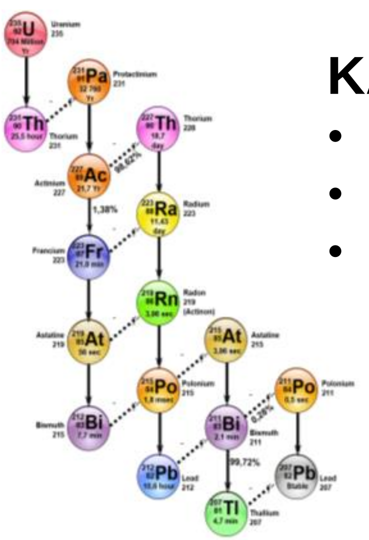
Simulation and measurement of the suppression of Rn-induced background in the KATRIN Experiment

Joachim Wolf (KATRIN Collaboration)

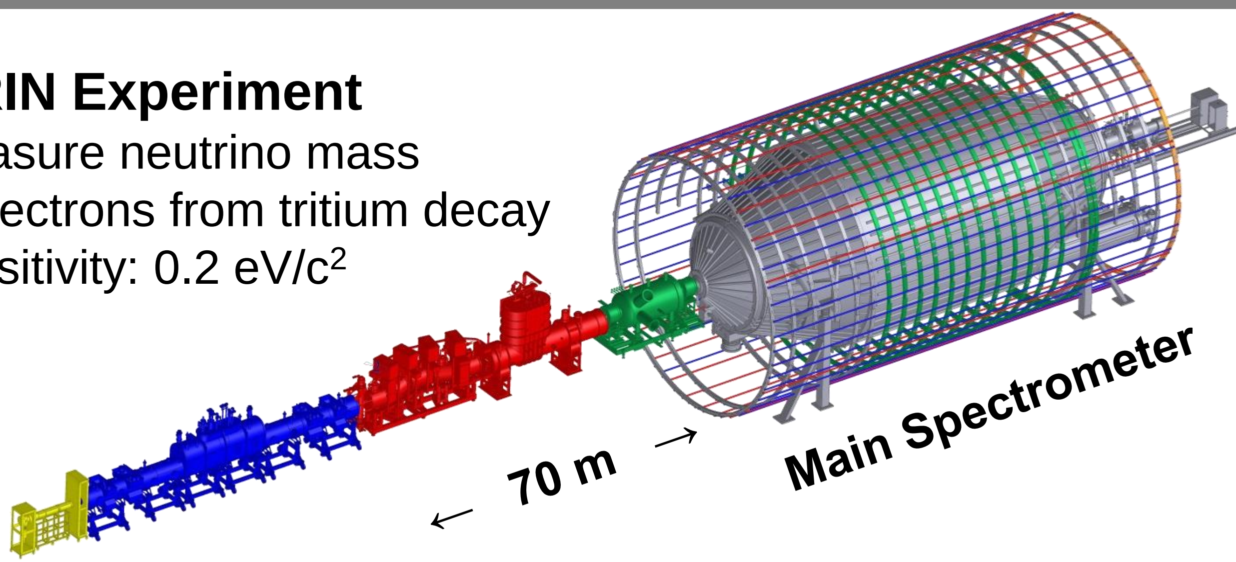
Institute of Experimental Nuclear Physics

LRT 2017, Seoul



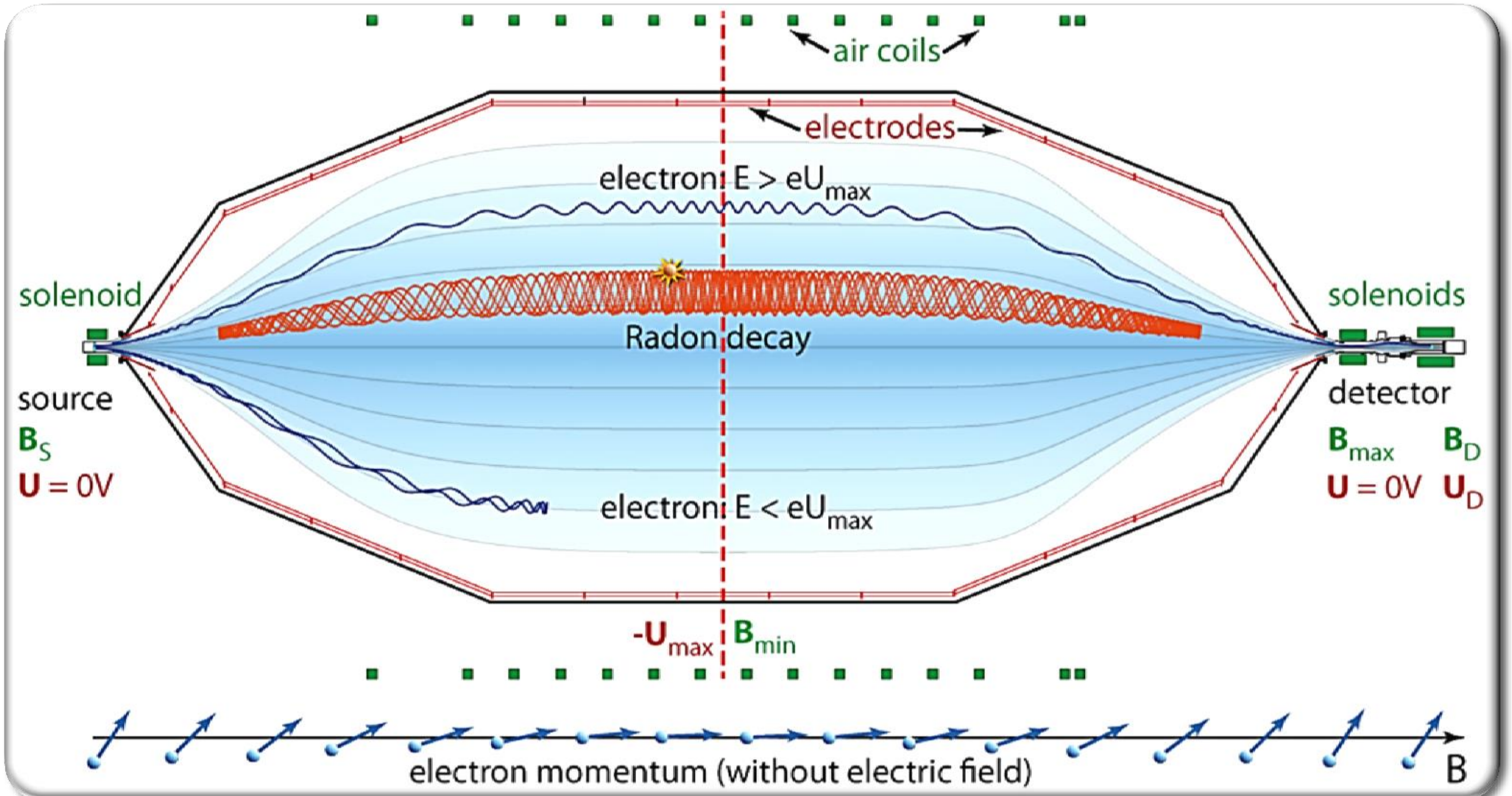
KATRIN Experiment

- measure neutrino mass
- β-electrons from tritium decay
- sensitivity: 0.2 eV/c^2



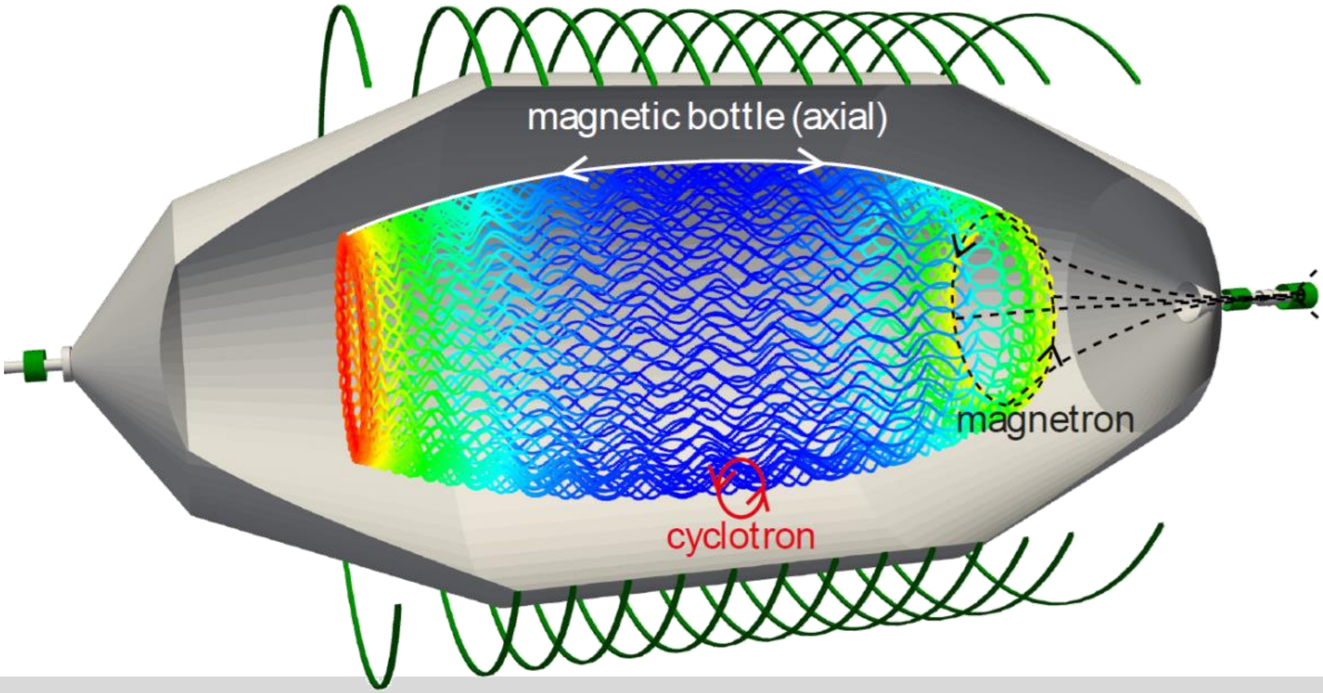
The KATRIN Main Spectrometer

- **MAC-E filter: high pass filter for e^-**
  - magnetic adiabatic collimation (B_{min} = 0.3 mT, B_{max} = 6 T)
  - electrostatic filter ($-U_{max}$ = -18.6 kV)
- **Detector:**
  - counts electrons that passed the filter



Radon background in the Main Spectrometer

- **Challenges:**
  - neutrino mass measurement requires **low background rates (< 10 mcps)**
  - **radon is emanated inside** the spectrometer
  - **radon decays** can produce **electrons**, which are **captured** in E, B fields
  - **primary electrons** ionize residual gas, producing **secondary electrons**
  - **increased background** rate for up to **several hours**



Radon background in the Main Spectrometer

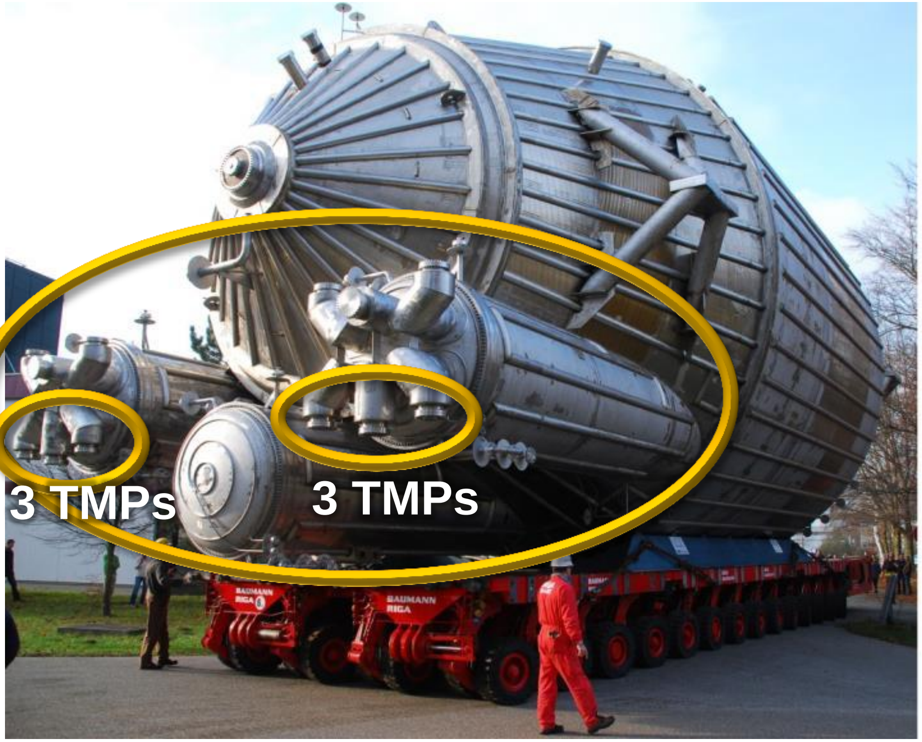
- **Challenges:**
  - neutrino mass measurement requires **low background rates (< 10 mcps)**
  - **radon is emanated inside** the spectrometer
  - **radon decays** can produce **electrons**, which are **captured** in E, B fields
  - **primary electrons** ionize residual gas, producing **secondary electrons**
  - **increased background** rate for up to **several hours**

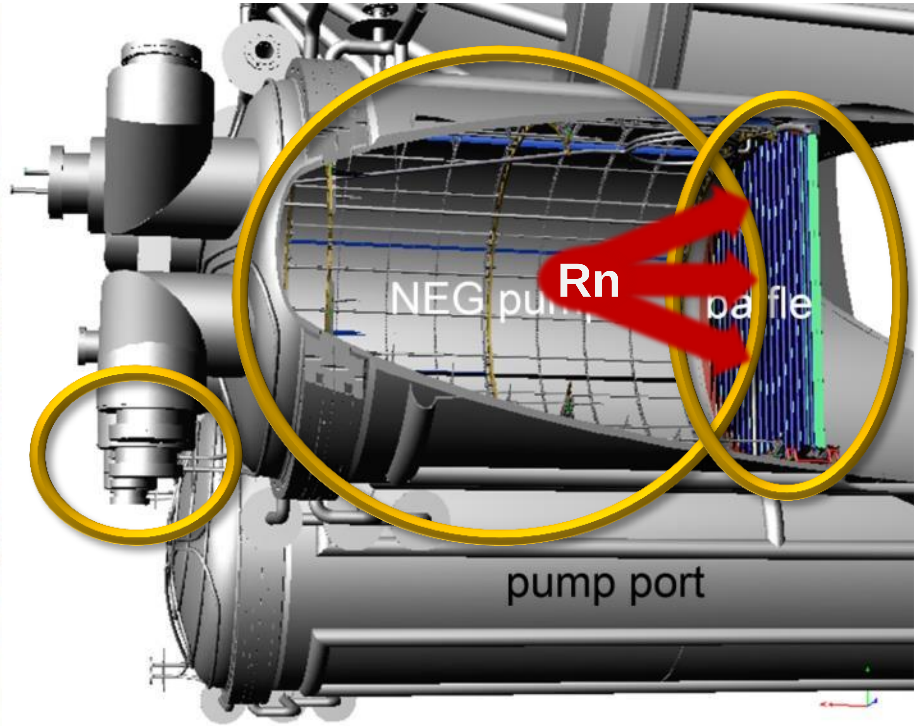
- **Goals:**
  - **prevent Rn from entering** the Main Spectrometer volume **($\rightarrow$ LN_2 baffle)**
  - **remove Rn quickly** from the main volume, before it decays **($\rightarrow$ LN_2 baffle)**

- **Vacuum Simulation:**
  - determine the **Rn decay rates** for different **pumping speeds**
  - uses TPMC code **MolFlow+** for ultra-high vacuum simulation
  - influence of **half-life** of different Rn isotopes ?

Main Spectrometer vacuum system

Karlsruhe Institute of Technology





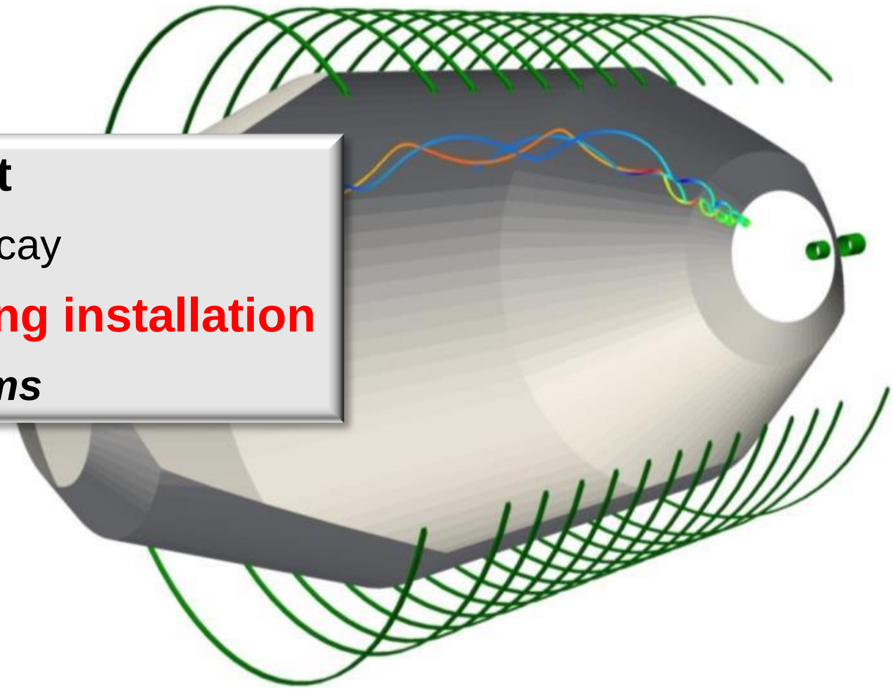
- stainless steel vessel (316LN): **23 m long, 10 m diameter**
- vacuum: **10^{-11} - 10^{-10} mbar**
- **6 turbo-molecular pumps** (Leybold MAG-W 2800): 10 000 ℓ/s (H_2)
- ~~3~~ 2 **NEG-pumps** (~~3~~2000 m SAES St707 getter strips): ~~~10^6 ℓ/s (H_2)~~ **250 000 ℓ/s**
- **3 cryogenic LN_2 Cu-baffles** against radon: ≤180 000 ℓ/s (Rn)

Possible radon sources

U-238 decay chain

$^{222}Rn : t_{1/2} = 3.8d$

- **quickly pumped out**
  - almost no direct decay
- **long exposure during installation**
  - ***see talk by F. Harms***



magnetic & electrostatic fields
do not shield the fluxtube
against **neutral unstable** atoms

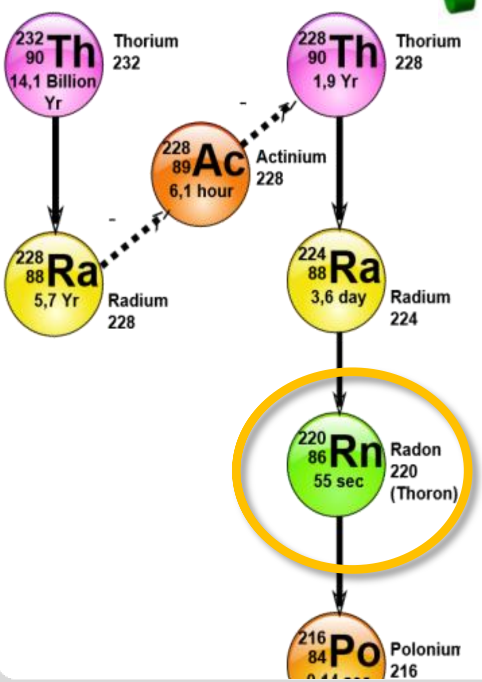
Possible radon sources

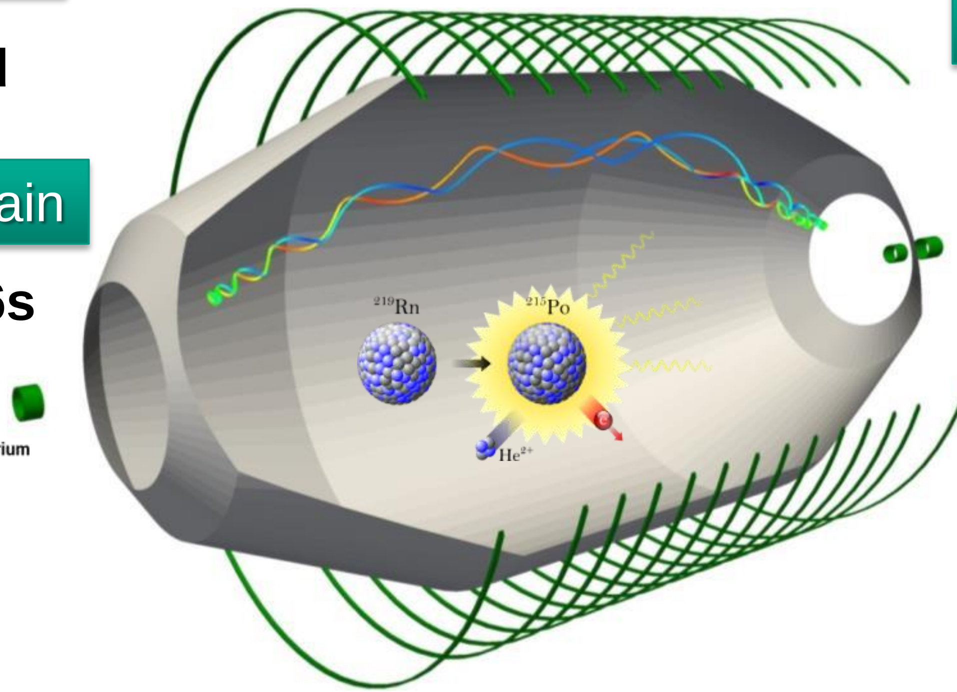
U-238 decay chain

$^{222}Rn : t_{1/2} = 3.8d$

Th-232 decay chain

$^{220}Rn : t_{1/2} = 55.6s$

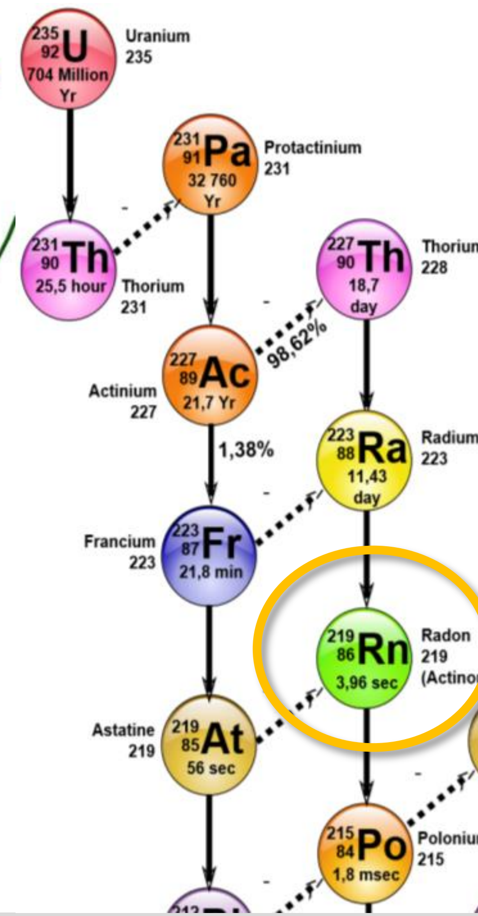




magnetic & electrostatic fields do not shield the fluxtube against **neutral unstable** atoms

U-235 decay chain

$^{219}Rn: t_{1/2} = 3.9s$



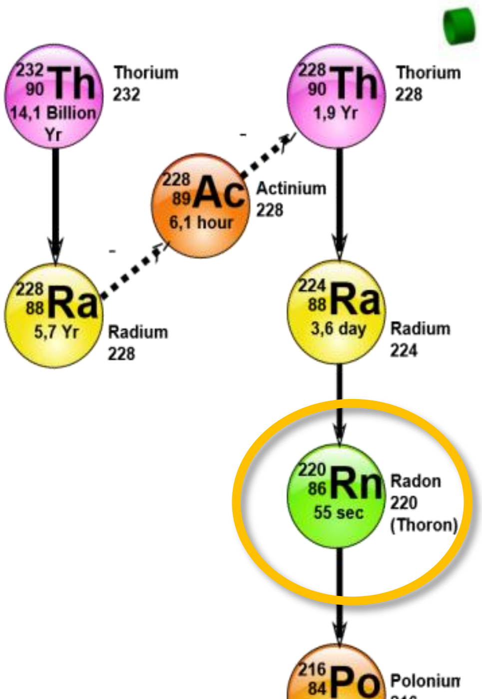
Possible radon sources

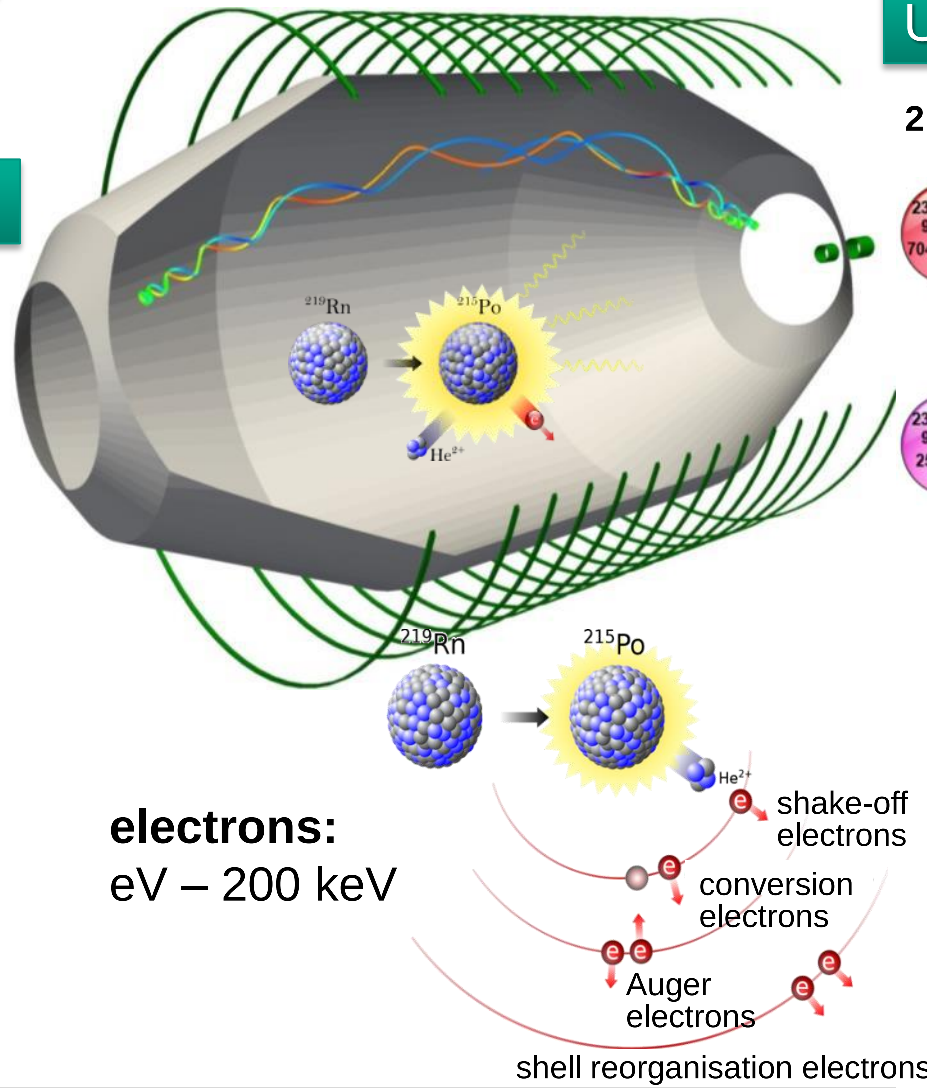
U-238 decay chain

^{222}Rn : $t_{1/2}$ = 3.8d

Th-232 decay chain

^{220}Rn : $t_{1/2}$ = 55.6s

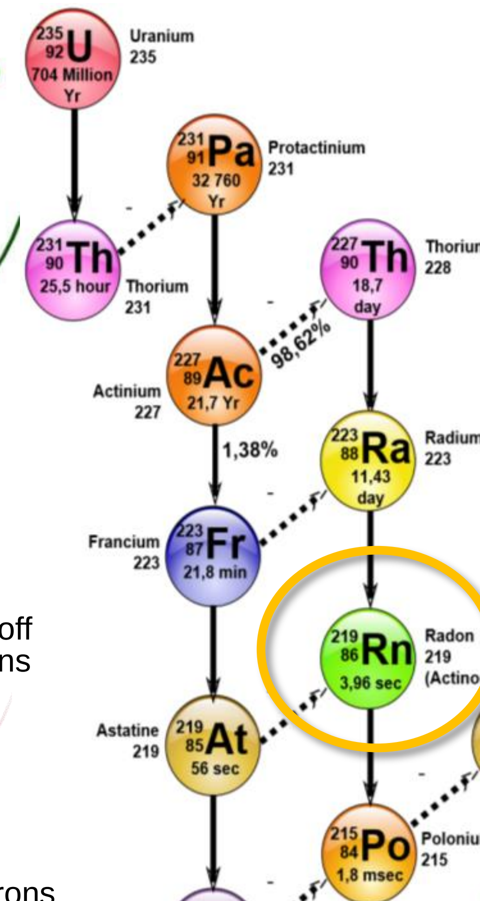




electrons:
eV – 200 keV

U-235 decay chain

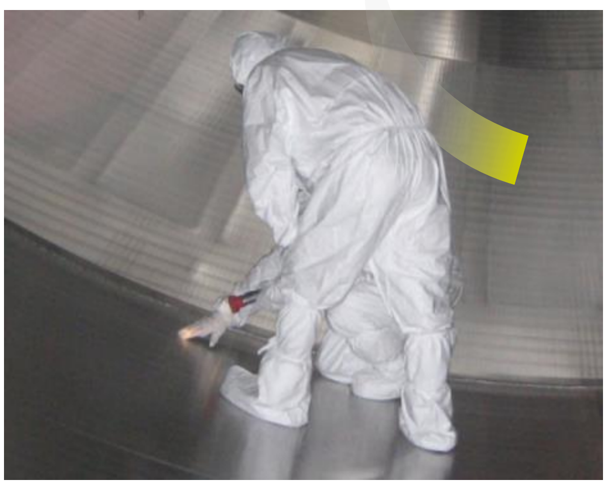
^{219}Rn: $t_{1/2}$ = 3.9s

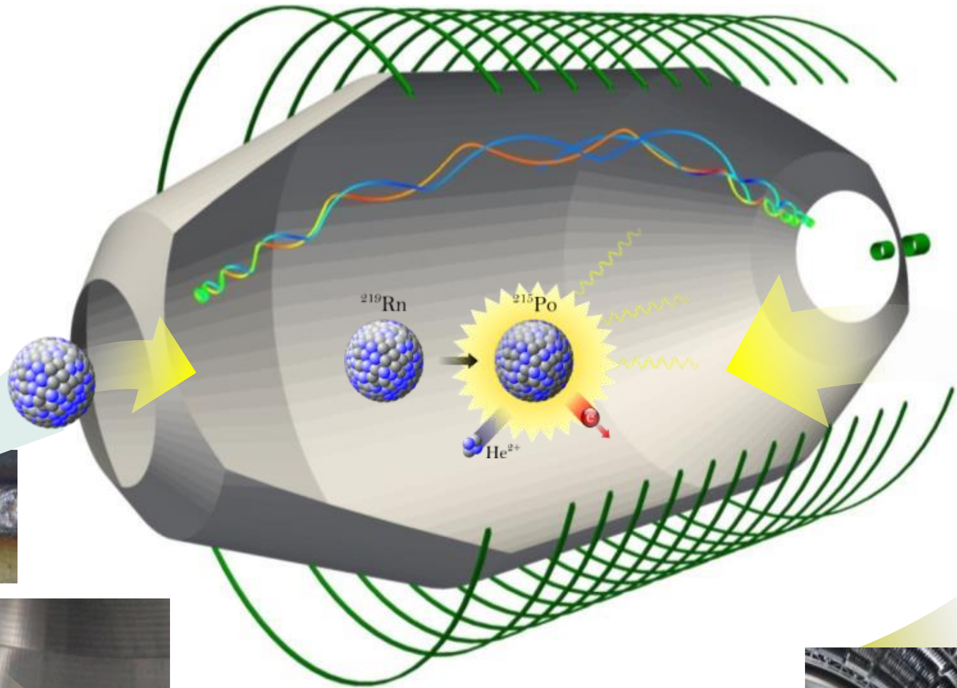


Possible radon sources

weld seams

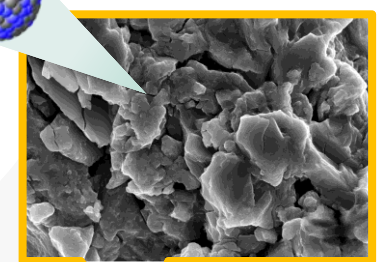
^{220}Rn emanation
(in main volume)

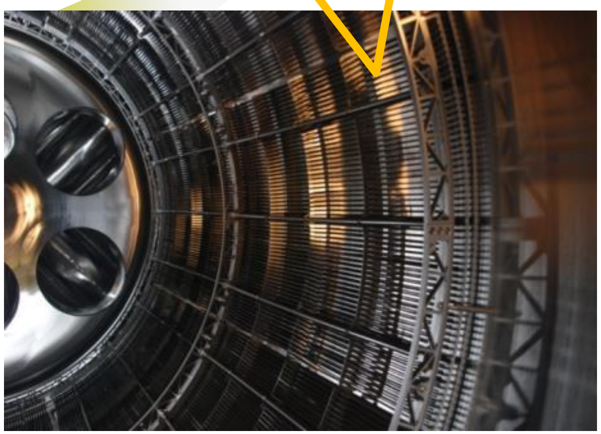




NEG pumps

^{219}Rn emanation
(behind baffle)





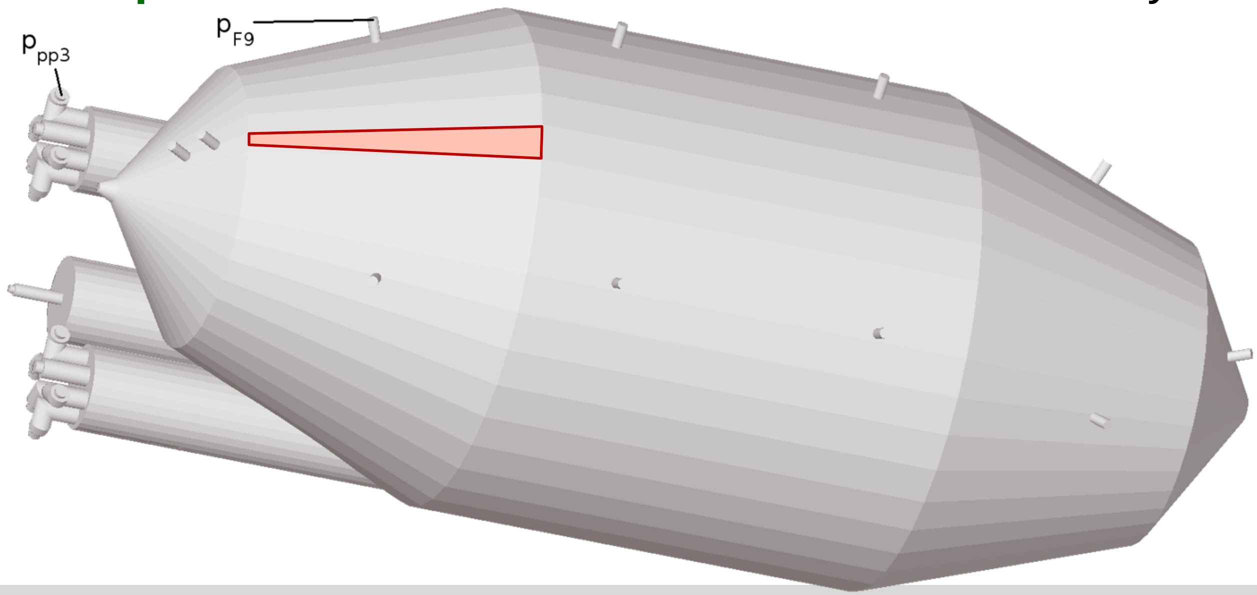
1222 m^2 316 LN

3000 m NEG strips

Simulation of the Main Spectrometer

- **MolFlow+:** Test Particle Monte Carlo code
  - **stable particles**, no radioactive decay
  - **adsorbed particles** stay on a surface indefinitely **(exit condition)**
  - **adsorption** on a surface element is controlled by the **sticking coefficient** α
- **Radon gas:**
  - **radioactive decay** ➔ decay in volume **(second exit condition needed)**
  - **finite sojourn time** on surface
  - **re-desorption** similar to diffuse **reflection** with time delay

$$\tau_{des} = \tau_0 \cdot \exp(\Delta H_{des}/R \cdot T_B)$$



Calculation of the Rn decay rate

Rn activity in spectrometer volume

$$A_{Rn} = \lambda_{\mathrm{Rn}} \cdot N_{Rn}$$

$$\frac{dN_{\mathrm{Rn}}}{dt} = Q_{\mathrm{Rn}} - A_{\mathrm{Rn}} - \frac{N_{\mathrm{Rn}}}{V} \cdot S_{\mathrm{eff}} = 0$$

$$A_{\mathrm{Rn}} = Q_{\mathrm{Rn}} \frac{\lambda_{\mathrm{Rn}}}{\lambda_{\mathrm{Rn}} + S_{\mathrm{eff}}/V}$$

N_{Rn} = Rn atoms in spectrometer

Q_{Rn} = **emanation rate** (desorption)

A_{Rn} = $N_{\mathrm{Rn}} \cdot \lambda_{\mathrm{Rn}}$ **= activity in spectrometer**

$T_{1/2}$ = radioactive half-life

λ_{Rn} = $\ln(2)/T_{1/2}$ = decay rate

V = spectrometer volume (1240 m^3)

S_{eff} = **effective pumping speed for Rn**

effective pumping speed S_{eff}

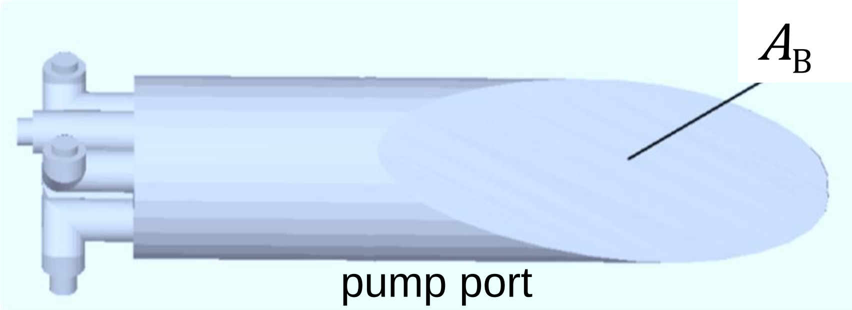
$$S_{\mathrm{eff}} = \frac{1}{4} \cdot \bar{c} \cdot A_{\mathrm{B}} \cdot \alpha_{\mathrm{eff}}$$

(simulation of pumping surface)

α_{eff} = effective sticking coefficient

A_{B} = opening area of the baffle

$\bar{c} = \sqrt{\frac{8 \cdot k_{\mathrm{B}} \cdot T}{\pi \cdot M}}$ = mean particle speed



Effective sticking coefficient for Rn

- probability for **(permanent) adsorption per hit:** α

Effective sticking coefficient for Rn

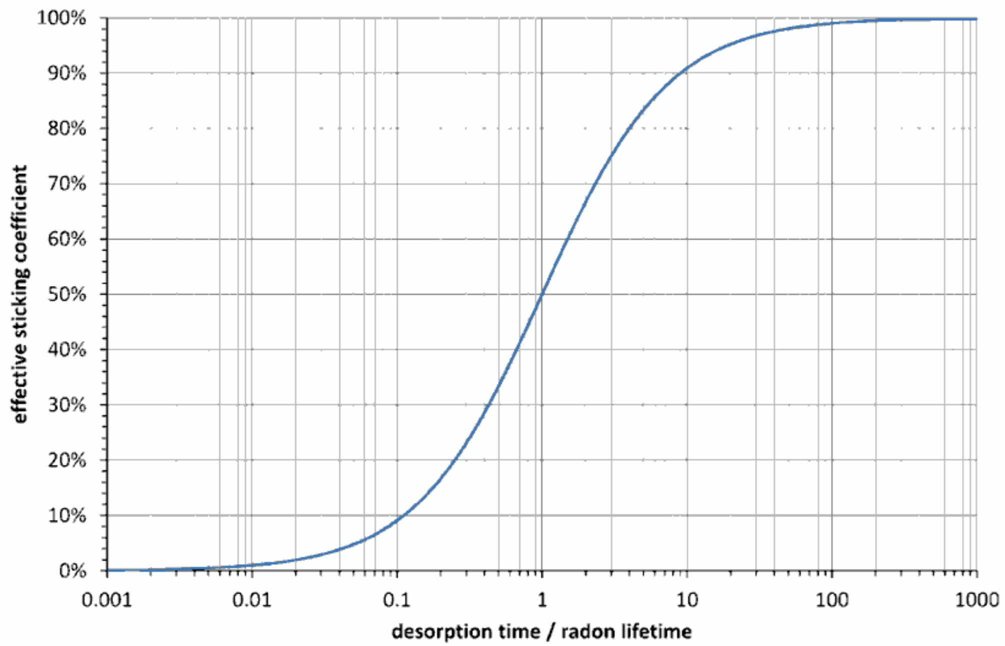
- probability for **hitting the baffle, and decay:** α_{eff}
- probability for **not decaying:** $\exp(-t/\tau_{Rn})$
- probability for **not desorbing:** $\exp(-t/\tau_{des})$
- **decay rate at time t:**

$$\frac{dN}{dt} = \lambda_{Rn} \cdot N(t) = \frac{N_0}{\tau_{Rn}} \cdot \exp\left(-t \cdot \left(\frac{1}{\tau_{Rn}} + \frac{1}{\tau_{des}}\right)\right)$$

- **integration from $t = 0$ to infinity:**

$$\alpha_{eff} = \alpha_0 \cdot \frac{1}{1 + \tau_{Rn}/\tau_{des}}$$

(here: $\alpha_0 = 1$)



MolFlow+ simulation of radon decays

$$\alpha_{eff} = \alpha_0 \cdot \frac{1}{1 + \tau_{Rn}/\tau_{des}}$$

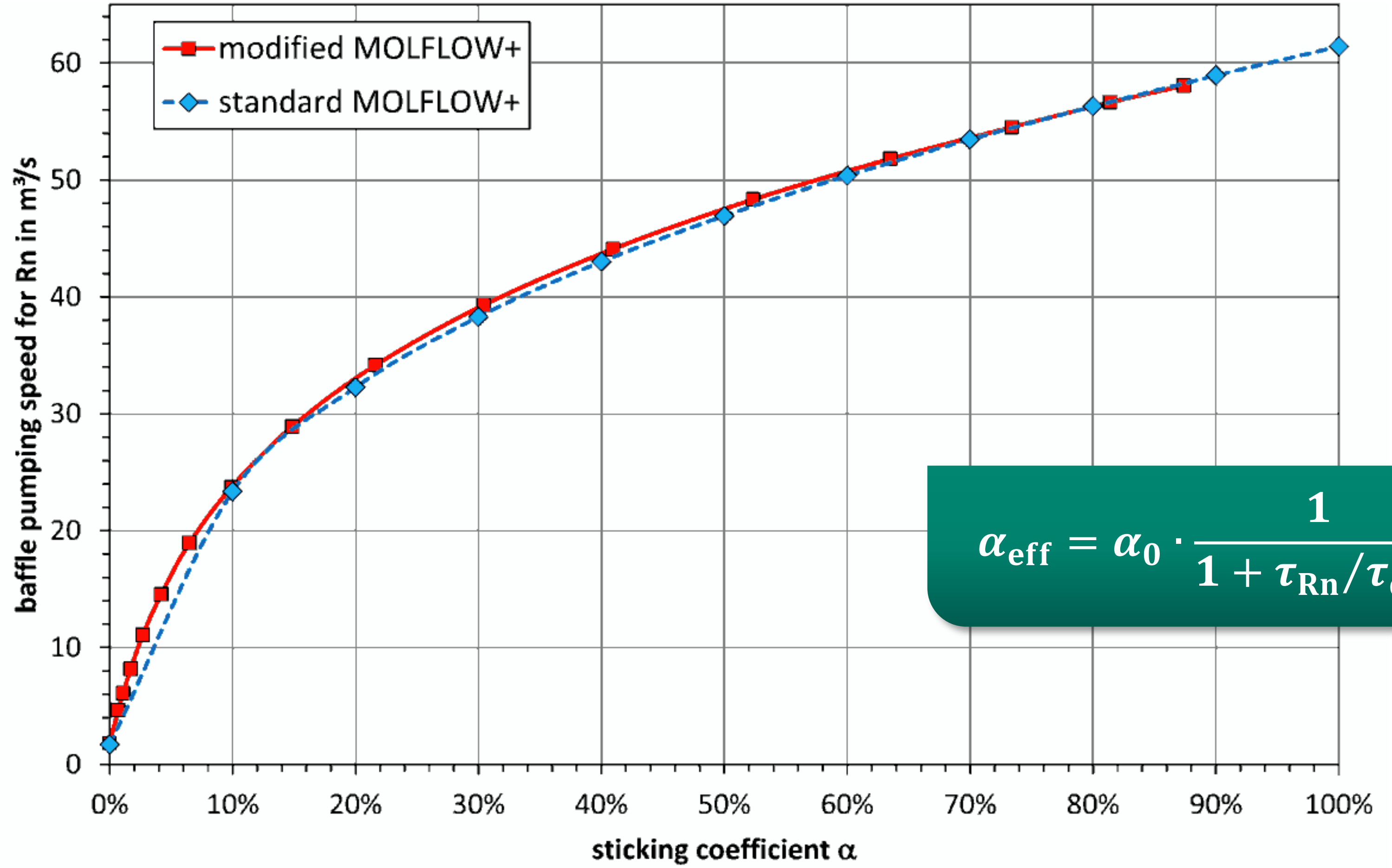
- **Standard MolFlow+** simulation:
  - use **effective sticking coefficient** for simulating **pumping speed S_{eff}**
  - apply simple **models for activity and transmission**
  - works for simple geometries
  - difficult for complex setups

$$A_{Rn} = Q_{Rn} \cdot \frac{\lambda_{Rn}}{\lambda_{Rn} + S_{eff}/V}$$

- **Extended version of Molflow+:**
  - individual **sojourn time τ_{des}** for each surface element ($\alpha_0 > 0$)
  - **life-time τ_{Rn}** assigned to particles
    - **decay while adsorbed** on surface: (**1st exit condition** = „pumped out“)
    - **decay in flight:** (**2nd exit condition**)
    - **3D coordinates saved**, if particle decays in flight ➔ **decay map**
  - works for arbitrary geometries, re-desorptions, and pumping configurations

Simulation examples: pumping speed

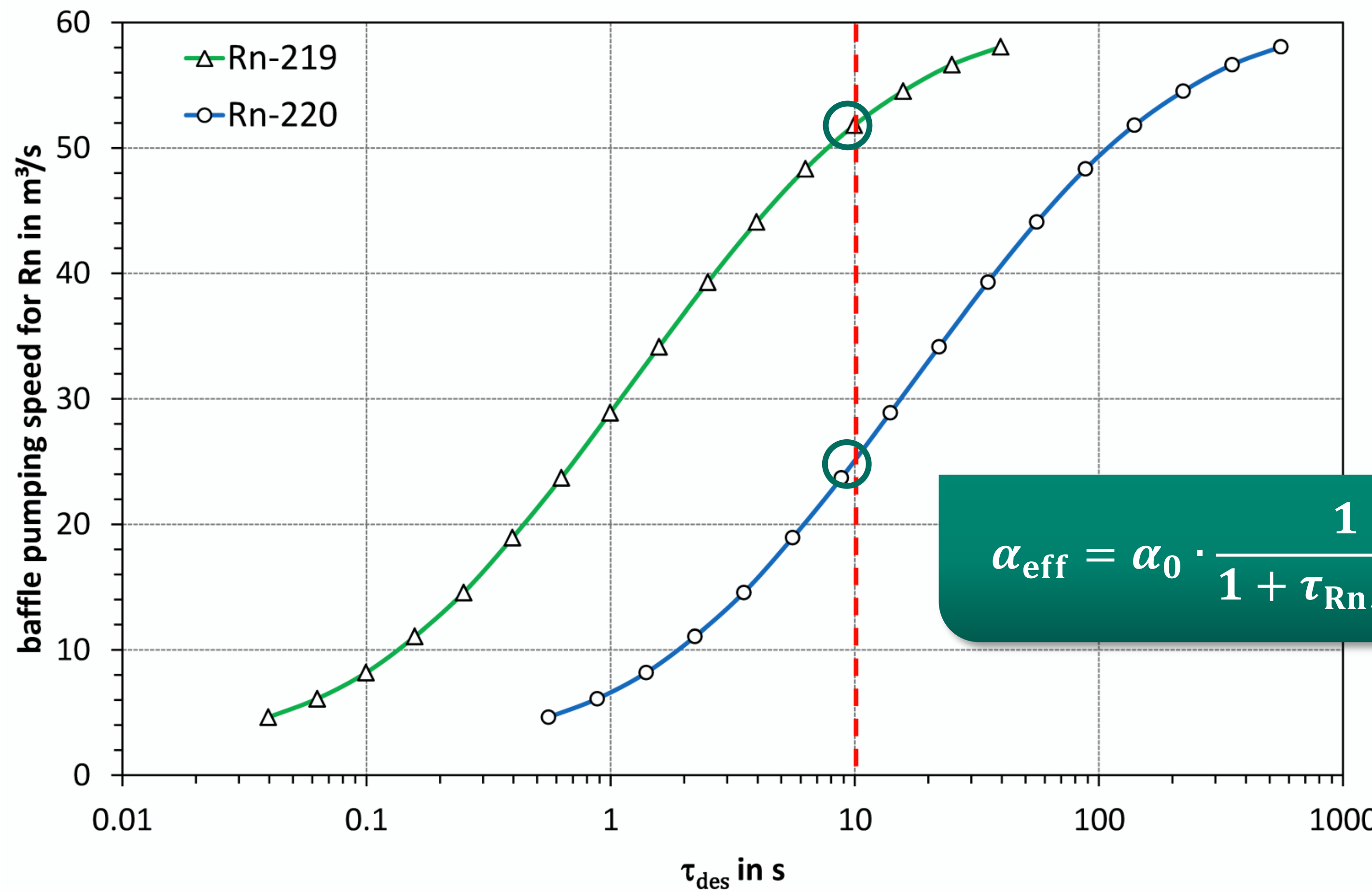
- Effective pumping speed for **6 TMPs: 3 400 ℓ/s**
- Effective pumping speed for **3 baffles: ~180 000 ℓ/s** (max)



$$\alpha_{\mathrm{eff}} = \alpha_0 \cdot \frac{1}{1 + \tau_{\mathrm{Rn}}/\tau_{\mathrm{des}}}$$

Simulation examples: pumping speed

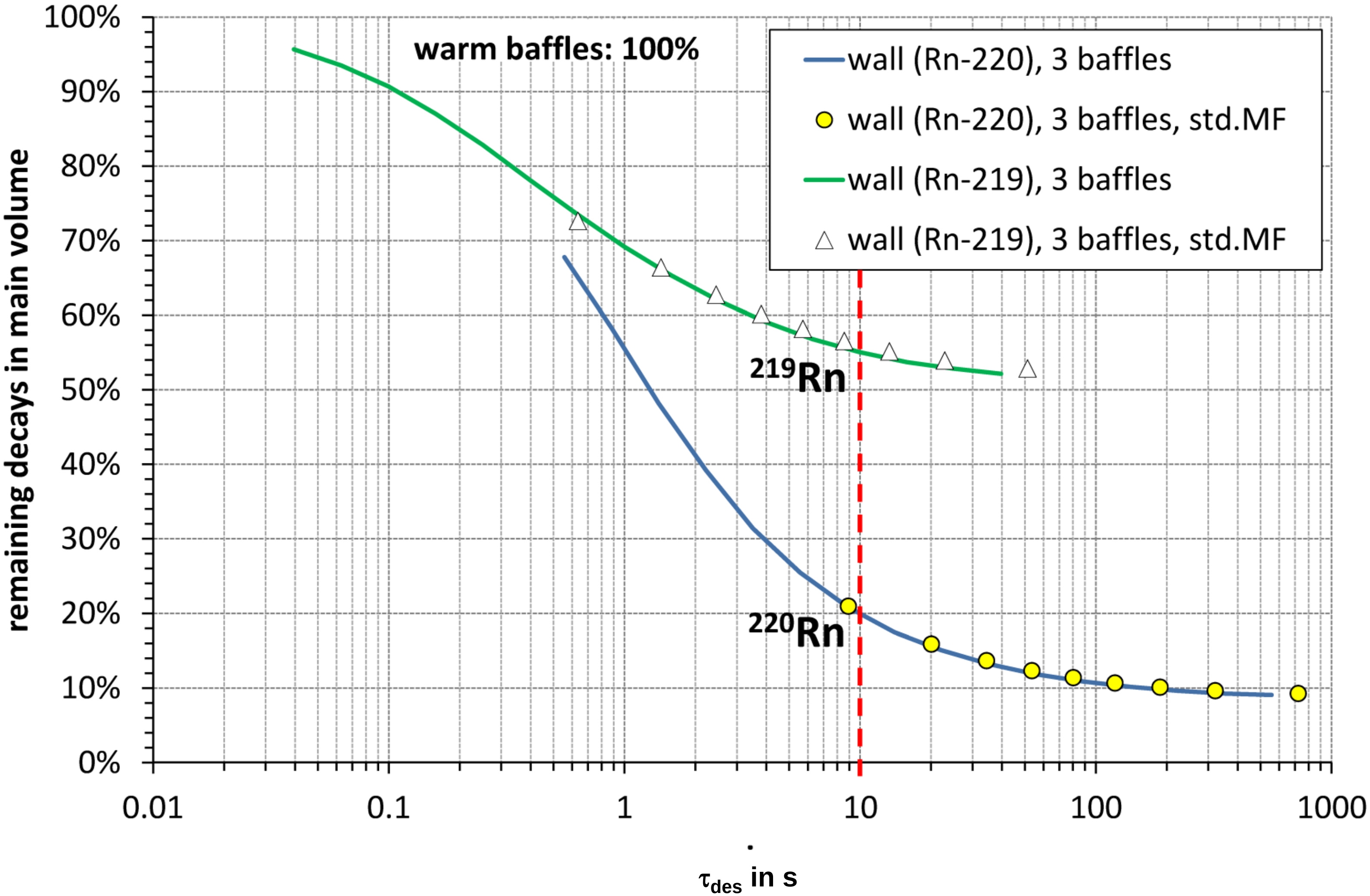
- Effective pumping speed for **6 TMPs: 3 400 ℓ/s**
- Effective pumping speed for **3 baffles: ~180 000 ℓ/s** (max)



$$\alpha_{\text{eff}} = \alpha_0 \cdot \frac{1}{1 + \tau_{\text{Rn}}/\tau_{\text{des}}}$$

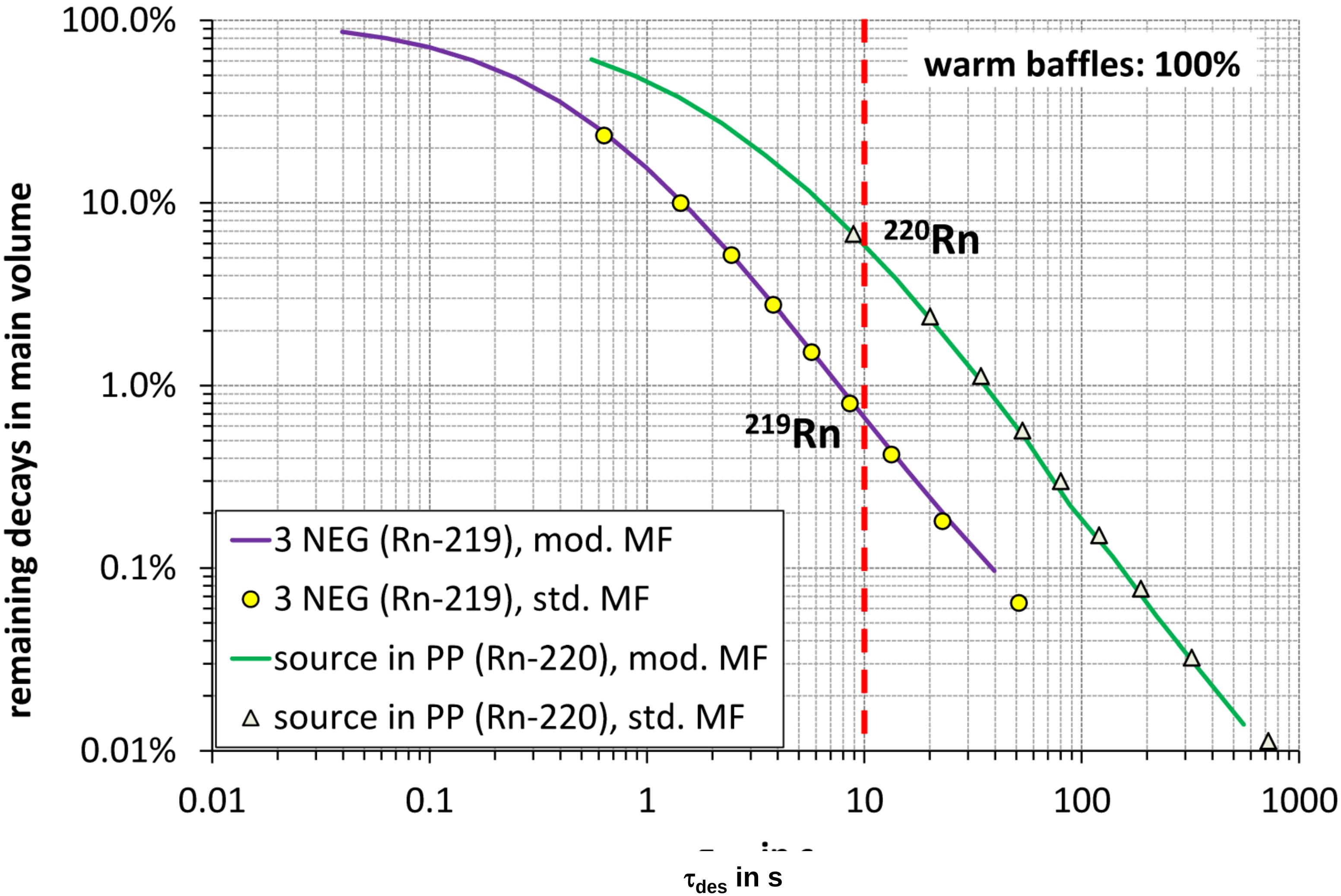
Simulation examples: baffle pumping

- reduction of Rn decays in the main volume



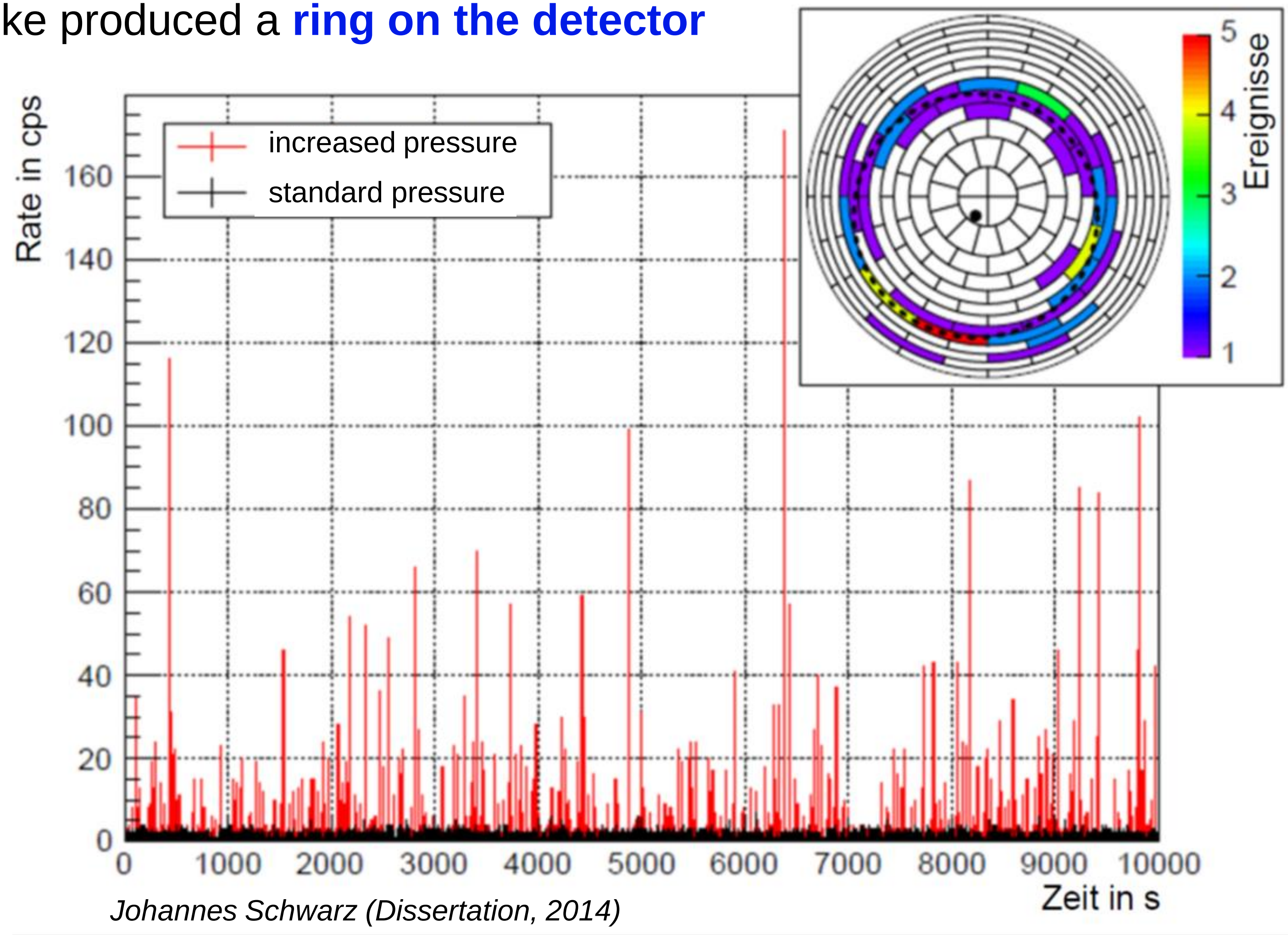
Simulation examples: baffle transmission

- reduction of Rn decays in the main volume



Measurement of Rn decays

- measurement with **increased pressure** (10^{-8} mbar)
- **spikes = secondary electrons** from individual Rn decays
- each spike produced a **ring on the detector**

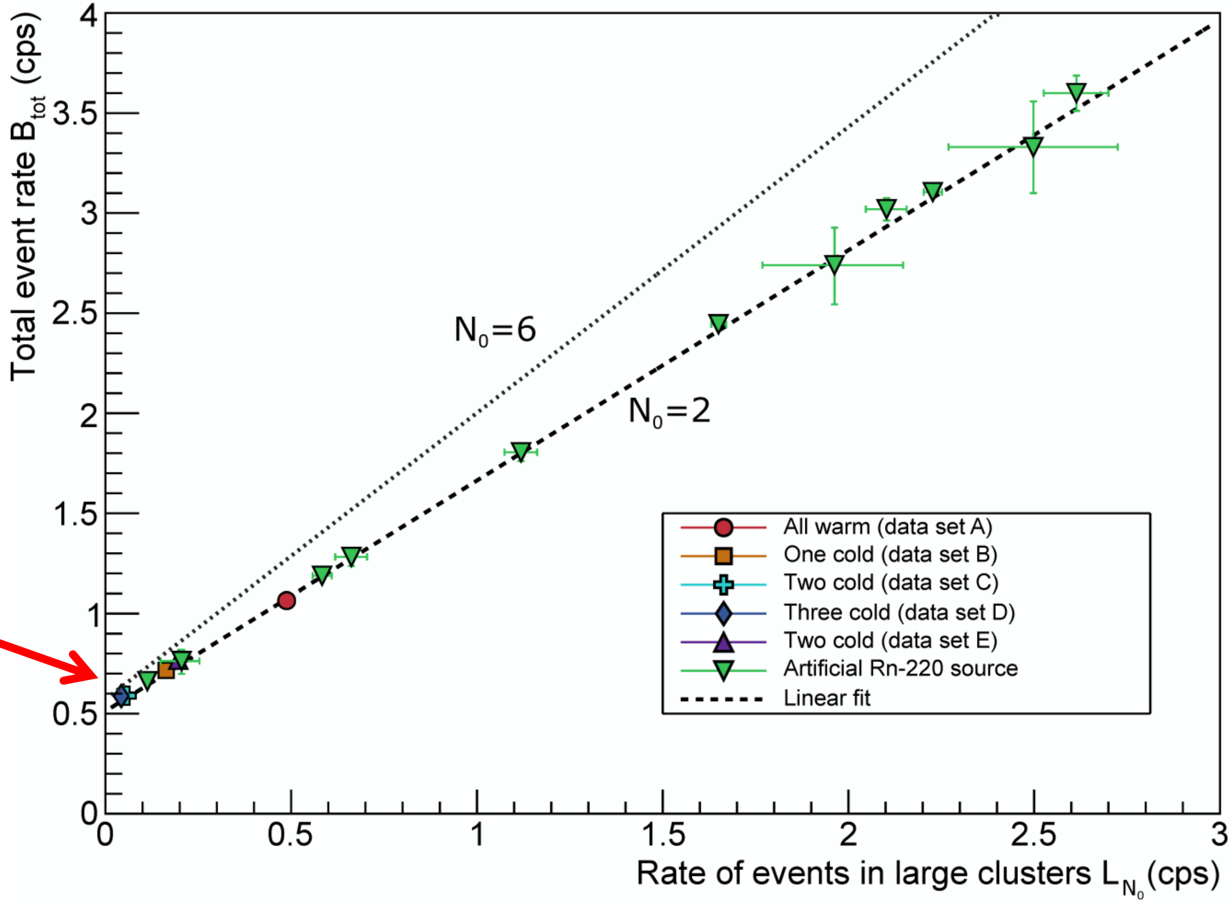


Johannes Schwarz (Dissertation, 2014)

Radon-Induced background measurement

- total background with **different radon source** and **baffle temperatures**
- total event rate vs. **clustered events** (almost no accidental background)
- remaining no-radon background: **thermal ionization of Rydberg atoms**

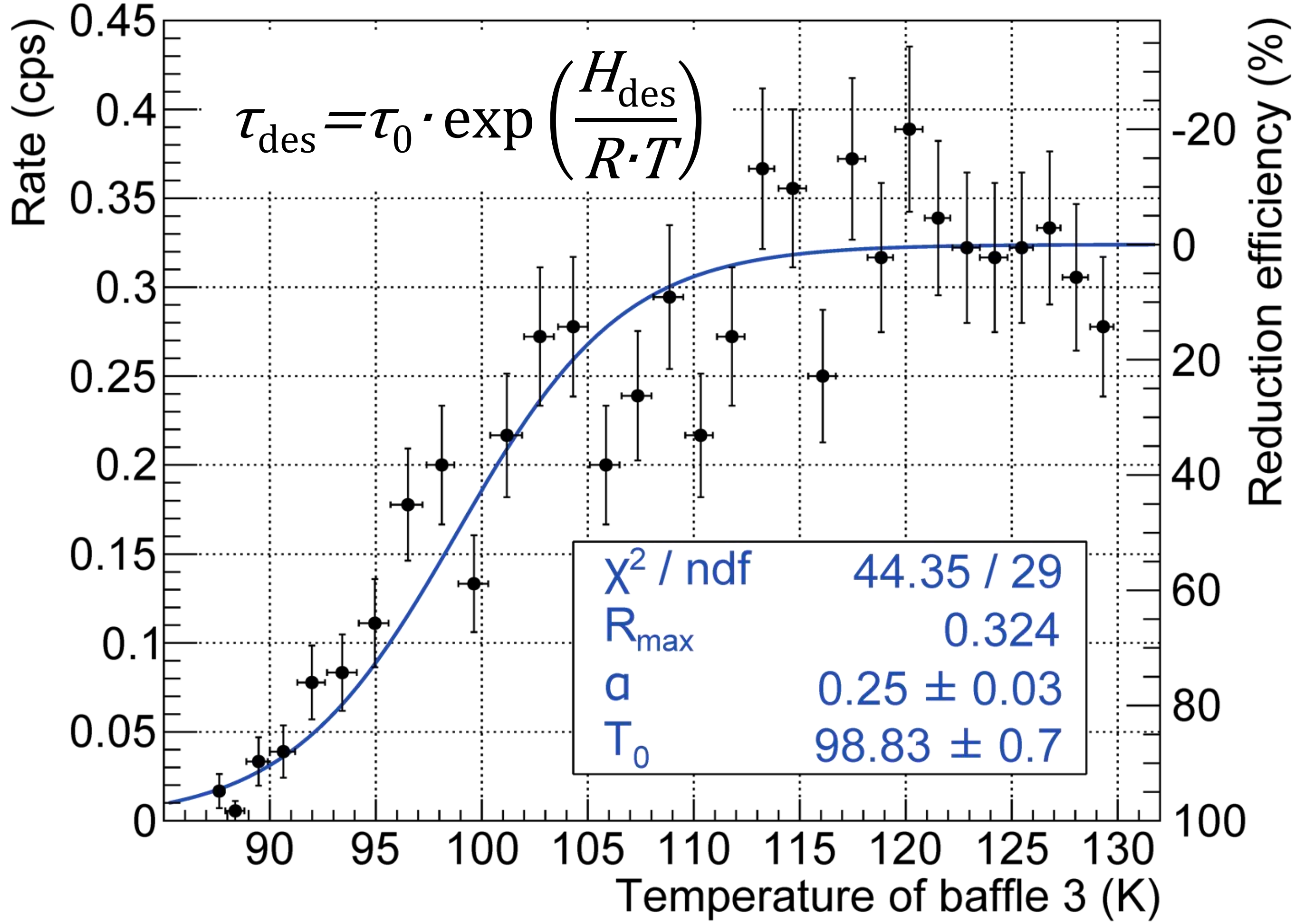
Rydberg background
(see talk by F. Harms)



Radon-Induced background measurement

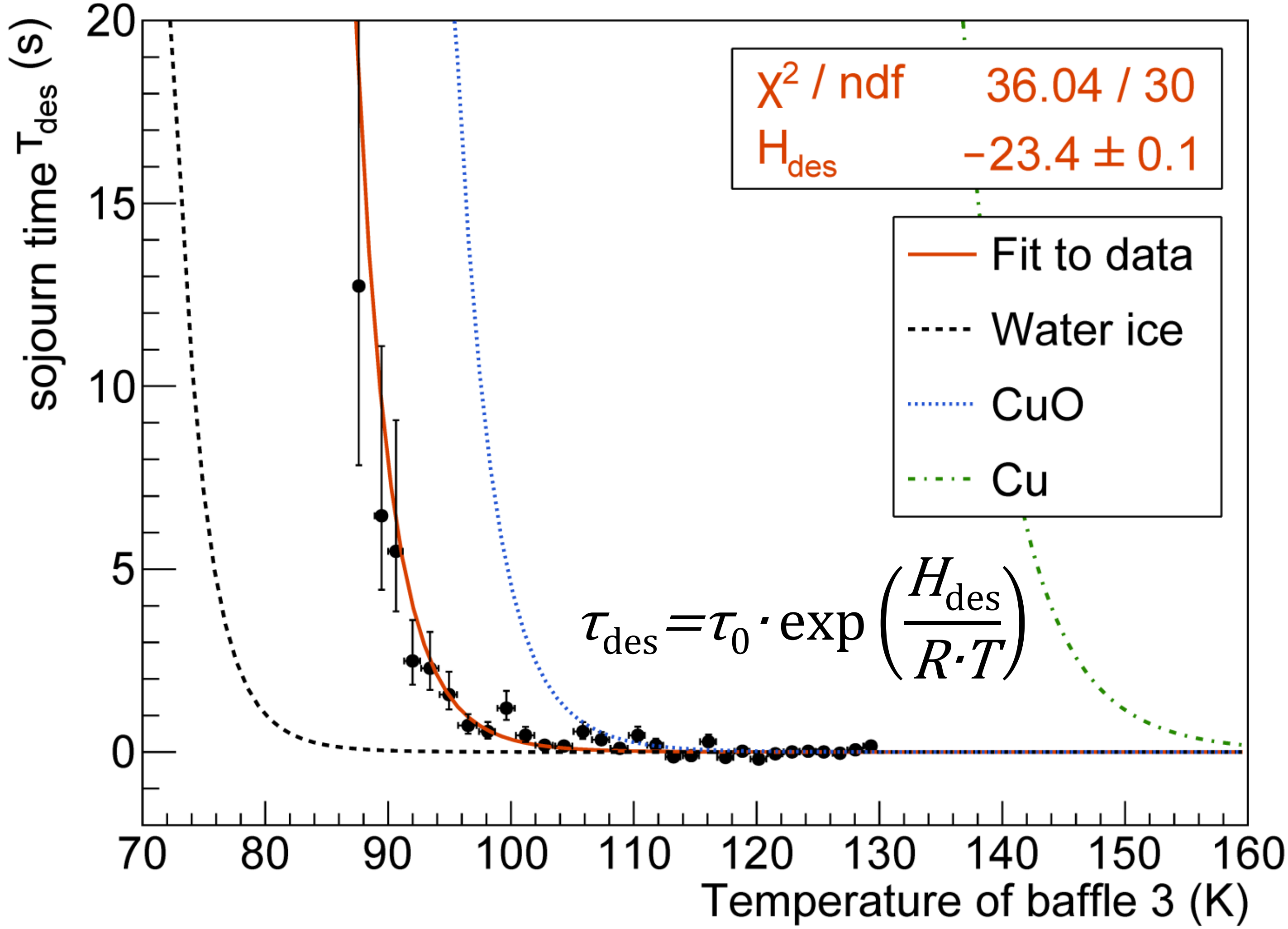
Karlsruhe Institute of Technology

- Radon cluster event rate for different baffle temperatures.
- Reduction efficiency: 0% (warm baffle background), 100% (no radon events)



Sojourn time of cold copper cryo panels

- measurements with different baffle temperatures



Conclusions

- **Radon is a serious background in the KATRIN Main Spectrometer**
  - vacuum vessel: **^{220}Rn**
  - getter pumps: **^{219}Rn**
  - background rate multiplied by magnetic bottle effect (stored electrons)
- **Vacuum simulation of radioactive decay rate**
  - **calculation** of decay rates possible for simple models using **„effective sticking coefficient“** with **standard MolFlow+**
  - **simulation** with **modified MolFlow+** source code
    - **life-time** of particles included
    - **finite sojourn tim**e for pumping surfaces included
  - **effective pumping speed depends on life-time** of radon isotopes
- **Radon background measurements**
  - **event cluster** vs. single event rate provides **radon related rate**
  - **cold baffles** reduce radon background **sufficiently**
  - **remaining single event background** studied ***(talk by F. Harms)***

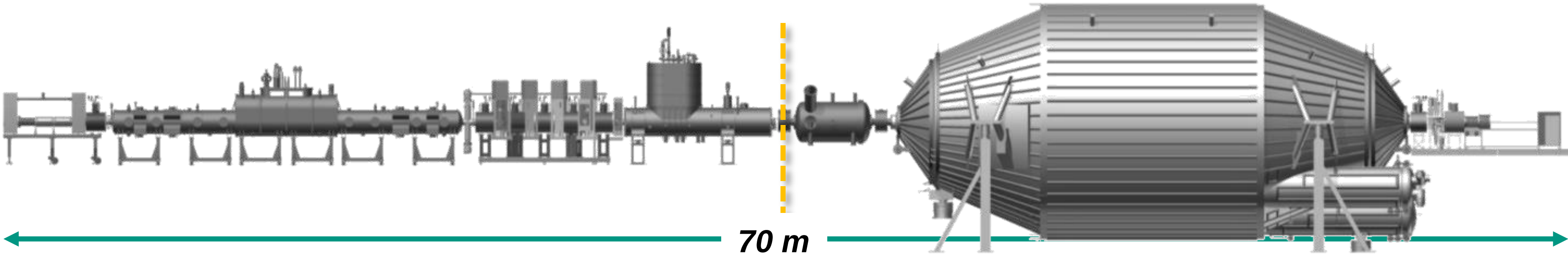
Thank you for your attention

Supported by

Federal Ministry
of Education
and Research

Backup slides

The KArlsruhe TRItium Neutrino Experiment

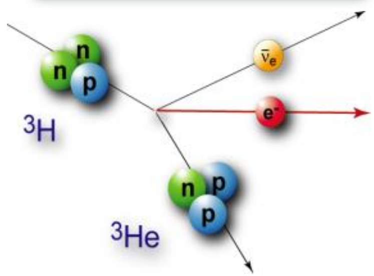


Source & Transport Section (STS) | **Spectrometer & Detector Section (SDS)**

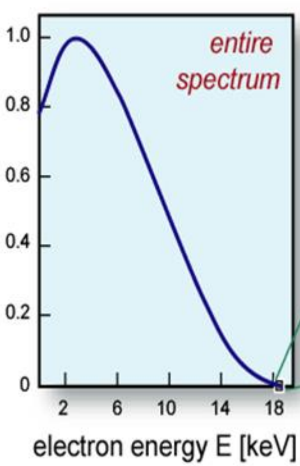
ideal
β-emitter

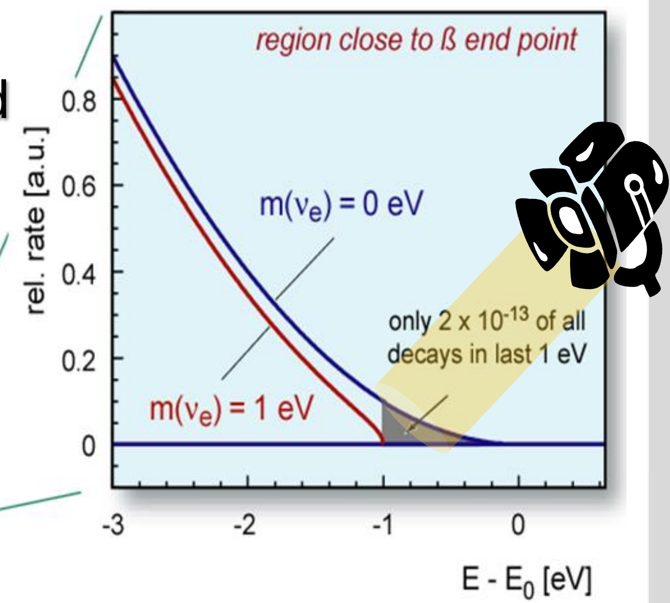
^3H: super-allowed	
E_0	**18.6 keV**
$t_{1/2}$	**12.3 y**

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



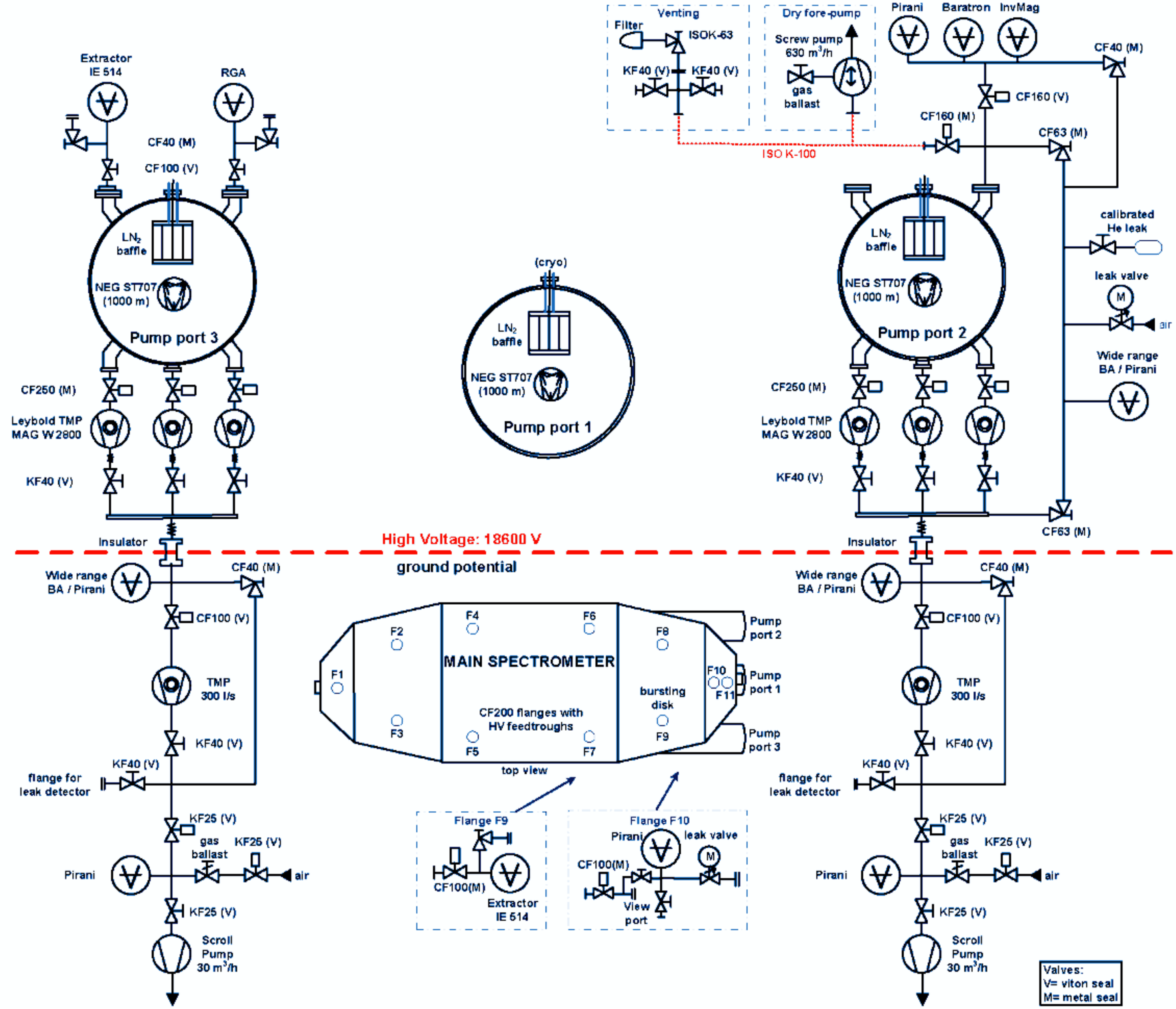
MAC-E-Filter
most sensitive method





G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, ***Current Direct Neutrino Mass Experiments (Review)***
Advances In High Energy Physics (2013) 293986

Vacuum scheme of the Main Spectrometer

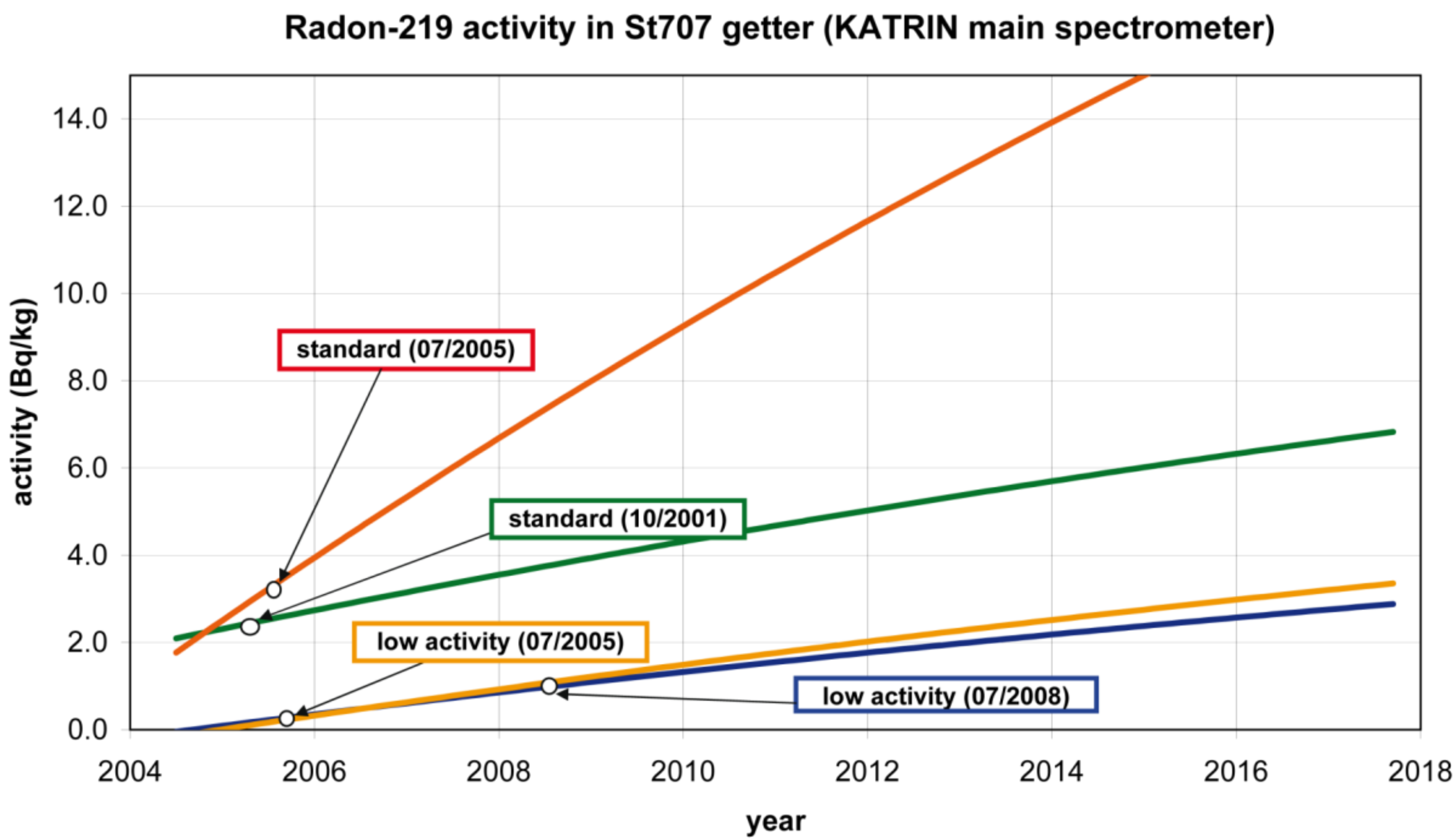


KATRIN Main Spectrometer

Component	Material	Temp.	Surface
Main Spectrometer vacuum vessel	316LN	20°C	690.0 m^2
Wires (23440 wires with a total length of 42400 m)	316L	20°C	33.6 m^2
Electrode frames (248 modules)	316L	20°C	436.8 m^2
Electrode rail system	316LN	20°C	58.0 m^2
Feedtrough flanges	316LN	20°C	2.0 m^2
Small components (frame NEG-pumps, etc.)	316L	20°C	1.5 m^2
Σ stainless steel	**316L(N)**	**20°C**	**1221.9 m^2**
Σ ceramic insulators	**Al_2O_3**	**20°C**	**5.8 m^2**
Σ anti-penning electrodes	**Ti**	**20°C**	**11.0 m^2**
Σ ground electrodes	**Al**	**20°C**	**1.3 m^2**
Σ surfaces at room temperature		**20°C**	**1240 m^2**
Σ cryogenic baffles	**Cu**	**77 K**	**31 m^2**
Σ NEG-strips	**St707**	**20°C**	**180 m^2**
Volume Main Spectrometer			**1240 m^3**

Reduction of Rn-induced background

- **Passive methods (before decay): low-activity materials**
  - use thorium-free **welding tips** (TIG welding)
  - activity monitoring of **stainless steel**
  - special batch of **SAES St 707** getter alloy



Reduction of Rn-induced background

- **Select materials** with low Rn content
- **remove Rn** from spectrometer before it decays (pumping)
- **prevent Rn from entering** spectrometer (cryo-trapping)

Rn activity in spectrometer volume

$$\frac{dN_{\mathrm{Rn}}}{dt} = E_{\mathrm{Rn}} - A_{\mathrm{Rn}} - \frac{N_{\mathrm{Rn}}}{V} \cdot S_{\mathrm{eff}} = 0$$

$$\boldsymbol{A_{\mathrm{Rn}} = \lambda_{\mathrm{Rn}} \cdot N_{\mathrm{Rn}} = E_{\mathrm{Rn}} \frac{\lambda_{\mathrm{Rn}}}{\lambda_{\mathrm{Rn}} + S_{\mathrm{eff}}/V}}$$

N_{Rn} = Rn atoms in spectrometer

E_{Rn} = **emanation rate** (desorption)

A_{Rn} = $N_{\mathrm{Rn}} \cdot \lambda_{\mathrm{Rn}}$ **= activity in spectrometer**

$T_{1/2}$ = radioactive half-life

λ_{Rn} = $\ln(2)/T_{1/2}$ = decay rate

V = spectrometer volume (1240 m^3)

S_{eff} = **effective pumping speed for Rn**

Goal:

- **reduce activity by maximizing pumping speed**: $S_{\mathrm{eff}} \gg V \cdot \lambda_{\mathrm{Rn}}$
- $V \cdot \lambda_{\mathrm{Rn}}$ = 2.6 ℓ/s for ^{222}Rn
- $V \cdot \lambda_{\mathrm{Rn}}$ = 15.5 m^3/s for ^{220}Rn
- $V \cdot \lambda_{\mathrm{Rn}}$ = 215 m^3/s for ^{219}Rn

^{222}Rn $T_{1/2}$ = 3.8 d

^{220}Rn $T_{1/2}$ = 55.6 s

^{219}Rn $T_{1/2}$ = 3.96 s

Rn adsorption on a cold surface

number of particles in the spectrometer

$$\frac{dN}{dt} = \lambda \cdot N \qquad N(t) = N_0 \cdot e^{-\lambda t}$$

number of particles on the baffle

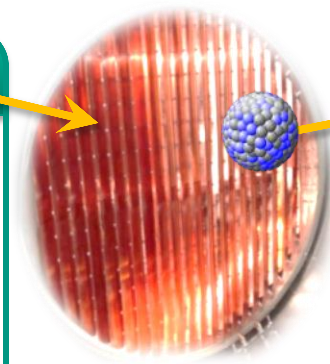
Rn adsorption

$$\lambda_{ads} = (\tau_{ads})^{-1} = S_B / V$$

$$S_B = {}^{1}/_{4} \cdot A_B \cdot \bar{c} \cdot \alpha$$

S_B = pumping speed baffle
V = spectrometer volume
A_B = baffle area
α = sticking coefficient (0…1)

maximise λ_{ads}



Rn desorption

$$\lambda_{des} = (\tau_{des})^{-1}$$

$$\tau_{des} = \tau_0 \cdot \exp\left(\frac{\Delta H_{des}}{R \cdot T_B}\right)$$

ΔH_{des} = desorption enthalphy
τ_0 = phonon osc. period
T_B = baffle temperature
R = molar gas constant

minimise λ_{des}

Radioactive decays

$$\lambda_{Rn} = \ln(2)/T_{1/2}$$

$\lambda_{Rn} \cdot N_{Sp}$ decays in volume: background

$\lambda_{Rn} \cdot N_B$ decays on baffles: $\lambda_{des} = 0$

Rn reduction and transmission probability

Karlsruhe Institute of Technology

- **reduction factor:** $R(T_1) = \frac{A(T_1)}{A(T_0)} = \frac{p(T_1)}{p(T_0)}$ with $T_0 = 293$ K
- **pressure:** $p(T_i) = \frac{Q_{\mathrm{NEG}}}{S_{\mathrm{eff}}(\alpha_i)+\lambda_{\mathrm{Rn}}\cdot V} \cdot Tr(\alpha_i)$
- **baffle transmission:** $Tr(\alpha_i) = \frac{Q_{\mathrm{MS}}}{Q_{\mathrm{NEG}}} = \frac{p(T_i)\cdot S_{\mathrm{eff}}(\alpha_i)}{Q_{\mathrm{NEG}}} \propto \frac{\mathrm{Hit_g}(T_i)}{\mathrm{Des}(T_i)} \cdot S_{eff}(\alpha_i)$

(standard MolFlow: stable particles)

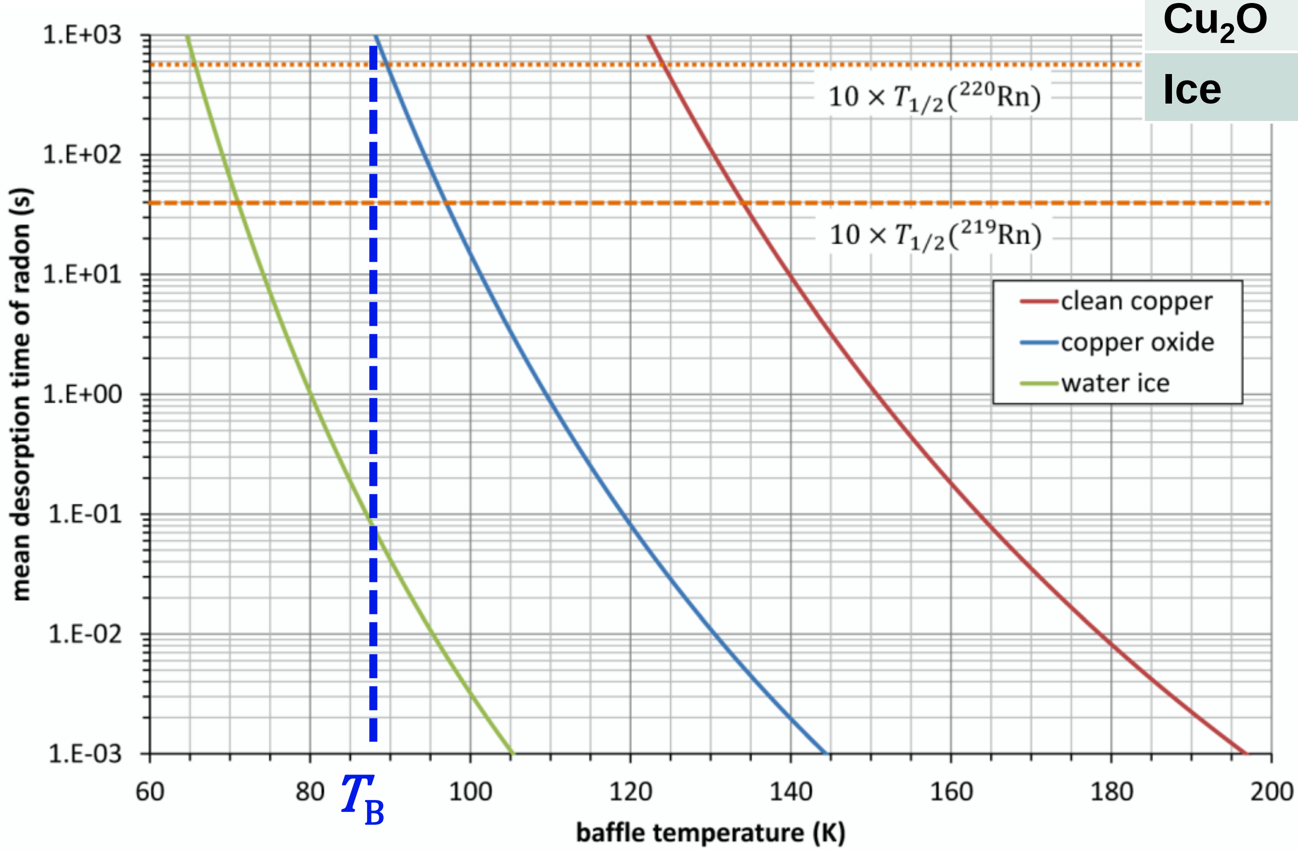
$$R(T_1) = \frac{\mathrm{Hit_g}(T_1)}{\mathrm{Hit_g}(T_0)} \cdot \frac{\mathrm{Des}\ (T_0)}{\mathrm{Des}\ (T_1)} \cdot \frac{S_{\mathrm{eff}}(\alpha_1)}{S_{\mathrm{eff}}(\alpha_0)} \cdot \frac{S_{\mathrm{eff}}(\alpha_0) + \lambda_{\mathrm{Rn}} \cdot V}{S_{\mathrm{eff}}(\alpha_1) + \lambda_{\mathrm{Rn}} \cdot V}$$

(all parameters simulated with **standard MolFlow+** and $\alpha_{\mathrm{eff}}(T_i)$)

Desorption time of copper cryo panels

- **possible problem:**
  - water ice on cryo-panels
  - strongly reduced desorption time

material	τ_0 in 10^{-13}s	H_{des} in kJ/mol
Cu	1.5 [2]	37 [4]
Cu_2O	3.9 [1]	26 [4]
Ice	3 [3]	19.2 [4]



[1] M. H. Manghnani et al (1974)

[2] B. Eichler et al (2000)

[3] B. Eichler et al (2000)

[4] R. Eichler et al (2002)

$$\tau_{des} = \tau_0 \cdot \exp\left(\frac{H_{des}}{R \cdot T}\right)$$

MolFlow+ simulation of radon

- **modified MolFlow+ code:**
  - particles can have a **mean lifetime**
  - facets can have a **finite residence time**
  - **sticking coefficient** usually set to **α = 1**

$$\tau_{Rn} = t_{1/2} / \ln(2)$$

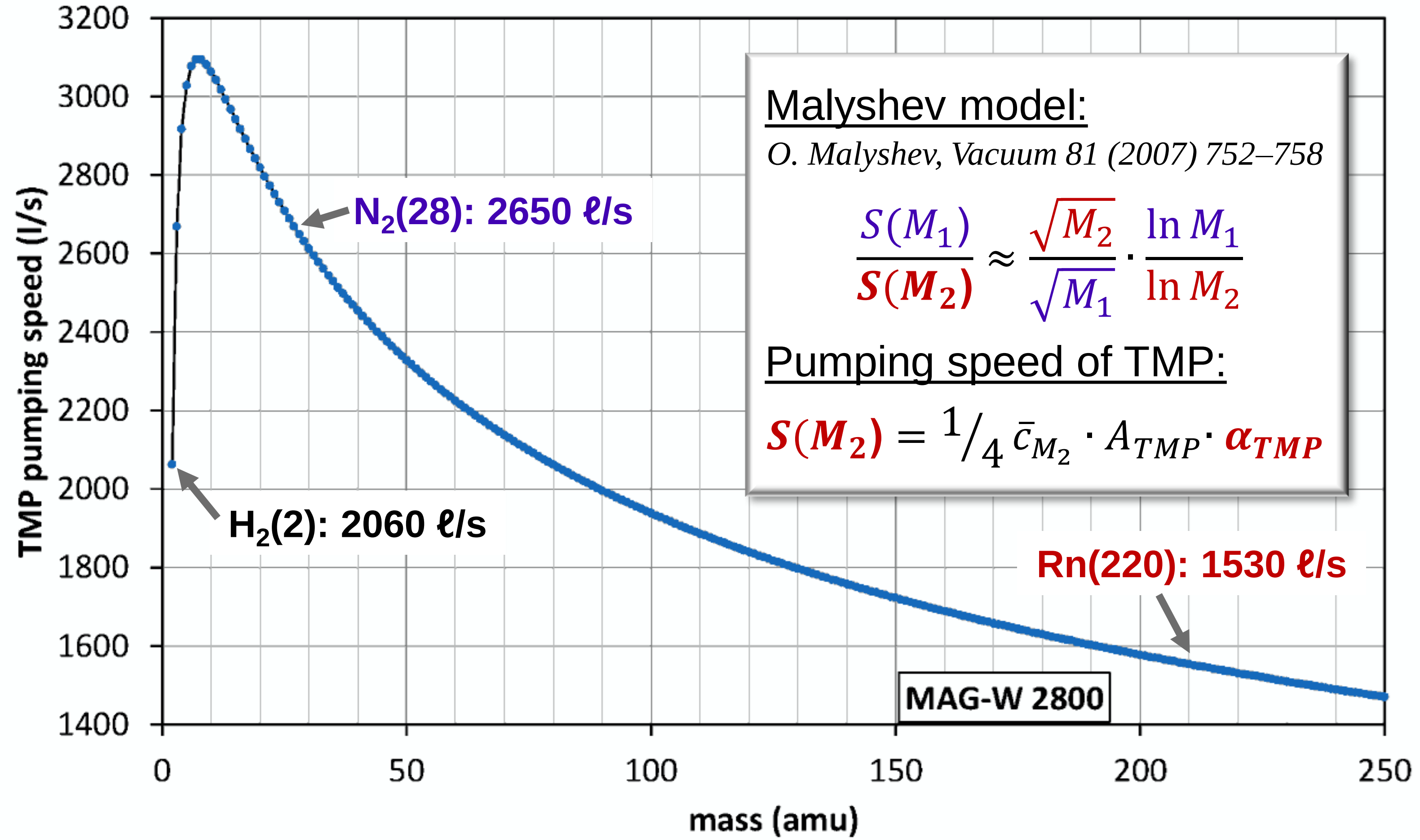
$$\boldsymbol{\tau}_{\mathbf{des}} = \boldsymbol{\tau}_{\mathbf{0}} \cdot \exp\left(\frac{\Delta H_{\mathrm{des}}}{R \cdot T_{\mathrm{B}}}\right) > \mathbf{0}$$

$$\boldsymbol{\tau}_{\mathbf{des}} = \infty \text{ if } \boldsymbol{\tau}_{\mathbf{des}} < \mathbf{0}$$

  - **absolute lifetime** (time of decay) calculated at the start of the tracking
  - **decay in volume**:
    - **time of flight** in vacuum (calculated by MolFlow+) subtracted from lifetime,
    - **3D coordinates** of decay position **stored** in file,
    - **#volume_decays** incremented
  - **decay on adsorbing surface**:
    - decay occurs within residence time on surface
    - **#adsorption(facet)** incremented
  - **re-desorption from surface**:
    - residence time subtracted from lifetime,
    - **#hits(facet)** incremented
    - **#re-desorptions(facet)** incremented

TMP simulation

- Determine pumping speed of TMP for **mass of gas particle** (Malyshev model)
- Simulate **pumping probability** $w = N_{ads}/N_{des}$
- **Effective pumping speed**: $S(M_2) = {}^1/_4\, \bar{c}_{M_2} \cdot A_{port} \cdot w$



Malyshev model:

O. Malyshev, Vacuum 81 (2007) 752–758

$$\frac{S(M_1)}{S(M_2)} \approx \frac{\sqrt{M_2}}{\sqrt{M_1}} \cdot \frac{\ln M_1}{\ln M_2}$$

Pumping speed of TMP:

$$S(M_2) = {}^1/_4\, \bar{c}_{M_2} \cdot A_{TMP} \cdot \alpha_{TMP}$$

Simulation of an effective pumping speed

- Simulate pump as surface with an **adsorption probability** α
- Determine **pumping probability**: $\boldsymbol{w} = N_{ads}/N_{des}$
- Calculate the **effective pumping speed**: $\boldsymbol{S} = {}^{1}/_{4}\,\bar{c}_M \cdot A_{port} \cdot \boldsymbol{w}$

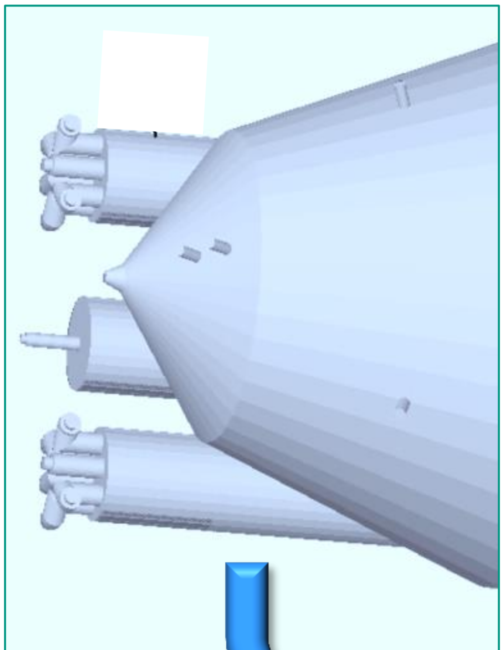
$\bar{c}$: mean molecular speed for mass M

$$\bar{c} = \sqrt{\frac{8k_{\mathrm{B}}T}{\pi M}}$$

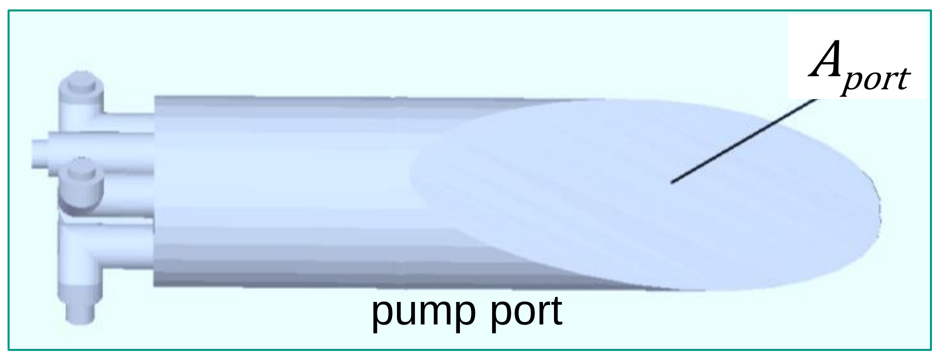
A_{port} : desorption area (virtual area)

N_{ads} : number of adsorptions in pump

N_{des} : total desorption number

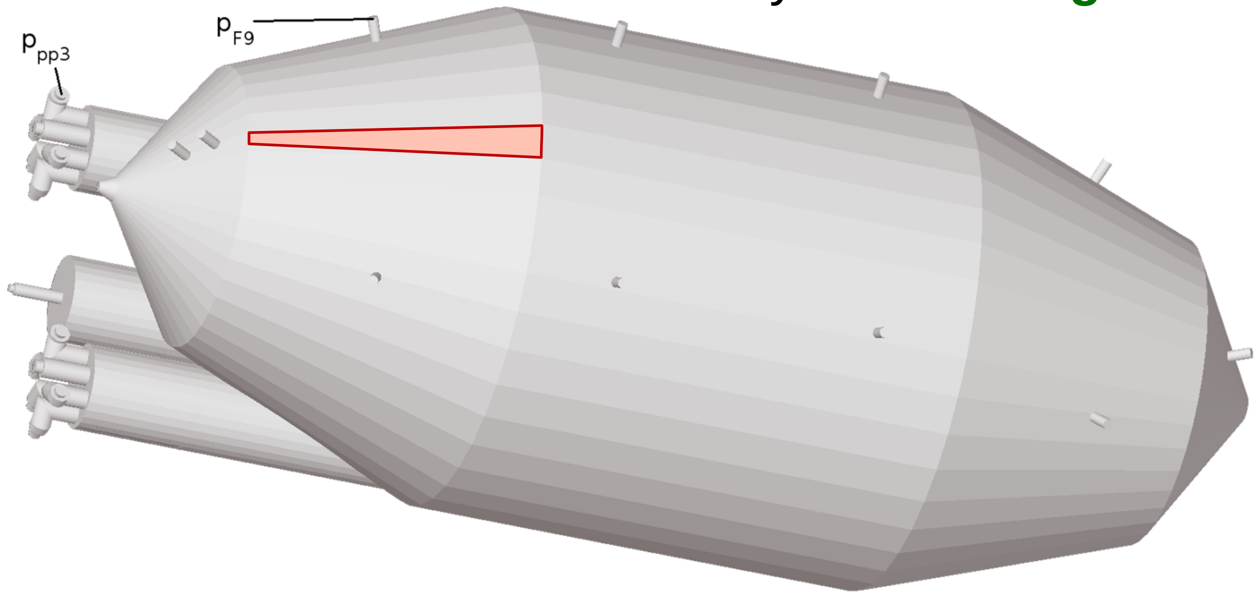


simplified model



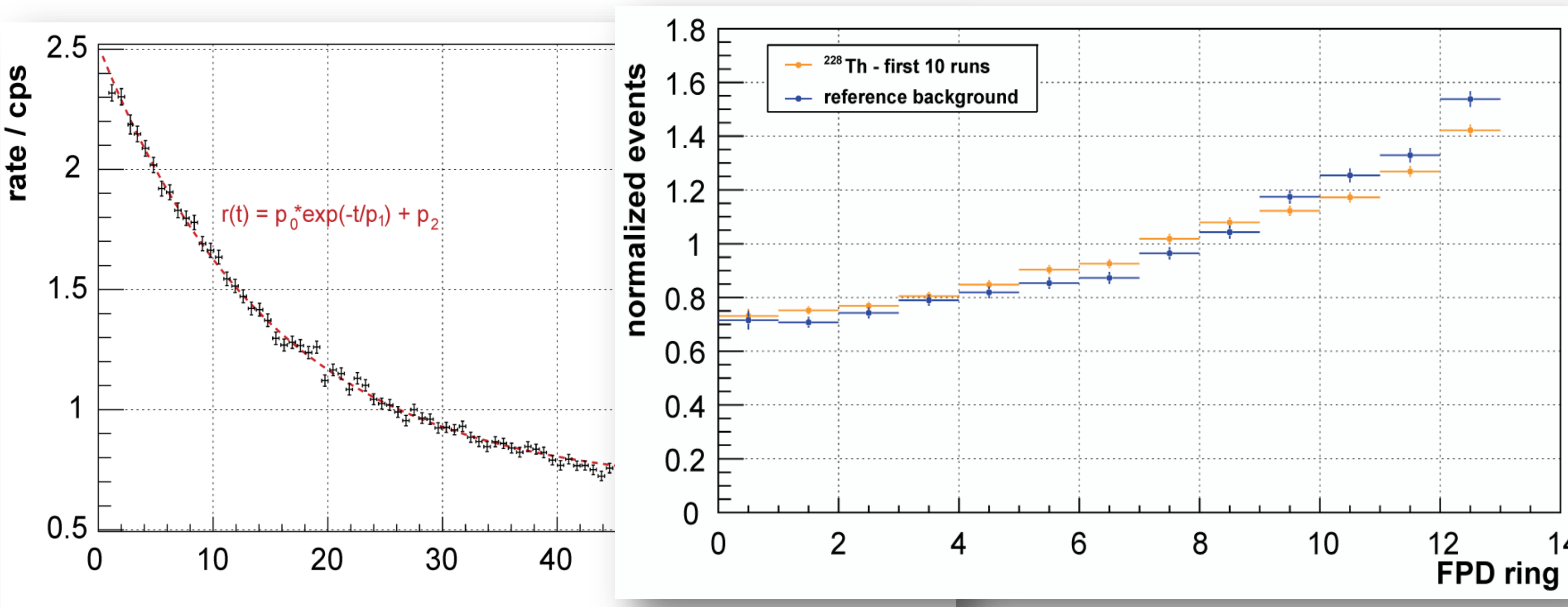
Simulation of the Main Spectrometer

- **MolFlow+:** Test Particle Monte Carlo code
- simplified model with **flat surface elements** (= *facets*)
- **particle tracked** until adsorbed (pumped out)
- each **facet** counts:
  - **#desorptions** (source)
  - **#hits** (pressure) → particle scattered or adsorbed,
  - **#adsorptions** (pumping),
- **adsorption** on a surface is controlled by the **sticking coefficient** α



KATRIN spectrometer status: Rydberg atoms

- **Test of Rydberg hypothesis with ^{228}Th source** (*courtesy of XENON collaboration*)
  - ^{220}Rn emanation (20 h exposure) → ^{212}Pb contamination of wall ($T_{1/2}$ = 10.6 h)
  - increased background rate
- **after seperation of source: exponential decay of rate ($T_{1/2}$ = 10.5 h)**
- **radial rate distribution same as Rydberg background**
- **Conclusion: ^{210}Pb from ^{222}Rn decays most likely cause of increased background rate**



Sensitivity and background

- Further **background reduction measures** being studied
- In addition: **several mitigation strategies** currently under investigation:

- optimized scanning
- range of spectral analysis
- flux tube compression by increasing B