THE MORA PROJECT

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RÉGION NORMANDIE

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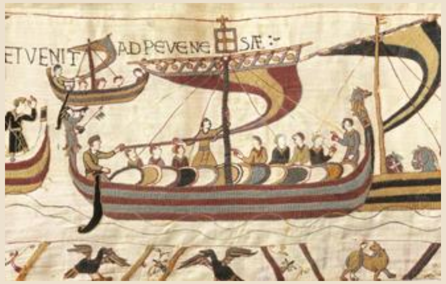


La MORA Bayeux tapestry

Proof-of-principle of ion-trap laser polarization of ^{23}Mg ions with MORA at IGISOL

Tommi Eronen on behalf of MORA collaboration

GANIL

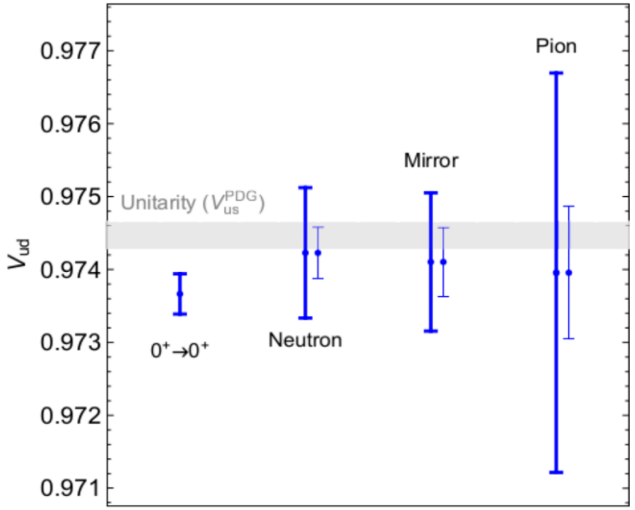
LPC CAEN

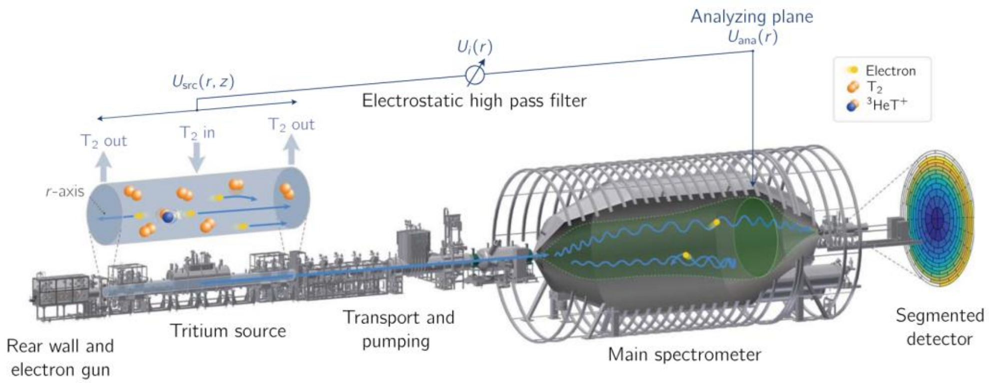
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

KU LEUVEN
NUCLEAR AND RADIATION PHYSICS

Low-energy nuclear physics experiments testing the Standard Model

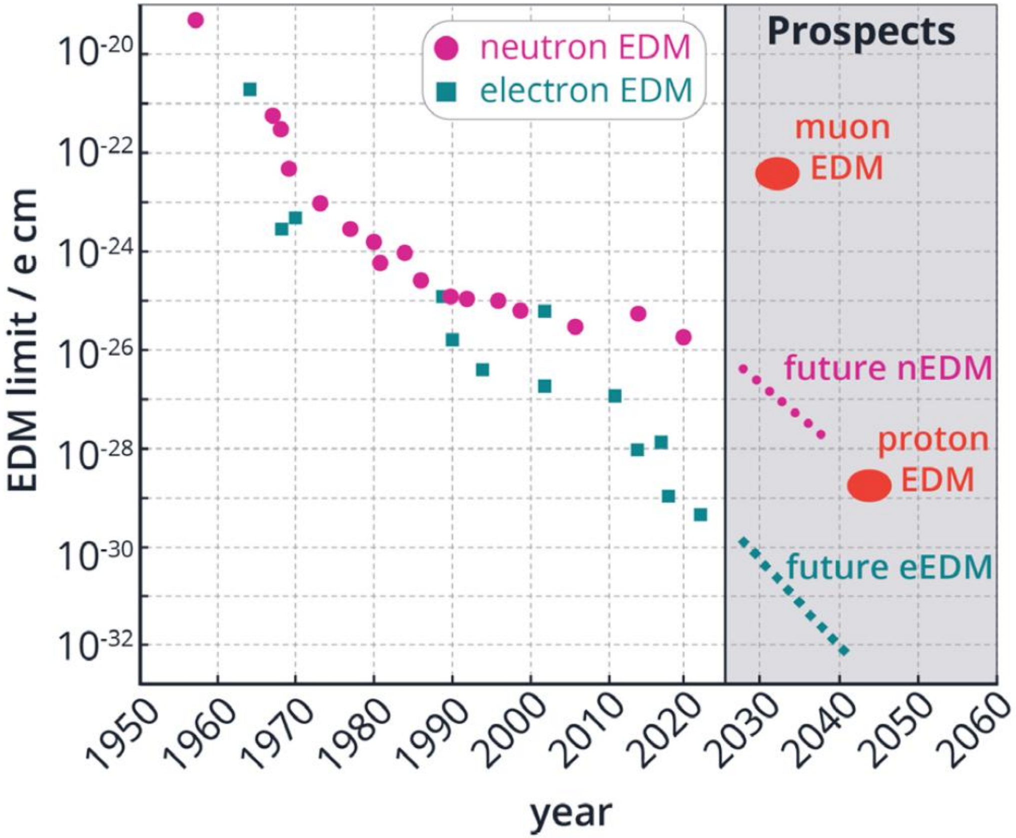
- MORA is under this category
- Utilize nuclear decays
- Some examples:
  - V_{ud} and CKM unitarity – scalar current, deviation from expectation
    - 2.4σ deviation from unitarity
      - Gorchtein, Seng Annu. Rev. Nucl. Part. Sci. 74, 230 (2024)
  - Massive neutrino, neutrinoless beta decay
    - Finite mass, neutrino its own antiparticle
    - KATRIN at Karlsruhe, $m_\nu < 0.45$ eV at 90% conf.
      - Aker et al. Science 388, 180 (2025)





More low-energy testing of the SM

- EDM – electric dipole moments
  - CP violation
- Correlations in nuclear β decay
  - MORA

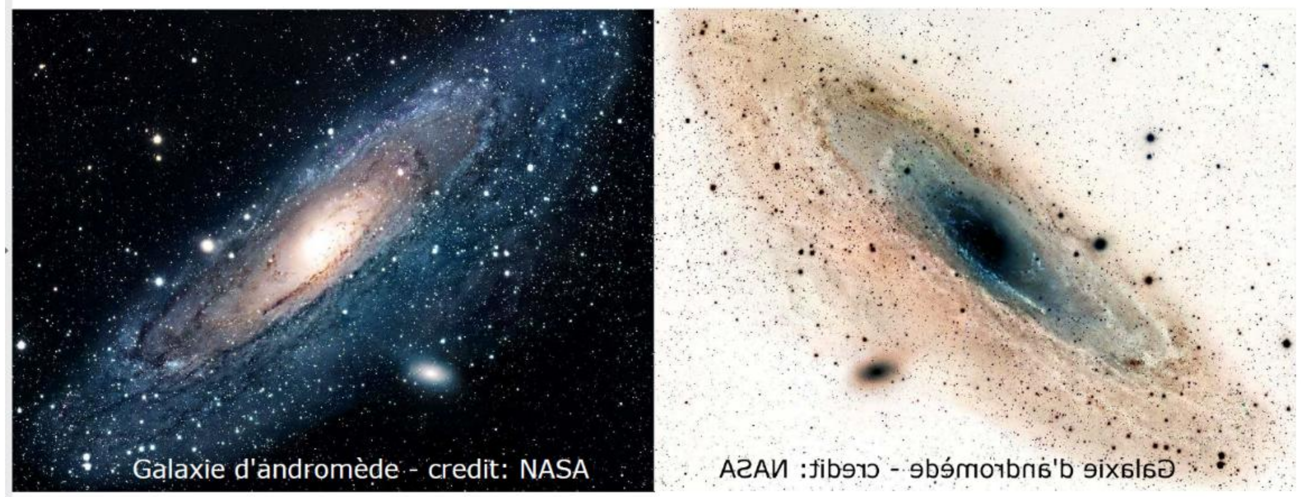


NuPECC long range plan 2024

- Symmetries and Fundamental Interaction chapter, pp. 78 – 89
  - Conveners P. Crivelli and P. Delahaye with 17 members + 2 liaisons

CP violation and baryogensis

- Big Bang should have produced equal amounts of matter and antimatter
- Sakharov 1967 with possible explanations (JETP Letters 5, 24, 1967)
  1. large C and **CP violation**
  2. violation of the baryonic number,
  3. a process out of thermal equilibrium.



- CP violation observed in K, B and D mesons
  - Not enough to explain baryogenesis

MORA - Matter's Origin from RadioActivity

THE MORA PROJECT

- Searching Beyond Standard Model Physics using β decay
- Beta decay with both Fermi and Gamow-Teller branches
- In a mixed β-decay the energy phase space can be written as

Jackson, J. D.; Treiman, S. B.; Wyld, H. W. (1957) Phy Rev 106(3), 517–521

$$\omega\left(\langle J\rangle | E_e,\ \Omega_e,\ \Omega_\nu\right) dE_e d\Omega_e d\Omega_\nu = \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$

$$\times\, \xi \left\{ 1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + c\left[\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{3E_e E_\nu} - \frac{(\mathbf{p}_e \cdot \mathbf{j})(\mathbf{p}_\nu \cdot \mathbf{j})}{E_e E_\nu}\right]\left[\frac{J(J+1) - 3\langle(\mathbf{J}\cdot j)^2\rangle}{J(2J-1)}\right]\right.$$

$$\left.\frac{\langle \mathbf{J}\rangle}{J} \cdot \left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu}\right]\right\}$$

- D is non-zero for T reversal violation
- Non-zero D can arise from CP violation

Determination of the D correlation

$$D \equiv \mathbf{sin}(\boldsymbol{\varphi_{AV}}) \cdot \underbrace{\frac{2\rho}{1+\rho^2} \cdot \left(\frac{J}{J+1}\right)^{1/2}}_{F(X)}$$

- F(X) is sensitivity – to be maximized
  - Case dependent
  - Proportional to GT-F mixture degree (ρ) and axial vector-vector phase

- Best measurements so far
  - Neutron: $D_n = (-0.94 \pm 1.89 \pm 0.97) \cdot 10^{-4}$ emiT collaboration, PRL 107, 102301 (2011)
  - ^{19}Ne: =(1±6)·10-4, *Calaprice, Hyp. Int. 22, 83 (1985)*

- New physics:
  - Direct constraints on CP-violating Wilson coefficients in the nucleon-level EFT, interest in 10^{-4} measurement
  - In 10^{-5} level – Final state interactions
    - $D_{FSI} \sim Z\alpha \frac{E_e}{M} \cdot A(\mu_f - \mu_i)$, Callan and Treiman, Phys. Rev. 162 (1967) 1494.
      - No direct measurement of FSI yet through D

Determination of the D correlation

- Measurement of D in 10^{-5} level (x10 better than so far)
  - New physics
  - Access FSI for the first time

- See Edoardo Alviani and Adam Falkowski: ***On the Coulomb corrections in nuclear beta decay***
  - arXiv:2412.17702 [hep-ph]

D correlation measurement candidates

$$D \equiv \sin(\varphi_{AV}) \cdot \underbrace{\frac{2\rho}{1+\rho^2} \cdot \left(\frac{J}{J+1}\right)^{1/2}}_{F(X)}$$

- Mirror nuclei N = Z-1
  - Mixed Gamow-Teller and Fermi between analog statues

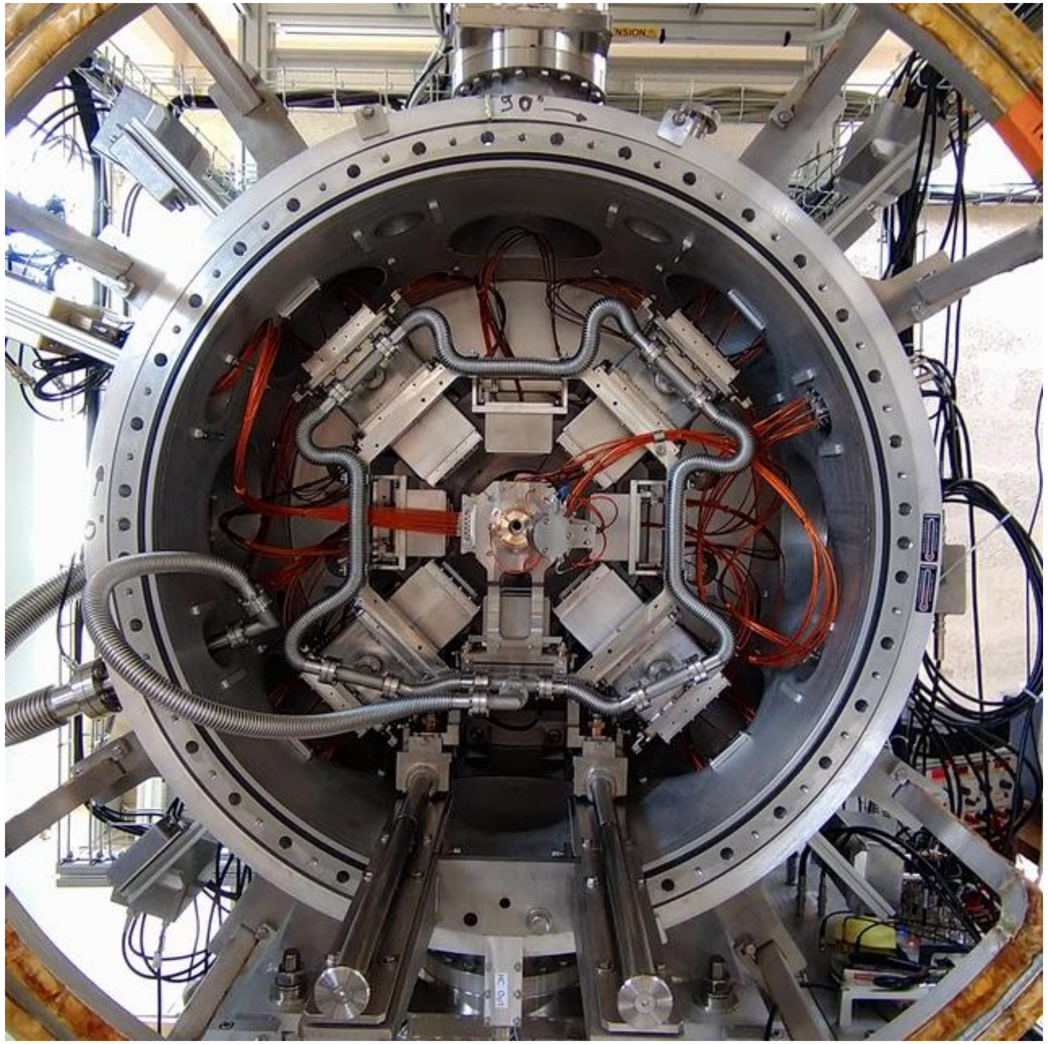
	n	^{19}Ne	^{23}Mg	^{35}Ar	^{39}Ca
Sensitivity *F(X)*	0.43	-0.52	-0.65	0.41	0.71
***D_1* (x10^{-4})**	0.11	2.31	2.64	0.43	-0.47
***D_2* (x10^{-4})**	0.02	0.17	0.16	0.01	-0.02

$$D_{FSI}(p_e) = \left(D_1 \cdot \frac{p_e}{p_{emax}} + D_2 \cdot \frac{p_{emax}}{p_e}\right) \times 10^{-4}$$

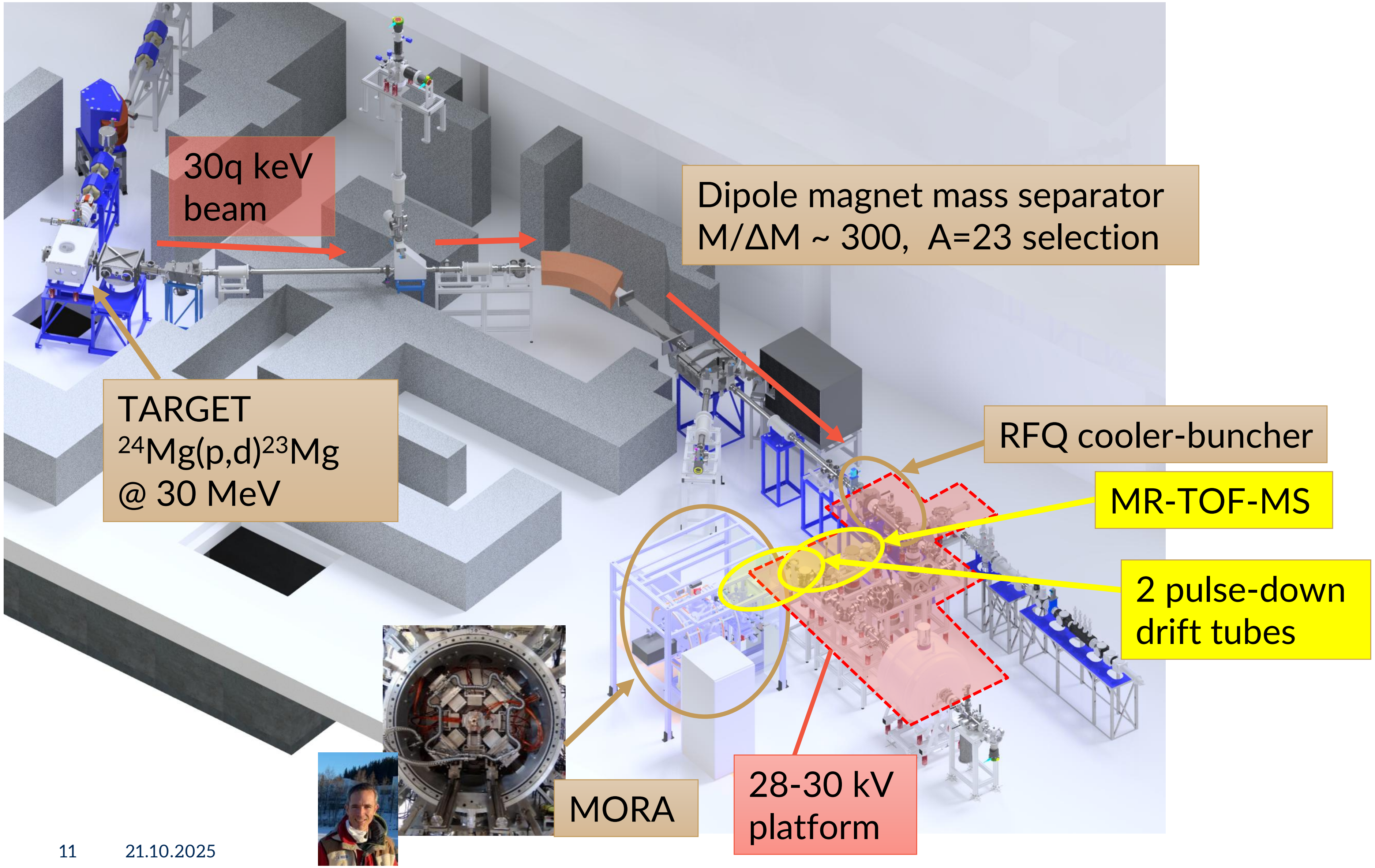
- ^{23}Mg: 10^5 pps at IGISOL. 10^8 pps eventually at DESIR
- ^{39}Ca: request 10^7 pps at DESIR

MORA apparatus

- D correlation of ^{23}Mg, ^{39}Ca to 10^{-5} level
- Required ingredients:
  - Trapping ions of interest
  - Polarize with lasers
  - Detect and correlate decays

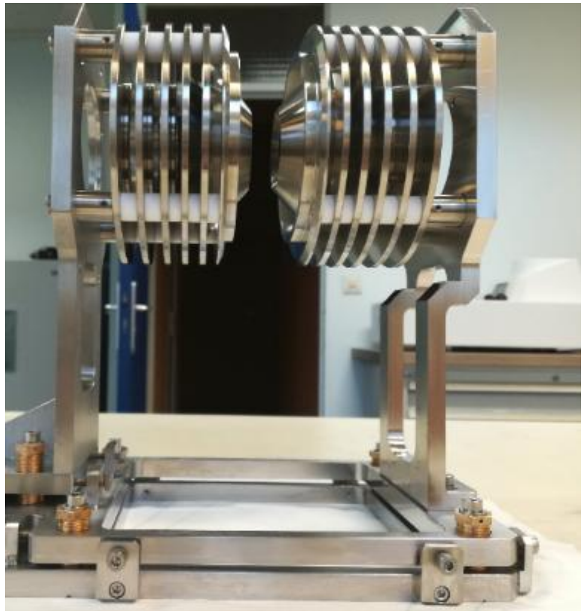


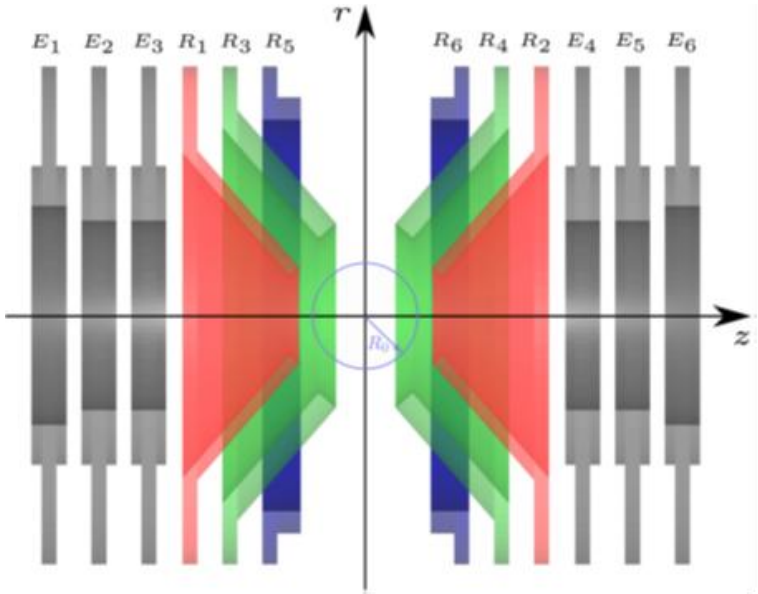
MORA @ IGISOL facility



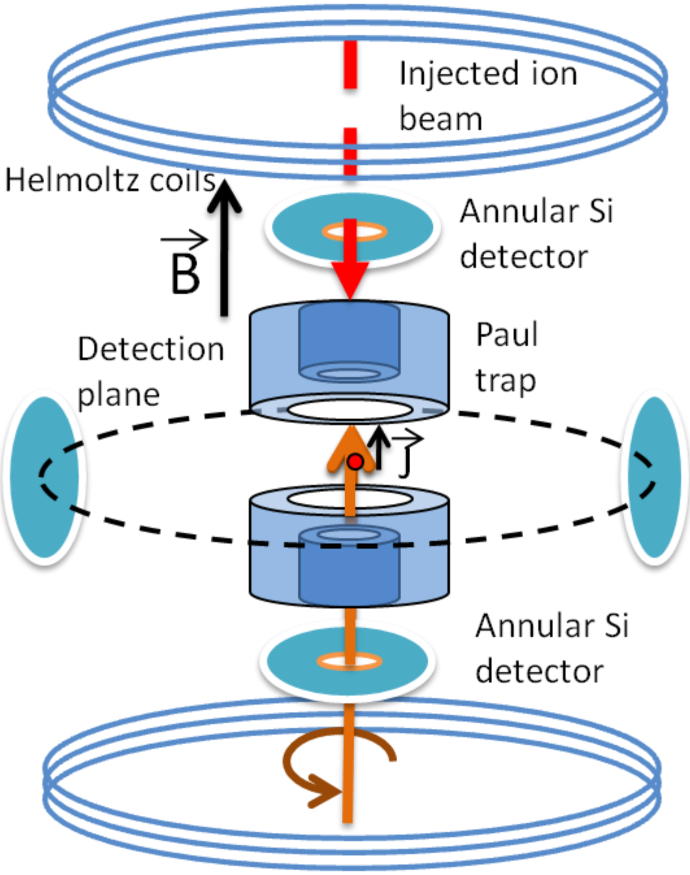
MORA trap design

- Paul trap, based on LPCtrap design (LPC Caen)
  - Open structure
  - 3 pairs of electrodes
  - Lenses before and after
- He buffer gas

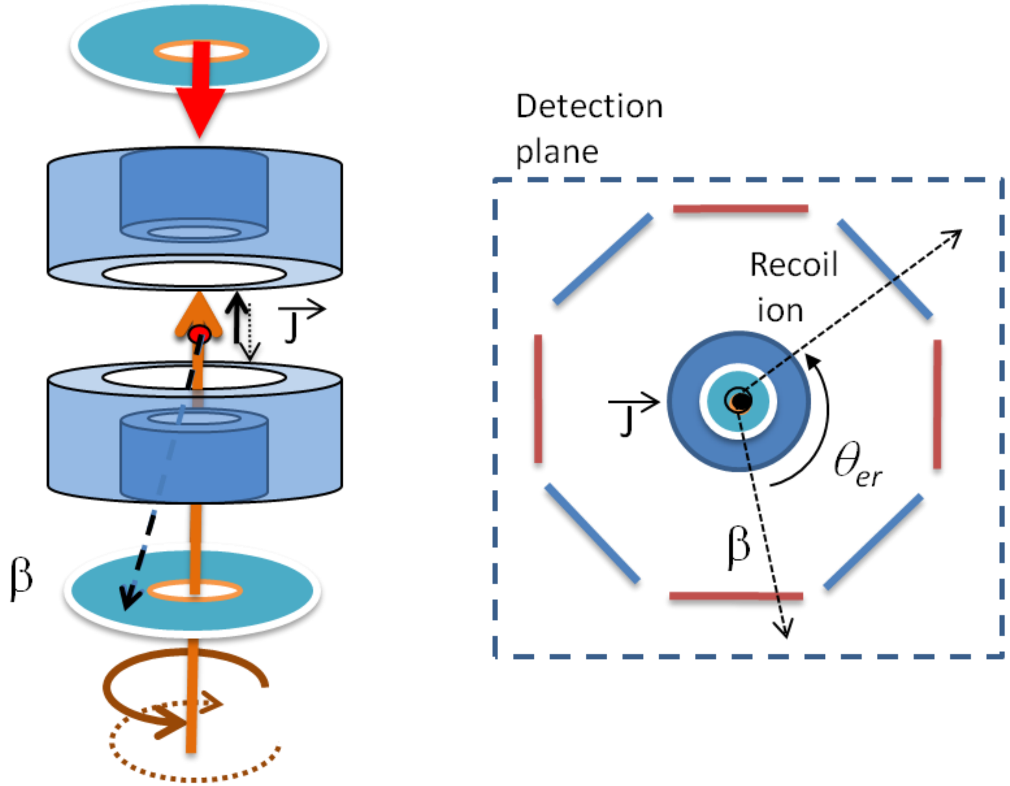




MORA principle of operation



Detection setups



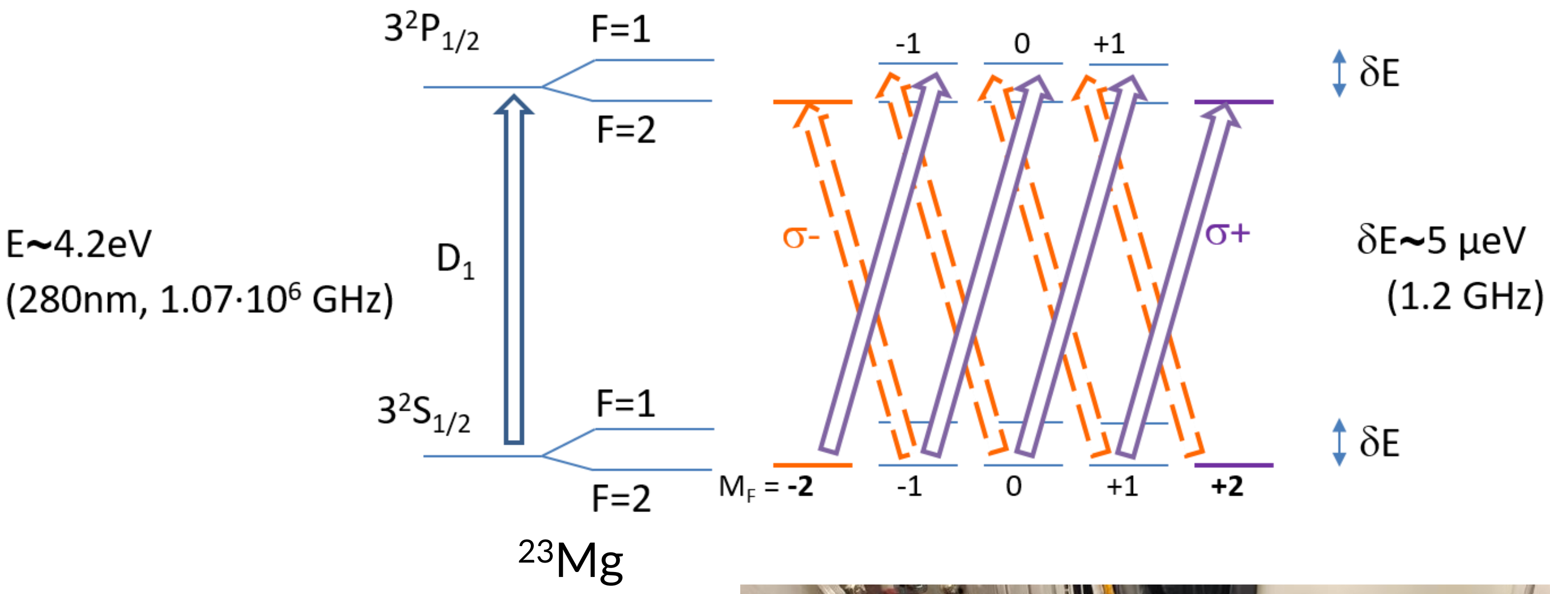
P measurement

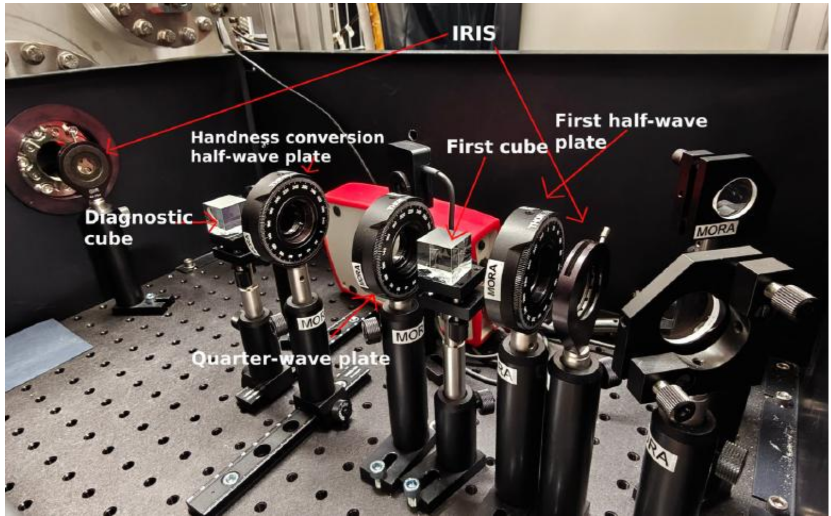
D correlation

Polarization of ^{23}Mg nuclei

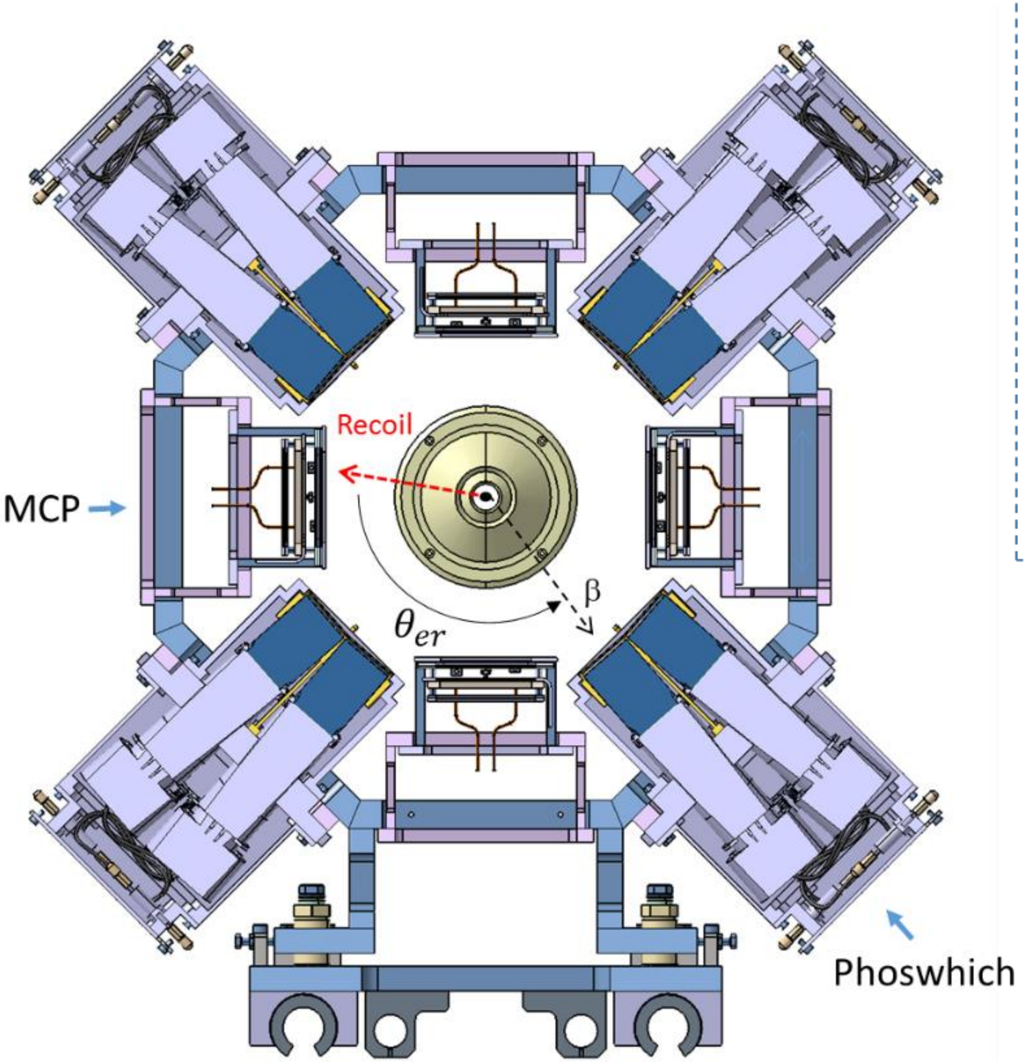
- Use of Helmholz coils
- D1 excitation, circularly polarized light
- Pump to M_F=+2 with σ+ or M_F=-2 with σ-
- One laser for ^{23}Mg (^{39}Ca needs two)

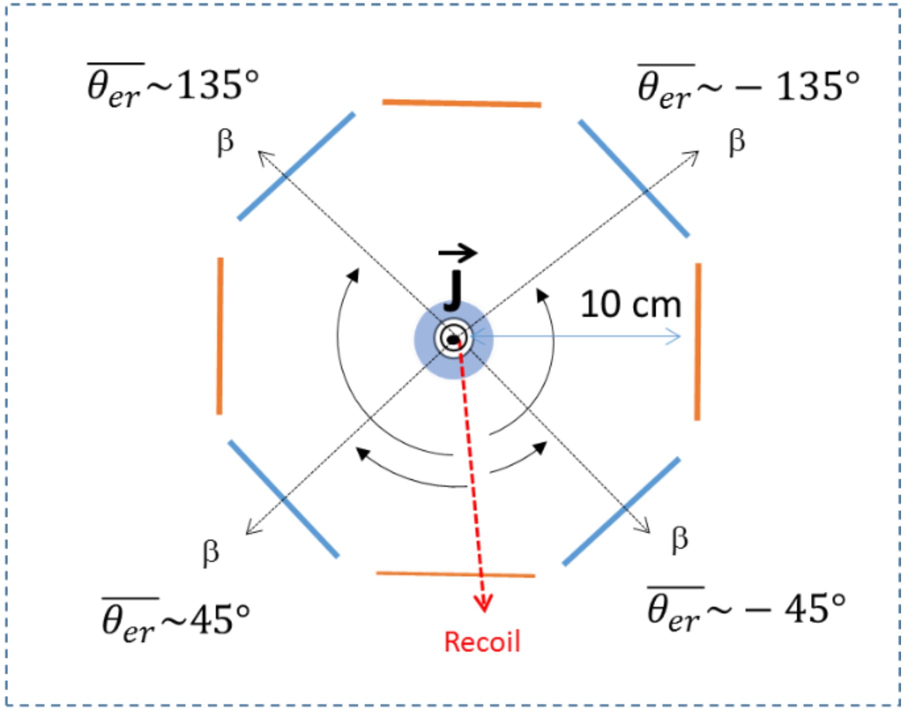
- 99% polarization within 1 ms
- Ion motion ~1.6 GHz
- Laser width ~4 GHz
- Collisions with gas does not depolarize

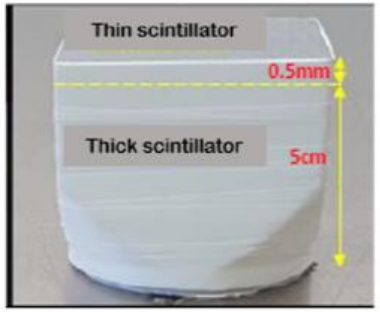


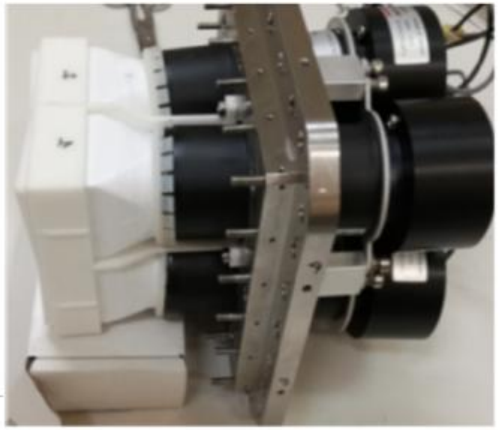


Detectors for D determination



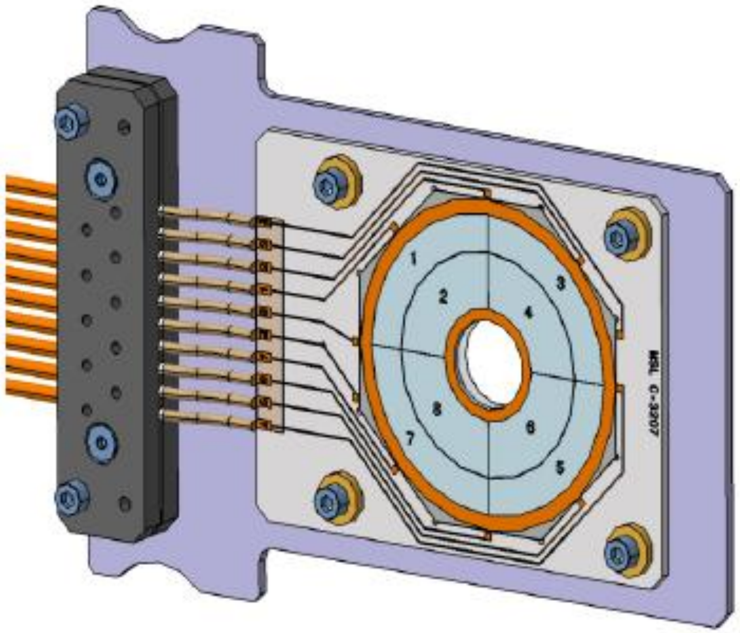


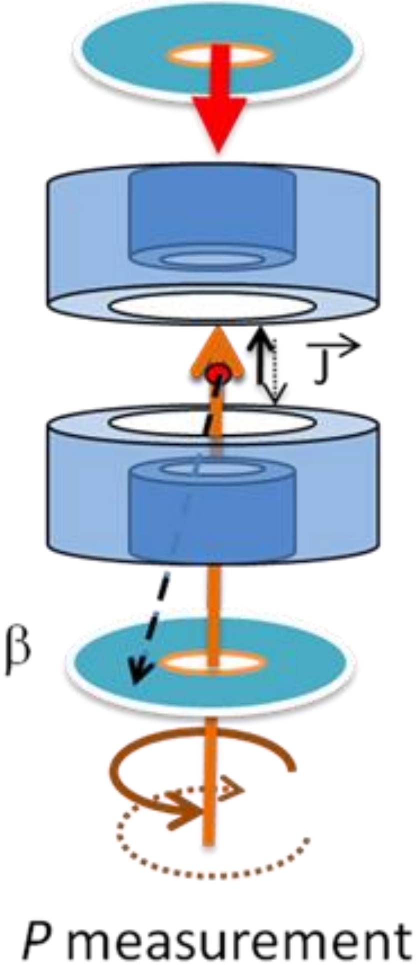




Continuous polarization monitoring

- Annular silicon detectors

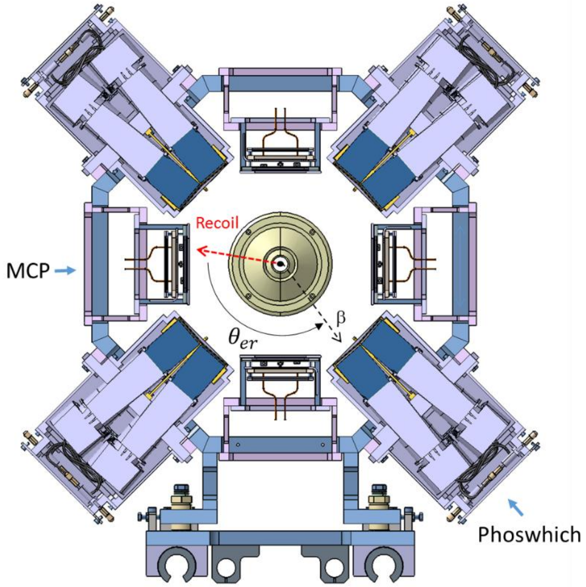


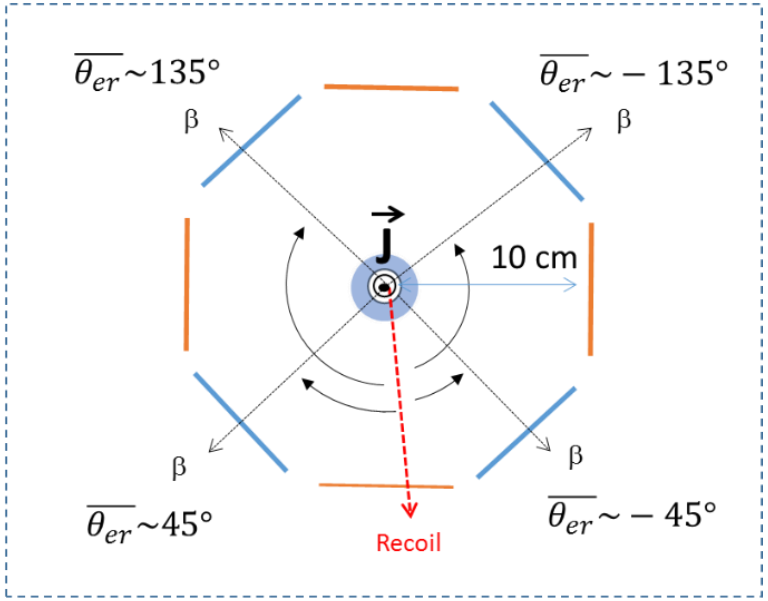


D correlation measurement

$$D\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p_e}}{E_e}\times\frac{\vec{p_\nu}}{E_\nu}\right)$$

- MCP - recoils
- Phoswhich - betas





$$D=\frac{1}{\delta\cdot P}\frac{N_{coinc}^{+45}+N_{coinc}^{+135}-N_{coinc}^{-45}-N_{coinc}^{-135}}{N_{coinc}^{+45}+N_{coinc}^{+135}+N_{coinc}^{-45}+N_{coinc}^{-135}}$$

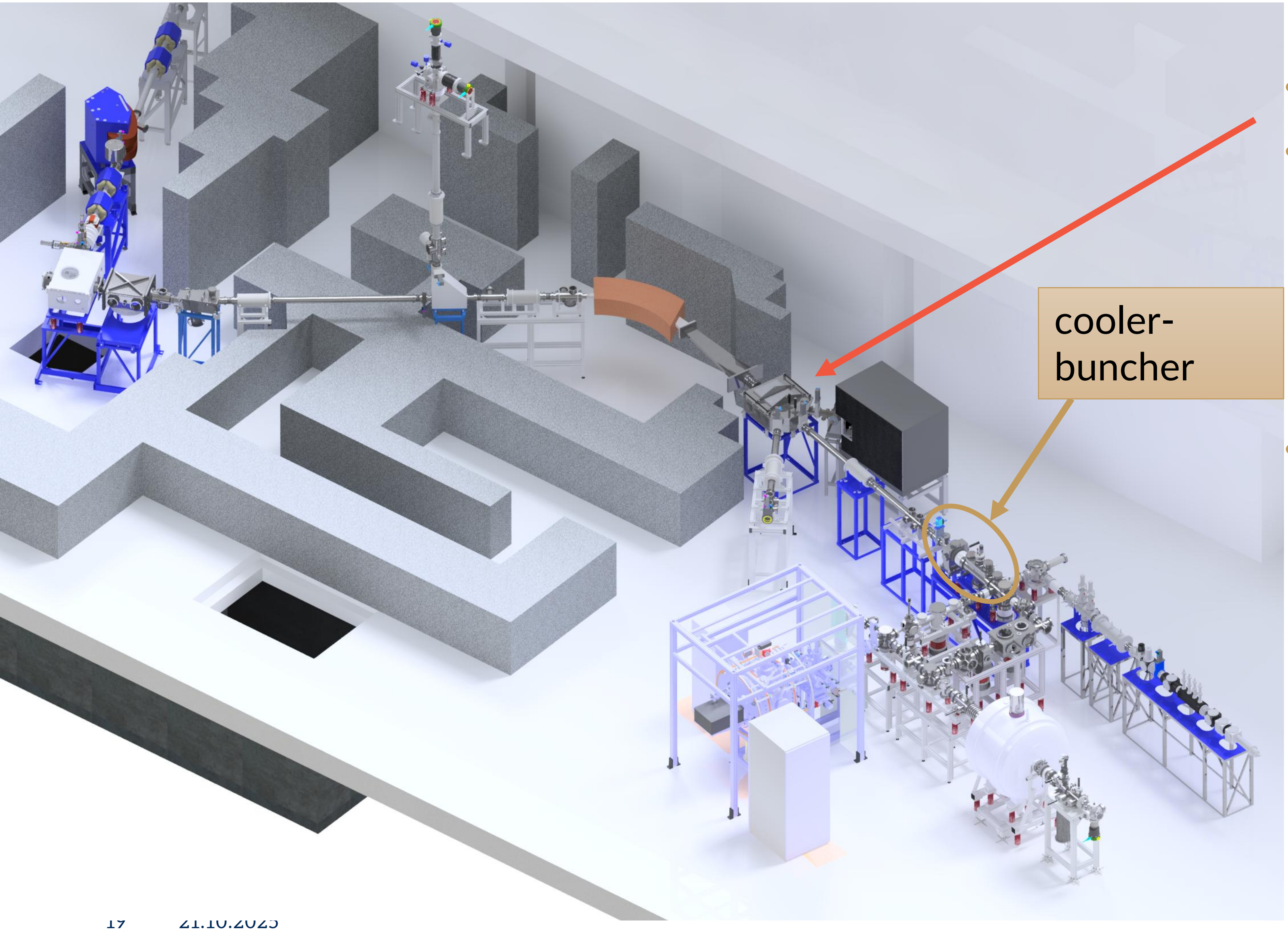
Sensitivity prospects

- MORA will stay in JYFL Jyväskylä until 2028
- Then to DESIR

Place and type of measurement	Trapped ions /cycle	Decays/s	Meas. time (days)	Detected coincidences (P)	σ_P stat (%)	Detected coincidences (D)	σ_D
JYFL: P - 23Mg	2,00E+04	1,23E+03	8	1,7E+05	**1,9E+00**	1,5E+06	1,0E-03
JYFL: D - 23Mg	2,00E+04	1,23E+03	32	6,7E+05	9,4E-01	6,1E+06	**5,2E-04**
JYFL: D - 39Ca	2,00E+04	1,61E+04	32	9,2E+06	2,0E-02	8,1E+07	**1,4E-04**
DESIR: D - 23Mg	5,00E+06	3,07E+05	24	1,3E+08	6,9E-02	1,2E+09	**3,8E-05**
DESIR: D - 39Ca	5,00E+06	4,03E+06	24	1,7E+09	1,5E-03	1,5E+10	**1,0E-05**

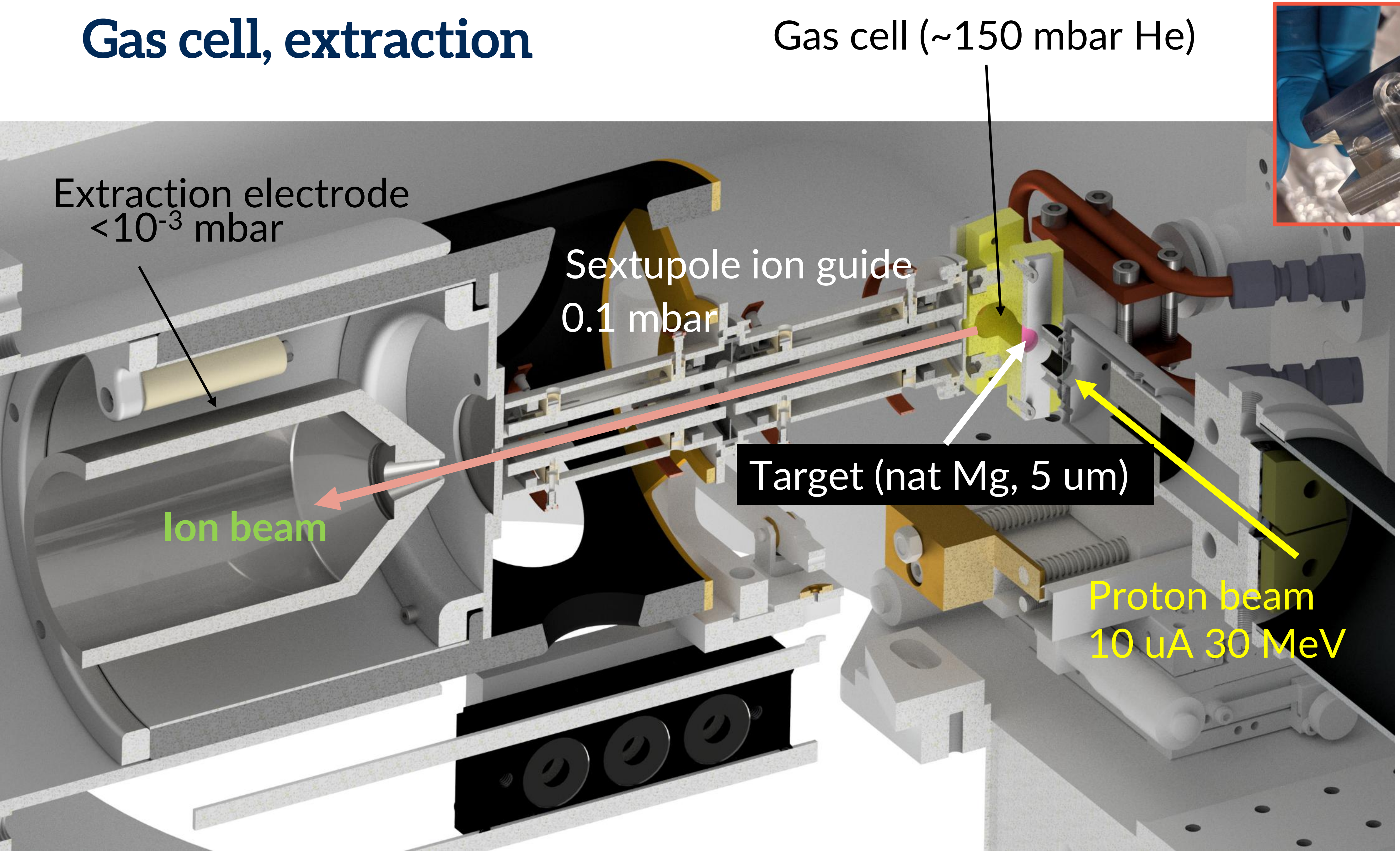
- Earlier works limited by statistics, e.g.
  - **D_n= (−0.94 ±1.89±0.97)·10^{-4}**
    - emiT collaboration, PRL 107, 102301 (2011), Phys. Rev. C 86 (2012) 035505

MORA @ JYFL since 2021. Challenges with ^{23}Na



- ^{23}Mg production rate record $5\text{x}10^5$ pps
- ^{23}Na stable contamination
  - Up to 10^4 more than ^{23}Mg
    - Talys expectation ^{23}Mg:^{23}Na 1:2
  - Saturation of cooler-buncher (10^5/bunch)
- Gas cell?

Gas cell, extraction



Everything that could affect

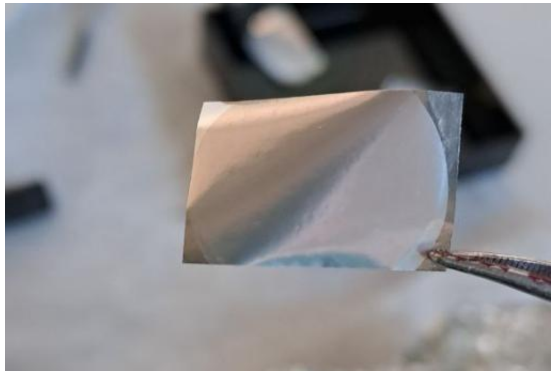
- Gas? No.
  - Tried gas mixtures

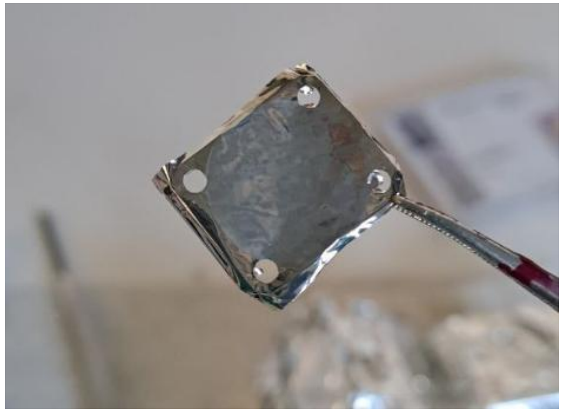
- Gas purification?
  - Tried zeolite, activated carbon, SiO_2

Everything that could affect

- Gas cell material?
  - Aluminum, graphite (with high T baking)

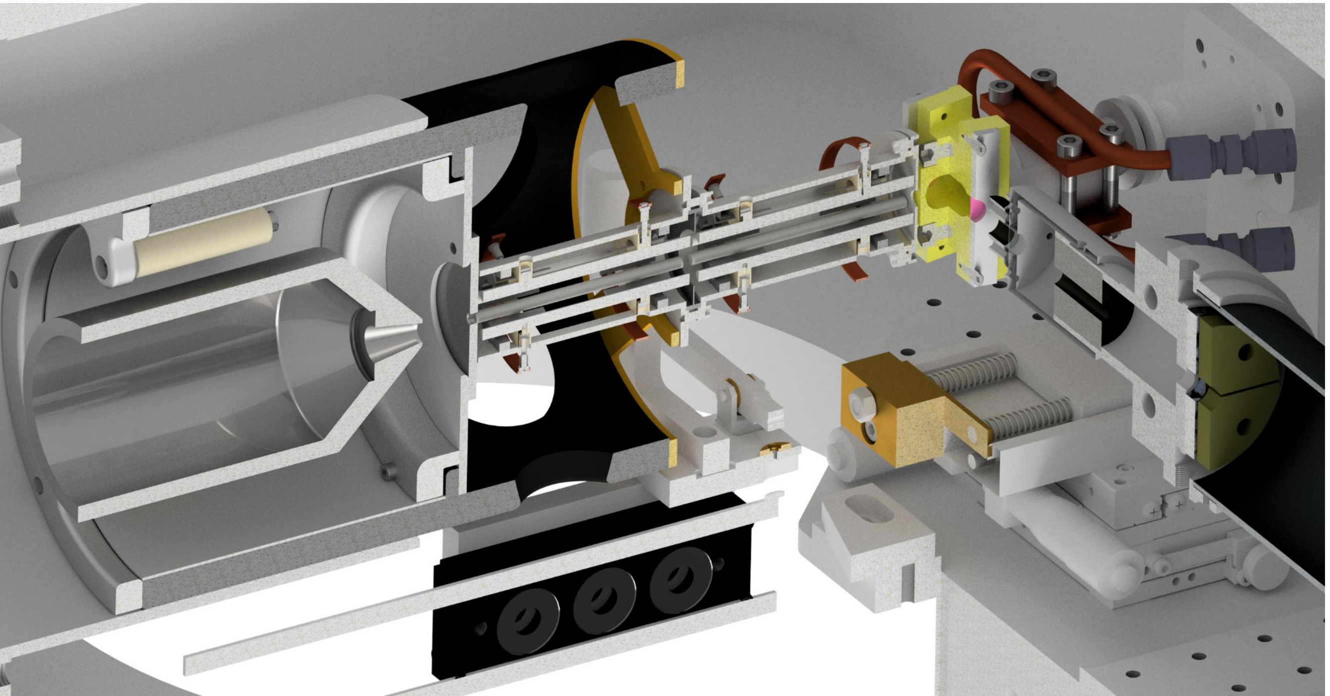
- Foils? Target? Gas tightening?

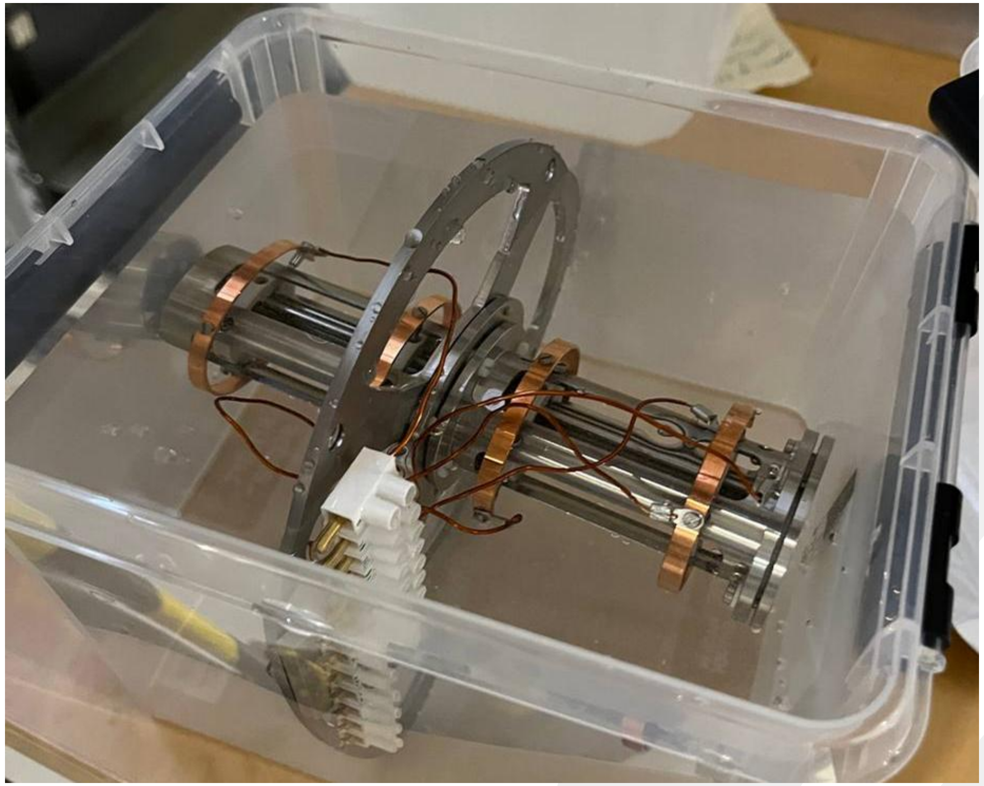




Everything that could affect

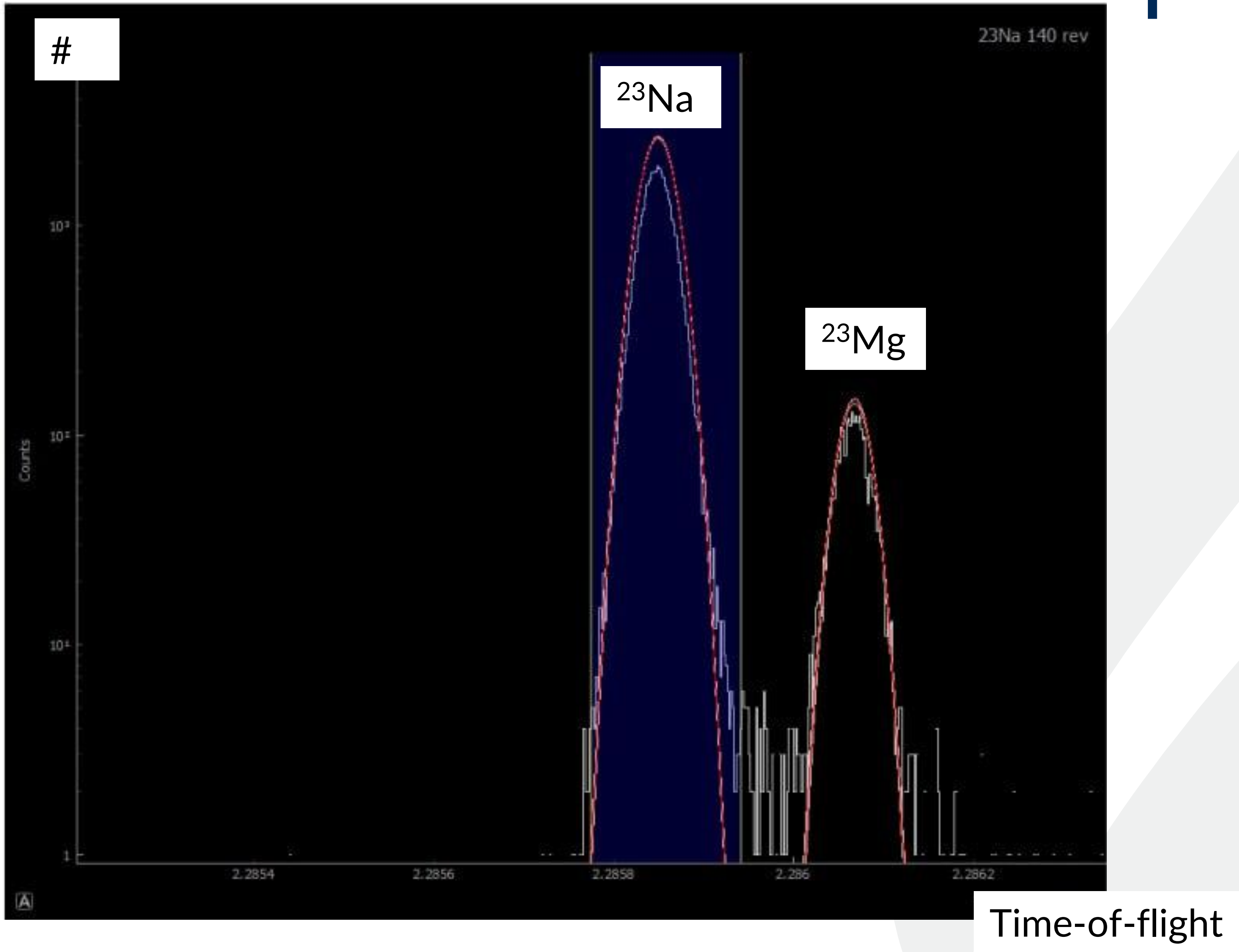
- Sextupole ion guide
  - Steel rods, Nb rods
  - Proper wash
  - Finally: DC tuning.. Accelerate ions carefully, prevent sputtering from rods





MR-TOF as beam composition diagnostics tool

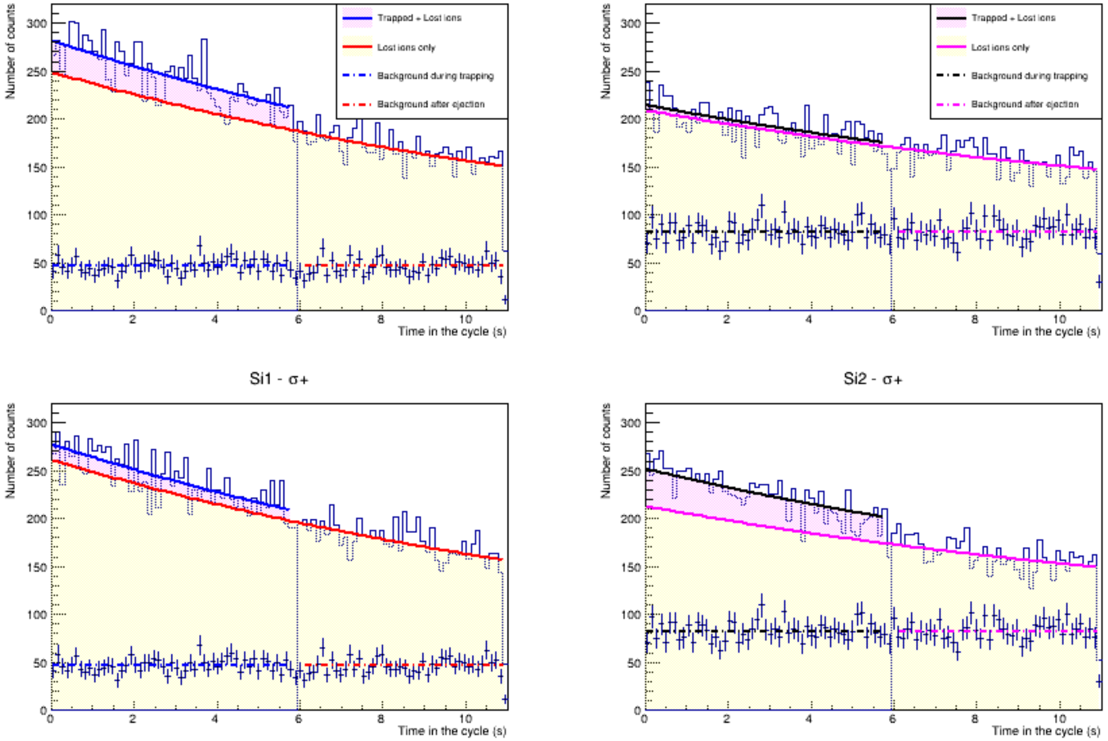
- Checking 23Na:23Mg ratio
- Here 1:15
- Best achieved 1:2 !

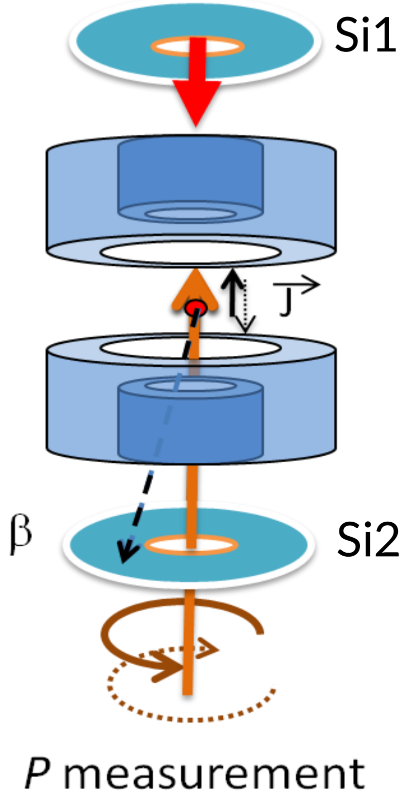


Polarization measurement

March 25, 2025

Si1 Si2



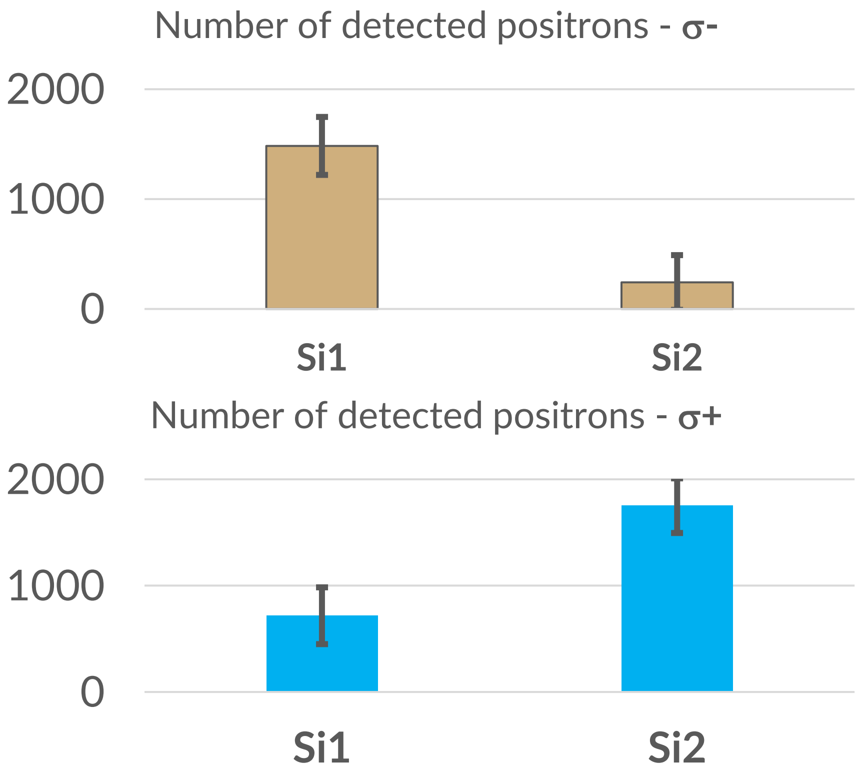


- Polarization σ- : $A^{-} = \frac{nSi_1 - nSi_2}{nSi_1 + nSi_2} = 0.72 \pm 0.25$
- Polarization σ+ : $A^{+} = -\ 0.42 \pm 0.16$
- Full polarization of the cloud (from simulations): $A^{-} = -A^{+} = 0.51 \pm 0.01$

Polarization measurement

σ−

σ+



- Polarization σ- : $A^{-} = \frac{nSi_1 - nSi_2}{nSi_1 + nSi_2} = 0.72 \pm 0.25$
- Polarization σ+ : $A^{+} = -0.42 \pm 0.16$
- Full polarization of the cloud (from simulations): $A^{-} = -A^{+} = 0.51 \pm 0.01$

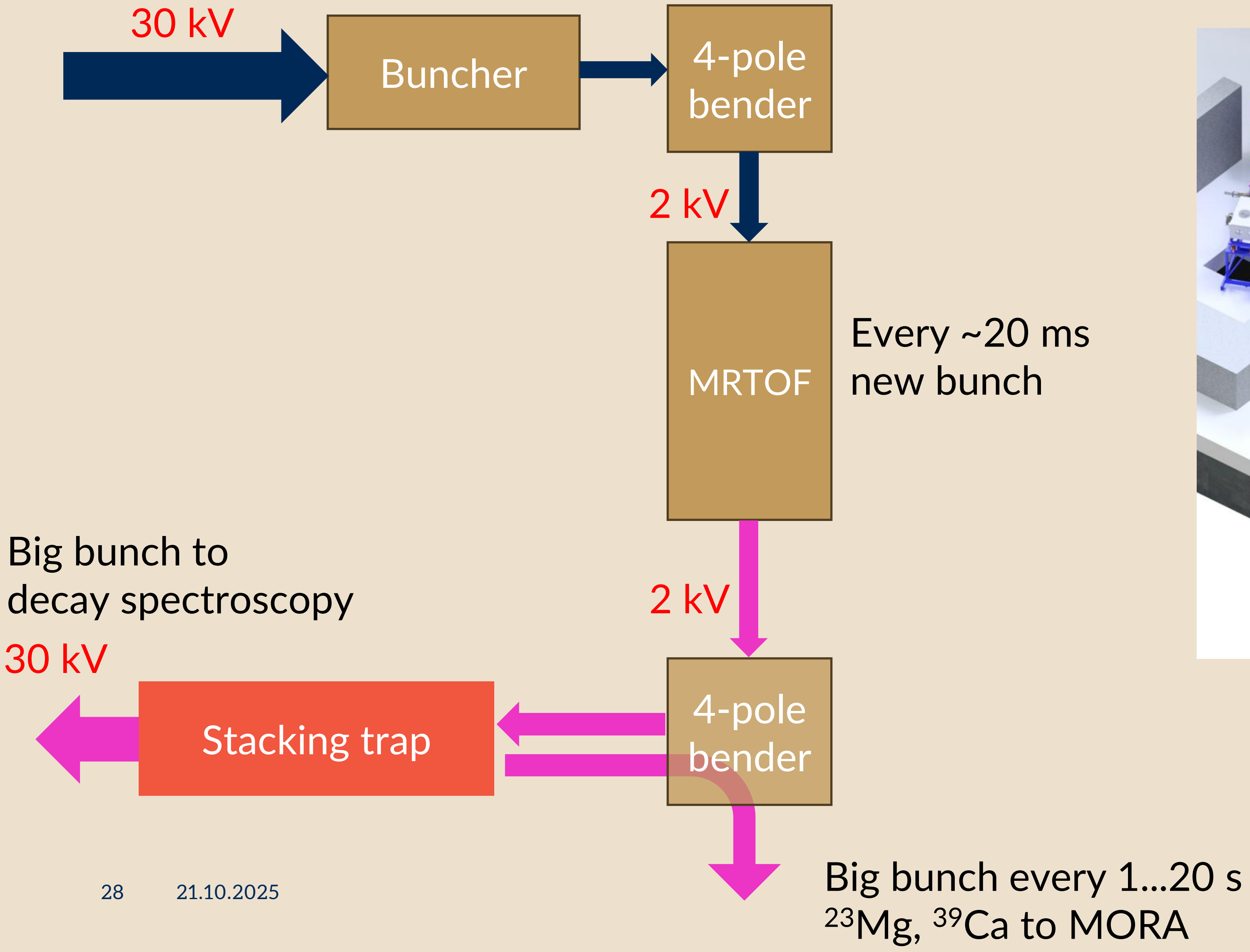
55%<P<100% at 90% C.L.

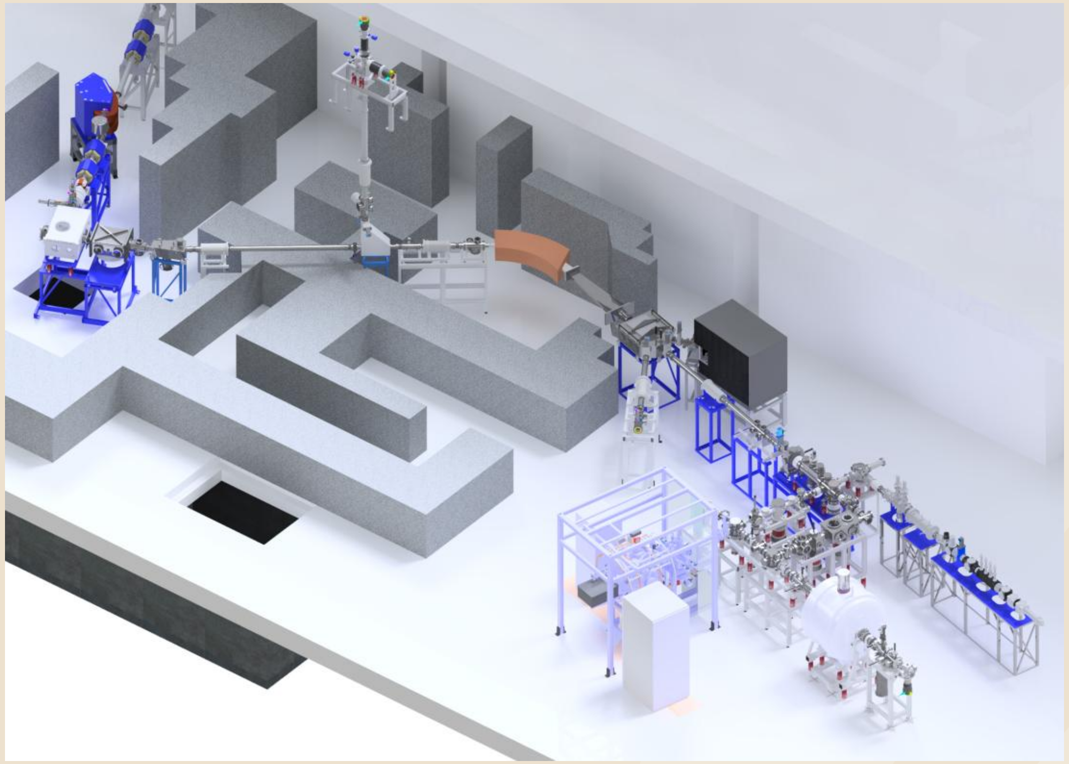
Summary

- Polarization with 55%<P<100% at 90 C.L., more data from July 2025 is being analysed
  - 1000 ions/cycle trapped, projected to be > 10^4 , enough for D measurement
- The beam purity issue at IGISOL is being tackled, mostly solved
- Capturing efficiency to MORA still can be improved (in-trap lift, trapping parameters)

- Funds to build a stacking trap after MRTOF approved! “ACCLAIM_MORA” project
- Beam development of ^{39}Ca at IGISOL being pursued

Stacking trap for accumulation of pure ion sample





MORA collaboration

Thanks a lot for your attention!

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In blue PhD and Master students hired for MORA

Thank you for listening!

- Thanks Pierre Delahaye and Luis Miguel Motilla-Martinez for slide material