Radon Removal System for the experiment XENONnT and beyond

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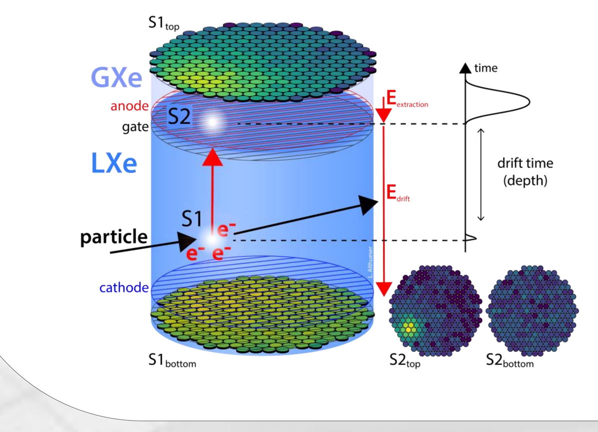
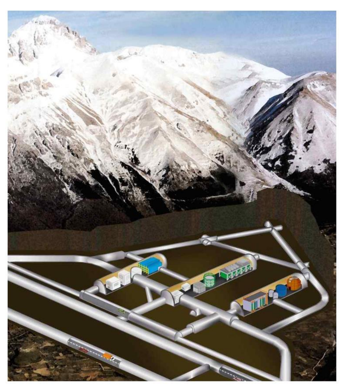
The XENONnT dark matter experiment

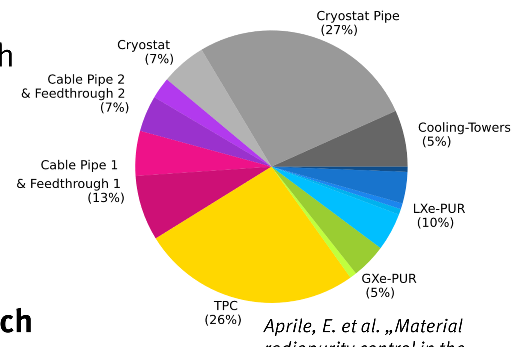
- Aimed at direct search for **WIMP** dark matter via nuclear recoils in xenon
- Located under 1500m of rock (3600 m.w.e) at LNGS, Italy
- Uses a LXe **dual phase time projection chamber (TPC)** filled with 5.9 t of xenon
- **Full 3D position** reconstruction using 494 PMTs (253 on top, 241 on bottom), z-position reconstructed via drift time between S1 and S2
- Benefits of using **xenon**:
  - Heavy nucleus (A~131) ⟶ high interaction with WIMPs (~A²)
  - High nuclear charge (Z=54) ⟶ very good self-shielding
  - Highly radiopure
- Projected WIMP sensitivity: $1.4 \cdot 10^{-48}$ cm² at 50 GeV



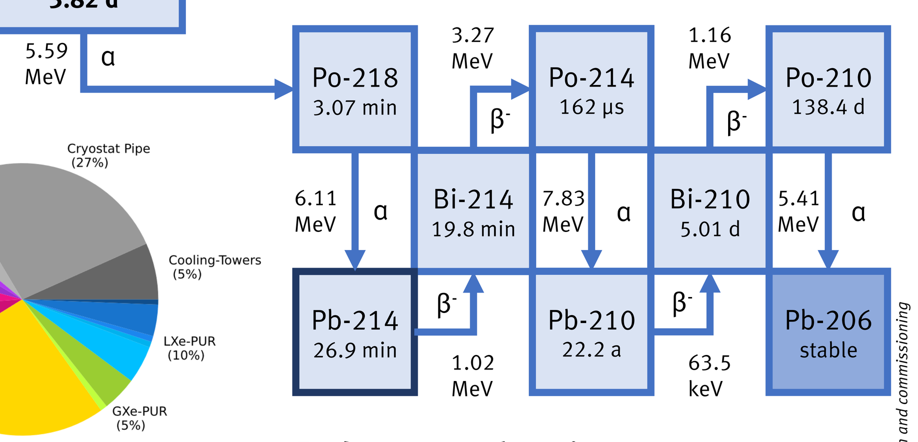


Intrinsic ^{222}Rn 3.82 d background

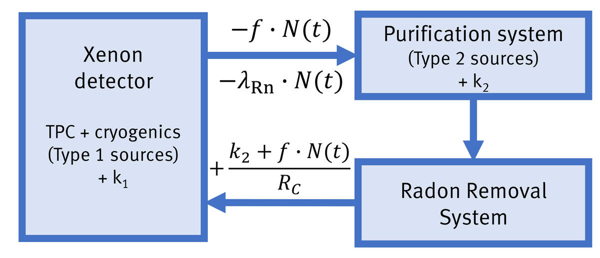
- Continuously emanated from detector material, getters, pumps, …
- Half-life of 3.82 d (long enough for homogeneous distribution)
- Decays to ^{214}Pb, β⁻-emitter **(1.02 MeV)** ⟶ ER background from ^{222}Rn spectrum leaks into **region of interest for WIMP search**
- As a noble gas, ^{222}Rn can not be removed by getter and cannot be shielded. **Mitigation** by
  - Extensive **material selection** and cleaning
  - Improved **surface/volume ratio** of the detector
  - Continuous **active removal** via cryogenic distillation
- Without removal: ≈ 3.3 µBq/kg = $3.3 \cdot 10^{-25}$
- Removal by continuous cryogenic online distillation required



Aprile, E. et al. „Material radiopurity control in the XENONnT experiment", Eur. Phys. J. C (2022) 82:599



Radon source locations:



Type-I
- Inside detector or after removal system
- Removal is flow dependent

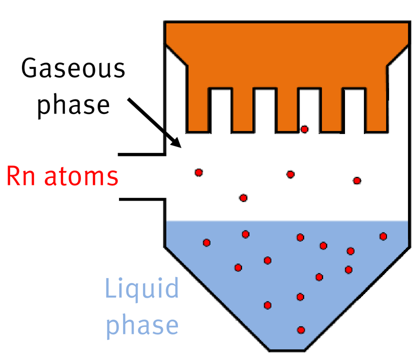
Type-II
- Before removal system
- Can be effectively removed

Schulte, D., PhD thesis: „Development, construction and commissioning of a novel cryogenic distillation system for radon removal to a sub-µBq/kg level in the XENONnT dark matter experiment", 2019

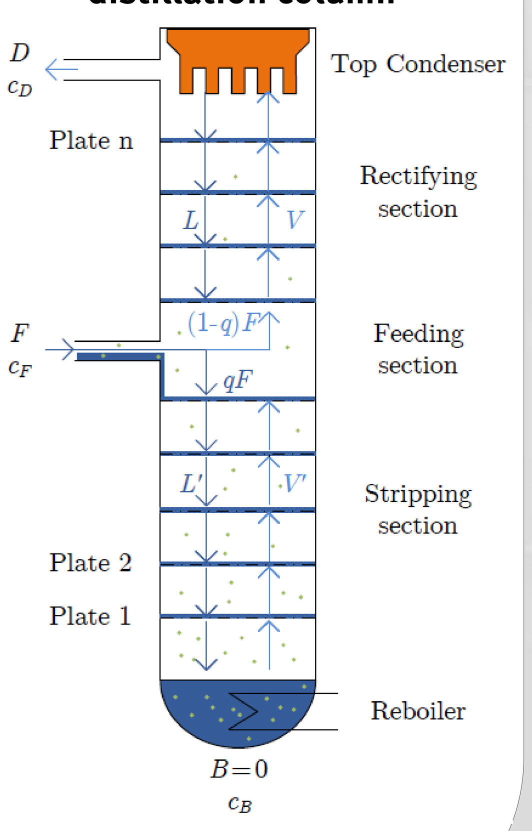
Cryogenic distillation

- Cryogenic distillation utilizes **difference in vapor pressure** between Rn and Xe
- Relative volatility $\alpha = \frac{P_{Rn}}{P_{Xe}} = 0.1$ at -98°C (LXe temperature)
- **Raoult's law** ⟶ Xe as the more volatile component is enriched in the gaseous phase, while Rn is enriched in the liquid phase
- Single distillation stage ⟶ **multistage** distillation column
- Modified **McCabe-Thiele** approach
- Top condenser: Vapor is partially liquefied and fed back to the column (partial reflux or **rectification**)
- Extract radon depleted xenon from the top
- **Radon is trapped** in LXe reservoir at the bottom ("reboiler") until decay ($T_{1/2} = 3.8$ d) ⟶ no extraction of contaminant enriched xenon ⟶ **no xenon loss**

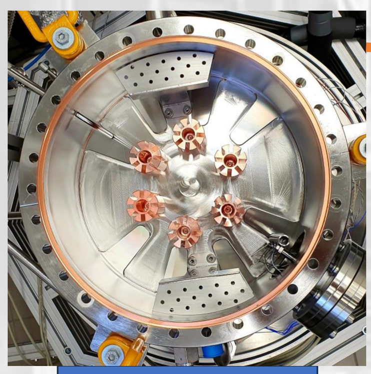
Single distillation stage



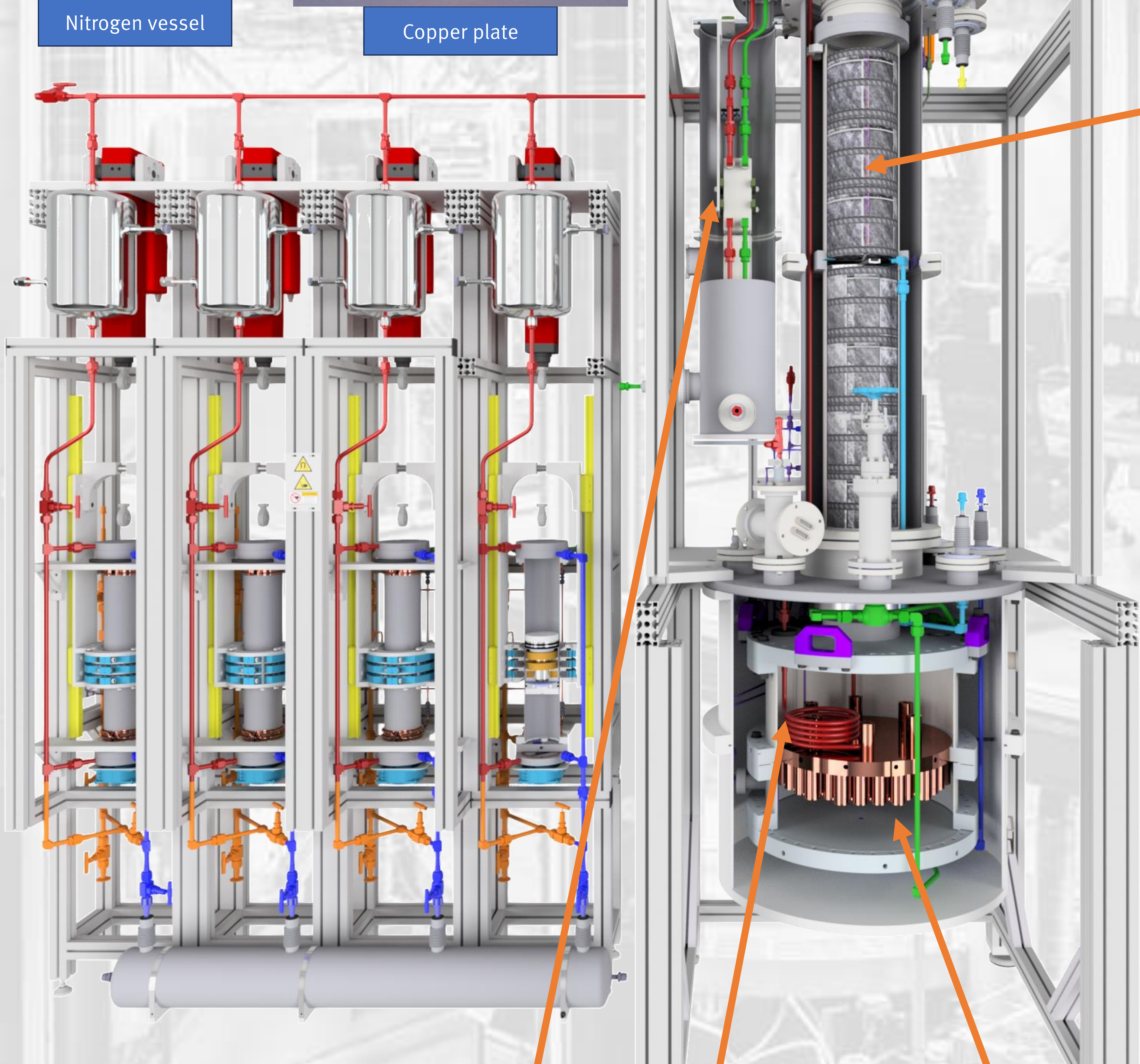
Multistage distillation column

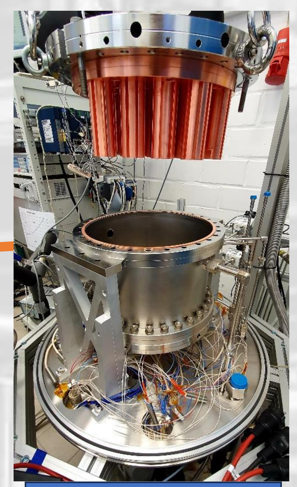


Murra, M., PhD Thesis, „Intrinsic background reduction by cryogenic distillation for the XENON1T dark matter experiment"

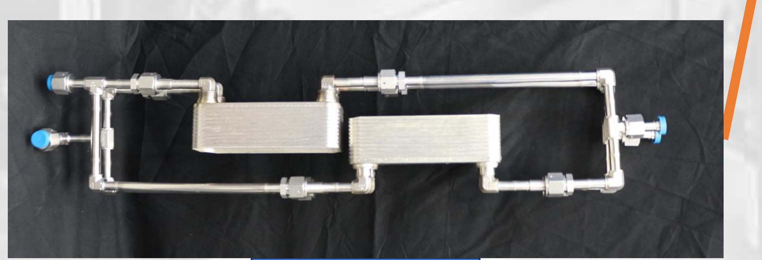

Nitrogen vessel


Copper plate

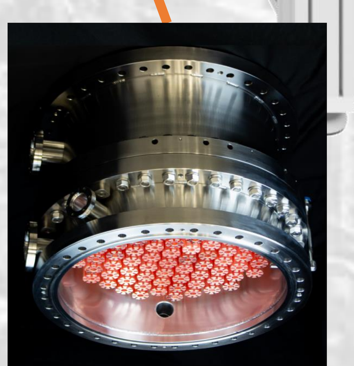



Top condenser


Package material

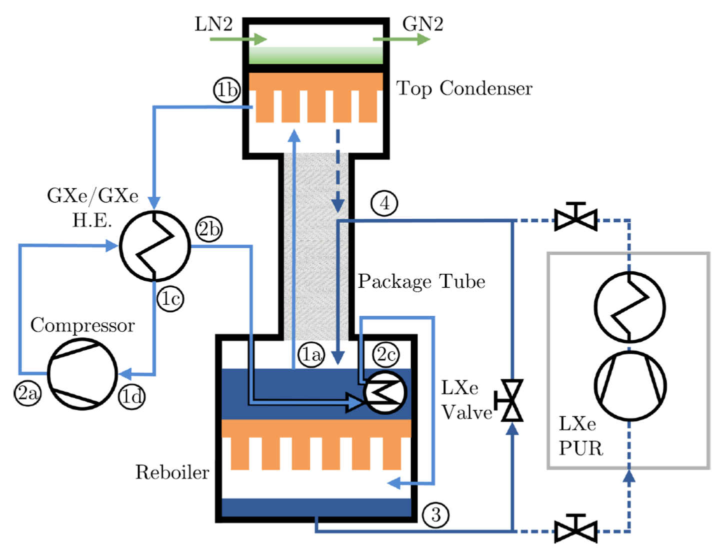

Heat exchanger


Top reboiler


Bottom reboiler

Radon distillation column

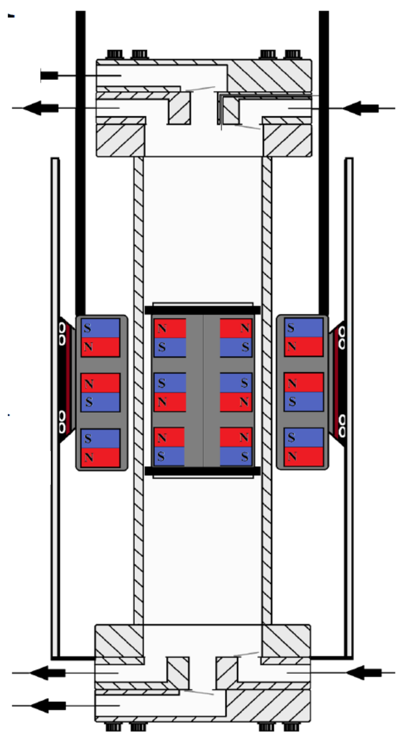
- 3.8m high, located on 2nd floor of XENONnT service building
- Four main components:
  - **Package tube:** Structured packaging material = multiple theoretical stages. Large surface for liquid-gas exchanges
  - **Reboiler:**
    - Top half traps ^{222}Rn until it decays
    - Serves as Xe-Xe heat exchanger to evaporate xenon into package tube and to re-liquefy purified xenon in the bottom
  - **Top condenser:** Creates reflux with ratio 0.5 and provides 1 kW of cooling power via LN2
  - **Compressor:** Four radon-free magnetically-coupled piston pumps re-liquefy GXe from top condenser
- Column can be run concurrently in **two independent modes**:
  - **LXe mode:** 200 slpm (1.7 tonnes/day) of xenon extracted from detector (after LXe PUR) ⟶ **Rn reduction factor 2**
  - **GXe mode:** Additional 25 slpm extracted from regions with high radon emanation (cables, feed lines, …) ⟶ **Rn reduction factor of 2** (close to 100% efficient in suppressing Rn emanated into gas phase)
- Depletion factor 100 at top, enrichment factor 1000 at bottom (with respect to the feed) ⟶ reduction factor $\mathcal{O}(10^5)$



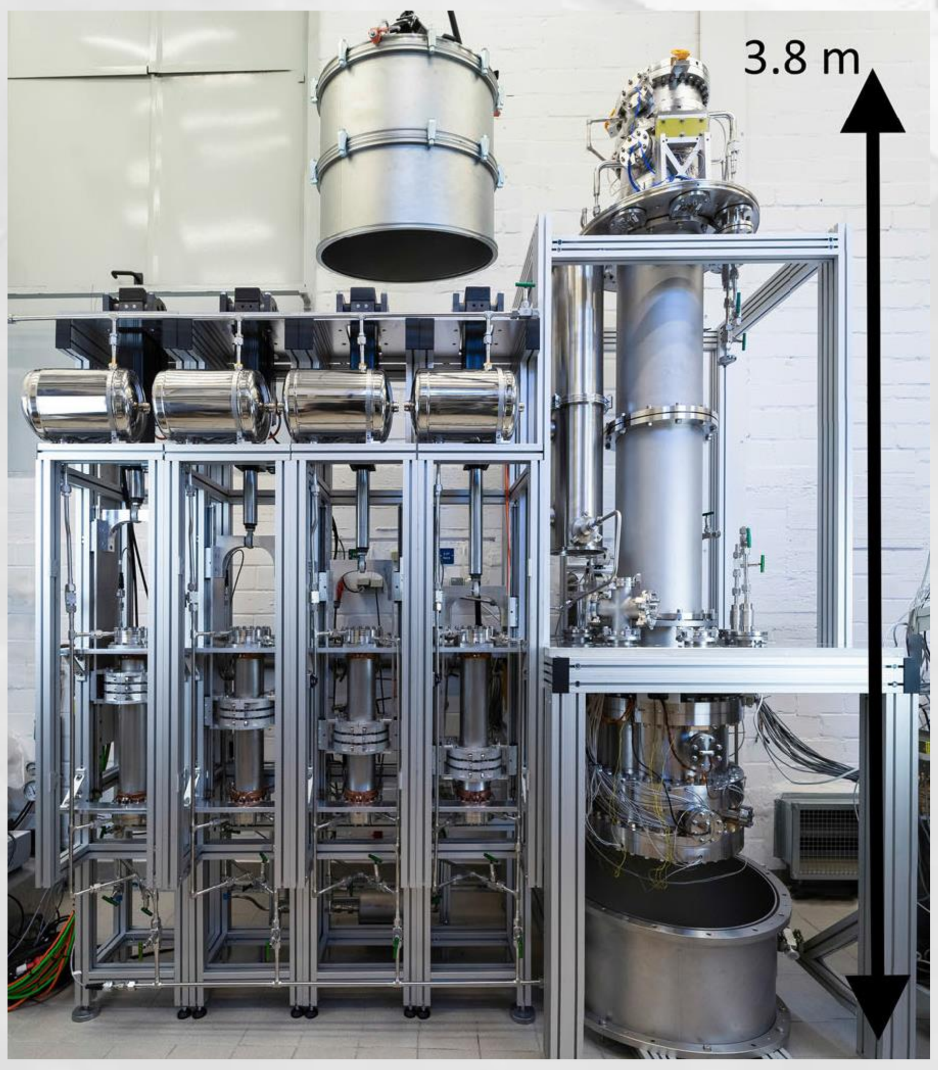
Murra, M. et al. „Design, construction and commissioning of a high-flow radon removal system for XENONnT", Eur. Phys. J. C (2022) 82:1104

Magnetically-coupled piston pumps

- Due to continuous Rn emanation, **reduction depends on flow, provided** by compressor, i.e., **the four piston pumps**
- Stainless steel cylinder
- **Magnetically-coupled** drive mechanism based on alternating magnet configuration
- **Complete isolation of the drive from the gas**
- Spring-steel flapper valves enable double stroke design, $\Delta P \approx 3$ bar
- Usage of clean and **radiopure components** (^{222}Rn emanation of only 110±3 µBq)
- Two commercial heat exchangers used to warm up outgoing purified xenon and cool down returning compressed xenon ⟶ acts as part of a **heat pump**

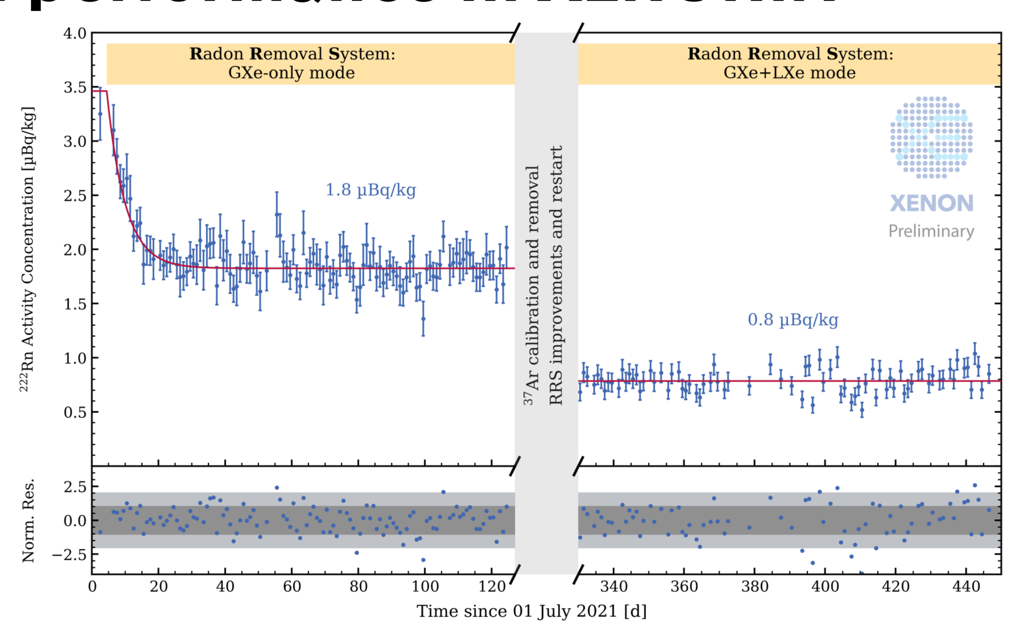


Brown, E. et al. „Magnetically-coupled piston pump for high-purity gas applications", Eur.Phys.J. C, vol. 78 (2018) 604



Measured performance in XENONnT

- ^{222}Rn concentration without distillation system: 3.3 µBq/kg
- During SR0: **GXe**-mode only:
  1.8 µBq/kg
- During SR1: **GXe+LXe** mode:
  0.8 µBq/kg
- Marks a **new world record** for any xenon dark matter experiment



Acknowledgements

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