Low background R&D for DARWIN

Hardy Simgen

Max-Planck-Institut für Kernphysik

Heidelberg

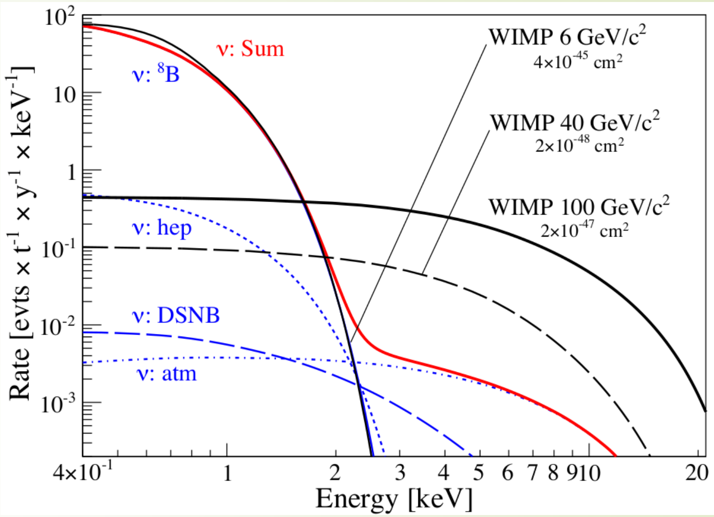
DMNet

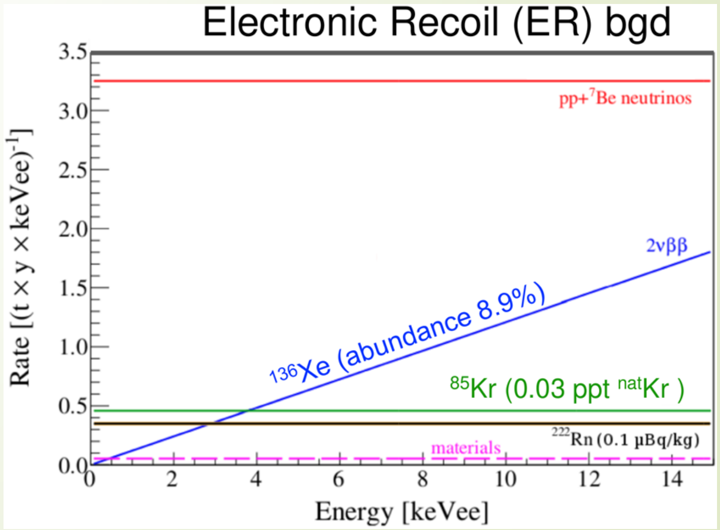
DARWIN

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

DARWIN background specifications

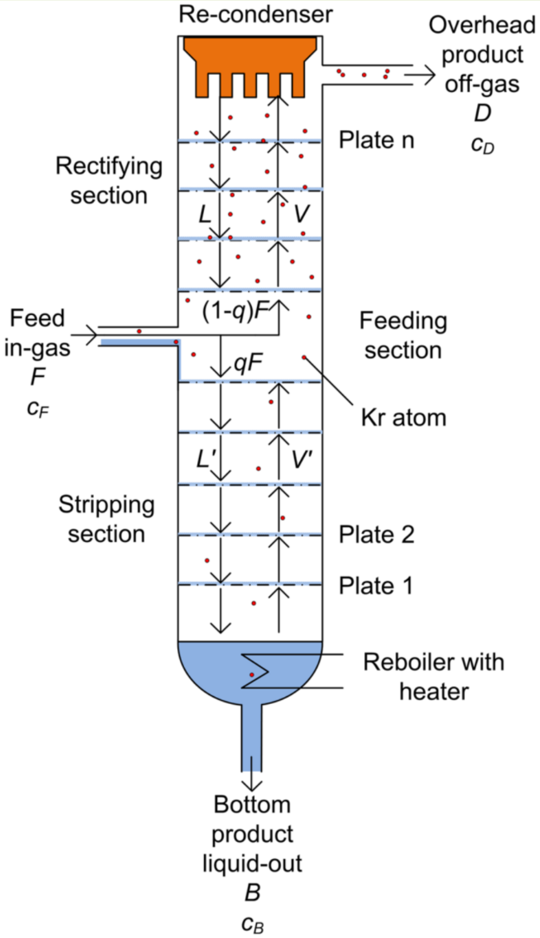
- Goal is to be completely neutrino dominated: JCAP11 (2016) 017
- Neutron-induced nuclear recoil (NR) background negligible
  - But requires radiopure materials
- Coherent solar neutrino scattering will be irreducible NR background
- Also Electronic recoil (ER) background dominated by solar neutrinos
- All other components to be at ~10% level
  - Most critical are dissolved impurities, in particular ^{222}Rn (**Factor 10 reduction w.r.t. XENONnT**)

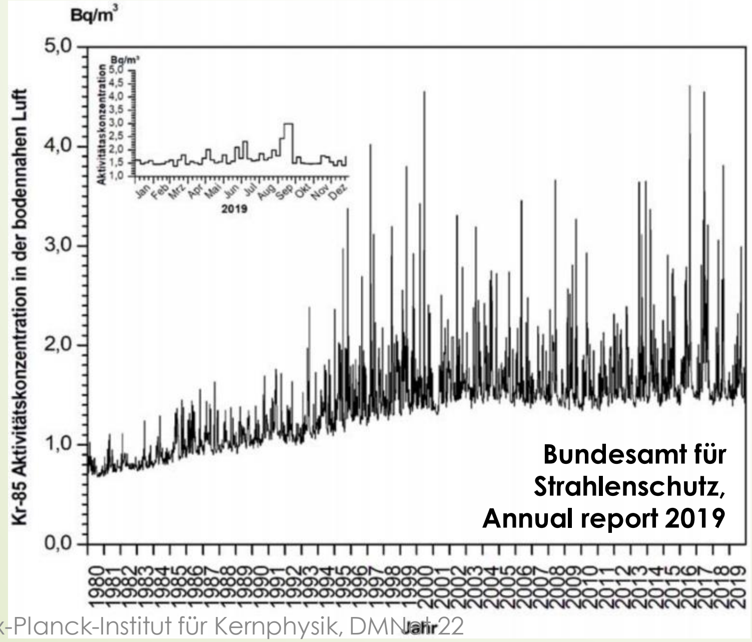


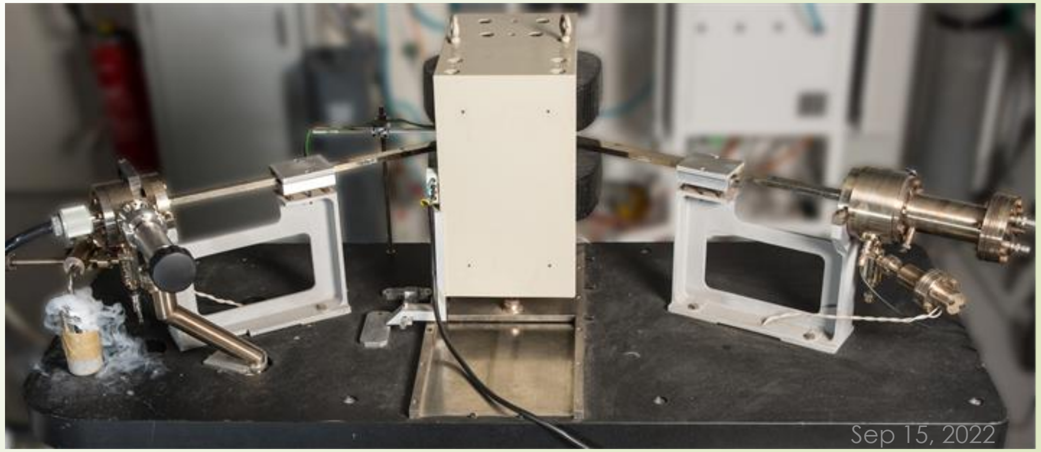


^{85}Kr control for DARWIN

- Xenon is produced from air → Traces of krypton (~50 ppb)
- ^{85}Kr due to anthropogenic nuclear activities: ^{85}Kr/^{nat}Kr = 2x10^{-11}
- Goal for **Kr in Xe 30 ppq** (1ppq = 1x10^{-15})
- Requires powerful Xe purification technique (distillation) and extremely sensitive analytics

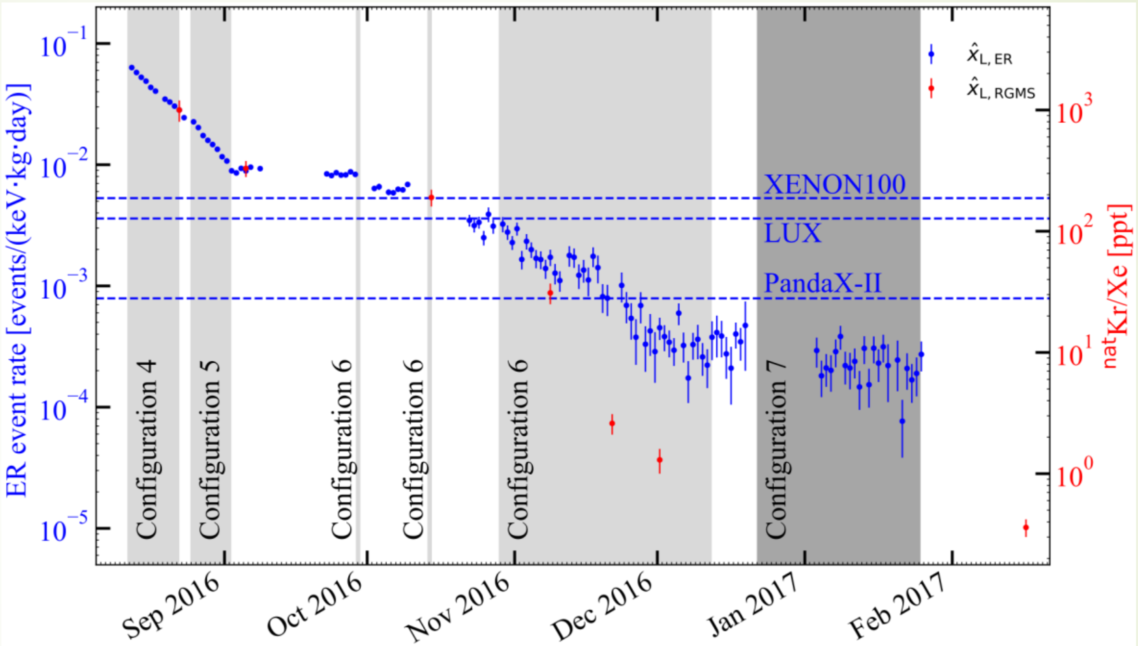






Kr removal in XENON1T / XENONnT

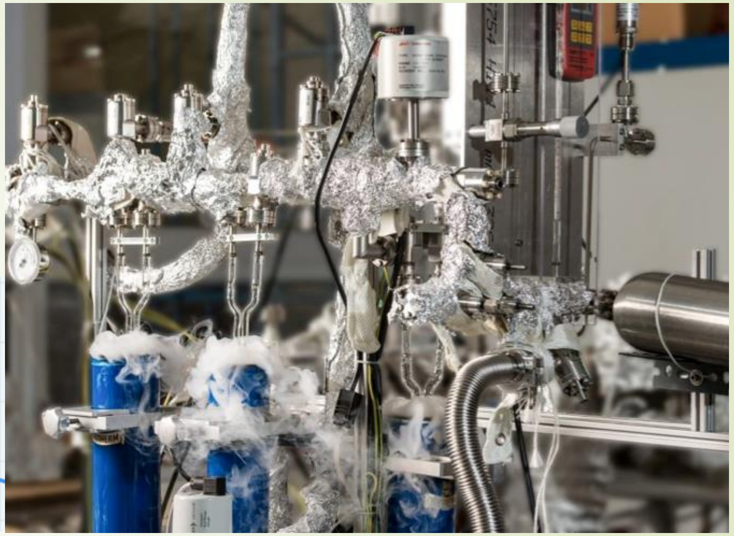
- Kr column built for XENON1T
- Measured separation ~640.000 with 99% Xe recovery: EPJC (2017) 77:275
- Stable up to 6.5 kg/h throughput
- **Lowest achieved concentration: 26 ppq**



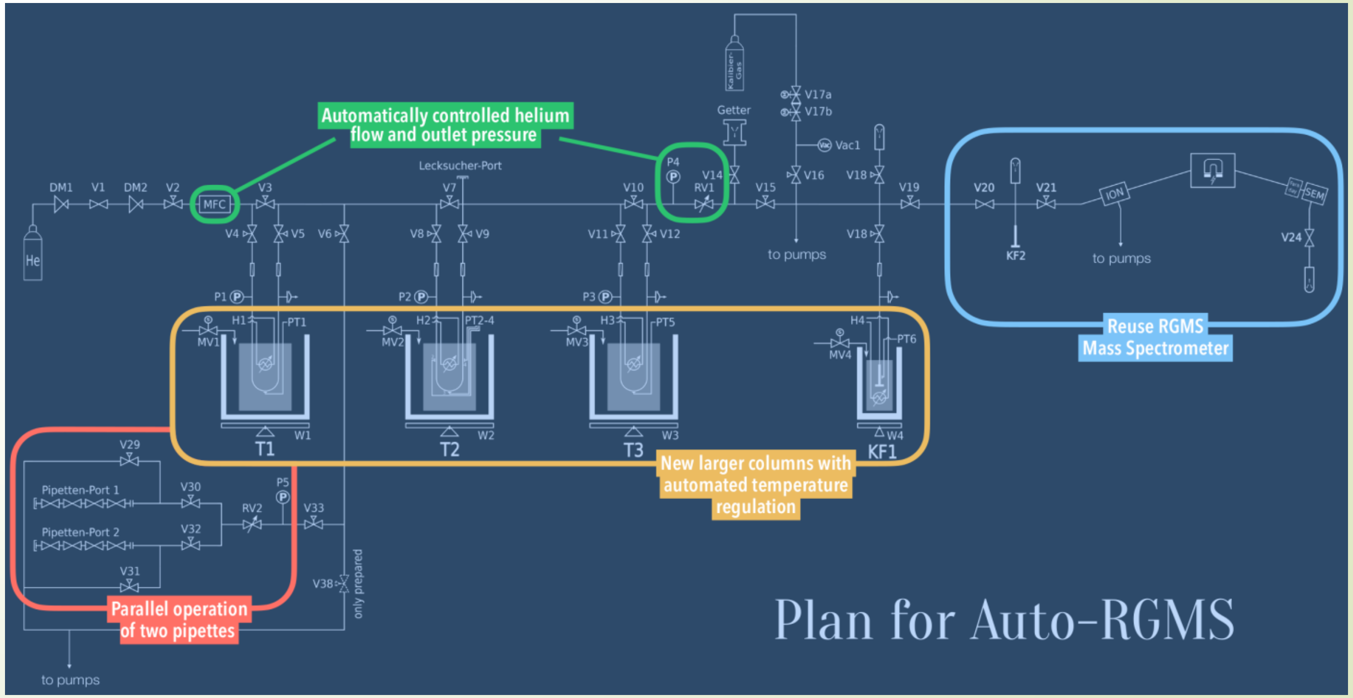
- Outlet concentration sufficient for DARWIN
- Sufficient for online distillation, but larger throughput needed for initial Xe purification
- Reliable Kr/Xe analytics with ppq-sensitivity required

Rare Gas Mass Spectrometry (RGMS) at MPIK

- Requires efficient removal of Xe → gas chromatography.
  - Homemade UHV-qualified system
  - Low mass packed columns
  - Thoroughly purified carrier gas (helium)
- → **8 ppq detection limit**: EPJC (2014) 74:2746



- Future: Automated RGMS (Auto-RGMS)
  - Fully automated operation
  - Optimized separation columns
  - Improved repeatability and robustness
  - Design is finished, construction has started
  - Expect commissioning in summer 2023
  - Eventually on-site online operation?



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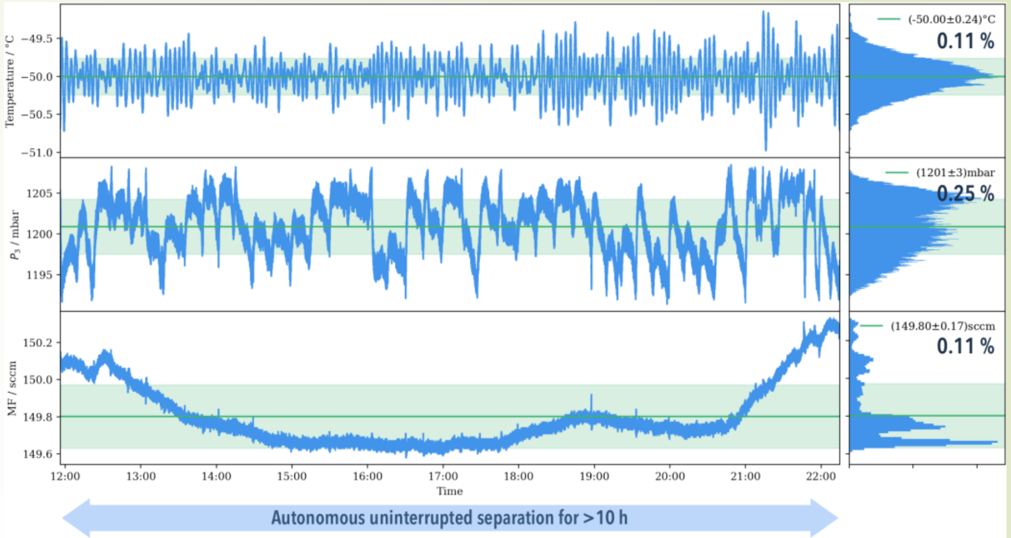

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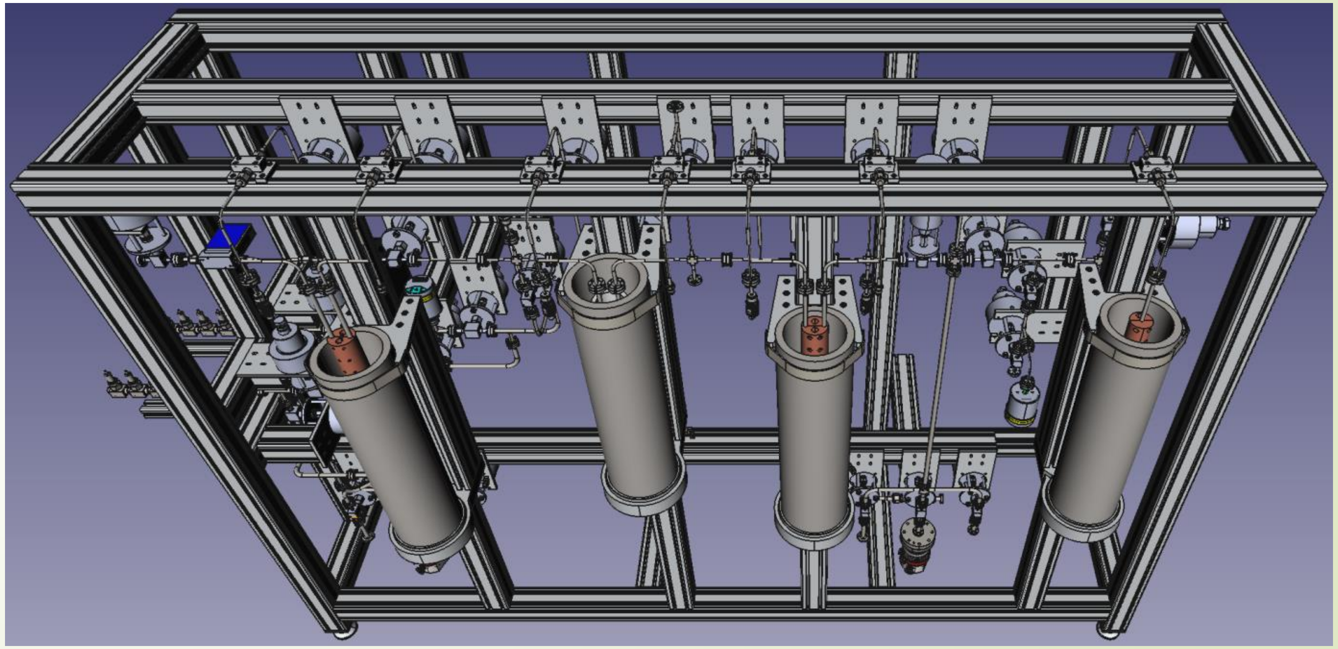
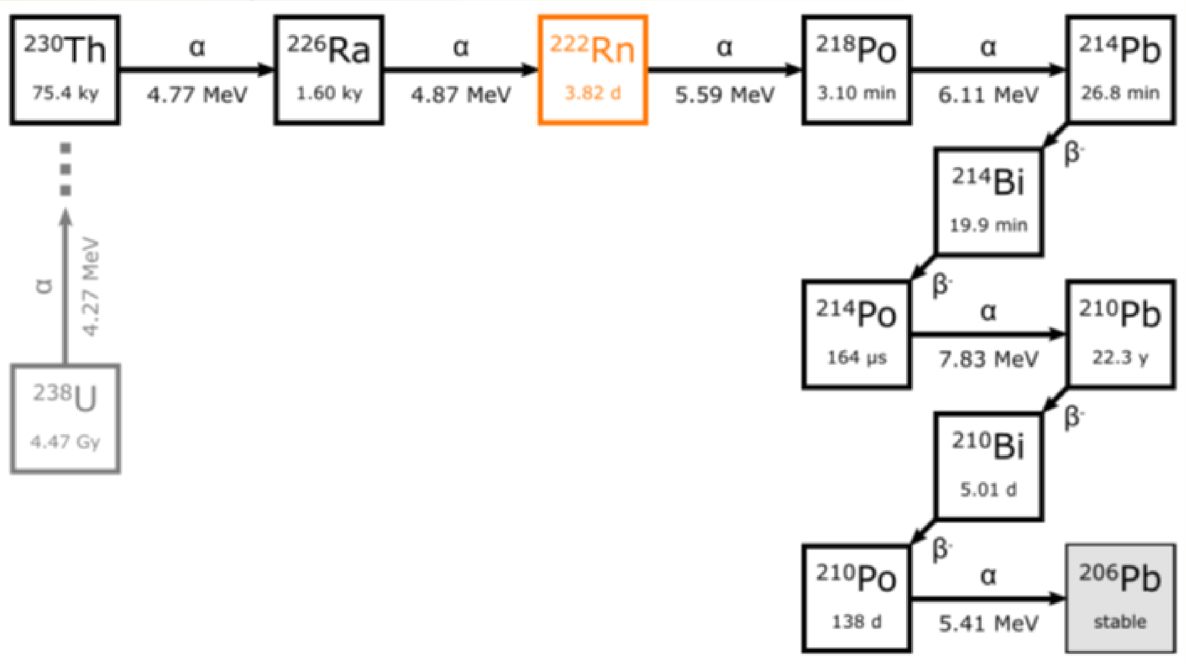


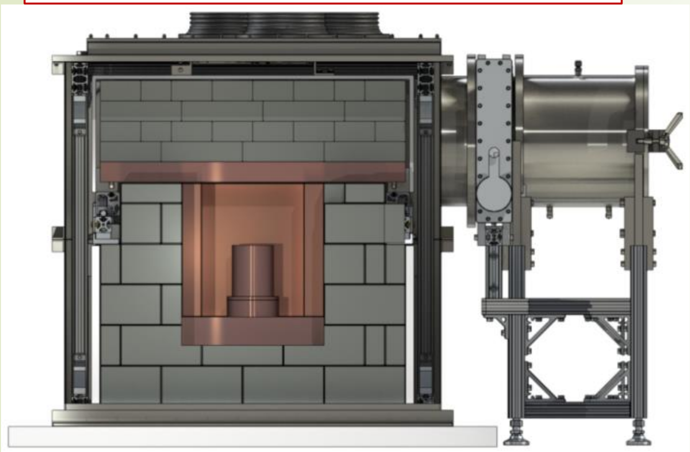
Radon mitigation techniques



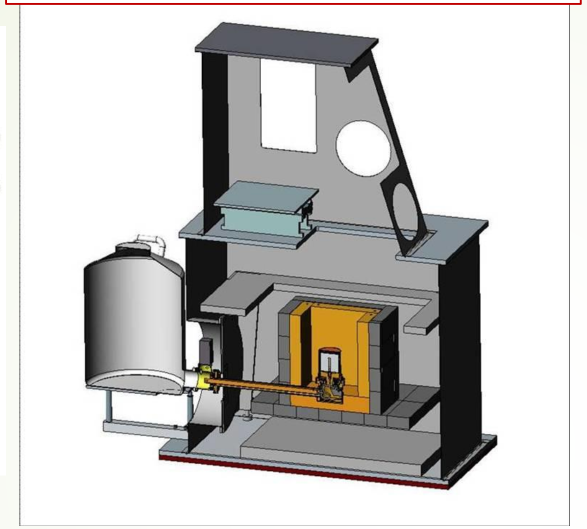
- ^{222}Rn is produced in situ by emanation from detector materials
- ^{222}Rn mitigation by:
  - Avoiding:
    - Material screening and selection
    - Removal of ^{222}Rn sources
  - Purification:
    - Distillation / Adsorption
  - Tagging
    - Analysis techniques

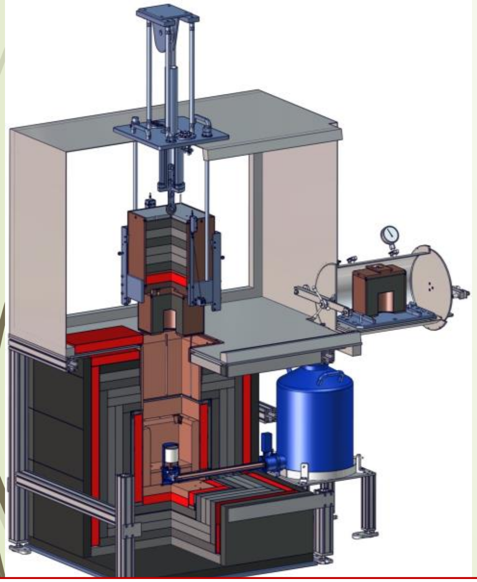
Material screening and selection

GATOR: JINST 17 (2022) P08010

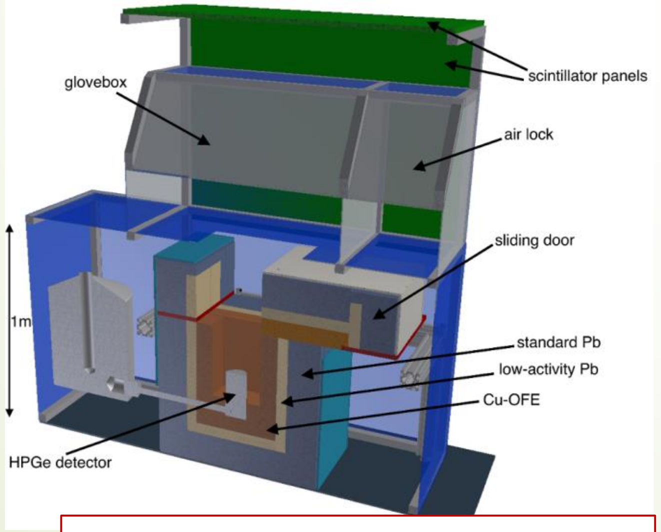


GeMPI I-IV: ARI 53 (2000) 191





GIOVE: EPJC (2015) 75:531



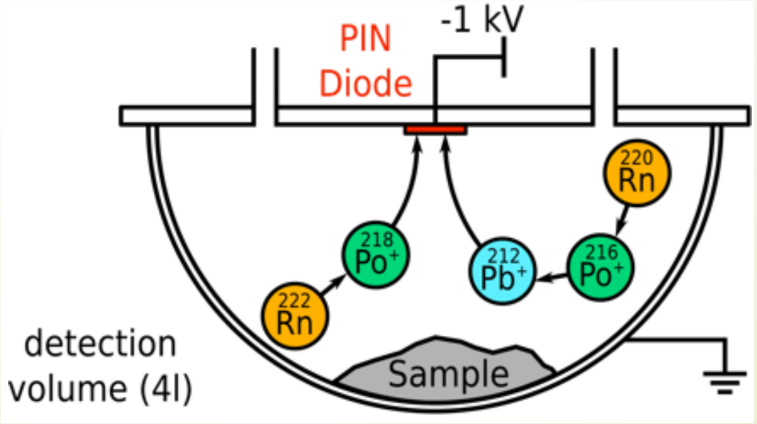
GeMSE: JINST 17 (2022) P04005

- Standard technique is HPGe gamma spectroscopy
- World's most sensitive spectrometers are owned by DARWIN groups: GeMPI I, II, II, IV, GATOR, GeMSE, GIOVE, …
- ^{226}Ra/^{228}Th detection limit down to **10 μBq/kg**
- But ^{222}Rn emanation rate is NOT strongly correlated to ^{226}Ra bulk contamination

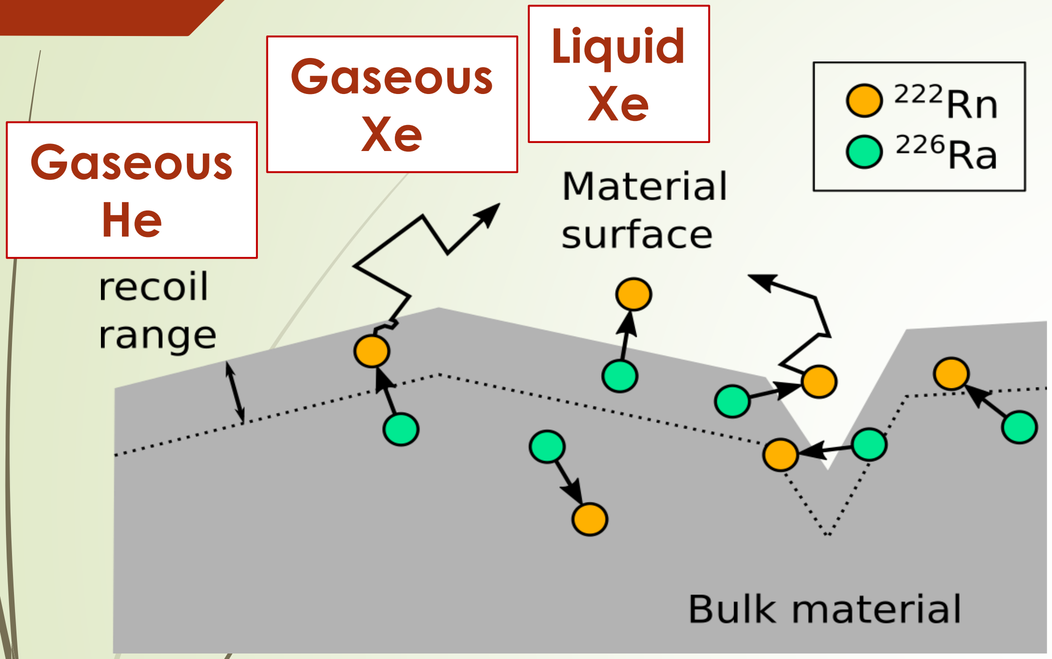
→ Dedicated ^{222}Rn screening facilities

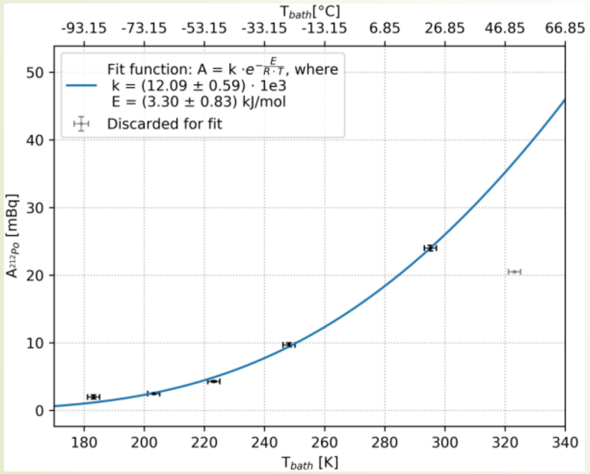
Material screening by ^{222}Rn emanation assay

- ^{222}Rn-emanation rate provides complementary information
- ^{222}Rn screening in DARWIN:
  - Electrostatic radon monitors
  - Ultralow background miniaturized proportional counters
    - Sensitivity: **~10 ^{222}Rn atoms**
- @MPIK: Fully automated ^{222}Rn concentration system (AutoEma) from up to 80 liters emanation chambers



Ongoing R&D related to radon emanation

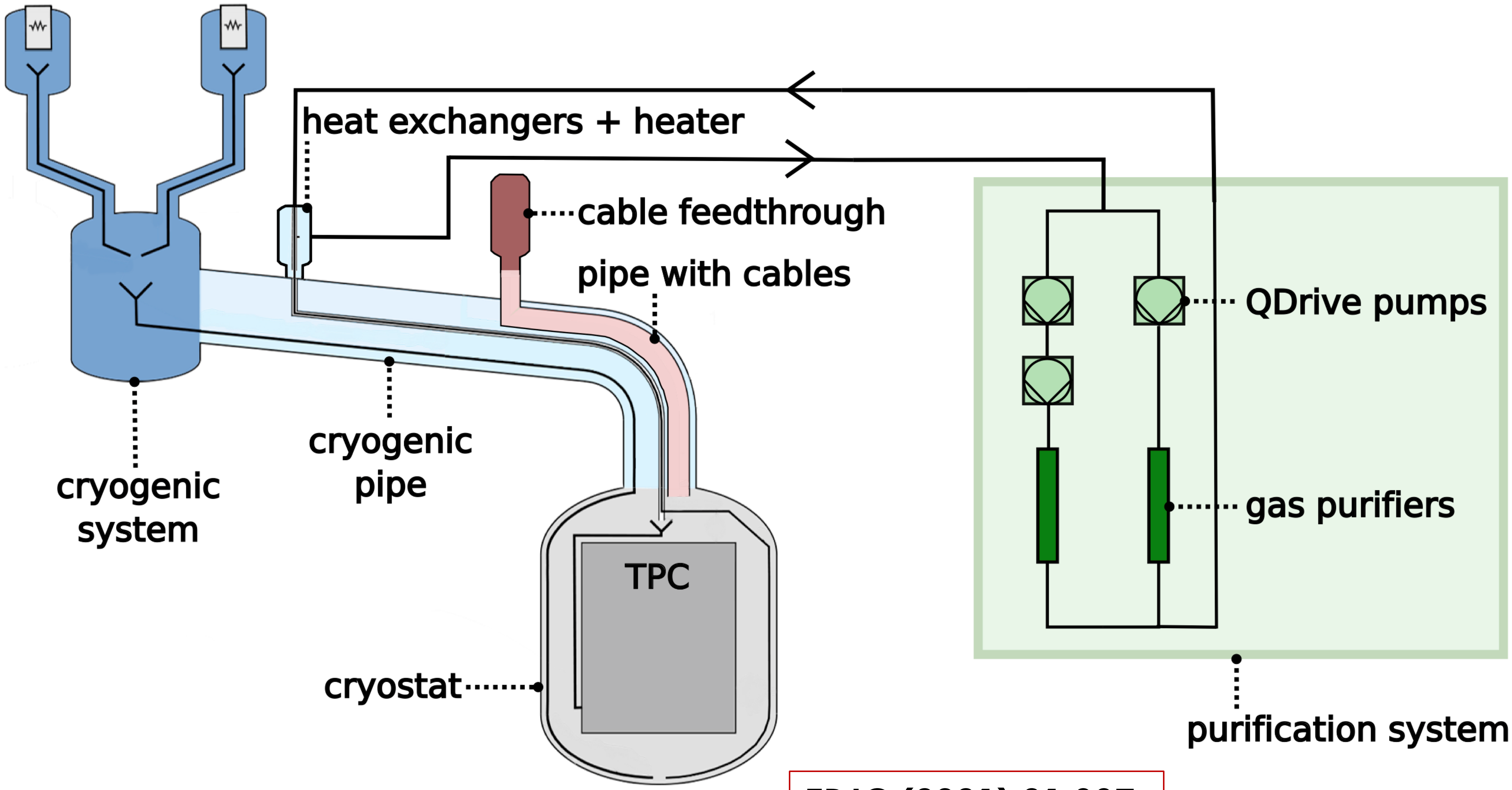




- Better understanding of emanation process.
- Recoil-driven versus diffusion-driven emanation
  - Dependency on temperature
  - Dependency on envrionment
    - Gas (helium, xenon, air, vacuum)
    - Humidity
    - Gaseous versus liquid
- Measurement of radon diffusion constant in different materials
  - Diffusion constants <10^{-22} cm^2/s in metals
- Radon self-trapping in porous materials
- …

Understanding ^{222}Rn source distributions

Example: XENON1T setup



EPJC (2021) 81:337

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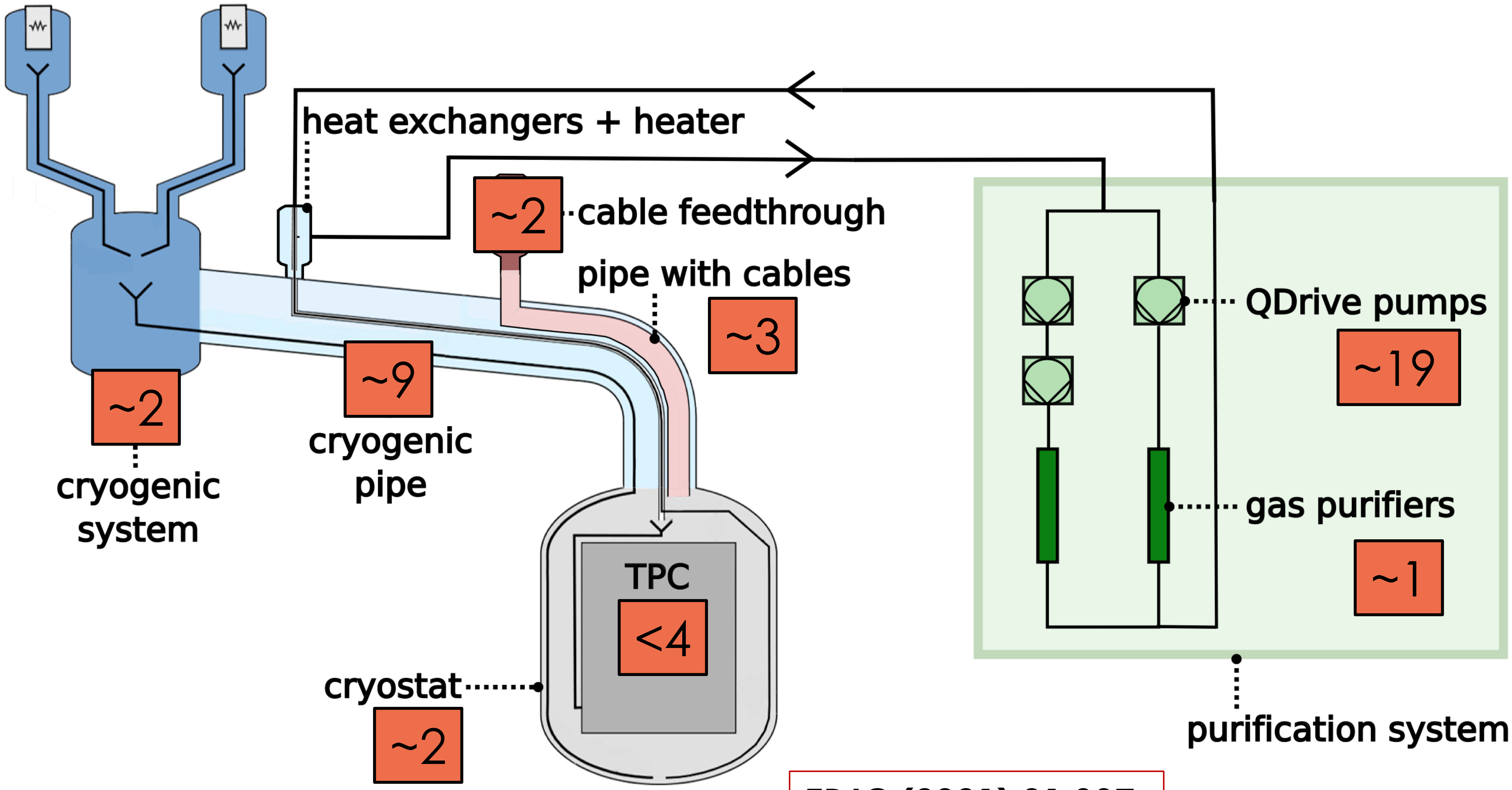

EPJC (2021) 81:337

Understanding ^{222}Rn source distributions

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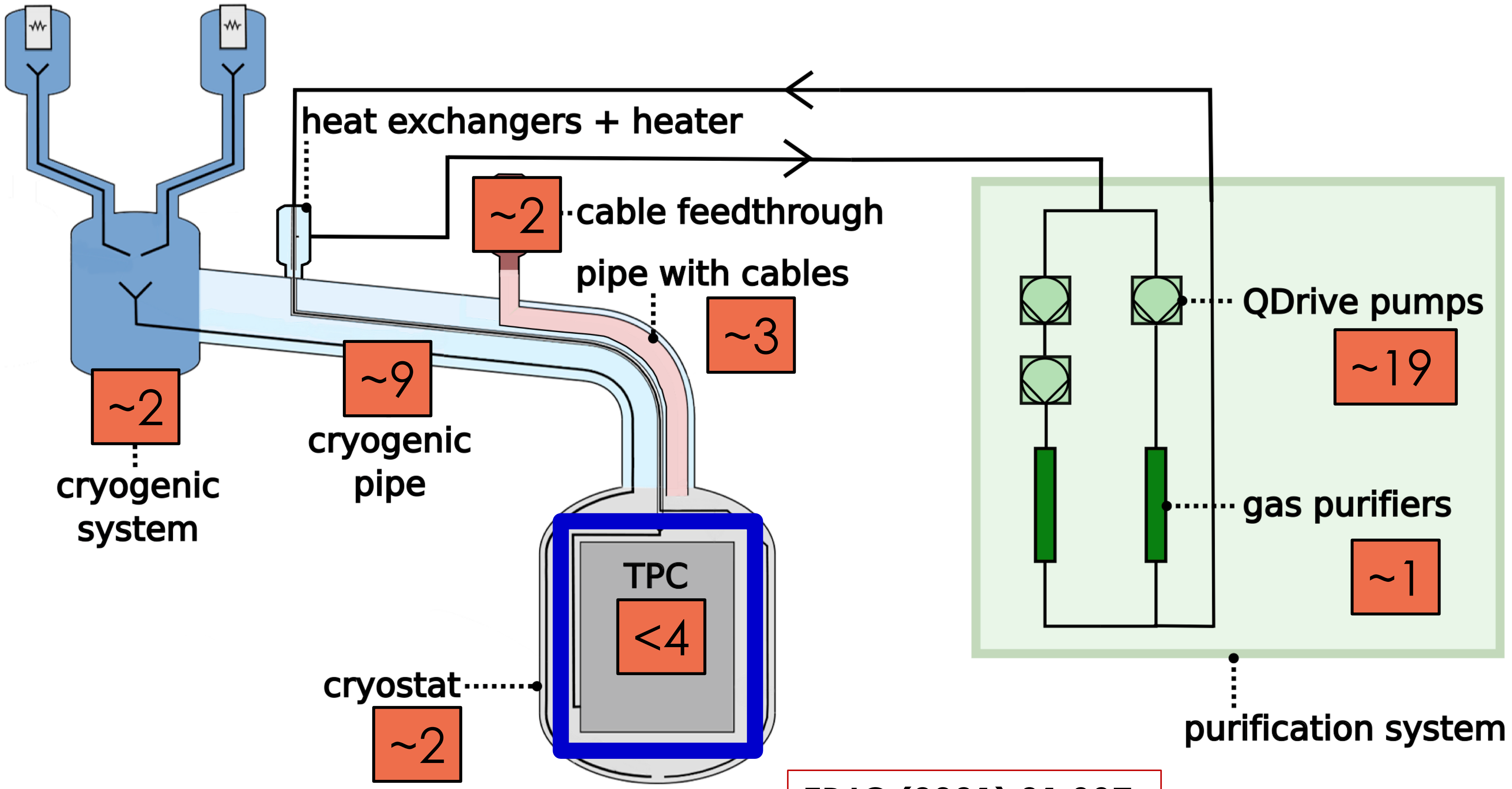
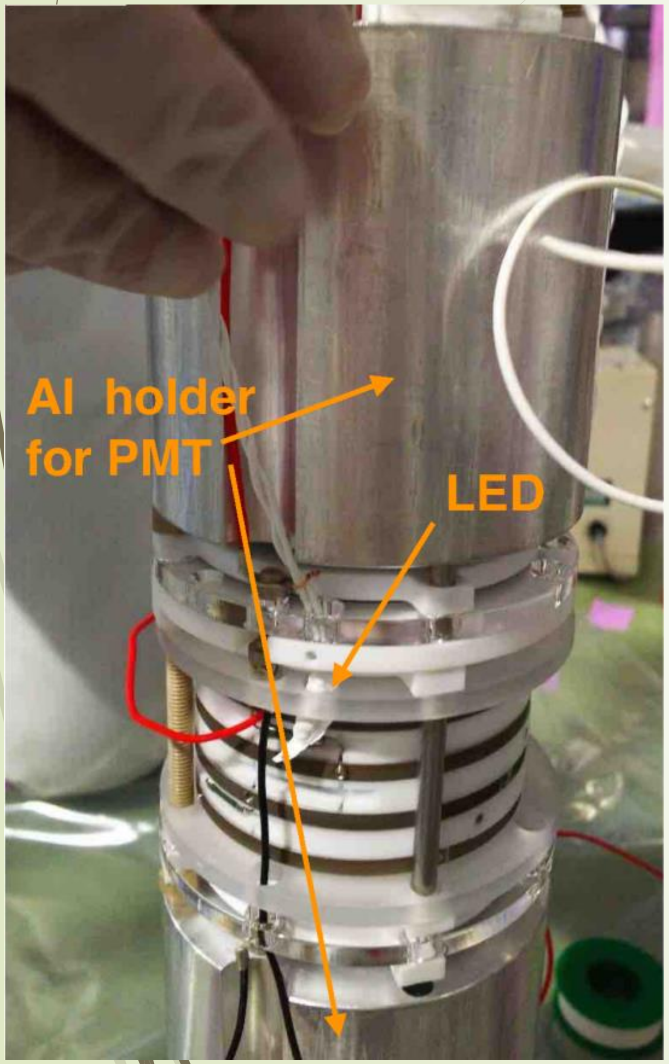
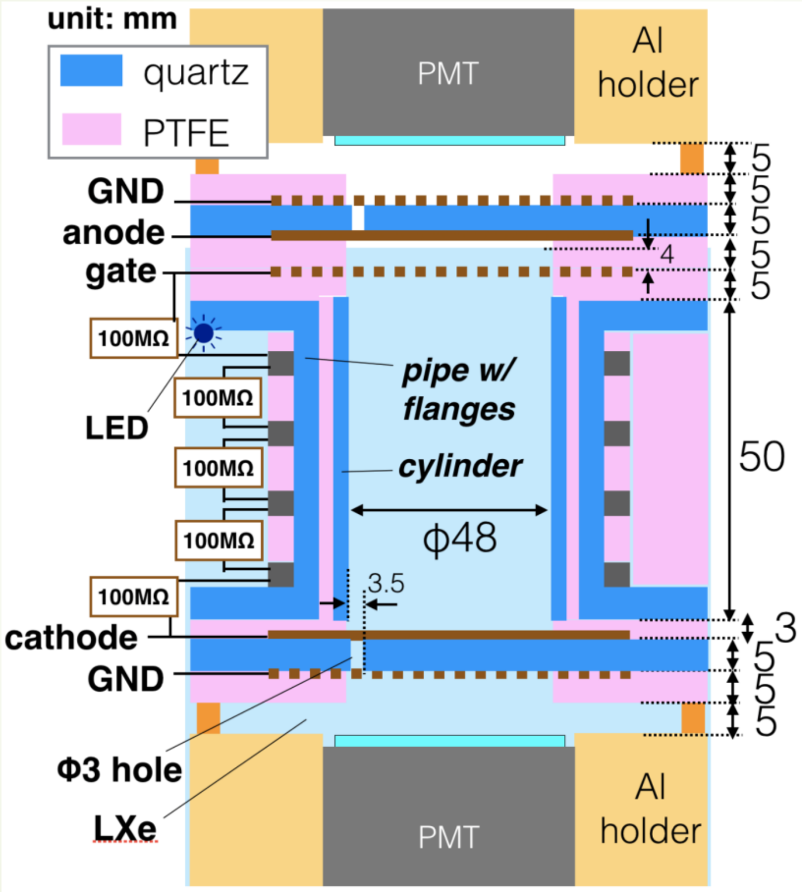


EPJC (2021) 81:337

Hermetic TPC with quartz chamber

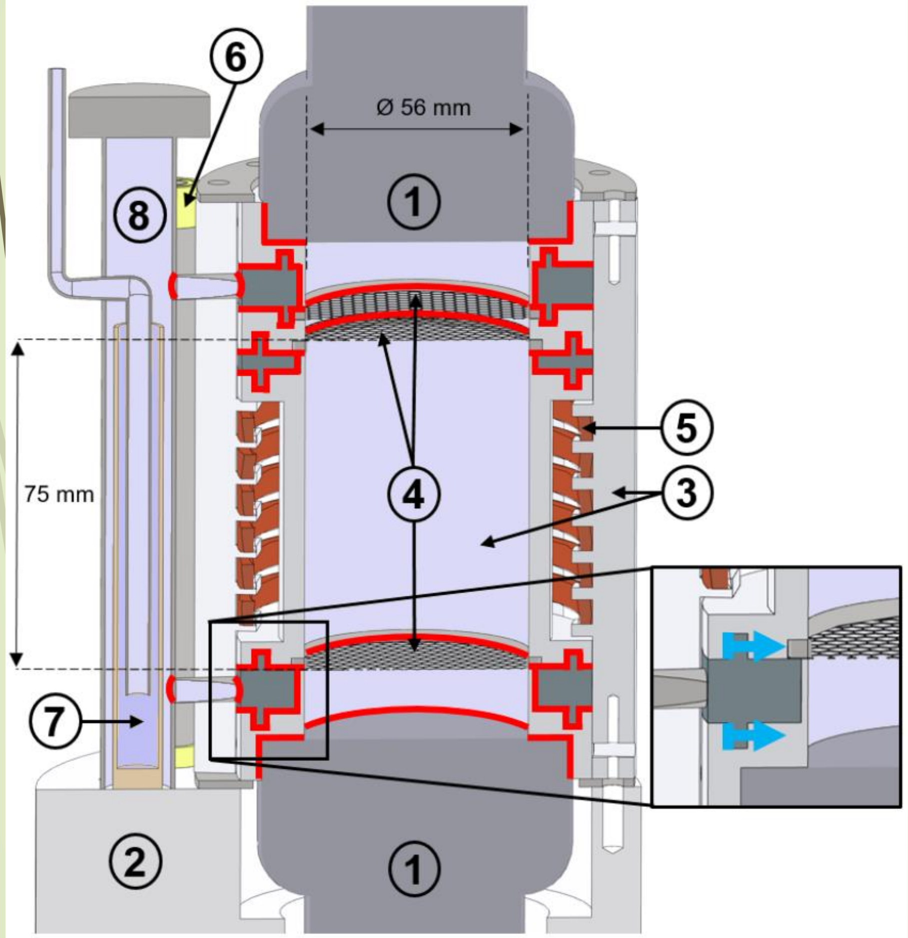


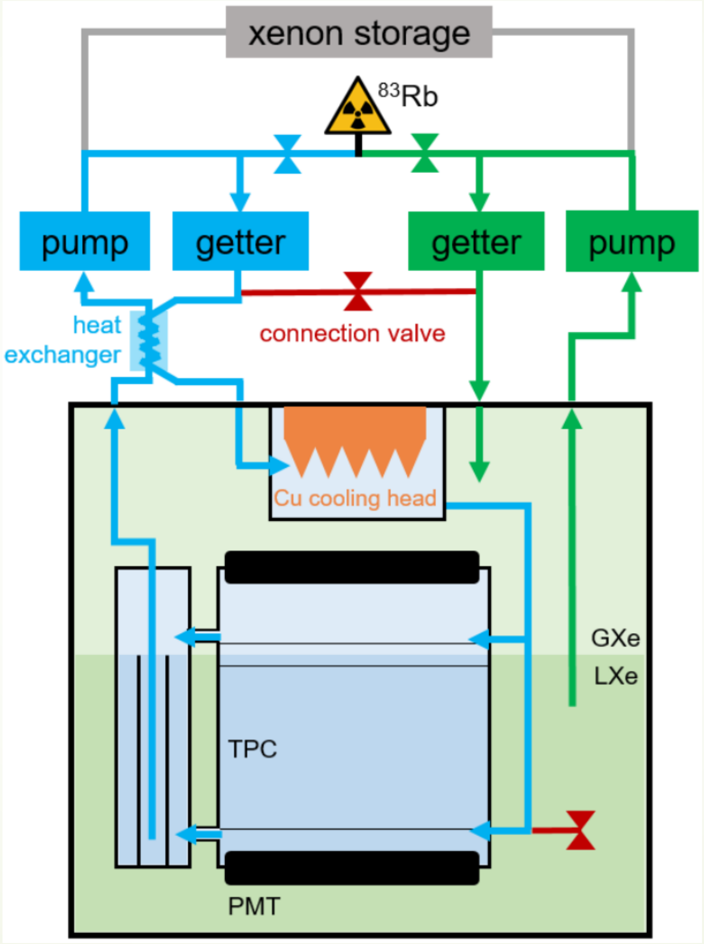


PTEP (2020) 113H02

- Hermetic TPC avoids ^{222}Rn contamination from outer volume
- Also reduces electro-negaative impurities
- Quartz is suitable chamber material
  - Low intrinsic radioactivity
  - UV-transparent
  - Avoids secondary electron emission
- Succesful operation of prototype as dual-phase TPC
- Ongoing: Optimization of hermeticity (quartz flange sealing)

Hermetic TPC with more conventional design



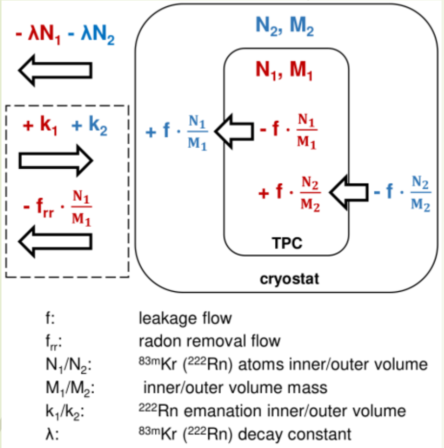


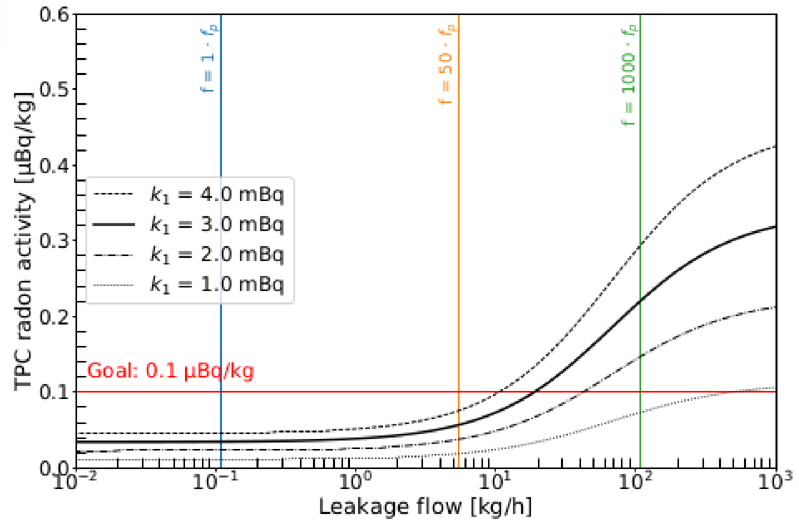
- Modified standard TPC design
- Sealing by cryofitting: Large PTFE shrinkage at low temperature seals against metals
- Succesful dual-phase TPC operation: Good performance
- Hermeticity test with ^{83m}Kr:
  - ~0.1 kg/h leakage rate
- Further improvement on sealing possible

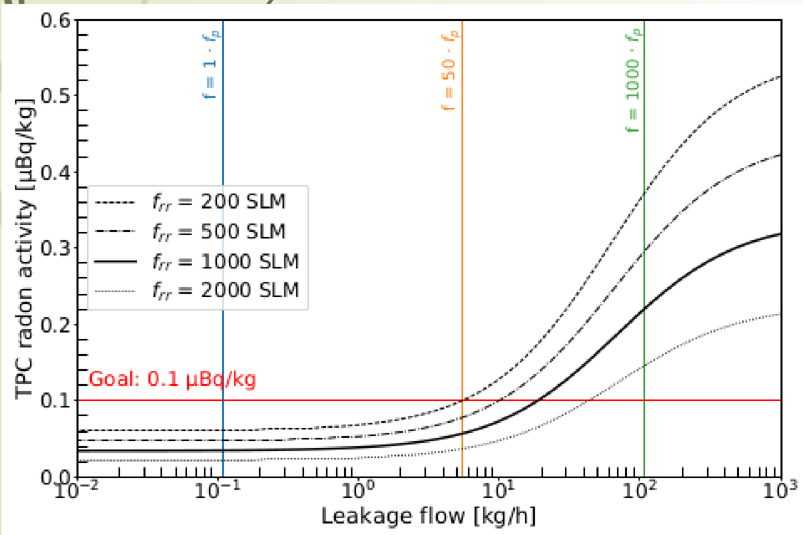
arXiv: 2209.00362

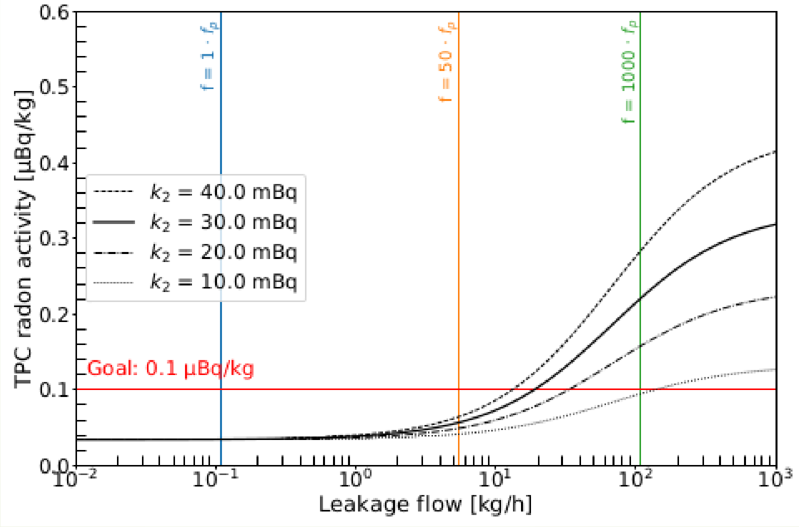
Scaling up: What does it mean for DARWIN?

arXiv: 2209.00362





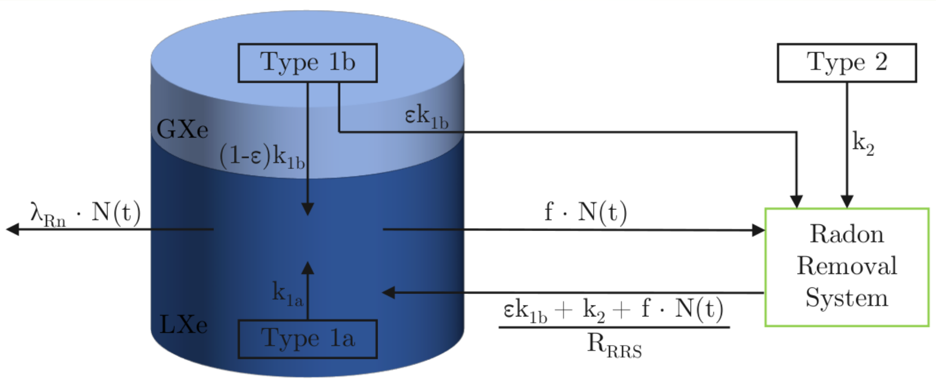


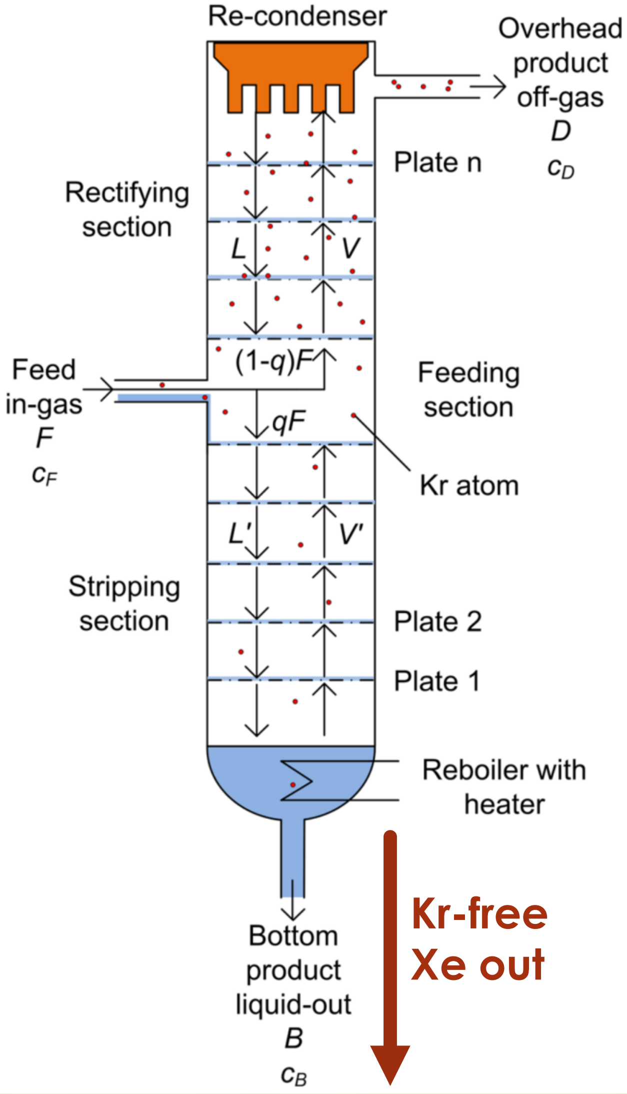


- Upscaling of results for 10^5 times larger DARWIN TPC
- Location of leak crucial
- Assumptions on ^{222}Rn emanation rates based on XENON1T / XENONnT screening results
- Online Rn purification included in model
- Darwin goal for ^{222}Rn is reachable, but requires combination of all ^{222}Rn reduction techniques

Radon removal by xenon distillation

- Radon is less volatile than xenon → reverse operation mode w.r.t. Kr removal
- Feasibility demonstrated in Xenon100: EPJC (2017) 77:358
- Applied in XENON1T: 4.5 μBq/kg achieved: EPJC (2021)81:337
- High flow radon removal system developed for XENONnT: arXiv: 2205.11492
- **1.7 μBq/kg achieved**





- Upscaling only possible for high throughput system
- Processing speed for DARWIN must be >=10 tons/day
- Efficiency in power consumption and xenon holdup versus radon reduction is crucial

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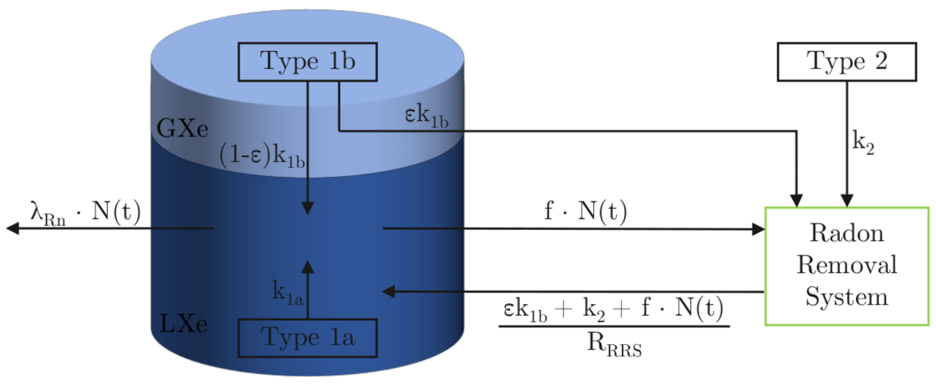

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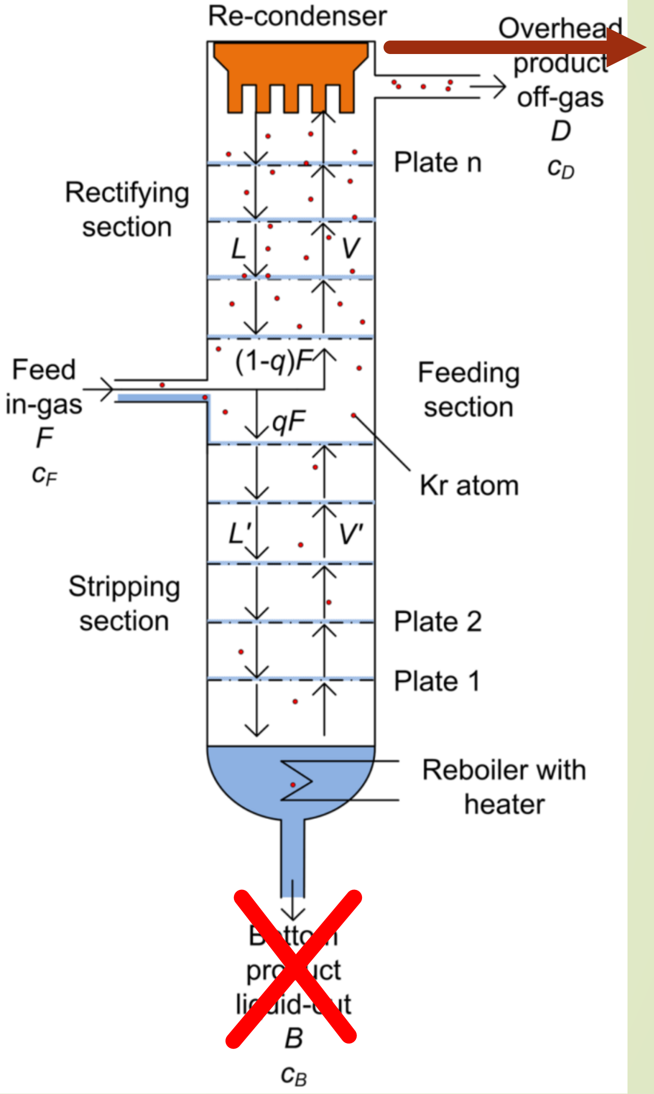
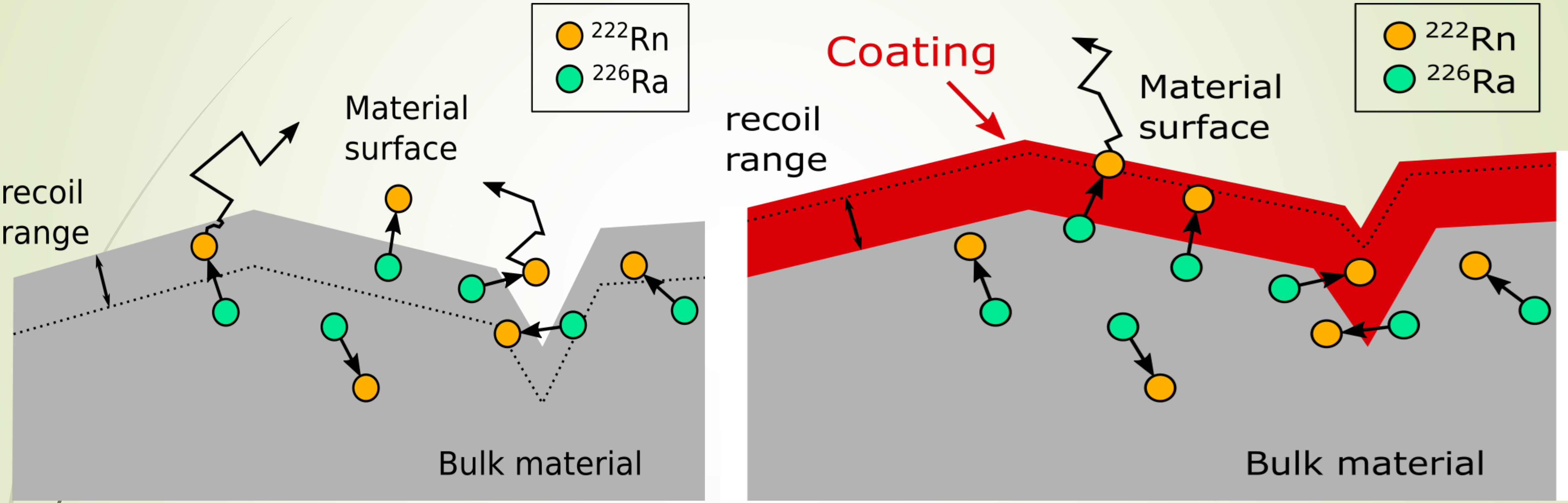
Rn-free Xe out



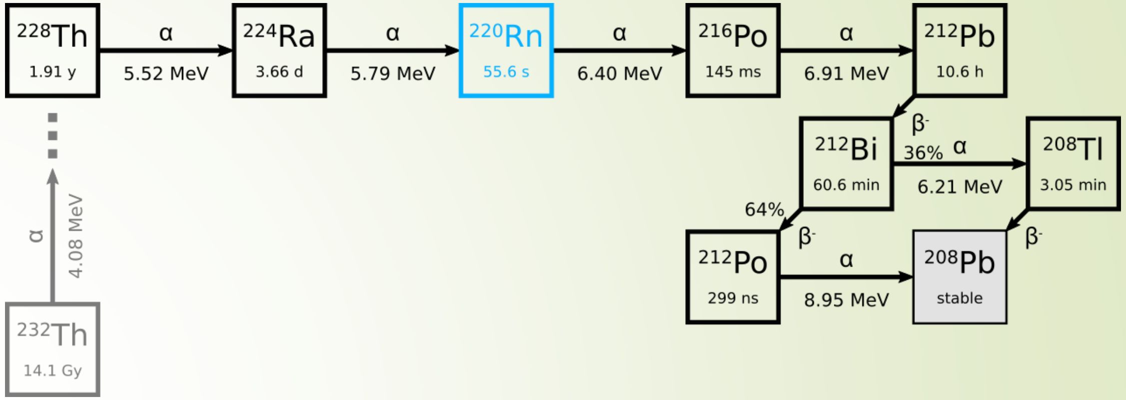
Radon mitigation by surface coating

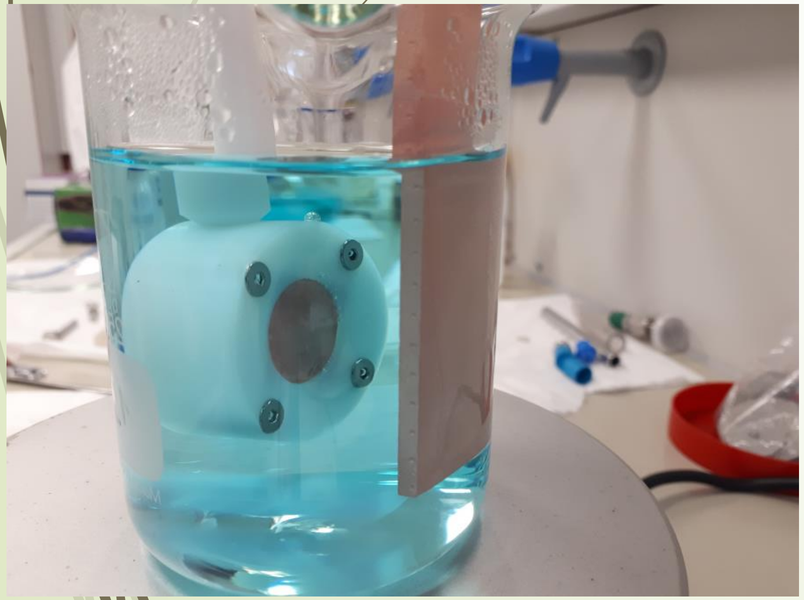


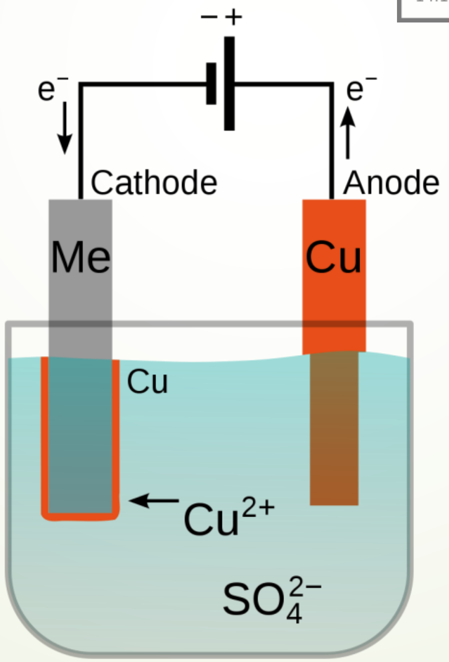
- A thin ^{222}Rn-tight, clean (^{226}Ra-free) surface coating should block ^{222}Rn
- Should work for recoil-driven AND diffusion-driven emanation
- Various techniques investigated: Vapor deposition (PVD, CVD), plasma etching, electrochemical coating

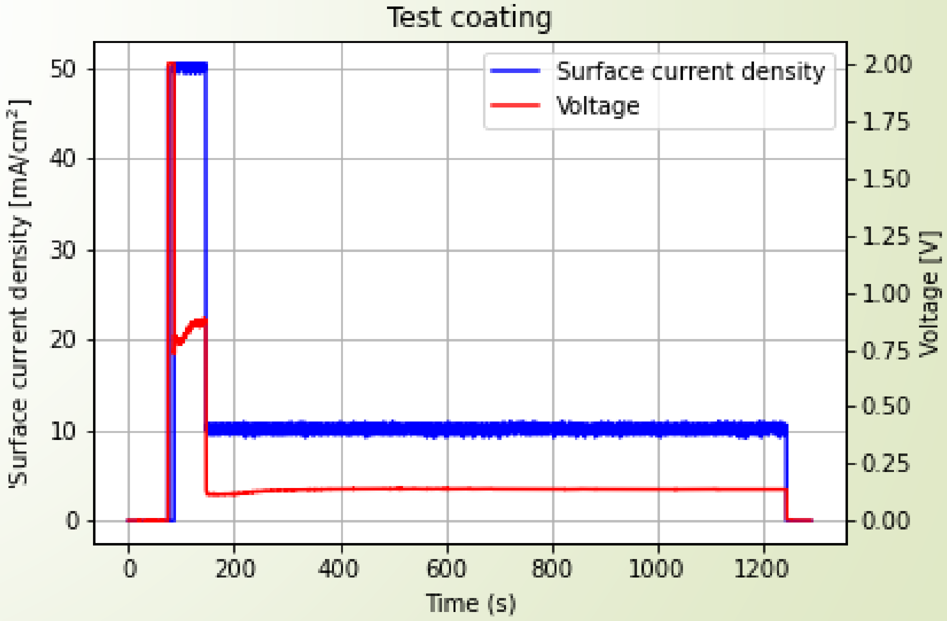
Electrochemical copper coating

- Initial tests with ^{220}Rn (thoriated welding rods and recoil-implanted stainless steel samples)
- Procedure for stable Cu coating was developed in-house at MPIK over the last few years
- Optimization (surface current / adhesion layer, …)

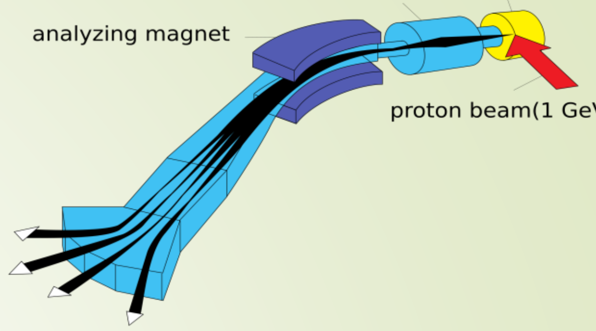






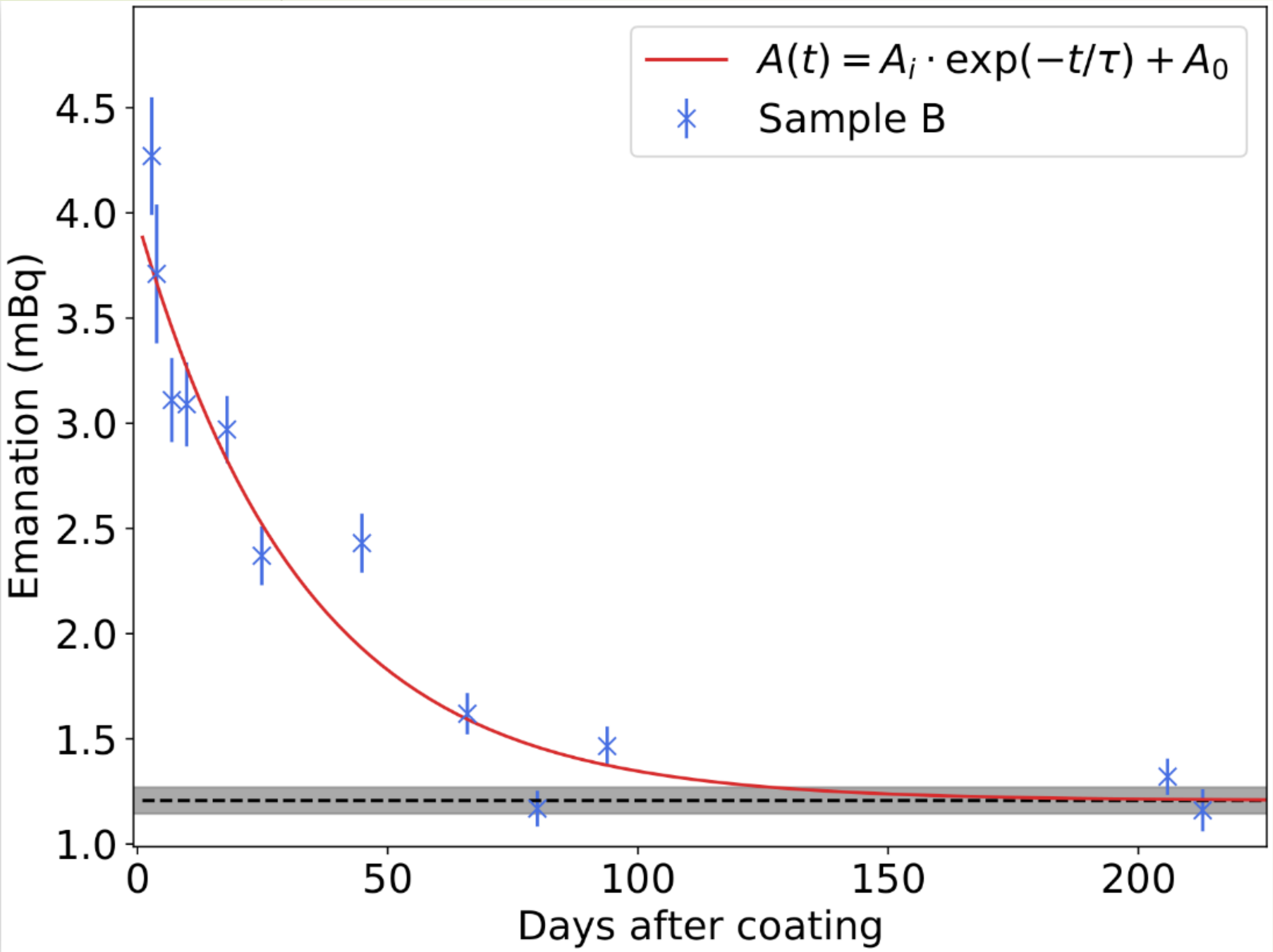


Coating of ^{222}Rn-emanating SS disc



- ^{226}Ra implanted SS disc produced at ISOLDE facility (CERN)
- 30 keV implantation energy
  - → 8 nm mean depth
- Full characterization of sample (α- and γ-spectroscopy, ^{222}Rn emanation rate)
- arXiv: 2205.15926
- ^{222}Rn emanation rate:
  - Before coating: (2.00 ± 0.05) Bq
  - After coating: (4.3 ± 0.3) mBq
- **^{222}Rn reduction factor: ~470**

Coated ISOLDE sample: Temporal development of ^{222}Rn emanation rate



- ^{222}Rn emanation rate was found to decrease
- Coating is getting "tighter"
- Oxidation?
  - But storage under protective atmosphere
- Re-crystallisation?
- **Final ^{222}Rn reduction factor: ~1700**
- Next step: Upscaling

Summary

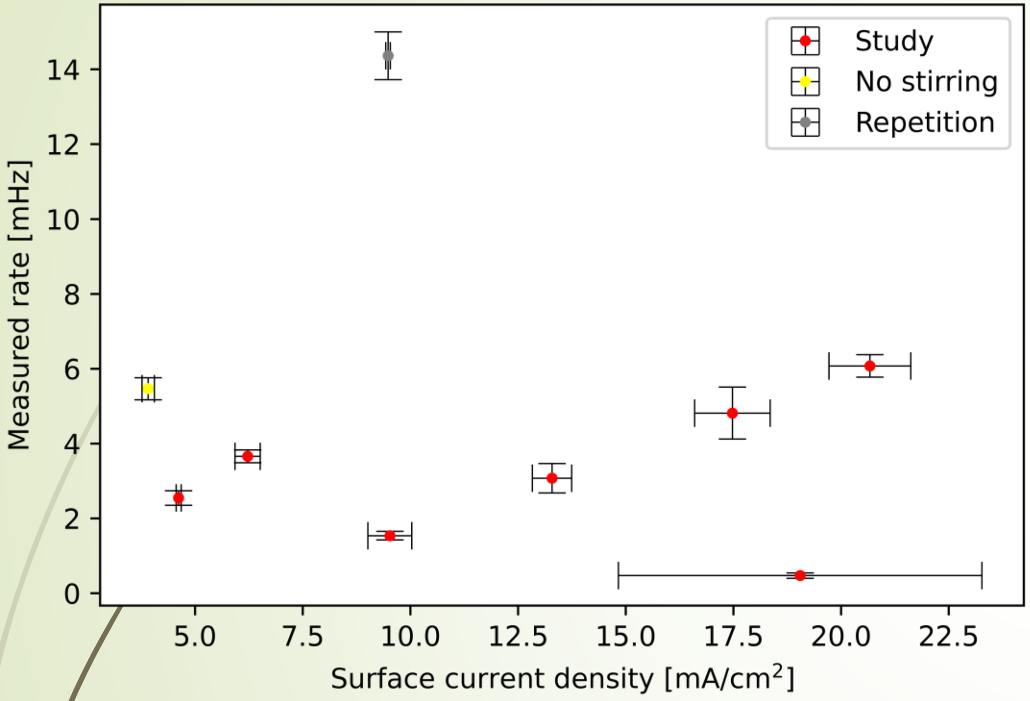
- Ultimate DARWIN experiment require ultiamtely low background level
- Dissolved noble gases dominate radioactive background
- Kr-control by cryo-distillation and ultrasensitive analytics techniques
- ^{222}Rn control is most challenging.
- **0.1 μBq/kg** will can only be achieved by combining
  - careful material selection
  - powerful online purification
  - novel ^{222}Rn mitigation techniques

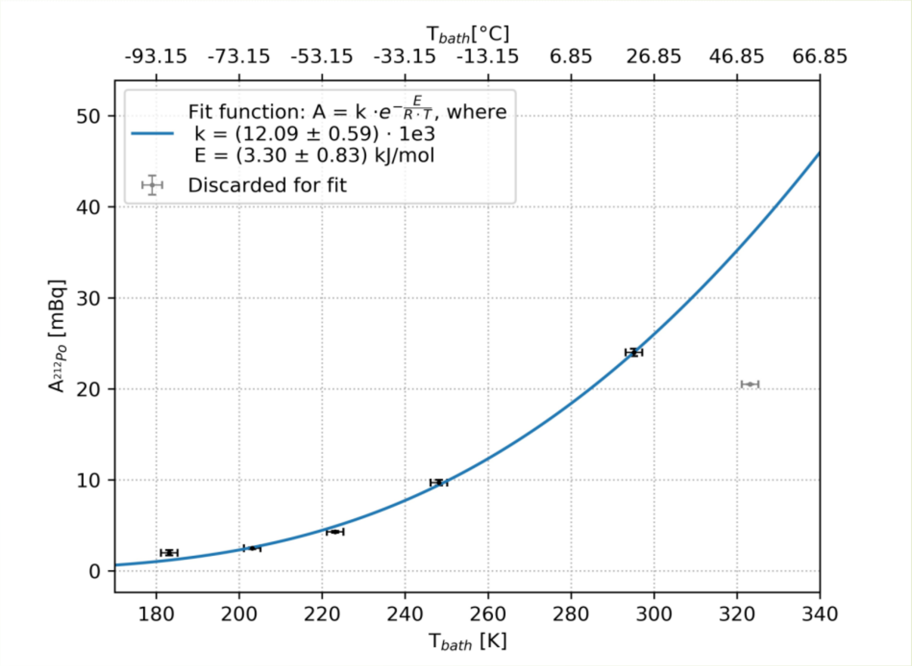
Backup

Comparison of sensitivity (following procedure outlined in EPJC (2015) 75:531)

	sample chamber configuration											
	class 1: small low-mass samples represented by point-source						class 2: large high-density samples represented by copper block					
	threshold activity [mBq]						threshold activity [mBq/kg]					
Isotope	Bruno	Corrado	GIOVE	GeMSE	Gator	GeMPI II	Bruno	Corrado	GIOVE	GeMSE	Gator	GeMPI II
^{238}U	56.08	39.95	12.01	3.64	2.24	1.86	168.57	16.26	3.23	1.22	0.68	0.67
^{226}Ra	1.06	0.70	0.19	0.069	0.083	0.042	3.75	0.36	0.071	0.030	0.029	0.019
^{228}Th	1.69	1.15	0.33	0.12	0.13	0.081	3.99	0.37	0.046	0.031	0.027	0.020
^{228}Ra	1.74	1.19	0.35	0.11	0.11	0.084	5.32	0.49	0.11	0.037	0.032	0.030
^{137}Cs	0.59	0.44	0.12	0.026	0.040	0.027	2.16	0.22	0.034	0.011	0.015	0.012
^{60}Co	0.40	0.28	0.13	0.066	0.028	0.023	1.03	0.09	0.025	0.016	0.0064	0.0062
^{40}K	11.60	4.07	1.68	0.47	0.50	0.35	29.96	1.34	0.22	0.13	0.12	0.10

Optimization of Cu coating procedure and ^{220}Rn reduction results

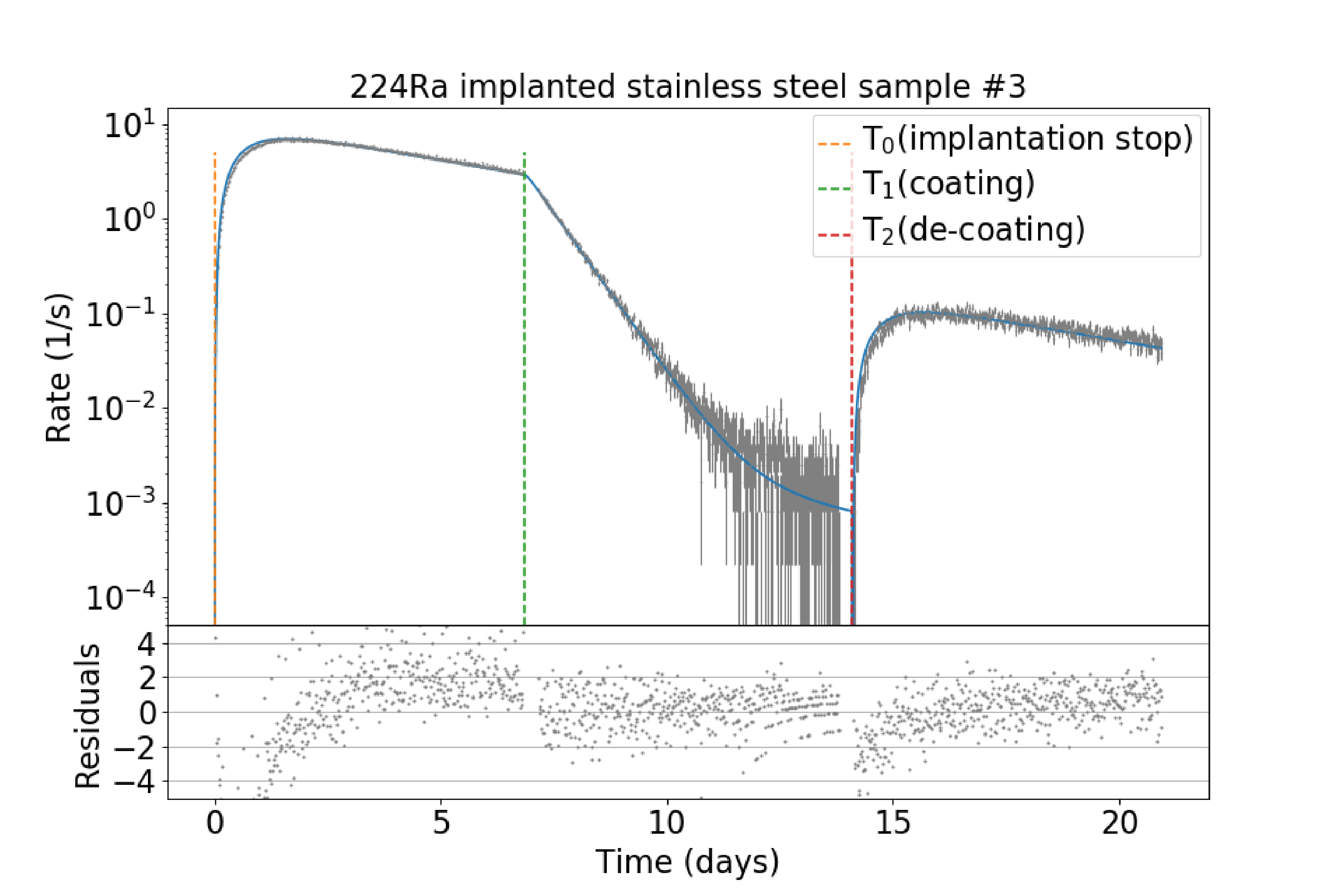


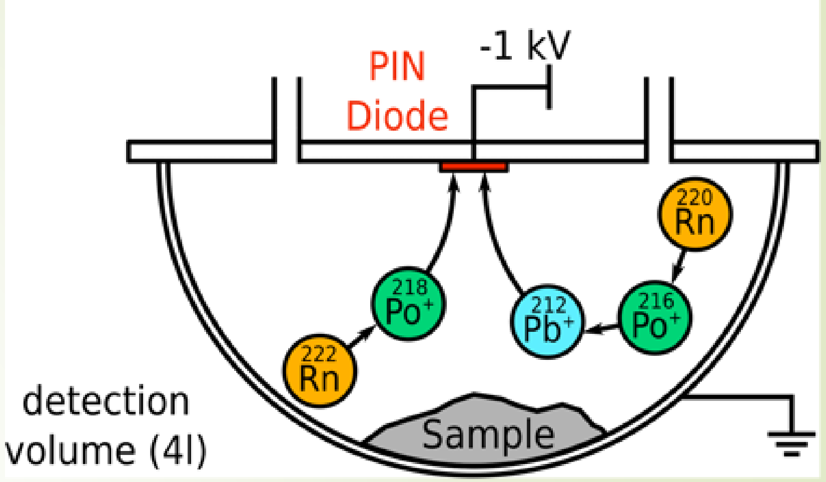


- Optimum surface current density identified
- Avoid whisker growing by careful parameter control

- ^{220}Rn reduction factor up to 100 achieved for 5 µm thick Cu coating
- Hints for ^{222}Rn reduction
- Recoil emanation fully stopped
- Diffusion-driven emanation confirmed by tests at different temperatures

Coating (and de-coating) of ^{224}Ra-implanted SS disc





- ^{224}Ra decays on SS disc
- ^{220}Rn is emanated and decays in electrostatic radon monitor
- Charged ^{212}Pb (^{220}Rn-daughter) is collected on PIN diode
- Counting of ^{212}Po alpha-decays
- ^{220}Rn reduction factor R: **20<R<1000**
- Upper limit from coating, lower limit from de-coating