Mitigation of radon background by surface coating for the next generation of liquid xenon dark matter detectors

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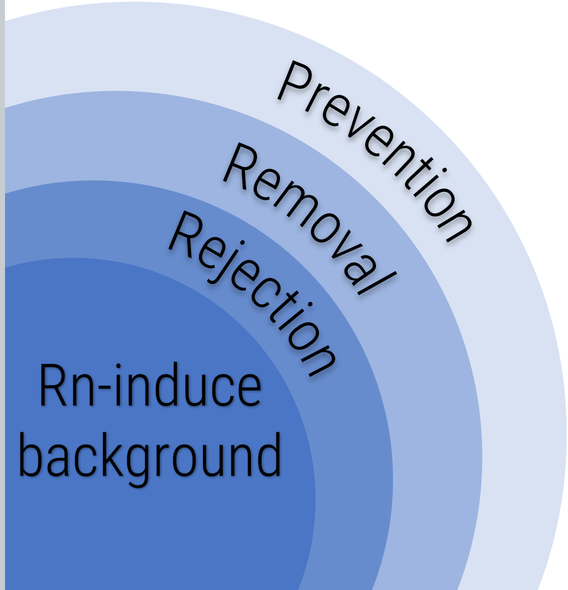
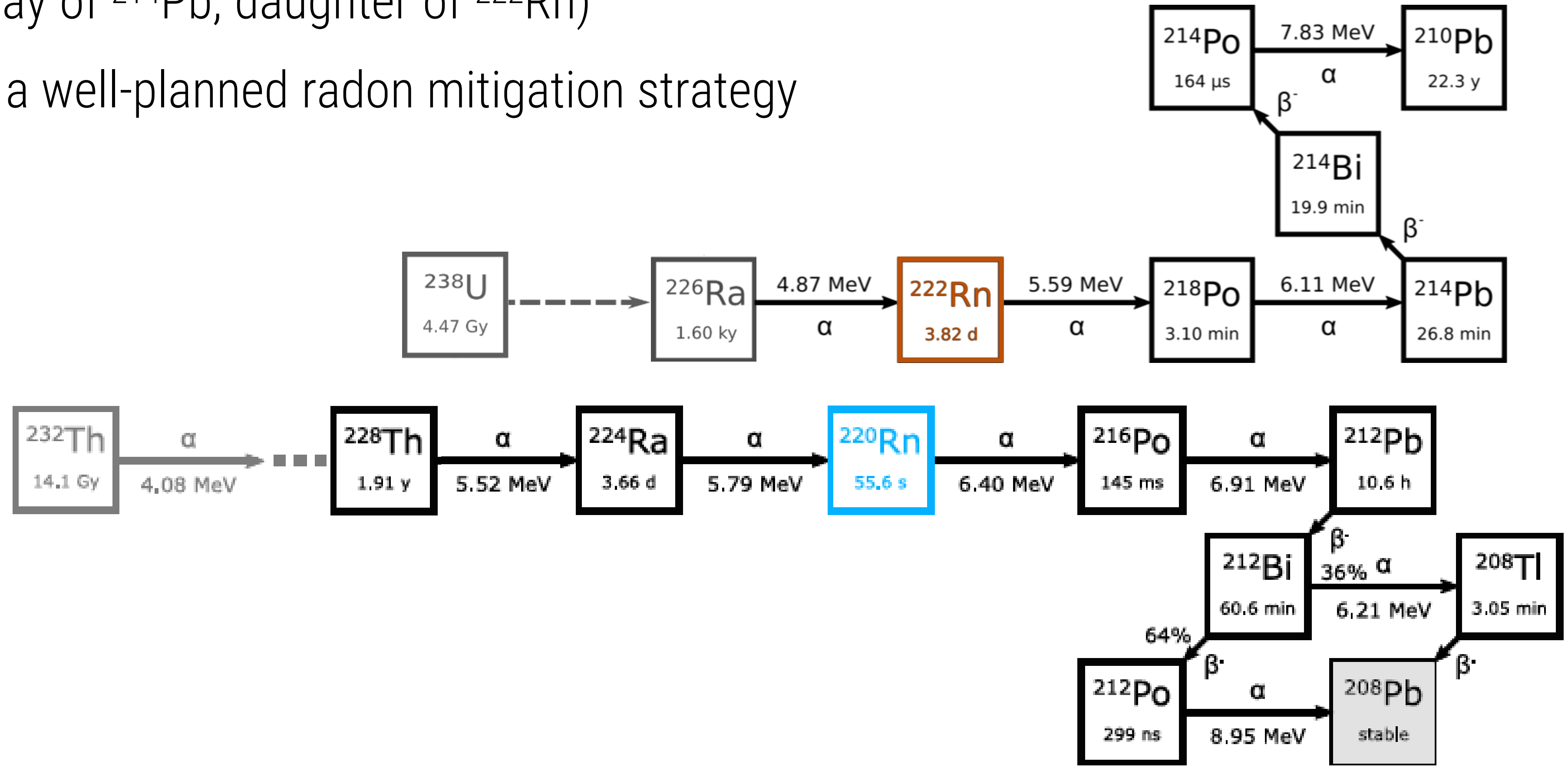
Radon background in rare event searches

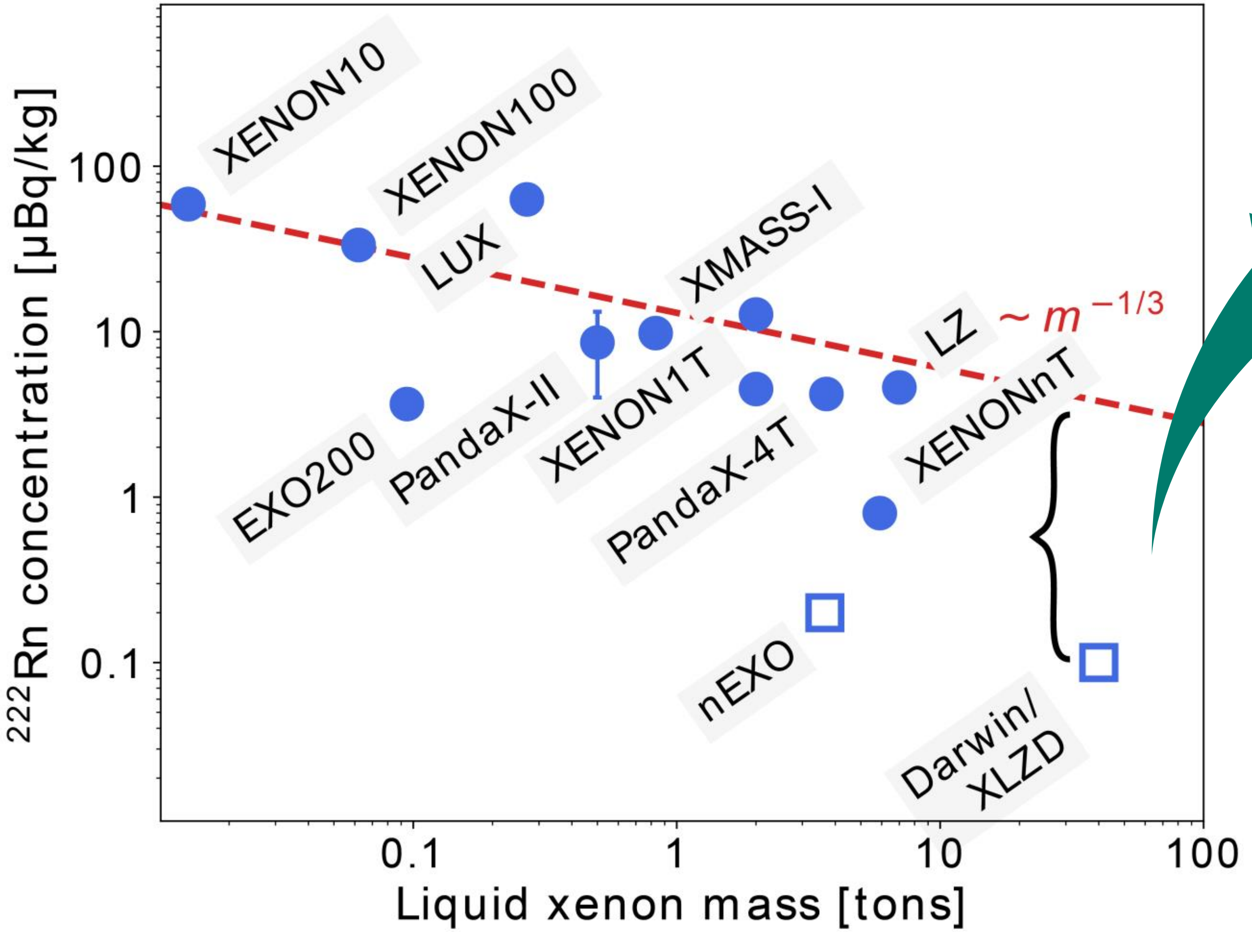
- Rn-induce background are of great importance in many rare-event searches (e.g, dark matter)
- Radon atoms are found naturally in the environment and in detector components as part of U/Th decay chains.
- Radon progeny radioactive decay within the energy range of WIMP searches hampers detector sensitivity (e.g., β decay of ^{214}Pb, daughter of ^{222}Rn)
- Its reduction requires a well-planned radon mitigation strategy





Radon requirement for future Xe-based detectors

- DARWIN/XLZD (≥40 t active LXe volume) aims for ×10 reduction in the radon content to probe WIMP-nucleon cross sections down to a few 10^{-49} cm^2 [1]
- The current technology and the volume dilution is not enough to reach ~0.1 µBq/kg



Largest background reduction challenge:

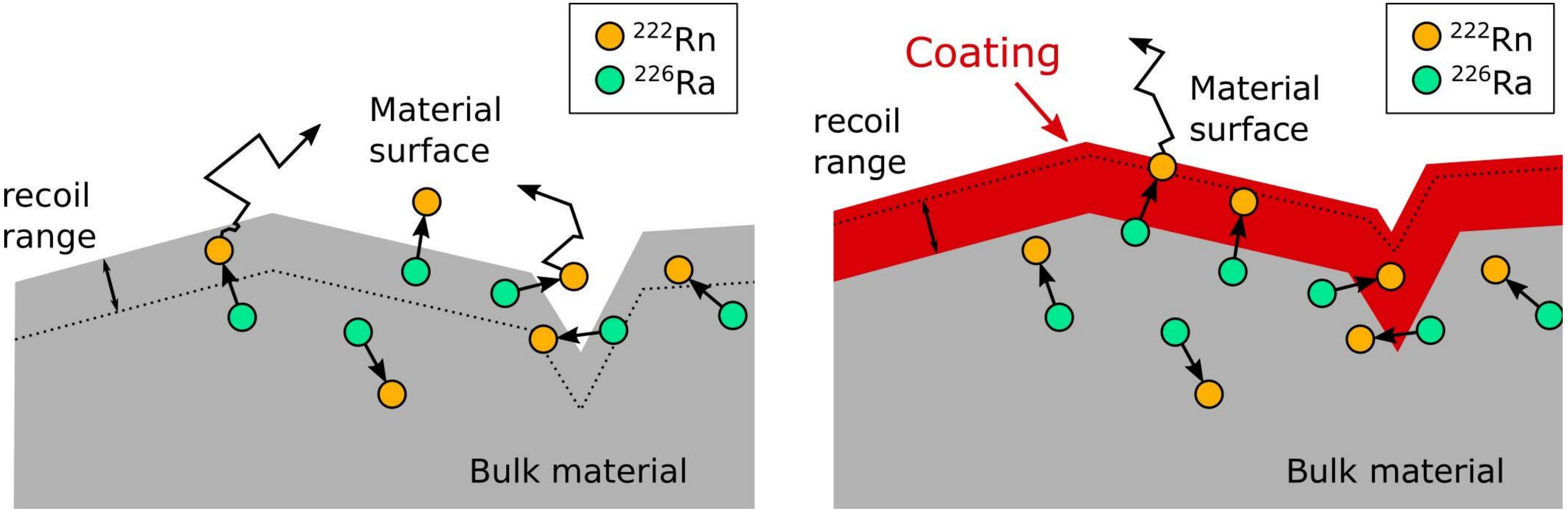
1. Aggressive ^{222}Rn assay campaign previous detector construction
2. Improvement of current purification techniques
3. Prevention of Rn emanation into the target
4. …

[1] Assuming a rejection of ERs at the 2×10^{-4} level at 30% NR acceptance

Surface coating: novel mitigation strategy

PhD thesis, Florian Joerg, Heidelberg University

IDEA - Reduce the radon released from a material by a thin coating layer which seals its surface



REQUIREMENTS

- Thick enough to contain the radon recoil ($O(10\ nm)$ for $E^{222Rn}_{recoil\ energy} = 86.2\ keV$, $E^{220Rn}_{recoil\ energy} = 103.4\ keV$)
- Sufficiently tight to prevent radon diffusion
- Must feature a high degree of radio purity, especially regarding ^{226}Ra

Investigated techniques

PhD thesis, Florian Joerg, Heidelberg University

- Radon reduction factor R was investigated for several techniques using thoriated welding rods
- $R = {A_{before}}/{A_{after}}$, where A is ^{220}Rn (^{222}Rn) the activity measured using electrostatic radon monitor (proportional counters)

Method	Coating Material	Thickness [µm]	Reduction	
			^{220}Rn	^{222}Rn
Sputtering	Titanium	0.4 – 0.8	4.5	~ 2.1
Plasma spraying	Copper	3	22	//
Epoxy resin	Stycast	≈ 200	≥ 74	//
Chemical Vapor deposition	Diamon like carbon	1	3	~ 1.4
Electrochemical plating	Copper	5	150	~ 7.4

Electrochemical plating (EPC) of copper

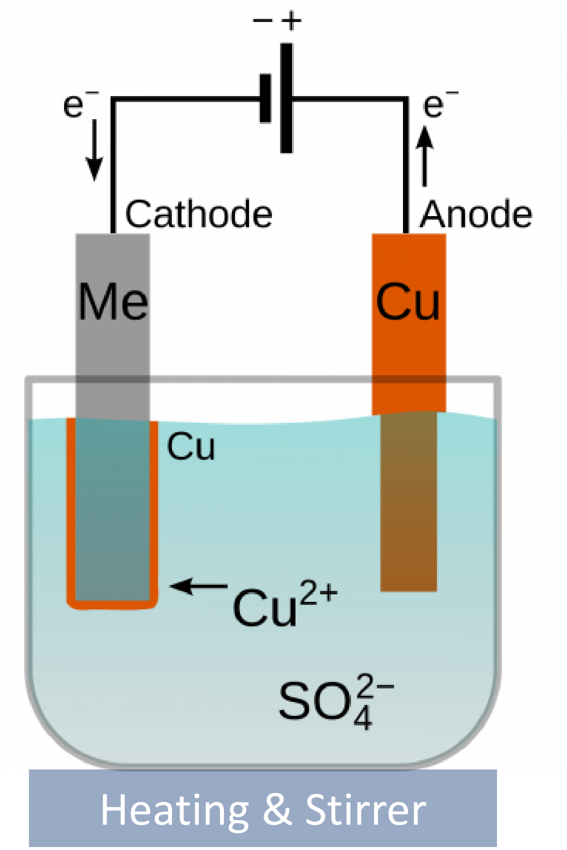
- ECP of copper performed with a local setup at MPIK laboratory
- Motivated literature results on radiopure electro-formed copper
- Electrolyte: 0.05 mol/l $CuSO_4$ + 1 mol/l H_2SO_4
- Solution heated to ~45°C and continuously stirred

Reduction at the metal workpiece:

$$Cu^{2+}_{(aq)} + 2e^{-} \rightarrow Cu_{(s)}$$

Best results obtained (for 5 µm layer) with

$$50\ \text{mA/cm}^2 \xrightarrow[1\ \mu m]{} 10\ \text{mA/cm}^2$$

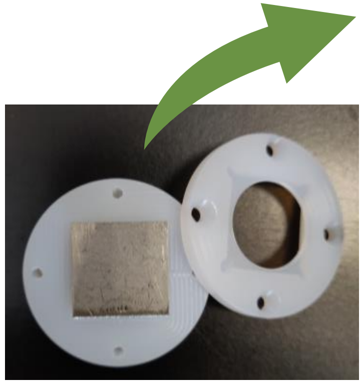


Giovanni Volta, 16 Feb 2024

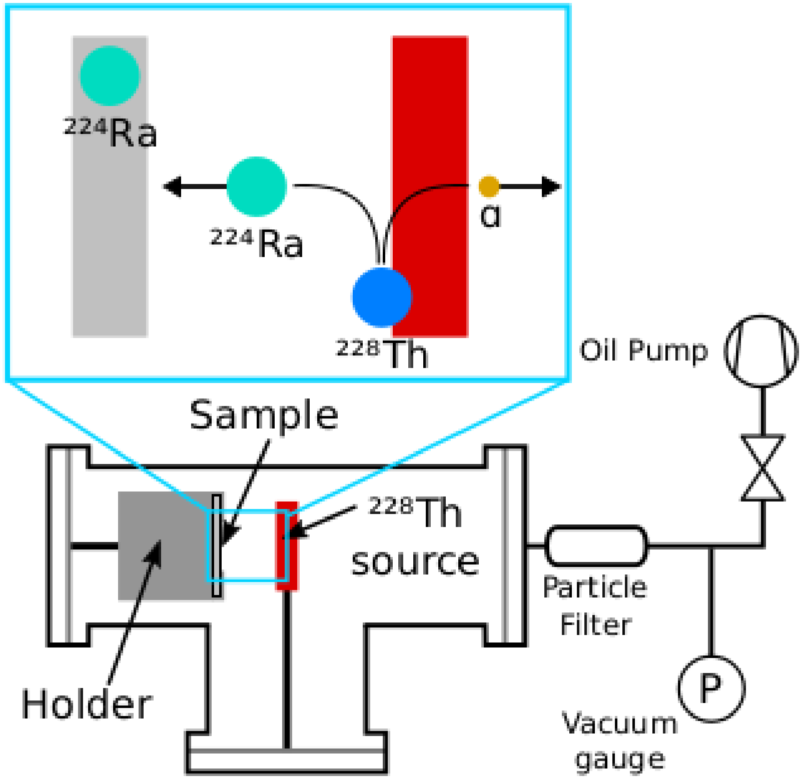
Validation with ^{224}Ra implanted samples

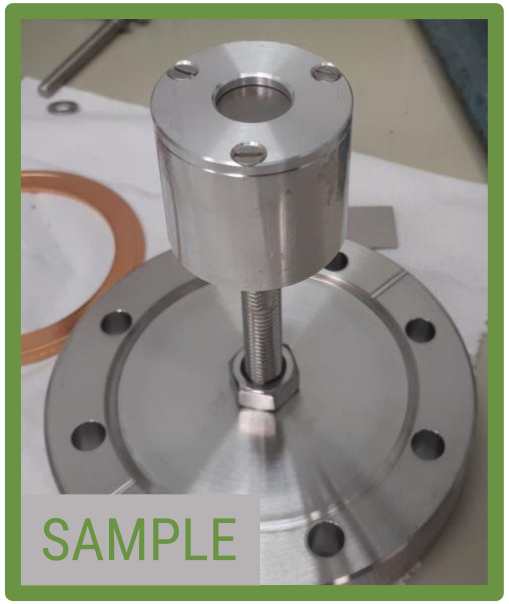
PhD thesis, Florian Joerg, Heidelberg University

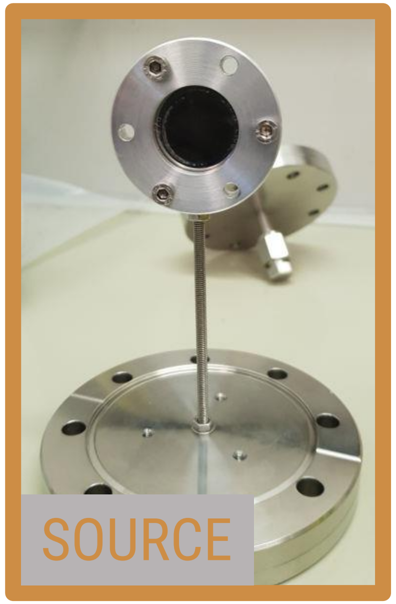
- Reproducibility of ECP procedure on stainless stell[1] verified using *homemade* ^{224}Ra recoil implanted stainless steel samples - $A_{implanted} = \mathcal{O}(10\text{Bq})$
- Rather superficial implantation and widely spread
- Challenging due to the short half-life of ^{224}Ra ($T_{1/2} \approx 3.6$ days)



$\Longrightarrow$ ^{220}Rn emanation source



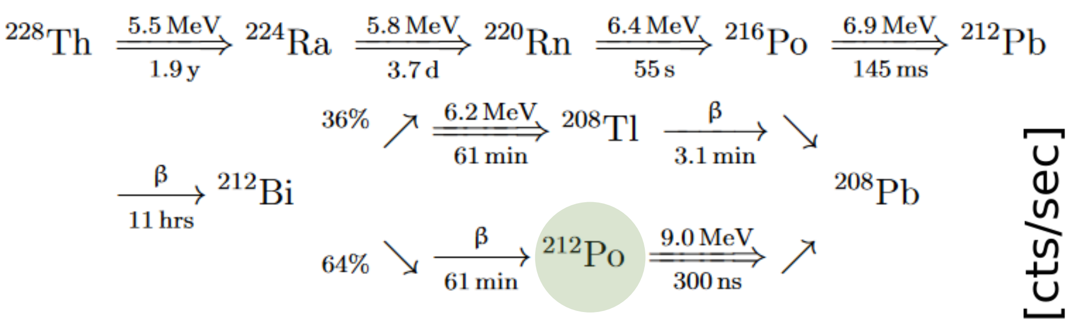


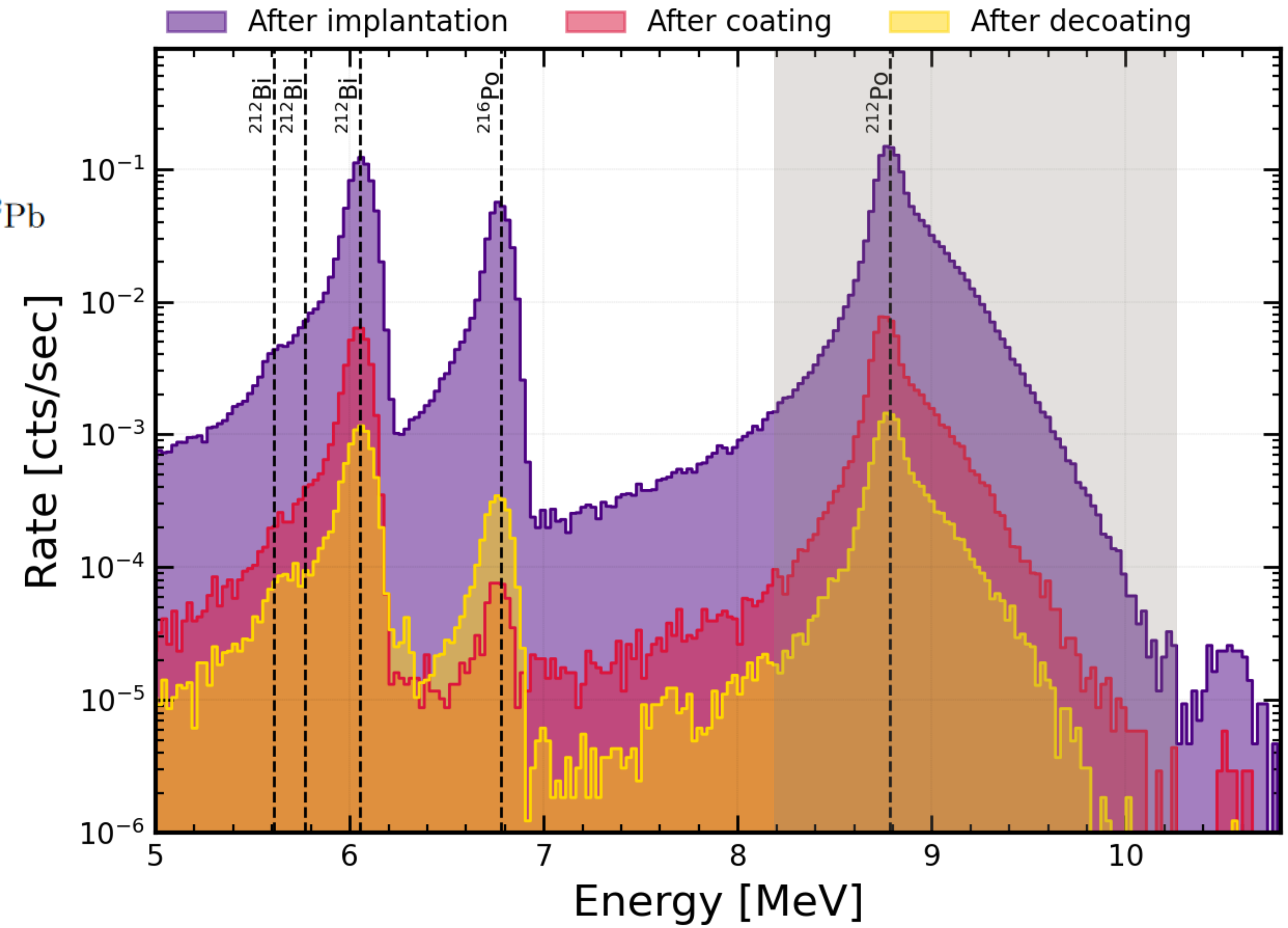


[1] 2 cm × 2 cm × 1 cm

^{220}Rn emanation measurements

- Three individual radon emanation measurements (~ one week each): before coating, after coating, after decoating
- The ^{220}Rn emanation rate estimated based on the detected ^{212}Po activity, accounting for the full decay chain (e.g., Bateman equation)





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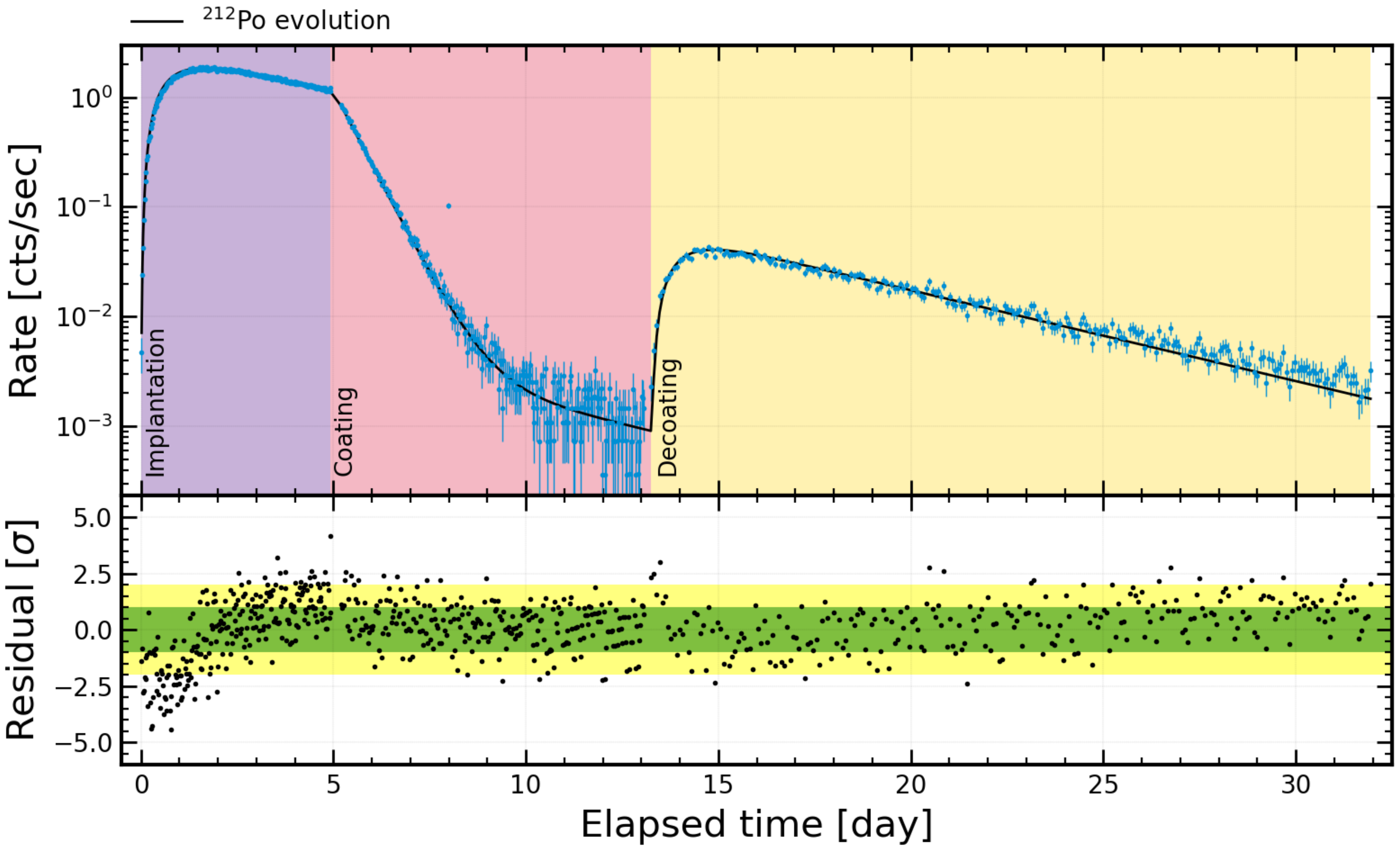
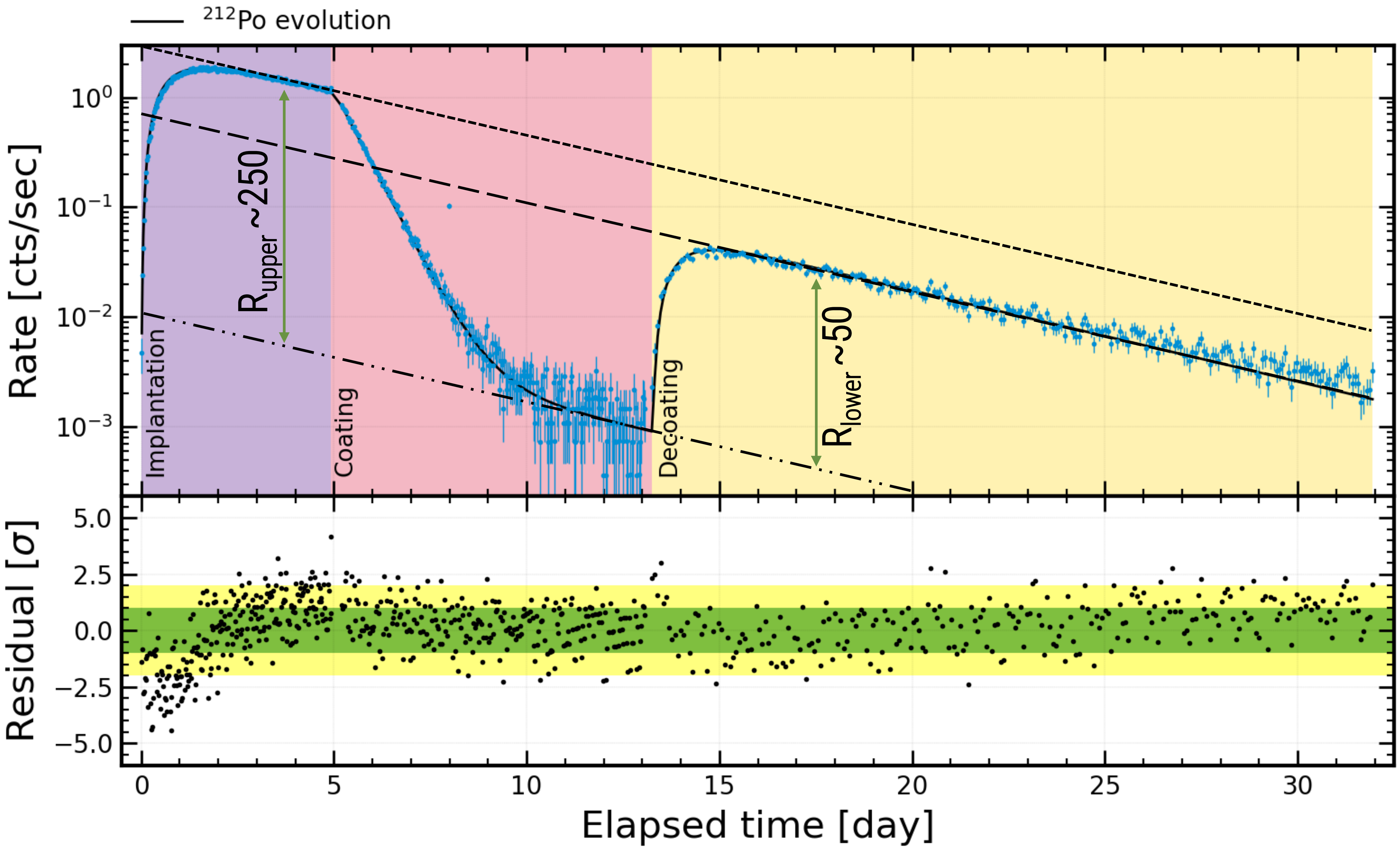
^{212}Po activity evolution



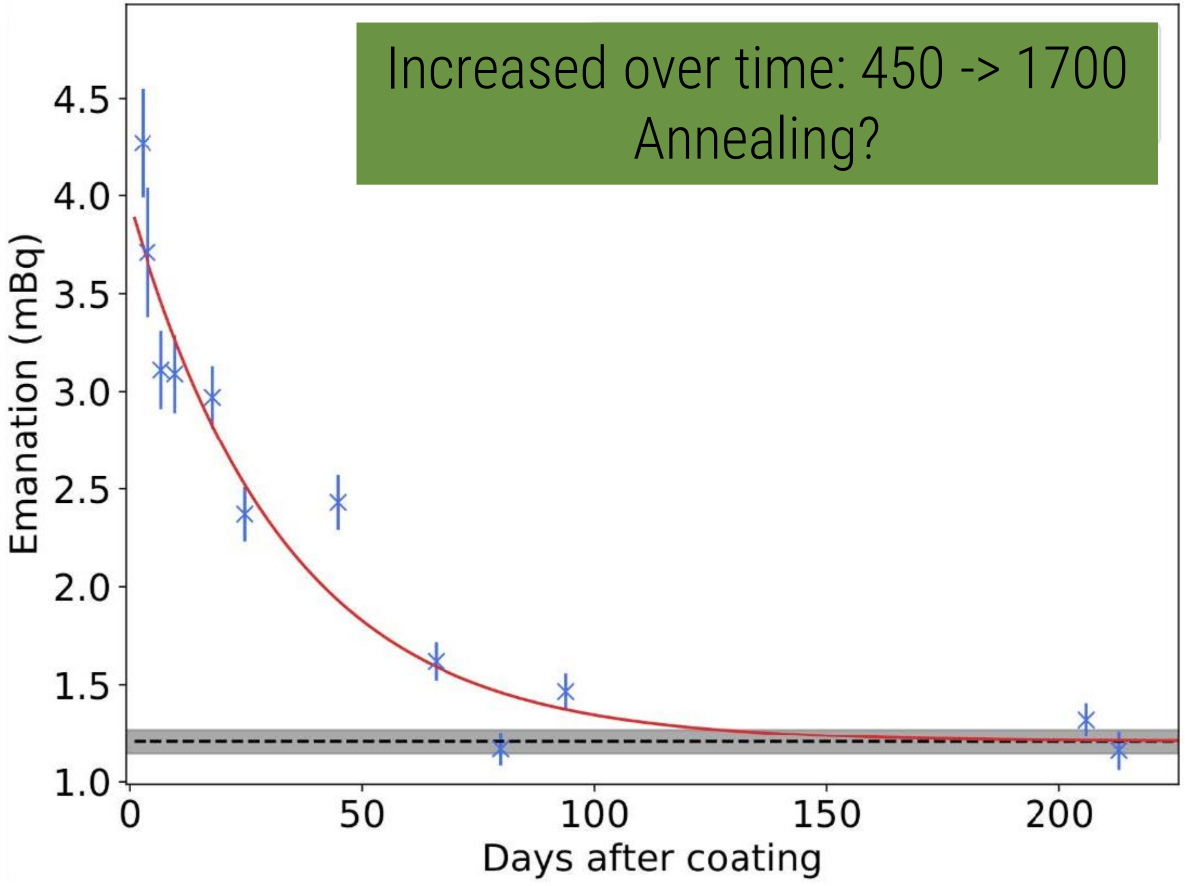
^{212}Po activity evolution

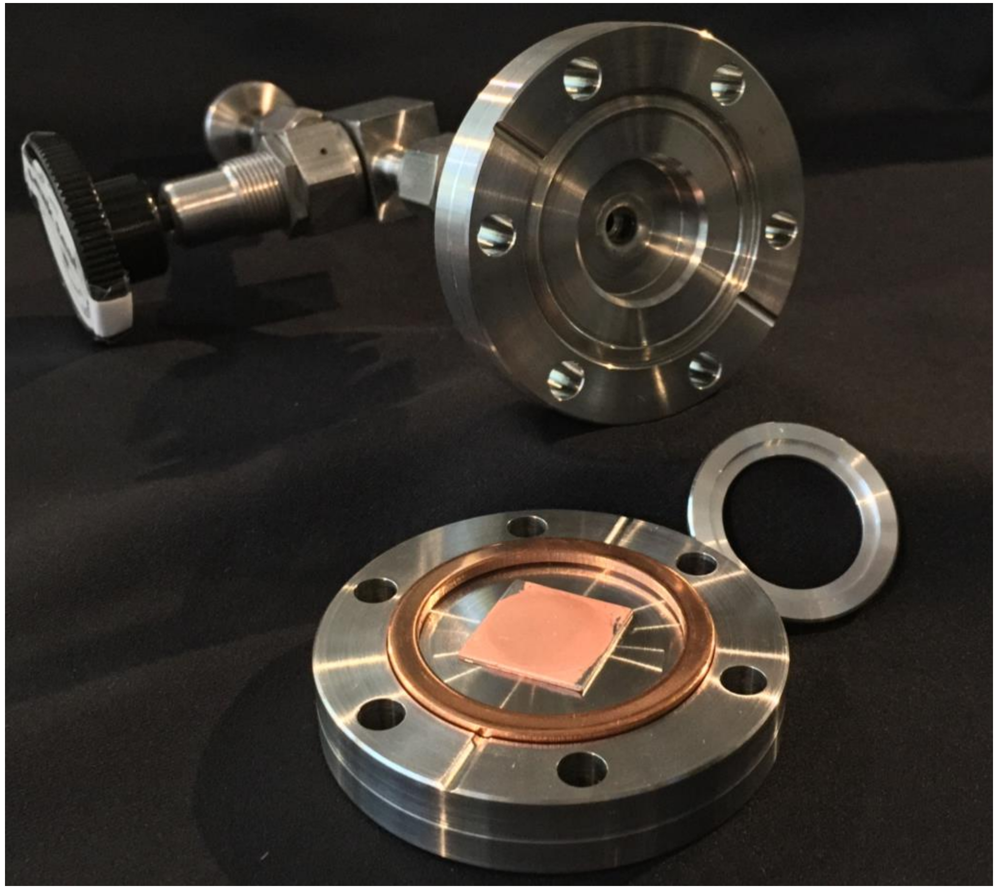


Test on ^{226}Ra implanted sample

PhD thesis, Florian Joerg, Heidelberg University
Production and characterization of a 222Rn-emanating stainless steel source, Joerg, F. and others

- Two stainless steel[1] ^{222}Rn sources produced at ISOLDE facility in 2017 via implantation of ^{226}Ra
- ~ 8 Bq implanted in 1 cm x 1 cm area at the center, with mean depth of 7.9 nm with a σ_{std} of 2.3 nm
- Unexpected large ^{222}Rn reduction factor!





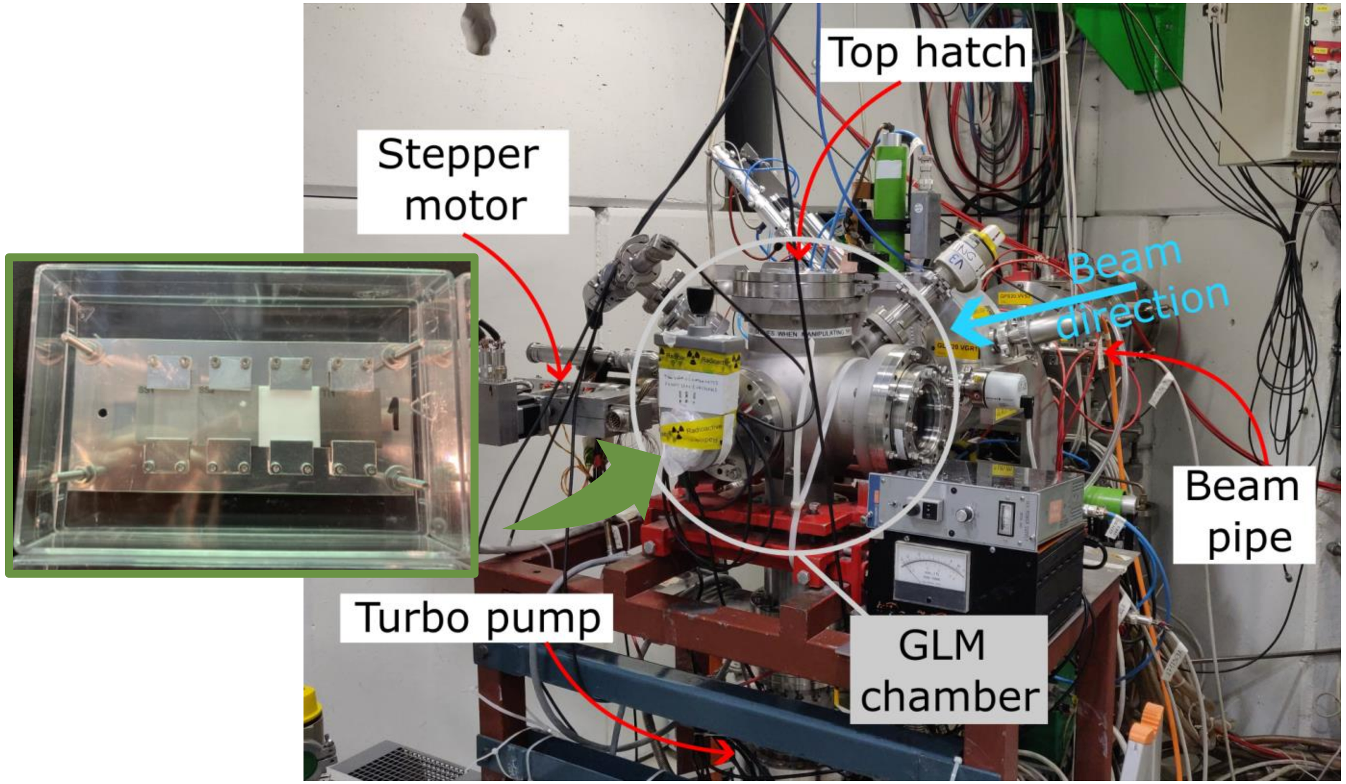
[1] 2 cm × 2 cm × 2 cm

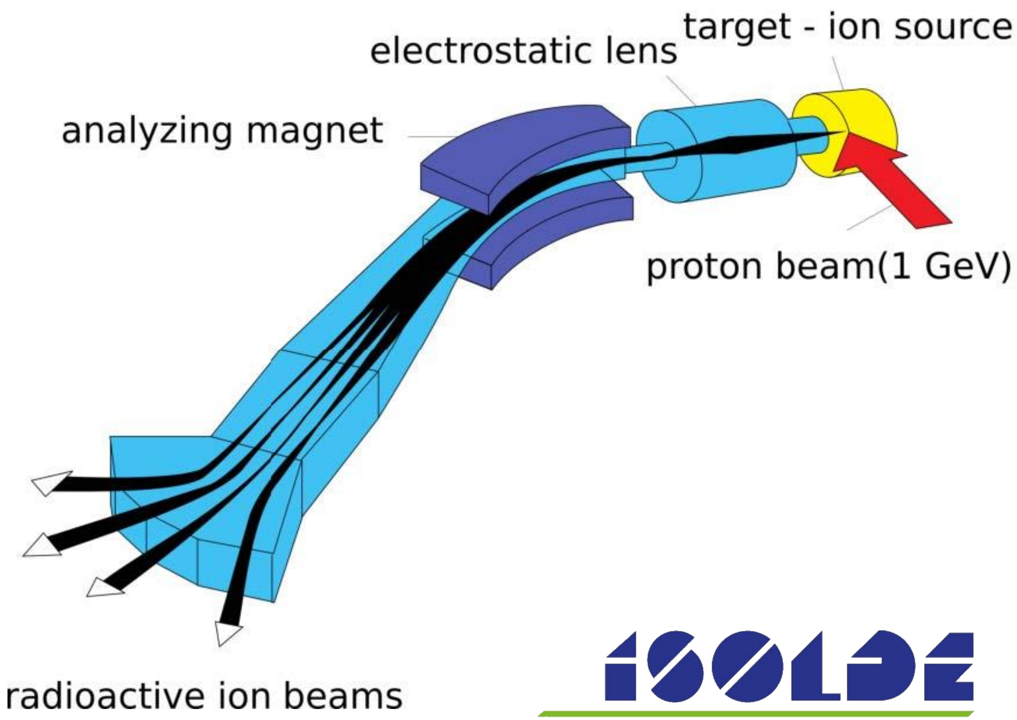
Short term goals:

- Verify ISOLDE ^{222}Rn reduction
- Investigate deeply coating morphology
- Scale up ECP setup
- Characterize further ECP procedure

New ISOLDE implantation campaign

- New ^{226}Ra implantation campaign performed last November
- Not only stainless steel but also other metals (copper, titanium, lead) as well as insulators (PTFE, acrylic, glass) and semiconductors (germanium and silicon)
- 30 keV ^{226}Ra ion beams guided into 2 cm × 2 cm samples hosted in vacuum chamber

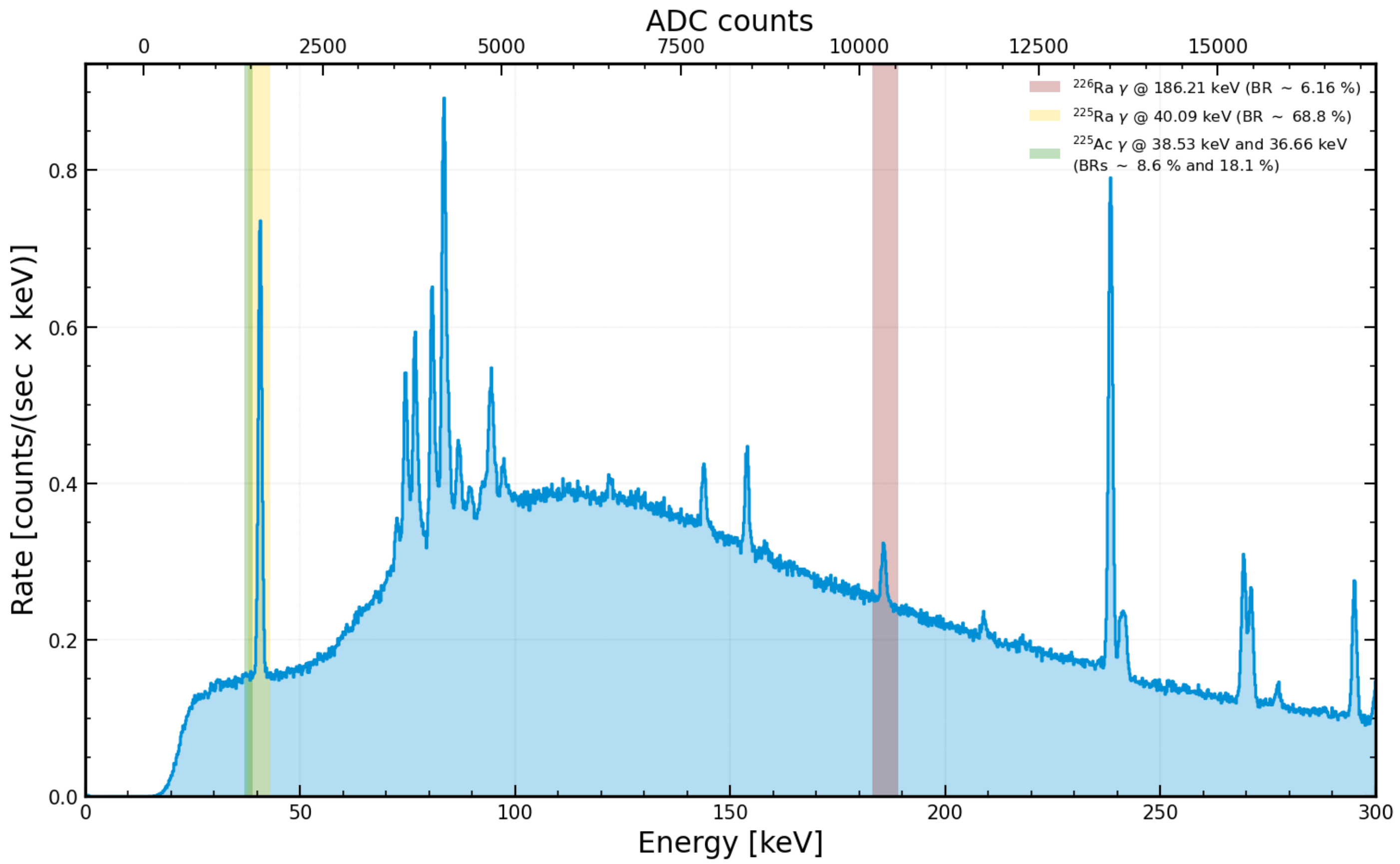




Available radon sources

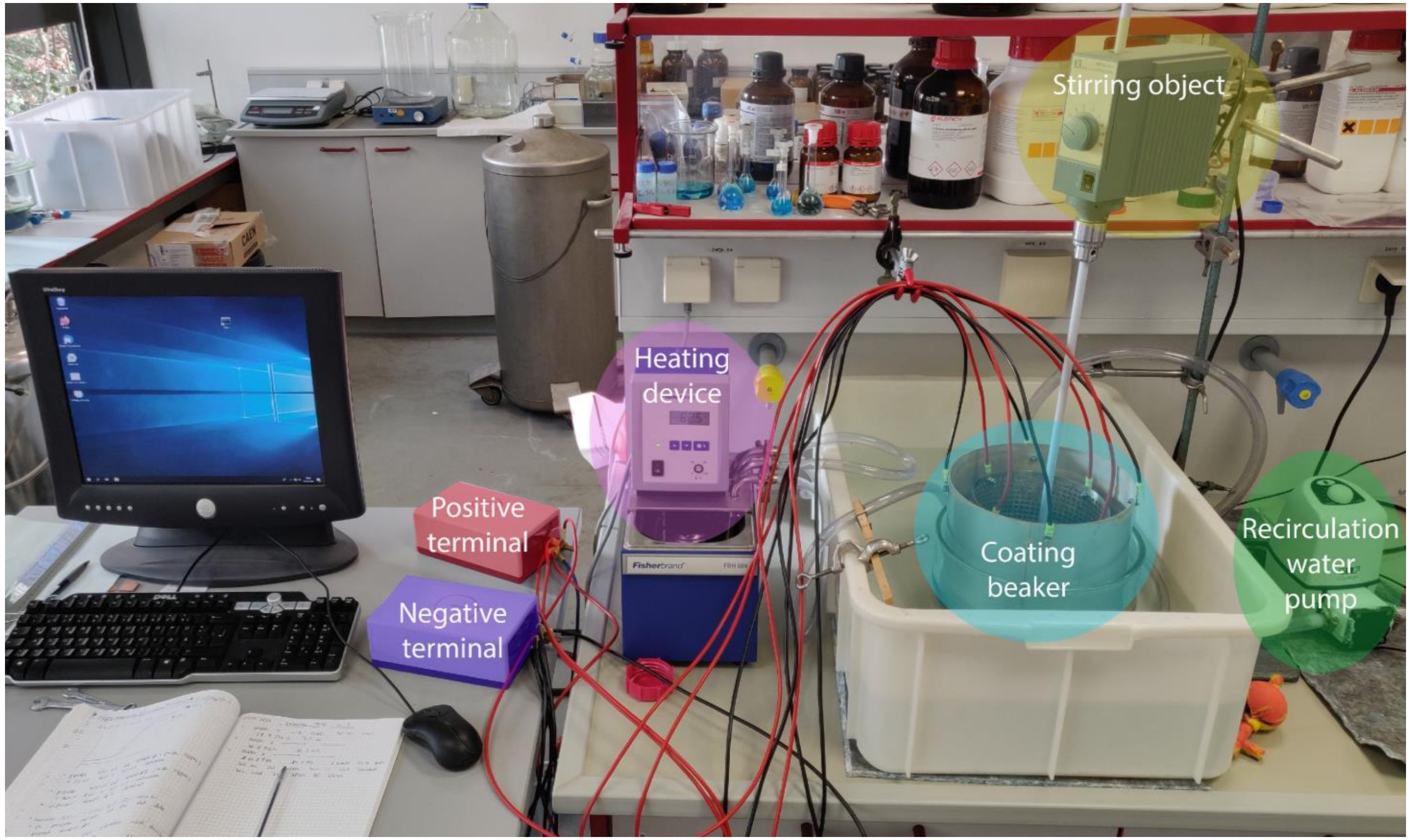
- Eleven new radon source with up to ~4 Bq of ^{226}Ra activity (verified w/ in-situ γ-spectroscopy)
- Sample arrived in February 2024 at MPIK: full characterization started (e.g., α- and γ- spectroscopy, and Rn emanation measurements)

Sample	^{226}Ra ions implanted [×10^{11}]	^{226}Ra expected activity [Bq]
SS #11	1.5	2.05
Ti #04	3.0	4.1
SS #10	0.03	0.04
Cu #02	3.5	4.8
SS #01	3.0	4.1
SS #02	3.0	4.1
PTFE #01	0.26	0.36
Ti #01	3.1	4.2
SS #07	2.2	3.02
SS #08	//	//
Pb #01	0.15	0.2



Scaling up ECP setup

- First ECP test with hollow stainless-steel cylinders
- Good mechanical adhesion obtained in all tests (e.g, survived tape test)
- Main limitation: current power supply (Delta Elektronika SM1540-D, I_{max}=40 A) and bulky setup



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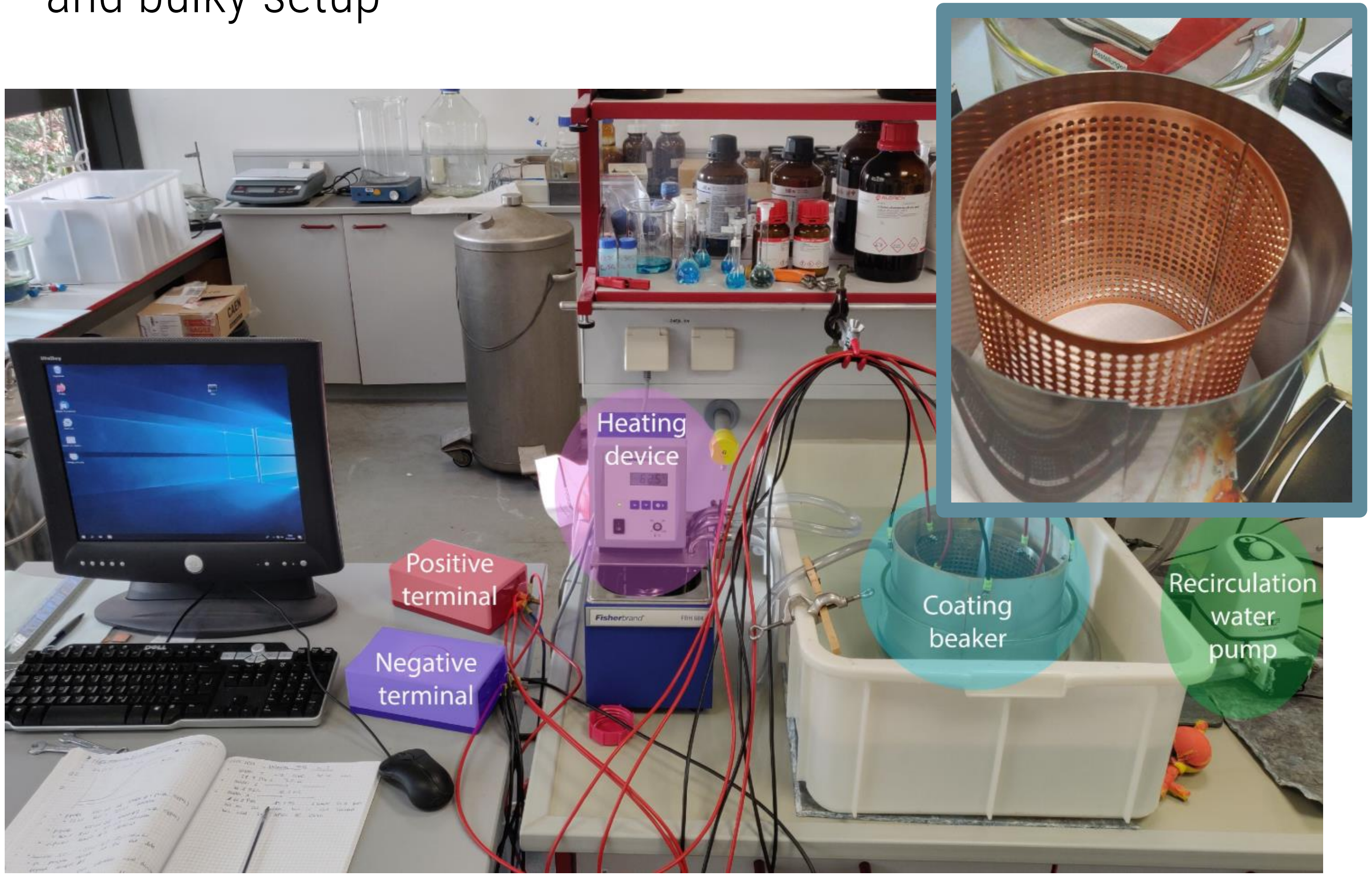

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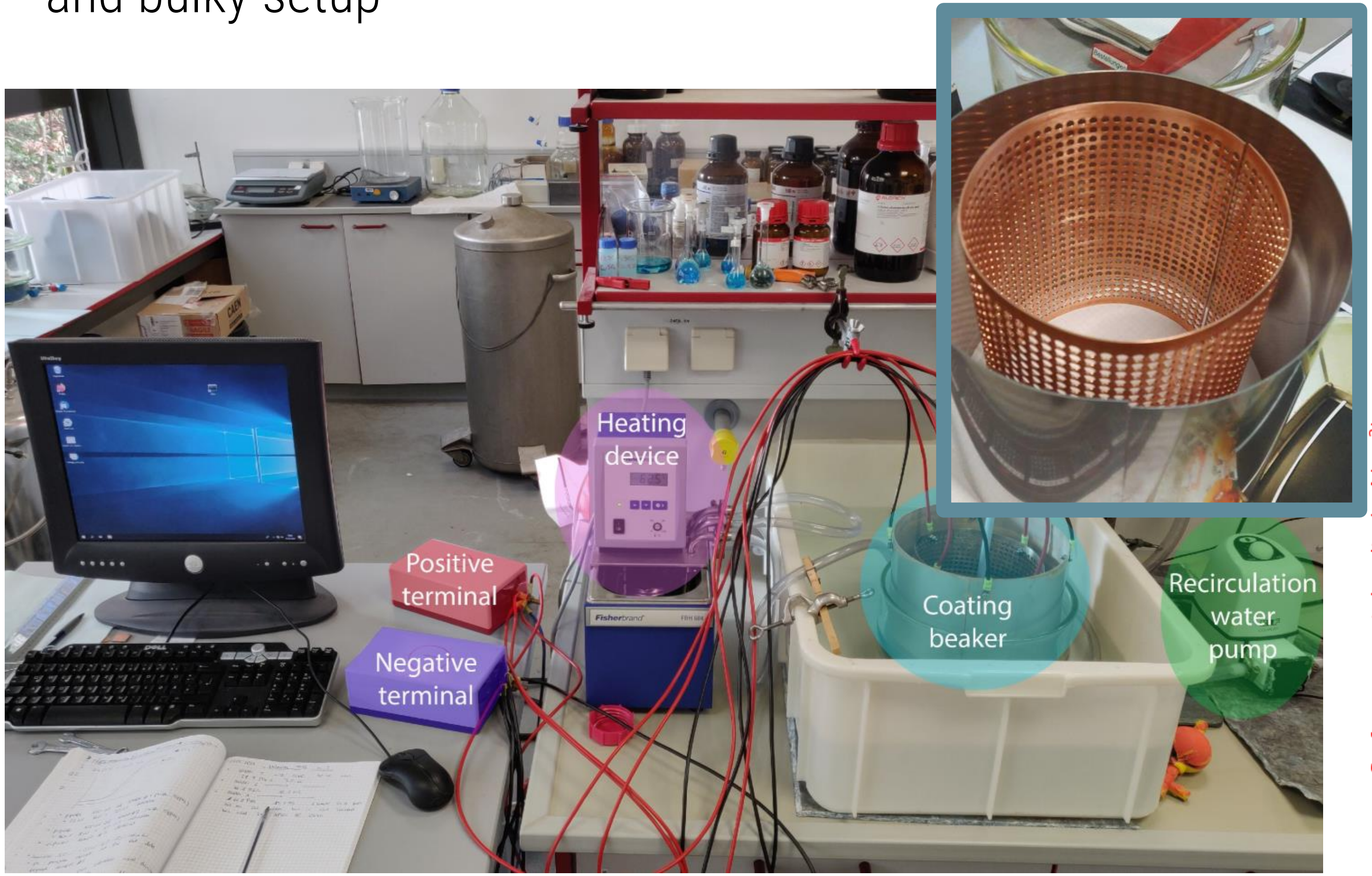

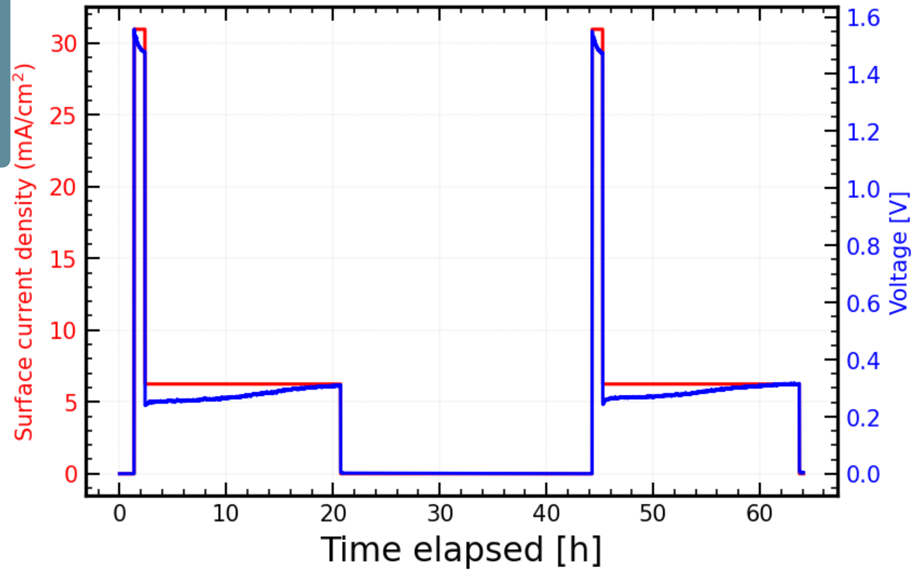

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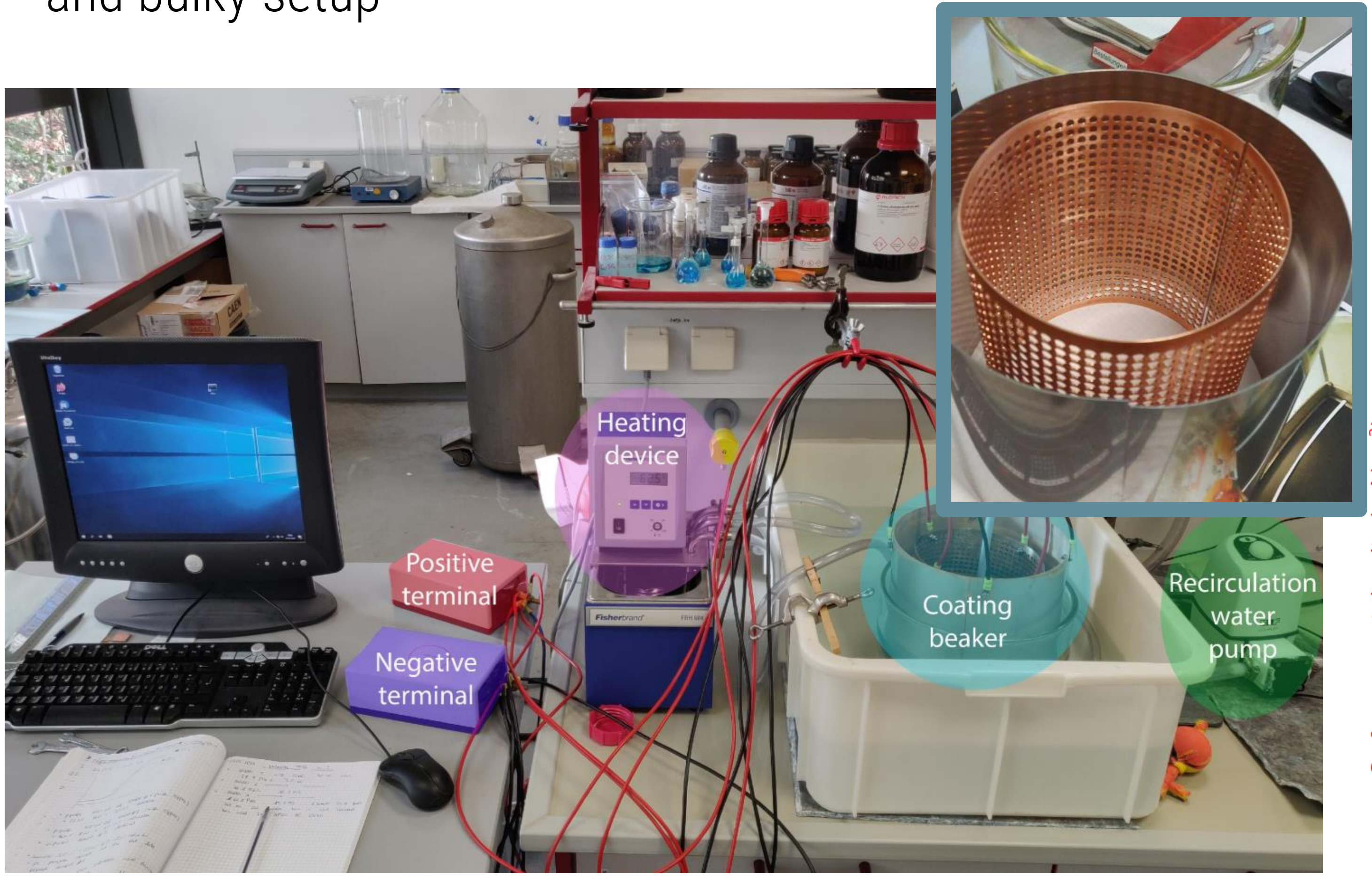
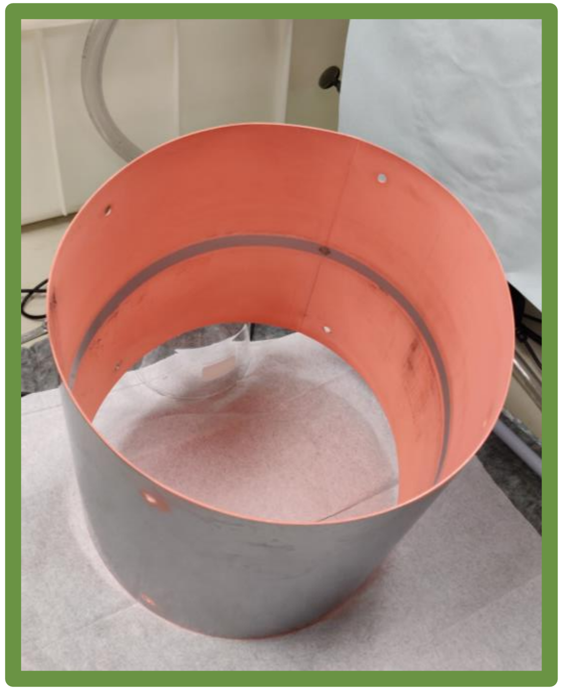
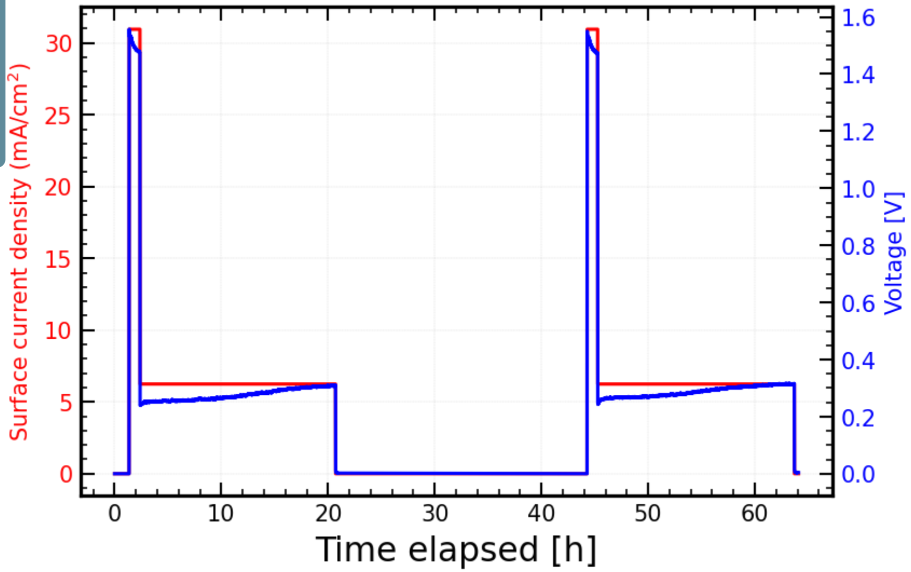




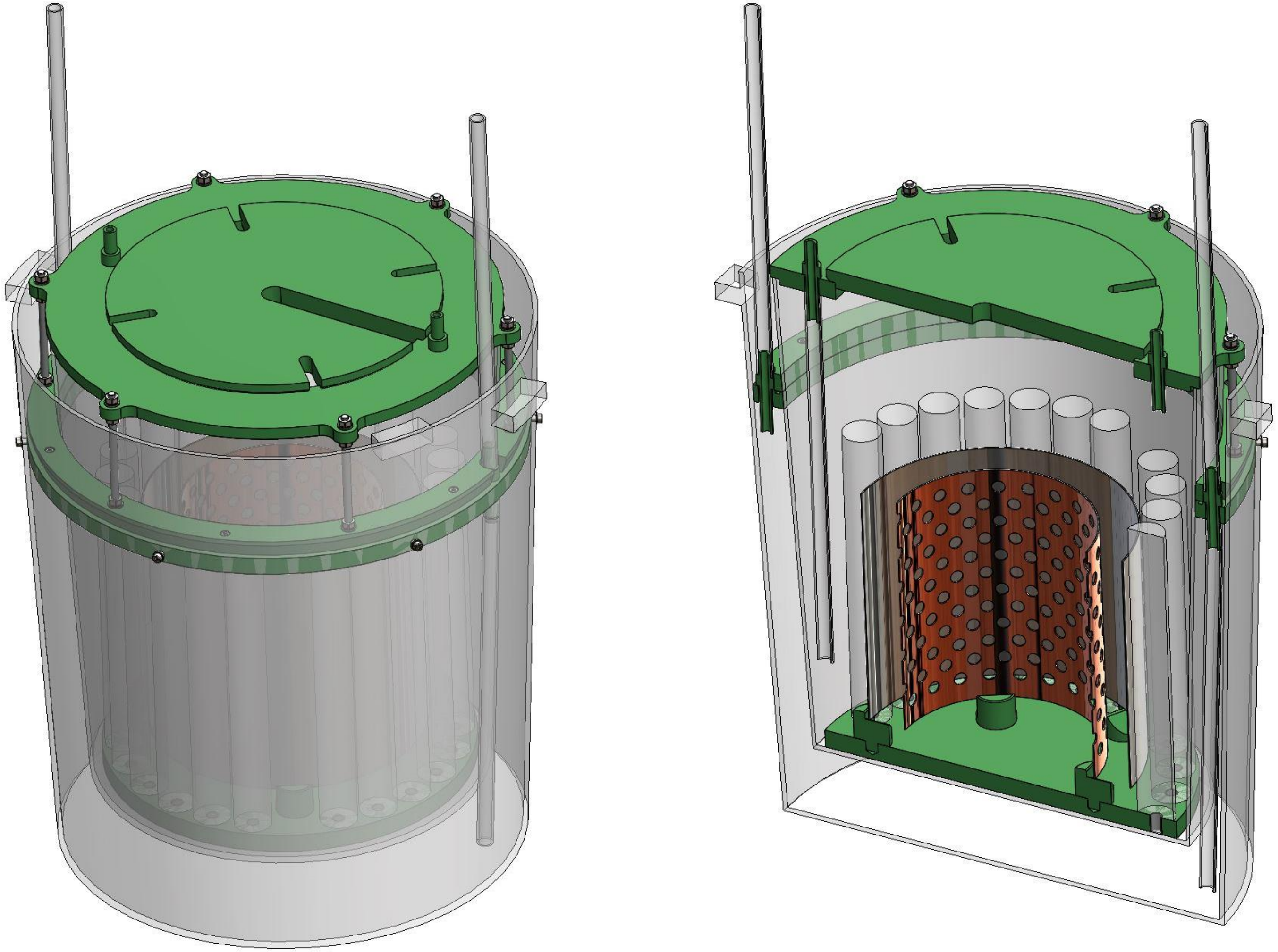


New ECP setup

- New setup in construction at MPIK: ~15-liter double-walled HDPE vessel
- New power supply (EA-PS 8080-510) with current (voltage) output up to 510 A (80 V)
- Perform coating of vessel-like geometry up to 1 m^2

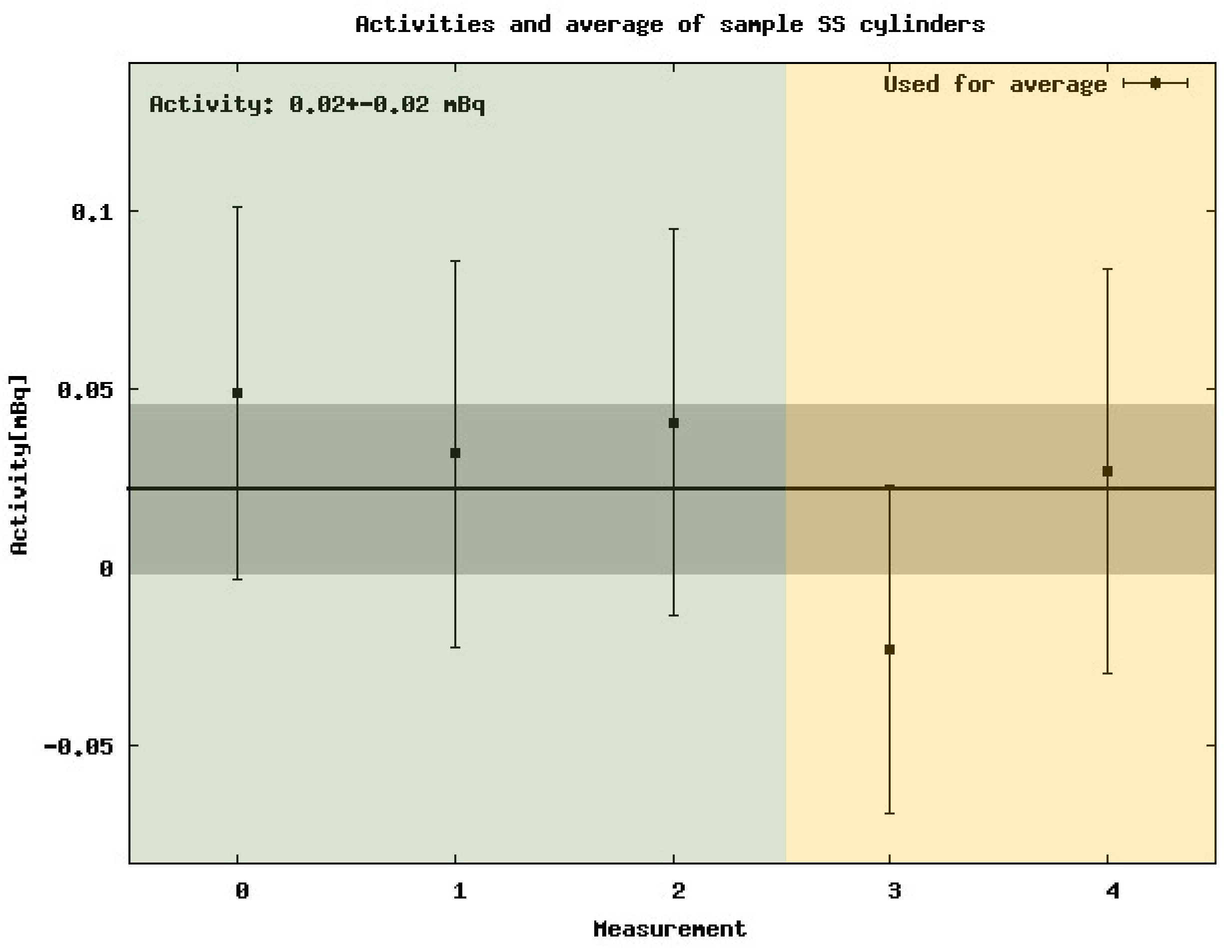
↓

Ultimate goal is to electroplate a radon emanation vessel



Radio purity of the coating layer evaluation

- ^{222}Rn emanation measurements w/ and w/o coating to assert the radio purity of the layer
- Measured performed with proportional counter setup at MPIK
- No evidence of additional Radium: UL at 90% of the Ra introduced is 80 μBq/m^2

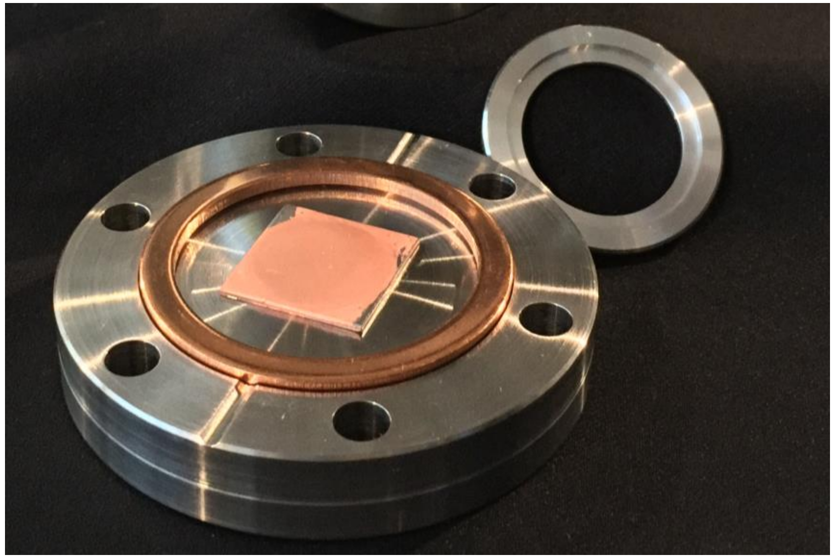


Summary

- Surface coating is a promising technology for Radon background reduction in future dark matter detector
- EPC showed the best reduction results
- New sources available for radon emanation studies
- Proved the scaling up of the setup to reasonable geometries

… what next?

- Characterization of new radon sources and validation of previous reduction results
- Commissioning of new coating setup and coating of vessel-like geometry
- Investigate further coating morphology and EPC procedure



Thank you for the attention!

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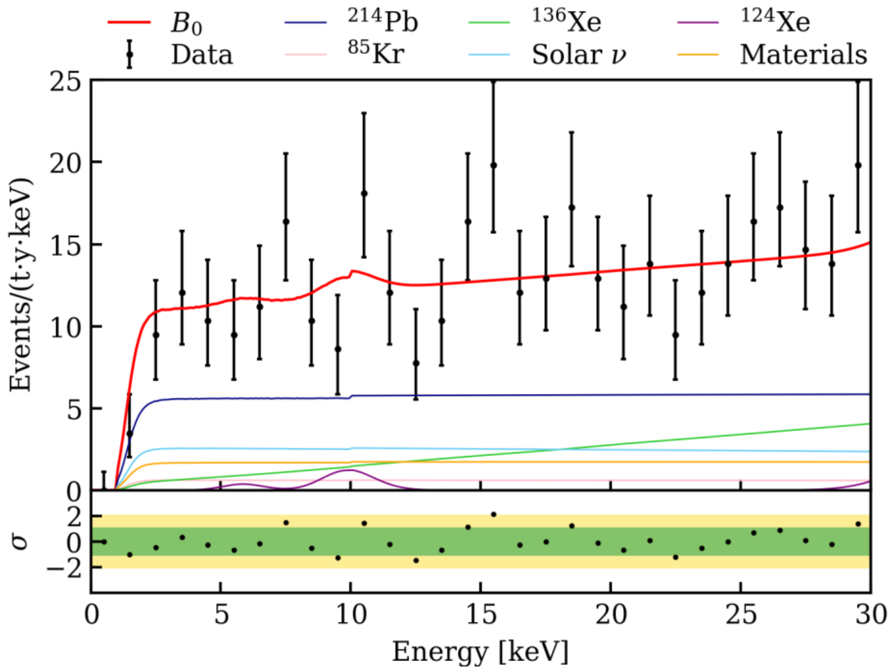
BACK-UP SLIDES

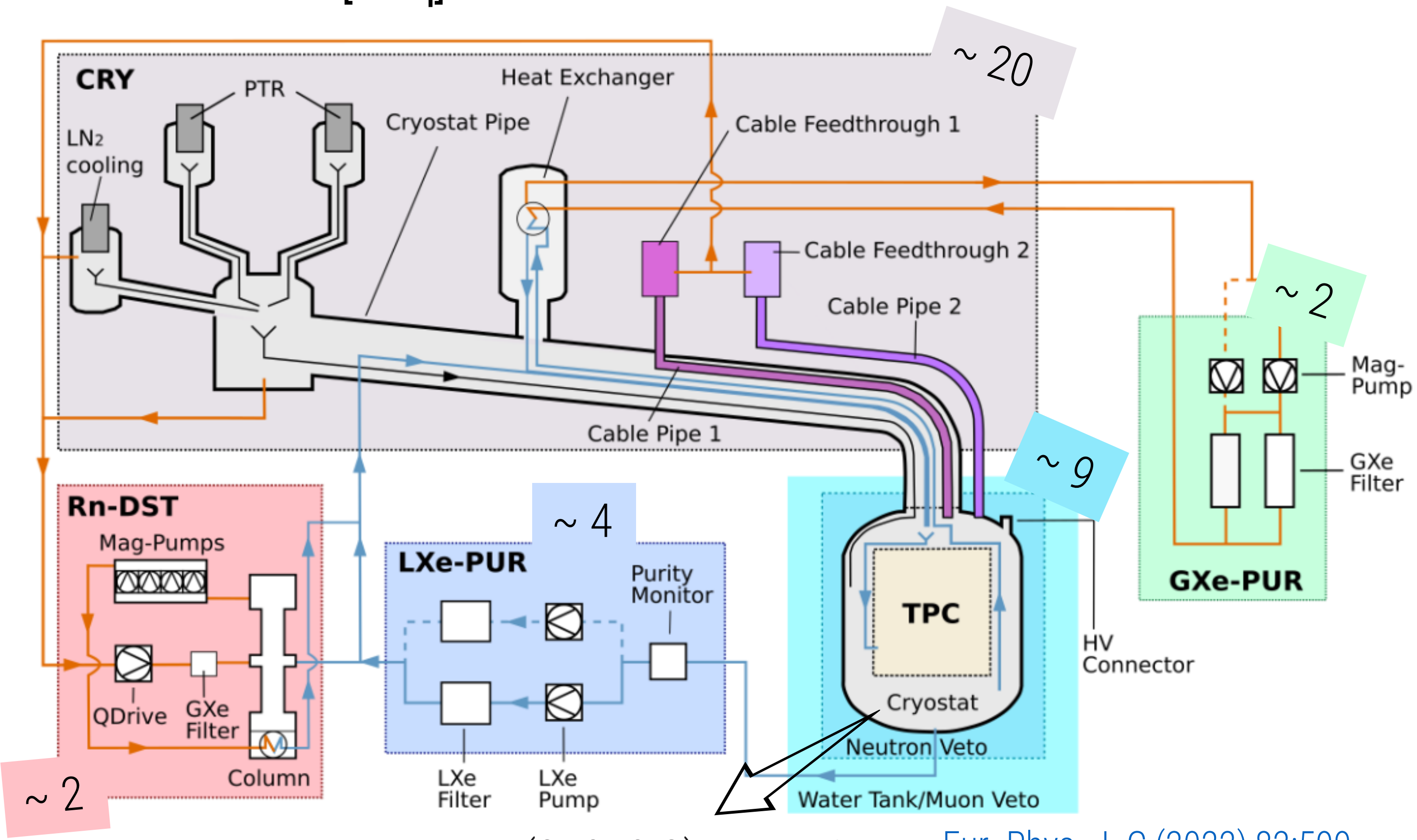
Radon background in XENONnT

- ^{222}Rn is dominant electronic recoil background in XENONnT ($A_{^{222}Rn}$ ~ 1 µBq/kg in SR0)
- Radon emanation measurements indicate a various sources distributed over entire experimental infrastructure

PhysRevLett.129.161805



222Rn emanation [mBq]



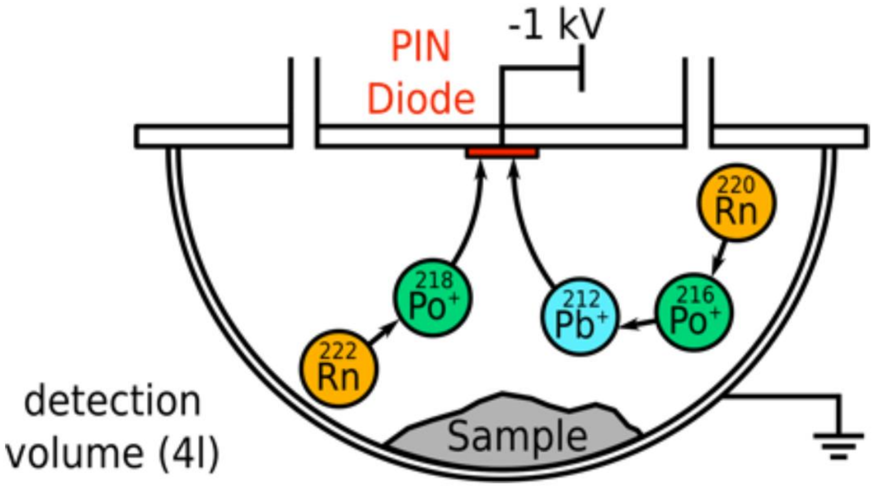
(210±0.2) µBq/m²

Eur. Phys. J. C (2022) 82:599

Radon detector at MPIK

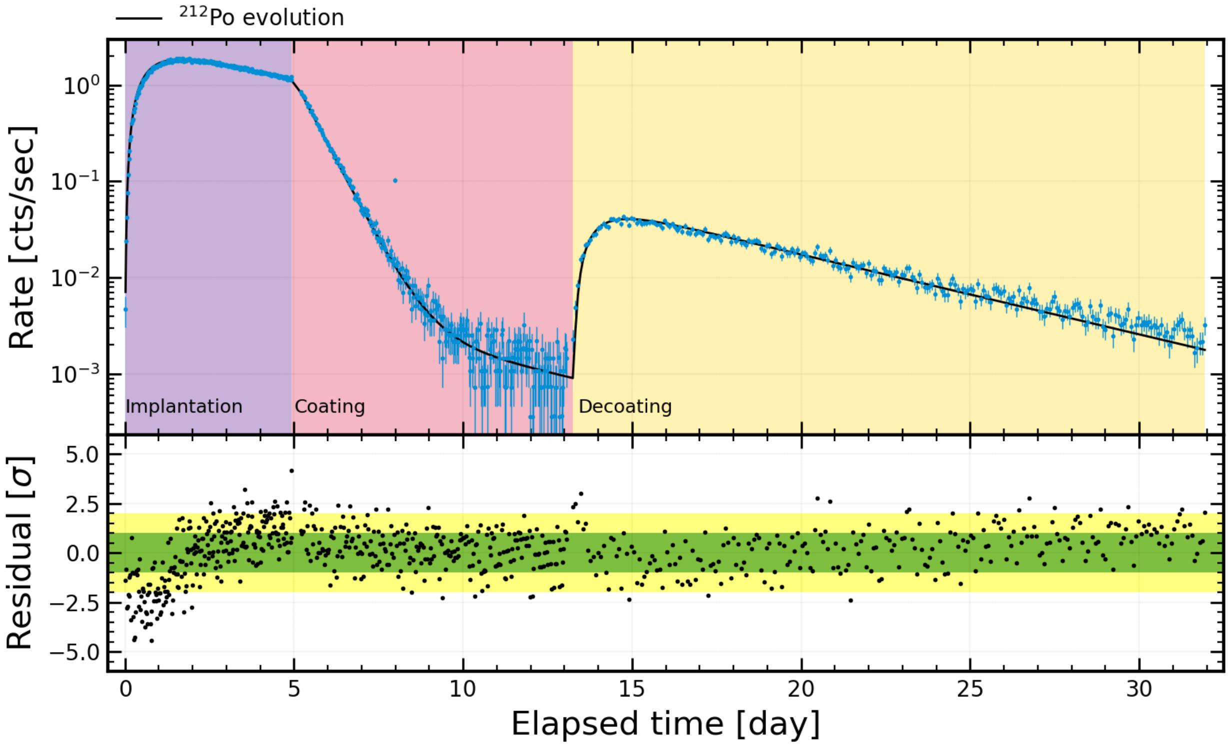
MPIK ^{222}Rn infrastructure:

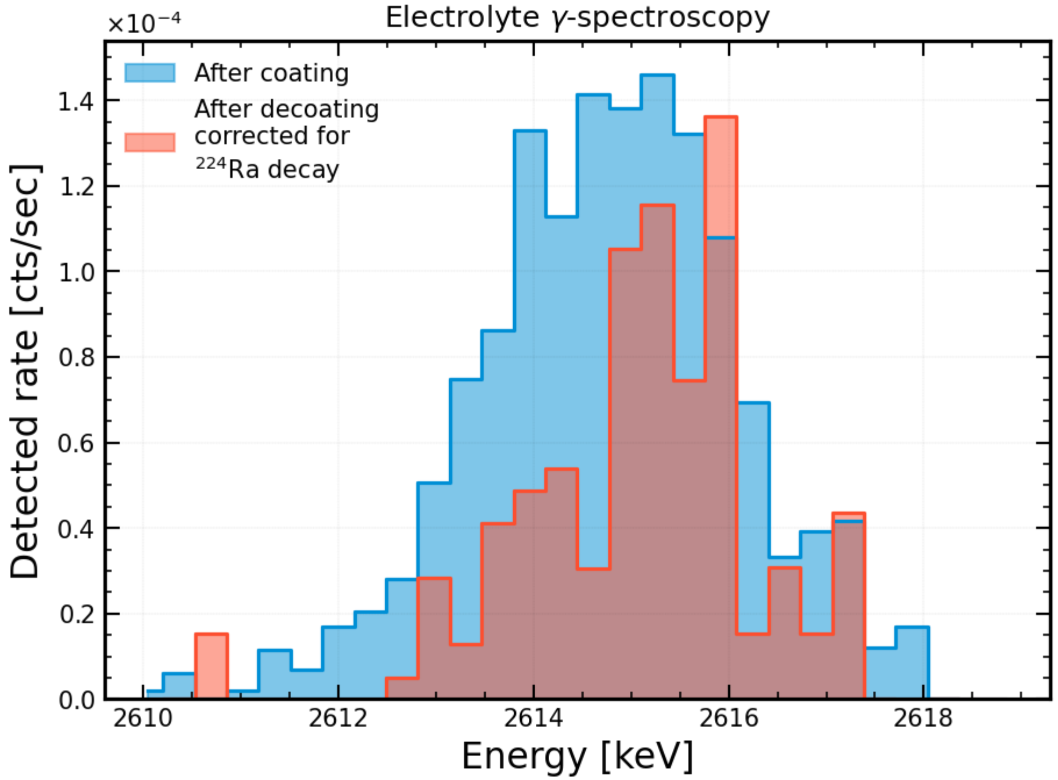
- >20 ultralow background miniaturized proportional counters
- Sensitivity: ~10 atoms.
- 8 parallel counting lines.
- Fully automated ^{222}Rn concentration system (AutoEma).
- ~15 sample vessels(0.1 –80 lit.).
- 3 electro-static ^{222}Rn monitors.



Radon emanation reduction factor

- Performed Ge spectroscopy of the electrolyte after coating and decoating: monitor ^{208}Tl γ line
- True reduction factor ∈ $[R_{lower}, R_{upper}]$ -> $50 \leq R \leq 250$!

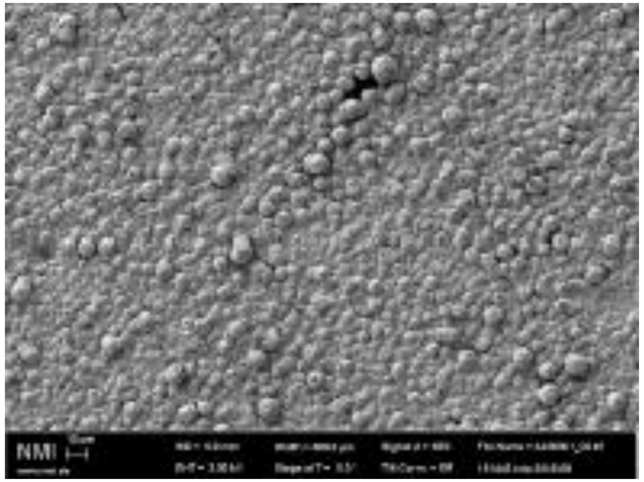


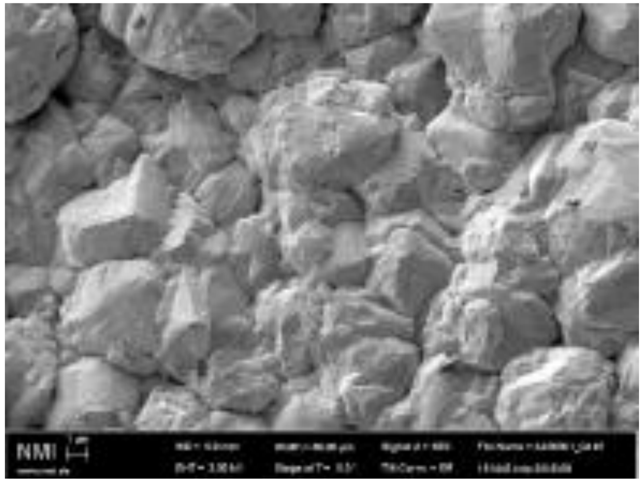


Coating morphology

- Secondary Electron Microscopy (SEM) investigation of coating

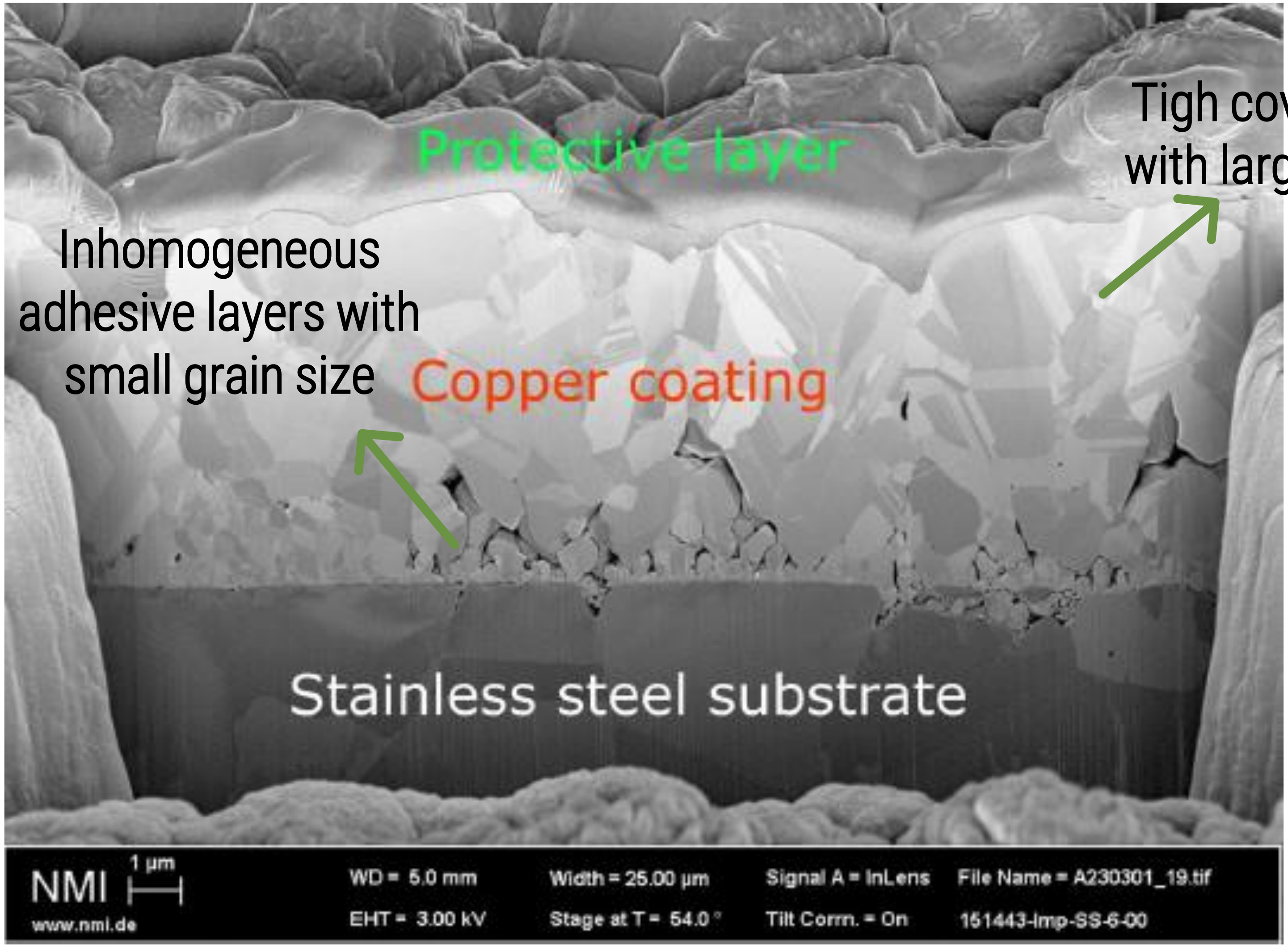
Rough surface with spherical structures





Inhomogeneous adhesive layers with small grain size

Tigh cover layer with large grains



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