Detectors for Thermal Neutron Detection Based on ^3He

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Outline

- Principle of neutron detection, why ^3He
- Proportional Counter
  - Efficiency
  - Gas amplification, wall effect, shaping
  - Example: Cold TAS, HZB
  - Stop gases
- Linear Position-Sensitive Tubes (LPSD)
  - Charge division method
  - Position resolution
  - Dead time
  - γ-sensitivity
  - Examples: SANS, EXED
  - Multi-Tube Detectors
  - Example: EXED
- Multi-Wire Proportional Chambers (MWPC)
  - Delay line readout,
  - Example: Flat Cone Diffractometer, Powder Diffractometer, CHARM Detector at FRM II
- Conclusion & Outlook

Thermal Neutrons – Where Is the Problem?

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Neutrons

Required for measurement

Converter

electrical neutral
weak interaction with matter
small kinetic energy (1-100 meV)

charged particle
thin solid or
gaseous converter
>100.000 electrons

~4 eV electron-hole pair in SC
~30 eV electron-ion pair in gas

1 Mio. – 100 Mio.

Neutron detection:
Conversion and multi-stage amplification and minimization of losses in every stage.

What Is Present in Nature?

84 stable elements: Out of 288 isotopes only 5 are technical usable

Basis of any detection process: Conversion by an exothermal nuclear reaction

Reaction	$^{3}He(n,p)t$	$^{10}B(n,^{4}He)^{7}Li$	$^{6}Li(n,^{4}He)t$	$^{235}U(n,f)f$	$^{157}Gd(n,^{158}Gd)$ conversions e^{-}
Abundance	0.00014%	19.9%	7.5%	0.7%	15.7%
Q Value [MeV]	0.764	2.13 (93%) 2.79 (7%)	4.78	~200	7.9 (29 – 180 keV)
σ [b] @1.81A	5333	3836	940	586	255.000
Form	^{3}He	$^{10}BF_3$, ^{10}B, $^{10}B_4C$	^{6}Li, ^{6}LiF, ^{6}LiI	^{235}U	^{157}Gd
State	gas	gas, solid	solid	solid	solid







Time Line of Neutron Detection with ^{3}He

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1932	Discovery of neutron
1937	First neutron detectors ^{10}B-lined proportional counters
1939	First detector using BF_3
1948	Enrichment of $^{10}BF_3$ is possible and used
>1980	^{3}He become available as neutron converter (byproduct of nucl. weapon production, decay of ^{3}H, $t_{1/2}$ = 12.3y)
>1995	^{3}He plays major role in neutron detection, price ~100 US$/liter
2009	^{3}He shortage is discovered by US government
2010	Research for alternative converters launched
>2014	Stockpile has recovered, but ^{3}He still rare and precious, (price ~1.500 – 4.000 US$/liter)

Other usage: Cryogenics <1K, laser research, medical imaging of lungs, neutron polarization, oil well logging

Production of ^{3}He: mainly in reactors breeding ^{3}H…. and waiting!

Efficiency of ^{3}He Detectors

$$\varepsilon = 1 - \exp((-\rho \cdot N_A \cdot \sigma / m_a) \cdot d \cdot p \cdot \lambda)$$

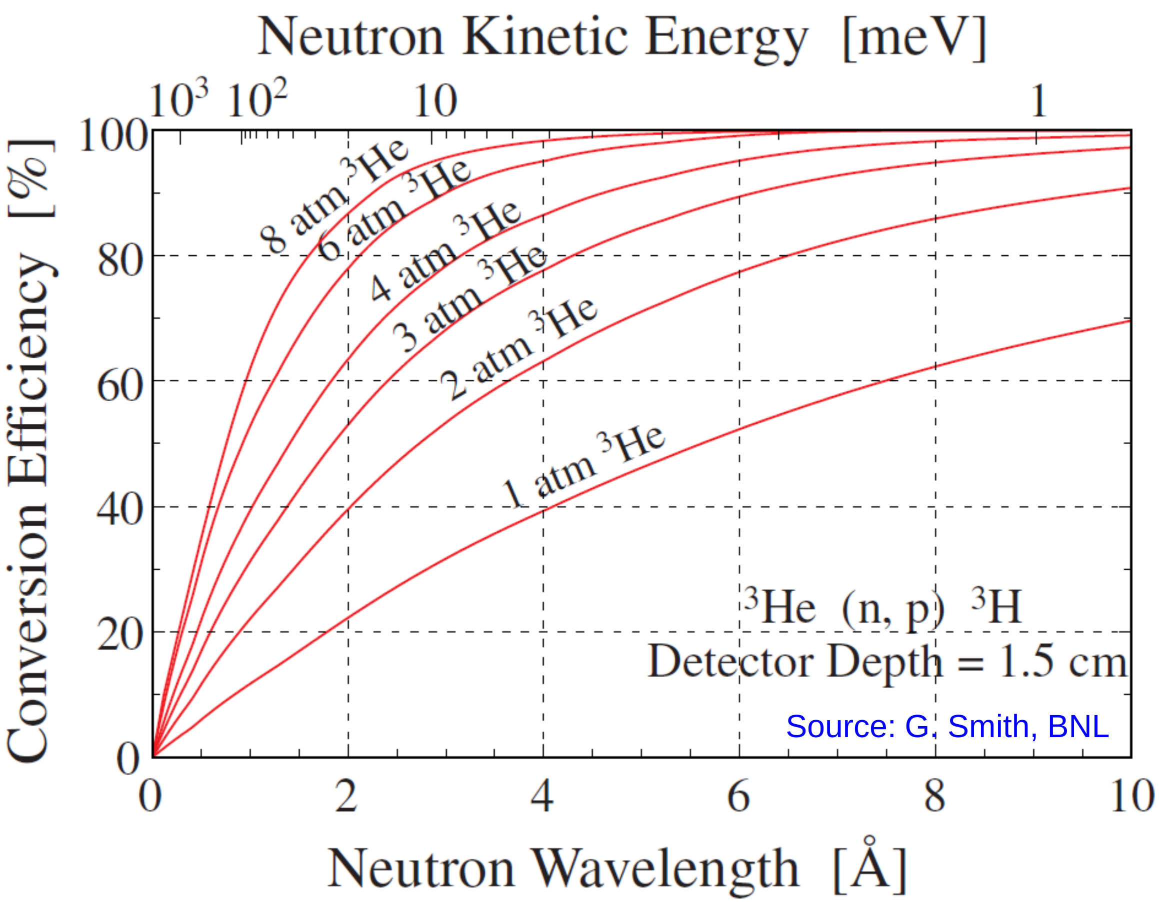
ε = Efficiency

d = thickness [cm]

p = pressure [bar]

λ = wavelength [Å]

$\rho \cdot N_A \cdot \sigma / m_a = 0.0715$



Acceptable efficiency for n_{th} req. ≥10 bar·cm

^3He Proportional Counter (Tube)

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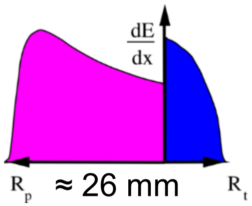
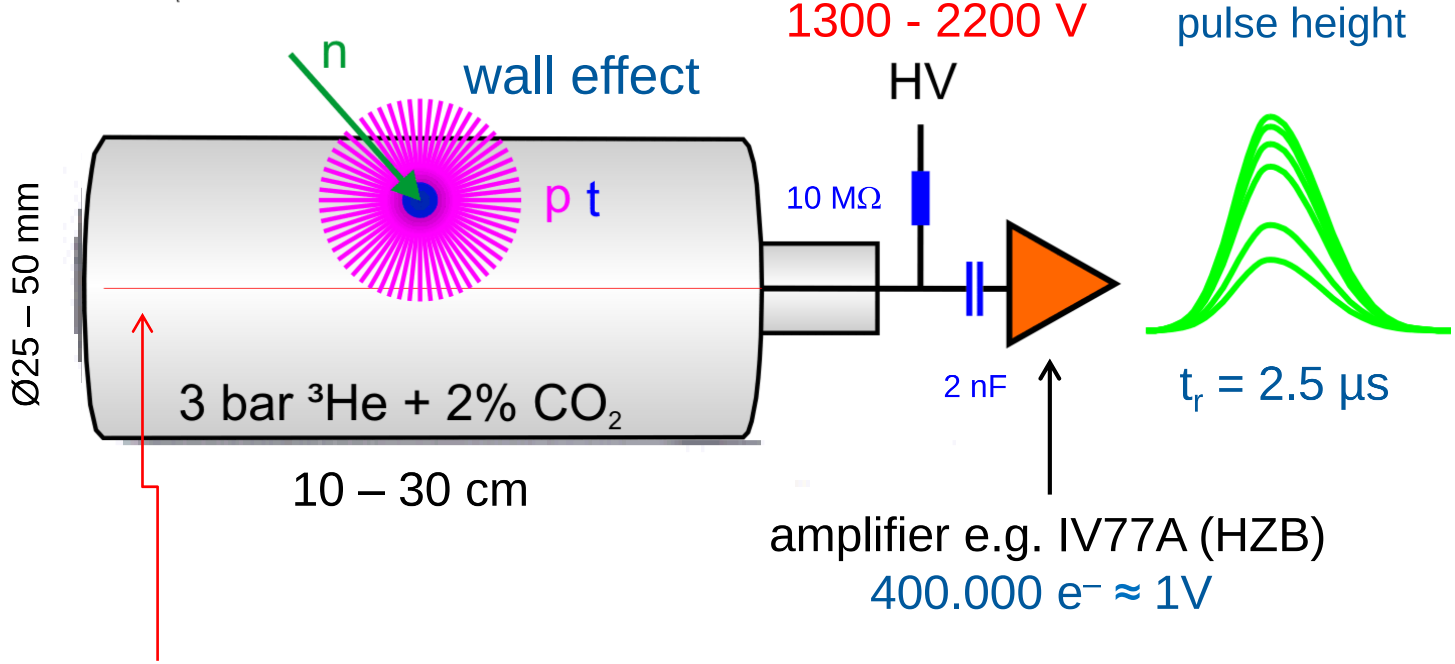
$^3He(n,p)^3H$ p = 573 keV , ^3H = 191 keV (E_{tot} = 764 keV, $q_p \approx 2.5\cdot10^4\ e^-$)



Bragg curve



amplifier e.g. IV77A (HZB)

400.000 e⁻ ≈ 1V

anode wire Ø ~ 50 µm

gas gain ≈ 15

Gas Amplification – How Does It Work?

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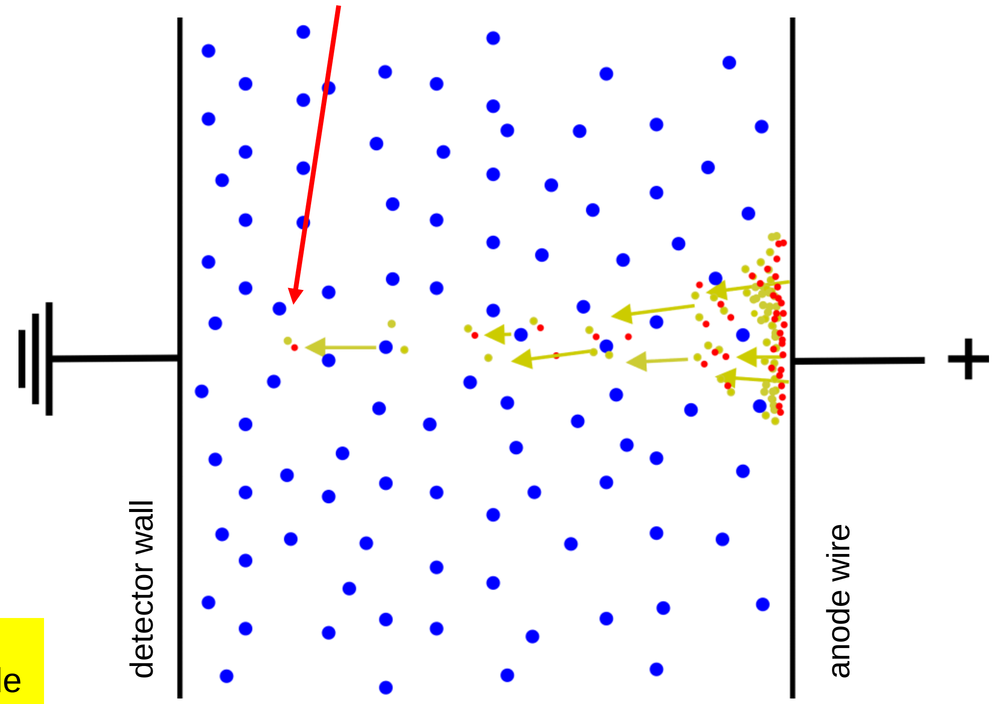
1. Detector is a confined volume with gas
2. An electron-ion pair is created
3. A high voltage is applied
   (detector is a capacitor)
4. Electrons are attracted by anode
   All processes take place simultaneously:
   - excitation of gas molecules
   - de-excitation → emission of light (UV)
     molecular gas added: e.g. CO_2 (few %)
   - ionization → creation of electron-ion pairs
   - recombination → loss of electrons
   - avalanche-like increase of # electrons
   - attachment → loss of electrons
   - diffusion → broadening
   - back drift of ions
5. In a cylindrical tube gas amplification takes
   place only few wire diameters away from anode
6. Signals are created by displacement of charge
   in the capacitor → mainly by motion of ions

All processes depending on:
- type of gas
- admixtures (impurities!)
- electrical field strength
- gas pressure

$$\frac{E}{P}$$

In fact ≈25.000 primary e^-



Electron avalanche is described by

$$n = n_0 \, e^{\alpha d}$$

α = number of e^--ion pairs per unit length
(first Townsend coefficient)

^{3}He-Tube – Signal Amplitude and Shape

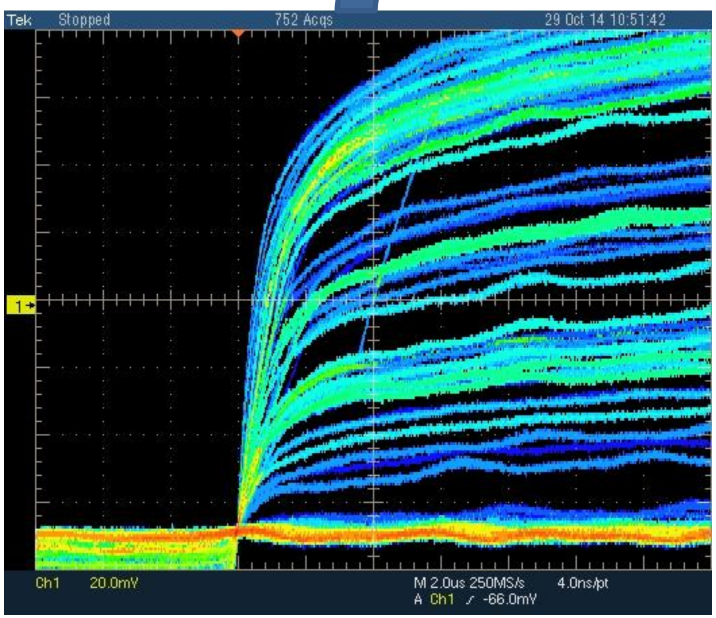
Source: G. Knoll
Radiation Detection and
Measurement

$$V_R(t) = \frac{Q}{C}\frac{1}{\ln\left(\frac{r_t}{r_w}\right)}\ln\sqrt{\left(2\mu\frac{V_0}{a^2 p \ln\left(\frac{r_t}{r_w}\right)}t + 1\right)}$$

- Signal increases with amount of charge Q
- Signal decreases inversely proportional to capacity C (cable length!)
- Signal increase (weakly) with smaller wire diameter r_w

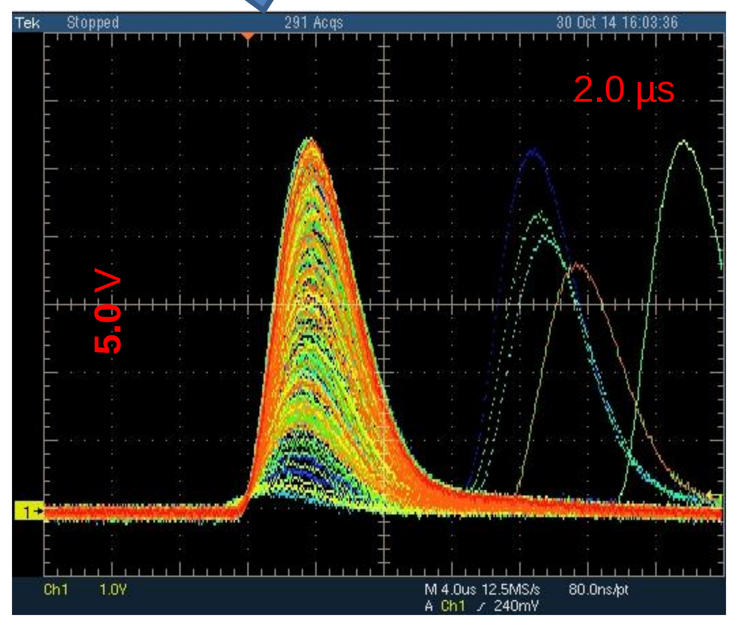
Shaping (differentiation)

low count rate



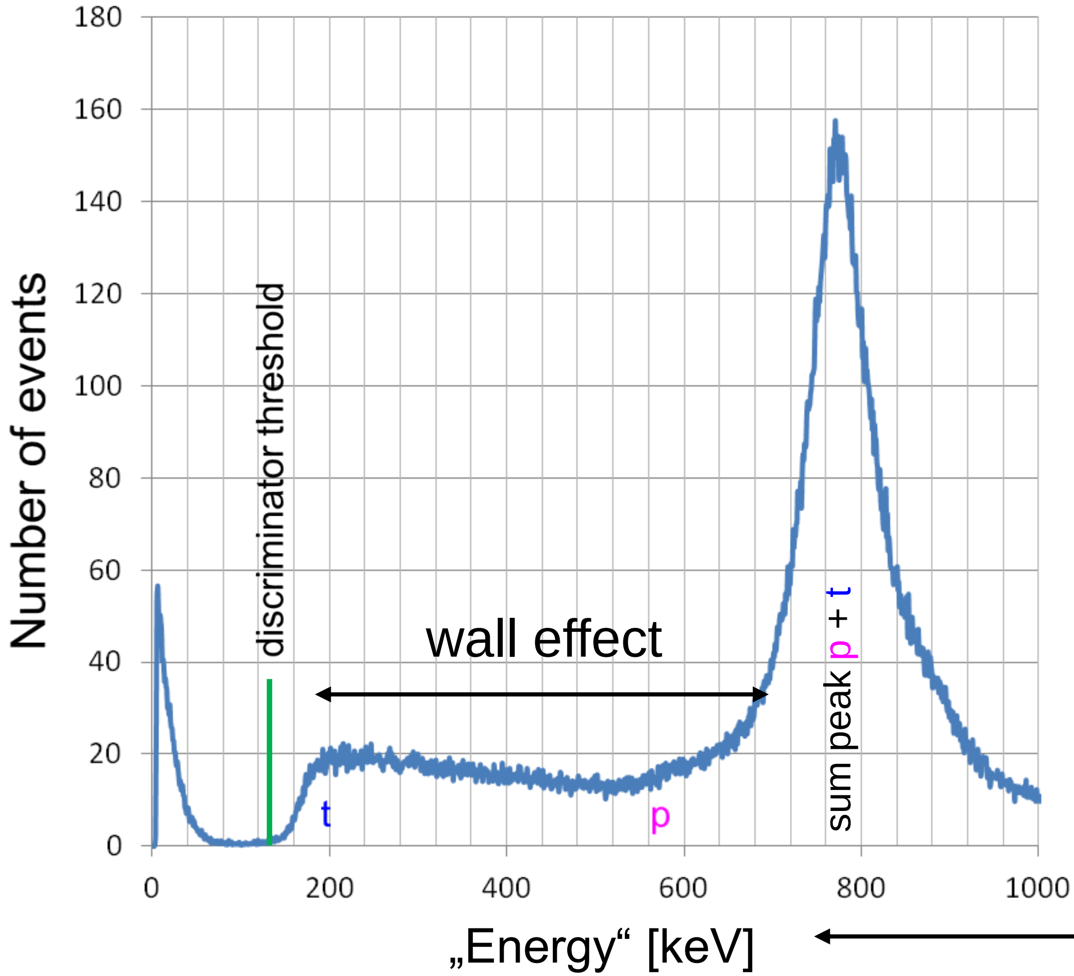
Charge sensitive amplifier

count rate ~10 kHz



Shaping amplifier

^{3}He-Tube – Pulse Height Spectrum



The pulse height spectrum is influenced by

- Pressure in tube
- Geometry (size vs. pressure)
- Gas composition & quality
- Properties of amplifier (shaping)
- γ-background
- Count rate
- BUT: not by neutron energy

^{3}He(n,p)t (Q = 764 keV)

155 ^{3}He-Tubes in Cold TAS MultiFLEXX (2015)

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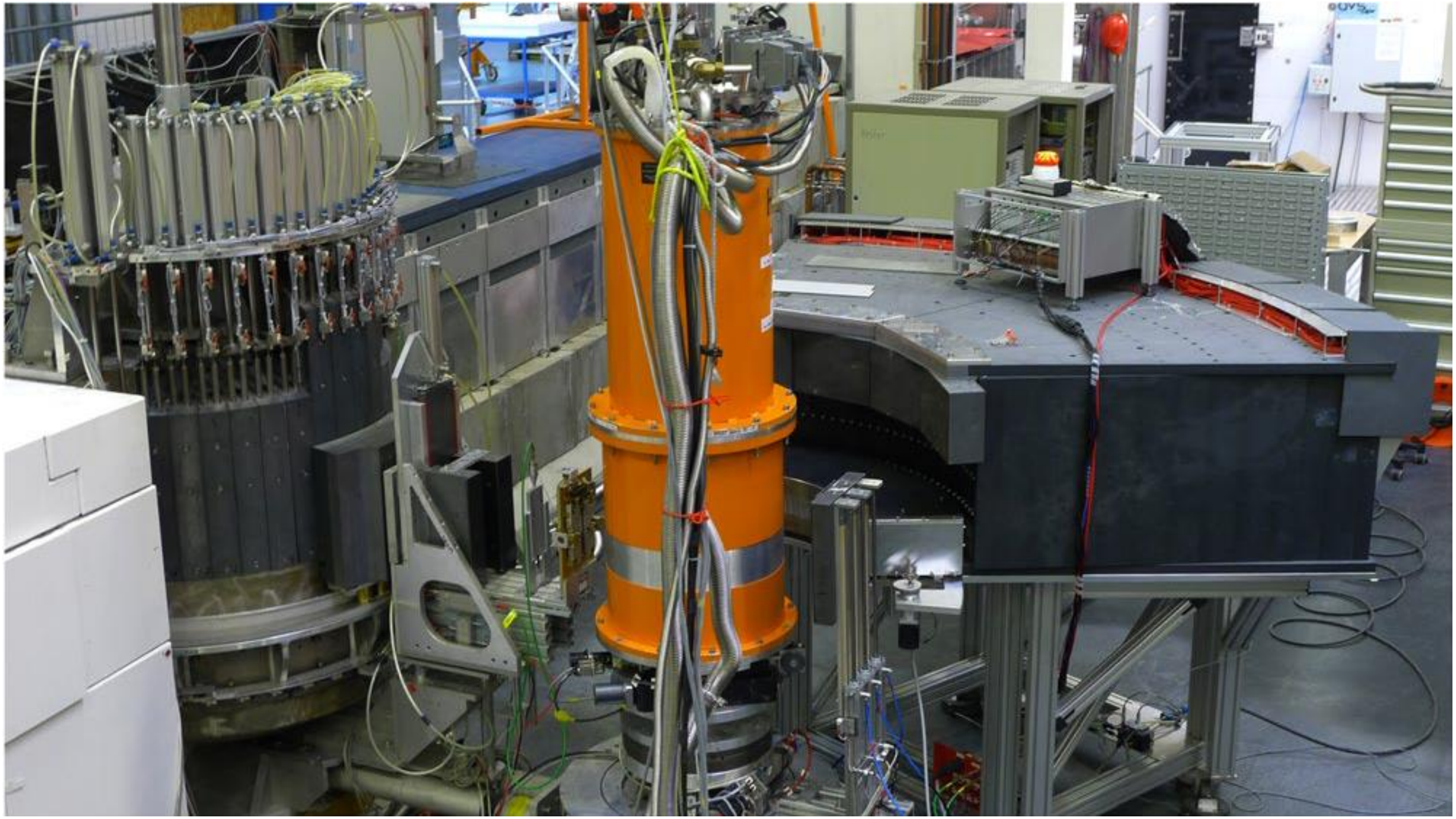

MultiFLEXX: Best suited for fast mapping and parametric study of samples.

SCIENTIFIC **REPORTS** | 7: *13637* | DOI:10.1038/s41598-017-14046-z

Position Resolution with ^{3}He – Detectors

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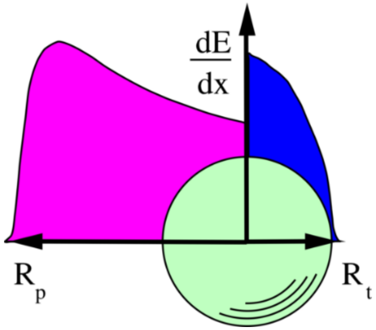
Energy loss in ^{3}He

$^3He(n,p)^3H$

p = 573 keV, t = 191 keV
range p **57 mm** in 1 bar ^{3}He
emission in arb. direction!

Bragg curve



Position Resolution limited by range of proton:

$dx \sim 0.7 \cdot R_p$

Range of p in possible stopping gases

Gas (1 bar)	Proton Range*)
^{3}He	57.3 mm
Ar	10.6 mm
CF_4	4.4 mm
C_3H_8**)	4.6 mm

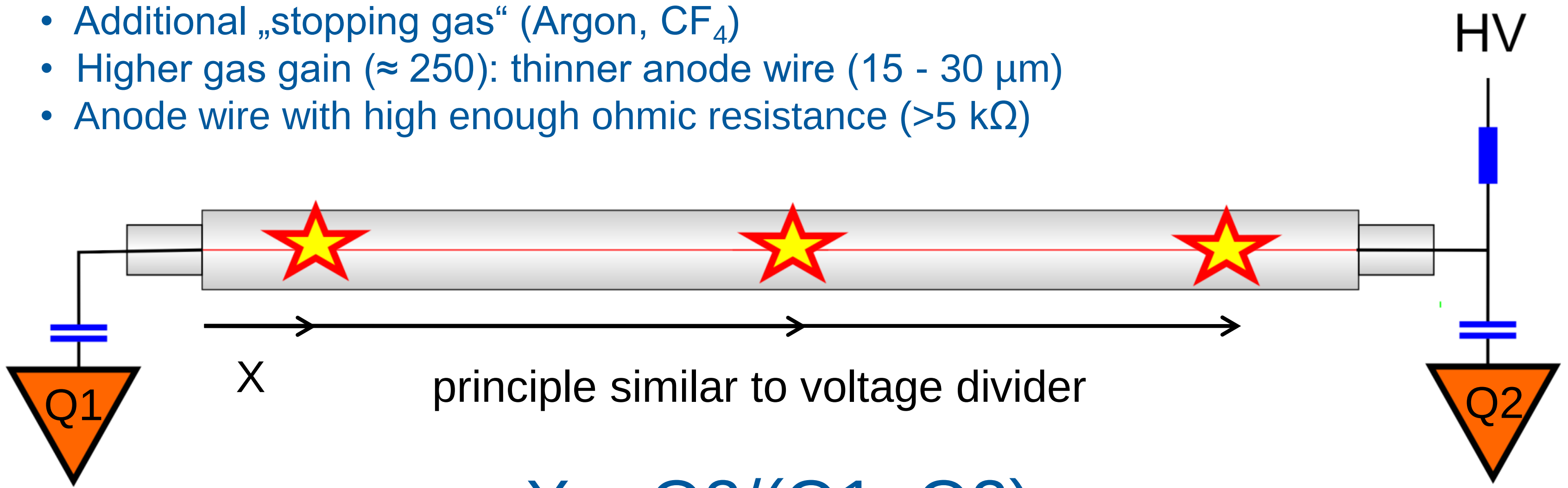
*) SRIM: www.srim.org
**) requires a cleaning system due to cracking

$$\frac{1}{R_{tot}} = \frac{P_{G1}}{R_{G1}} + \frac{P_{G2}}{R_{G2}}$$

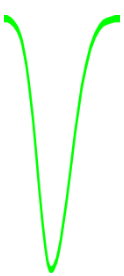
4.5 bar ^{3}He	dx ~ 9.0 mm
4.5 bar ^{3}He + 1.5 bar CF_4	dx ~ 1.7 mm
4.5 bar ^{3}He + 3.0 bar Ar	dx ~ 1.9 mm
4.5 bar ^{3}He + 1.5 bar C_3H_8	dx ~ 1.7 mm

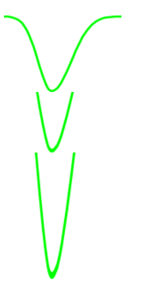
LPSD with charge division method requires:

- Proportional counter with small diameter (Ø 8 - 25 mm, length = 0.5 - 4 m)
- Higher ^{3}He-pressure (10-15 bar)
- Additional „stopping gas“ (Argon, CF_4)
- Higher gas gain (≈ 250): thinner anode wire (15 - 30 µm)
- Anode wire with high enough ohmic resistance (>5 kΩ)



$$X = Q2/(Q1+Q2)$$



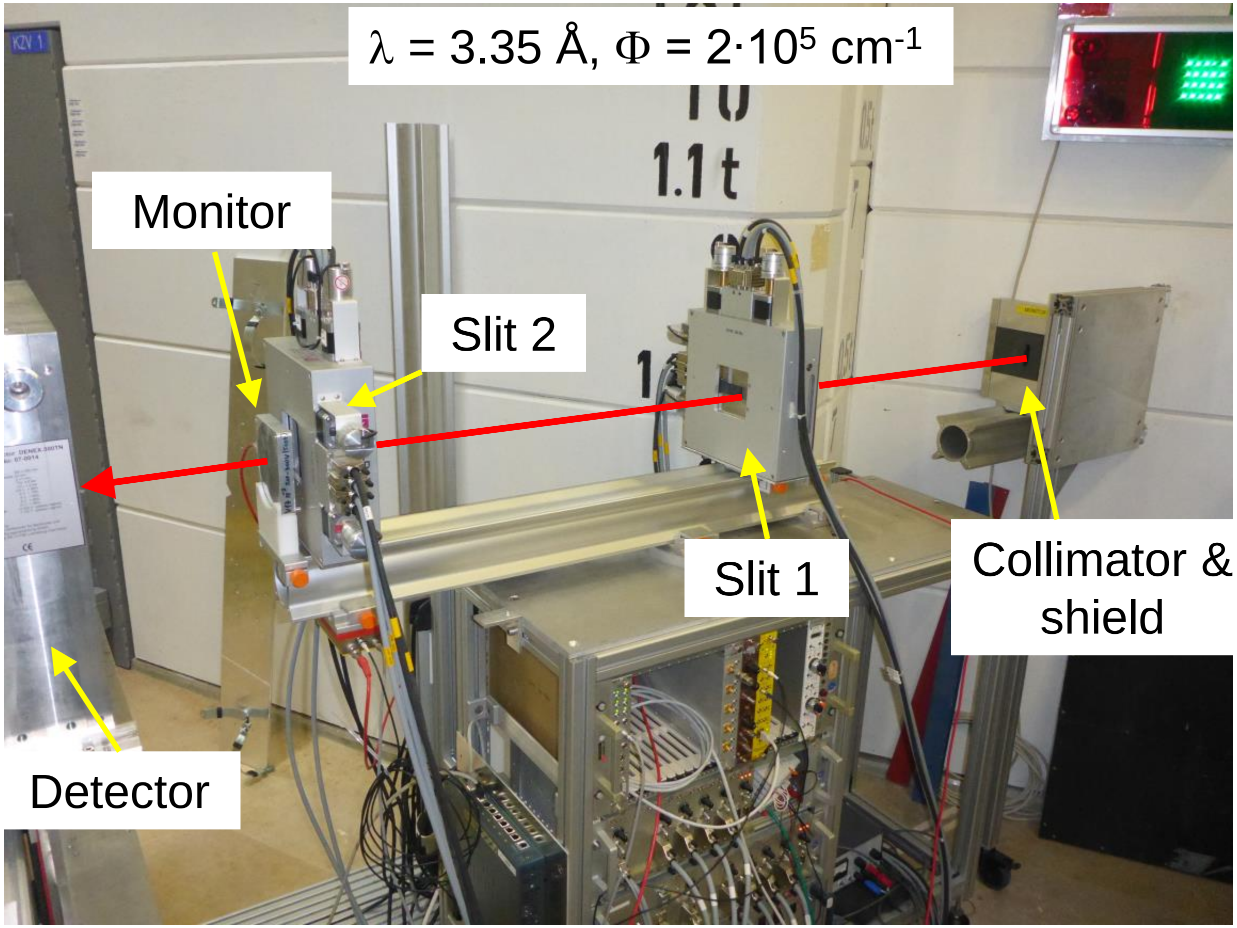


Position resolution ~ 0.8% of length
(determined by amount of charge at wire)
the higher – the better

2D-detectors realized by many adjacent LPSDs

Manucatures: www.gemeasurement.com/radiation-measurement , www.lndinc.com , www.canberra.com

Detector Teststand V17 at HZB



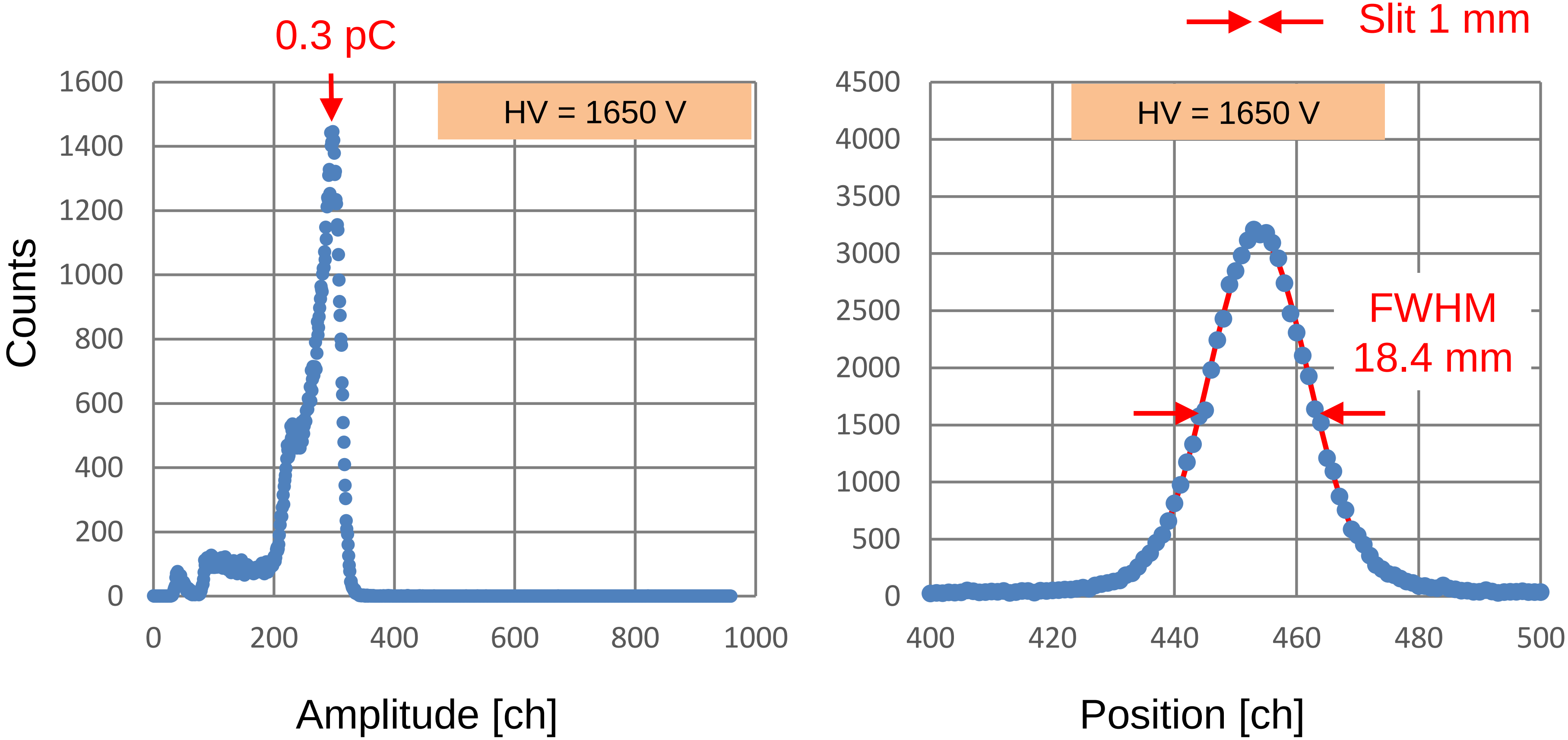
Detector ≤ 100 kg, x ± 400 mm, y ± 500 mm (25 µm)

Slit system x,y: 0 – ±50 mm (10 µm)

Determination of Position Resolution @1650 V

Ø 12.7 mm, 900 mm, 9.9 bar ^{3}He + 3.0 bar Ar + CO_2

dx = 1.55 mm



Conversion gain: 1 pC/960 ch

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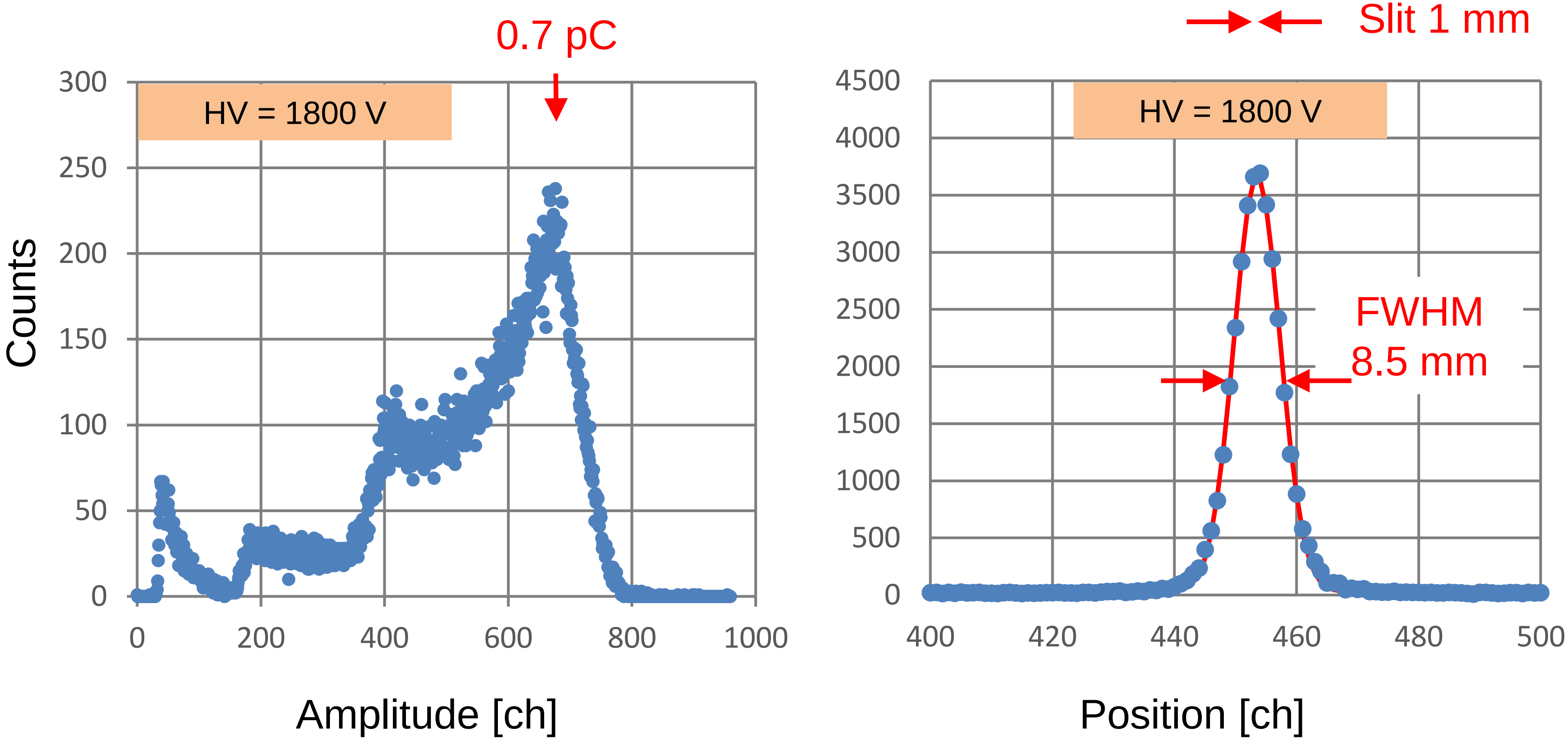
Determination of Position Resolution @1800 V

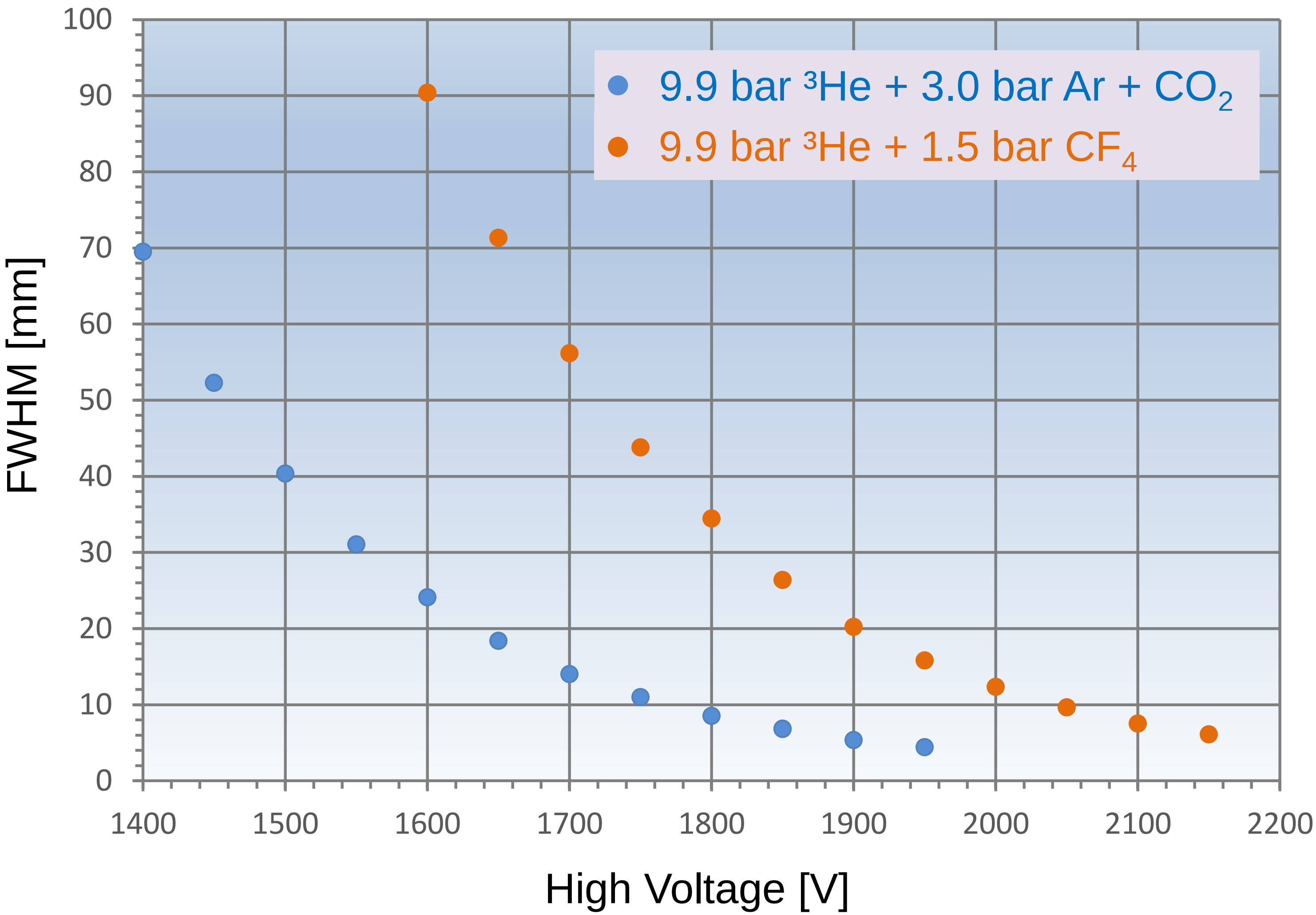
Ø 12.7 mm, 900 mm, 9.9 bar ^{3}He + 3.0 bar Ar + CO_2

dx = 1.55 mm

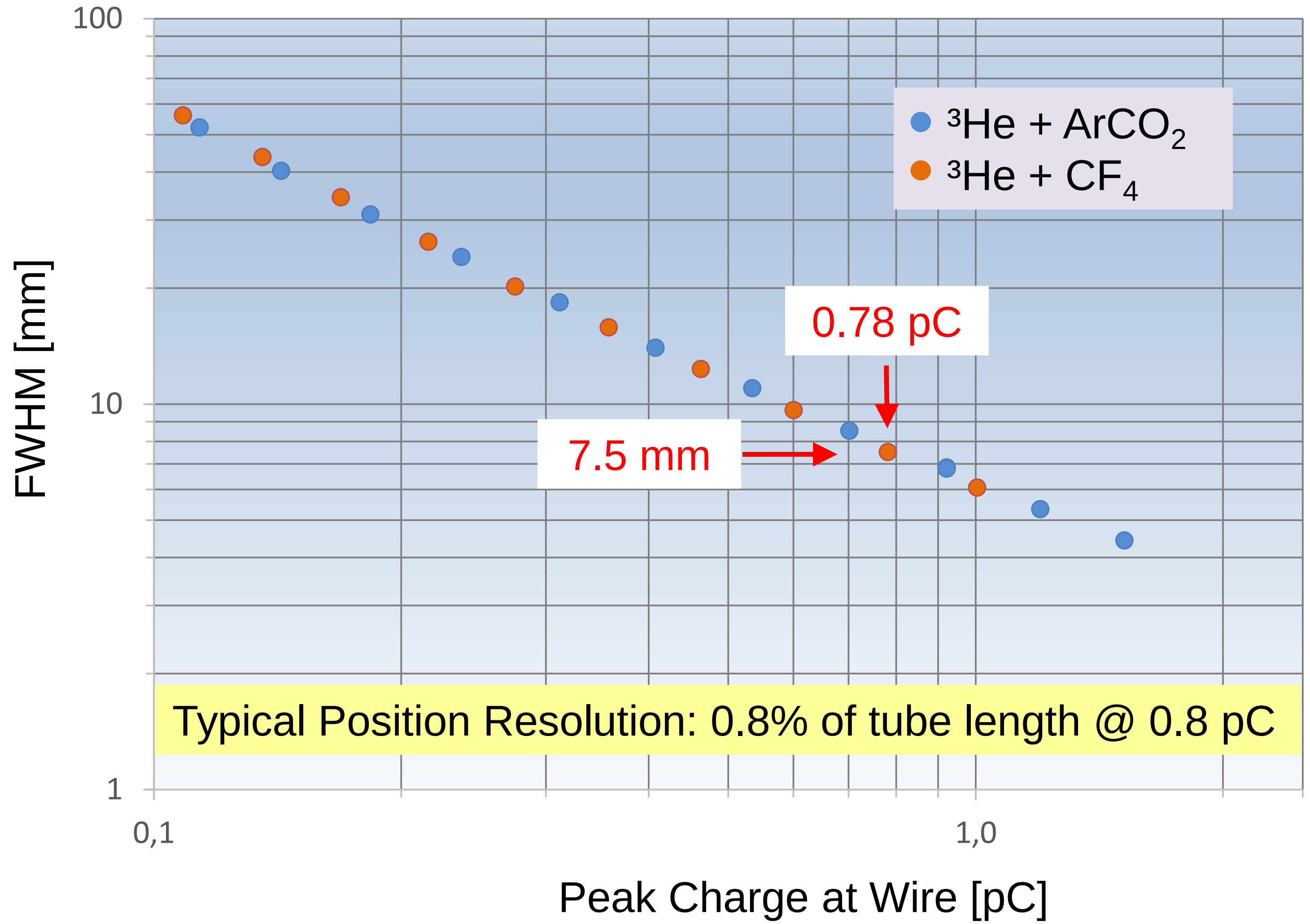


Conversion gain: 1 pC/960 ch

Comparison of Two Stopping Gases



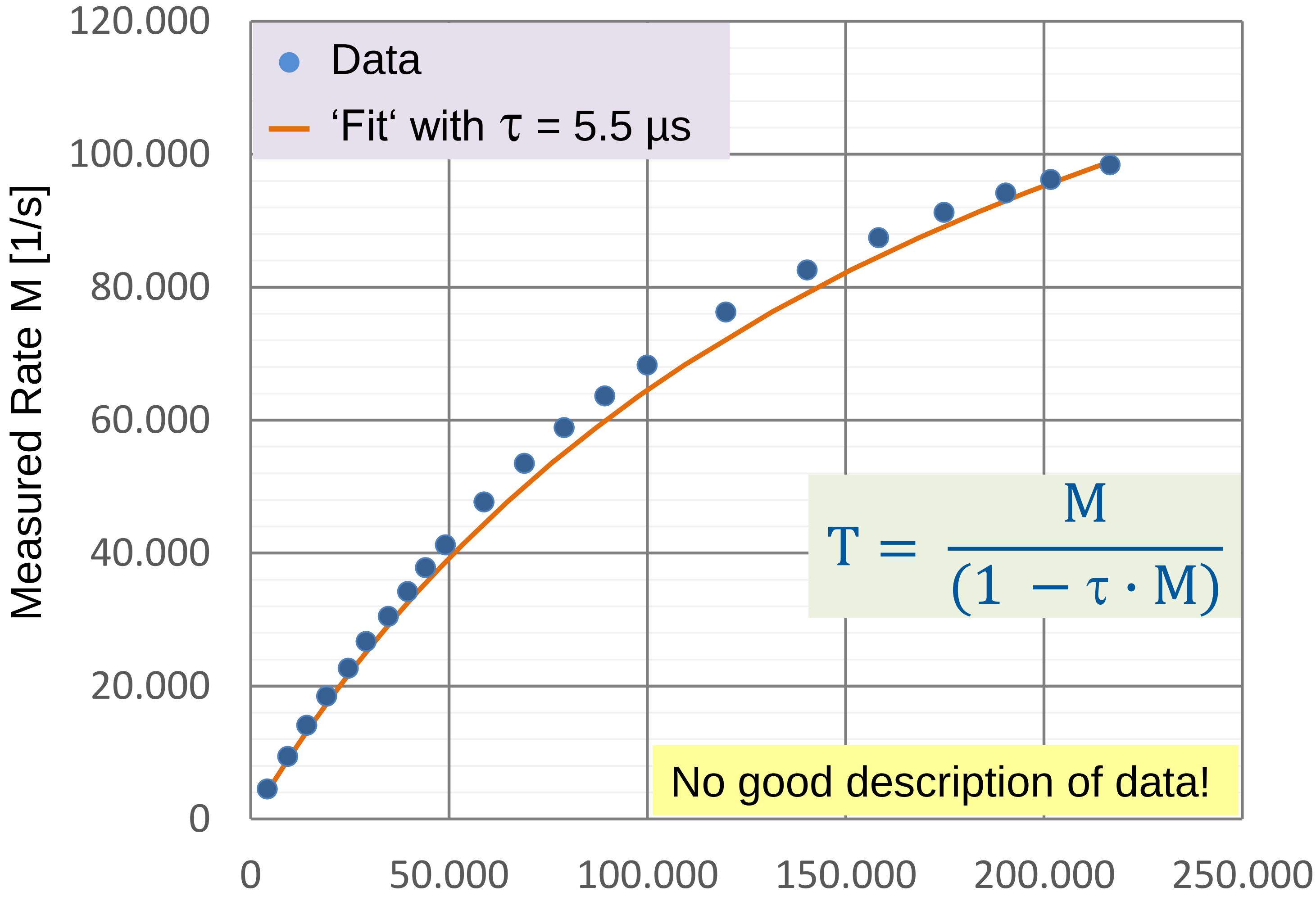
Position Resolution - Conclusion



Typical Position Resolution: 0.8% of tube length @ 0.8 pC

Dead Time Determination 1

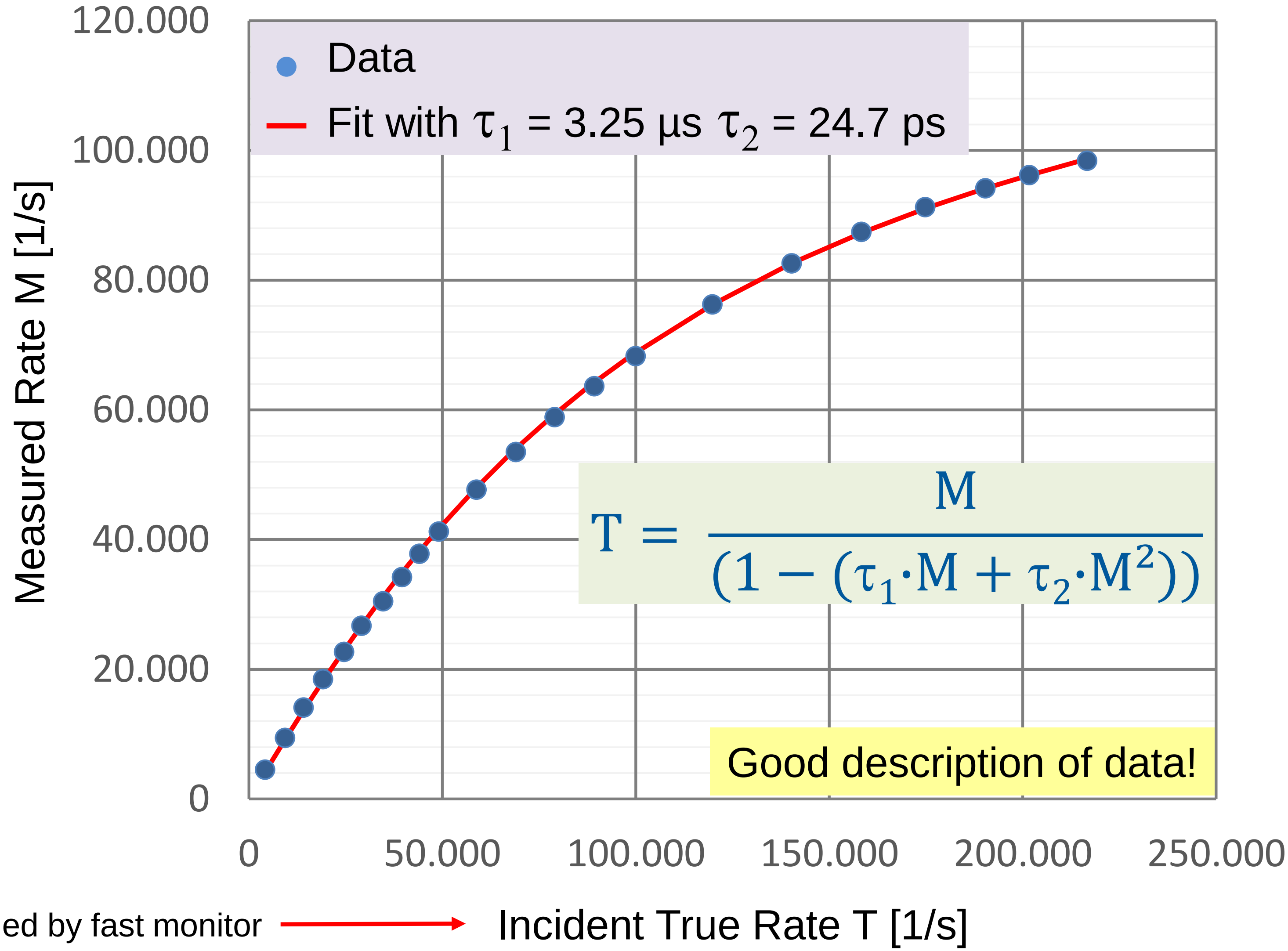
$^3He + ArCO_2$



Scaled by fast monitor → Incident True Rate T [1/s] → ← Slit 1 – 40 mm

Dead Time Determination 2

$^3He + ArCO_2$



Scaled by fast monitor →

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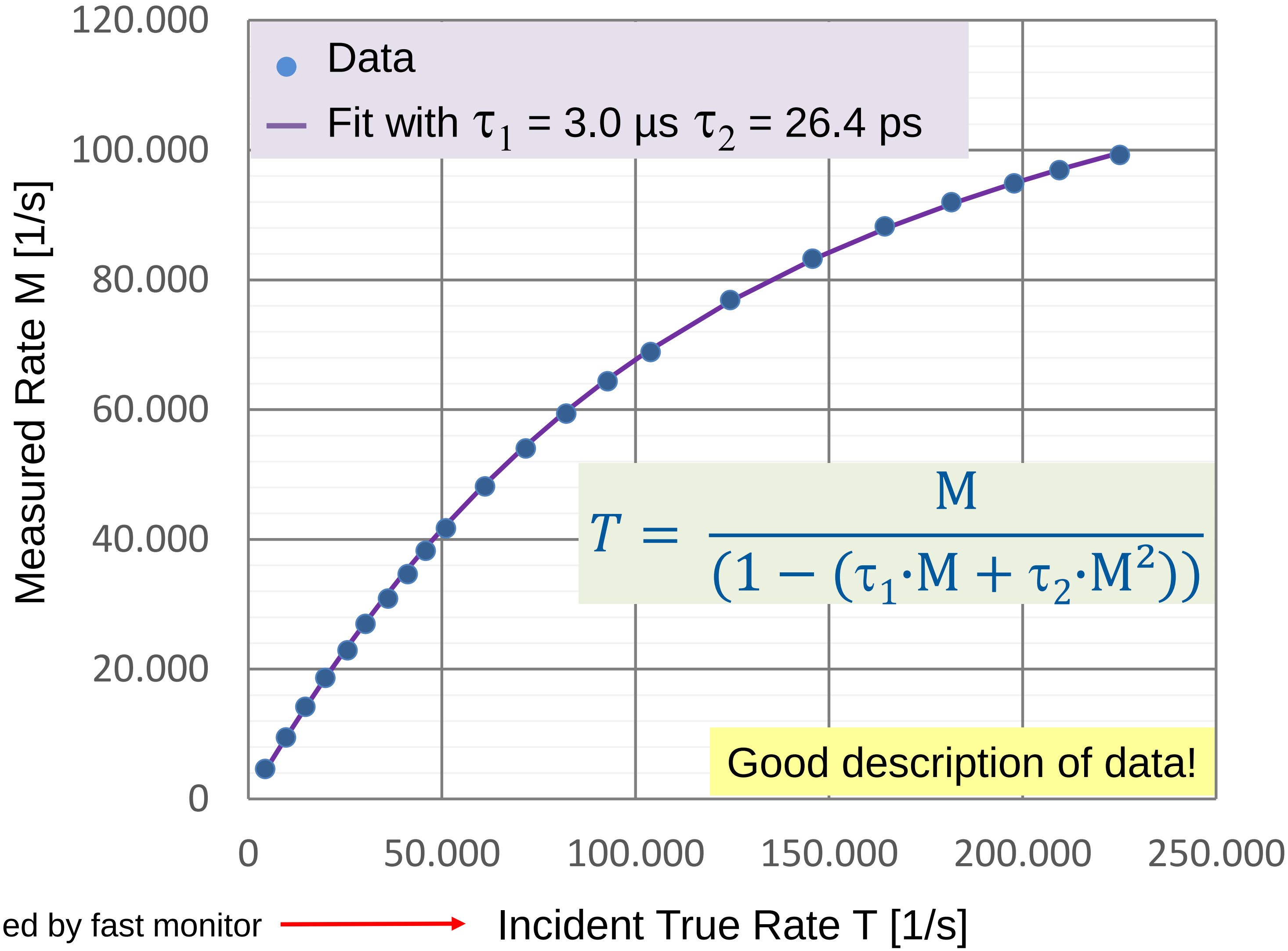
Dead Time Determination 3

$^3He + CF_4$

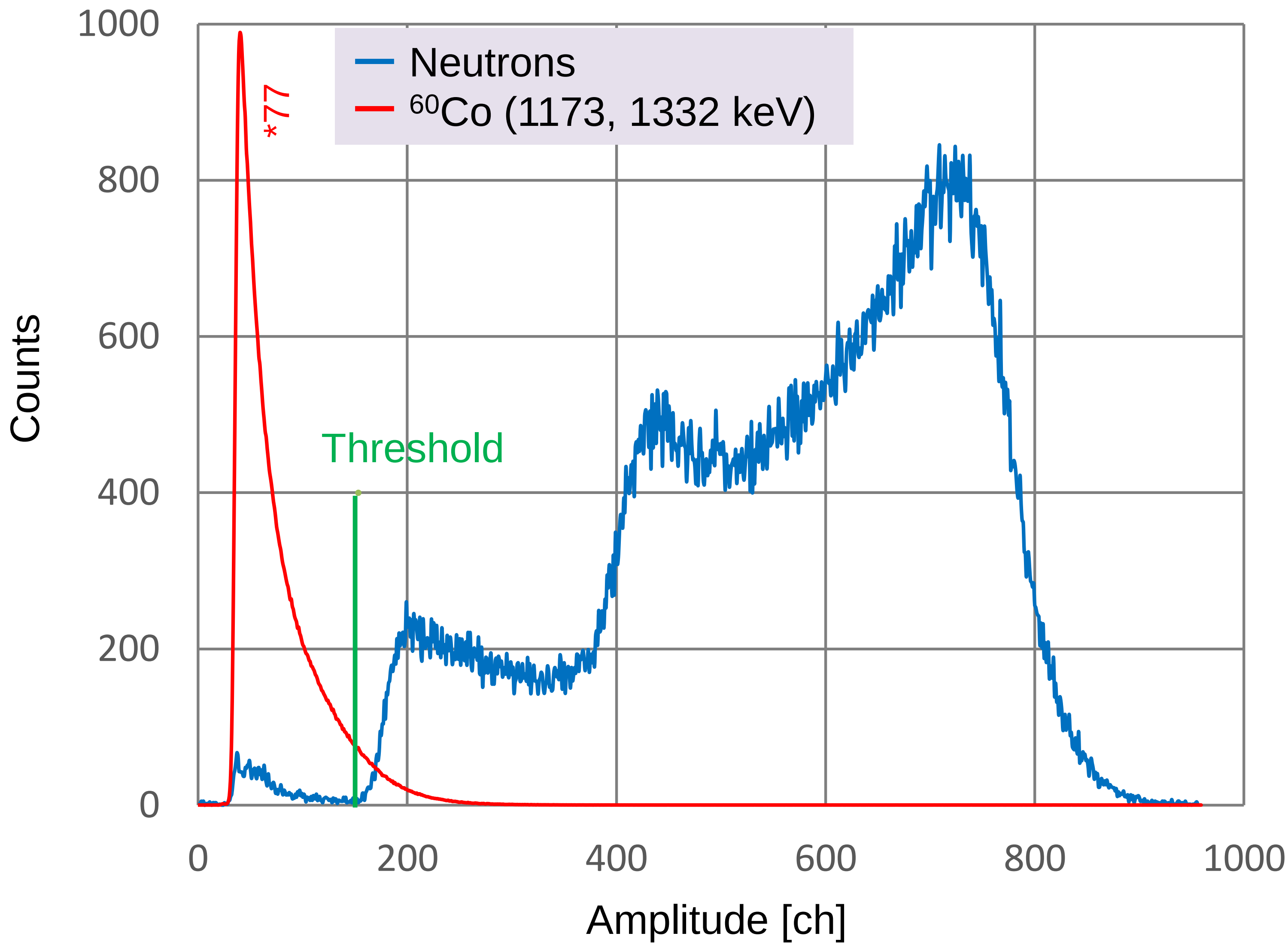


$$T = \frac{M}{(1 - (\tau_1 \cdot M + \tau_2 \cdot M^2))}$$

Scaled by fast monitor →

Gamma Sensitivity

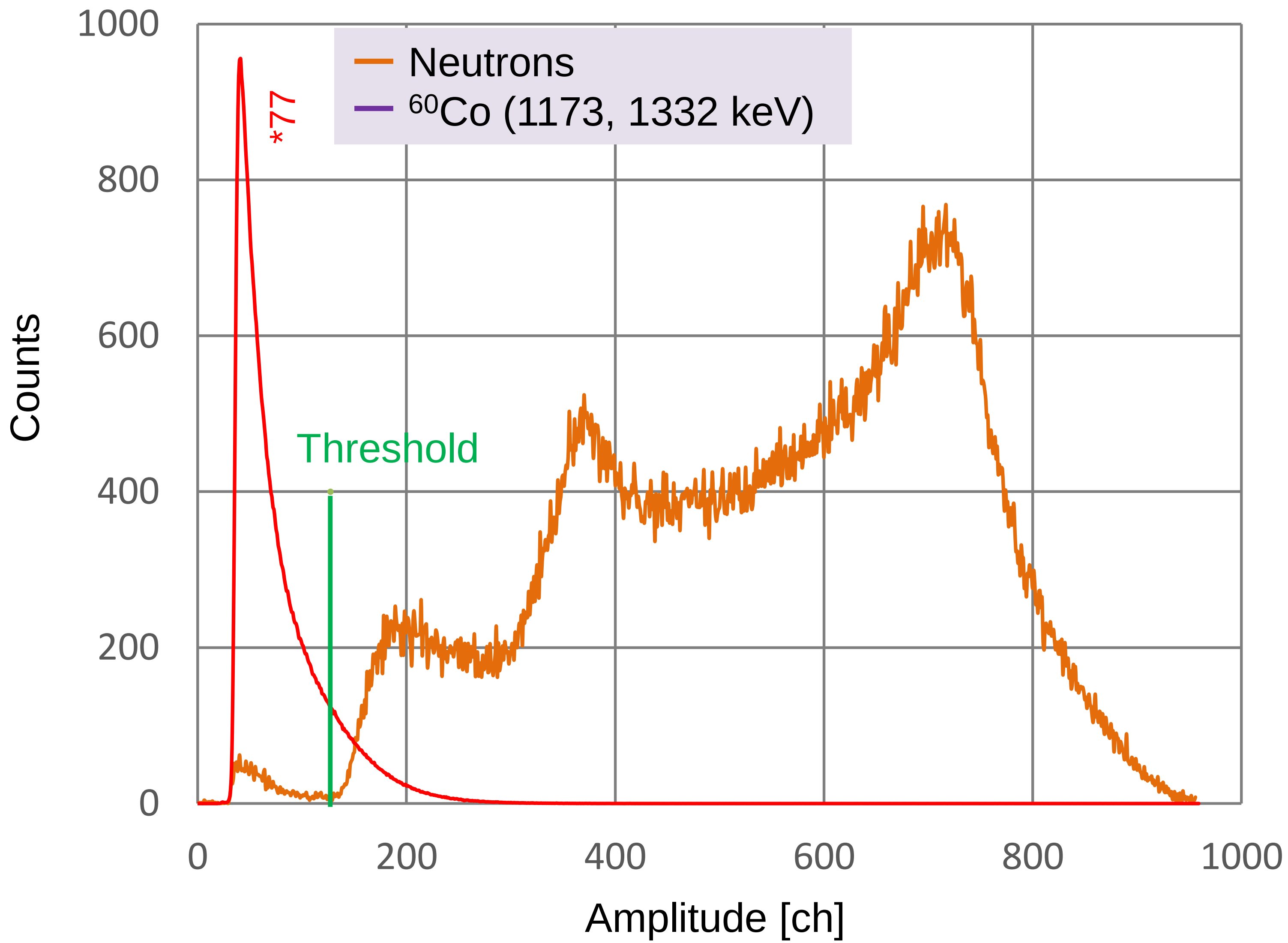
^{3}He + $ArCO_2$



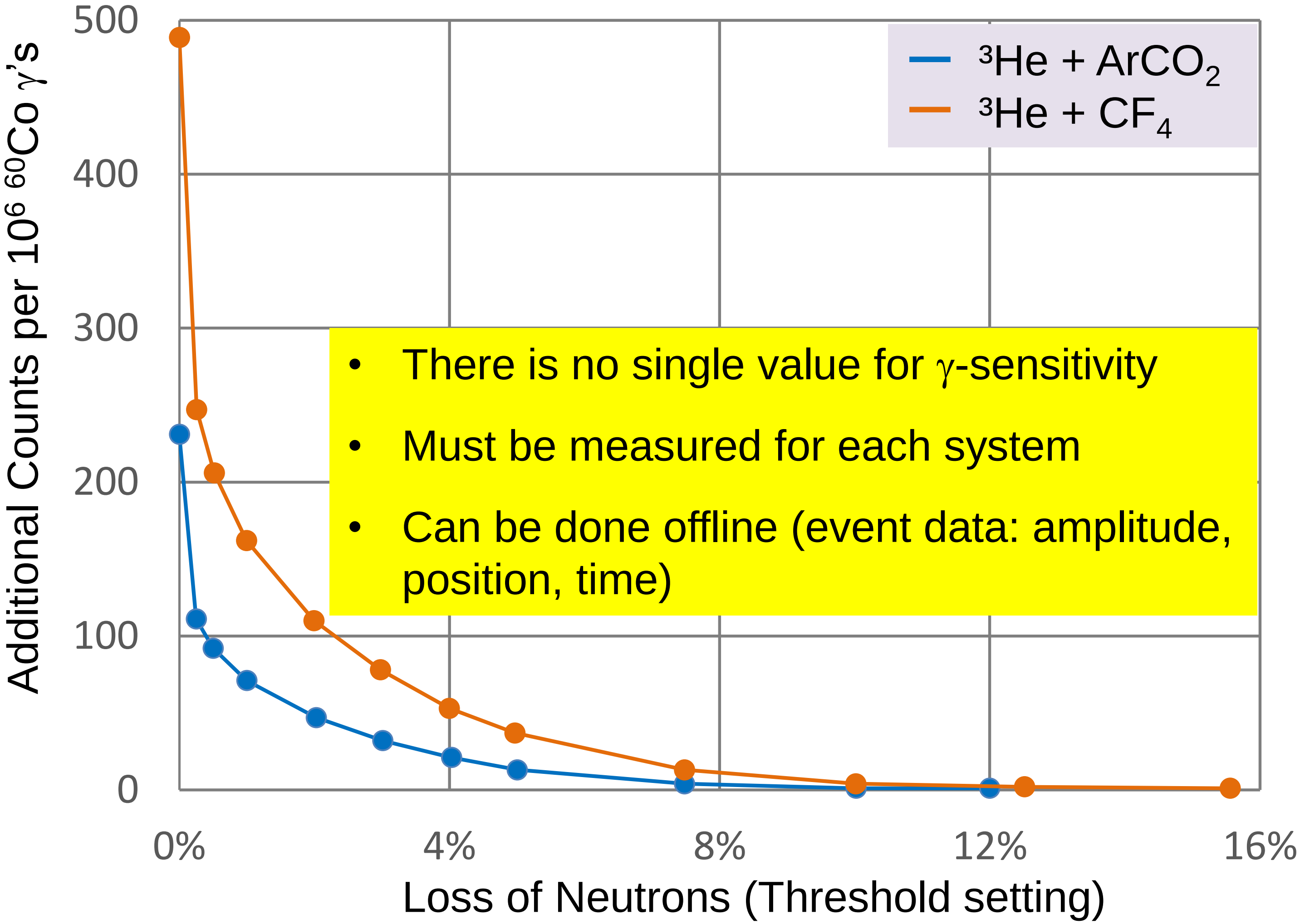
Linear Position-Sensitive ^{3}He-Detector (LPSD)

Gamma Sensitivity

$^3He + CF_4$



Minimization of "γ-pollution" by threshold setting



- There is no single value for γ-sensitivity
- Must be measured for each system
- Can be done offline (event data: amplitude, position, time)

Linear Position-Sensitive ^{3}He-Detector (LPSD)

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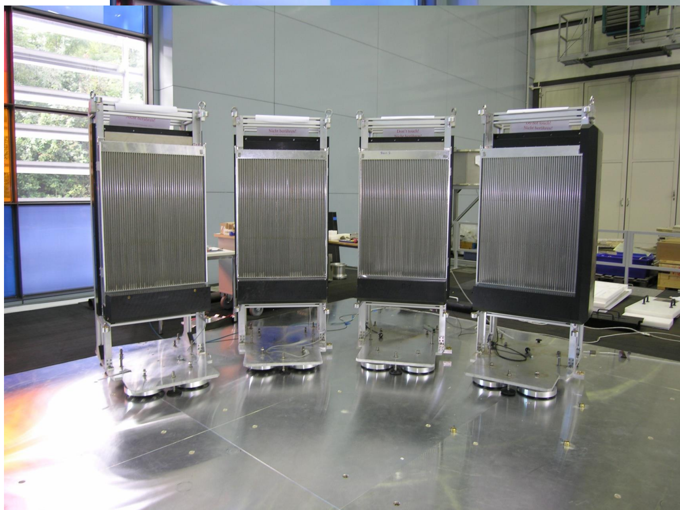
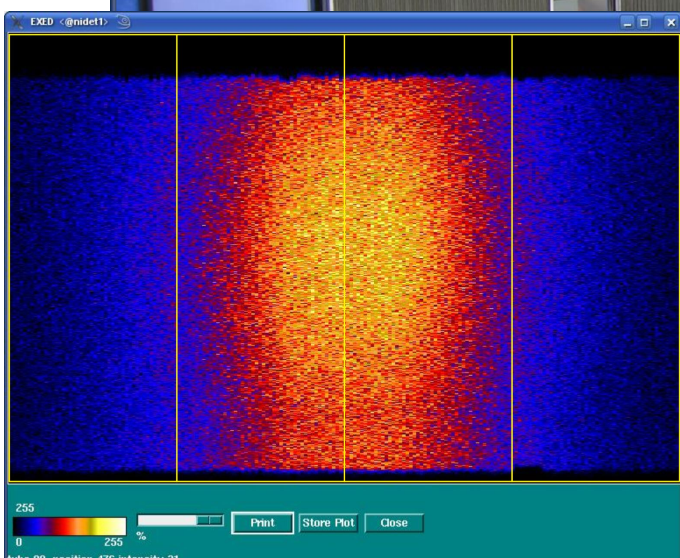


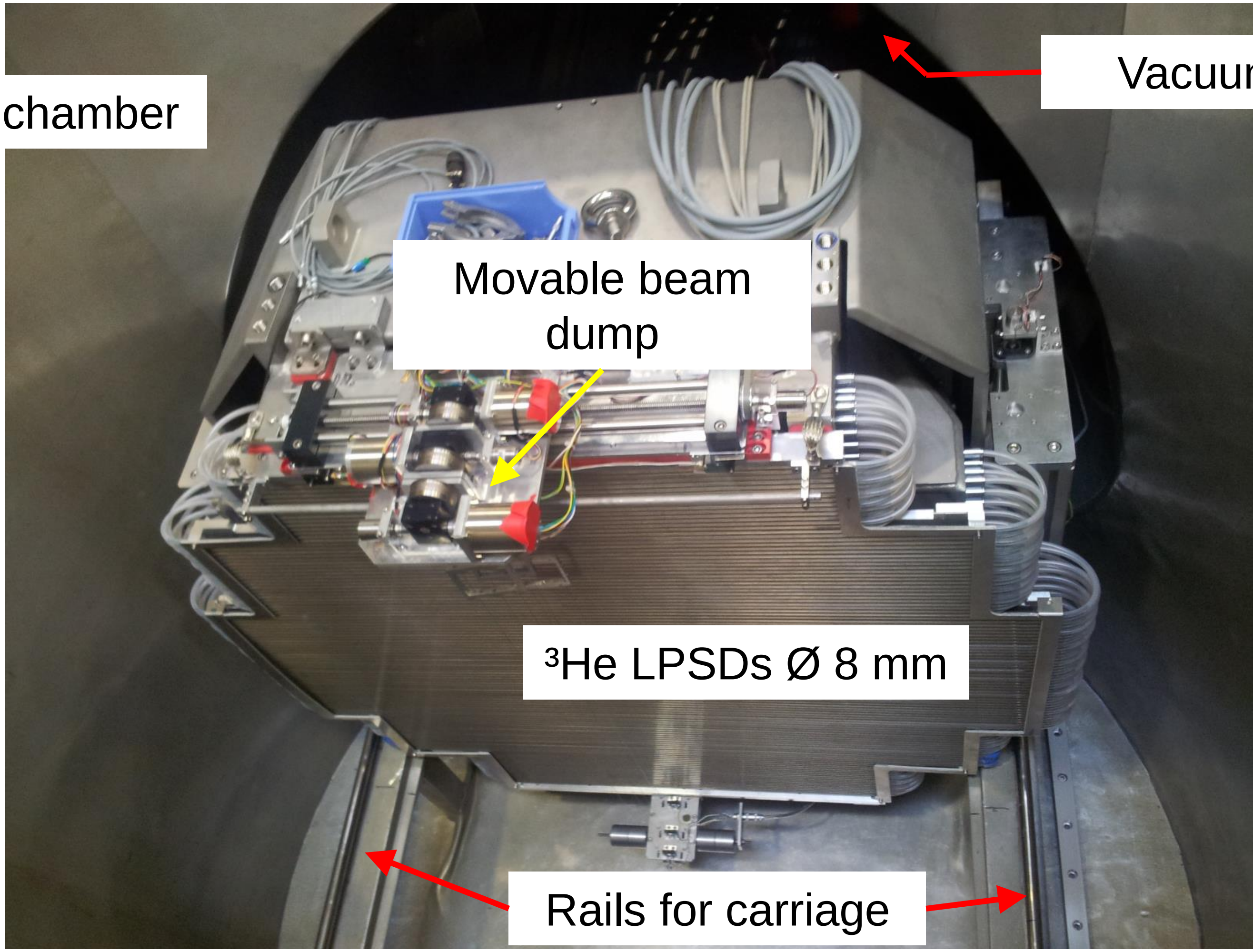


EXED Detection System 2011

- EXED: Extrem Environment Diffractometer
  HFM: Strongest magnet in the world, 26 T (2015)
- 192 ^{3}He-tubes ($ArCO_2$), Ø ½“, 900 mm length
- 4 panels, each 48 tubes
- Operated at air
- Mesytec Electronics*)
  Frontend amplifiers and coding
  4 Ethernet uplinks to fast PC
  time-stamp mode
  complete design non-magnetic

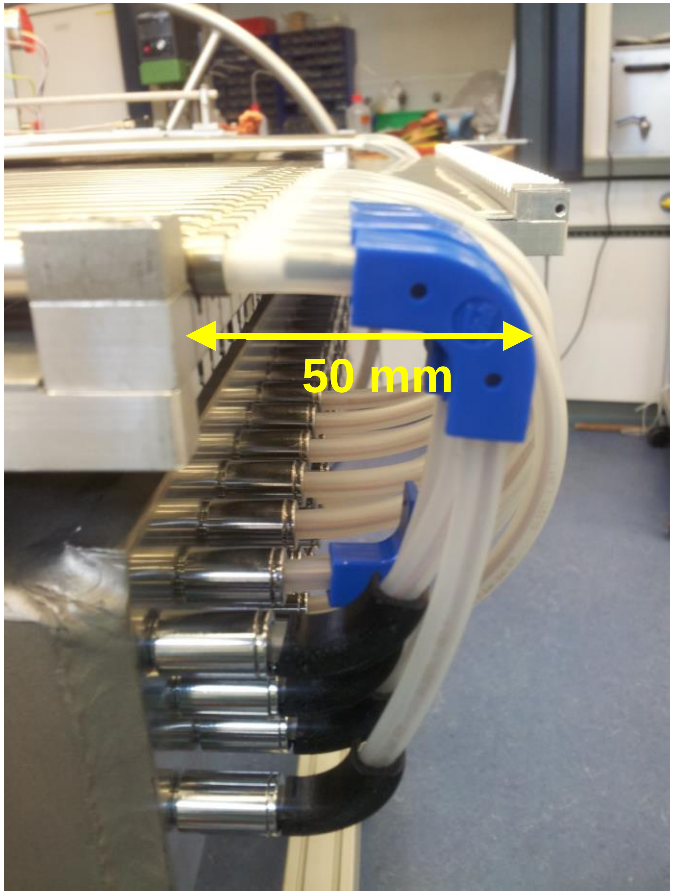
*) www.mesytec.com

HZB SANS Detector – Front side



HZB-SANS Detector- Compact Design

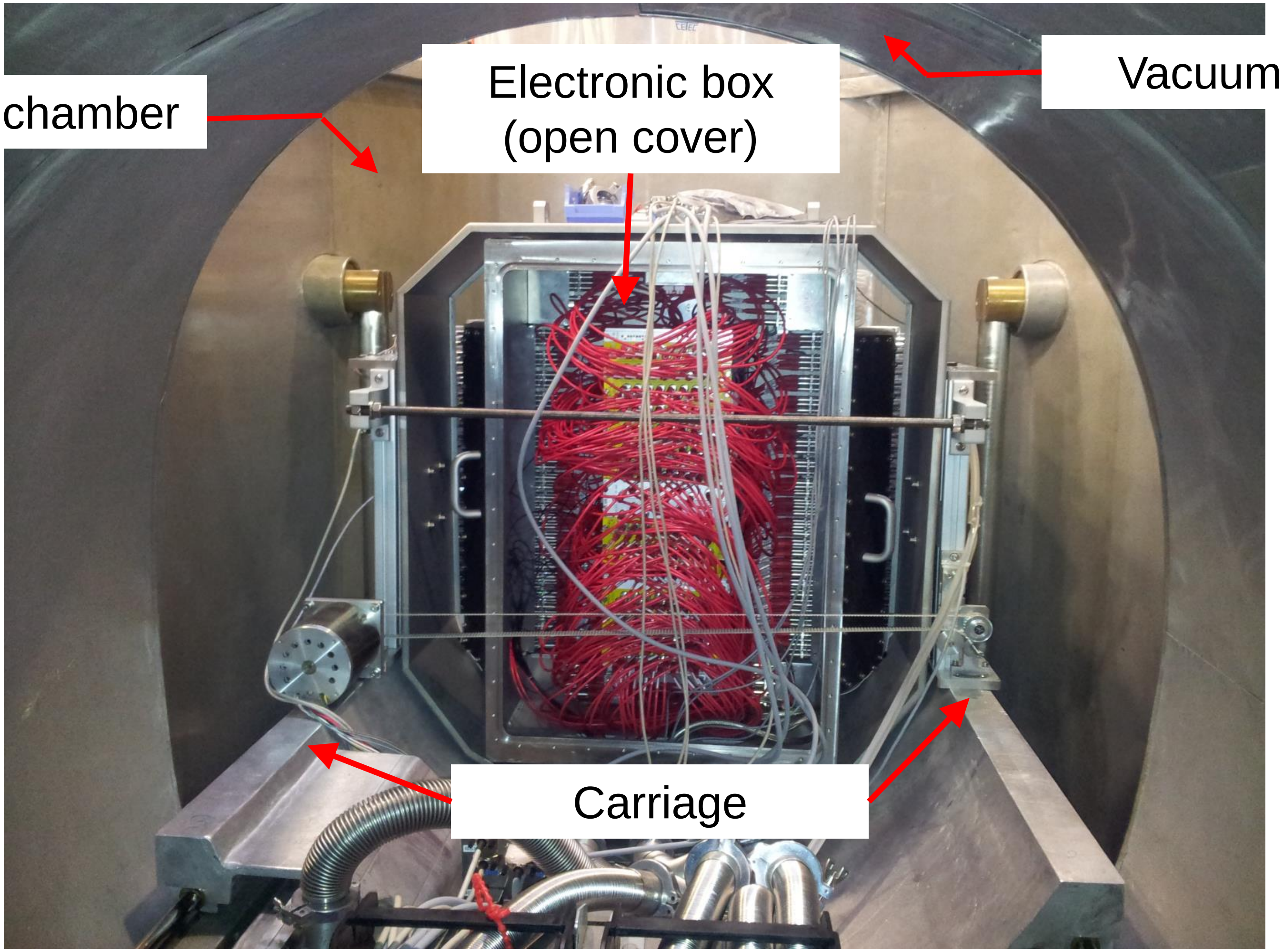
³He LPSDs, Ø 8 mm



Transparent(!) plastic tubes around HV cables

Very small dead space at the ends (≤ 50 mm) in special cases.

HZB-SANS Detector - Backside



Parameters of HZB SANS Detector

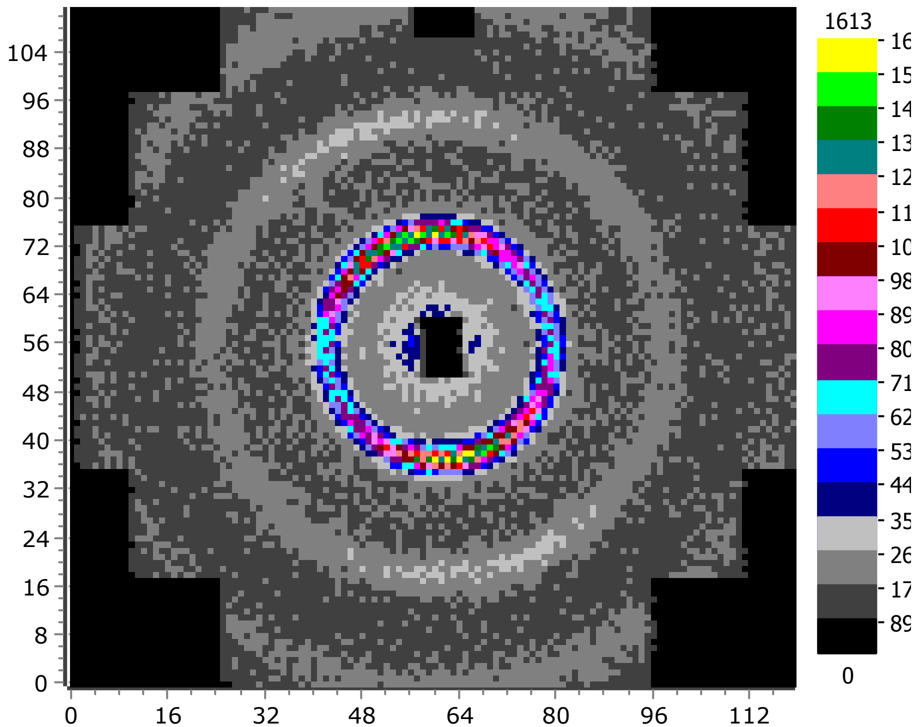
SANS Detection System 2012

- 112 ^{3}He-tubes 9.9 bar ($ArCO_2$, 3 bar), Ø 8 mm
- Length 1000 mm (40), 865 mm (40), 610 mm (32)
- Very compact design
- Operated in vacuum

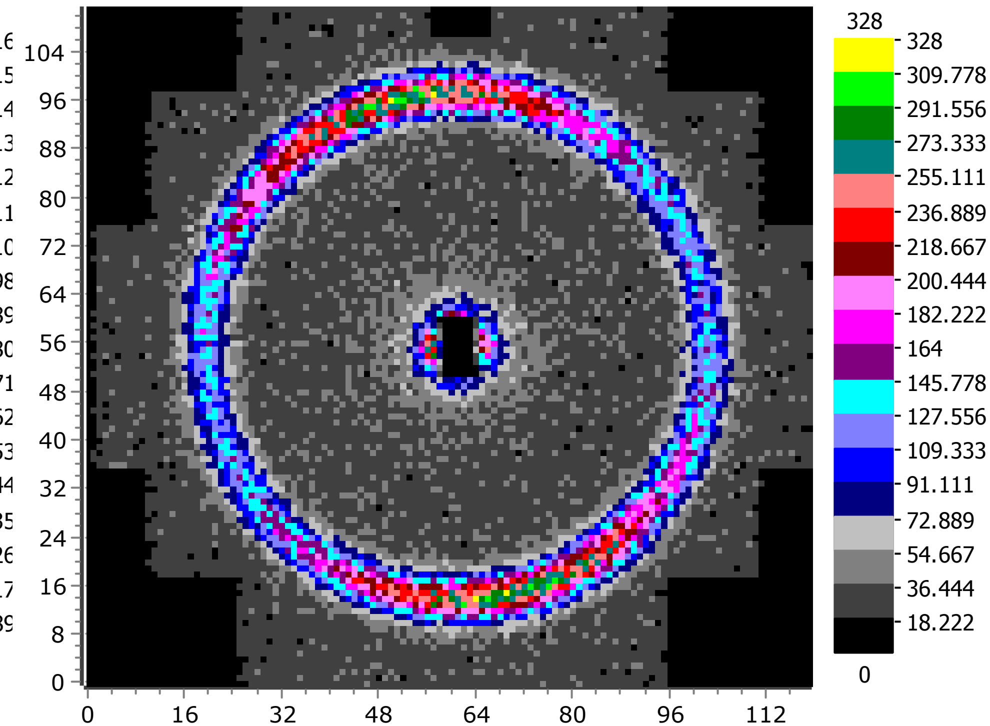
  Plastic tubes around HV cables to maintain air pressure
  Electronics on backside in box at normal pressure
  Vibration and pressure sensor with interlock
  No movement while HV is applied to detector!

Similar detectors: D22 (ILL), SANS-1 (FRM II), KWS-2 (FRM II), …

Calibration of SANS Detector with Silver Behenate

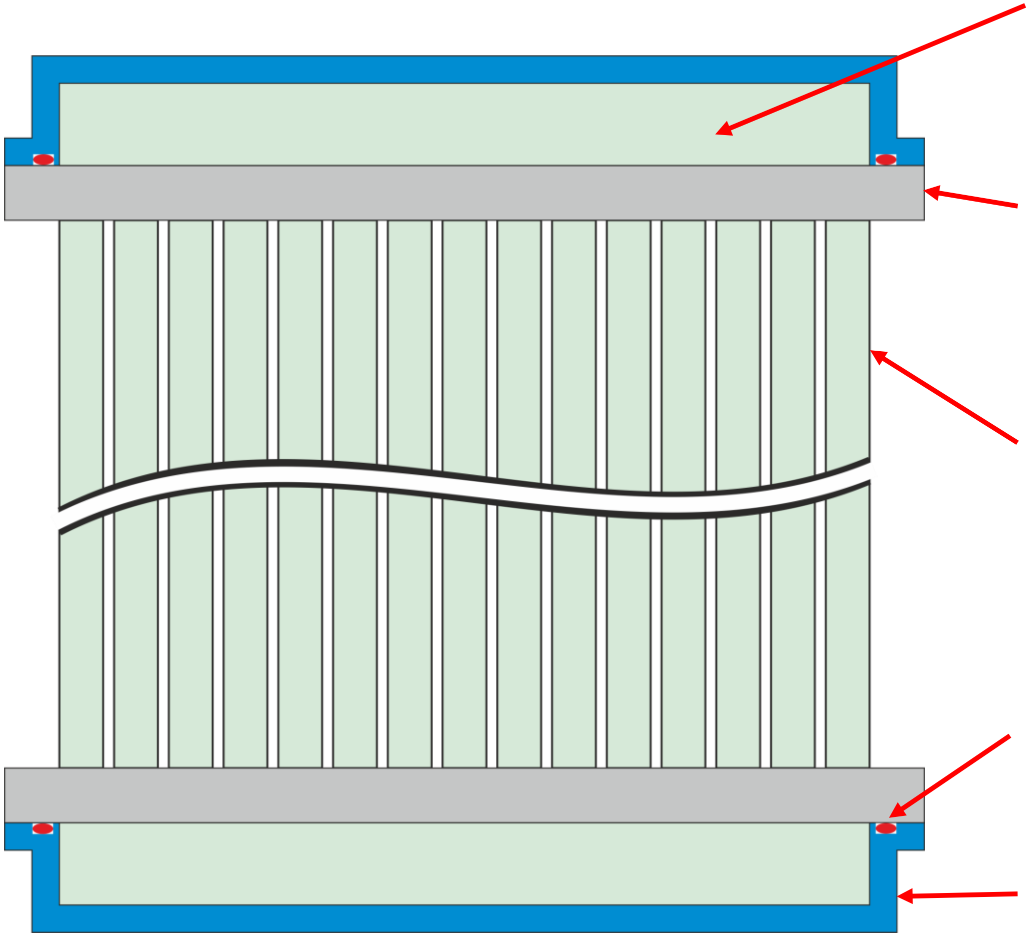


Lambda = 4.5 Å



Lambda = 10 Å

Scheme of Design Principle



Common gas volume: $^{3}He+ArCO_2$

Flange (20 mm thick)

Tubes:
length 1 m – 4 m
diameter ¾“ – 1“
wall thickness 0.5 mm

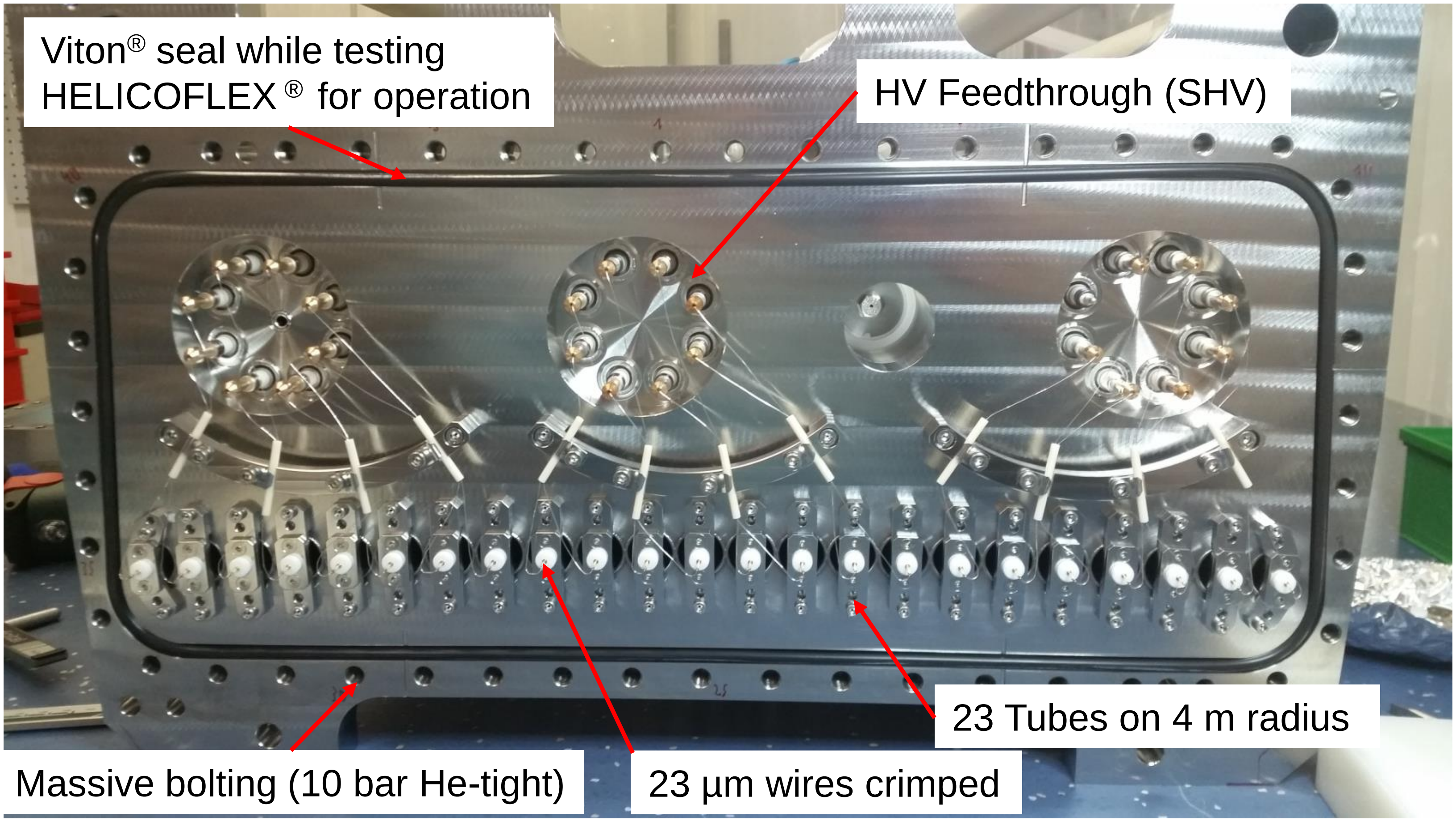
Metallic seals

Cover

*) Patented by ILL, Grenoble/France

Multi-Tube Detectors for EXED*)

Flange with detailed view



*) Built in collaboration with ILL Grenoble/France

Multi-Tube Detectors for EXED (2016)

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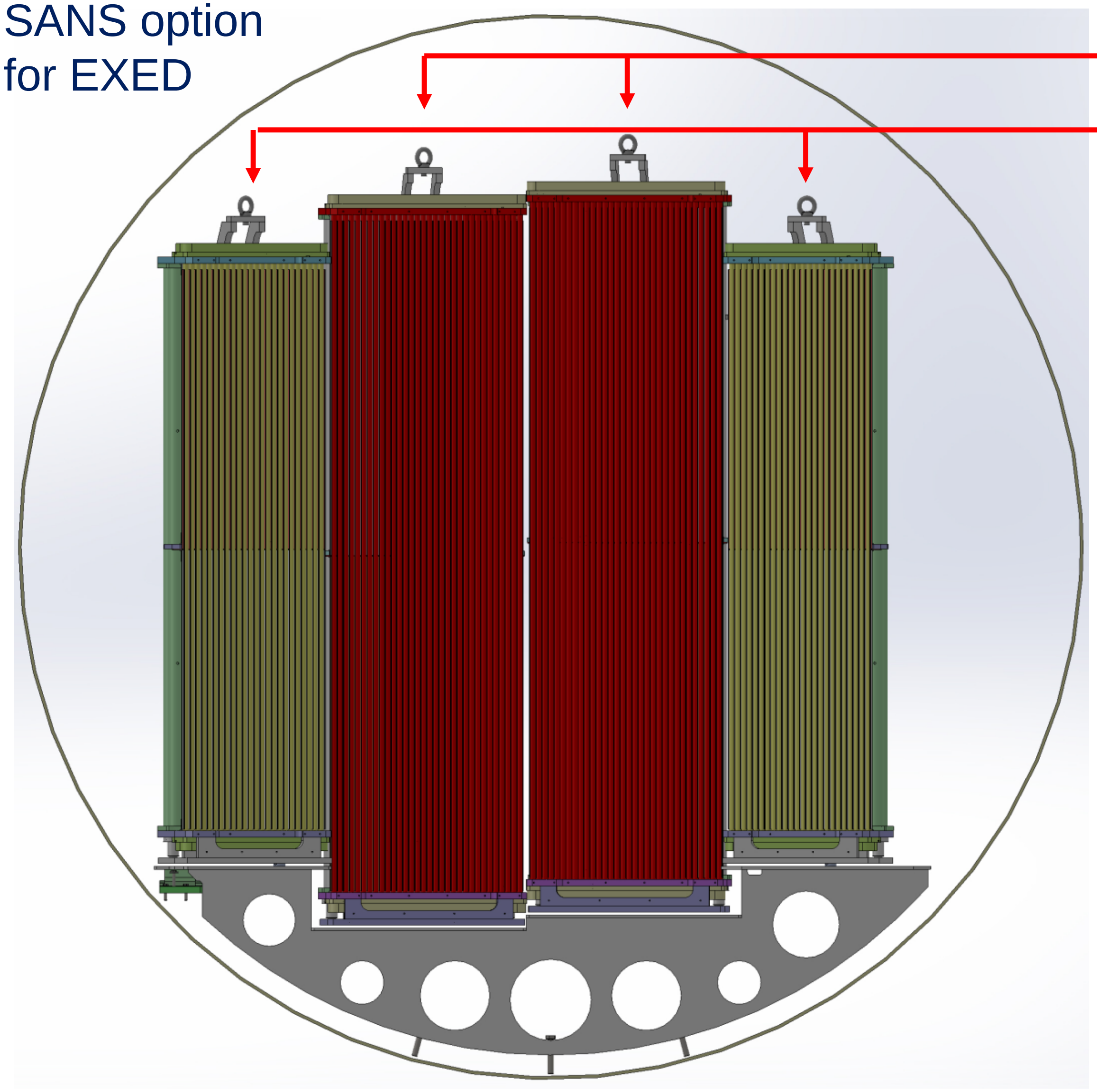
SANS option for EXED



31 tubes, Ø 19 mm, 2.5 m

23 tubes, Ø 19 mm, 2.0 m

Installation in vacuum

Pressure:
  8.75 bar ^3He
+ 1.00 bar Ar
+ 0.25 bar CO_2

HV cables in 3 m long hoses (normal pressure)

Electronics*) outside of vacuum chamber

*) www.mesytec.com

Multi-Tube Detectors for EXED (2016)

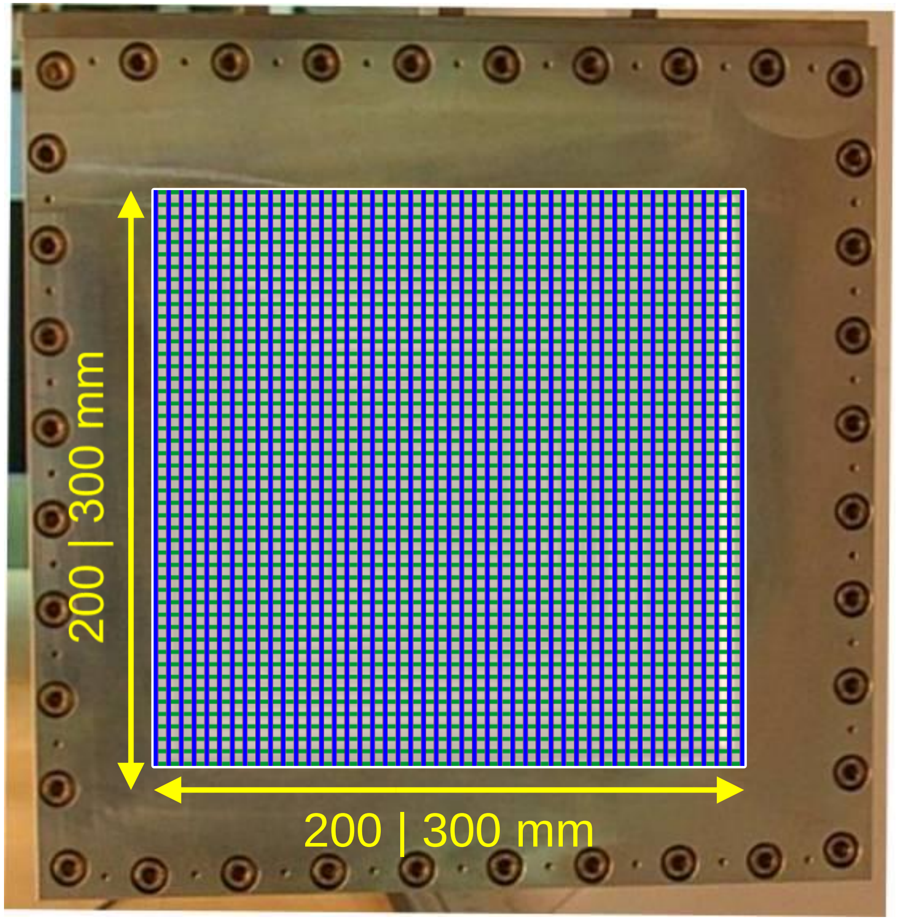
Module with 23 tubes
on test bench in lab

3 Modules in place at EXED
in detector chamber

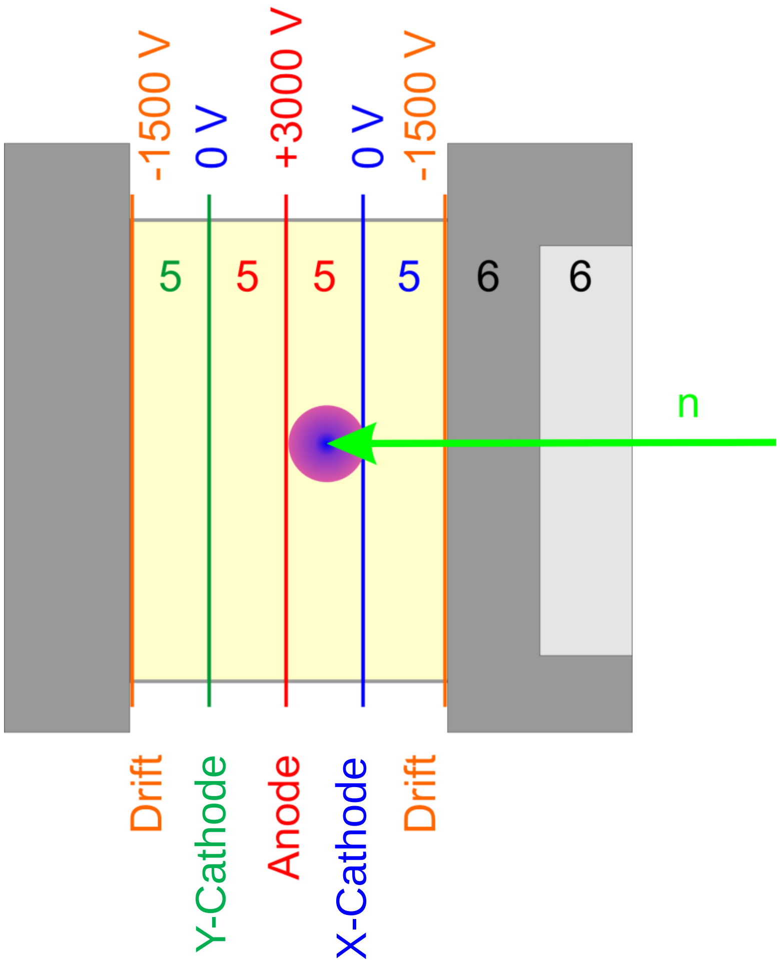
Similar detector: IN5 (ILL)

MWPC requires:

- ³He pressure (4.5 bar), „stop gas“ (CF_4), 2D pressure vessel: thick window
- Gas amplification >1000: anode wire (6-8 µm), usage of fast electron component



Each electrode consists of 200 wires



MWPC – Analog Signals

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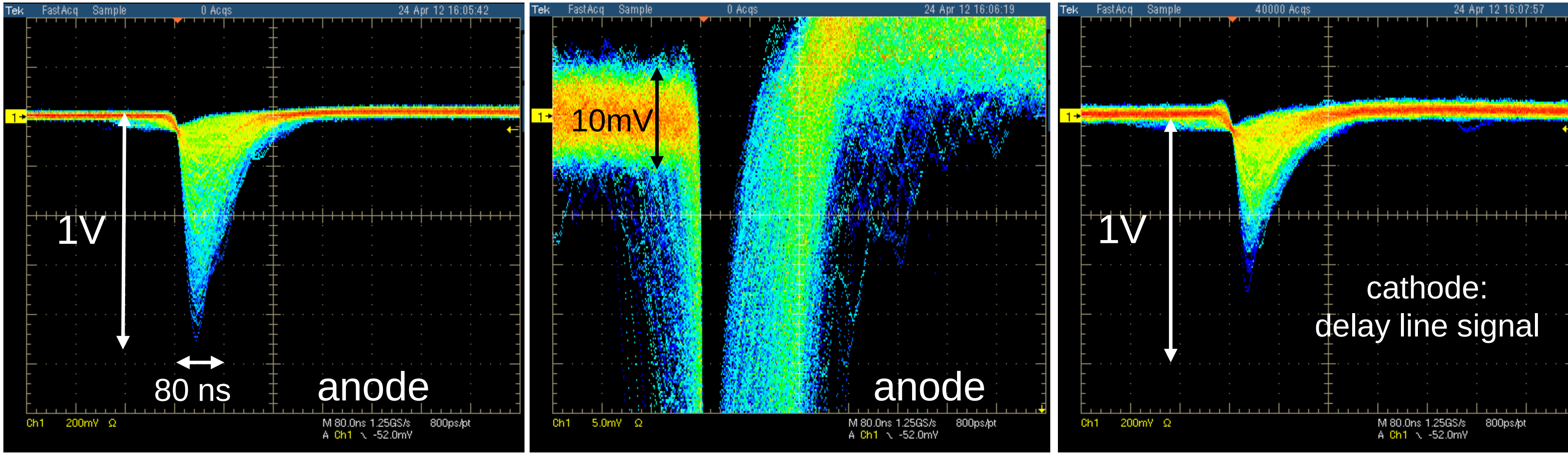
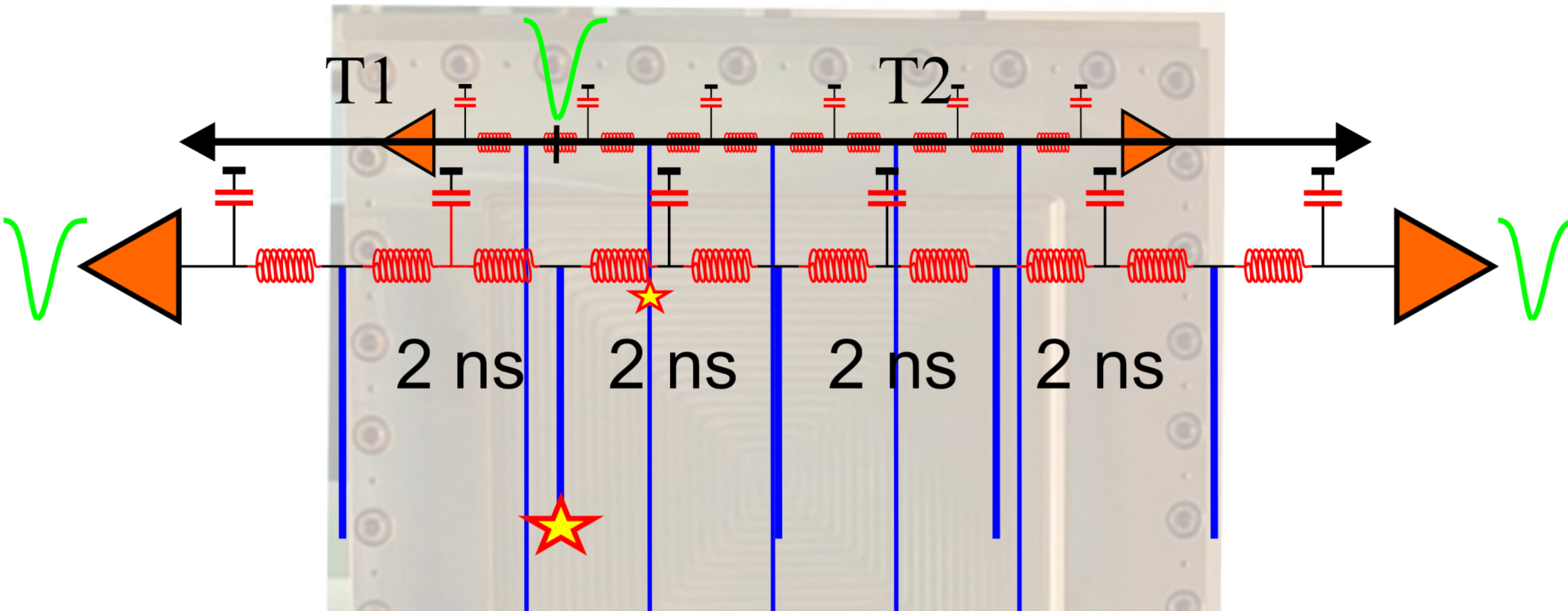


- Fast signals: fall time ≈10 ns
- Broad spectrum of amplitude, down to noise level
- Low discriminator thresholds for best efficiency
- Signal/noise ~ 100/1
- Only with HZB-amps IV110/IV111/IV112 possible! Noise figure 1.6 dB

Development: B. Namaschk / HZB (NP-AUN)

Position Encoding by Delay Line

Position of neutron is measured indirectly by time differences



$$X,Y = T1 - T2 + DL$$

$$DL = T1 + T2 \text{ (disentangle multi-hit events)}$$

⇨ Advantage: position resolution ≈2 mm, at higher rates (100 kHz)

Readout of such detectors with DeLiDAQ: PCI board + SW (FLNP/JINR & HZB/HMI)

Levchanovsky, et al., NIM A 529 (2004) 413, Levchanovsky, et al., NIM A 569 (2006) 900

³He MWPC – Position Resolution Limits

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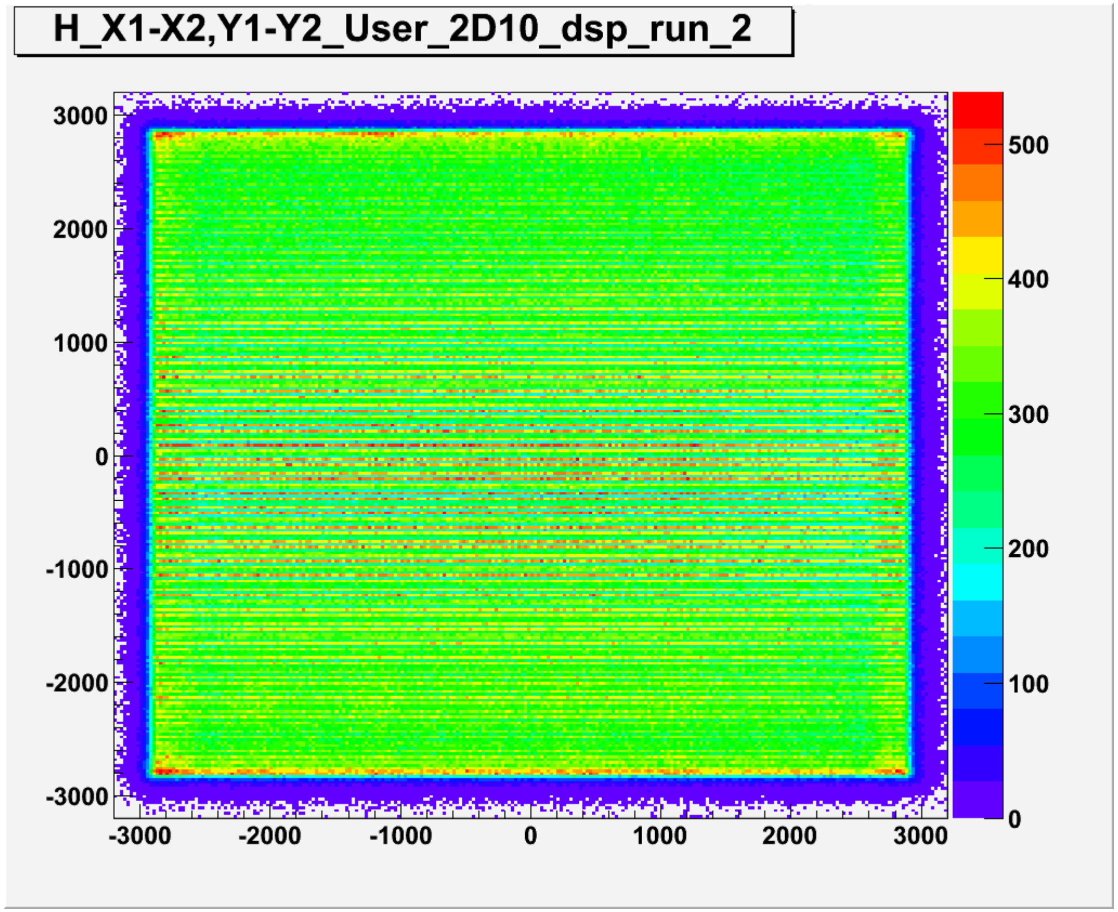
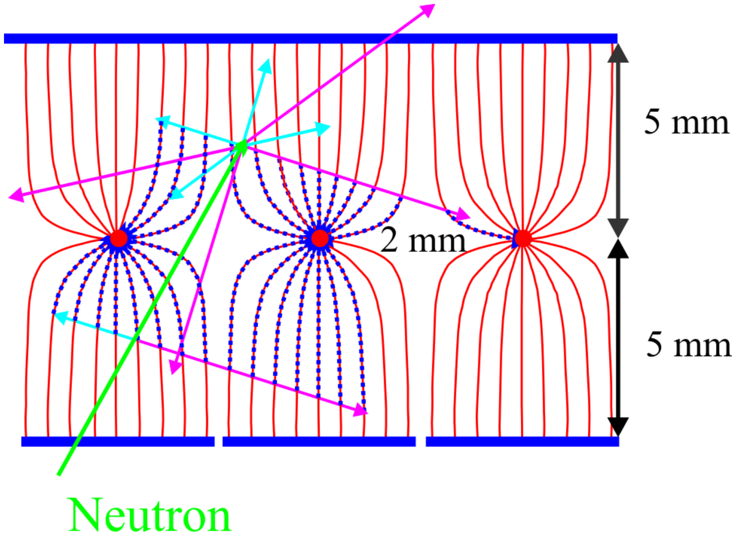
Response on flat field irradiation



Position resolution limited

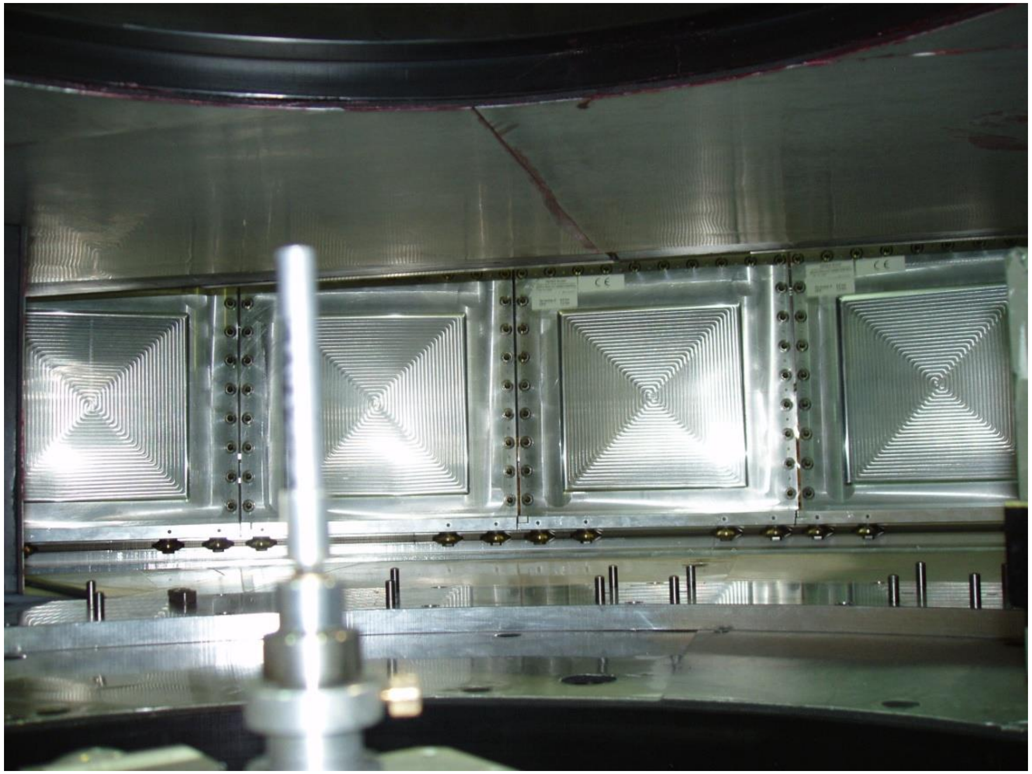
- x-coord.: R_p
- y-coord.: R_p & anode pitch



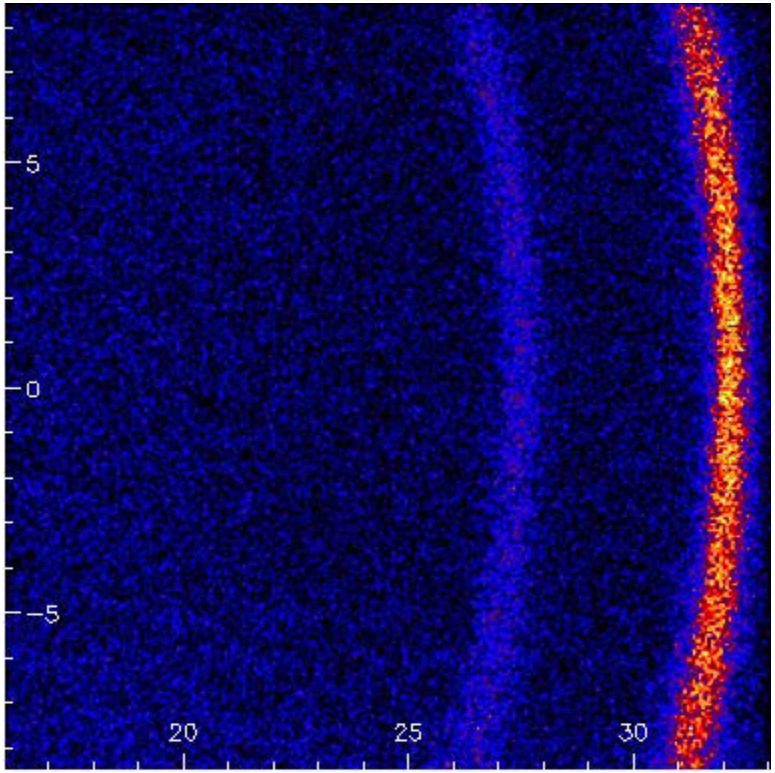
higher differential non-linearity for Y

24 2D-MWPCs are used at 12 Instruments at HZB

4 DENEX*) detectors at Flat Cone Diffractometer E2



YIG powder measured at PD E6

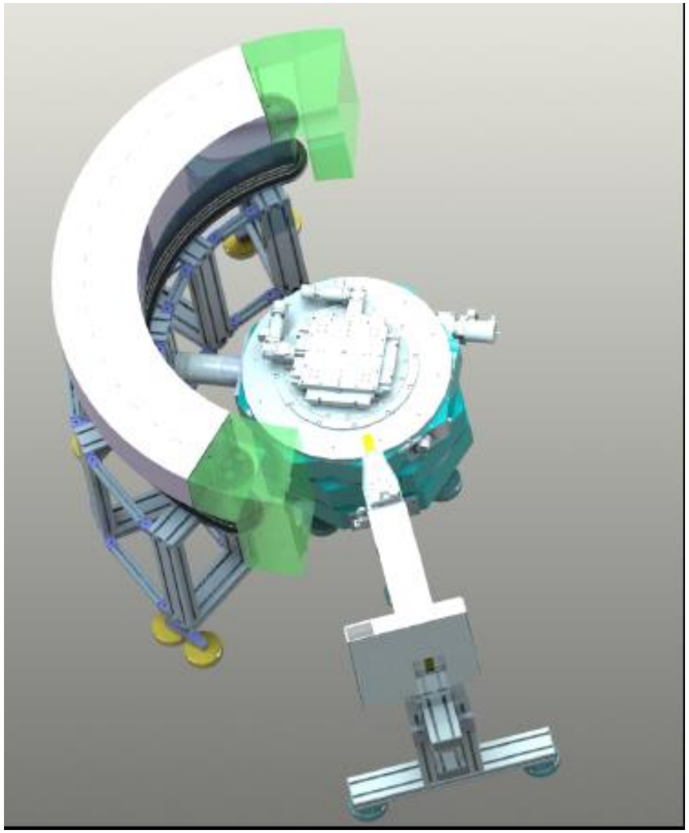


*) www.denex-gmbh.de

‘CHARM’ Detector at FRM II

HZB Helmholtz Zentrum Berlin

ERWIN: A new powder diffractometer @ FRM II



Curved ^3He-based MWPC covering 120°

- *MWPC design closely derived from BNL-design*
- *30°- demonstrator built in collaboration with ILL & PSI*

Slide provide by K. Zeitelhack – FRM II

CHARM detector

8 MWPC segments mounted seamless in a pressure vessel

Fully modular design

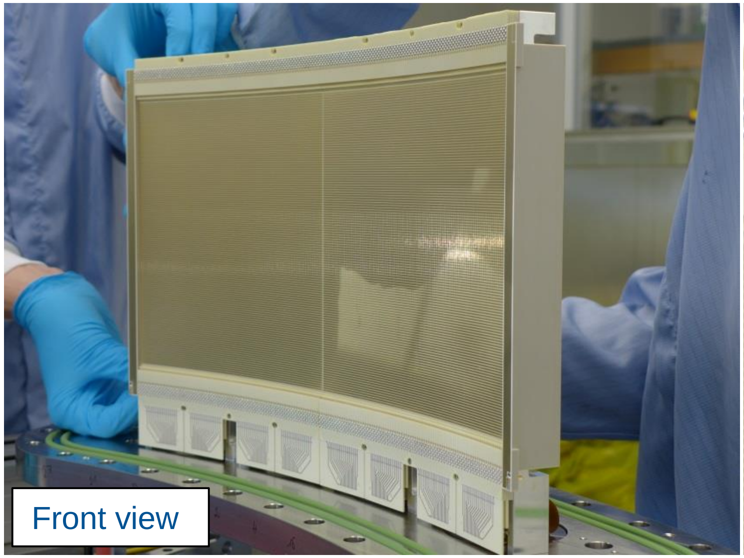
Individual wire / strip readout

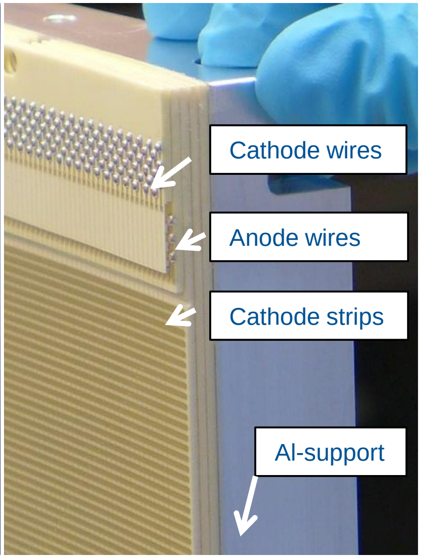
ToT-based CoG algorithm for position determination

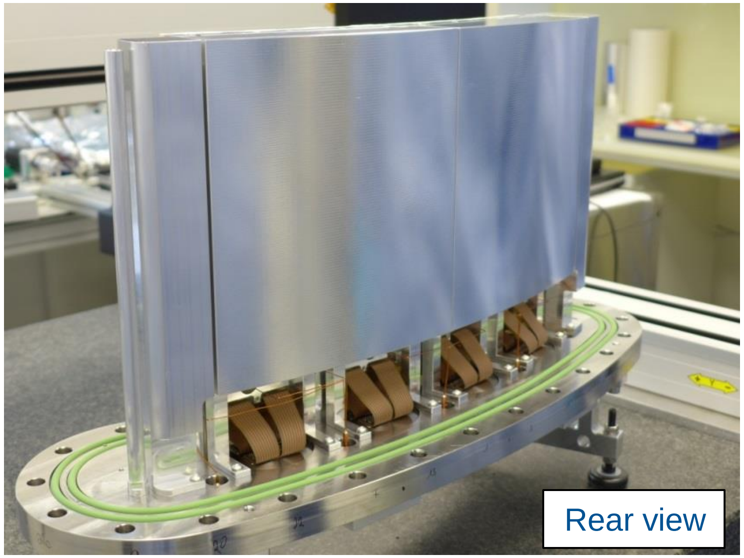
2D-position, time & energy data

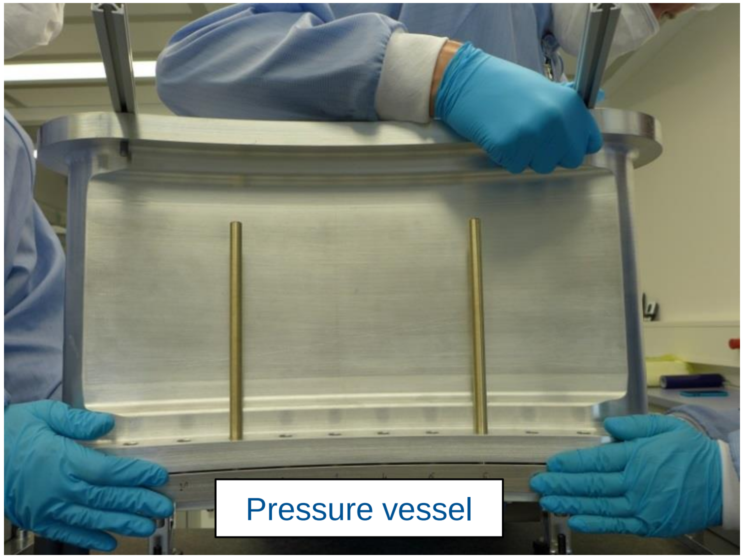
Specifications:

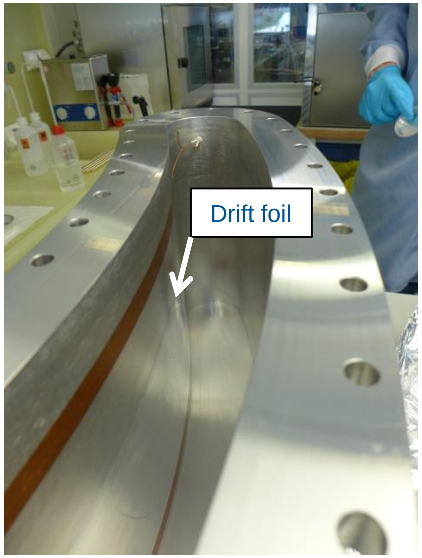
Radius	800 mm
Aperture horizontal	≥ 118°
Wire pitch	1.6 mm
Wire gap	1.6 mm
Resolution horizontal	0.125°
Aperture vertical	200 mm
Strip pitch	1.6 mm
Resolution vertical	0.125°
Count rate	50 kHz / wire 200 kHz / segment
$^3He+CF_4$	6.5bar + 1.5 bar
Efficiency	75 % @ 1.8A

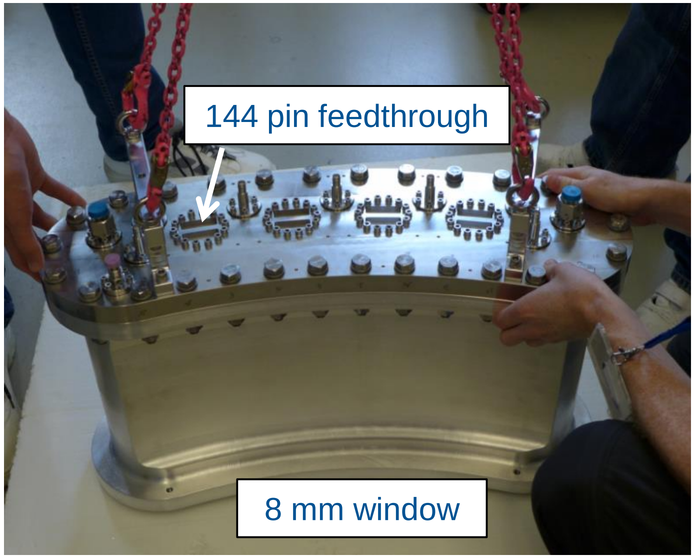












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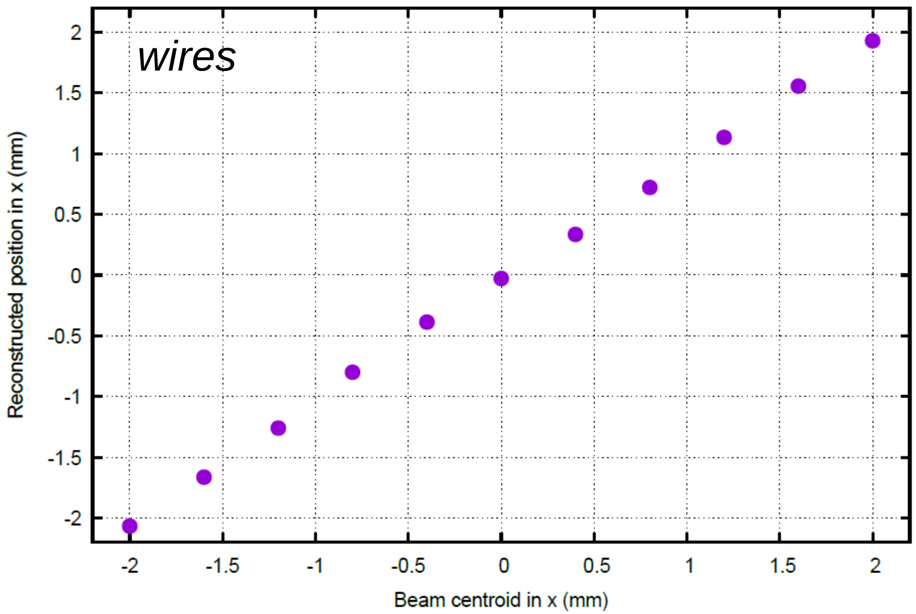
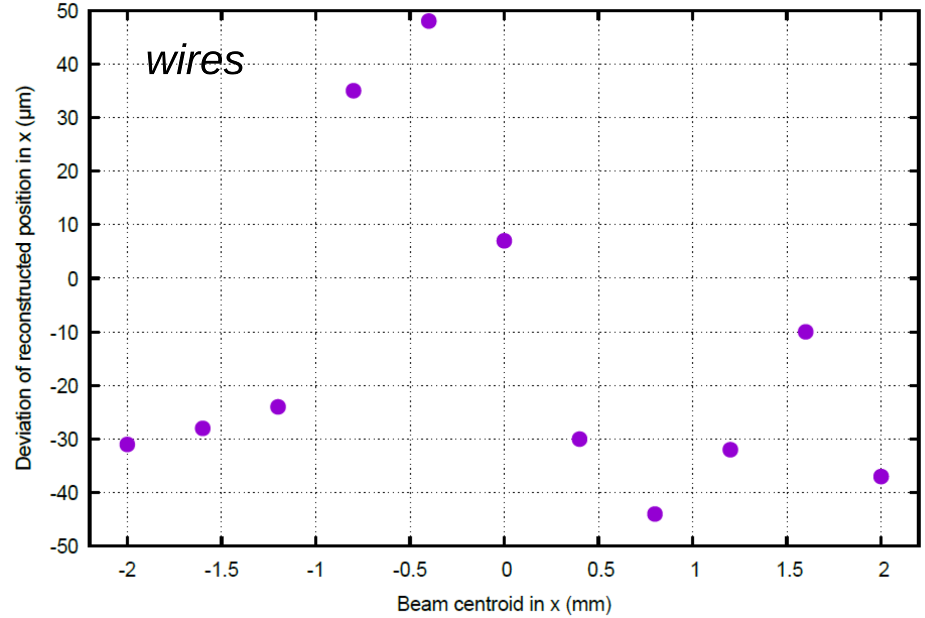
Linearity of position determination

- *Scan with a collimated beam in 0.4 mm steps*
- *Position by ToT-based Centre-of-Gravity algorithm*

Measured vs. true position in x



Deviation from true position in x



⇨ Differential non-linearity ≤ ± 50µm

Same result for y-coordinate!

Slide provide by K. Zeitelhack – FRM II

Conclusion & Outlook

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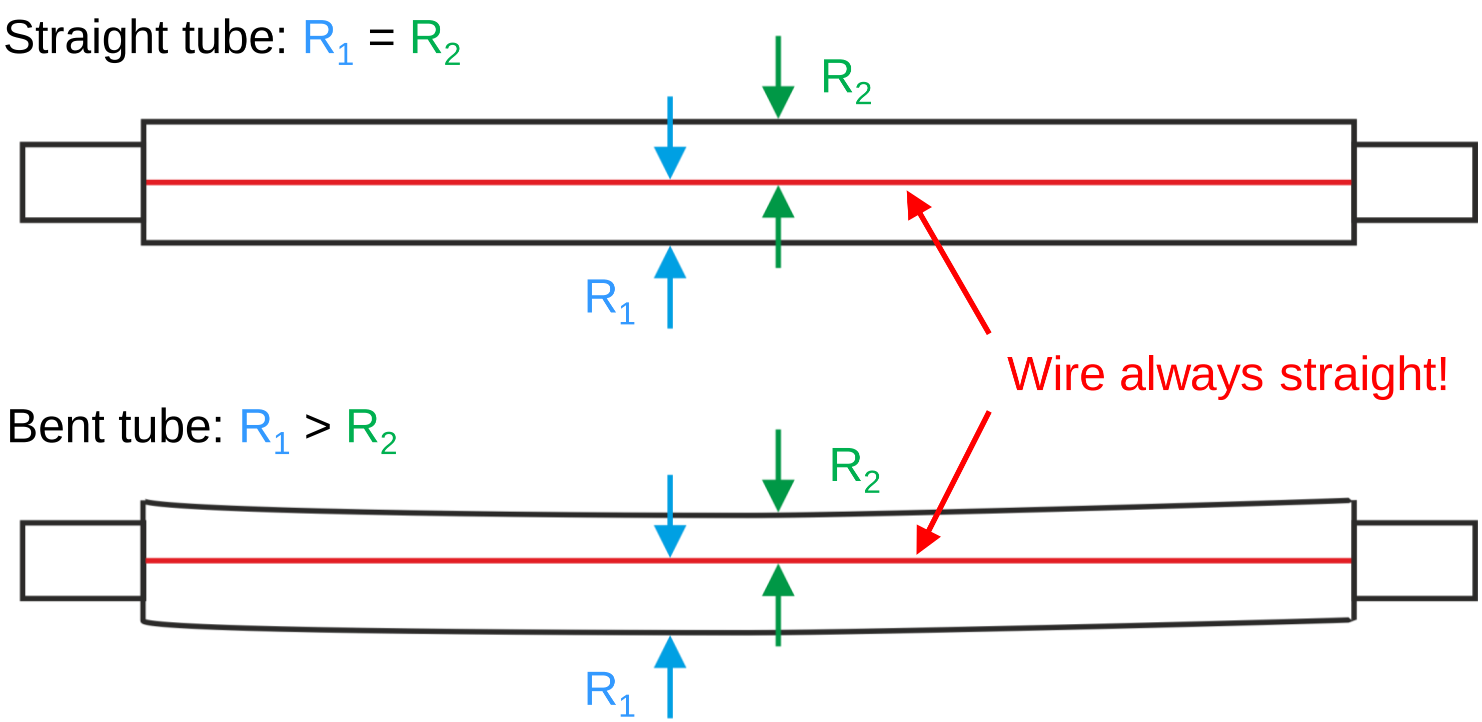
- A variety of different types and geometries of ^{3}He-filled neutron detectors has been developed in the last decades.
- ^{3}He detectors are the backbone of neutron detection in many neutron centers.
- Since the ^{3}He crisis this gas became rare and precious, triggering research for alternatives, especially for large TOF-instruments.
- New developments of detectors with ^{3}He are on the way, not least because of unique features this neutron converter.
- Careful handling of ^{3}He and
- Complete Recovery from obsolete detectors is demanded.

Thank you for your attention!

Спасибо за ваше внимание!

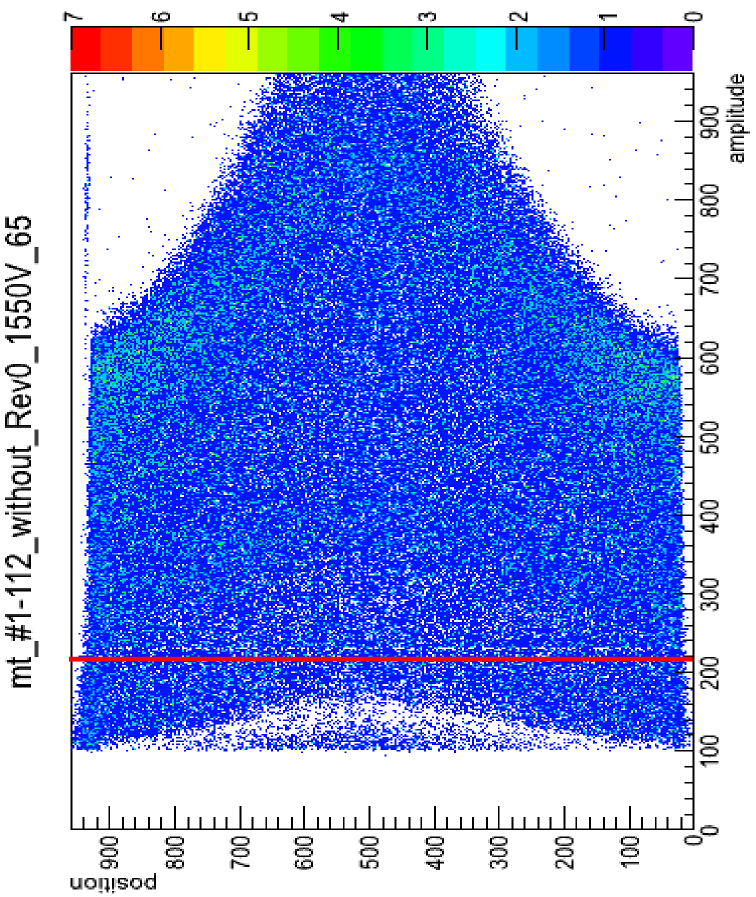
Slightly curved tubes – big effect!

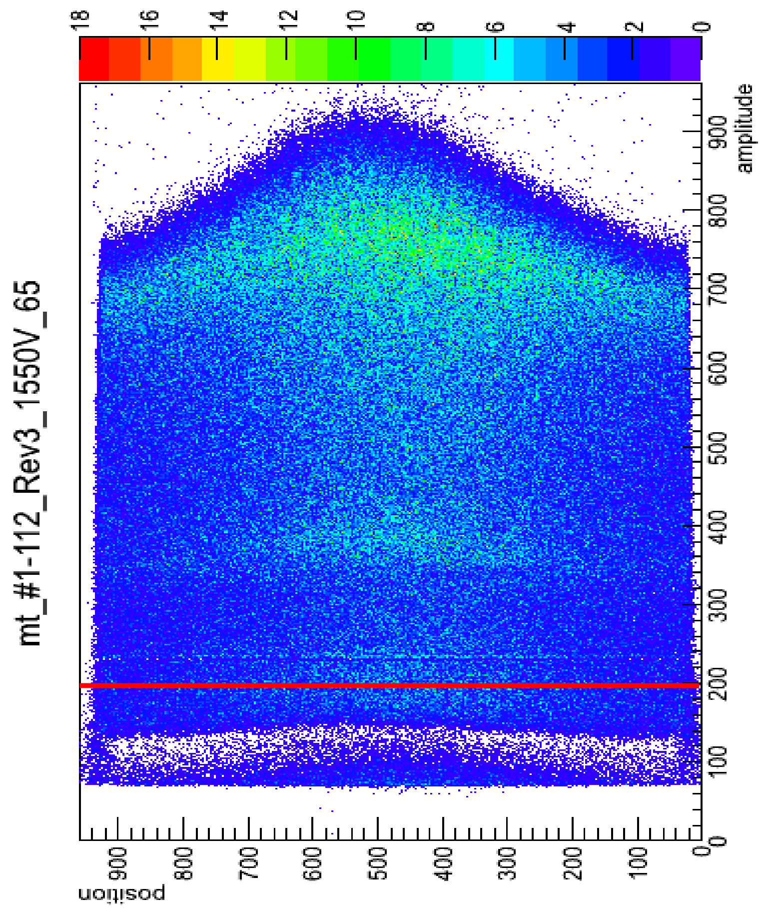


Result: Higher electrical field in center

This effect limits the maximum tube length to 4 m

Result of bent tubes of 1 m length





R_1 = 4.3 mm, R_2 = 3.7 mm

R_1 = 4.15 mm, R_2 = 3.85 mm

Measuring position and amplitude is extremely useful!