A model for Rydberg-atom induced backgrounds resulting from deposition of Rn-progeny in the KATRIN Main Spectrometer

Fabian Harms for the KATRIN Collaboration, LRT Conference, Seoul 2017

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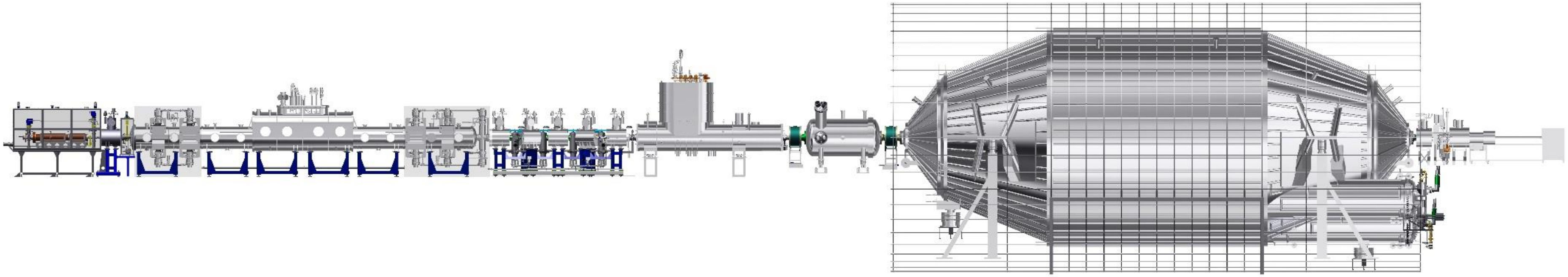


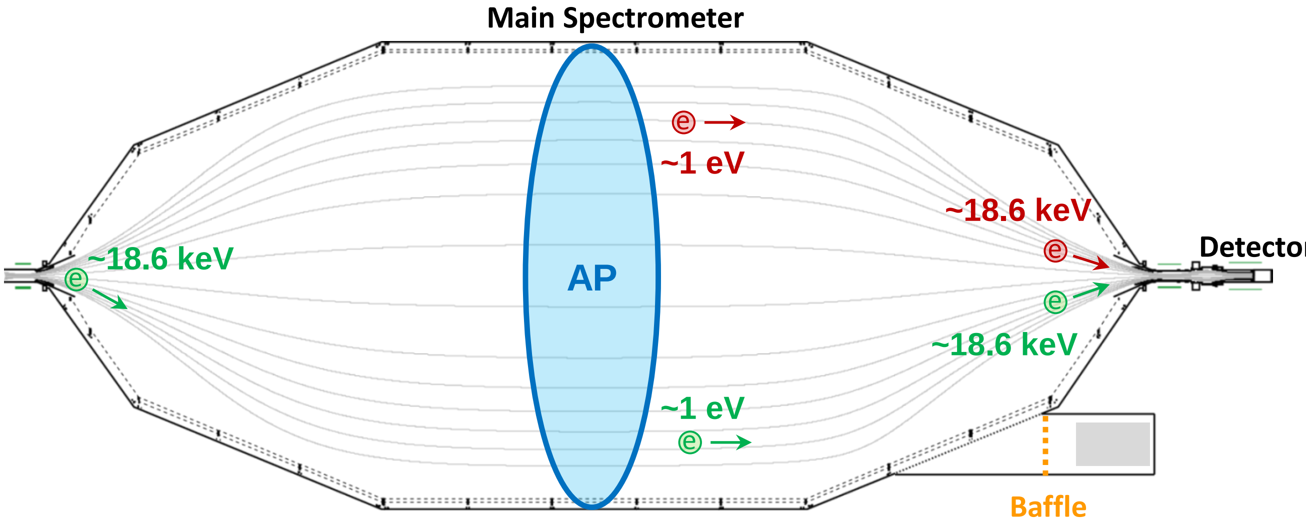
Outline

- Background characteristics at KATRIN
- The Rydberg-atom based background model
- Radon progeny in the Main Spectrometer
- Conclusion & Outlook

Background characteristics at KATRIN

Overview

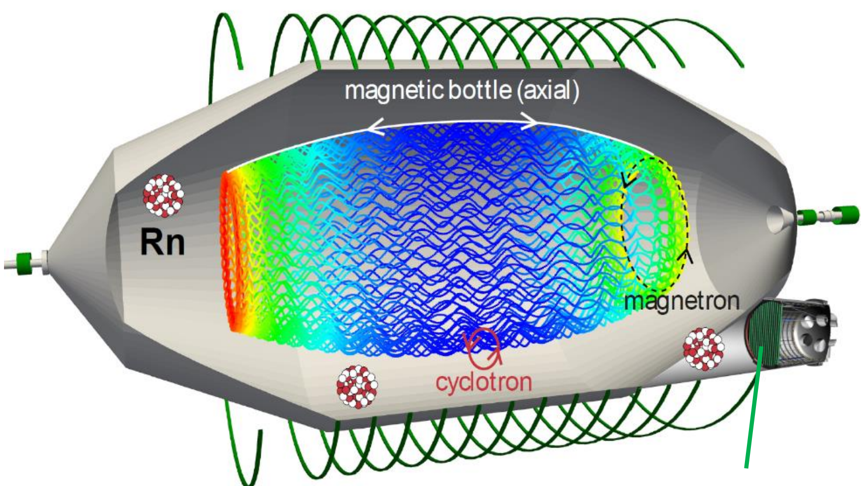
- Count rate of ~10 mcps close to tritium endpoint → Design background level in same order of magnitude.
- Main Spectrometer (1240 m³) represents main source of background.
- Current background level is ~200 - 600 mcps depending on electromagnetic field setting.



Background characteristics at KATRIN
Expected background sources

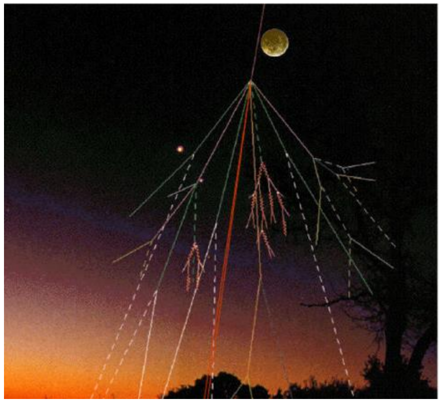
- Two main sources expected from earlier experiments with MAC-E filter spectrometers:

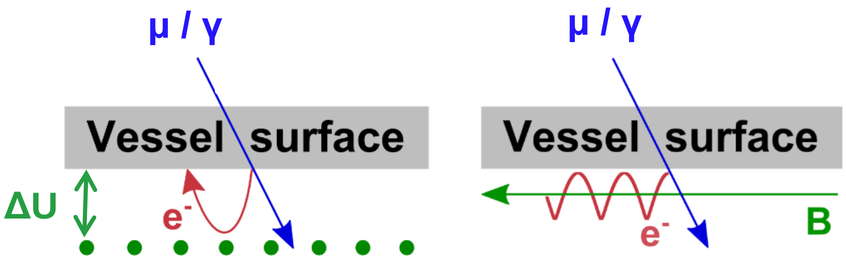
Stored-particle related



LN_2-cooled baffle system

Secondary-electron emission related





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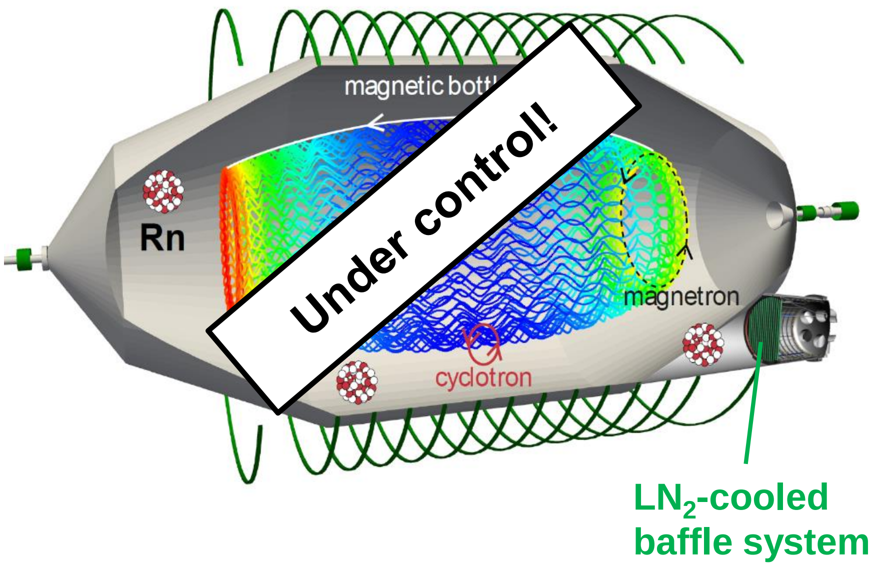
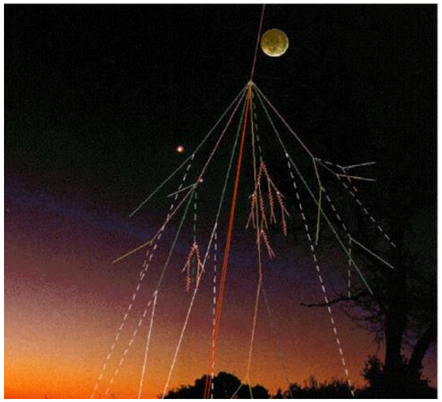
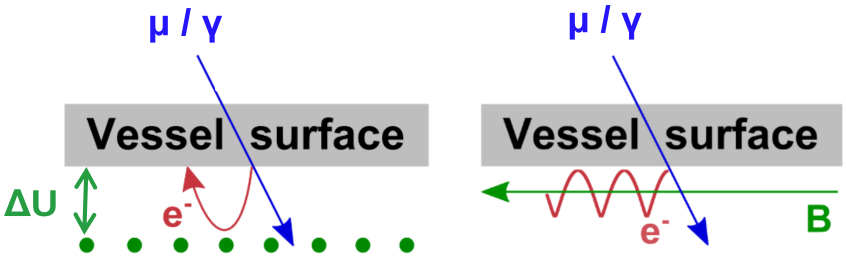
Stored-particle related



➡ **See talk by J. Wolf**

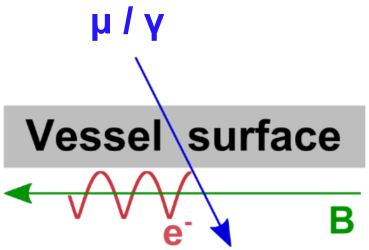
Secondary-electron emission related

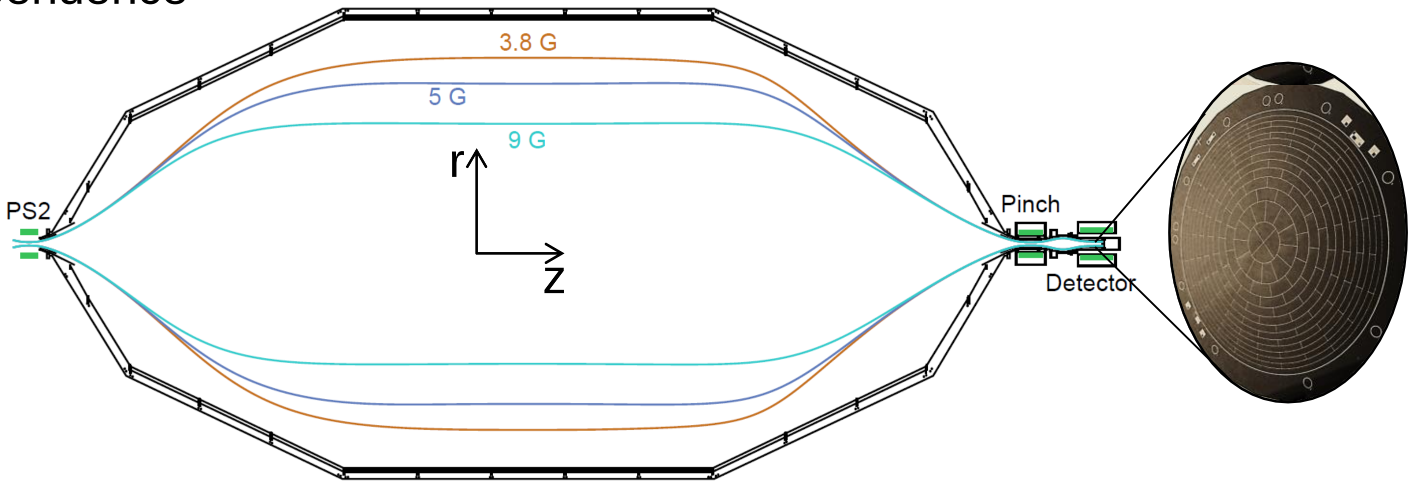


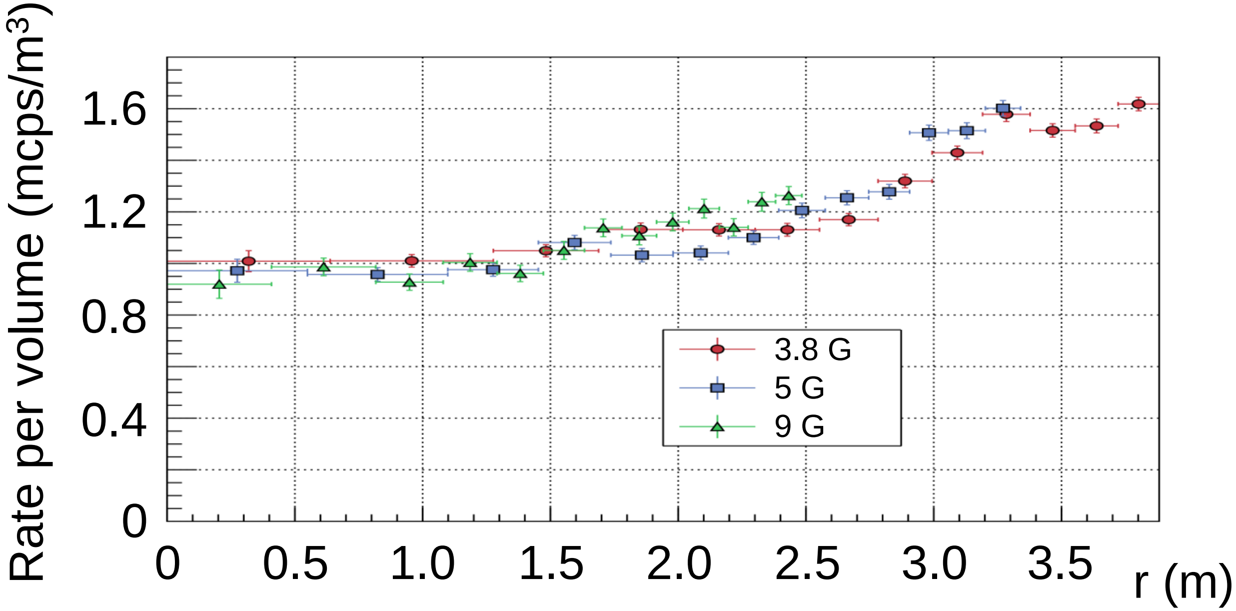


Background characteristics at KATRIN

Magnetic-field dependence





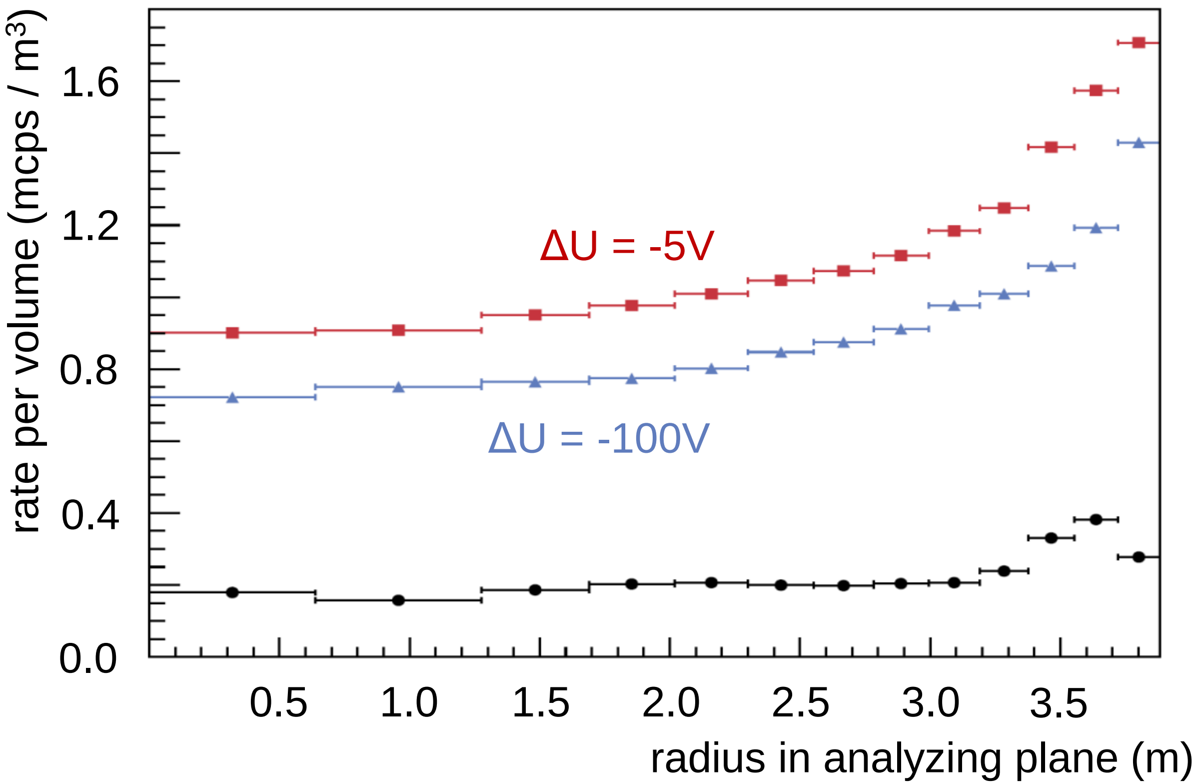


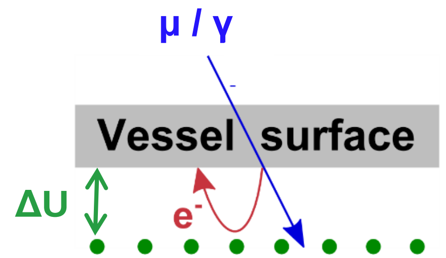
→ Background turns out to be independent of magnetic field strength

→ Purely volume dependent

Background characteristics at KATRIN
Electrostatic shielding

- Impact of electrostatic shielding on radial background distribution





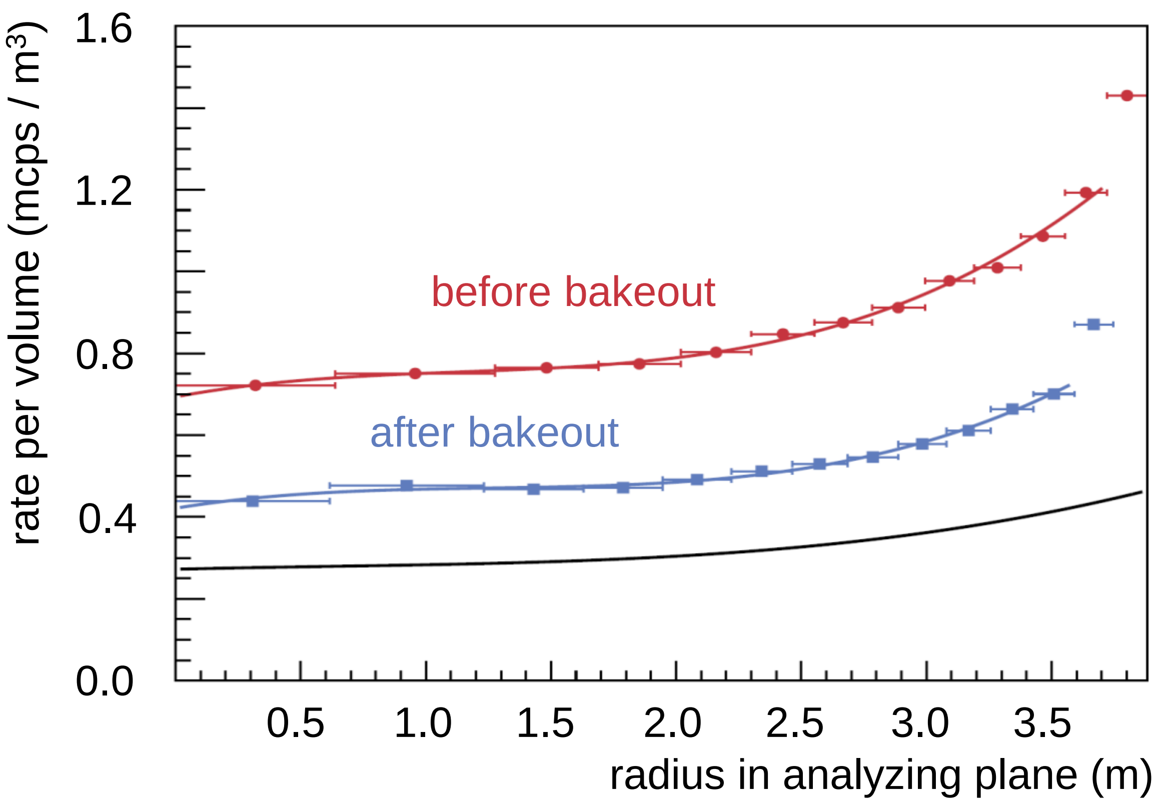
→ Shielding impacts background radial independently

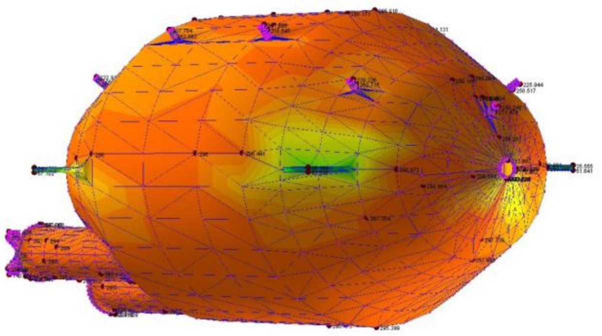
→ Contradicts model of secondary-electron emission induced background

Background characteristics at KATRIN

Spectrometer bakeout

- Impact of spectrometer surface conditions on radial background profile





→ Shielding impacts background radial independently

→ Contradicts model of secondary-electron emission induced background

The Rydberg-atom based background model

Characteristics

How to combine volume dependent background
with surface conditions and ΔU-dependence?

The Rydberg-atom based background model
Characteristics

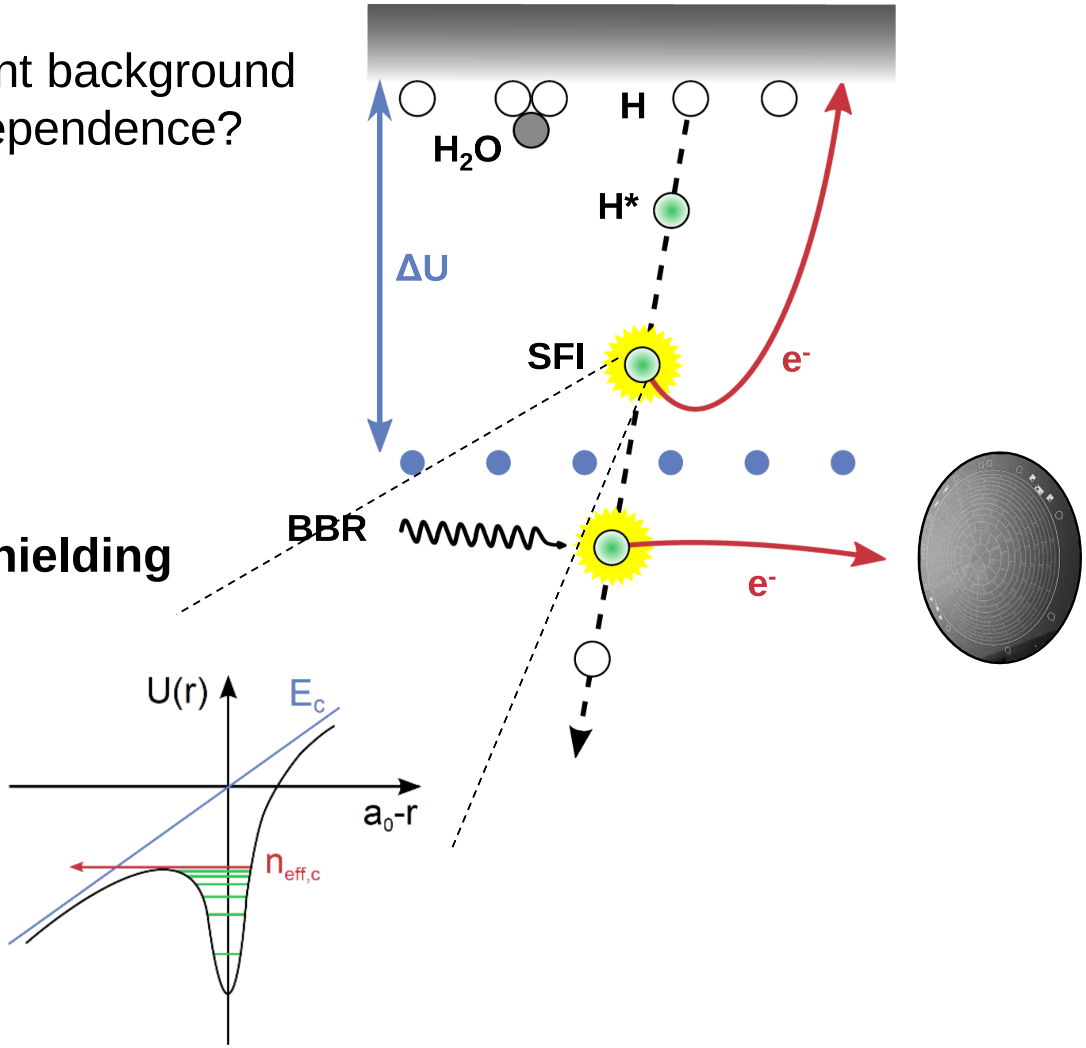
How to combine volume dependent background with surface conditions and ΔU-dependence?

→ **Neutral messenger particles (Hydrogen Rydberg atoms)**

→ Explains volume dependence.

→ **Explains impact of electric shielding**

→ Explains impact of bake-out.



The Rydberg-atom based background model

Characteristics

How to combine volume dependent background with surface conditions and ΔU-dependence?

→ **Neutral messenger particles (Hydrogen Rydberg atoms)**

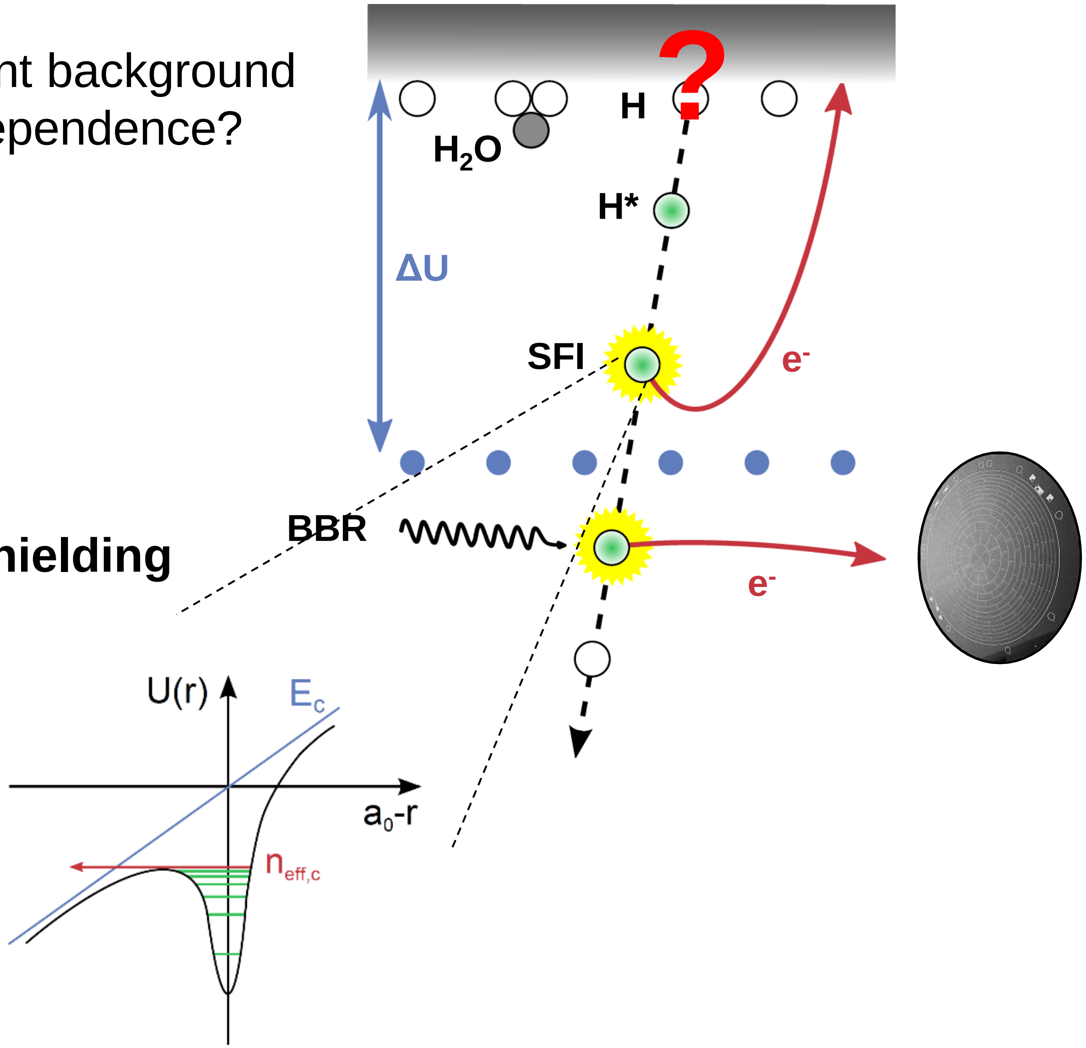
→ Explains volume dependence.

→ **Explains impact of electric shielding**

→ Explains impact of bake-out.

→ Explains low-energy background electrons.

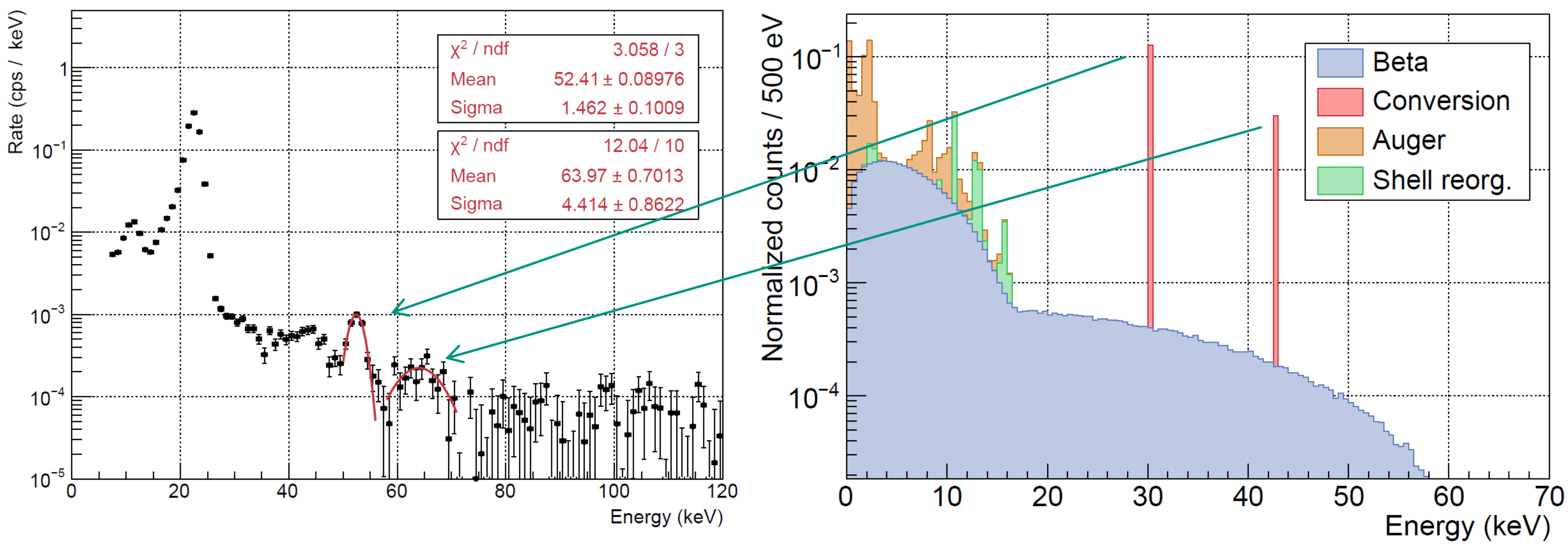
→ **Generation mechanism?**



Radon progeny in the Main Spectrometer

Observation of ^{210}Pb signature

- Found small traces of ^{210}Pb contamination in the Main Spectrometer (≈1Bq / m^2).

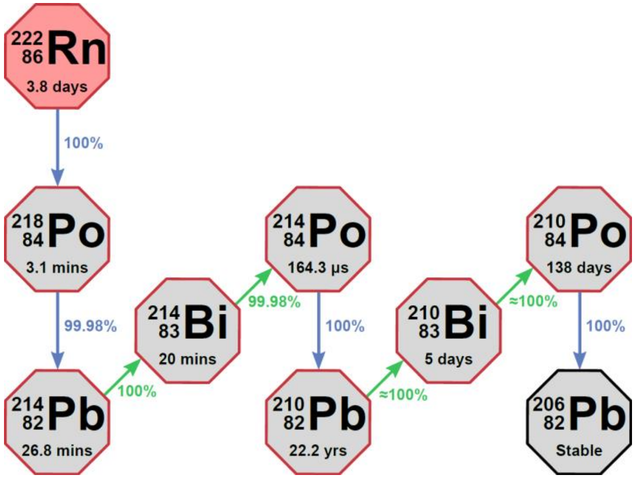


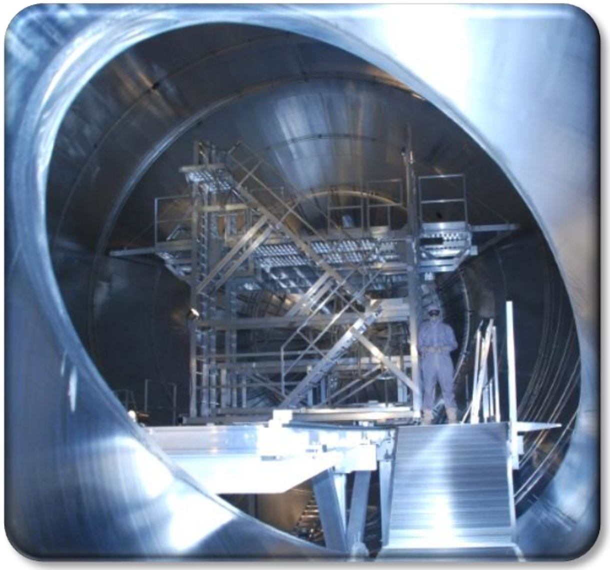
- ^{210}Pb must have been deposited in spectrometer over the course of inner electrode assembly and commissioning.

Radon progeny in the Main Spectrometer

Deposition mechanism

- Spectrometer was vented to ambient air for years during installation of inner electrode system.

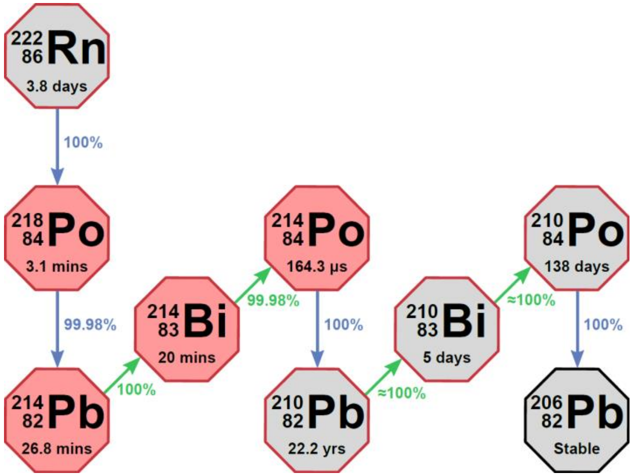




Radon progeny in the Main Spectrometer

Deposition mechanism

- Spectrometer was vented to ambient air for years during installation of inner electrode system.
- Rn-progeny is plated-out on spectrometer surfaces by various transport mechanisms.



A Radon Progeny Deposition Model

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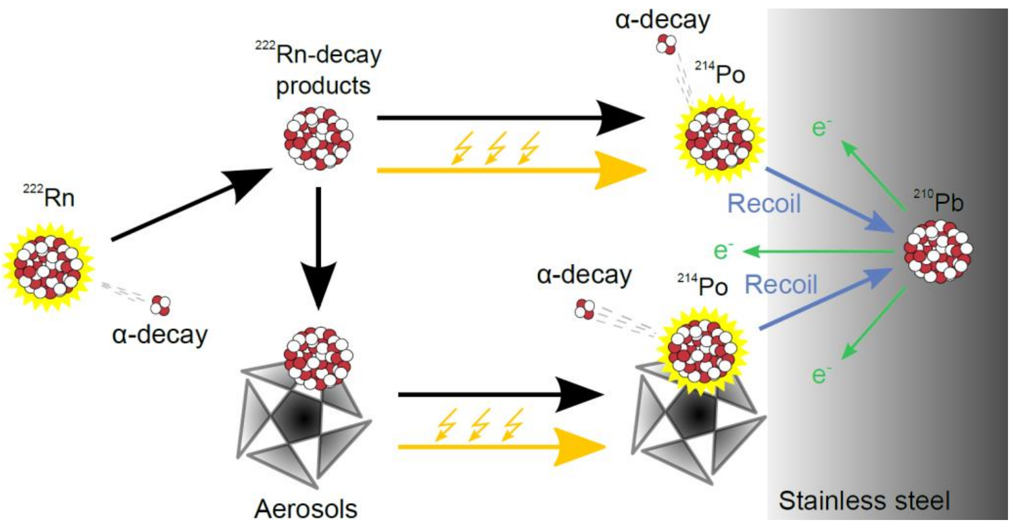
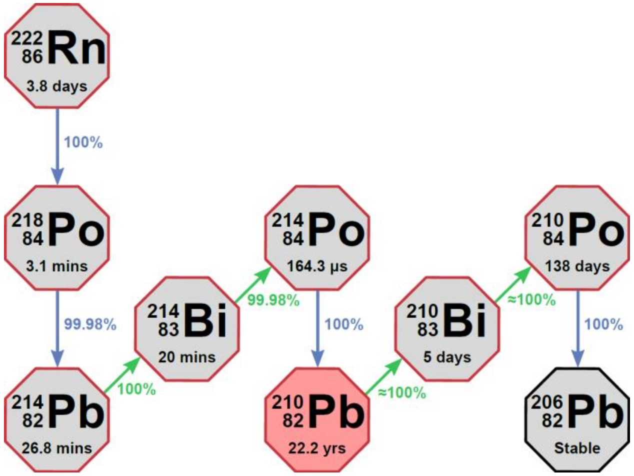
Abstract. The next generation low-background detectors operating underground aim for unprecedented low levels of radioactive backgrounds. Although the radioactive decays of airborne radon (particularly ^{222}Rn) and its subsequent progeny present in an experiment are potential backgrounds, also problematic is the deposition of radon progeny on detector materials. Exposure to radon at any stage of assembly of an experiment can result in surface contamination by progeny supported by the long half life (22 y) of ^{210}Pb on sensitive locations of a detector. An understanding of the potential surface contamination from deposition will enable requirements of radon-reduced air and clean room environments for the assembly of low background experiments. It is known that there are a number of environmental factors that govern the deposition of progeny onto surfaces. However, existing models have not explored the impact of some environmental factors important for low background experiments. A test stand has been constructed to deposit radon progeny on various surfaces under a controlled environment in order to develop a deposition model. Results from this test stand and the resulting deposition model are presented.

Keywords: radon, low background, surface contamination
PACS: 29.40.-n, 23.40.-s, 95.35.+d

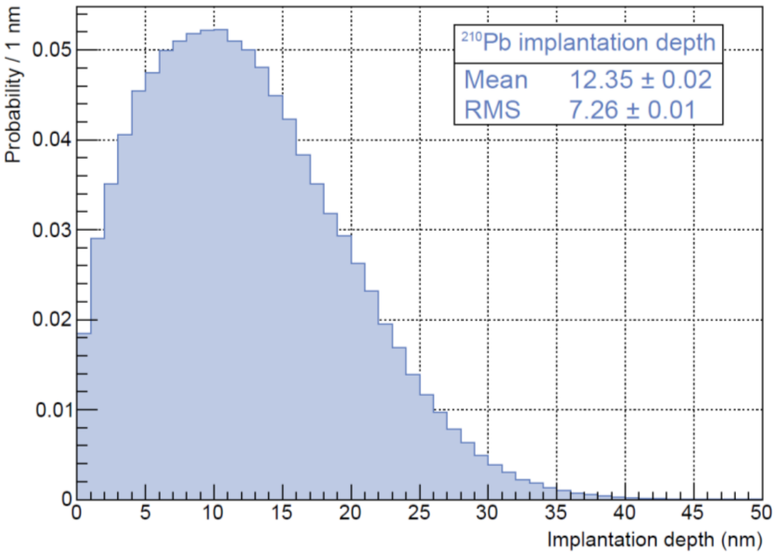


Radon progeny in the Main Spectrometer

Deposition mechanism



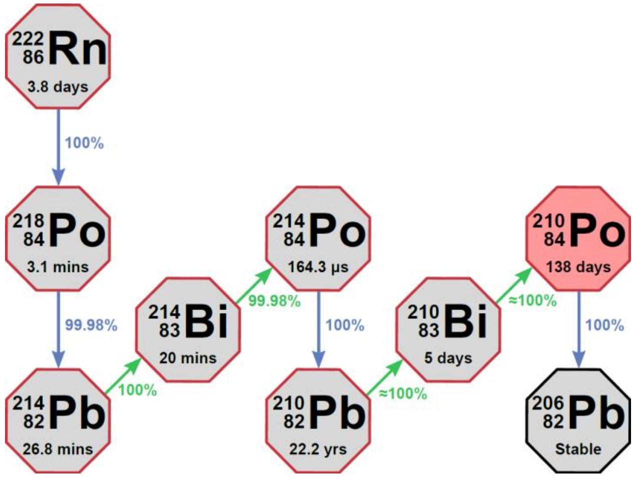
- Spectrometer was vented to ambient air for years during installation of inner electrode system.
- Rn-progeny is plated-out on spectrometer surfaces by various transport mechanisms.
- Implantation of ^{210}Pb into sub-surface layers due to recoil of ^{214}Po.
- No direct background contribution by ^{210}Pb in KATRIN standard operation.

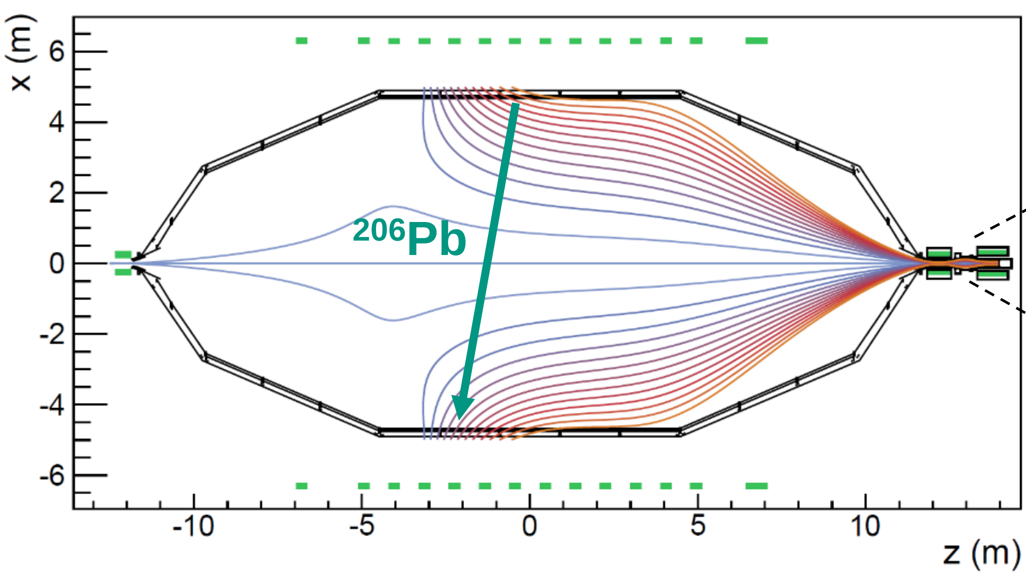


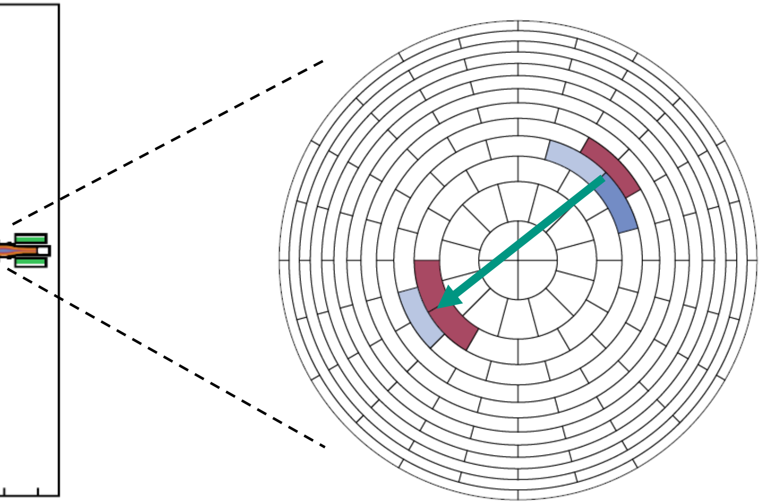
Radon progeny in the Main Spectrometer

Consequences

- Recoil of ^{210}Po α-decay causes sputtering on the inner surfaces of the Main Spectrometer.
- Short bursts of secondary electron emission on ms-timescale.

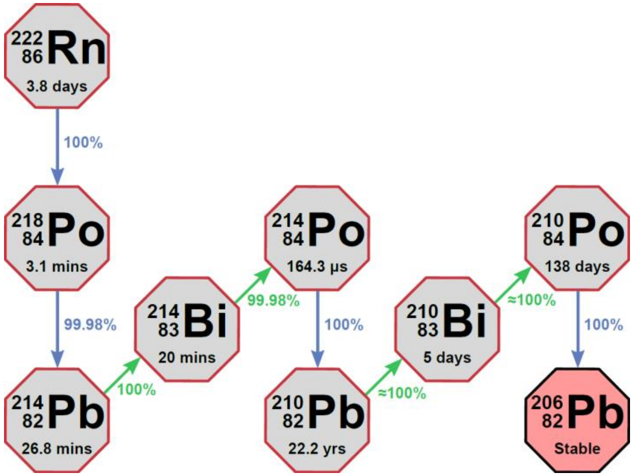






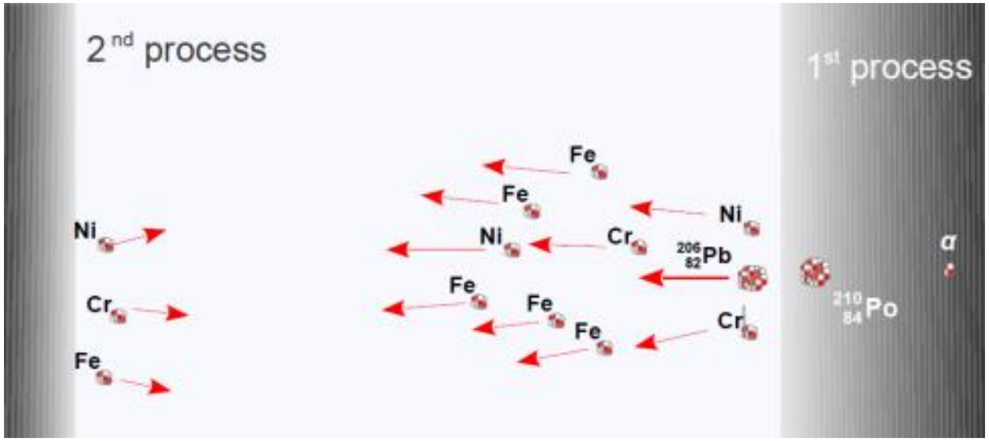
Radon progeny in the Main Spectrometer

Consequences



- Recoil of ^{210}Po α-decay causes sputtering on the inner surfaces of the Main Spectrometer.
- Short bursts of secondary electron emission on ms-timescale.
- **Idea: Rydberg atoms are generated in sputtering process.**

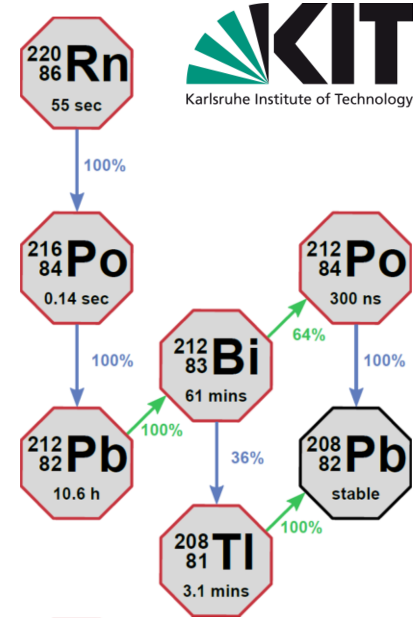
Ion-Stimulated Desorption (ISD)

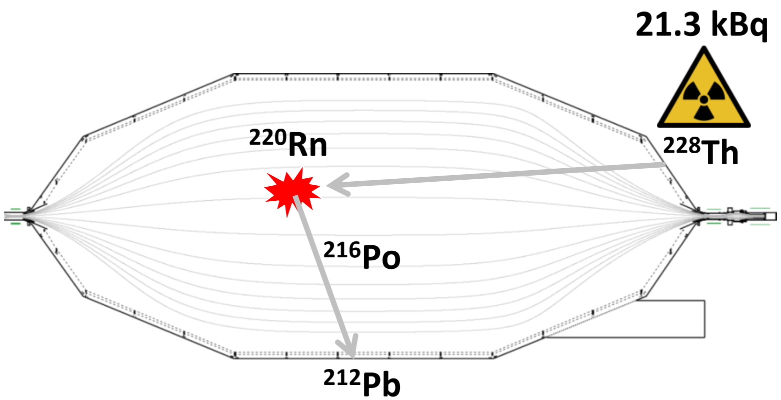


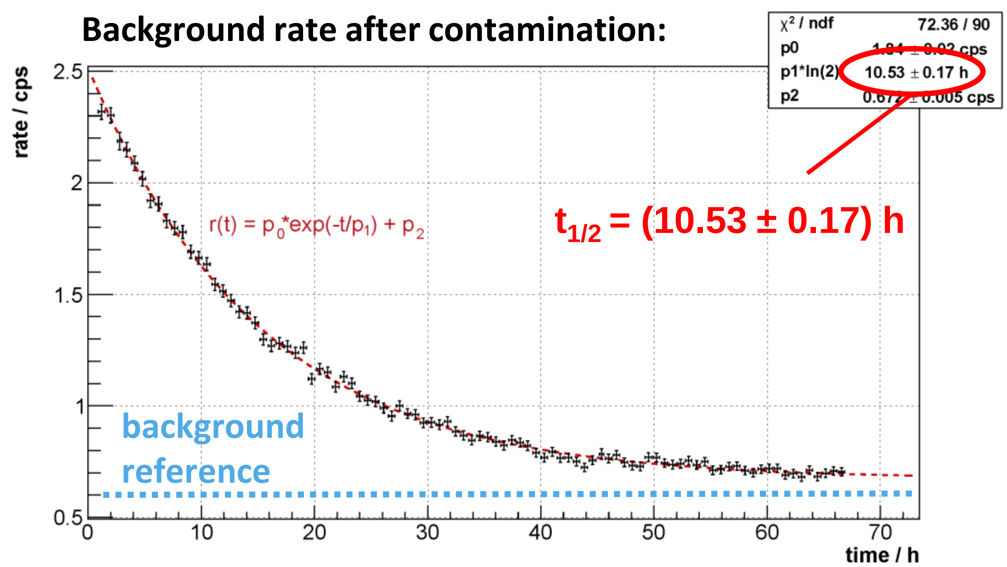
Radon progeny in the Main Spectrometer

Experimental test

- Idea: Use short-lived alternative for ^{210}Pb → **^{212}Pb.**
- Artificially contaminate Main Spectrometer surfaces.





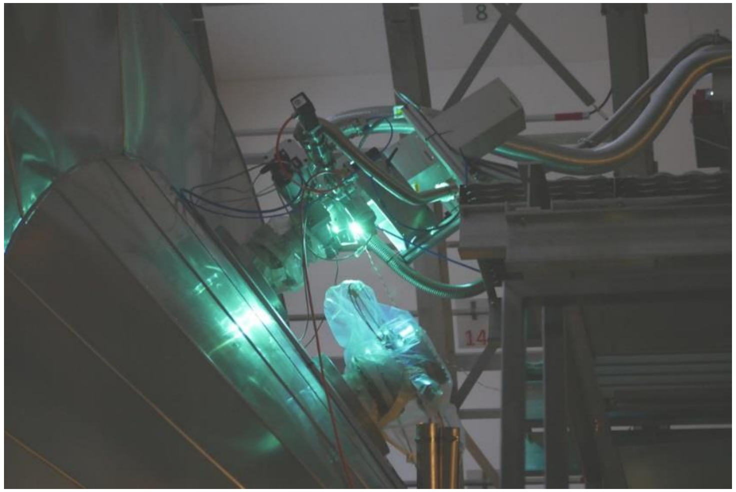


→ **^{210}Pb contamination in Main Spectrometer is root cause of elevated background rate at KATRIN!**

Radon progeny in the Main Spectrometer

Countermeasures against Rydberg background

- Cleaning inner surfaces to get rid of radon progeny.
  - → Well established techniques from other experiments (Borexino, Gerda, etc.)
  - → Difficult to carry out in case of KATRIN (vessel size, electrode system, etc.)
- Using strong UV light source (LightHammer) to reduce hydrogen reservoir on the inner spectrometer surface.
  - **→ Tests are currently ongoing.**



Radon progeny in the Main Spectrometer

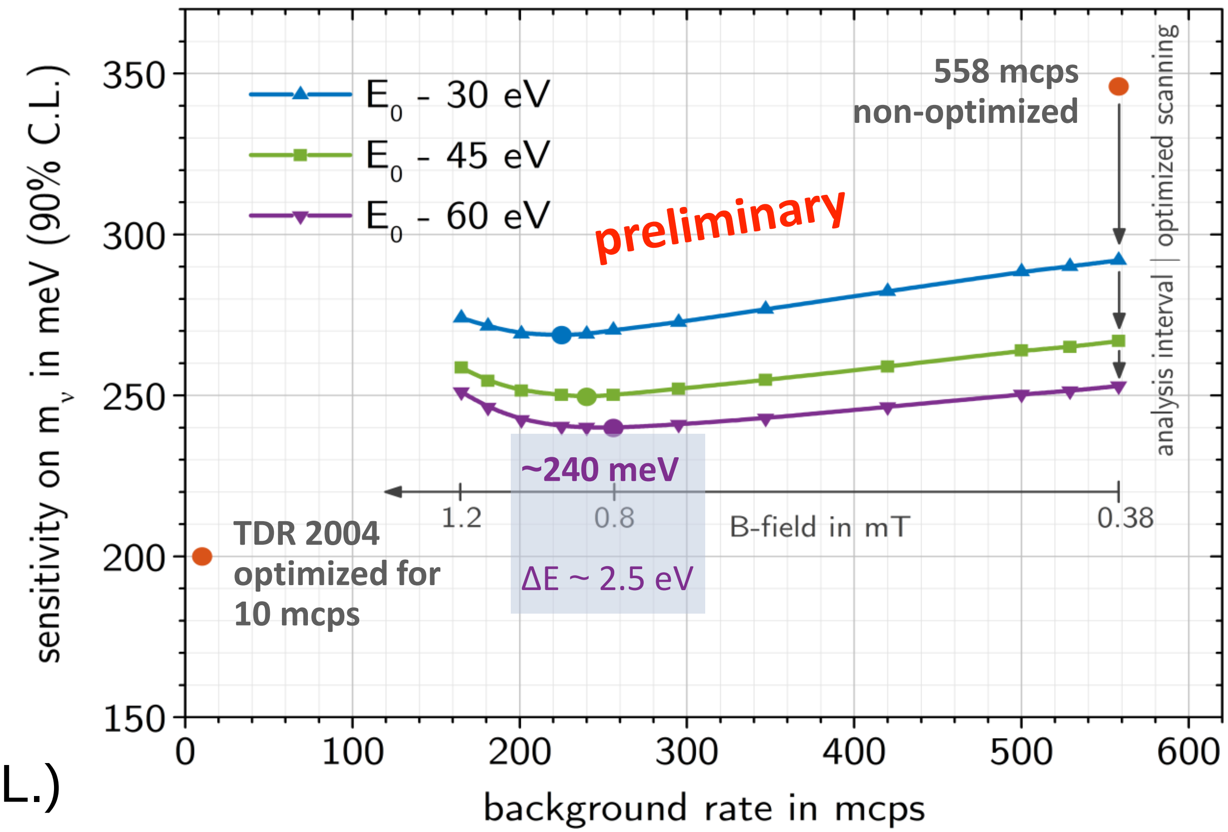
Consequences of Rydberg background for KATRIN

- Measured background level is 56x higher than design level. Without any optimizations this worsens the KATRIN sensitivity to ~350 meV.

- Optimizations:

→ Scanning strategy
→ Analysis interval
→ Reduce volume with drawback of worse energy resolution

- KATRIN still reaches a sensitivity of 240 meV (90% C.L.)



Conclusion & Outlook

- Current background level at KATRIN significantly higher than design.
- Background not related to background sources observed in predecessor experiments.
- Background characteristics indicate neutral messenger particles from spectrometer walls that are being ionized in the volume

  → Model of Rydberg atom induced background.
- Recent measurement results prove direct link between deposition of Rn-progeny on inner spectrometer surfaces and background level.
- Tests of intense UV light source as potential countermeasure are ongoing.
- Even with elevated background level, KATRIN can reach sensitivity of 240 meV / c^2 (90% C.L.).

The KATRIN Collaboration

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Westfälische Wilhelms-Universität Münster

BERKELEY LAB

The Czech Academy of Sciences

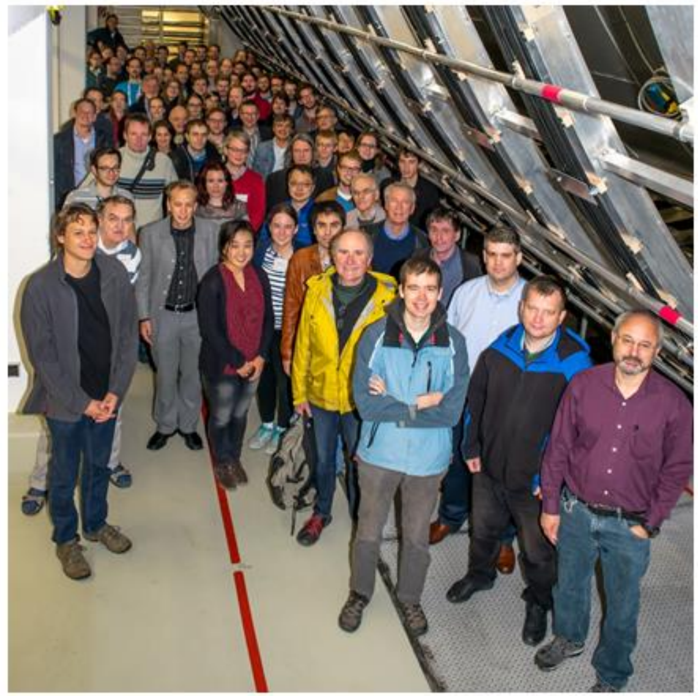
Massachusetts Institute of Technology

Hochschule Fulda
University of Applied Sciences

Russian Academy of Sciences

Max-Planck-Institut für Physik

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL



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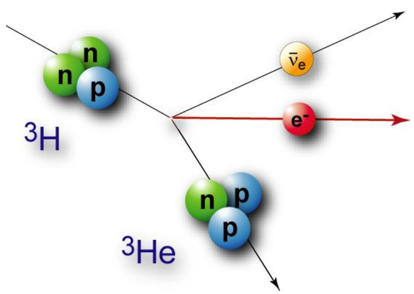
Backup Slides

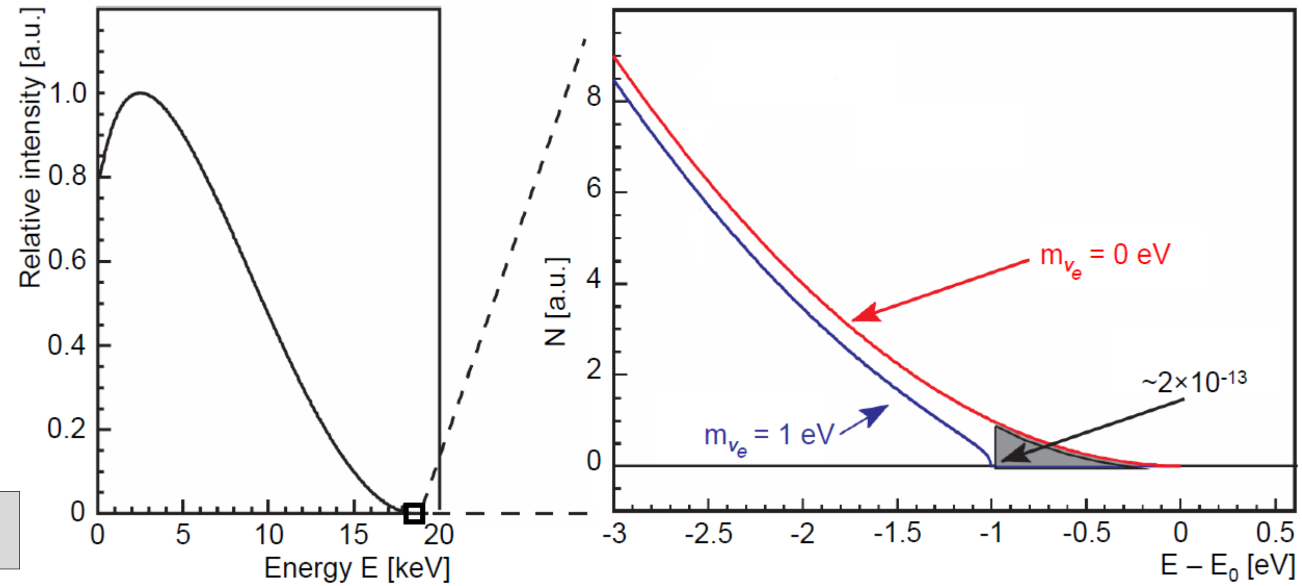
The KATRIN experiment

Single beta decay

Karlsruhe Institute of Technology



$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$



$t_{1/2}$ = 12.3 a

E_0 = 18.6 keV

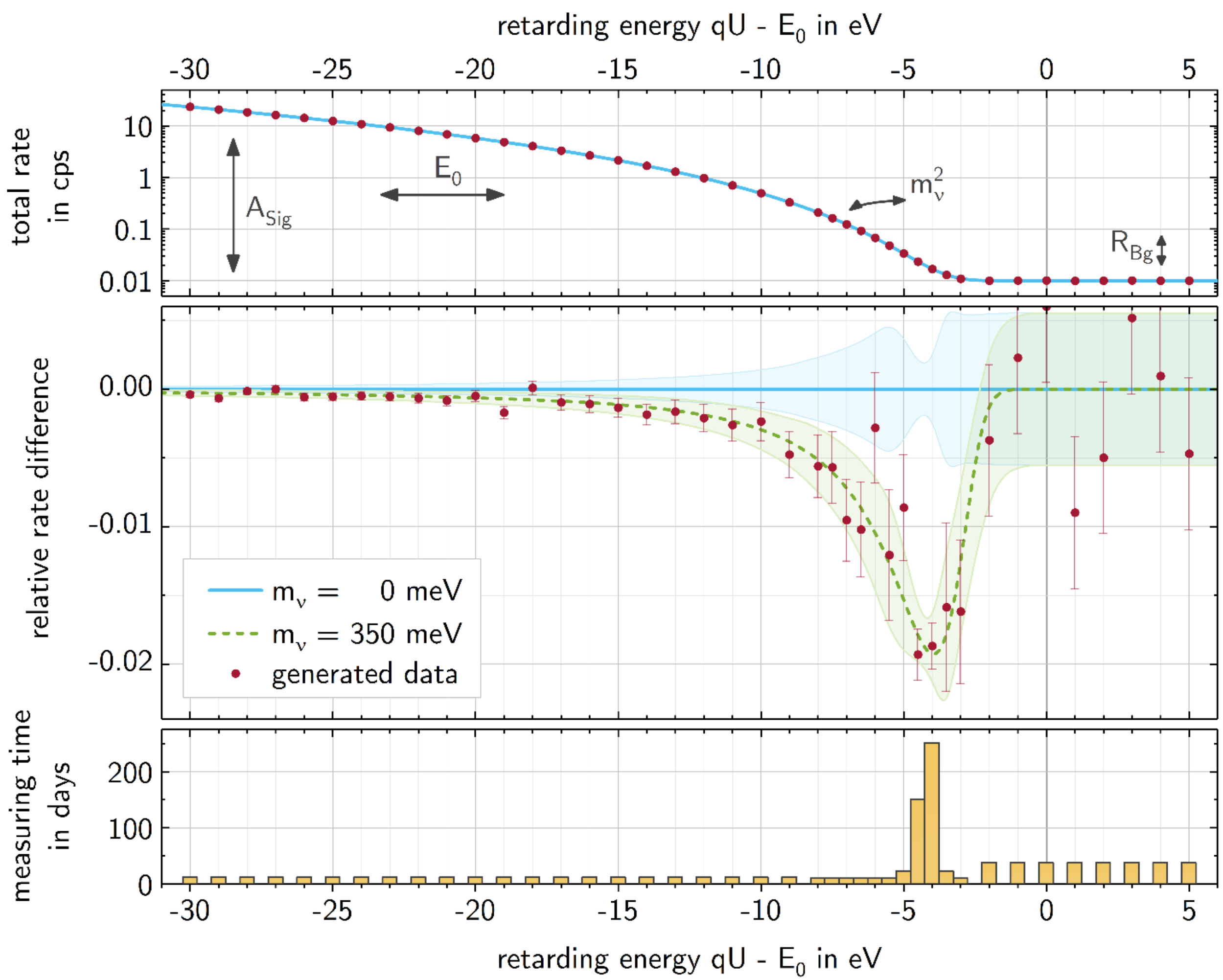
$$\frac{d\Gamma}{dE} = C\, p\, (E + m_e)\,(E_0 - E)\,\sqrt{(E_0 - E)^2 - m_{\nu_e}^2}\, F(E)\, \theta(E_0 - E - m_{\nu_e})$$

m_ν < 0.2 eV (90 % C.L.)

$$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

The KATRIN experiment

Measurement principle



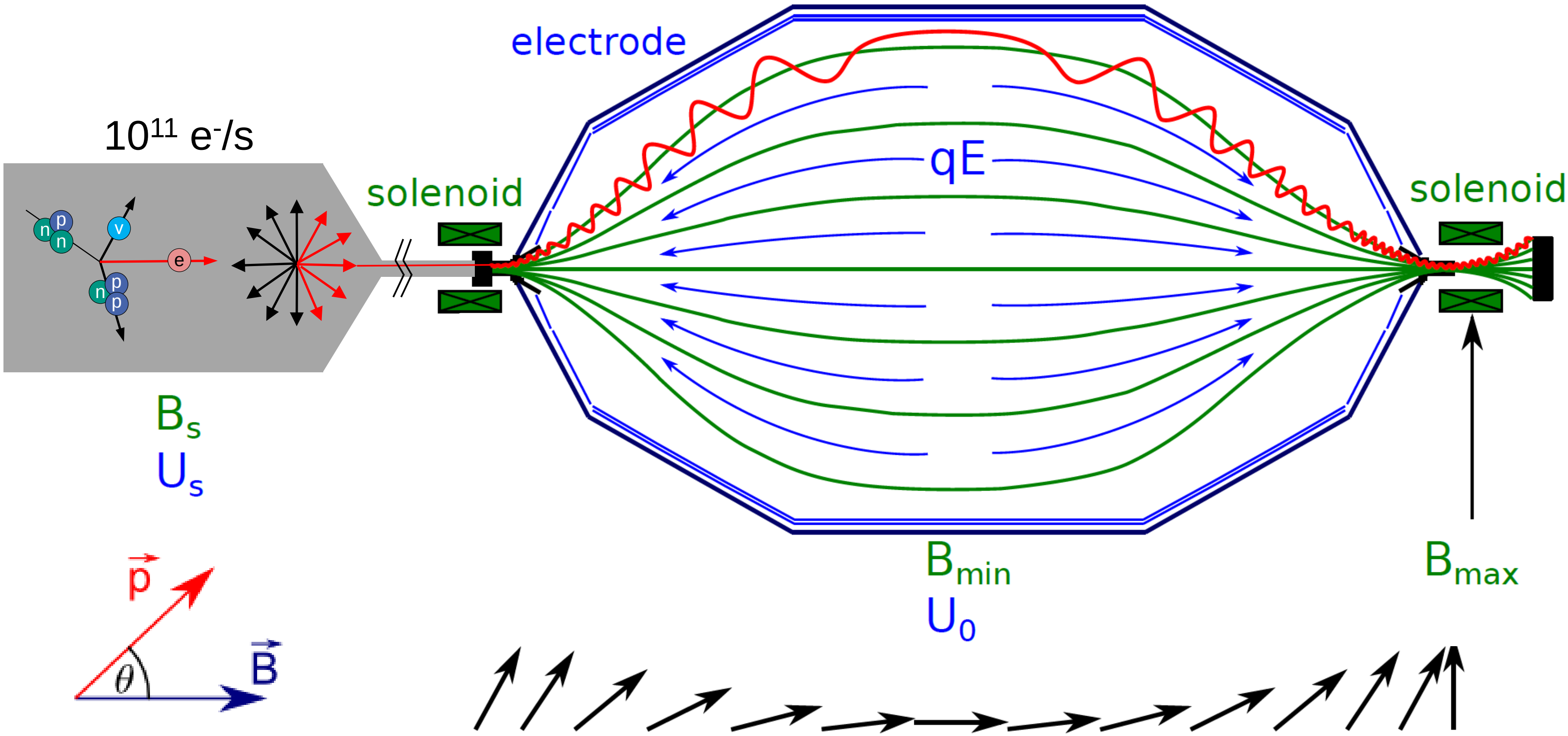
Integrated T_2 β spectrum close to kinematic endpoint at E_0 = 18.6 keV

Impact of nonzero m_ν on spectral shape is most pronounced a few eV below E_0

Optimized measurement time distribution to increase sensitivity

The KATRIN experiment

MAC-E filter



$$\mu = \frac{E_\perp}{B} = const.$$

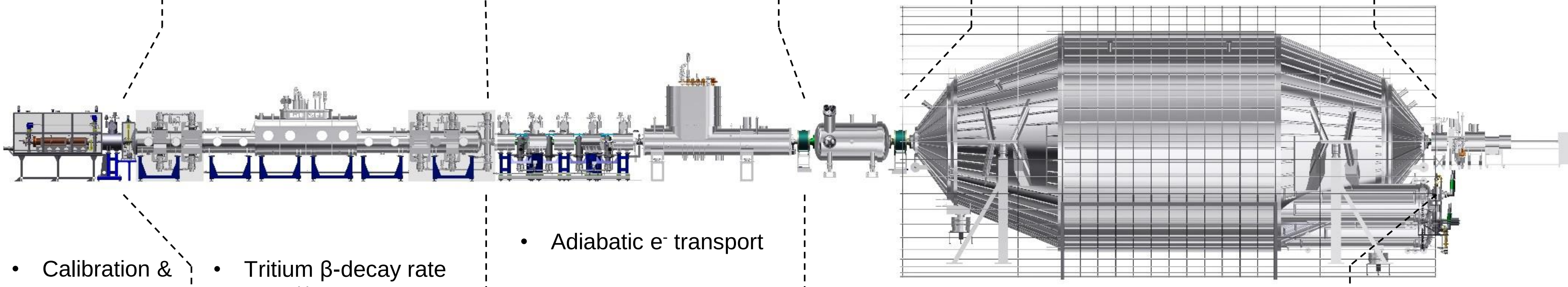
$$E_{kin} = E_{||} + E_\perp$$

$$\Delta E = 0.93 \text{ eV}$$

The KATRIN experiment

Experimental beamline

Rear Section | Windowless gaseous tritium source | Transport Section | Pre-spectrometer | Main Spectrometer | Detector



Rear Section
- Calibration & monitoring
- Artificial electron source

Windowless gaseous tritium source
- Tritium β-decay rate of 10^{11} 1/s
- Operating parameters (T, p, etc.) stabilized at 10^{-3} level

Transport Section
- Adiabatic e^- transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$

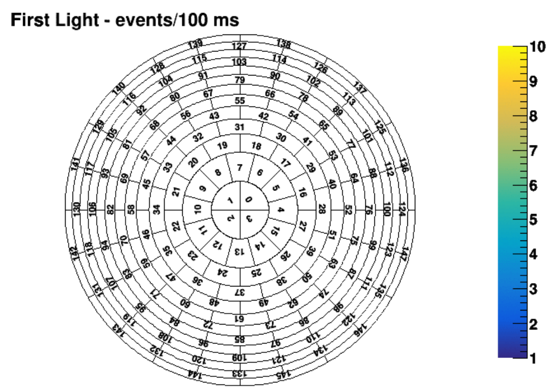
Main Spectrometer
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Operated at UHV conditions ($<10^{-10}$ mbar)

Detector
- Si-PIN diode array
- Highly efficient e^- counting

~70 m

➡ Closed beamline at **23^{rd} September 2016**

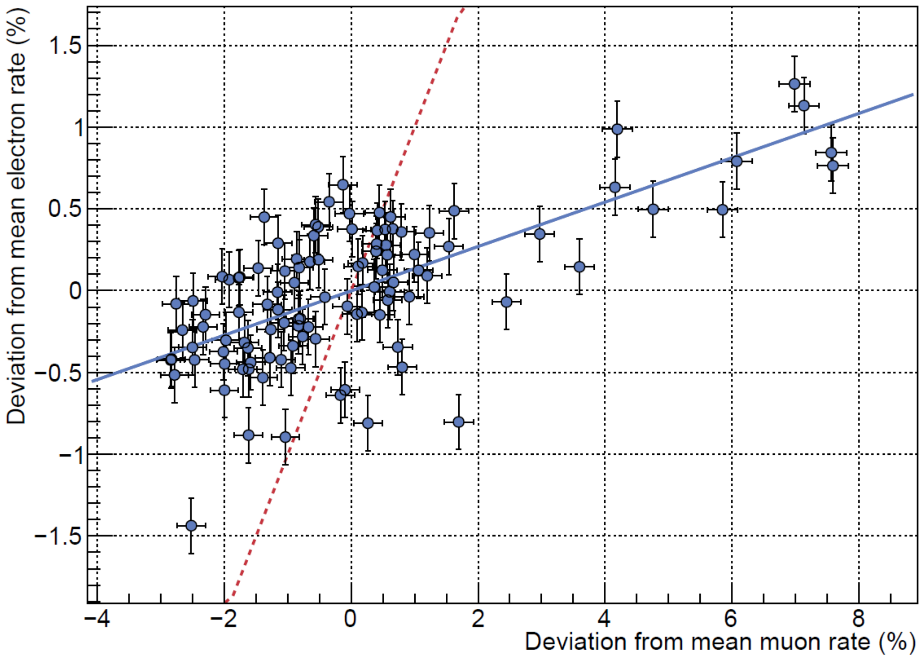
➡ First Light event on **14^{th} October 2016**

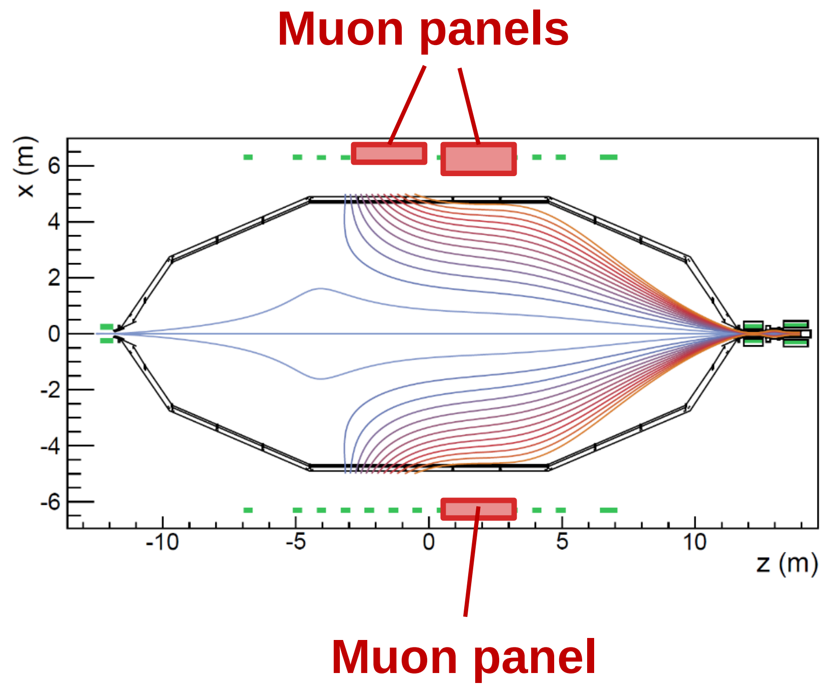


Background characteristics at KATRIN

Expected background sources

- Investigated muon vs. secondary electron correlation.
- Small fraction of secondary electron rate is found to be muon induced.





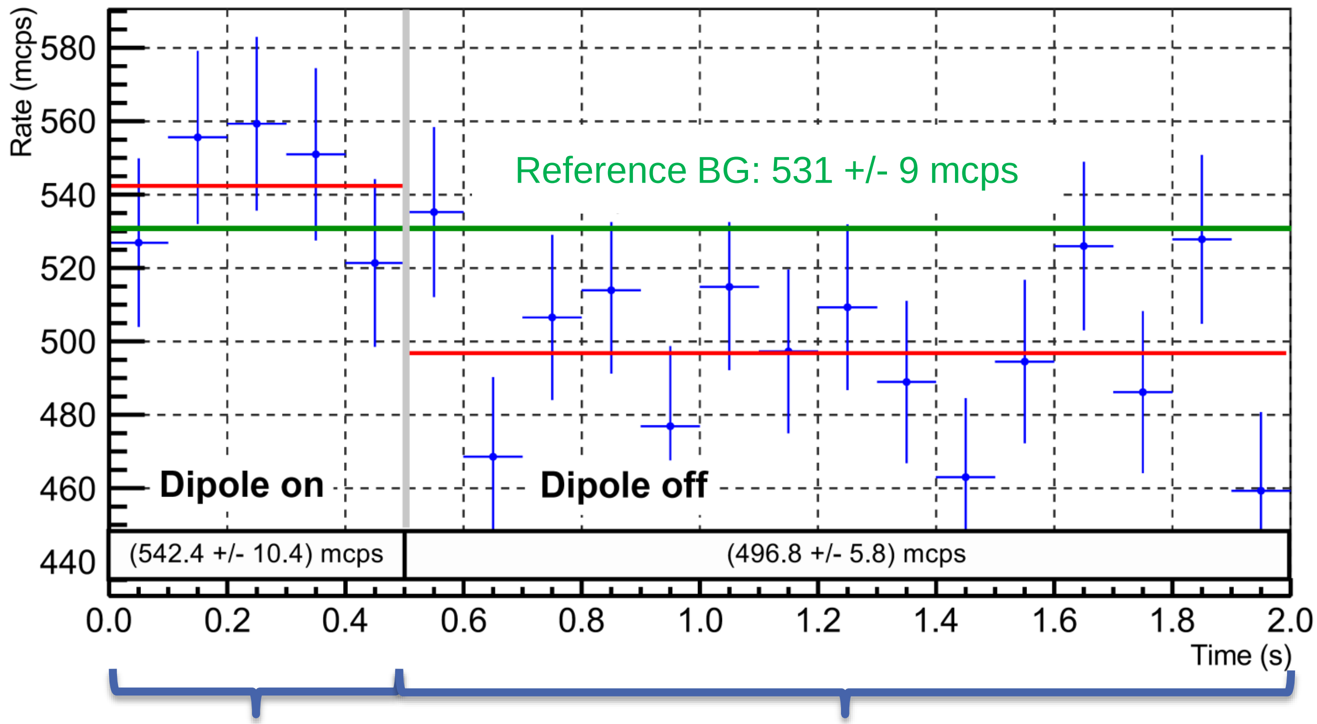
$$a = 13.6 \pm 0.8\ \%$$

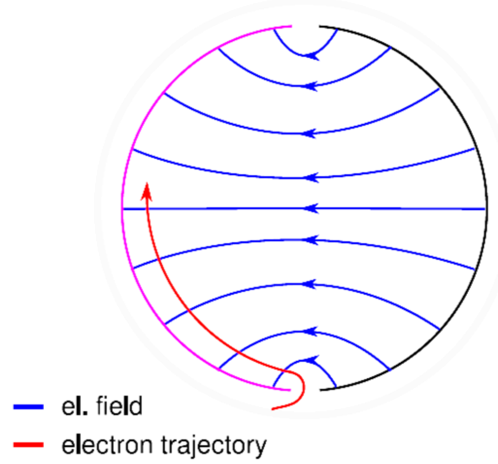
For symmetric case no correlation was found!

Background characteristics at KATRIN

Effect of electric dipole

- Electric dipole to drift-out stored particles of energies E > 1 eV.





Dipole active:
542 +/- 10 mcps

Dipole inactive:
497 +/- 6 mcps

→ No significant impact of electric dipole on background level observed.

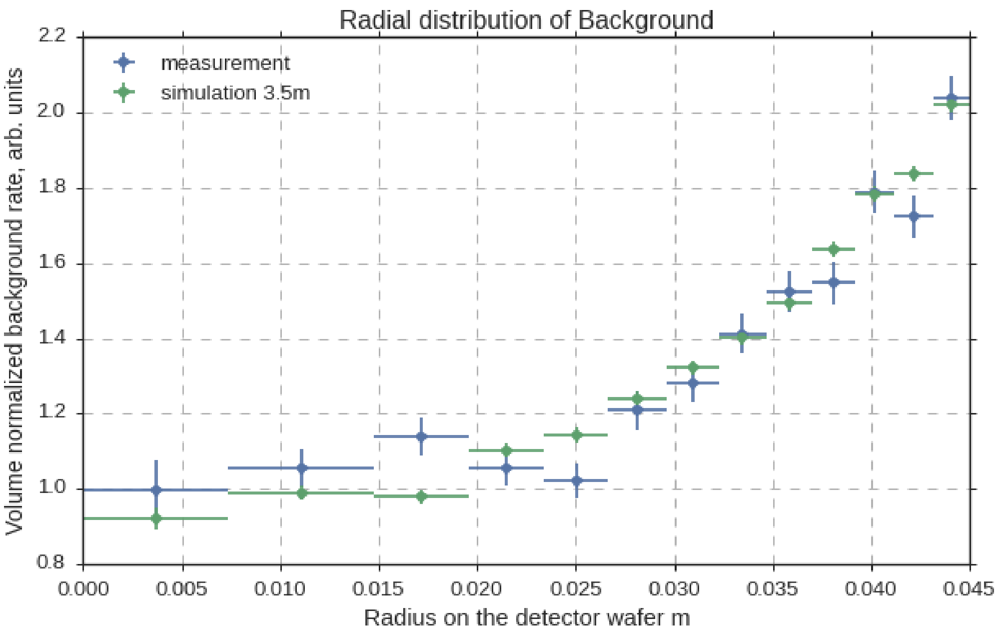
→ Background electrons must be low-energetic (E < 1 eV).

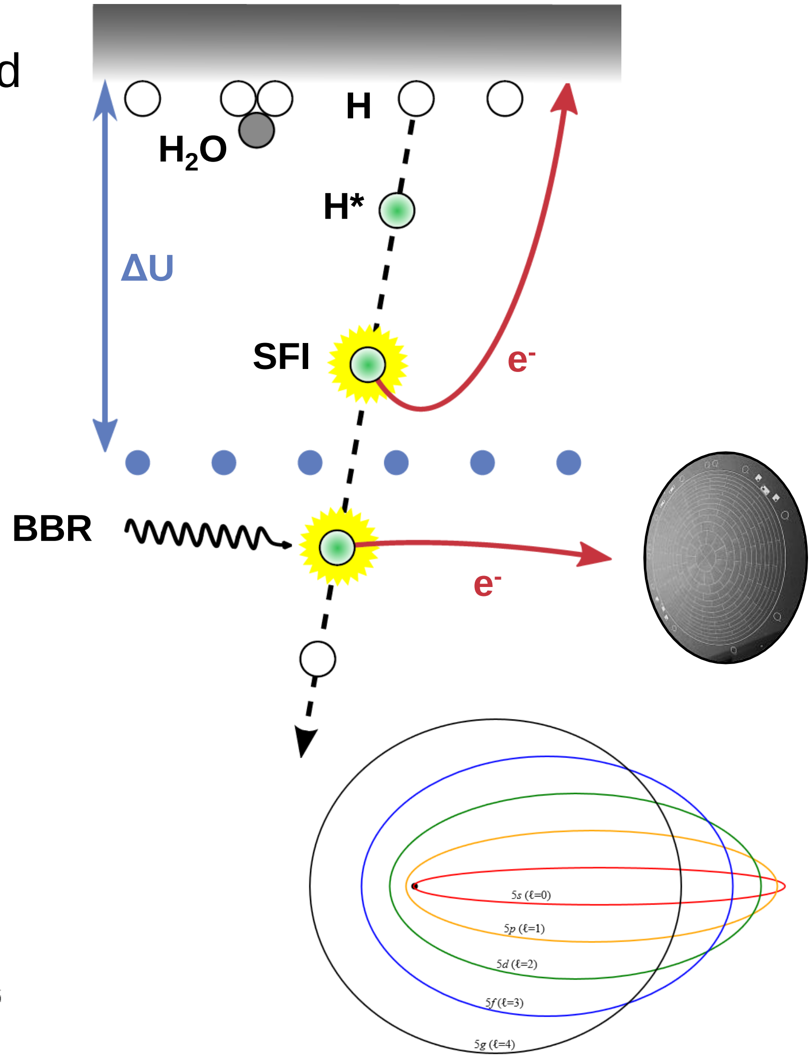
The Rydberg-atom based background model

Characteristics

How to combine volume dependent background with surface conditions and ΔU-dependence?

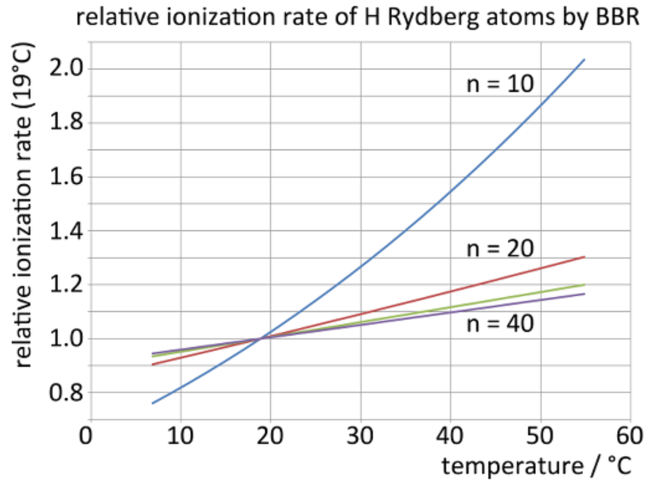
→ **Neutral messenger particles (Hydrogen Rydberg atoms)**



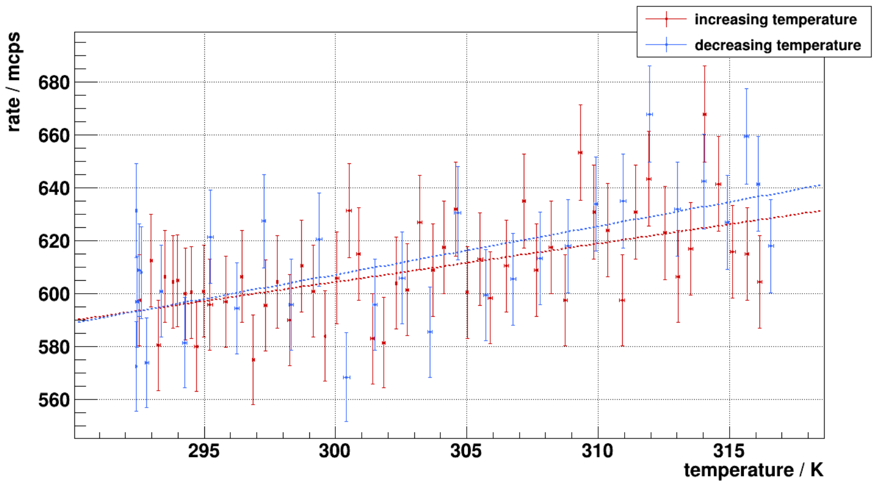


Rydberg model – temperature dependence

- Spectrometer temperature was increased from 19°C to 43°C
- Linear increase expected for large n
- Most of background could be due to Rydberg atoms



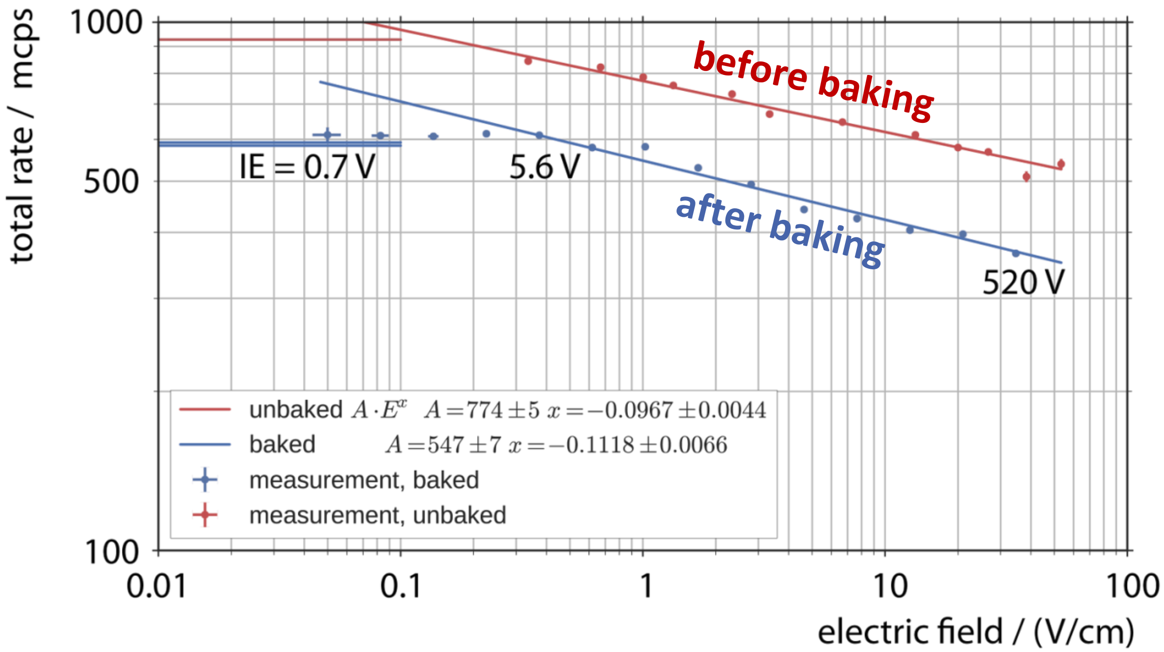
G.W. Lehman, “Rate of ionisation of H and Na Rydberg atoms by black-body radiation”, J. Phys. B, 1983

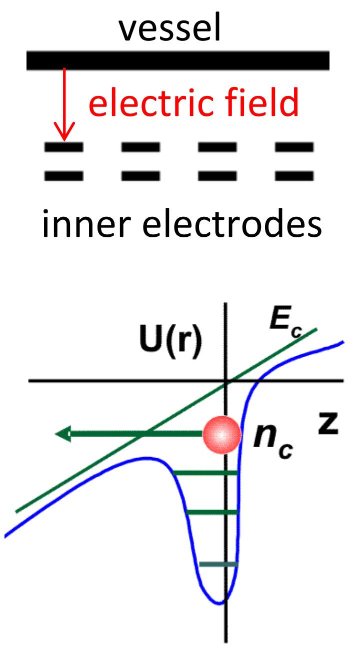


normalized slope (average): 0.79 ± 0.12

correlation factor: 0.6

Rydberg model – selective field ionization

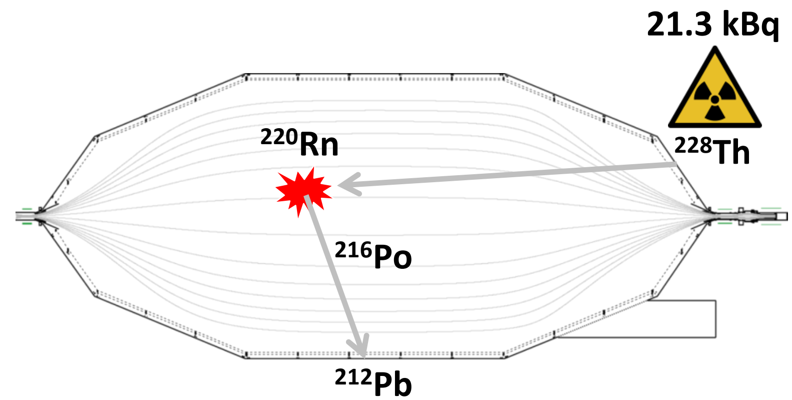


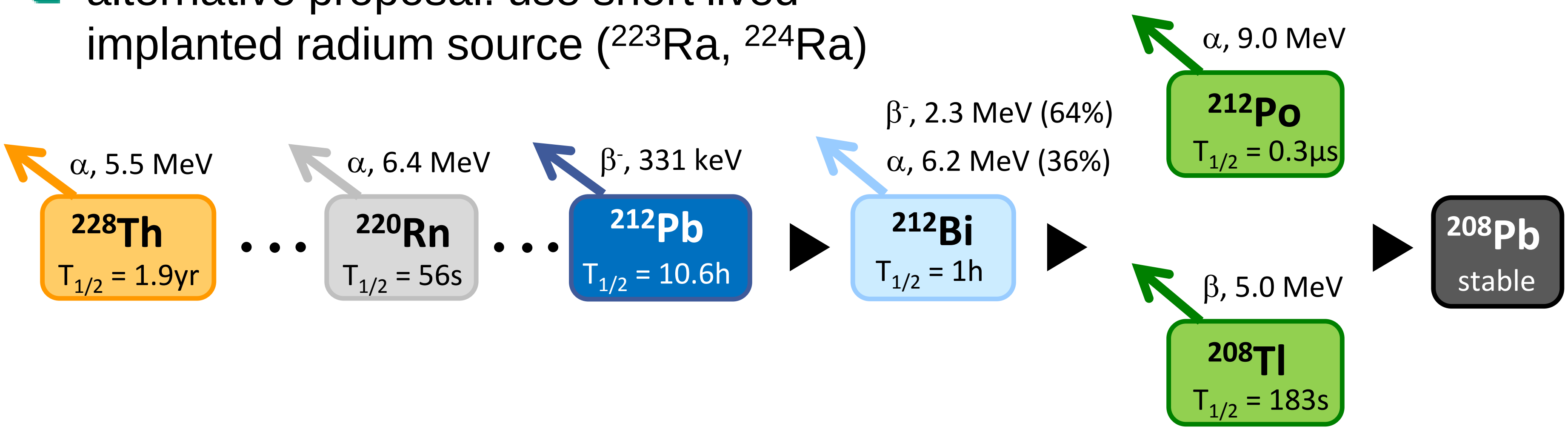


- Spectrometer baking improved background, but same behavior after baking
- Rydberg atoms are ionized by the electric field between vessel and electrodes and hence can not reach the inner spectrometer volume

Rydberg model test

- attach ^{228}Th source to main spectrometer
- “contaminate” inner surface with ^{212}Pb
- close valve to ^{228}Th source and check for exponentially decaying background rate
- alternative proposal: use short lived implanted radium source (^{223}Ra, ^{224}Ra)

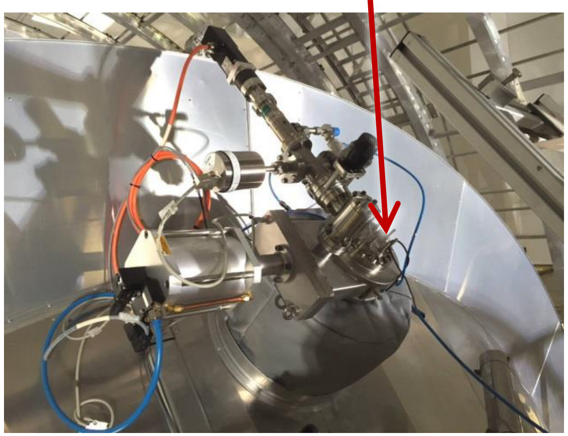




^{228}Th source – contamination phase

^{228}Th source (21.3 kBq)

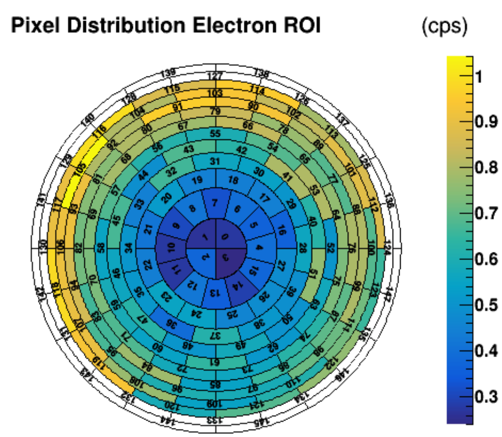
filter



MS pump port 100

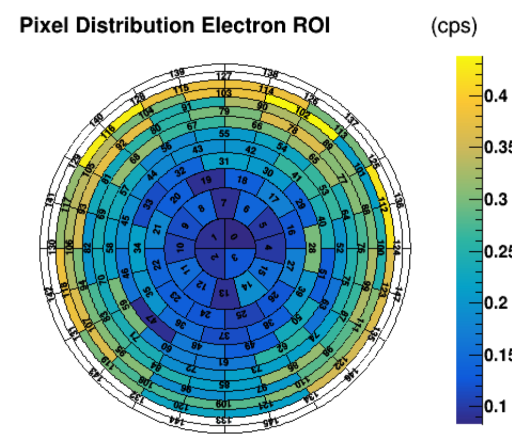
- Source courtesy of XENON collaboration (Thanks to V. Hannen / C. Weinheimer)
- Exposure started on Dec 1st, 2016
- Exposure time 20h 6min (about $2 \times T_{1/2}$, 73%)

rate after opening valve to source (warm baffles):



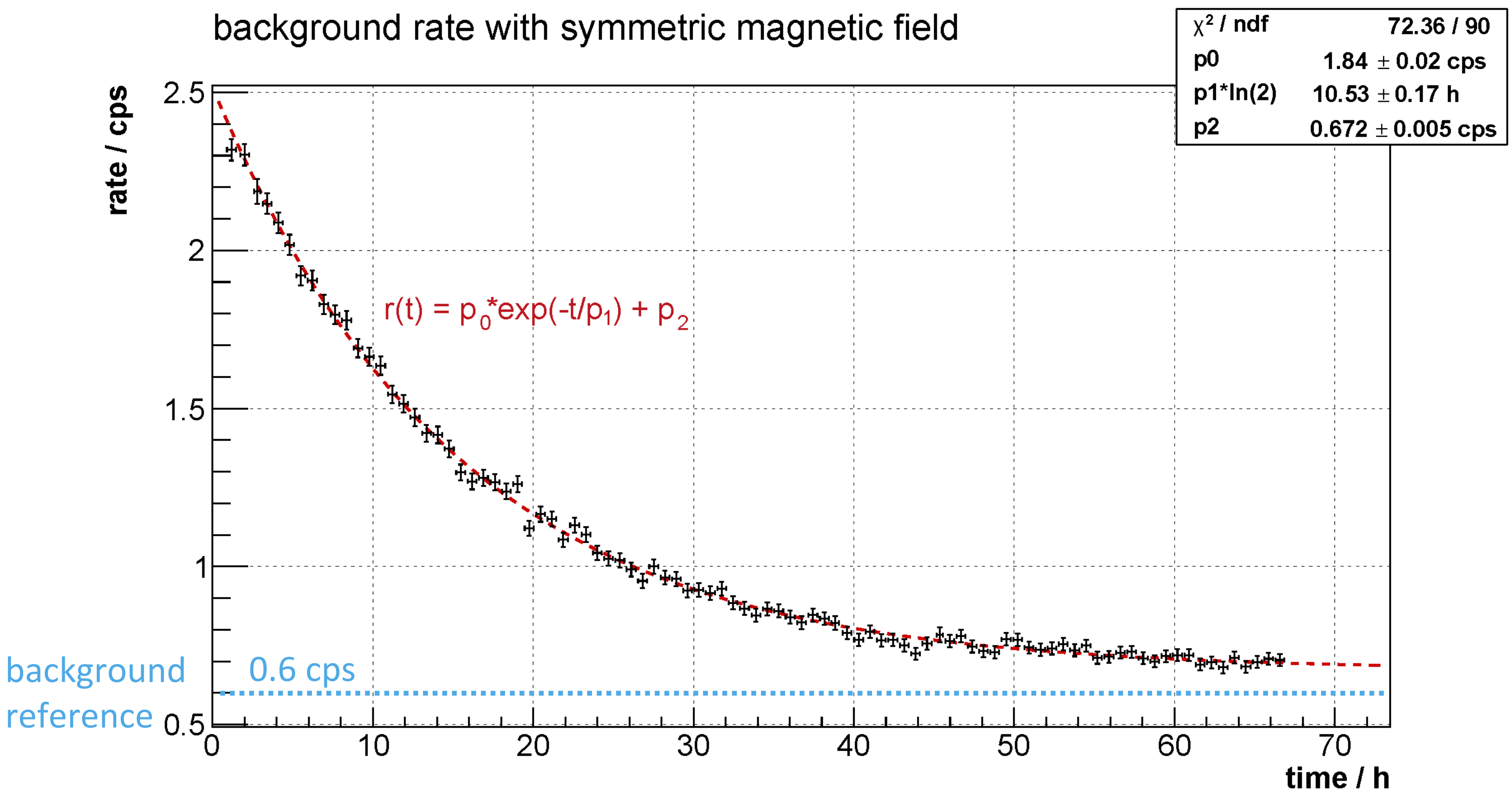
78 ± 0.8 cps

rate before closing valve to source (cold baffles):



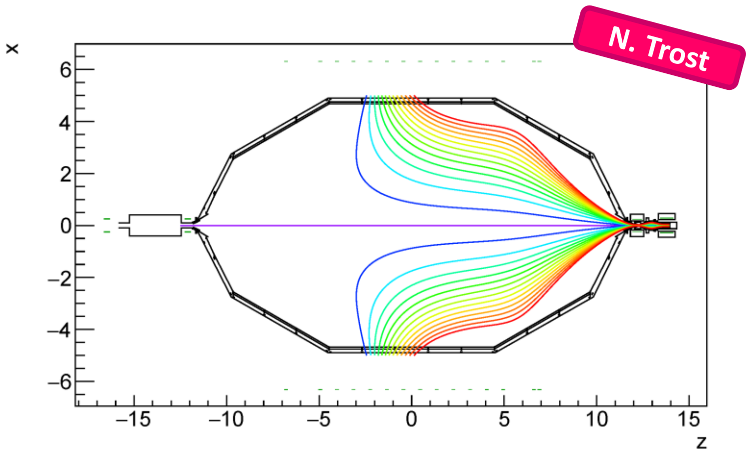
28 ± 0.5 cps

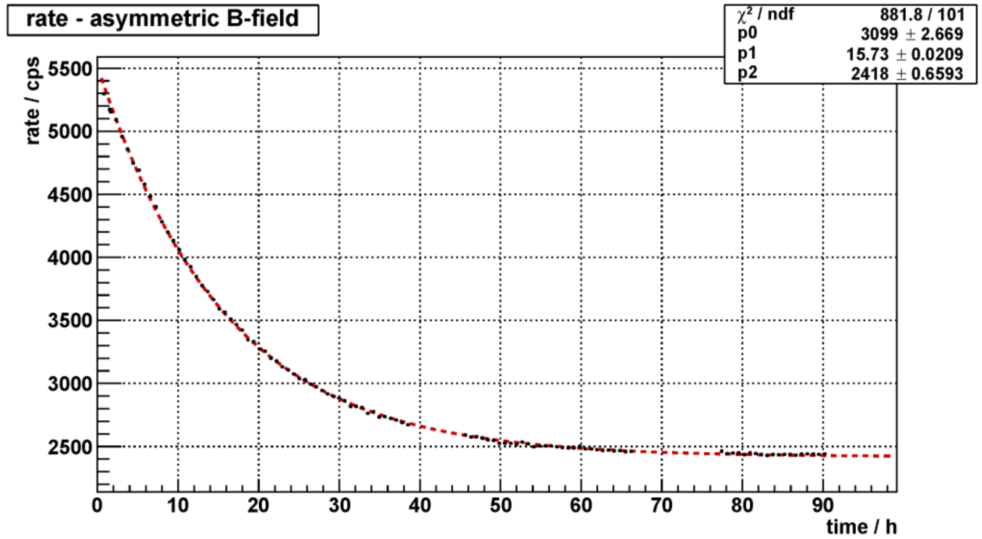
^{212}Pb contamination – decay phase

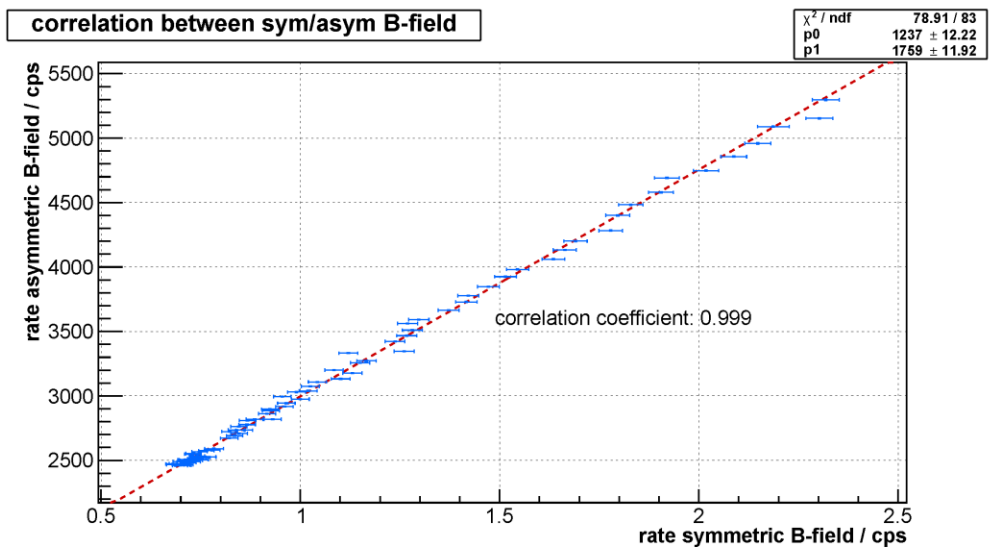


- Observed half-life matches ^{212}Pb literature value of 10.64 ± 0.01 very well
- Assuming similar processes, ^{210}Pb contamination < 5.1 kBq

^{212}Pb contamination – decay phase



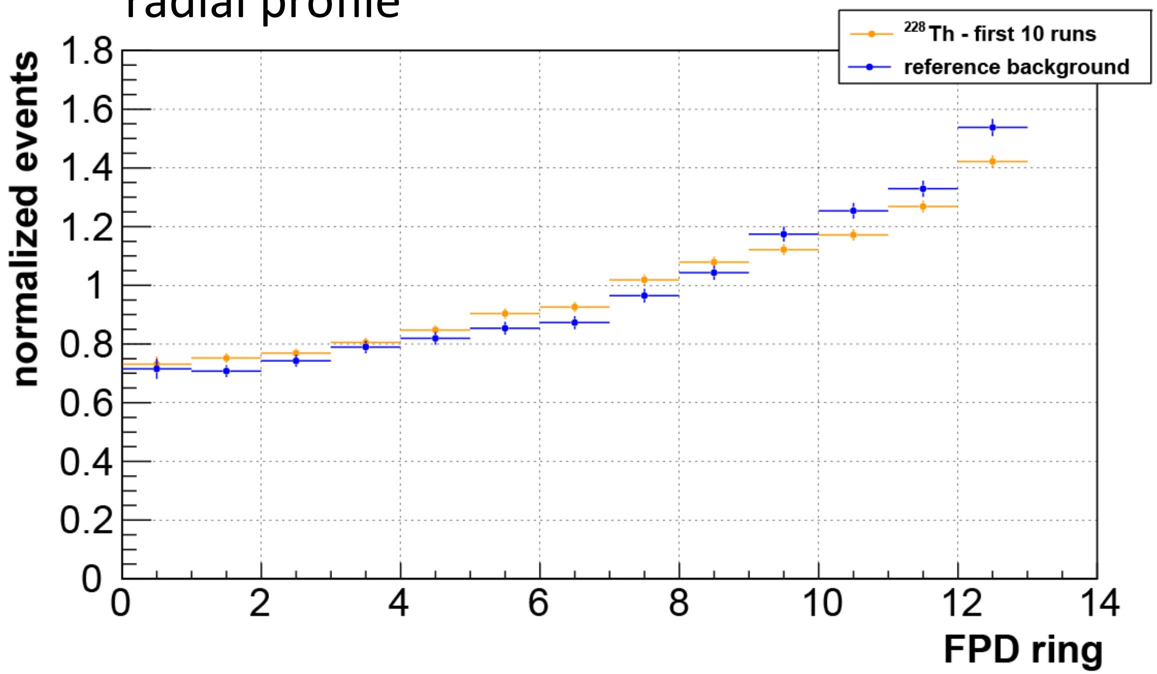




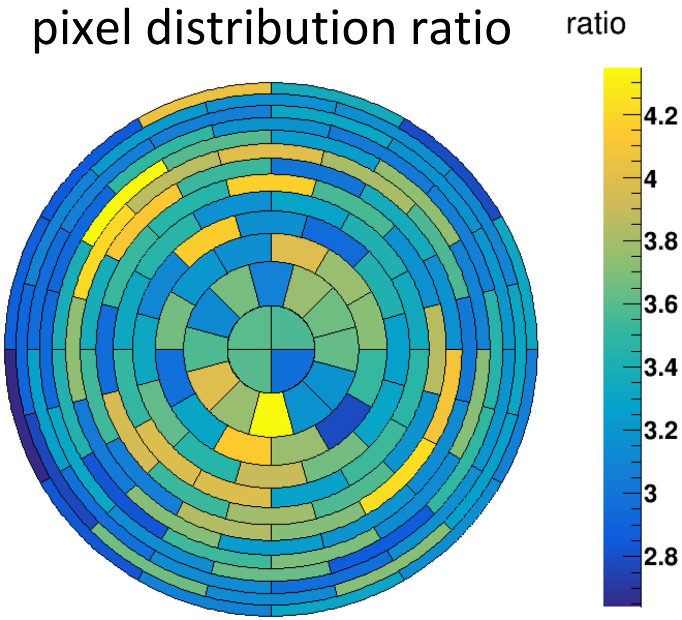
- rate from vessel wall shows the same exponential decay ($T_{1/2}$ = 10.9 h)
- There is a very strong correlation between electrons from the vessel wall and electrons from the spectrometer volume

Background signature

radial profile



pixel distribution ratio

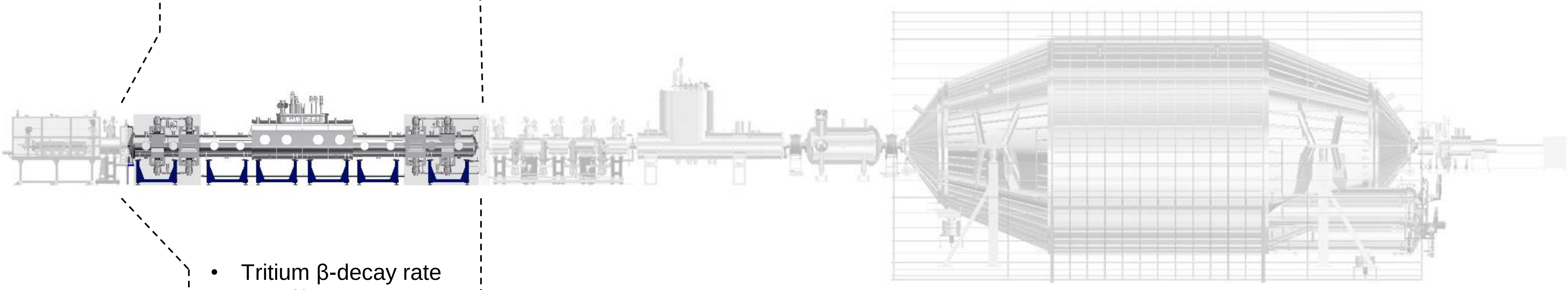


- induced background has the same behavior as existing background

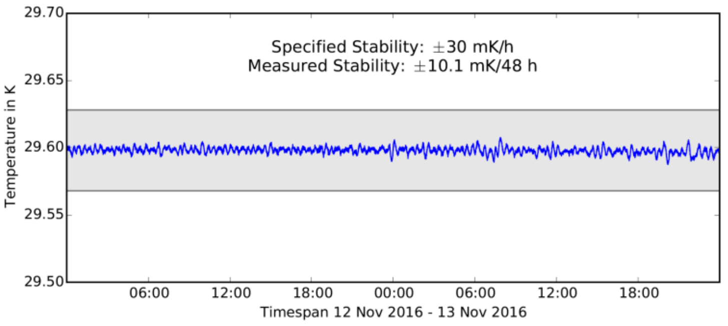
→ main spectrometer ^{210}Pb contamination is root cause of background

The experimental beamline
Overview

Windowless gaseous tritium source

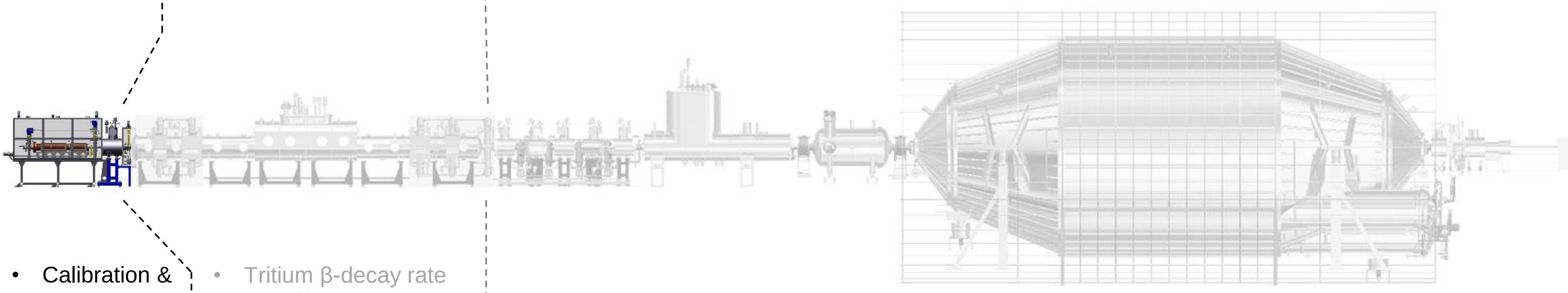


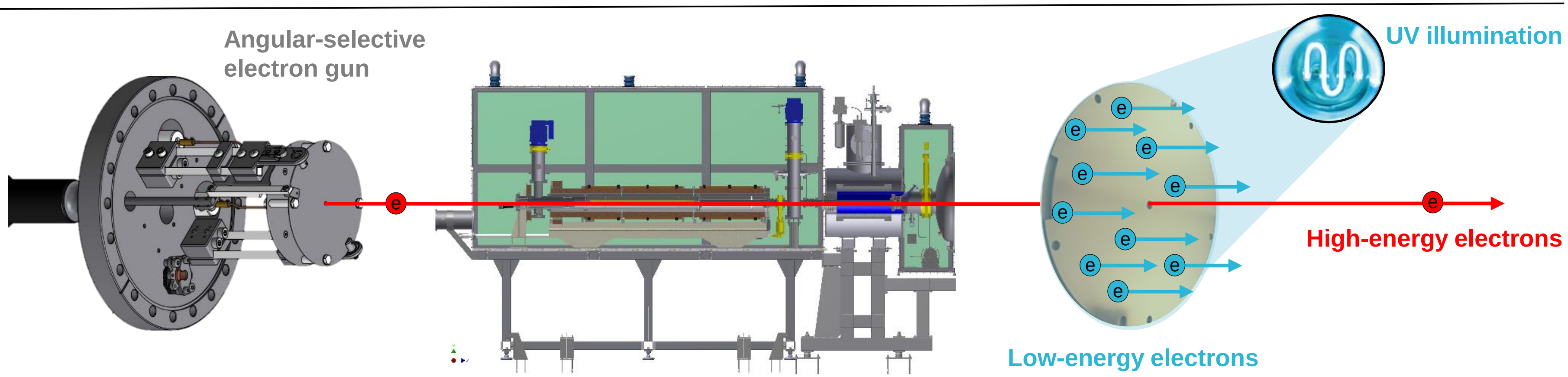
- Tritium β-decay rate of 10^{11} 1/s
- Operating parameters (T, p, etc.) stabilized at 10^{-3} level



The experimental beamline
Overview

Rear Section	Windowless gaseous tritium source
• Calibration & monitoring • Artificial electron source	• Tritium β-decay rate of 10^{11} 1/s • Operating parameters (T, p, etc.) stabilized at 10^{-3} level





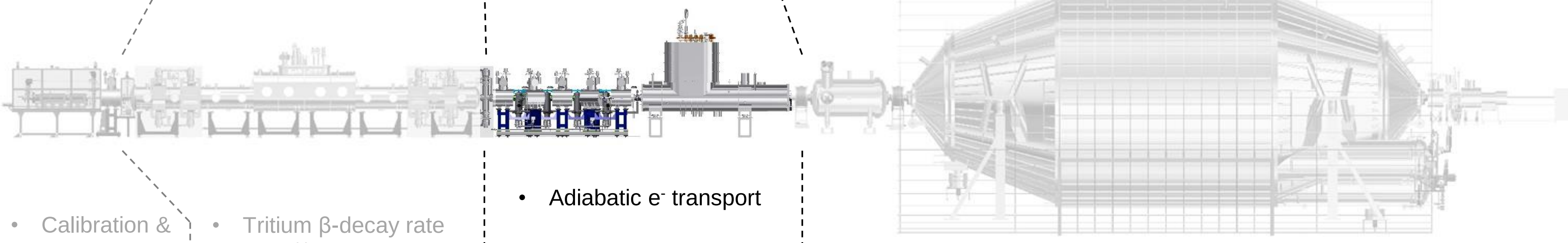
The experimental beamline

Overview

Rear Section

Windowless gaseous tritium source

Transport Section



Rear Section:

- Calibration & monitoring
- Artificial electron source

Windowless gaseous tritium source:

- Tritium β-decay rate of 10^{11} 1/s
- Operating parameters (T, p, etc.) stabilized at 10^{-3} level

Transport Section:

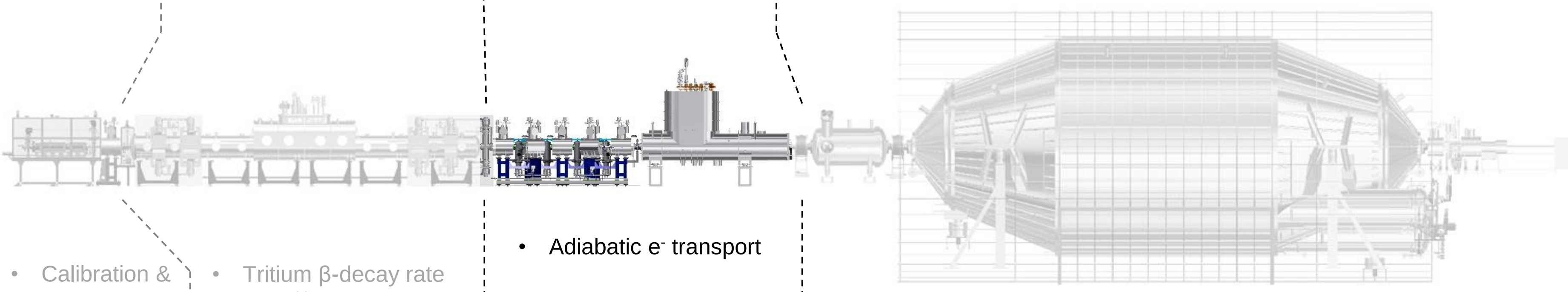
- Adiabatic e^- transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$

Differential pumping section

Ion blocking and ion drift electrodes

The experimental beamline

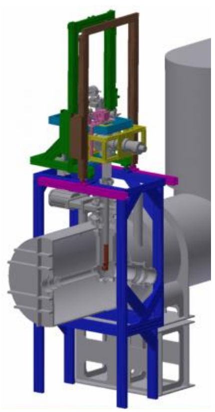
Overview



Rear Section:
- Calibration & monitoring
- Artificial electron source

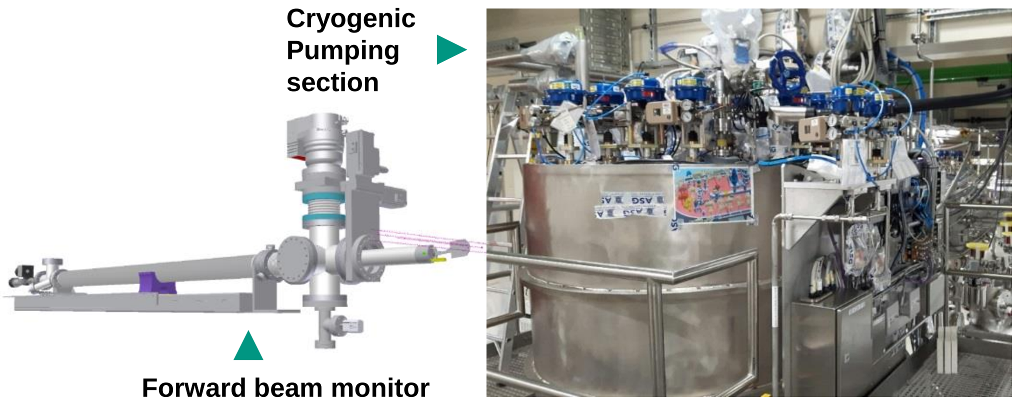
Windowless gaseous tritium source:
- Tritium β-decay rate of 10^{11} 1/s
- Operating parameters (T, p, etc.) stabilized at 10^{-3} level

Transport Section:
- Adiabatic e^- transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$



Condensed ^{83m}Kr source

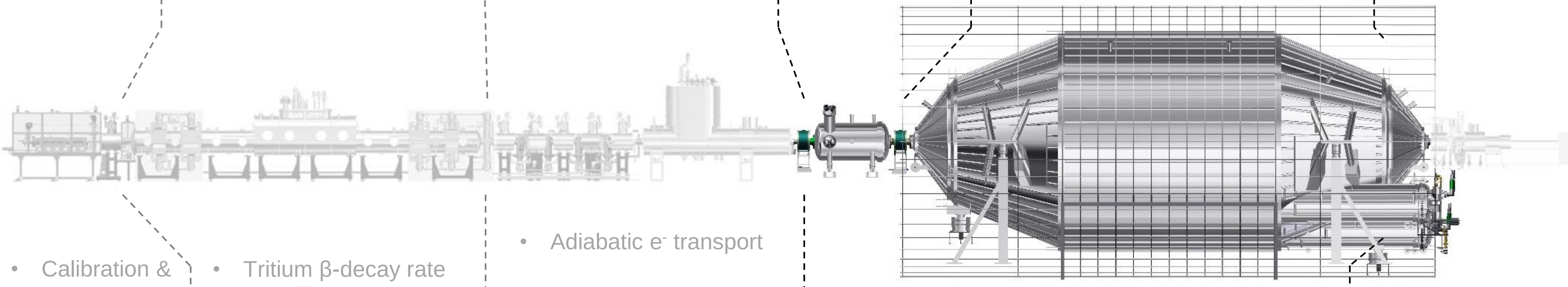
Cryogenic Pumping section



Forward beam monitor

The experimental beamline
Overview

Rear Section | Windowless gaseous tritium source | Transport Section | Pre-spectrometer | Main Spectrometer



Rear Section
- Calibration & monitoring
- Artificial electron source

Windowless gaseous tritium source
- Tritium β-decay rate of 10^{11} 1/s
- Operating parameters (T, p, etc.) stabilized at 10^{-3} level

Transport Section
- Adiabatic e^- transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$

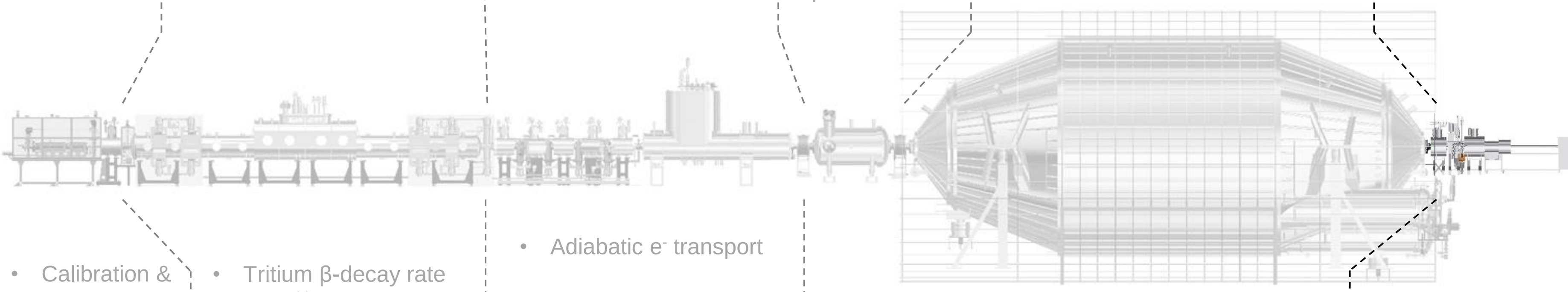
Main Spectrometer
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Operated at UHV conditions ($<10^{-10}$ mbar)

Main Spectrometer ▶

◀ **Pre-Spectrometer**

The experimental beamline

Overview



Rear Section
- Calibration & monitoring
- Artificial electron source

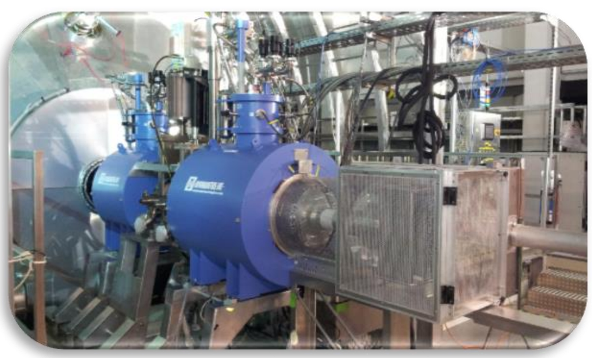
Windowless gaseous tritium source
- Tritium β-decay rate of 10^{11} 1/s
- Operating parameters (T, p, etc.) stabilized at 10^{-3} level

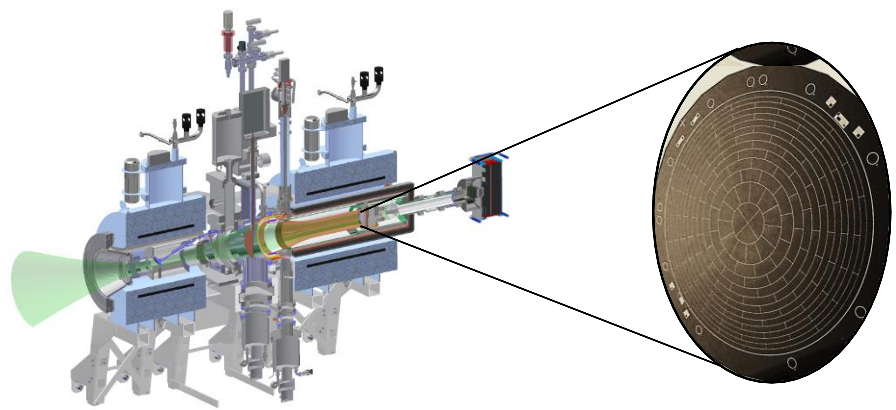
Transport Section
- Adiabatic e^- transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$

Pre-spectrometer

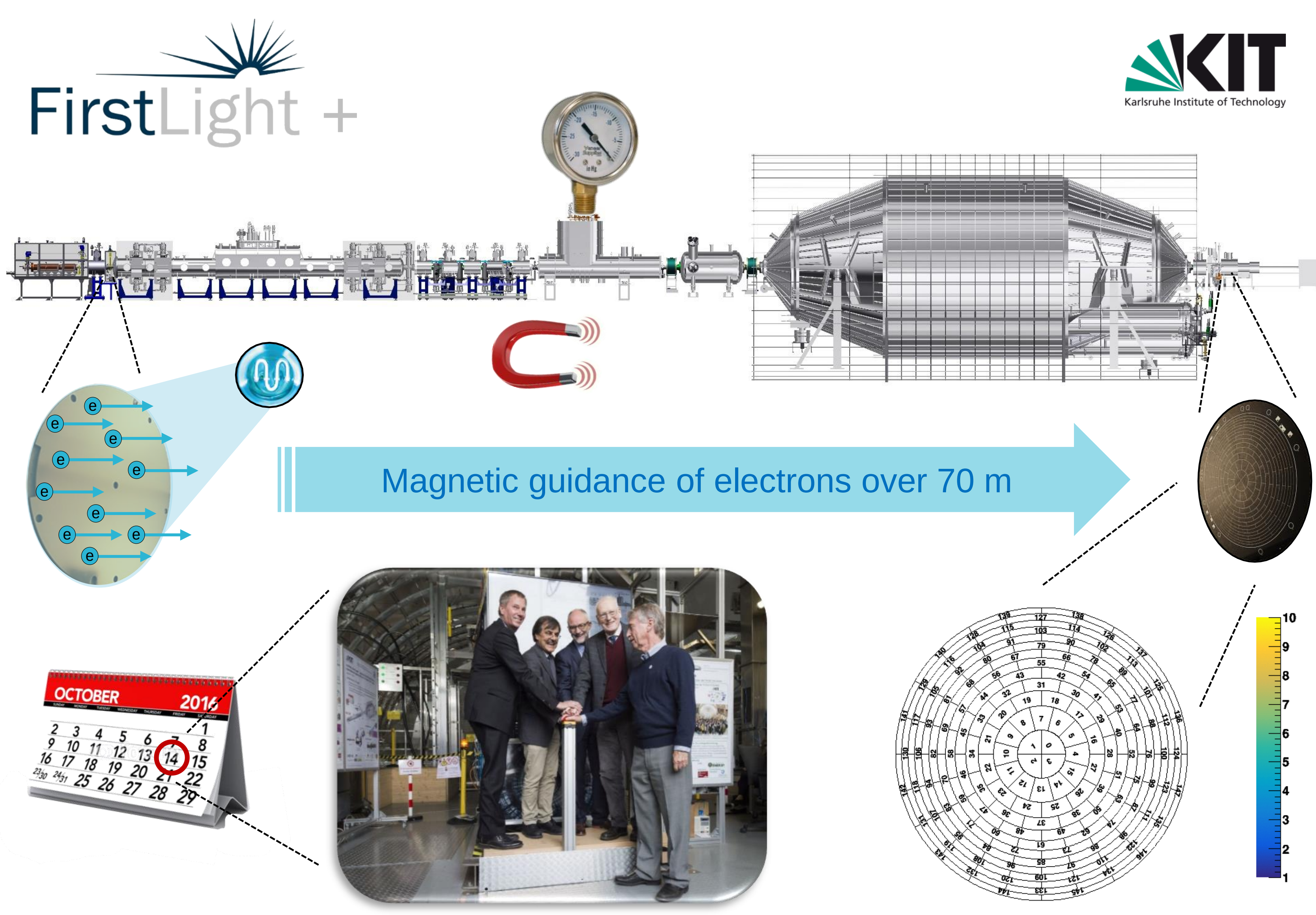
Main Spectrometer
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Operated at UHV conditions ($<10^{-10}$ mbar)

Detector
- Si-PIN diode array
- Highly efficient e^- counting



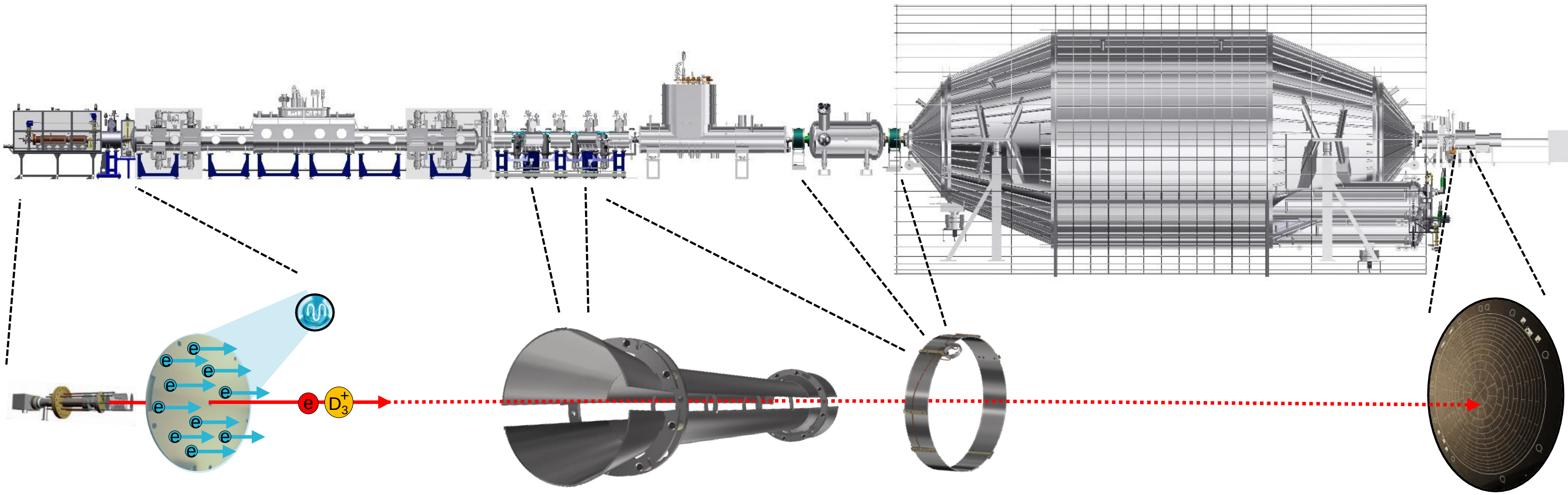


The detector wafer

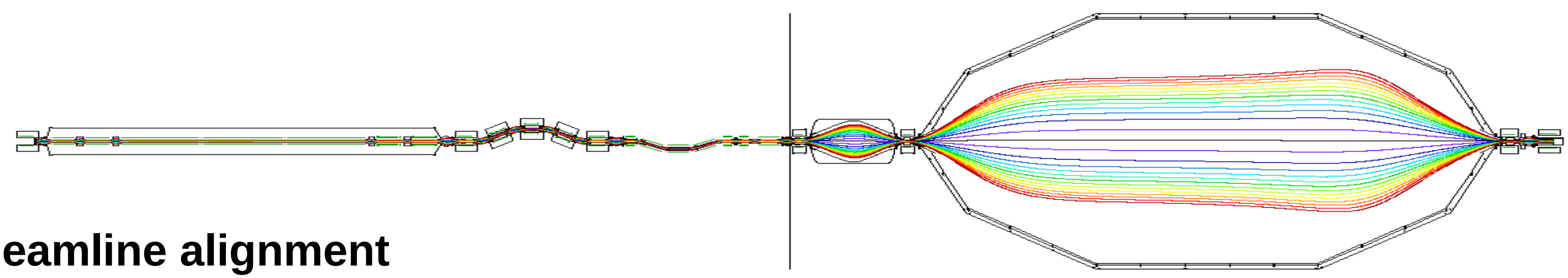

FirstLight +
KIT
Karlsruhe Institute of Technology
Magnetic guidance of electrons over 70 m
OCTOBER
2016

First Light

Measurements



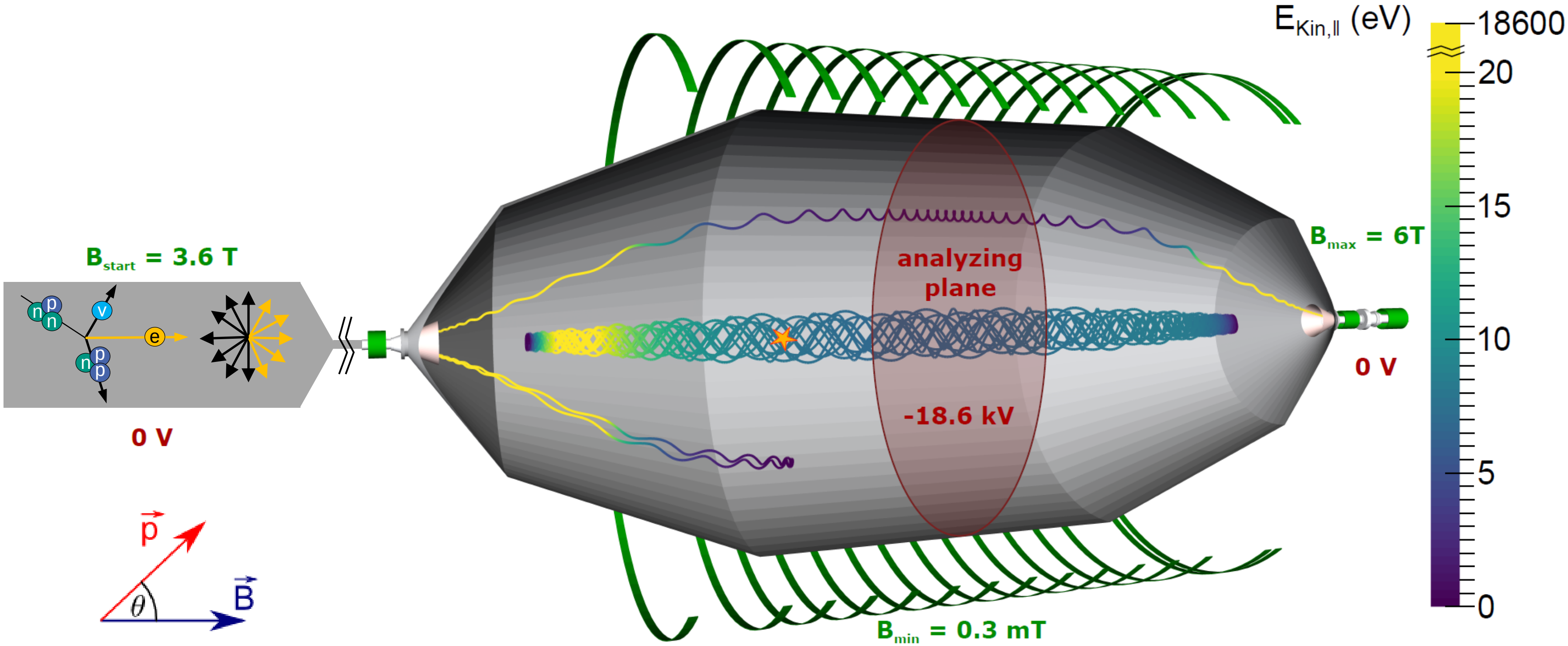
Ion investigations



Beamline alignment

Neutrino-mass measurement with KATRIN

Measurement principle – The MAC-E filter

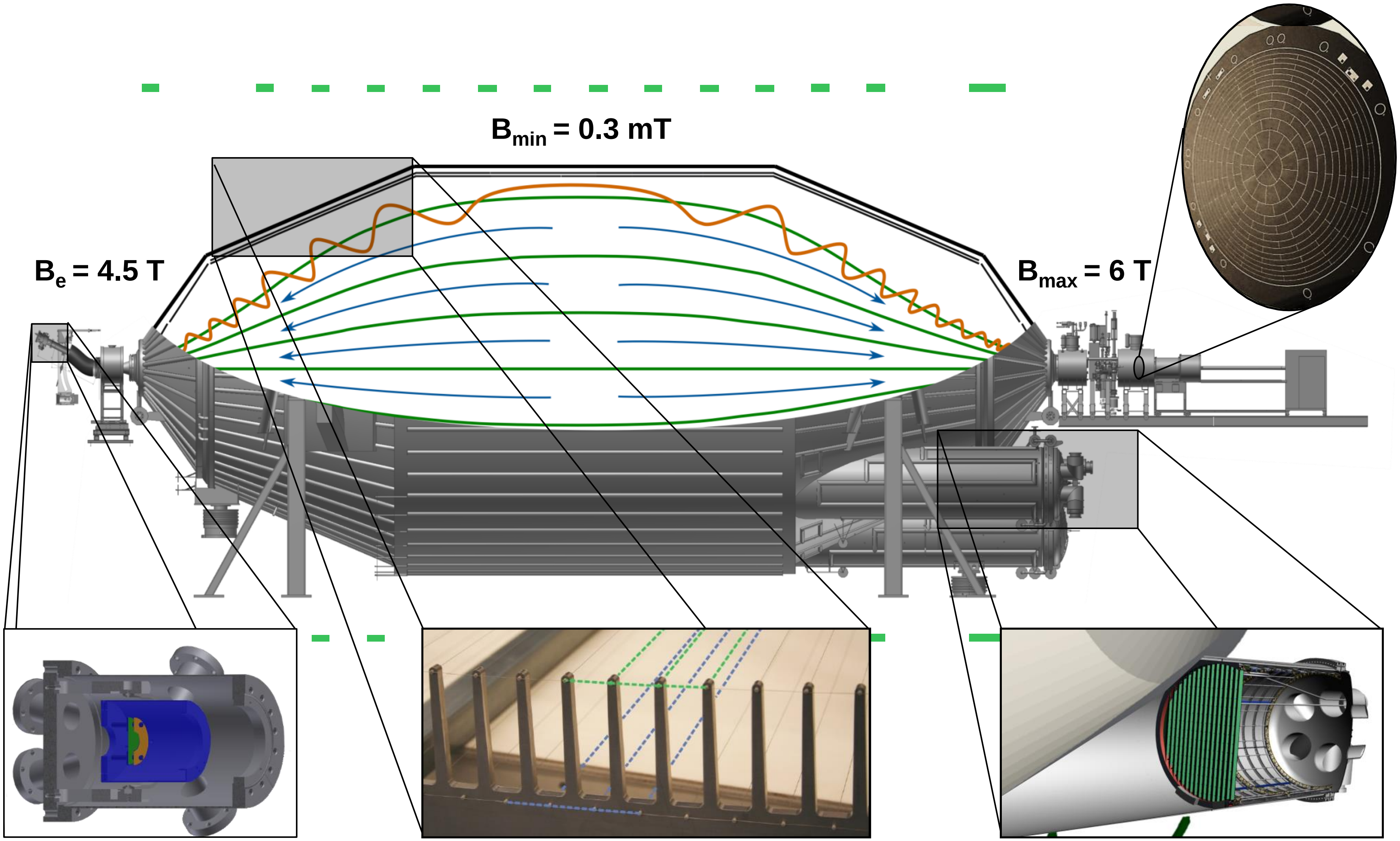


$$E_{kin} = E_{||} + E_{\perp}$$

$$\mu = \frac{E_{\perp}}{B} = const.$$

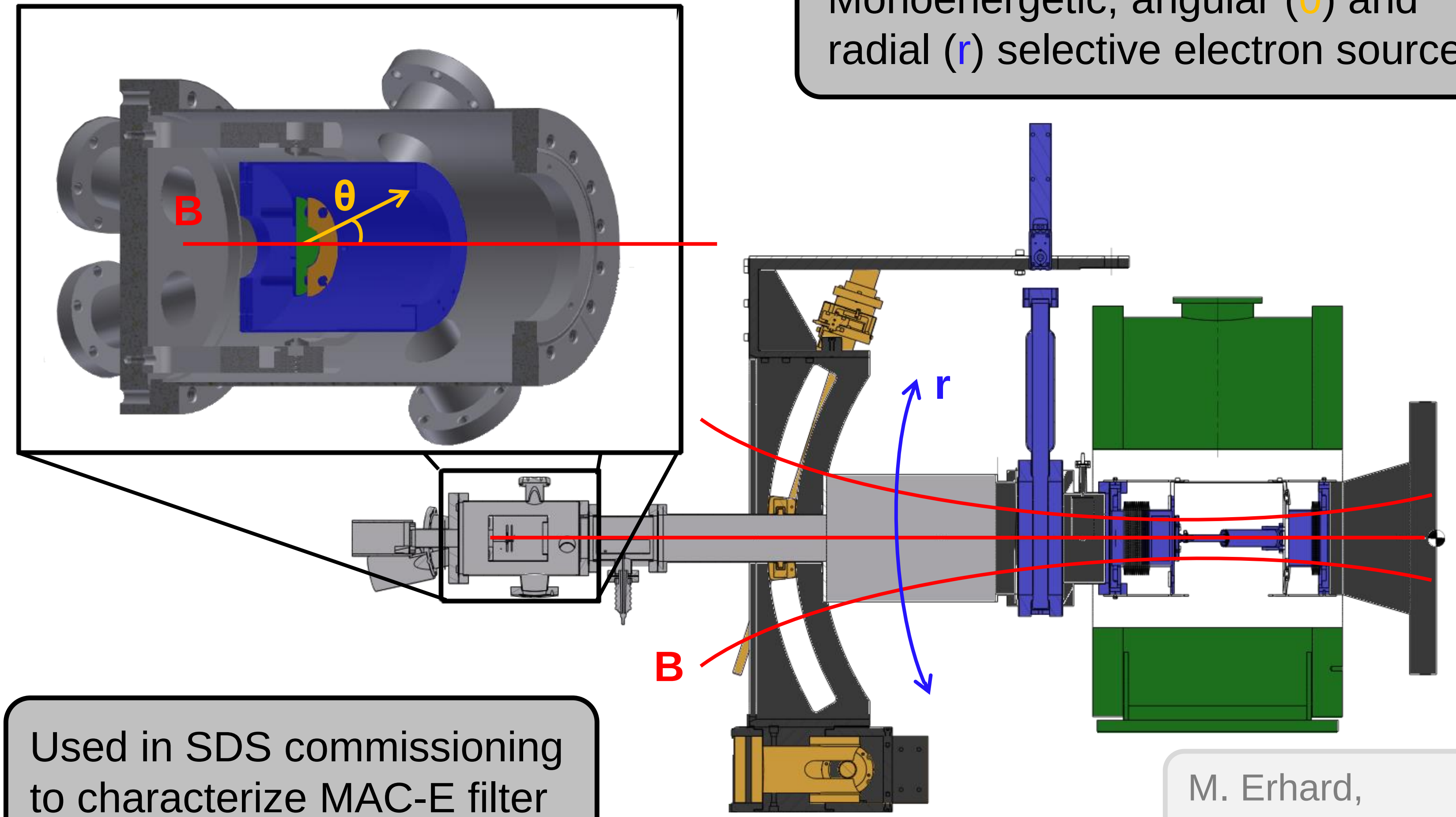
$$\Delta E = \frac{B_{min}}{B_{max}} \cdot 18.6 \text{ keV} = 0.93 \text{ eV}$$

Backup



Backup

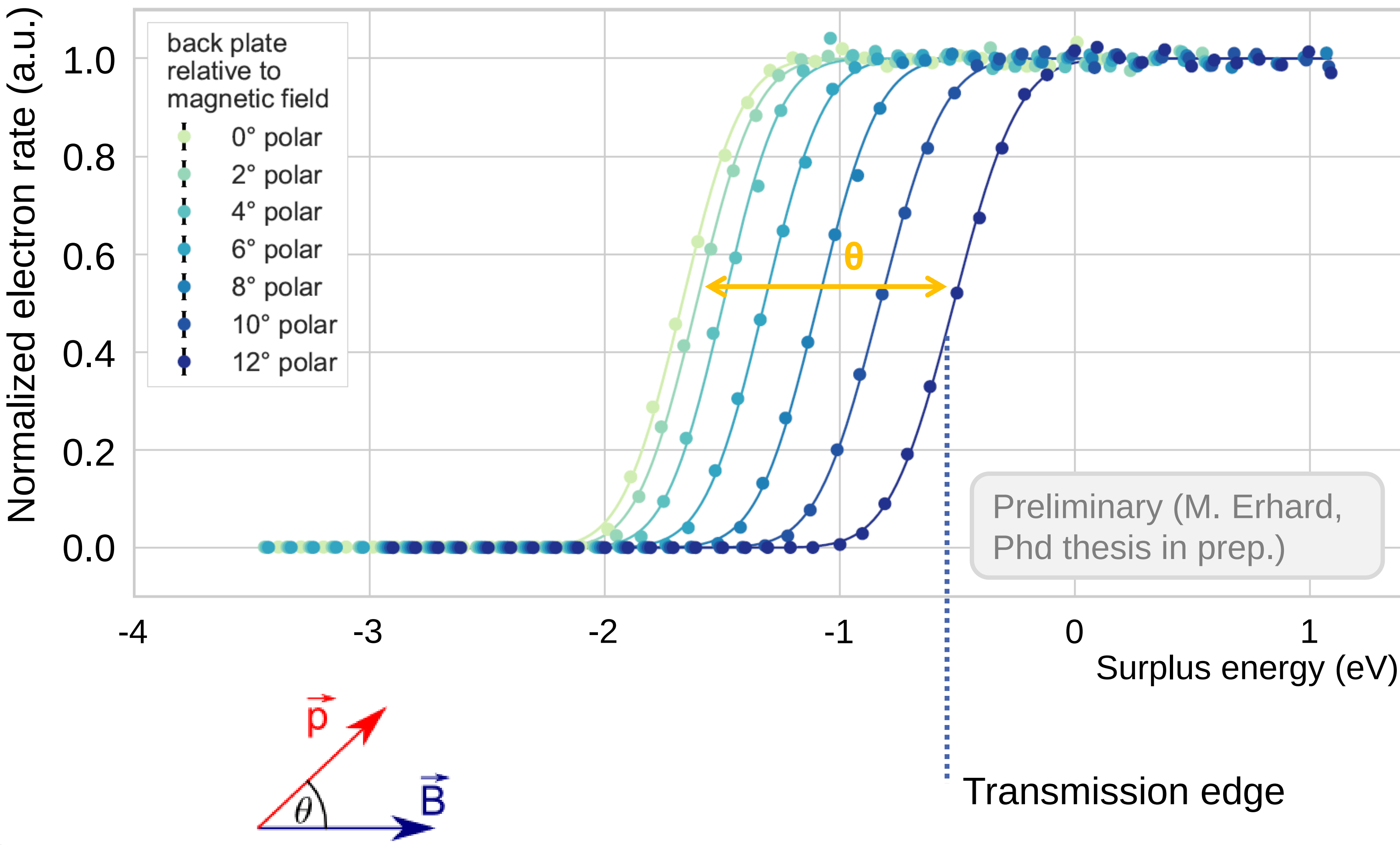
Monoenergetic, angular (θ) and radial (r) selective electron source.



Used in SDS commissioning to characterize MAC-E filter

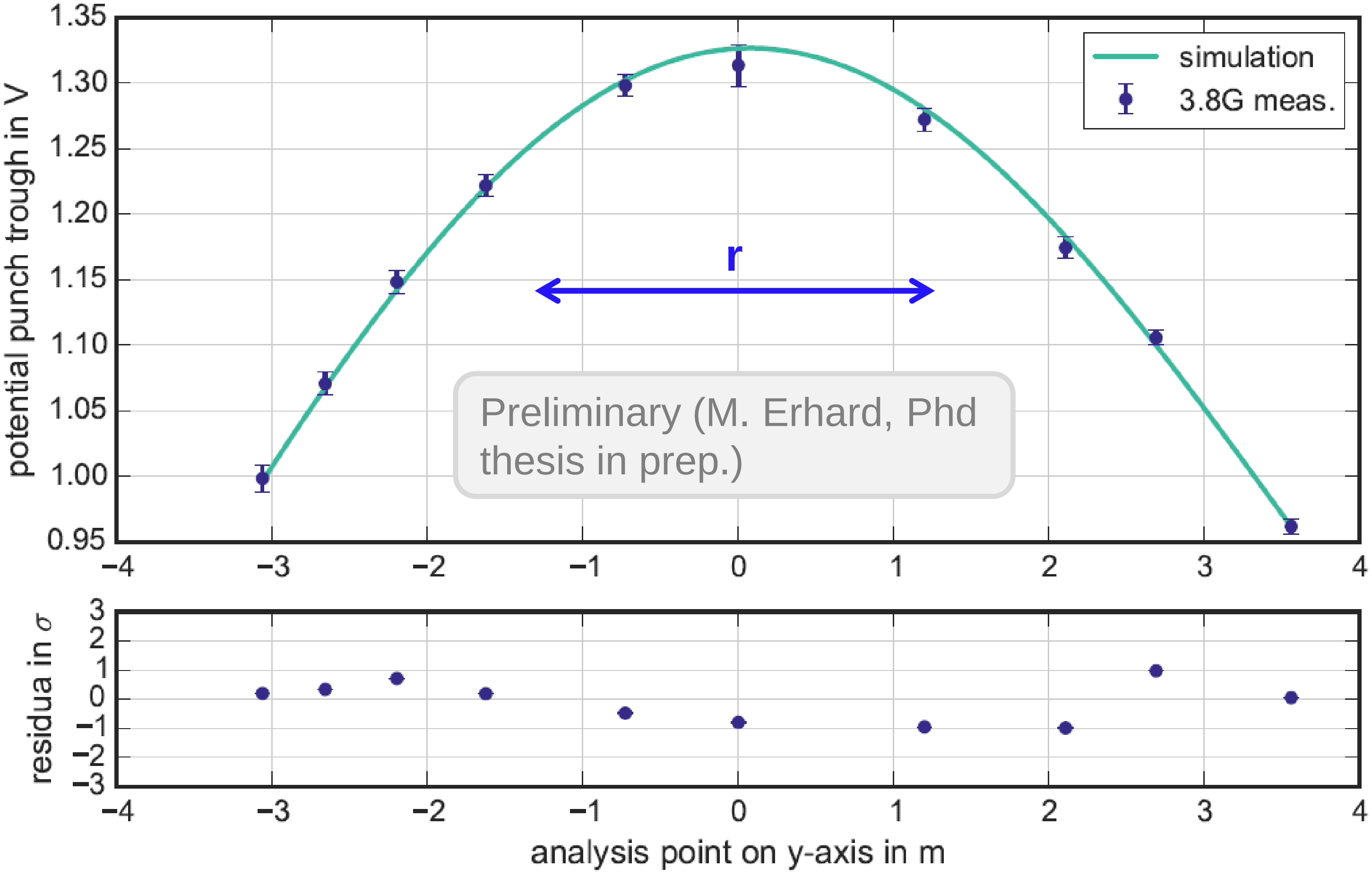
M. Erhard,
Phd thesis in prep.

Backup



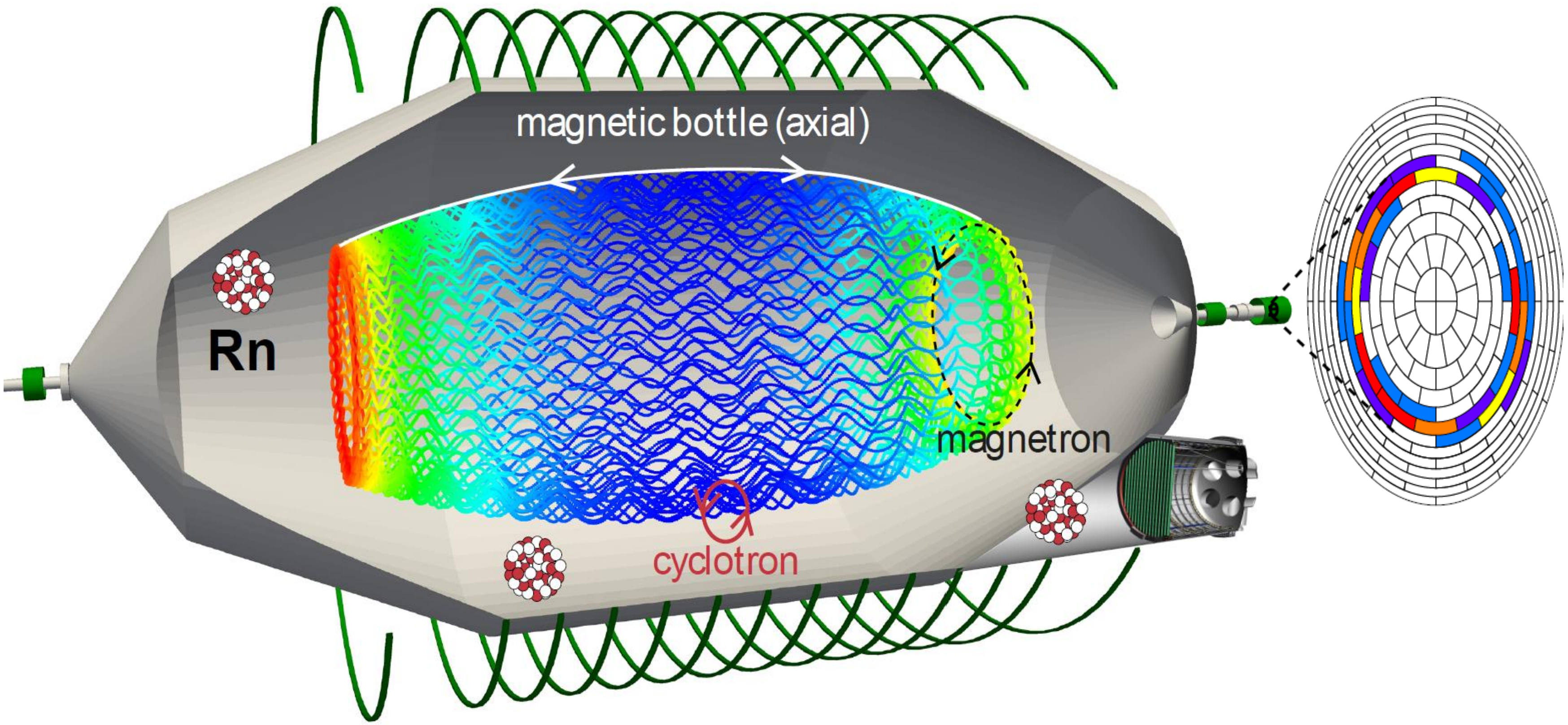
Normalized electron rate (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
back plate
relative to
magnetic field
0° polar
2° polar
4° polar
6° polar
8° polar
10° polar
12° polar
θ
Preliminary (M. Erhard,
Phd thesis in prep.)
-4
-3
-2
-1
0
1
Surplus energy (eV)
p
B
θ
Transmission edge

Backup



1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
potential punch trough in V
simulation
3.8G meas.
r
Preliminary (M. Erhard, Phd thesis in prep.)
−4
−3
−2
−1
0
1
2
3
4
residua in σ
analysis point on y-axis in m

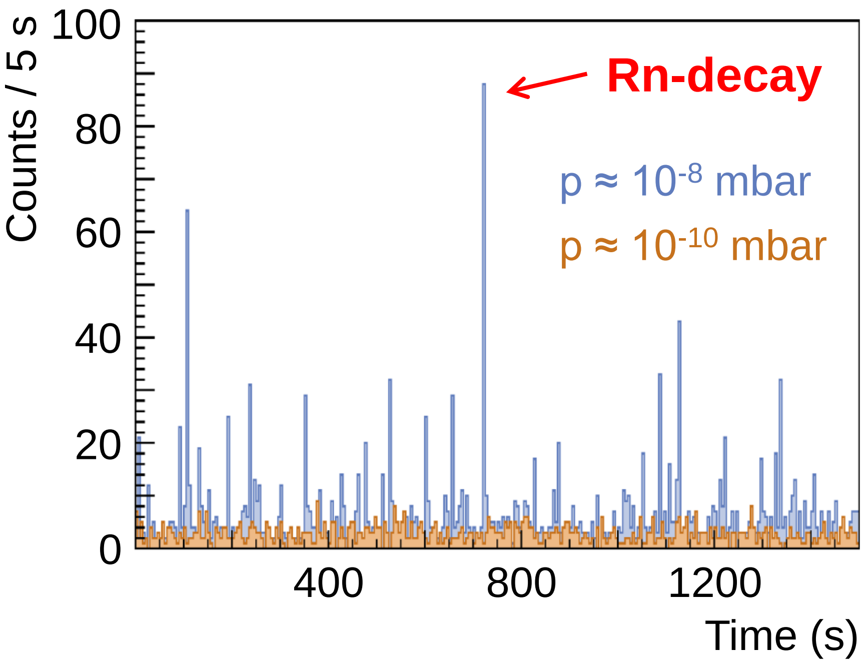
Backup

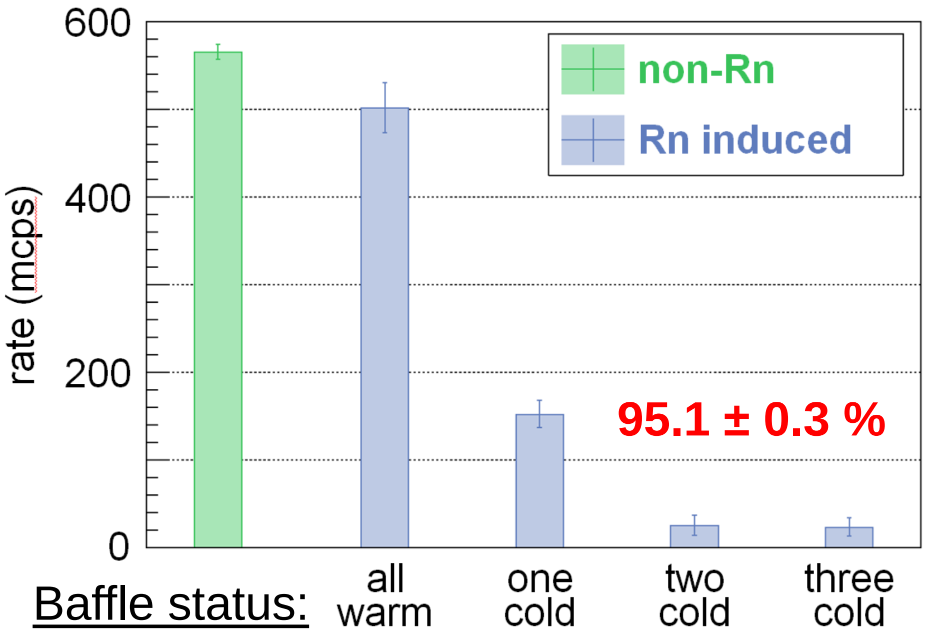


Storage of keV-electrons emitted in radioactive decays

Backup

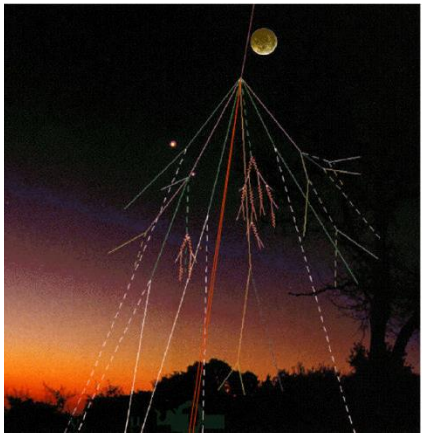
- Artificially elevate pressure in the spectrometer to reduce cool-down times.
- Identify single radon decays as spike in the background rate.
- Determine efficiency of LN_2-baffle system as Rn countermeasure.

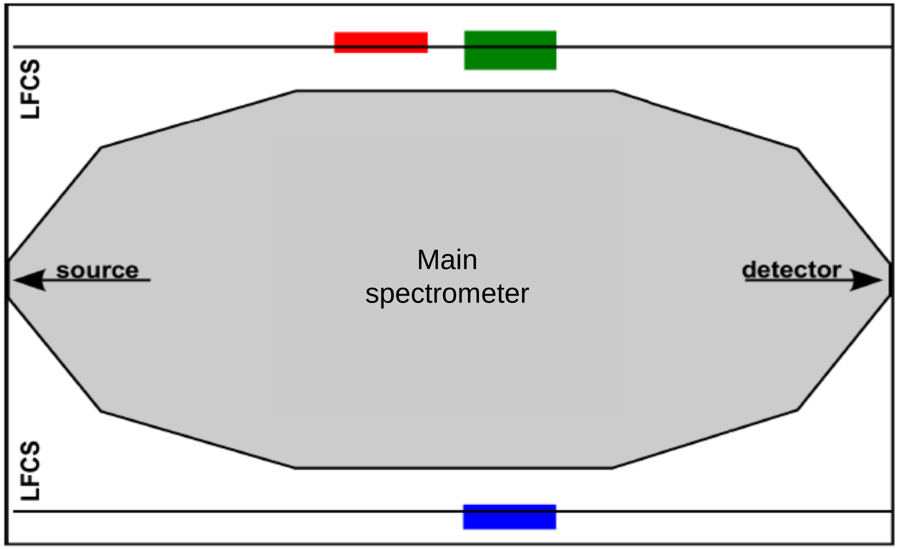


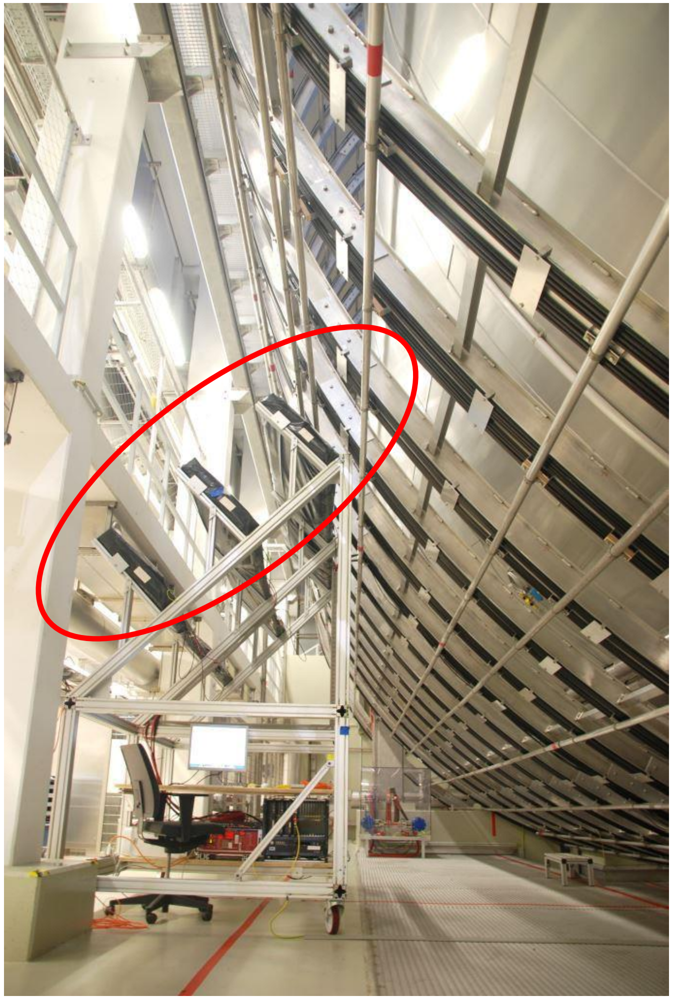


Backup

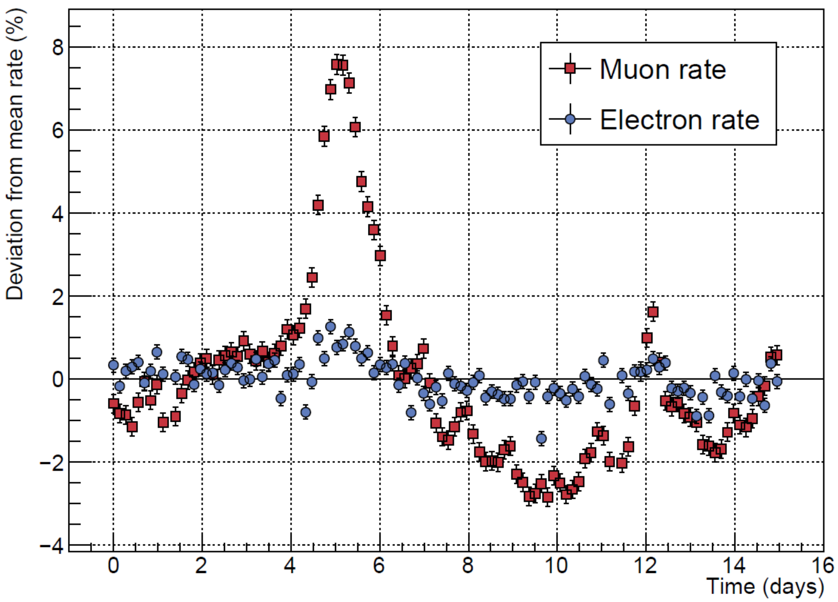
- 75 000 muons / second
- Use muon veto to correlate flux to electron rate







Backup

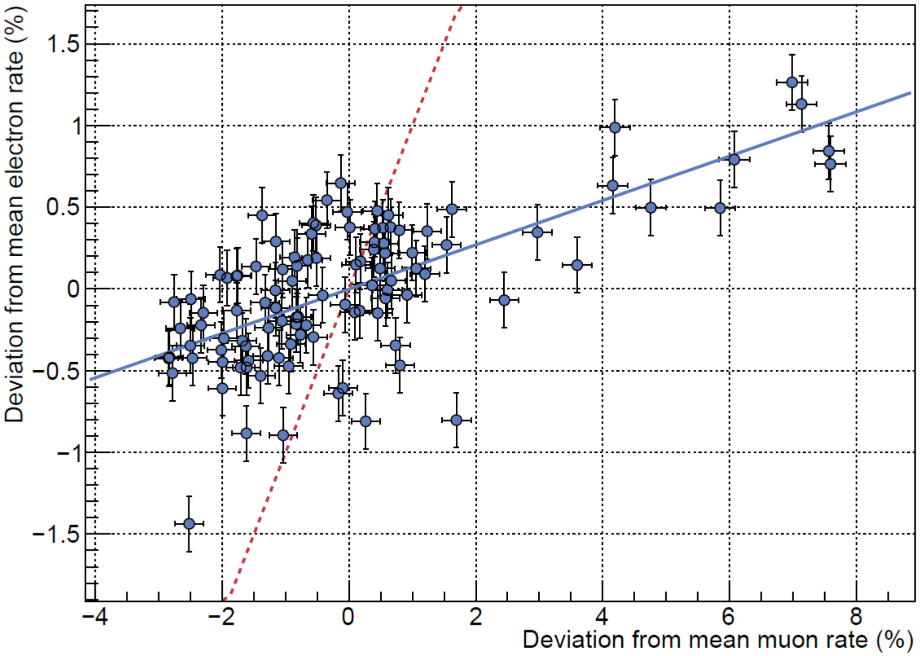


$$R_e(t) = \alpha \cdot R_\mu(t) + C$$

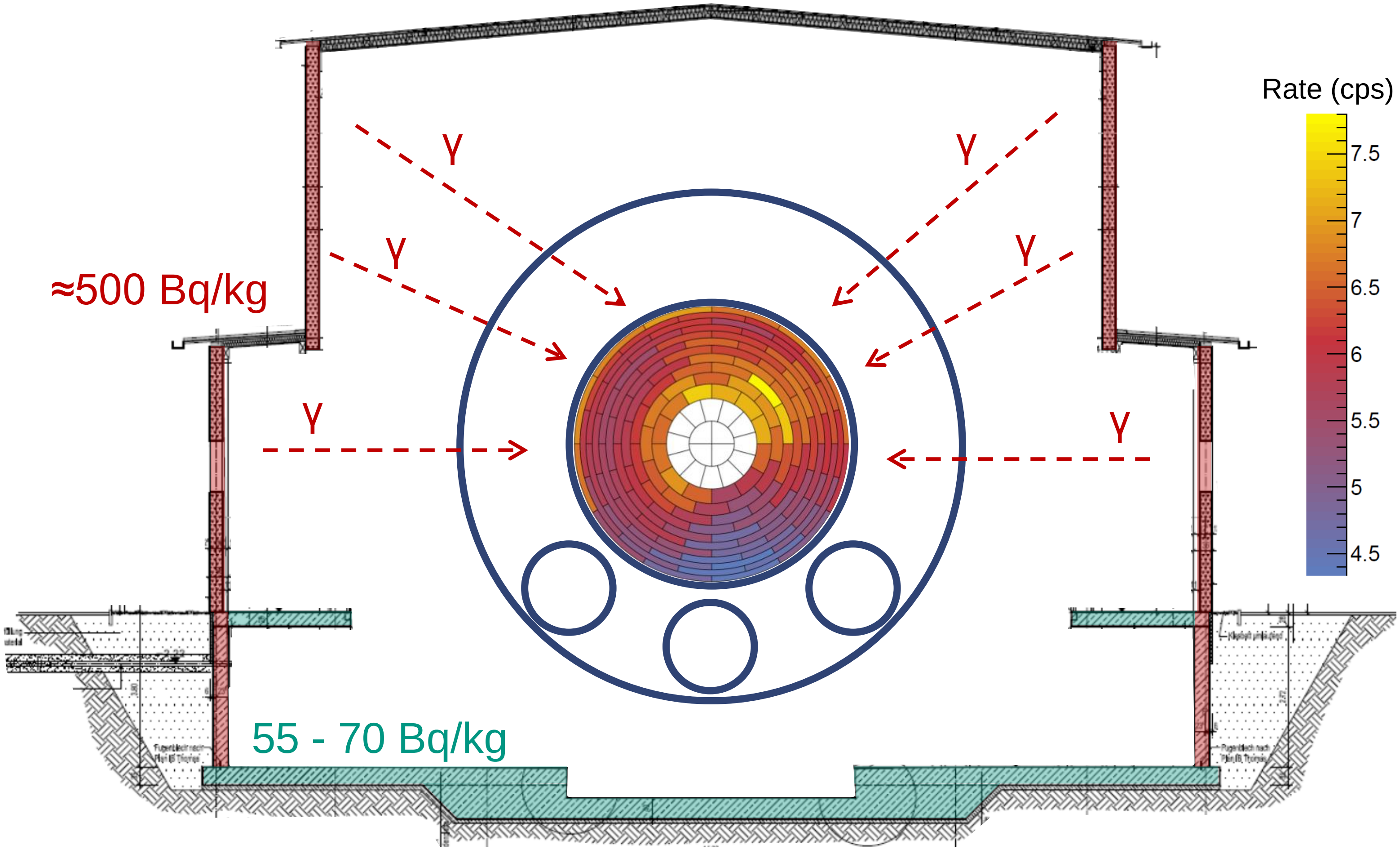
$$\frac{R_e(t)}{\overline{R_e}} = \underbrace{\alpha \cdot \frac{\overline{R_\mu}}{\overline{R_e}}}_{a} \cdot \frac{R_\mu(t)}{\overline{R_\mu}} + \underbrace{\frac{C}{\overline{R_e}}}_{1-a}$$

$$a = 13.6 \pm 0.8\ \%$$

→ Only small fraction of secondary electrons are caused by muons!



Backup

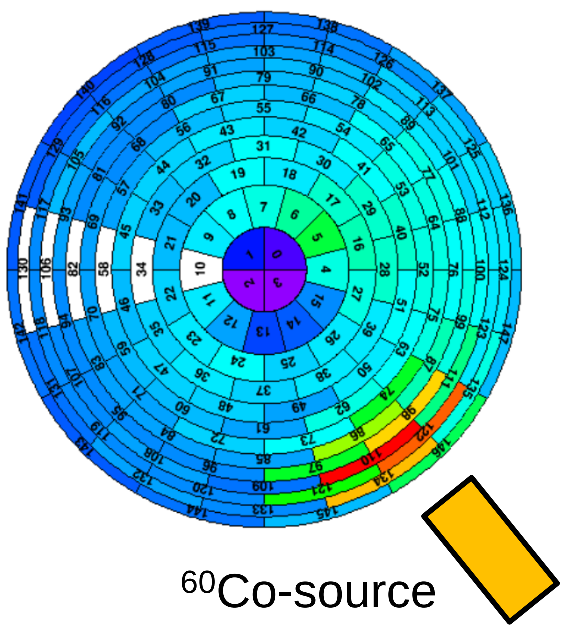


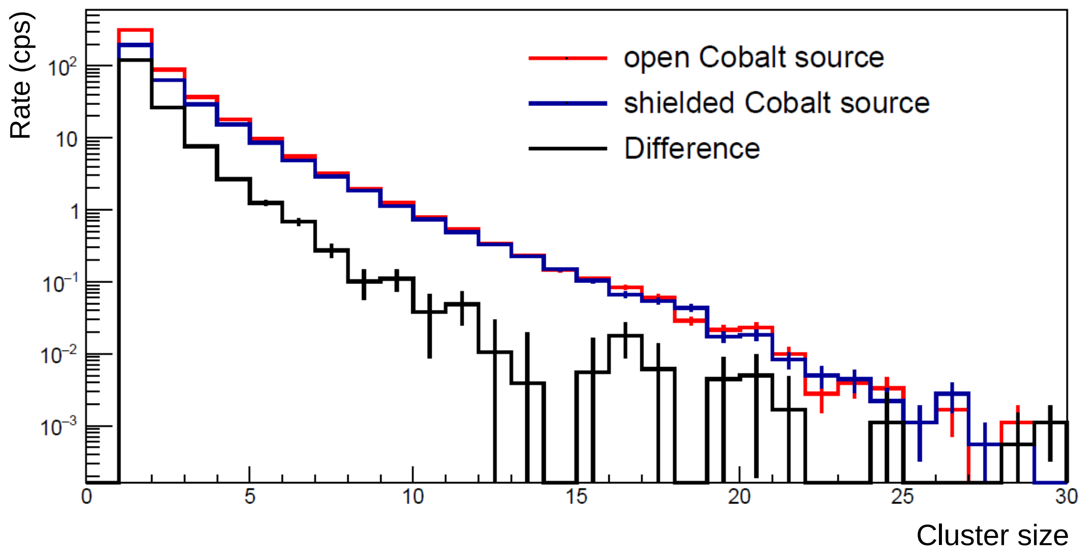
Backup

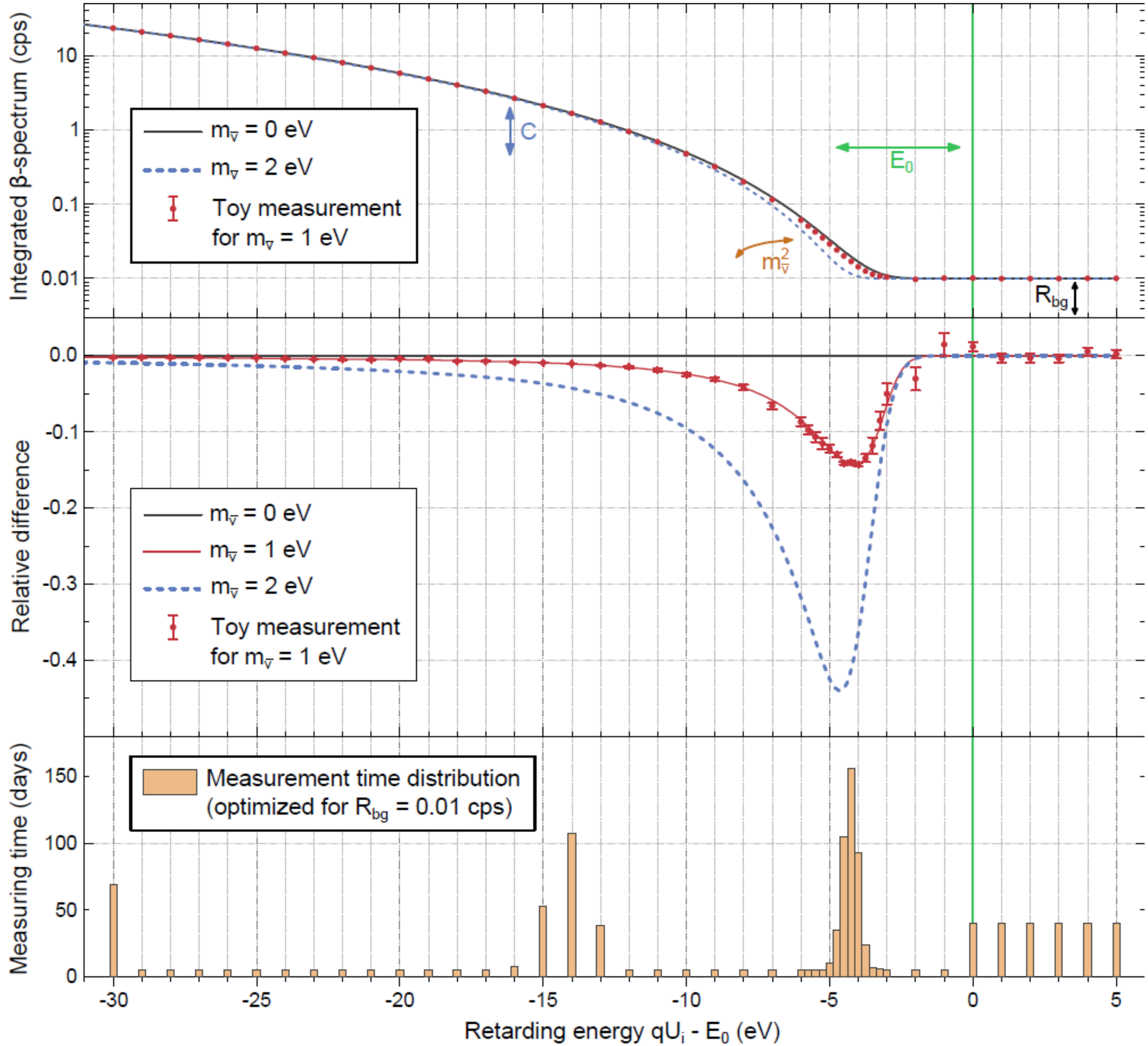
- Measurements with water shielding showed no significant background reduction.

- Characteristic clustering of secondary emission observed

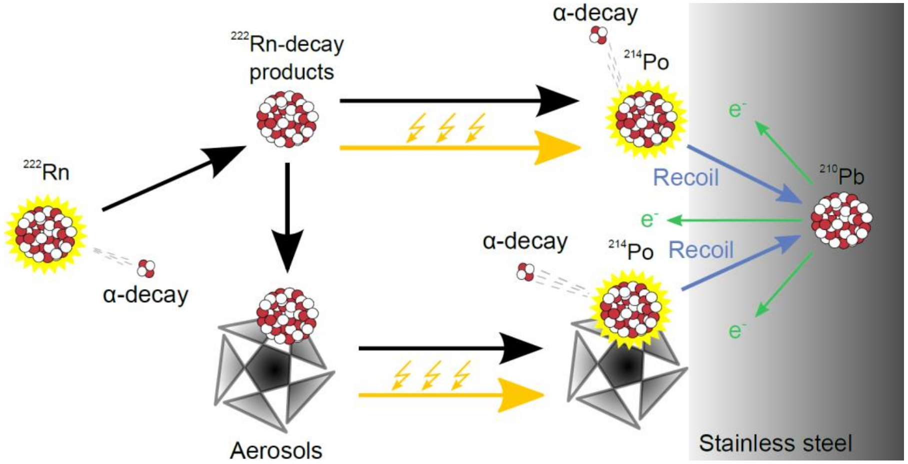
  → Use artificial γ-source to check for clustering of events.



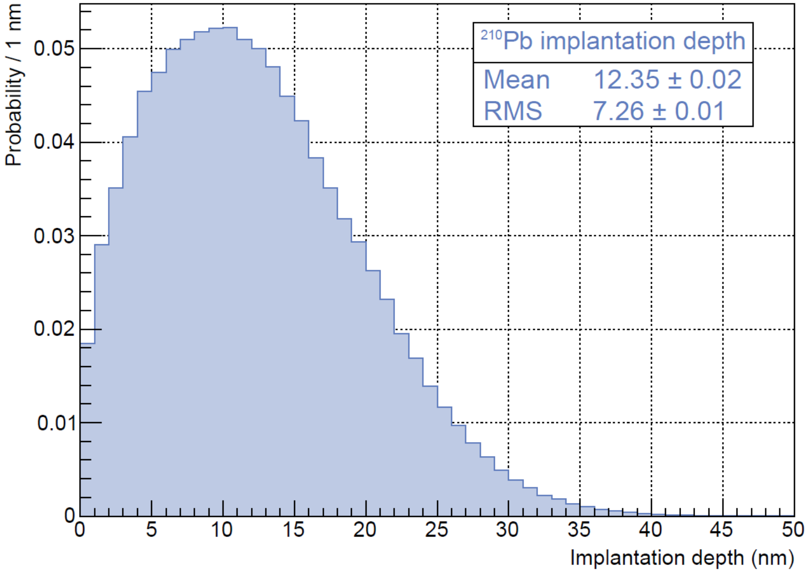




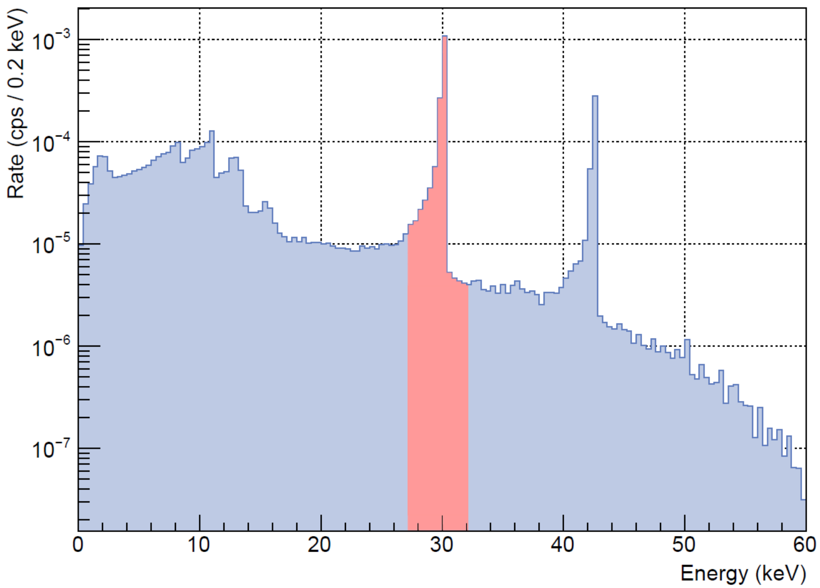
Karlsruhe Institute of Technology



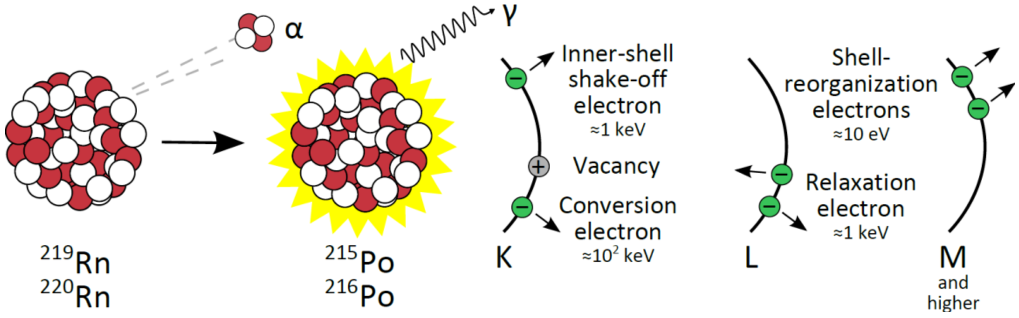
²²²Rn
α-decay
²²²Rn-decay products
Aerosols
α-decay
²¹⁴Po
e⁻
Recoil
²¹⁰Pb
e⁻
α-decay
²¹⁴Po
Recoil
e⁻
Stainless steel

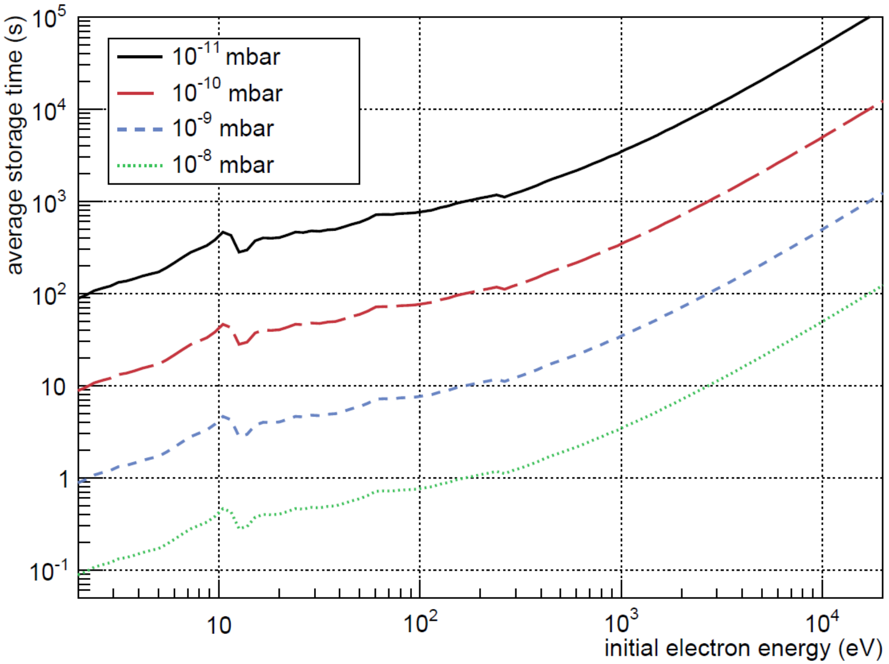


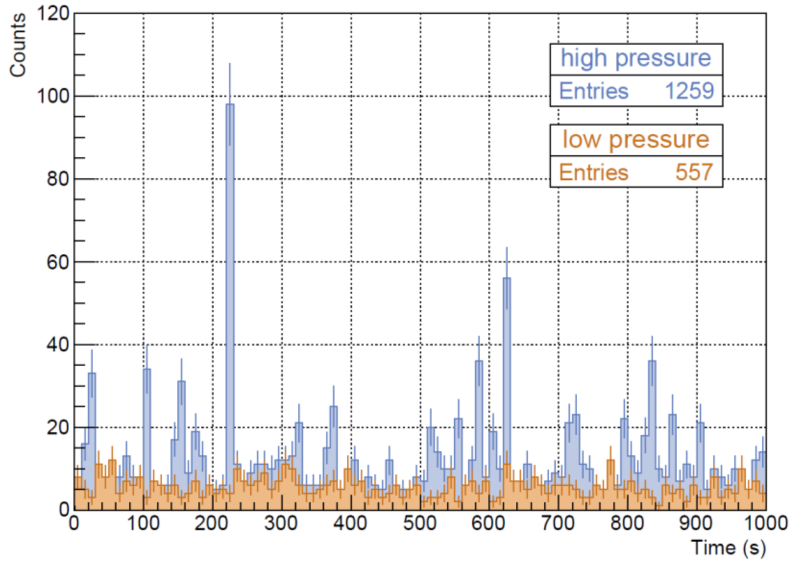
²¹⁰Pb implantation depth
Mean 12.35 ± 0.02
RMS 7.26 ± 0.01
Probability / 1 nm
Implantation depth (nm)

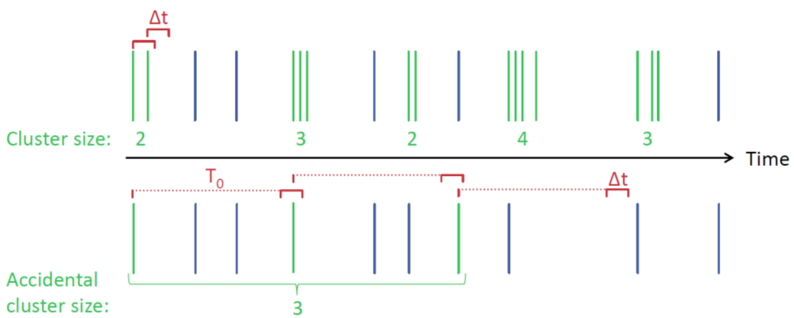


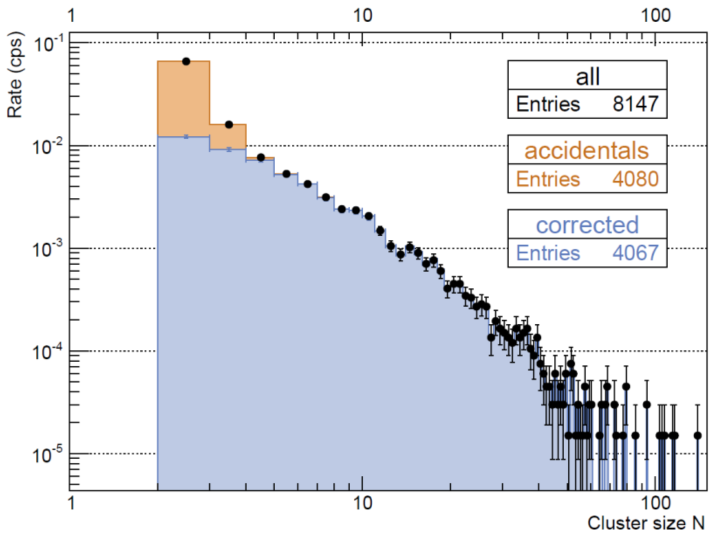
Rate (cps / 0.2 keV)
Energy (keV)


α
γ
Inner-shell shake-off electron
≈1 keV
Vacancy
Conversion electron
≈10² keV
Shell-reorganization electrons
≈10 eV
Relaxation electron
≈1 keV
K
L
M
and higher
219Rn
220Rn
215Po
216Po

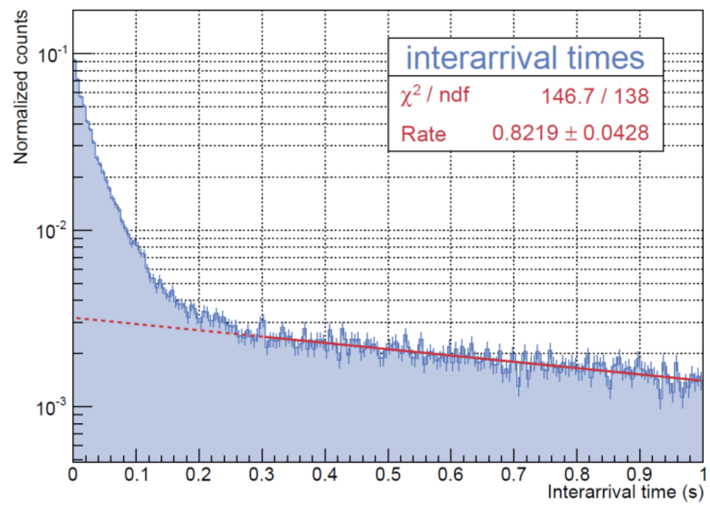

average storage time (s)
initial electron energy (eV)
10^-11 mbar
10^-10 mbar
10^-9 mbar
10^-8 mbar


Counts
Time (s)
high pressure
Entries 1259
low pressure
Entries 557

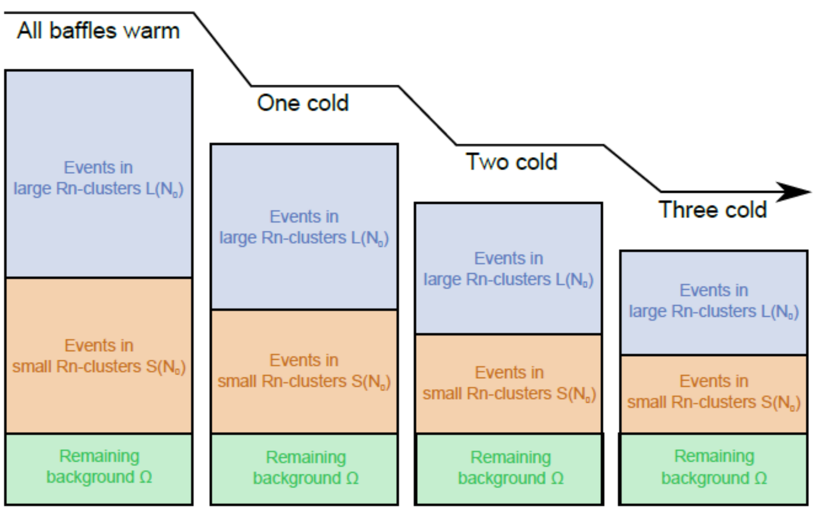

Δt
Cluster size:
2
3
2
4
3
Time
T0
Δt
Accidental cluster size:
3



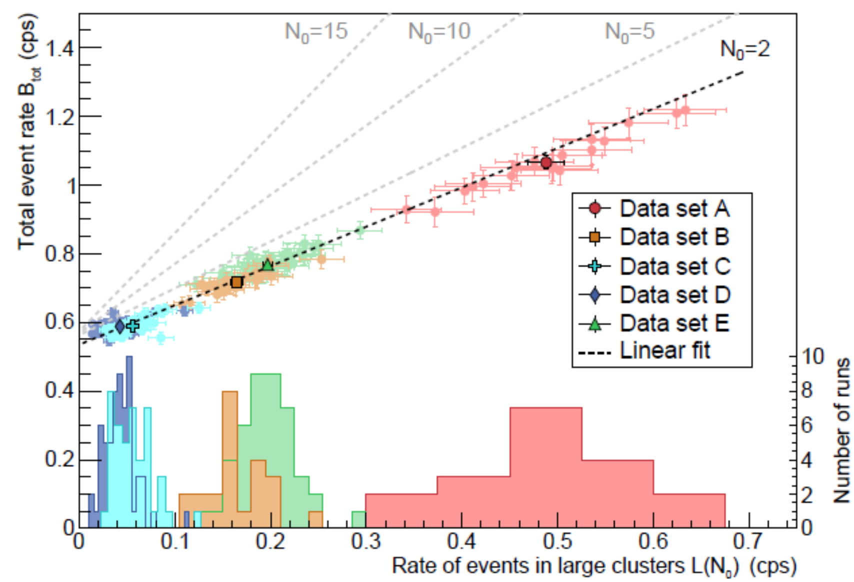
Rate (cps)
all
Entries 8147
accidentals
Entries 4080
corrected
Entries 4067
Cluster size N



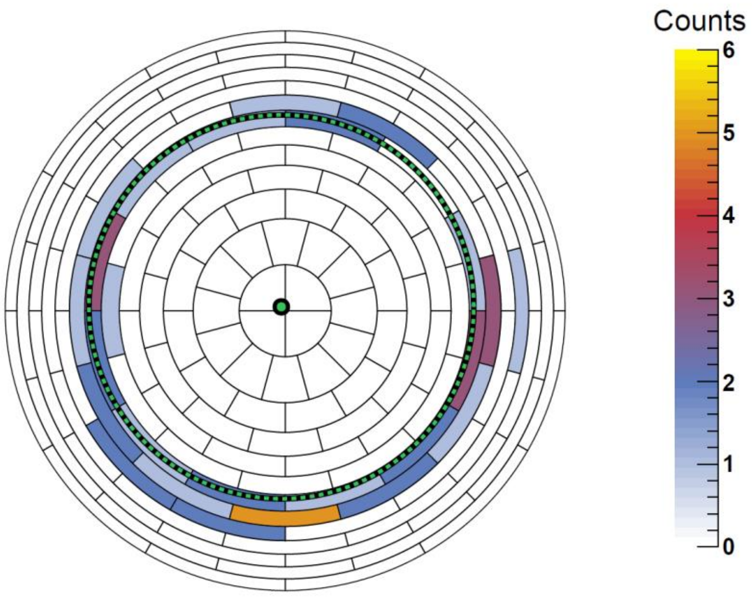
Normalized counts
interarrival times
χ^2 / ndf 146.7 / 138
Rate 0.8219 ± 0.0428
Interarrival time (s)

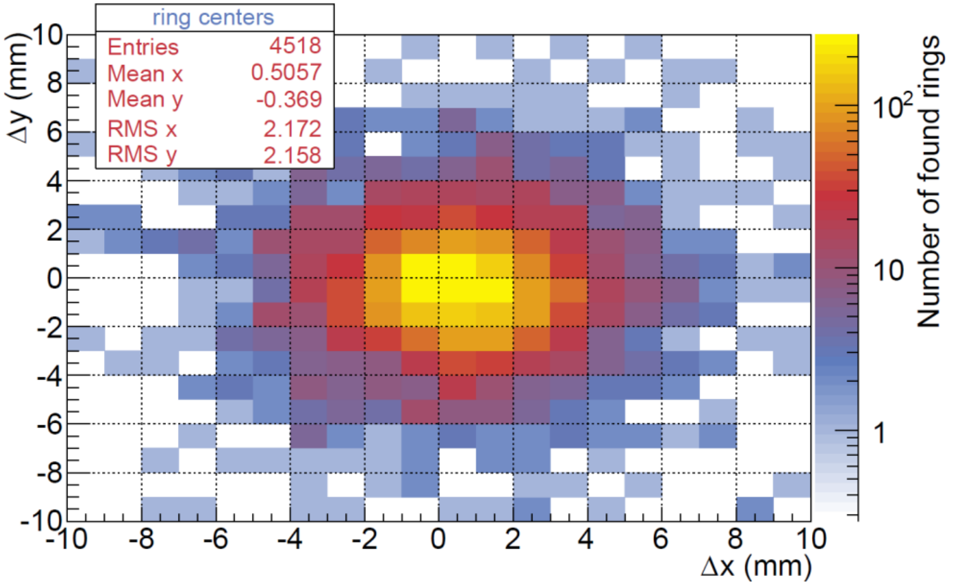


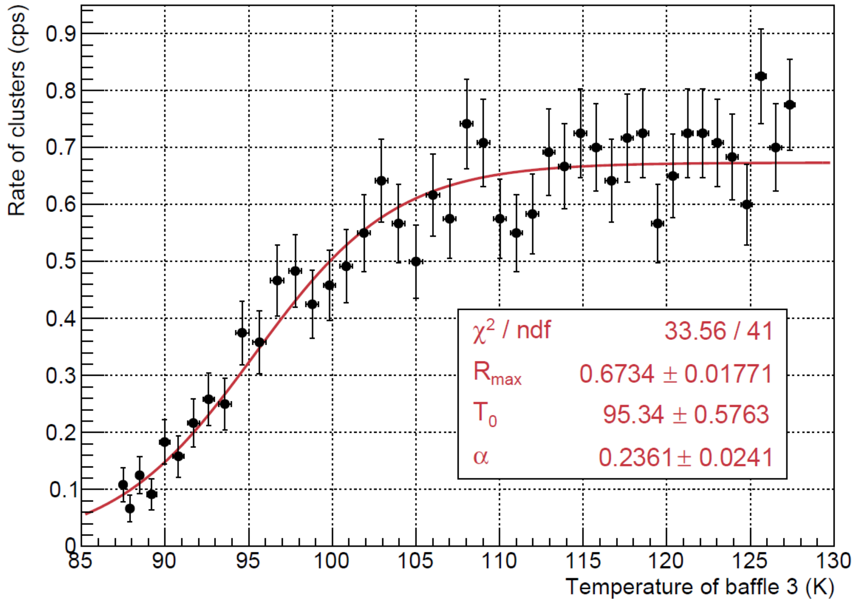
All baffles warm
One cold
Two cold
Three cold
Events in large Rn-clusters L(N$_0$)
Events in small Rn-clusters S(N$_0$)
Remaining background Ω

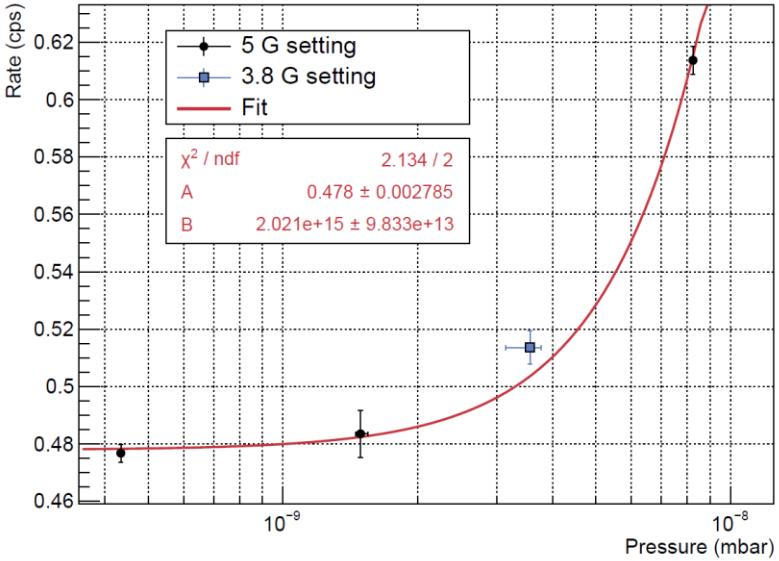


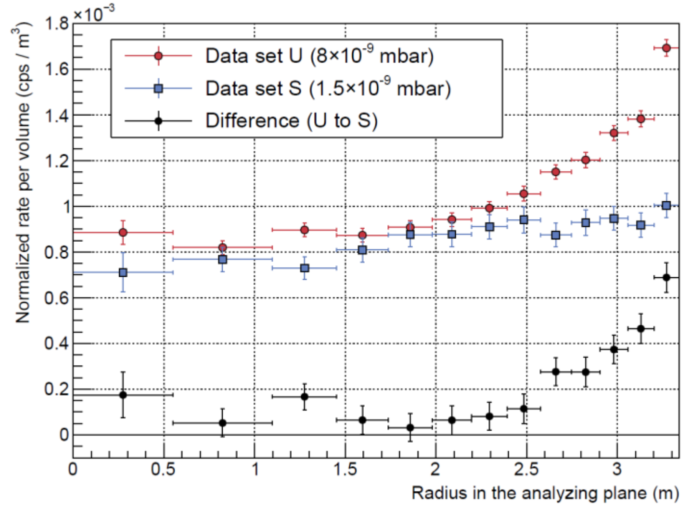
Total event rate B$_{tot}$ (cps)
N$_0$=15
N$_0$=10
N$_0$=5
N$_0$=2
Data set A
Data set B
Data set C
Data set D
Data set E
Linear fit
Number of runs
Rate of events in large clusters L(N$_0$) (cps)


Counts
0
1
2
3
4
5
6


ring centers
Entries 4518
Mean x 0.5057
Mean y -0.369
RMS x 2.172
RMS y 2.158
Δy (mm)
Δx (mm)
Number of found rings
1
10
10²


Rate of clusters (cps)
Temperature of baffle 3 (K)
χ² / ndf 33.56 / 41
R_max 0.6734 ± 0.01771
T_0 95.34 ± 0.5763
α 0.2361 ± 0.0241





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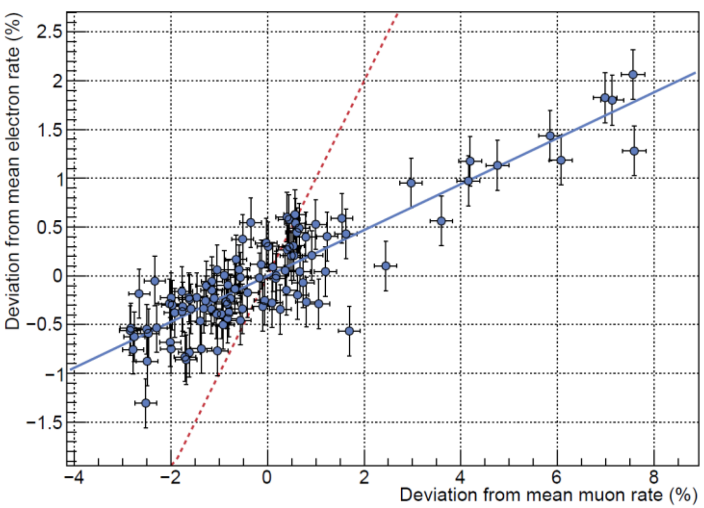

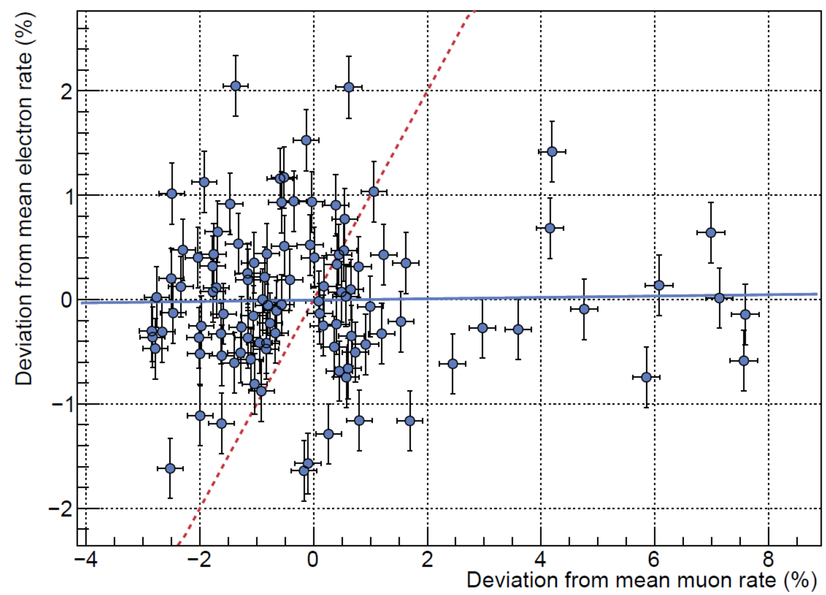

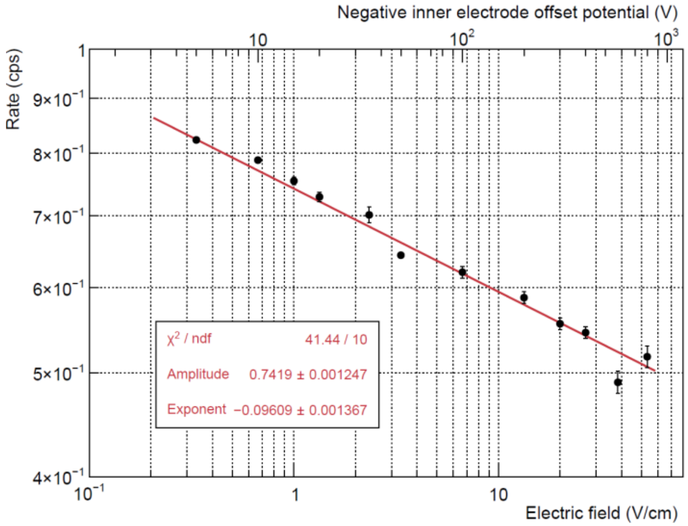

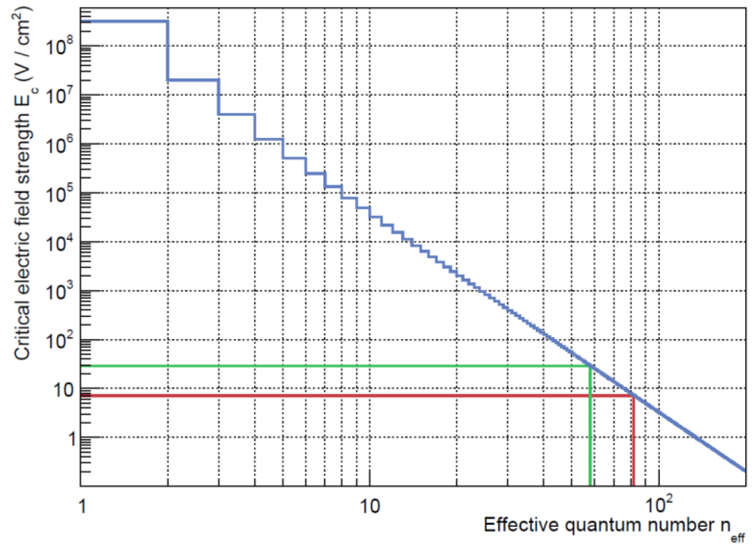

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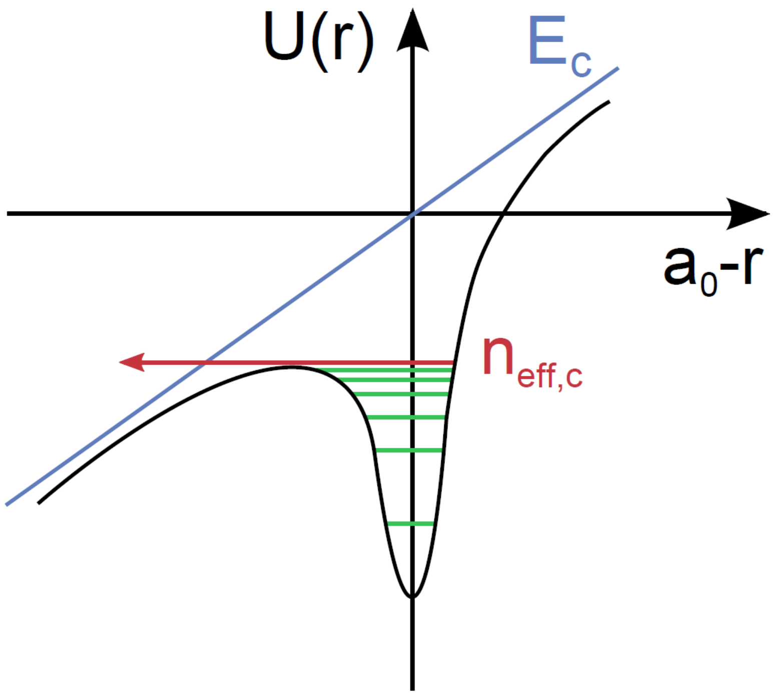
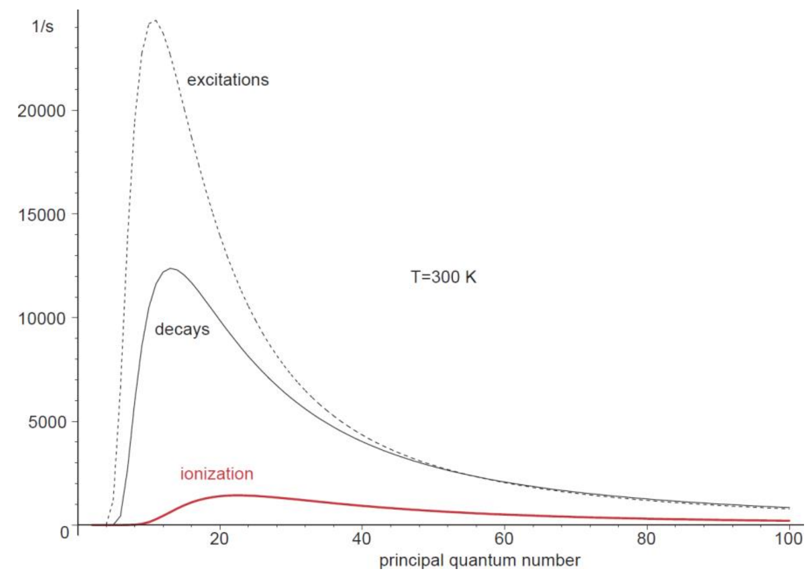
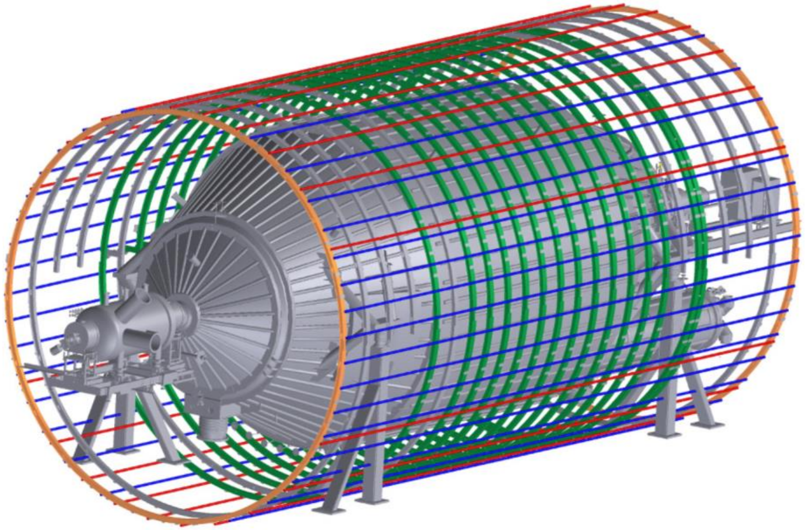
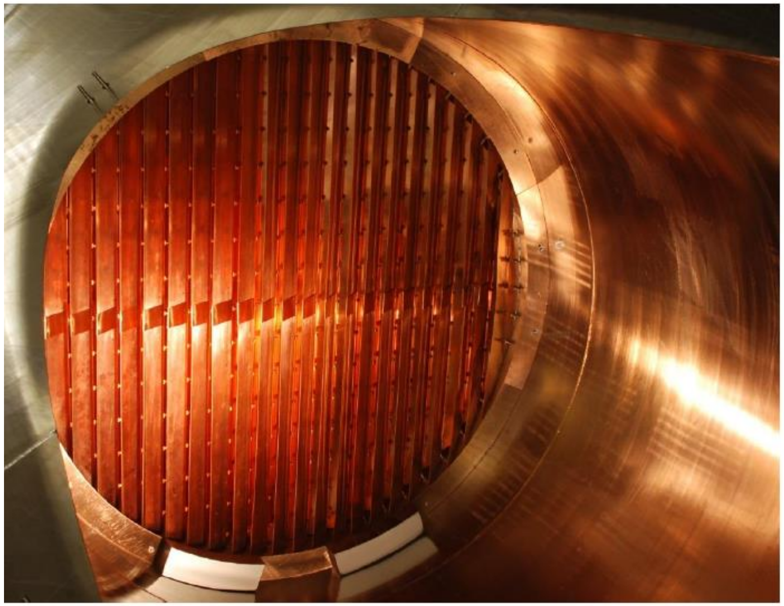
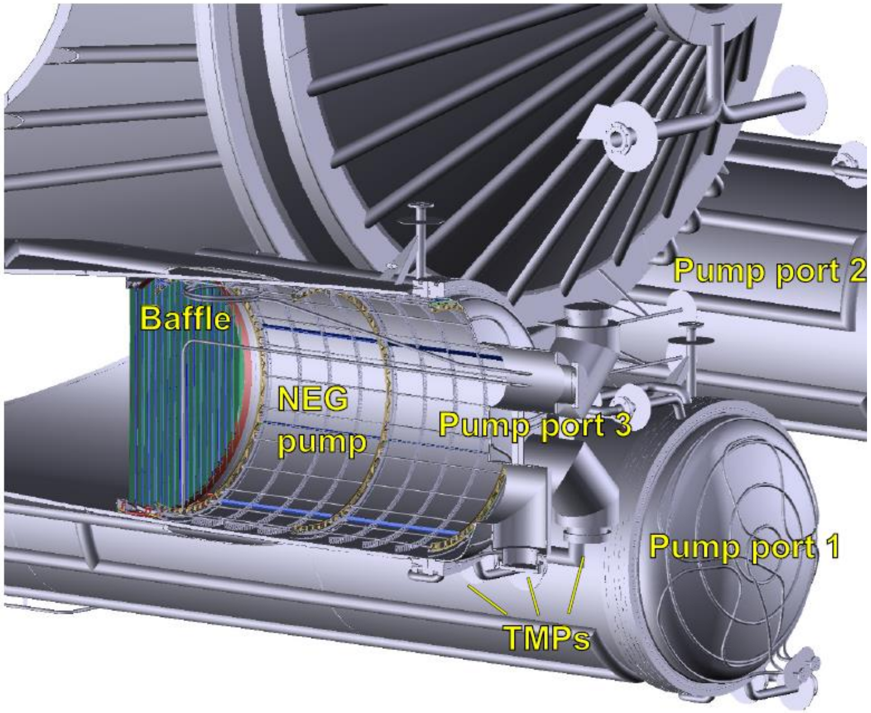
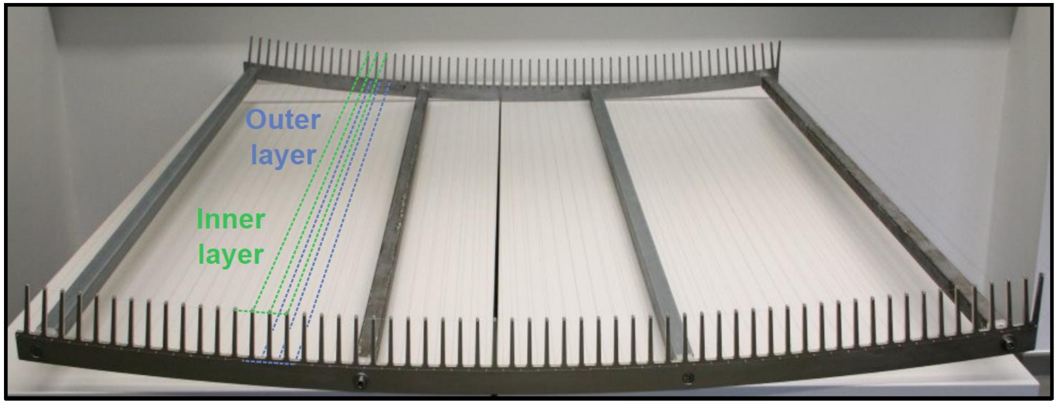


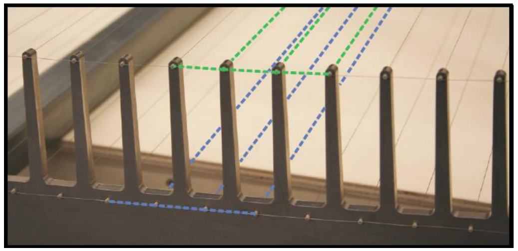


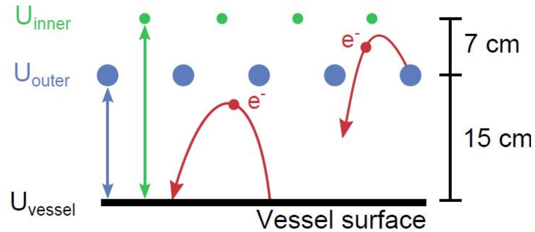


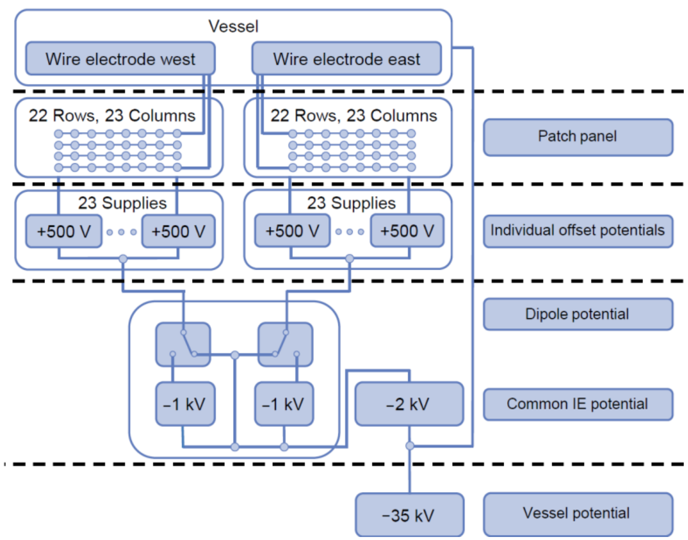


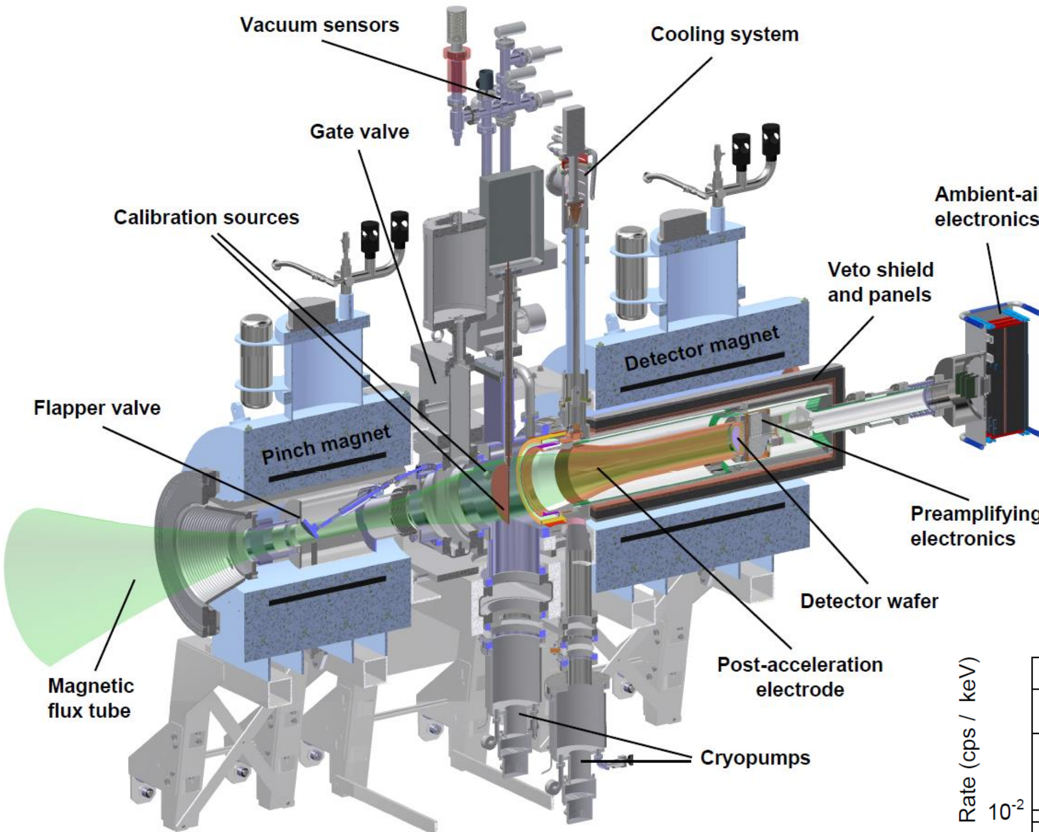

Pump port 2
Baffle
NEG
pump
Pump port 3
Pump port 1
TMPs

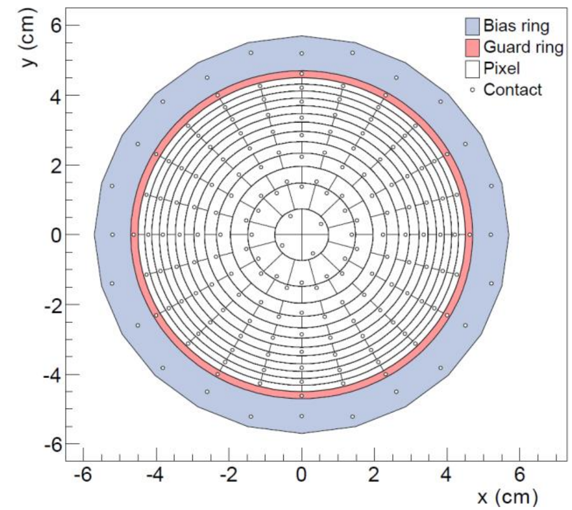

Outer layer
Inner layer

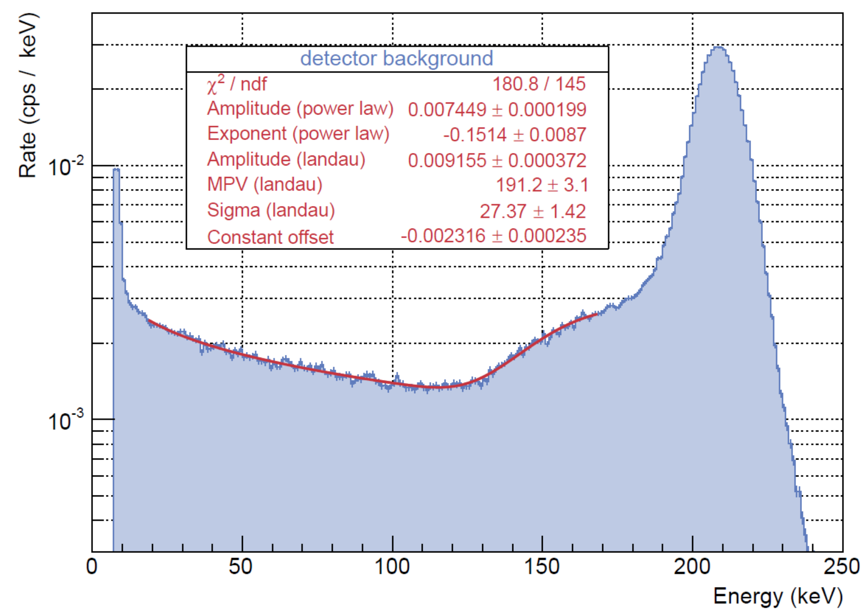


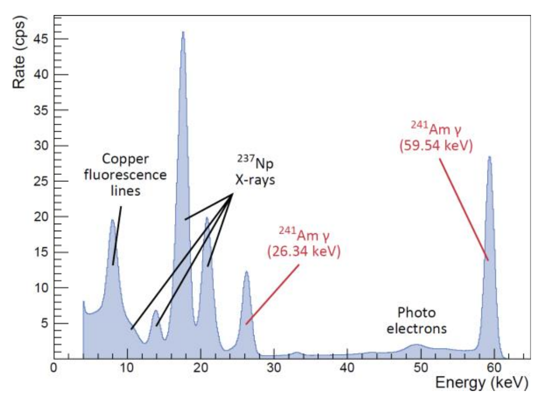

U_{inner}
U_{outer}
U_{vessel}
e^-
e^-
7 cm
15 cm
Vessel surface

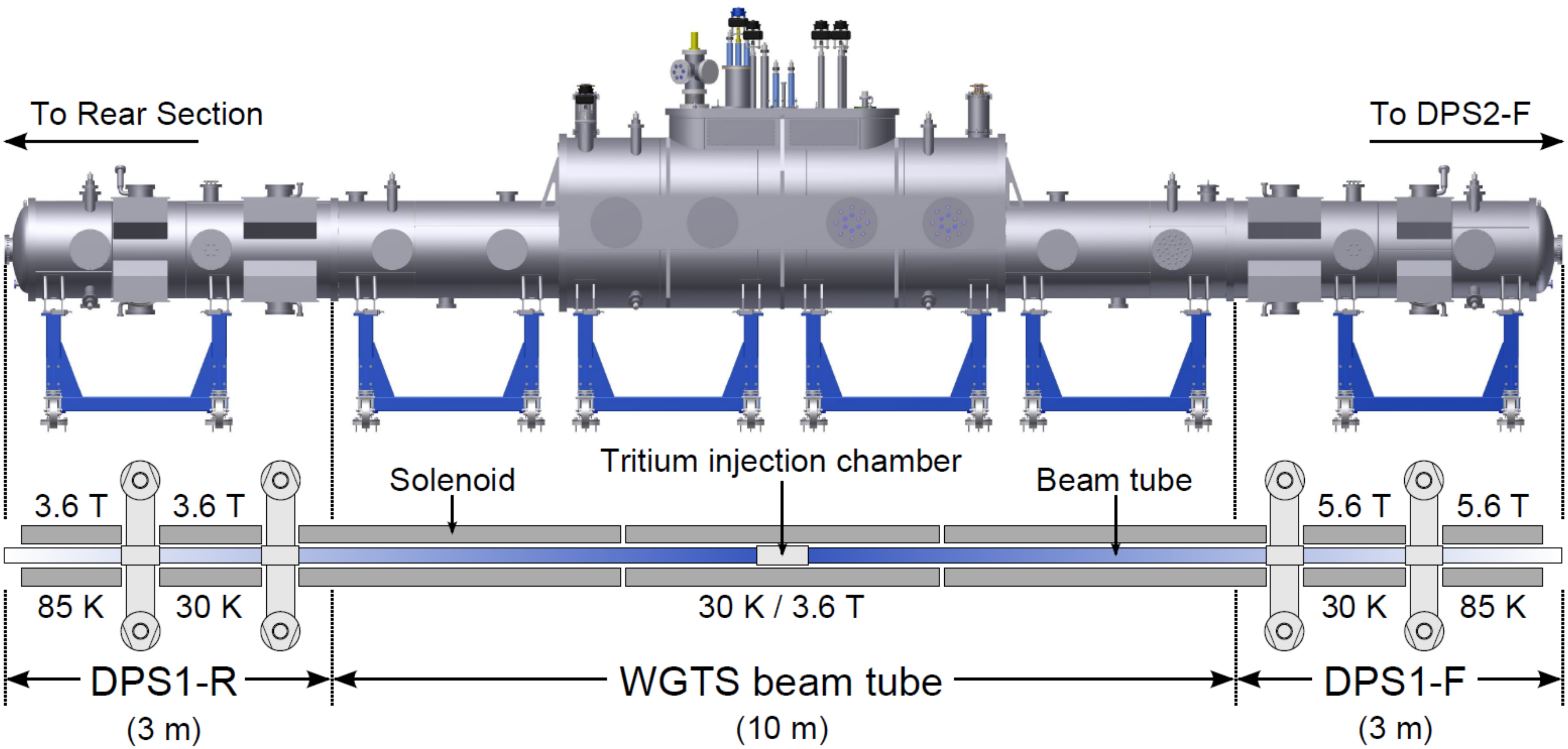

Vessel
Wire electrode west
Wire electrode east
22 Rows, 23 Columns
22 Rows, 23 Columns
Patch panel
23 Supplies
+500 V
+500 V
23 Supplies
+500 V
+500 V
Individual offset potentials
Dipole potential
−1 kV
−1 kV
−2 kV
Common IE potential
−35 kV
Vessel potential

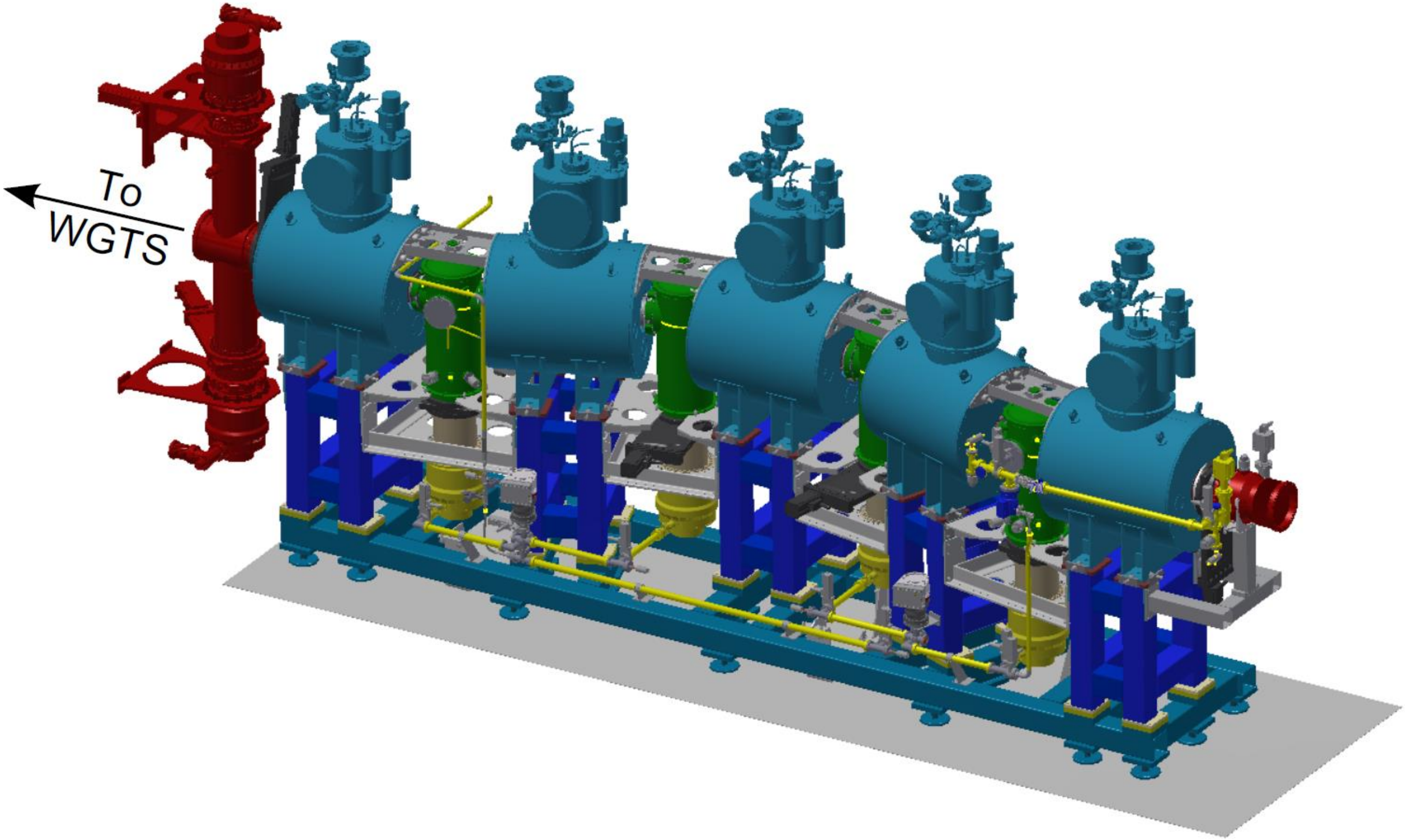

Vacuum sensors
Cooling system
Gate valve
Calibration sources
Ambient-air electronics
Veto shield and panels
Detector magnet
Flapper valve
Pinch magnet
Preamplifying electronics
Detector wafer
Post-acceleration electrode
Magnetic flux tube
Cryopumps

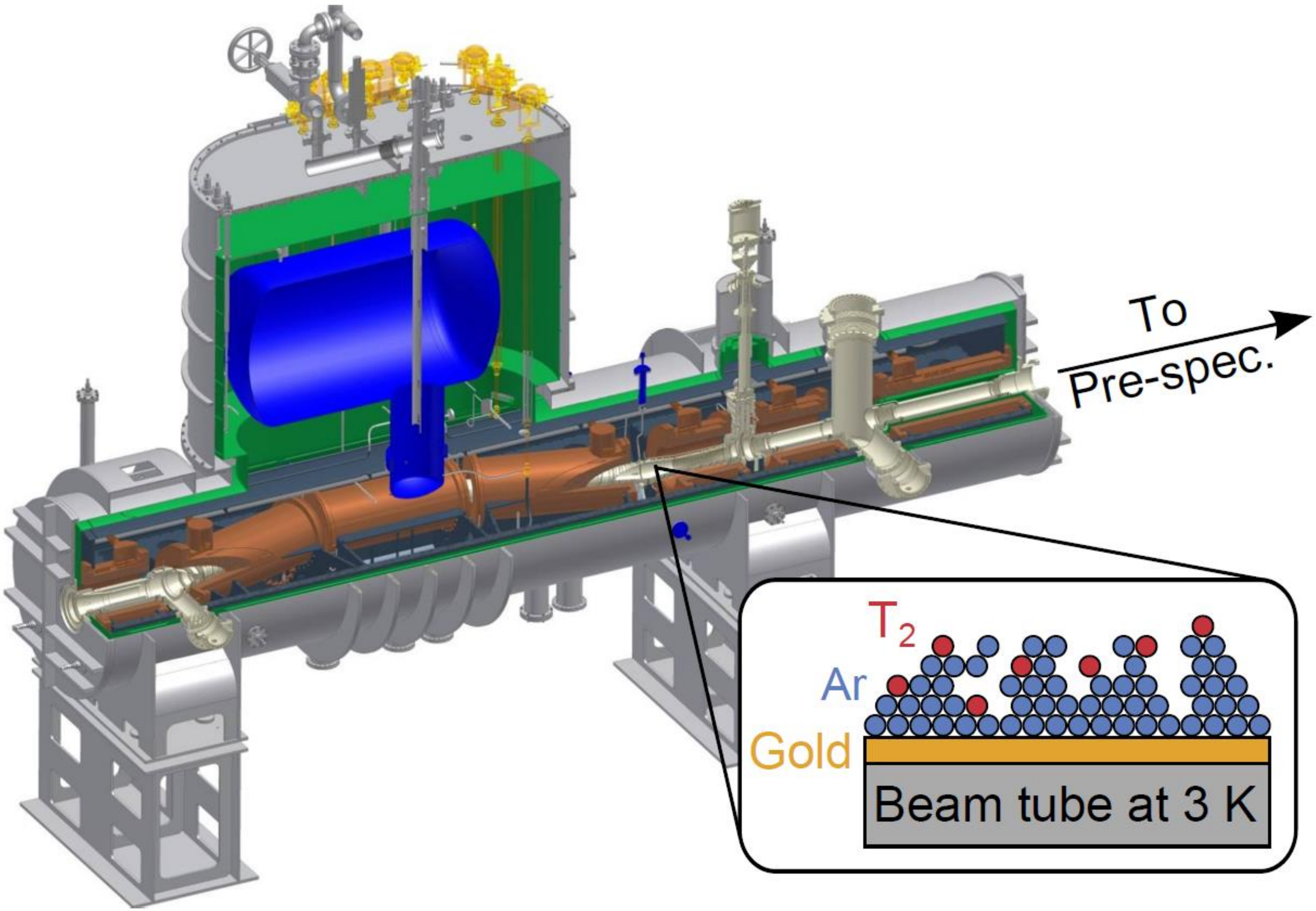

Bias ring
Guard ring
Pixel
Contact
y (cm)
x (cm)


detector background
χ^2 / ndf 180.8 / 145
Amplitude (power law) 0.007449 ± 0.000199
Exponent (power law) -0.1514 ± 0.0087
Amplitude (landau) 0.009155 ± 0.000372
MPV (landau) 191.2 ± 3.1
Sigma (landau) 27.37 ± 1.42
Constant offset -0.002316 ± 0.000235
Rate (cps / keV)
Energy (keV)

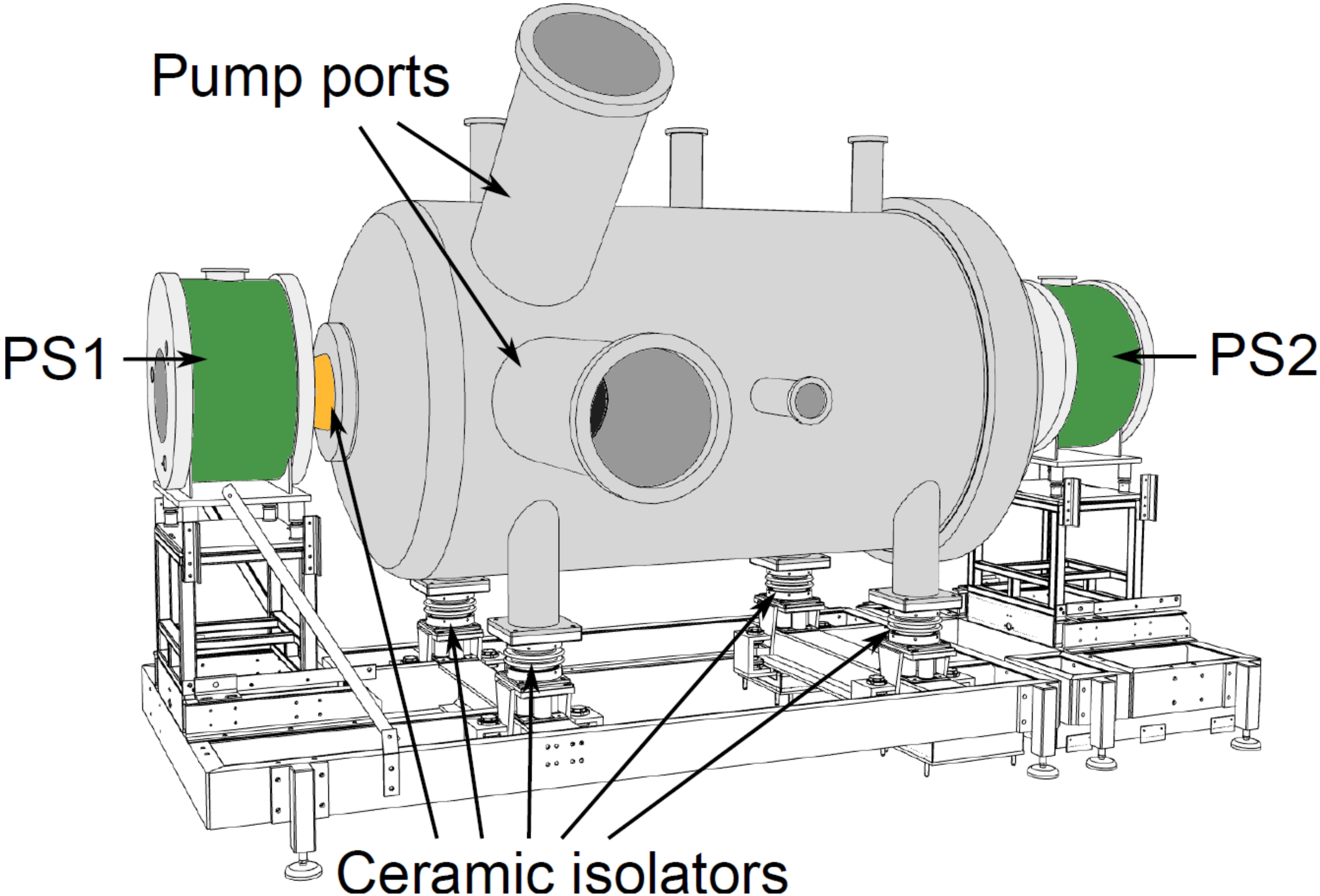

Rate (cps)
Copper fluorescence lines
^{237}Np X-rays
^{241}Am γ (26.34 keV)
^{241}Am γ (59.54 keV)
Photo electrons
Energy (keV)


To Rear Section
To DPS2-F
Tritium injection chamber
Solenoid
Beam tube
3.6 T
3.6 T
5.6 T
5.6 T
85 K
30 K
30 K / 3.6 T
30 K
85 K
DPS1-R
(3 m)
WGTS beam tube
(10 m)
DPS1-F
(3 m)


To
WGTS



To
Pre-spec.
T_2
Ar
Gold
Beam tube at 3 K


Pump ports
PS1
PS2
Ceramic isolators