# Investigations of the KATRIN interspectrometer Penning trap

M. Fedkevych for the KATRIN collaboration,
Westfälische Wilhelms-Universität, Institut für Kernphysik, Münster

## The KATRIN experiment

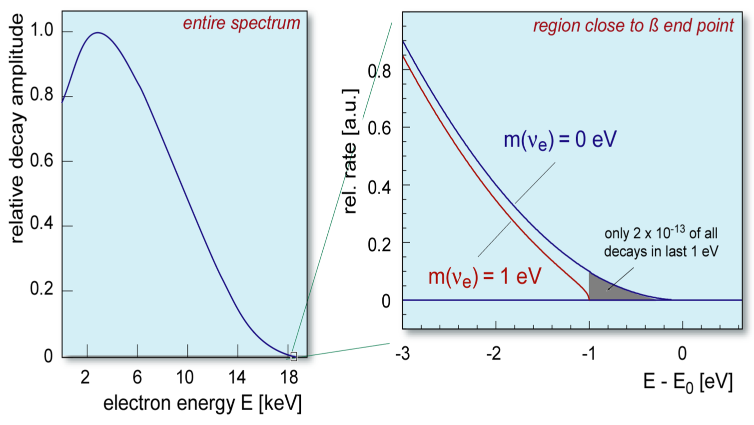
### Kinematic determination of m($\nu_e$)

$$\frac{d\Gamma}{dE} = C\, p\,(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_{\nu_e}^2}\,F(Z+1,E)\,\Theta(E_0-E-m_\nu)\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C |M|^2$$

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

(modified by final states, recoil corrections, radiative corrections, ...)




**Requirements**

- low endpoint energy
- high source luminosity
- high energy resolution
- very low background
- stability of the experimental parameters on the per mil to ppm level

→ MAC-E filter concept

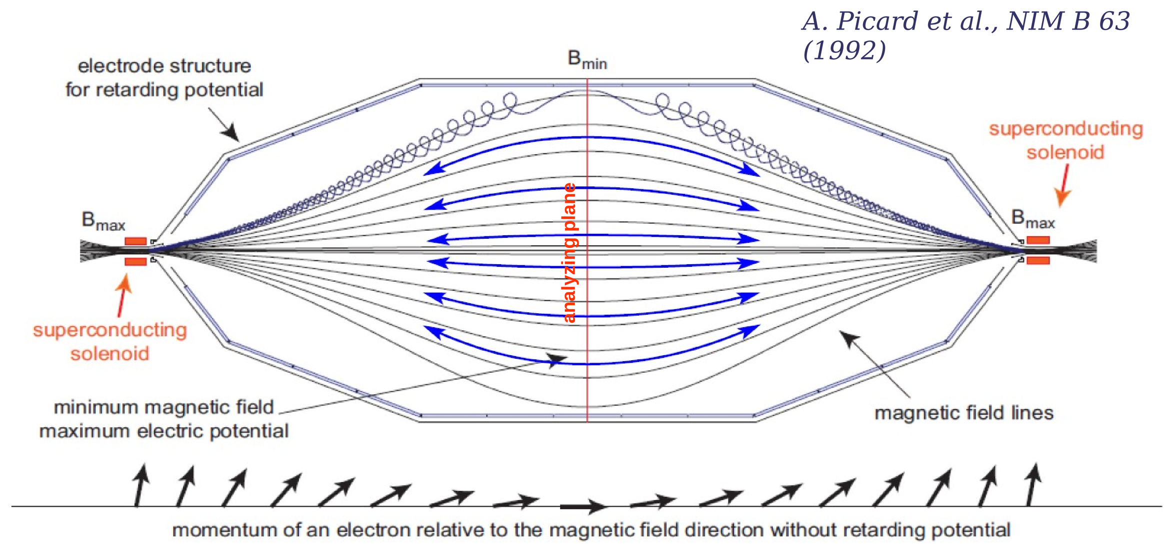
**Tritium β-decay**

$E_0$ = 18.6 keV, $T_{1/2}$ = 12.3 a
S(E) = 1 (super-allowed)

### MAC-E filter concept

**M**agnetic **A**diabatic **C**ollimation with **E**lectrostatic Filter

*A. Picard et al., NIM B 63 (1992)*



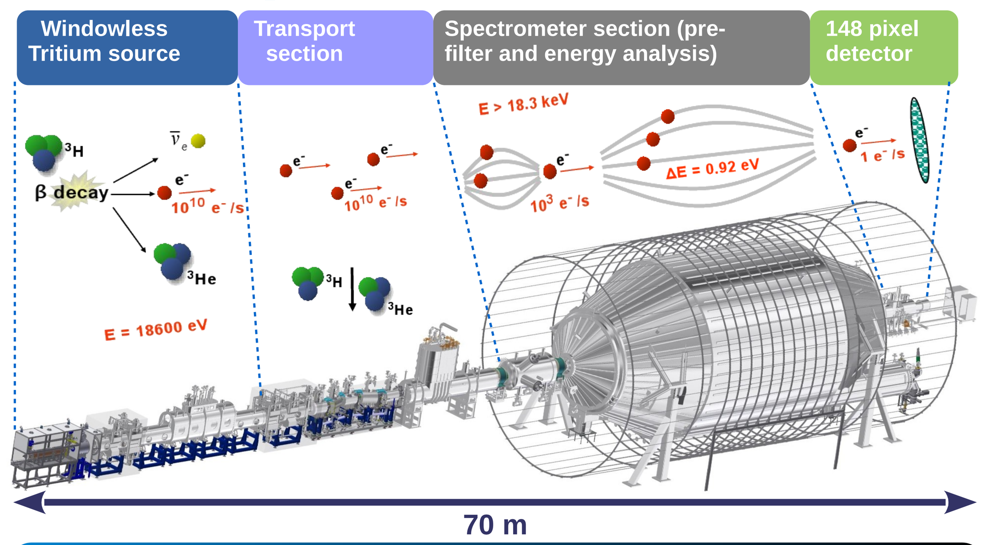

Adiabatic transport → $\mu = E_\perp / B$ = const (conserved)

B drops by $2\cdot10^4$ from solenoid to analyzing plane → $E_\perp \to E_\parallel$

Only electrons with $E_\parallel > eU_0$ can pass the retarding potential

Energy resolution $\Delta E = E_{\perp,max,start} \cdot B_{min} / B_{max} \approx 1$ eV

### KATRIN experiment at KIT



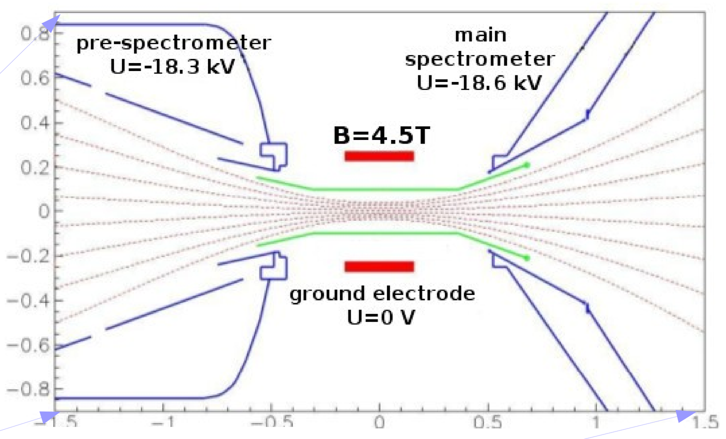

| | |
|---|---|
| KATRIN design sensitivity: | statistical uncertainty for $m^2(\nu_e)$: $\sigma_{stat} \approx 0.018$ eV² <br> planned systematic uncertainty for $m^2(\nu_e)$: $\sigma_{sys,tot} \approx 0.017$ eV² |
| 5 year measurement (eff. 3 y of data) | → sensitivity for $m(\nu_e)$ upper limit: 0.2 eV (90% C.L.) <br> → observable with 5σ: $m(\nu_e)$ = 0.35 eV |

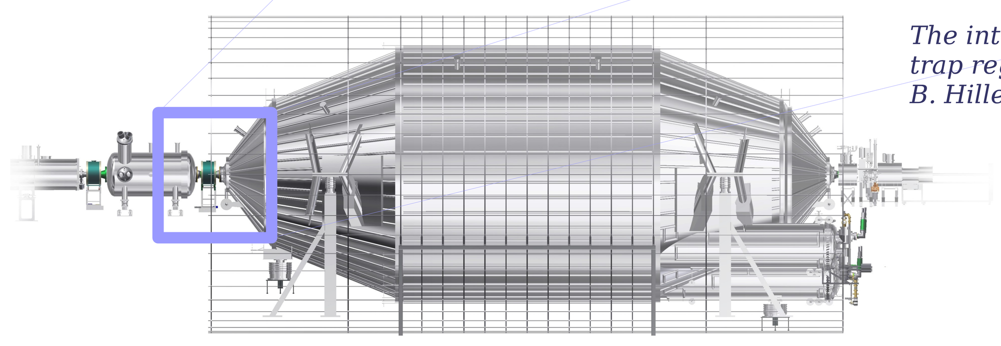
## Interspectrometer Penning trap

**The configuration between the two KATRIN spectrometers constitutes a Penning trap where background electrons can accumulate.**

**The trap is formed by:**

- **Magnetic field of the solenoid between the spectrometers;**
- **Retarding potentials of both spectrometers.**



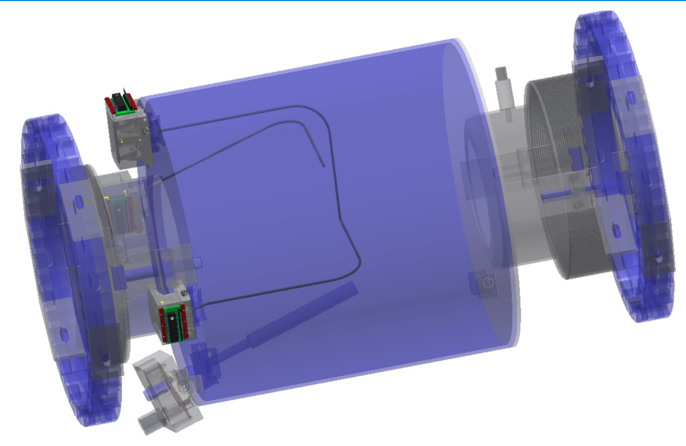



*The interspectrometer Penning trap region (from PhD thesis of B. Hillen).*

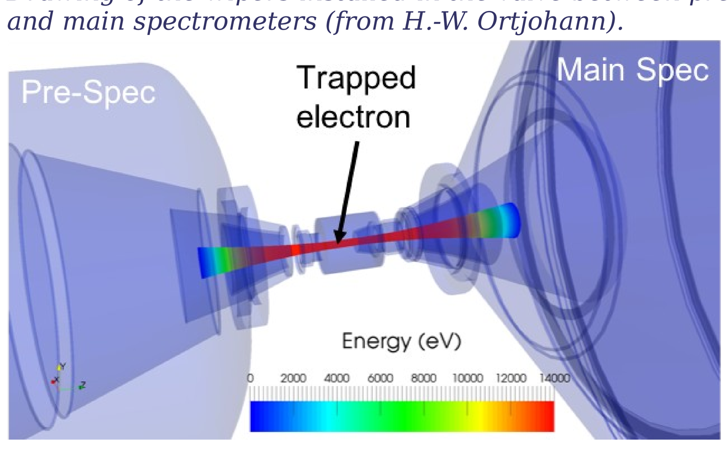
**The trap is fed dominantly by background electrons from both spectrometers**

- **Creation of additional background by residual gas ionization;**
- **Danger of Penning discharges: possibility of damaging the KATRIN detector and nearby isolators.**

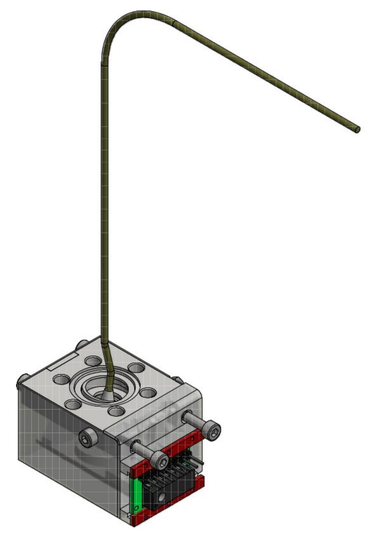
## Solution: Penning wipers



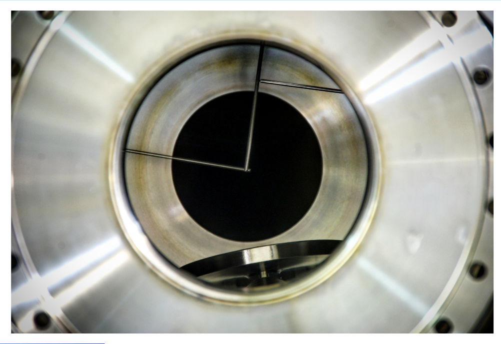
*Drawing of the wipers installed in the valve between pre- and main spectrometers (from H.-W. Ortjohann).*



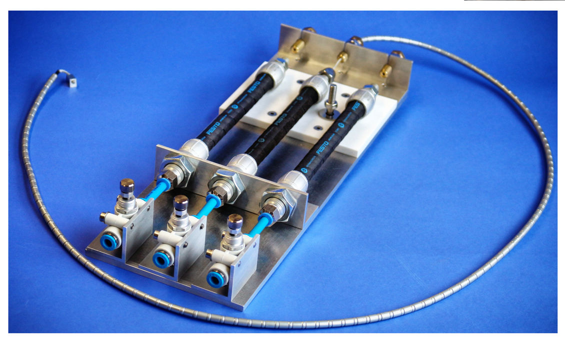

*Simulation of an electron trapped inside the interspectrometer Penning trap (from L. Kippenbrock).*



*Drawing of the wiper system (from H.-W. Ortjohann).*



*View of installed wipers (two moved inside the flux tube, one staying outside).*



*Pneumatic muscles for wiper movement.*

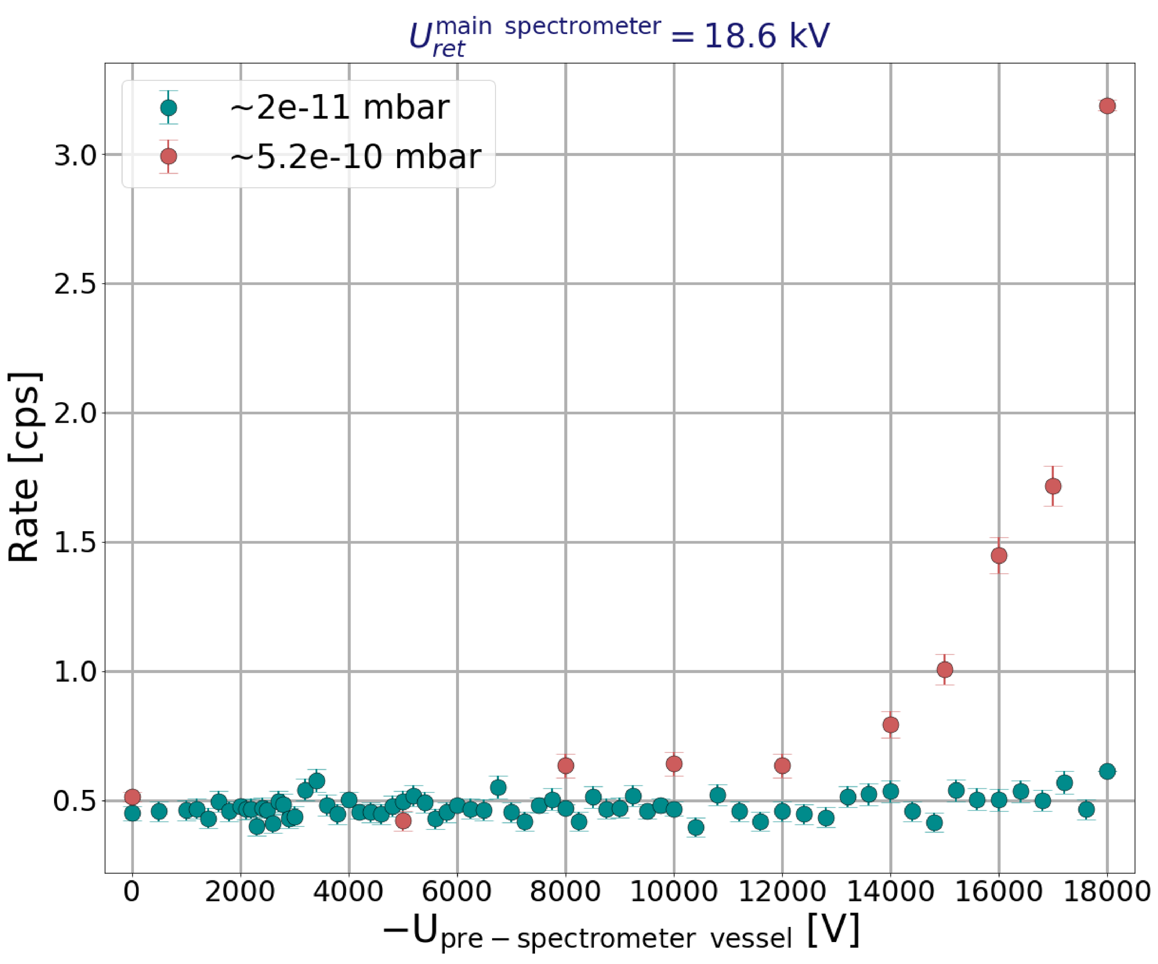
**Metal rod (titanium Grade 5) to empty the Penning trap:**

- **Collects electrons when moved into the flux tube, since stored electrons will hit the wiper within sub-ms time scale due to their magnetron motion;**
- **Mechanical movement by a pneumatic muscle;**
- **Can be operated in different modes with different frequencies via ORCA (object-oriented real-time control and acquisition) software;**
- **3 Penning wipers for the KATRIN measurement time;**
- **Photo-diode sensor gives signal when the wiper is inside the flux tube.**

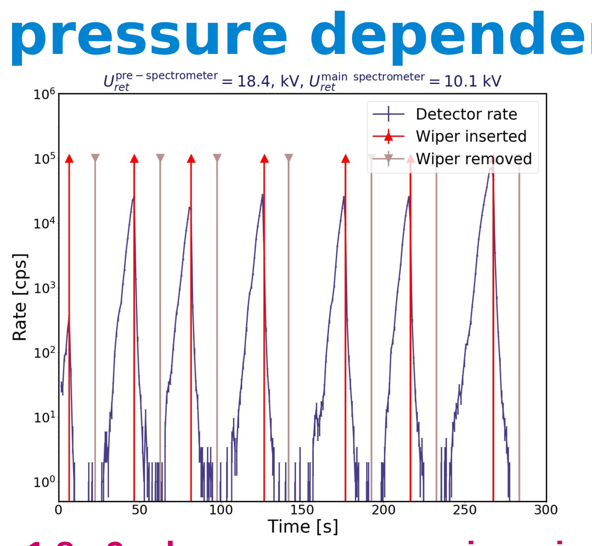
## Measurements

### Background dependence on pre-spectrometer voltage

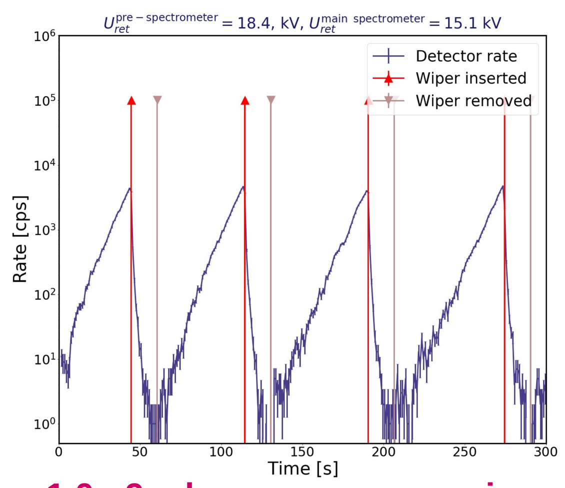
- **Effect of the Penning trap on background rate becomes pronounced at high pressures.**
- **As expected from effect of the Penning trap, background rate increases with voltage applied to the pre-spectrometer (with main spectrometer set up to nominal 18.6 kV retarding potential).**



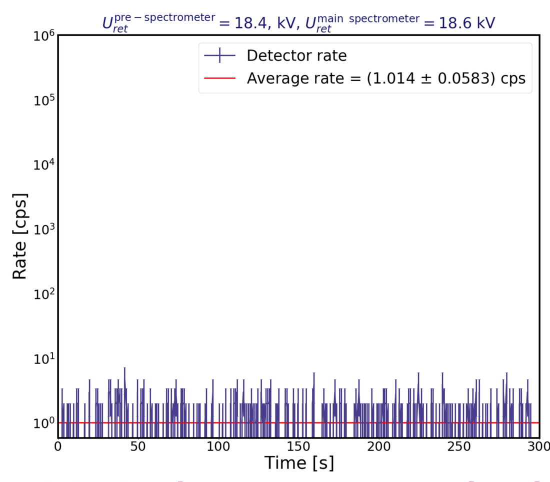

### Effectiveness of Penning wiper in discharge counteraction and pressure dependence



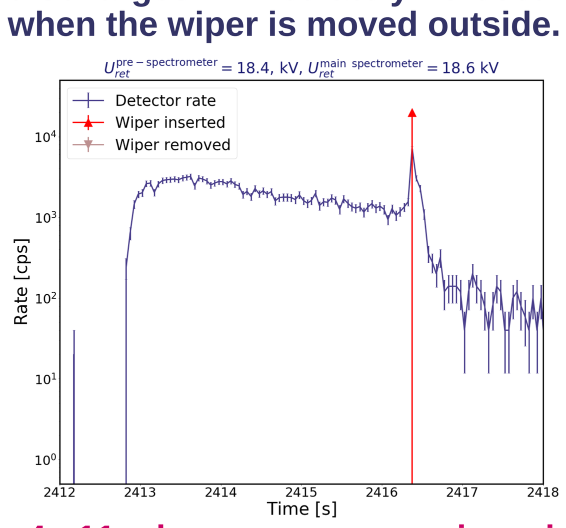

**~1.8e-9 mbar pressure, moving wiper:**
**discharges immediately re-occurring when the wiper is moved outside.**



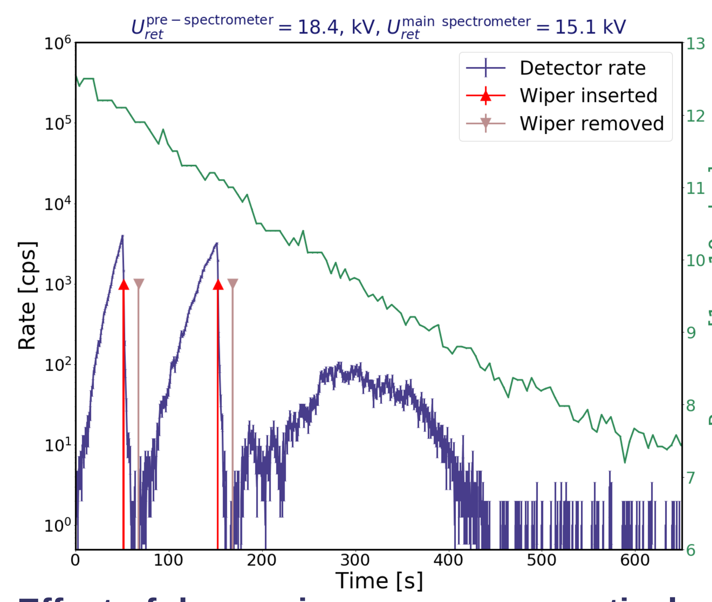

**~1.0e-9 mbar pressure, moving wiper:**
**discharges are slower, but similar behavior.**




**~1.0e-9 mbar pressure, static wiper:**
**system free of discharges.**

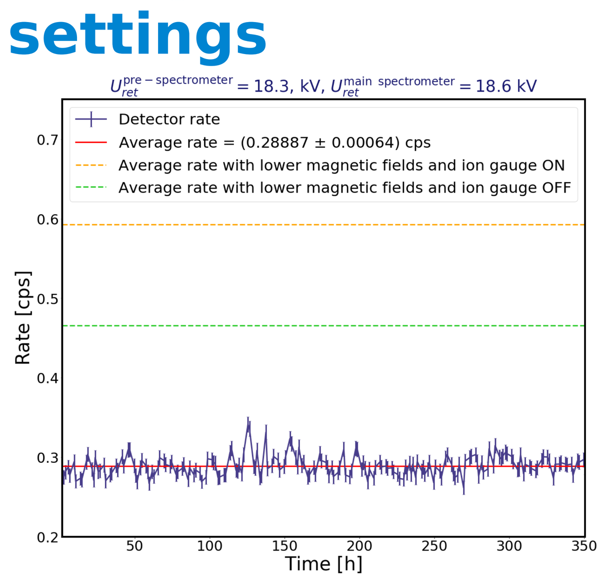



**~4e-11 mbar pressure, moving wiper:**
**a single Penning discharge occurred during few-days background measurement was effectively counteracted by the wiper, which was automatically triggered by ORCA safety script at 10 kcps.**




**Effect of decreasing pressure on actively discharging Penning trap.**

### Background measurement at nominal KATRIN settings




- **During a concluding two-week measurement with nominal spectrometer settings and pressure (~4e-11 mbar) no discharges were observed.**
- **Lower background because extractor ion gauge was switched off and due to higher magnetic field and therefore smaller flux tube.**

### Summary/Outlook

- **Pressure was shown to be a crucial parameter affecting Penning trap background activity and strength and probability of discharges.**
- **The extractor ion gauge at the pre-spectrometer was identified as an extra source of background which very likely feeds the Penning trap additionally. The gauge was deactivated for the final Penning trap tests.**
- **The Penning wipers effectively clean out trapped particles and stop discharges and were shown to be a good safety backup. With longer intervals the wipers can be used precautionary to ensure free-of-discharges measurements with tritium.**
- **We have shown the possibility to use both spectrometers in tandem at nominal voltages and pressure for the final KATRIN measurements.**

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