The Focal-Plane Detector System of KATRIN

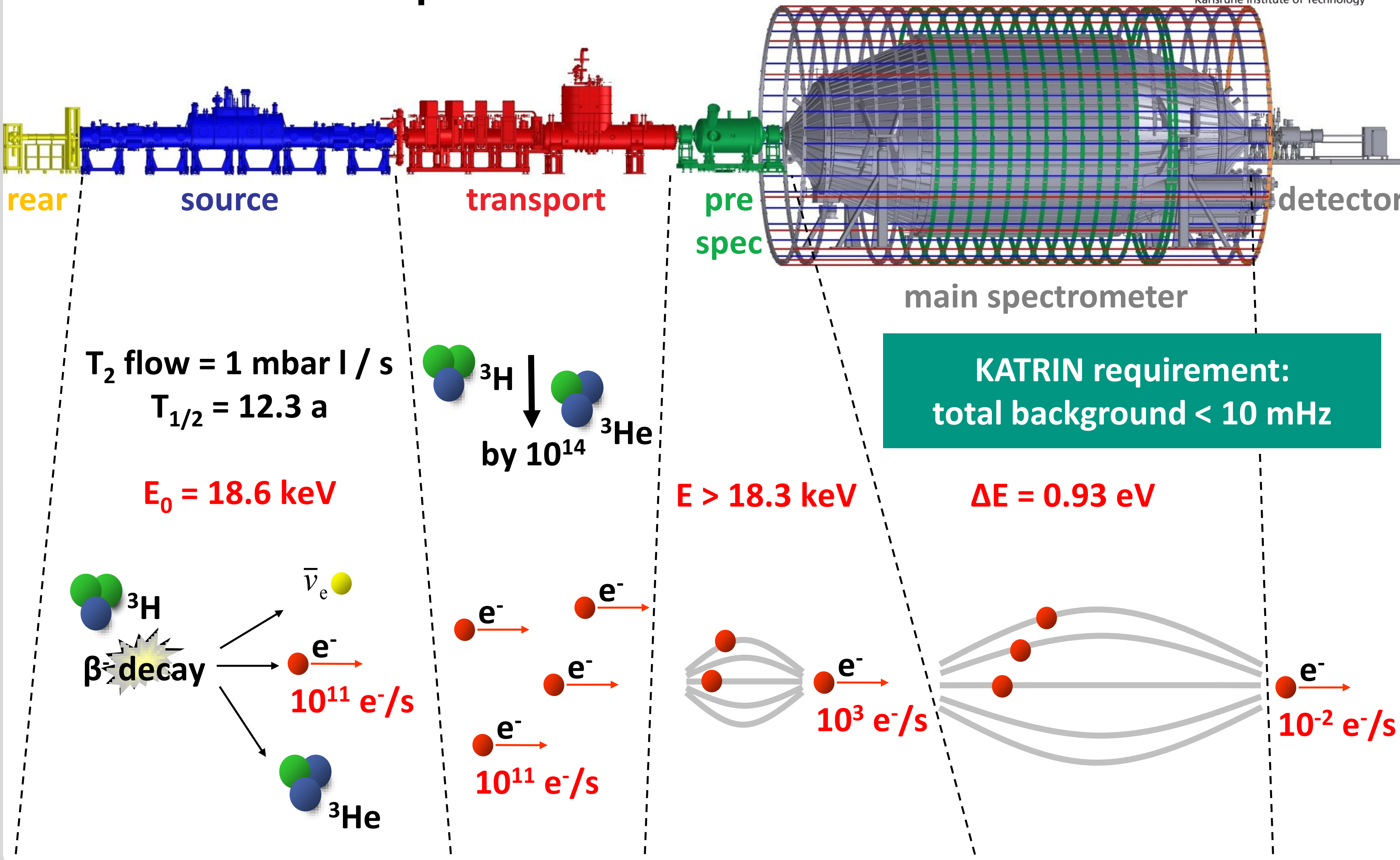
GRK Workshop Bad Liebenzell 2013

Johannes Schwarz (EKP)

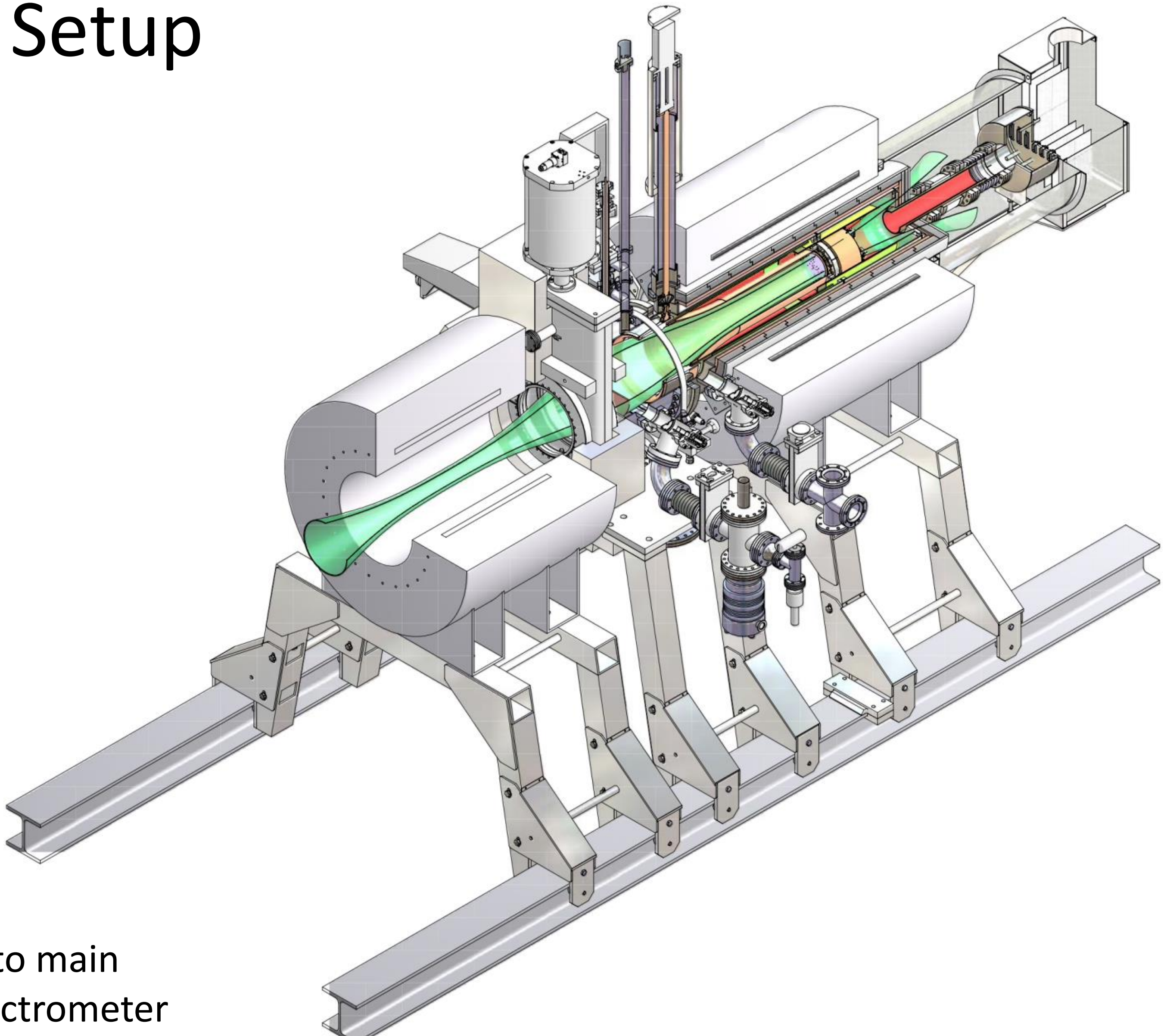
Outline

- FPD Setup
- Detector Characterization
- Main-Spectrometer Background
- Summary

KATRIN Setup

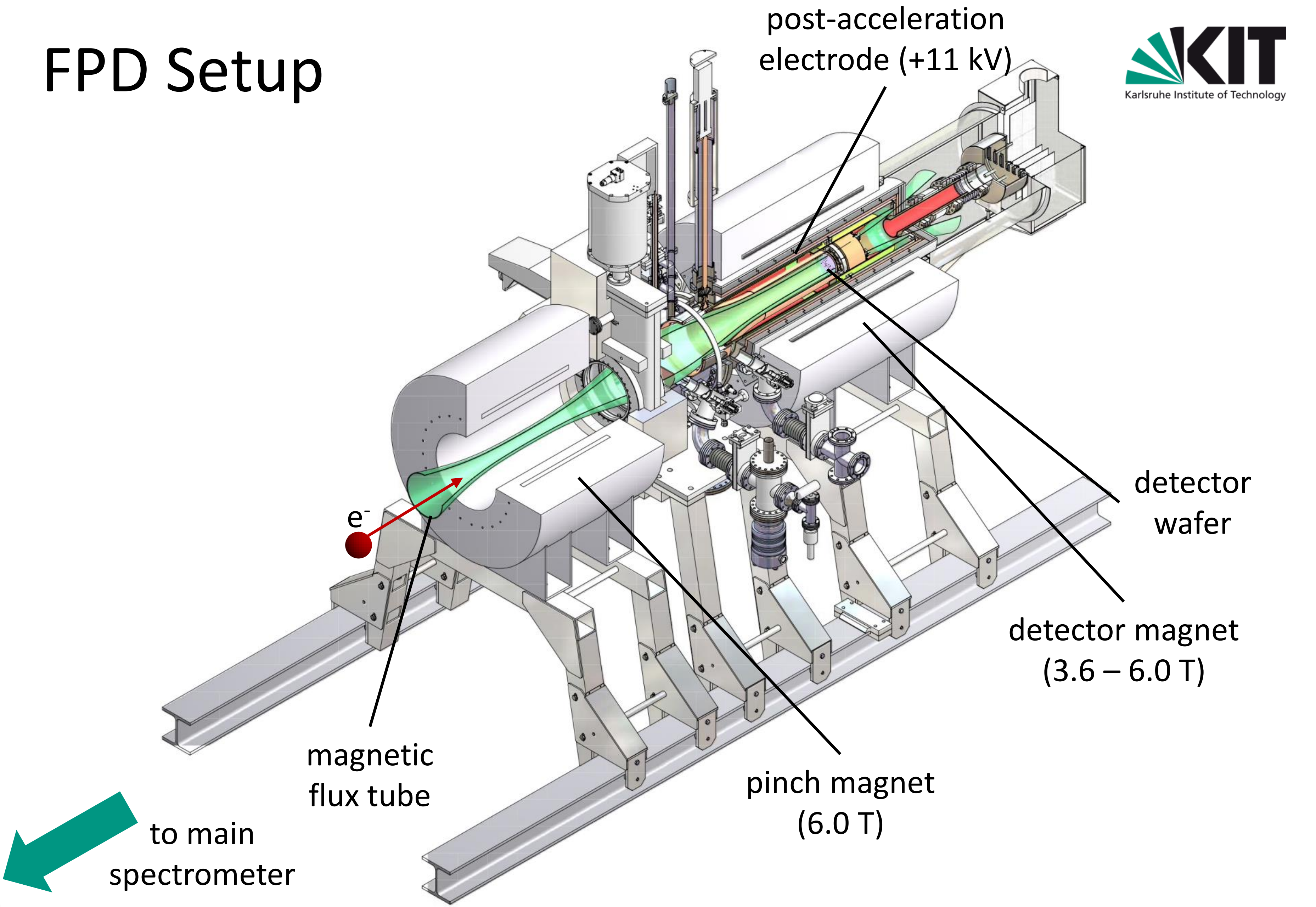


FPD Setup

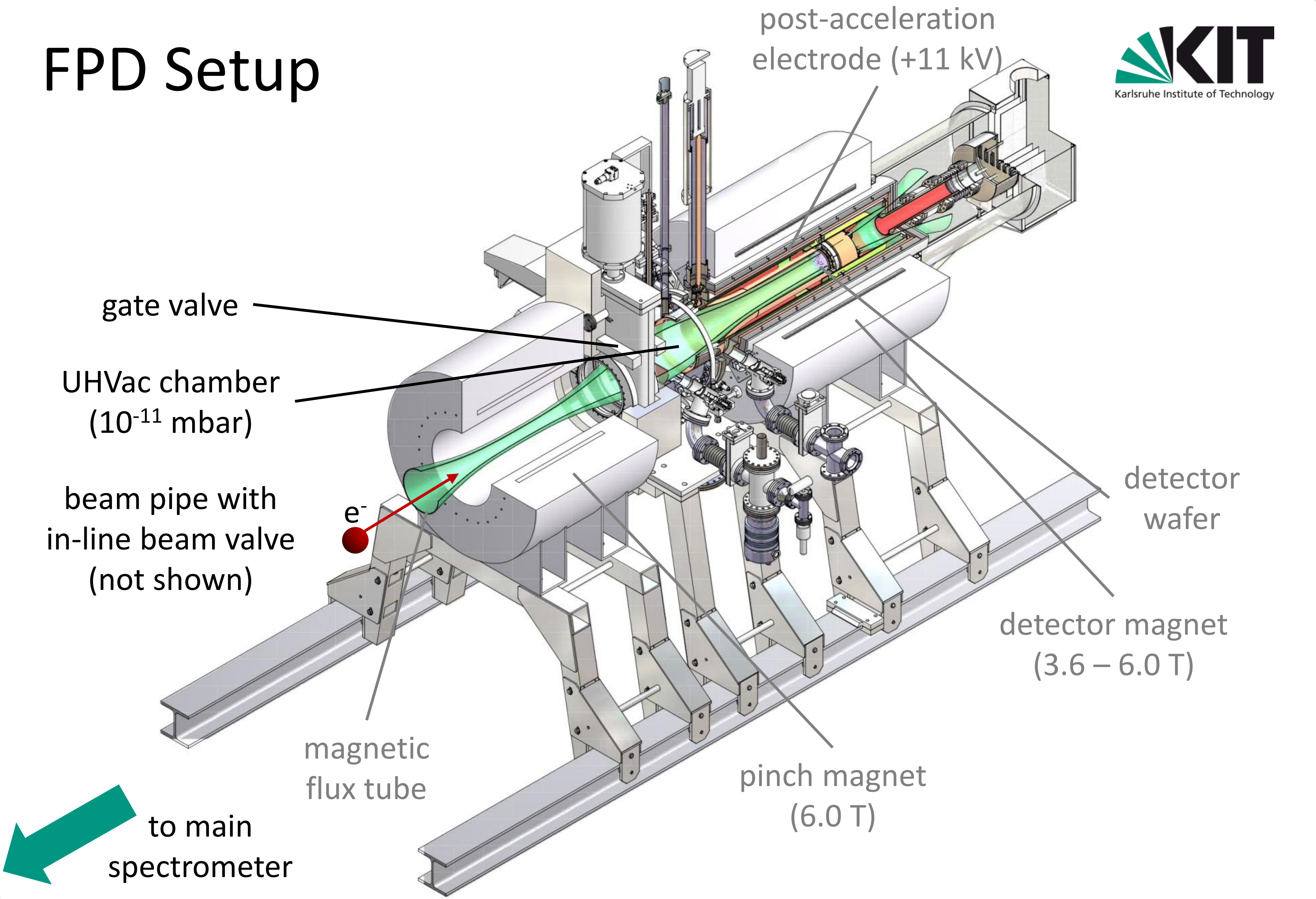


to main spectrometer

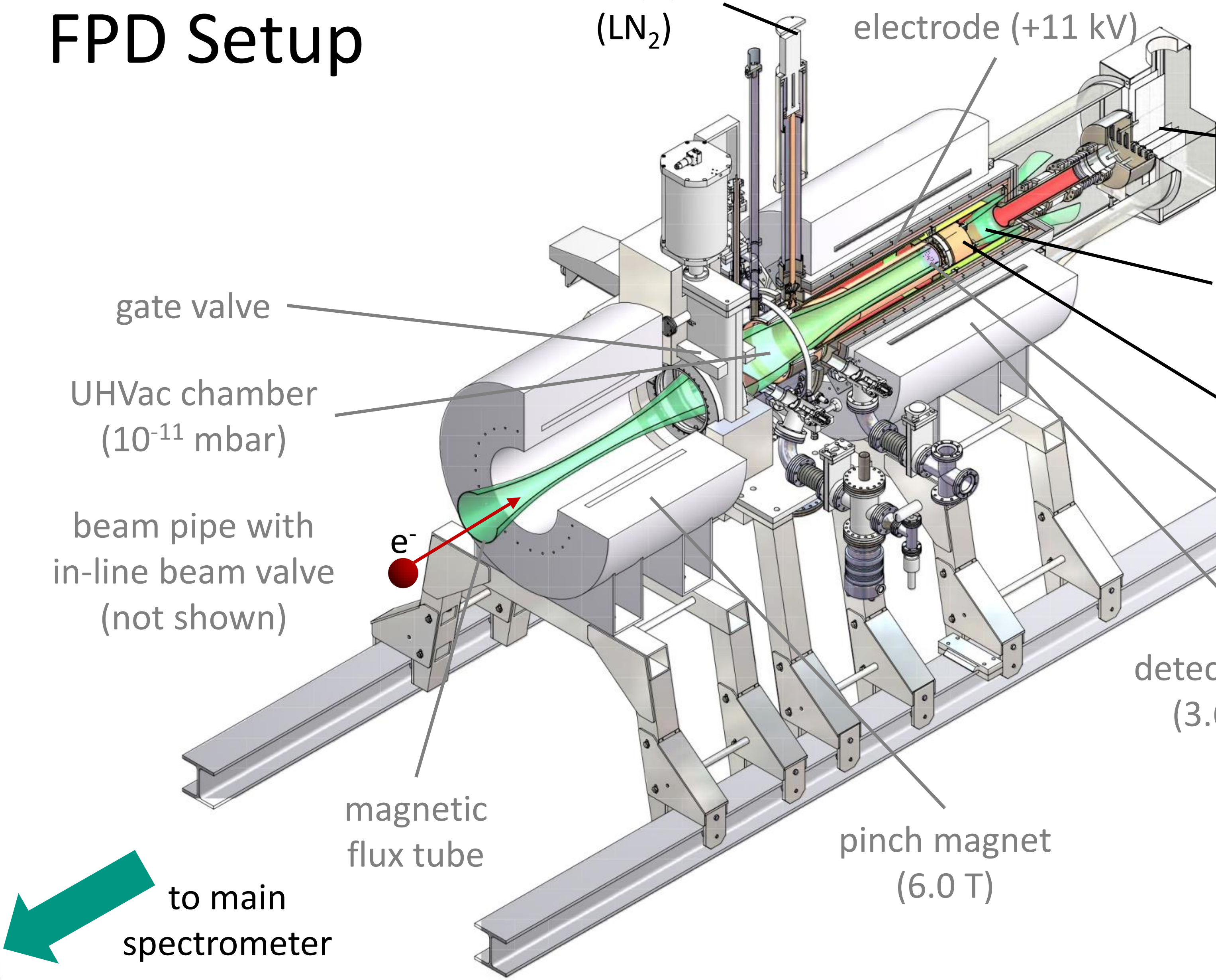
FPD Setup


post-acceleration
electrode (+11 kV)
detector
wafer
detector magnet
(3.6 – 6.0 T)
e-
magnetic
flux tube
pinch magnet
(6.0 T)
to main
spectrometer

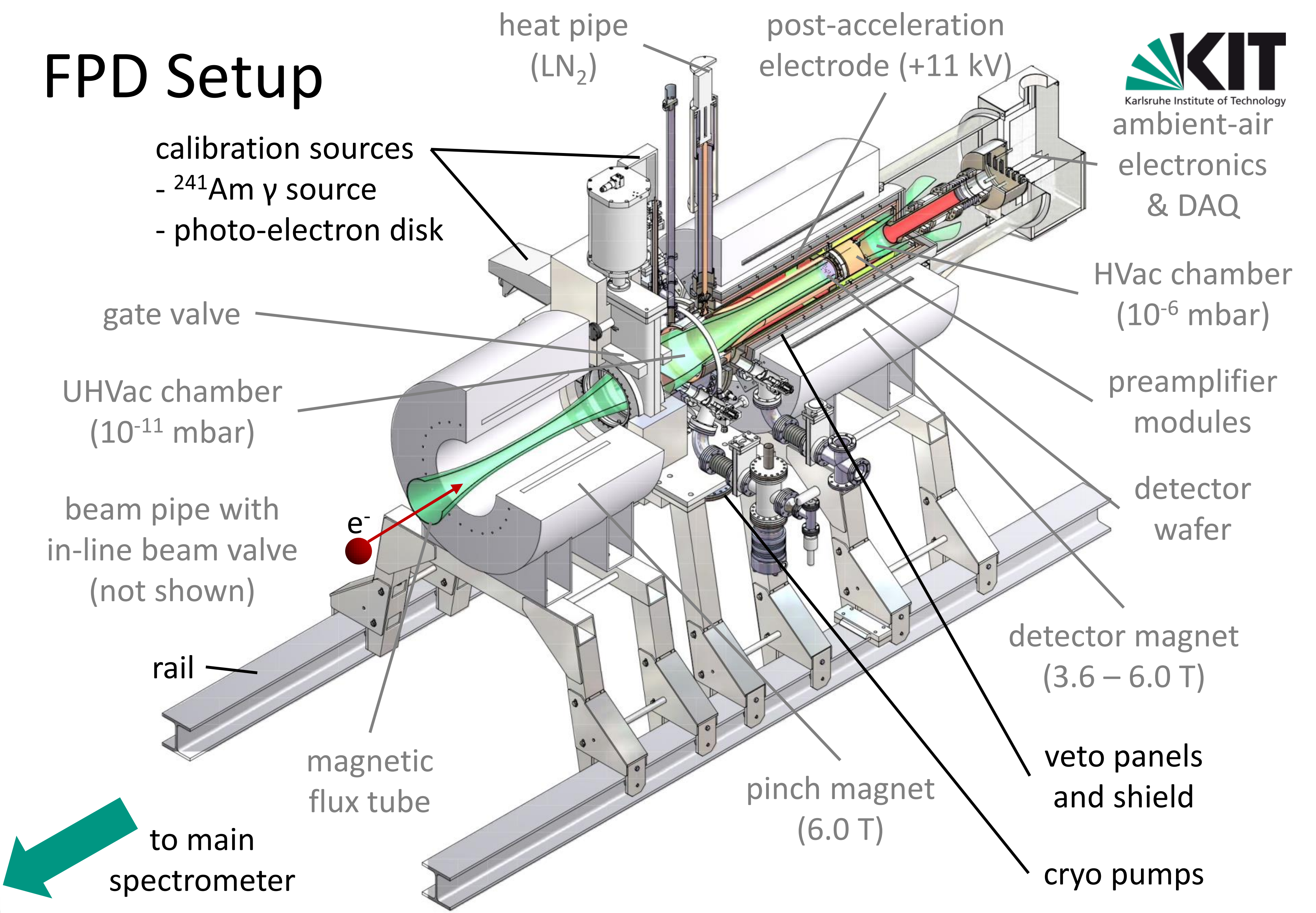
FPD Setup


post-acceleration
electrode (+11 kV)
gate valve
UHVac chamber
(10^{-11} mbar)
beam pipe with
in-line beam valve
(not shown)
e-
detector
wafer
detector magnet
(3.6 – 6.0 T)
magnetic
flux tube
pinch magnet
(6.0 T)
to main
spectrometer

FPD Setup

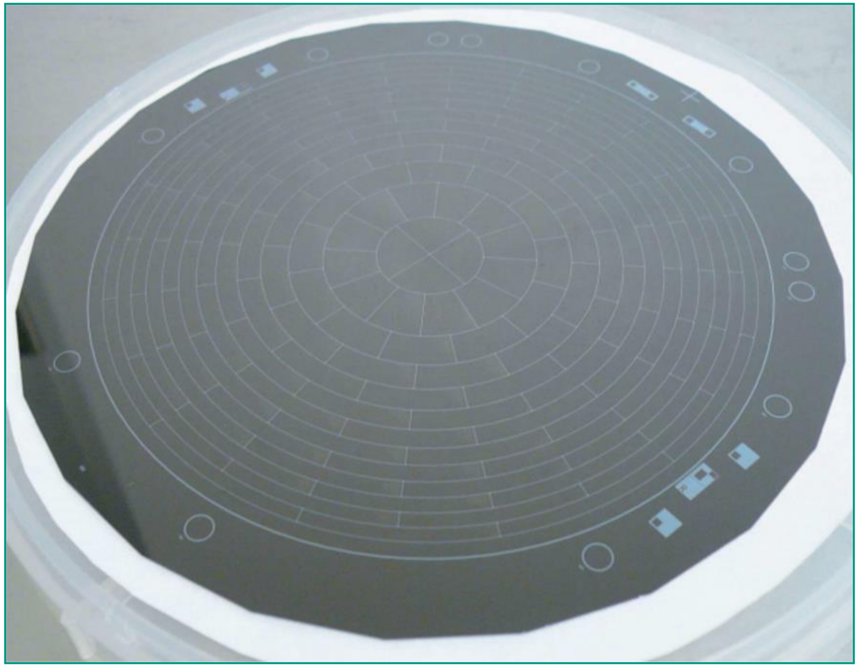

heat pipe
(LN_2)
post-acceleration
electrode (+11 kV)
ambient-air
electronics
& DAQ
HVac chamber
(10^{-6} mbar)
preamplifier
modules
detector
wafer
detector magnet
(3.6 – 6.0 T)
pinch magnet
(6.0 T)
magnetic
flux tube
gate valve
UHVac chamber
(10^{-11} mbar)
beam pipe with
in-line beam valve
(not shown)
e^-
to main
spectrometer

FPD Setup


heat pipe
(LN$_2$)
post-acceleration
electrode (+11 kV)
calibration sources
- ^{241}Am γ source
- photo-electron disk
ambient-air
electronics
& DAQ
gate valve
HVac chamber
(10^{-6} mbar)
UHVac chamber
(10^{-11} mbar)
preamplifier
modules
detector
wafer
beam pipe with
in-line beam valve
(not shown)
e^-
rail
detector magnet
(3.6 – 6.0 T)
magnetic
flux tube
pinch magnet
(6.0 T)
veto panels
and shield
cryo pumps
to main
spectrometer

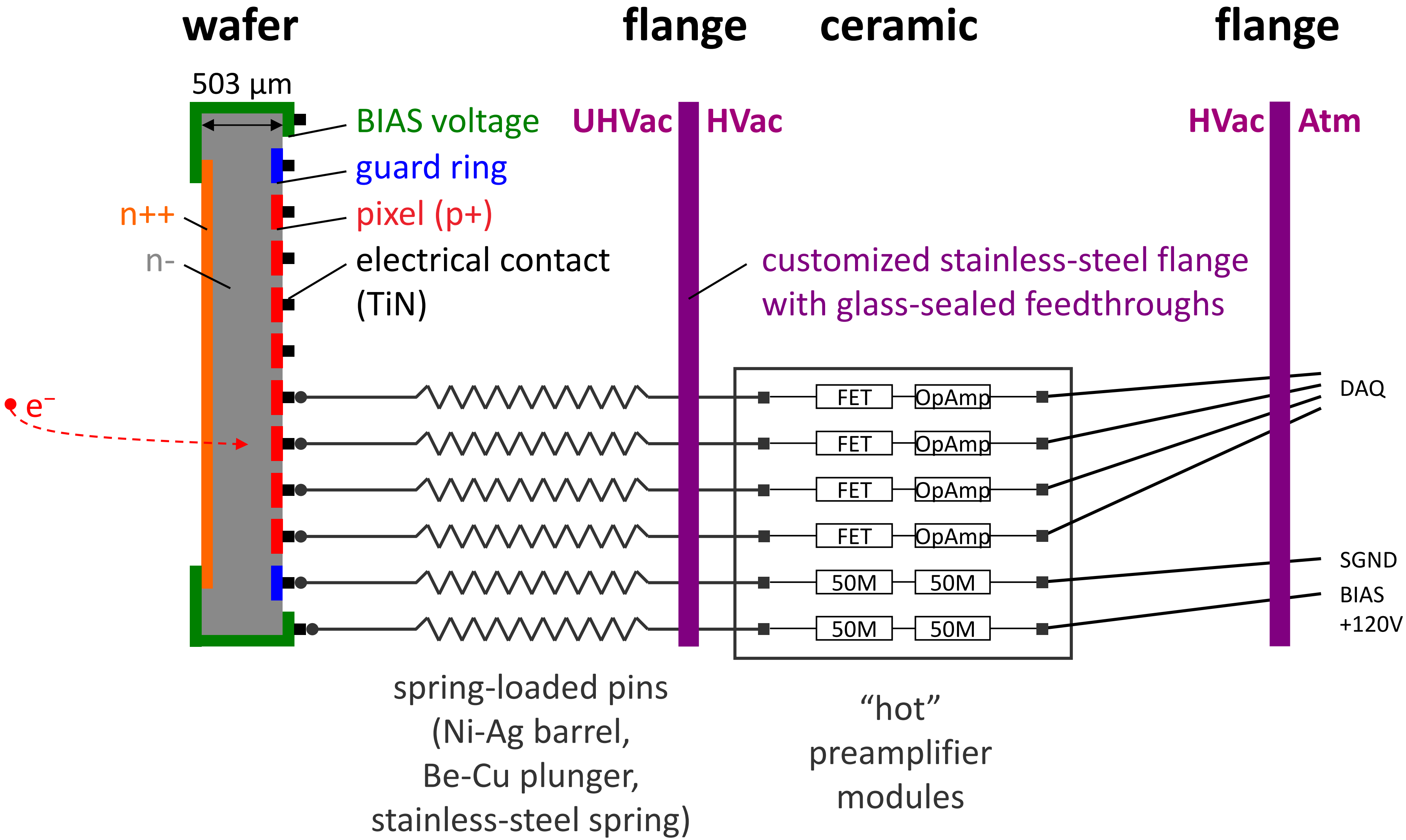
Detector Wafer

- Monolithic 148-pixel Si PIN diode by Canberra Belgium
- Thickness: 503 µm
- Diameter: 125 mm
  - Sensitive diameter: 90.0 mm
  - Guard ring: 2.0 mm
  - Bias ring: 15.5 mm
- Crystal orientation: <111>
- Unsegmented n^{++}-type side with ≈ 100-nm dead layer
- Segmented p^{+}-type side
  - A_{Pixel} = 44 mm², C_{Pixel} = 8.2 pF
  - Pixels separated by 50 µm with R > 1 GΩ
  - Non-oxidizing TiN coating for electrical connections



▲ detector wafer (segmented back side)

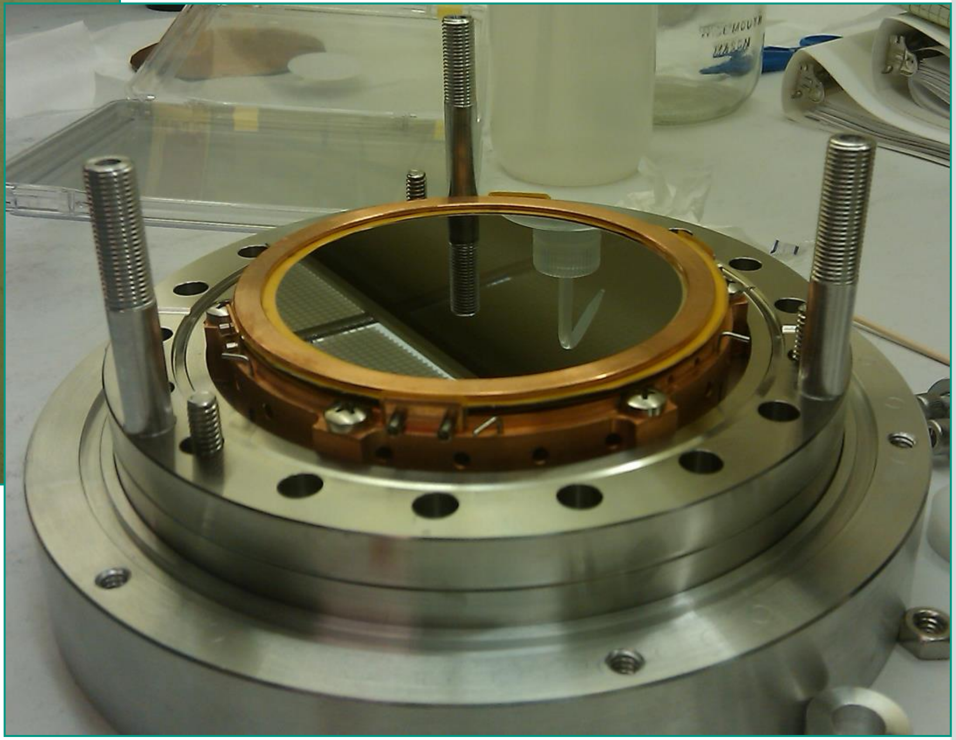
Detector Wafer

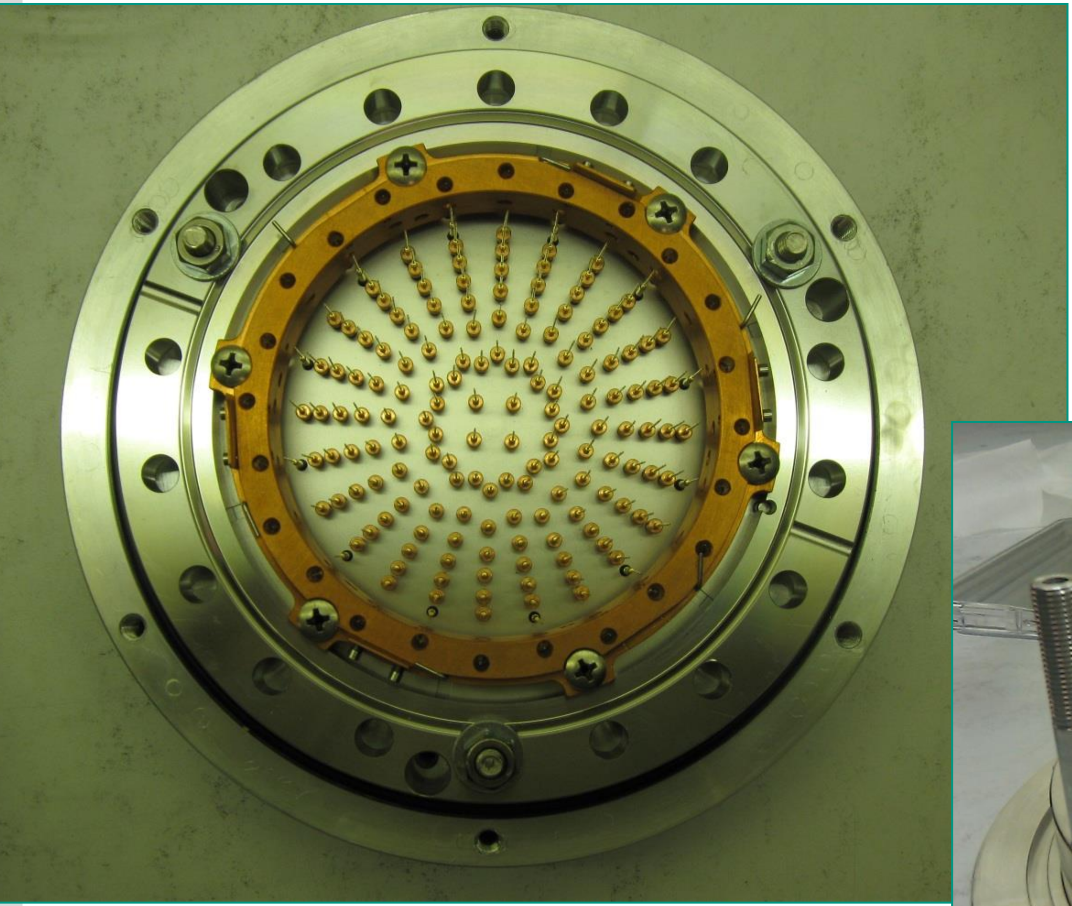


Detector Wafer

spring-loaded pin

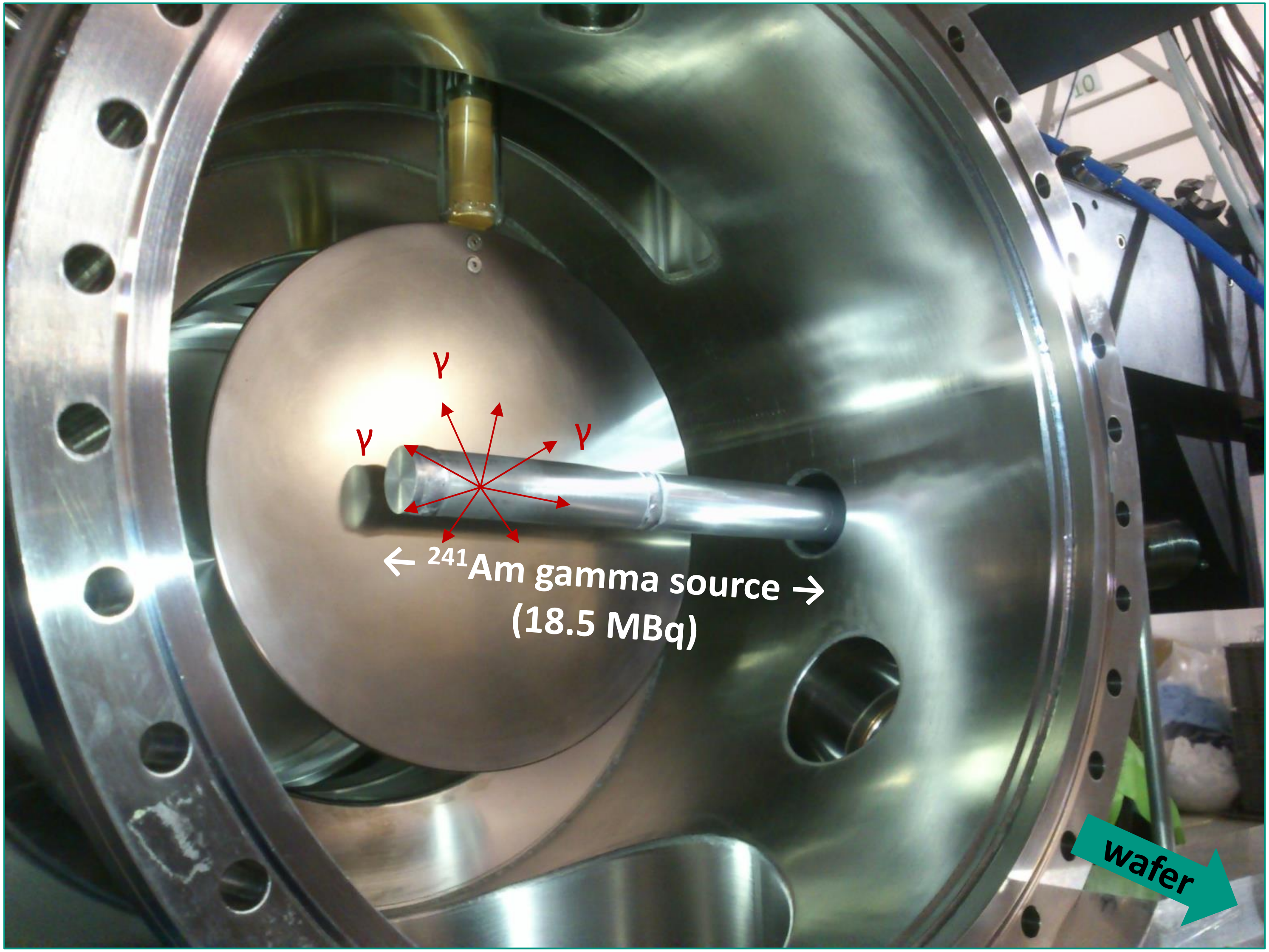
detector wafer mounted on feedthrough flange



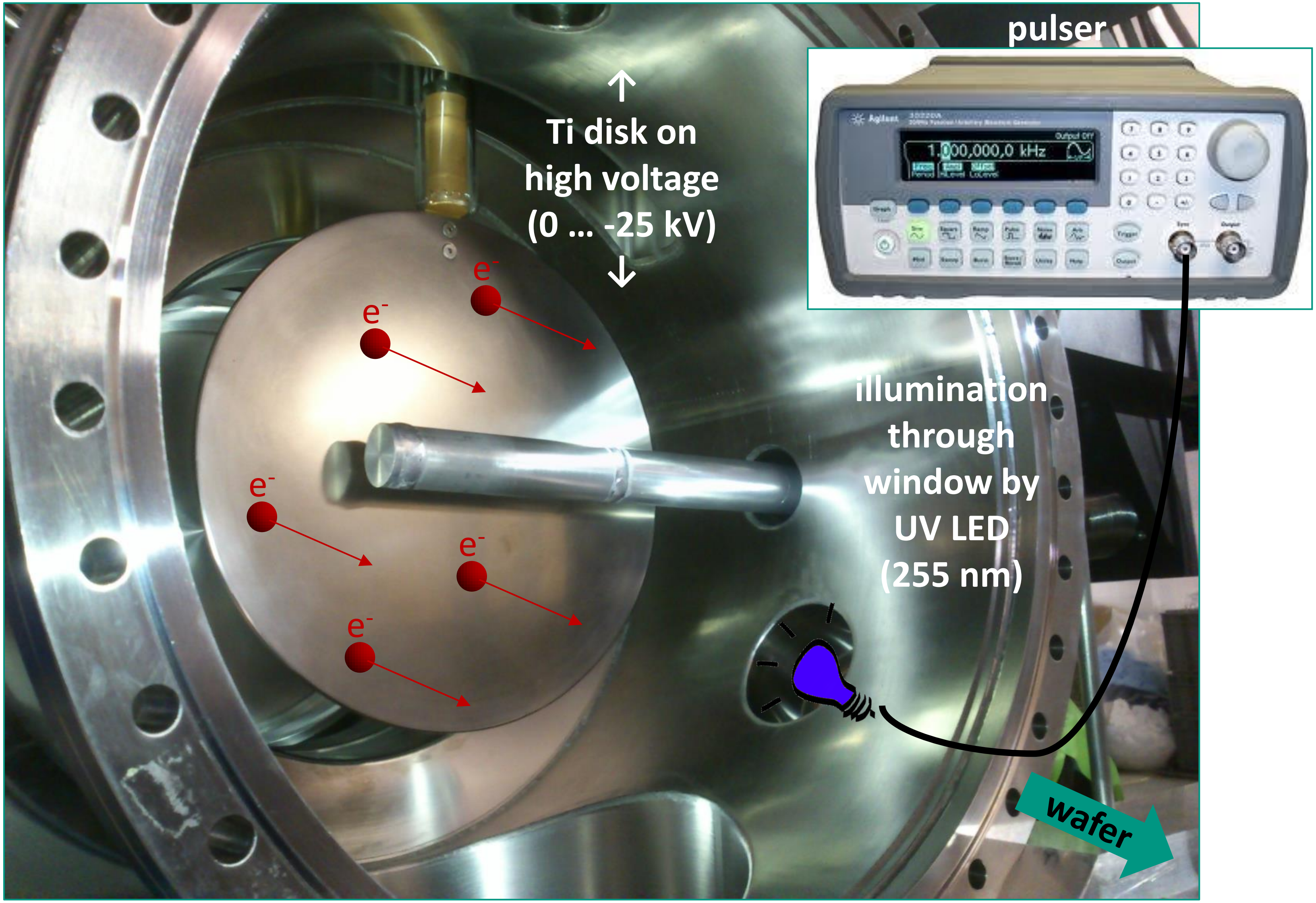


feedthrough flange (front side) with 184 spring-loaded pins (148 pixels, 12 guard-ring contacts, 24 bias-ring contacts) + shielding

Calibration Sources

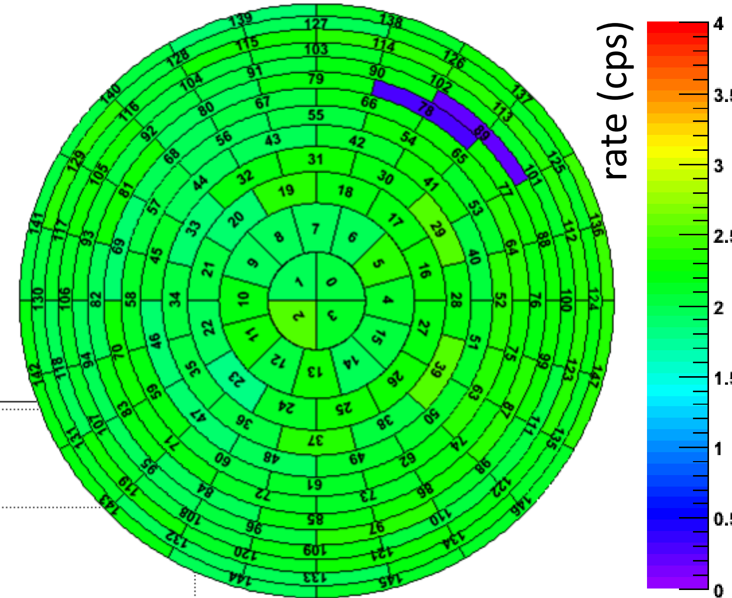


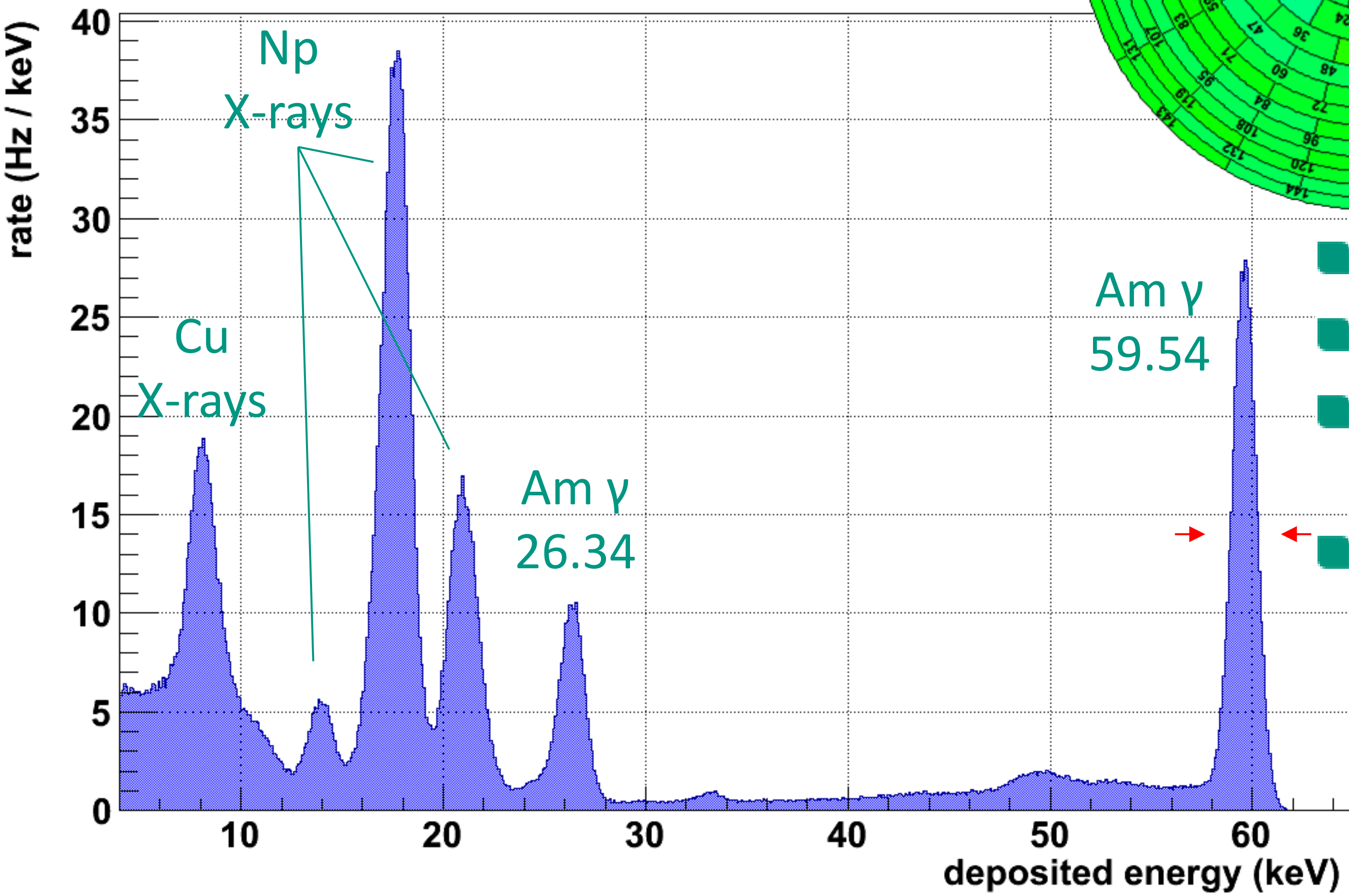
Calibration Sources



Energy Calibration

Detector response on ^{241}Am source

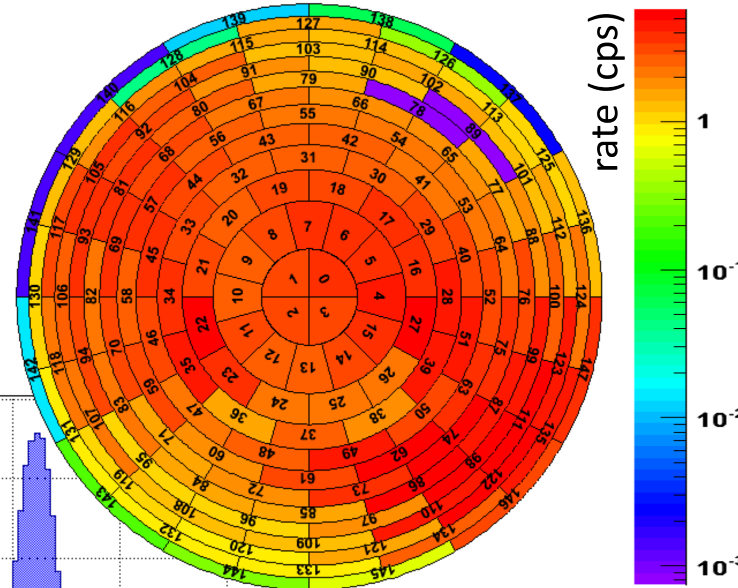


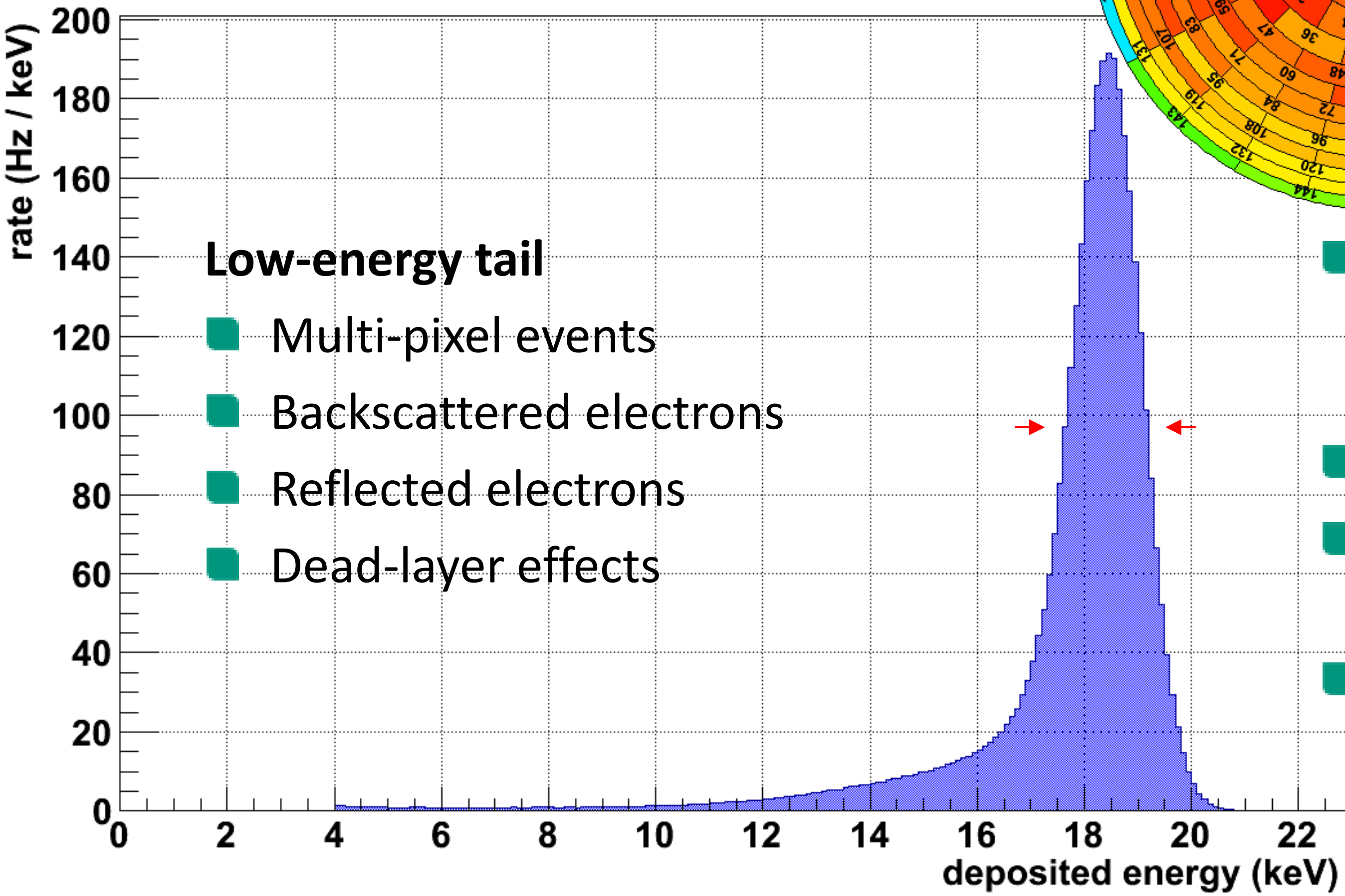


- 146 working pixels
- Hit rate: ≈ 300 cps
- Energy threshold: 3 – 4 keV
- Energy resolution at 59.54 keV: $\Delta E = 1.40 \pm 0.01$ keV (FWHM)

Energy Resolution

Detector response on 18.6-keV photo-electrons
at nominal magnetic field





Low-energy tail

- Multi-pixel events
- Backscattered electrons
- Reflected electrons
- Dead-layer effects

- Few outer pixels show no response
  ➔ Misalignment
- Variable hit rate
- Homogeneity of illumination: ≈ 1:10
- Energy resolution at 18.6 keV:
  $\Delta E = 1.65 \pm 0.05$ keV (FWHM)

Energy Resolution

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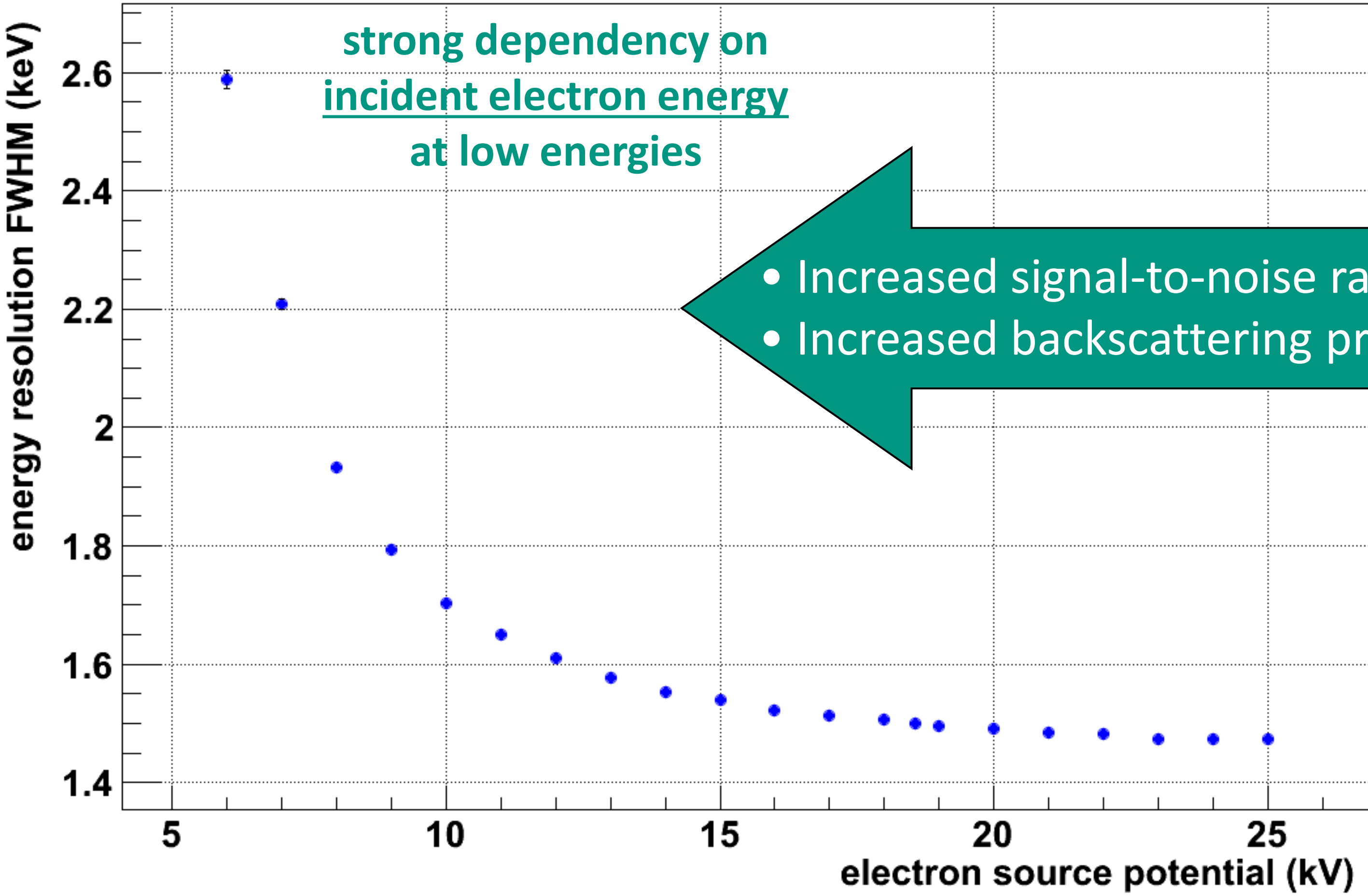
Detector response on mono-energetic photo-electrons at nominal magnetic field

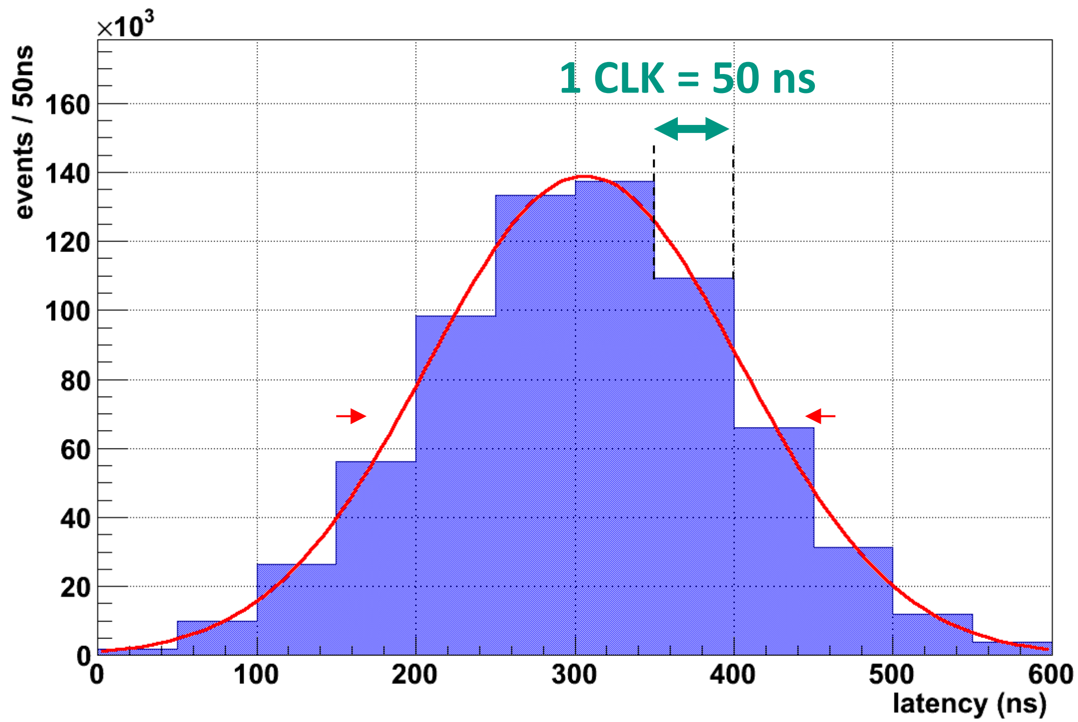


strong dependency on <u>incident electron energy</u> at low energies

- Increased signal-to-noise ratio
- Increased backscattering probability

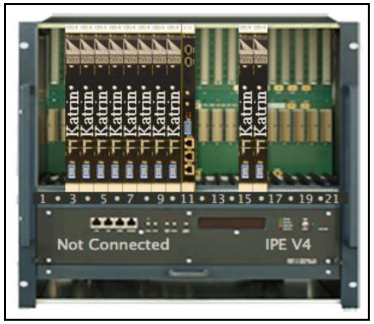
Time Resolution

Detector response on 18.6-keV photo-electrons
at nominal magnetic field



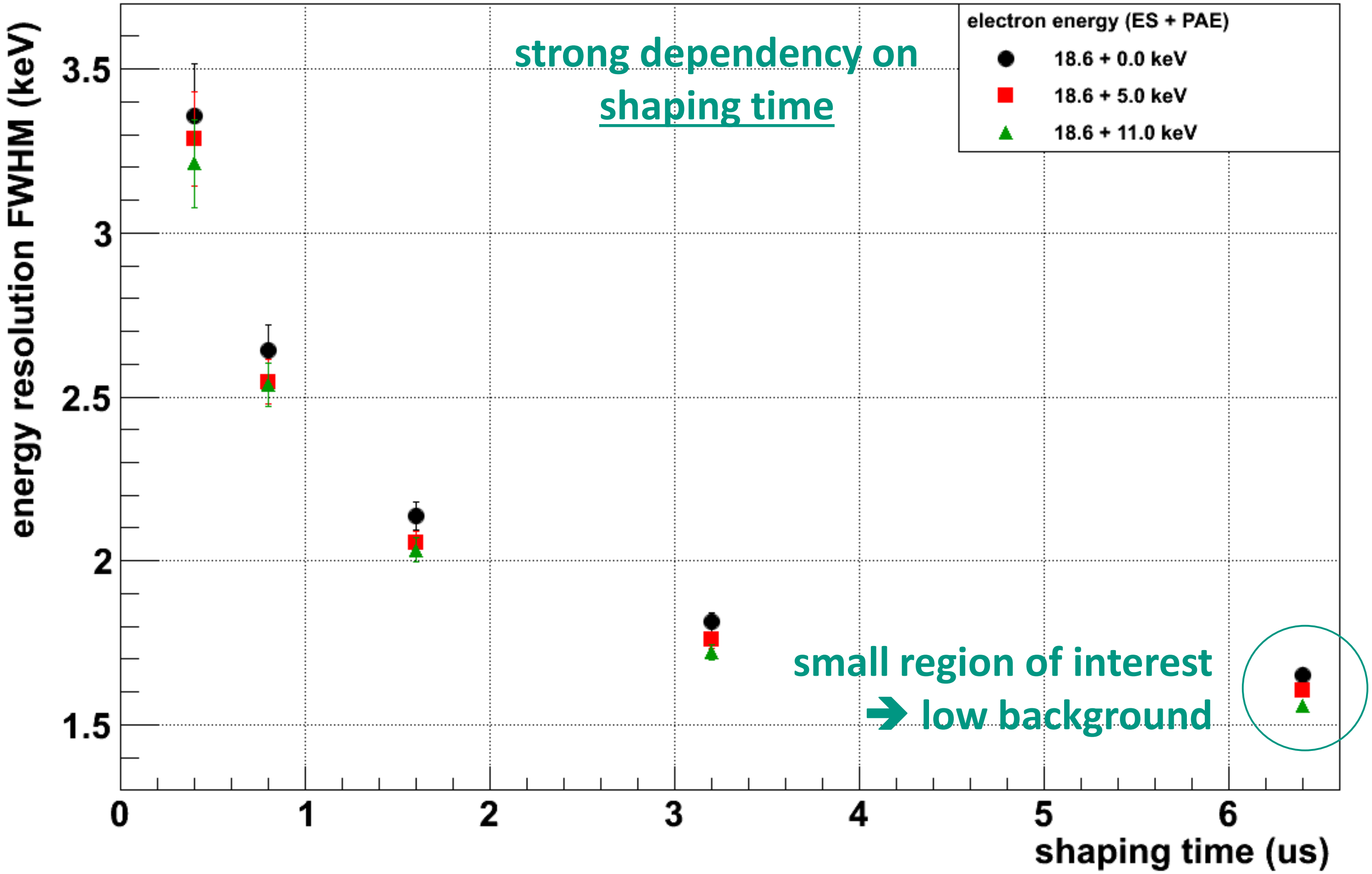
Δt = 232.3 ± 0.2 ns (FWHM)
latency = 306.1 ± 0.1 ns

DAQ system:
20 MHz sampling
12 bit ADCs



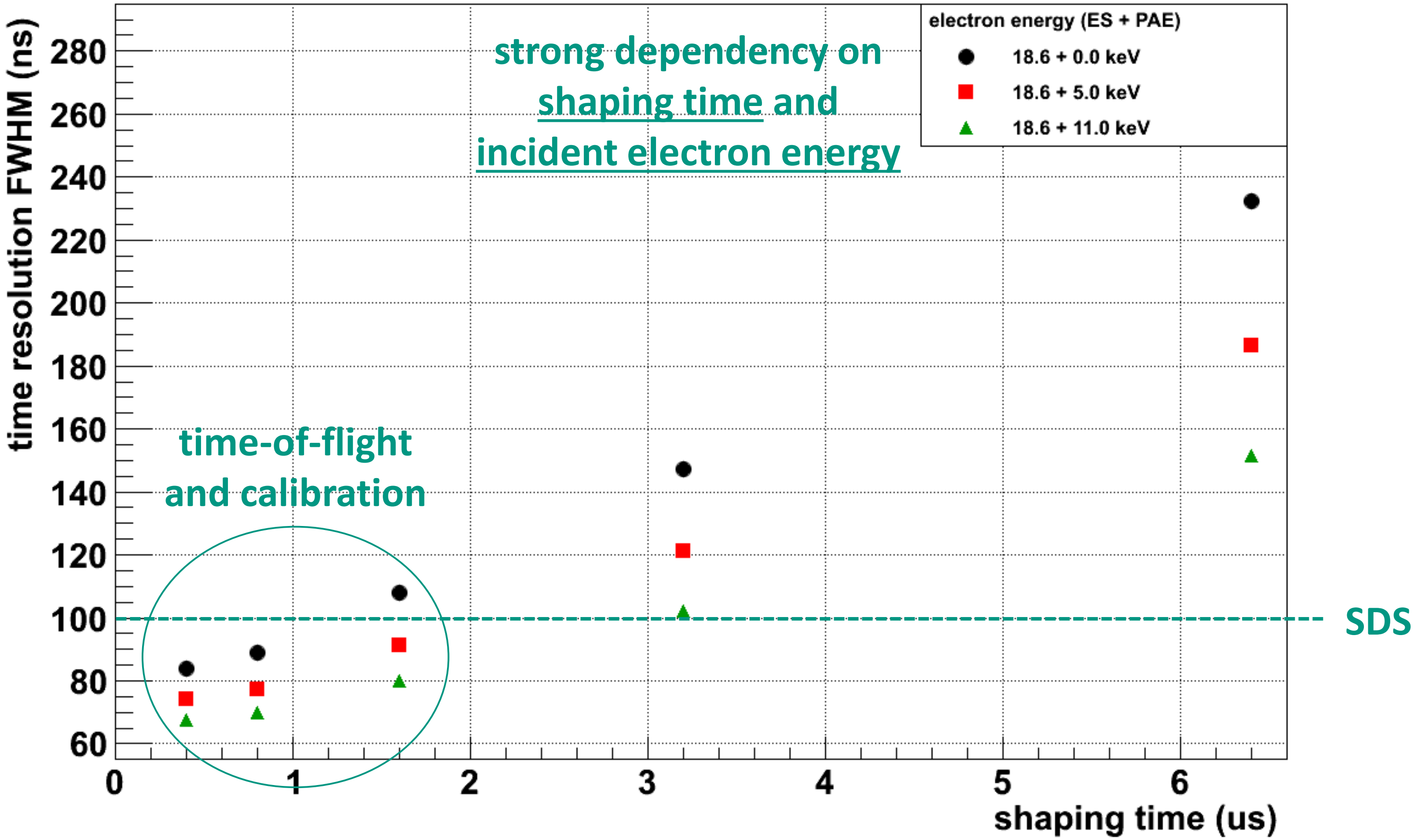
Optimization: Energy Resolution

Detector response on mono-energetic photo-electrons at nominal magnetic field

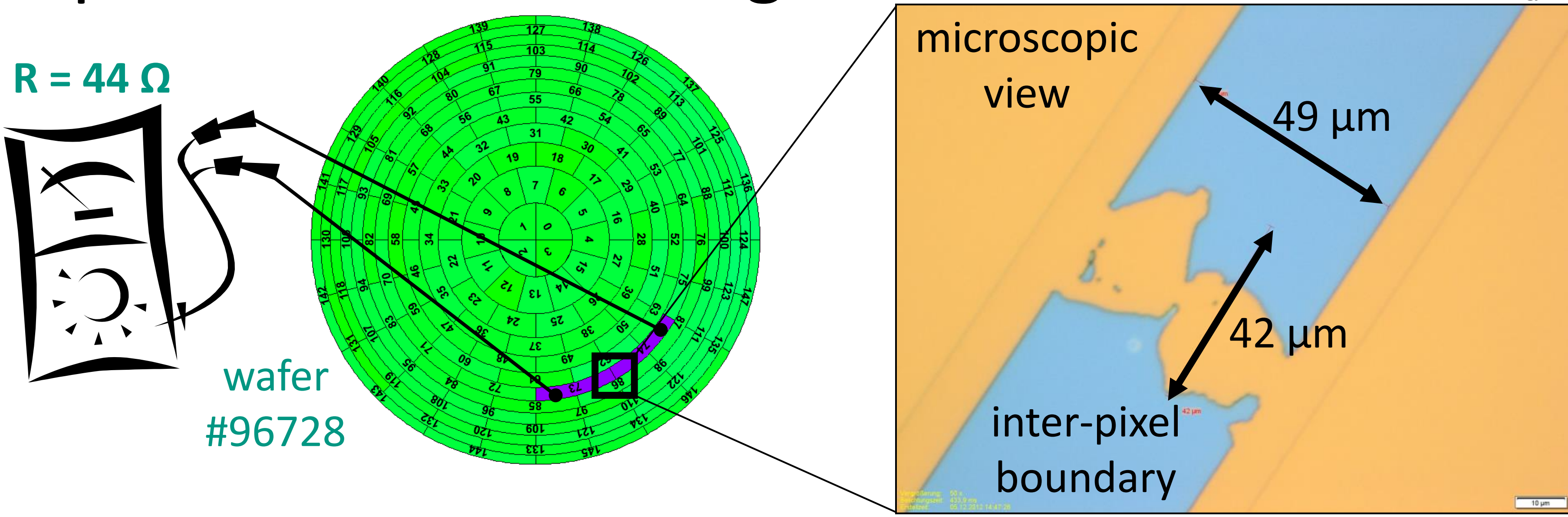


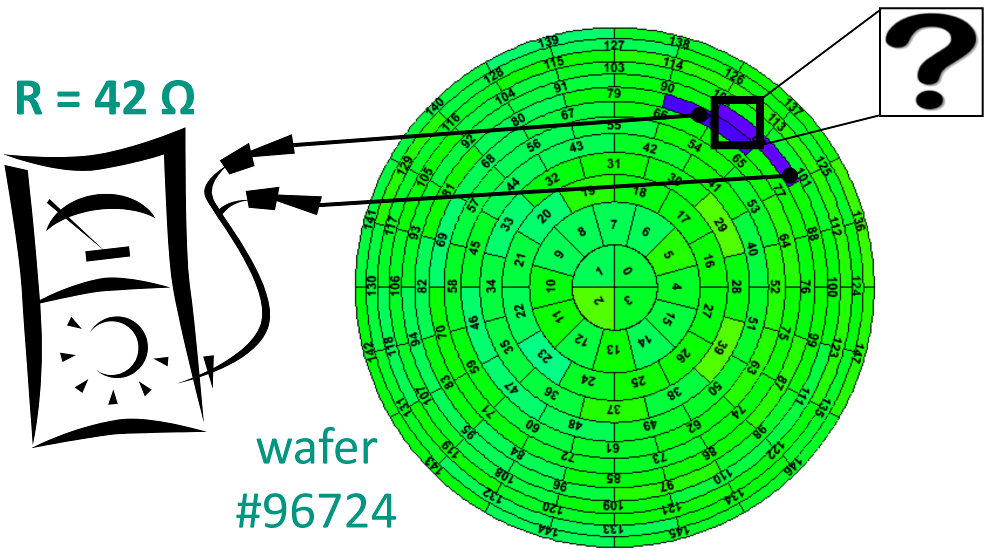
Optimization: Time Resolution

Detector response on mono-energetic photo-electrons at nominal magnetic field



Optimization: Working Pixels





	wafer	nonworking channels
UW	#96728	17
KIT I	#96728	19
KIT II	#96728	2
KIT III	#96724	2

Intrinsic Detector Background

PAE = 0 kV
83.3 hours

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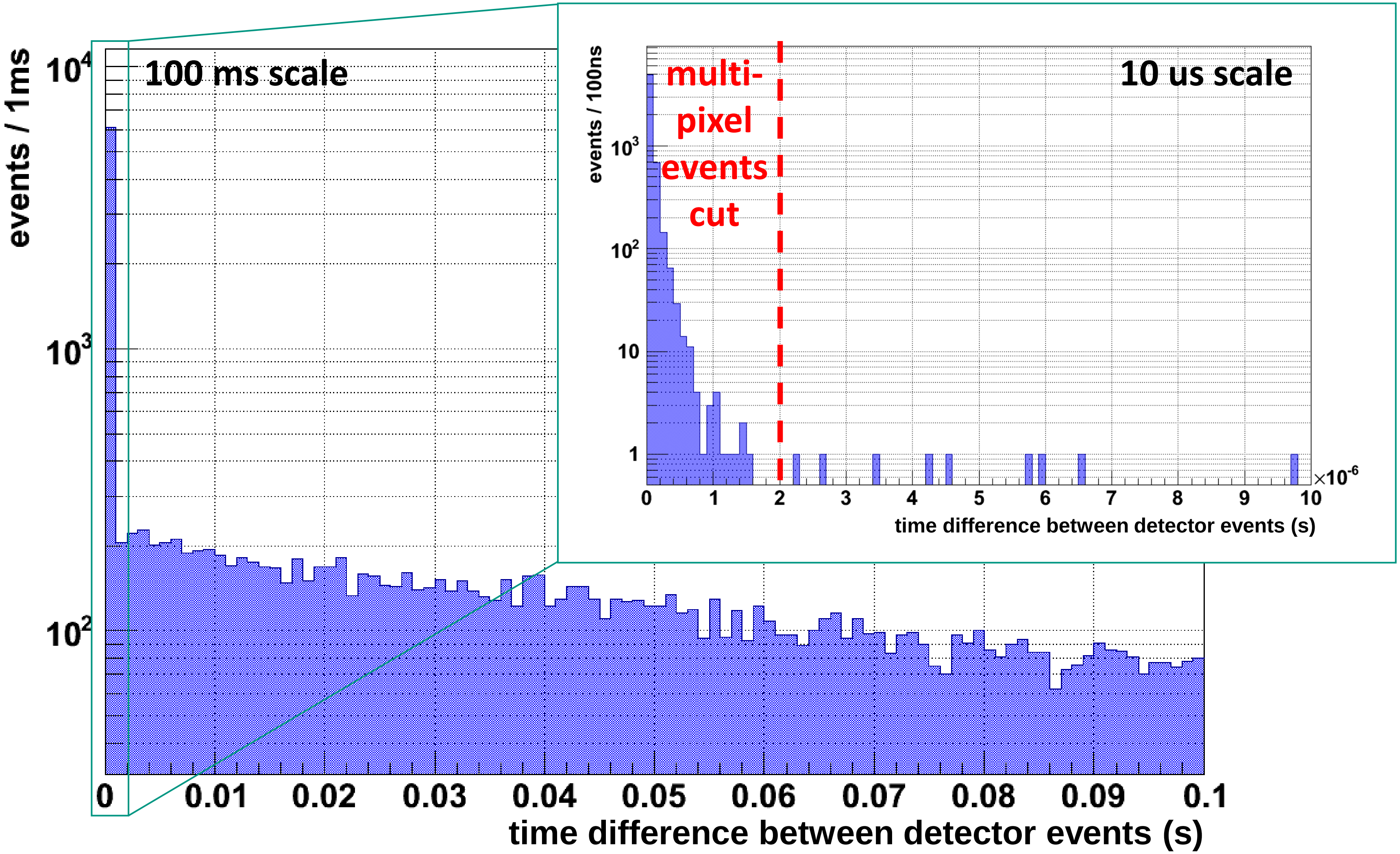

Intrinsic Detector Background

PAE = 0 kV
83.3 hours

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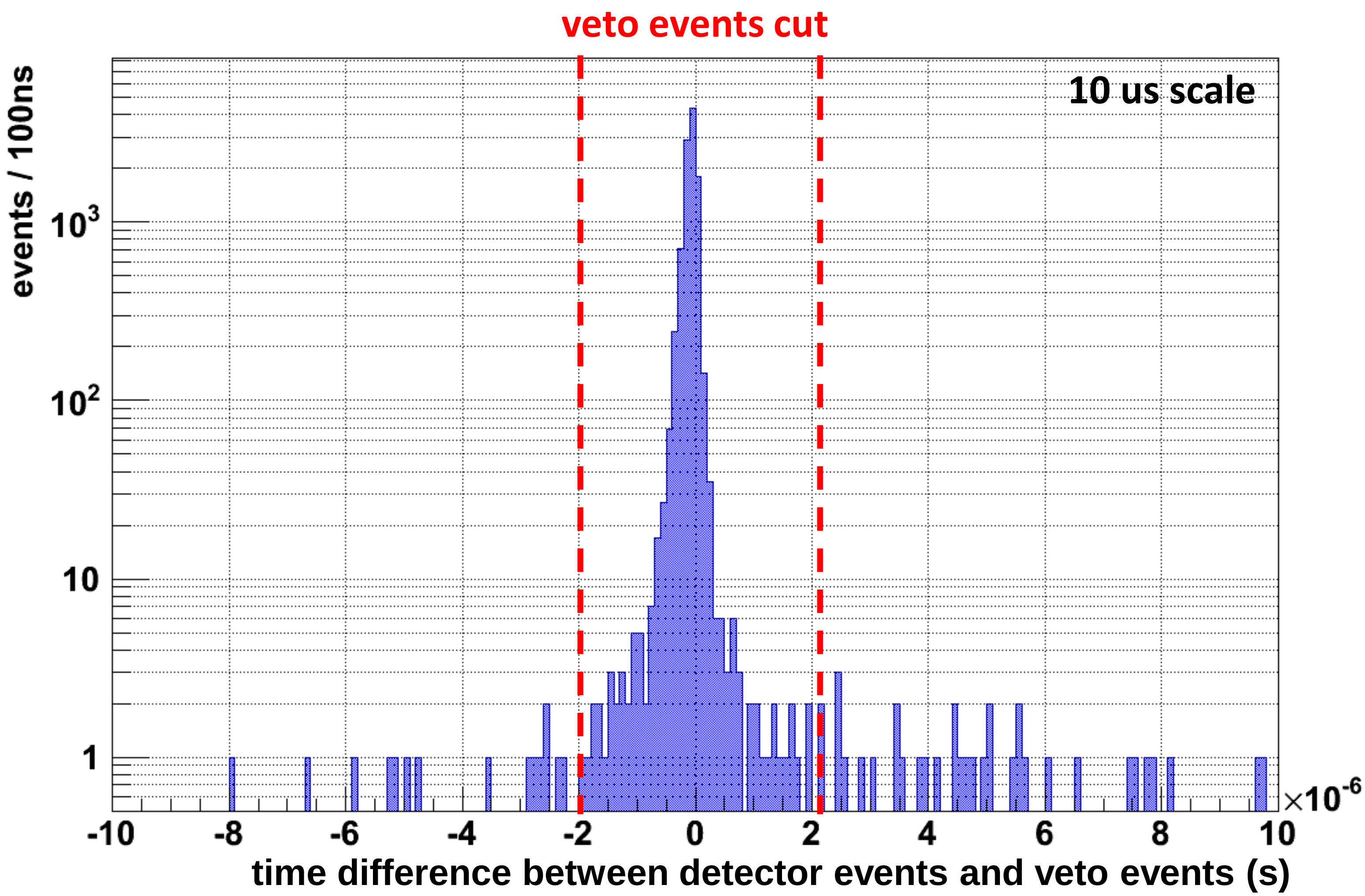
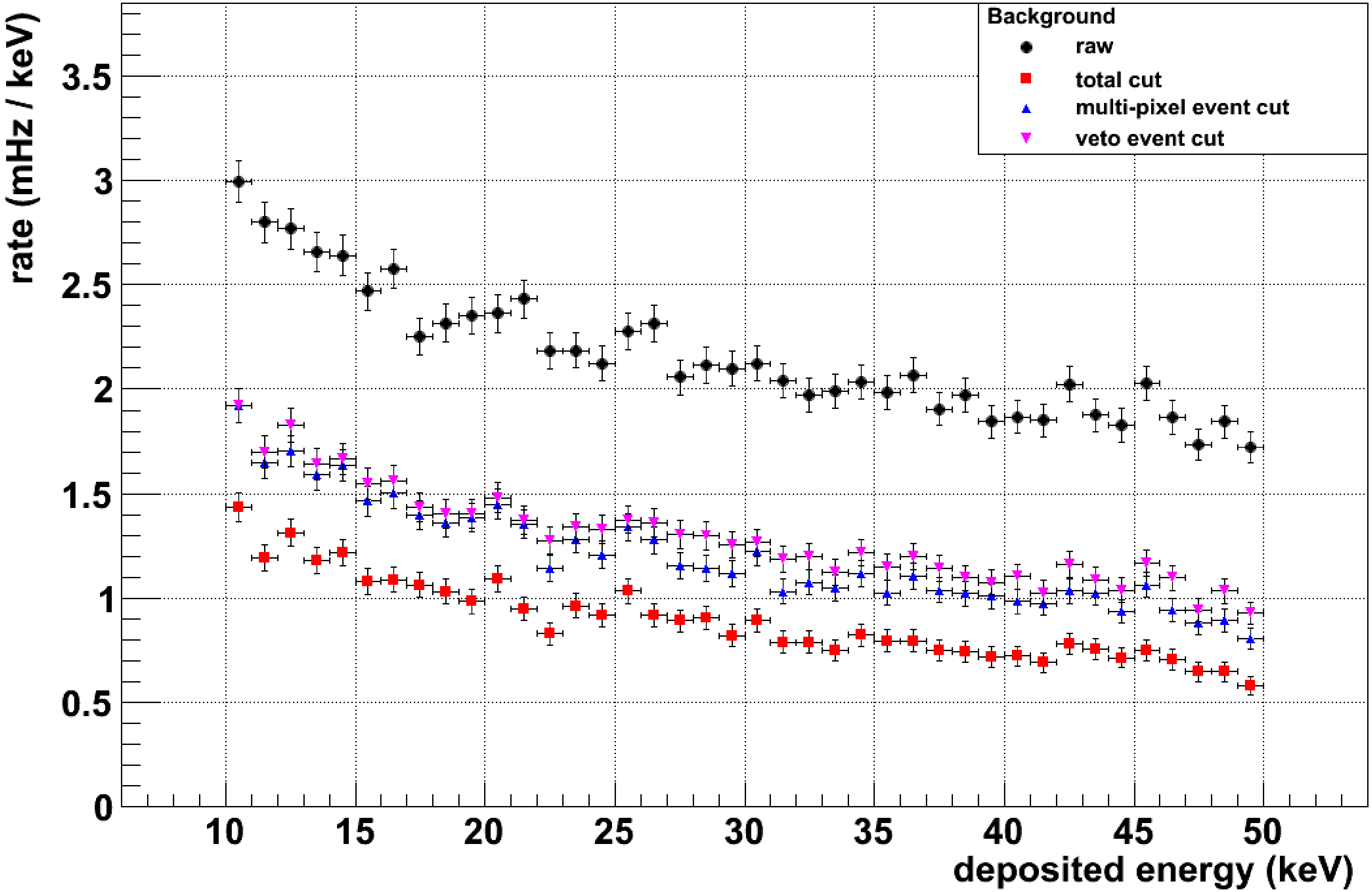


Intrinsic Detector Background

PAE = 0 kV
83.3 hours



Intrinsic Detector Background

PAE = 11 kV
64.0 hours

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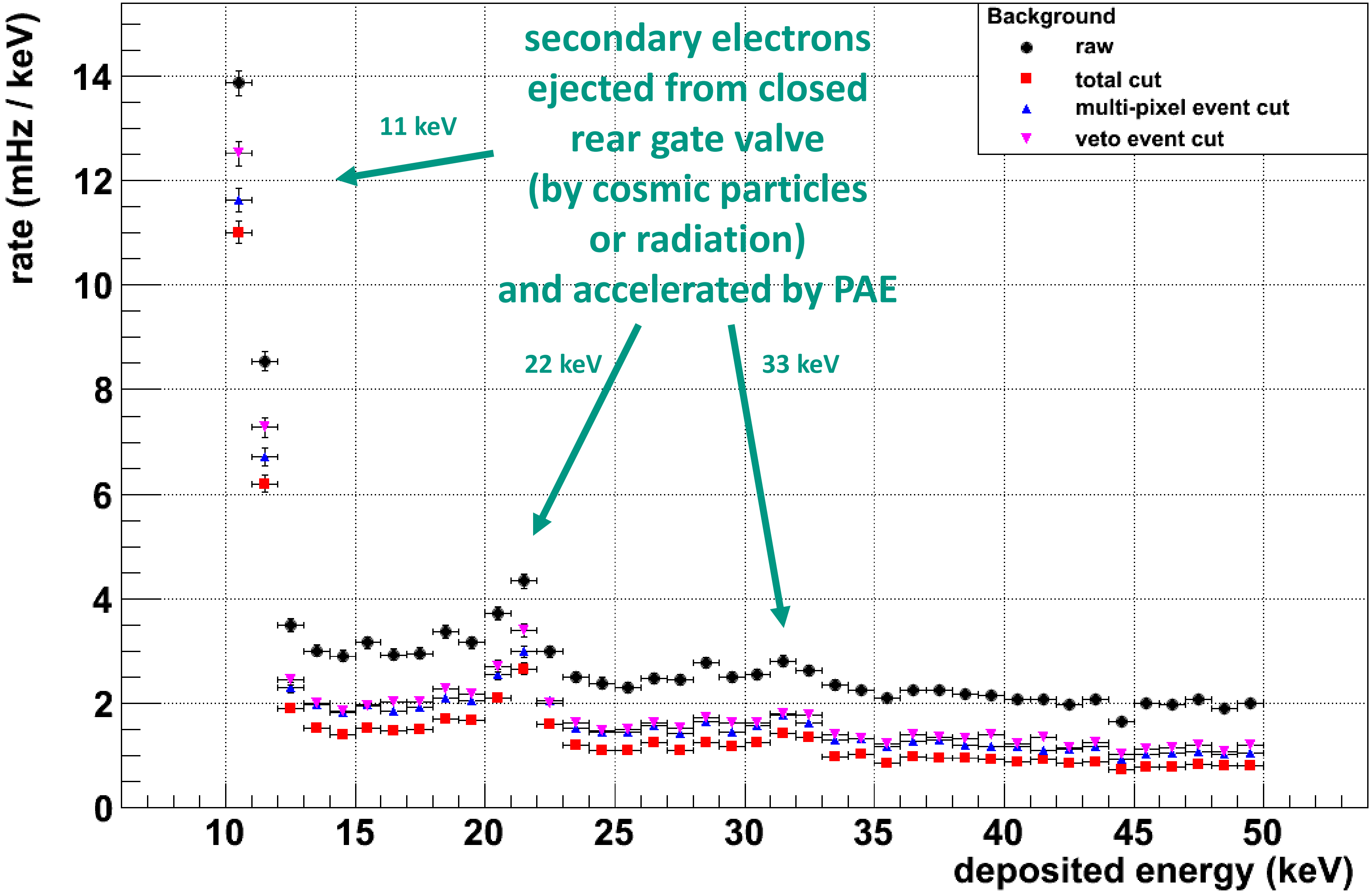

Figure Of Demerit

Statistical uncertainty for m_ν^2 for a given region of interest (ROI):

$$\sigma(m_{\bar{\nu}}^2) = \frac{k b_{ms}^{1/6}}{r^{2/3} t^{1/2}} \underbrace{\frac{\left(f(E_L, E_U) + \frac{b_{det}(E_L, E_U)}{b_{ms}}\right)^{1/6}}{f(E_L, E_U)^{2/3}}}_{\text{Figure of demerit F}}$$

$k = (16/27)^{1/6}$

b_{ms} = background main spectrometer (assumed to be 10 mHz)

r = normalized KATRIN count rate in Hz/eV³

t = KATRIN run time in s

f = fraction of measured electron spectrum

(E_L, E_U) = ROI, lower bound, upper bound

b_{det} = intrinsic detector background

tradeoff between **energy resolution** and **background**

Figure Of Demerit

ideal detector:
f = 1 and b_{det} = 0 → F = 1

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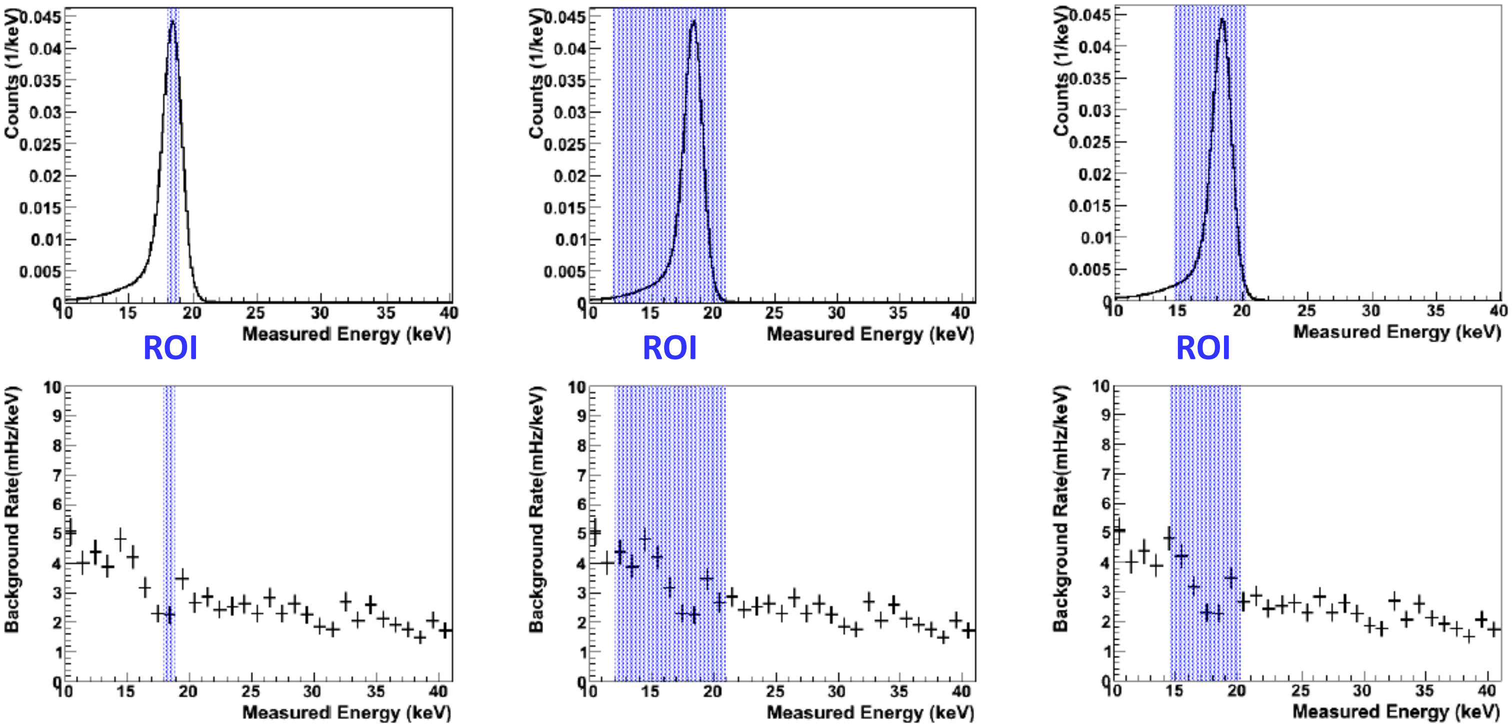
- Minimizing: $$F(E_L, E_U) = \frac{\left(f(E_L, E_U) + \frac{b_{det}(E_L, E_U)}{b_{ms}}\right)^{1/6}}{f(E_L, E_U)^{2/3}} \geq 1$$
- Principle:

normalized 18.6-keV (+ PAE) electron spectrum

background spectrum



ROI	too small	too large	optimum
F	large	large	minimum

Figure Of Demerit

PAE = 0 kV
83.3 hours

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BG	F	E_L (keV)	E_U (keV)	b_{det} (mHz)	f
raw	1.196 ± 0.002	15.27 ± 0.010	19.92 ± 0.010	11.10 ± 0.19	0.912
cut	1.122 ± 0.002	14.63 ± 0.010	20.04 ± 0.010	5.68 ± 0.14	0.932

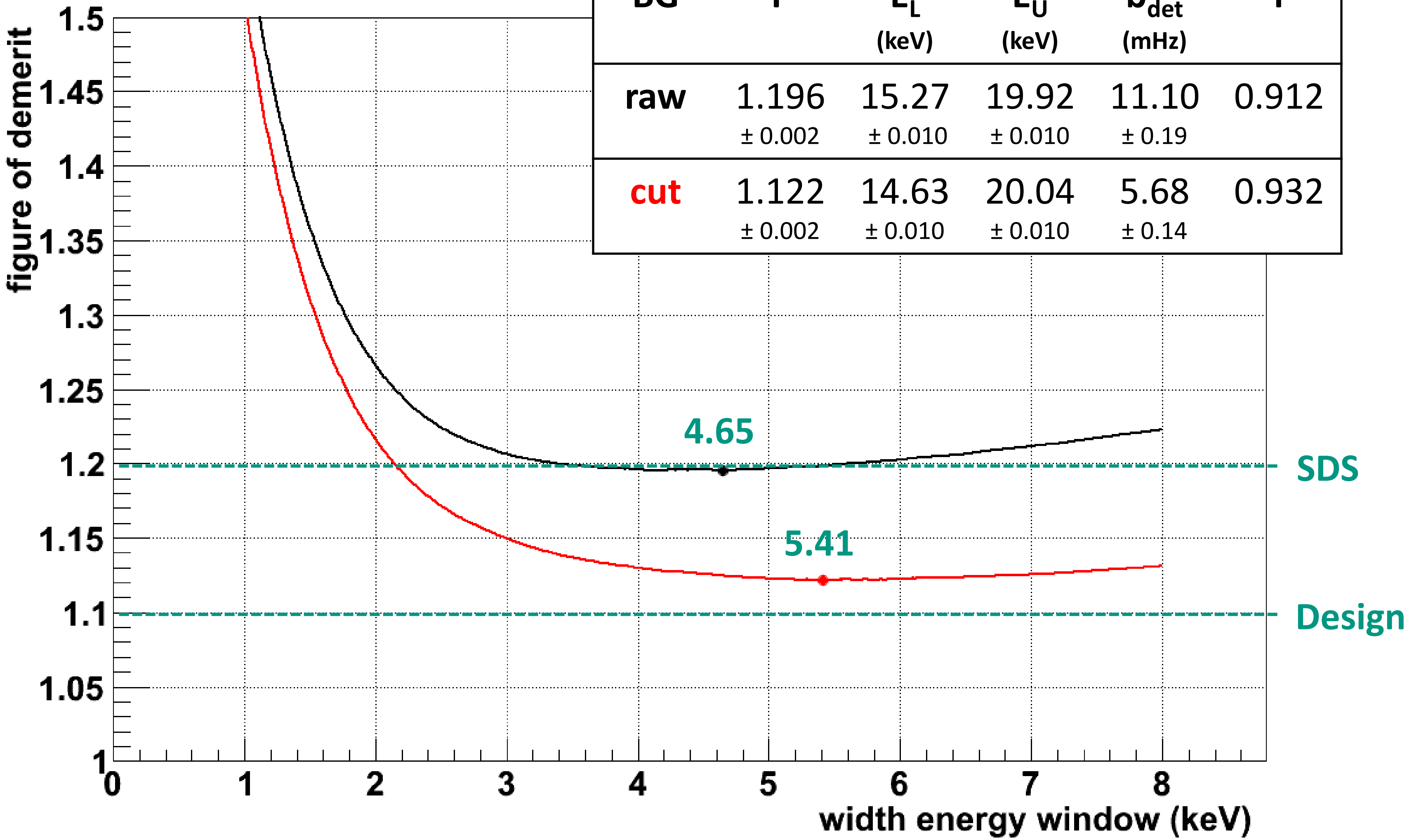
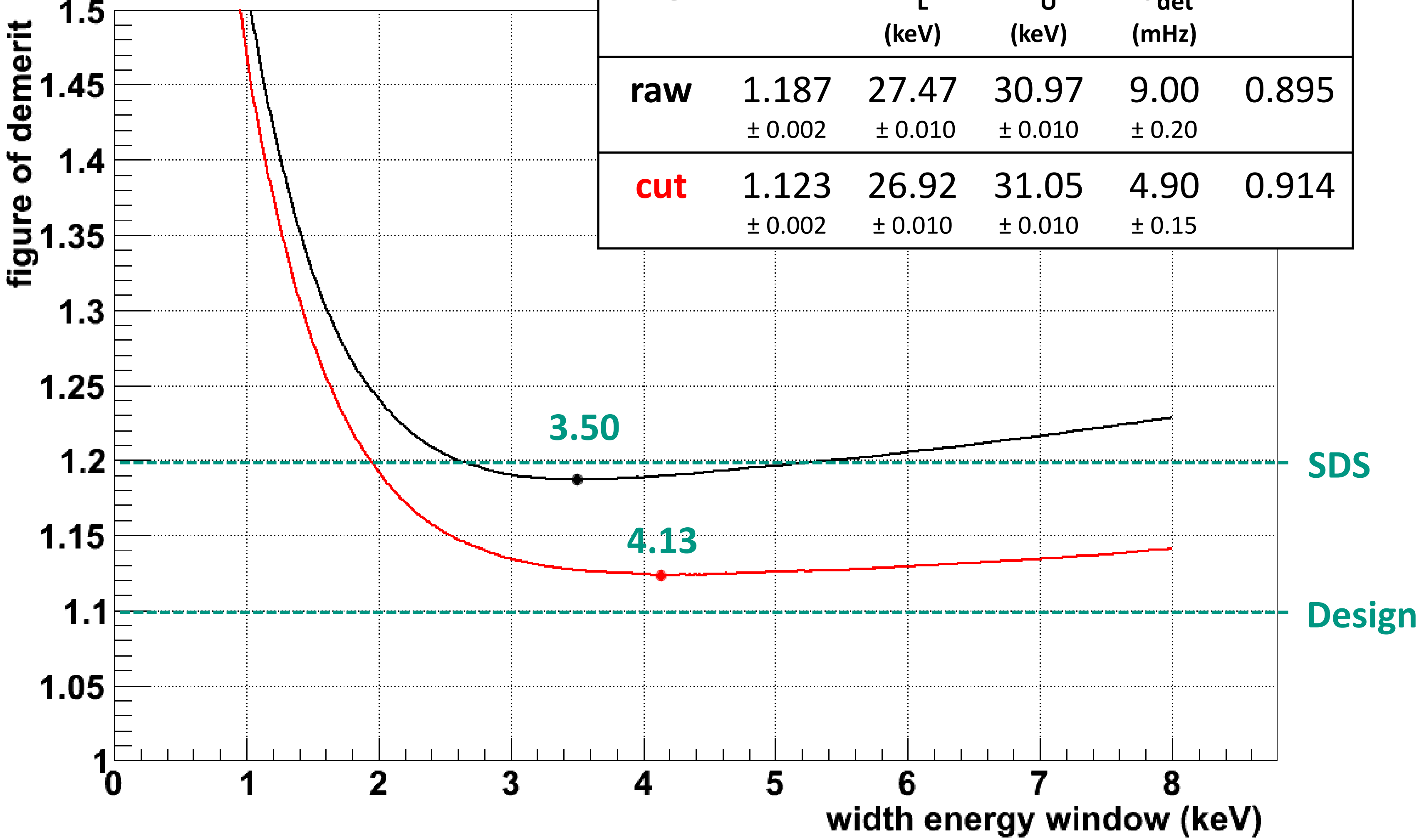


Figure Of Demerit

PAE = 11 kV
64.0 hours

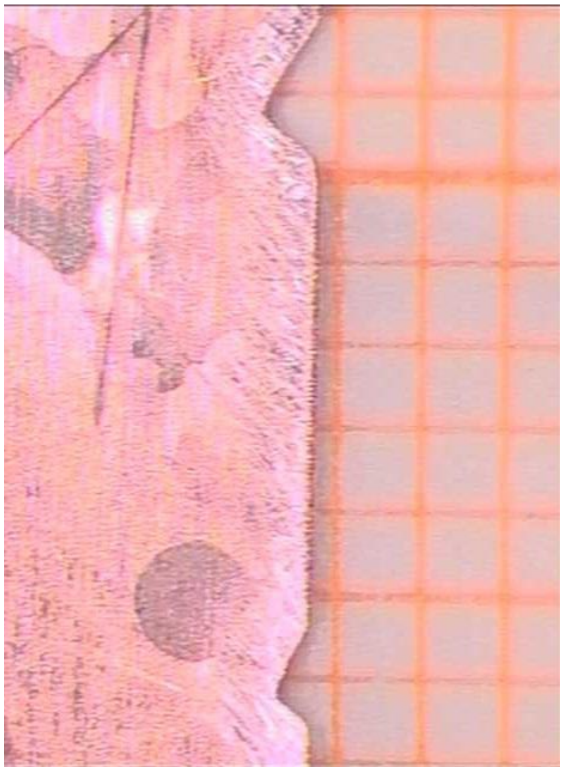
BG	F	E_L (keV)	E_U (keV)	b_{det} (mHz)	f
raw	1.187 ± 0.002	27.47 ± 0.010	30.97 ± 0.010	9.00 ± 0.20	0.895
cut	1.123 ± 0.002	26.92 ± 0.010	31.05 ± 0.010	4.90 ± 0.15	0.914



Main-Spectrometer Background Sources

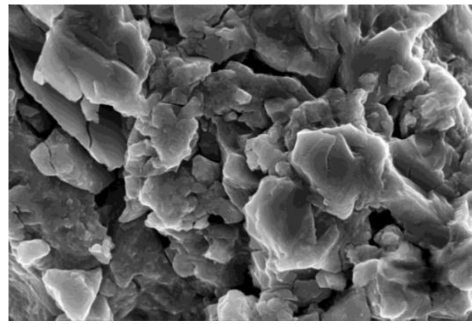
FIELD EMISSION

E > 10^9 V/m

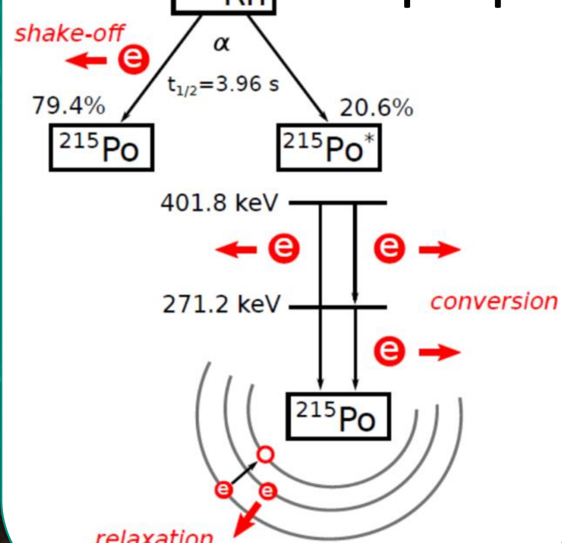


wire module

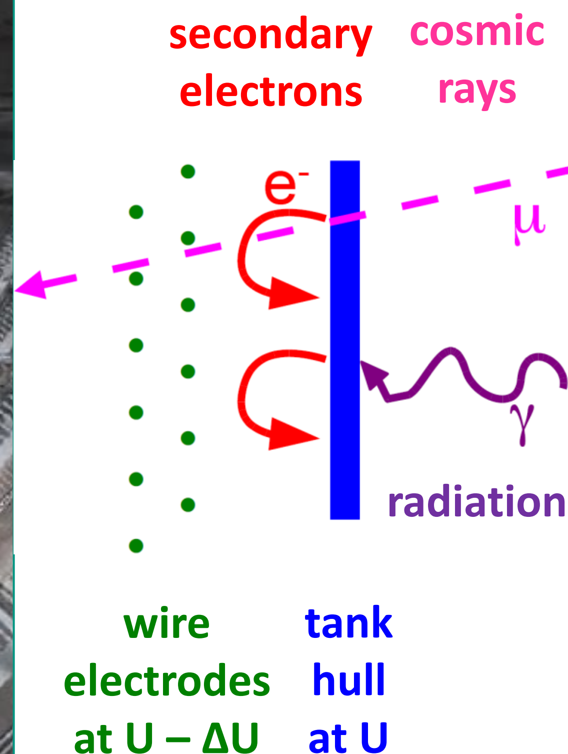
RADON INDUCED



NEG pump



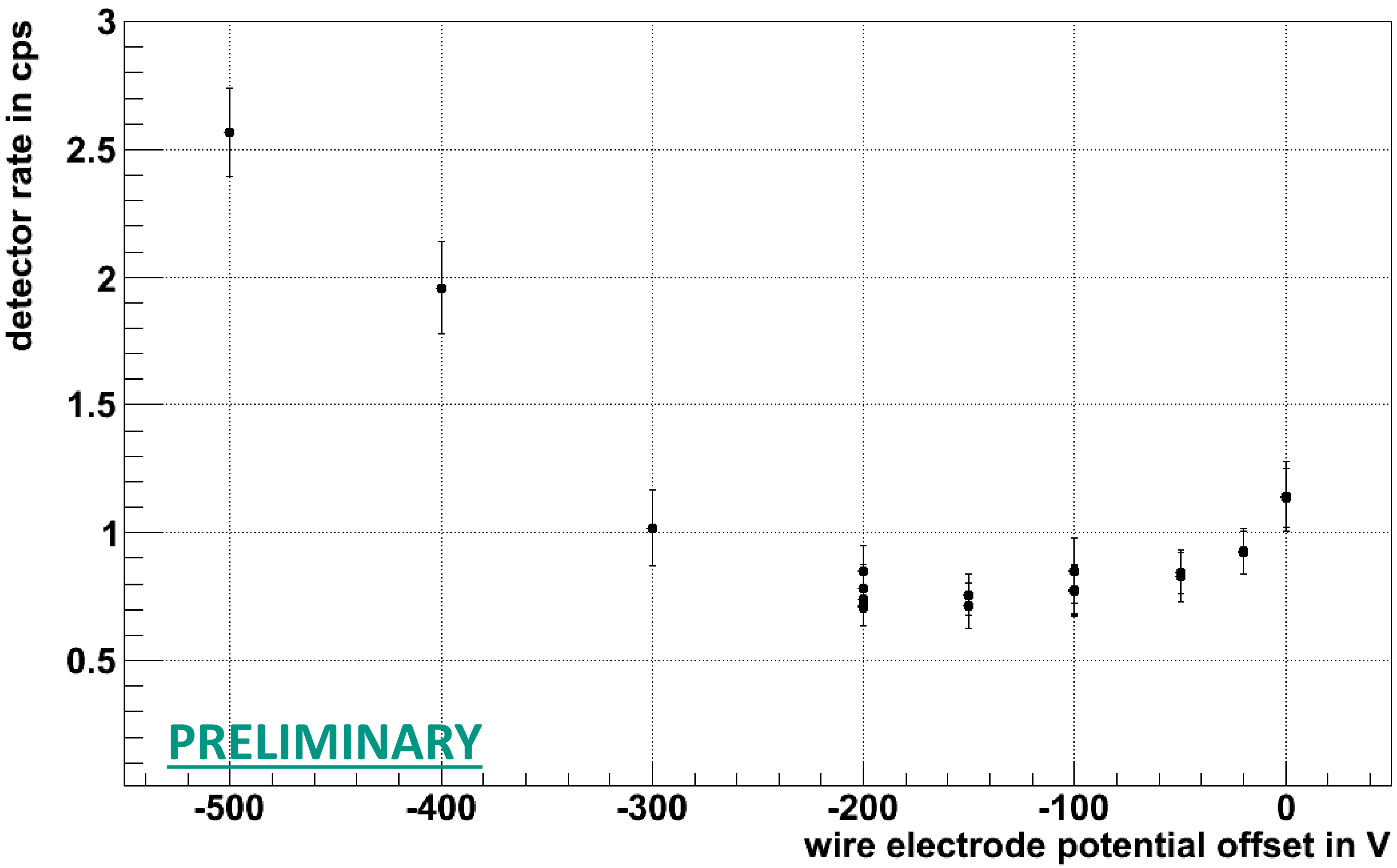
COSMICS INDUCED



ca. 23000 wires

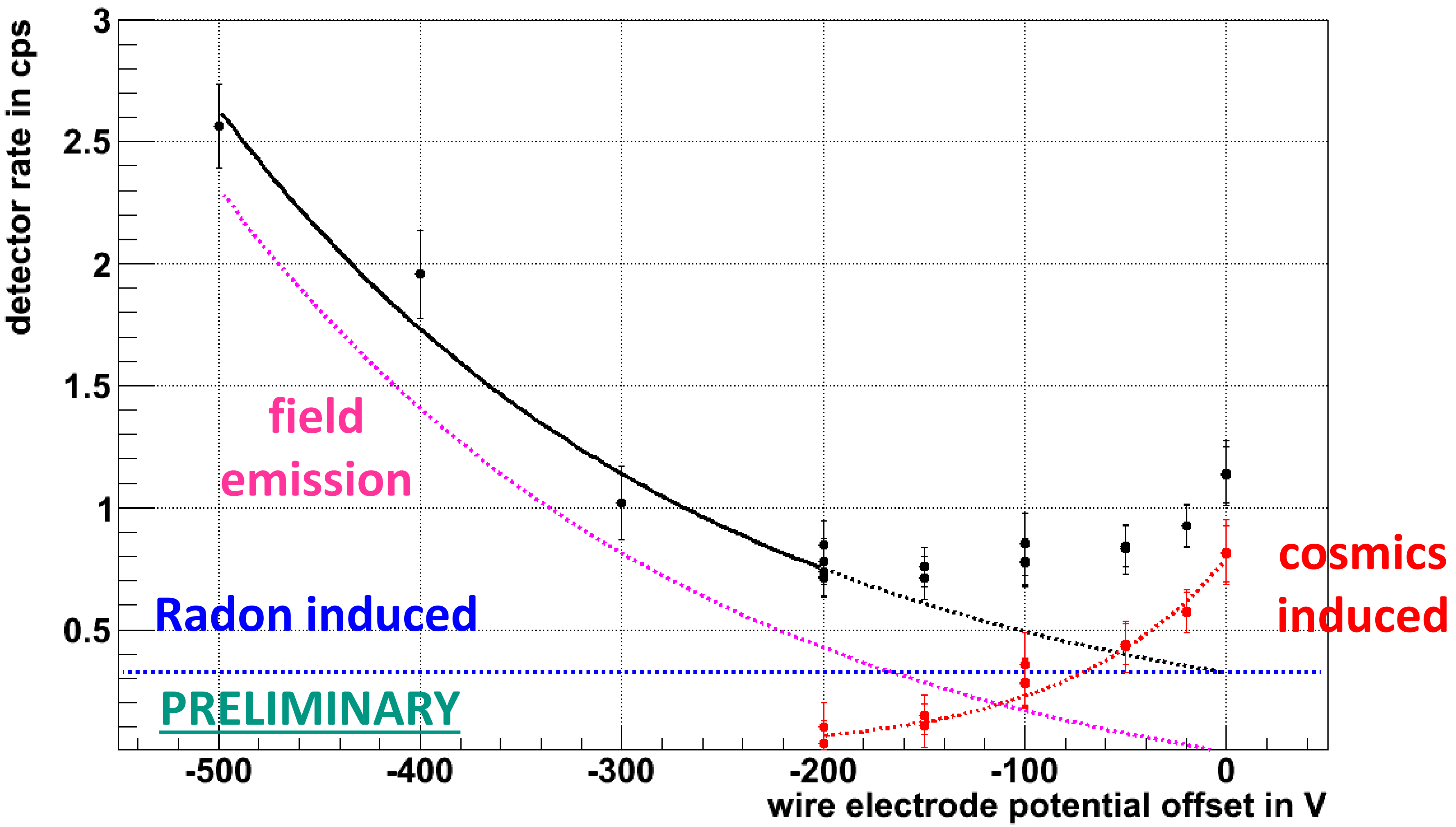
Main-Spectrometer Background

Wire electrodes at -18.6 kV. Tank hull at -18.6 kV - ΔU. PAE at +10 kV.



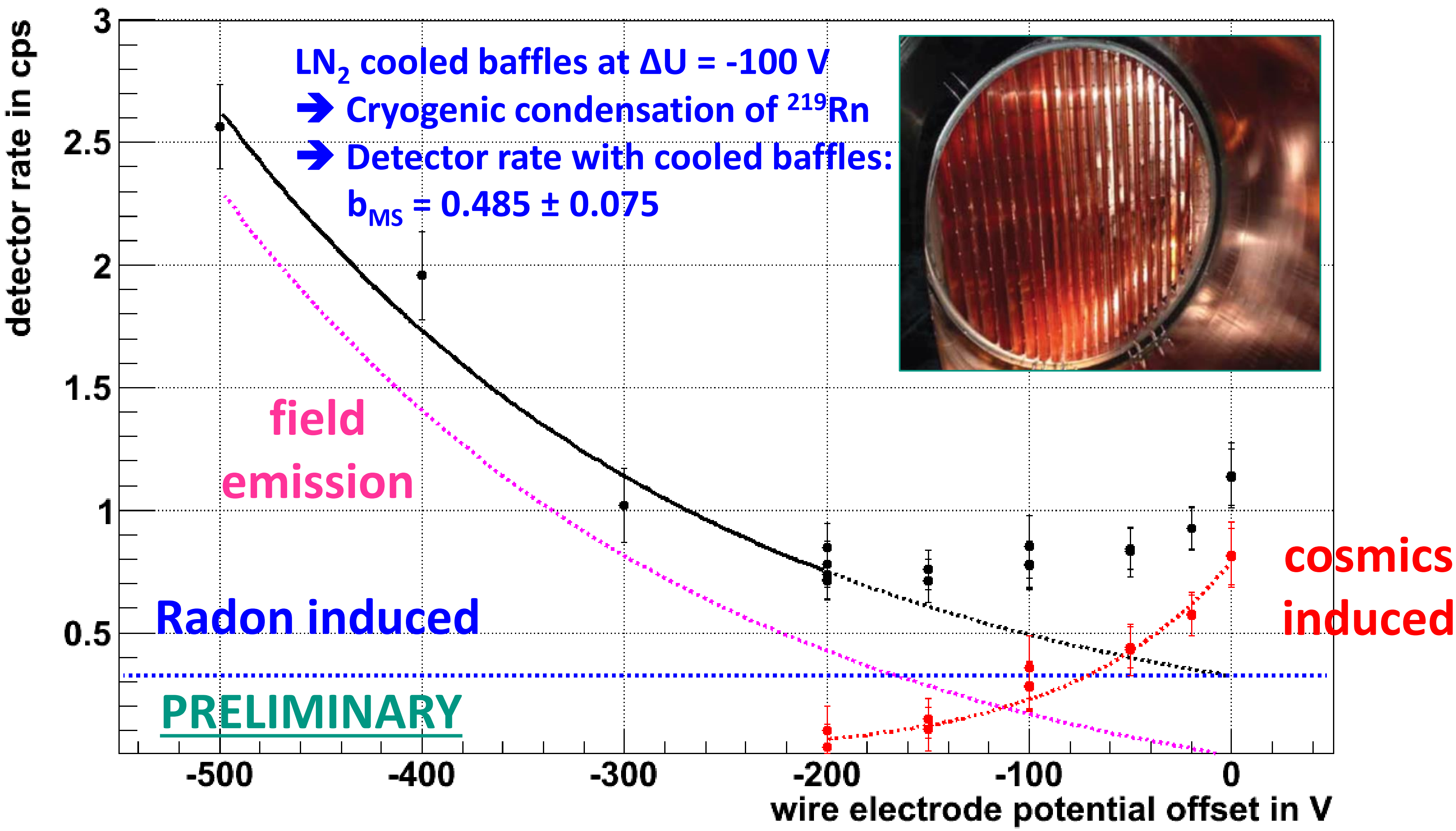
Main-Spectrometer Background

Wire electrodes at -18.6 kV. Tank hull at -18.6 kV - ΔU. PAE at +10 kV.



Main-Spectrometer Background

Wire electrodes at -18.6 kV. Tank hull at -18.6 kV - ΔU. PAE at +10 kV.



Main-Spectrometer Background

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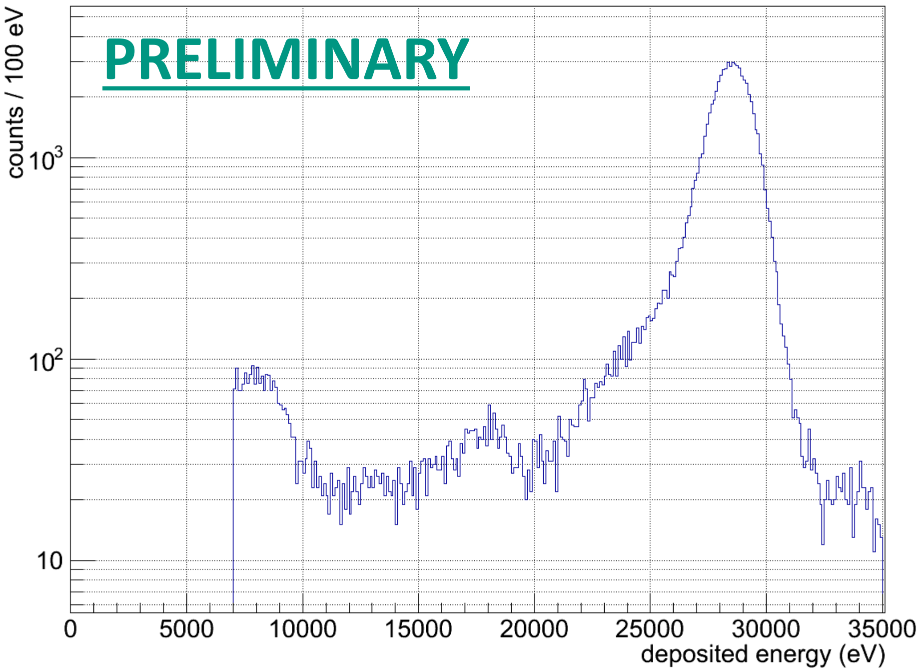
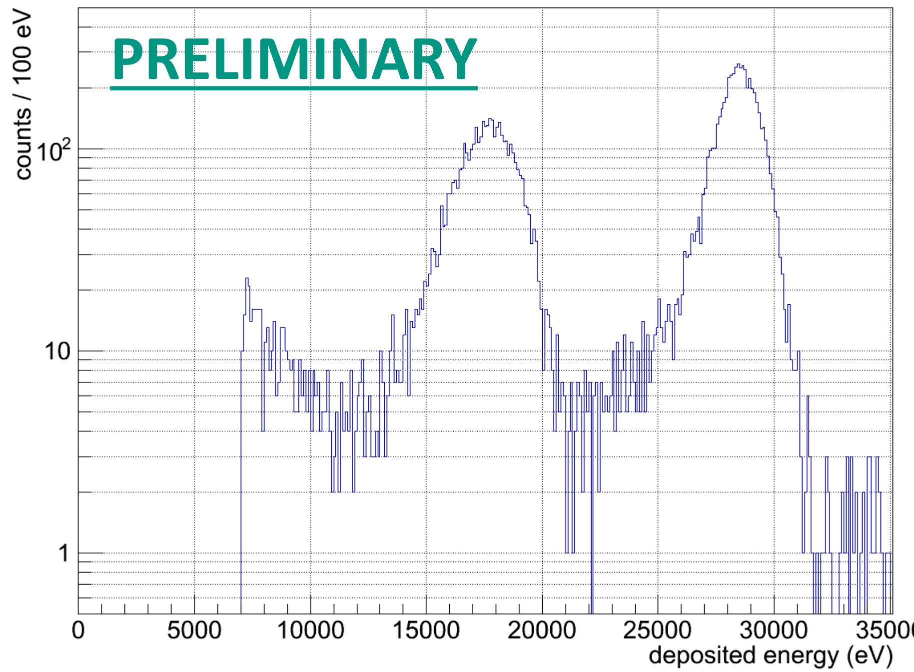
Wire electrodes at -18.6 kV. Tank hull at -18.6 kV - ΔU. PAE at +10 kV.

ΔU = -100 V (24 h)



ΔU = -300 V (1.5 h)



➔ **additional background at 17.7 keV**

Main-Spectrometer Background

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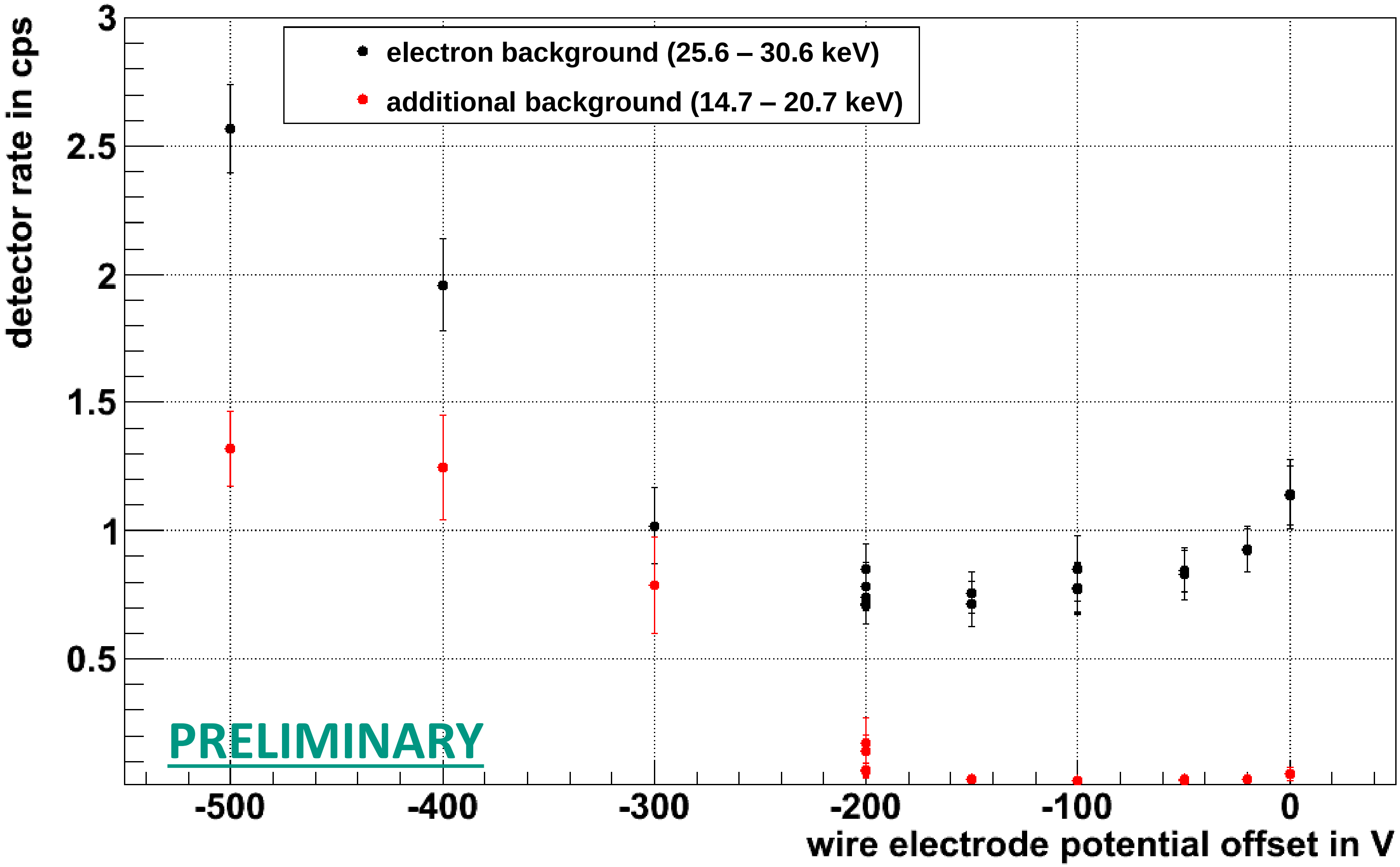
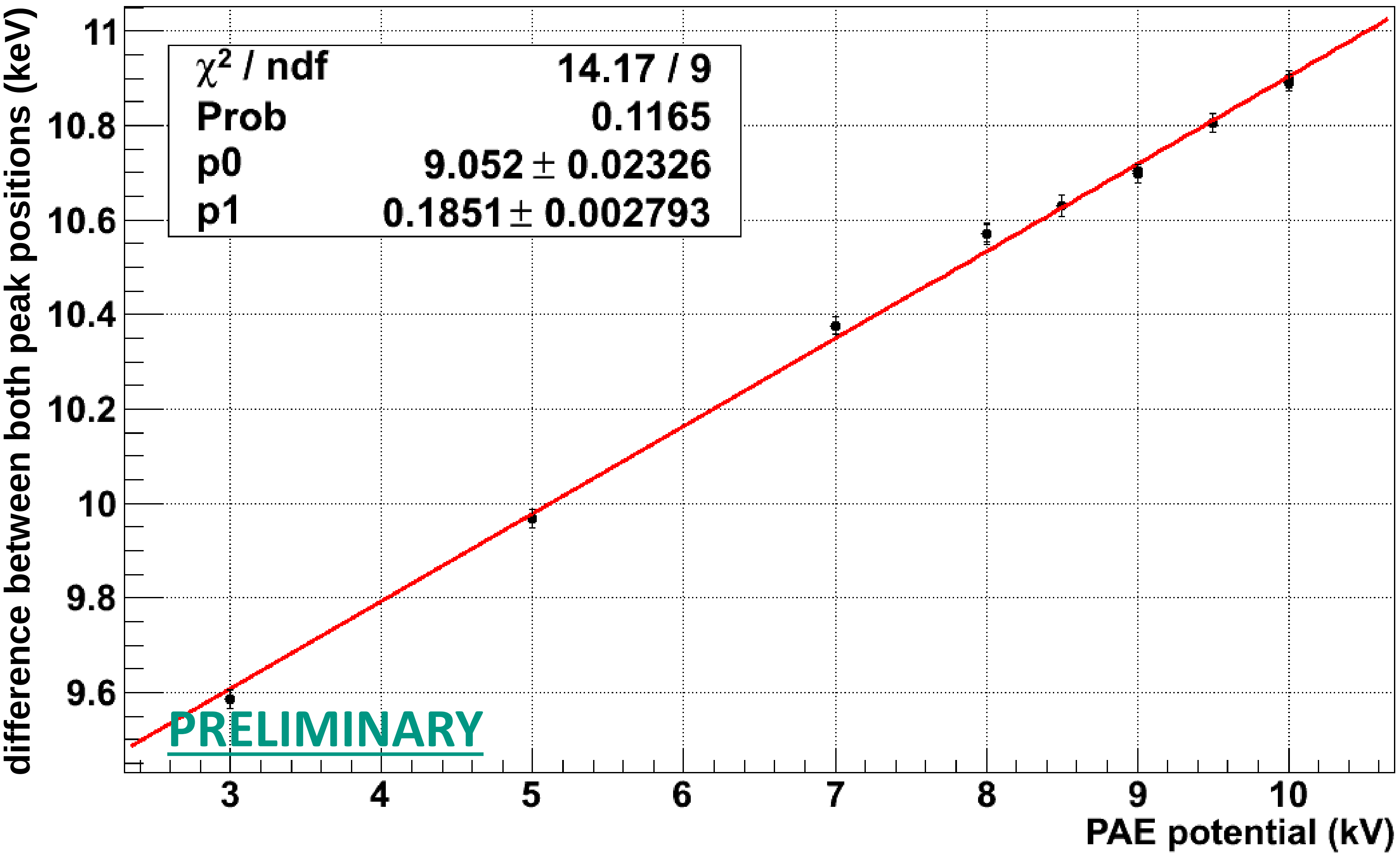
Wire electrodes at -18.6 kV. Tank hull at -18.6 kV - ΔU. PAE at +10 kV.



Main-Spectrometer Background

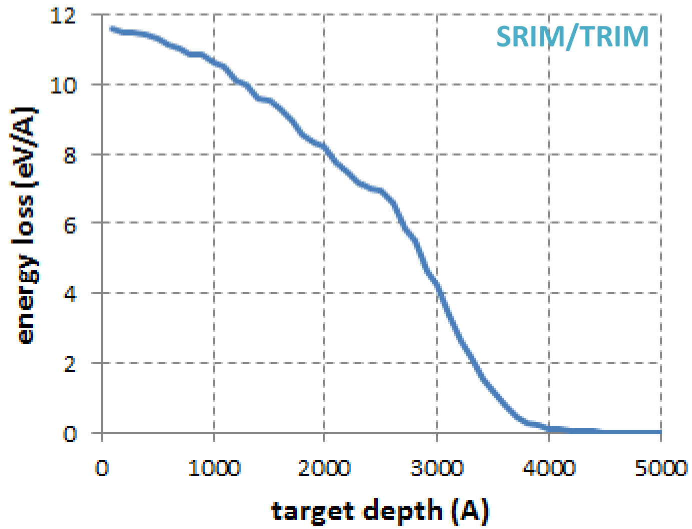
Wire electrodes at -18.6 kV. Tank hull at -18.1 kV. PAE varied.



Main-Spectrometer Background

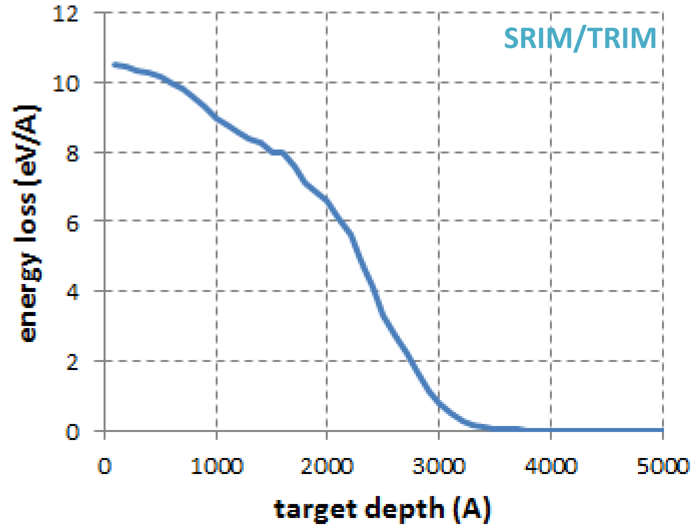
- H^- ions lose a lot of their incident energy in the non-sensitive detector dead-layer ➔ additional background by H^- ions

28.6 keV (PAE at 10 kV)



first 100 nm: 11.2 keV

21.6 keV (PAE at 3 kV)



first 100 nm: 9.9 keV

- Possible application: dead-layer determination
- Angular distribution under investigation with Kassiopeia 2.5

Summary

- FPD system integrated successfully to KATRIN experiment.
- FPD setup:
  - Detector wafer with 98.6 % working pixels.
  - Independent working calibration sources.
- FPD characterization and optimization:
  - Trade off between energy and time resolution.
  - Intrinsic detector background around 1 mHz/keV.
  - Optimization of ROI by figure of demerit: $b_{det} < 5$ mHz.
- Main-spectrometer background:
  - 3 major sources: Cosmics induced, Radon induced, field emission.
  - First background model with open questions!?
  - Additional background by H^- ions.

FPD Setup

05/2011 **11/2011**

07/2011: Arrival at KIT
08/2011: Installation at KATRIN
11/2011: First data and commissioning at KATRIN