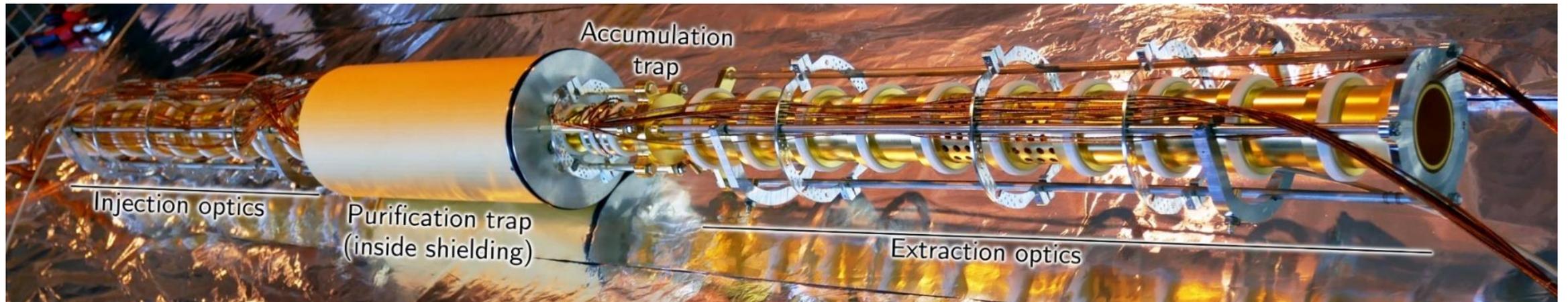


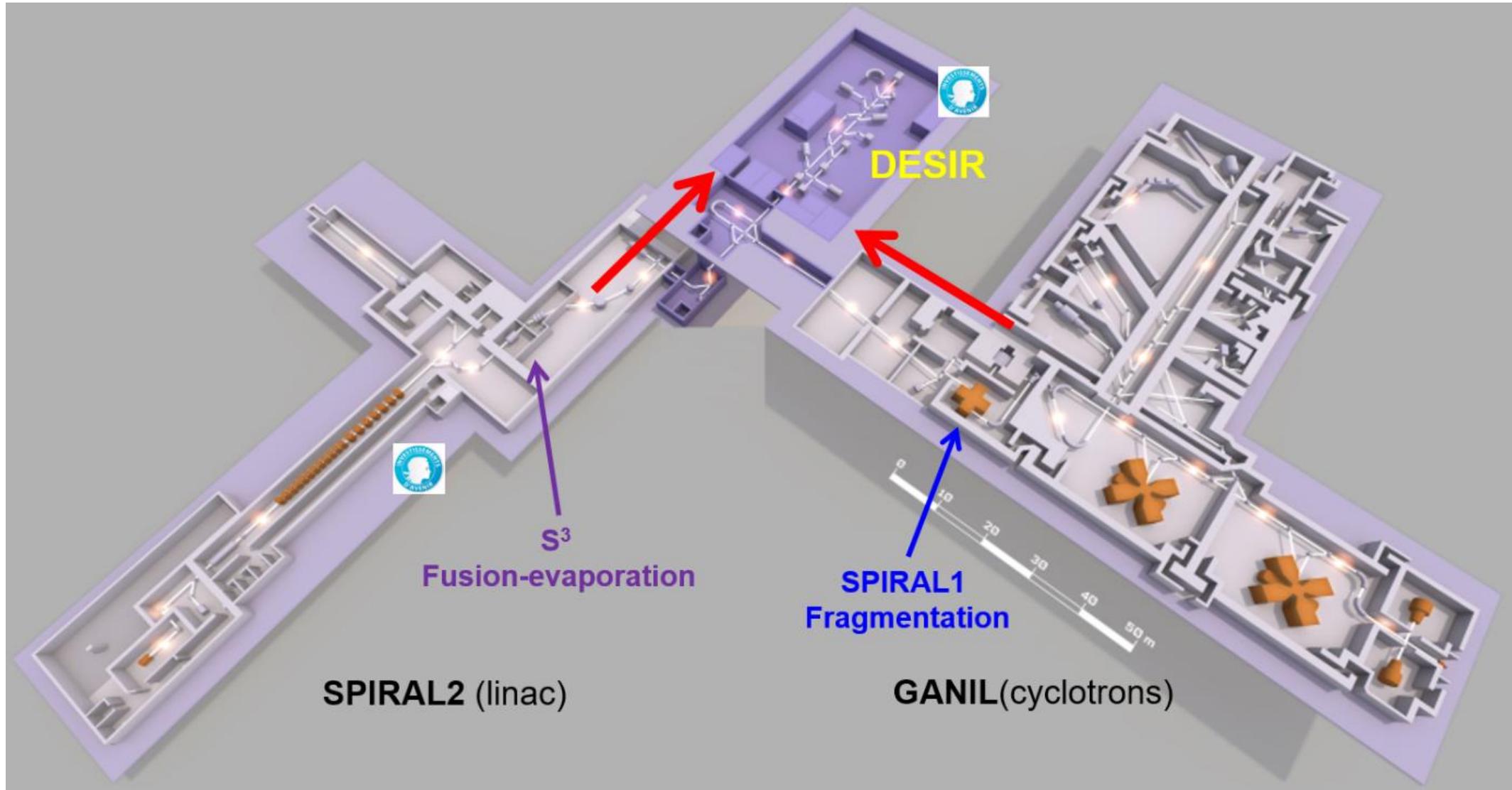
The double Penning trap mass spectrometer PIPERADE for DESIR/SPIRAL2



A. de Roubin for the PIPERADE collaboration

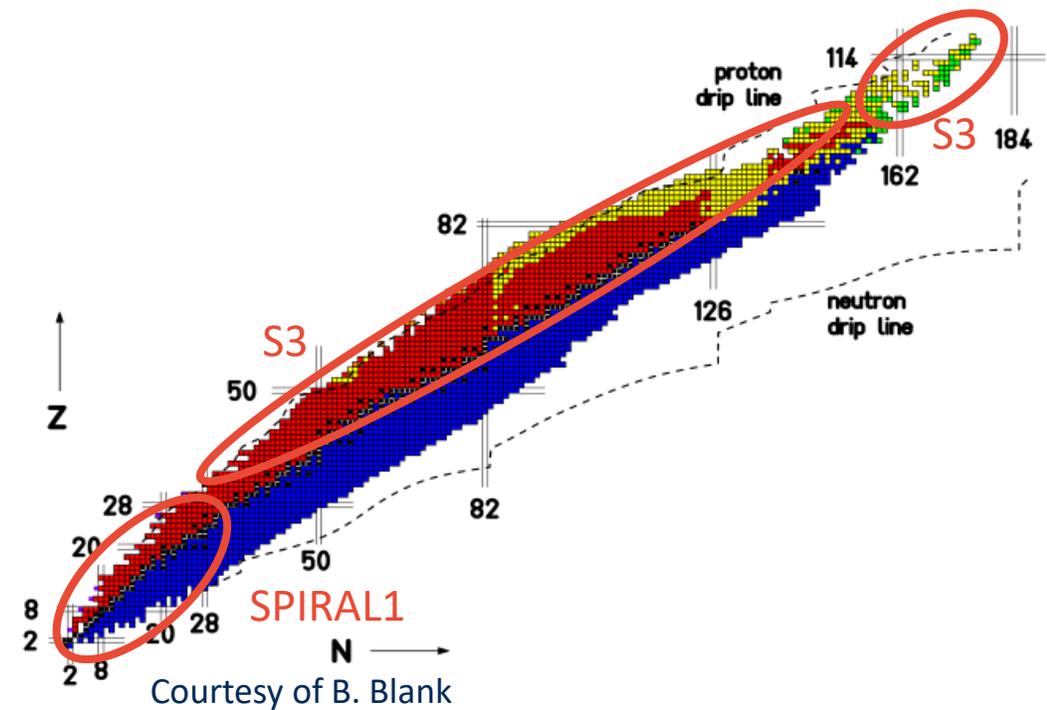
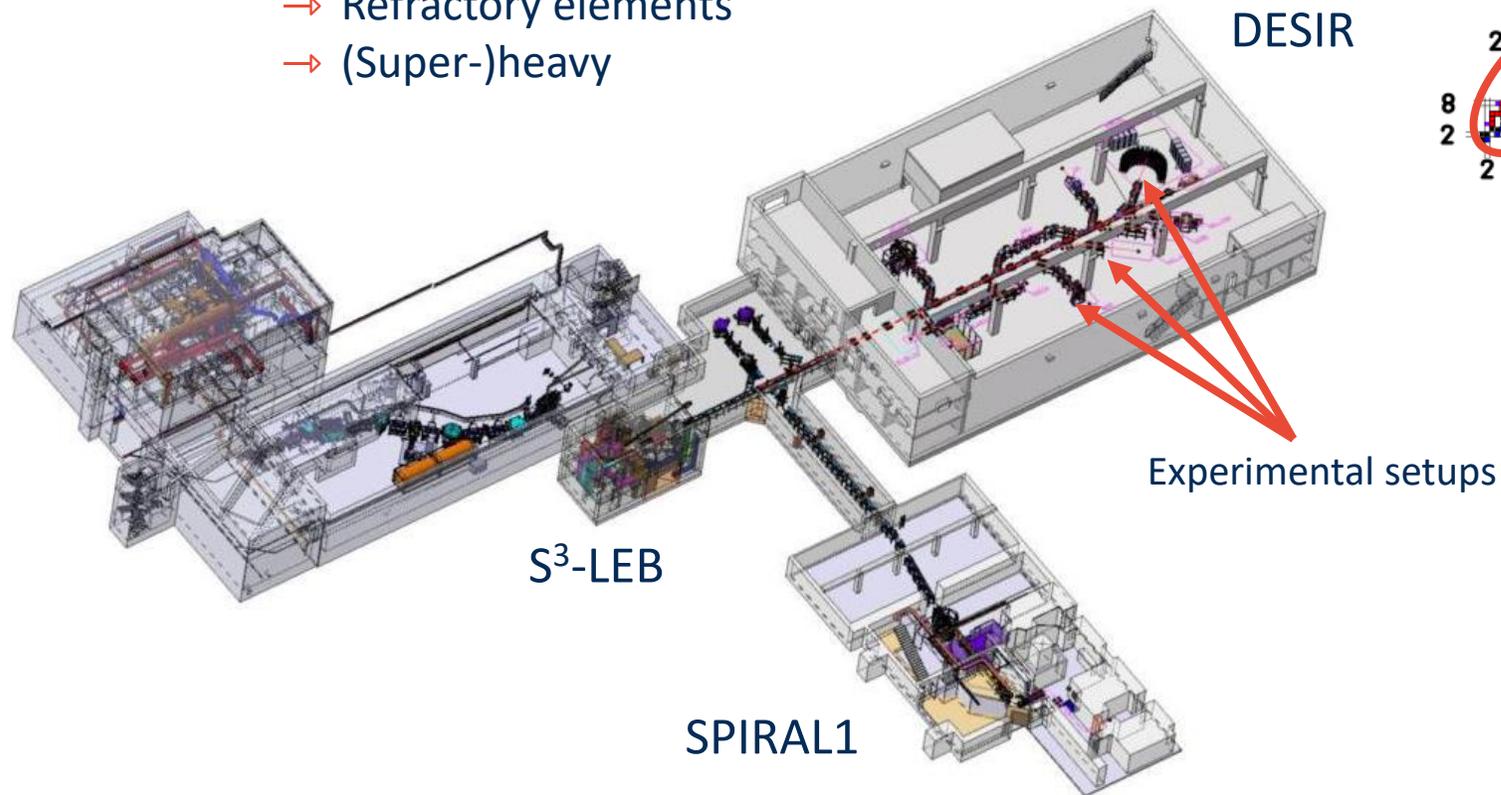


GANIL 2026



GANIL 2026

- Large variety of beams
 - Target/beam fragmentation at SPIRAL1 (ISOL)
 - Light n-rich and n-deficient nuclei
 - Fusion evaporation at S3 (in-flight)
 - p-rich elements
 - Refractory elements
 - (Super-)heavy

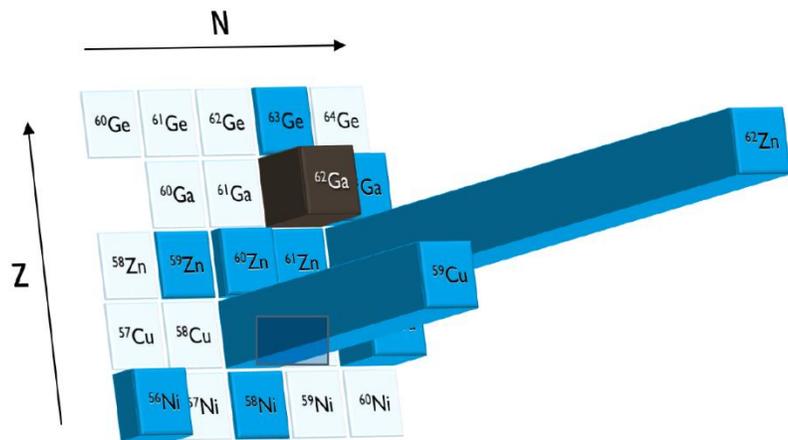


- Three main setup categories
 - β -decay spectroscopy
 - Laser spectroscopy
 - Mass spectrometry
- To study
 - Nuclear structure
 - Astrophysics
 - Weak interaction
 - Application...

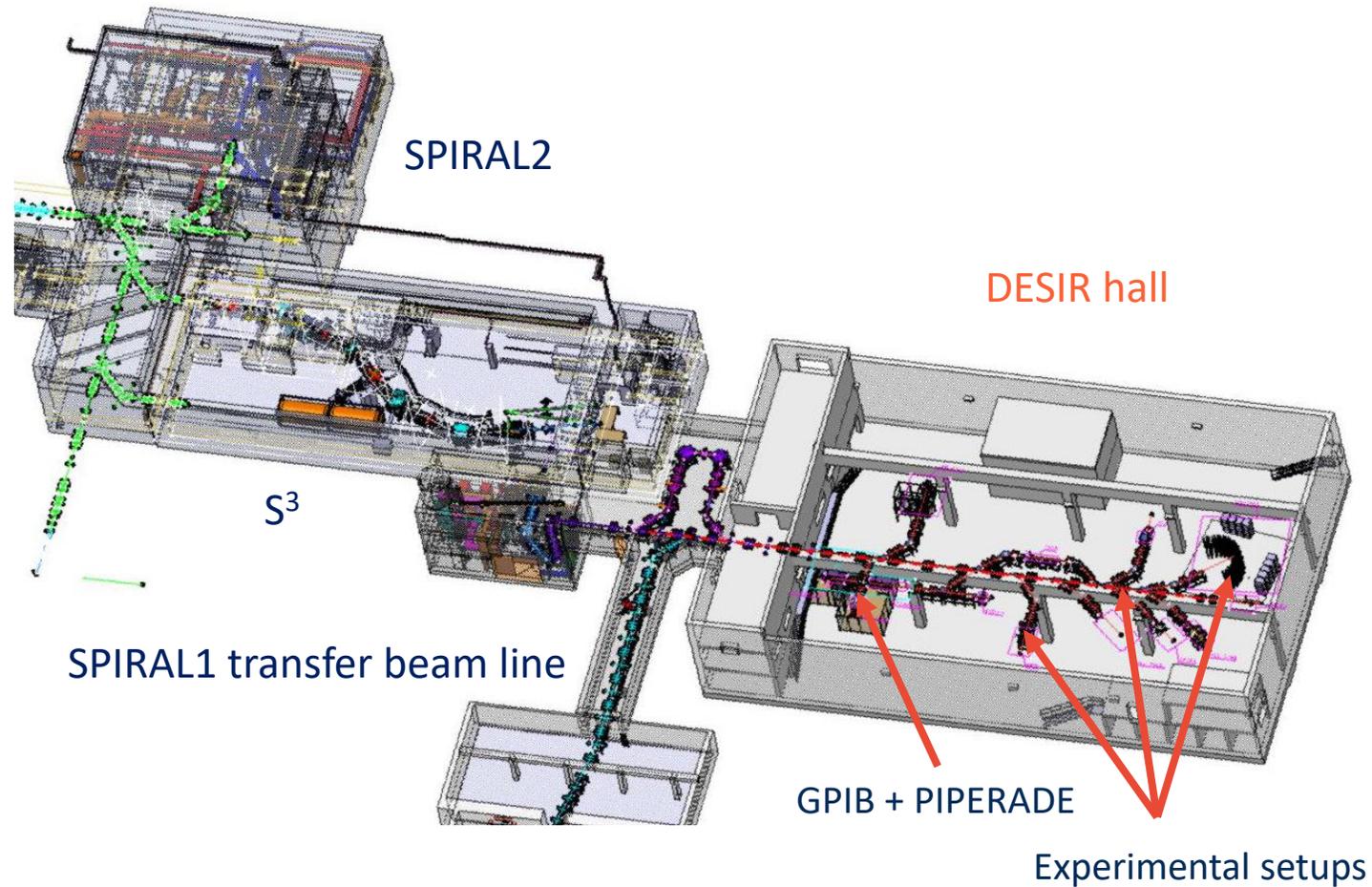
The DESIR hall

Aim for high precision measurements

- High purity beam
 - We need to purify isobars (or even isomers)
- High quality beam
 - Low longitudinal and transverse emittance



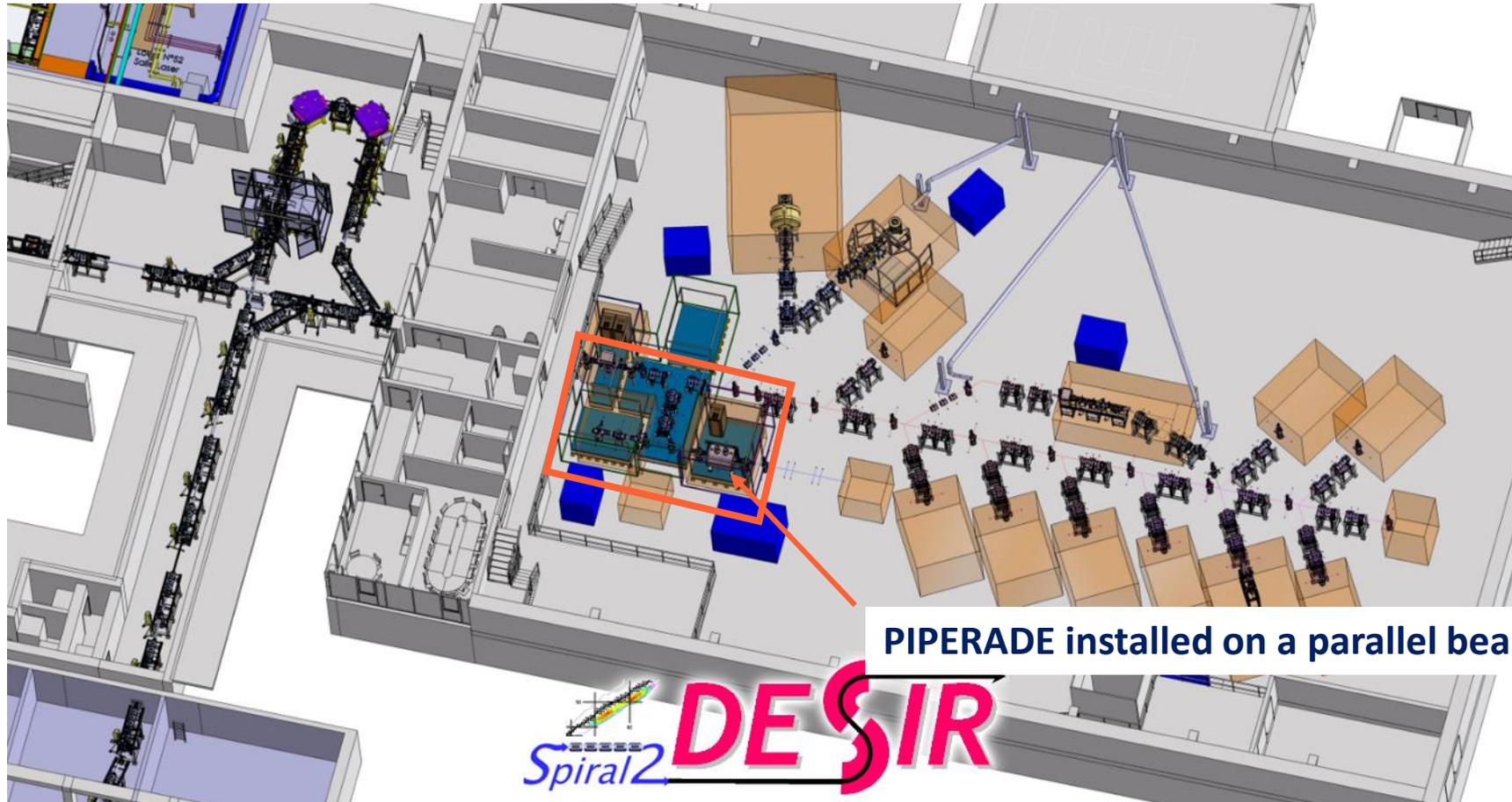
Courtesy of M. Gerbaux



High quality/purity beams

- SHIRaC
- HRS
- GPIB
- PIPERADE ...

The DESIR hall

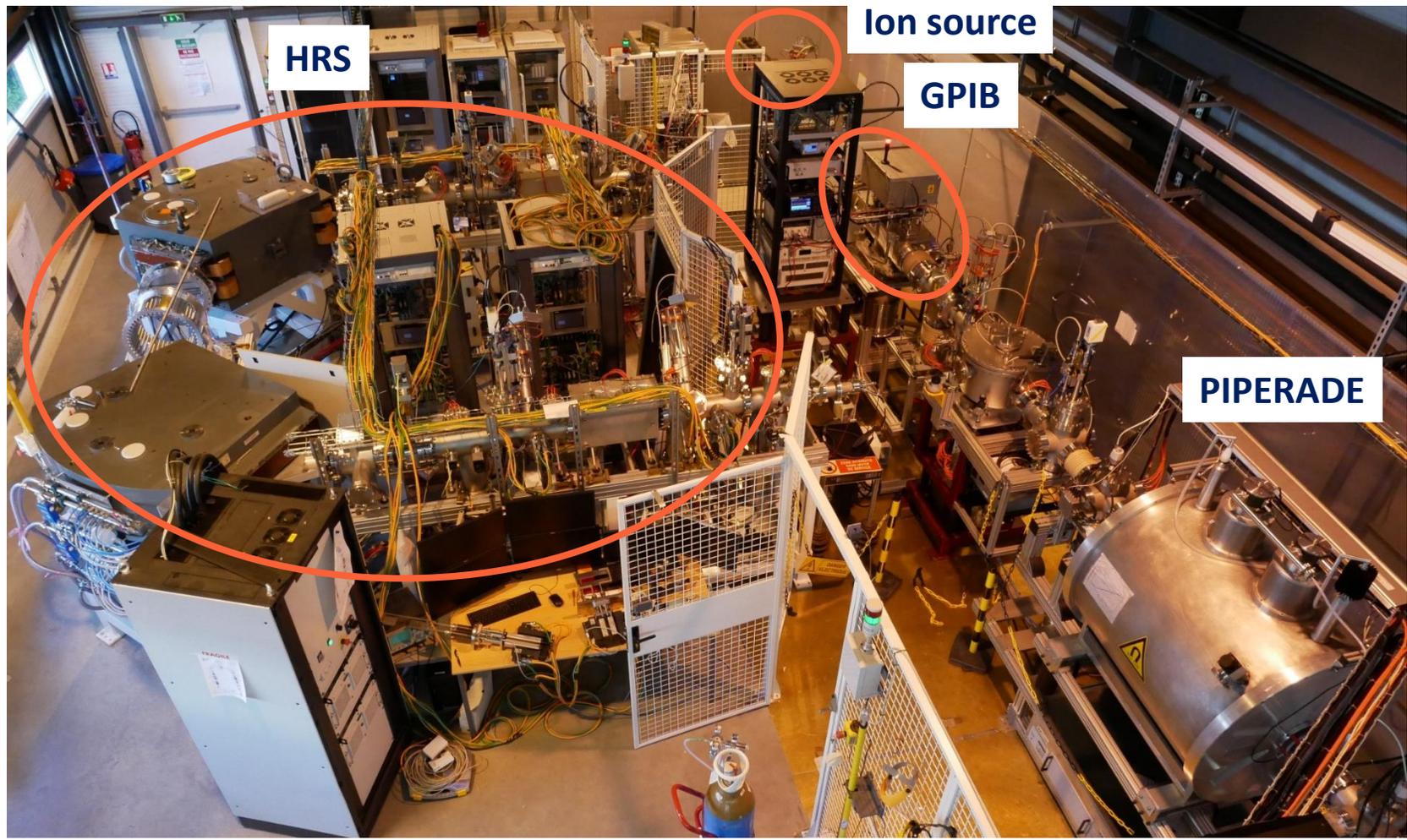
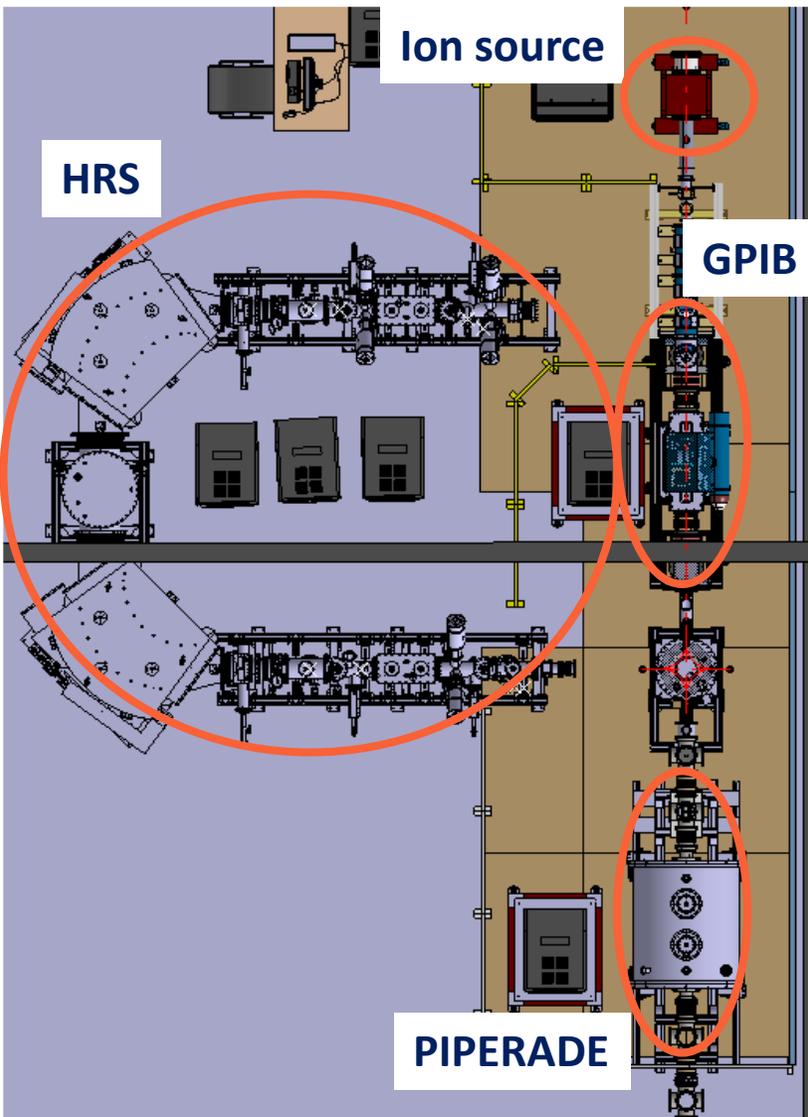


PIPERADE installed on a parallel beam line

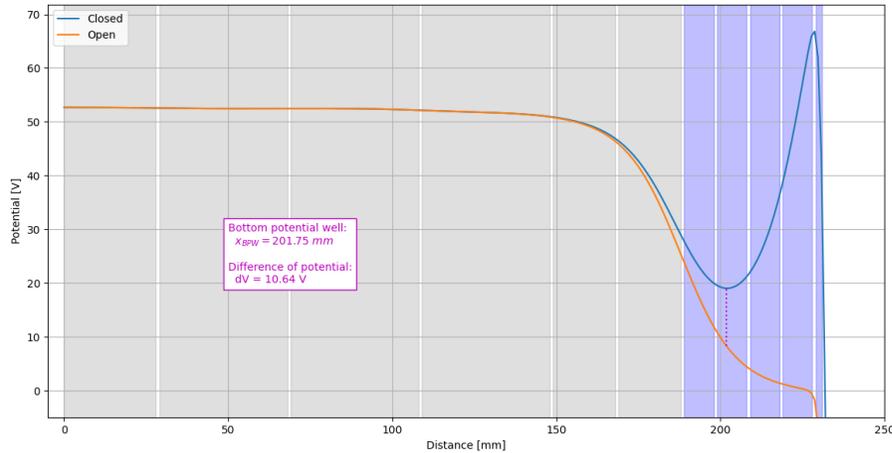


Beam preparation zone

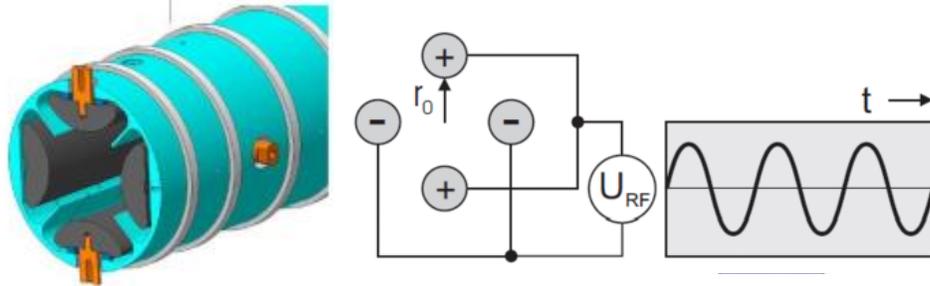
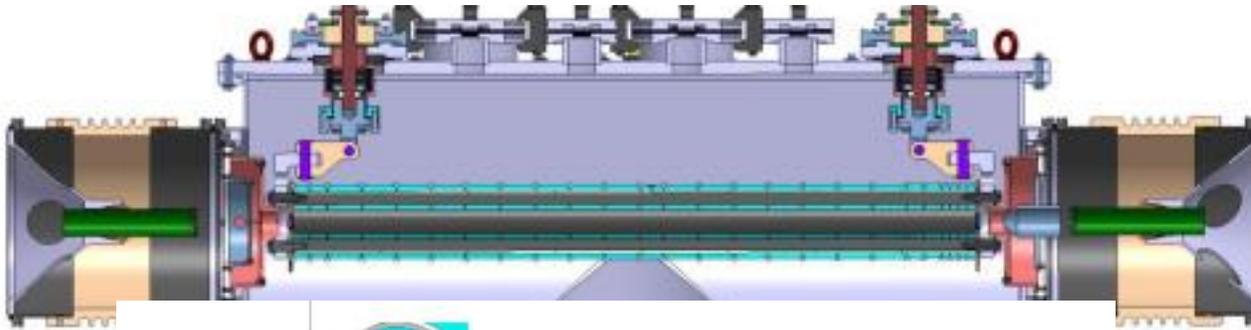
GPIB and PIPERADE @ CENBG



GPIB – General Purpose Ion Buncher



- 30 keV continuous beam enters a 30 - ϵ kV platform
- Radial confinement via RF
- Buffer gas cooling of ion residual energy
- DC gradient + axial trapping
 - guide the ions
 - accumulate
- Periodical release of ions as bunches



M. Gerbaux et al., to be submitted

Why do we want to bunch the continuous beam?

- Ion traps work in sequences
- Control of the energy spread
- Control of the TOF dispersion

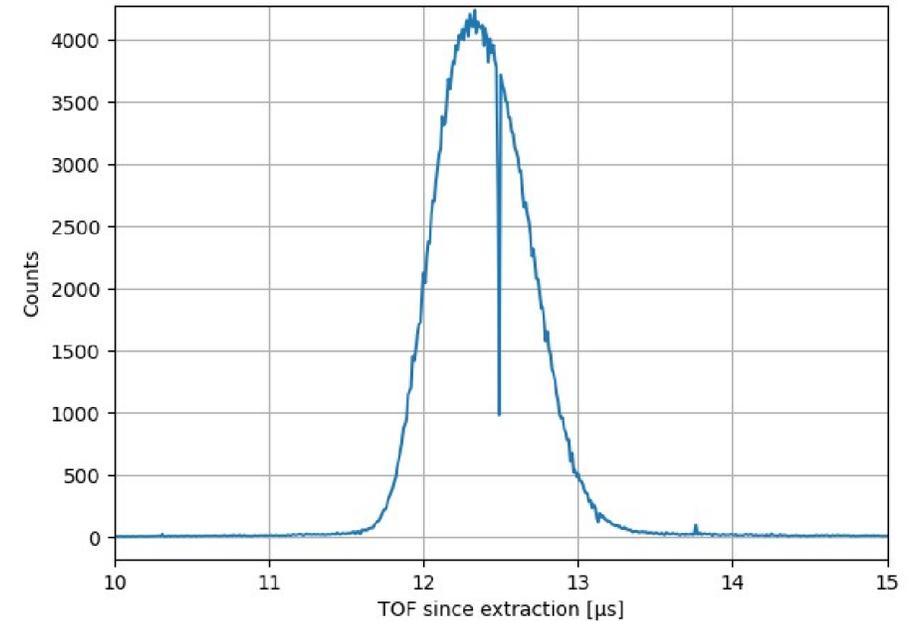
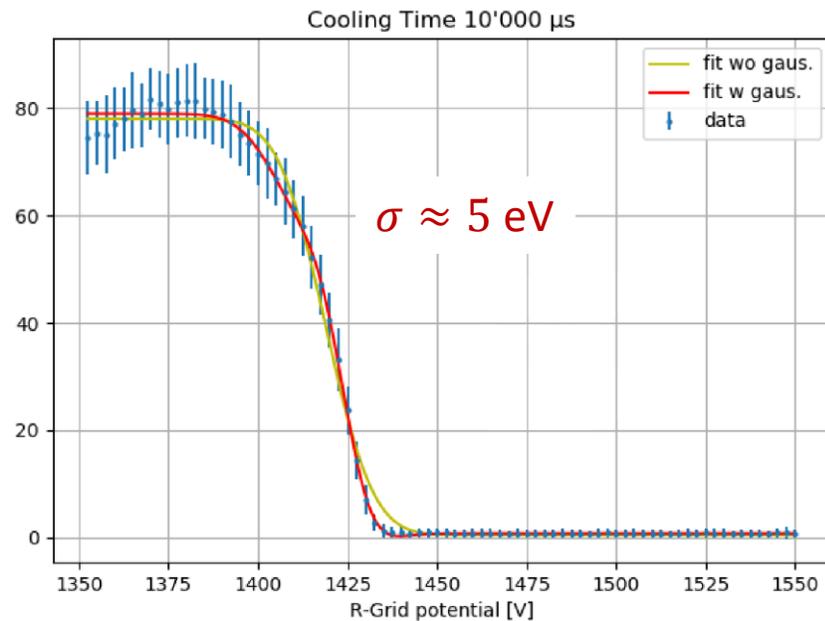
Bunching mode

Time-of-flight dispersion:

- 1 – 2 μs FWHM at 30 keV
- 0.5 – 0.7 μs FWHM at 3 keV
- Extraction potentials can still be optimized for better bunch compression

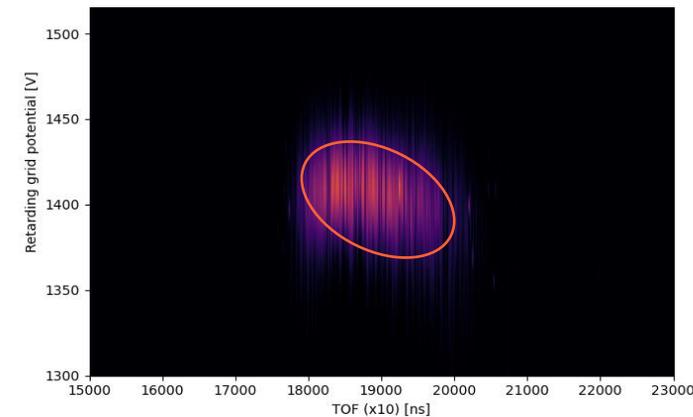
Energy spread

- ≈ 5 eV in 10 ms cooling time
- Cooling sequence optimization in progress



Next steps:

- Transverse emittance measurements at 3 keV and 30 keV
- Longitudinal emittance measurements

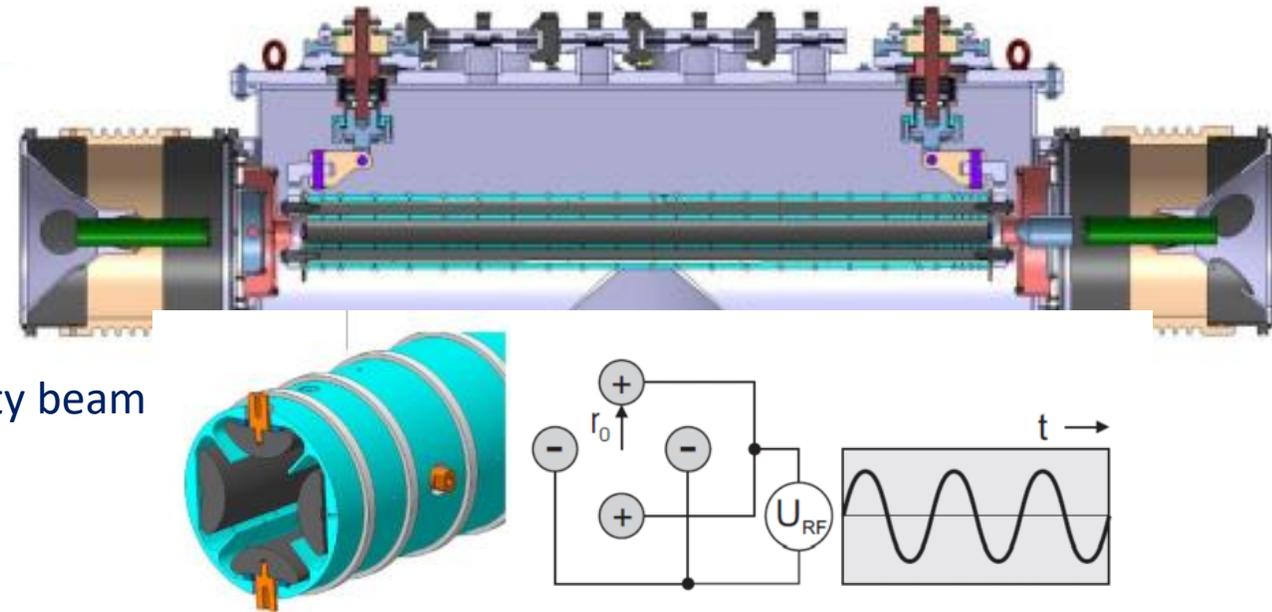


M. Gerbaux et al., to be submitted

GPIB – General Purpose Ion Buncher

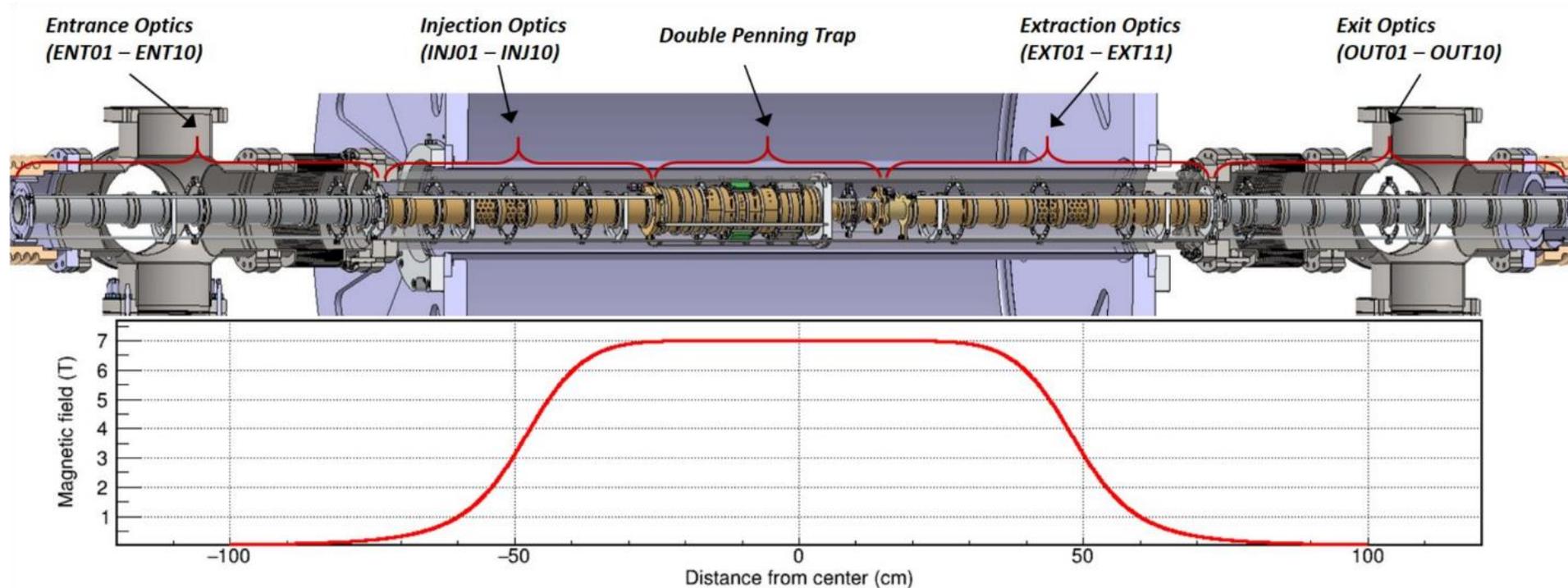
Two operation modes, bunching mode and

- CW mode
 - Test and characterization with $^{\text{nat}}\text{K}$ ($^{39}\text{K} + ^{41}\text{K}$)
 - Beam cooling: $2.9(5)\pi$ mm.mrad @ 30 keV
 - Transmission \rightarrow 80 % @ 30 keV
92 % @ 3 keV
- ISCOOL mechanical design ($r_0 = 20$ mm) for high intensity beam
- New RF system
 - Increased U_{rf} up to 8 kV_{pp} (hopefully)
 - Frequency \rightarrow 220 kHz – 2 MHz
- Command and control system \rightarrow EPICS/Python based



M. Gerbaux et al., to be submitted

PIPERADE



PIPERADE double Penning trap:

- 7 T superconducting magnet
- Homemade switches
- Command and control system
 - EPICS/Python

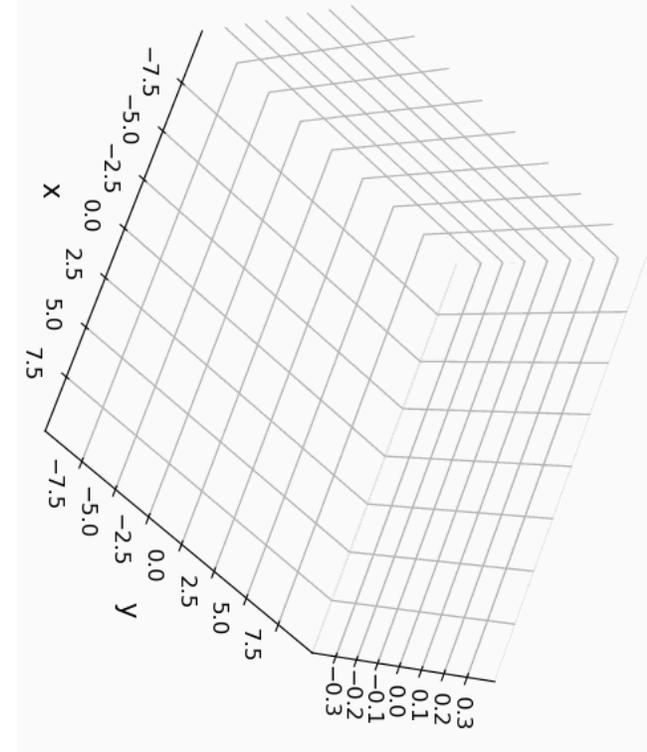
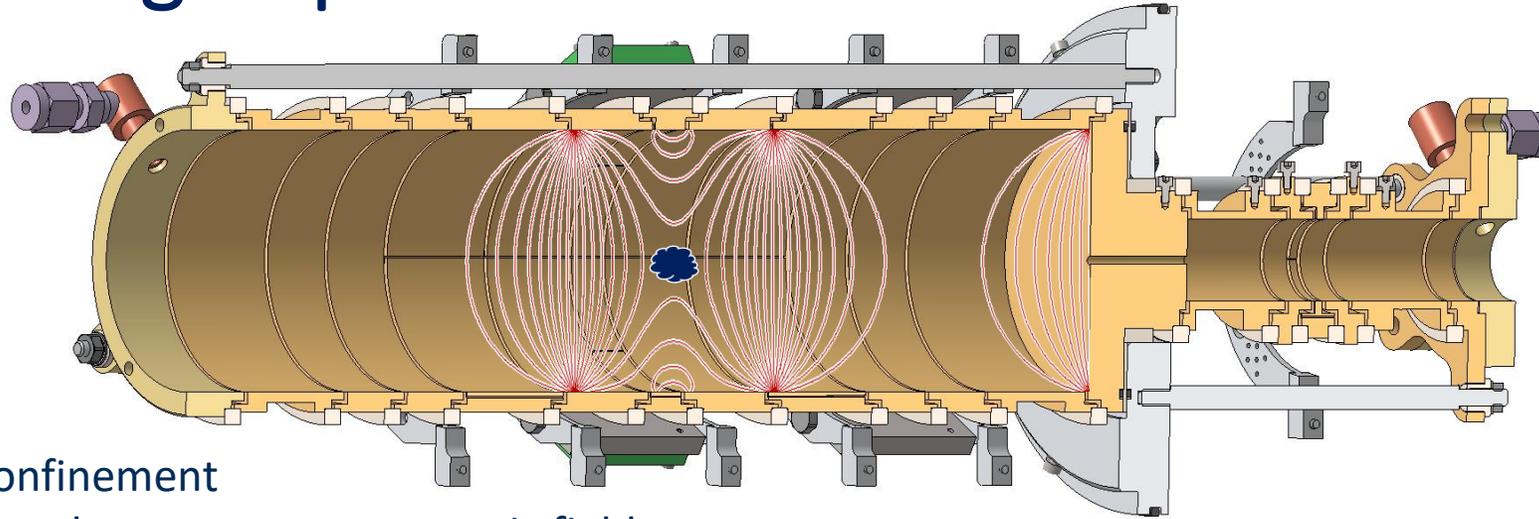
First trap – Purification trap

- Beam purification
- Large inner radius
 - Minimize space charge effects
 - $> 10^4$ ions per bunch

Second trap – Measurement trap

- Accumulation
- Isomeric purification
- Mass measurements

Penning trap



- \ Radial confinement
 - strong homogeneous magnetic field
- \ Axial confinement
 - electric field

3 ion motions



3 ion frequencies

- Axial v_z
- Magnetron v_-
- Reduced cyclotron v_+

$$v_z = \frac{1}{2\pi} \sqrt{\frac{U_0 q}{d^2 m}}$$

$$v_{\pm} = \frac{1}{2} \left(v_c \pm \sqrt{v_c^2 - 2v_z^2} \right)$$

Invariance theorem

$$v_c^2 = v_-^2 + v_+^2 + v_z^2$$

Cyclotron frequency

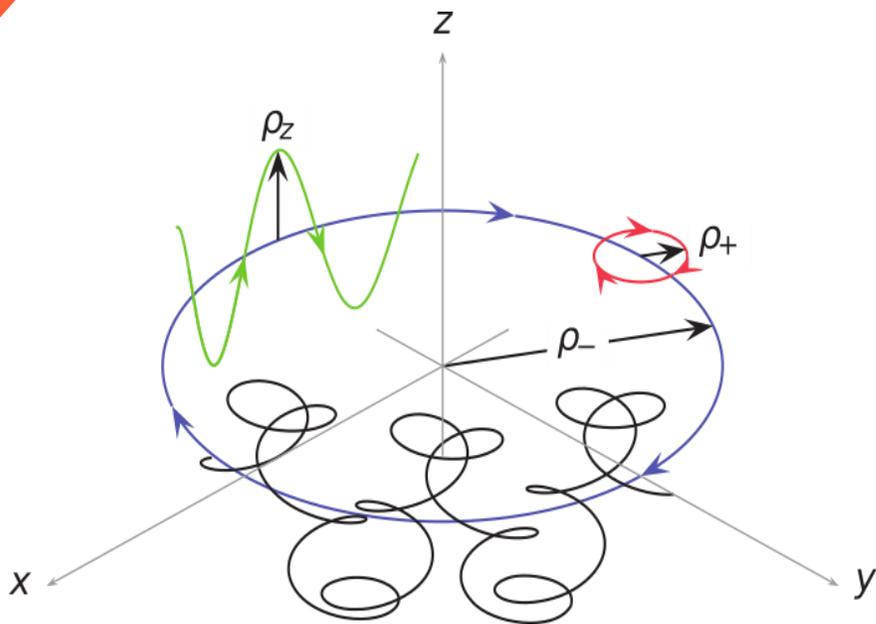
$$v_c = v_- + v_+$$

Cyclotron frequency

$$v_c = \frac{1}{2\pi} \frac{q}{m} B$$

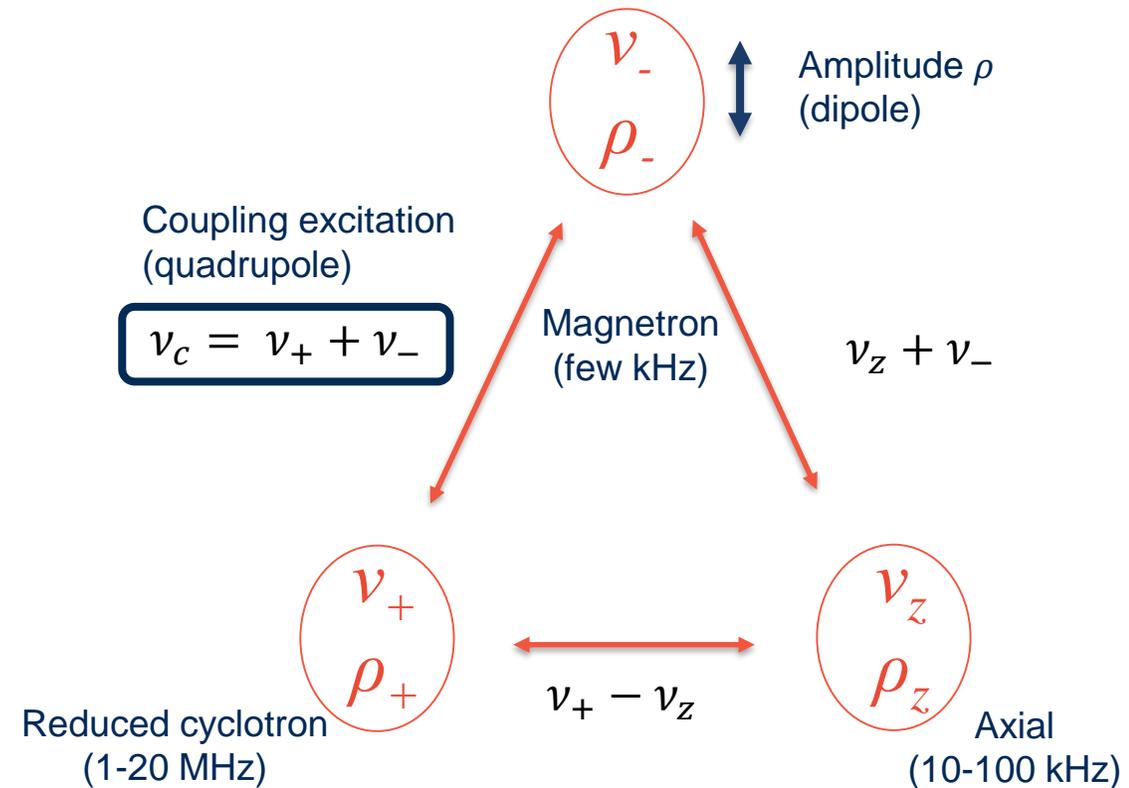
q : electric charge
B : magnetic field
m : mass

Penning trap



Control amplitudes

 Convert motions



3 ion motions



3 ion frequencies

- Axial ν_z
- Magnetron ν_-
- Reduced cyclotron ν_+

$$\nu_z = \frac{1}{2\pi} \sqrt{\frac{U_0 q}{d^2 m}}$$

$$\nu_{\pm} = \frac{1}{2} \left(\nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2} \right)$$

Invariance theorem

$$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

Cyclotron frequency

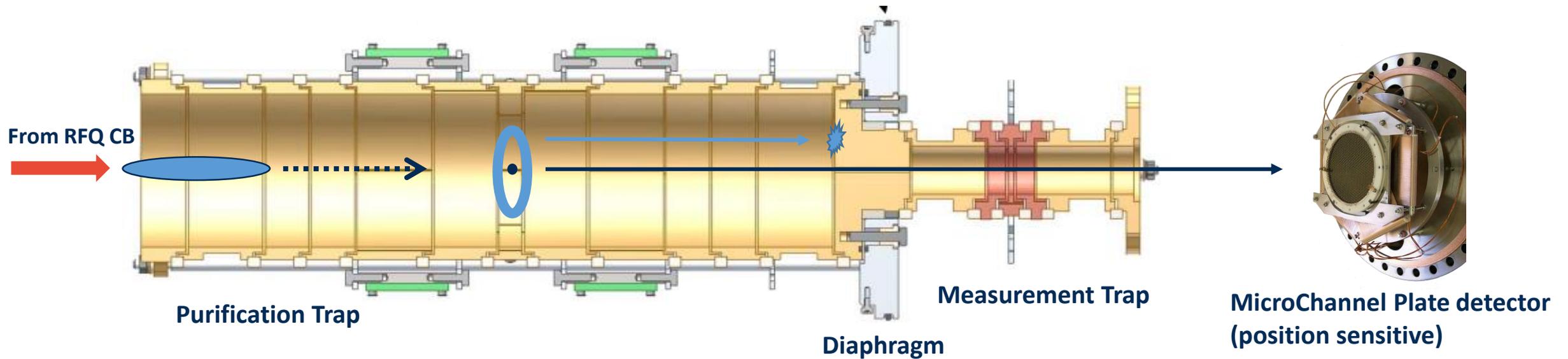
$$\nu_c = \nu_- + \nu_+$$

Cyclotron frequency

$$\nu_c = \frac{1}{2\pi} \frac{q}{m} B$$

q : electric charge
 B : magnetic field
 m : mass

Buffer gas cooling technique



Buffer gas cooling technique

1. Magnetron excitation: ν_-
 - 10 ms
2. Quadrupole excitation: $\nu_c = \nu_+ + \nu_-$
 - Convert the radial magnetron motion (ν_-) into modified cyclotron motion (ν_+)
 - 40 – 400 ms
 - Centering the « good guys »

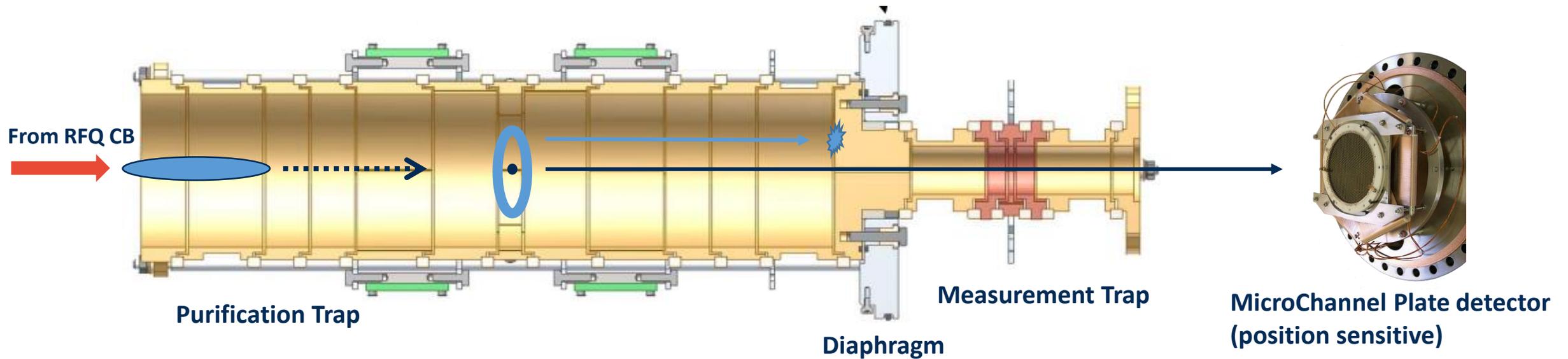


- ν_- is mass **independent**
- Magnetron motion is amplified



- ν_c excitation is mass **dependent !!**
- modified cyclotron motion is damped

Buffer gas cooling technique



Mass resolving power of Penning trap

$$R = \frac{M}{\Delta M} = \frac{\nu_c}{\Delta \nu_c} \propto \frac{1}{\Delta \nu_c} \left(\frac{q}{m} B \right) \rightarrow \text{Scaling}$$

Constant for each method 0.1 ... 100 Hz

Rule of thumb:

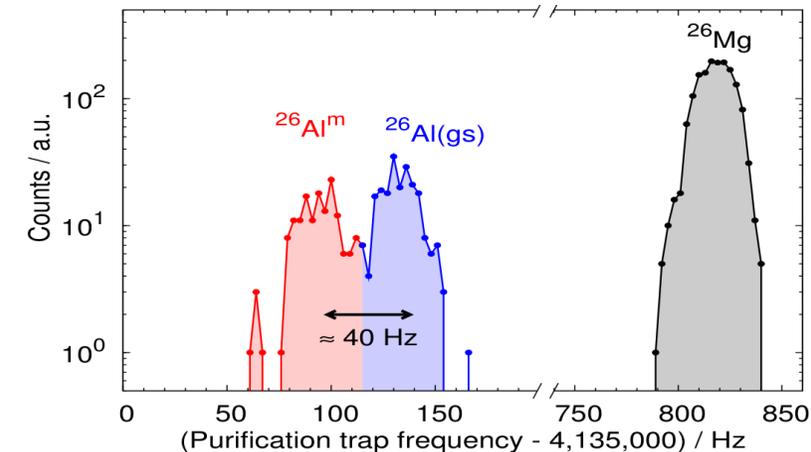
$$B = 7 \text{ T}, q = 1e, m = 100u$$

$$\rightarrow \nu_c \sim 1 \text{ MHz}, 100 \text{ keV/Hz}$$

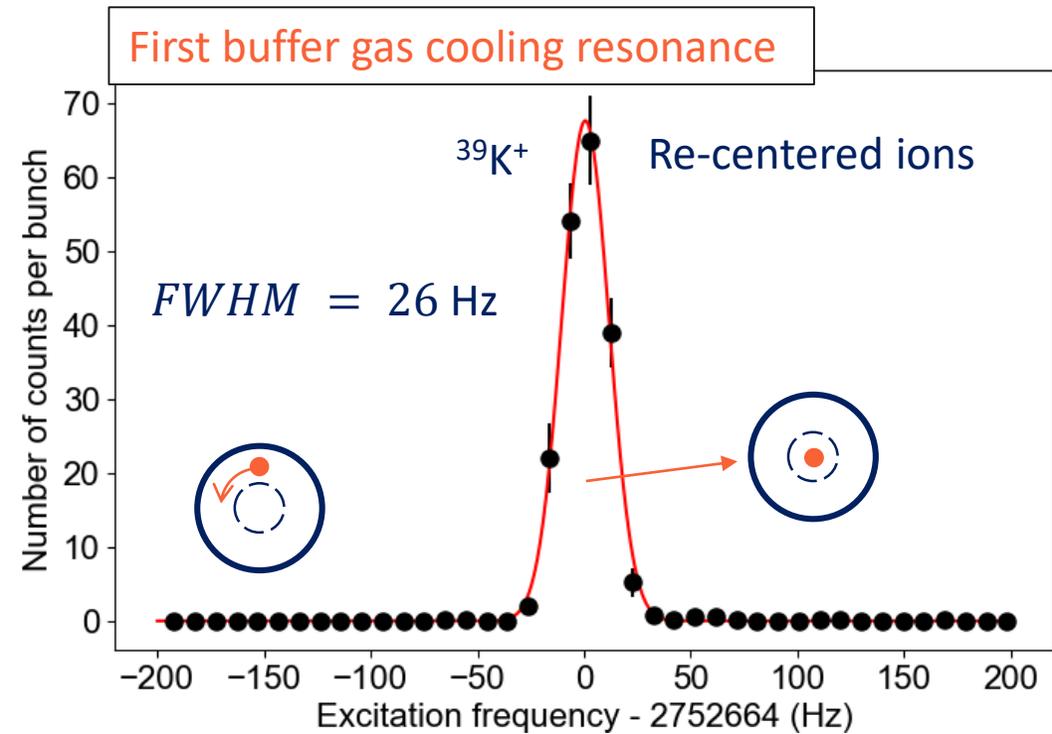
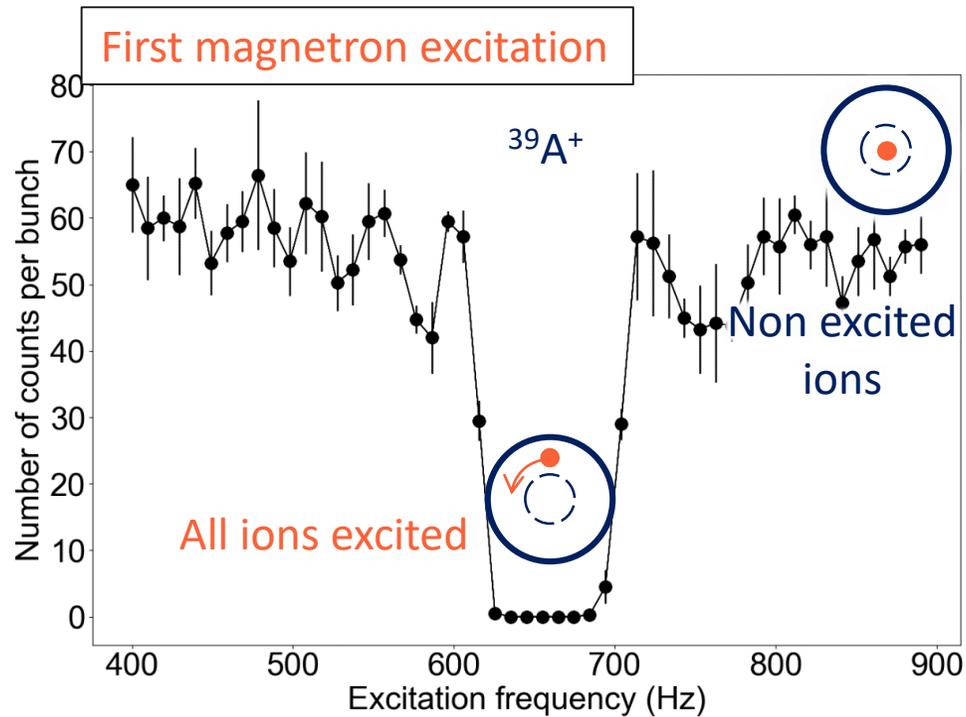
Buffer gas cooling technique

- Gas filled purification trap
- Separation
 - 10 ... 100 Hz
 - $R = 10^4 \dots 10^5$
- Also cooling

G. Savard et al., Phys. Lett. A **158** (1991) 247–252



Buffer gas cooling technique



- Technique tested on

- ^{39}K
- ^{40}Ca
- ^{41}K

- Resolving power of 10^5 reached

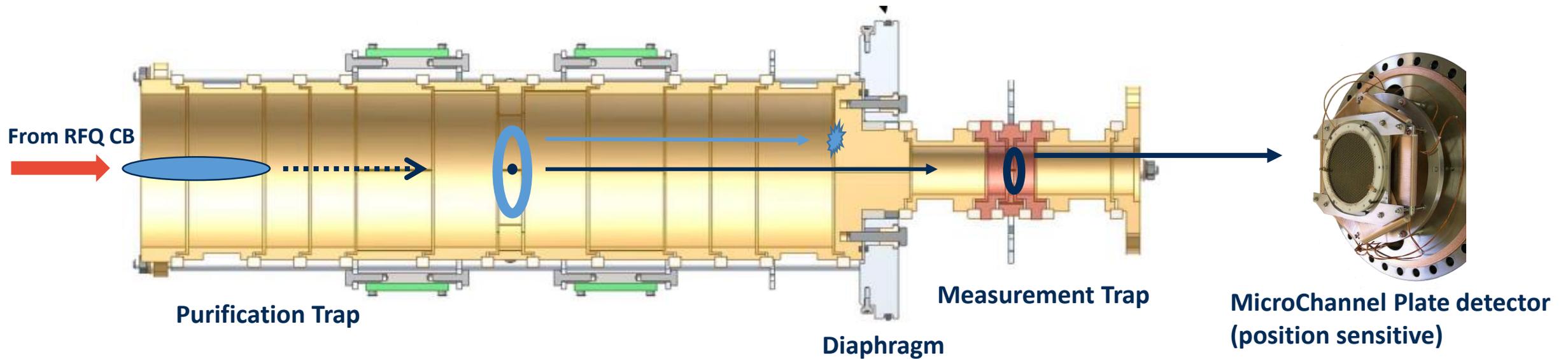
$$R = \frac{\nu_c}{FWHM}$$

$$R \approx 106000$$

- On-going studies to improve the resolution and the re-centering efficiency

P. Ascher et al., Nucl. Instrum. Methods Phys. Res. A, 1019, 165857 (2021)

TOF-ICR technique



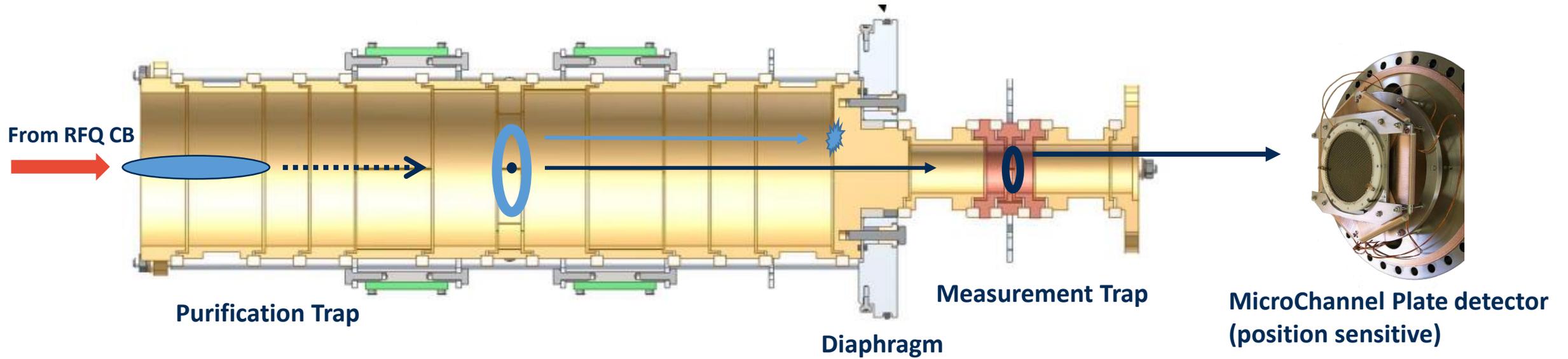
TOF-ICR technique

1. Magnetron excitation: \mathbf{v}_-
 - 10 ms
 - Give a slow radial motion to the ions
2. Quadrupole excitation: $\mathbf{v}_c = \mathbf{v}_+ + \mathbf{v}_-$
 - Convert the radial magnetron motion (\mathbf{v}_-) into modified cyclotron motion (\mathbf{v}_+)
 - 5 – 400 ms



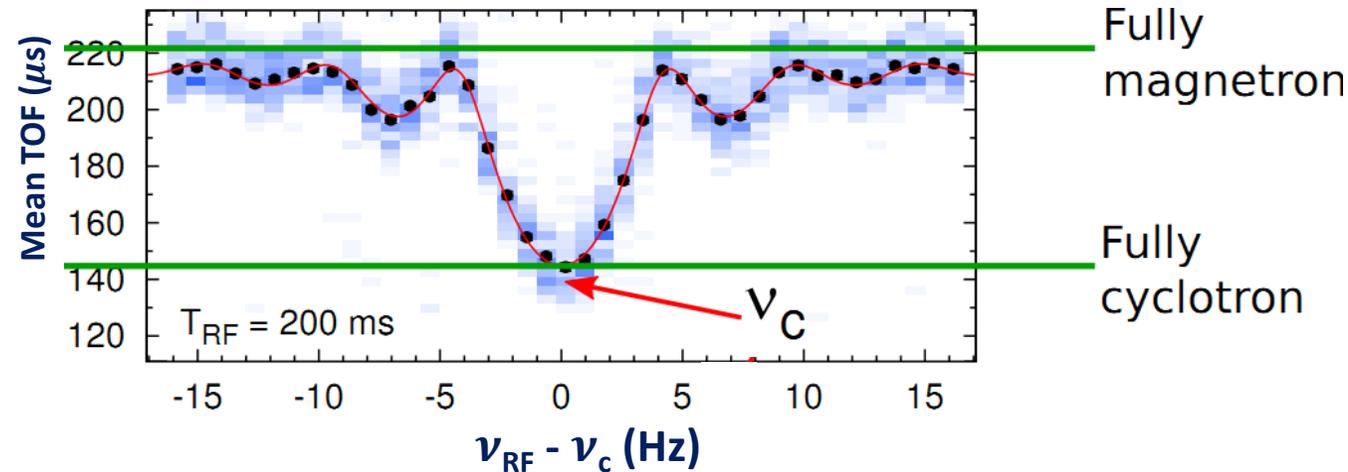
- The modified cyclotron motion is a fast motion
- The ions are not recentered (no gas)
- Extraction towards the MCP

TOF-ICR technique

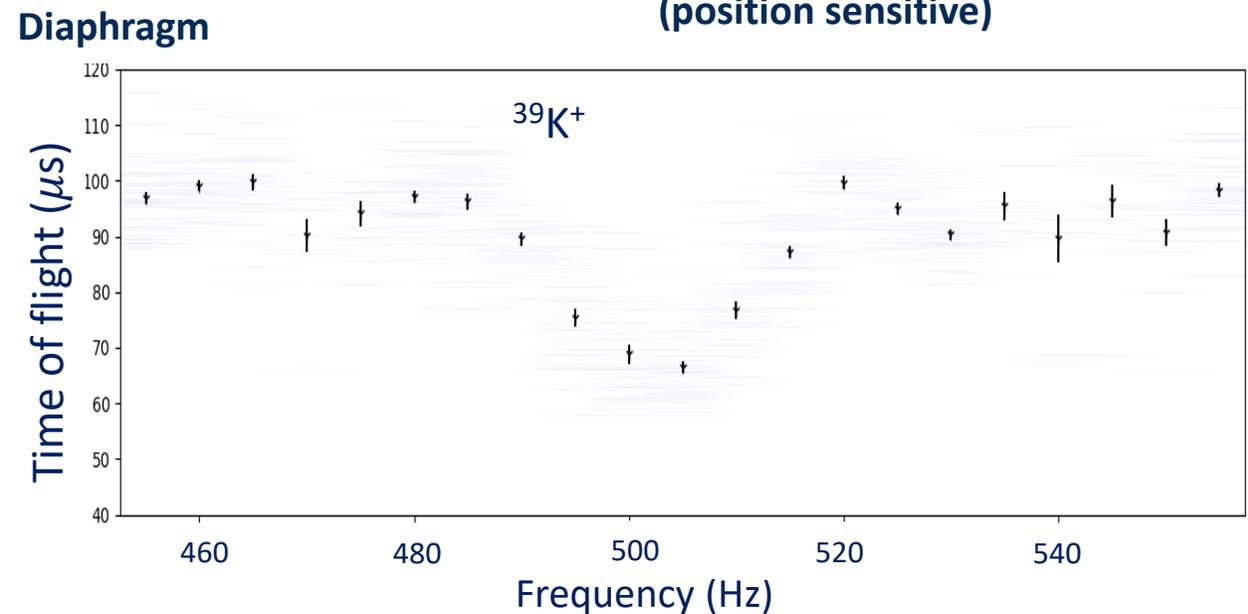
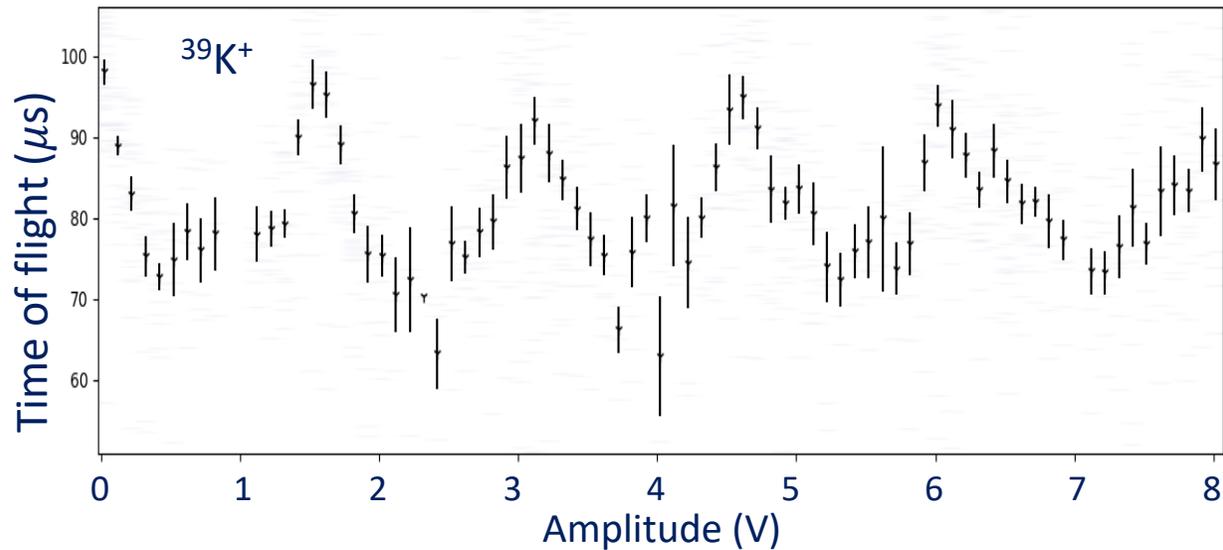
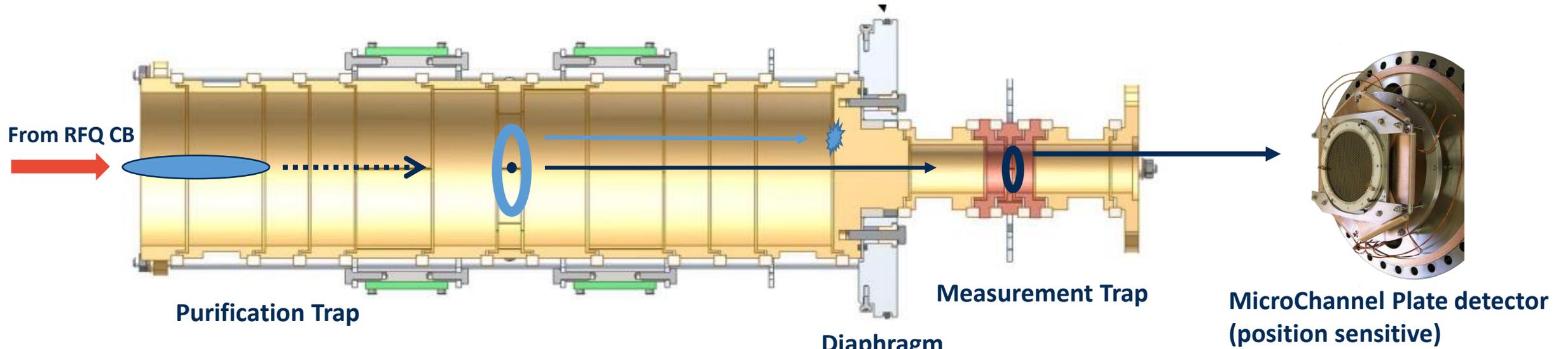


TOF-ICR technique

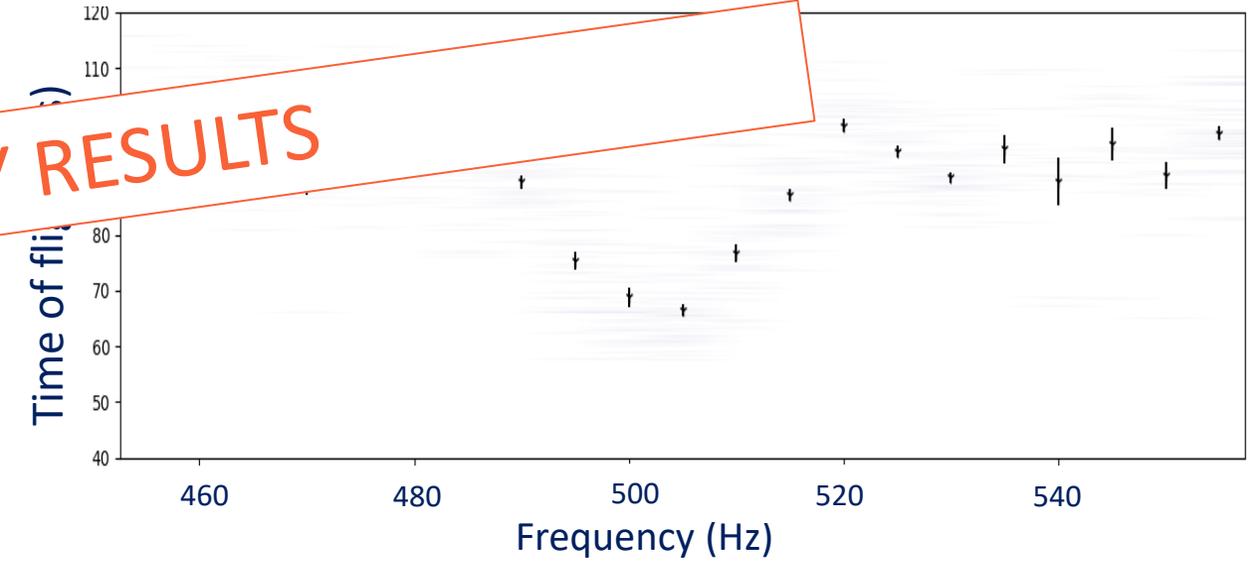
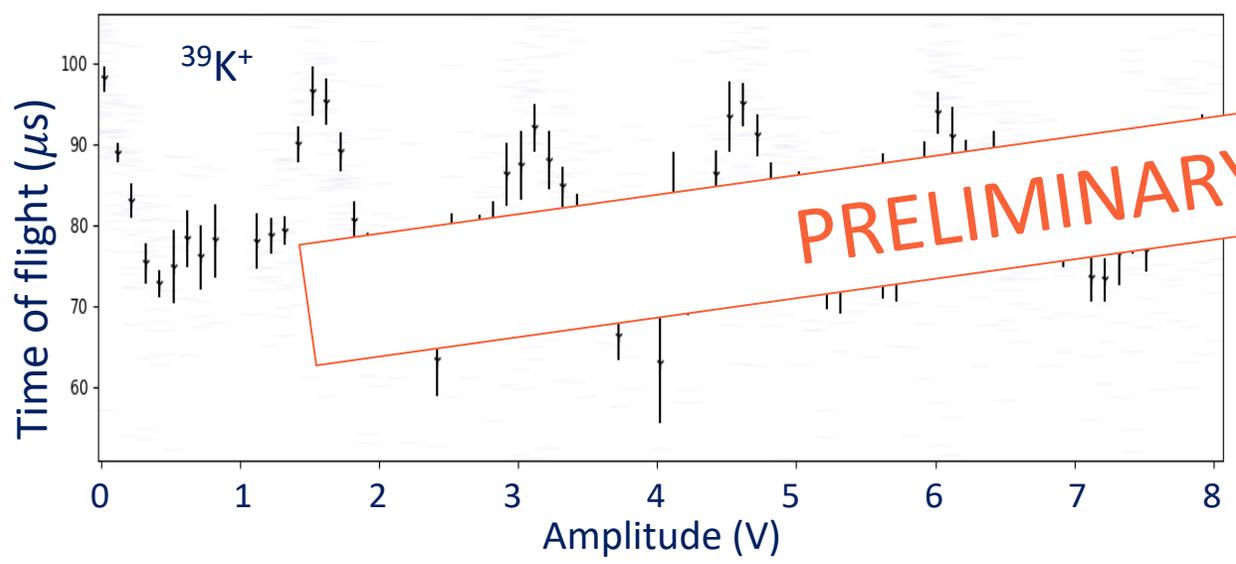
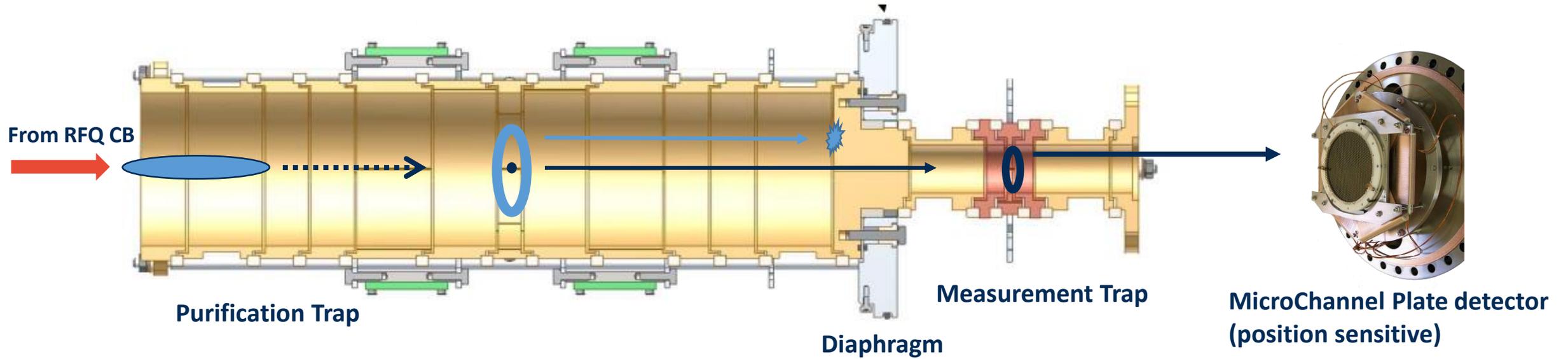
- Excitation around ν_c
 - / Large magnetic moment (ν_+ amplitude)
 - $\mu \sim \omega_+^2 \rho_+^2 - \omega_-^2 \rho_-^2 \quad (E_p = -\vec{\mu} \cdot \vec{B})$
- Extraction
 - / Radial kinetic energy change to axial energy
- ToF is reduced



TOF-ICR technique

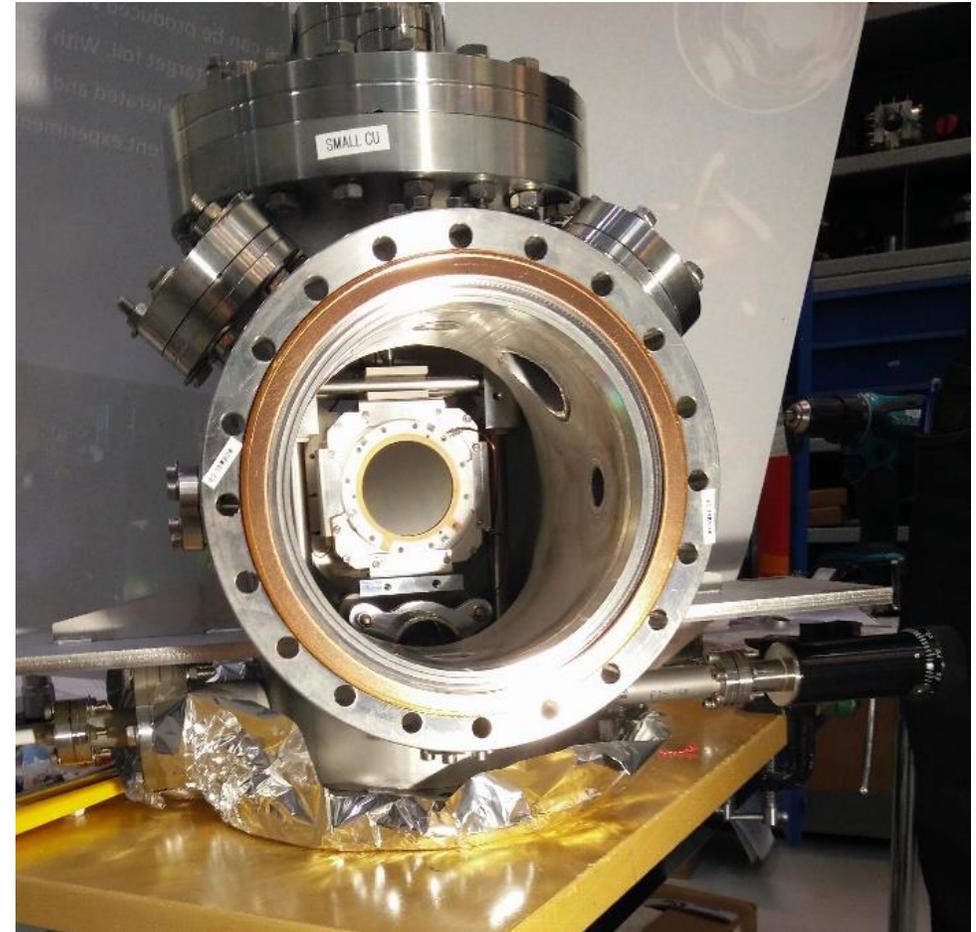
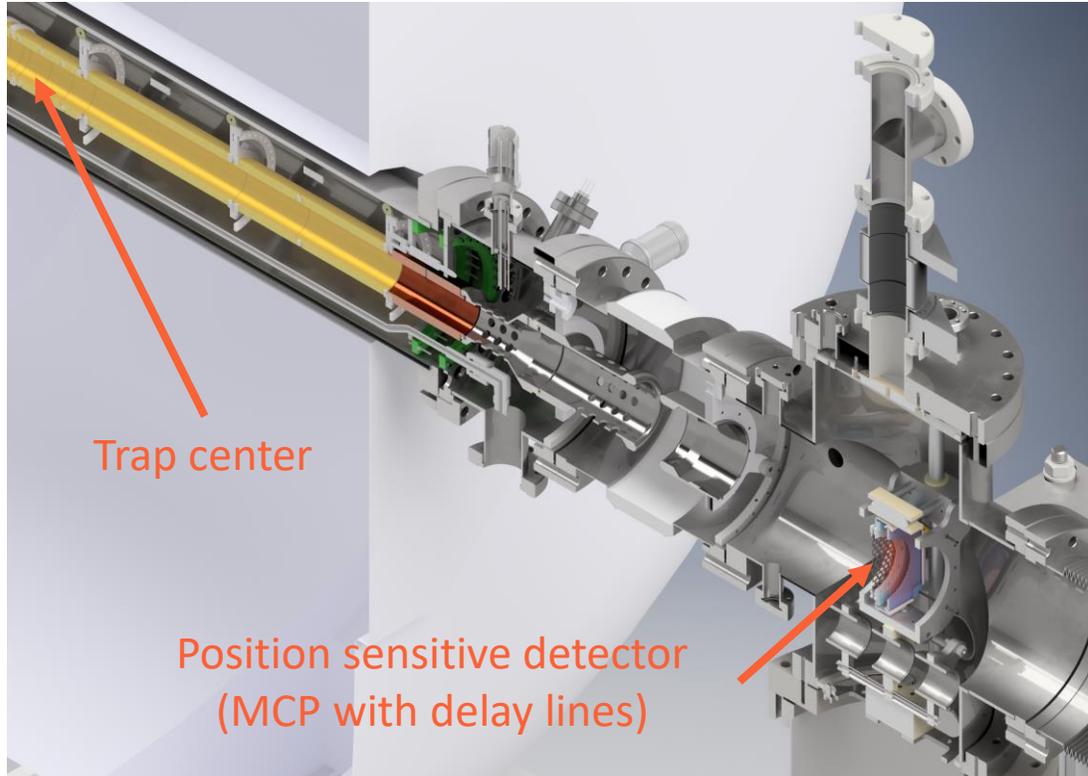


TOF-ICR technique

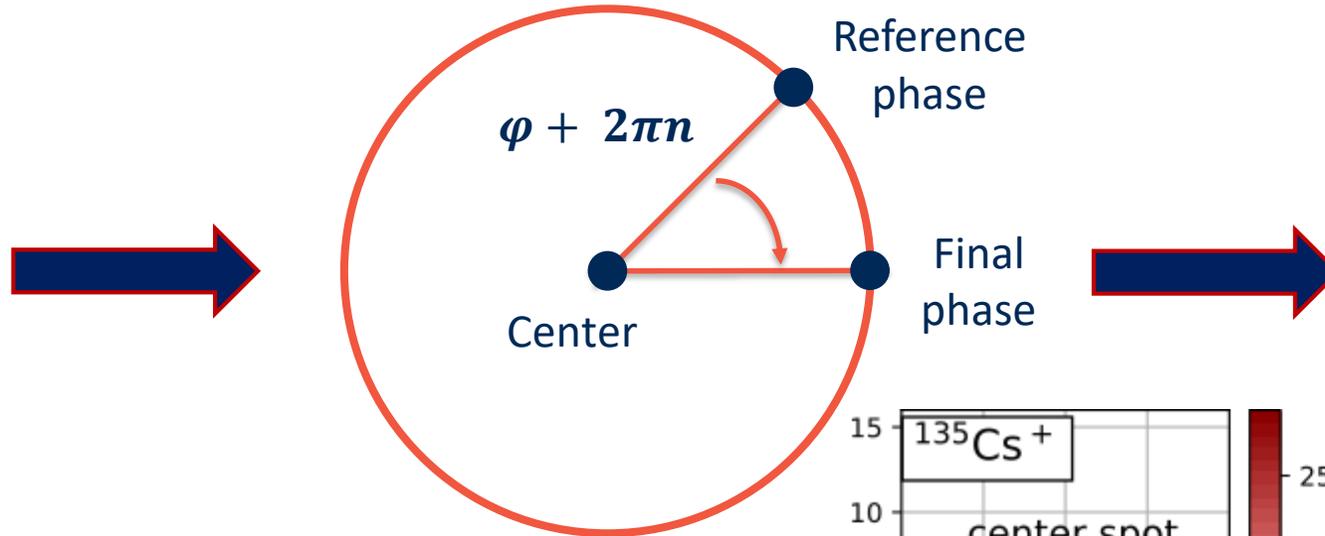
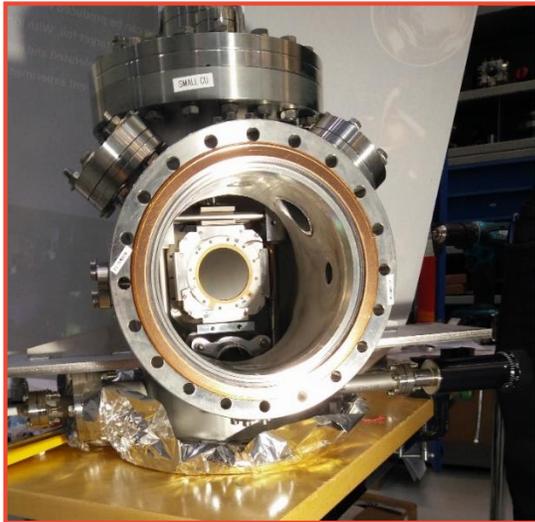


PRELIMINARY RESULTS

Next step: PI-ICR technique



Next step: PI-ICR technique



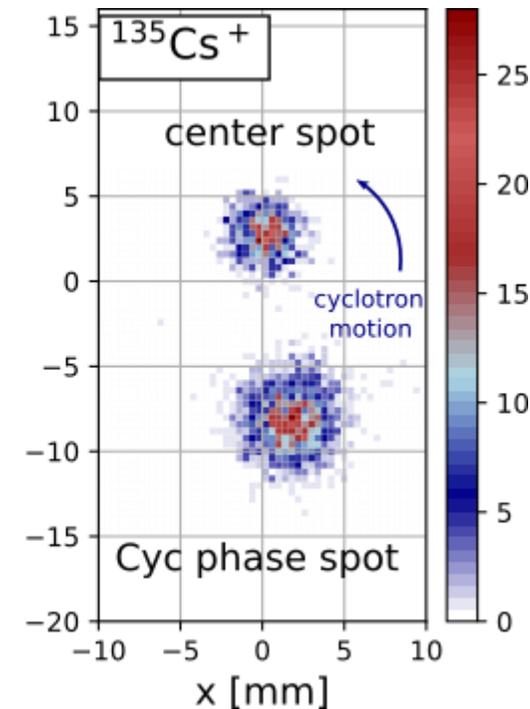
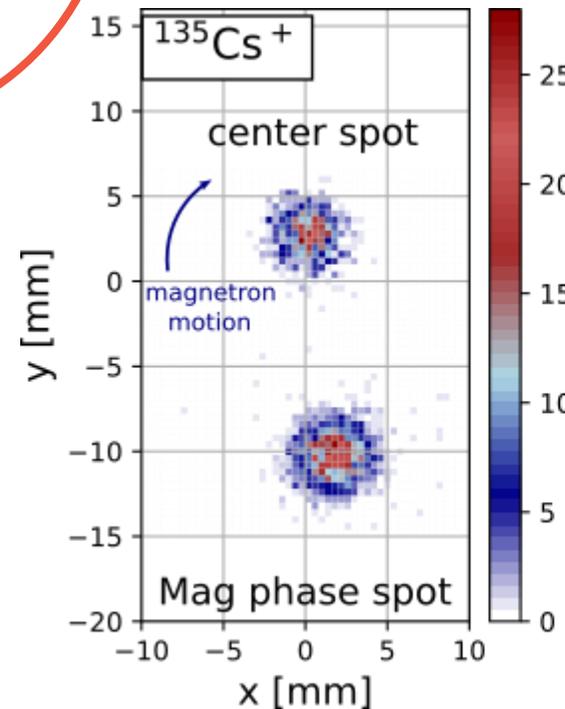
$$\nu = \frac{\varphi + 2\pi n}{2\pi t}$$

Advantages of PI-ICR:

- No scanning
- Data collection to one spot
- $\times 40$ faster $\times 5$ increase in precision

But:

- Need to prepare the ion more carefully
 - Damping of ion motions; longer setting up time
- Sensitive to voltage fluctuations



A. de Roubin et al., Phys. Lett. A **124** (2020) 222503

Concluding remarks

GPIB cooler buncher

- Two different modes operational
- TOF dispersion of $\sim 0.5 \mu\text{s}$ reach
- Energy spread < 10 eV routinely
 - Still room for improvement
 - Next steps \rightarrow emittance measurements

PIPERADE mass spectrometer

- Fully assembled
- Ion trapped routinely
- Detection system operational

Preparation trap (PT)

- Dipolar and quadrupolar excitations functional
- First buffer gas cooling resonance obtained

Measurement trap (MT)

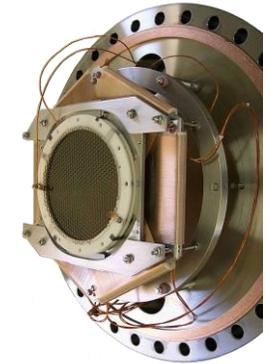
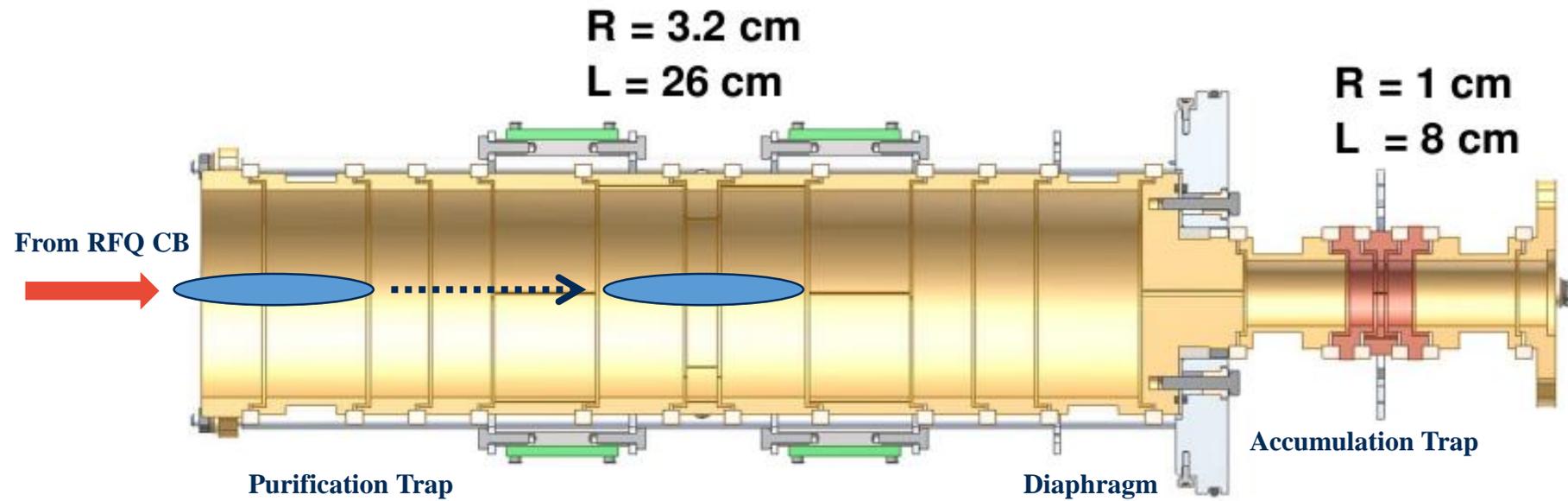
- Dipolar and quadrupolar excitation functional
- First TOF-ICR resonance obtained
- Next steps \rightarrow PI-ICR method !!!

Thank you for your attention

The PIPERADE collaboration:

P. Ascher, L. Daudin, M. Flayol, M. Gerbaux, S. Grévy, M. Hukkanen, A. Husson, A. de Roubin, P. Alfaut, B. Blank, K. Blaum, B. Lachacinski, D. Lunney, E. Minaya Ramirez, S. Naimie, S. Perard, B. Thomas

Buffer gas cooling technique

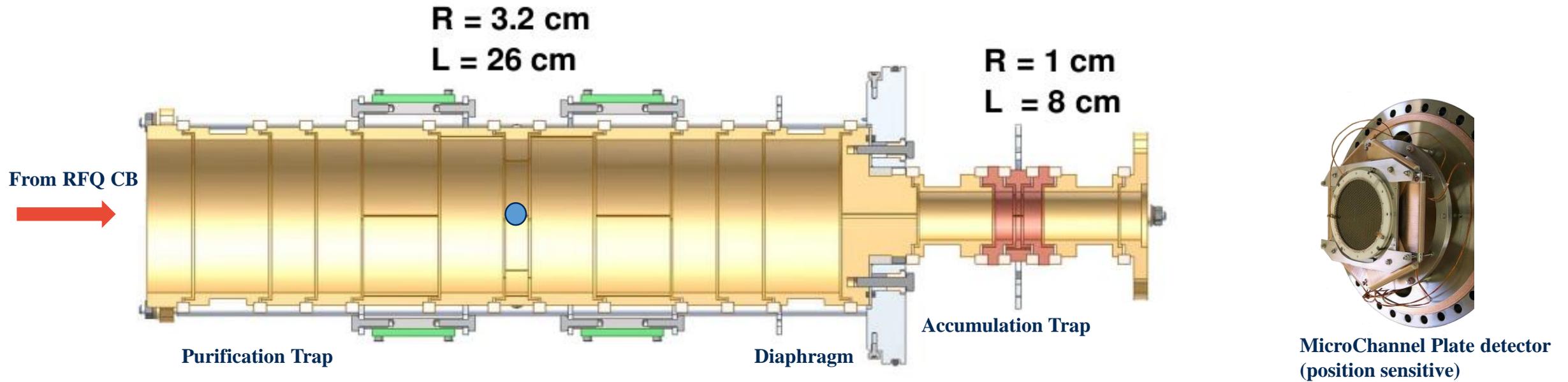


MicroChannel Plate detector
(position sensitive)

Injection and capture of the ions

➤ $100 \mu\text{s}$

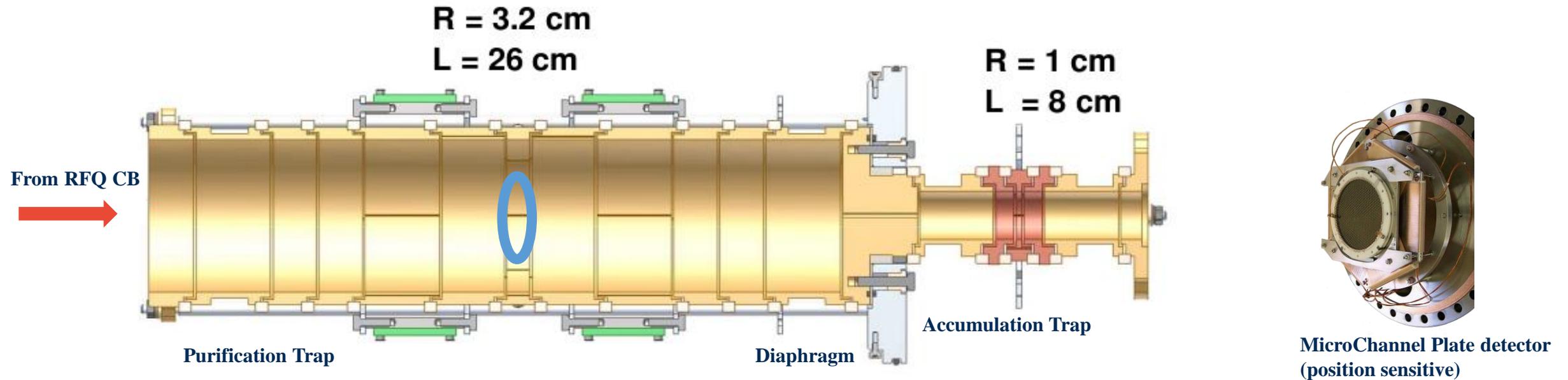
Buffer gas cooling technique



Cooling of radial and axial motions

➤ 30 - 100 ms

Buffer gas cooling technique



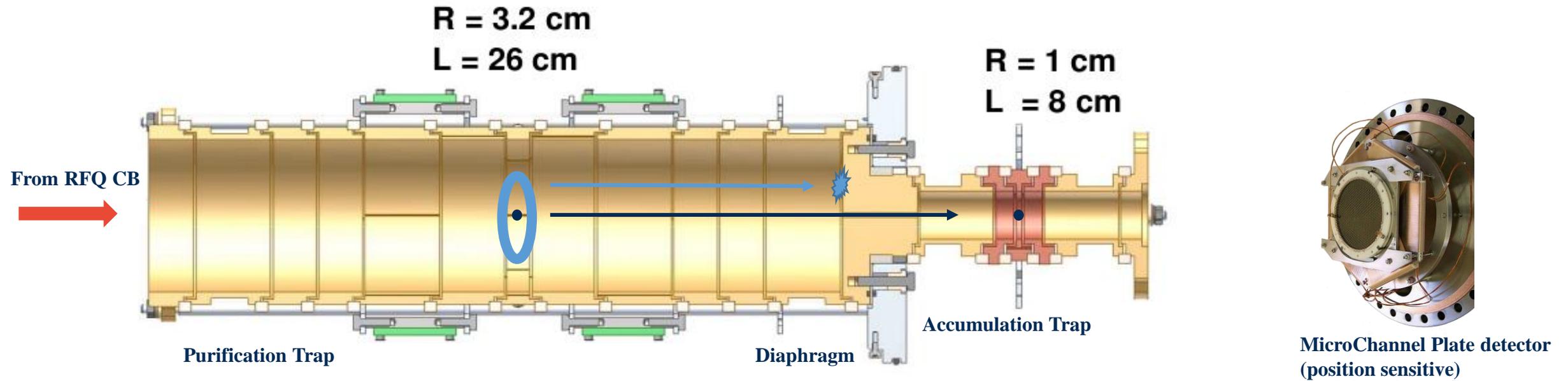
Buffer gas cooling technique

1. Magnetron excitation: ν_{\perp}
➤ 10 ms



This excitation is mass **independent**

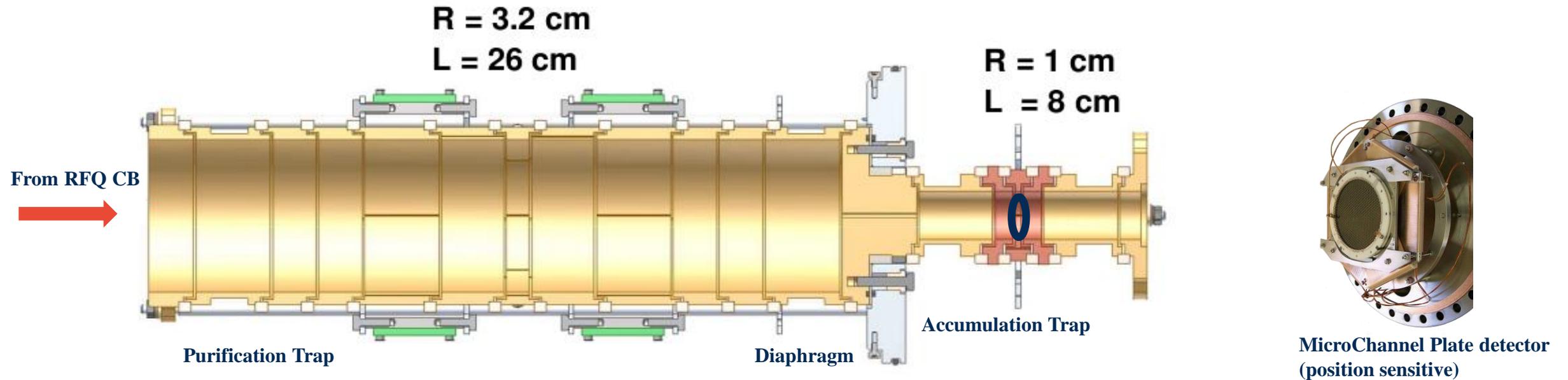
Time-of-flight ion cyclotron resonance technique (ToF-ICR)



ToF-ICR technique (Time-of-Flight Ion Cyclotron Resonance)

 Transfer of the clean ion sample to the measurement trap

Time-of-flight ion cyclotron resonance technique (ToF-ICR)



ToF-ICR technique

1. Magnetron excitation: ν_{-}
 - 10 ms
 - Give a slow radial motion to the ions

Time-of-flight ion cyclotron resonance technique (ToF-ICR)

