A cryogenic Paul trap setup for the determination of the ionic radiative lifetime of $^{229m}Th^{3+}$

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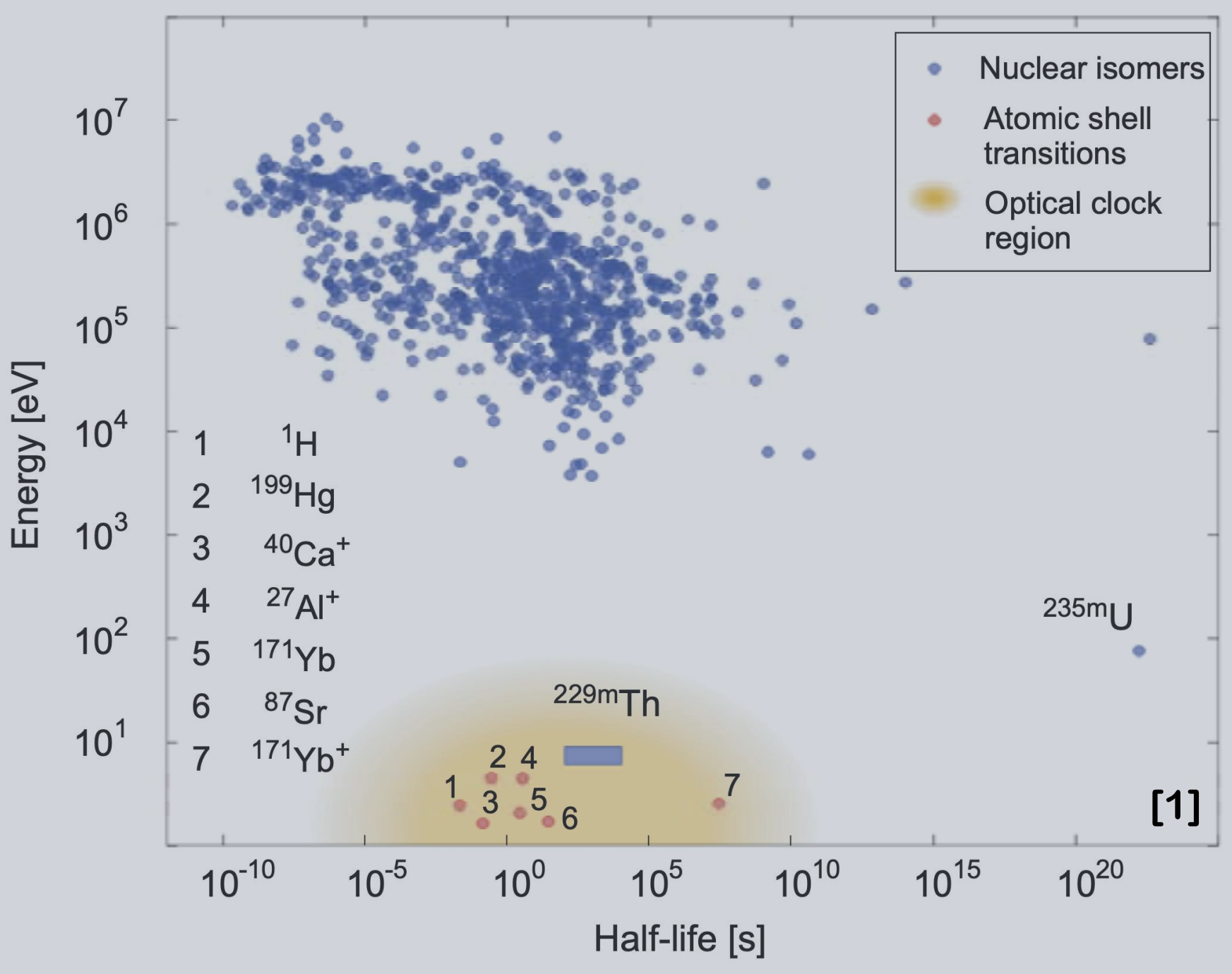
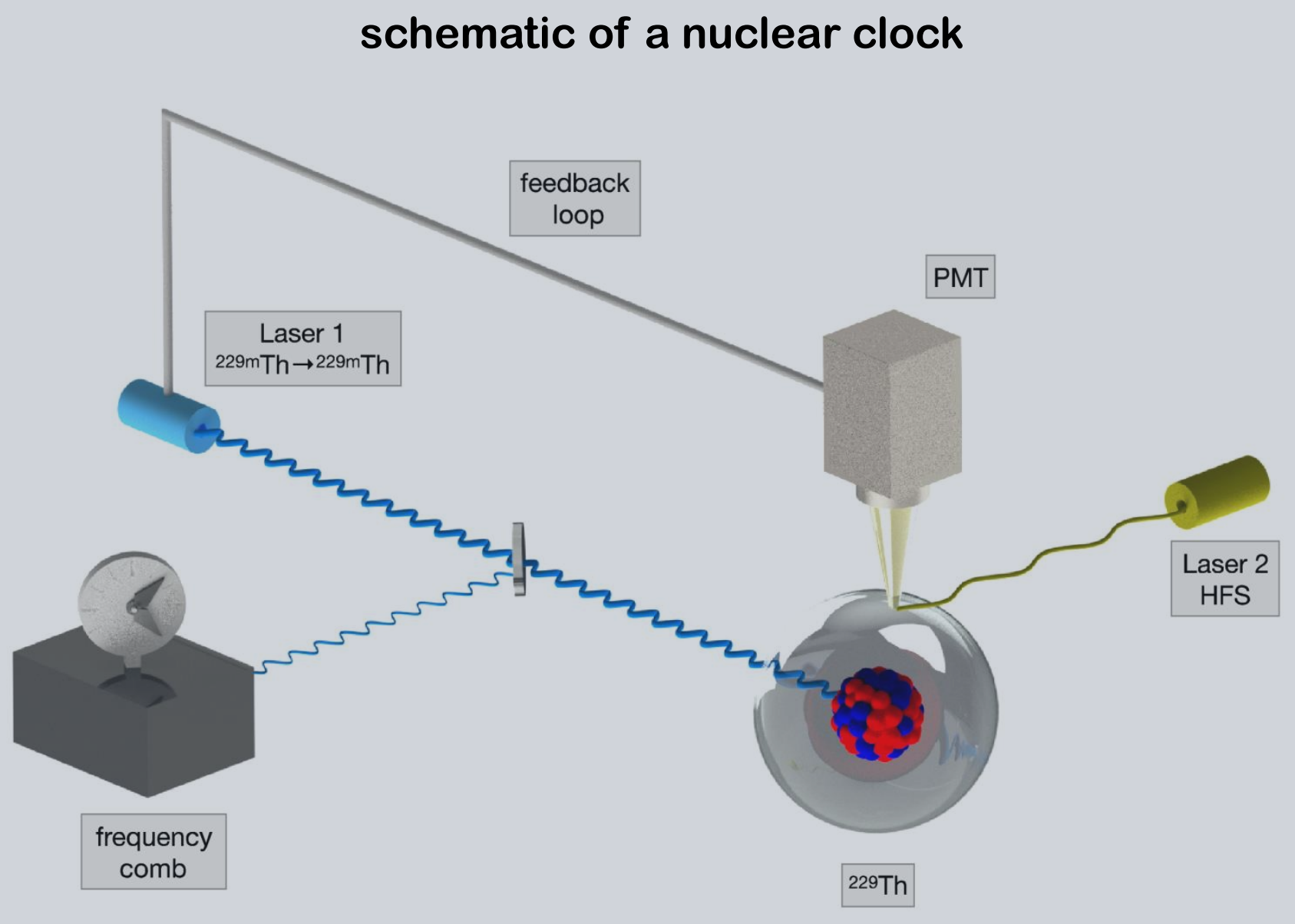
Why ^{229m}Th?

- unique standing amongst all presently known nuclides: lowest excited nuclear state
- suitable (and currently only) candidate for direct laser excitation
- possible use as frequency standard (“nuclear clock”)




schematic of a nuclear clock

Nuclear Clock Applications

- unique quantum sensor beyond timekeeping [2,3]
- ^{229m}Th provides largely enhanced sensitivity to temporal variations of fundamental constants as predicted by theory [3, 4, 5]
- possible search for Dark Matter [3,6]
- theoretically predicted frequency uncertainty in the range of 10^{-19} allows for detection of gravitational shifts in the mm region [6]
- improved precision of satellite-based navigation [6]

What is known so far?

- proof of existence by direct detection of internal conversion decay [1]
- lifetime of the neutral isomer:
  $\tau_{IC} = 7 \pm 1\ \mu s$ [7]
- hyperfine structure measured via collinear laser spectroscopy of $^{229m}Th^{2+}$ [8]
- first direct and precise measurement of the excitation energy:
  via IC:
  $E_{ex} = 8.28 \pm 0.17\ eV$ [9]
  via magnetic microcalorimetry
  $E_{ex} = 8.10 \pm 0.17\ eV$ [10]

What is still missing?

- ionic lifetime τ_γ

→ theoretical prediction:
$\tau_{\gamma,theo} = 10^3 - 10^4\ s$
(problem: trapping at room-temperature only achievable for around 1 minute)

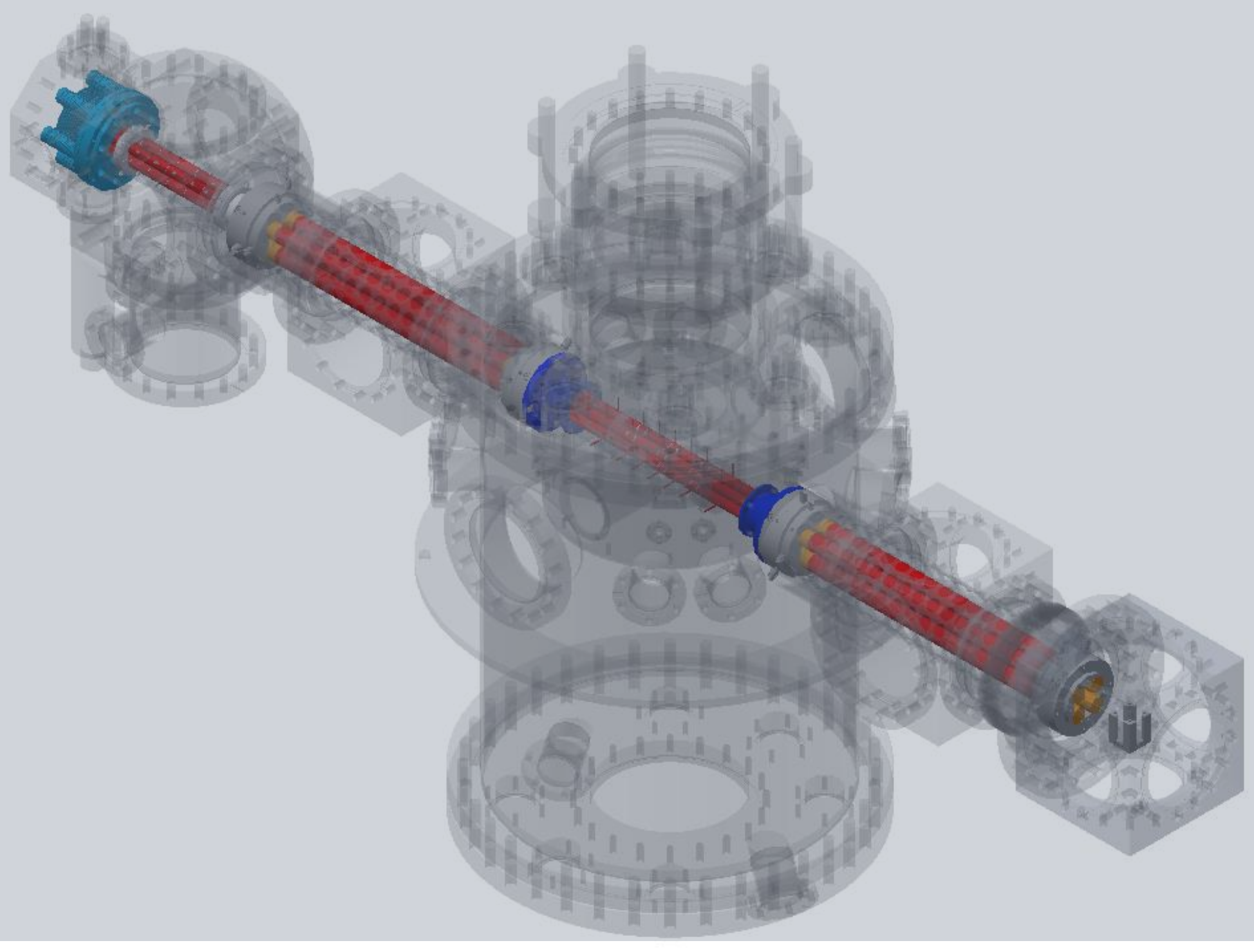
Confine $^{229m}Th^{3+}$ ions in cryogenic Paul trap to achieve long storage times!

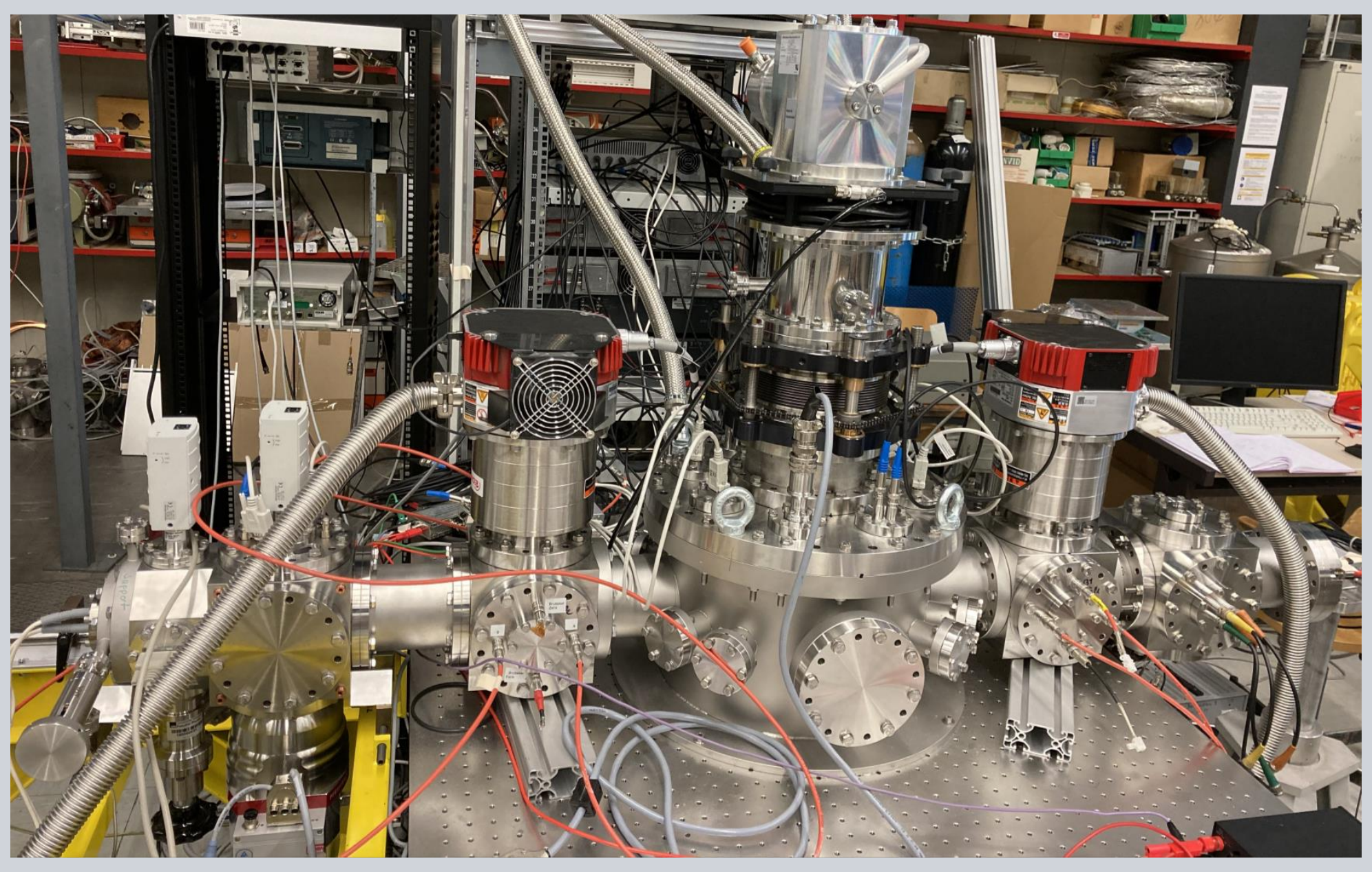
Overview of the setup:

- sufficiently long storage times for $^{229m}Th^{3+}$ to be achieved by operating the linear Paul trap at cryogenic temperatures & sympathetic laser cooling of the Th ions using $^{88}Sr^+$
- two separate pathways towards the cryogenic linear Paul trap in the center of the setup:

  „injection line“: consisting of the buffer gas stopping cell, the extraction radio frequency quadrupole (RFQ) and an quadrupole mass separator (QMS1); delivers the ^{229m}Th ions to the trap

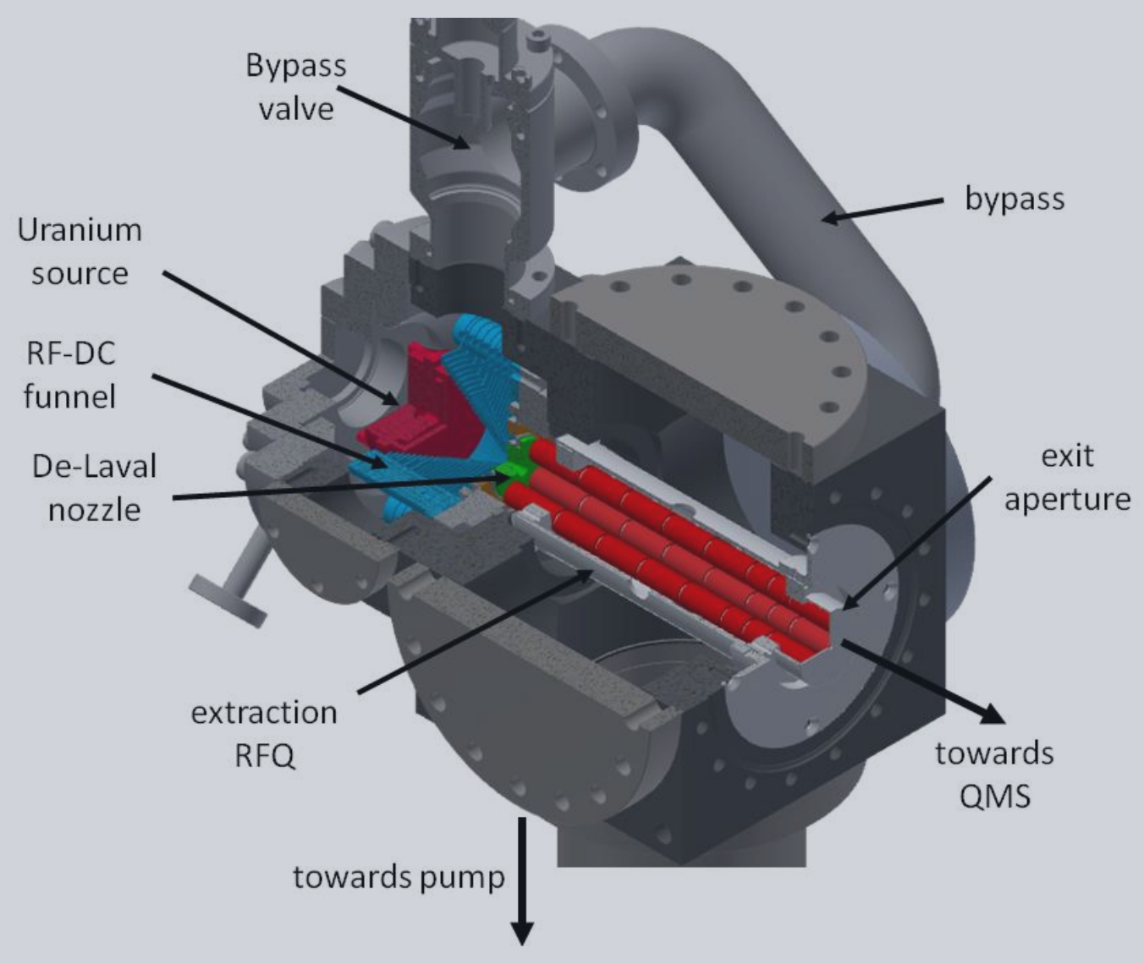
  „extraction- /Sr-injection line“: consisting of a second quadrupole mass separator (QMS2), a 90° degree bending quadrupole as well as the Sr source and an MCP detector (both mounted off-axis); delivers $^{88}Sr^+$ to the trap and allows for investigation of possible changes in the charge states of the trapped ions
- the setup allows for optical access to the trapped ions for laser cooling and fluorescence diagnostics and will be useable as platform for the realization of a nuclear clock





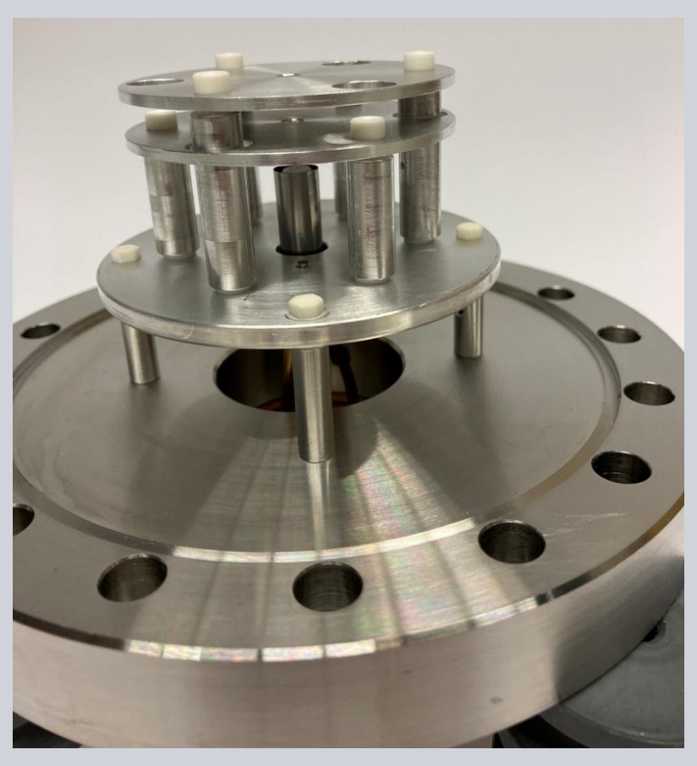
The buffer gas stopping cell:

- α-decay of ^{233}U provides ^{229m}Th with branching ratio BR ≈ 2%
- thermalization of ^{229m}Th and other decay products in buffer gas stopping cell (volume ≈ 750 ccm) using ultra pure He
- ^{229m}Th extractable in the charge states 1+,2+ and 3+
- extraction from cell through RF-DC funnel in combination with supersonic De-Laval nozzle
- subsequent RFQ provides phase space cooling of extracted ions



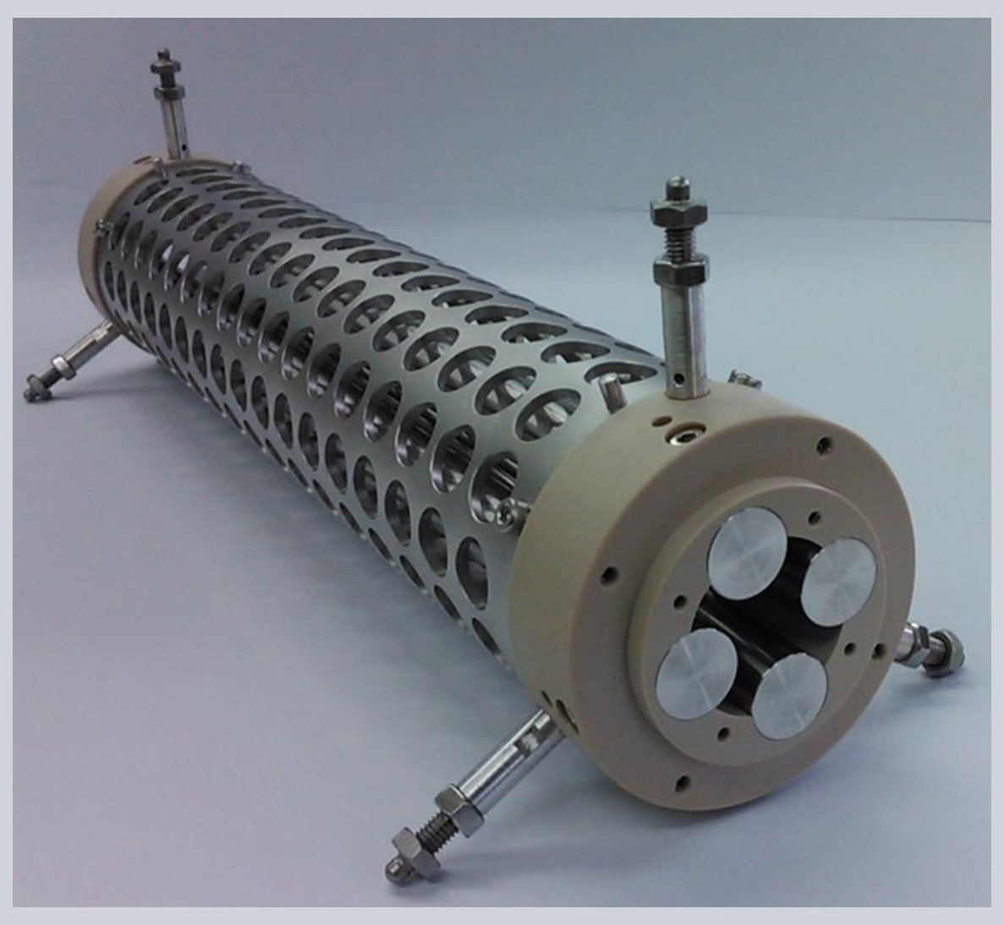
The $^{88}Sr^+$ source & laser cooling:

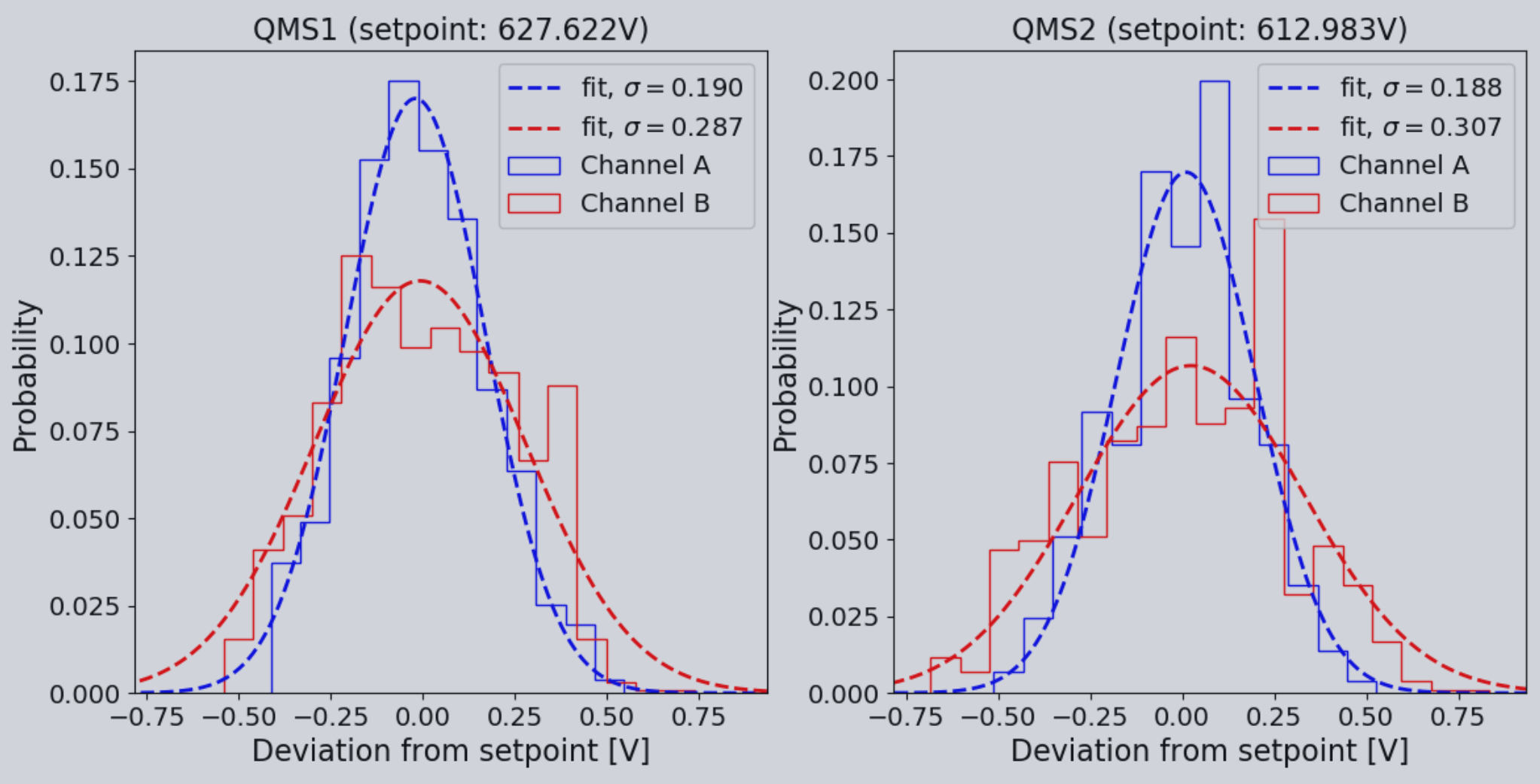
- $^{88}Sr^+$ provided by heated dispenser source
- source is mounted off-axis in order to prevent thermal radiation from entering the Paul trap
  → 90° bending quadrupole used to inject Sr ions into the QMS
  → allows for laser manipulation along the ion axis through entire setup, as the ^{233}U source carries a center hole
- details regarding the laser setup for the laser cooling can be found on the poster by K. Scharl


Mounting of Sr ion source

The quadrupole mass separators:

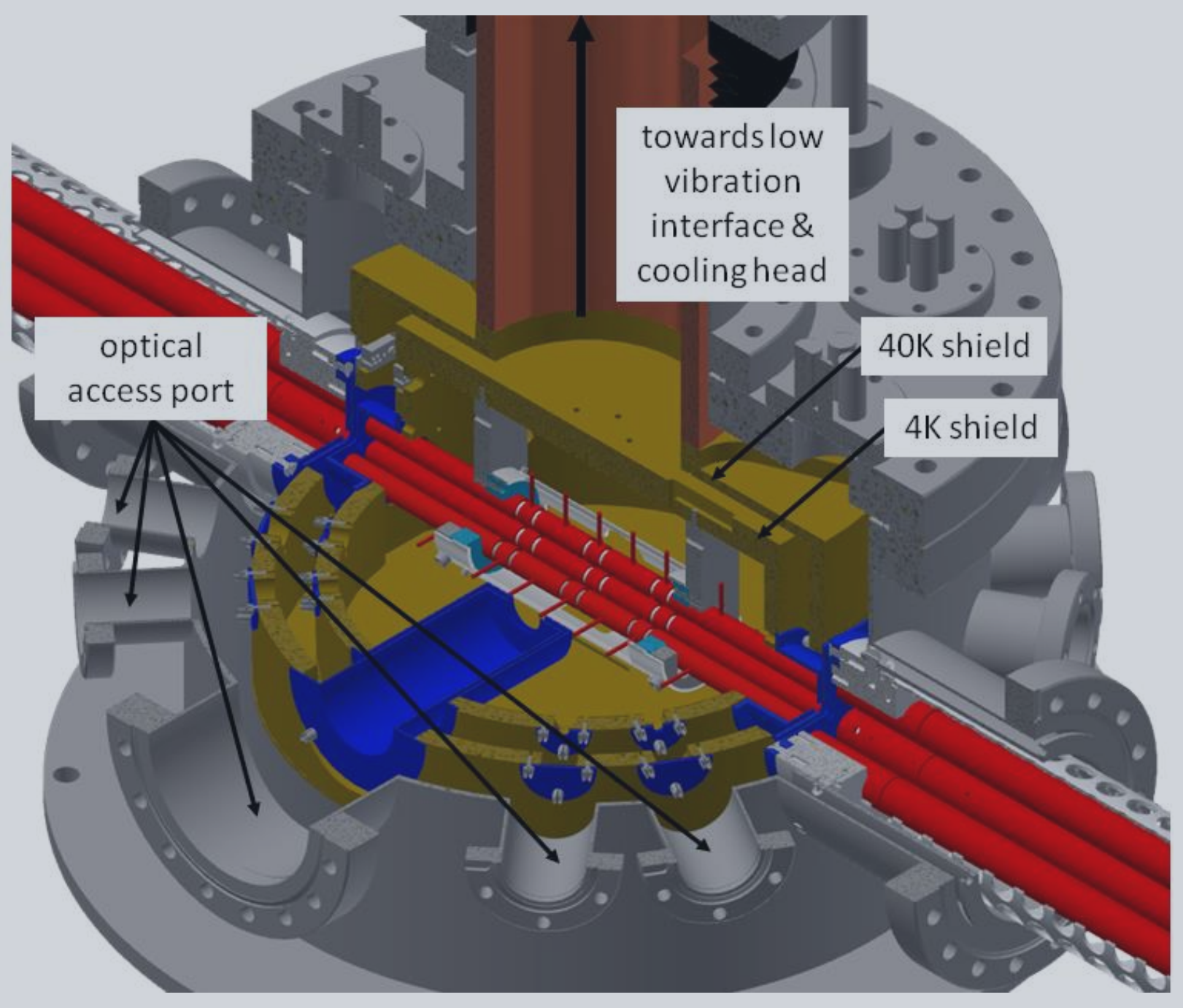
- purpose of the two quadrupole mass separators:
  QMS1: separating the ^{229m}Th ions from other daughter products of the ^{233}U decay chain extracted from the buffer gas cell
  QMS2: separating $^{88}Sr^+$ from other Sr isotopes and Rb impurities contained in the source, allows for investigation of possible changes in the charge state of trapped ions
- dimensions:
  length: 300 mm mass selective region + 50 mm Brubaker lenses at each end
  rod configuration: $\frac{d}{d_0} = \frac{18\ mm}{15{,}98\ mm} = 1{,}128$
- targeted resolution: $R = \frac{m}{\Delta m} \approx 150$ → required voltage precision: $\frac{\Delta U}{U} \leq \frac{1}{2R} \approx 3.3 \times 10^{-3}$
- achieved voltage precision: $\frac{\Delta U(FWHM)}{U} \approx 9.5 \times 10^{-4}$ (QMS1); 1.2×10^{-3} (QMS2)

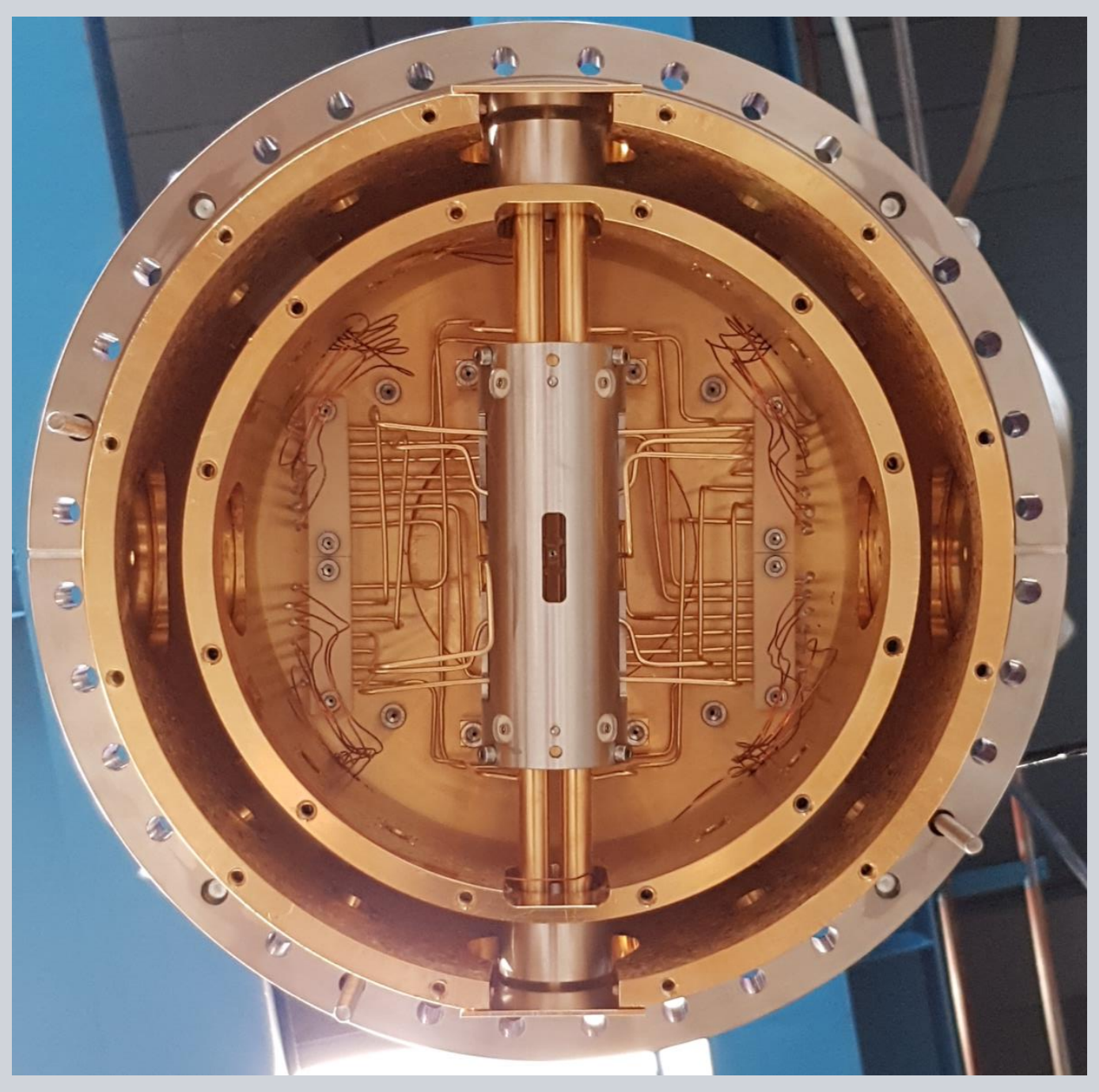




The Paul trap and its cryogenic environment:

- dimensions of the trap:
  overall length: 282 mm; 3 separate trapping regions with 8 mm length
  rod diameter: 11 mm
  inner diameter of rod configuration: 9.6 mm
- cooling provided by two-stage pulse tube cryocooler Sumitomo RP-082B2:
  1st stage: 40 W at 45 K
  2nd stage: 1.0 W at 4.2 K
- heat shields are mounted to the cooling stages of the cryocooler through ultra low vibration interface
- the housing provides a total of 10 ports (→ 5 optical axes) to allow optical access for laser cooling and fluorescence detection





Conclusion: The presented setup lays the foundation for the upcoming determination of the ionic lifetime of $^{229m}Th^{3+}$ and will be a centerpiece of the nuclear clock to be realized at LMU

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