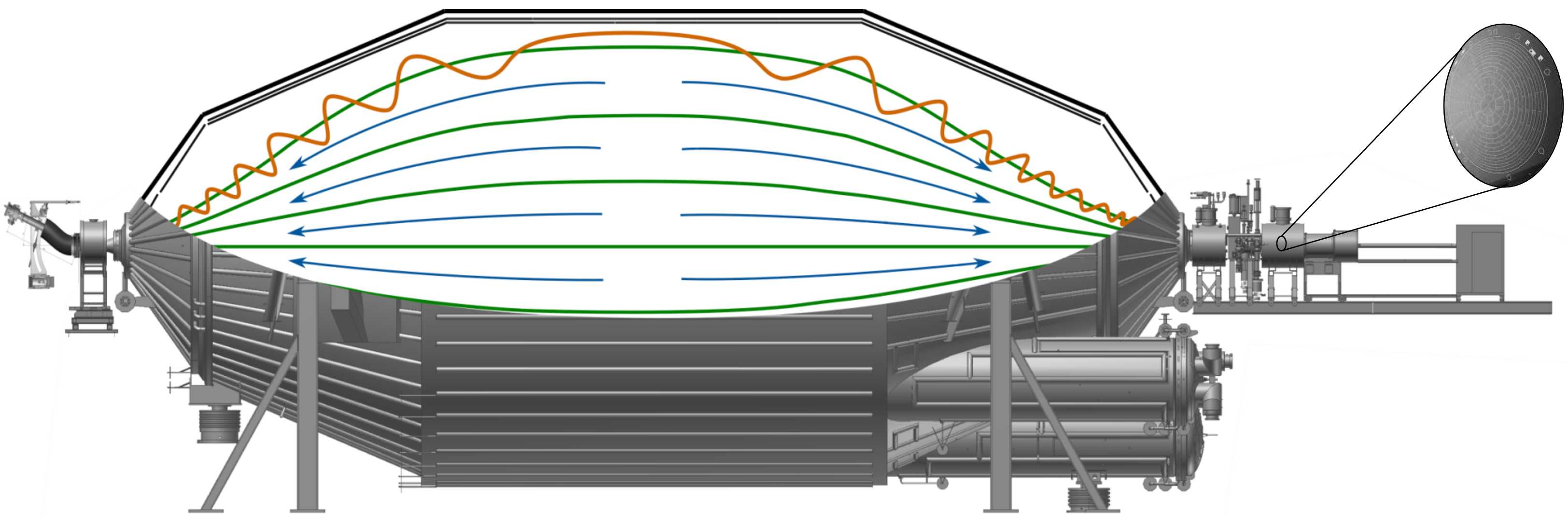
Commissioning Measurements at the KATRIN Main Spectrometer

3rd KSETA Plenary Workshop, 24th February 2016

Fabian Harms, Institute for Experimental Nuclear Physics (IEKP), Karlsruhe Institute of Technology (KIT)

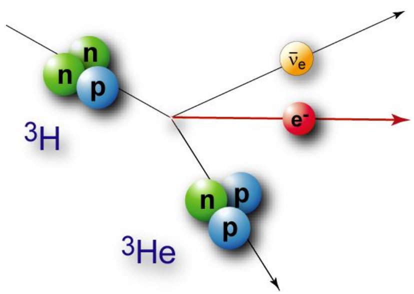


Outline

- The KATRIN Experiment
- Commissioning of the Main Spectrometer
- Transmission Studies
- The Background Model
- Summary and Outlook

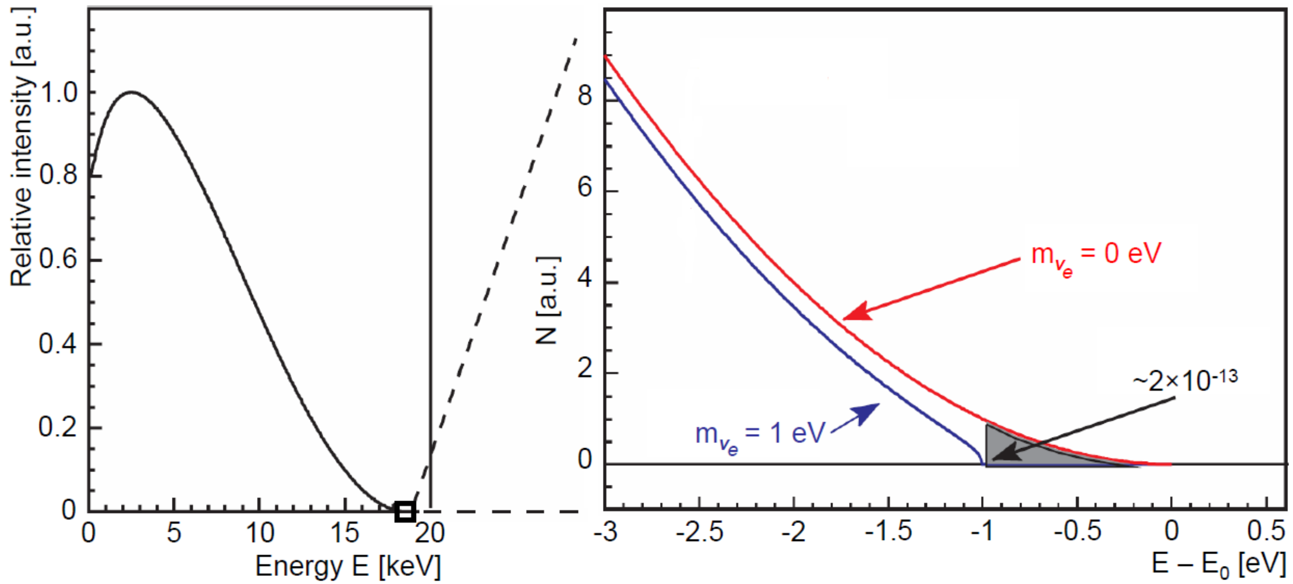
The KATRIN Experiment

Theory



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

$t_{1/2}$ = 12.3 a



E_0 = 18.6 keV

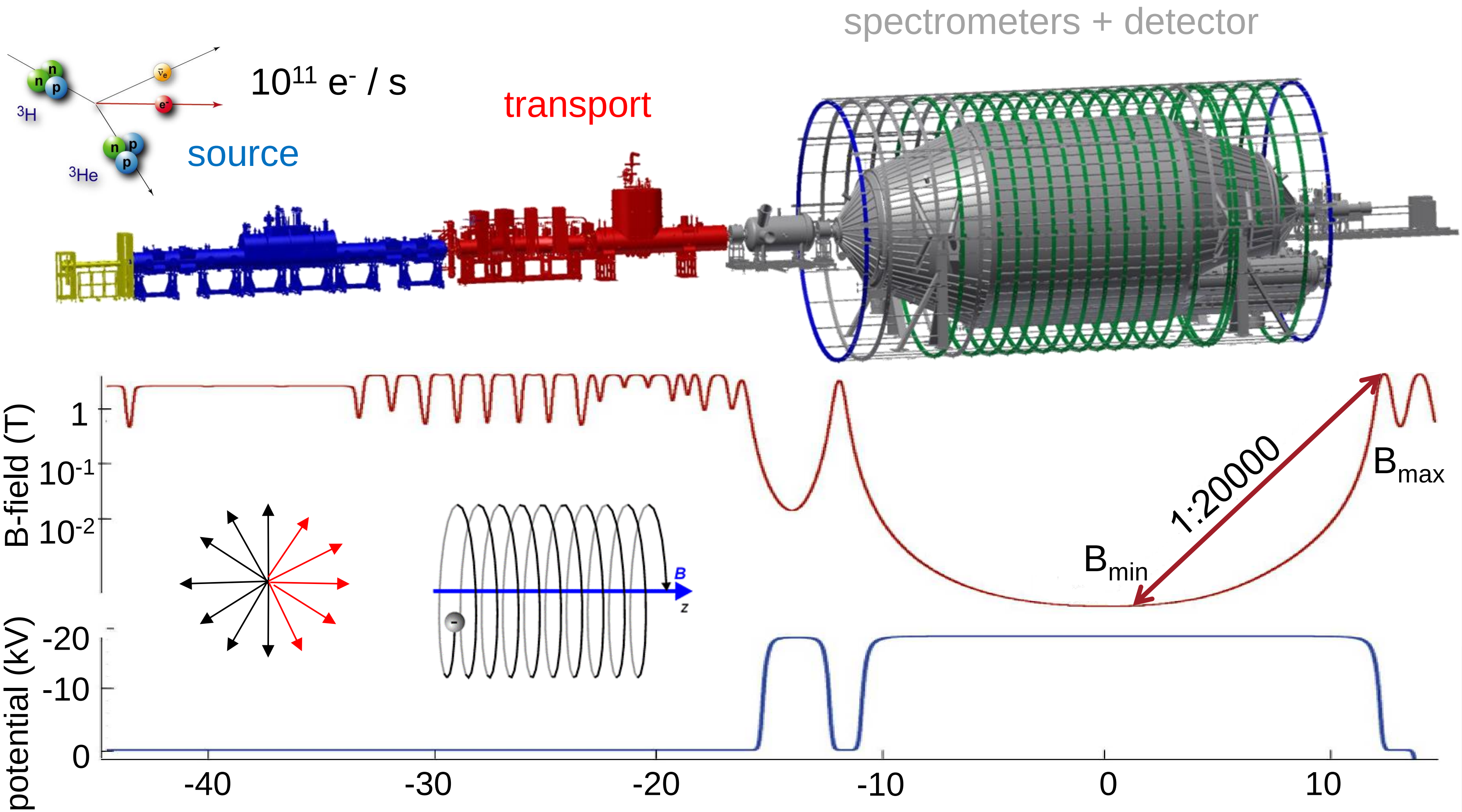
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = C\,p\,(E+m_e)\,(E_0-E)\,\sqrt{(E_0-E)^2 - m_{\nu_e}^2}\,F(E)\,\theta(E_0-E-m_{\nu_\epsilon})$$

m_ν < 200 meV (90 % C.L.)

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

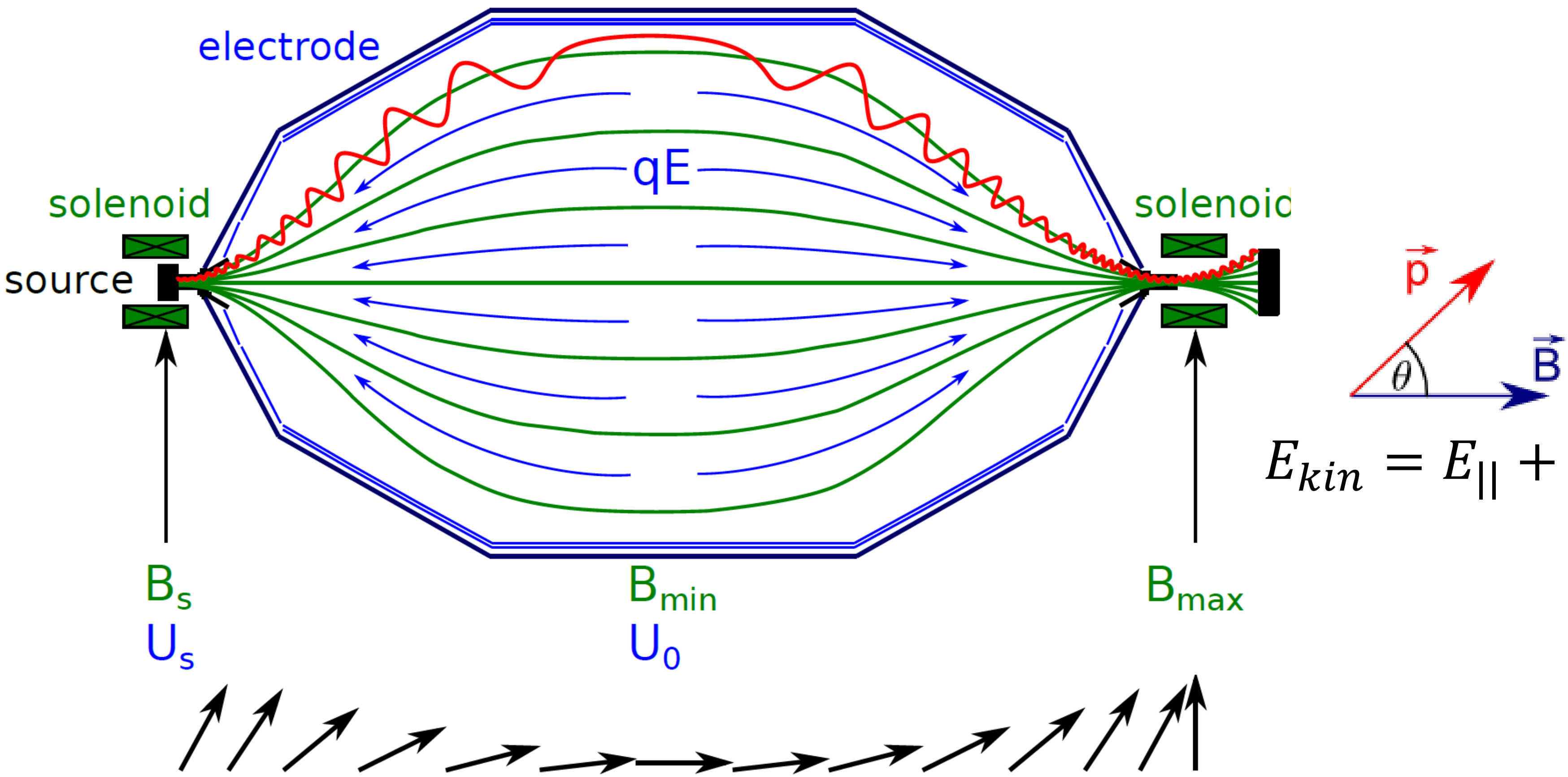
The KATRIN Experiment

Experimental Overview



The KATRIN Experiment

MAC-E Filter



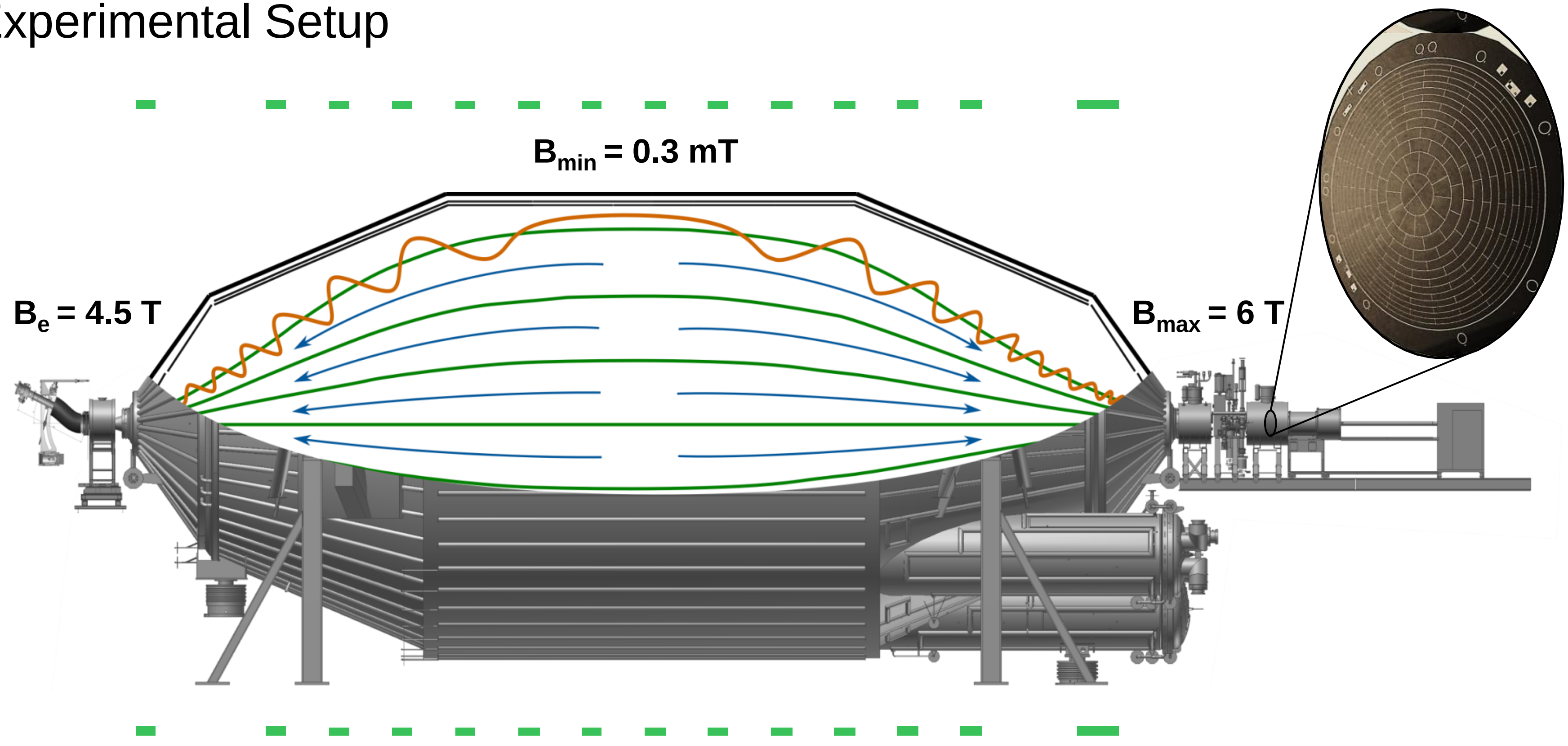
$$E_{kin} = E_{||} + E_{\perp}$$

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

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

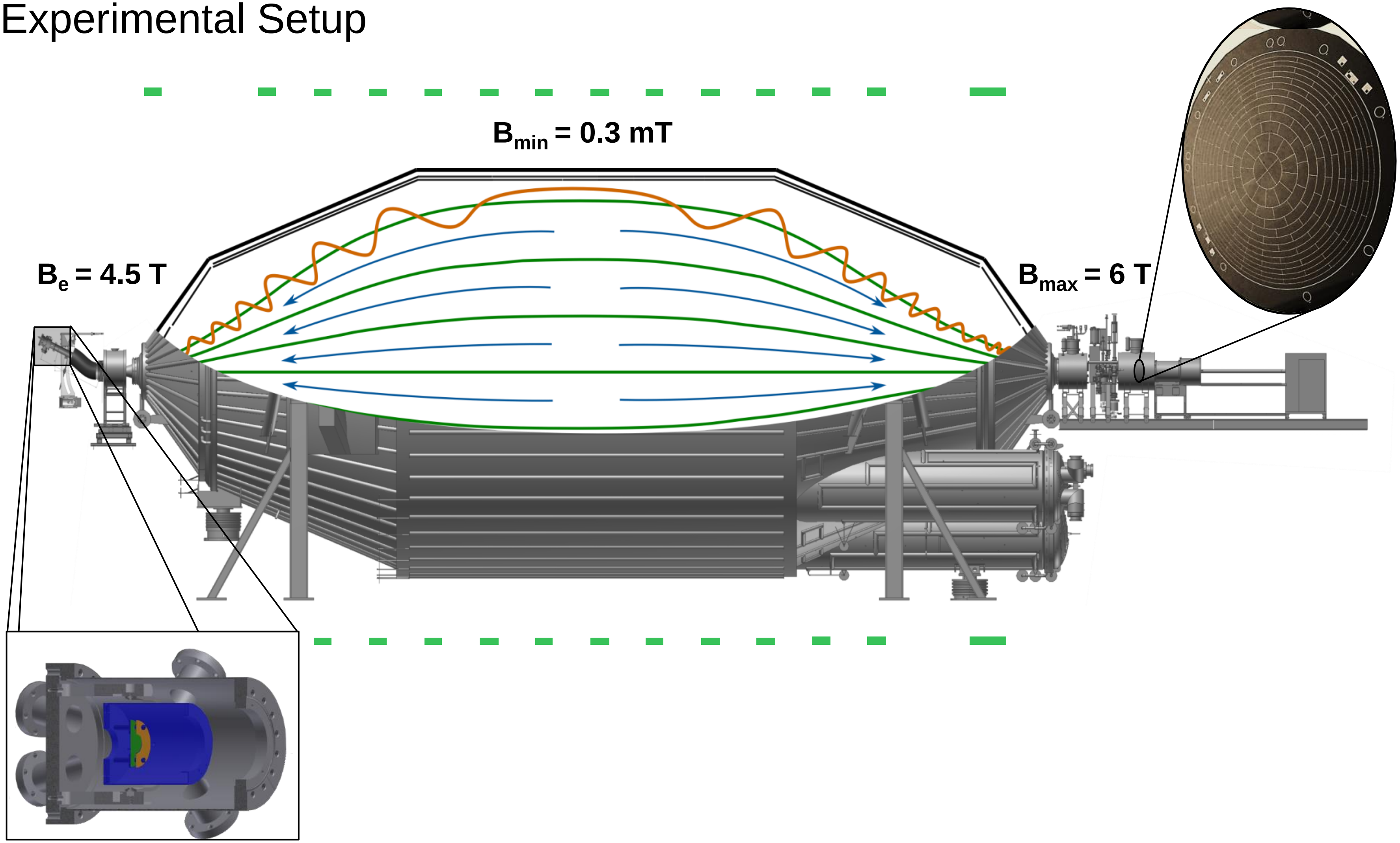
SDS Commissioning

Experimental Setup

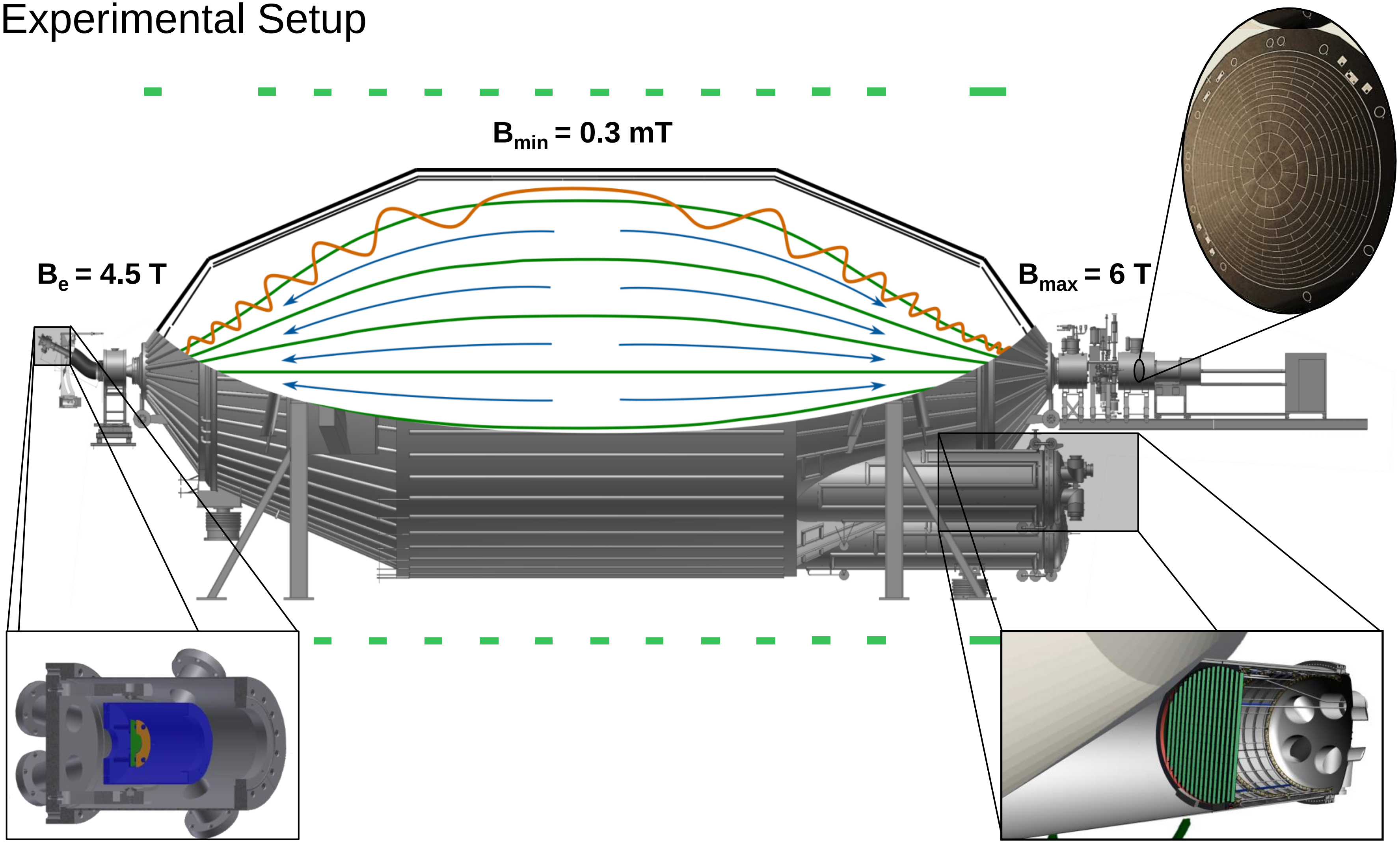


SDS Commissioning

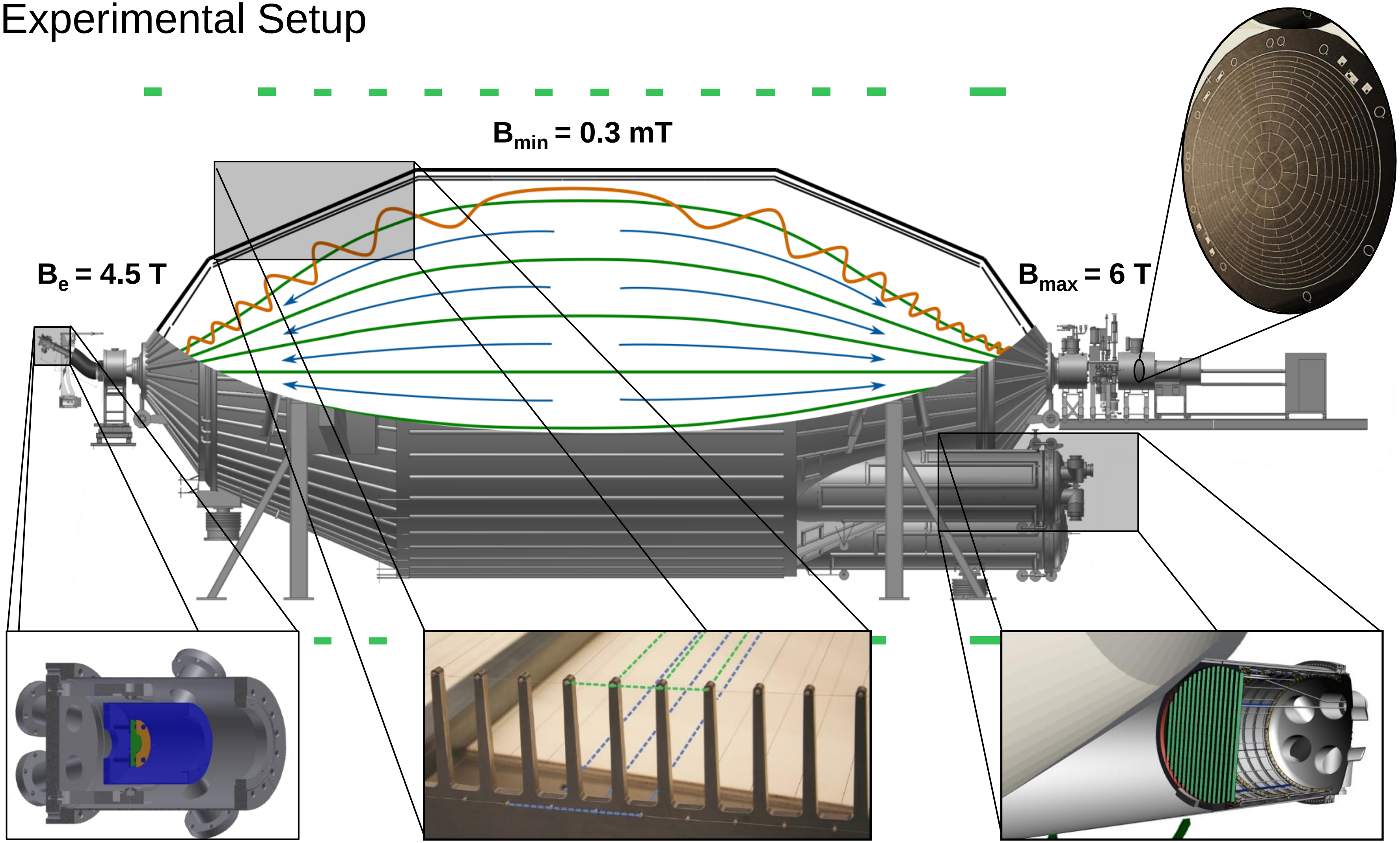
Experimental Setup



SDS Commissioning
Experimental Setup



SDS Commissioning
Experimental Setup



SDS Commissioning
Overview

- 05/2013 – 09/2013 SDS-I measurement phase

  Improvements in vacuum system, baffle system, inner-electrode, HV, detector, electron gun, …

- **10/2014 – 09/2015 SDS-II measurement phase**

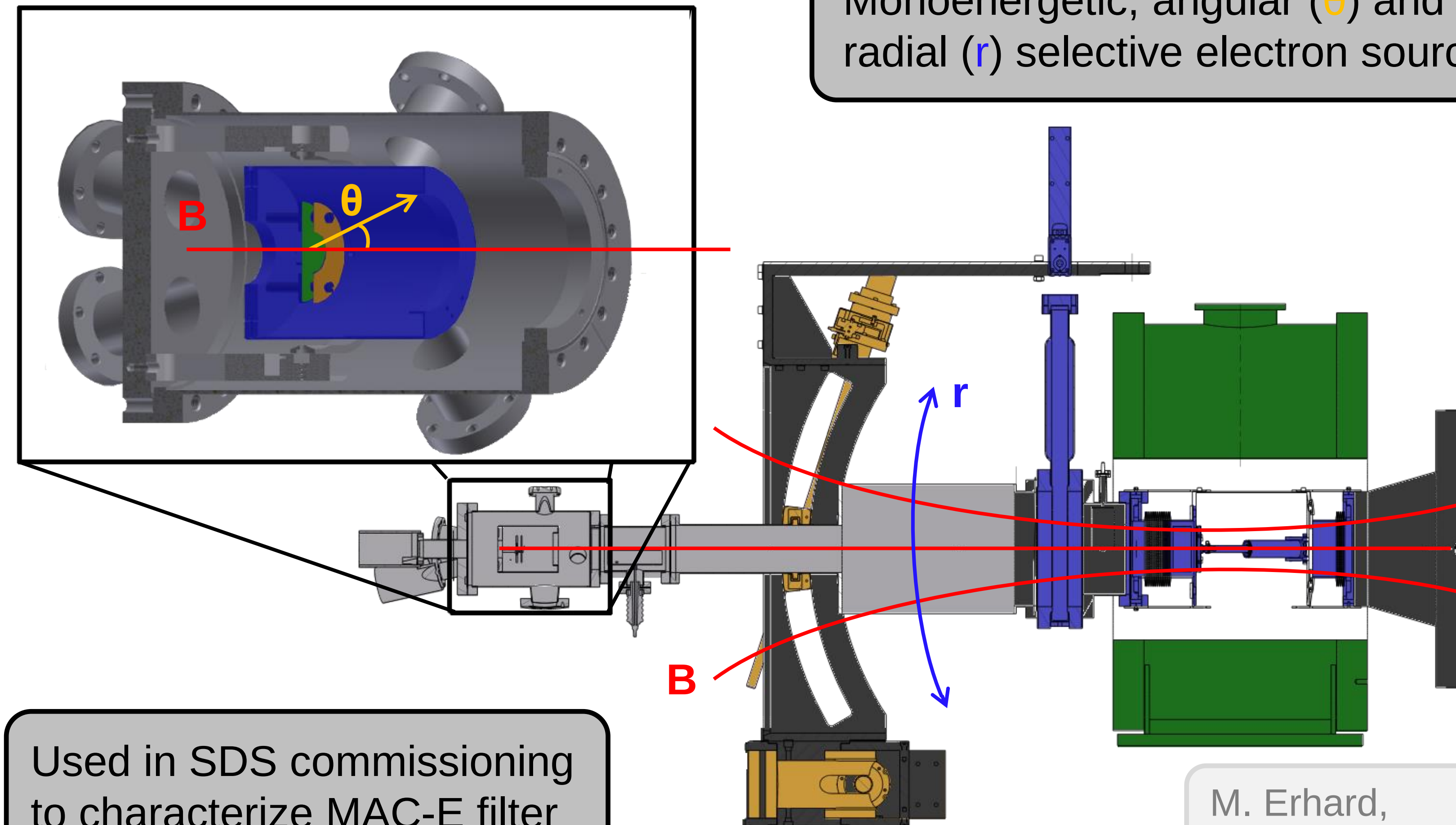
  → Characterize performance of MAC-E filter

  → Investigate background processes in the spectrometer

Transmission Studies

Electron Gun

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

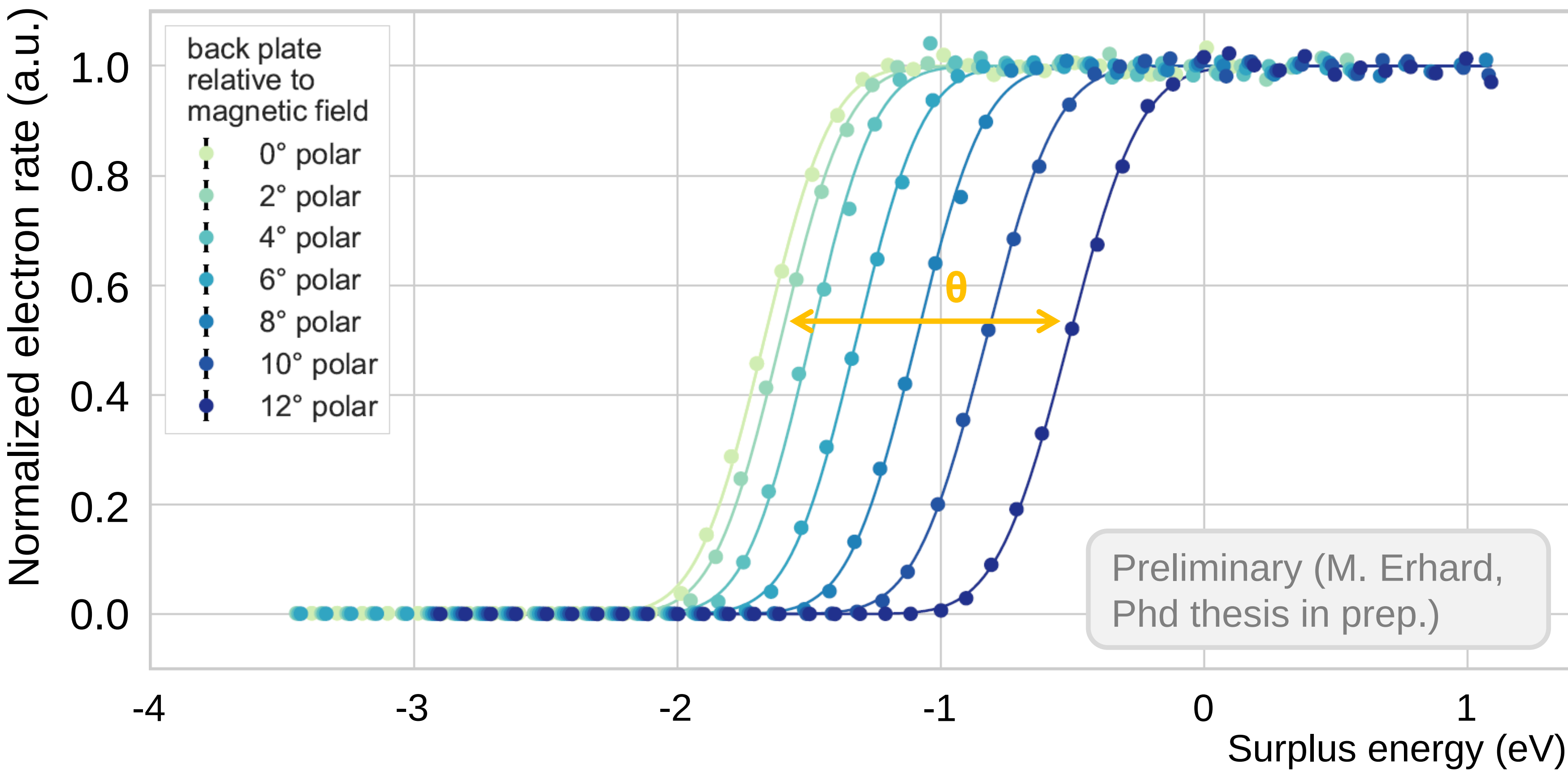


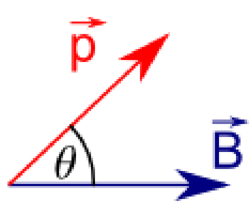
Used in SDS commissioning to characterize MAC-E filter

M. Erhard,
Phd thesis in prep.

Transmission Studies

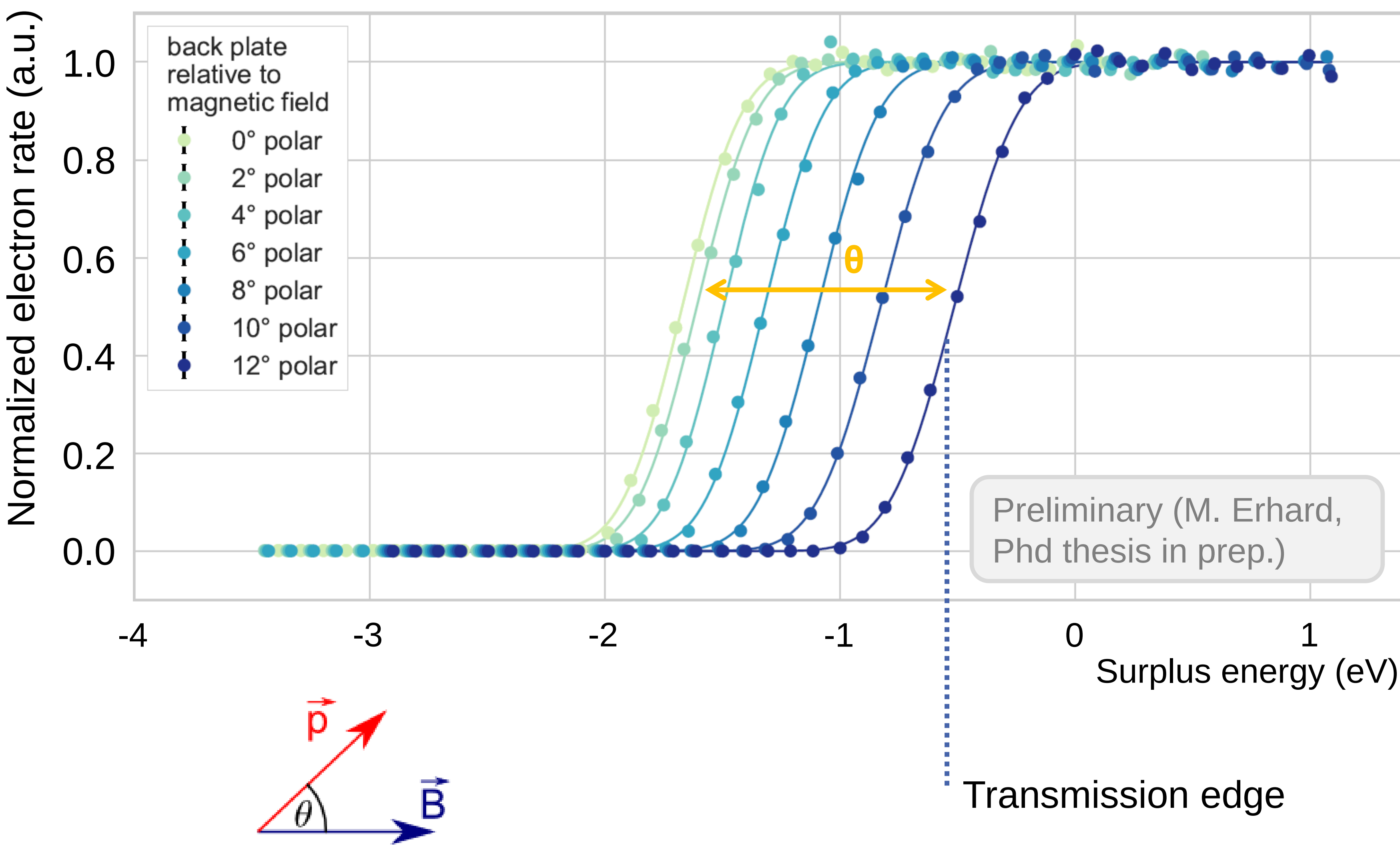
Measurements





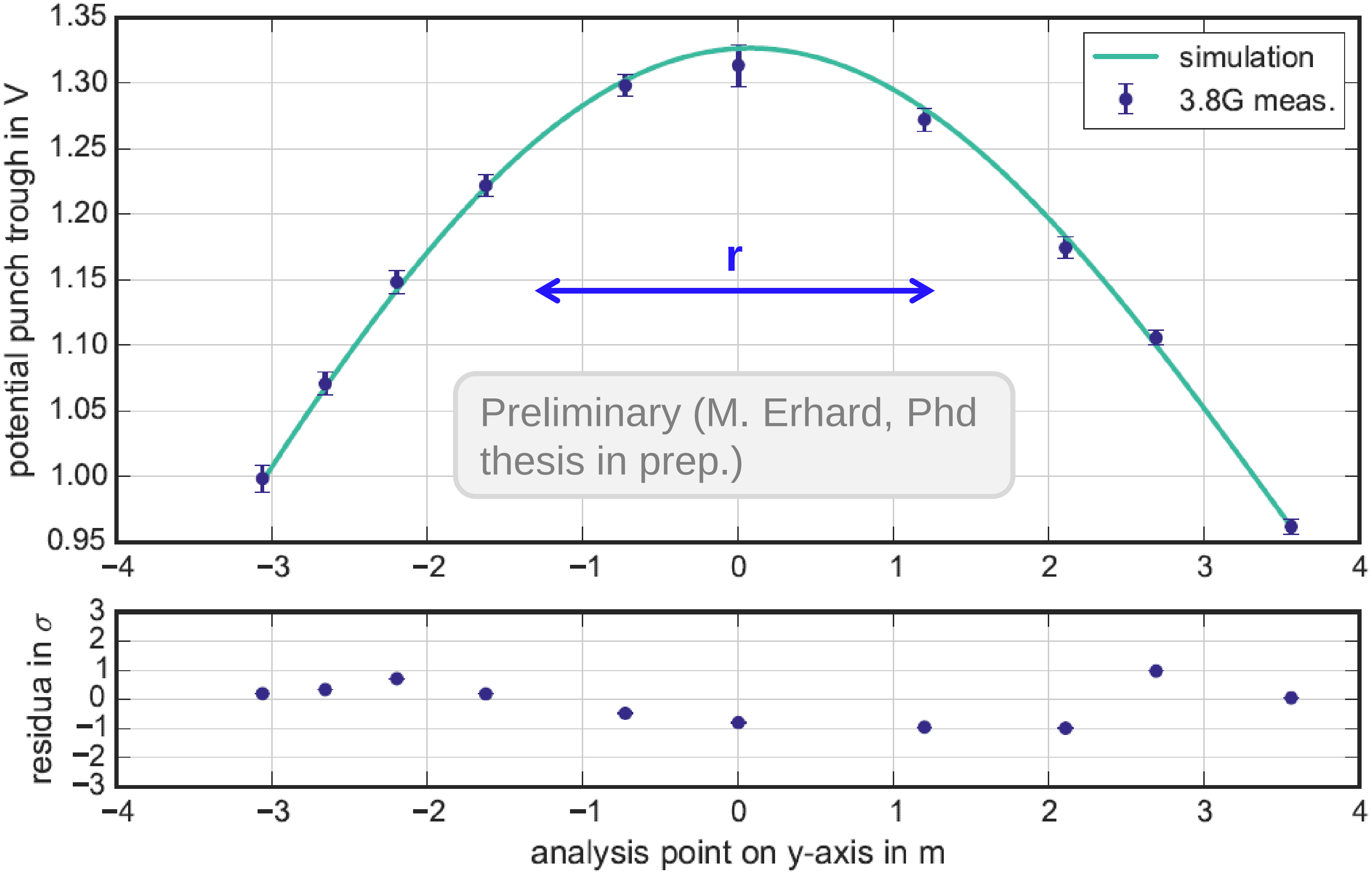
Transmission Studies

Measurements



Transmission Studies

Measurements



The Background Model

Overview

KATRIN design: **10 mcps**

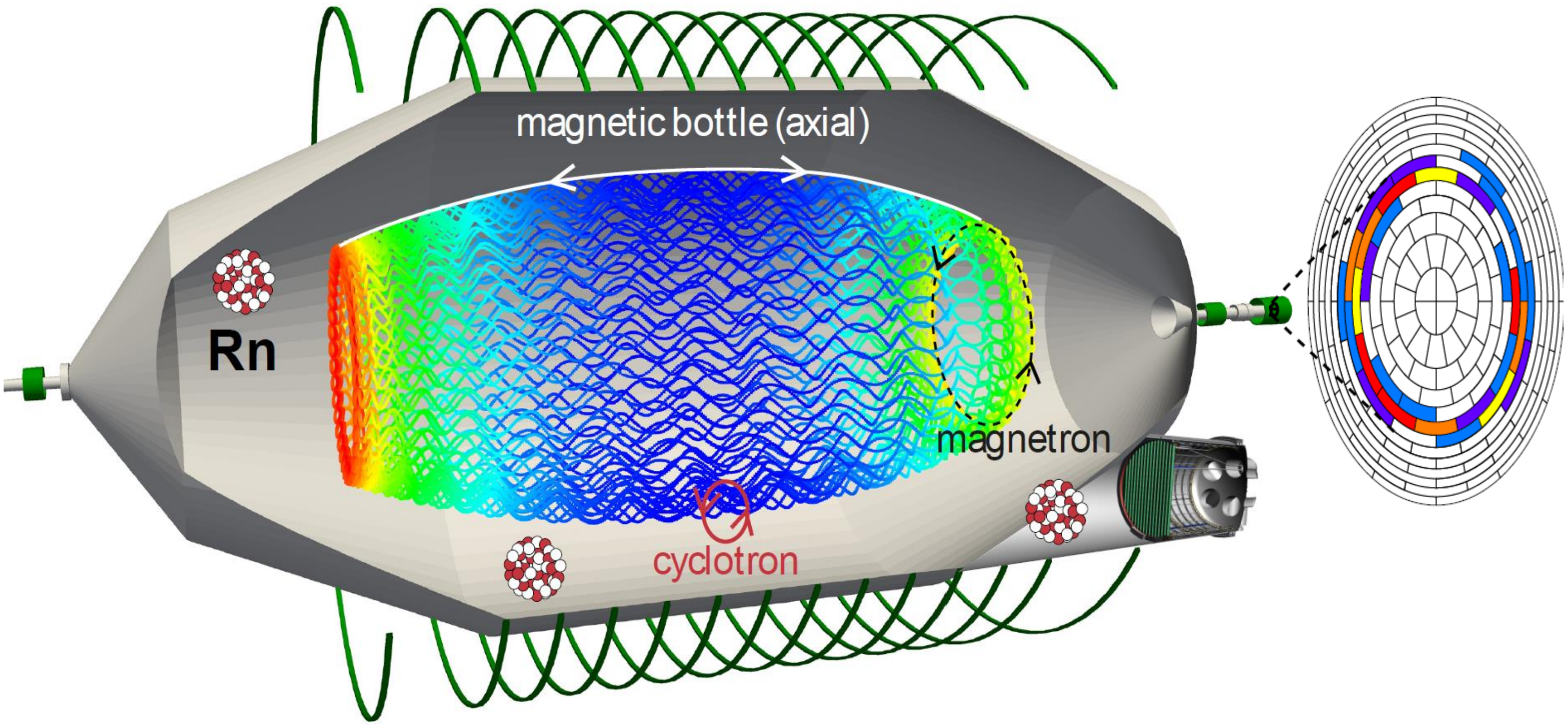
During SDS-I: **≈1000 mcps** (depends on operating parameters)

Potential Sources:

- Intrinsic detector background **< 5 mcps**
- Field-electron emission **not observed**
- Penning traps **in standard configuration**
- **Radioactive decays in the spectrometer volume (radon, tritium)**
- **Secondary electron emission**
- **Neutral messenger particles (Rydberg model)**

The Background Model

Radioactive Decays in the Spectrometer Volume

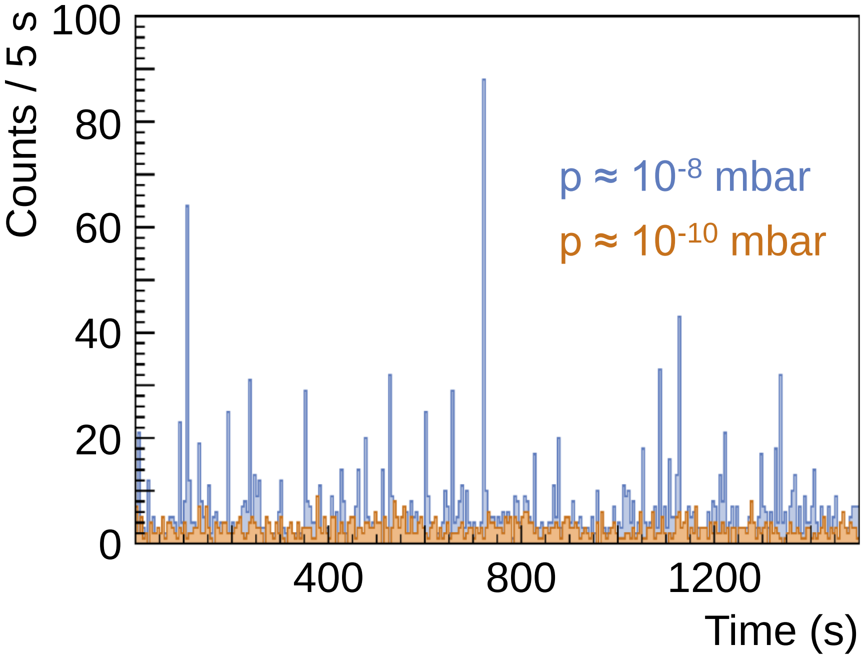


Storage of keV-electrons emitted in radioactive decays

The Background Model

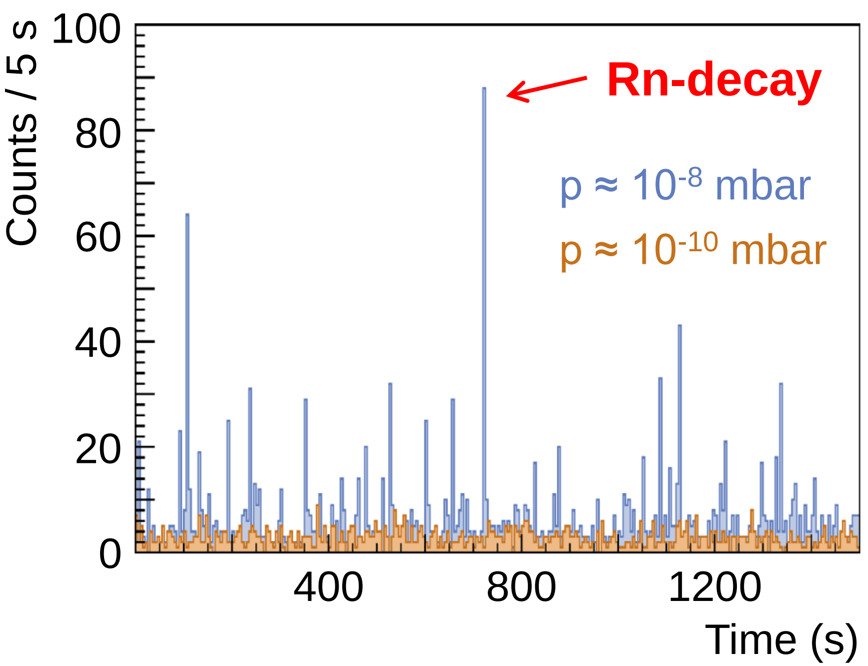
Radioactive Decays in the Spectrometer Volume

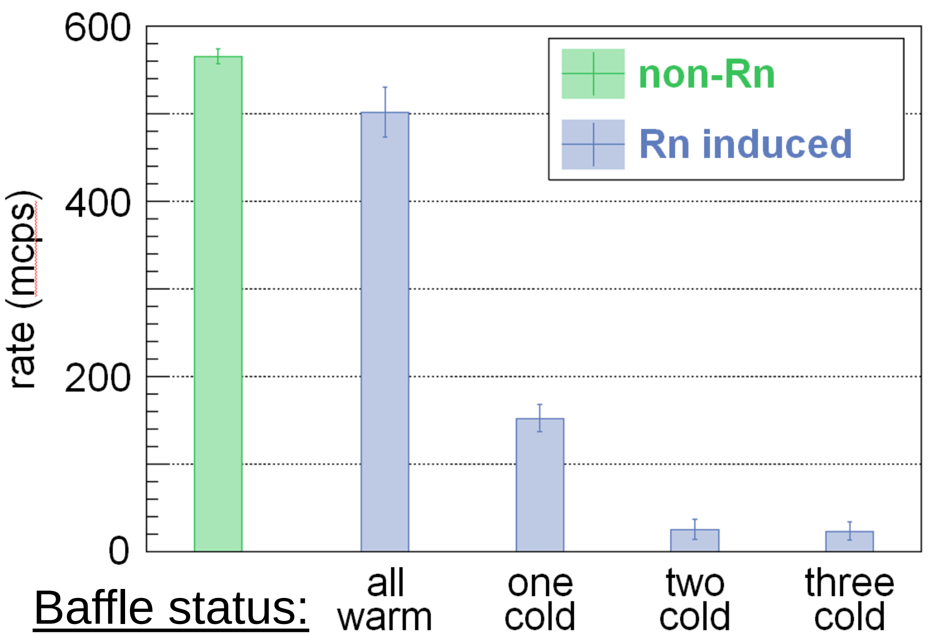
- Artificially elevate pressure in the spectrometer to reduce cool-down times.



The Background Model
Radioactive Decays in the Spectrometer Volume

- Artificially elevate pressure in the spectrometer to reduce cool-down times.
- Identify single radon decays as spike in the background rate.

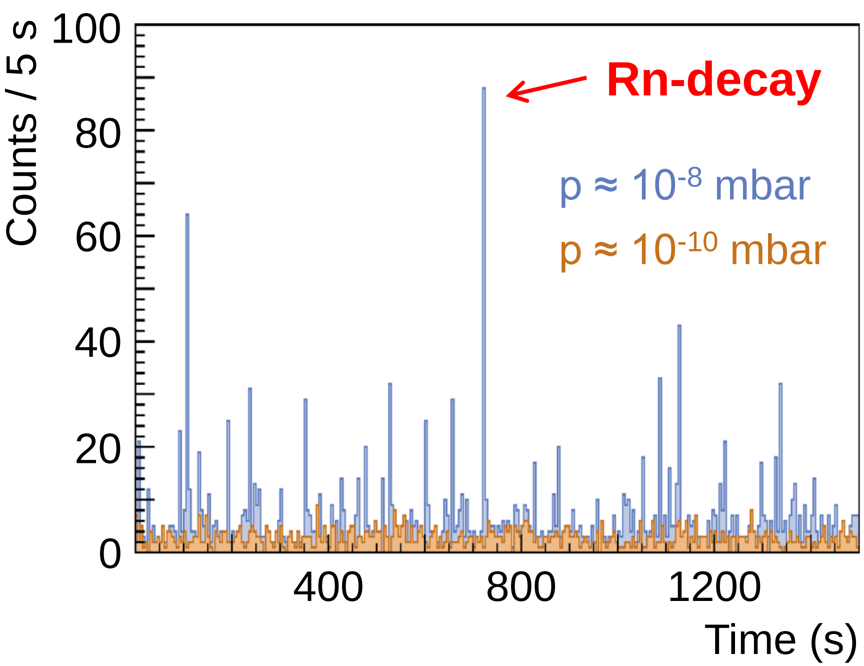


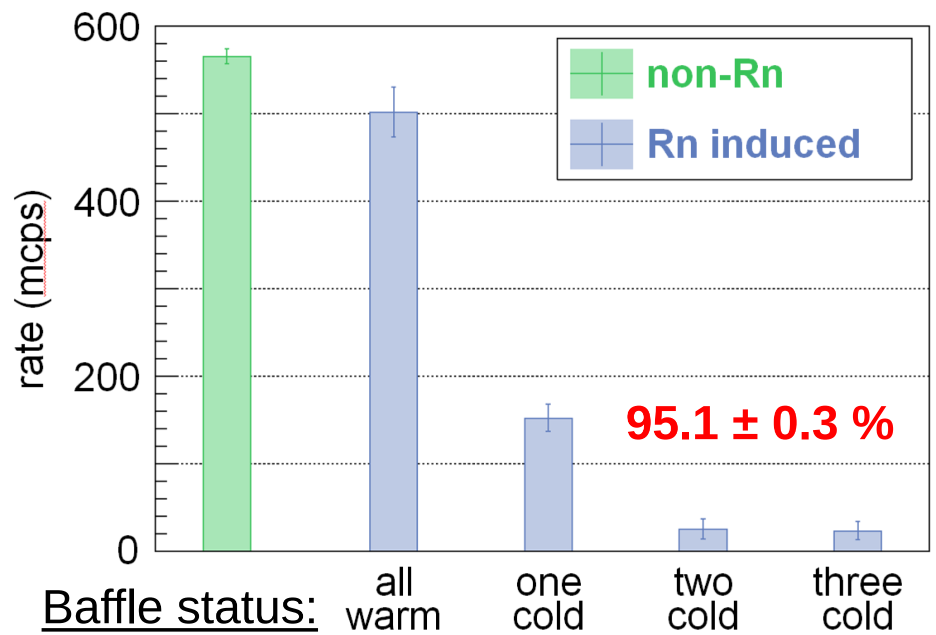


The Background Model

Radioactive Decays in the Spectrometer Volume

- 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.

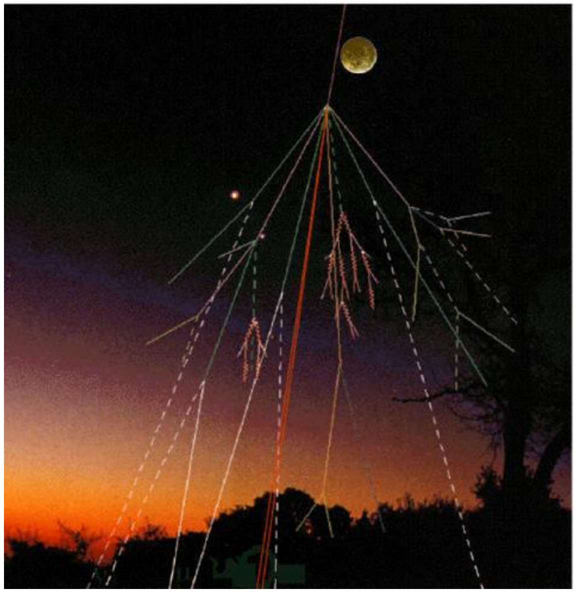




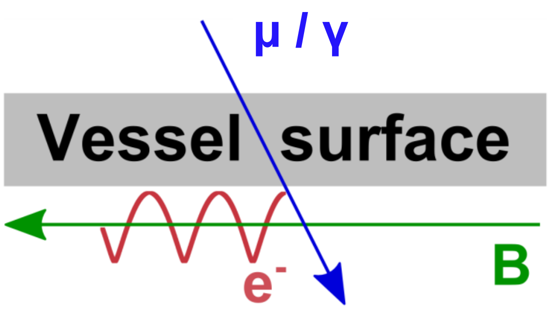
The Background Model

Secondary Electron Emission

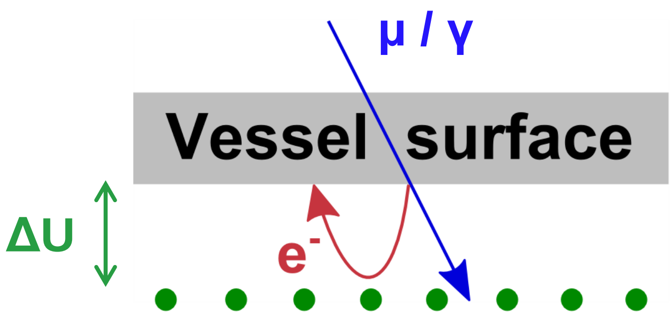
- 690 m^2 stainless steel surface.
- 75 000 muons / second
- Secondary electrons emitted from inner vessel surface are potential source of background
- For decades expected as main background source in large-scale MAC-E filter spectr.



Magnetic shielding



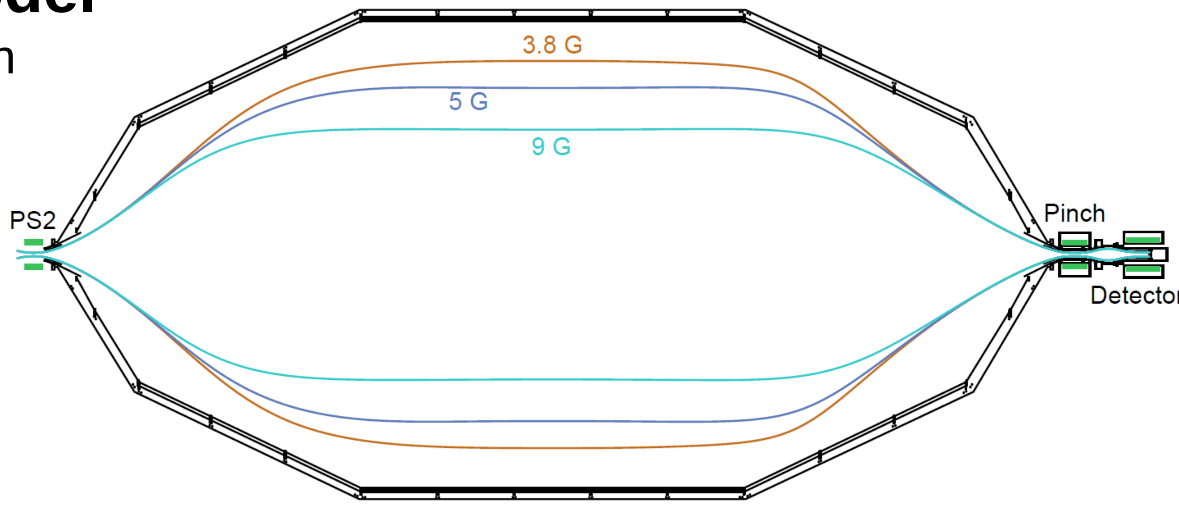
Electrostatic shielding



The Background Model

Secondary Electron Emission

- Background depends on magnetic field in spectrometer:
- 3.8 G → 890 mcps
- 5 G → 645 mcps
- 9 G → 349 mcps



The Background Model

Secondary Electron Emission

- Background depends on magnetic field in spectrometer:
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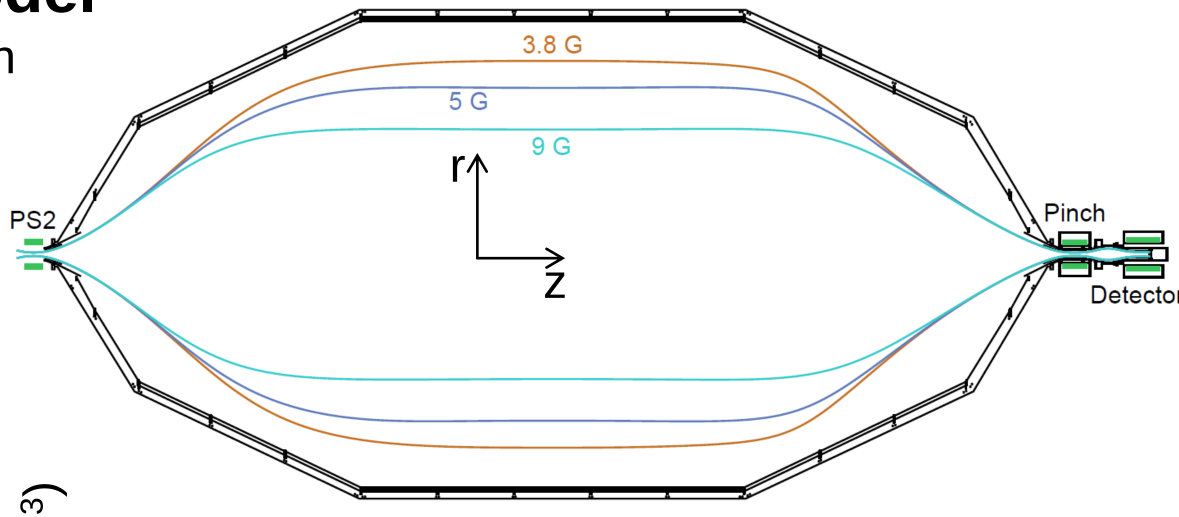
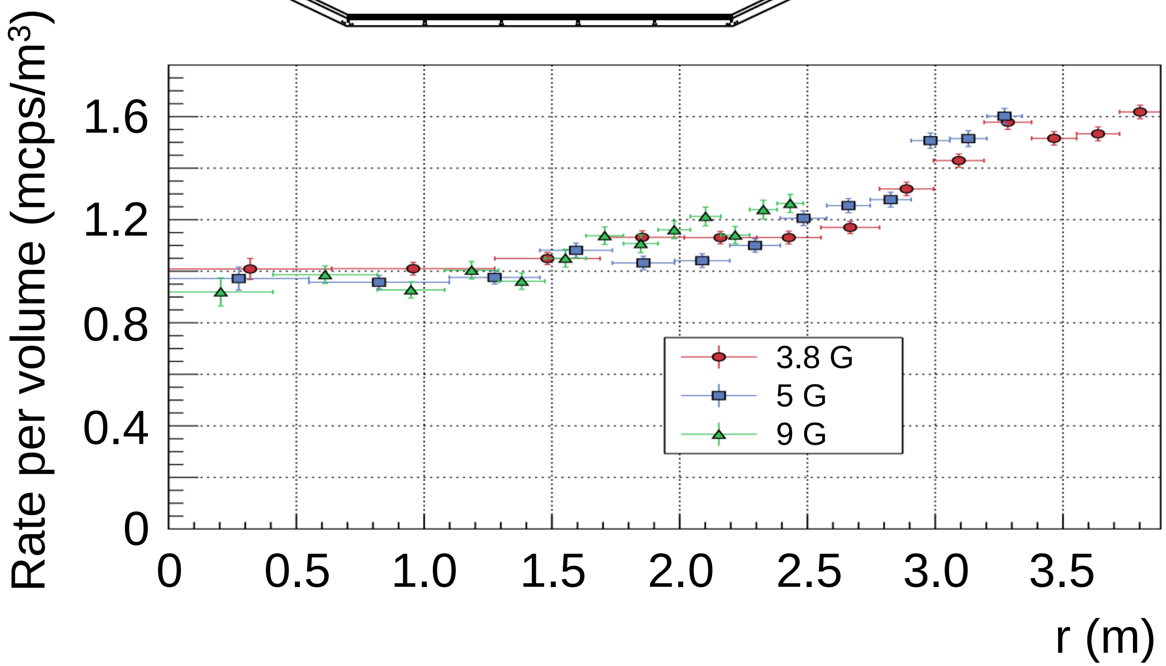
→ Turns out to be a volume effect!

→ Use volume normalized representation!





The Background Model

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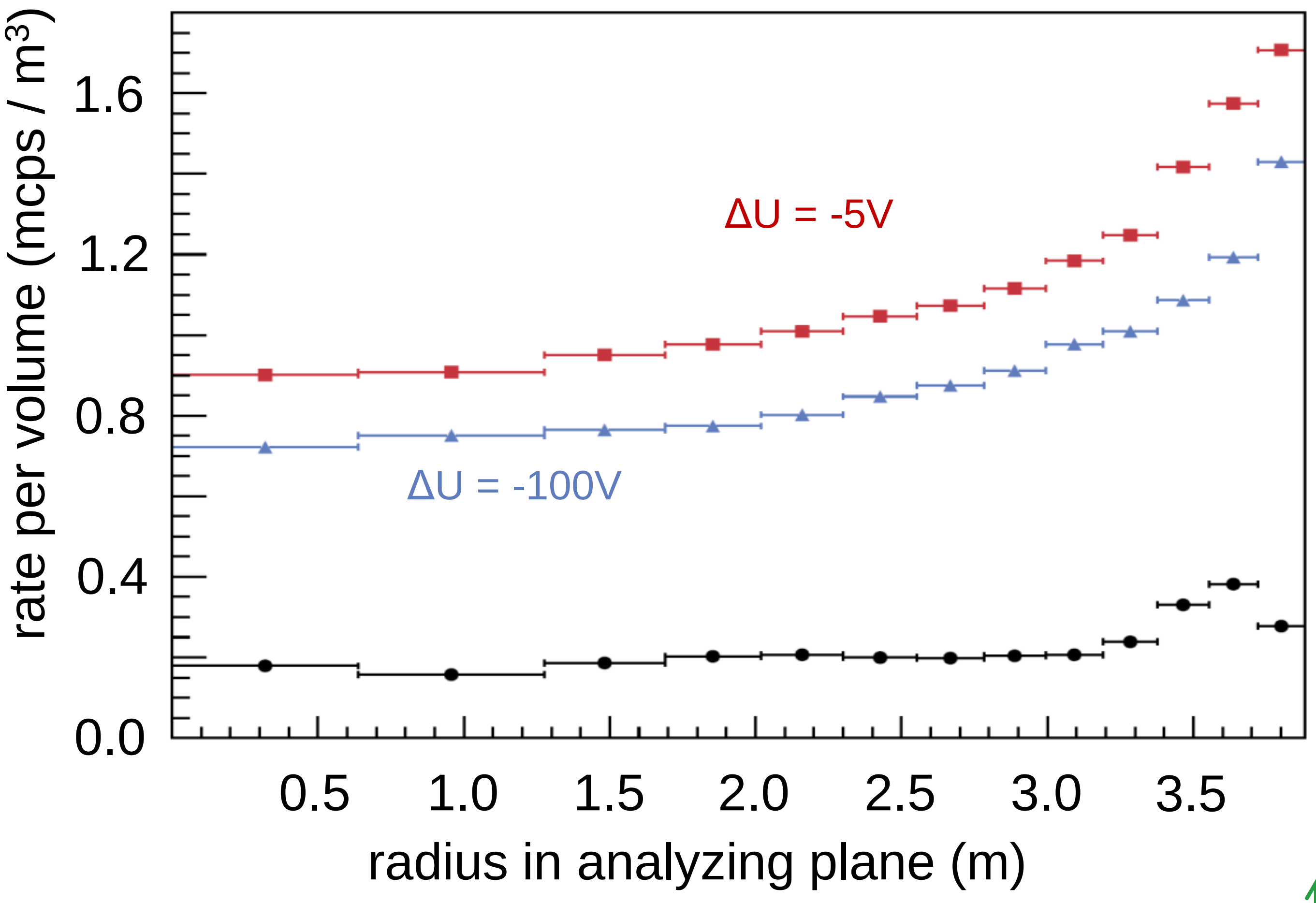
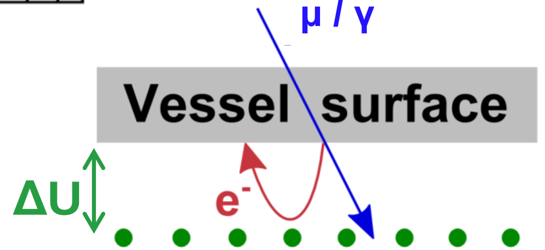
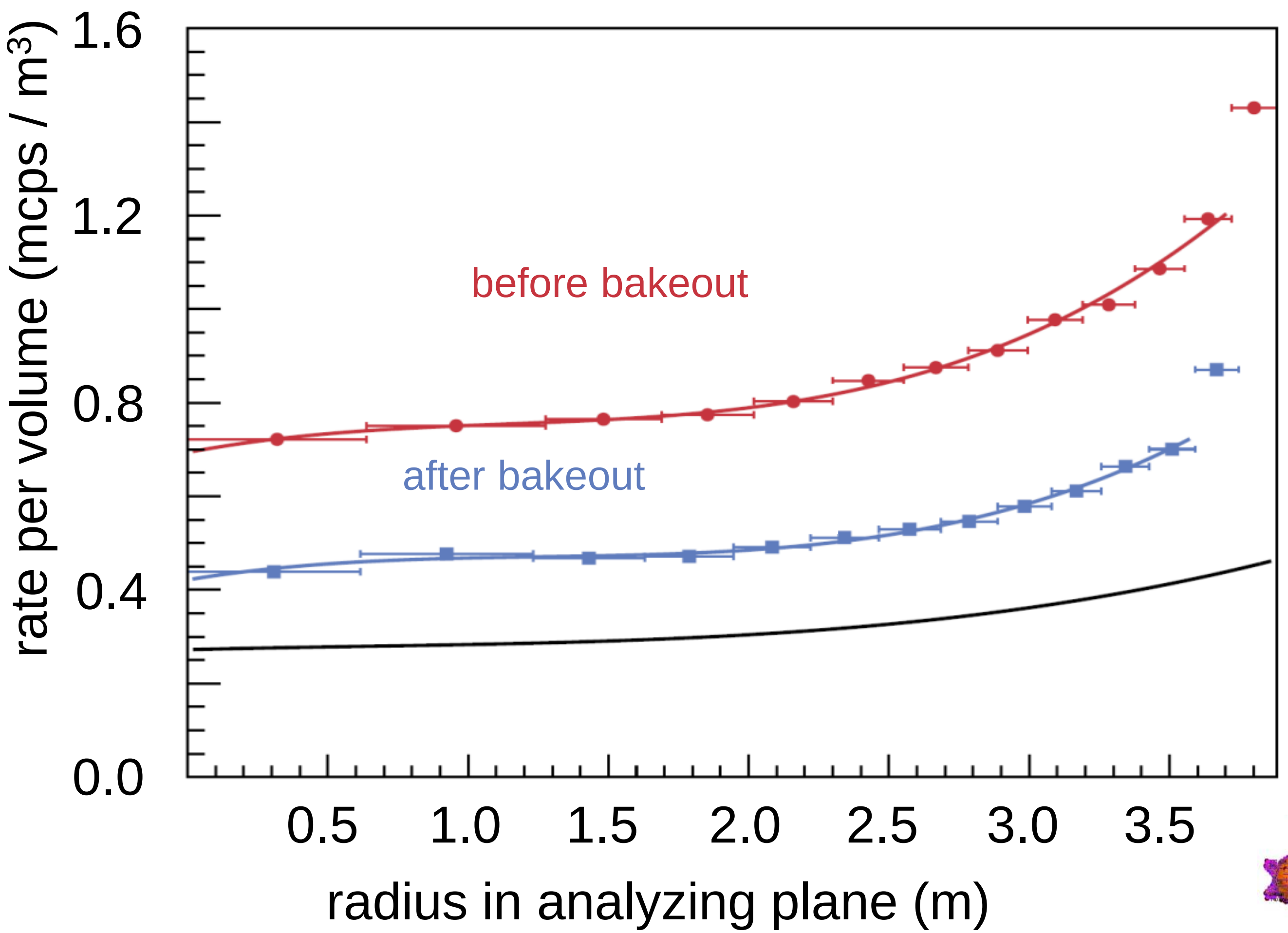
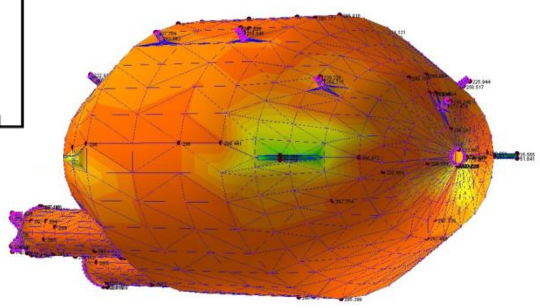




The Background Model

Secondary Electron Emission





The Background Model

Neutral Messenger Particles

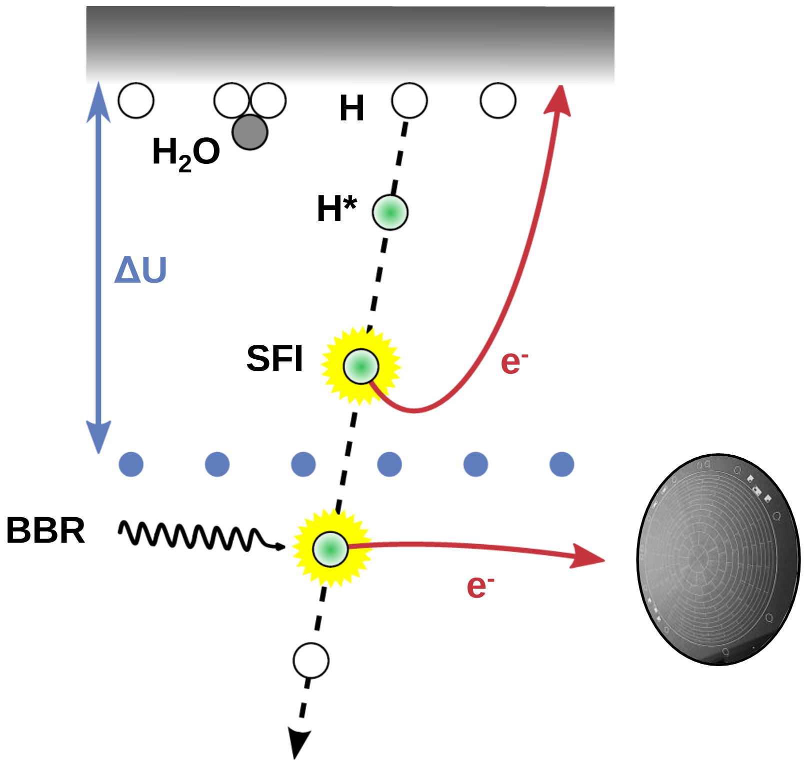
How to combine volume dependent background with surface conditions and ΔU-dependence?

The Background Model

Neutral Messenger Particles

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

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



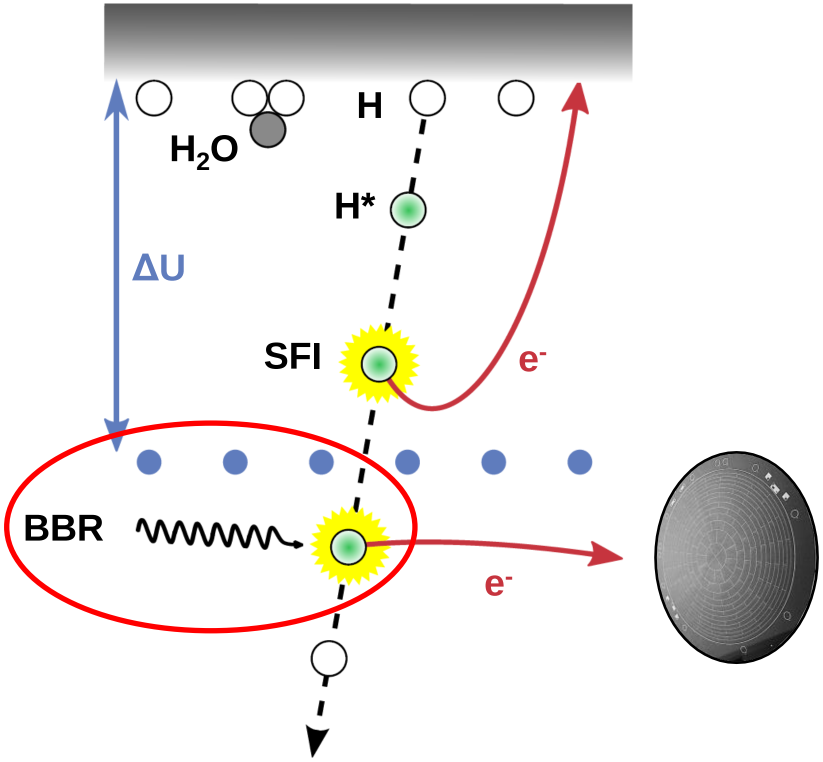
The Background Model

Neutral Messenger Particles

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

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

→ Explains volume dependence.



The Background Model

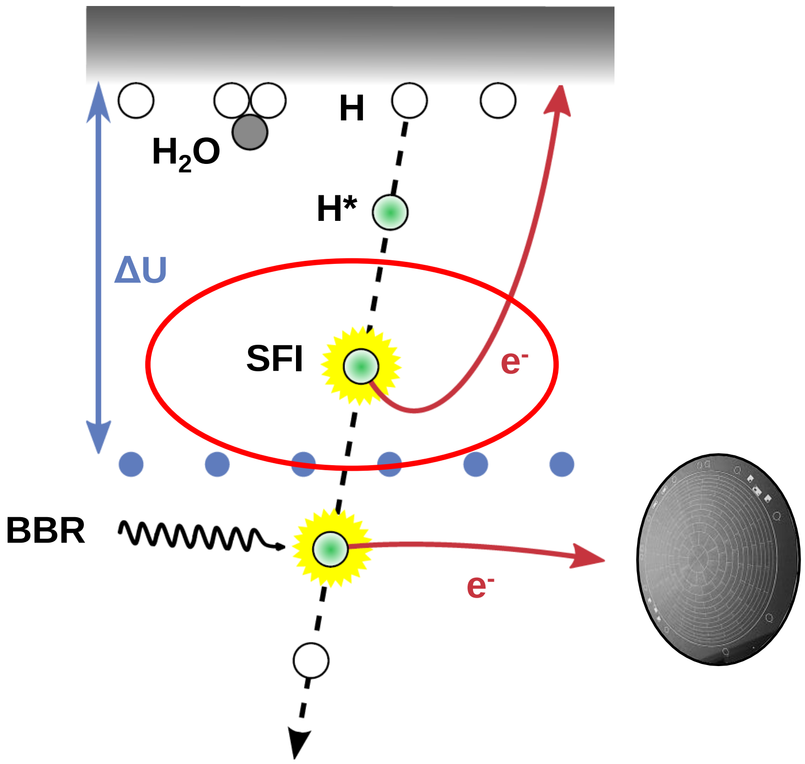
Neutral Messenger Particles

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.



The Background Model

Neutral Messenger Particles

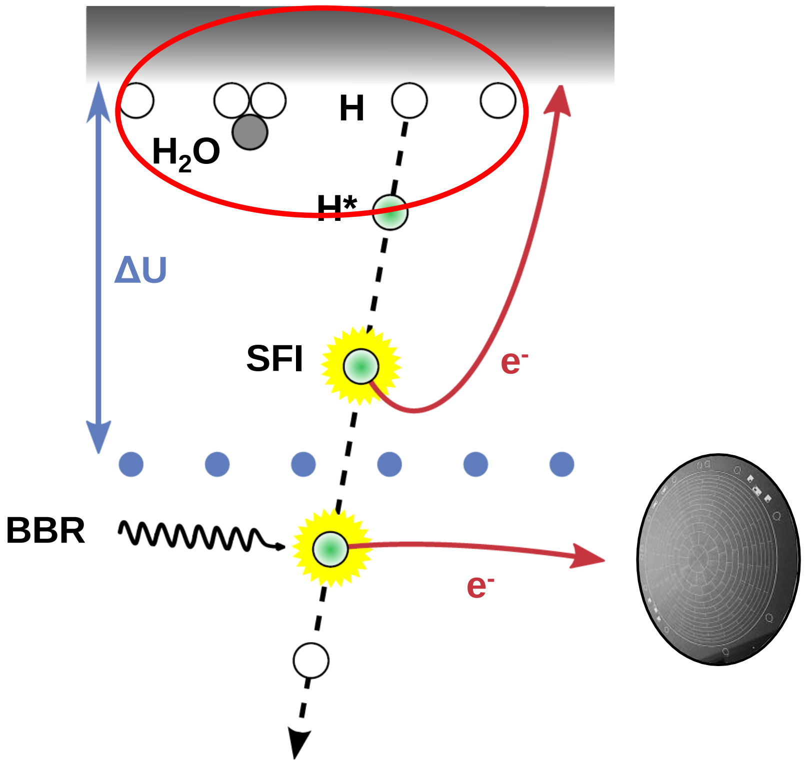
How to combine volume dependent background with surface conditions and ΔU-dependence?

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

→ Explains volume dependence.

→ Explains impact of electric shielding.

→ Explains impact of bake-out.



The Background Model
Neutral Messenger Particles

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

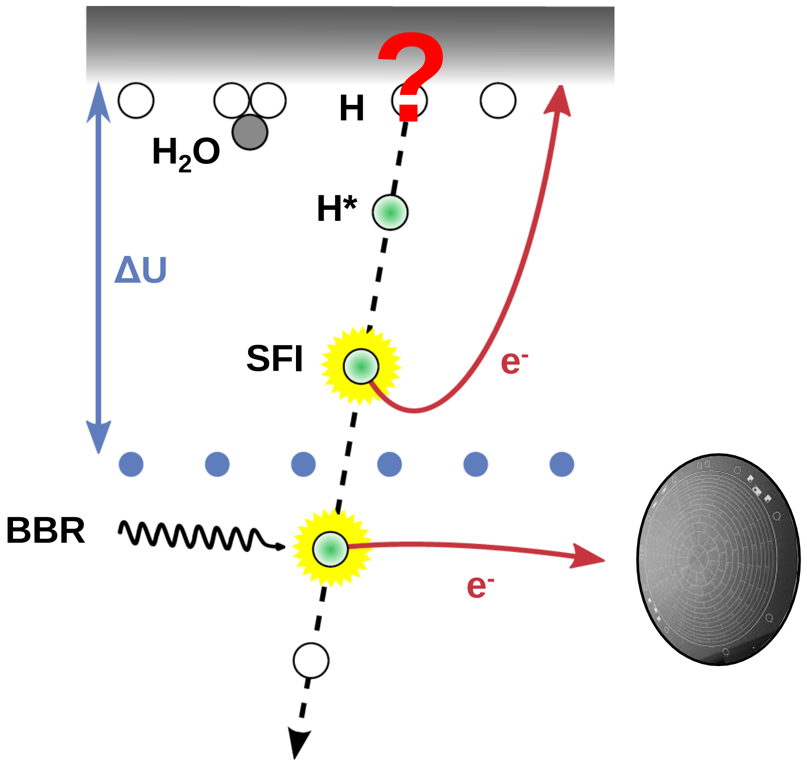
→ **Neutral messenger particles (Hydrogen Rydberg atoms)**

→ Explains volume dependence.

→ Explains impact of bake-out.

→ Explains impact of electric shielding.

→ Generation mechanism?



The Background Model

Neutral Messenger Particles

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

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

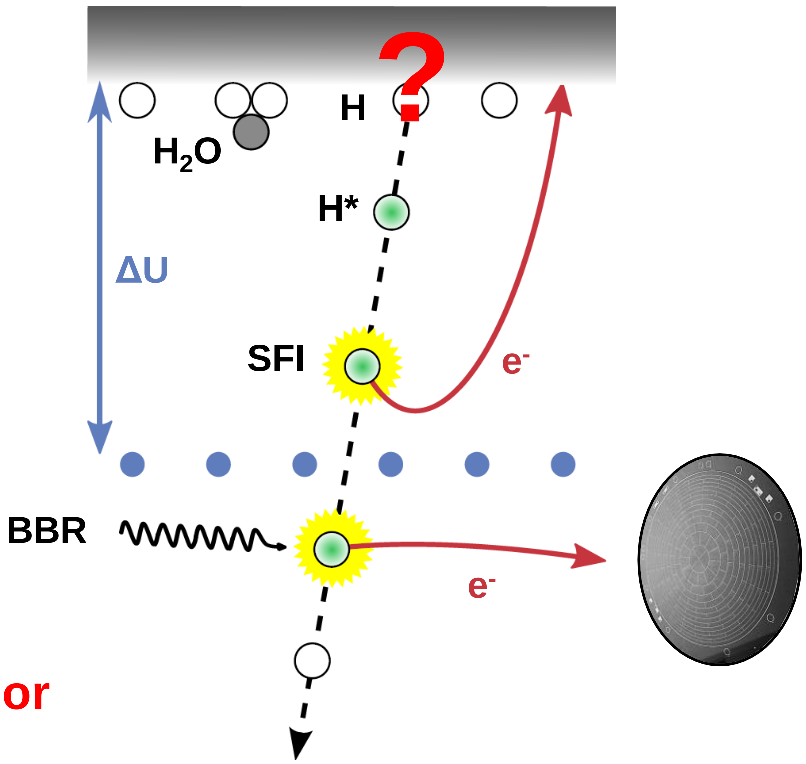
→ Explains volume dependence.

→ Explains impact of bake-out.

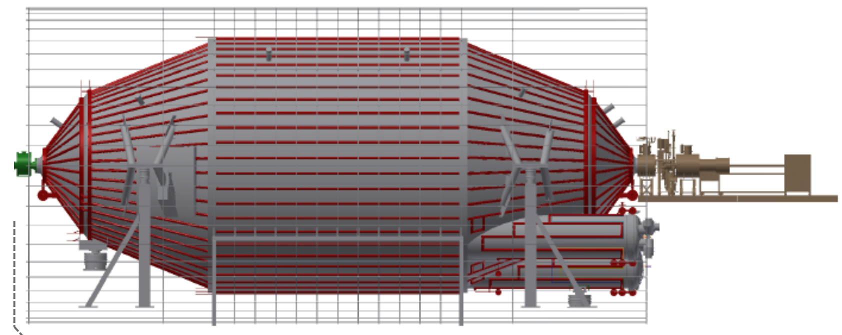
→ Explains impact of electric shielding

→ Generation mechanism?

→ **Possible source: Radioactive decays on or close to spectrometer surface.**

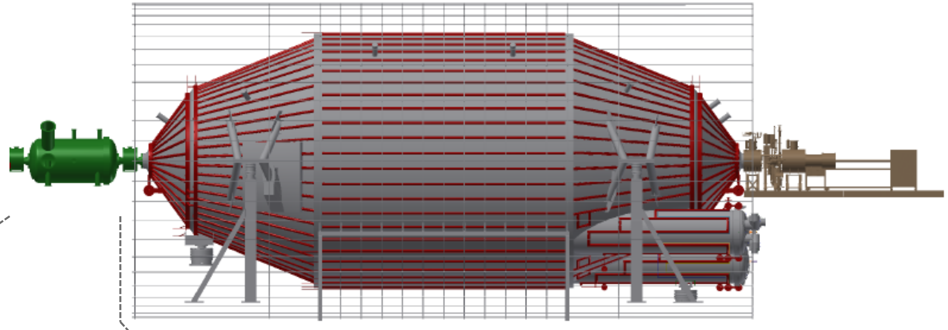


Summary and Outlook



- Successfully commissioned
- Works as MAC-E filter
- Background: ≈ 400 mcps
- Derived background model
- Currently: Test model, establish reduction techniques

Summary and Outlook



- Used in past as test facility
- Combined operation with main spectrometer starts in summer 2016

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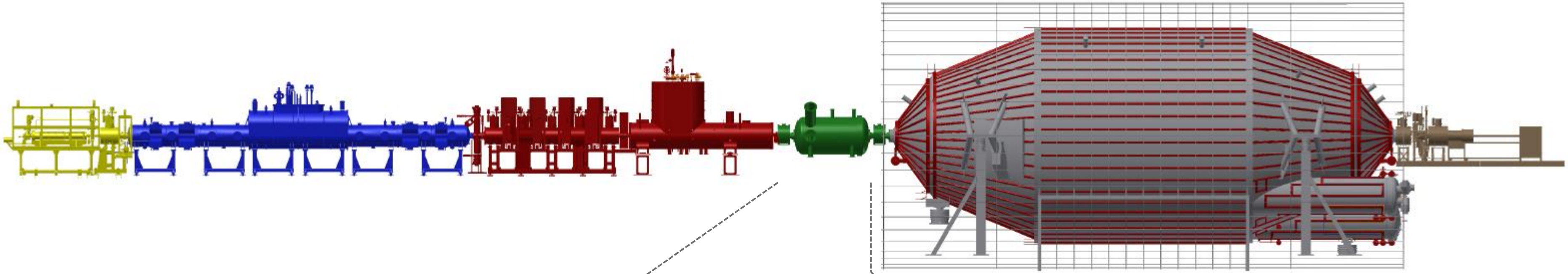
Summary and Outlook



- All components on site since summer 2015
- Currently being commissioned
- Start of commissioning measurements of full beam line: Autumn 2016

- Used in past as test facility
- Combined operation with main spectrometer starts in summer 2016

- Successfully commissioned
- Works as MAC-E filter
- Background: ≈ 400 mcps
- Derived background model
- Currently: Test model, establish reduction techniques

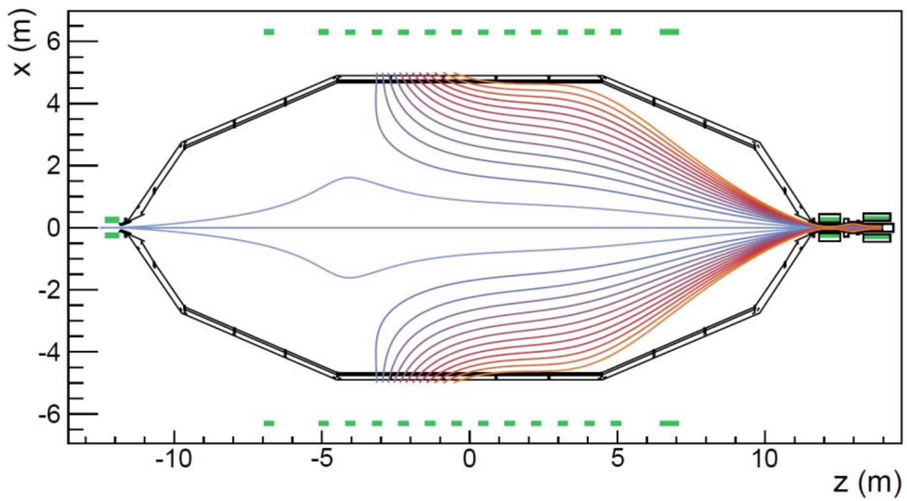
Thank you for your attention!

Backup Slides

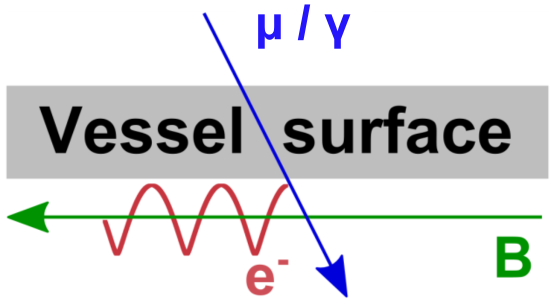
The Background Model

Secondary Electron Emission

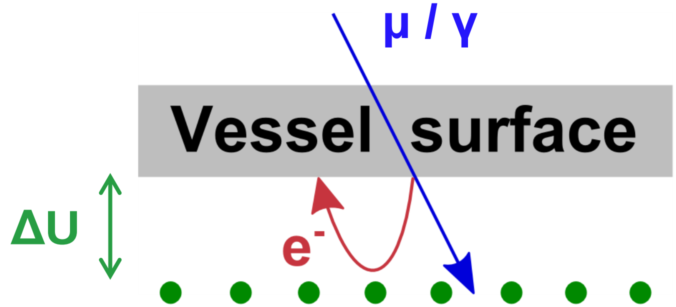
- 690 m^2 stainless steel surface.
- Secondary electrons emitted from inner vessel surface are potential source of background
- For decades, expected as main background source in large-scale MAC-E filter spectrometers



Magnetic shielding



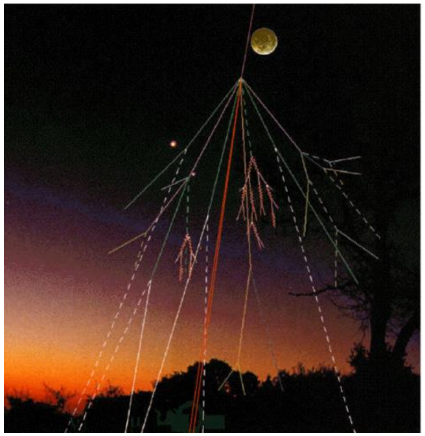
Electrostatic shielding

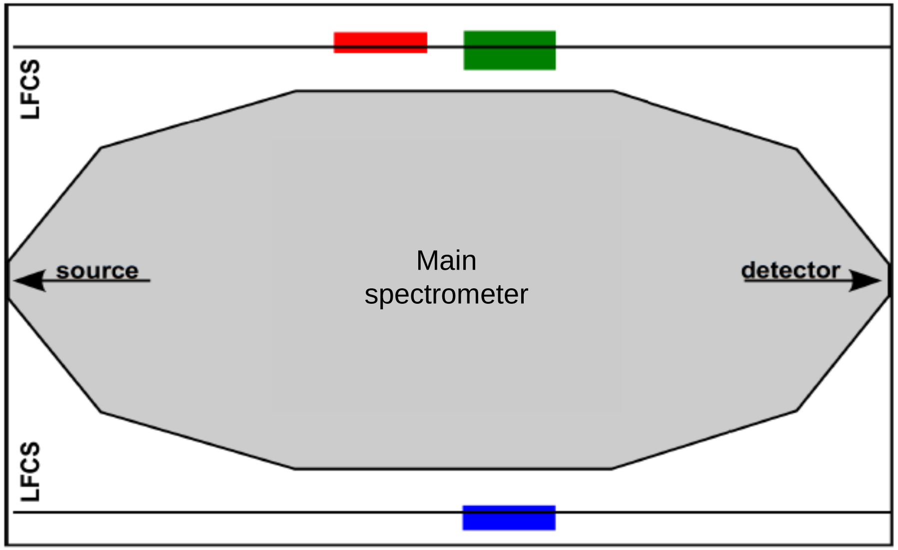


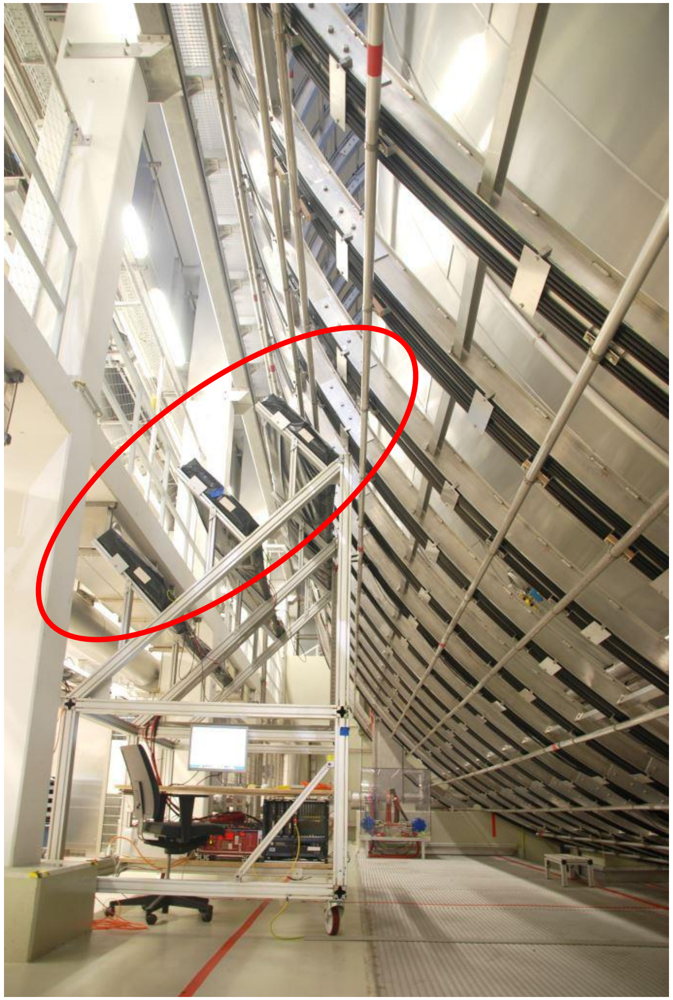
The Background Model
Muon-induced background

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

J. Linek, master thesis

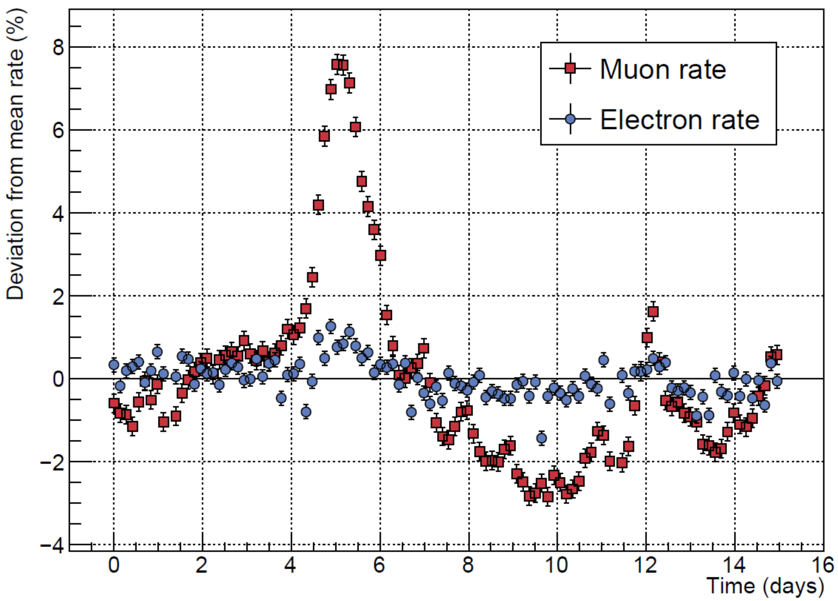






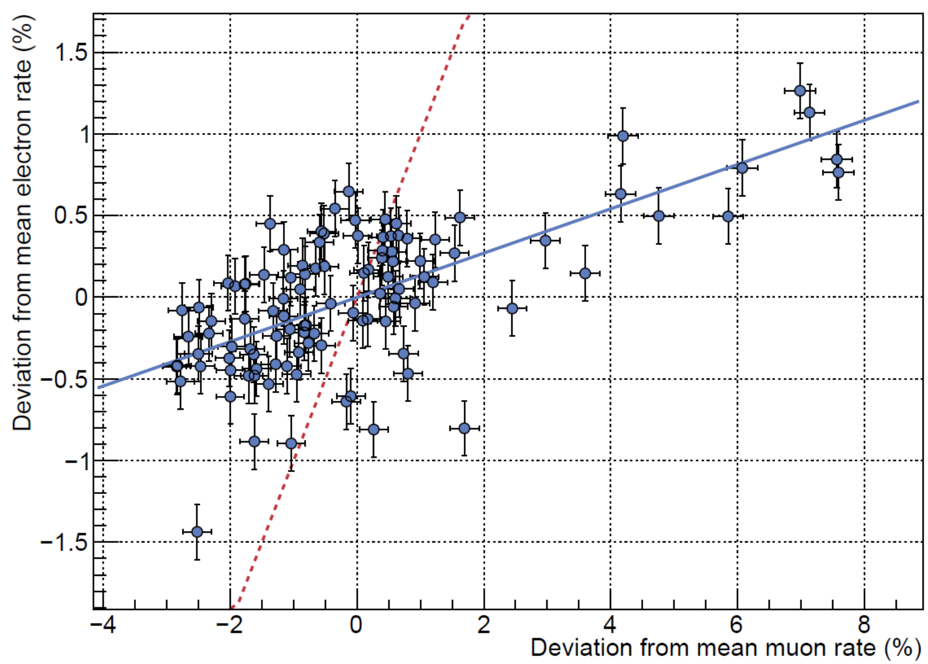
The Background Model

Muon-induced background



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

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

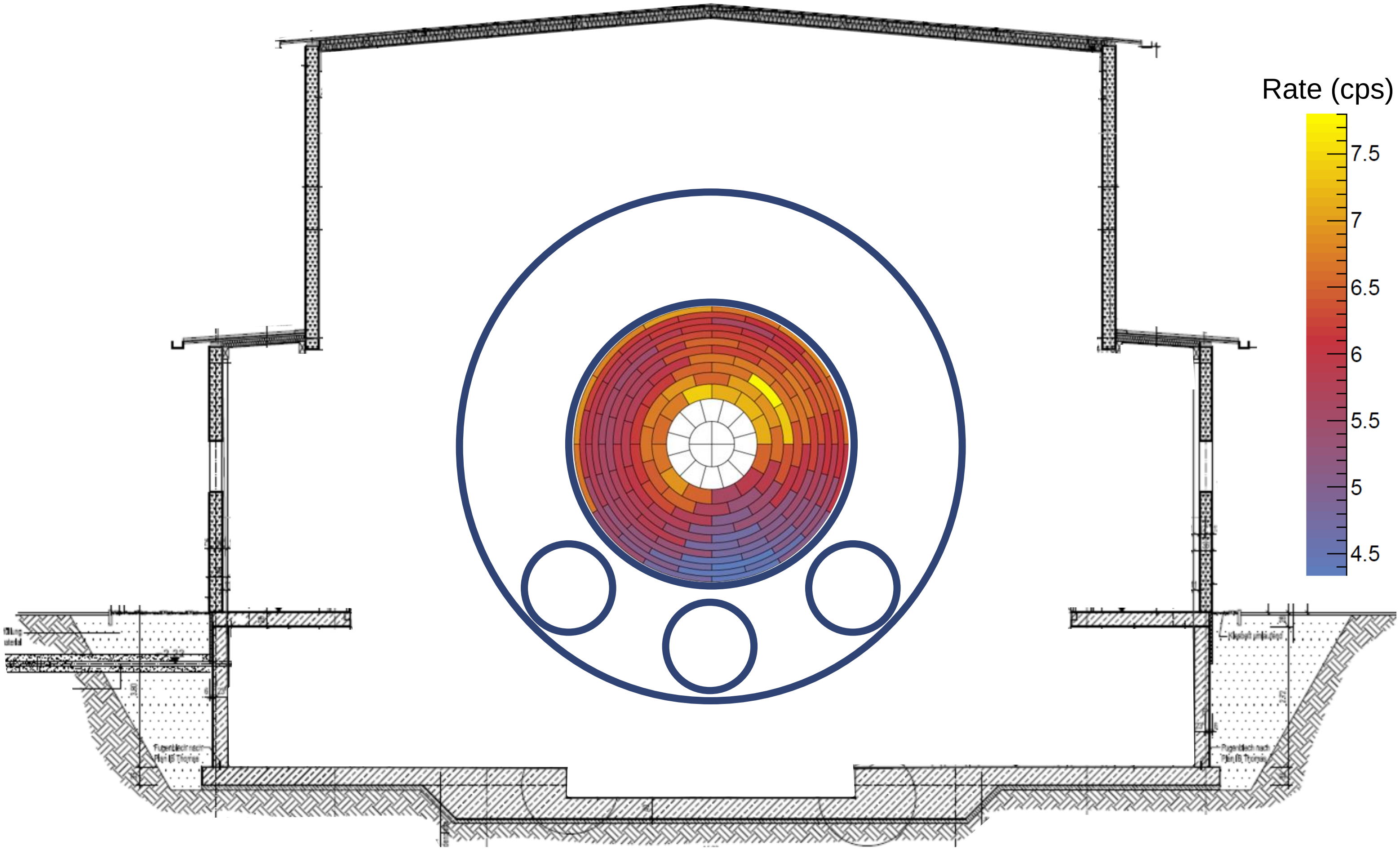


$$\boxed{a = 13.6 \pm 0.8\ \%}$$

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

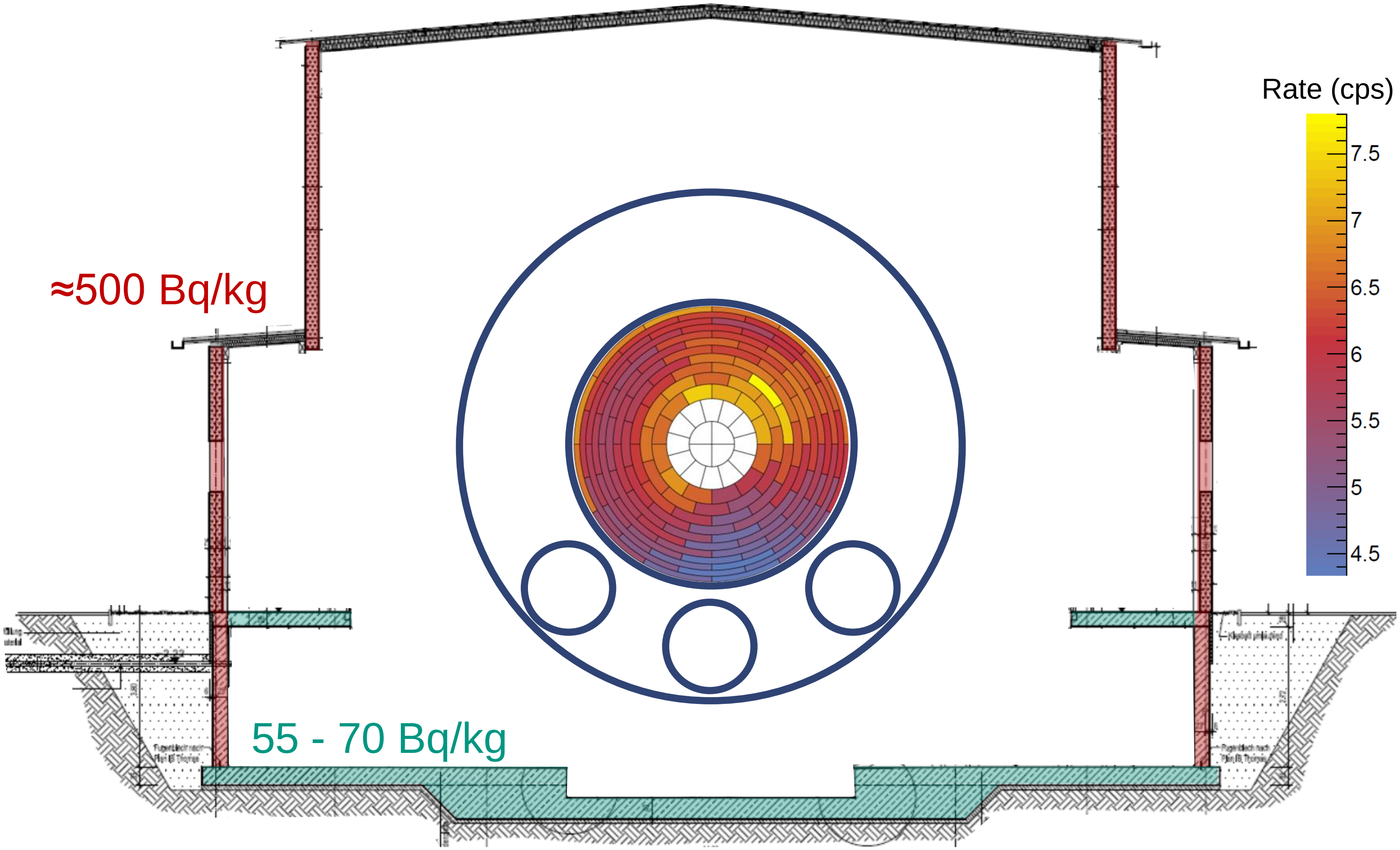
The Background Model

Environmental γ-radiation



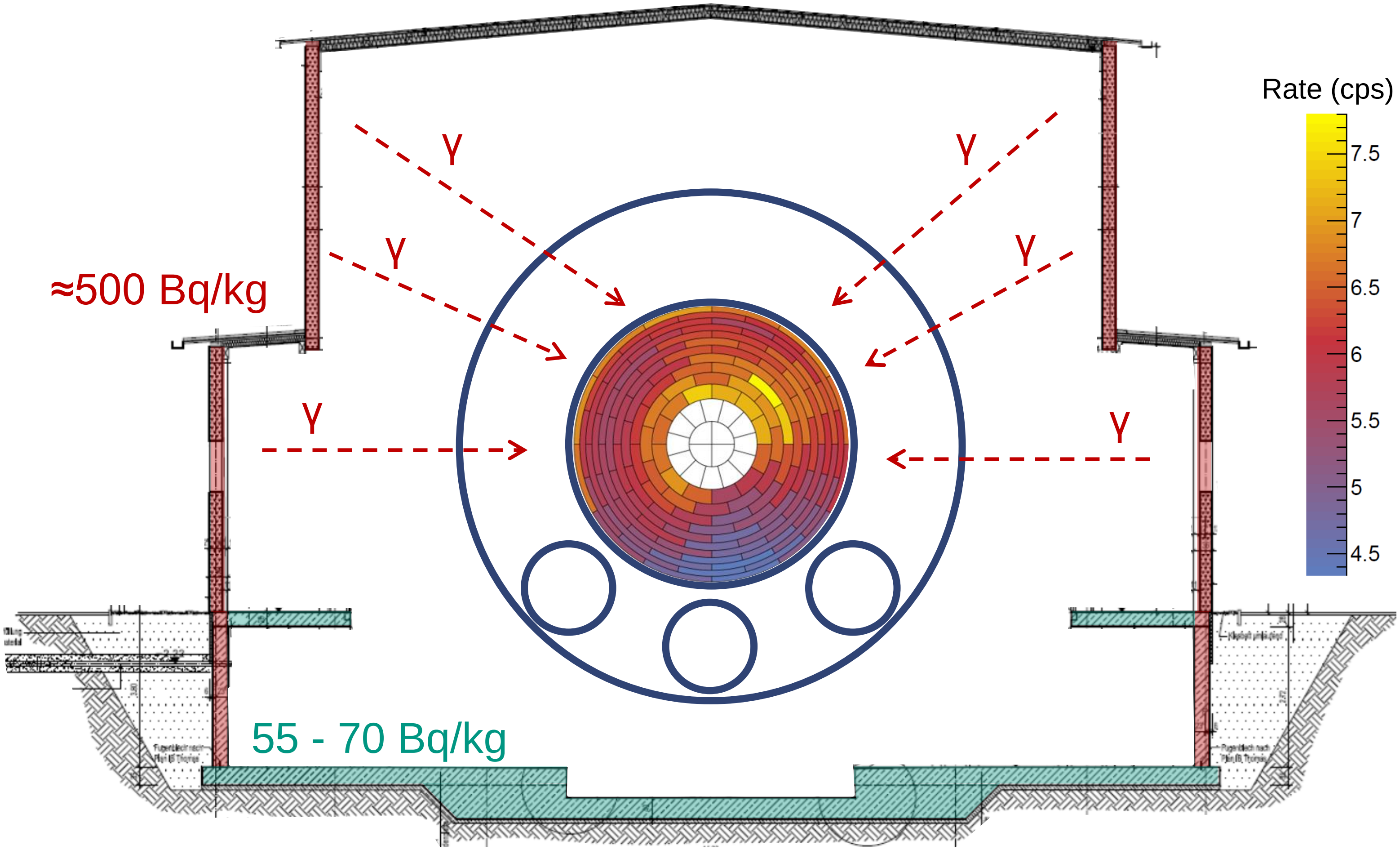
The Background Model

Environmental γ-radiation



The Background Model

Environmental γ-radiation



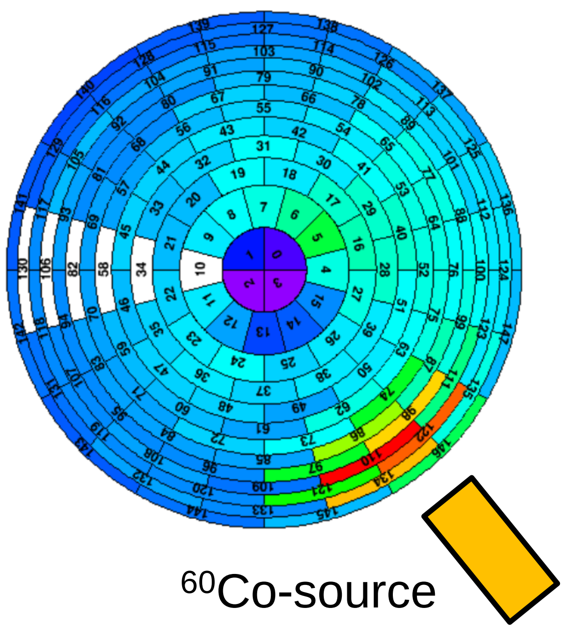
The Background Model

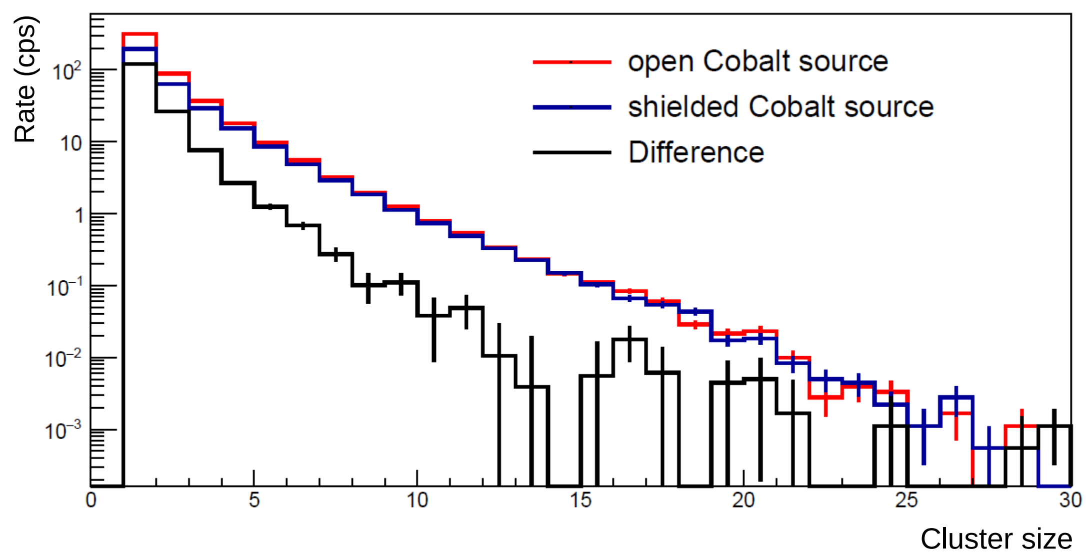
Environmental γ-radiation

- 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.

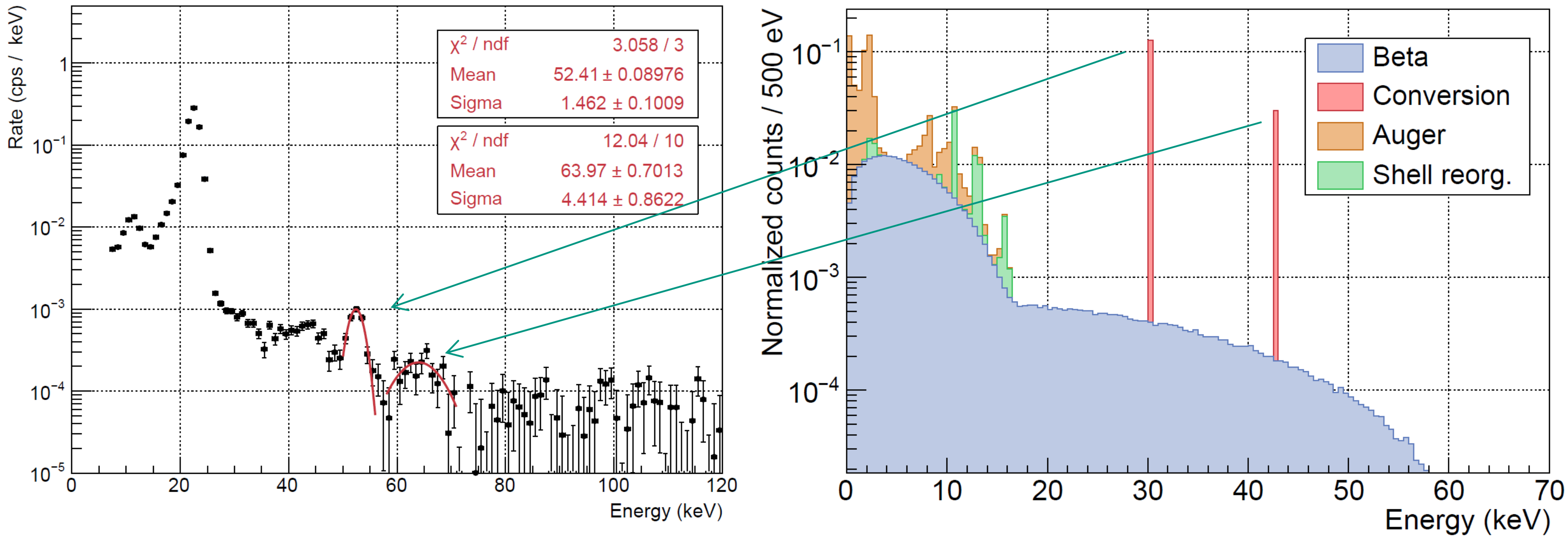




The Background Model

^{210}Pb Traces

→ Found small traces of ^{210}Pb contamination in main spectrometer (≈1Bq / m^2).



→ ^{210}Pb must have been deposited in spectrometer over the course of commissioning.

The Background Model
^{210}Pb Traces

→ ^{210}Pb is part of uranium decay series.

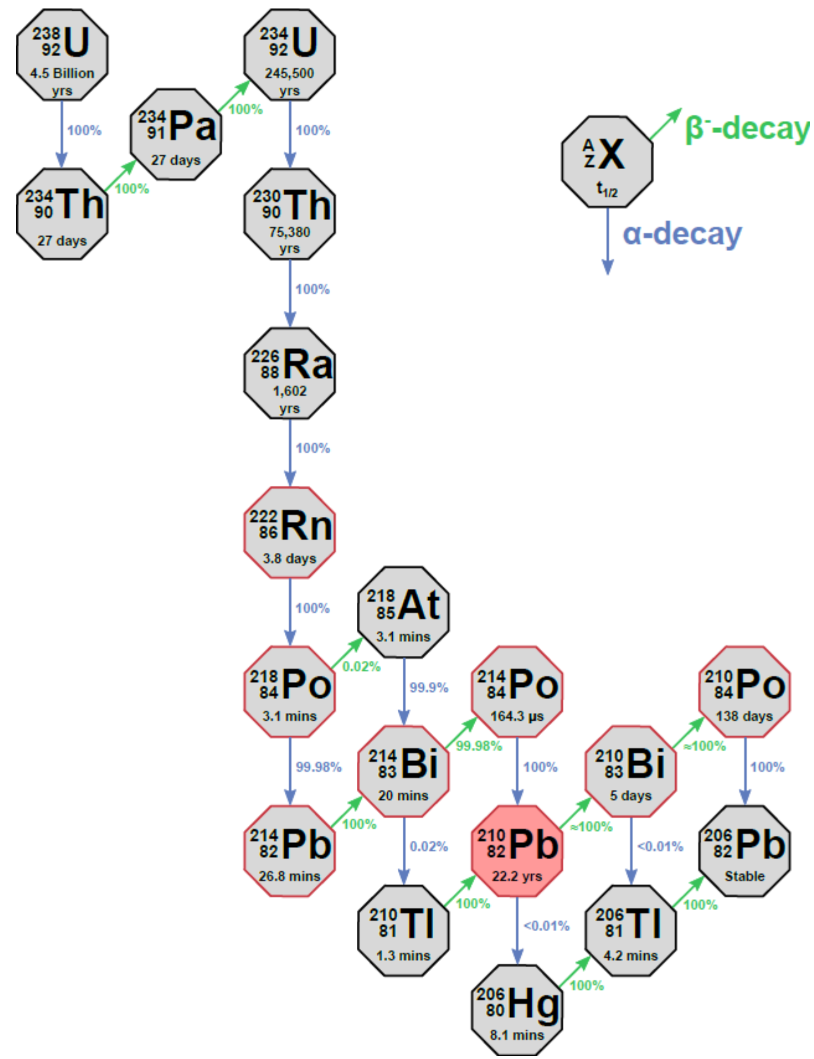
→ ^{222}Rn is present in ambient air.

→ Radon progeny will deposit on surfaces.

→ ^{214}Po decay gives ^{210}Pb recoil energy of ≈146 keV.

→ Implantation of small traces of ^{210}Pb in stainless steel walls.

→ Decay of ^{210}Po releases 103 keV of recoil energy for ^{206}Pb atom.



The Background Model

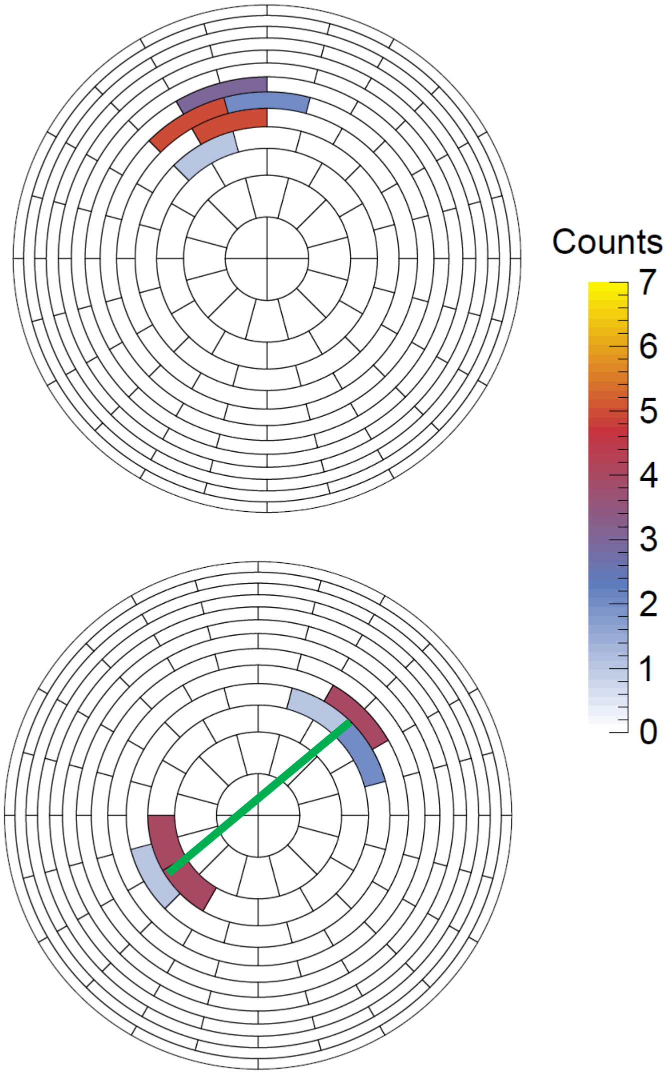
^{210}Pb Traces

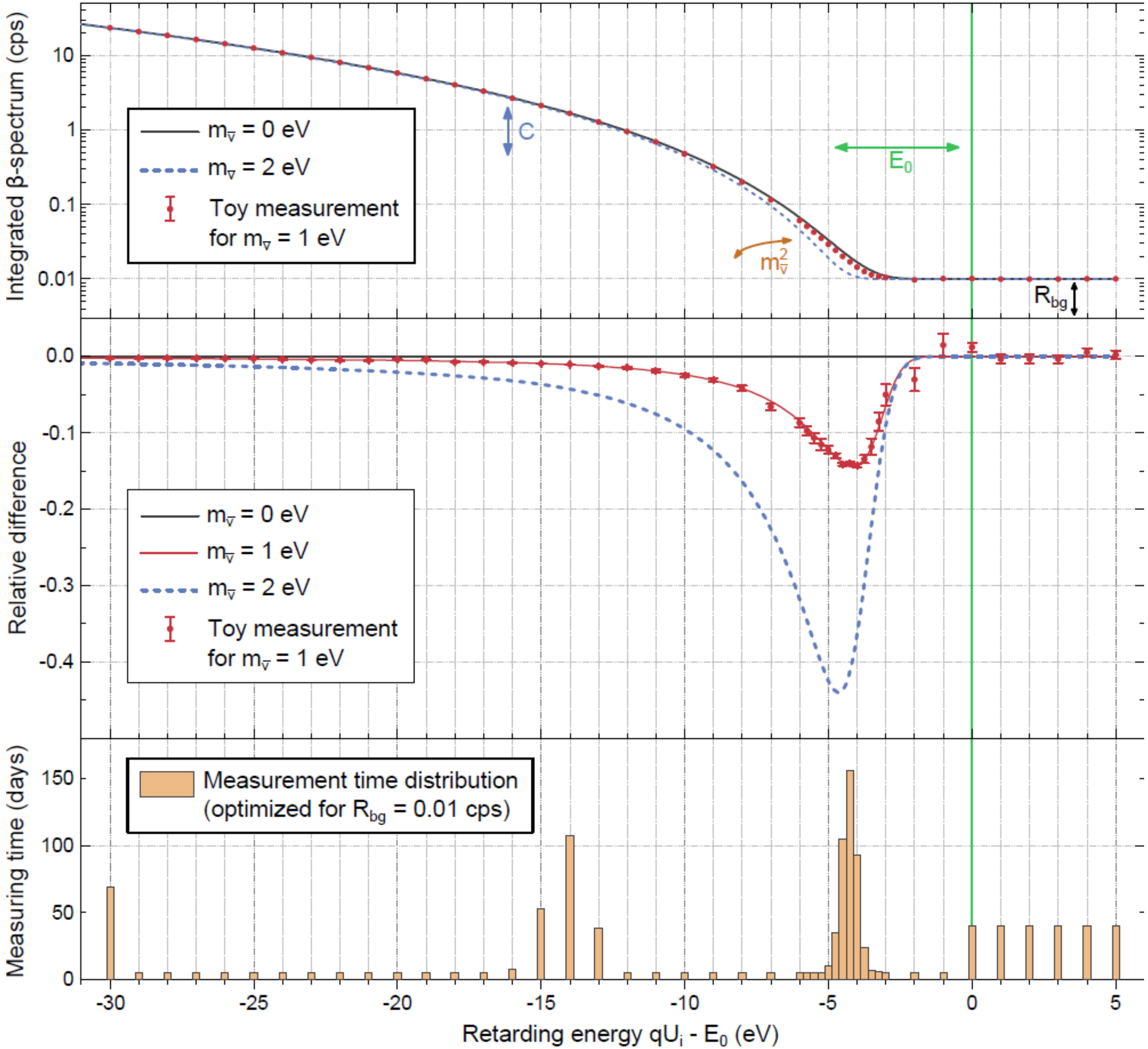
→ Idea: Event clusters are due to ^{206}Pb atoms passing surface of vessel.

→ Could be related to Rydberg production.

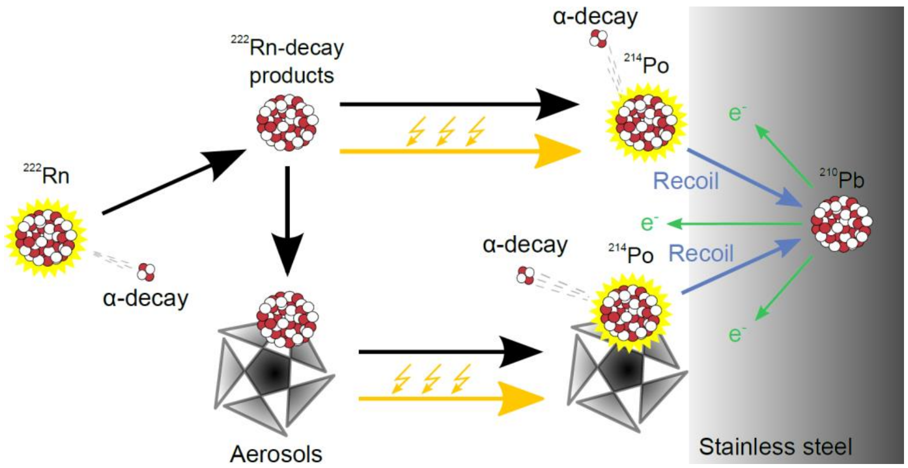
→ Currently further investigated:

1. Relate event clusters to ^{206}Pb recoils.
2. Relate event clusters to Rydberg background.
3. Establish minimal invasive methods for cleaning the inner spectrometer surface.

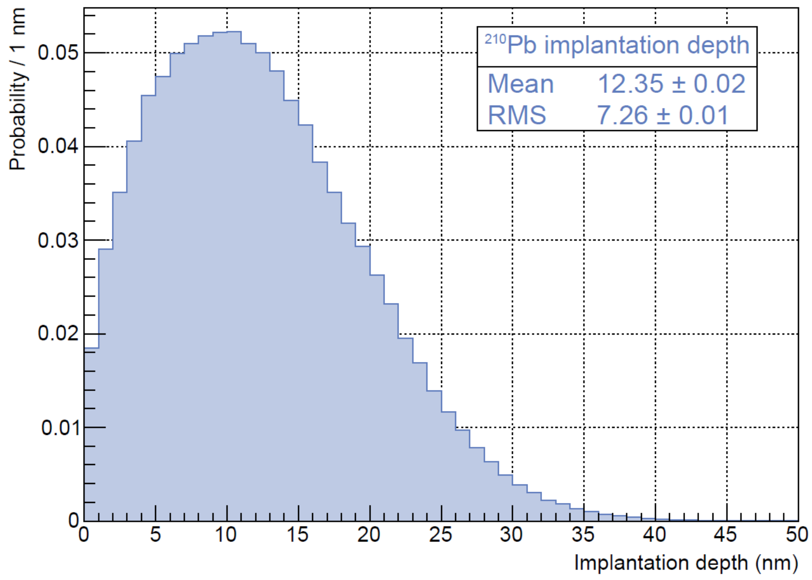




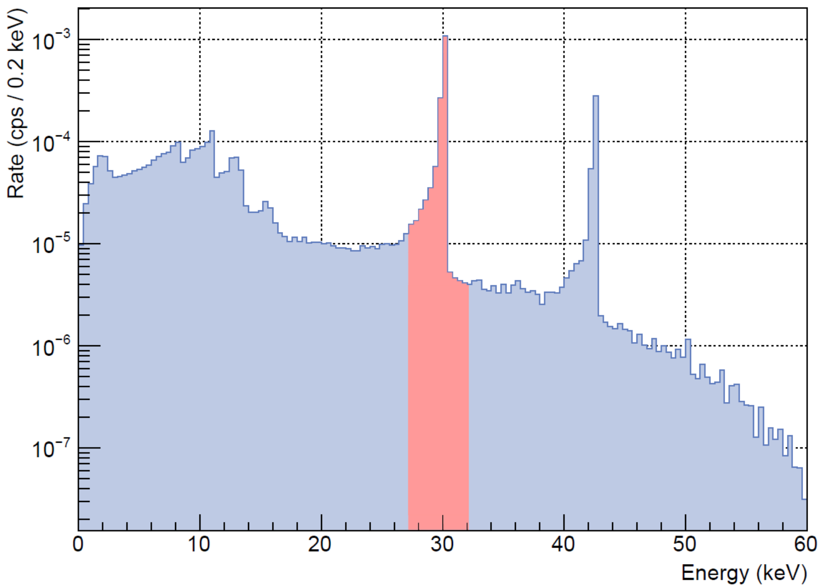
Integrated β-spectrum (cps)
$m_{\bar\nu}$ = 0 eV
$m_{\bar\nu}$ = 2 eV
Toy measurement for $m_{\bar\nu}$ = 1 eV
C
E_0
$m^2_{\bar\nu}$
R_{bg}
Relative difference
$m_{\bar\nu}$ = 0 eV
$m_{\bar\nu}$ = 1 eV
$m_{\bar\nu}$ = 2 eV
Toy measurement for $m_{\bar\nu}$ = 1 eV
Measuring time (days)
Measurement time distribution (optimized for R_{bg} = 0.01 cps)
Retarding energy $qU_i - E_0$ (eV)



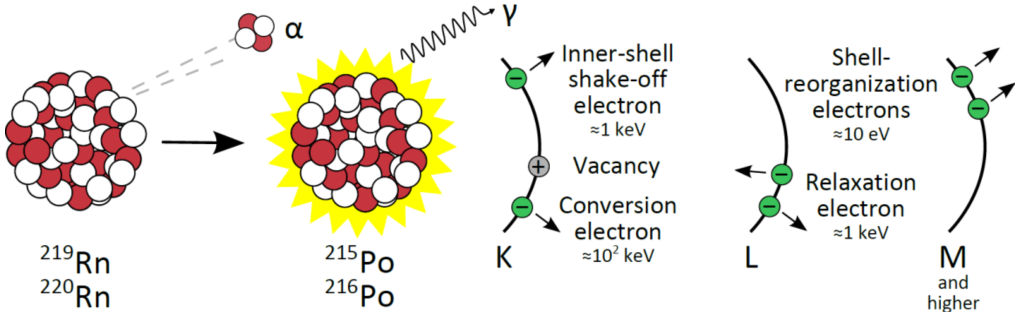
^{222}Rn-decay products
α-decay
^{214}Po
^{222}Rn
α-decay
e$^-$
Recoil
^{210}Pb
e$^-$
α-decay
^{214}Po
Recoil
e$^-$
Aerosols
Stainless steel



^{210}Pb implantation depth
Mean 12.35 ± 0.02
RMS 7.26 ± 0.01
Probability / 1 nm
0.05
0.04
0.03
0.02
0.01
0
0 5 10 15 20 25 30 35 40 45 50
Implantation depth (nm)



Rate (cps / 0.2 keV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0 10 20 30 40 50 60
Energy (keV)



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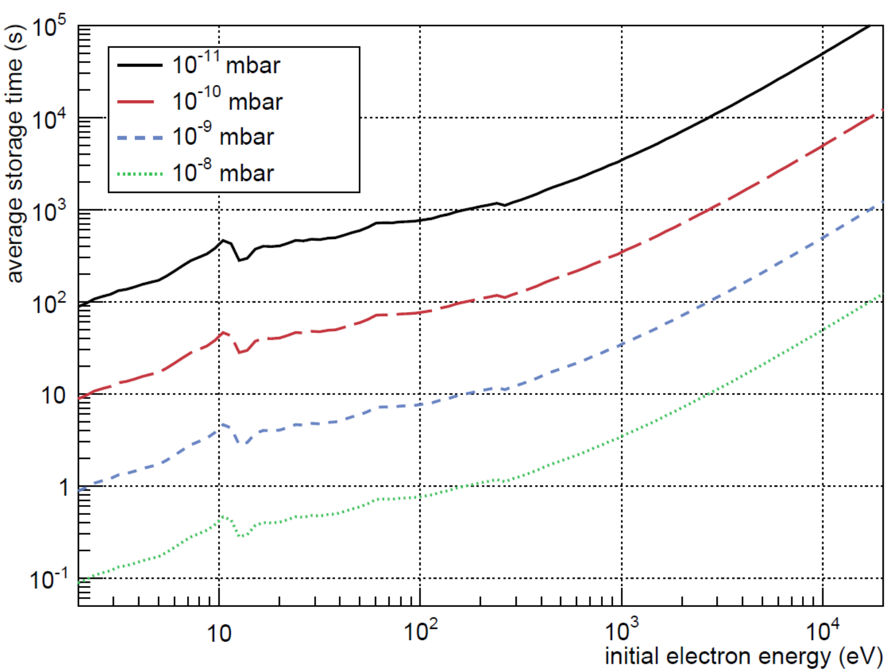
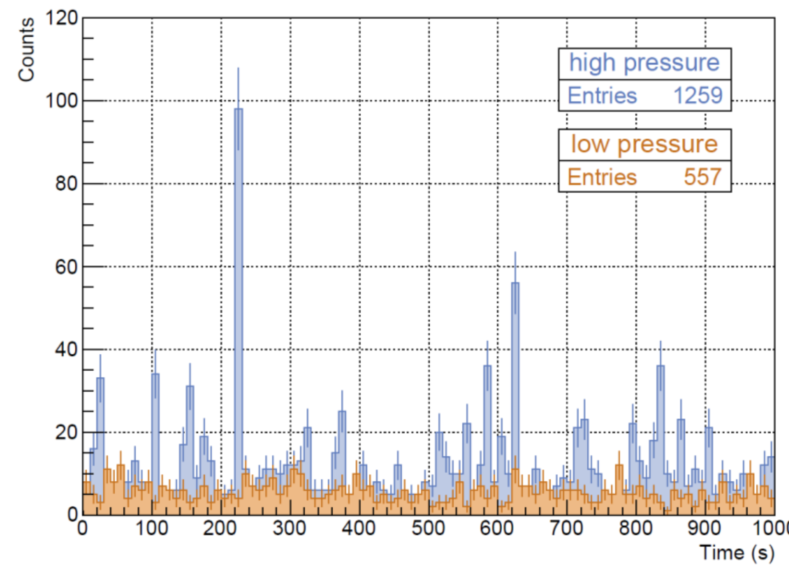
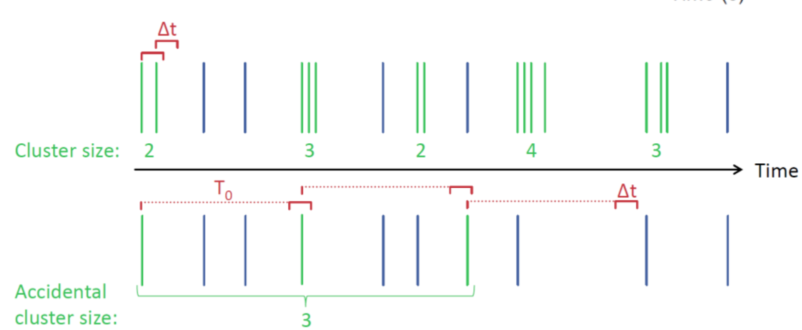
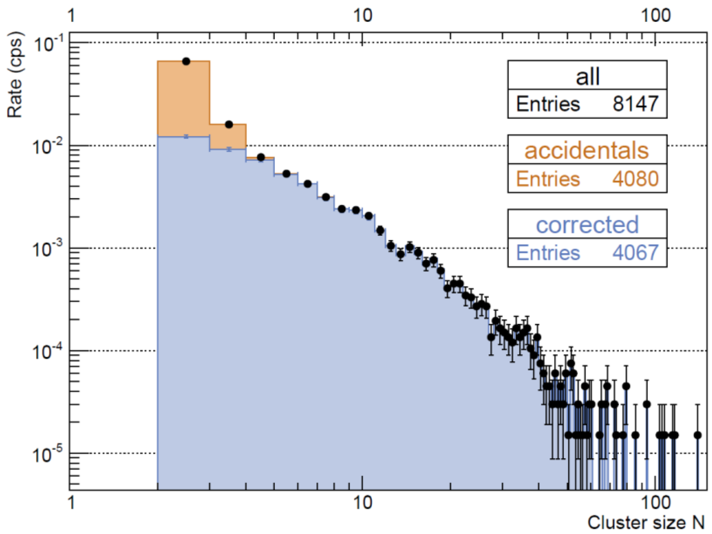
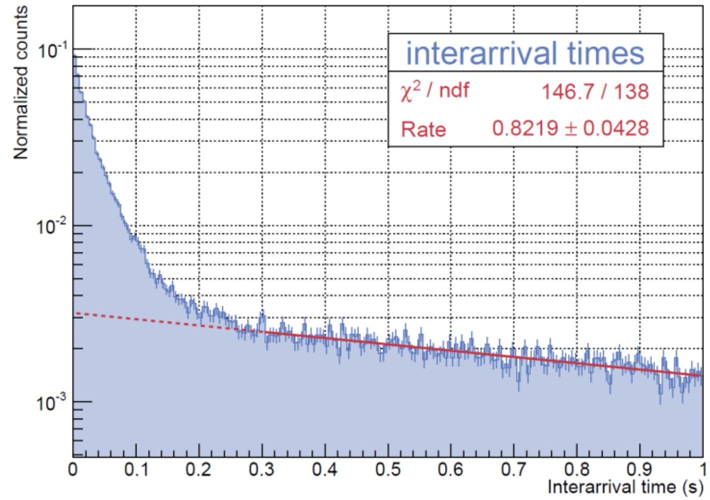




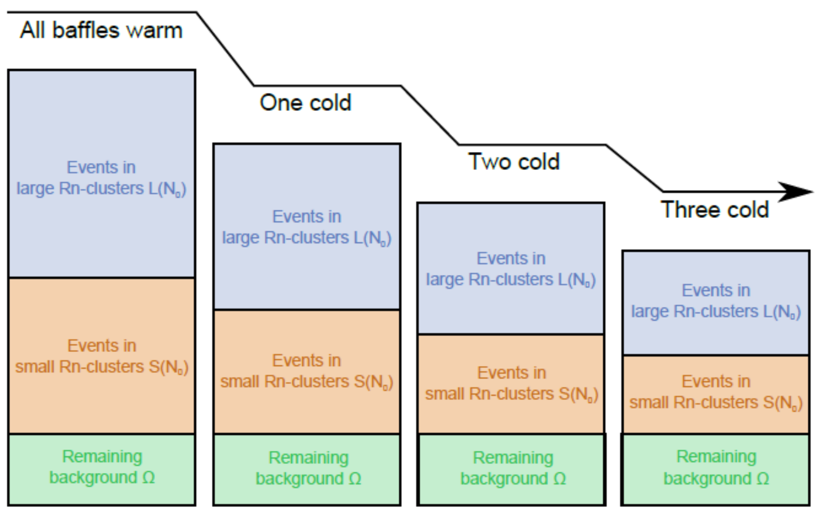




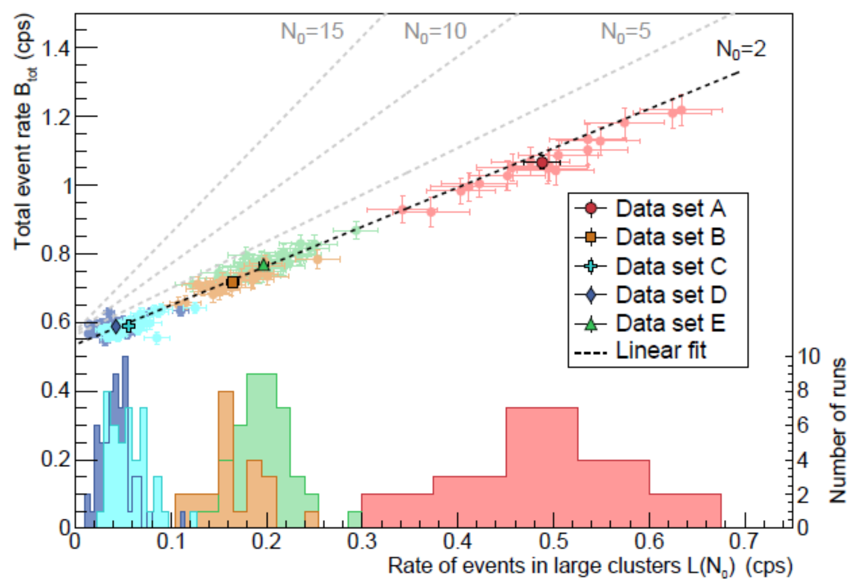
Rate (cps)
Cluster size N
all
Entries 8147
accidentals
Entries 4080
corrected
Entries 4067



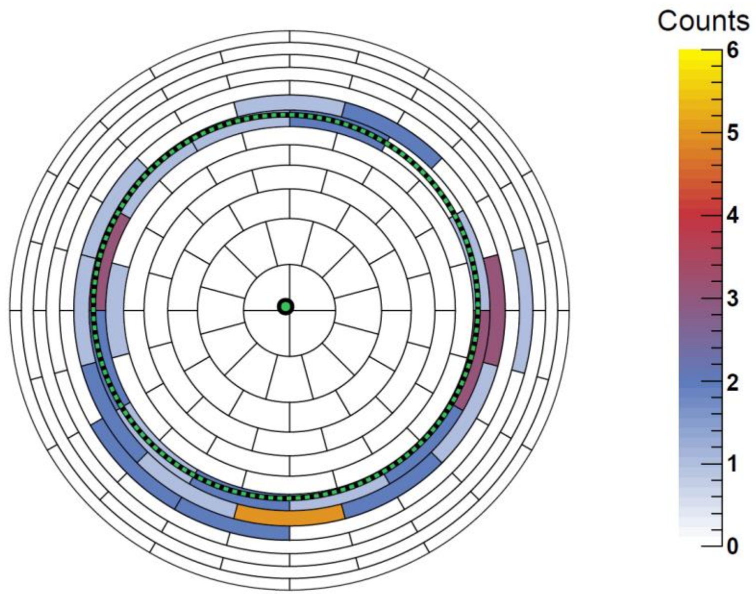
Normalized counts
Interarrival time (s)
interarrival times
χ^2 / ndf 146.7 / 138
Rate 0.8219 ± 0.0428

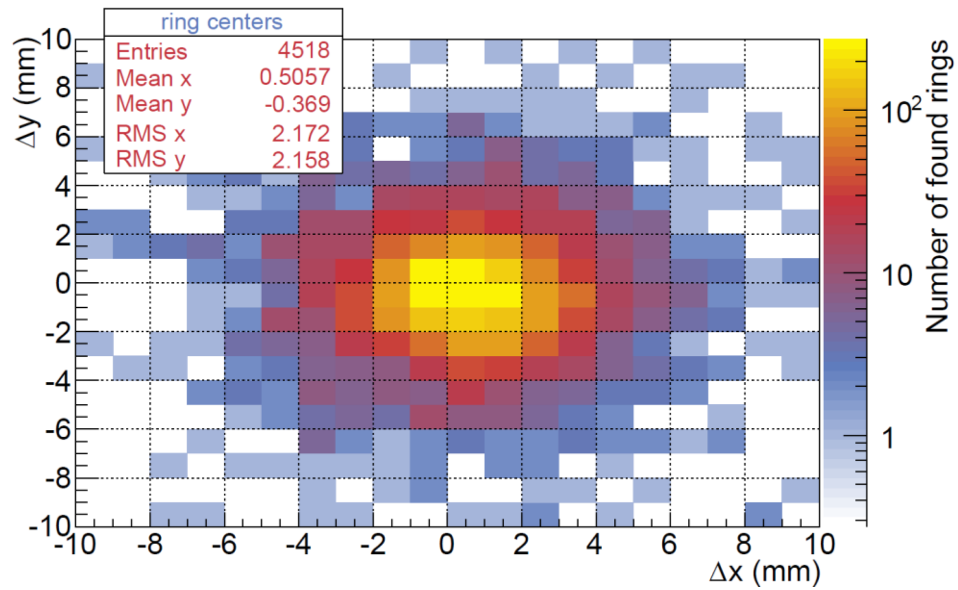


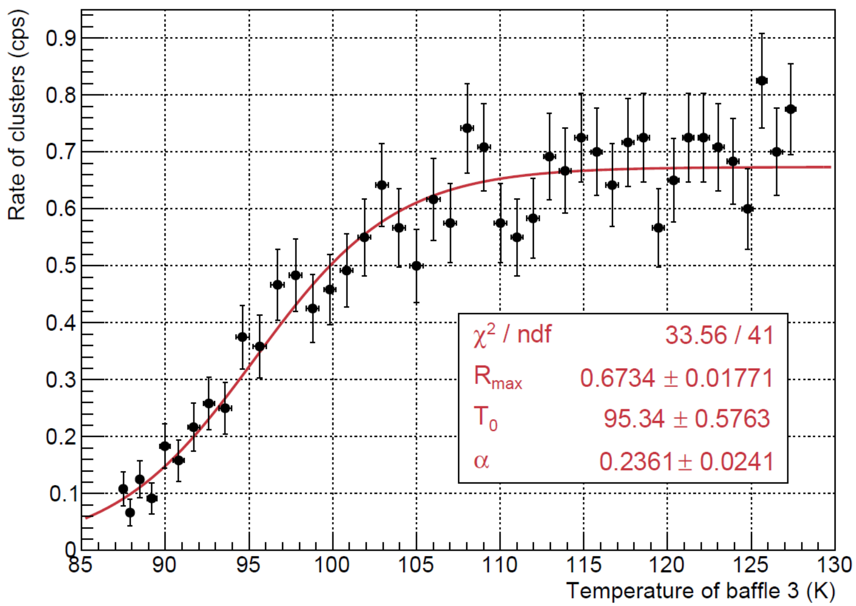
All baffles warm
One cold
Two cold
Three cold
Events in large Rn-clusters L(N_0)
Events in small Rn-clusters S(N_0)
Remaining background Ω

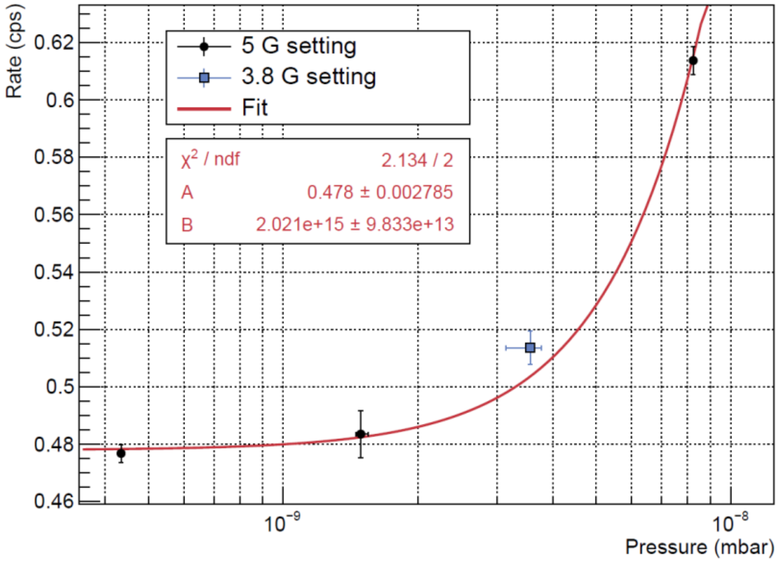


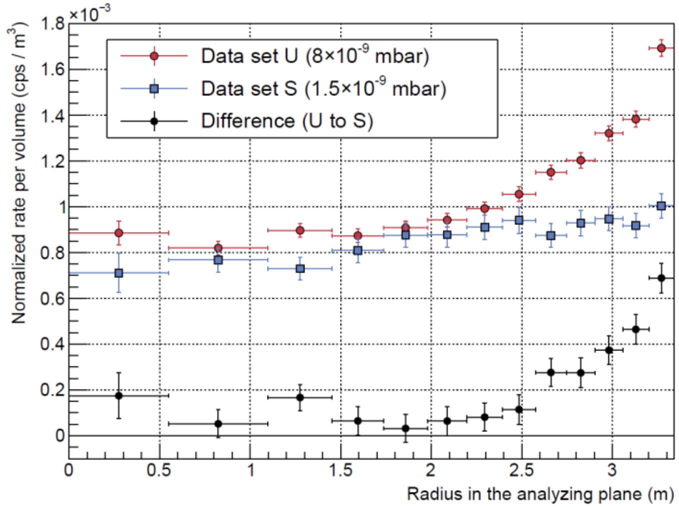
Total event rate B_{tot} (cps)
Rate of events in large clusters L(N_0) (cps)
Number of runs
N_0=15
N_0=10
N_0=5
N_0=2
Data set A
Data set B
Data set C
Data set D
Data set E
Linear fit

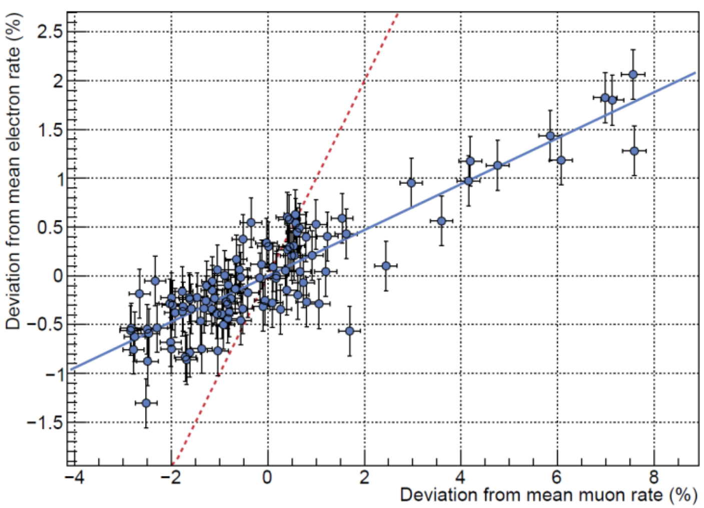

Counts
6
5
4
3
2
1
0

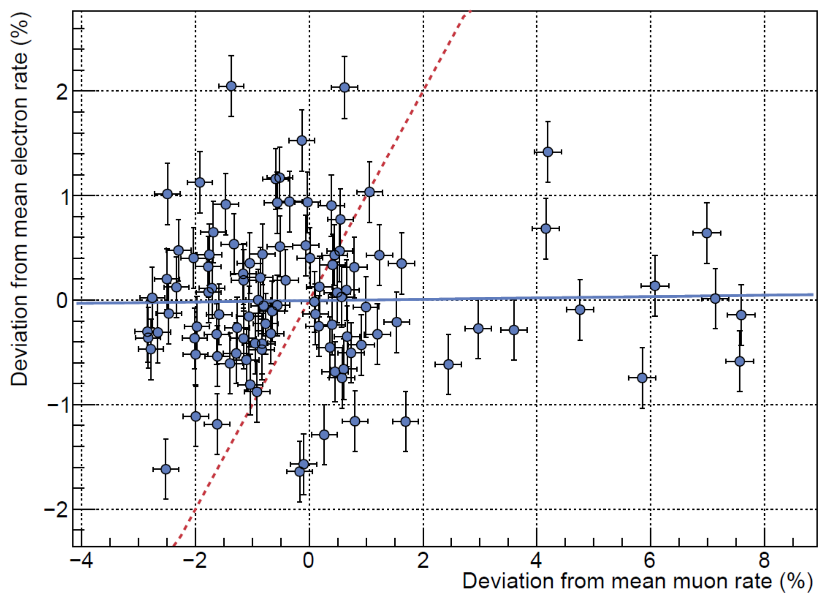

ring centers
Entries 4518
Mean x 0.5057
Mean y -0.369
RMS x 2.172
RMS y 2.158
Δy (mm)
Δx (mm)
Number of found rings

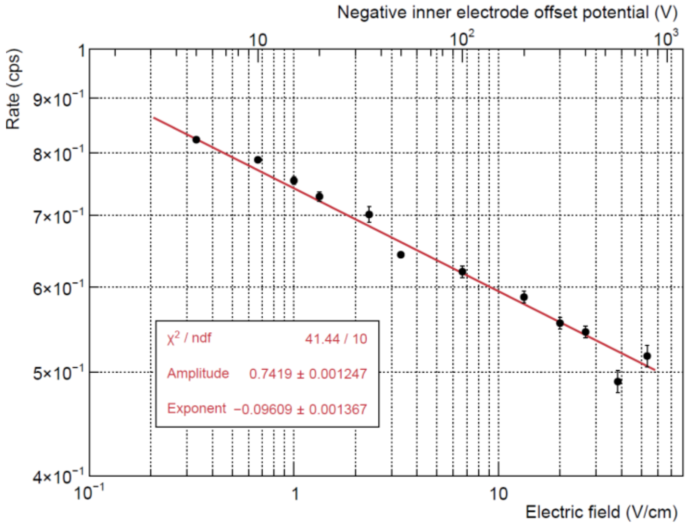

Rate of clusters (cps)
Temperature of baffle 3 (K)
χ² / ndf 33.56 / 41
R_max 0.6734 ± 0.01771
T_0 95.34 ± 0.5763
α 0.2361 ± 0.0241

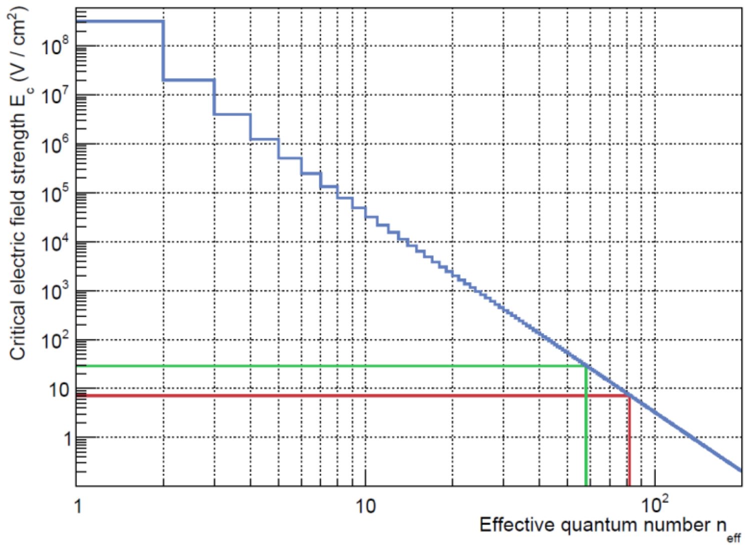

Rate (cps)
5 G setting
3.8 G setting
Fit
χ^2 / ndf 2.134 / 2
A 0.478 ± 0.002785
B 2.021e+15 ± 9.833e+13
10^{-9}
10^{-8}
Pressure (mbar)


$\times 10^{-3}$
Normalized rate per volume (cps / m^3)
Data set U (8×10^{-9} mbar)
Data set S (1.5×10^{-9} mbar)
Difference (U to S)
Radius in the analyzing plane (m)


Deviation from mean electron rate (%)
Deviation from mean muon rate (%)


Deviation from mean electron rate (%)
Deviation from mean muon rate (%)





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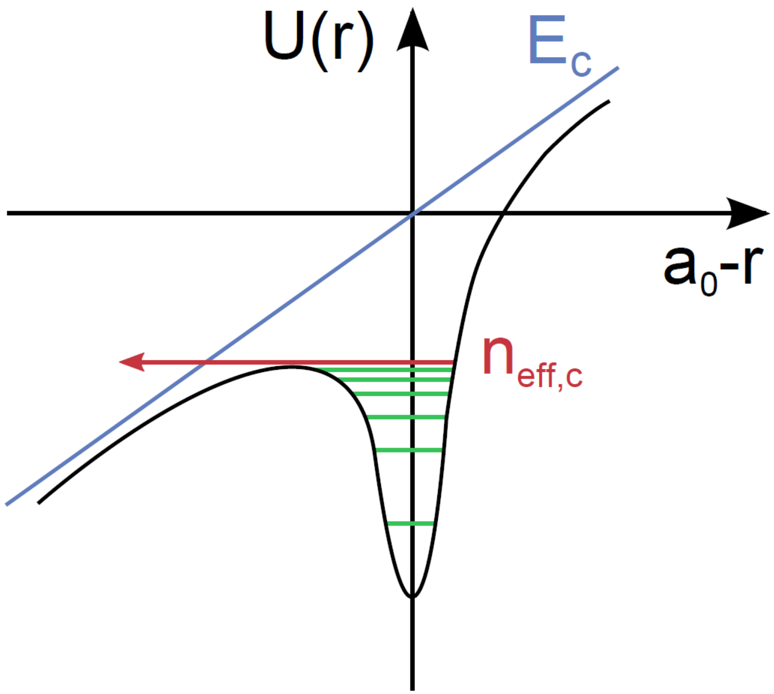
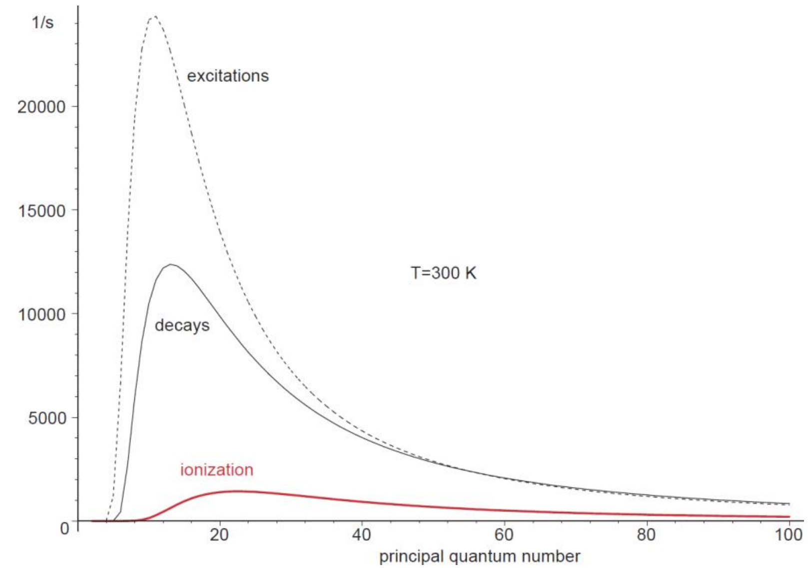
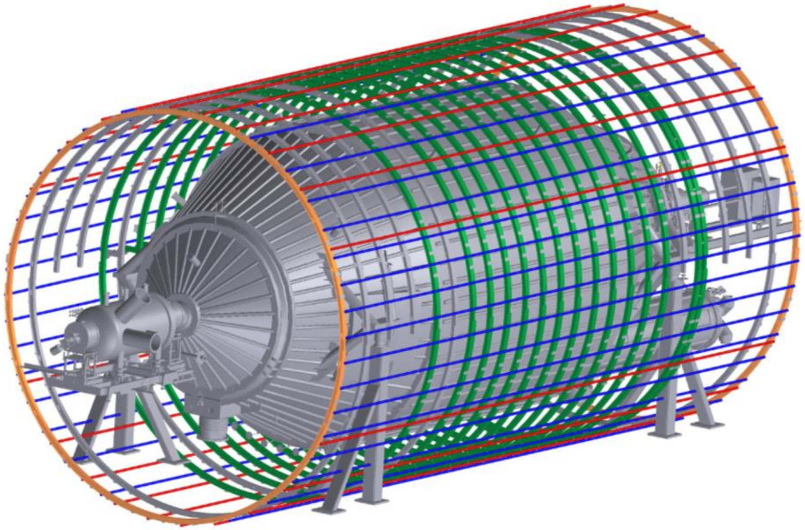
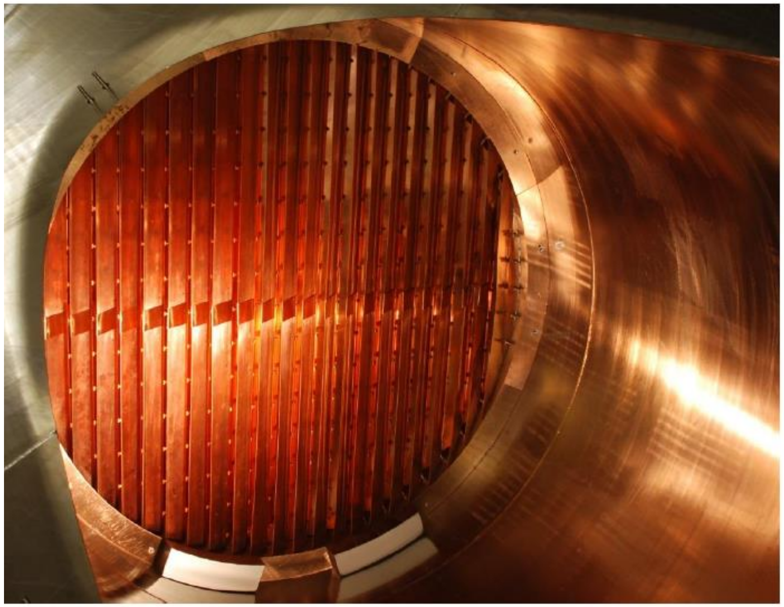
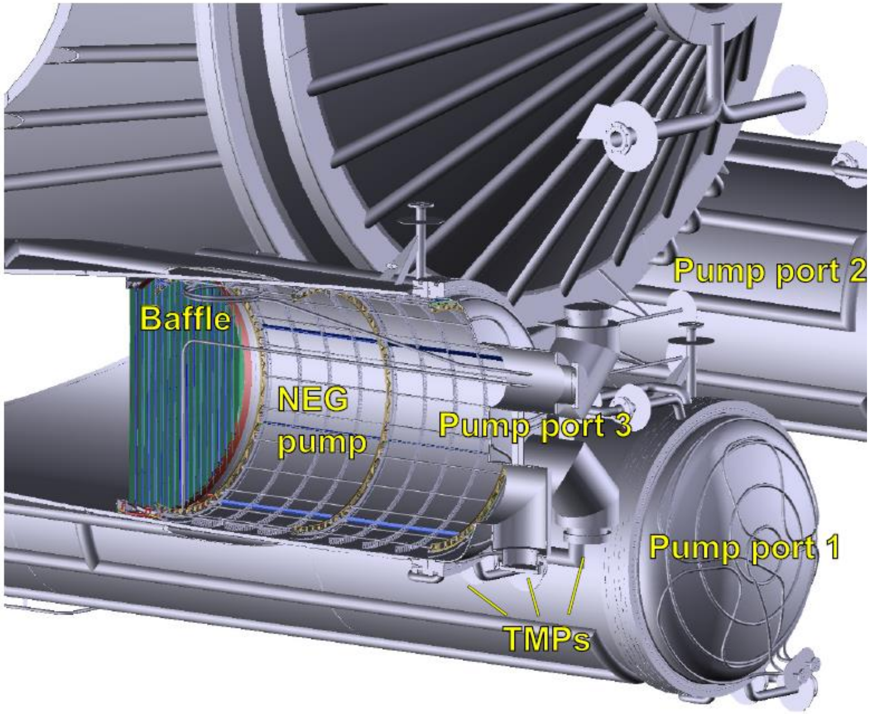
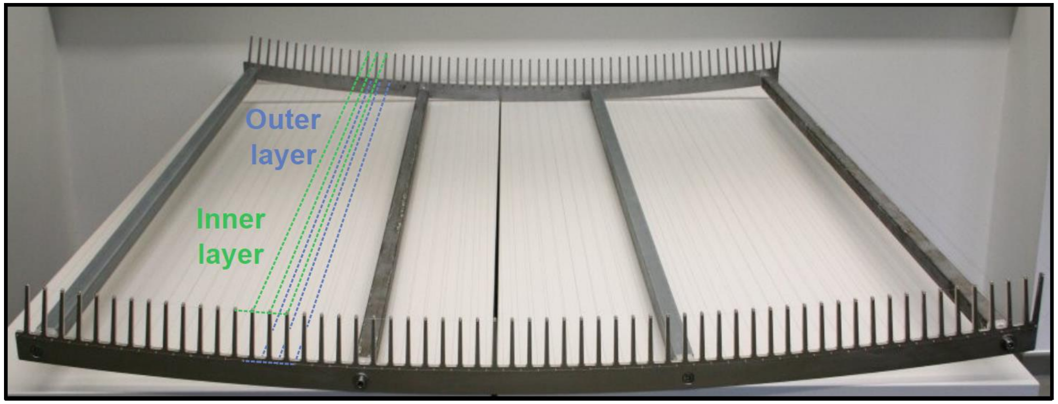


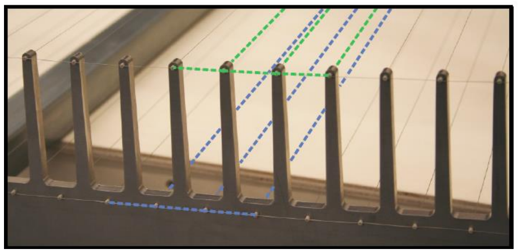


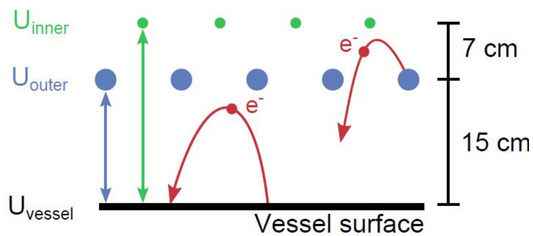


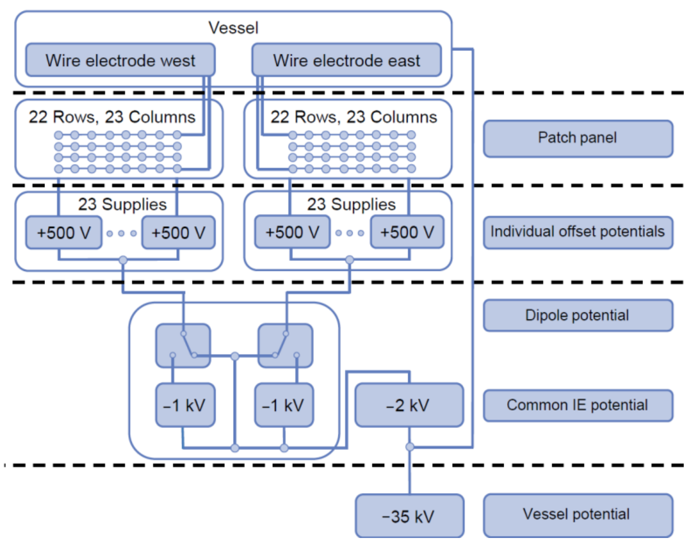


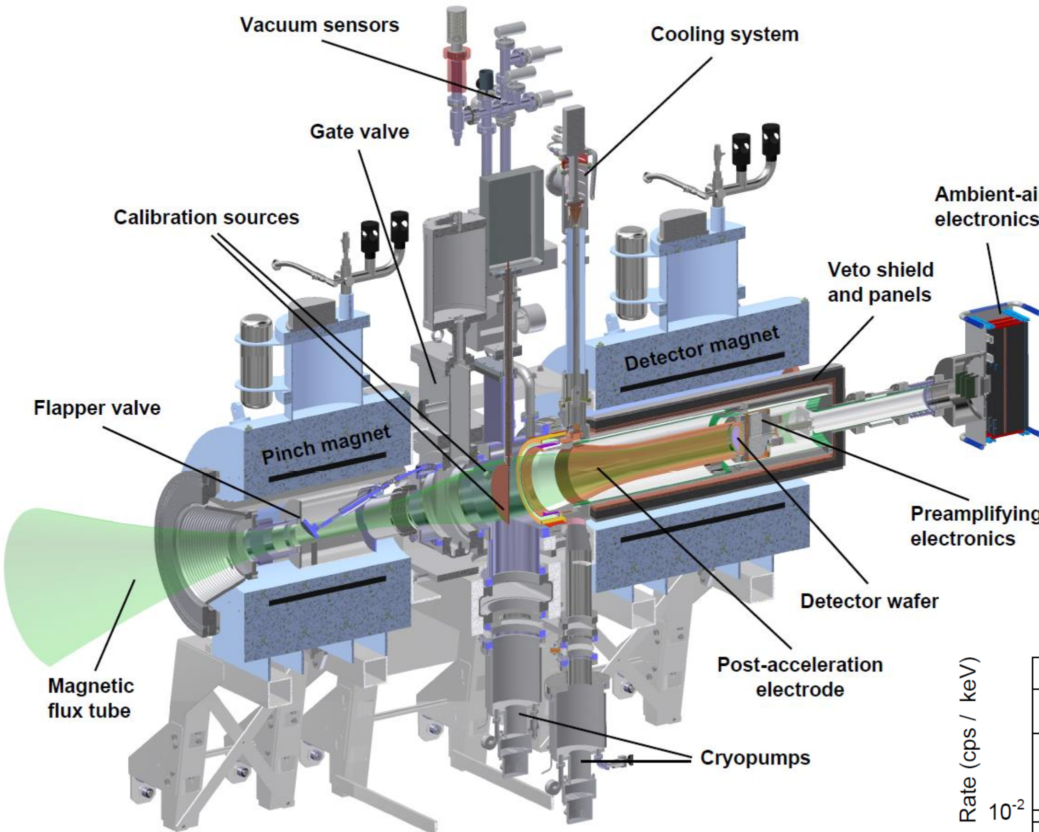

Pump port 2
Baffle
NEG
pump
Pump port 3
Pump port 1
TMPs

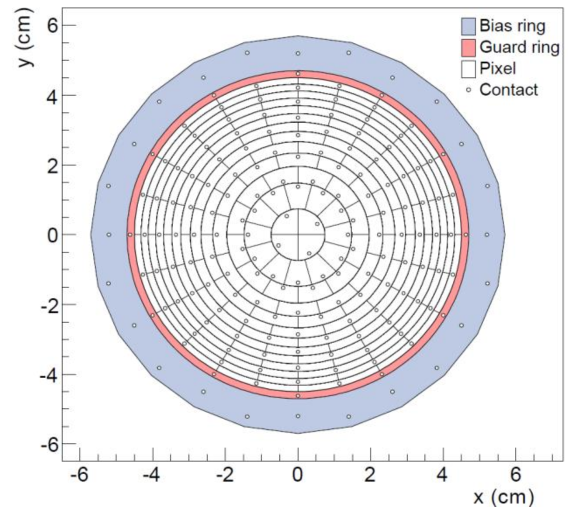

Outer layer
Inner layer

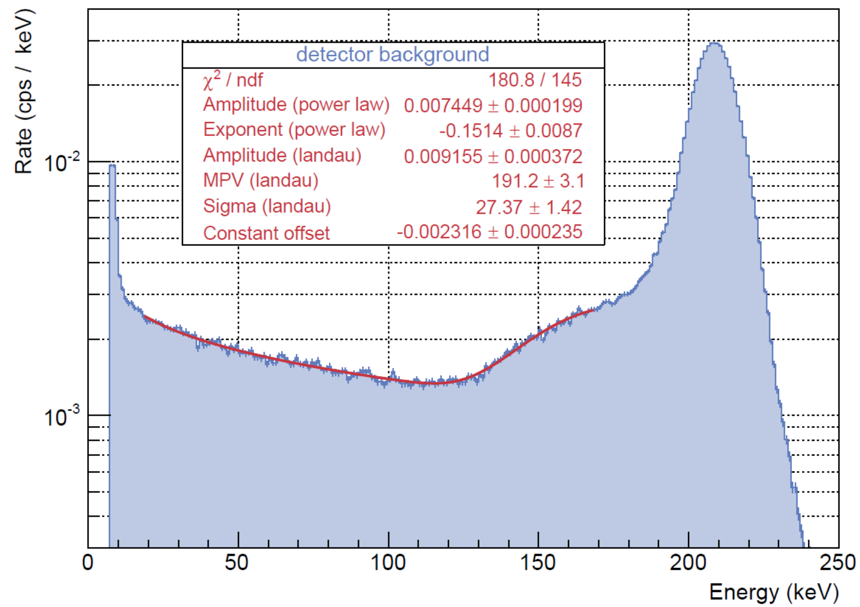


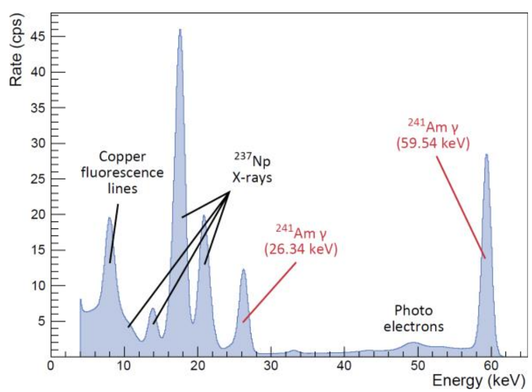

U_{inner}
U_{outer}
U_{vessel}
e^-
e^-
7 cm
15 cm
Vessel surface

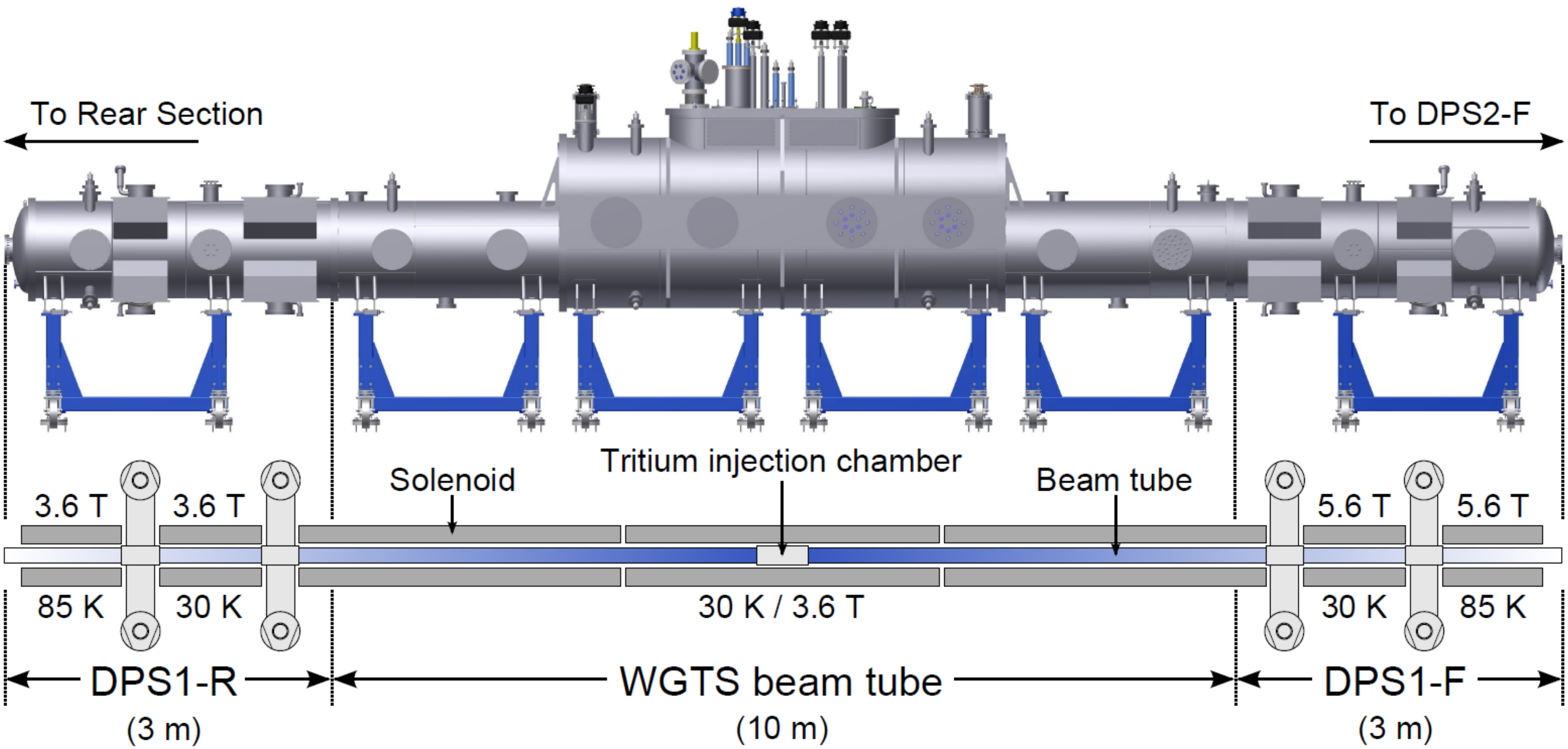

Vessel
Wire electrode west
Wire electrode east
22 Rows, 23 Columns
22 Rows, 23 Columns
Patch panel
23 Supplies
23 Supplies
+500 V
+500 V
+500 V
+500 V
Individual offset potentials
Dipole potential
−1 kV
−1 kV
−2 kV
Common IE potential
−35 kV
Vessel potential

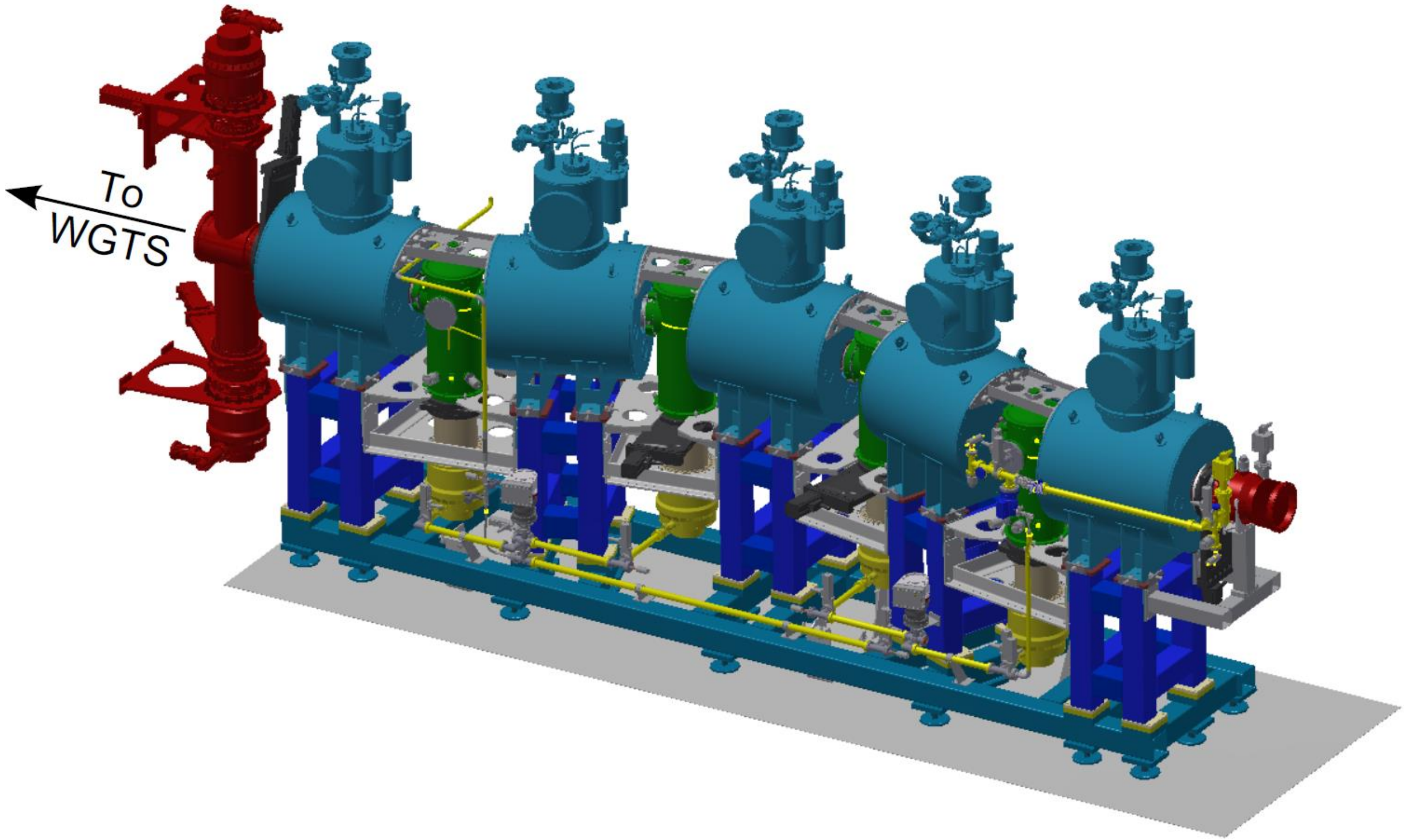

Vacuum sensors
Cooling system
Gate valve
Calibration sources
Ambient-air electronics
Veto shield and panels
Detector magnet
Flapper valve
Pinch magnet
Preamplifying electronics
Detector wafer
Post-acceleration electrode
Magnetic flux tube
Cryopumps

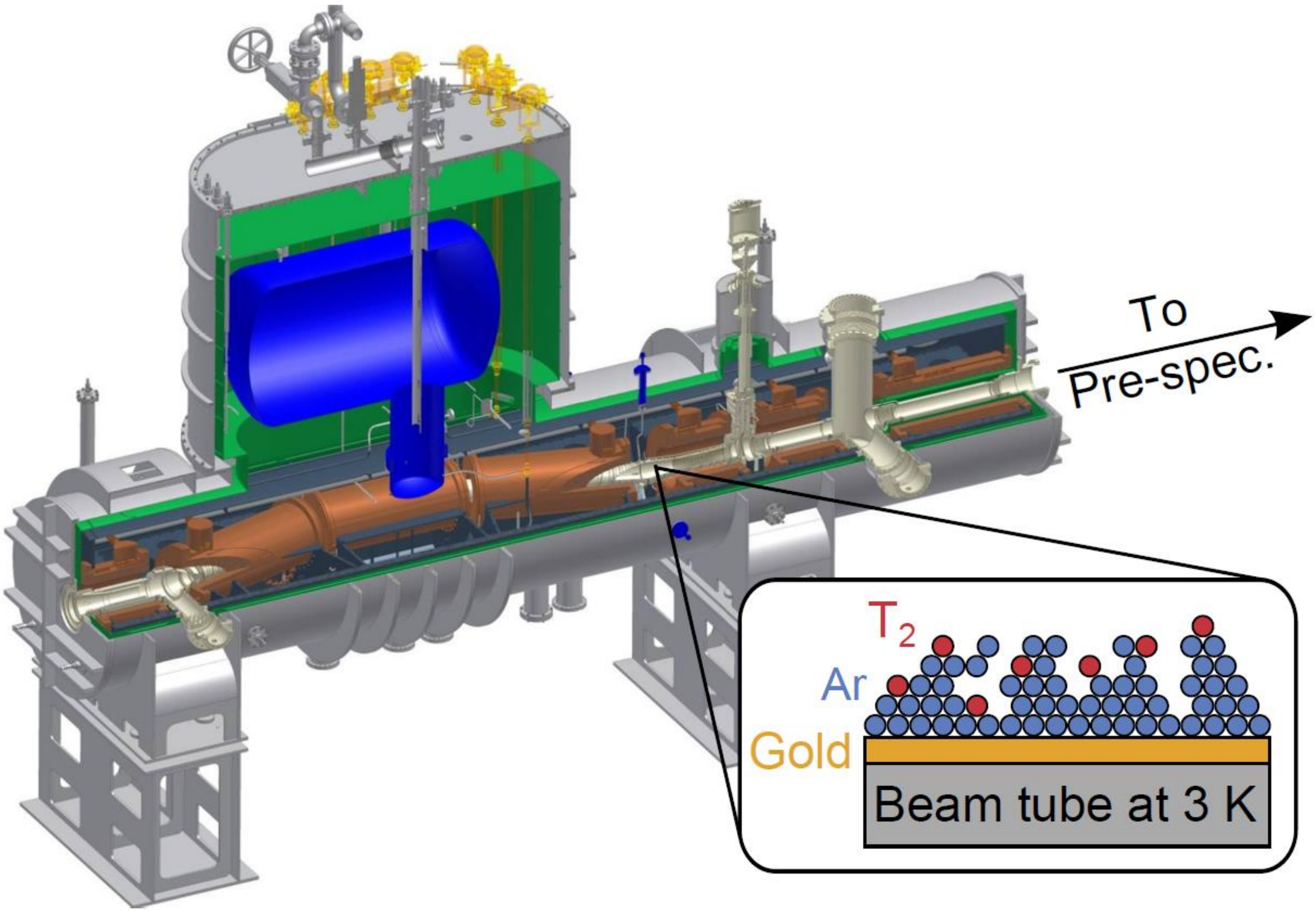

Bias ring
Guard ring
Pixel
Contact
y (cm)
x (cm)

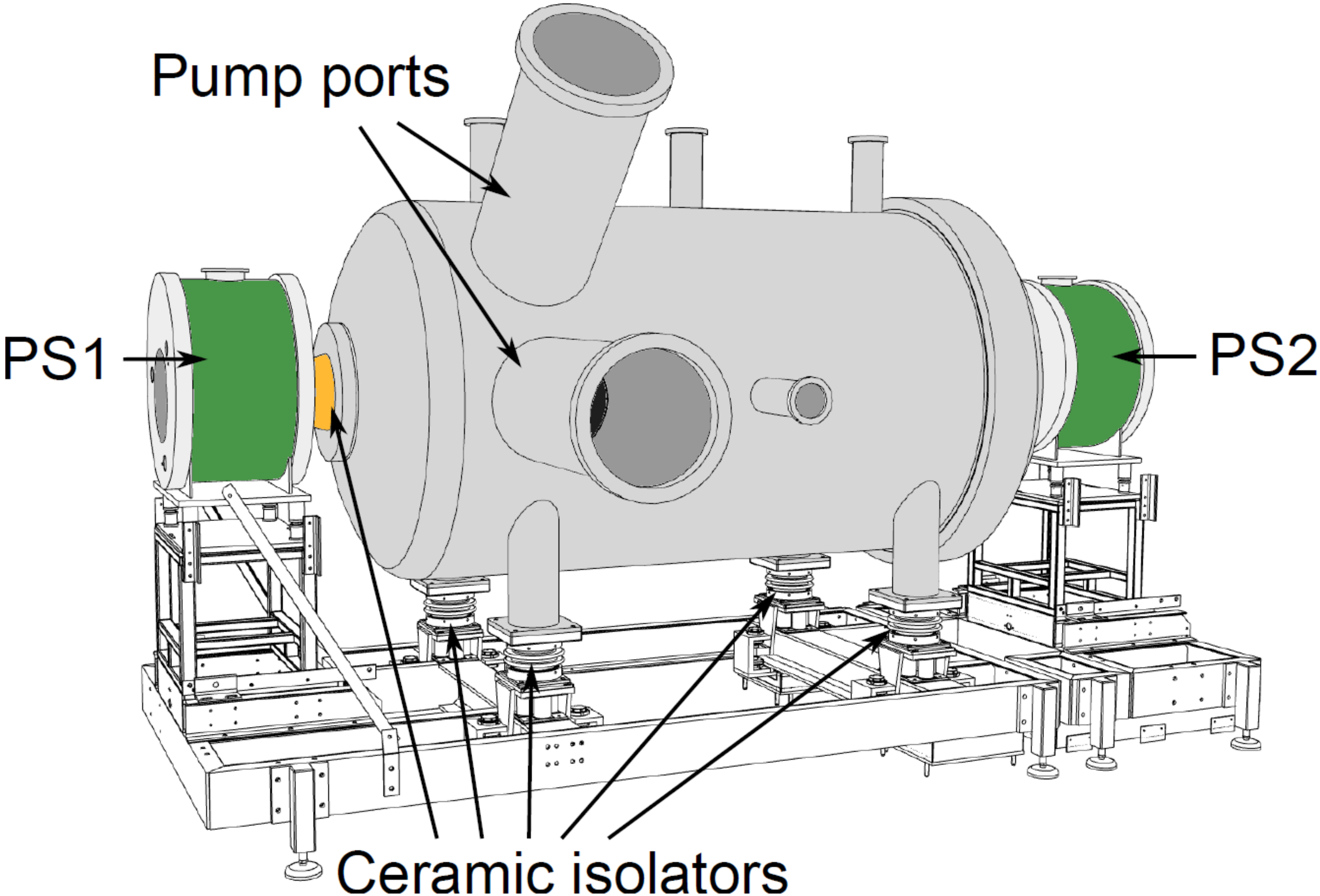

detector background
χ^2 / ndf 180.8 / 145
Amplitude (power law) 0.007449 ± 0.000199
Exponent (power law) -0.1514 ± 0.0087
Amplitude (landau) 0.009155 ± 0.000372
MPV (landau) 191.2 ± 3.1
Sigma (landau) 27.37 ± 1.42
Constant offset -0.002316 ± 0.000235
Rate (cps / keV)
Energy (keV)


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
Solenoid
Tritium injection chamber
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