Training Course on Neutron Dosimetry, Radiobiology and Instrumentation

Potential of Medipix devices for neutron metrology

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Thu. 25/6/2015, 13:30 – 14:30 am

25.6.2015

Outline

- International structure of the metrology system – BIPM, CIPM MRA
- Neutron metrology standards at Czech Republic
  - Primary standard of neutron emission
  - Thermal neutron fluence standard
  - Primary standard of neutron spectral fluence
- Applications of neutron metrology
- Evolution of the detectors from the Medipix family
  - Medipix 1
  - Medipix 2 / Timepix
  - Medipix 3
  - Timepix 3
- Sensitive volume
  - Semiconductor
  - Gas (GEM)
- Timepix potential for metrology and dosimetry

International Bureau of Weights and Measures (BIPM) - www.bipm.org

The BIPM was created by the Meter Convention, which was signed on 20 May 1875, before the development of law of intergovernmental organizations:

- To coordinate the realization and improvement of the world-wide measurement system to ensure it delivers accurate and comparable measurement results.
- To undertake selected scientific and technical activities that are more efficiently carried out in its own laboratories on behalf of Member States.
- To promote the importance of metrology to science, industry and society, in particular through collaboration with other intergovernmental organizations and international bodies and in international forums.
- The unique role of the BIPM enables it to achieve its mission by developing the technical and organizational infrastructure of the International System of Units (SI) as the basis for the world-wide traceability of measurement results. This is achieved both through technical activities in its laboratories and through international coordination.

International equivalence of measurements - CIPM MRA

- The International Committee for Weights and Measures, Mutual Recognition Arrangement (CIPM MRA) is the framework through which National Metrology Institutes demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue.

- The outcomes of the Arrangement are the internationally recognized (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes. Approved CMCs and supporting technical data are publicly available from the CIPM MRA database (the KCDB).

Neutron metrology

- Basic quantity in neutron metrology is neutron spectral fluence (rate)
  - Huge energy range 1×10^{-9} to 1×10^{3} MeV
  - Impossible to cover satisfactorily with one instrument
- Radionuclide neutron sources are characterized by the neutron emission (rate)
  - Necessary to measure in defined intervals due to isotopical inpurity of the sources
- Neutron metrology is very expensive and complicated but the needs for them are small

Neutrons	Kinetic energy
Cold	E_n < 25 meV
Thermal	25 meV < E_n < 0.5 eV
Epithermal	0.5 eV < E_n < 100 eV
Resonance	0.1 keV < E_n < 1 keV
Middle energy	100 keV < E_n < 1 MeV
Fast	1 MeV < E_n < 20 MeV
Very fast	20 MeV < E_n

Primary standard of neutron emission (rate)

Manganese bath

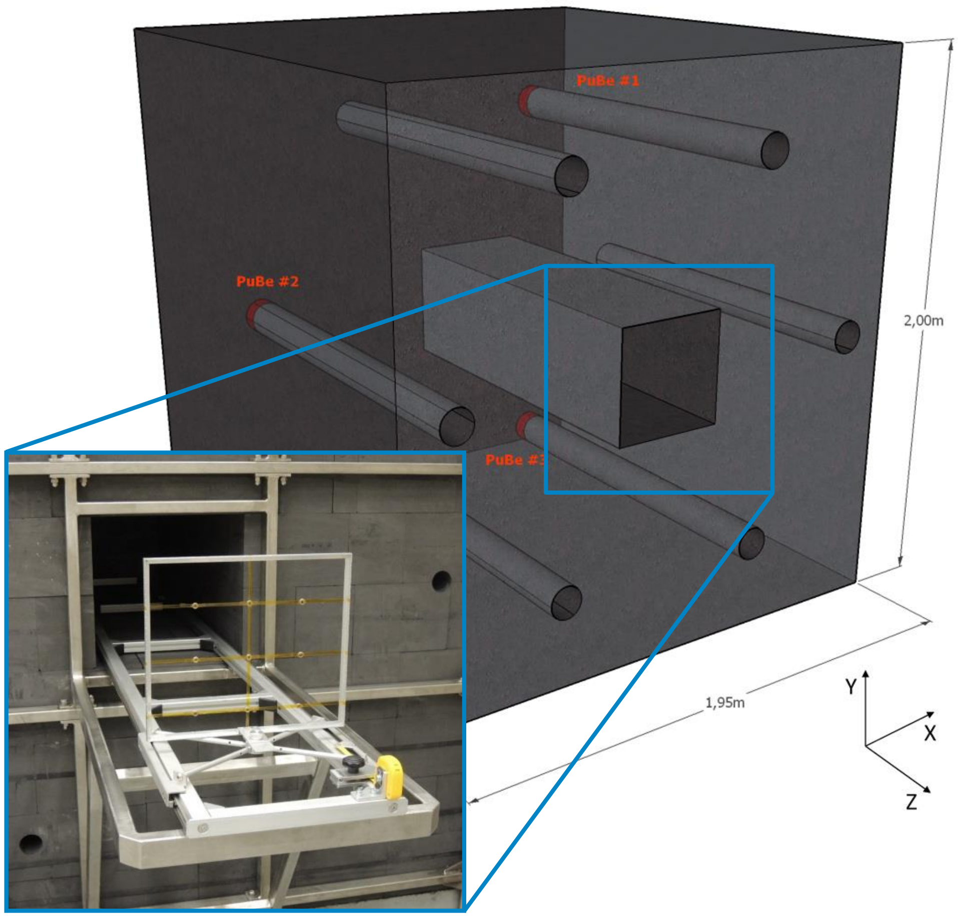
Primary standard of neutron emission (rate)

- 1 m in diameter
- Solution of manganese sulphate in water - $MnSO_4(H_2O)$
- Neutron emission is measured by means of activation of the ^{55}Mn isotope.
- Suitable for neutron emission rate range 10^4 - 10^8 s^{-1}
- Traceable to the national primary standard of activity
- Absolute uncertainty below 1 %

Thermal neutron fluence (rate) standard

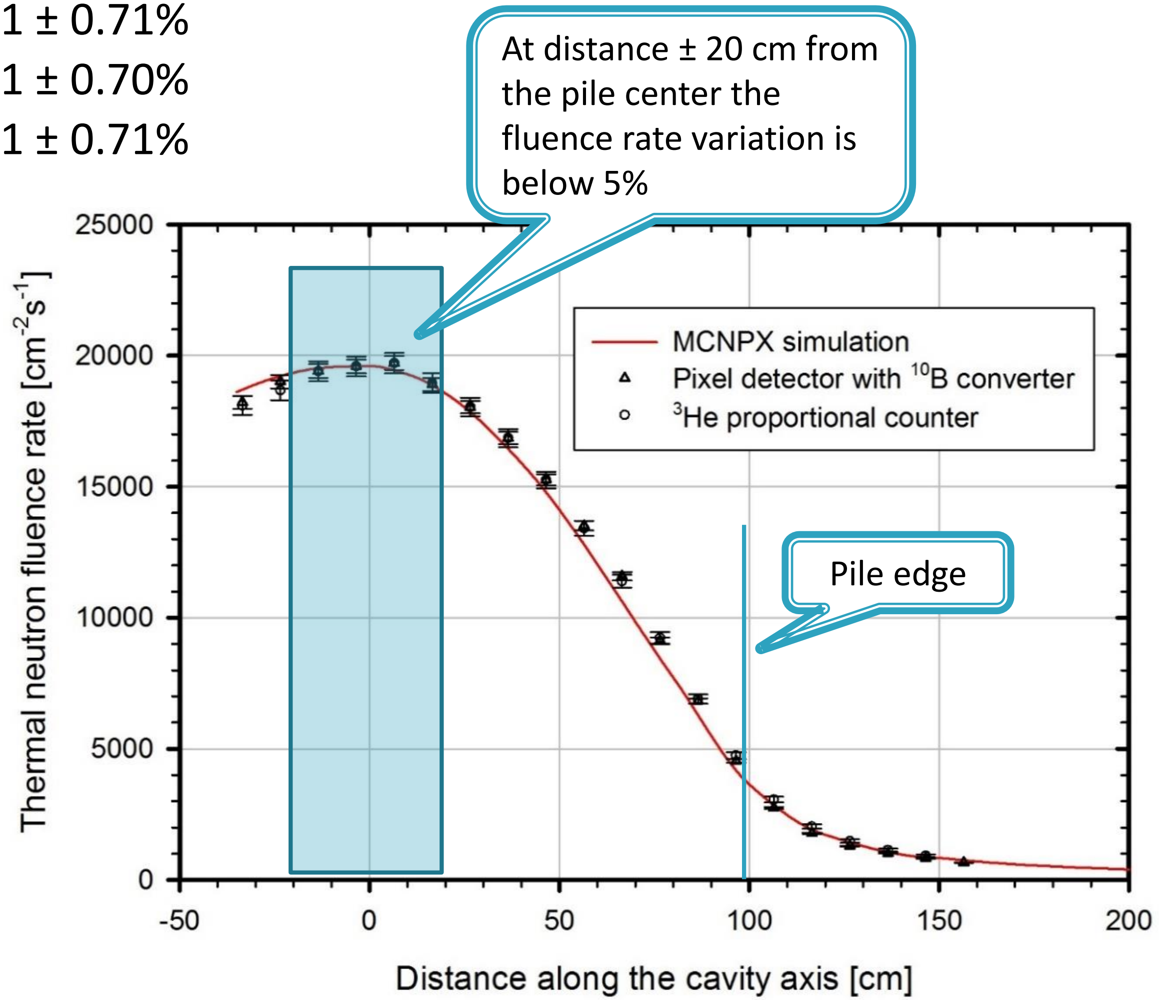
Graphite pile:
Construction

- A graphite pile, which should serve as a standard source of thermal neutrons, has been built at the Czech Metrology Institute.
- External dimensions are 1.95 m (W) × 1.95 m (L) × 2.0 m (H)
- At the distance of 80 cm from the channel axis, there are six symmetrically located holes for the placement of the radionuclide neutron sources of Am-Be and/or Pu-Be type.
- Experimental channel dimensions are 40 cm × 40 cm × 135 cm (depth)



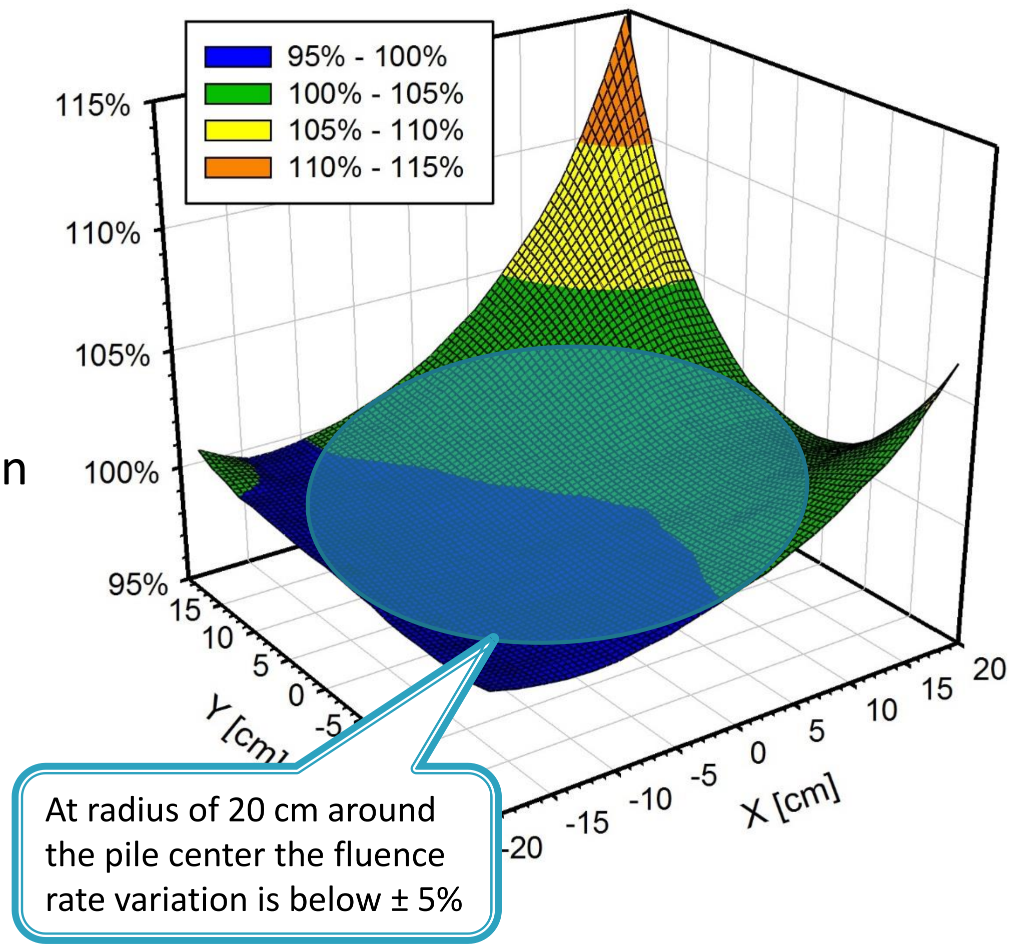
Graphite pile:
Thermal neutron fluence along the channel axis

- Currently equipped with three Pu-Be sources:
  - Pu-Be #1: B = 8.190E+7 s-1 ± 0.71%
  - Pu-Be #2: B = 4.578E+7 s-1 ± 0.70%
  - Pu-Be #3: B = 4.893E+7 s-1 ± 0.71%
- Measured with:
  - bare Au foils
  - Au foils in Cd capsules
  - ^{3}He proportional counter
  - Timepix pixel detector
- Thermal neutron fluence at the center:
  - 1.97×10^4 cm^{-2} s^{-1} (± 1%)
  - cadmium ratio 35.5



Graphite pile:
Thermal neutron fluence spatial distribution

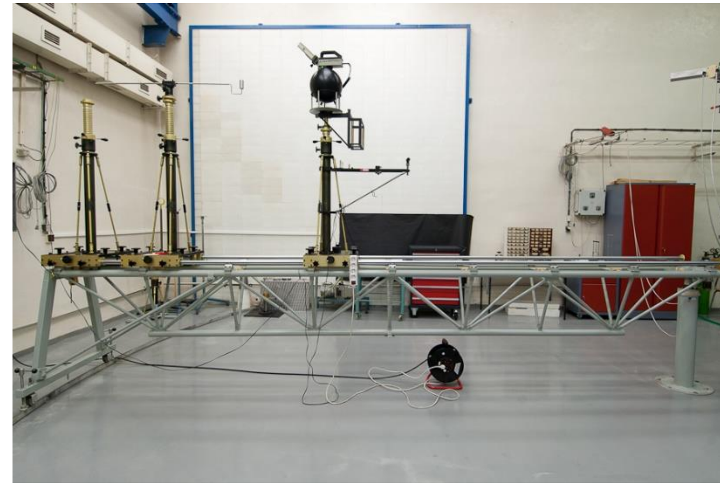
- Measured with Au foils in matrix with 10 cm steps
- Thermal neutron fluence at the center:
  - 1.97×10^{4} cm^{-2} s^{-1} (± 1%)
  - cadmium ratio 35.5
- With current source configuration the cylinder ∅ 40 cm × 40 cm centered in the pile center represents the volume in which thermal neutron fluence rate homogeneity is below ± 5%
- Different source configurations



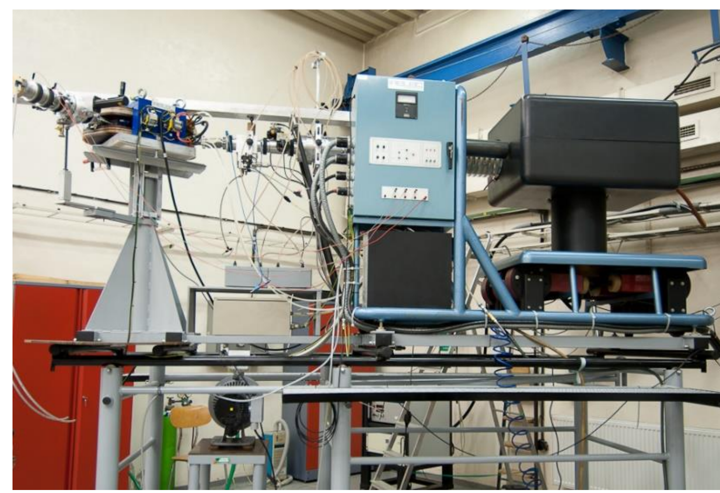
Primary standard of neutron spectral fluence (rate)

Neutron spectral fluence standard

- Set of standard radionuclide sources (emissions to the March 2015):
  - ^{252}Cf B = 5.9×10^{7} s^{-1}
  - ^{241}Am-Be B = 2.2×10^{7} s^{-1}
- Set of "exotic" radionuclide sources
  - ^{239}Pu-Be B = 8.2×10^{7} s^{-1}
  - ^{241}Am-B B = 8.0×10^{4} s^{-1}
  - ^{241}Am-F B = 1.3×10^{5} s^{-1}
  - …
- Traceable to the national primary standard of neutron emission

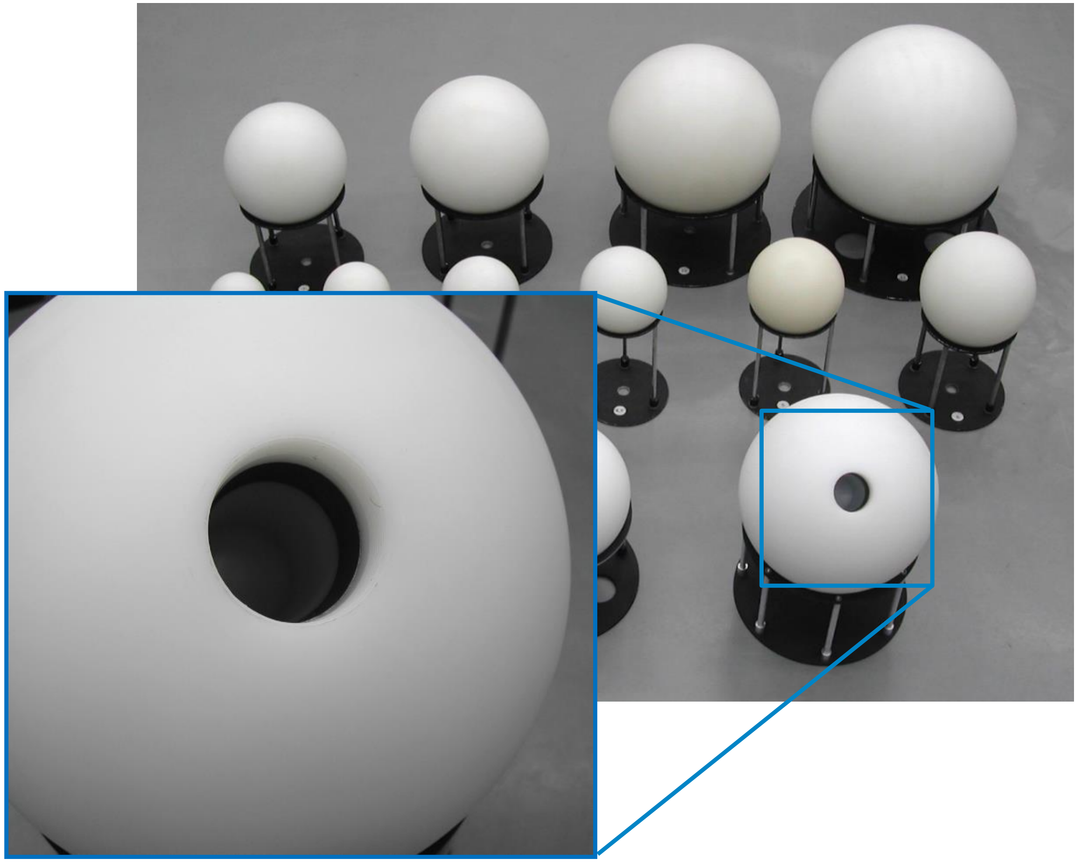


- Neutron generator
  - 14 MeV neutrons from D-T reaction B = 1x10^{10} s^{-1}
- Traceable to the national primary standard of activity



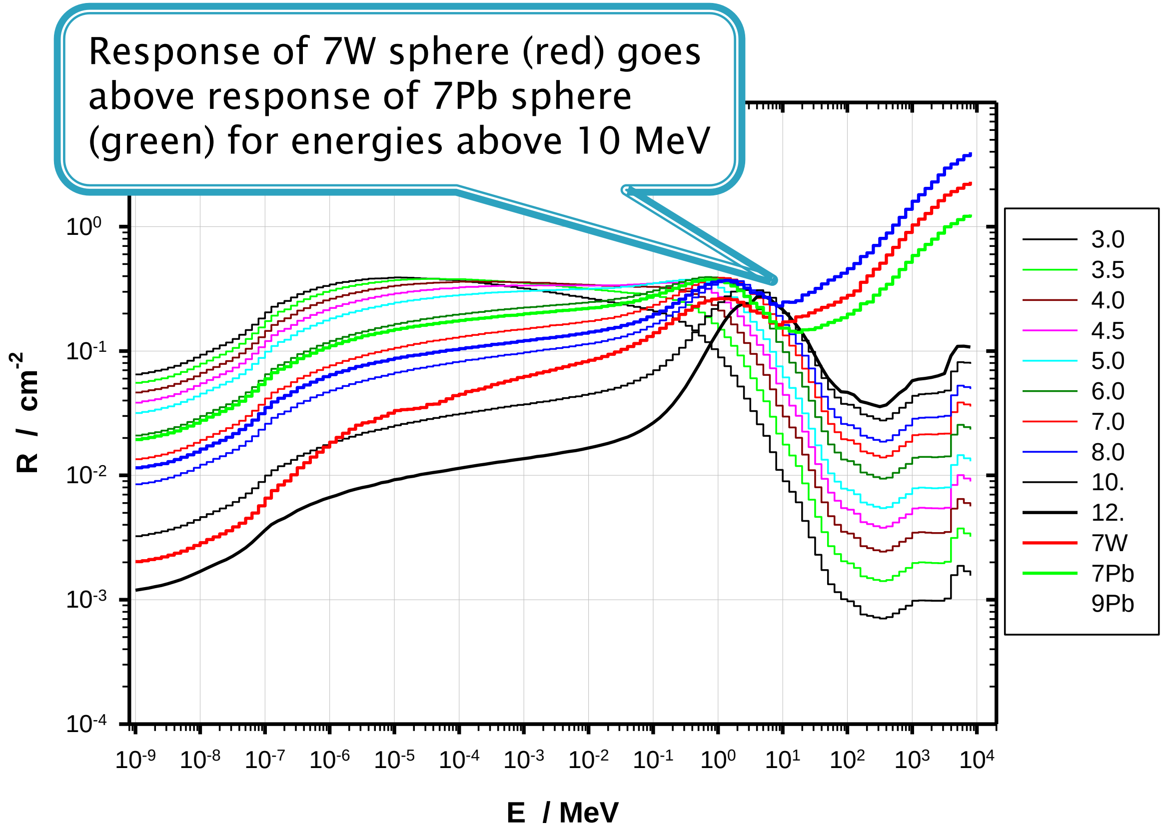
Neutron spectrometry above 20 MeV:
Extended Bonner Spheres Spectrometer (EBS)

- Integral part of the Czech national primary standard of neutron fluence and spectral fluence rate
- Comprises of 10 pure PE spheres which has been supplemented with three spheres with Pb and W layer
- It can be used with different active and passive detectors to measure neutron spectra above 20 MeV
  - SP9
  - LMT - 0.5NH1/1K
  - Timepix
  - Mn foils
  - TLD chips



Extended Bonner Sphere Spectrometer:
Response functions

- Response functions has been calculated using MCNP6.0 simulation package up to 10 GeV for different active and passive detectors
- Response functions has been normalized in ^{252}Cf fission spectrum



Response functions calculated for LMT-0.5NH1/1K detector from LCC Thomson, France (^{3}He proportional counter)

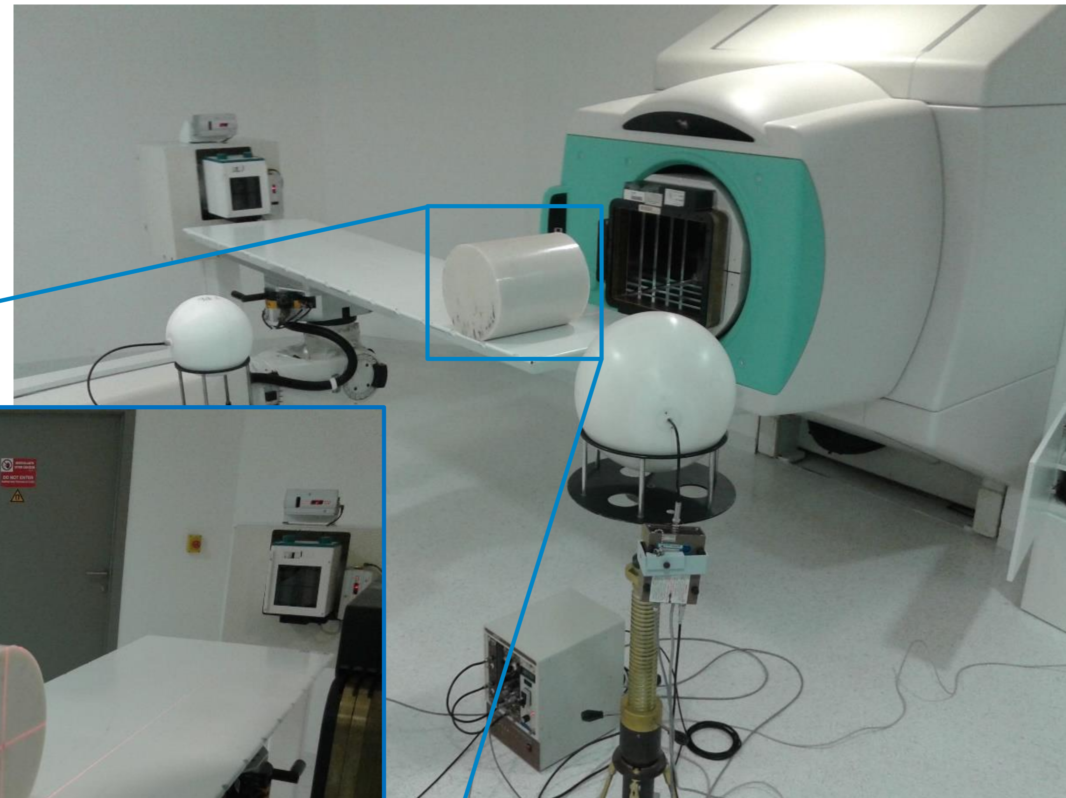
Applications for the neutron metrology

Calibration and routine verification of neutron personal dosimeters

Extended Bonner Sphere Spectrometer:
Measurements

Proton Therapy Center Prague

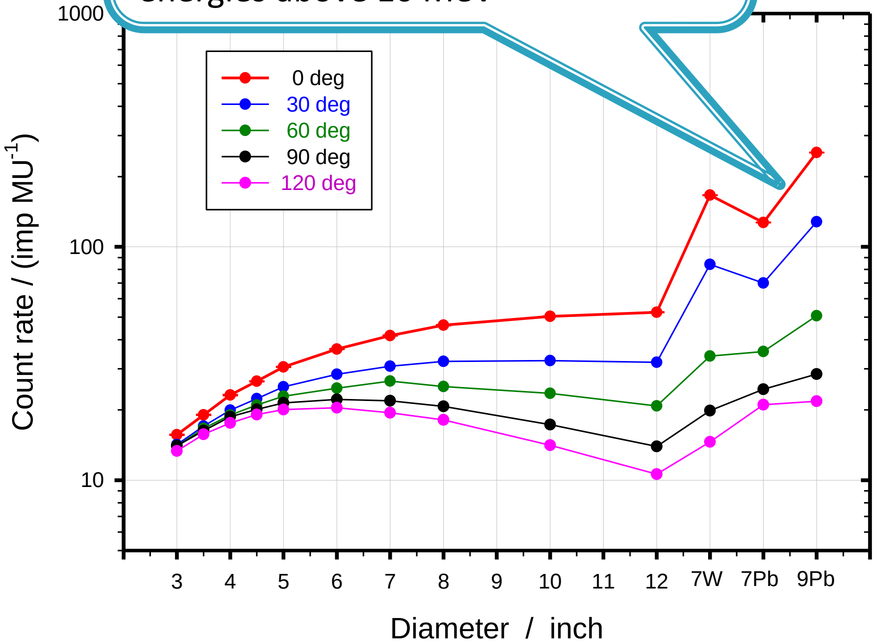
- Fixed beam treatment room
  - Proton pencil beam
  - E_p = 200 MeV (monoenergetic)
  - I_p = 3 - 30 nA (continuous)
- Nylon-6 cylindrical phantom
  - Diame
  - Lengt
  - Front locate
- EBS with detecto

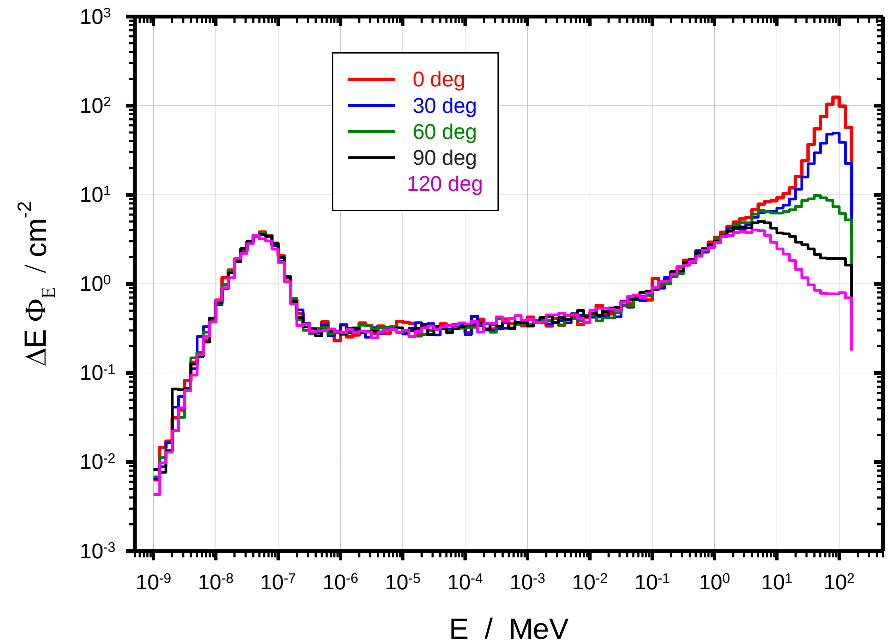


Extended Bonner Sphere Spectrometer:
Results

- Measurement of the angular distribution of the neutron spectral fluence
- Detector response normalized to MU (monitoring unit, proportional to beam d
- U avel)

Difference in response of 7W sphere compared to 7Pb sphere immediately indicate the intensity of the neutron energies above 10 MeV





Applications for the neutron metrology

Calibration and routine verification of neutron personal dosimeters

Personal dose equivalent
Operational (measurable) quantity

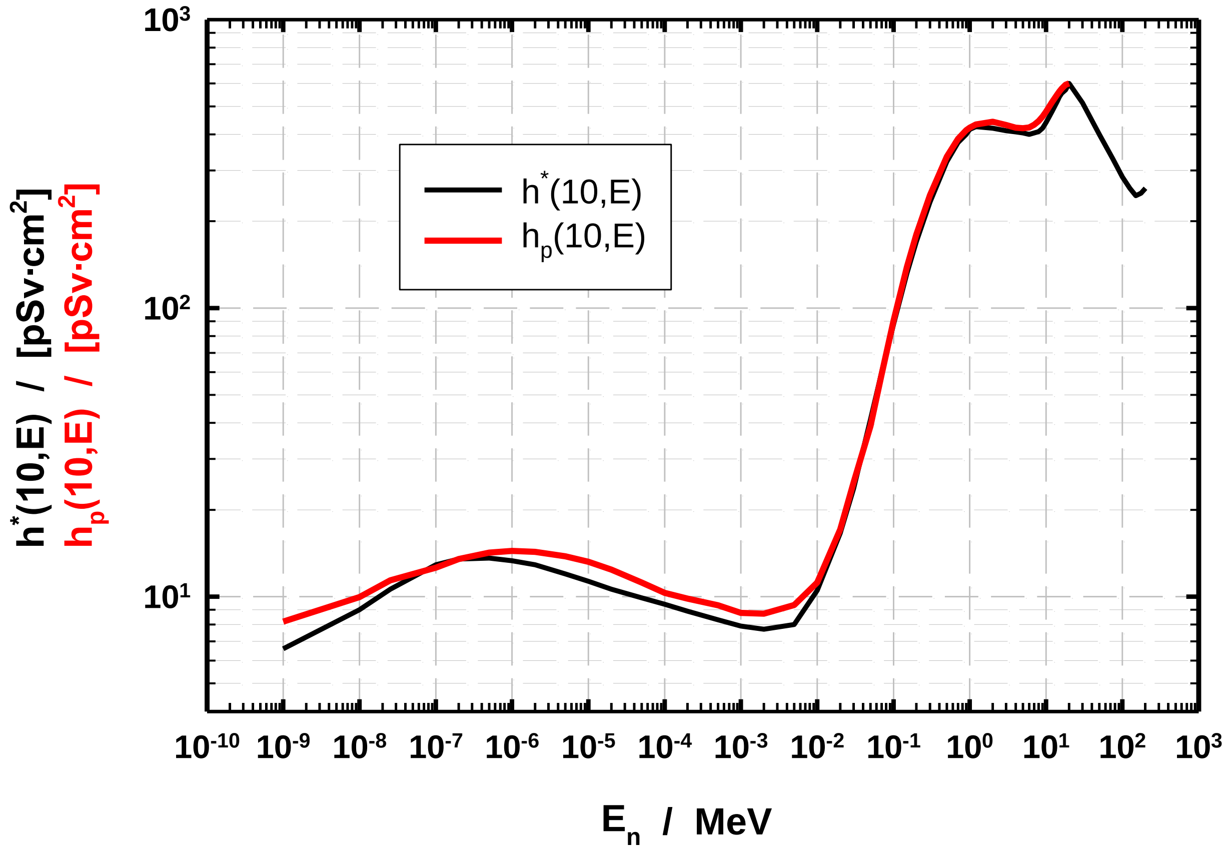
Conventionally true value of the neutron personal dose equivalent rate on the phantom surface irradiated with small radionuclide neutron source is determined according to the following formula:

$$\dot{H}_p(10) = h_p(10) \cdot \frac{B \cdot F_I(\theta)}{4\pi d^2} \cdot \exp(-\Sigma \cdot d)$$

- *Hp(10)* is personal dose equivalent rate [Sv/s]
- $h_p(10)$ is conversion coefficient neutron fluence to personal dose equivalent for specified neutron source, e.g., parallel beam and normal incidence $h_p(10)$ = 400 pSv·cm^2 for ^{252}Cf and 411 pSv·cm^2 for Am-Be; ISO 8529-3[(10)]
- *B* is neutron emission rate of the source [s^{-1}]
- $F_I(\theta)$ is the source anisotropy correction factor
- *d* is the distance from the center of the source to the center of the face wall of the ISO water slab phantom [cm]. Recommended d = 75 cm according to ISO 8529-2
- Σ is linear attenuation coefficient of air averaged over the spectral distribution of the neutron source, (e.g., $\Sigma = 1.055 \cdot 10^{-4}$ cm^{-1} for ^{252}Cf and $8.90 \cdot 10^{-5}$ cm^{-1} for Am-Be; ISO 8529-2).

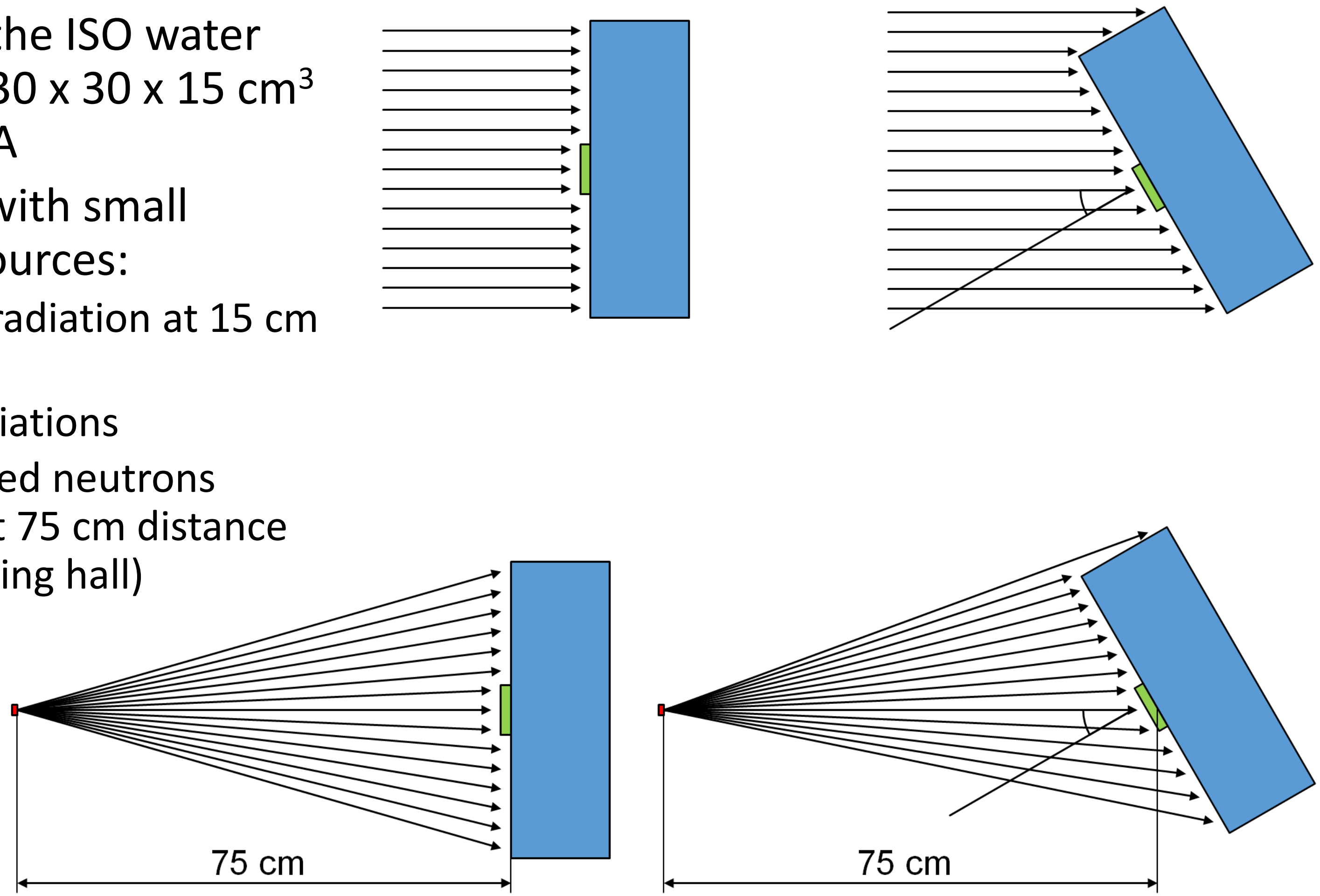
Ambient/personal dose equivalent

Recommended by International Commission on Radiation Protection (ICRP 74) and International Commission on Radiation Units (ICRU 57).

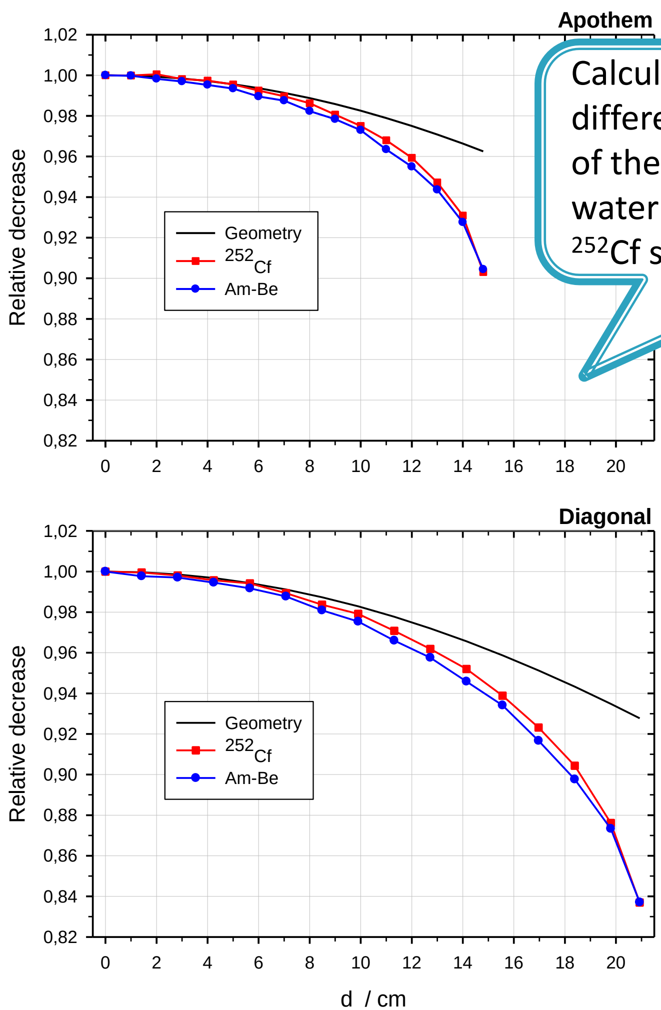


Calibrations and tests of neutron personal dosimeters

- ISO 29661 standard
- Irradiation on the ISO water slab phantom 30 x 30 x 15 cm^3 made of PMMA
- Known issues with small radionuclide sources:
  - Geometry (irradiation at 15 cm diameter)
  - Spectrum variations
  - Room scattered neutrons (Irradiation at 75 cm distance in low scattering hall)



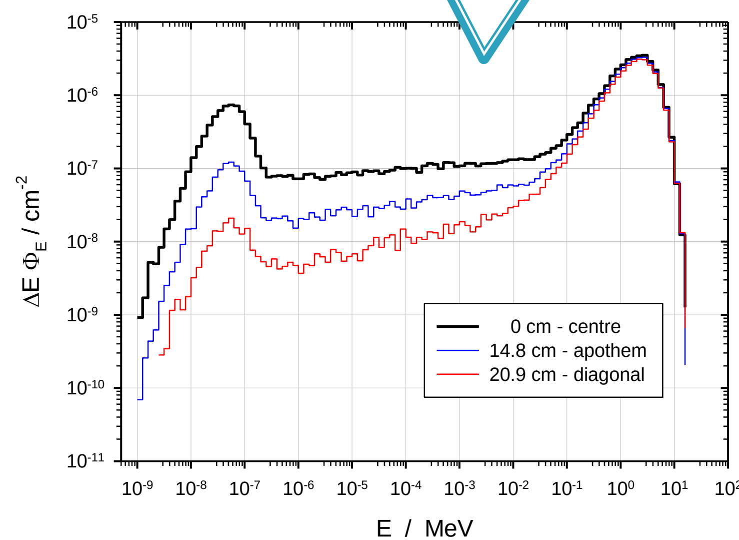
Calibrations and tests of neutron personal dosimeters



- Calibrations and tests of neutron area and ...s in ISO 8529-1 neutron fields ...^{252}Cf and ^{241}Am-Be sources ...ers ...n (
  Practical issues as bei... testing, verification ar... standardized so far) a... dosimeters IEC 61526 has b... ...udied.

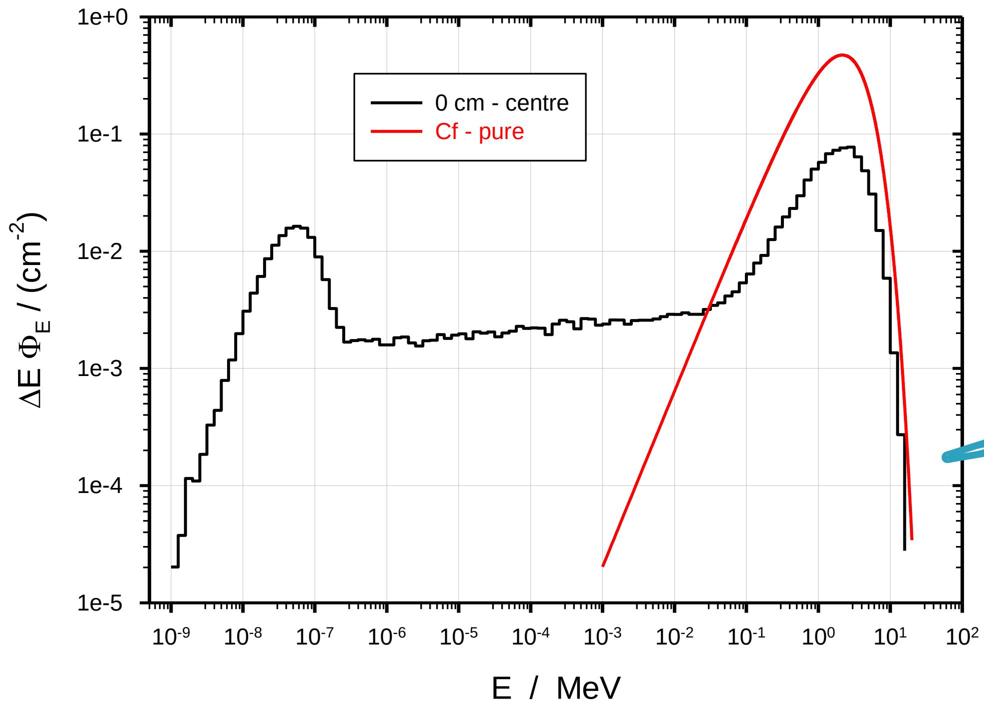
Calculated spectral fluence at different distances from the centre of the front face wall of the ISO water phantom irradiated by point ^{252}Cf source.

Calculated decrease of personal dose equivalent on the apothem and diagonal of ISO water phantom. Distance is measured from the center of the front face wall.



Calibrations of personal dosimeters:
ISO water phantom × free-in-air

- Large scale personal dosimetry providers commonly use free-in-air irradiation of instruments while determining a correction factor between free-in-air and on the ISO water phantom configurations.
- However, the irradiation spectrum differs for both cases.



Comparison of spectral fluence at the centre of the front face wall of the ISO water phantom and bare ^{252}Cf source. For easier comparison both spectra are normalized to unity (i.e. their integral is equal to one).

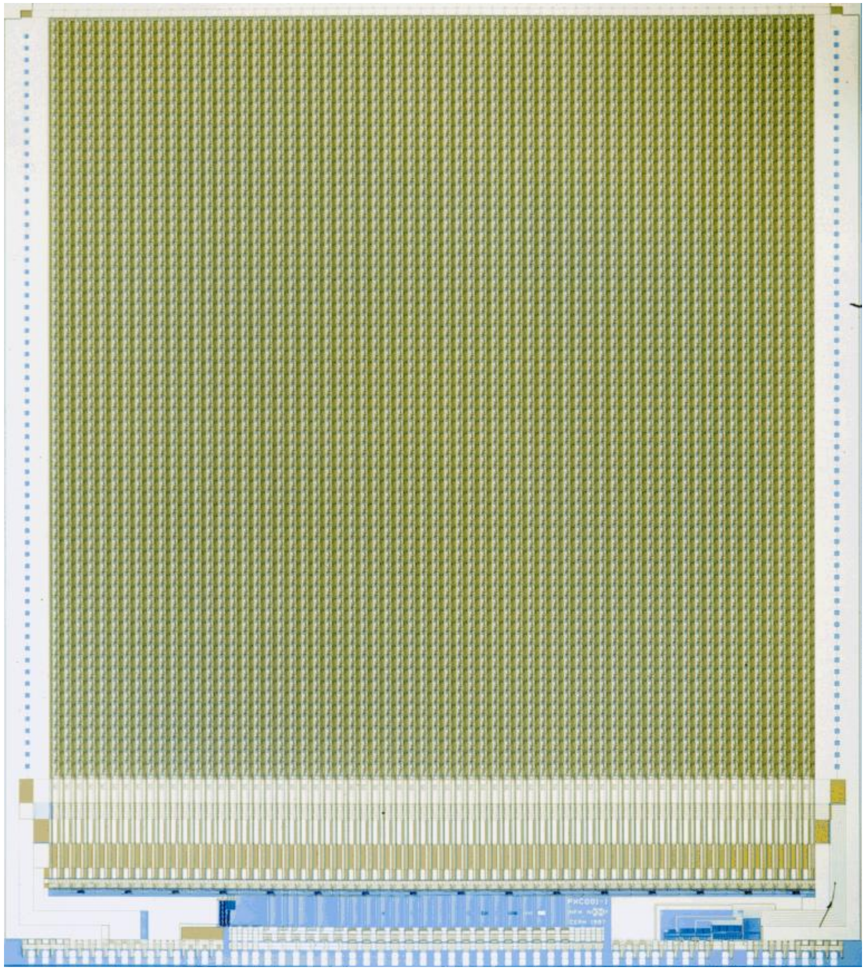
Detectors from the Medipix family

Medipix 1 detector:

Evolution of the detectors from Medipix family (1997)

www.cern.ch/medipix

- 64 x 64 square pixels of 170 µm side-length.
- Active area of the chip: ~1.2 cm^2.
- Sensitive to positive charge. Leakage current compensation at the input.
- Maximum count rate: ~2 MHz per chip
- 1 comparator per pixel with 3 bits fine tuning for a homogeneous threshold distribution within the pixel matrix.
- Minimum threshold ~1500 e (~5.5 keV charge deposition in a Si sensor).
- 15 bit counter per pixel to store up to 32767 single events.
- Variable acquisition time.
- 1 µm CMOS, 2-metal, 1.6 M transistors.

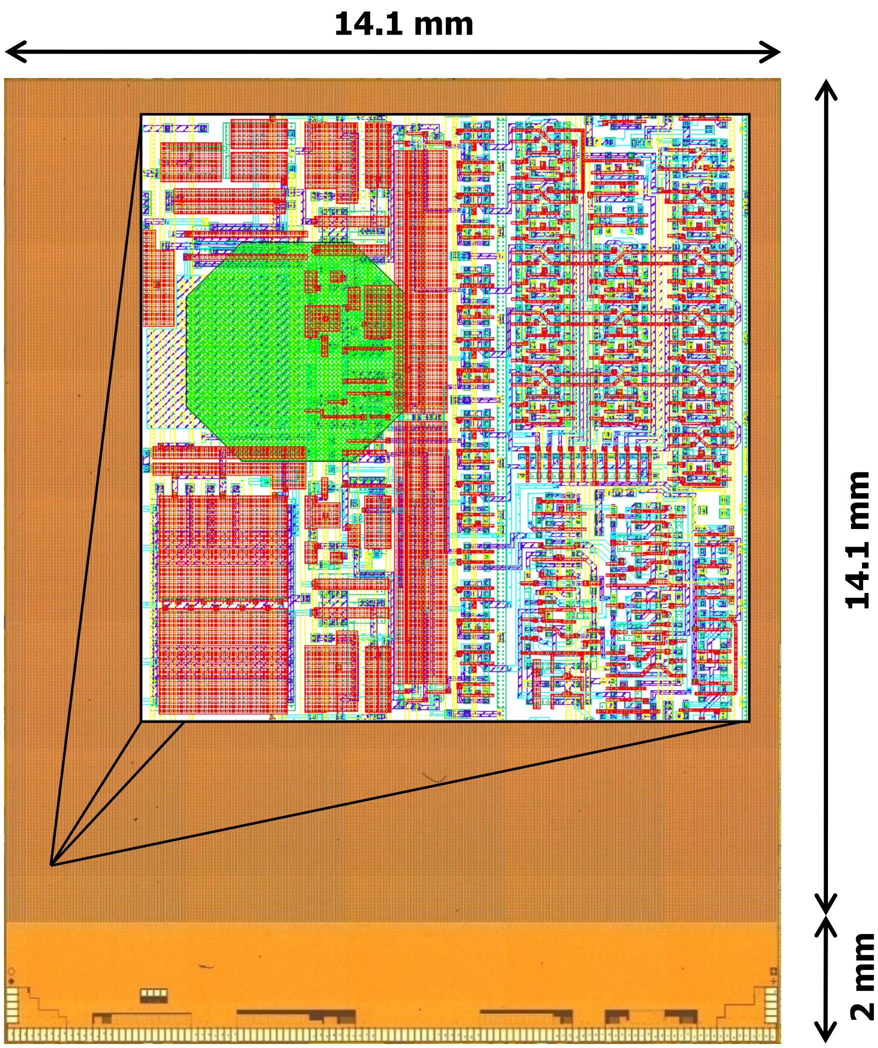


Medipix 2 detector:

Evolution of the detectors from Medipix family (2002)

www.cern.ch/medipix

- 256 x 256 square pixels of 55 µm in size.
- Sensitive area of ~2 cm² (87% of chip).
- The chip is designed to accept either positive or negative charge input in order not to restrict the choice of the sensor material (Si, GaAs, CdZnTe,...).
- Maximum count rate: ~100 kHz per pixel
- Amplifier, two discriminators and a 13-bit counter in each pixel cell. It is possible to select a window in energy. Upper and lower threshold can be adjusted pixel wise with 3 bits.
- Parallel and serial read-out.
- 3-side buttable for large area coverage.
- 0.25 µm CMOS, 6-metal, 35 M transistors

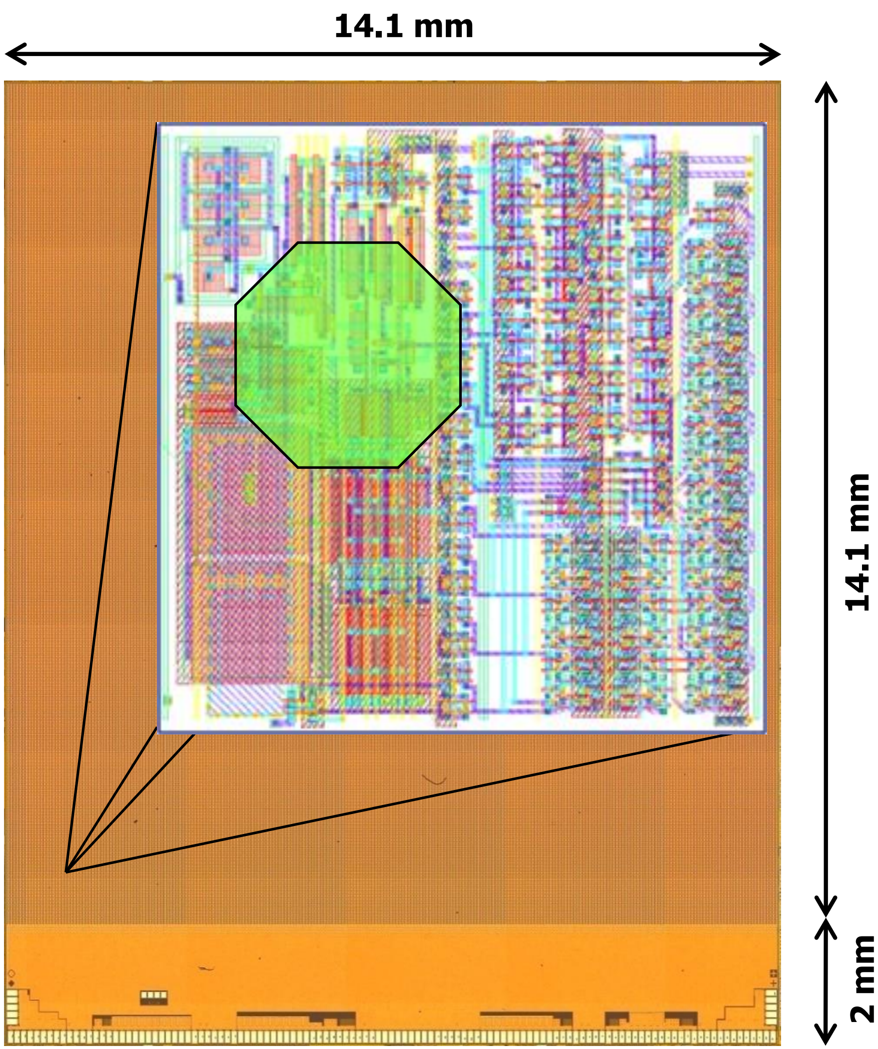


Timepix detector:

Evolution of the detectors from Medipix family (2006)

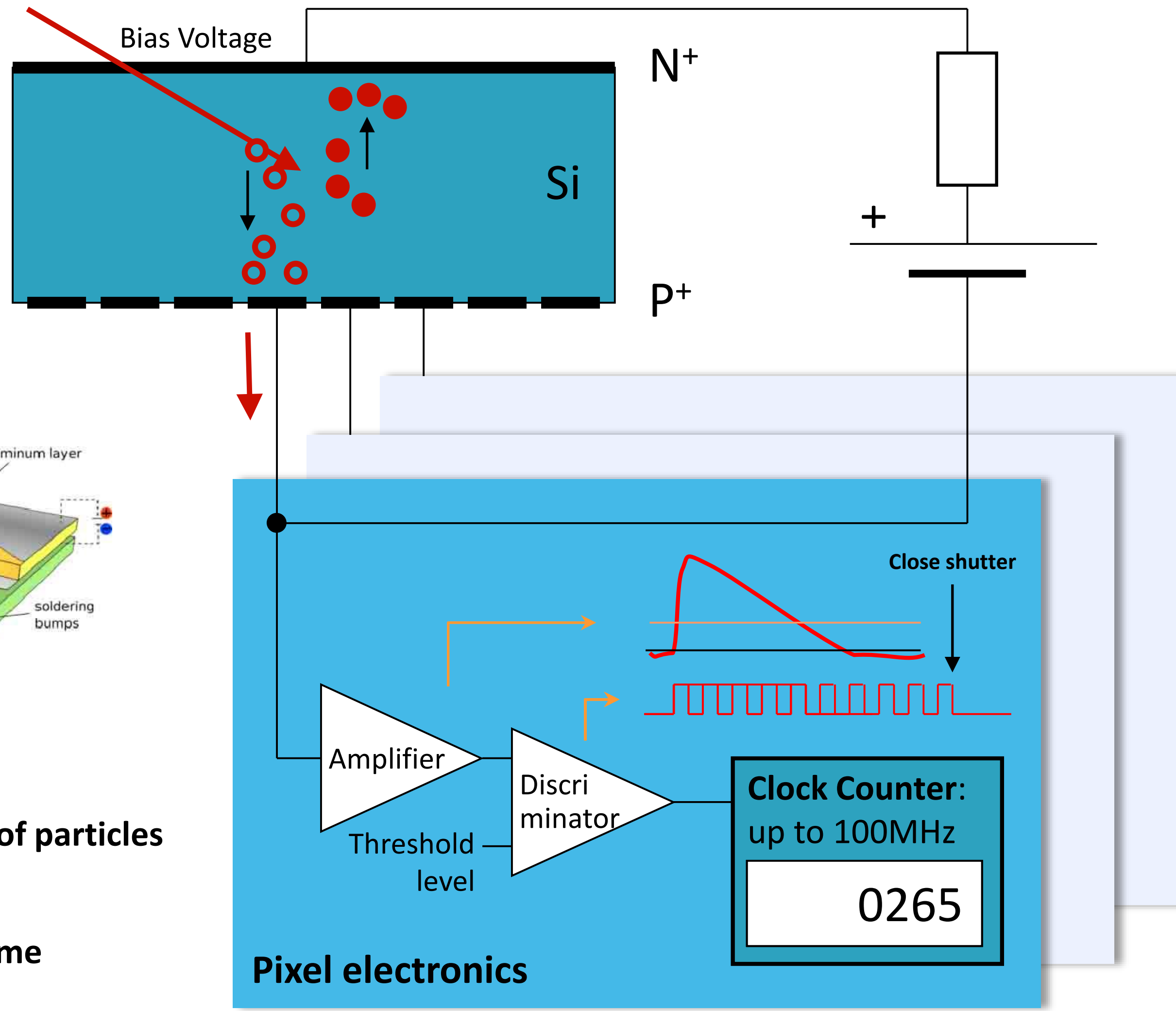
www.cern.ch/medipix

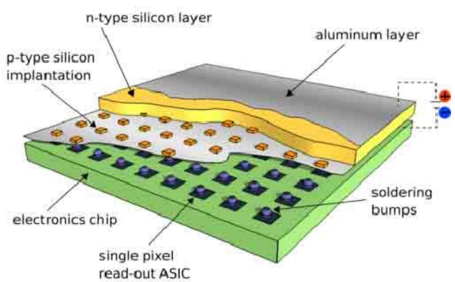
- 256 x 256 square pixels of 55 µm pitch
- Single energy threshold
- Energy range from 5 keV to 1 MeV per pixel
- Each pixel can be programmed to work in one of 3 modes:
  - Single particle counting (Medipix mode)
  - Time over Threshold (ToT)
  - Time of Arrival (ToA)
- 13-bit data counter counting up to 11810 counts
- Each pixel can count rates 10^{-5} to 10^{5} s^{-1} of randomly arriving particles
- Parallel and serial read-out
  - Serial readout speed 100 fps
  - Parallel readout speed 1000 fps
- 0.25 µm CMOS, 6-metal, 35 M transistors



Timepix detector:

Direct measurement of particle *energy* or its *arrival time*





Counter value ~ Number of particles

Counter value ~ Energy

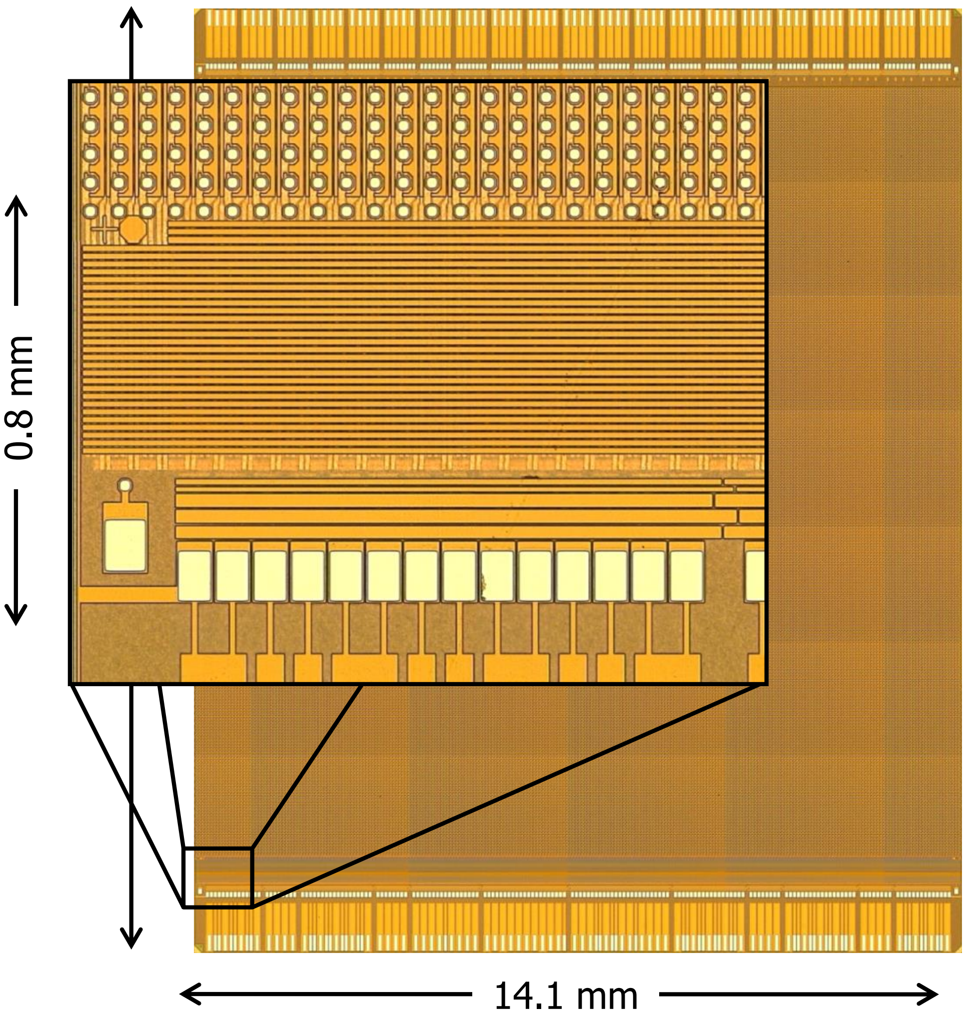
Counter value ~ Arrival time

Medipix3 detector:

Evolution of the detectors from Medipix family (2009)

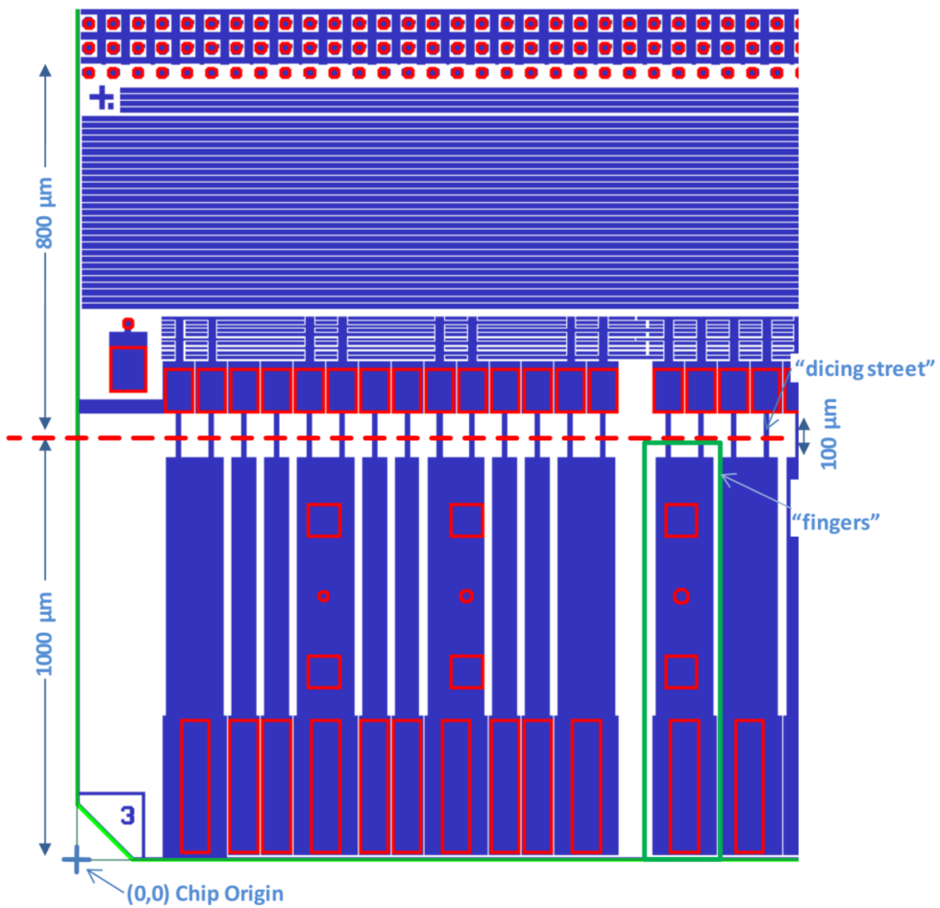
www.cern.ch/medipix

- Matrix of 256 x 256 pixels, 55 µm each
- New pixel architecture
  - Single pixel mode
  - 4x4 super pixel pixel mode
- 2 energy thresholds and 2 configurable counters with variable depth.
  - Continuous read/write mode (one counter is read out while the other counts)
  - Sequential read/write mode with 2 different thresholds.
- 2x2 super pixel - color mode
  - 4 separate thresholds in simultaneous read/write mode
  - 8 thresholds in sequential read/write mode.
- 0.13 µm CMOS, 8-metal, 72 M transistors
- TSV ready!

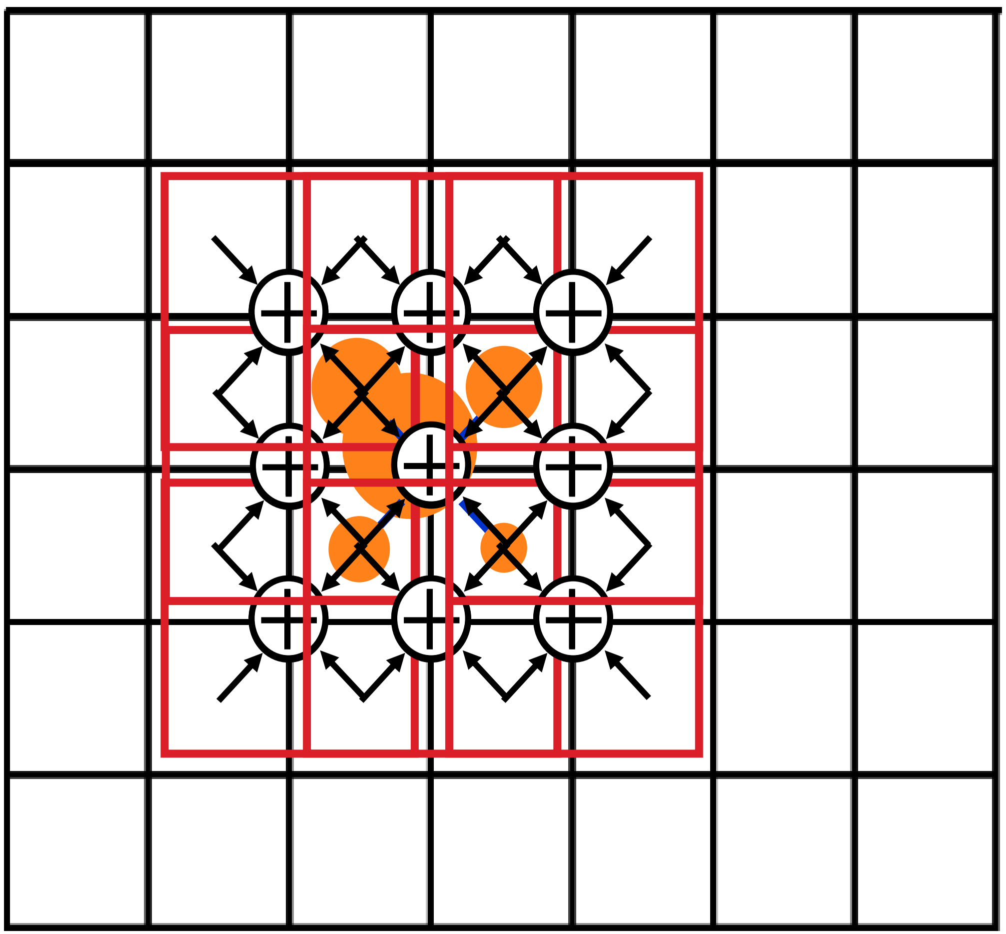


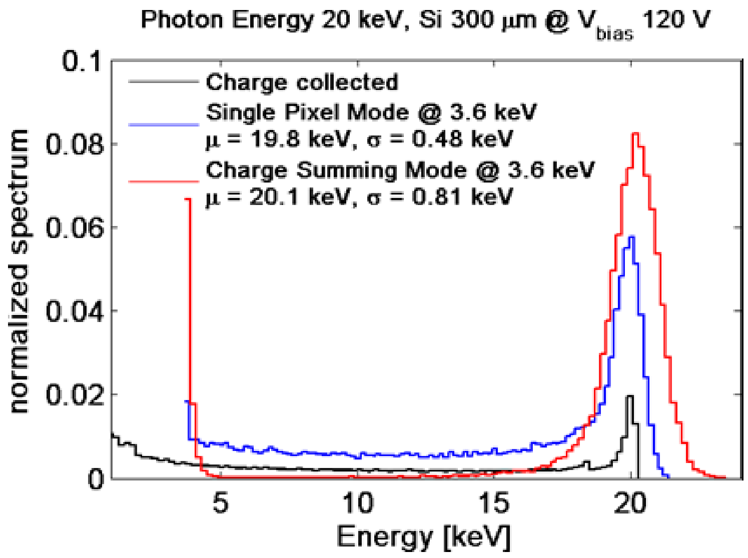
Medipix3 detector:
Through Silicon Via (TSV)

- Several CMOS post processing steps on the wafer level for a large detector arrays:
  - Wafer thinning (below 100 μm)
  - Etching of the holes from the wafer back-side to metal 1-2
  - Filling of the holes with conductive material (polysilicon)
  - Redistribution of the signals over the back-side of the chip (copper)
  - Metallization and insulation of the contacts
- Wire bonding pads can be diced away reducing the insensitive periphery width to 0.8 mm.



Medipix3 detector:
Charge summing and allocation concept



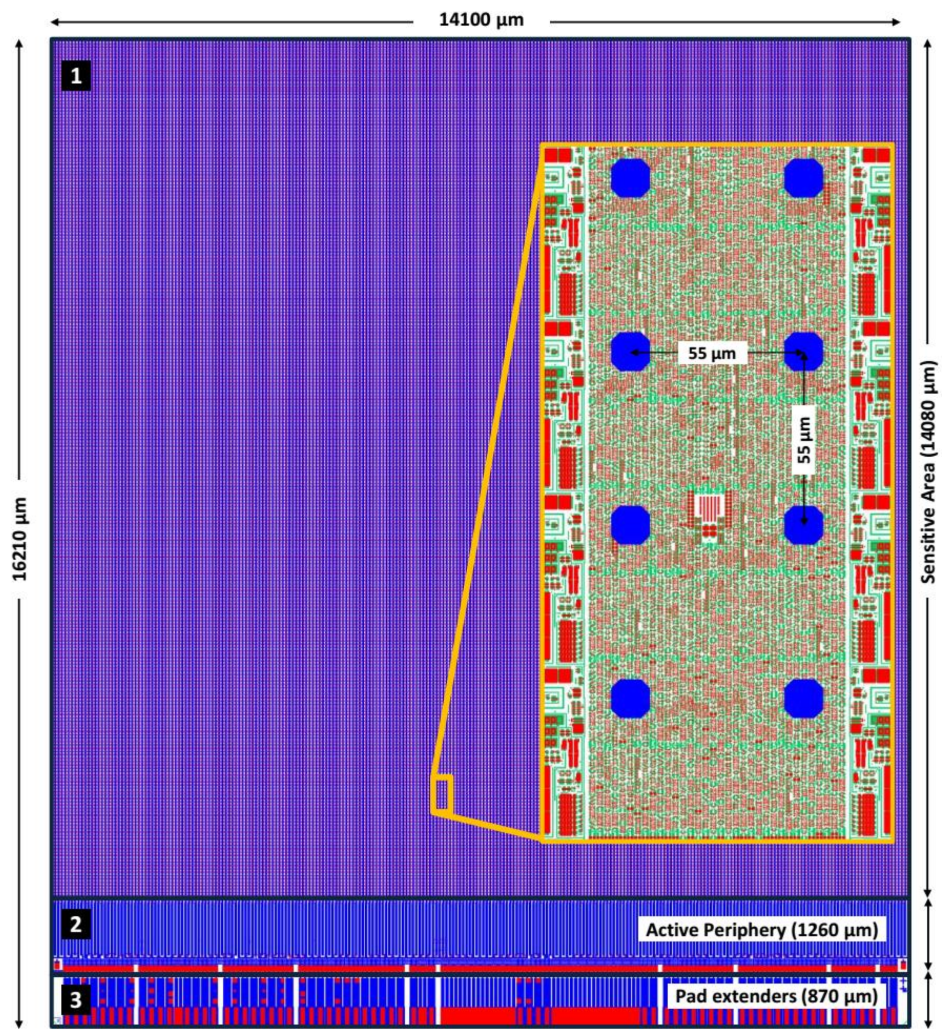


- Pixel spectrum is reconstructed
- Immune to threshold variations

Timepix 3 detector:
Evolution of the detectors from Medipix family (2014)

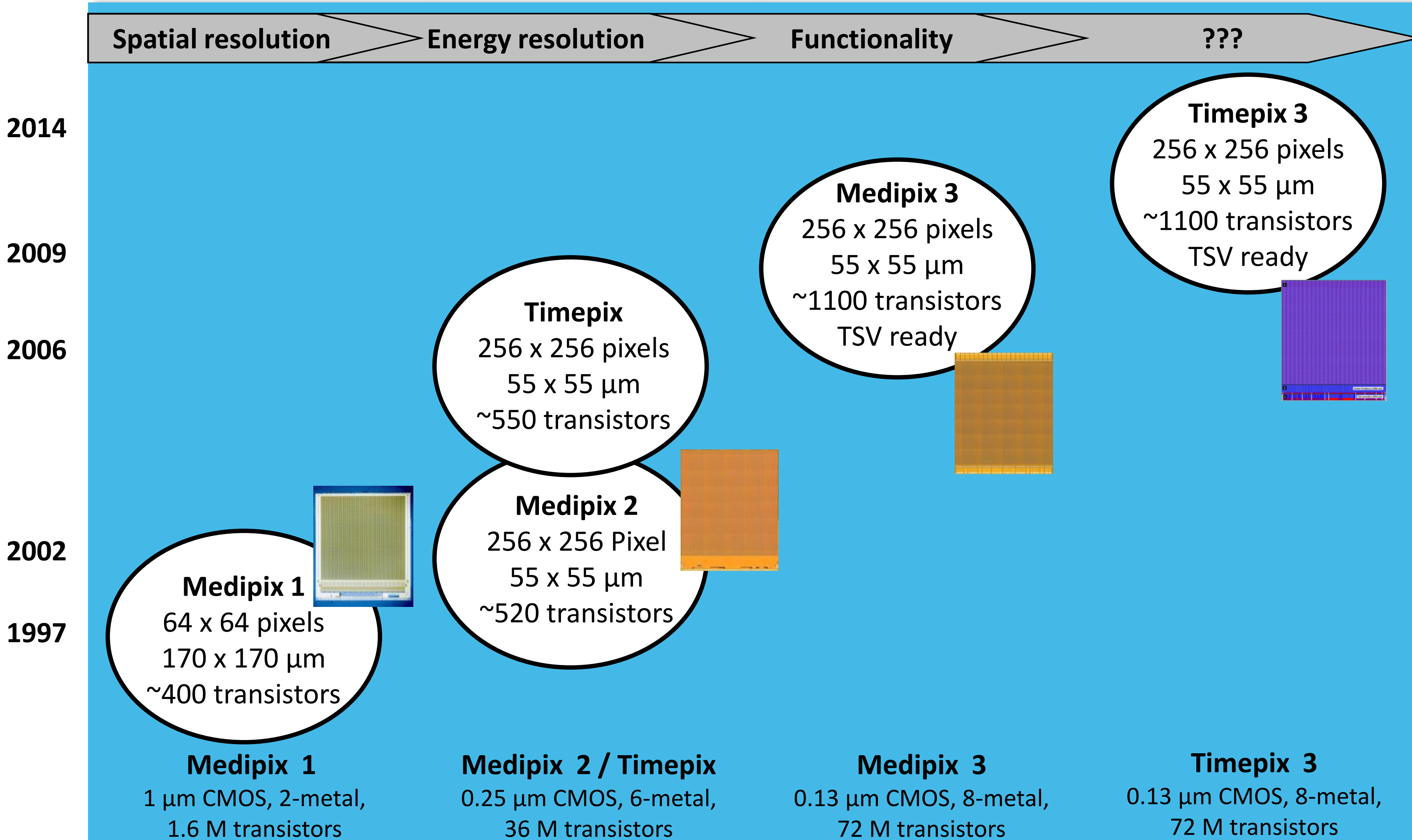
www.cern.ch/medipix

- Matrix of 256 x 256 pixels, 55 µm each
- Simultaneous arrival time and charge measurements in 6 operation modes
- Three configurable counters per pixel
  - 14 bit ToA counter @ 40 MHz
  - 4 bit ToA counter @ 640 MHz
  - 10 bit ToT counter @ 40 MHz
- 4x2 SuperPixel readout architecture
  - Data-driven zero suppressed
  - Frame-based zero suppressed
- Dead time free count rate:
  - 40 Mhits/s/cm^2
  - 1.2 kHz/pixel
- 1-8 fast SLVS DDR readout lines
- 0.13 µm CMOS, DM 4-1, ~72 M transistors
- TSV ready with 1.2 mm periphery width



1)Sensitive area, 2) Active Periphery and 3) IO pad extenders

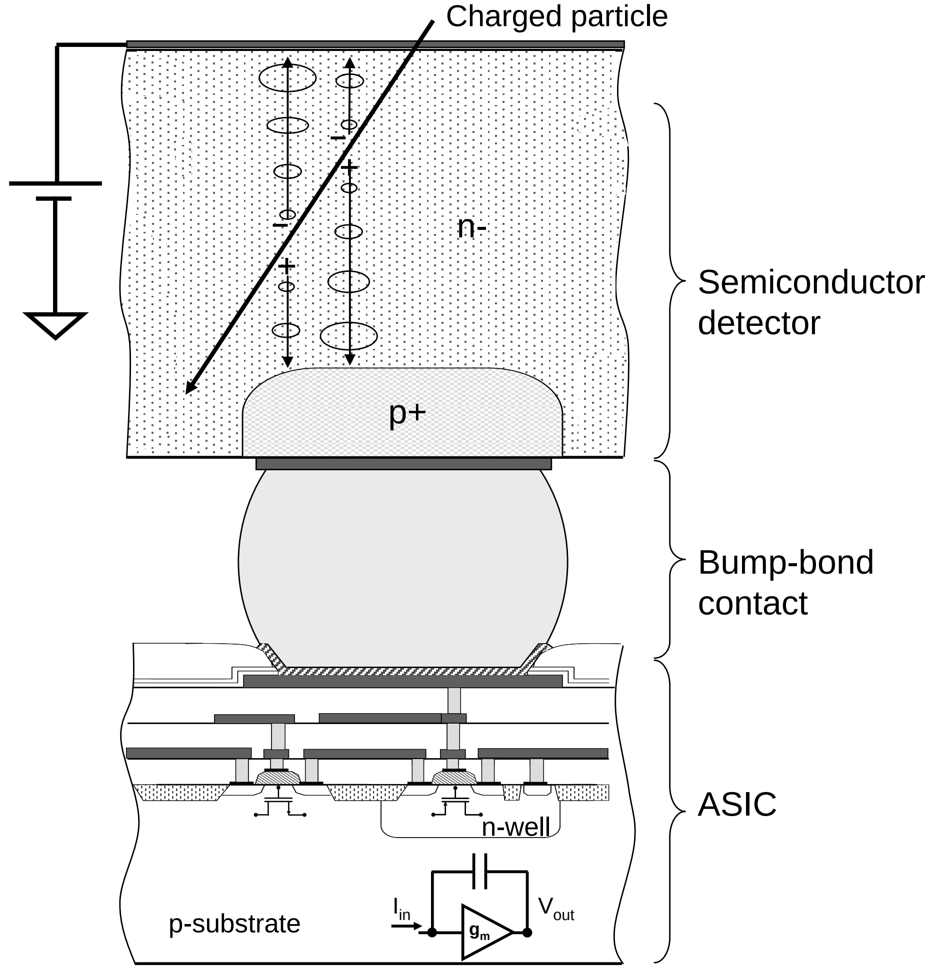
Evolution of the detectors from Medipix family



Sensitive volume

Semiconductor (Silicon)

- The opposite polarity doping of the bulk material corresponding to the pixel matrix step.
- P-N junction connected to the reversed polarity forms a charge carriers free volume.
- Electrons released by the ionizing particle drift towards the electrodes where are collected

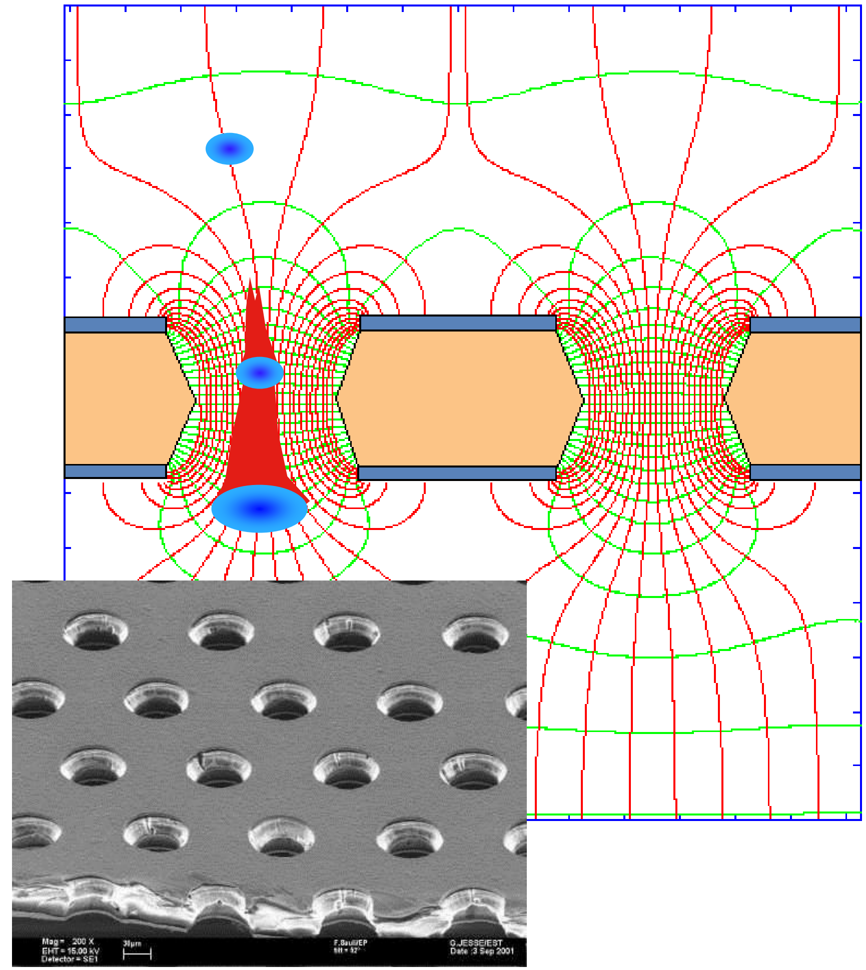


  - Silicon fabrication is high purity and well developer technology
  - High resistivity material allows for low bias operation
  - High energy resolution (3.6 eV per electron-hole pair production)
  - Radiation hardness

Gas Electron Multiplier (GEM)

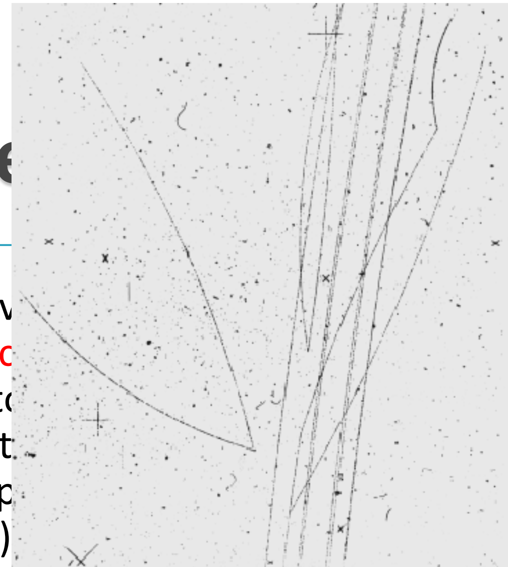
- A difference of potentials of ~ 500V is applied between the two GEM electrodes.
- The primary electrons released by the ionizing particle, drift towards the holes where the high electric field triggers the electron multiplication process.
- Multiple GEM layers can be placed above each other for signal high enough to be recorded directly at the Medipix input pad.
- Electron multiplication structures can be fabricated directly at the wafer level (Micromegas, InGrid,…)

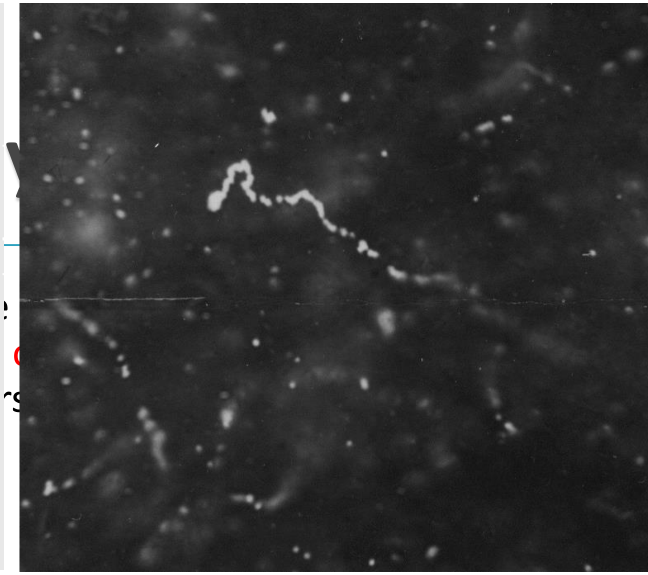
  - Gas is radiation hard
  - Easy to fabricate large volumes
  - High voltage necessary
  - 30 eV per electron-ion pair
  - Risk of discharge and damage to pixel electronics



Timepix potential for metrology and dosimetry

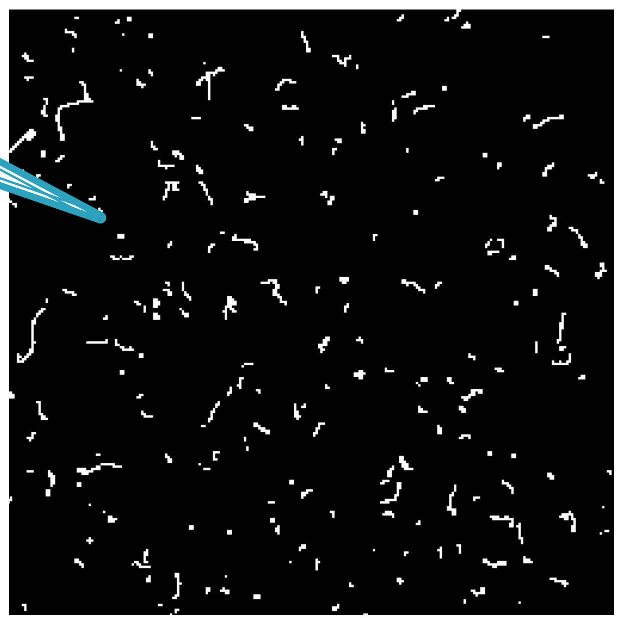
Particle track (pixe y

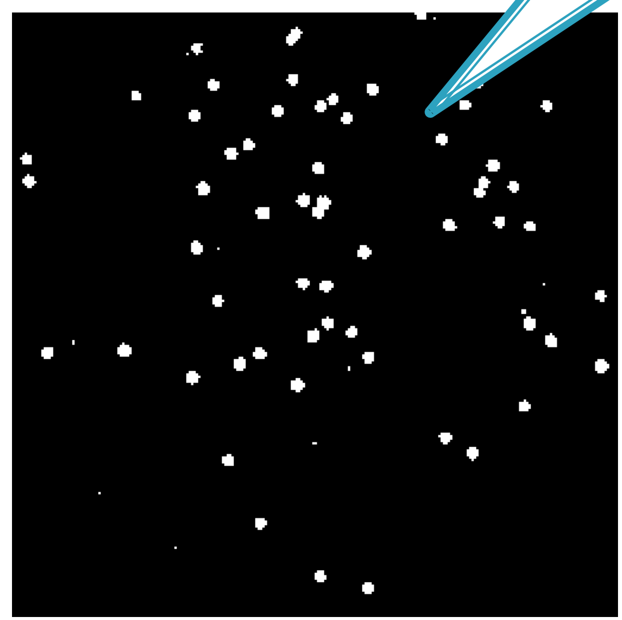




Each particle depositing energy abov e
visualized as it's characteristic trac c
criteria can be established in order t rs

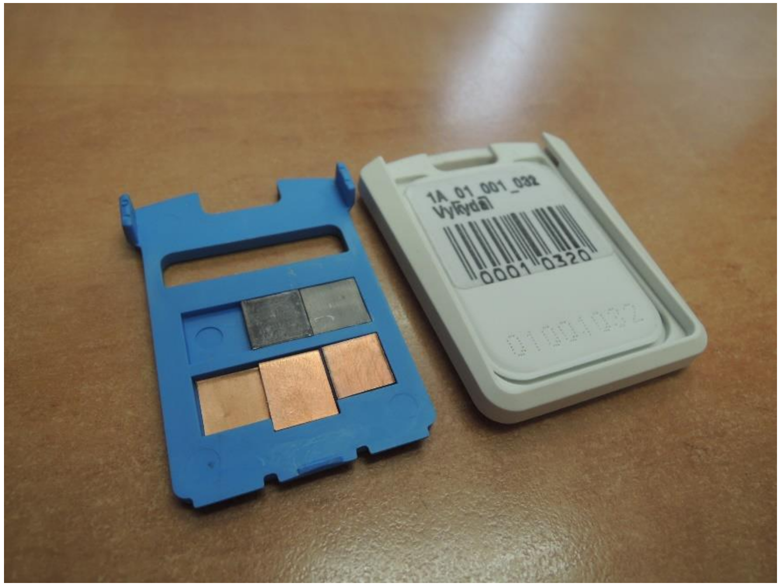
- Area (number of pixels) of a clust
- Height (maximal local energy dep
- Volume (total energy deposition)
- Roundness (surface compared to length of the border)
- Linearity (possibility to interleave track with line)
- …



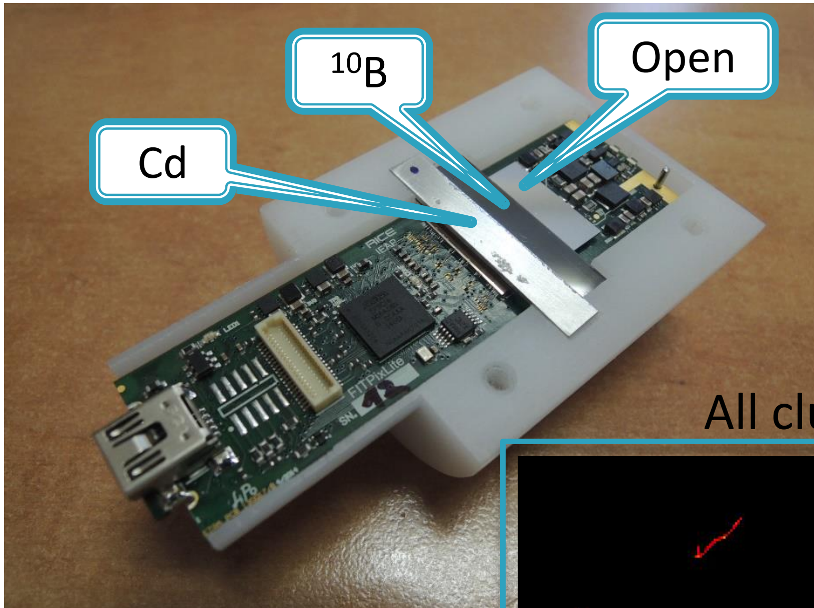


Imaging as tool for radiation detection

- Placement of a known object in front of a detector, measuring in generally unknown radiation field, changes the detector response in defined way and provides additional information on the measured field
- Similarly to the 2D sensitive film detectors one can partly cover the Timepix detector sensitive area by different filters and/or converters
- Contrary to the film detector one can simultaneously use the tracking capabilities of Timepix to enhance the difference in response of a different regions



Timepix adaptation for neutron detection @ EBS

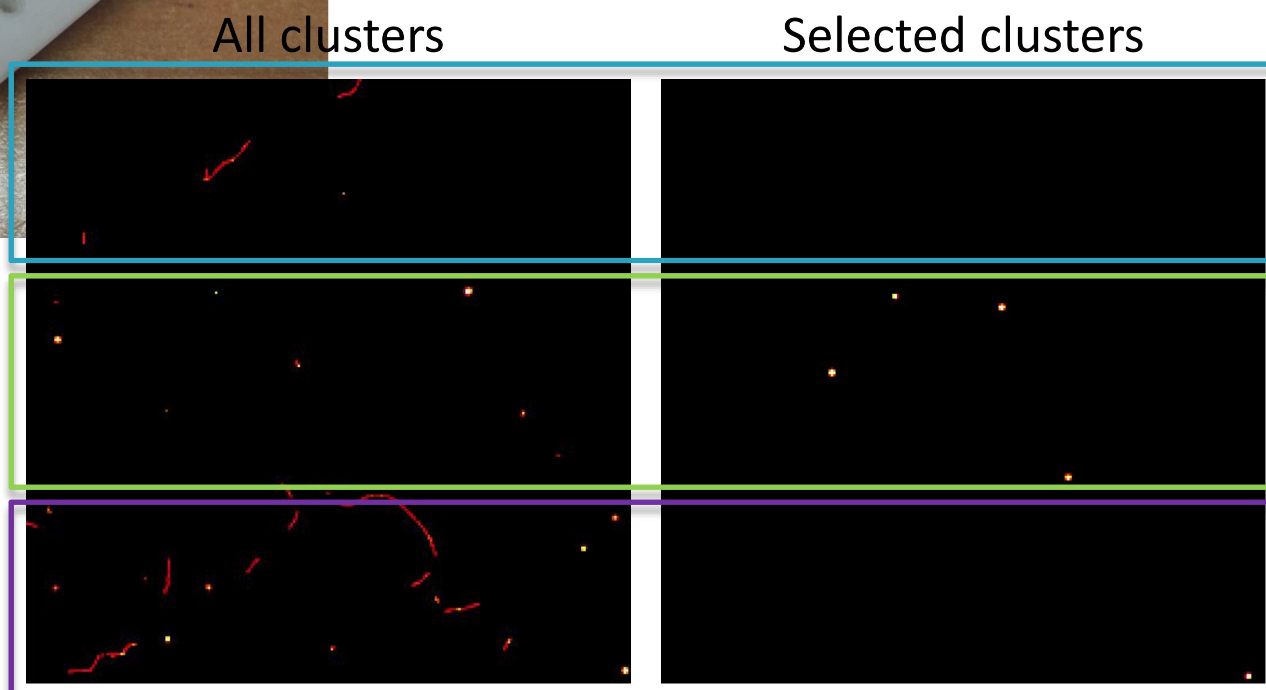


$n + {}^{10}B \rightarrow \alpha$ (1.78 MeV) + $^{7}Li^{*}$ (1.01 MeV) + γ (0.48 MeV)

σ (25 meV) = 3842 b

$n + {}^{113}Cd \rightarrow {}^{114}Cd + \gamma$ (0.56 MeV) + conversion electron

σ (25 meV) = 20743 b



Irradiation conditions:

- Thermal neutron fluence rate: 1.97E+04 $cm^{-2}.s^{-1}$
- Cadmium ratio: 35.5
- Integration of 1000 frames, 50 ms each.

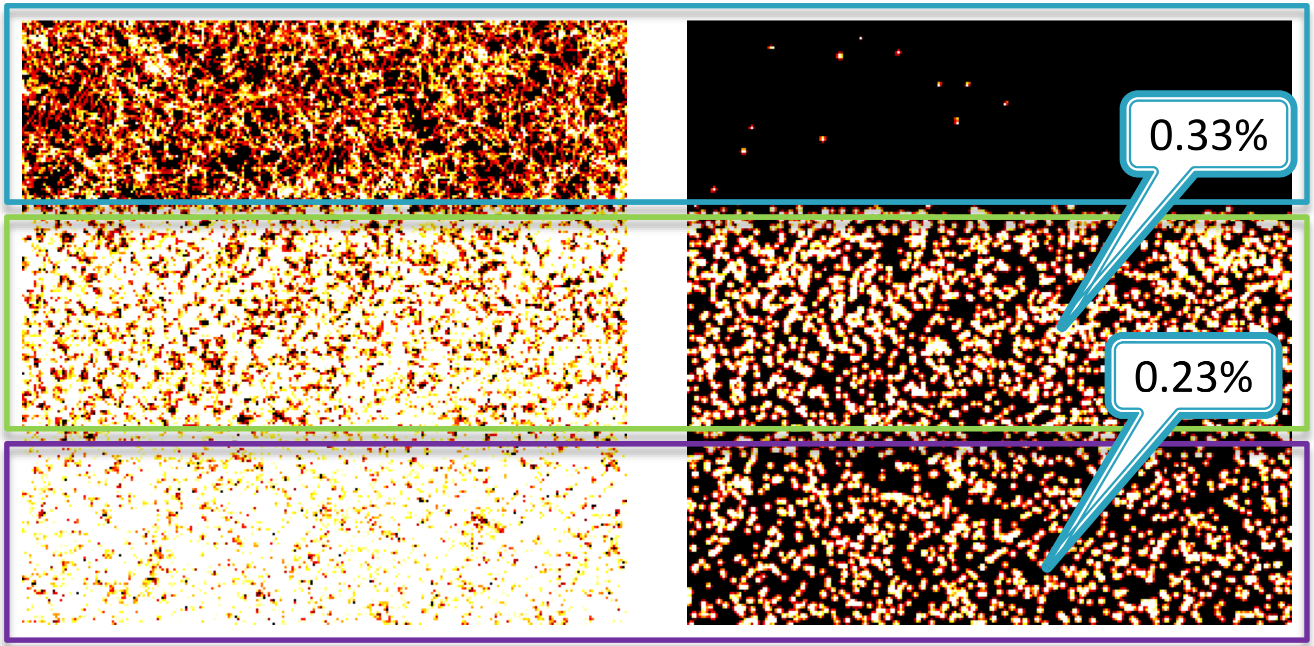
Timepix neutron detector efficiency calibration

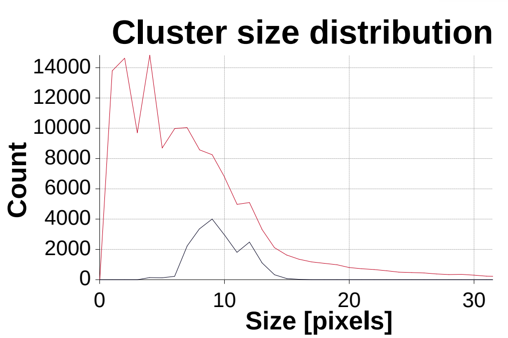
All clusters | Selected clusters

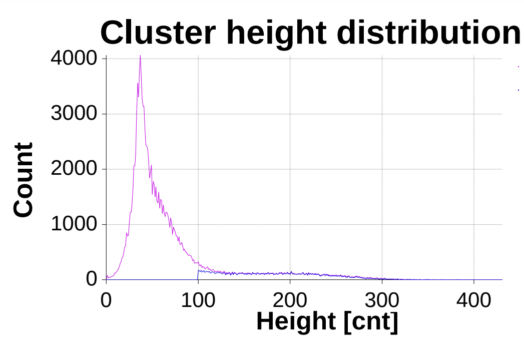
Uncovered

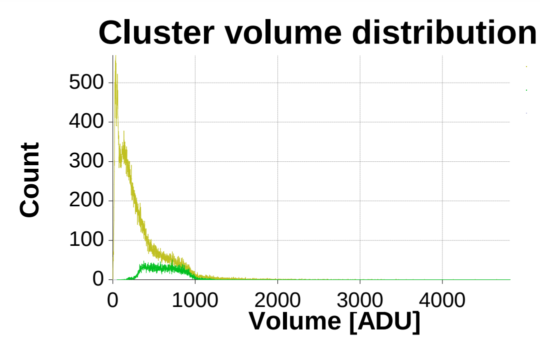
Covered by 20 µm thick ^{10}B layer on a 100 µm polyester foil

Covered by 20 µm thick ^{10}B layer on a 100 µm polyester foil and 1mm Cd foil









Radiation protection and safety

- Dose equivalent is defined on the base of quality factor that is function of linear energy transfer and represents biological effectiveness of different radiation types

$$H = D.Q \quad [Sv]$$

L [keV/μm]	Q(L)
$L < 10$	1
$10 < L < 100$	$0.32 \times L - 2.2$
$100 < L$	$300 \times L^{-0.5}$

- On the base of this definition the conversion coefficient from particle spectral fluence to personal dose equivalent is calculated by Monte Carlo for standardized ICRU phantoms.

- In the practice the radiation field is always a mixture of several particle types (photons, electrons, heavy charged particles, neutrons,…) and measurement of the particle spectral fluence is not trivial.

Timepix application for radiation protection and safety

- Detectors of the Medipix type can provide very complex information on the mixed radiation field by means of the interaction cluster characteristics
- This multidimensional cluster characteristics can be used for calculation of the dose equivalent as well as can be calibrated to the actual biological effects e.g. cell population damage of certain type

Irradiation at calibration facility

Dose equivalent @ well defined calibration field => biological effects

Measured multidimensional cluster characteristics => biological effects

In the field irradiation

Dose equivalent @ unknown field => rough prediction of biological effects

Measured multidimensional cluster characteristics => more precise prediction of the biological effects

Thank you for your attention!