Development of a Radio Frequency Dipole Mass Filter for the Francium Permanent Electric Dipole Moment Search

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Motivation

- Search for the permanent **e**lectric **d**ipole **m**oment of the electron d_e
- Probe for time reversal symmetry violation

Towards the next level of precision[1,2]

d_e

Current upper limit: $< 1.1 \times 10^{-29}\ e\ \mathrm{cm}$

Beyond Standard Model ?

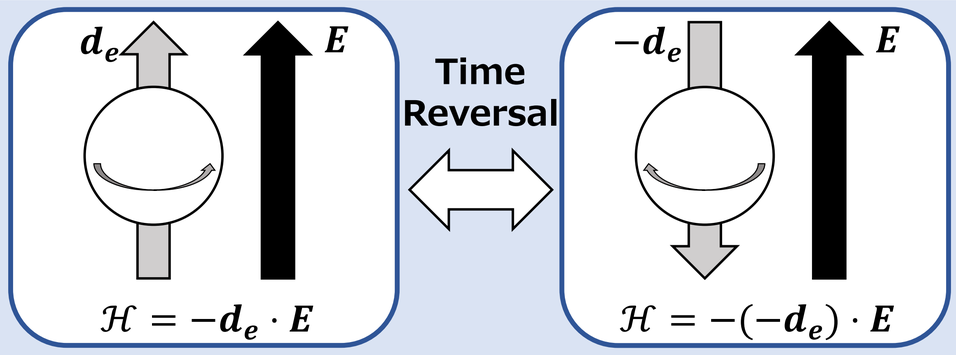
Standard Model: $\sim 10^{-39}\ e\ \mathrm{cm}$

$$\delta d_e \sim \frac{h}{2\pi E T \sqrt{nN}} \frac{1}{K}$$

[1] ACME Collaboration *et al.*, Nature **562**, 355 (2018).
[2] N. Shitara *et al.*, J. High Energ. Phys. **2021**, 124 (2021).
[3] H S Nataraj *et al.*, J. Phys.: Conf. Ser. **80**, 012050 (2007).

Development goals

- E: Electric field → 100 kV/cm
- T: Coherence time → 3 s
- n: Number of measurements → 10^4
- N: Number of atoms → 10^8
- K: **Francium (Fr)** EDM enhancement factor →799



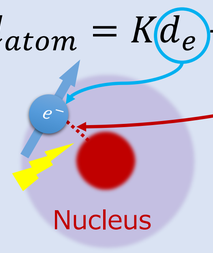
EDM of paramagnetic atom

$$d_{atom} = K d_e + S C_N^{S-PS(0)}$$

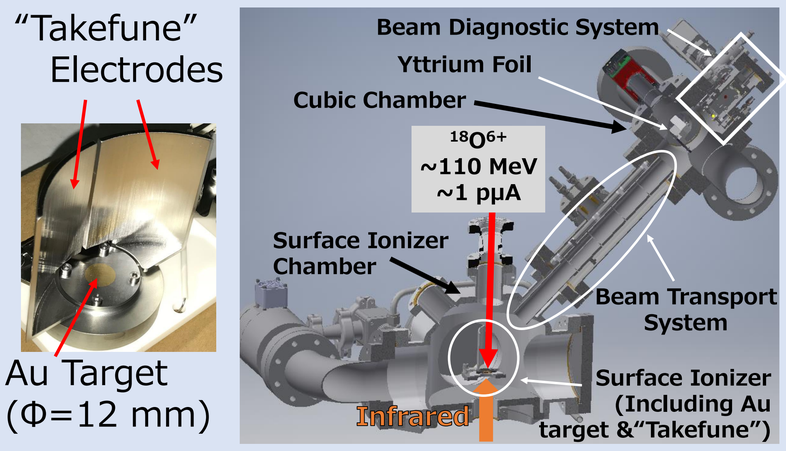
Due to relativistic motion of unpaired valence electron, $K \propto Z^3$

	Rb	Cs	Fr
K	24.6	125.9	799

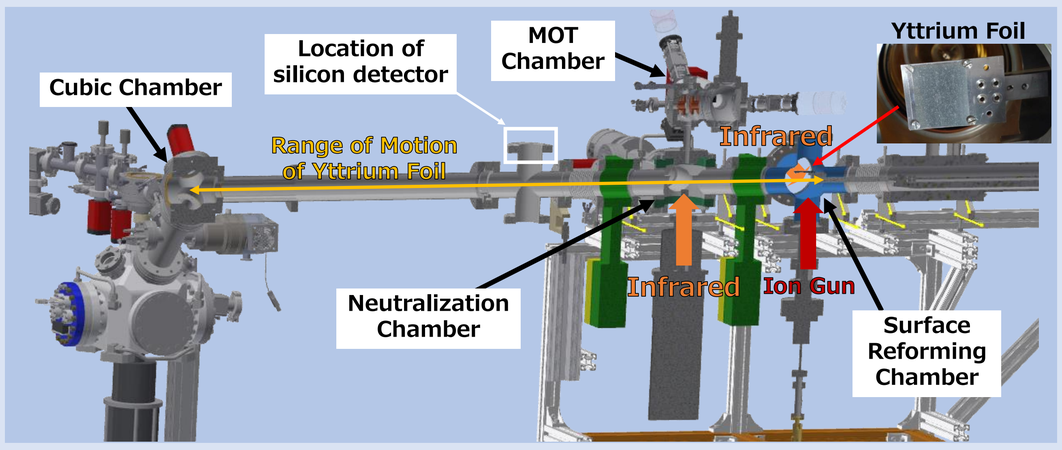
[2,3]



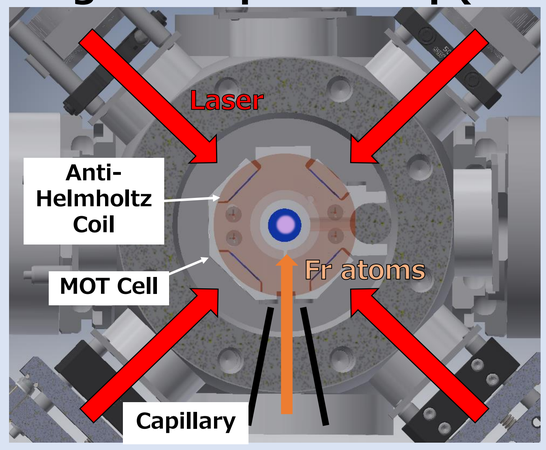
Fr Production & Extraction



Fr Neutralization

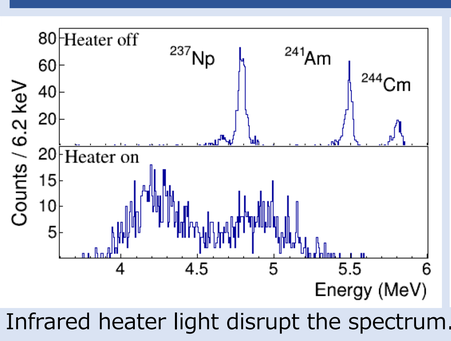


Fr Magneto-Optical Trap(MOT)

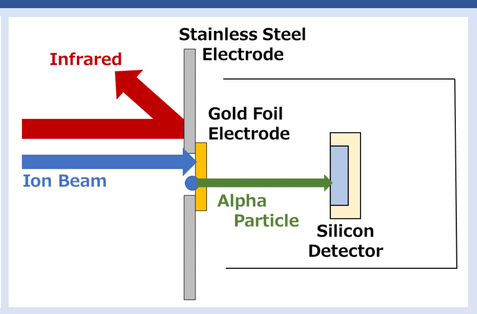


Purpose of this study: Increasing efficiency of various components and N by **improvement of Fr beam purity**
→Development of a **Radio Frequency Dipole Mass Filter** & **Simultaneous Beam Diagnostic System**

Simultaneous Beam Diagnostic System



Infrared heater light disrupt the spectrum.

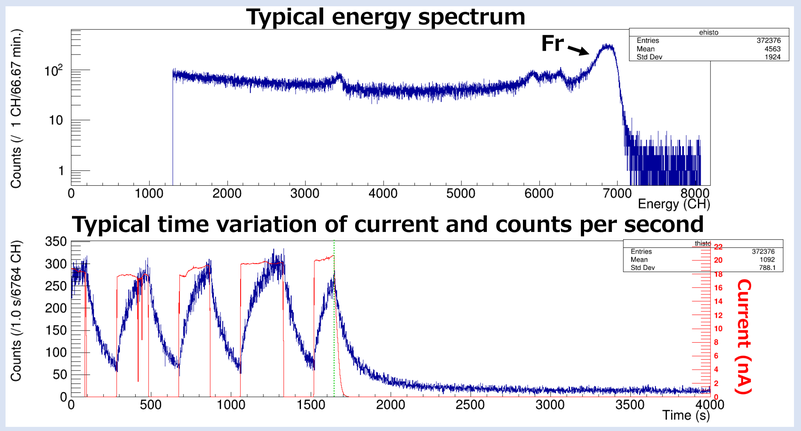


Schematic Drawing of SBDS.

Simultaneous real-time measurement of **beam current** & **decay alpha radiation** of isotopes in the beam.

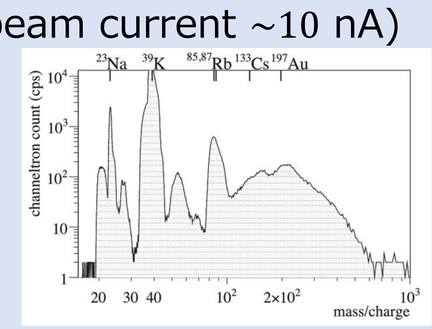
Gold foil was used for shielding the silicon detector(SSD) from infrared heater light.

Data obtained by SBDS →



Radio Frequency Dipole Mass Filter

- ^{210}Fr beam intensity $< 5 \times 10^6$ /s
  VS All beam intensity $\sim 10^{10} - 10^{11}$ /s (beam current ~10 nA)
- Beam impurities cause contamination of yttrium surface.
  →Loss of reproducibility.
  Decline of neutral Fr production efficiency.
  Deterioration of MOT chamber vacuum.

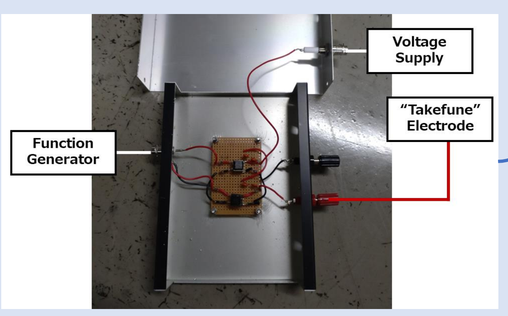


Mass-to-charge ratio spectrum of the beam obtained from a similar experiment at Tohoku University[4]

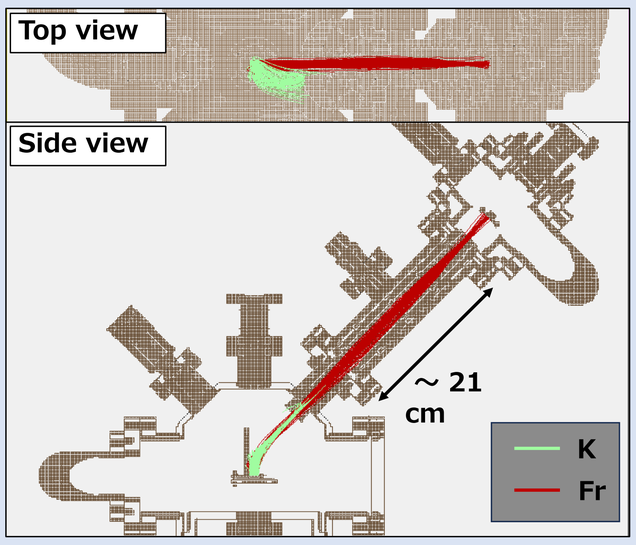
- **R**adio **F**requency **D**ipole **M**ass **F**ilter
  Apply an oscillating voltage of opposite phase to the pair of "Takefune" electrodes.

Mass separation of low-energy beam in a compact space

$$V_L(t) = \frac{V_{pp}}{2} \sin\left(2\pi f t + \frac{\pi}{2}\right) + V_{0L}$$
$$V_R(t) = \frac{V_{pp}}{2} \sin\left(2\pi f t - \frac{\pi}{2}\right) + V_{0R}$$



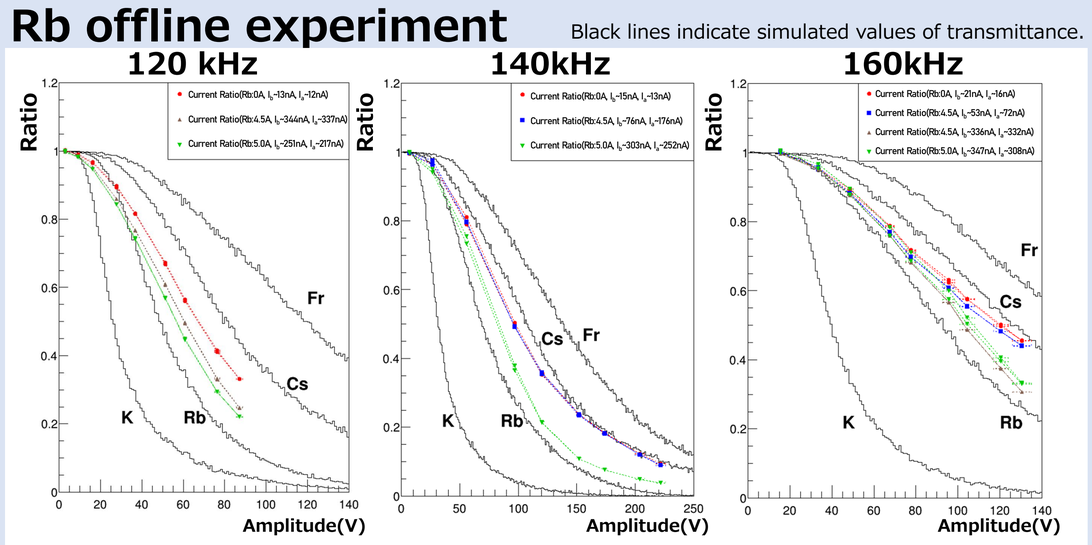
AC circuit for RFDMF



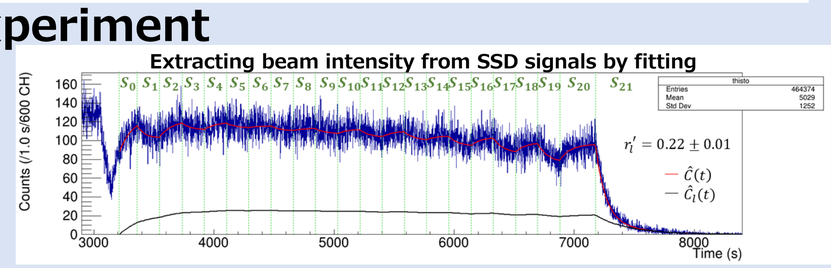
[4] Hirokazu Kawamura *et al.*, Rev. Sci. Instrum. **87**, 02B921 (2016)

Rb offline experiment

Black lines indicate simulated values of transmittance.

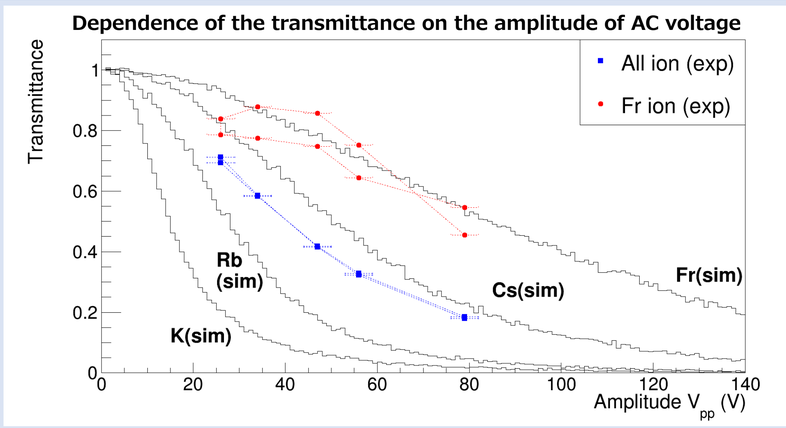


Fr online experiment



Indefiniteness by beam intensity ratio

Improvement rate of apparent beam purity **~2.9**



Conclusion & Outlook

- Qualitative evaluation showed an improvement in apparent beam purity. ➡ Proof of principle.
- Quantitative evaluation included indefiniteness. ➡ The beam diagnostic system needs to be improved.
- Further improvement of beam purity requires modification of the beam transport system.