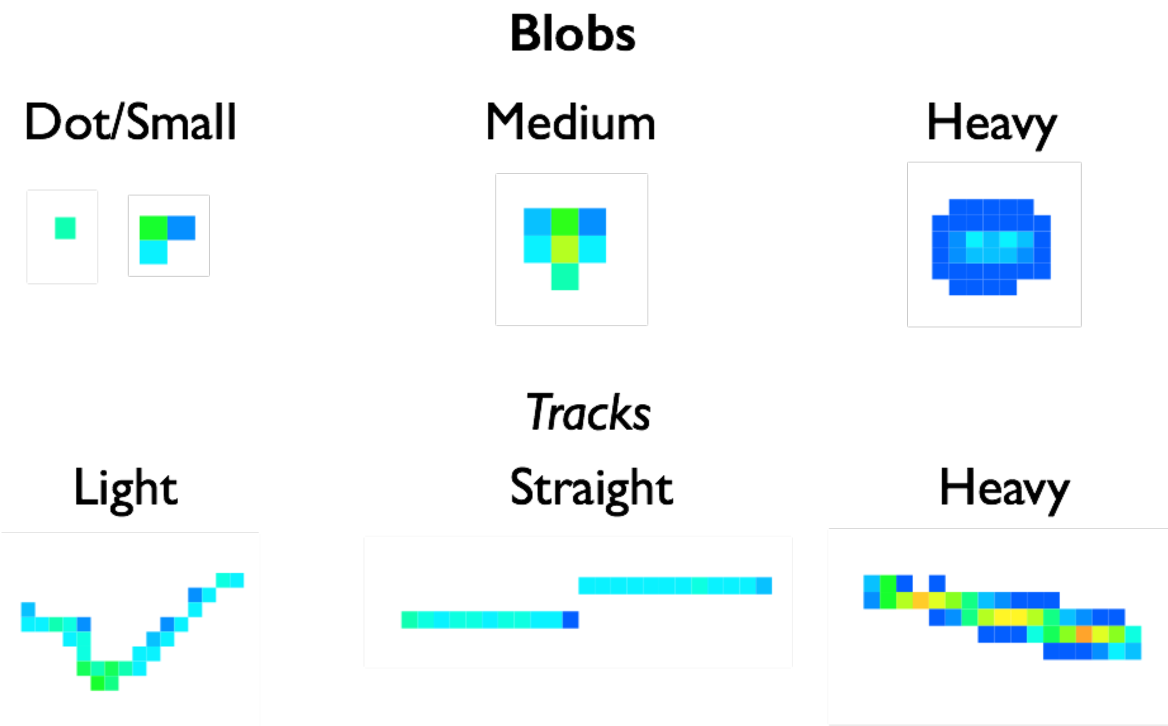


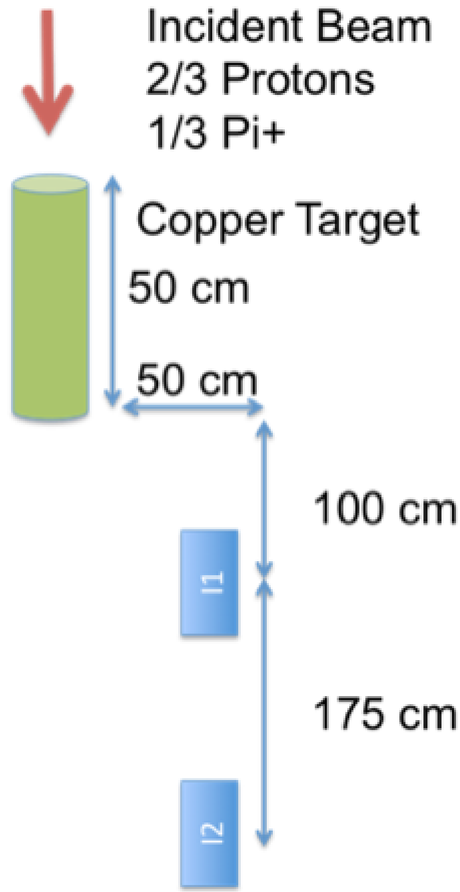
USB-Lite Interface

- USB Lite interface is miniaturized version
- Very compact size of 60 mm x 15 mm

Mixed field analysis with Timepix at CERF

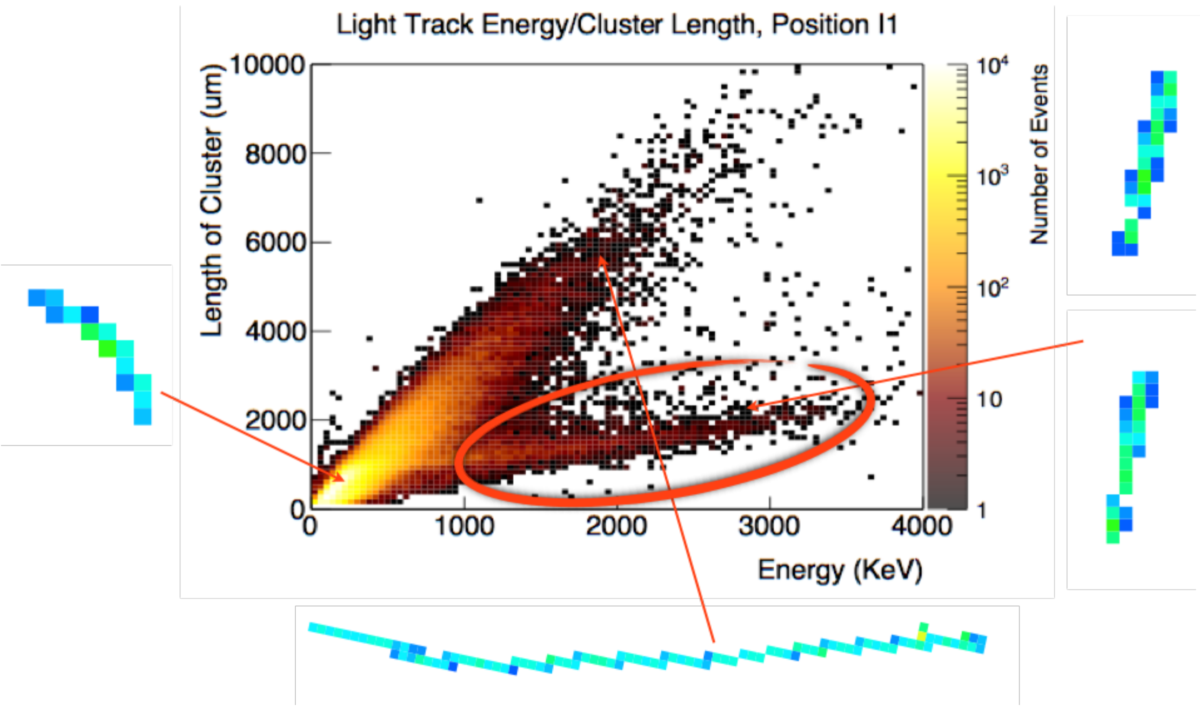
Stuart P. George, CERN and University of Wollongong

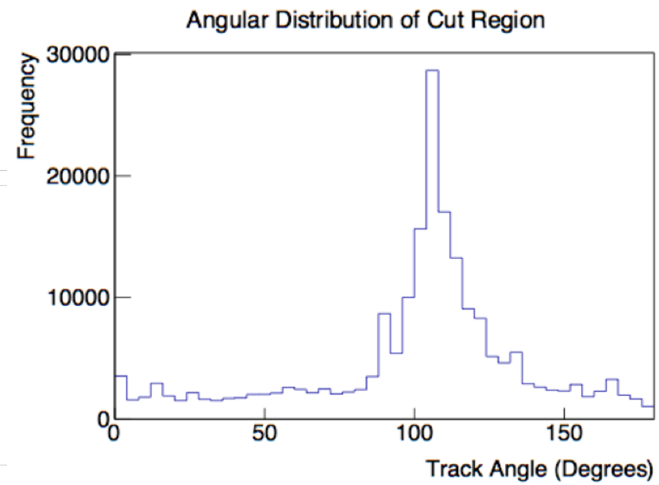




Mixed field analysis with Timepix at CERF

Fast protons look naively like electrons, but are highly directional





Electrons ~200 keV

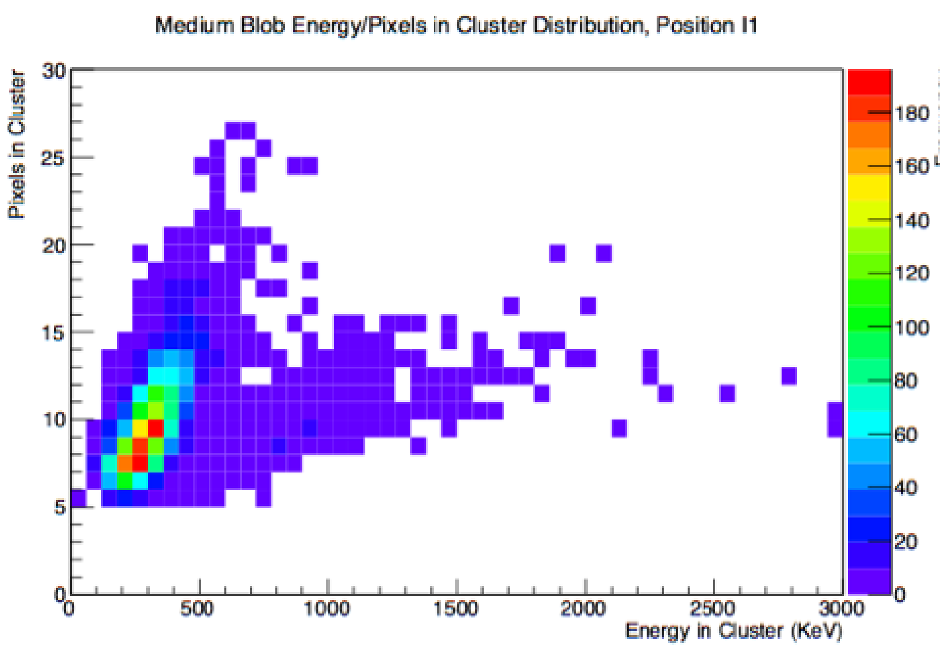
Electrons ~MeV

Protons > 30 MeV

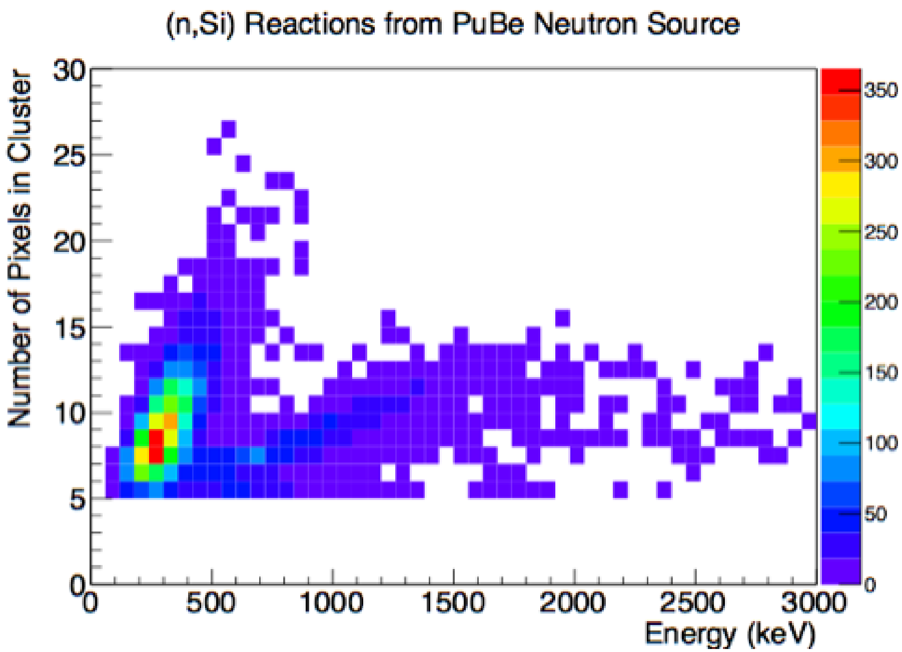
Tracks in cut (red) region show strong angular dependence

Mixed field analysis with Timepix at CERF

- Low energy (n,Si) events deep in Silicon create ‘medium’ blobs
- Either from low incidence fast protons, or (n,Si) reactions deep in silicon. CERF has no source of low incidence fast protons.



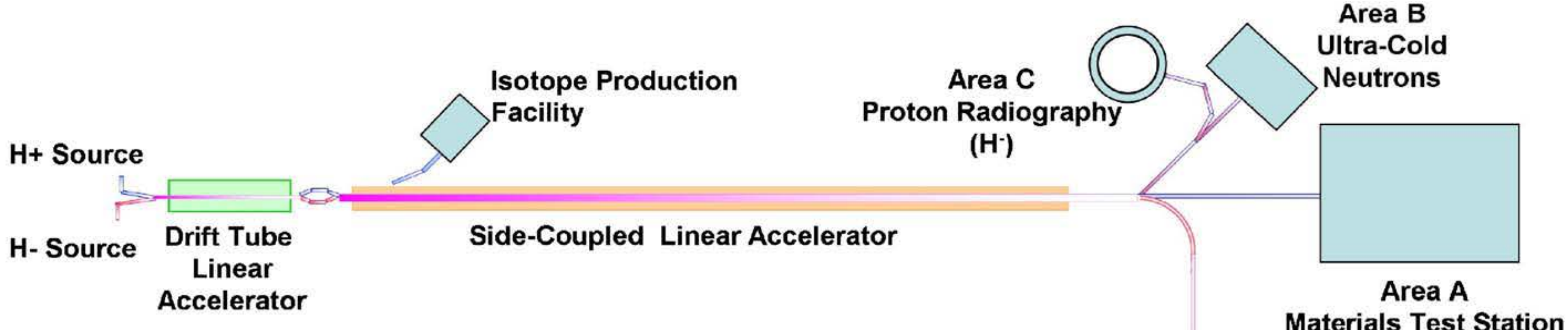
Medium blob distribution at CERF



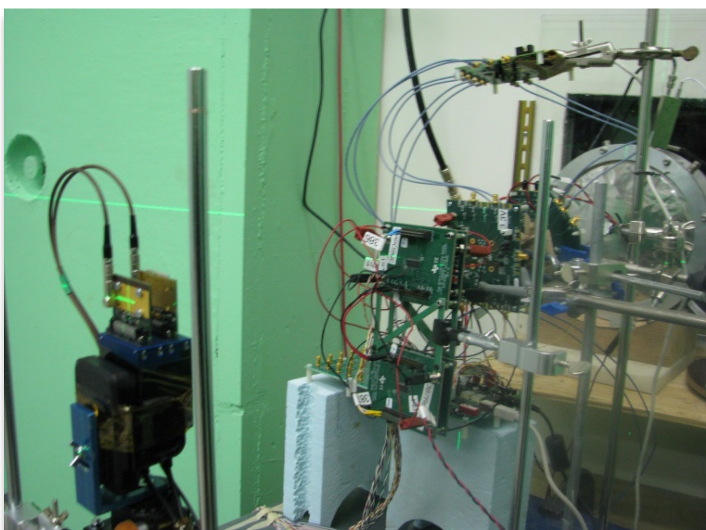
Medium blob distribution from PuBe field

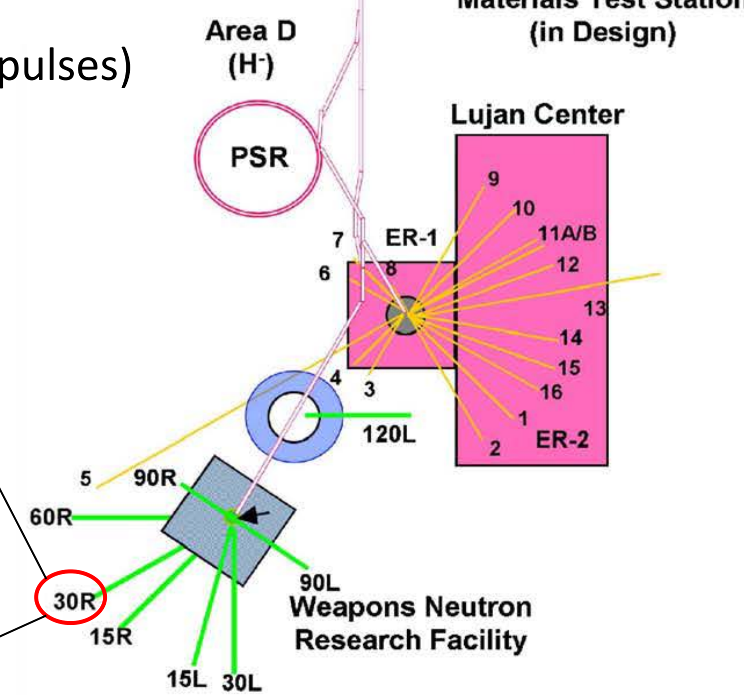
Neutrons at Los Alamos Neutron Science Center

Benedikt Bergmann, CTU



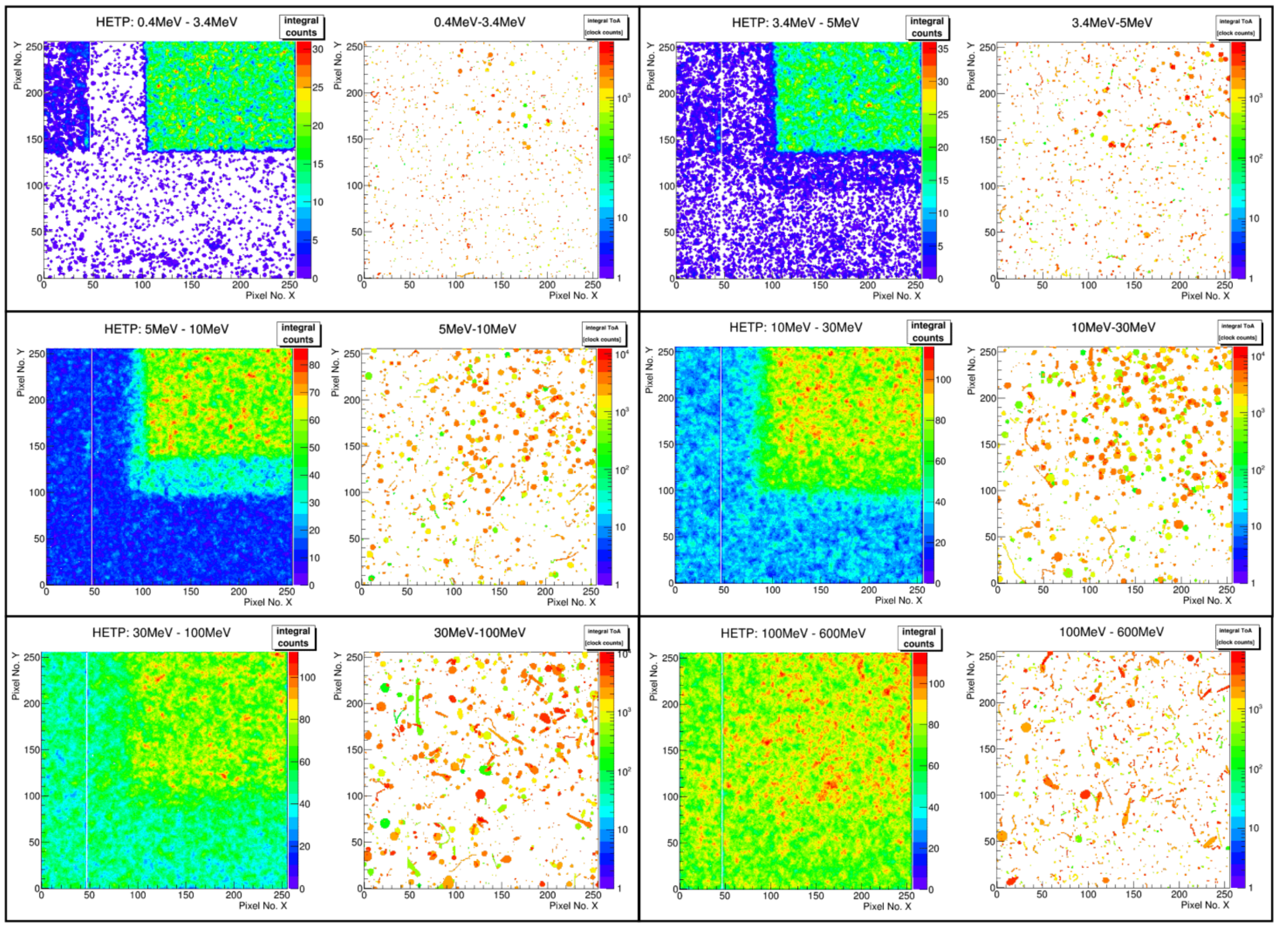
- Pulsed beam with repetition rate 1.8 µs (micropulses)
- Kinetic neutron energies up to 600 MeV

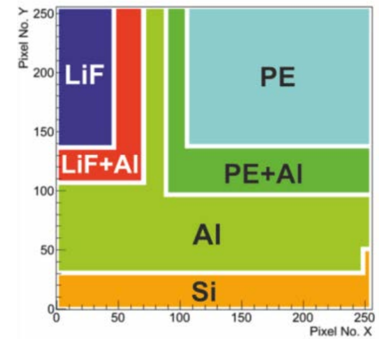




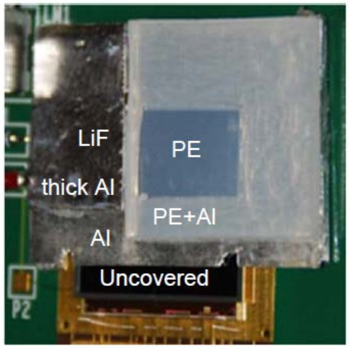
Detector response to different neutron kinetic energies

- Converter foils attached to the top of the silicon sensor layer to enhance the reponse to neutrons of different kinetic energies



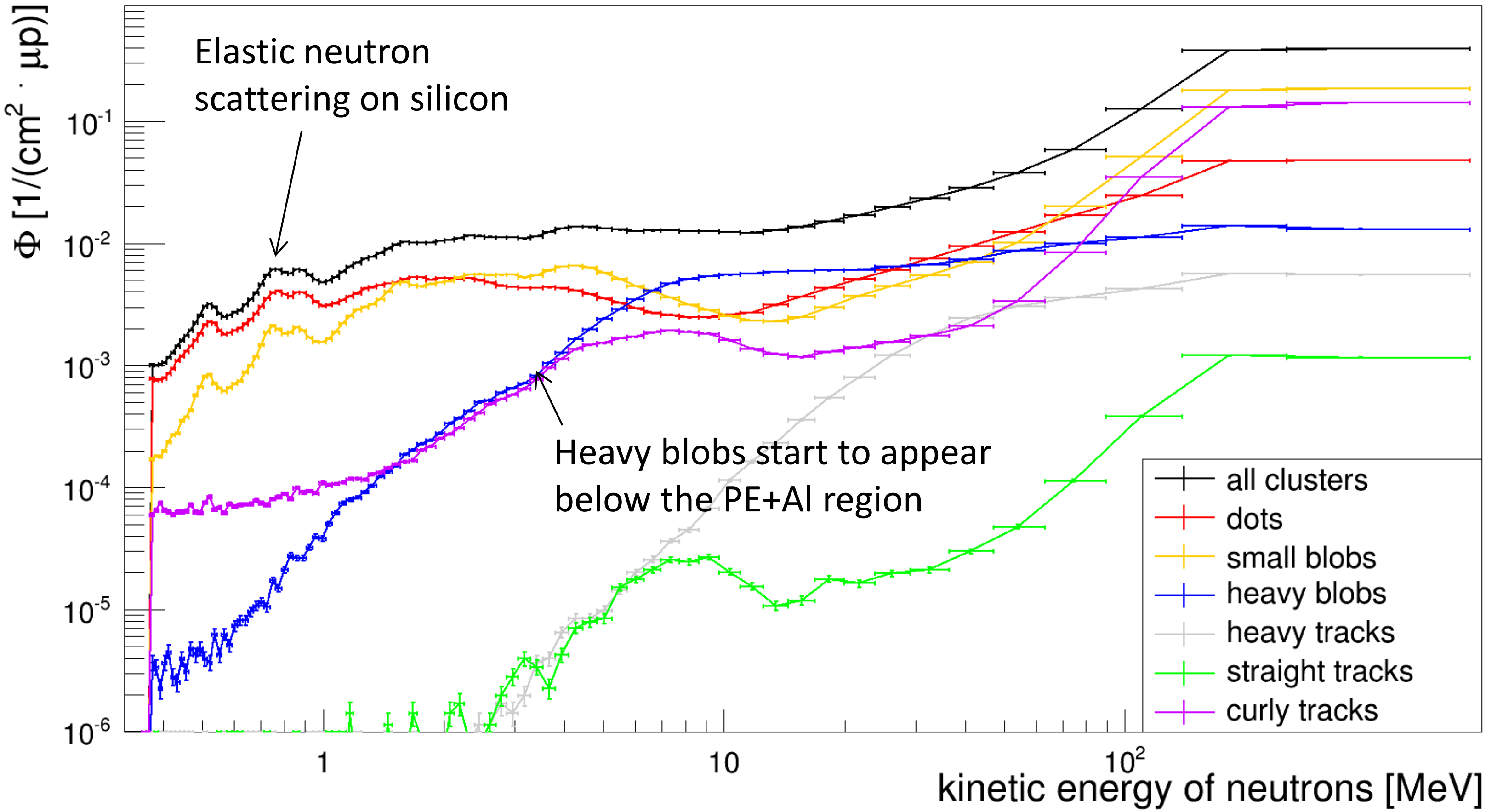


Detector response to HETP (right) and 1000 representative interactions for the neutron kinetic energy interval (left).



Fluxes of different cluster types as a function of energy

- Contribution of different cluster types varies over energy
- For neutron detection especially fluences of **H**igh **E**nergy **T**ransfer **P**articles ("Heavy Tracks" and "Heavy Blobs") are of interest

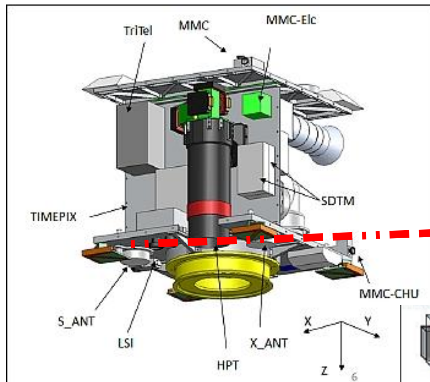


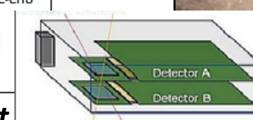
Timepix-based Space Radiation Micro-tracker

Ivan Caicedo, CTU

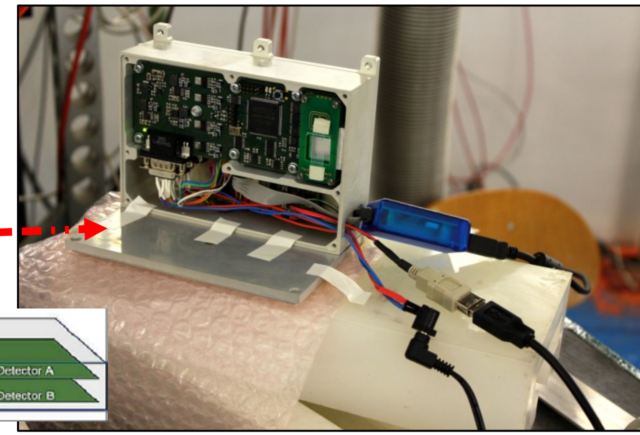
Stability tests of dedicated hardware and software for a two-layer Timepix design to be located on the RISESAT satellite.

(https://directory.eoportal.org/web/eoportal/satellite-missions/r/risesat)



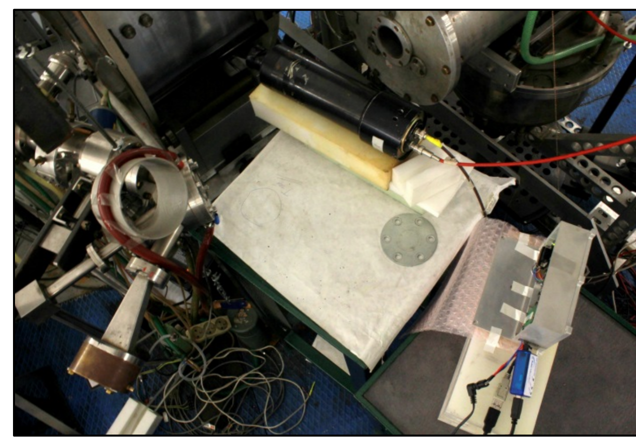


Payload side view RISESat
(Image: RISESat consortium)



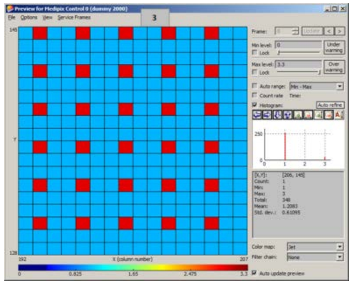
Variables to be tested: response vs temperature and pressure variations, synchronization stability, data acquisition for long periods (considering probable variations in the radiation field flux and energies).

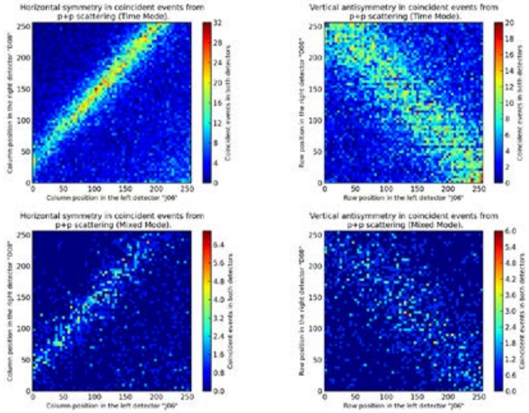
Tests at the CTU IEAP VdG accelerator: *Detection of fast neutrons and alpha particles resulting from d+t reactions at energies of a few MeV (data analysis ongoing)*



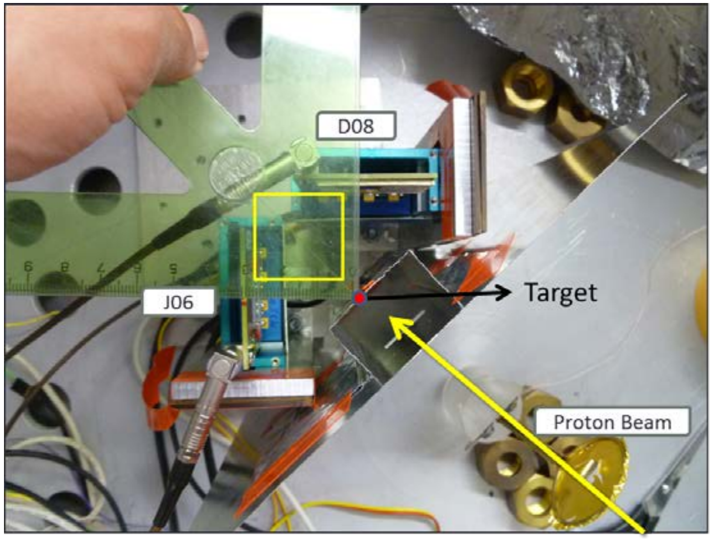
Spatial and spectroscopic evaluation of coincident events on synchronized Timepix detection layers

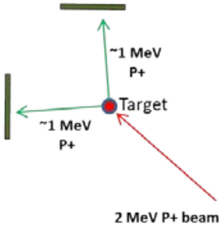
Measuring energy and arrival time at the same time → Event-by-event energy deposition in different detection layers



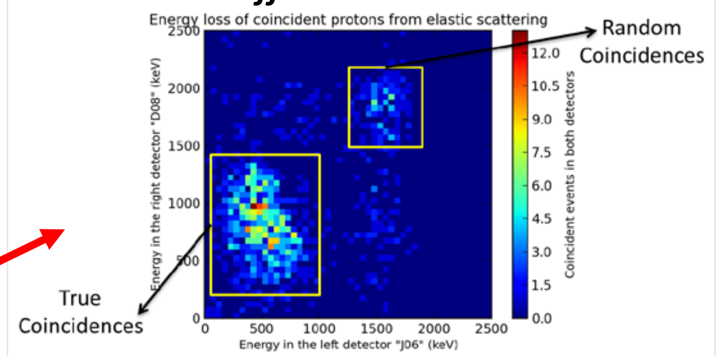


Spatial correlation of coincident events in "Arrival Time" mode and using a "Time+TOT" Chess-like mask, for two different detectors





Detection and characterization of coincident protons from elastic proton-proton scattering

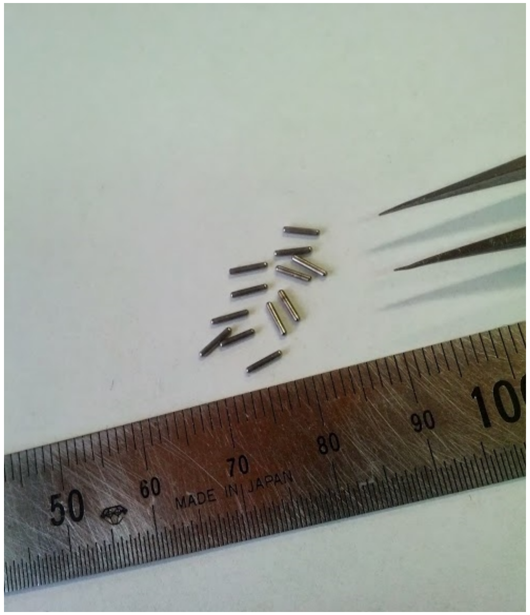


Energy-loss correlation for coincident events in two synchronized Timepix devices

Medical applications

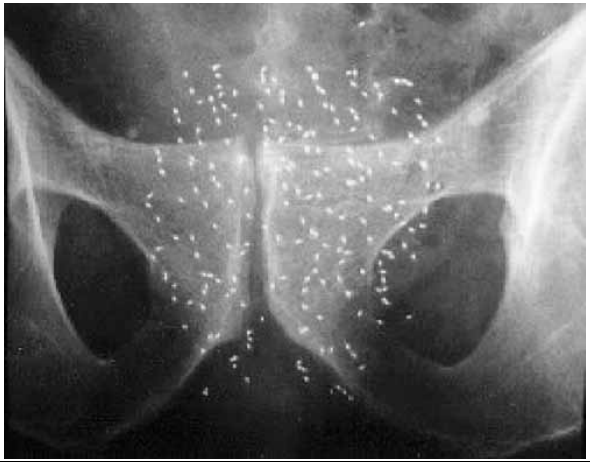
BrachyView – Medipix in cancer treatment

Kevin Loo, CTU and University of Wollongong



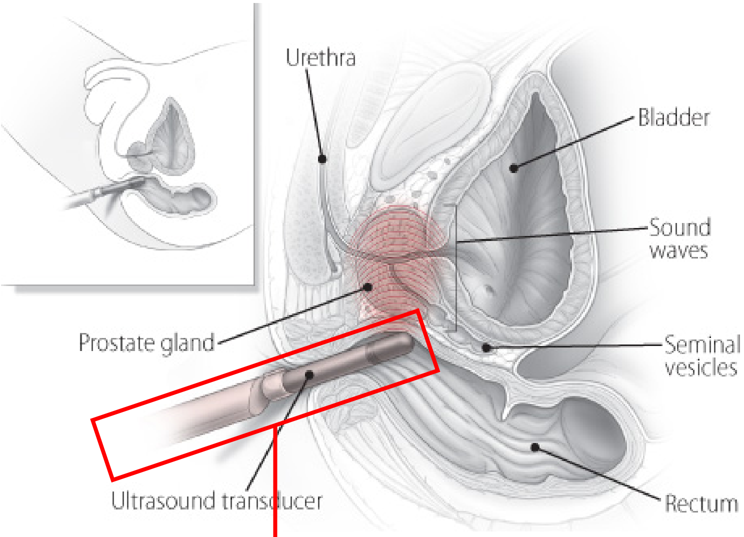
Brachytherapy

- Small radioactive sources permanently implanted directly into tumour site via stainless steel needles
- Low dose rate (LDR): ^{125}I photons
- Create therapeutic cloud of dose within prostate gland

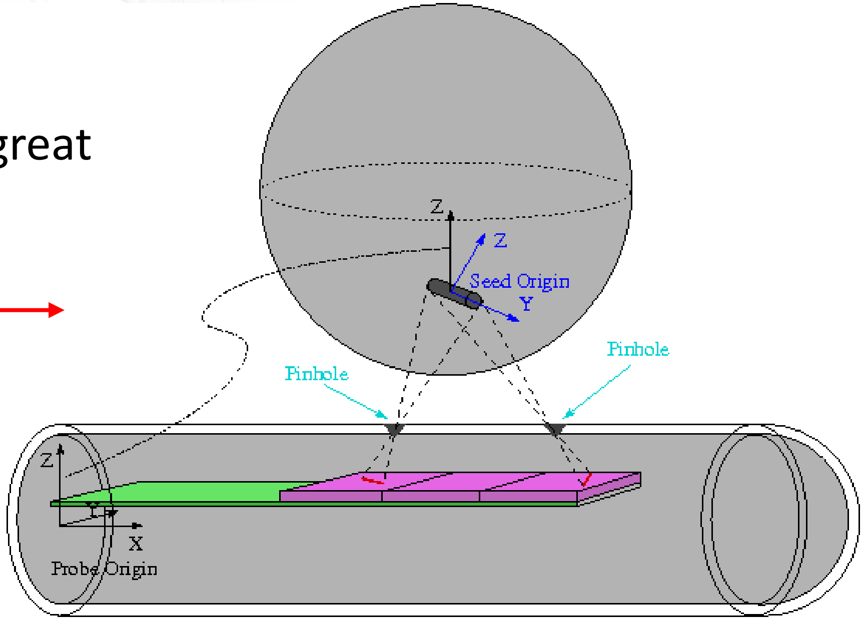


BrachyView – Medipix in cancer treatment

- Use Medipix to develop brand new, ultra-functional, in-body imaging probe
- Currently, doctors use a combination of ultrasound, X-rays, CT for implant verification

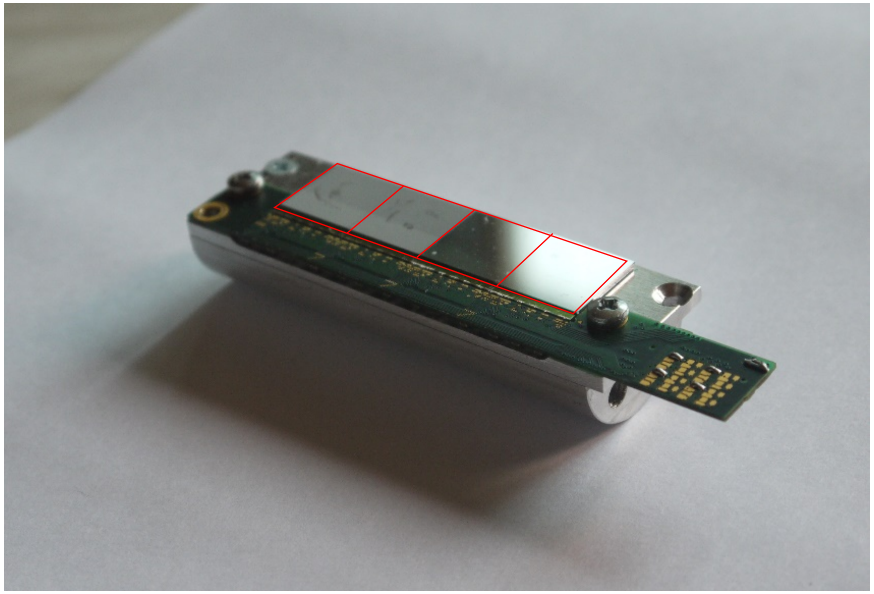


- Close collaboration with clinical facilities, with great interest in the project
- BrachyView will be able to cover all the requirements of these imaging systems in one single, cost-effective device
  - Soft tissue diagnostic imaging
  - Pinhole gamma camera
  - CT post-implant dosimetry



BrachyView
Intraoperative treatment planning

- By introducing Medipix detectors into the brachytherapy procedure, critical organs at risk can be avoided and areas of under-dosage can be compensated for in real-time
- Perform dynamic dose planning and post-implant QA dosimetry
- Feasibility study completed with further experimental results being prepared for publication



Prototype for BrachyView detector system utilising a novel tiled Medipix detector design

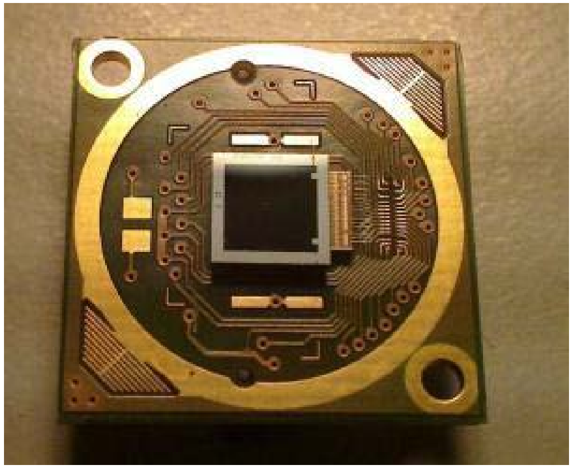
Dosepix for medical quality assurance

Francesca Bisello, IBA Dosimetry and University of Erlangen

DOSEPIX : General Overview

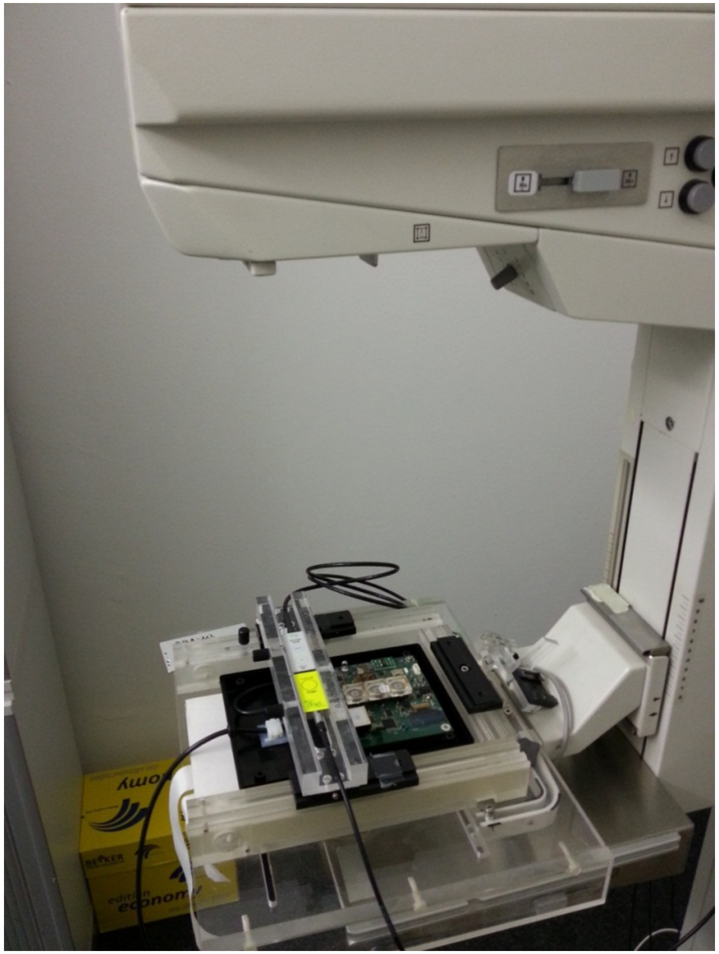
Hybrid pixel detector for single photon counting

PARAMETER	SPECIFICATION
Pixel Pitch	220 µm x 220 µm
No. of Rows	16
No. of Columns	16
Sensitive Area	3.52 mm x 3.52 mm
Sensor Material	Silicon
Sensor Thickness	300 µm



Energy Binning Mode: 16 Energy Binning for each pixel

Dosepix for medical quality assurance



*"One of the most important parameters of diagnostic X-RAY EQUIPMENT is the voltage applied to the X-RAY TUBE, because both the **image quality** in diagnostic radiology and the **DOSE received by the PATIENT** undergoing radiological examinations are dependent on the X-RAY TUBE VOLTAGE."*
(IEC 616776)

End point of the impinging spectra provides the kV of the X-ray tube

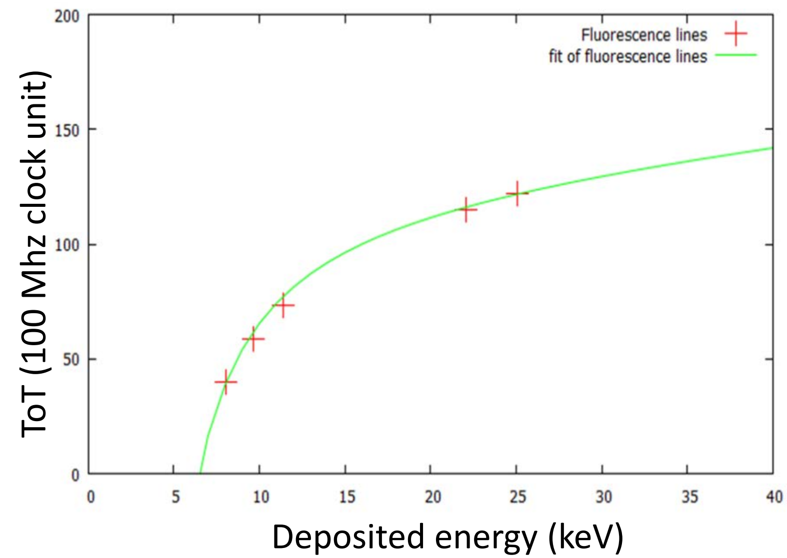
"The standard RADIATION QUALITIES RQR are described by a set of parameters :
- an emitting target of tungsten
- an X-RAY TUBE VOLTAGE
- an adjusted TOTAL FILTRATION of the X-RAY SOURCE ASSEMBLY
- the first HALF–VALUE LAYER
- the HOMOGENEITY COEFFICIENT"
(CEI IEC 61267)

Deconvolution of the spectra to extract information about the total filtration within the X-ray tube and the HVL of the impinging radiation

Characterization with fluorescence lines

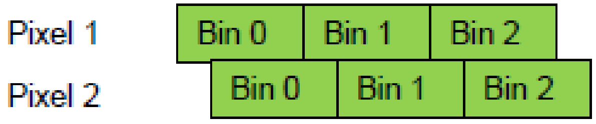
Energy calibration with fluorescences lines:

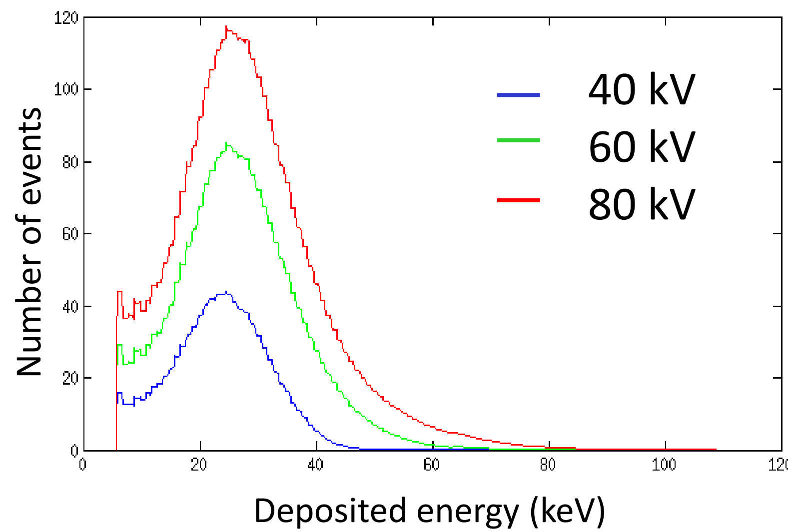
Characterization	
Analog Threshold	~ 65 mV (2000 e⁻)
Energy Threshold	3.29 ± 1.67 keV
Energy Resolution (8-25 keV)	10 %



Impinging bremsstrahlung spectra at different tube energy

Spectra obtained overlapping the energy bins

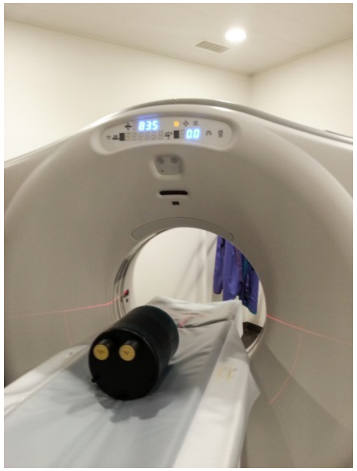


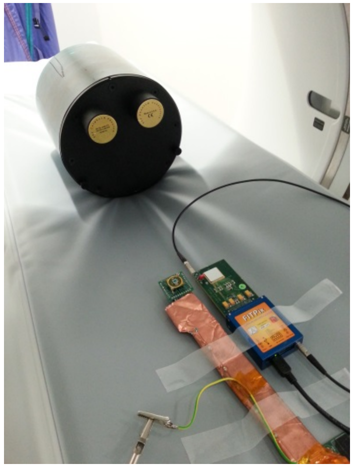


Scattered radiation in a CT room

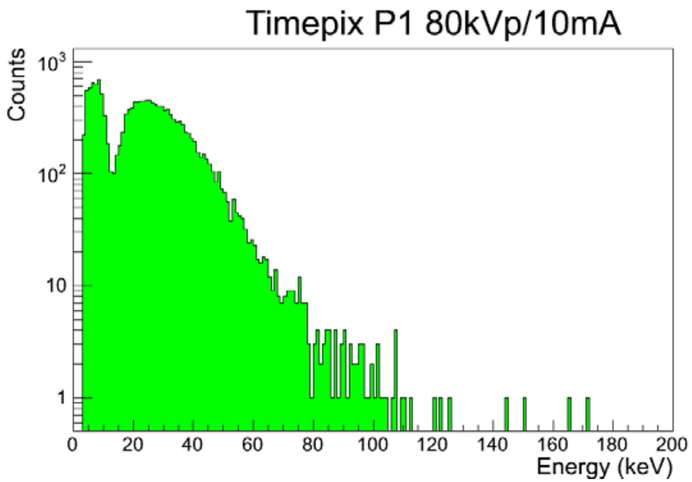
Erik Frojdh, CERN and Mid-Sweden University

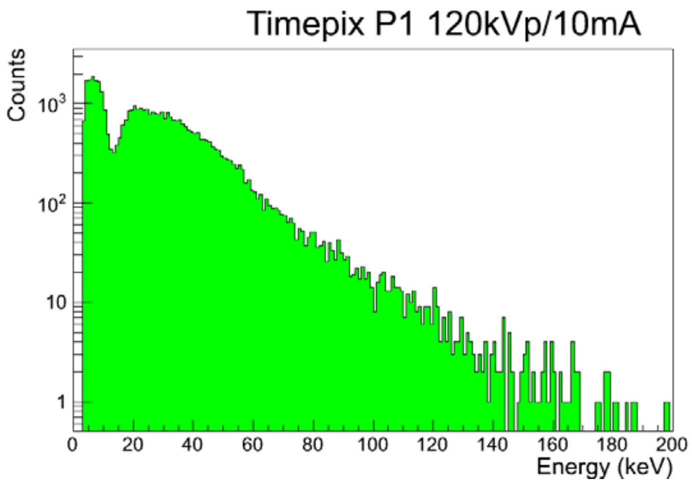
- **Dosepix** and **Timepix** detectors with a 300 µm Si sensor
- Measurements performed at CHUV in Lausanne
- Ge Medical Systems Discovery CT750 HD CT-scanner
  - at 80 kVp and 120 kVp
- Measured scattered radiation during **scan of an abdomen phantom**

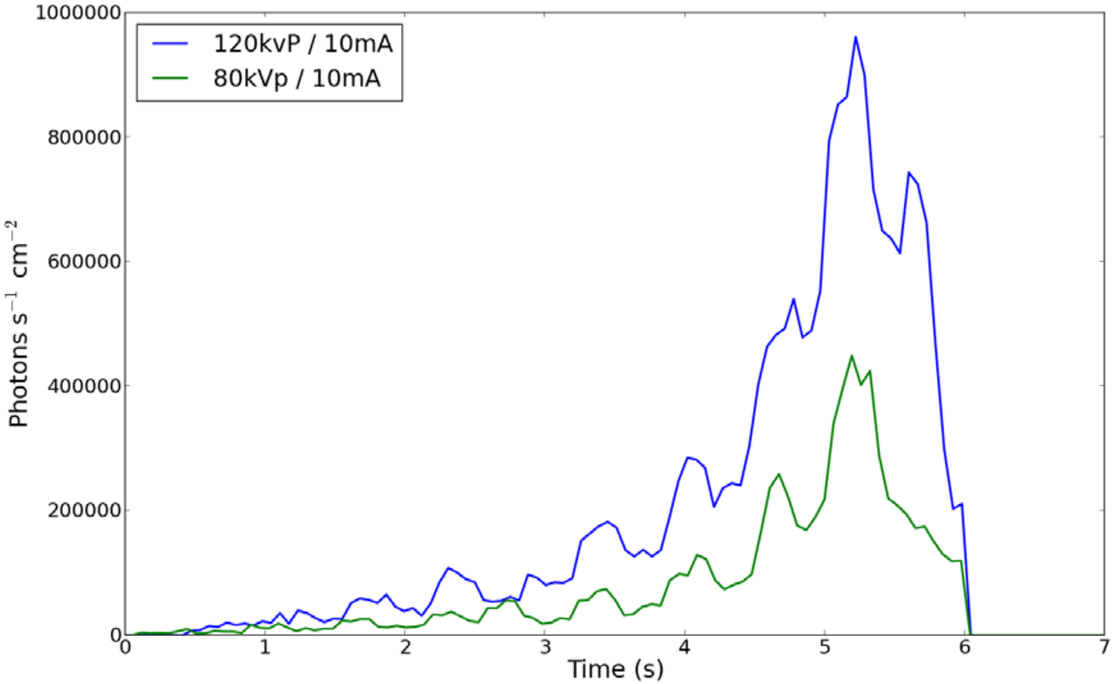




Timepix pos1 ON cradle -25 cm

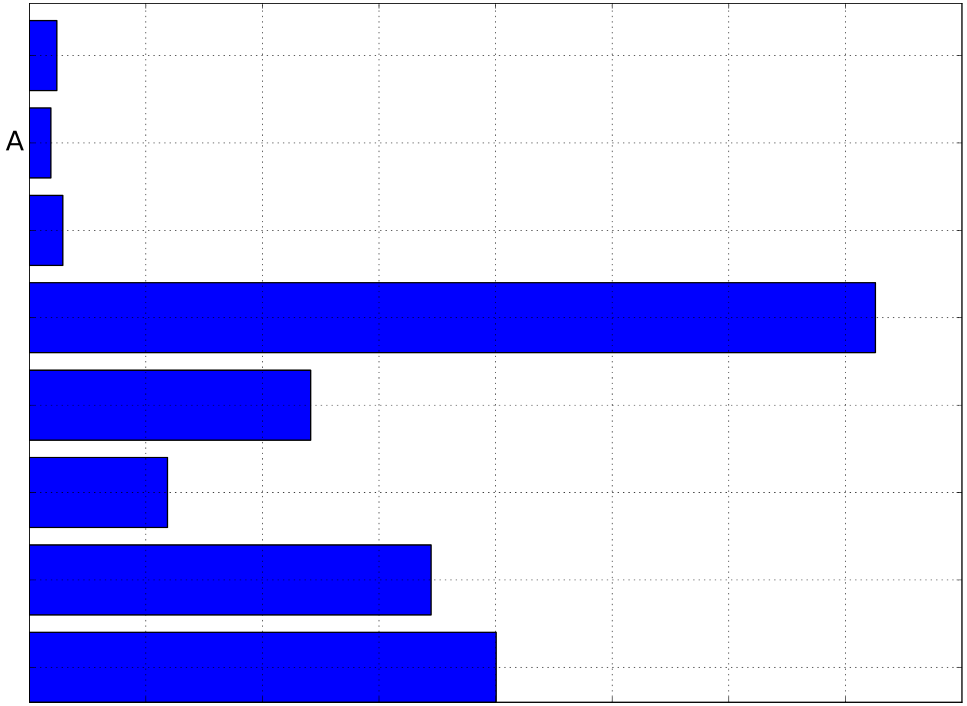


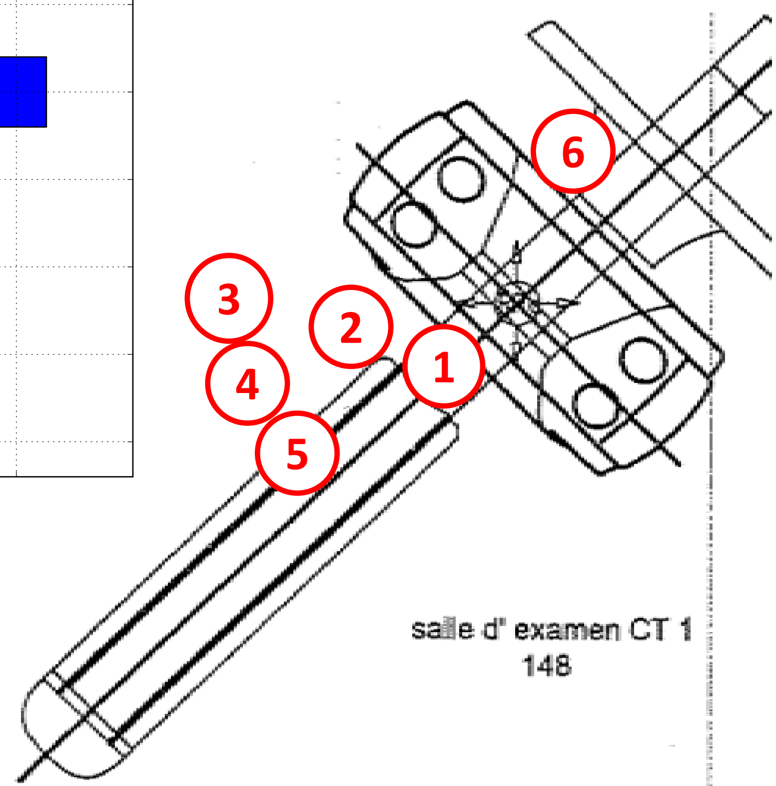




Each bump corresponds to one rotation of the gantry

Integrated energy, Timepix





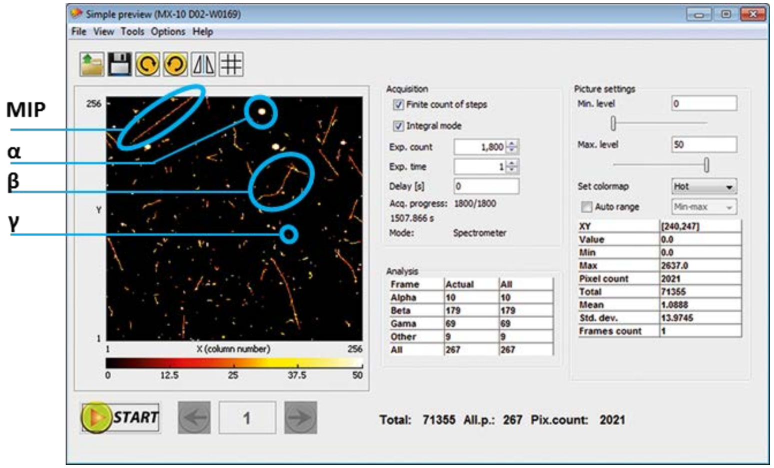
It scales with the mA setting
Fairly independent of exposure time

Medipix educational kit

Vijayaragavan Viswanathan, Jablotron

- Educational kit
  - Take research outcome to society
  - Use advanced technology and innovative solutions for teaching
  - Simplify radiation detection by visualization
- Advantages of Medipix technology in education
  - Differentiation of particles (e.g alpha, beta, gamma, MIP..)
  - Real time visualization of particles
  - Histograms on energy values
  - Portable device
- Taking to students
  - Outreach activity of ARDENT
  - Visiting schools to introduce the technology

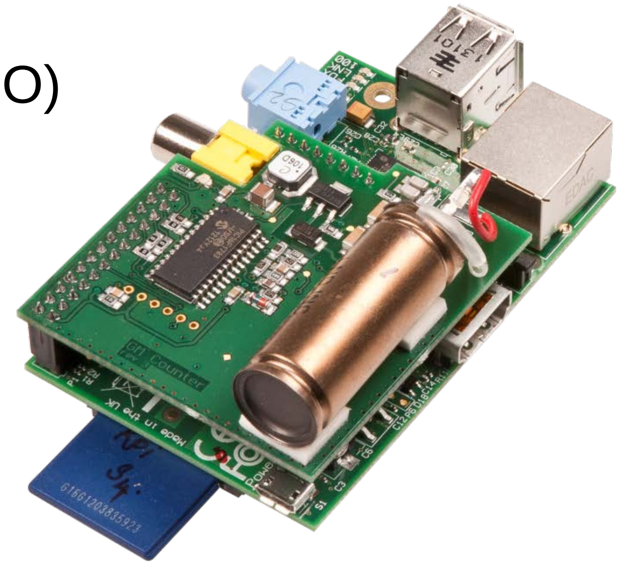
MX-10 : Medipix based educational kit

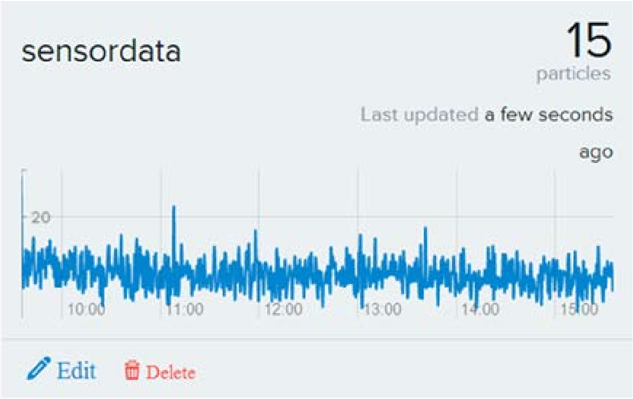


Visualization of particles using Pixelman software

Development of low cost radiation monitor

- Czech Radiation Protection Institute (SURO)
  - Low cost radiation monitors
  - Deploy all across the country
  - Wired or wireless based device
  - Cloud connectivity to monitor remotely
- Prototype
  - Raspberry-Pi based device
  - First prototype ready
  - Ongoing experiments and calibration activity
- Next steps
  - Include other blocks like Temperature, Humidity, Pressure
  - Ensure the device environment
  - Mechanical design
  - Testing and deployment



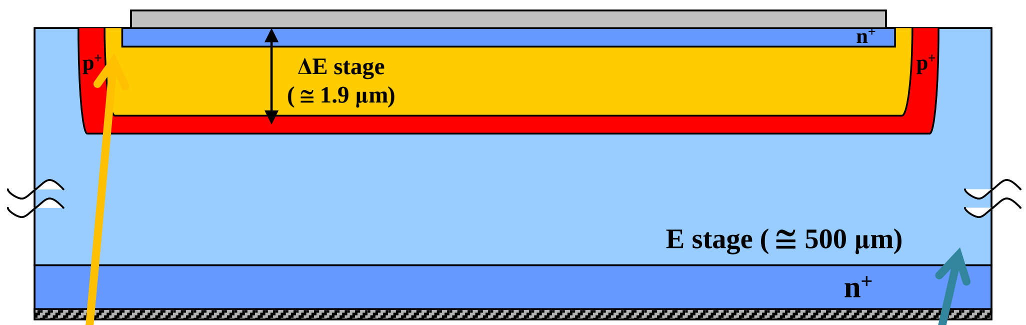


Remote monitoring

Silicon microdosimeter

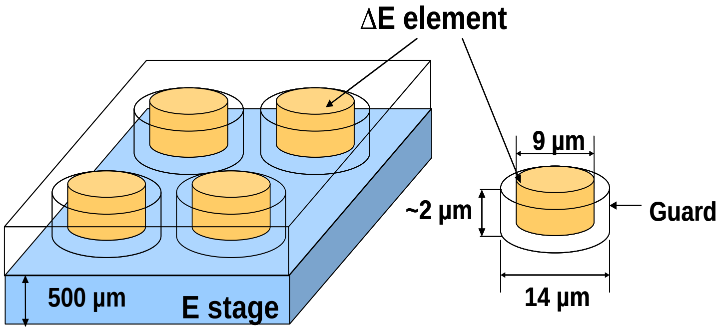
Elena Sagia, Polytechnic of Milano

Monolithic silicon telescope



<u>Silicon telescope</u>:
a thin ΔE stage (1.9 μm thick) coupled to a residual energy stage E (500 μm thick) on the same silicon wafer.

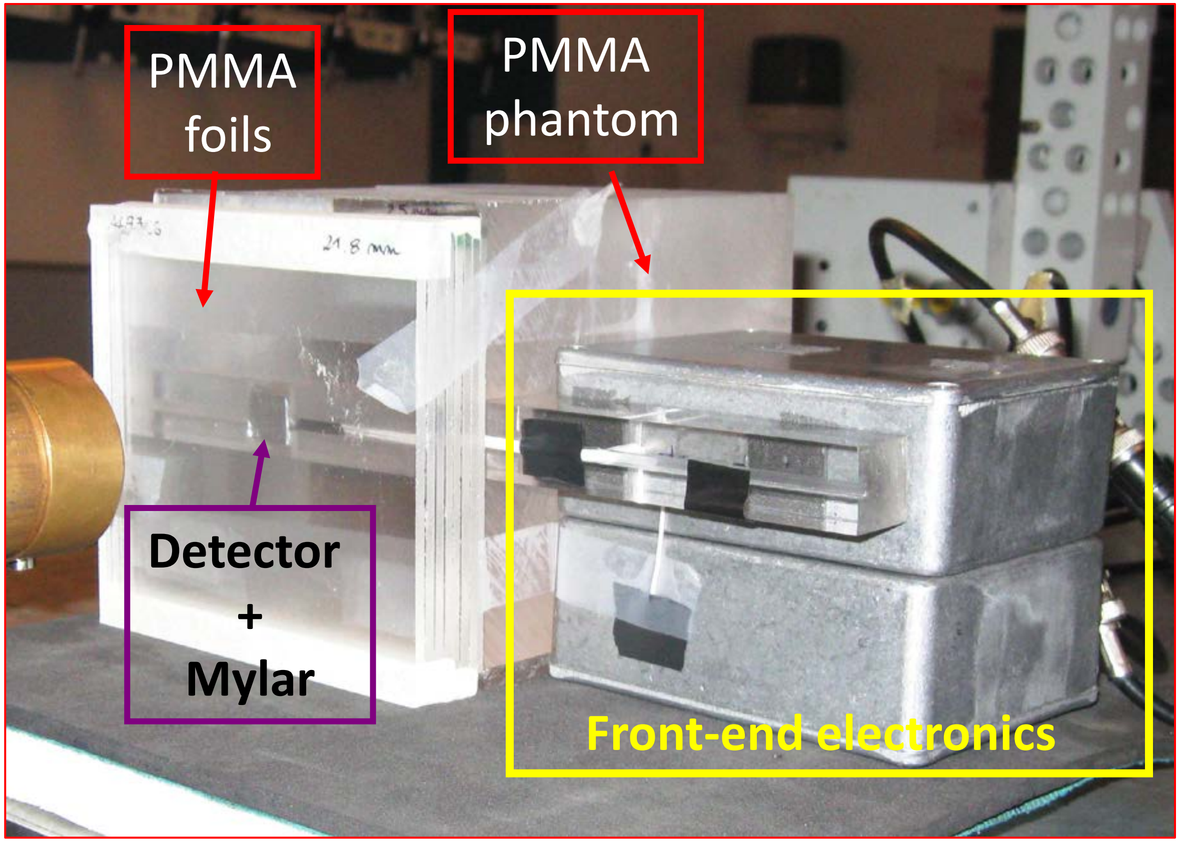
- Segmented ΔE stage

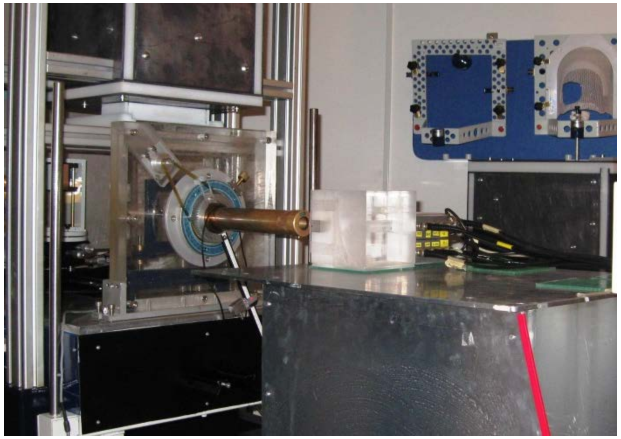


- **7000 pixels in parallel**
- **Sensitive area 0.5 mm^2**
- **Minimum detectable energy limited to about 20 keV by the electronic noise**

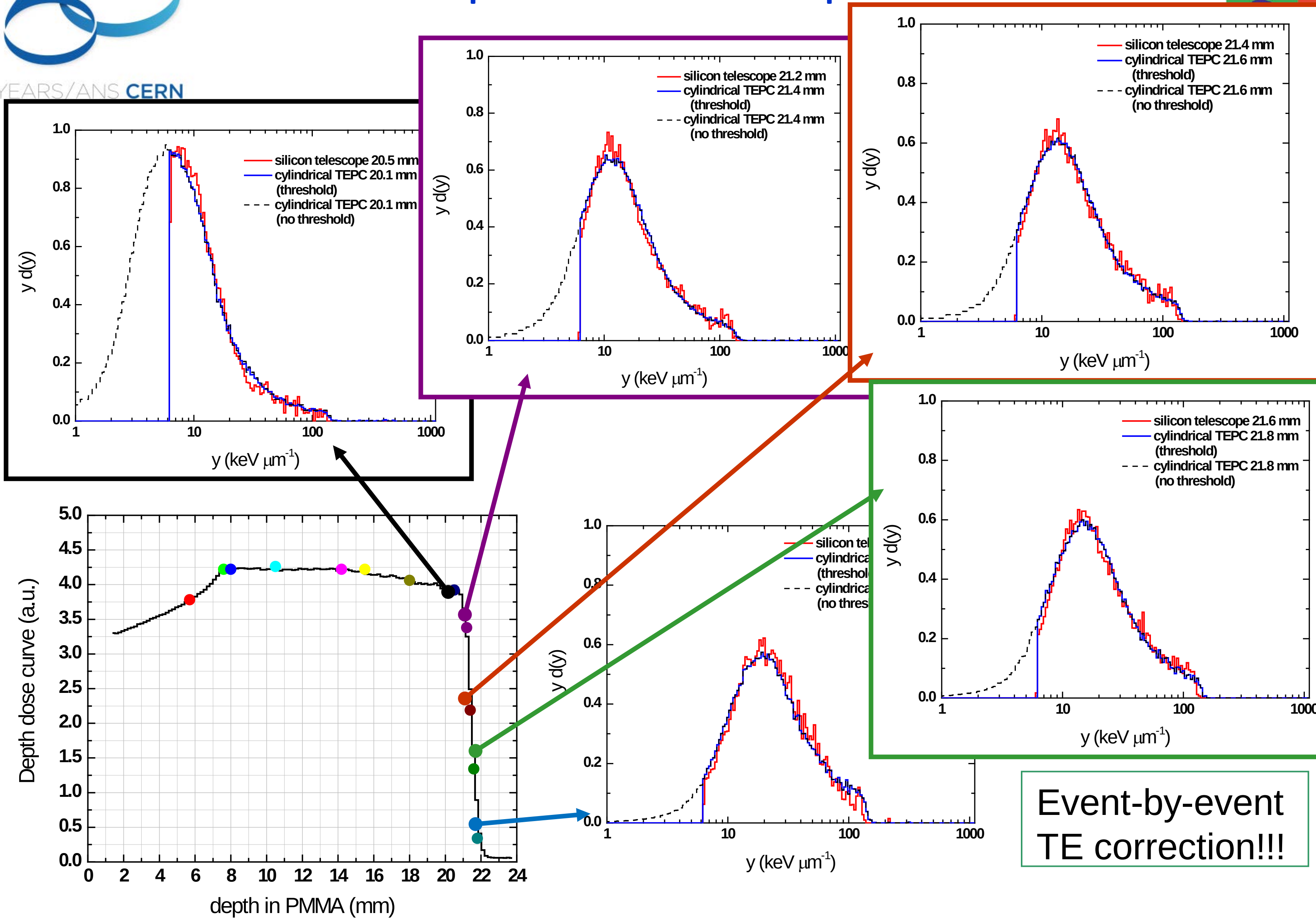
Irradiation with 62 MeV protons

Segmented silicon telescope irradiated inside a PMMA phantom exposed to the 62 MeV proton beam at the INFN-LNS CATANA facility.



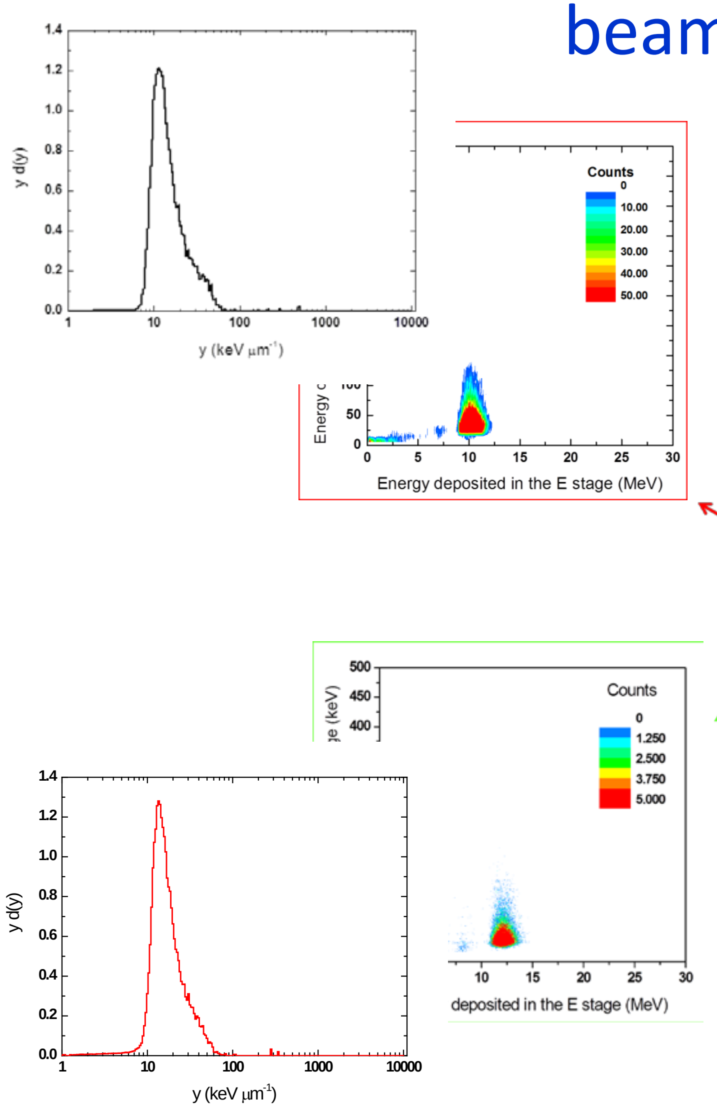


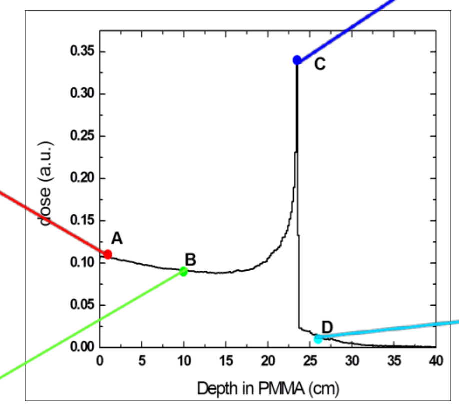
62 MeV proton – Distal part of SOBP

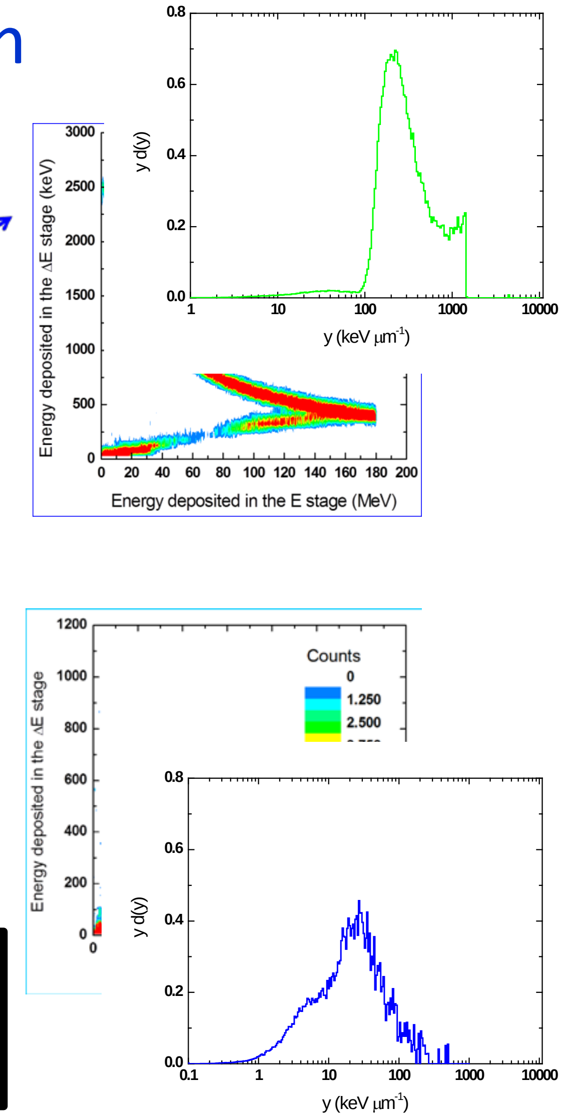


Event-by-event TE correction!!!

Preliminary simulation results for irradiations with a 400 AMeV carbon ion beam in PMMA phantom





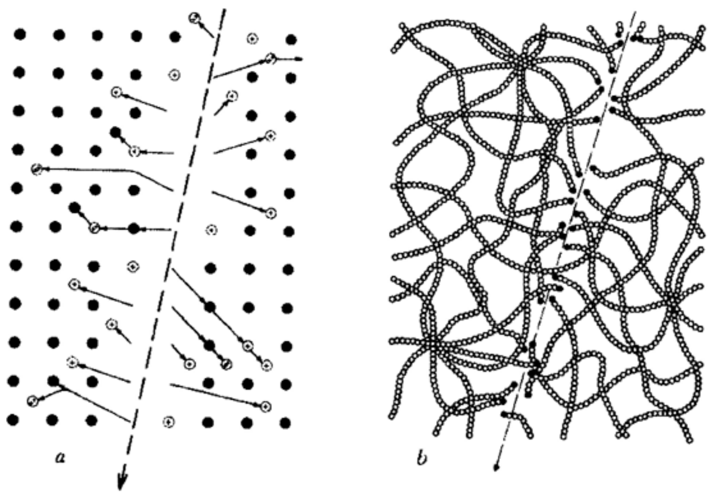


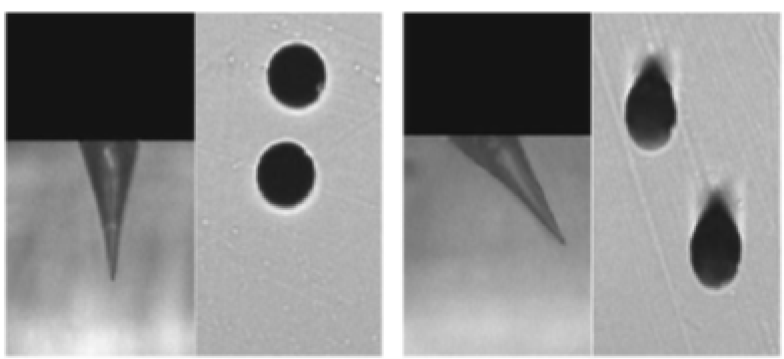
Measurements at HIMAC just performed with 290 MeV/u ^{12}C
Data analysis in progress

Track detectors

Neutron dosimetry with CR-39 detectors

Alvin Sashala Naik, MI.AM and POLIMI





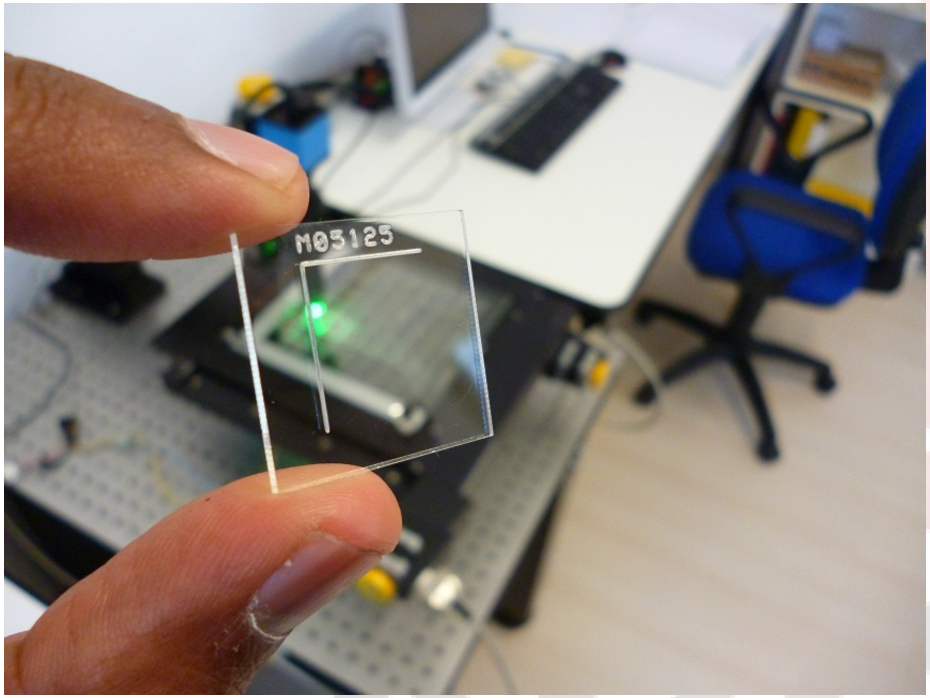
B. Dorschel et al. / Radiation Measurements 37 (2003) 563 – 571

Physics of track detectors

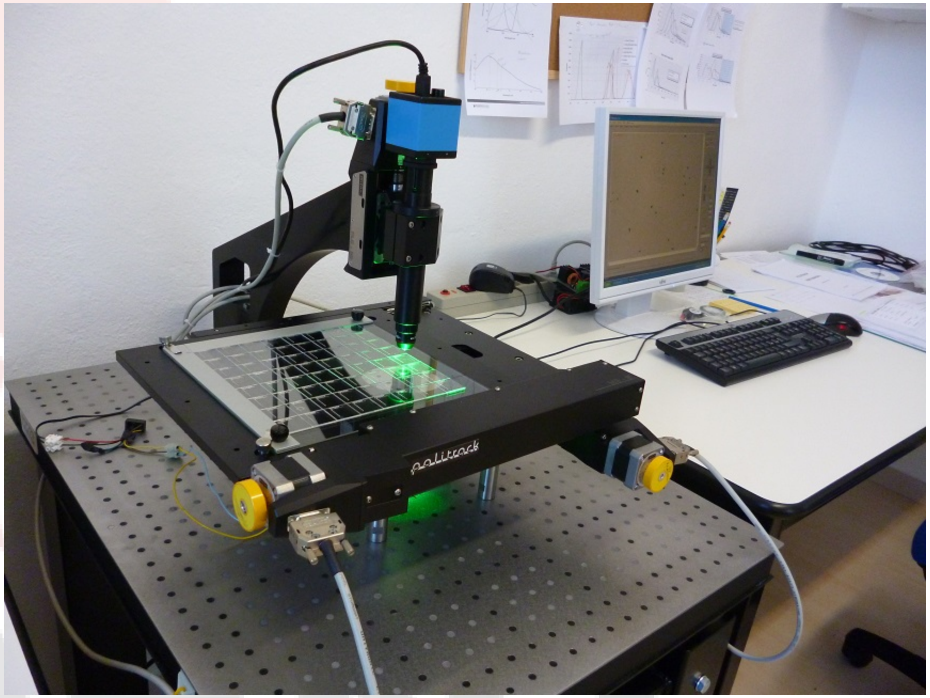
When an ionizing charged particle passes through a dielectric material the transfer of energy to electrons results in a trail of damaged molecules along the particle’s track.

The tracks can be made visible by etching in NaOH at 98°C for 90 minutes. The opening of the track is then of about 5-20 μm depending on the type and energy of the hadrons.

Neutron dosimetry with CR-39 detectors



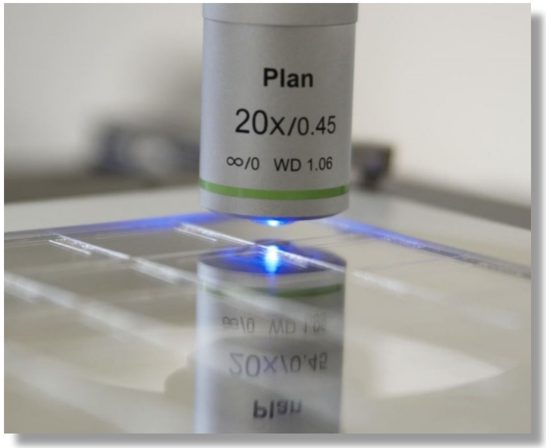
Intercast™ CR-39 detector



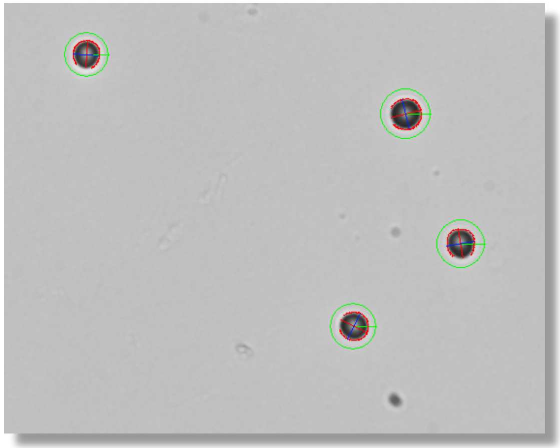
Politrack™ Reader

CR-39 detector analysis with POLITRACK^{TM}

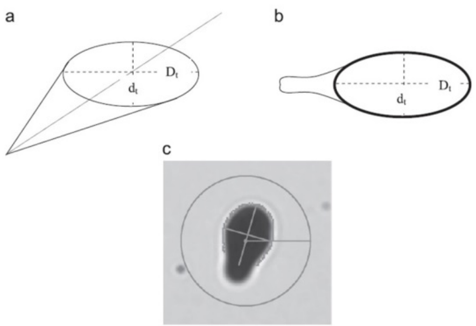
- Automatic counting and geometrical analysis of the tracks by POLITRACK (a)
- Track filtering (account for dust particles or surface defects) (b)
- V_t and LET_{nc} and impinging angle determination (c)
- LET_{nc} distribution (d)



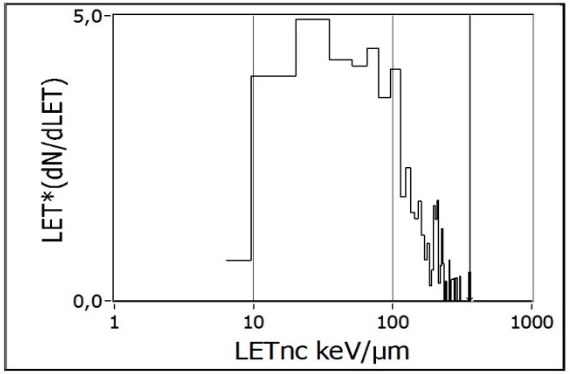
(a)



(b)

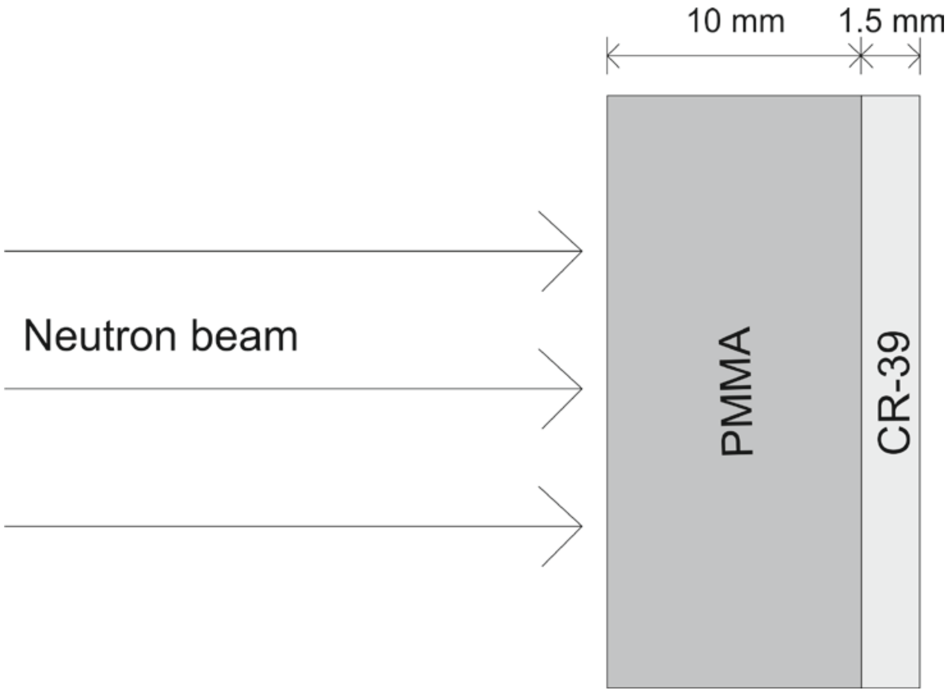


(c)



(d)

Calibration campaigns in quasi-monoenergetic 0.5 MeV to 100 MeV neutron beams



In the PMMA radiator, the type of secondary particles produced is strongly dependent on the neutron beam energy (E_n):

$E_n < 10$ MeV : (n,p) reactions

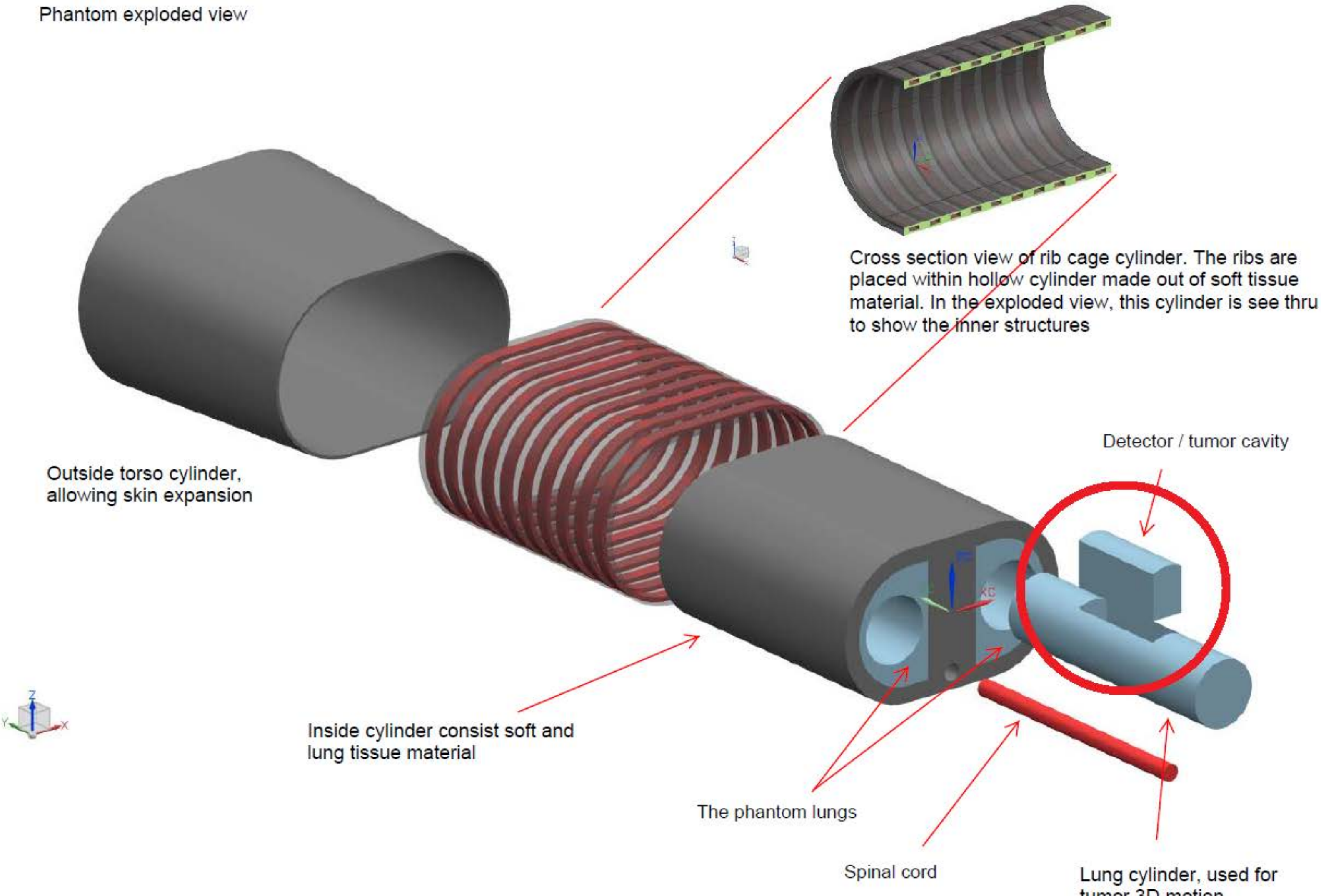
$E_n > 10$ MeV : (n,p) reactions
+ (n,α) reactions
+ (n,d) reactions
+ (n,t) reactions

http://www.oecd-nea.org/janis/

Fragmentation of O and C atoms occurs due to inelastic scattering as the neutron cross section becomes non-negligible for $E_n > 10$ MeV

Heterogeneous Breathing Thorax Phantom

Andrej Sipaj, AIT and Medical University of Vienna



CONCLUSIONS

- More developments are underway, e.g.:
- Timepix3 characterization (E. Frojdh)
  - Simultaneous time over threshold and time of arrival
  - Wafers arrived at CERN and electrical tests ongoing
  - Data driven read out
  - Pixel dead time < 500 ns
    (~ 1000 times less than Timepix)
  - Max Count Rate of ~40Mhits/s/cm^2
- GEMPIX (F. Murtas)
  - ^{55}Fe determination
  - Microdosimetry
  - …