LP2i Bordeaux

Spiral2 DESIR

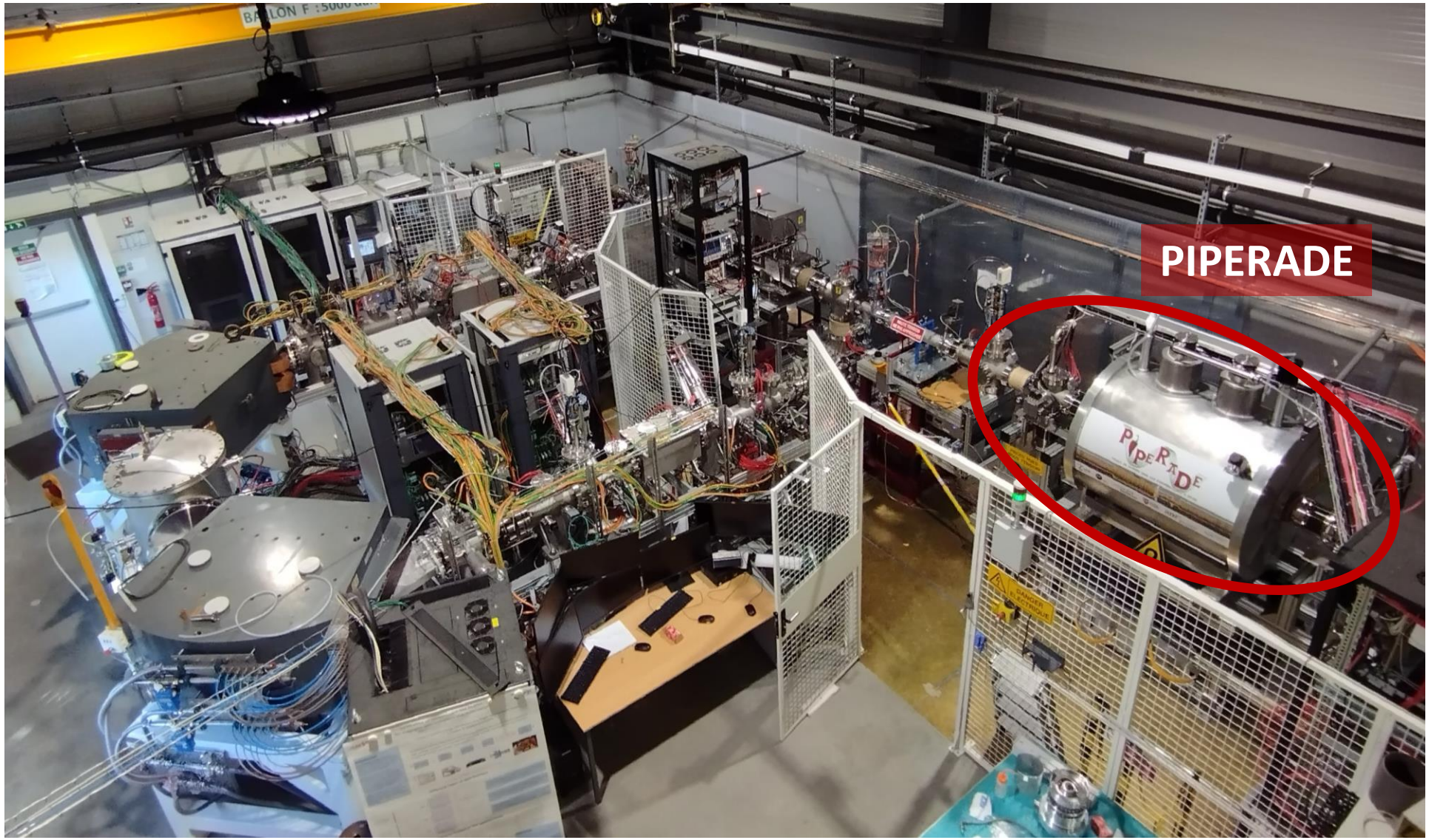
PIPERADE

PIEGES DE PENNING POUR LES RADIONUCLEIDES A DESIR

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

cnrs IN2P3 Les deux infinis

PIPERADE @LP2iB



PIPERADE @LP2iB

Produce ion samples

30 kV

Preparation of sample

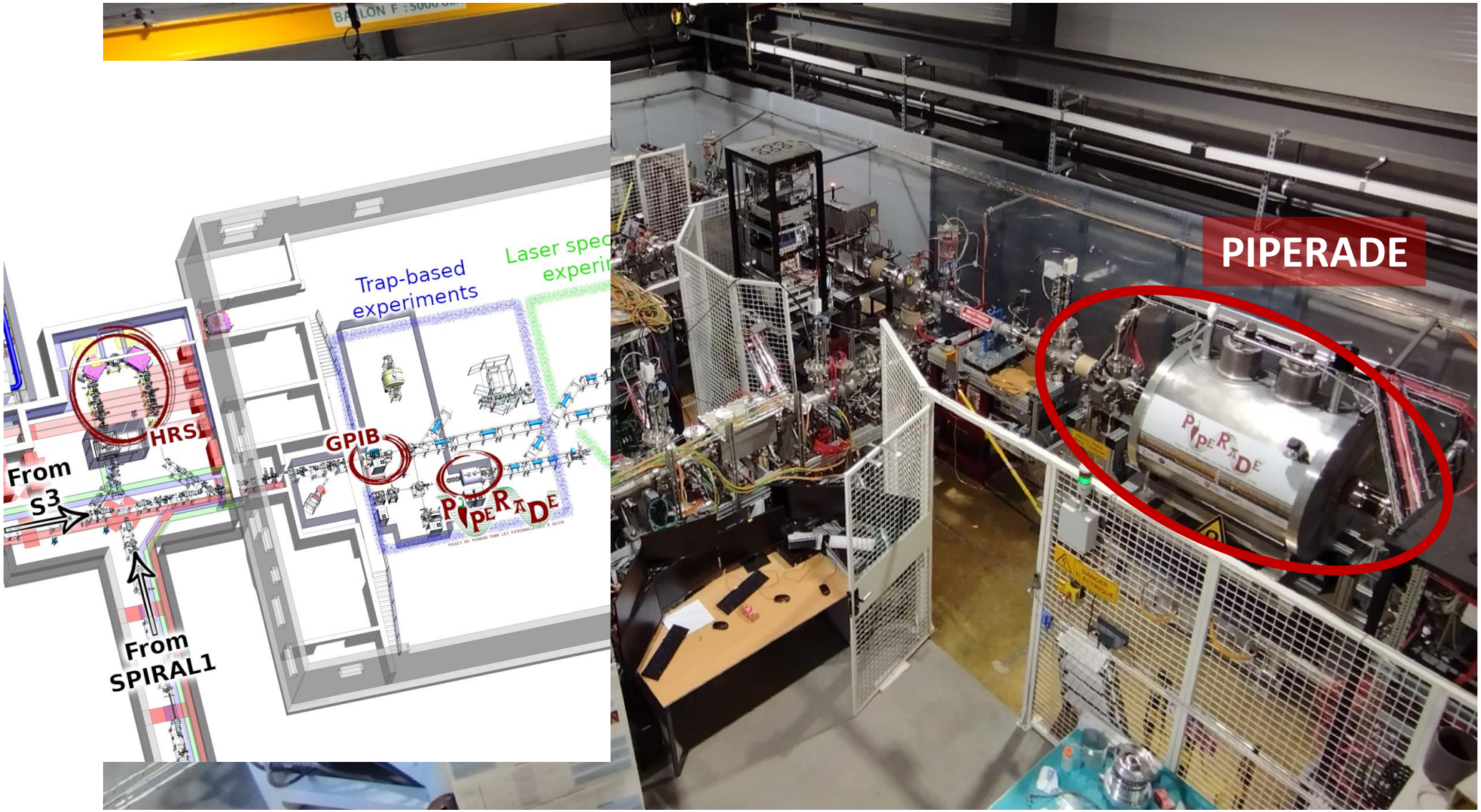
29.9 kV

27 kV

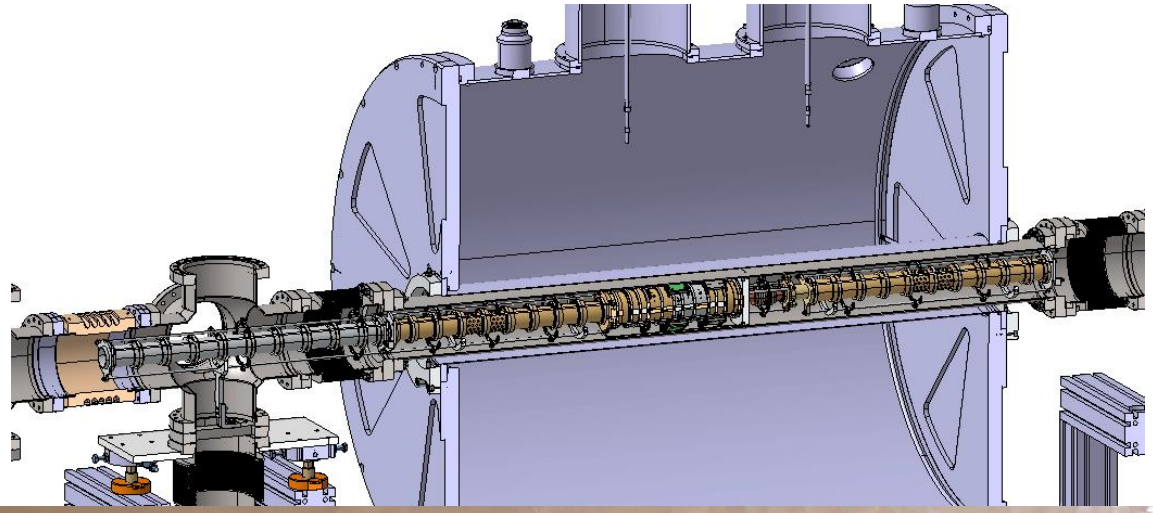
Analysis of the sample

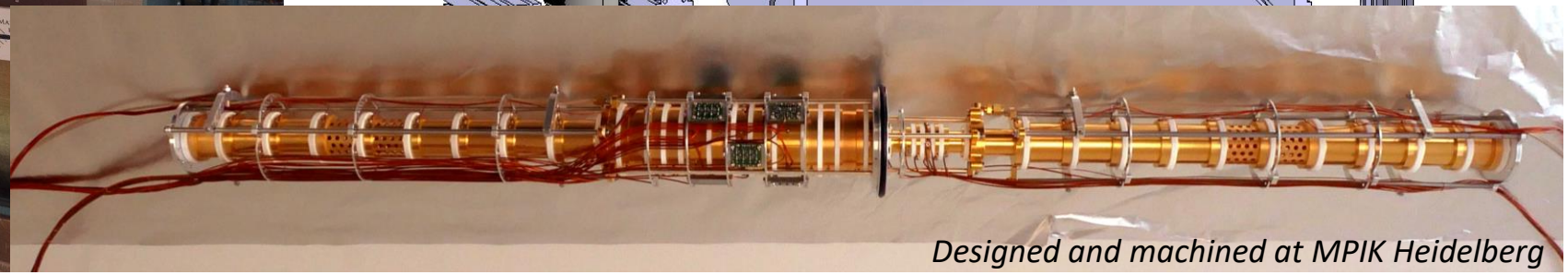
29.9 kV

PIPERADE @LP2iB and @DESIR

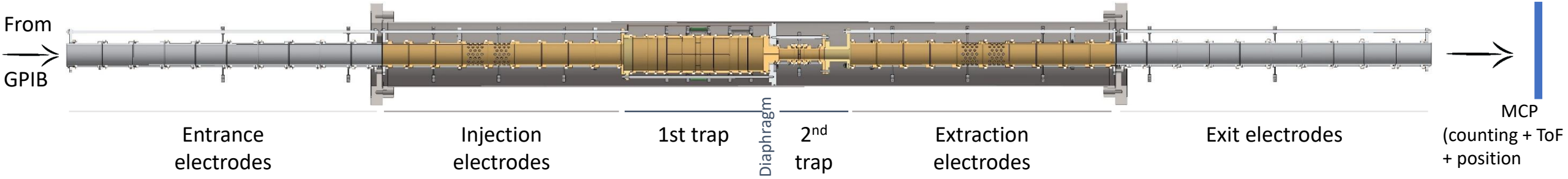


PIPERADE = 2 cylindrical traps in a 7-Tesla magnet





P. Ascher *et al.*, *PIPERADE: A double Penning trap for mass separation and mass spectrometry at DESIR/SPIRAL2*, Nucl. Instrum. Methods Phys. Res. A 1019 (2021) 165857



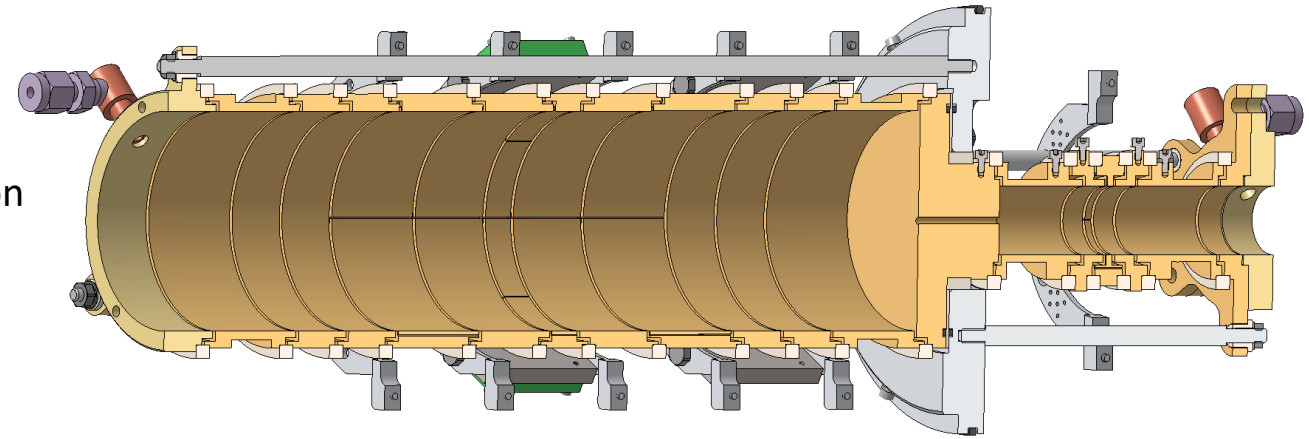
Ion motions in a Penning trap

- Strong homogeneous magnetic field : radial confinement
  (2 homogeneous regions < 1 ppm over 1 cm^3)

- Weak quadrupolar electrostatic field : axial confinement (correction electrodes to limit the anharmonicities)

→ Superposition of 3 motions with 3 eigen frequencies:

  - ν_z : Axial motion (~100 kHz)
  - ν_+ : Reduced cyclotron motion (~ MHz)
  - ν_- : Magnetron motion (~ kHz) (mass-independent)



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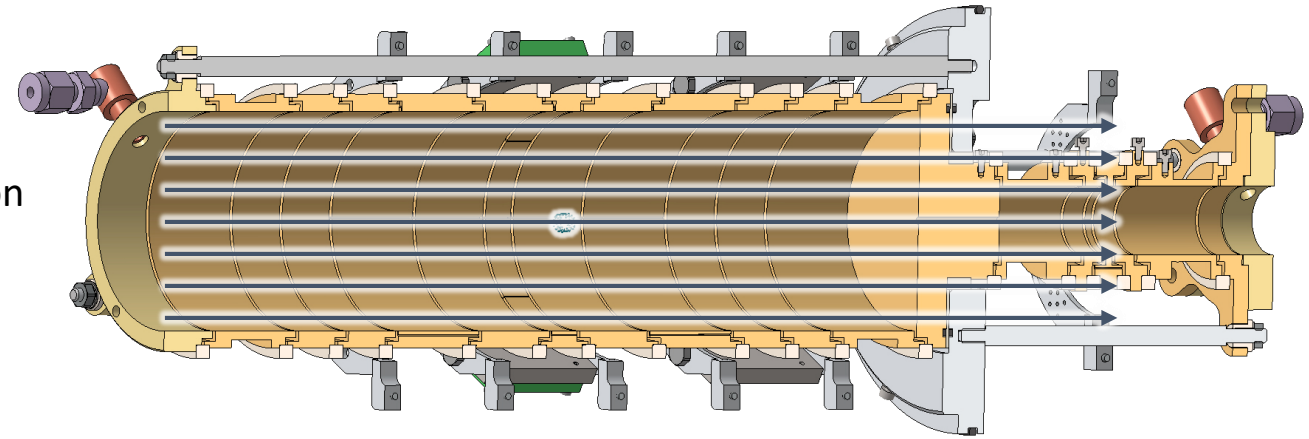

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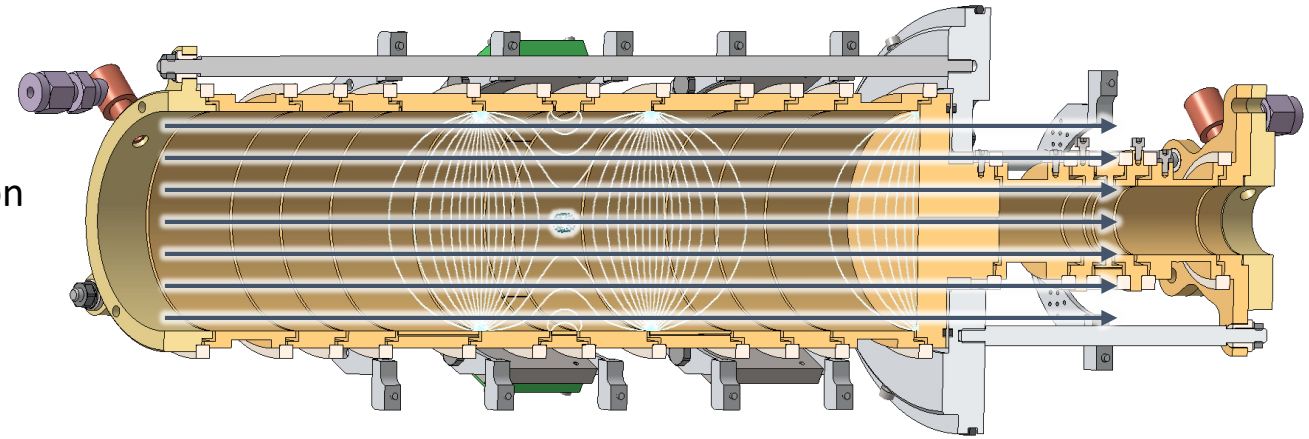

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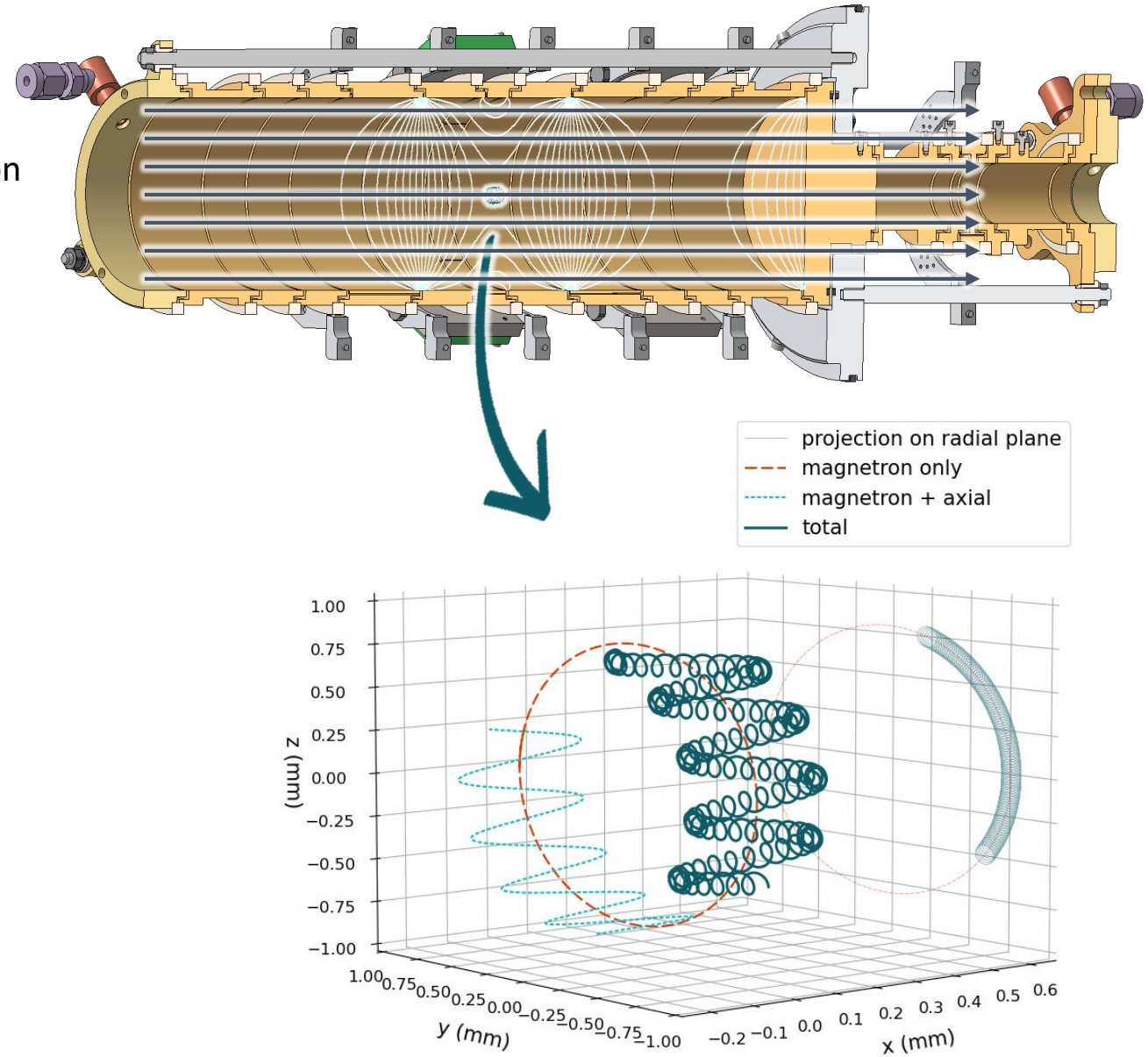

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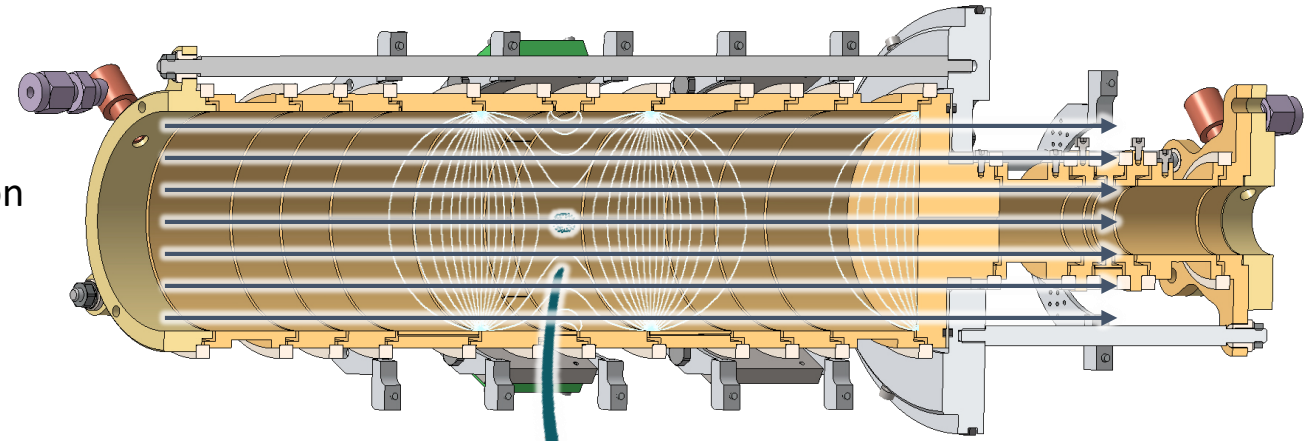
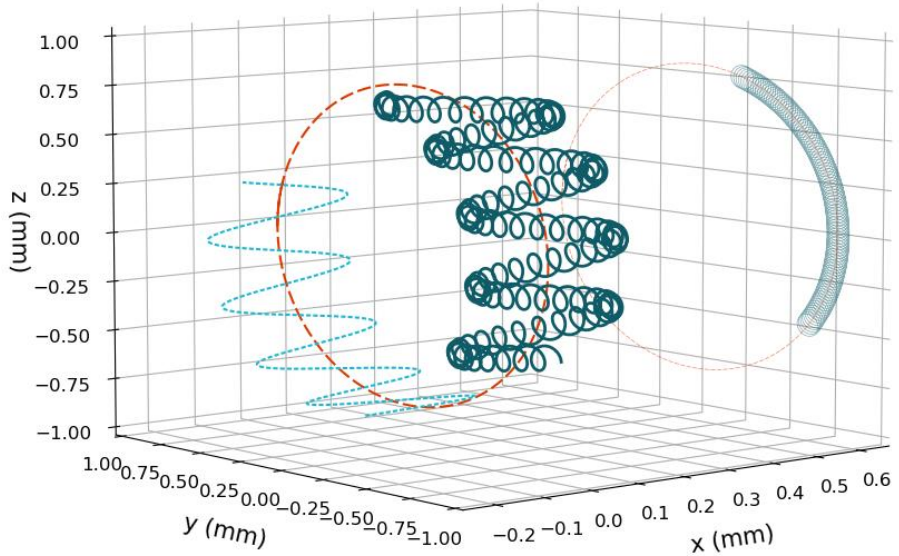
Cyclotron frequency $\boldsymbol{\nu_c} = \frac{\boldsymbol{qB}}{\boldsymbol{2\pi m}}$ $\quad \nu_c \approx \nu_+ + \nu_-$





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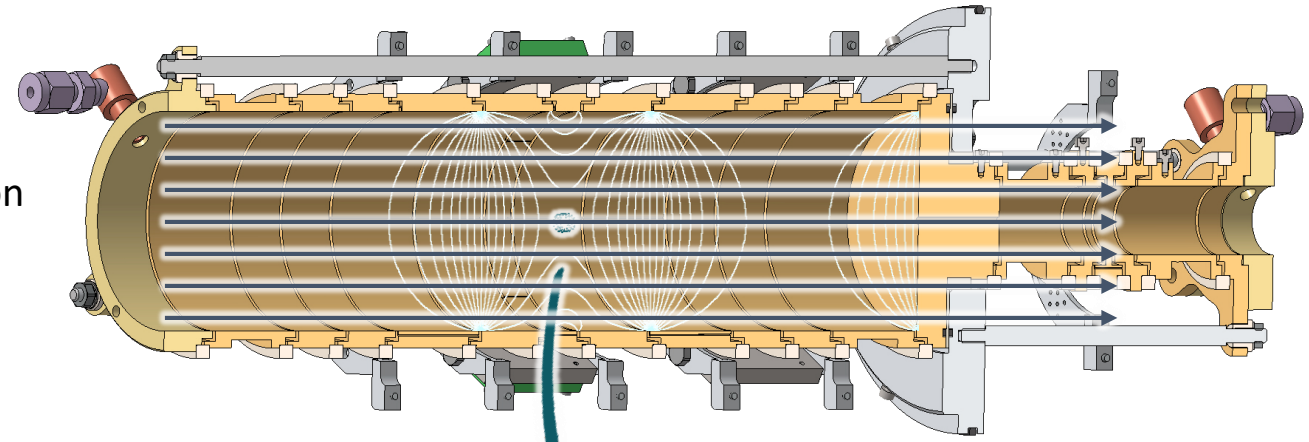
Reduced by the gas



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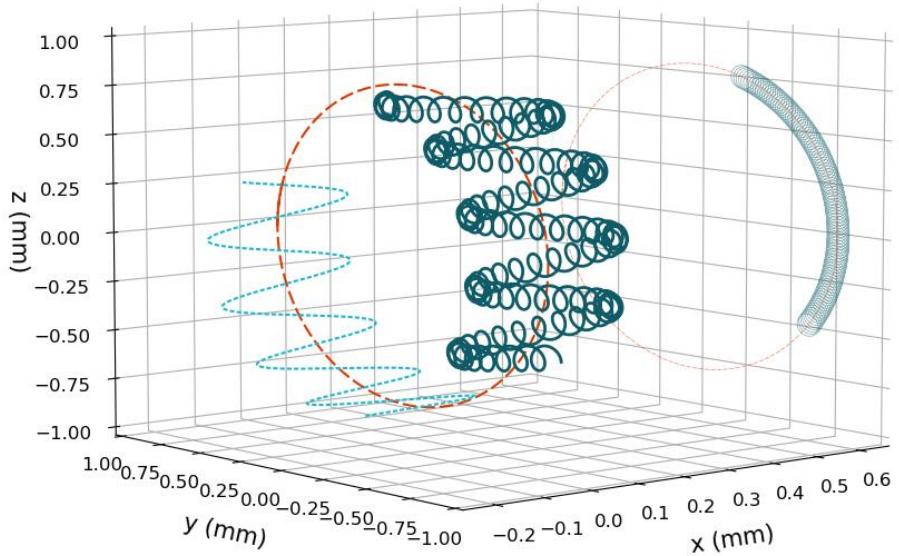
Amplitude of these motions can be modified by buffer gas or RF-excitations

- ✓ Dipolar to increase/decrease a motion
- ✓ Quadrupolar to convert one motion into another one



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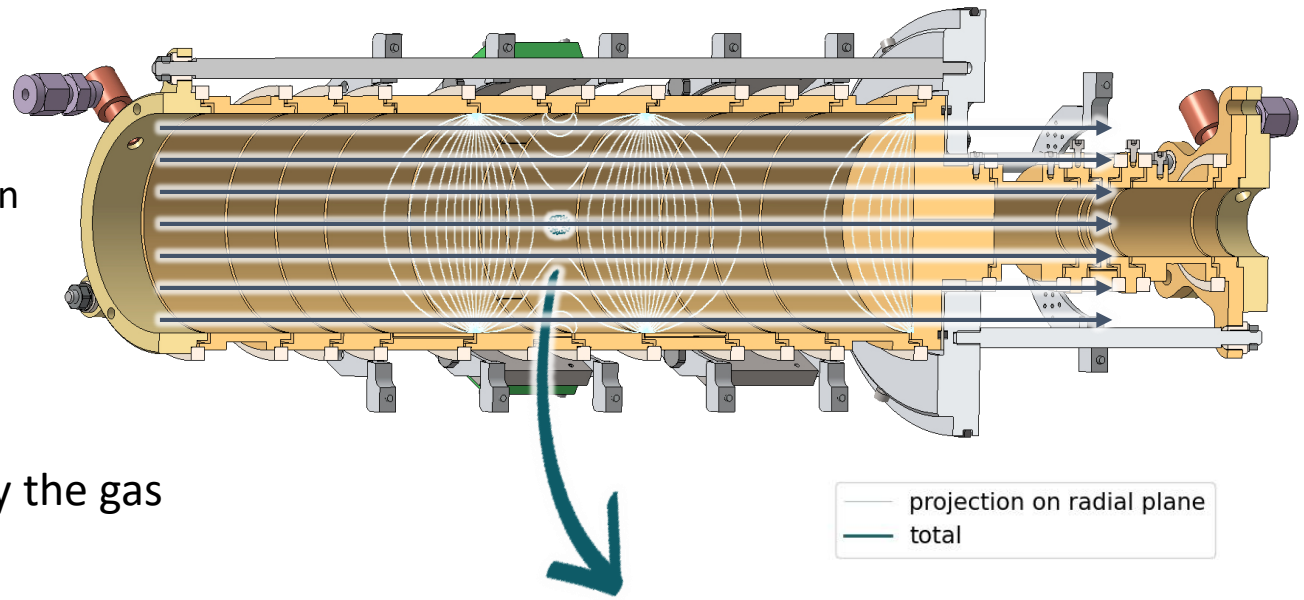

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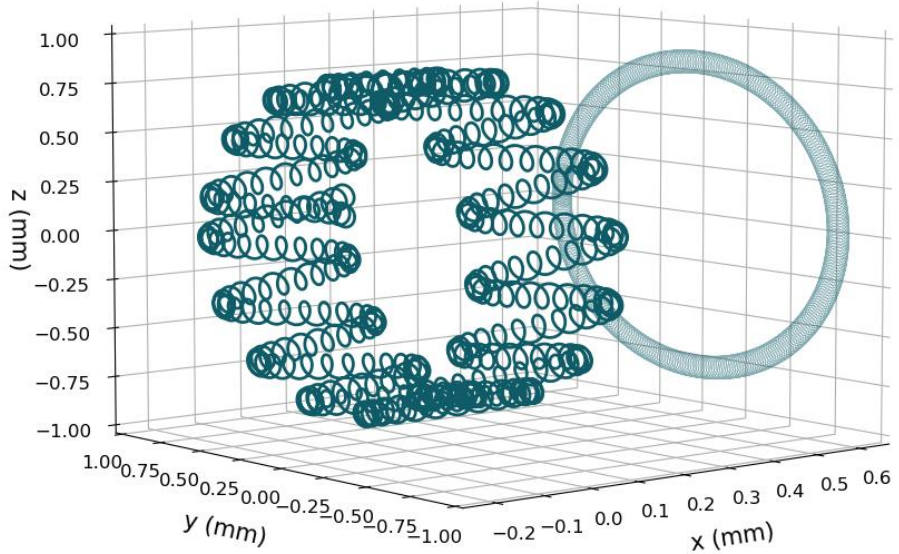
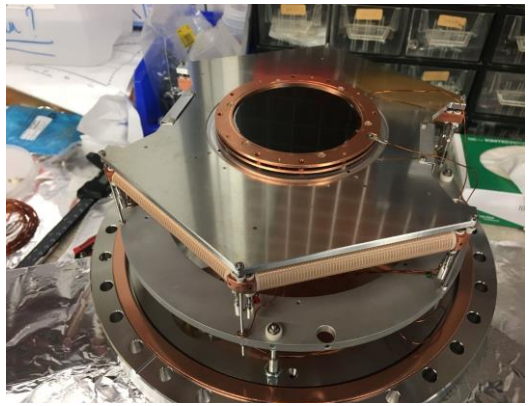


Three main purification/measurement techniques :
- Buffer gas cooling
- Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR)
- Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR)

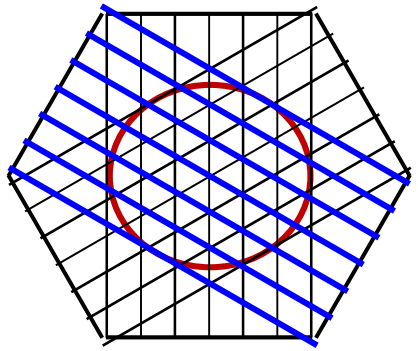
Technical developments on PIPERADE

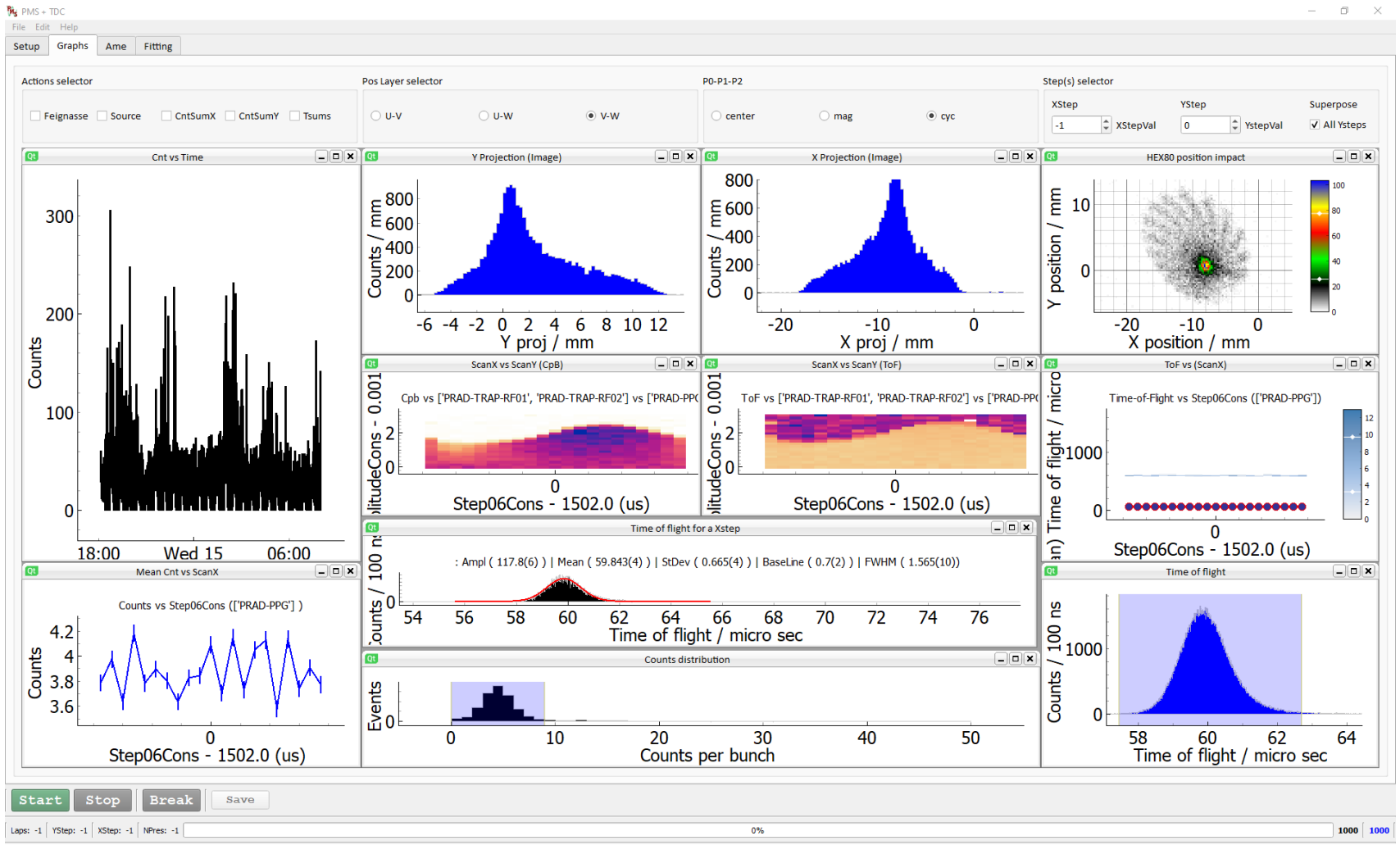
New position sensitive MCP
+ Reconstruction of the position on the user interface (PIPERADE Trap Scanner for DESIR) :

MCP + Delay line



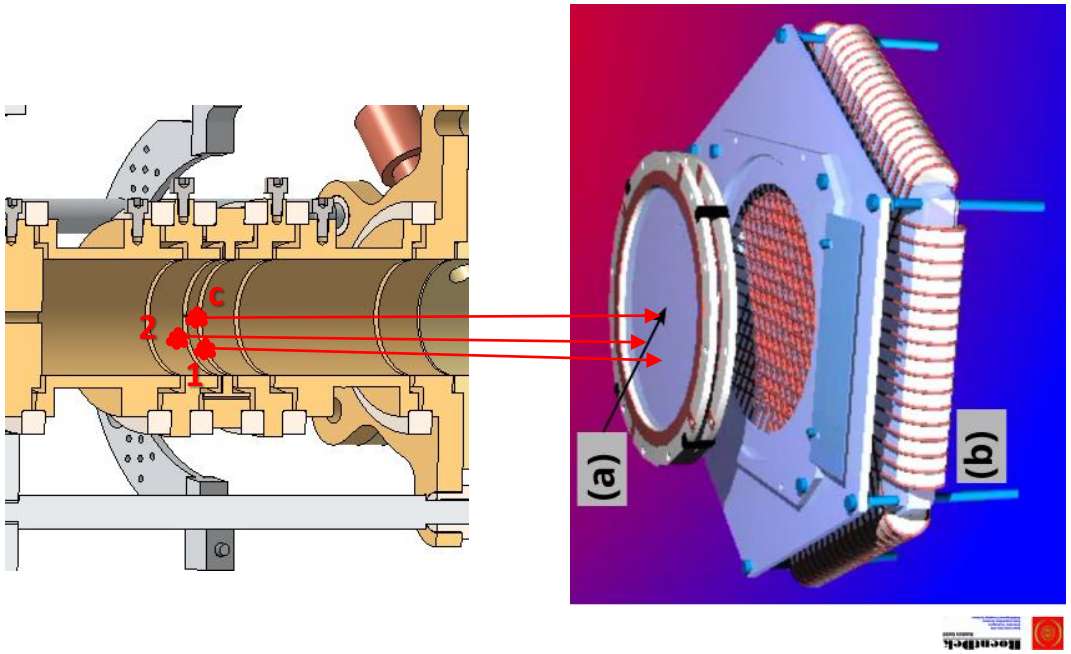
Schematic view of a delay line

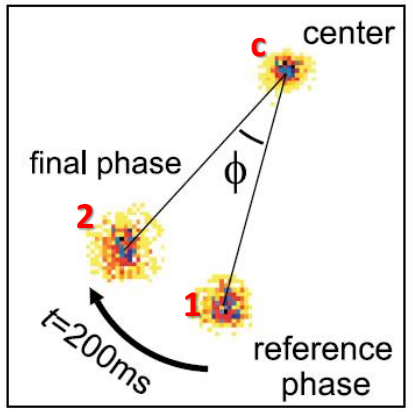




PI-ICR (Phase-Imaging Ion-Cyclotron-Resonance)

Projection of radial motion phases on a position-sensitive detector

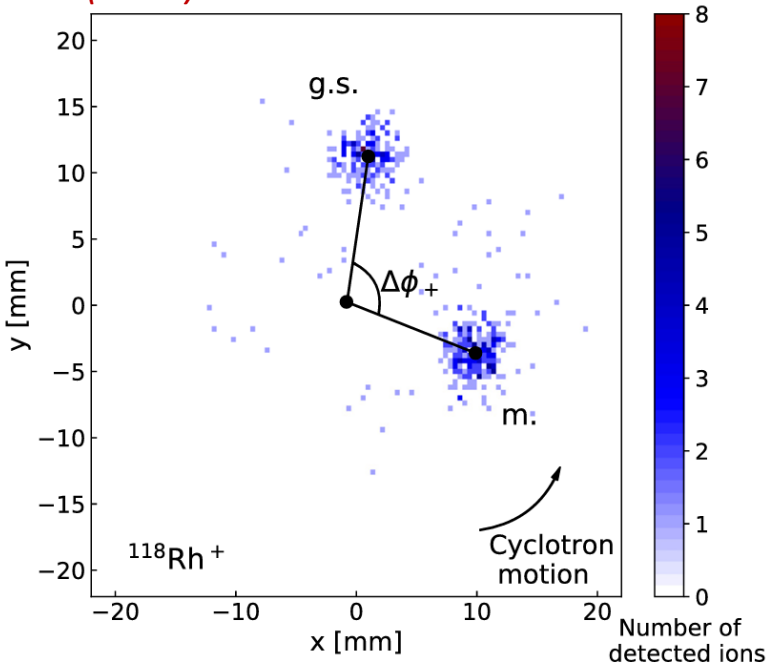




$$\nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m}$$

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

M. Hukkanen et al. Phys. Rev. C ***107*** *(2023) 014306*

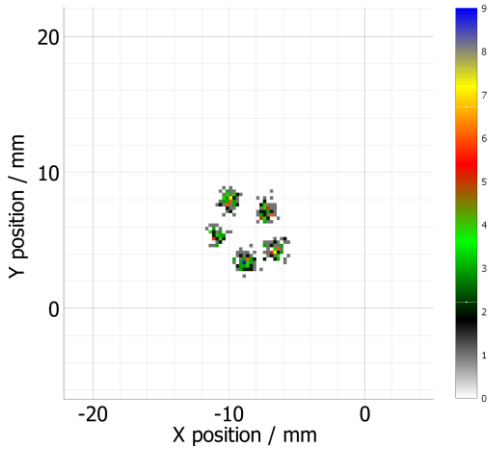


- High sensitivity (“non scanning method”)
- Gain of a factor of 5-10 in precision and 40 in resolution compared to ToF-ICR (up to R = 10^7)

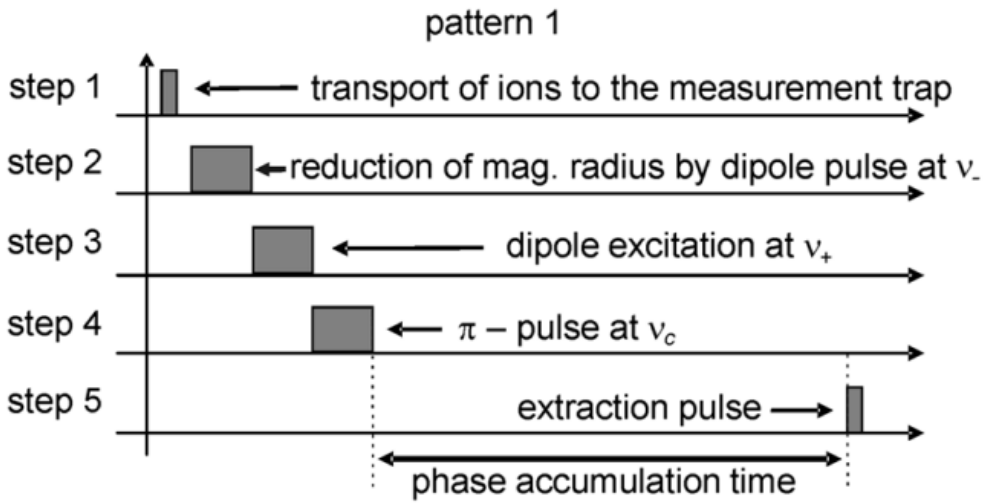
- Measurement of ground state masses and isomer excitation energies
- Capable of separate isomers → high-resolution purification for DESIR

PI-ICR at PIPERADE

Initial conditions



Step 1



*Eliseev, S et al. Appl. Phys. B **114** (2014) 107–128*

PI-ICR at PIPERADE

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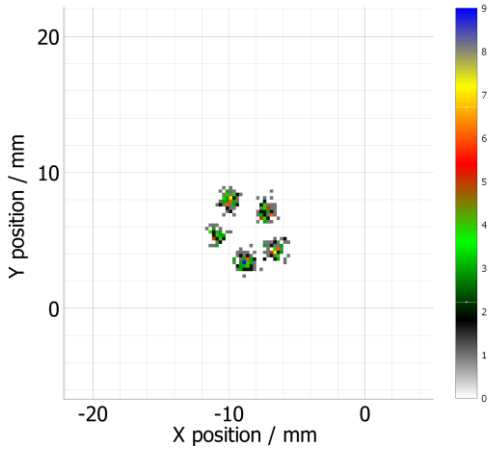
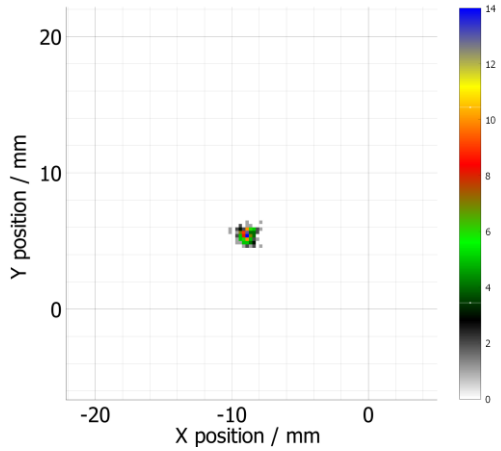
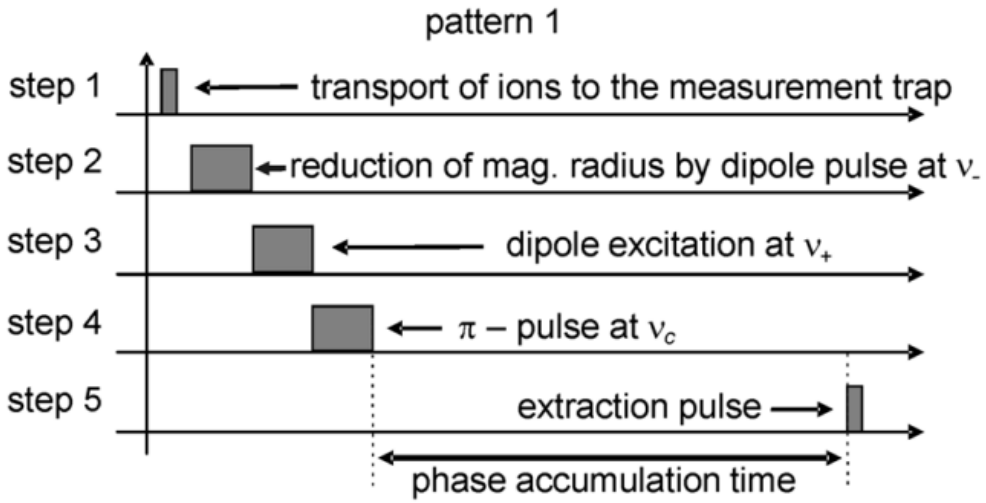


Magnetron damping



Step 1 Step 2



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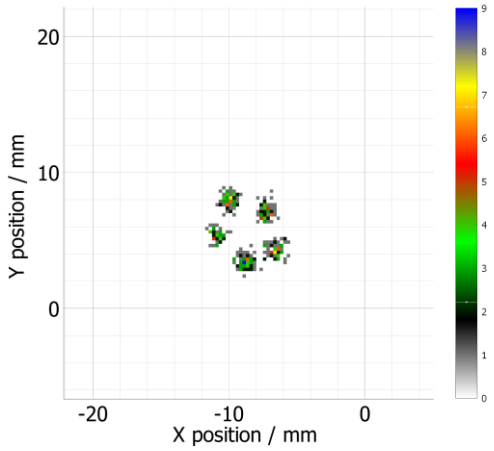

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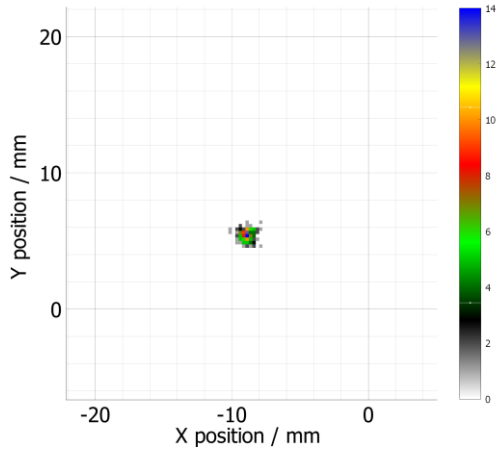
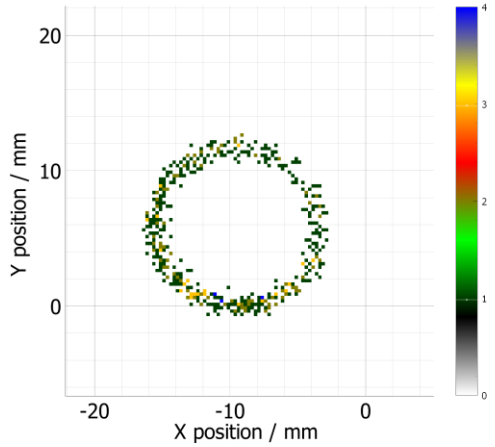
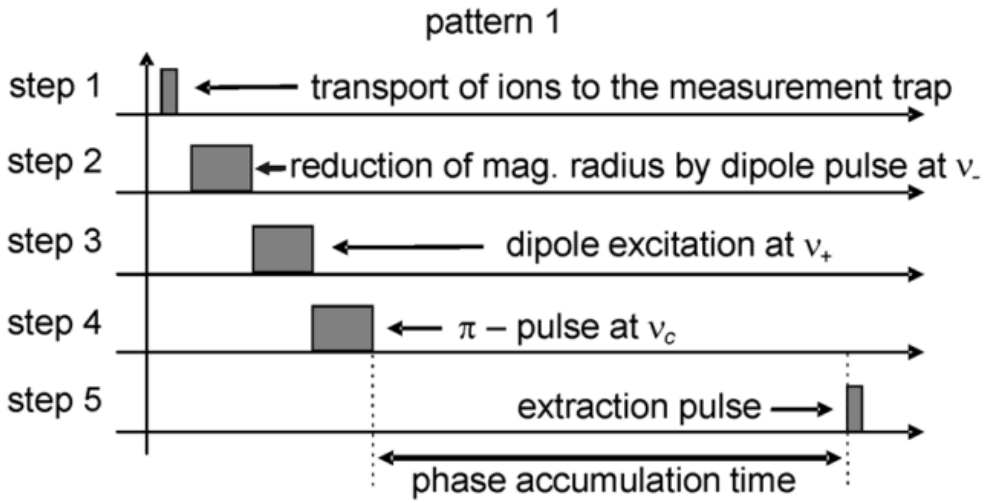


ν_+ excitation



Step 1 — Step 2 — Step 3



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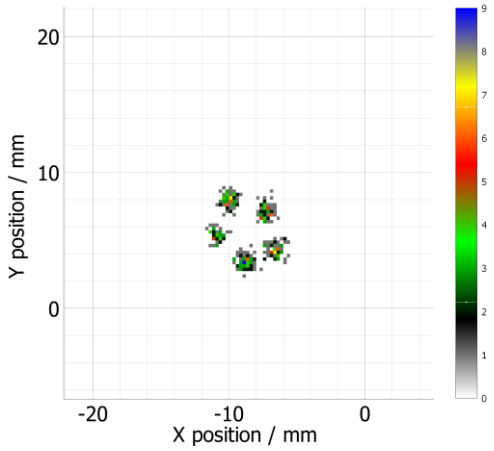

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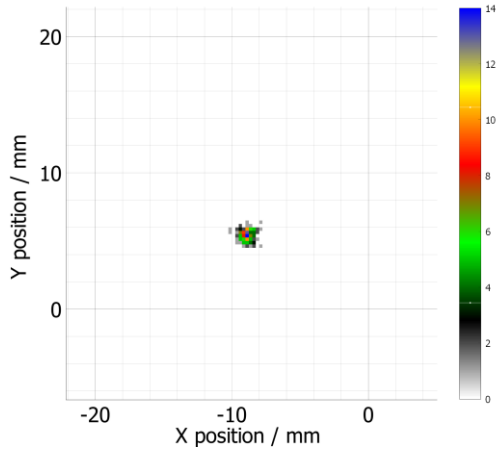

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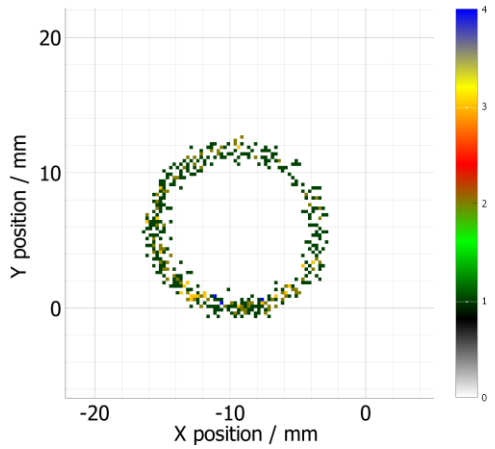
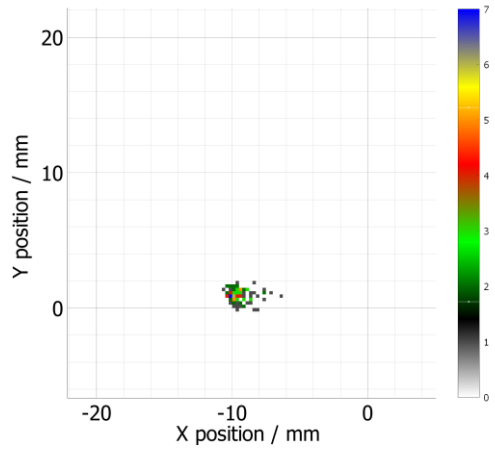
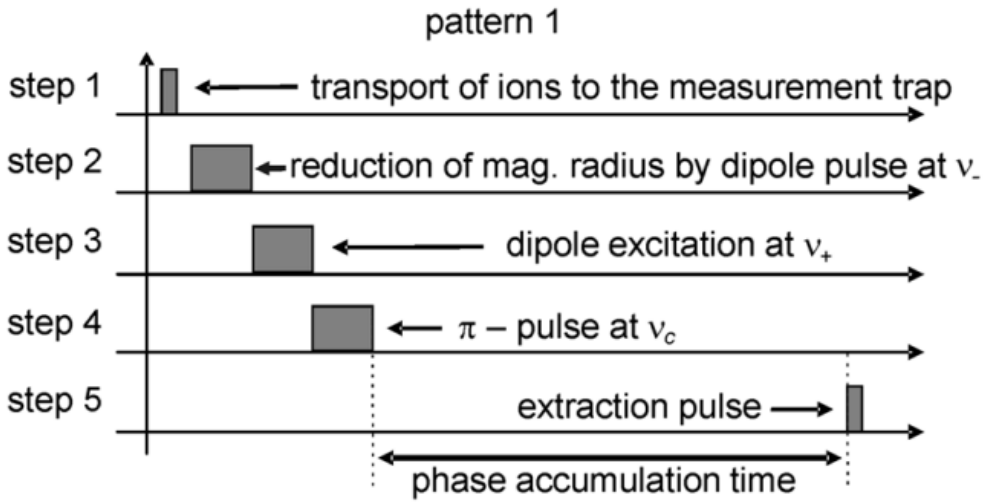


Conversion magnetron



Step 1 — Step 2 — Step 3 — Step 4



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PI-ICR at PIPERADE

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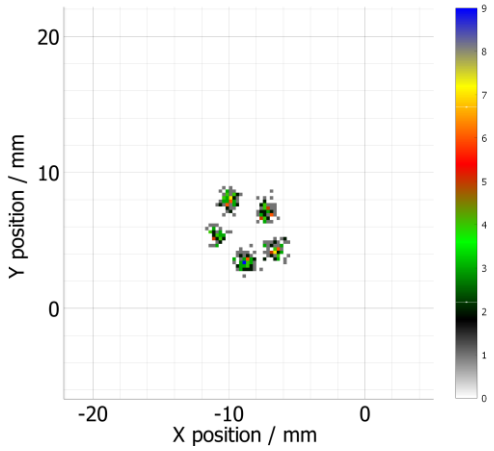

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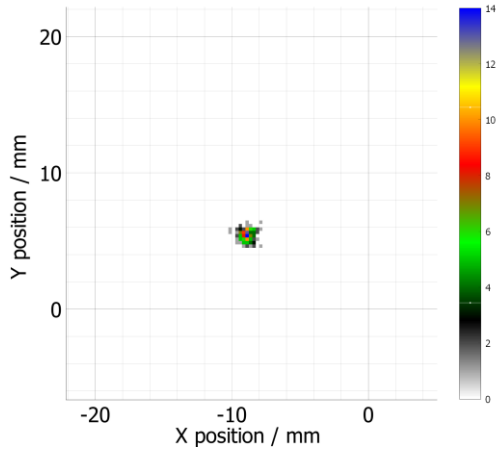

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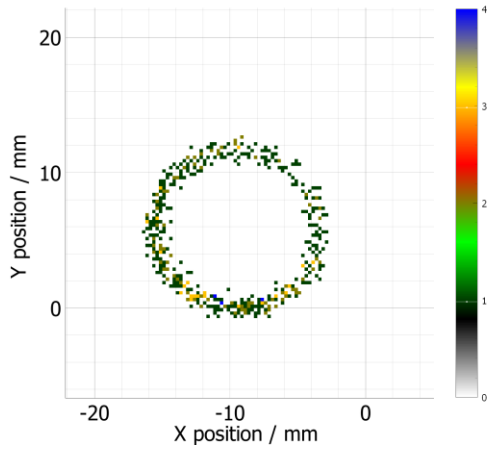

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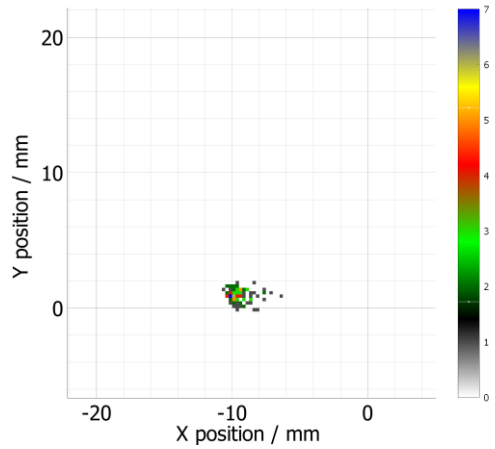
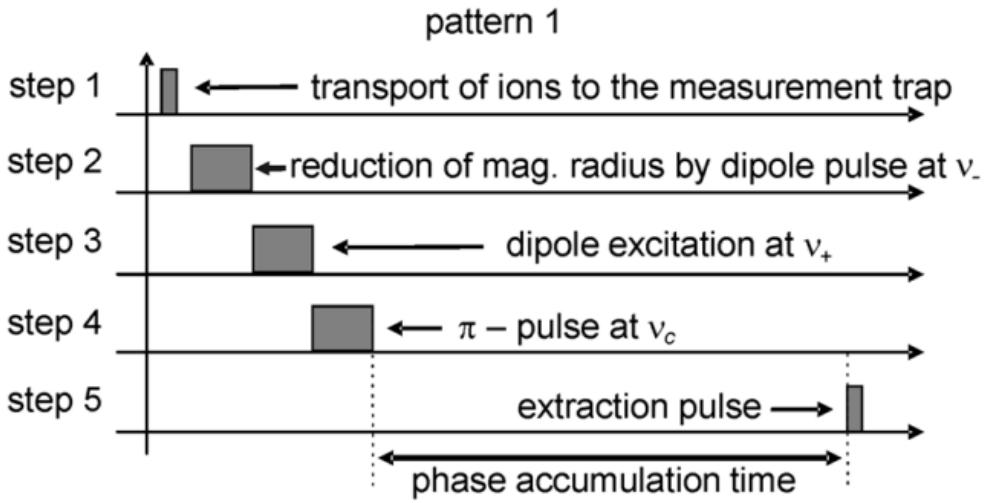


Step 1 — Step 2 — Step 3 — Step 4 — Step 5



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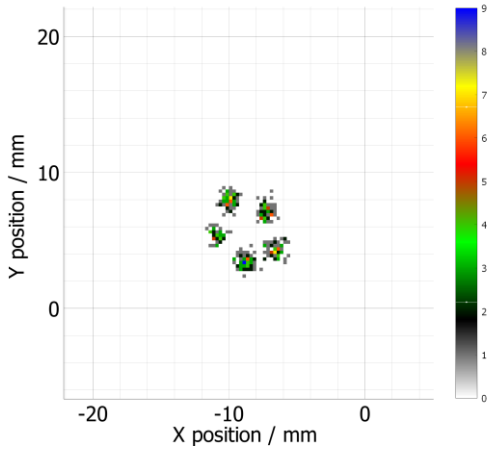

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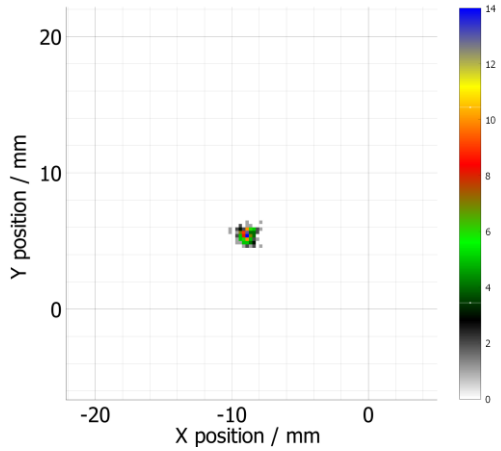

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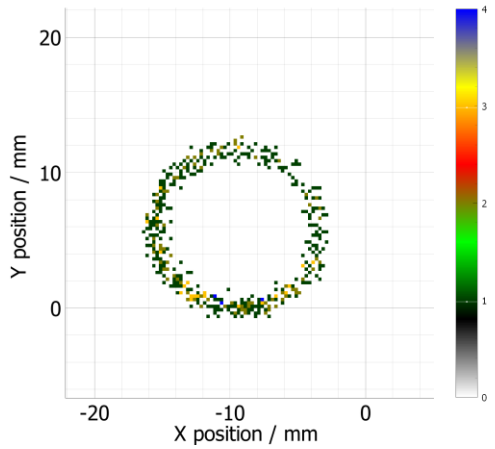

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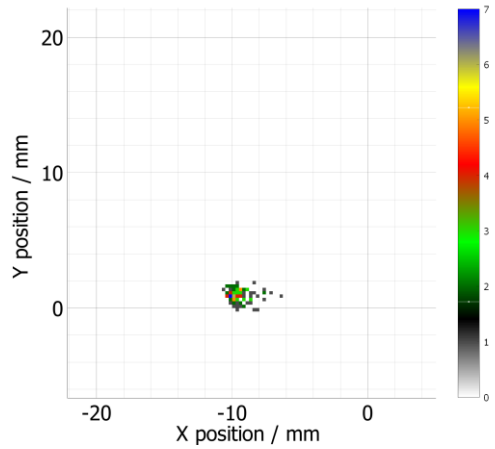
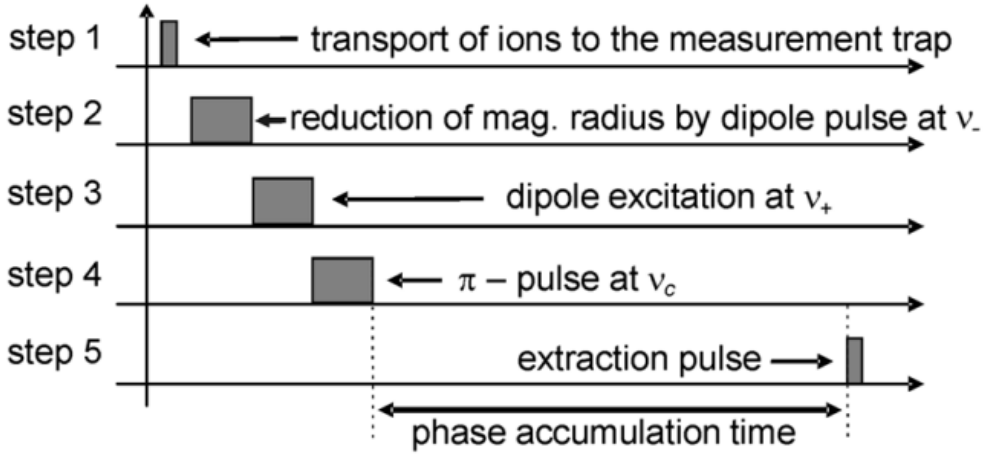
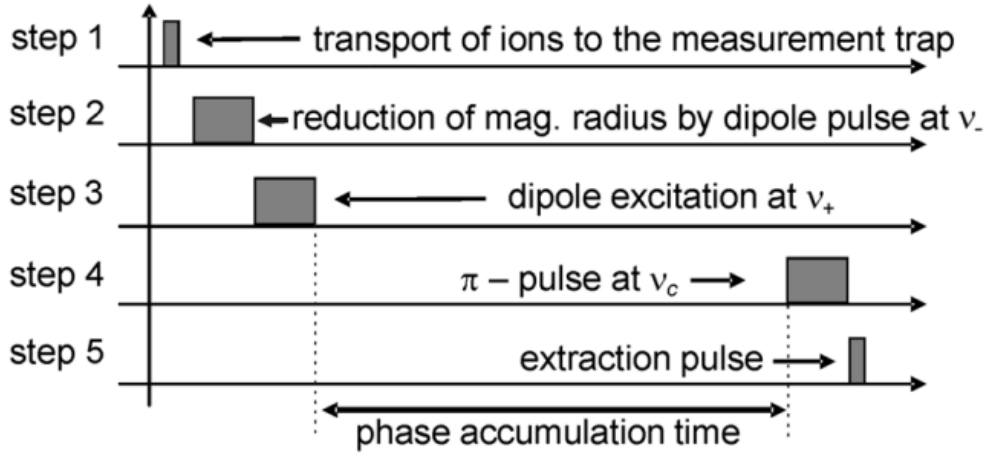


Step 1 | Step 2 | Step 3 | Step 4 | Step 5

pattern 1



pattern 2



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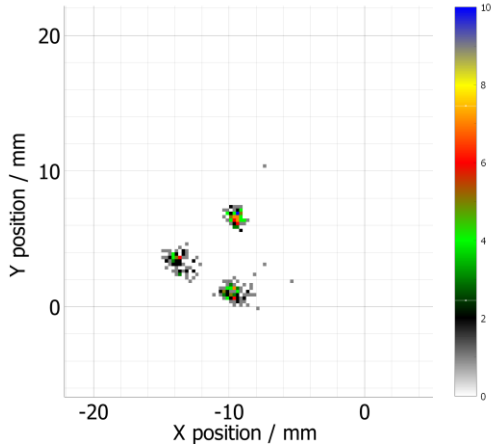
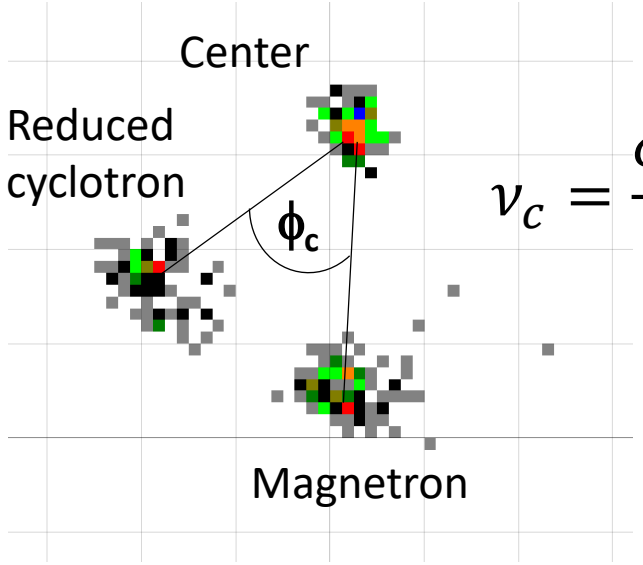
PI-ICR at PIPERADE

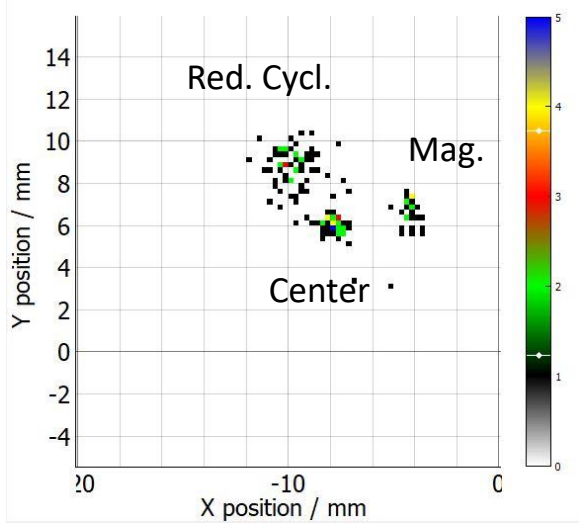
PI-ICR Tacc = 5ms

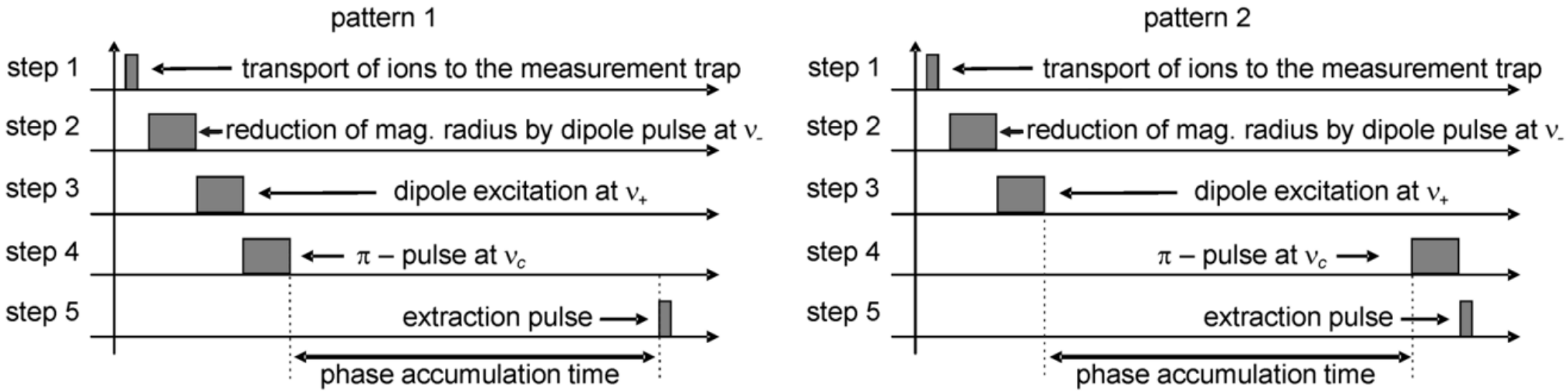




$$\nu_c = \frac{\phi_c + 2\pi n}{2\pi t}$$

First 1-sec PI-ICR in February

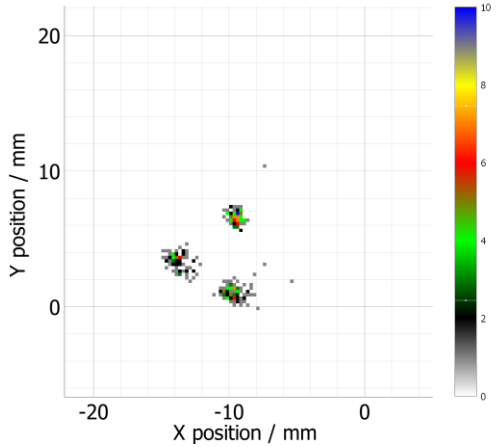


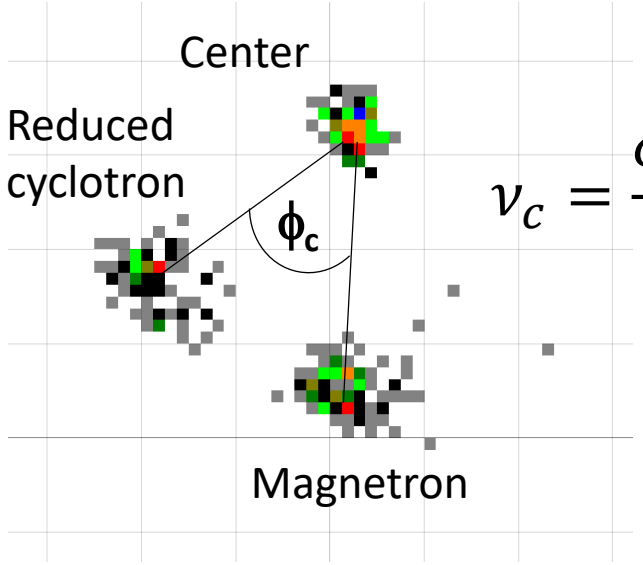


*Eliseev, S et al. Appl. Phys. B **114** (2014) 107–128*

PI-ICR at PIPERADE

PI-ICR Tacc = 5ms





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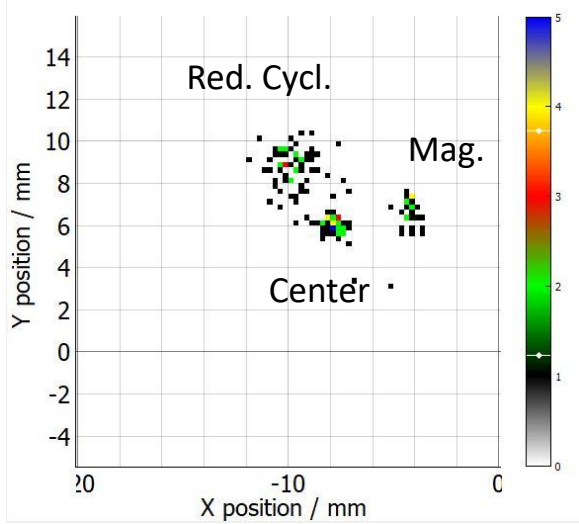


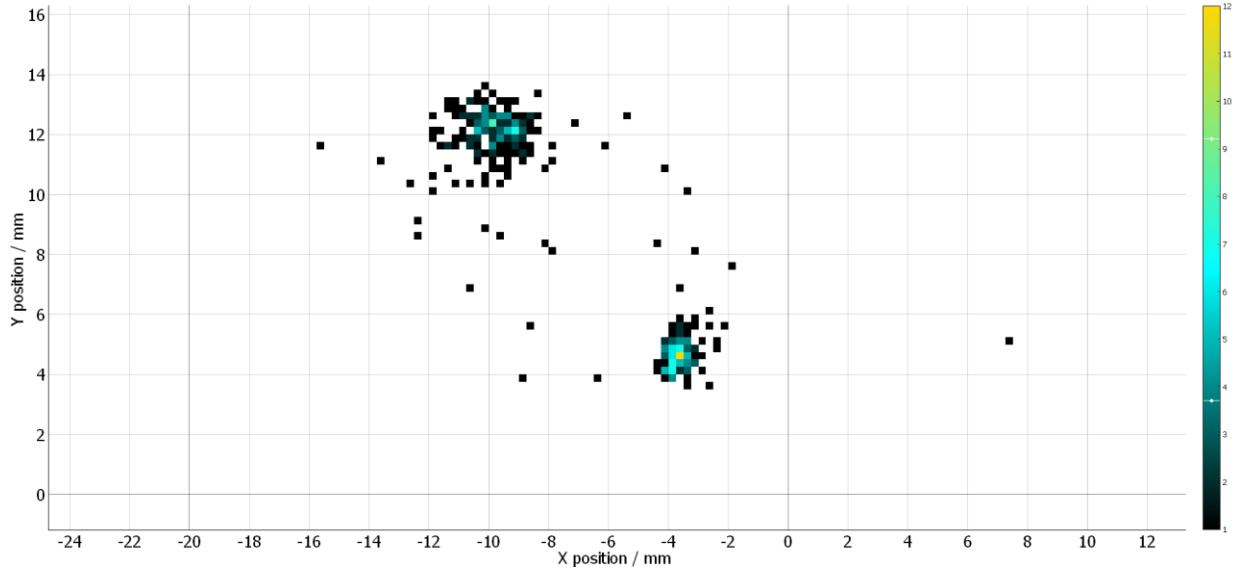
First PI-ICR frequency measurement with PIPERADE :

Choose t so that $\phi_c = 0$ and thus $\nu_c = \frac{N}{t}$

For ^{39}K, we obtain :

$$\nu_c(PI\text{-}ICR) = 2740730{,}1 \pm 0{,}1\ Hz$$

$$\nu_c(ToF\text{-}ICR) = 2740730{,}25 \pm 0{,}05 Hz$$



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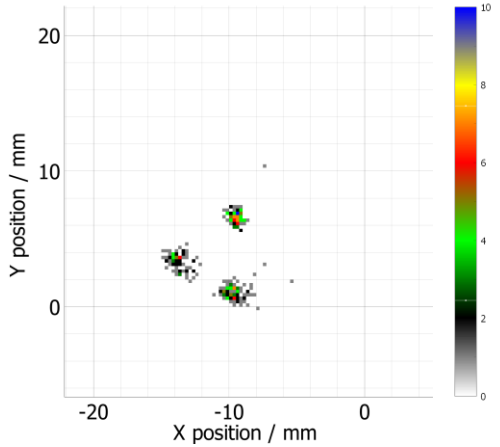

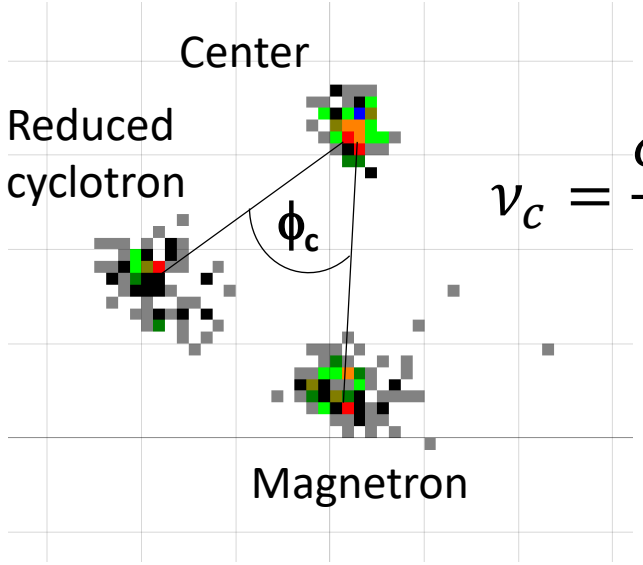

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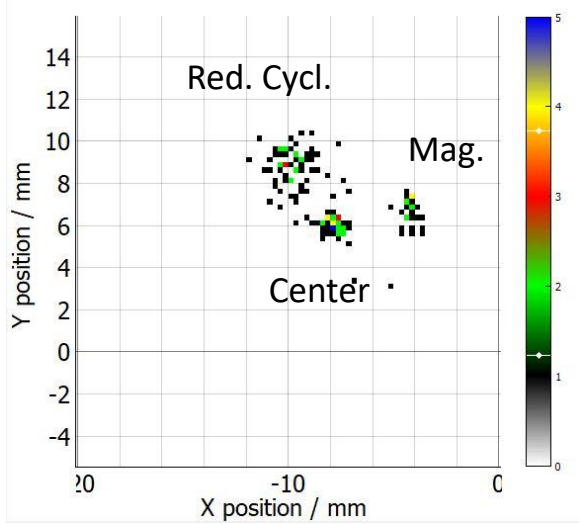

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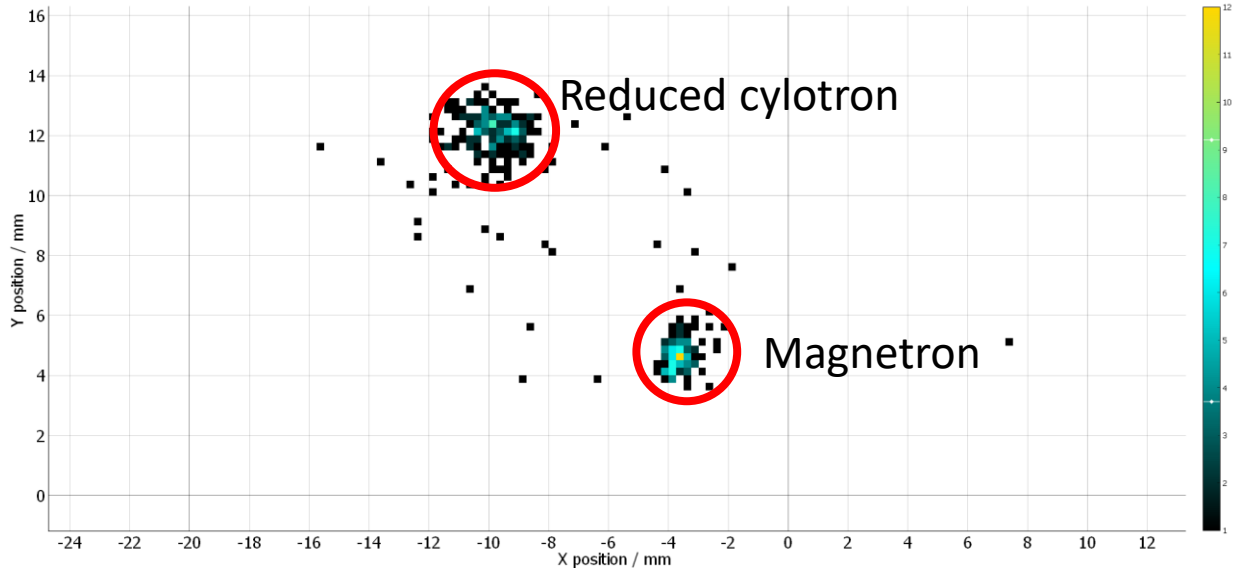

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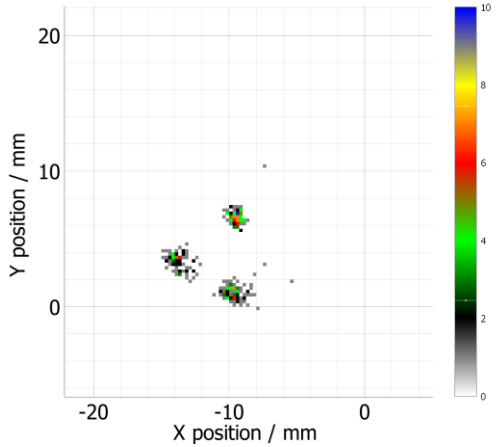

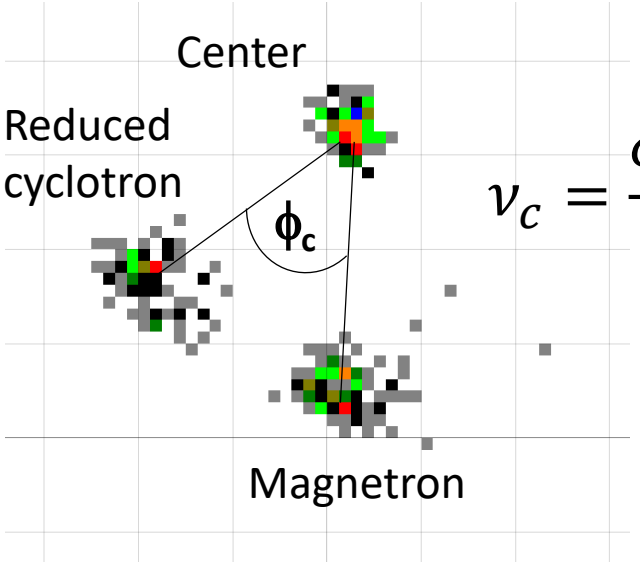

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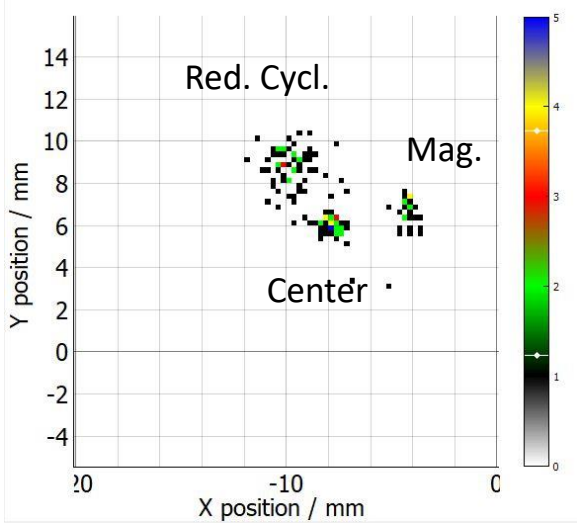
First 1-sec PI-ICR in February



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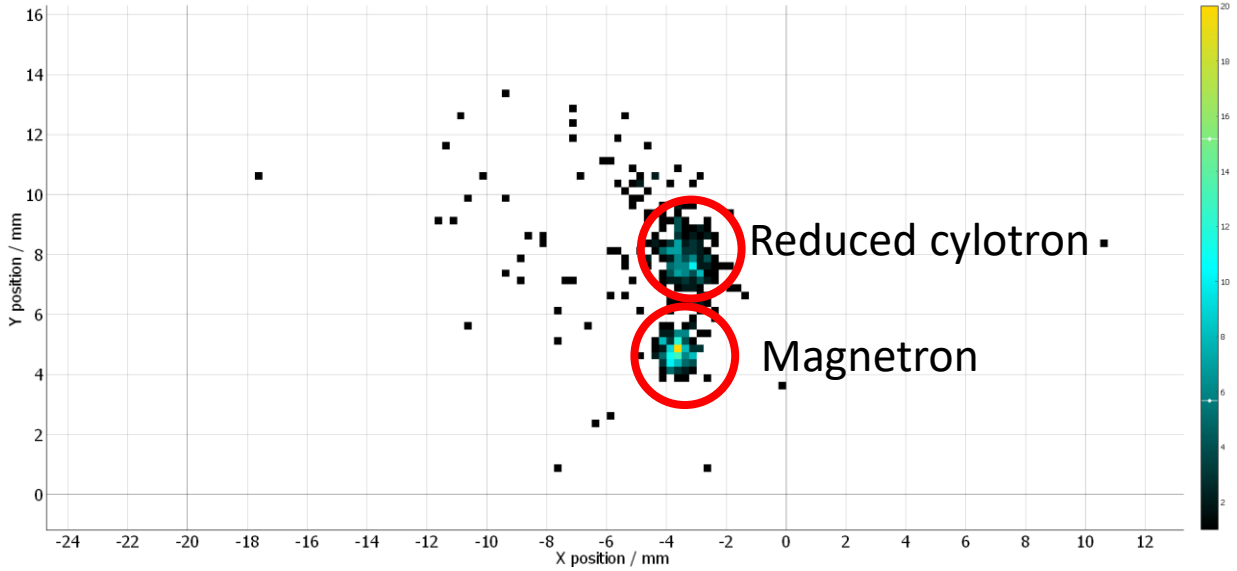

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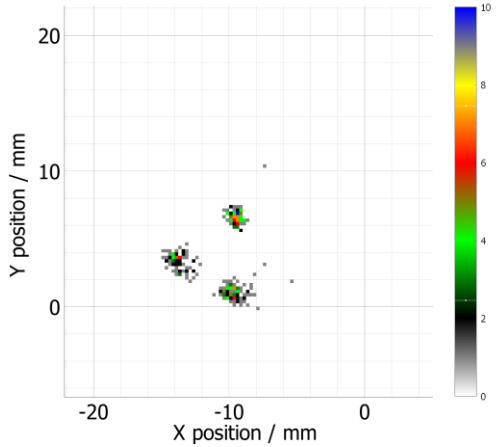

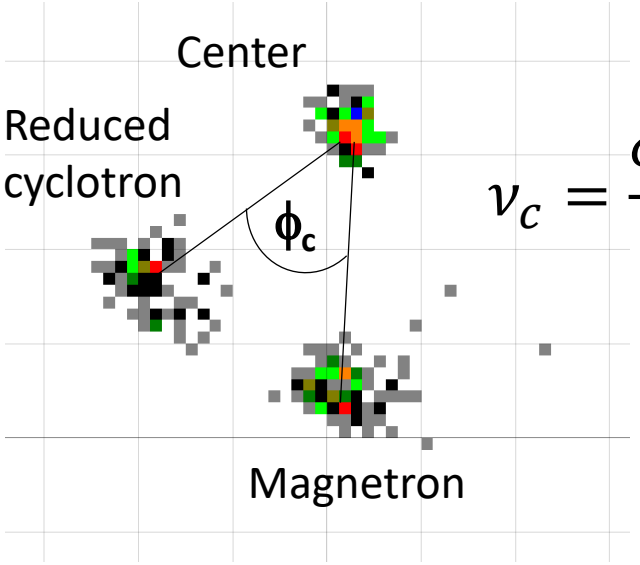

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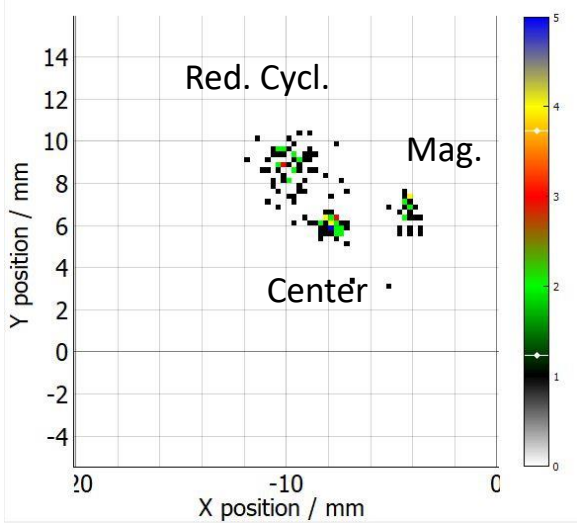

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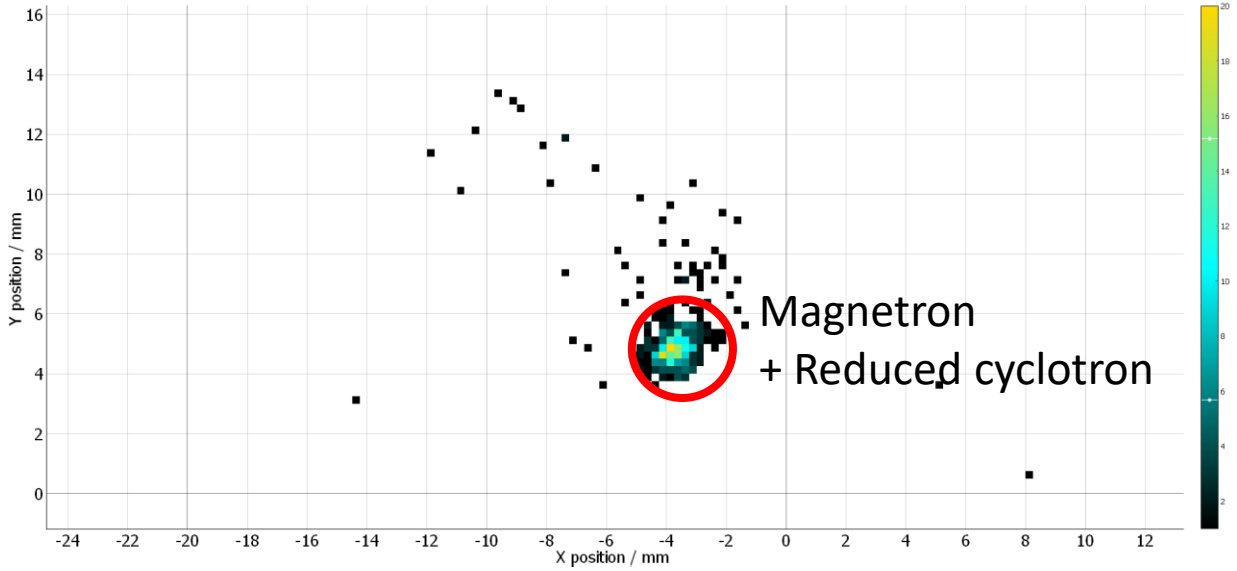
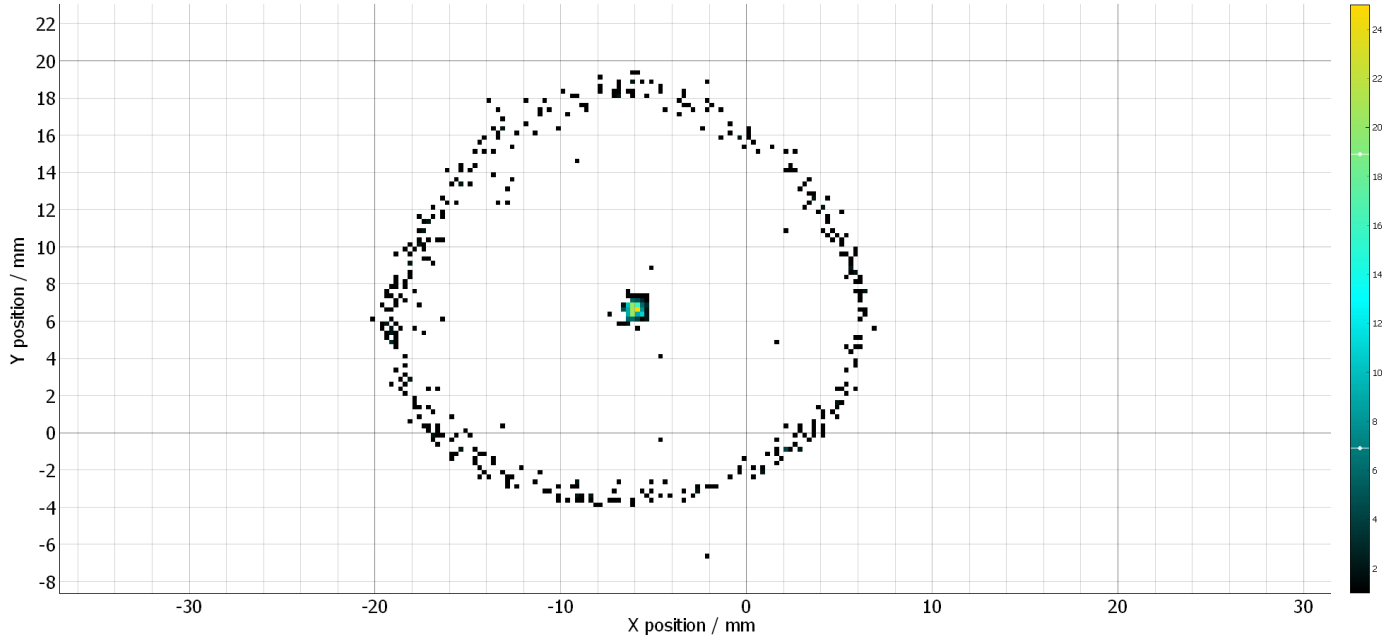


Conclusion and perspectives

However we still have some issues :

- Deformation of the image on the final detector



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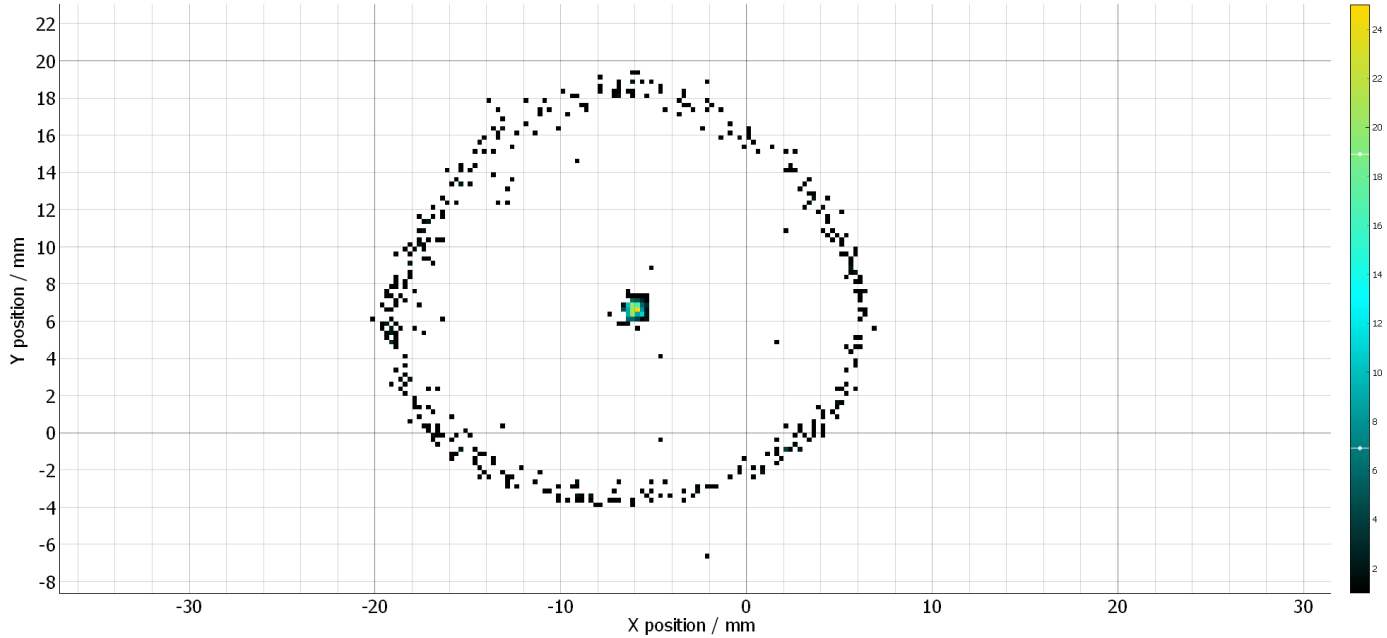
- Issues with electrode switch



Conclusion and perspectives

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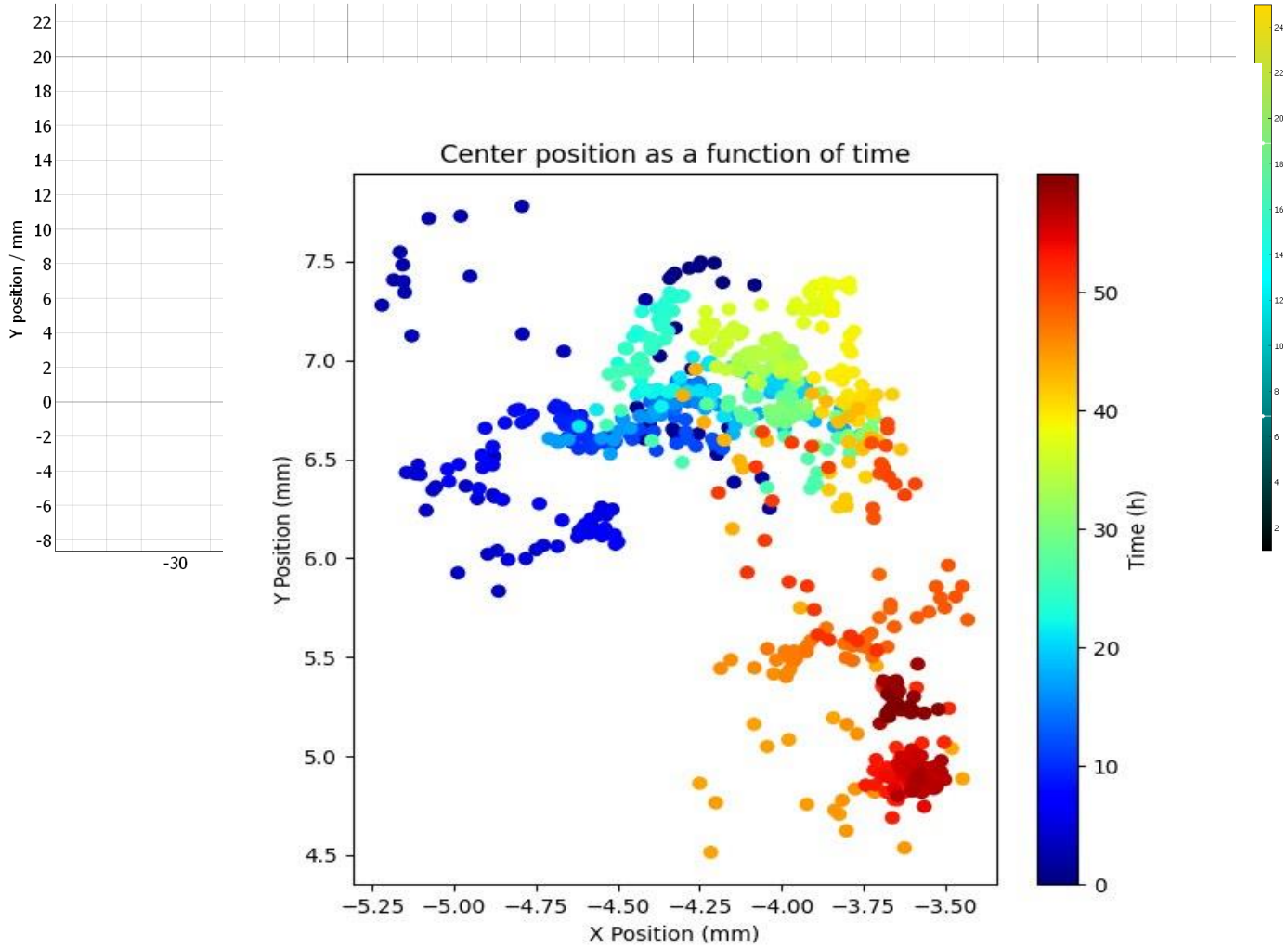
- Deformation of the image on the final detector
- Issues with electrode switch
- Trap center is moving



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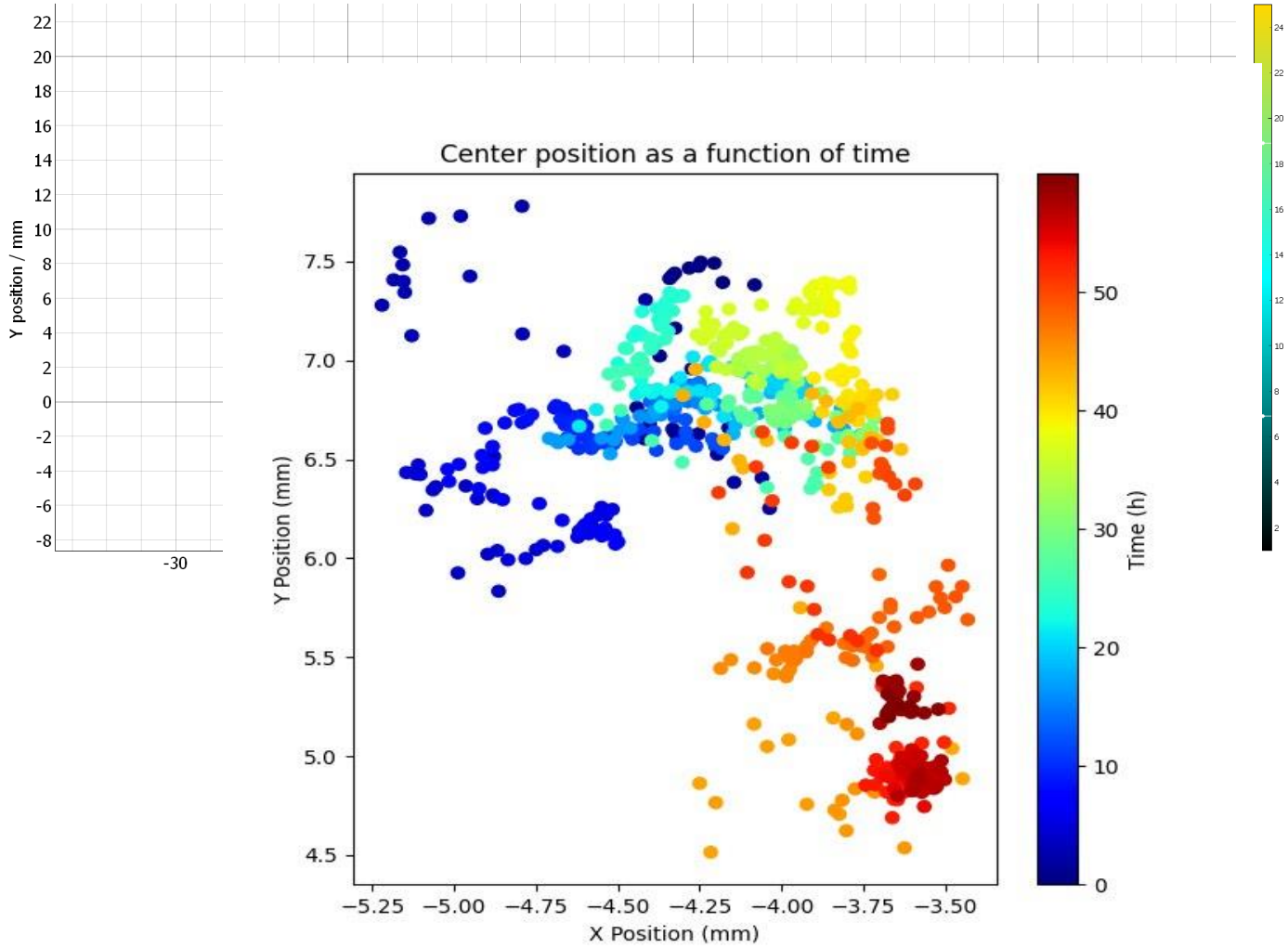
- Mass measurements with PI-ICR



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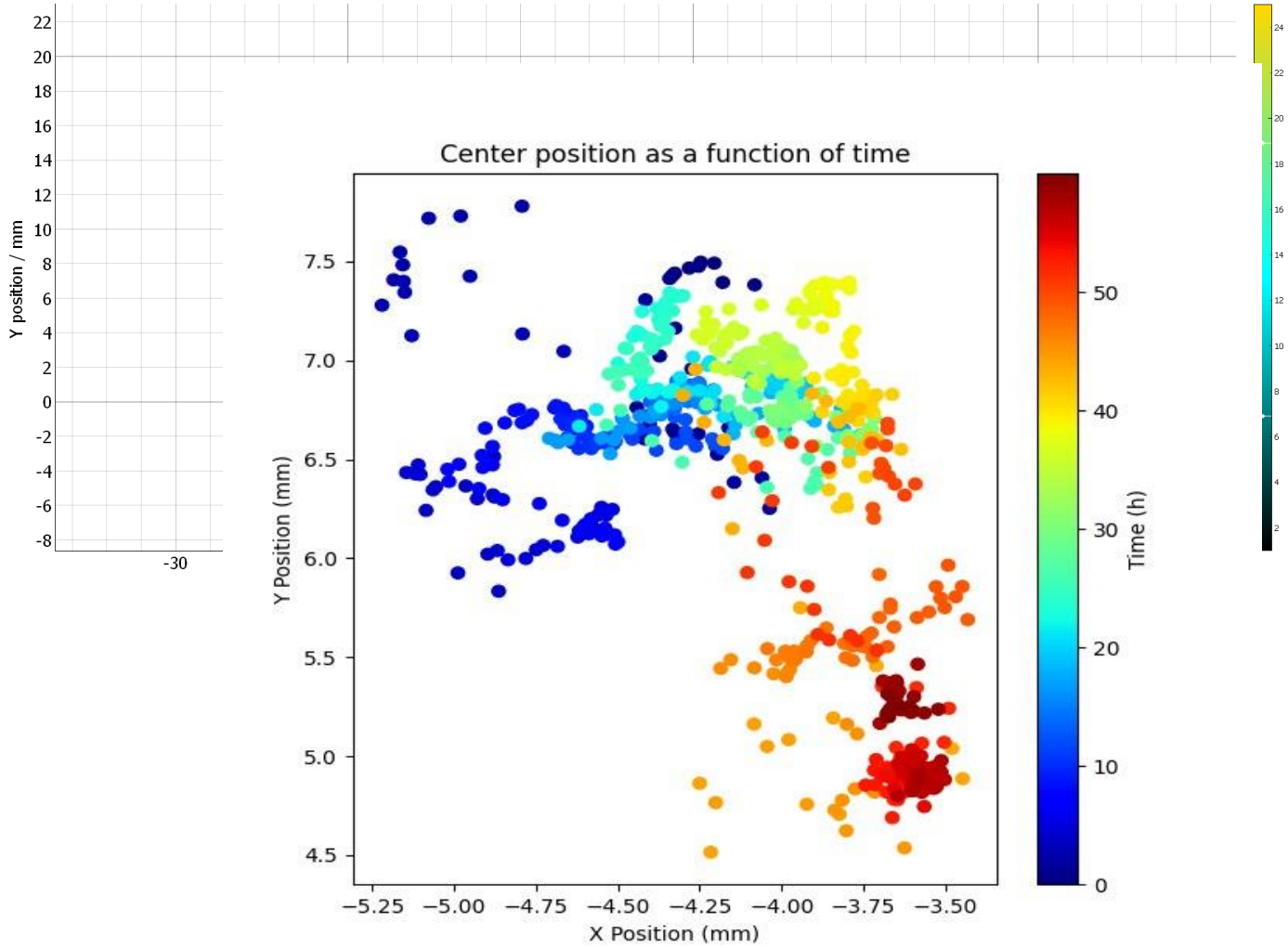
- Mass measurements with PI-ICR
- Investigation of systematic errors



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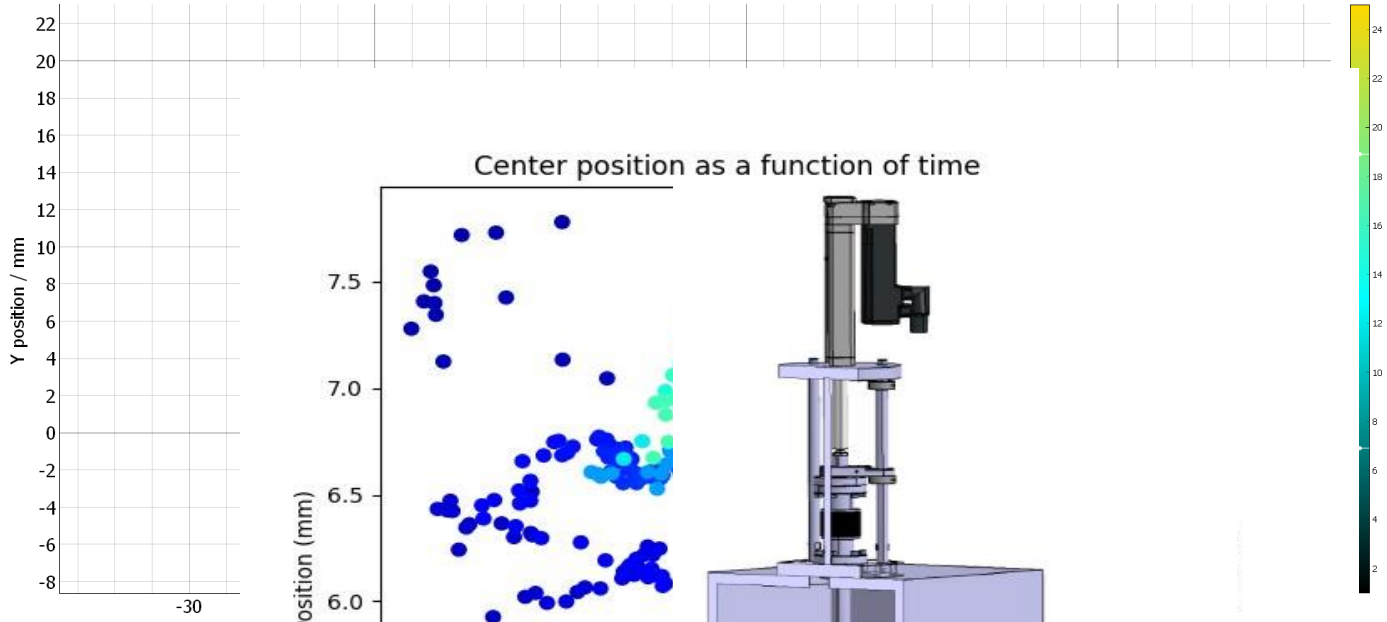

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- Investigation of systematic errors
- Investigation of buffer gas cooling for large bunches (>100)
  (Need for a new MCP chamber)

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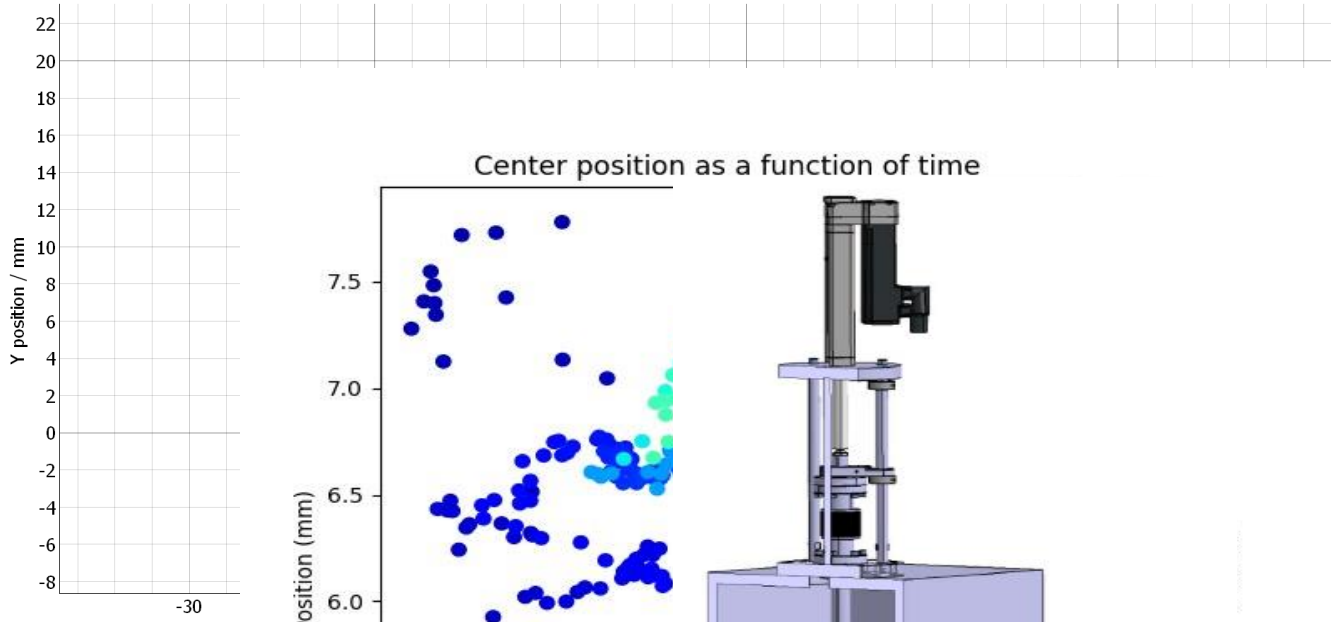

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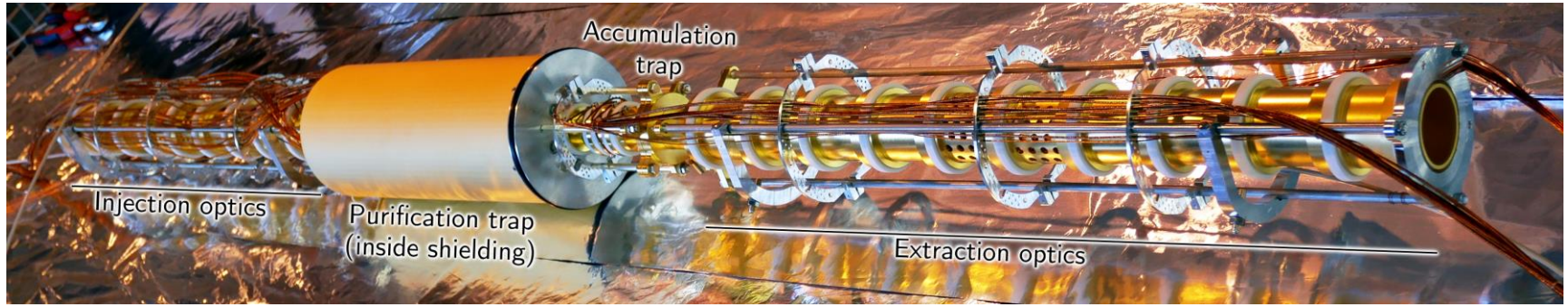
Before moving to GANIL (beginning of 2026)



Spiral2 DESIR

Thanks for your attention !

and to **D. Atanasov (former Post-Doc), M. Flayol (PhD),**
P. Alfaurt, P. Ascher, B. Blank, L. Daudin, M. Gerbaux, S. Grévy, M. Hukkanen,
A. Husson, B. Lachacinski, S. Perard, A. de Roubin, C. Roumegou (new post-doc)

PIPERADE
PIEGES DE PENNING POUR LES RADIONUCLEIDES A DESIR

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR
ANR
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK
cnrs IN2P3

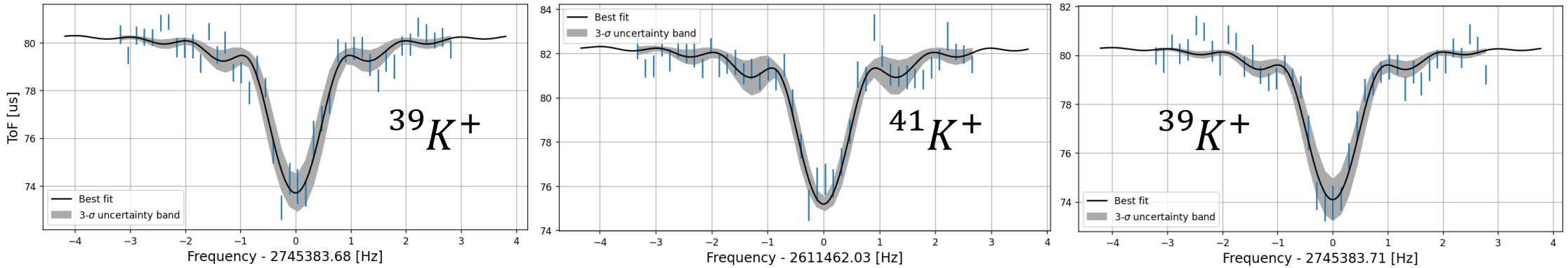
ToF-ICR mass measurements

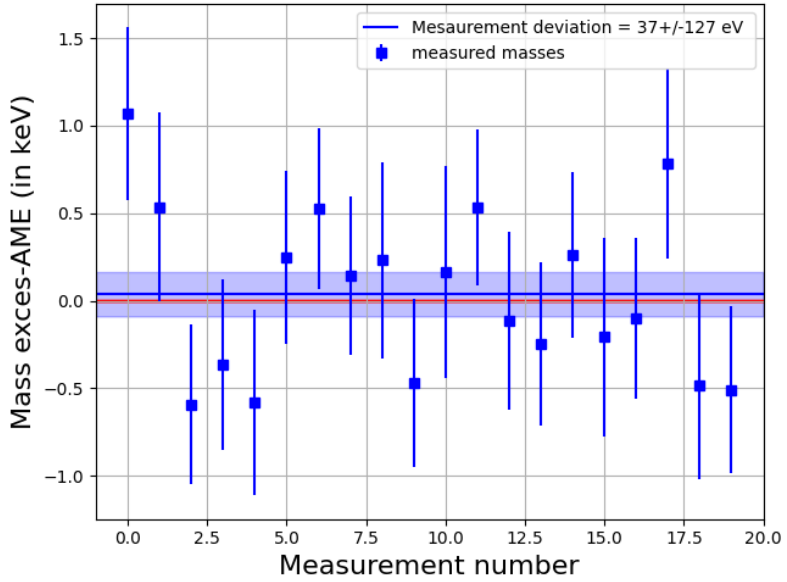
+1 ↘ ↙ Measured thanks to a reference (well-known mass)

$$\nu_c = \frac{qB}{2\pi m}$$

Experimentally, we measure $r = \frac{\nu_c(^{39}K)}{\nu_c(^{41}K)}$

Mass determination → $m_{^{41}K} = r\left(m_{^{39}K} - m_e\right) + m_e$



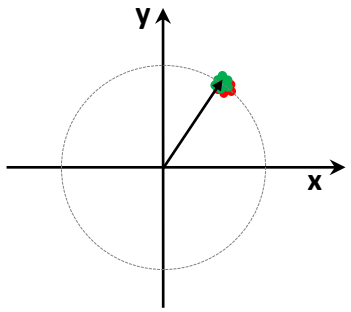


→ Precision : $\frac{\delta m}{m} \approx 3 * 10^{-9}$

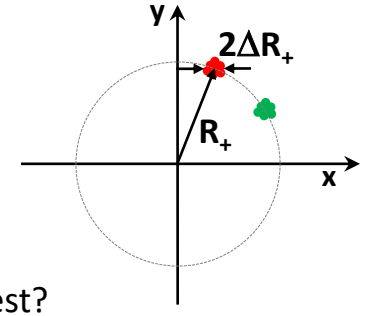
Studies of systematical uncertainties in progress (magnetic field fluctuations, number of ions, mass of the reference, etc…)

High-resolution phase separation

Non-selective dipole excitation at ν+



After a number of turns: phase separation



How to select the ions of interest?

π-pulse to convert cyclotron to magnetron

Magnetron damping to recenter the ions and extraction

$$\frac{\nu_+}{\Delta\nu_+} = \frac{\pi\nu_+ tR_+}{\Delta R_+}$$

At PIPERADE with A = 85, ν_+ = 1.26 MHz

If $\Delta R_+/R_+ = 0.1$

for t =100 ms → **R = 4.10^6** **SELECTIVITY**
(corresponds to 20 keV)

for R=10^5 → **t = 3 ms** **RAPIDITY**

Possible future improvement @DESIR: laser cooling ?
« Doppler and sympathetic cooling for the investigation of short-lived radioactive ions », S. Sels et al., Phys. Rev. Research 4, 033229 (2022)