Multi-Wire 3D Gas Tracker for Searching New Physics in Nuclear Beta Decay

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✓ Theory approach

✓High Precision Beta Spectrum shape study – miniBETA project

✓ Multiwire 3D gas tracker for precision measurements

✓Results of spectrometer characterisation

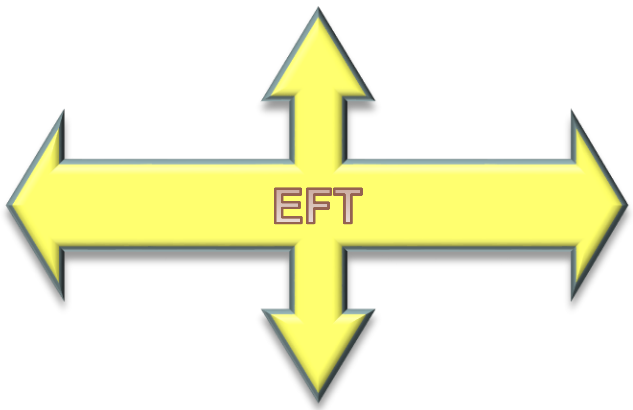
✓Plans for a future measurements

✓Application to neutron decay correlation experiment
– BRAND project

✓Conclusions and outlook

Searching for new physics beyond the Standard Model

High energy Frontier
- HE accelarators



Low Energy Frontier
- precision measurements

Nuclear and neutron beta decay:

✓ precision beta spectrum shape measurements

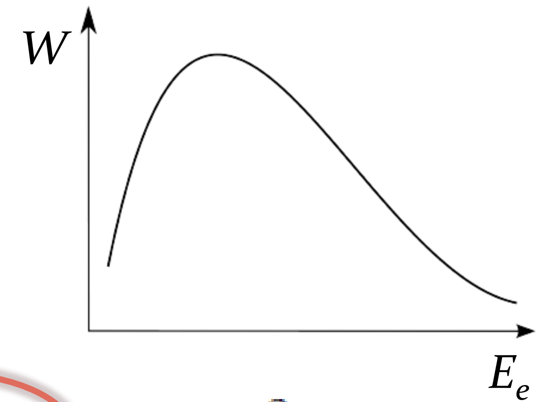
✓ neutron correlation coefficient measurements

Beta spectrum shape measurements

$$W(E_e)dE_e = \underbrace{pE_e(E_0 - E_e)^2}_{\text{phase space}} \underbrace{F(\pm Z, E_e)}_{\text{Fermi function}} \underbrace{B(Z, E_e)}_{\text{any other correction}} \underbrace{f_1(E_e)}_{\text{spectral function}} dE_e$$

$B(Z, E_e)$ – corrections for:

- ❑ final size of nucleus
- ❑ final mass of nucleus
- ❑ radiative corrections



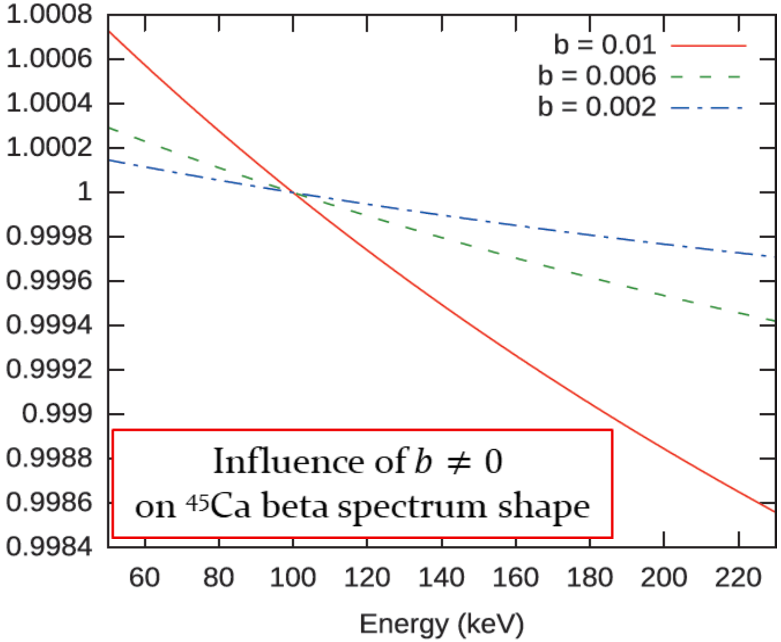
Spectral function:

$$f_1(E_e) = C_0 + C_1 E_e + C_{-1}/E_e + C_2 E_e^2$$

C_{-1} – Fierz term *b* (scalar / tensor weak currents)

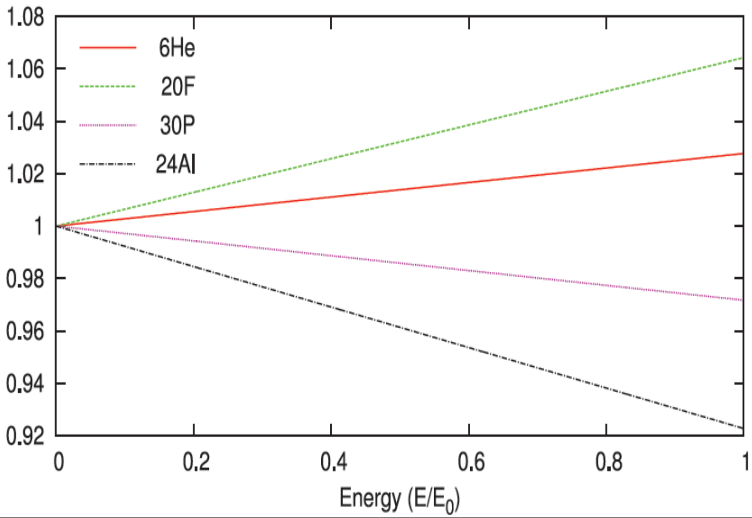
C_1 – weak magnetism (Standard Model term)

both terms have different energy dependency!



Fierz interference

- search for tensor (Gamow-Teller) and scalar (Fermi) weak coupling constants
- current limits on the percent level for tensor type coupling constants



Weak magnetism

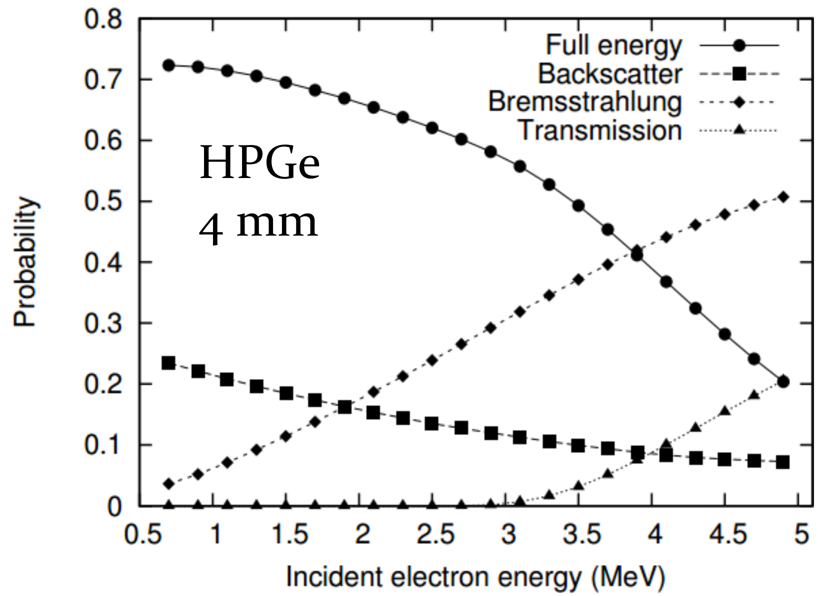
- the effect of the strong interaction on the decaying quarks (QCD renormalisation effect)
- influences the values of correlation coefficients in decay up to a percent level

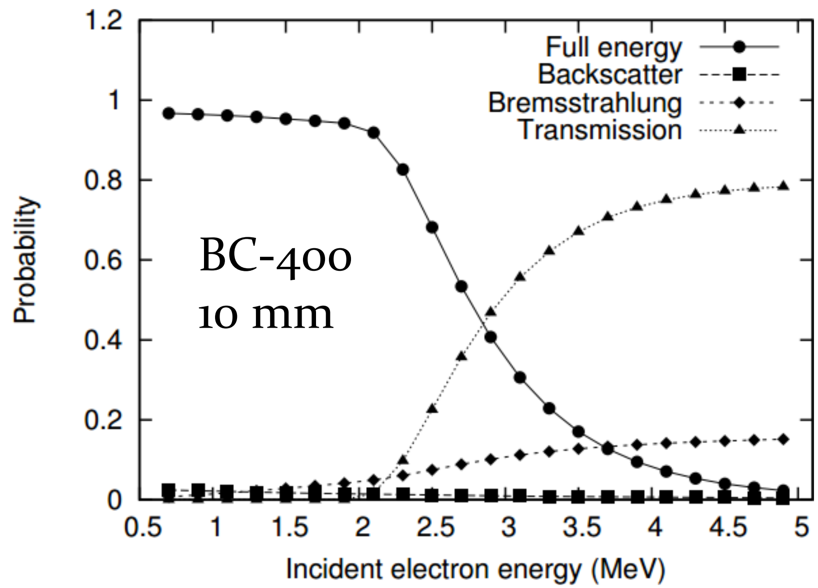
Detector characteristics

Persistent problem in precision spectrum shape measurements:
particle and energy losses in detectors

Probability of a particular scenario when a detector is hit by an electron:

- ❑ full energy deposition;
- ❑ energy partially deposited due to:
  - backscattering;
  - bremsstrahlung;
  - transmission;





G. Soti; KUL, PhD thesis (2013)

Issue:

MS simulations uncertainty ~10%.
10% backscattering * 10% uncertainty
→ 1% beta spectrum shape uncertainty

The goal is precision of ~0.1%

✓ Multiwire 3D gas tracker for precision measurements

Goal:

- ❑ **Precise β spectrum shape measurements: comparison with SM, search for new physics;**
- ❑ **Better understanding of the MS processes;**

Why do we want to apply MWDC?

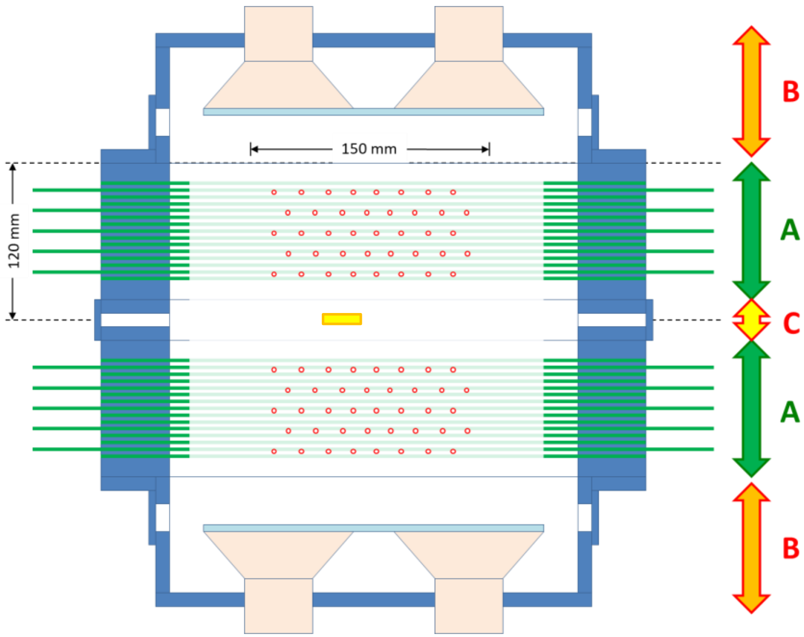
Electron tracking can be helpful:

- ❑ identification of backscatterred electrons;
- ❑ gamma/electron discrimination using the coincidence between gas detector and scintillator;
- ❑ light construction to reduce background from gammas created inside chamber due to collisions with gas molecules or with wires;

What precision do we need to reach goal?

- ❑ Position resolution: X-Y position < 0.5 mm; Z- position < 10 mm;
- ❑ Energy resolution: ~50 keV @ 1 MeV;

miniBETA spectrometer



- Energy detector + wire chamber:

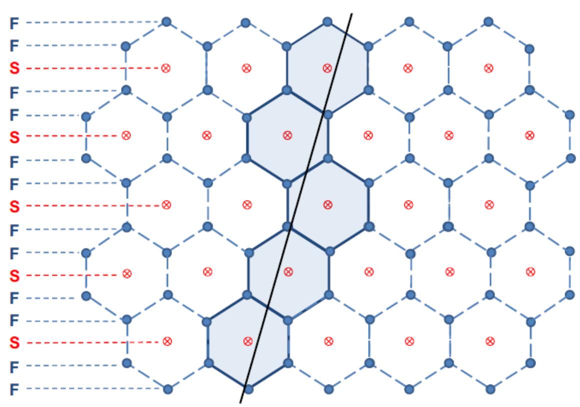
  energy readout from the scintillator + backscattering detection;
- XY positioning: drift time measurement: $t_{TDC} = t_{Stop} - t_{Start}$

  - t_{Start} : scintillator

  - t_{Stop} : signal from a wire
- Z positioning: charge division;
- 80 hexagonal cells

  (10 signal planes with 8 wires each);
- Filled with He-Iso mixture with pressure < 1000 mbar;
- β source inside with automatized 2D positioning system;

Cell configuration:



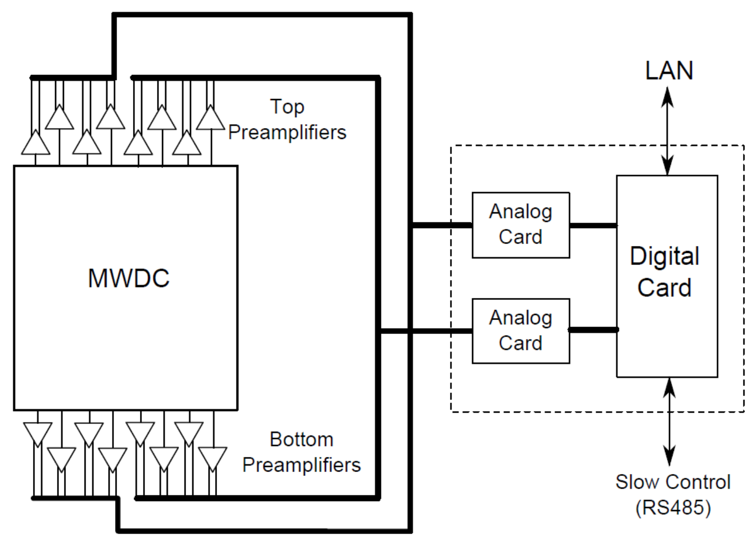
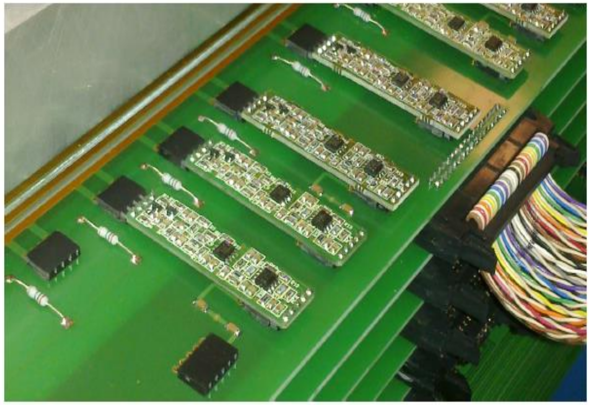
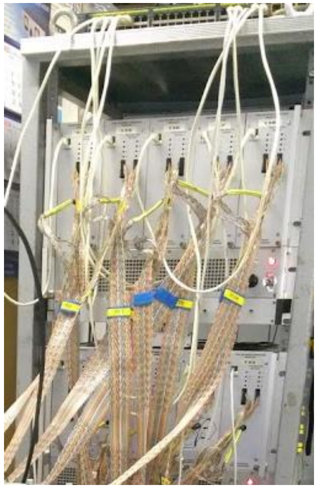


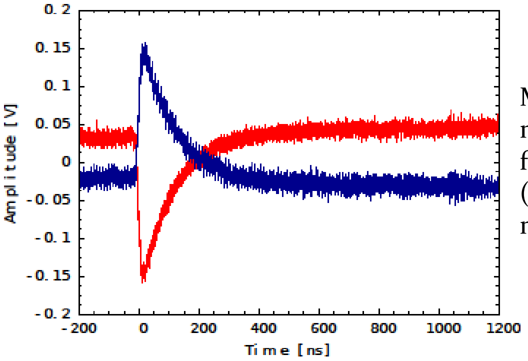
Fig. 1: Schematic of the data acquisition architecture.

Prototype A/D module (for 8 wires):

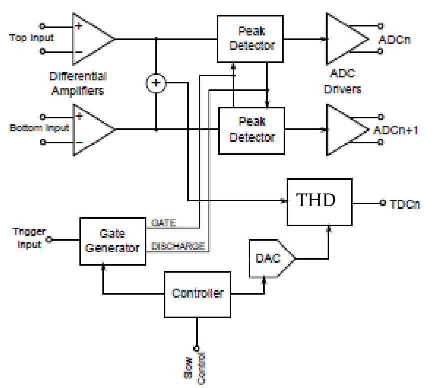
- 2 analog cards for readout of 16 wire ends)
- 1 digital card (16 ADCs and 8 TDCs)
- 10 A/D modules for 2x80 readout channels



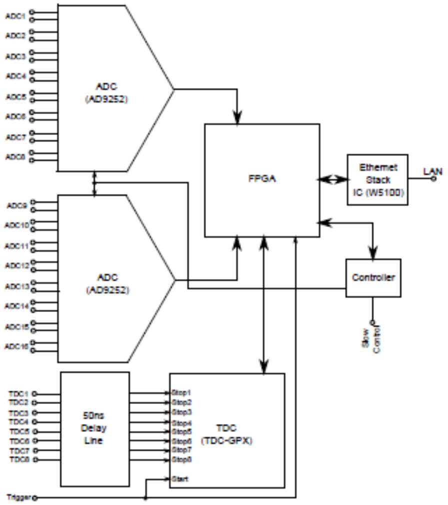




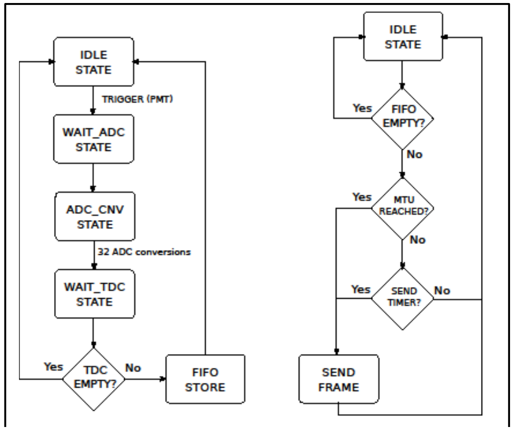
Measured positive and negative output signal from the preamplifier (read out in differential mode).



Block diagram of the analog board



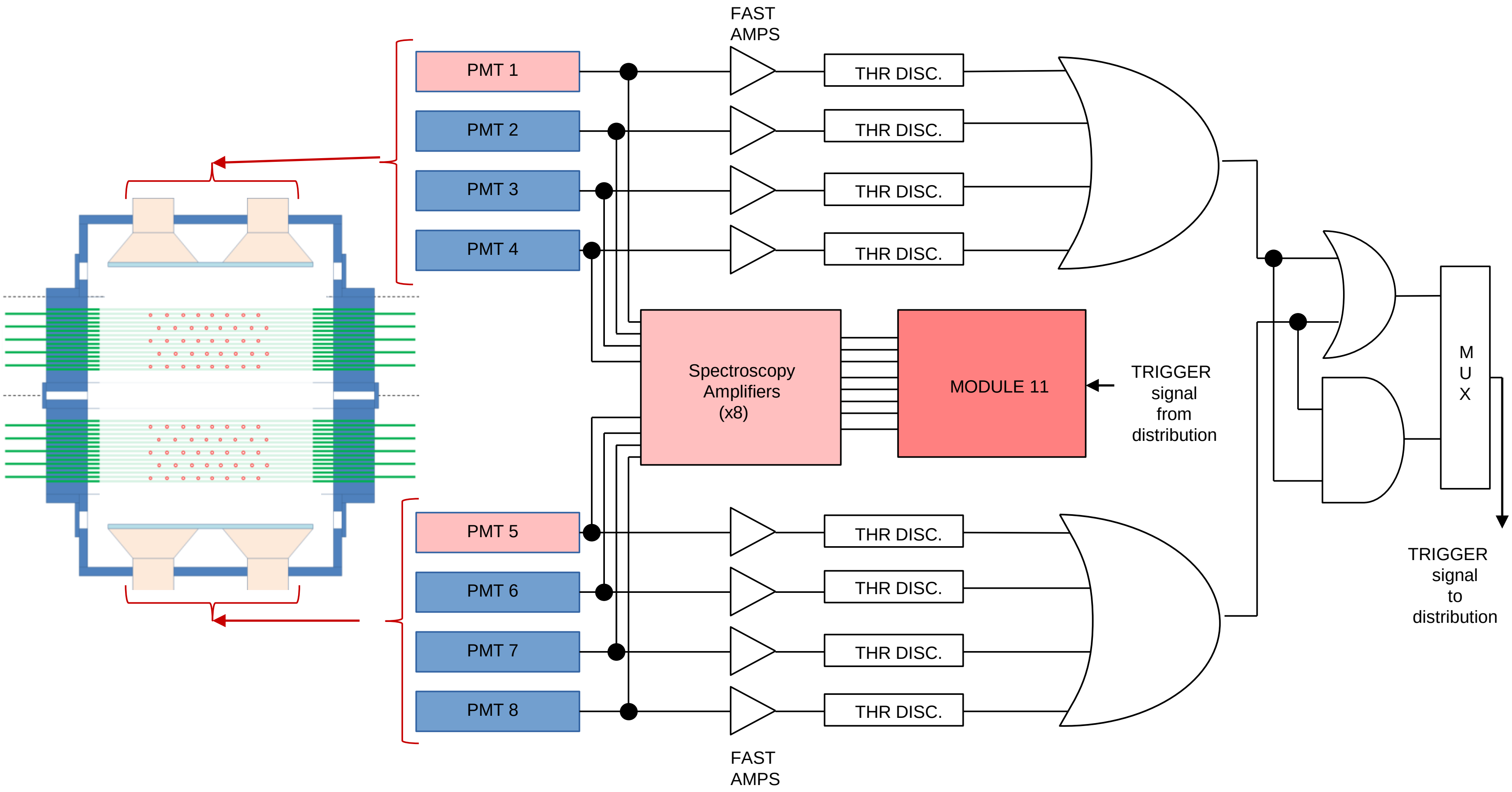
Block diagram of the digital board



Flow diagram of the DAQ algorithm (left panel) and of the data transmission algorithm (right panel)

K. Lojek, D. Rozpedzik et al., Nucl. Instrum. Meth. Phys. Res. A 802 (2015) 38.

Trigger implementation in spectroscopy module



Electronics contribution to drift time and charge division measurements

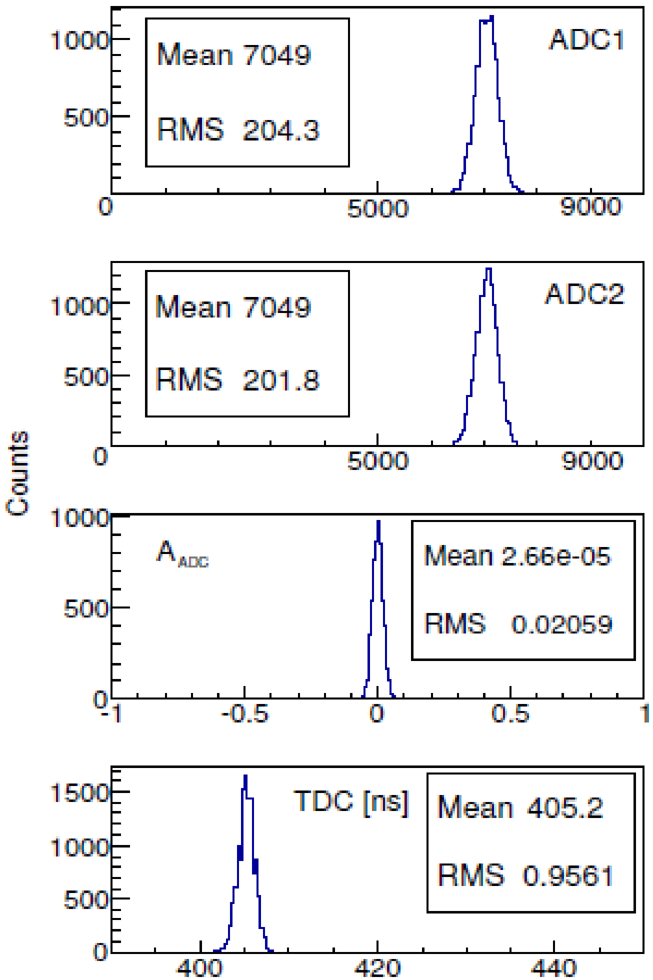


Fig. 17: Sample results for a single channel of one acquisition module. The two top plots present collected ADC values corresponding to both the upper part and the lower part of the wire. The two lower plots show the ADC asymmetry and converted TDC values in nanoseconds.

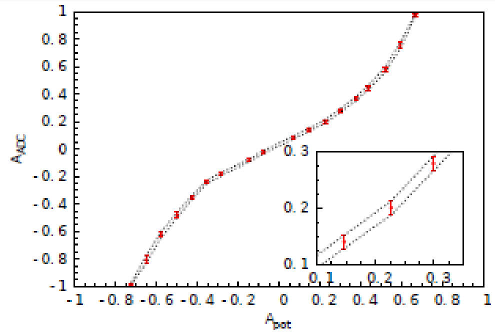


Fig. 18: ADC pulse height asymmetry (centroids of the peaks from Fig. 16) as a function of the resistance asymmetry A_{pot} (Eqn. 2). The insert is a zoomed part of the graph showing the error bars equal to $\pm 1\sigma$ of the peak distributions plotted in Fig. 16. Dotted lines interpolate the error bar ends.

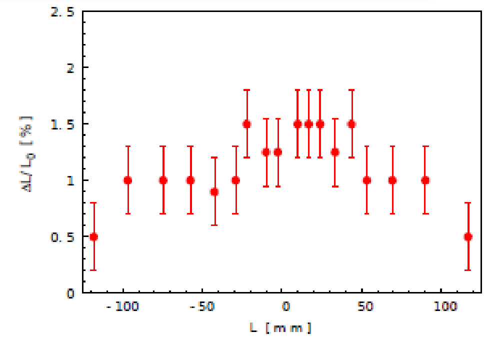


Fig. 19: Position resolution $\Delta L/L_0$ expressed in units of length of the wire deduced from Fig. 18. A 500 ohm wire resistance was assumed which corresponds to a 25 μm NiCr wire of L_0= 240 mm length. The uncertainty is connected with the interpolation procedure (see text).

Contributions to:

- ❑ charge division - varies from 0.5 % at wire ends to 1.5 % in the center corresponding to 1.2 and 3.6 mm for 24 cm long wires (25 μm NiCr)
- ❑ drift time - less then 1 ns corresponding to 250μm position uncertaintly at the expected drift velocities

The necessary spatial resolution of the electron track position determined from the drift time need not to be better than 500 μm

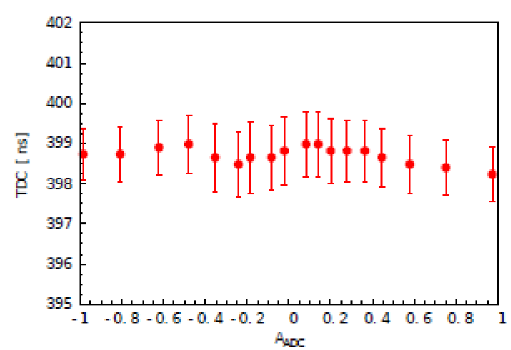
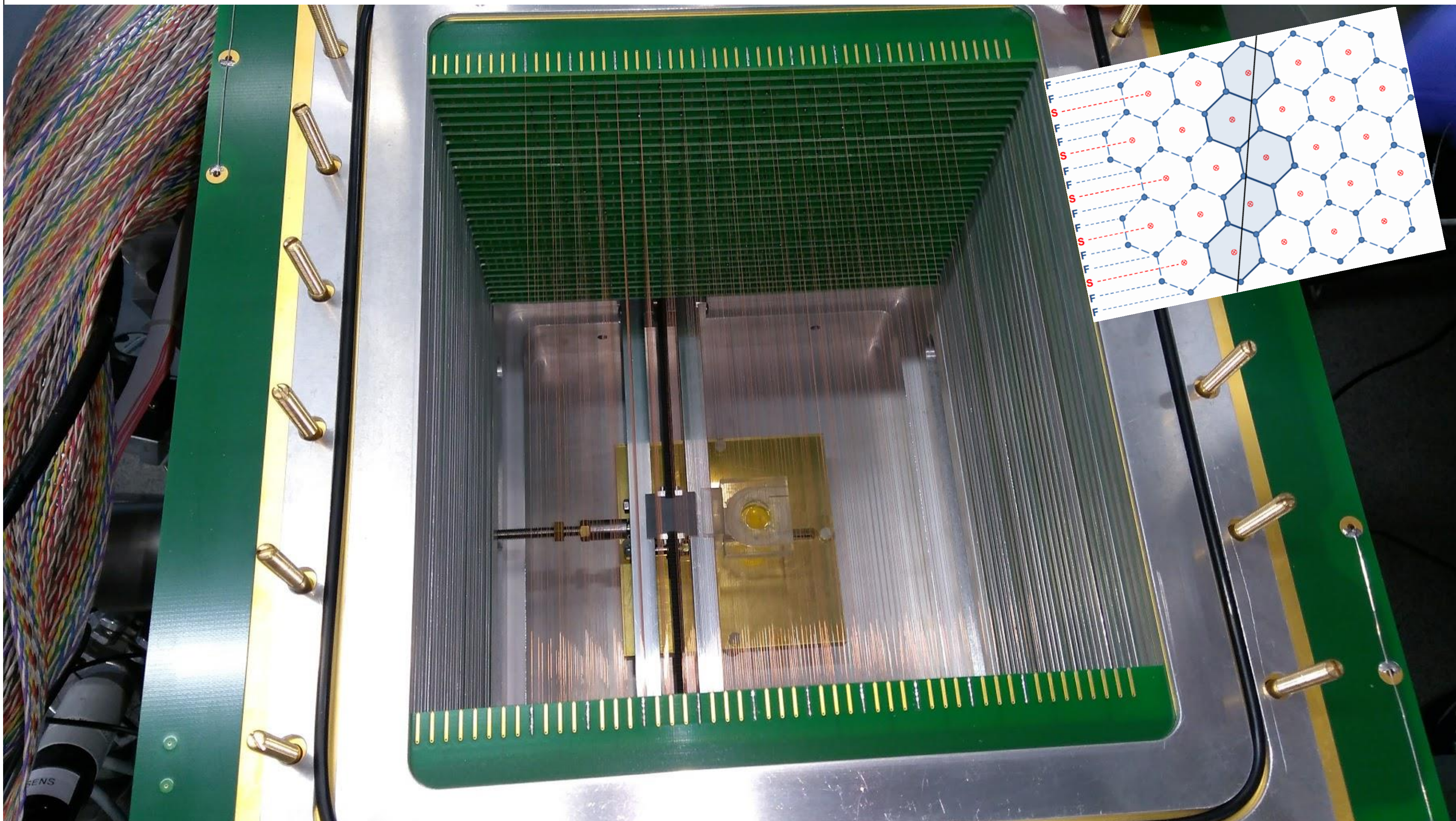


Fig. 20: TDC values as a function of the ADC asymmetry. The error bars correspond to the standard deviation of the TDC histogram.

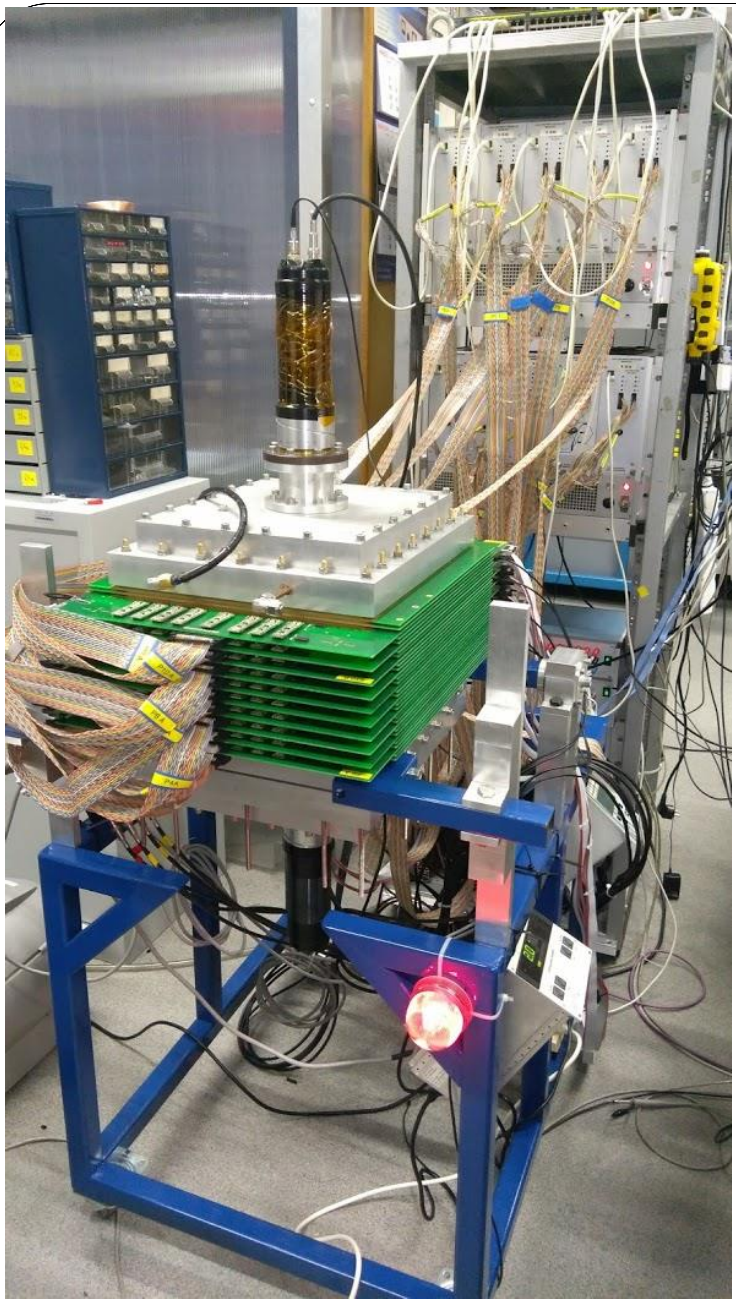
K. Lojek, D. Rozpedzik et al., Nucl. Instrum. Meth. Phys. Res. A 802 (2015) 38.

Inside view of MWDC

- Anode wires – NiCr, Ø 25 µm
- Cathode wires – CuBe , Ø 75 µm

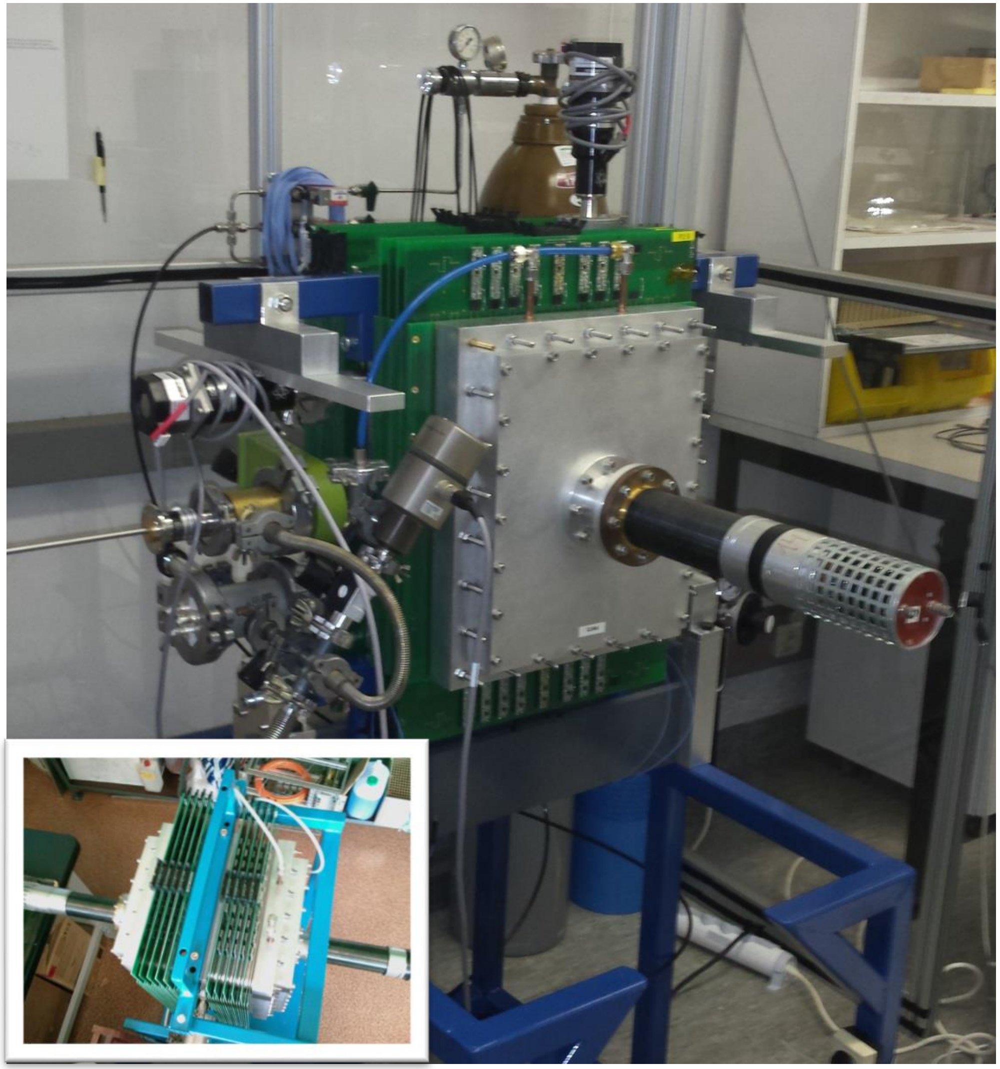


Modular and reconfigurable design



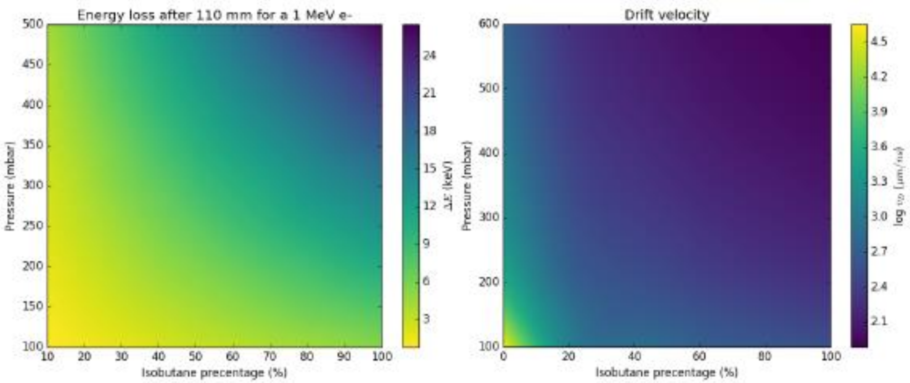
10 planes on one side

5 + 5 planes: beta source in the middle



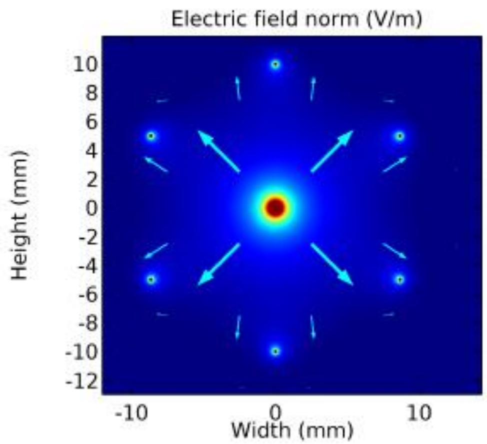
Optimizing conditions for planned measurements and for stability of MWDC (Geant4, Garfield))

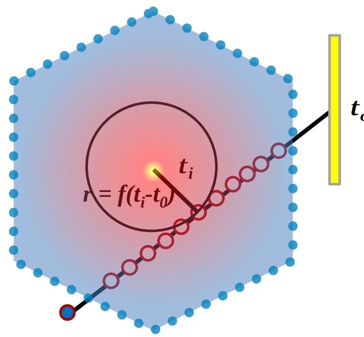
- Gas mixture:
  - Helium → lowest electron straggling (but UV product)
  - Isobutene → highest ionization



- Pressure:
  - Low → small ionization, small signals but small straggling
  - High → higher ionization, higher signals, but higher straggling

Drift time measurements → R → (X-Y):



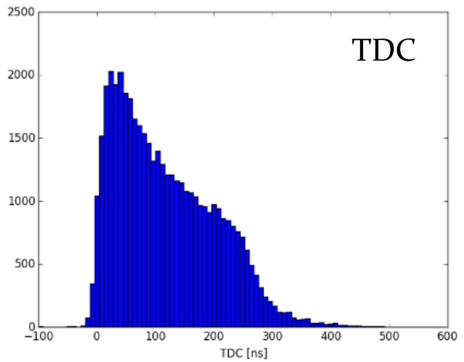


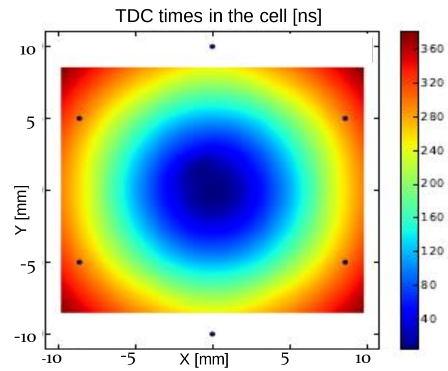
- An electron emitted from the source is traversing the chamber ionizing the gas along its way and hits the scintillator at **time t_o**.
- Electrons from the ionization drift towards the cell center. The fastest primary ionization electrons arrive to anode at **time t_i**.
- Knowing the drift velocity we can calculate the distance from the anode wire forming a ring (assuming central symmetric electric field) to which the trajectory of emitted electron is tangent.

✓ Current status of spectrometer characterisation

Plots thanks to M. Perkowski, JU@KUL, PhD Thesis (2018)

Chamber performance (cosmic muons, Iso-He 50-50 mix at 600 mbar):





Homogeneous illumination:

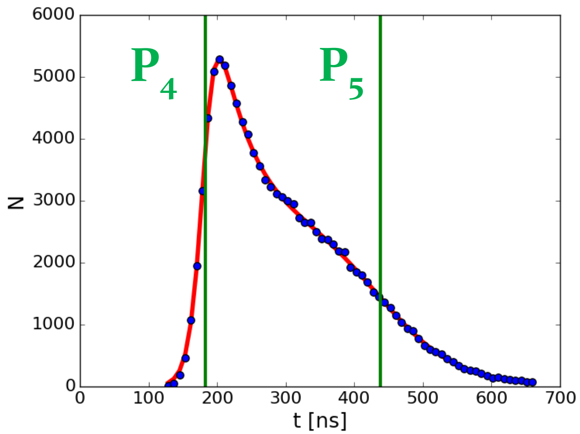
$$\frac{dn}{dr} = const = \frac{N_0}{r_{max}}$$

$$r = \int_{t_{start}}^{t_{stop}} v(t)dt$$

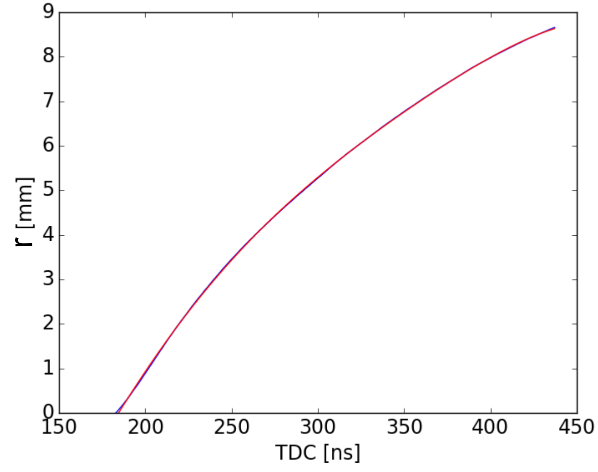
$$v(t) = \frac{dr}{dt} = \frac{dr}{dn}\frac{dn}{dt} = \frac{r_{max}}{N_0}\frac{dn}{dt}$$

$$r(t) = \frac{r_{max}}{N_0}\int_0^t \frac{dn}{dt'}dt'$$

With initial $r(t)$ dependency

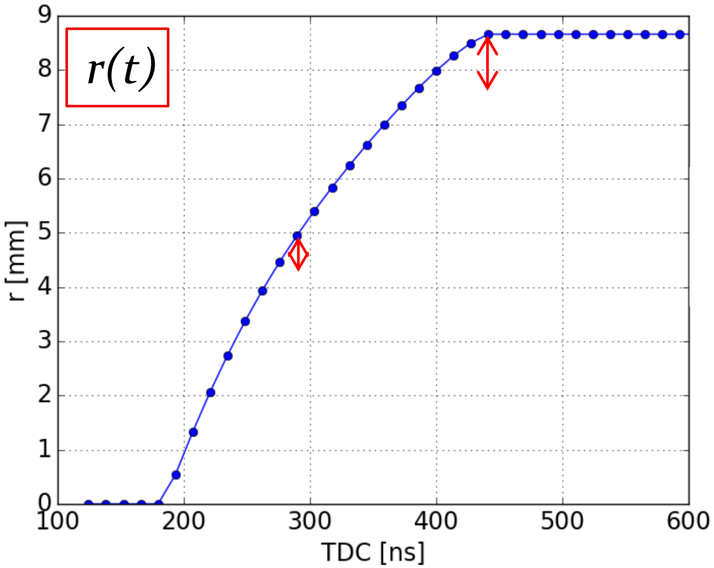


$$\frac{dn}{dt} = P_0 + \frac{P_1\left(1 + P_2 \exp\left(\frac{P_4 - t}{P_3}\right)\right)}{\left(1 + \exp\left(\frac{P_4 - t}{P_6}\right)\right) + \left(1 + \exp\left(\frac{t - P_5}{P_7}\right)\right)}$$



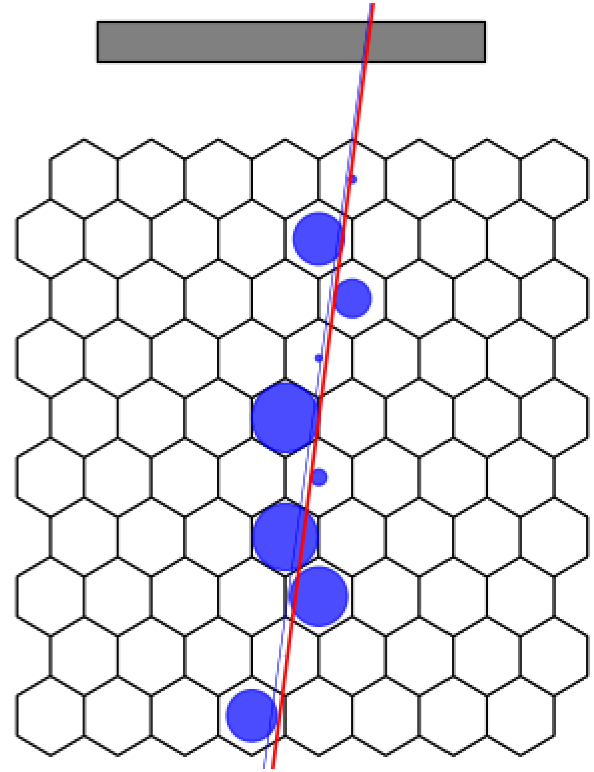
G. Avolio et al., Nucl. Instrum. Meth. Phys Res. A 523 (2004) 309–322

Iterative procedure until residuals are centered at 0 for full range of distances r

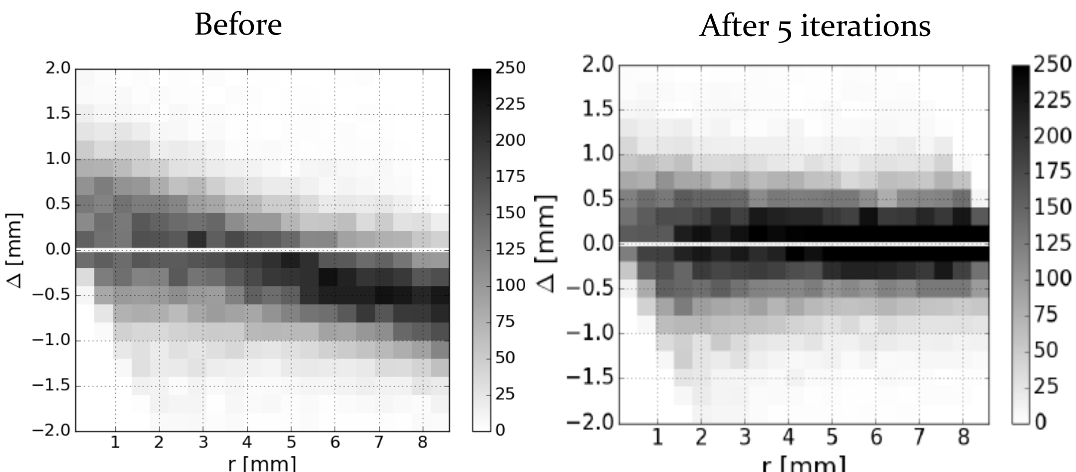


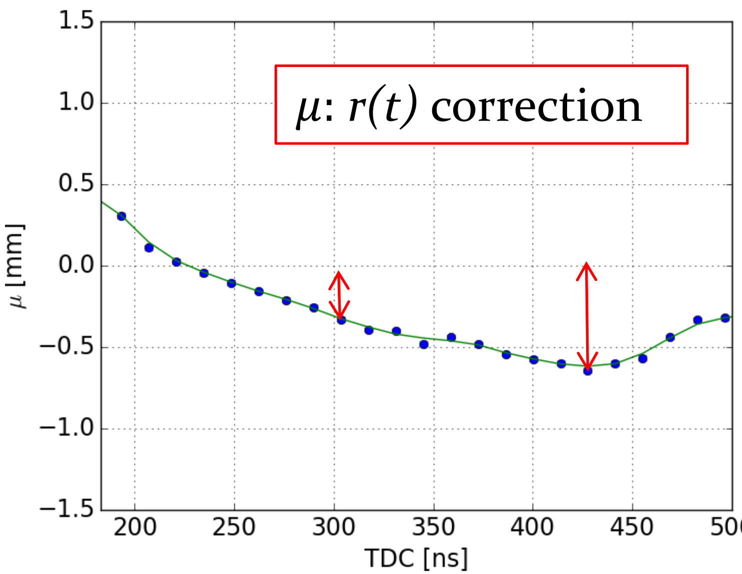
$$\Delta_i = d_i - r_i$$

$$d_i = \frac{|Ax_{C_i} - y_{C_i} + B|}{\sqrt{A^2 + 1}}$$



M. Perkowski et al. Acta Physica Pol. B 49 (2018)3

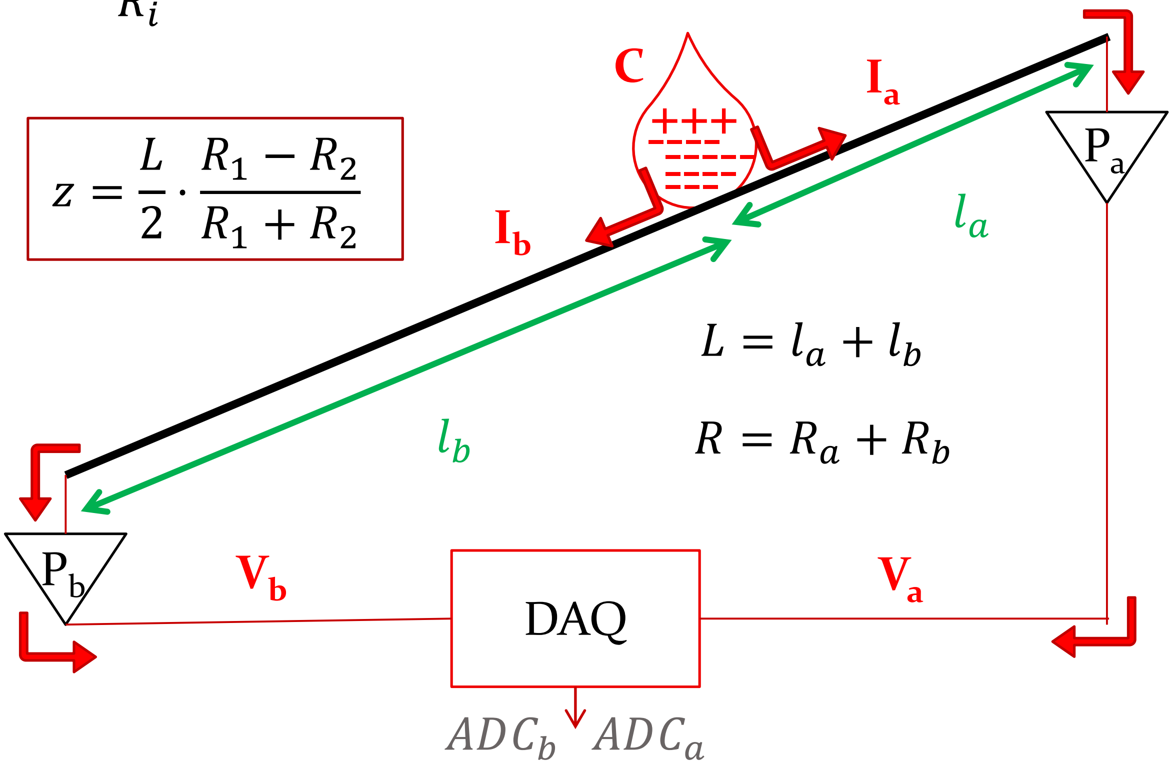




Charge division technique in Z-direction needed for 3D tracking algorithm

$$I_i \propto \frac{1}{R_i} \qquad R_i \propto l_i \qquad V_i \propto I_i$$

$$z = \frac{L}{2} \cdot \frac{R_1 - R_2}{R_1 + R_2}$$



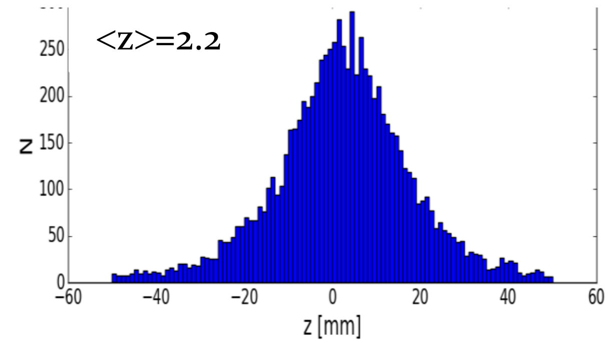
$$L = l_a + l_b$$

$$R = R_a + R_b$$

$$ADC \sim V \qquad A = \frac{ADC_a - ADC_b}{ADC_a + ADC_b}$$

$$ADC_i = O_i - f_i(V_i)$$

$$A \in [-1,1]$$



$$V_A = c_1 I_1; \qquad z = \frac{L}{2} \cdot \frac{V_2 - c' V_1}{V_2 + c' V_1}$$

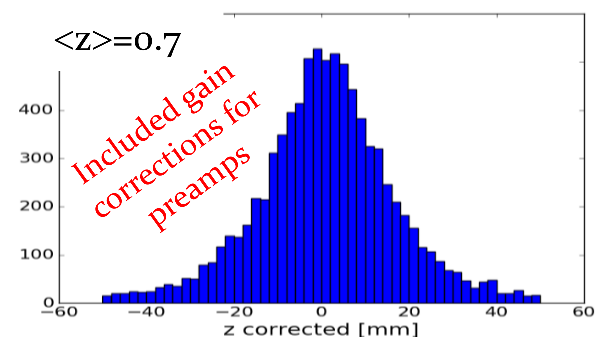
If z=0 (source at the center, slit on the scintillator at z=0):

$$z: (l_1 = l_2) \Rightarrow z = 0$$

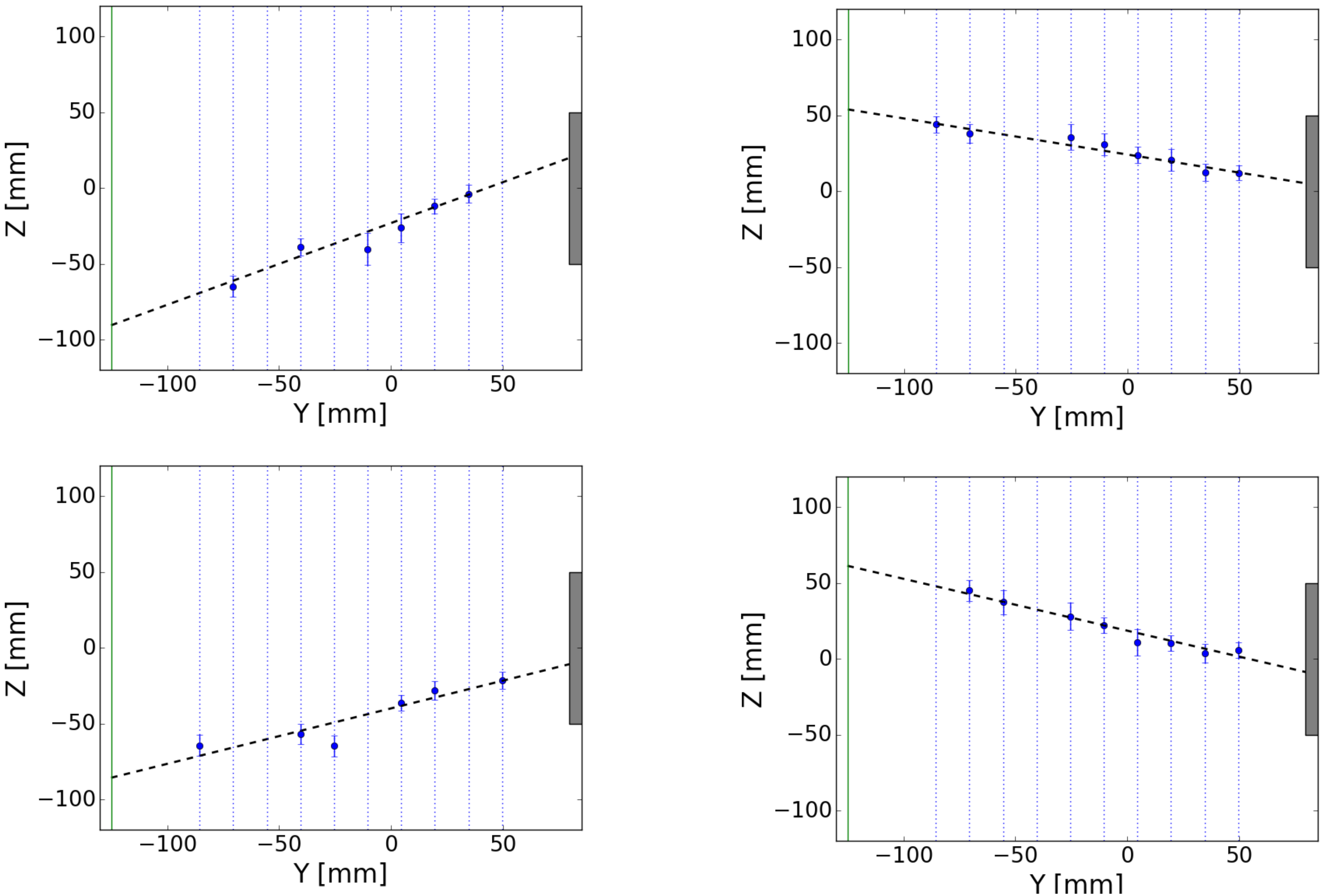
$$I_1 = I_2$$

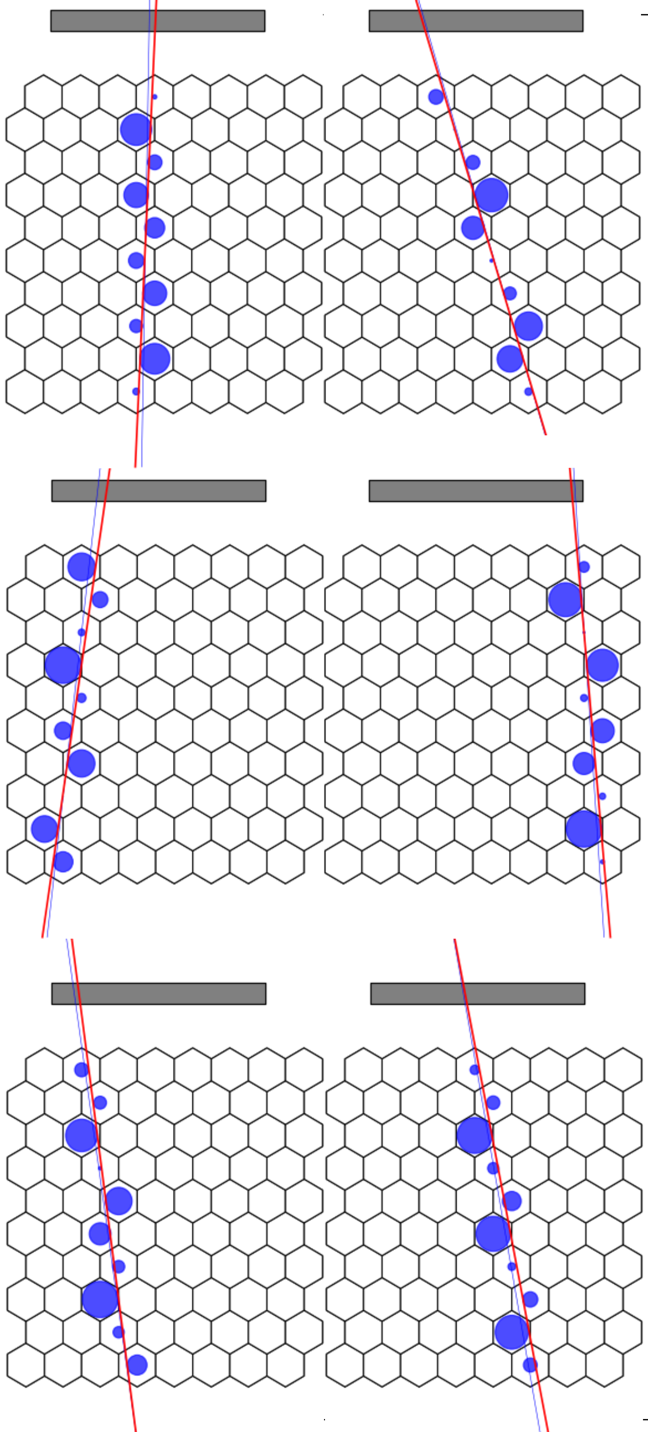
$$\frac{V_1^0}{c_1} = \frac{V_2^0}{c_2}$$

$$c' = \frac{c_2}{c_1} = \frac{V_2^0}{V_1^0}$$



Calibration of Z-resolution using cosmic muons





3D tracking performance

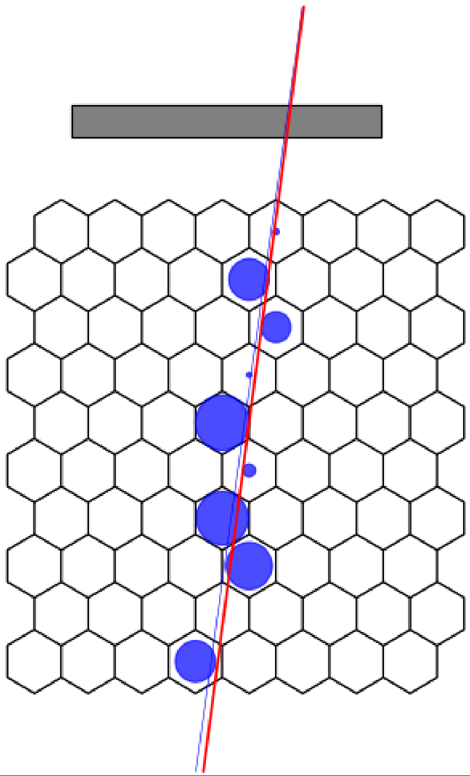
(for single wire hits)

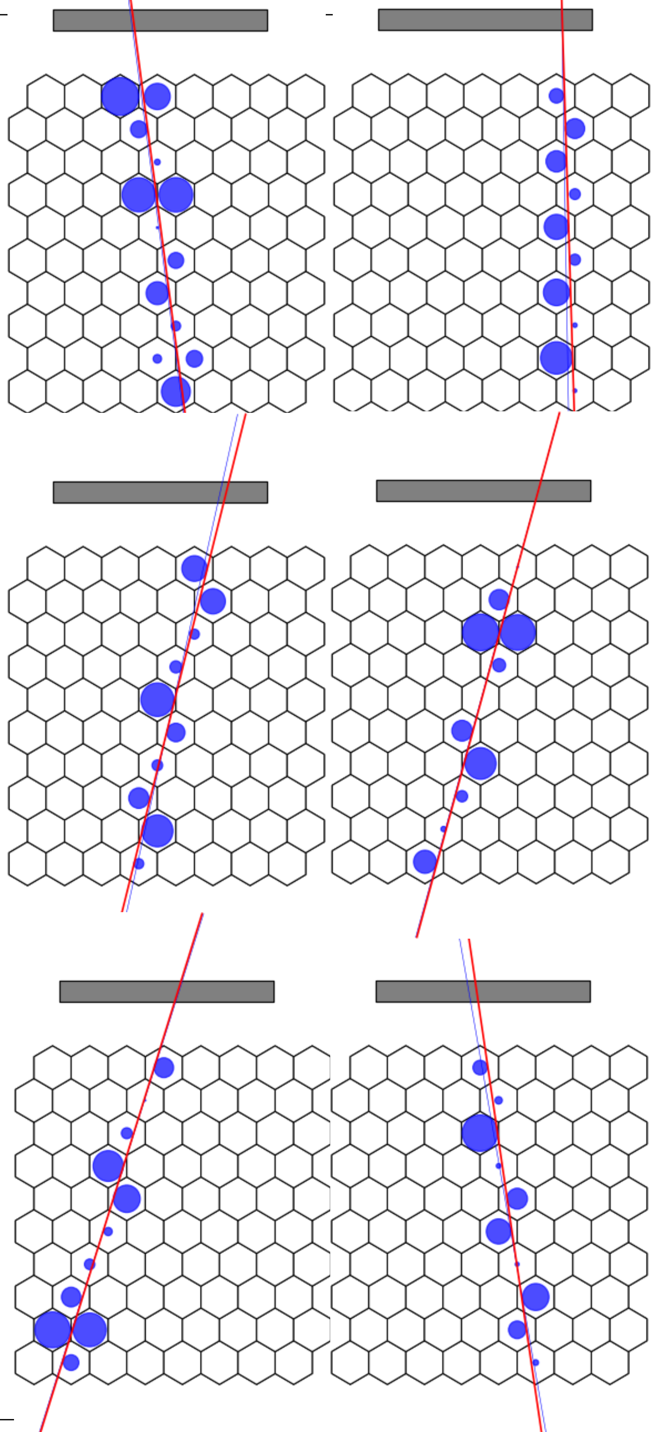
X-Y resolution:

~0.5 mm

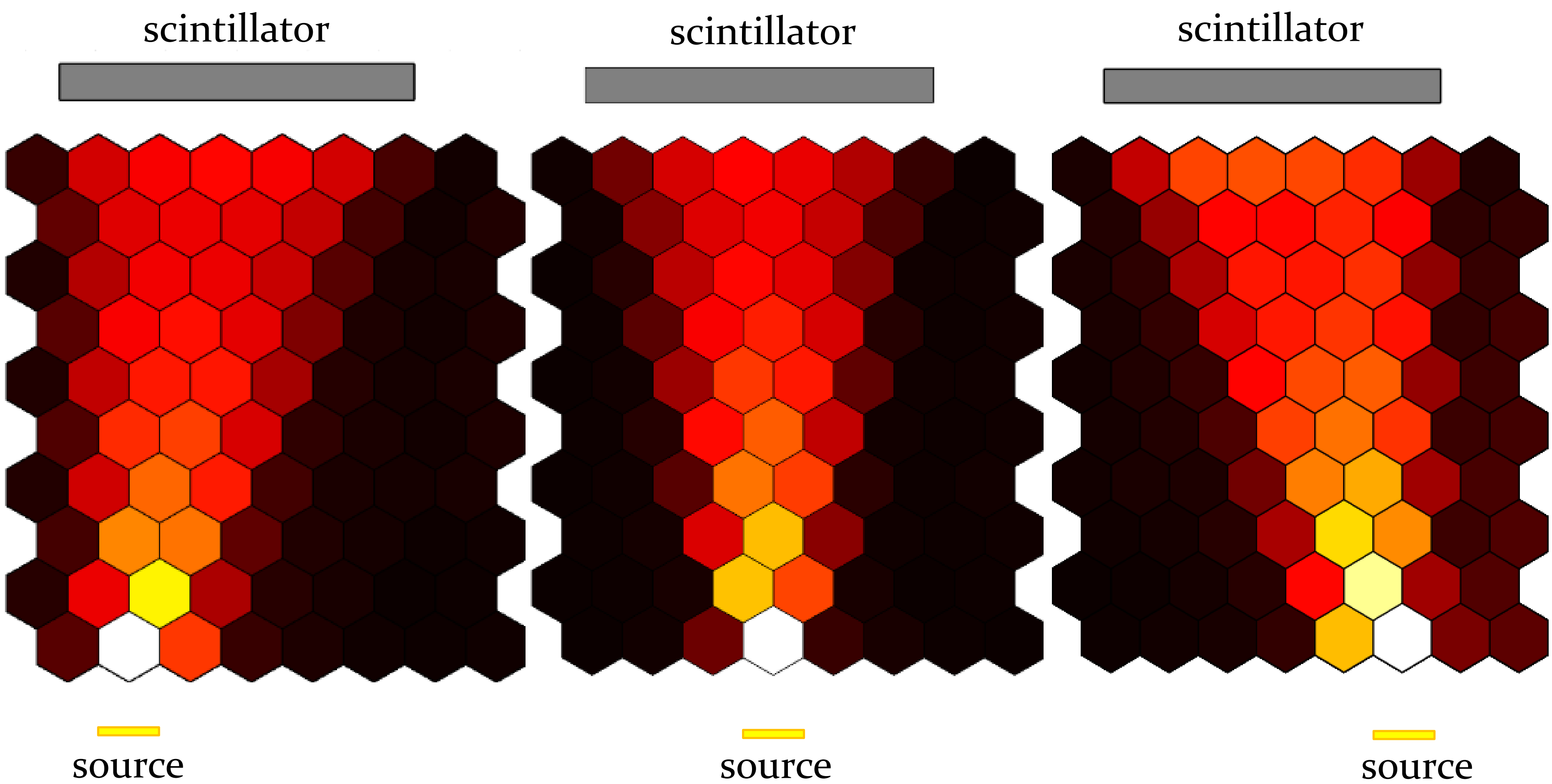
Z resolution:

3 – 7 mm

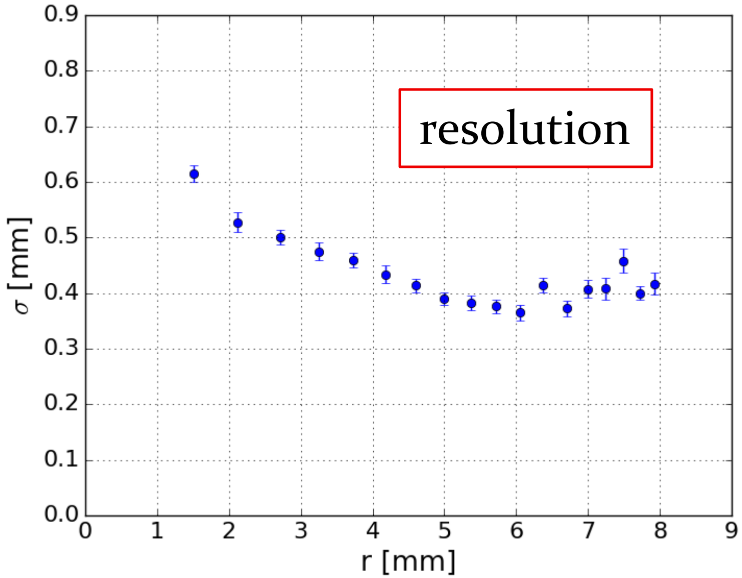


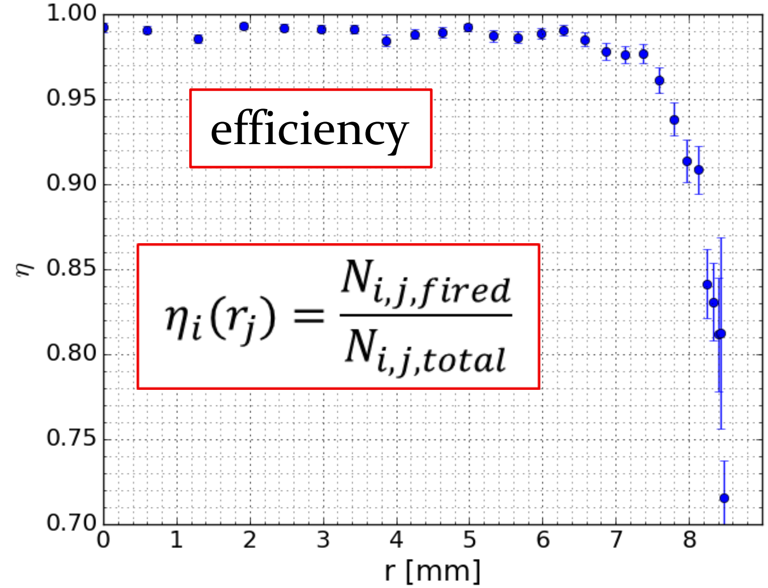


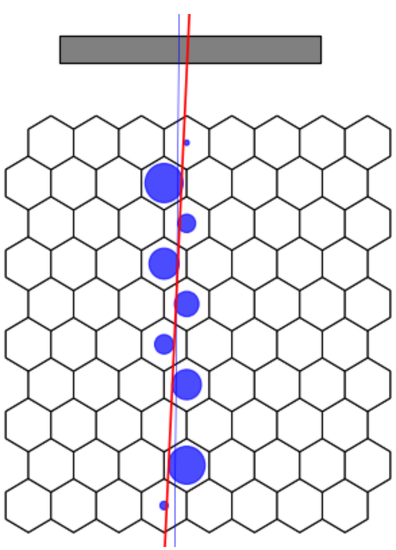
Illumination of MWDC cells by a collimated beta source



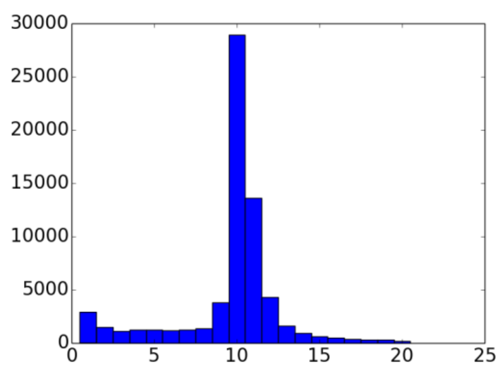
Gas mixture (He/Iso) 50/50 @ 600 mbar



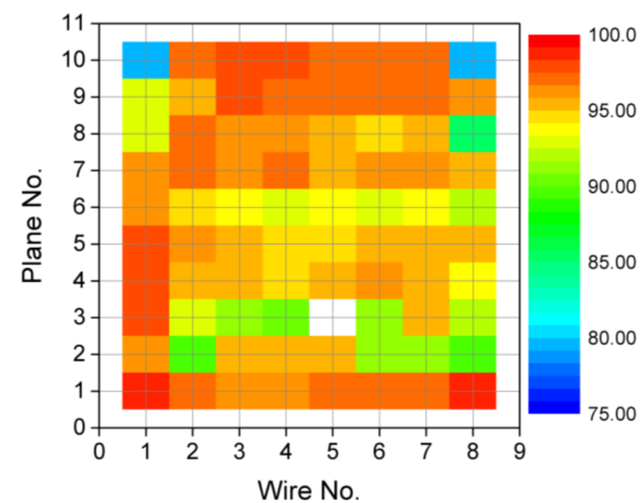




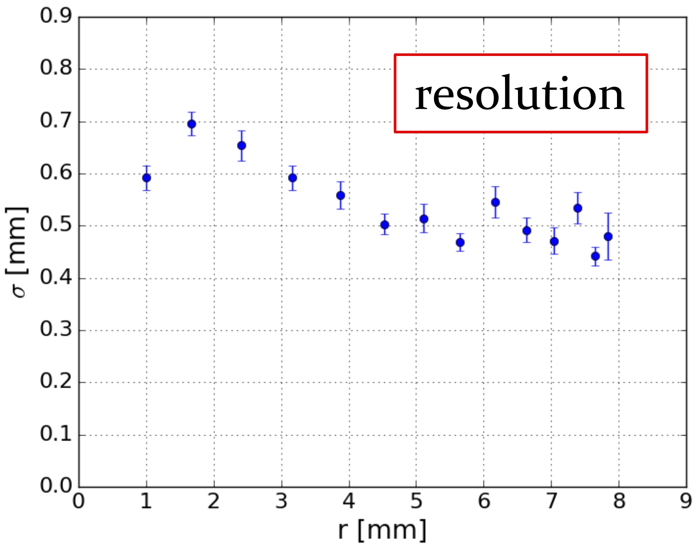
Hit multiplicity,
10 active planes

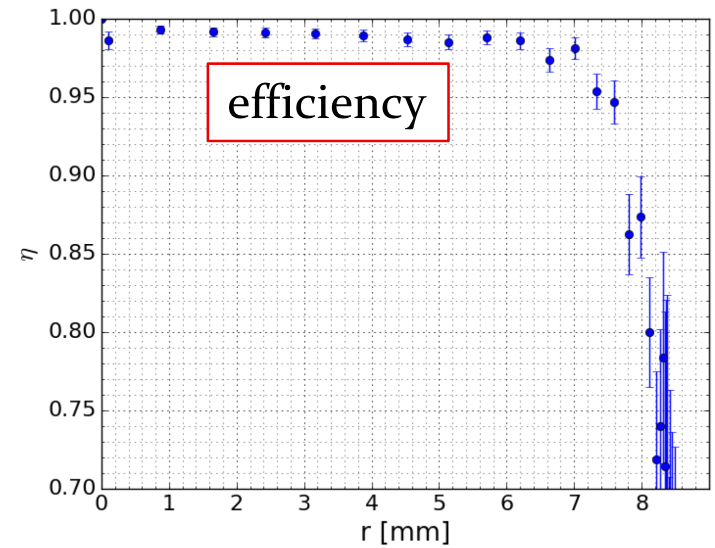


Average efficiency (over whole cells)

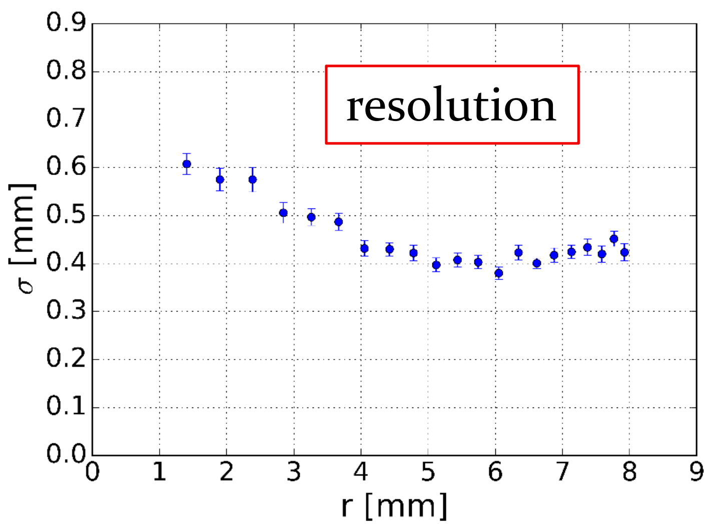


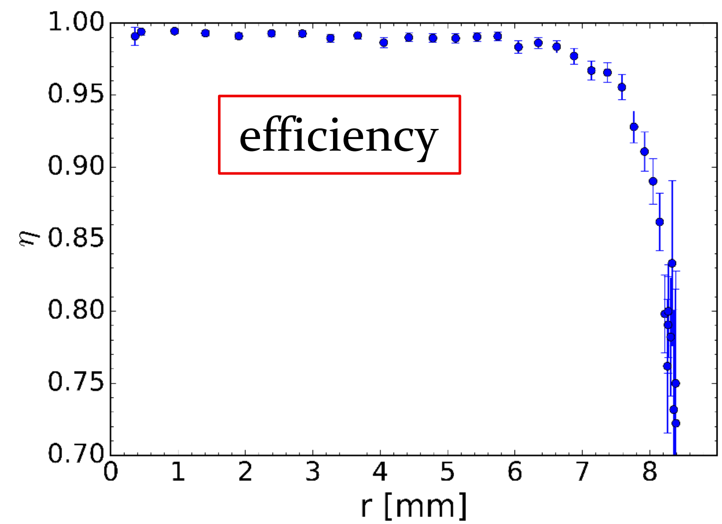
Pure Isobutane @ 300 mbar



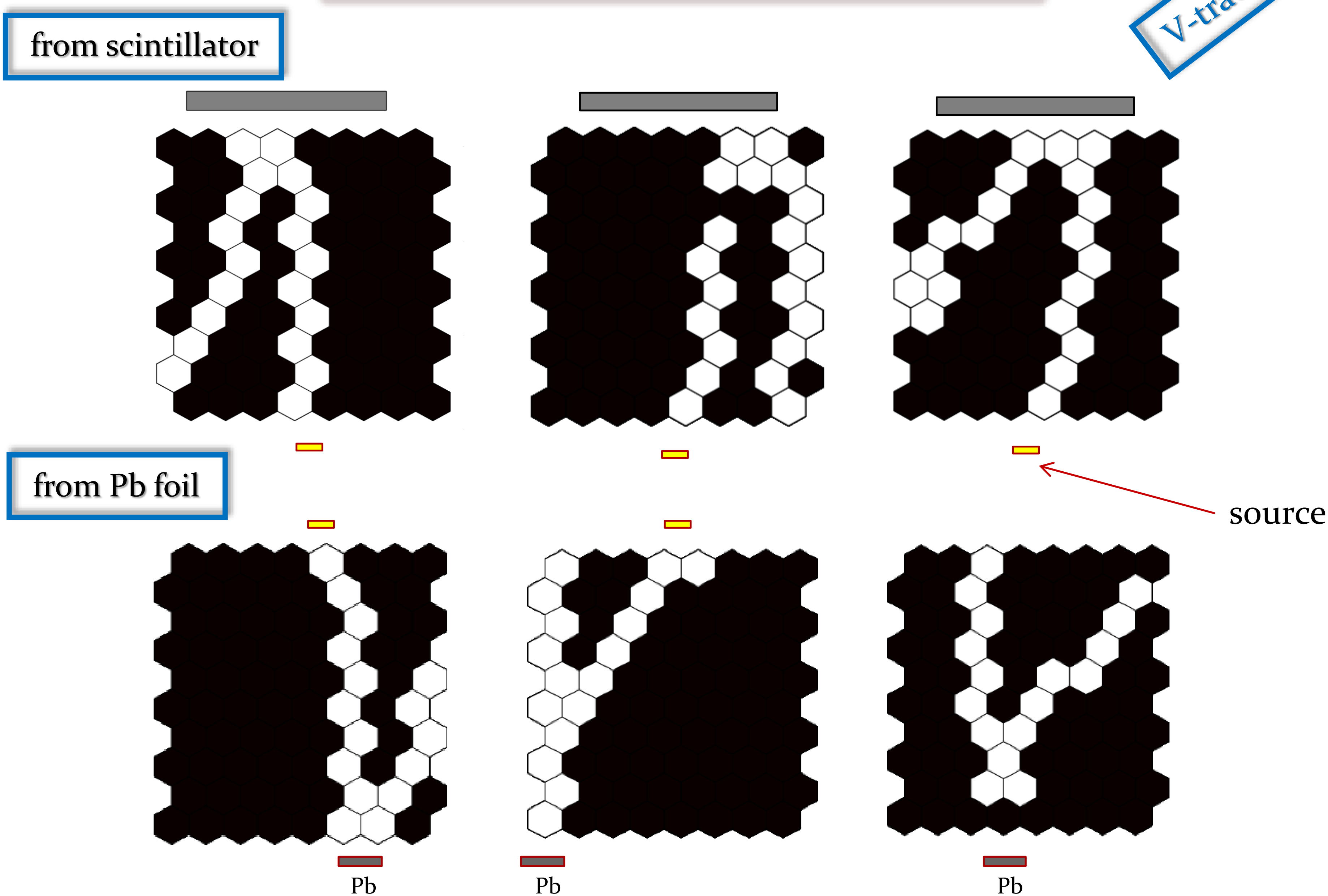


Gas mixture (He/Iso) 70/30 @ 600 mbar



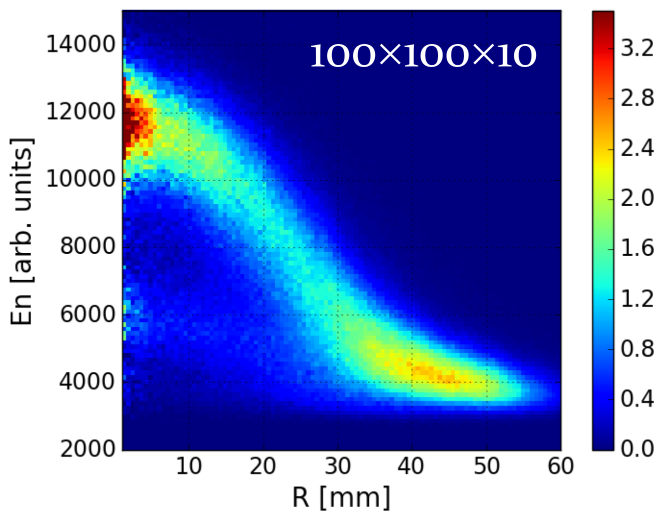


Observed first backscattering events

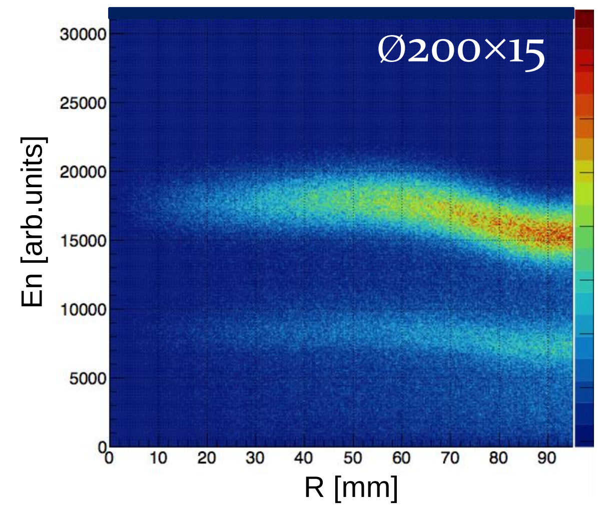


Electron energy measurements with plastic scintilator

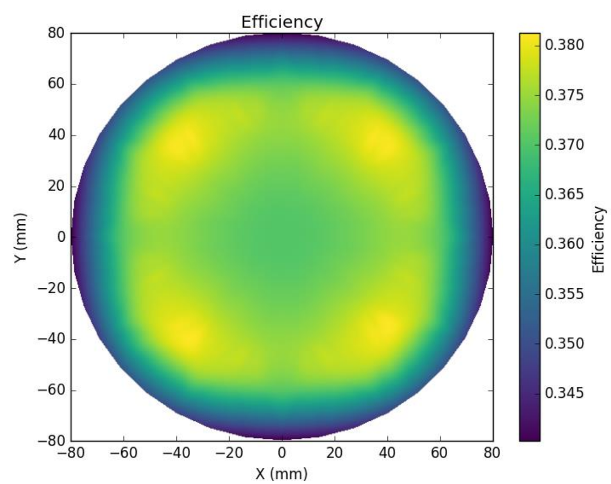
Light collection versus radial distance
(1 PMT, old scintillator and old lightguide)



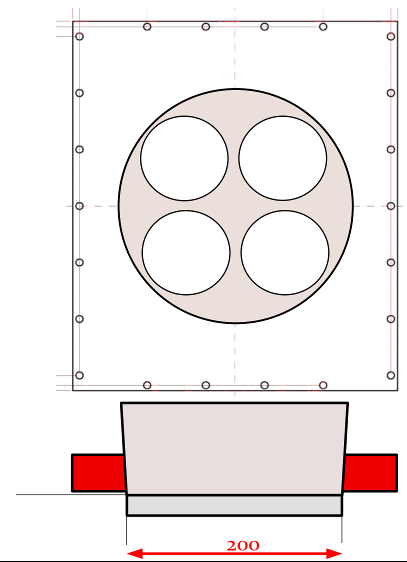
Light collection versus radial distance
(4 PMTs, new scintillator and lightguide)



^{207}Bi



L. De Keukeleere, KUL, PhD thesis



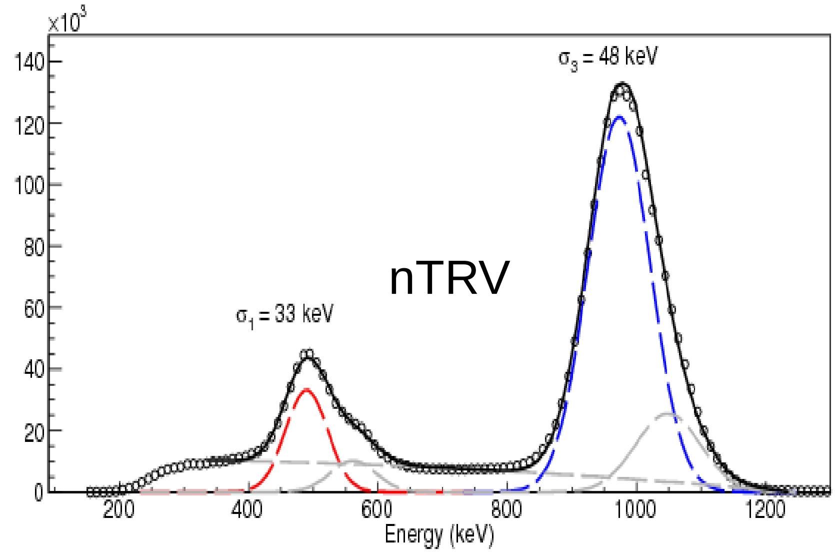
Goal:

- ❑ Achieve maximum gain and response uniformity across the scintillator surface
- ❑ Apply position dependent calibration

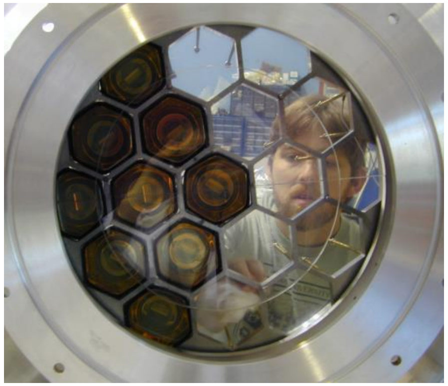
Energy resolution of scintillator

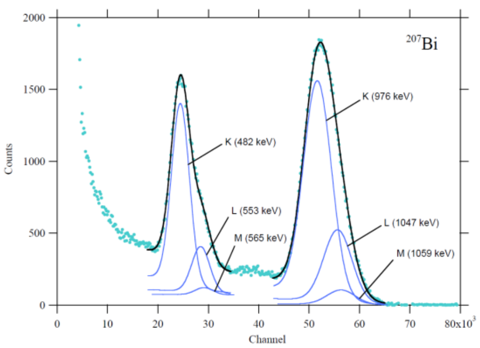
- Simulations show that resolution of 20 keV around 1 MeV can be achieved

- Guidelines from previous work: in the nTRV experiment at PSI we achieved σ ~50 keV for a plastic scintillator with size of 600×600×10 mm³ read out with 12 PMTs (3”)



- Also aCORN experiment at NIST achieved σ < 50 keV at 1 MeV (F. E. Wietfeldt, presentation at PPNS workshop, Grenoble 2018)





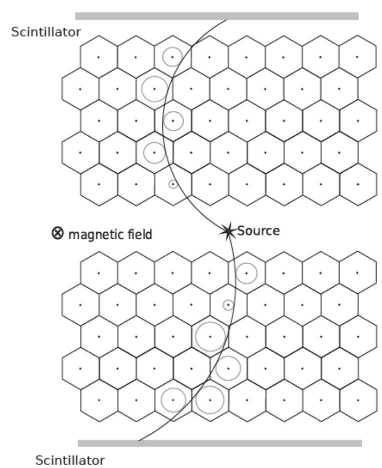
✓ Plans for the future measurements

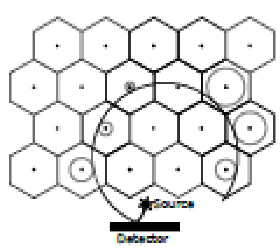
Recoil term

Transition	Spin sequence	$T_{1/2}$	E_0 [keV]
$^{32}P \rightarrow ^{32}S$	$1^+ \rightarrow 0^+$	14.27 d	1711
$^{56}Mn \rightarrow ^{56}Fe$	$3^+ \rightarrow 2^+$	2.58 h	2850
$^{61}Co \rightarrow ^{61}Ni$	$7/2^- \rightarrow 5/2^-$	1.65 h	1254
$^{114}In \rightarrow ^{114}Sn$	$1^+ \rightarrow 0^+$	71.9 s	1989

Plastic scintillator/ Si(Li)

→ external magnetic field can be applied so the tracks become curved, which then provides an additional measurement of energy





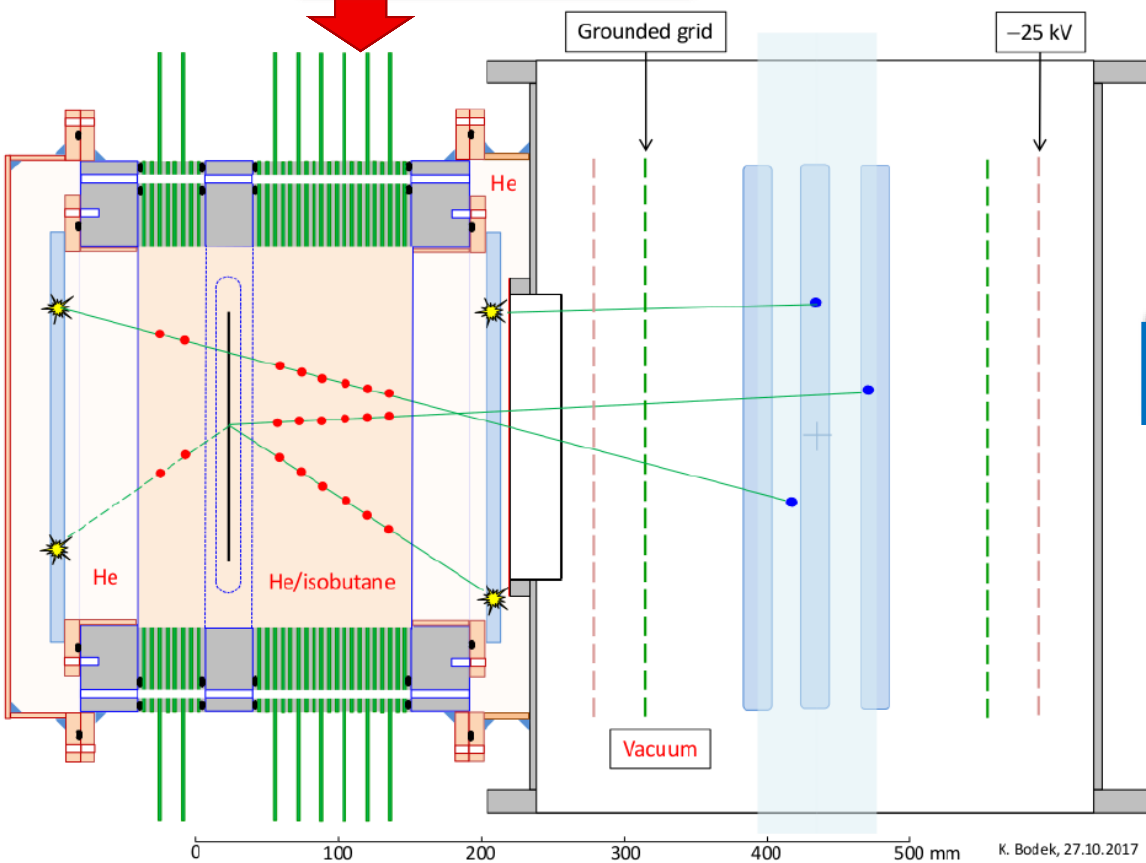
✓ miniBETA technique application to neutron decay correlation experiment – BRAND project

K. Bodek, et al. Physics Procedia 17 (2011) 30
K. Bodek Acta Phys. Pol. B 47 (2016) 349

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}}{E_e} + B\frac{\mathbf{q}}{E_\nu} + D\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu}\right]$$
$$+\sigma_\perp\cdot\left[H\frac{\mathbf{q}}{E_\nu} + L\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu} + N\frac{\langle\mathbf{J}\rangle}{J} + R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}}{E_e}\right.$$
$$\left.\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + U\frac{\mathbf{q}}{E_\nu}\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}}{E_e} + V\frac{\mathbf{q}}{E_\nu}\times\frac{\langle\mathbf{J}\rangle}{J}\right]$$

BRAND – initial phase:

miniBETA-bis



BRAND project

a, *A*, *B*, *D*, *H*, *L*, *N*, *R*, *S*, *U*, i *V*

Electron tracking:

- ❑ Decay electrons from free neutron decay
- ❑ Mott scattering for electron spin analysis

✓ Conclusions and outlook

- miniBETA spectrometer consisting of a low-mass, low-Z 3D-tracker and a plastic scintillator for energy detection – in commissioning phase
- Energy of beta particles can be obtained either directly from the energy deposited in the scintillator and from the curvature of their trajectories
- Scattering effects are inherently small:
  - 5 μm thick source foil
  - He/isobutane gas mixture, low pressure (100 mbar neo-pentane considered)
  - Hexagonal geometry and both end signal readout minimizes number of wires needed
- Further optimization of the plastic scintillator (light collection, gain uniformity) – ongoing
- First physics goal: spectral function $f_1(E_e)$ for $^{114}In \rightarrow {}^{114}Sn$ and $^{32}P \rightarrow {}^{32}S$ (weak magnetism term)

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Thank you for your attention!