Improving the resolving power of the preparation Penning trap

SHIPTRAP

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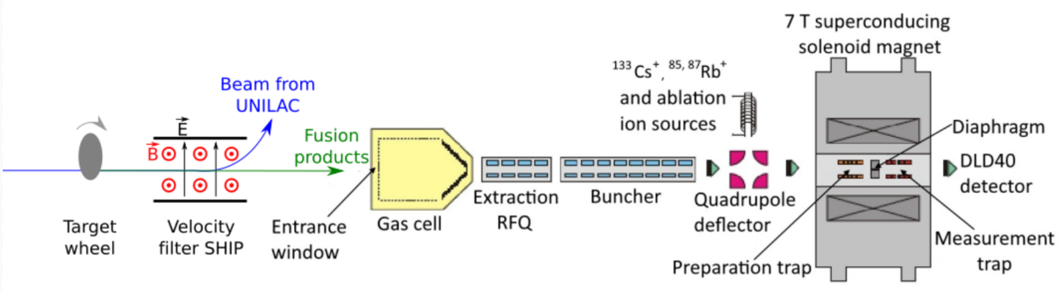
GSI Summer School

Overview

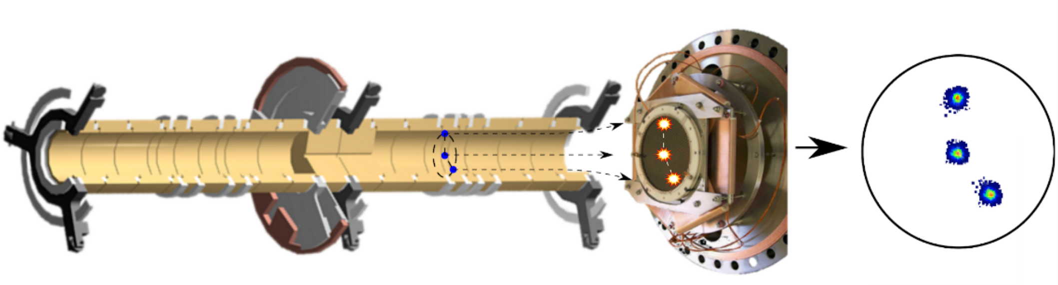
SHIPTRAP

The ion path through SHIPTRAP



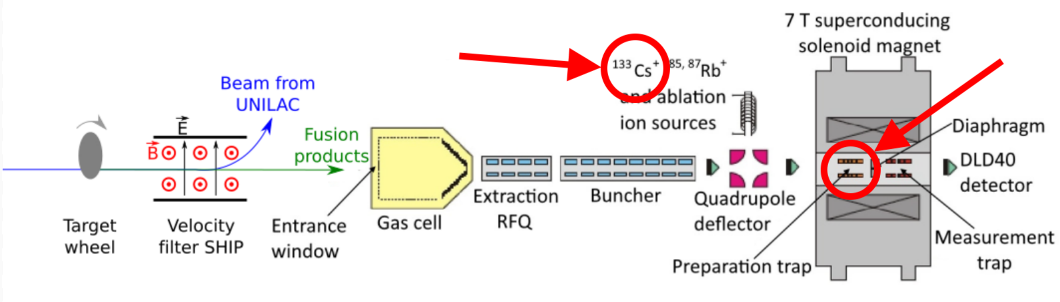
- Mass measurements of heavy & superheavy elements
- Low yields: < 1 ion per hour
  Cryogenic stopping gas cell improves efficiency
- Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique
  many-fold more precise and sensitive than previous techniques

The SHIPTRAP Penning traps



- Preparation trap (PT)
  - mass selection
- Measurement trap (MT)
  - freq. measurement
- Detector
  - position projection

Research: SHIPTRAP preparation trap



Focus of this research:

→ optimization of preparation trap (PT)

→ using $^{133}Cs^+$ ions

What happens in a Penning trap?

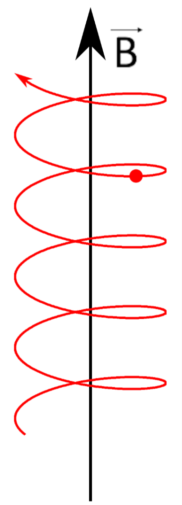
Only $\vec{B}$:

cyclotron freq. $\nu_c = \frac{q}{m}\frac{|\vec{B}|}{2\pi}$

- Mass dependent
- Conduct high-precision frequency measurements

$\Rightarrow$ High-precision mass measurement

Requires axial confinement...



What happens in a Penning trap?

with $\vec{E}$ & $\vec{B}$:

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

ν_- = magnetron freq.
ν_+ = modified cyclotron freq.

Frequencies depend on U, $\vec{B}$, m only

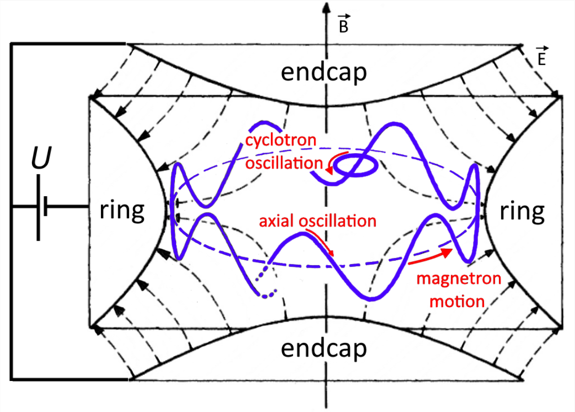


Figure adapted from L. S. Brown and G. Gabrielse, Rev. Mod. Phys., vol. 58, pp. 233–311, 1 Jan. 1986.

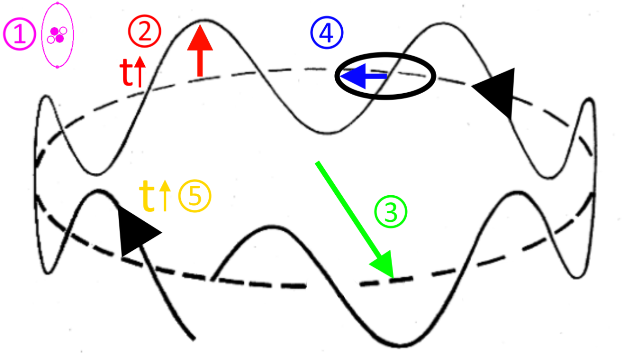
The sequence in the PT

1. Injection
    - beam-line / surface ions or laser ablation
2. Axial cooling
    - energy loss through thermalization with buffer gas
3. Applied magnetron excitation
    - all ions driven out to larger radius
4. Applied centering
    - recentering of ions of interest
5. Ejection
    - recentered ions pass through diaphragm towards MT

How to prepare an ion in the PT - parameters

Five parameters:

1. Helium buffer gas
2. Axial cooling time
3. Magnetron driving
4. Cyclotron driving
5. Cyclotron cooling



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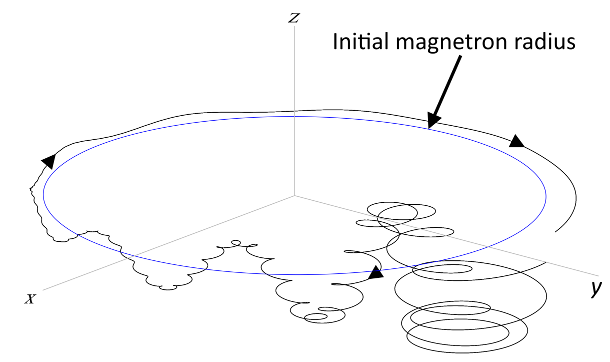
How to prepare an ion in the PT: injection & axial cooling time

Mass selection in PT:

Initial condition dependency
- → injection method
- → must be studied for each ion source

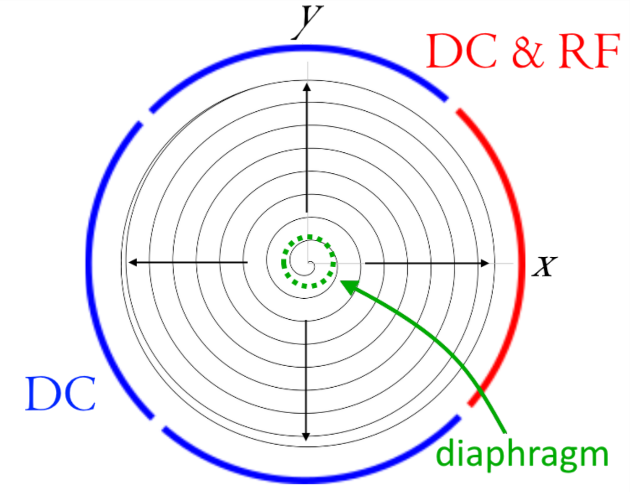
Buffer gas: Helium
- → cyclotron/axial amplitude decrease
- → magnetron radius increases *slowly*



How to prepare an ion in the PT: magnetron driving - amplitude

Apply dipolar magnetron driving RF field to drive ions out

ν_- *not* mass dependent
$\rightarrow$ all ions are driven out



How to prepare an ion in the PT: cyclotron driving - amplitude and duration

Apply quadrupolar cyclotron driving RF field to recenter selected ions

ν_c *is* mass dependent → specific mass recentered

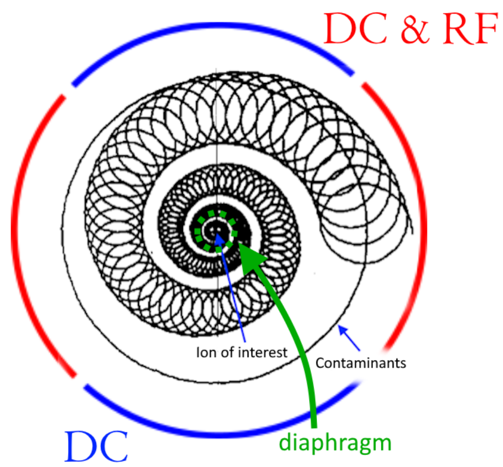
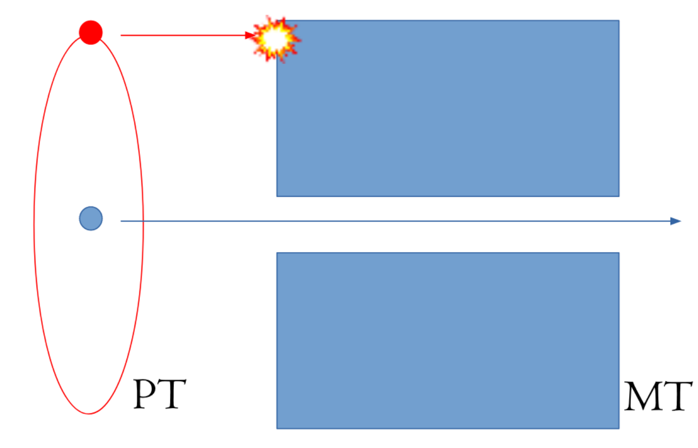


Figure adapted from G. Savard, S. Becker, et al., Physics Letters A 158 (1991), vol. 158, no. 5, pp. 247–252, Jul. 1991.

How to prepare an ion in the PT: mass selection

IF **mass resolving power** is high enough...



Research & Motivation

The performance of the PT

PT should:

- provide repeatable initial conditions for MT
- select one single species
- remove all other species - same atomic number (isobaric contaminants)

$\Rightarrow$ Improve performance of MT

Two observables which this research optimizes:

1 Mass resolving power (MRP)

2 Spot size

The mass resolving power

① $\text{MRP} = m / \Delta m$

Examples:

① Db-257, Rf-257

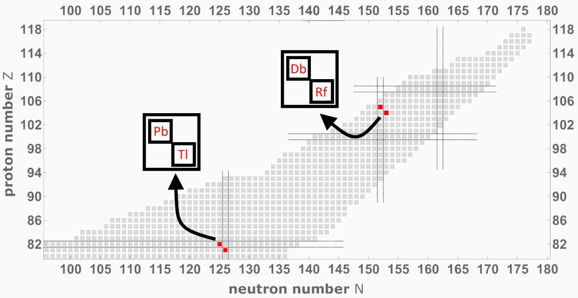
$\Rightarrow \Delta m \approx 4600 \cdot 10^{-6}\ \text{u}$

$\Rightarrow \text{MRP} \geq \frac{257\ \text{u}}{4600 \cdot 10^{-6}\ \text{u}} \approx 56\,000$

② Pb-207, Tl-207

$\Rightarrow \Delta m \approx 1500 \cdot 10^{-6}\ \text{u}$

$\Rightarrow \text{MRP} \geq \frac{207\ \text{u}}{1500 \cdot 10^{-6}\ \text{u}} \approx 140\,000$

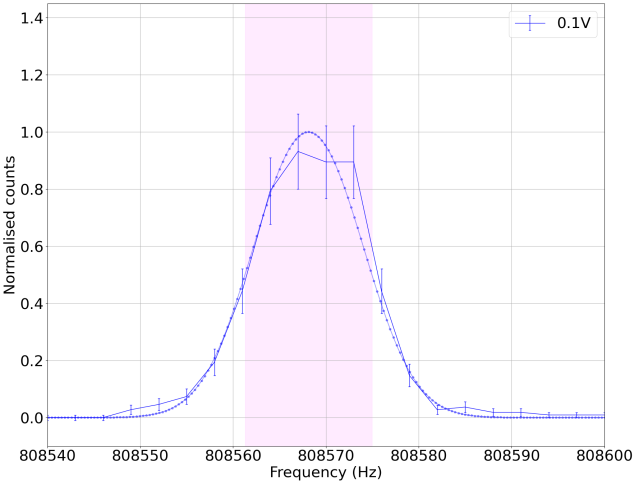


Experimental mass resolving power

$\mathrm{MRP}_{\mathrm{exp}} = \nu_c$ / FWHM

Frequency scan around ν_c

(Normal operation at ν_c
- freq. scan only to
determine MRP)



The spot size

2 Spot size

Distribution of hits on detector

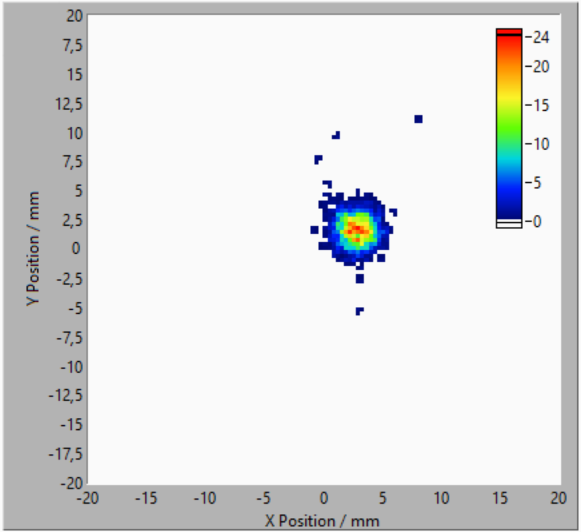
Determined by centering of ions in PT (MT not in use)

MT measurement method requires small spot size

Spot size from the detector

Gaussian distribution of counts

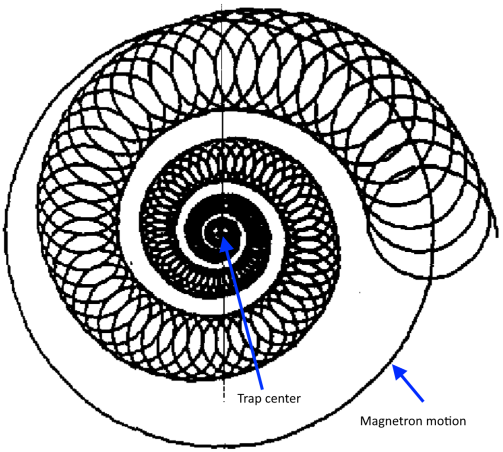
$$r = \sqrt{x^2_{\mathrm{FWHM}} + y^2_{\mathrm{FWHM}}}$$



Spot size

Well-centered ions produce a smaller spot size

Requires optimization of all parameters



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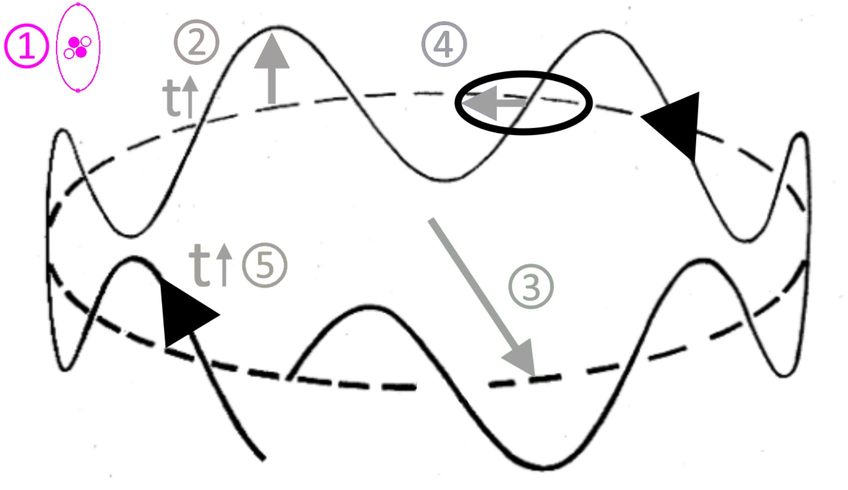
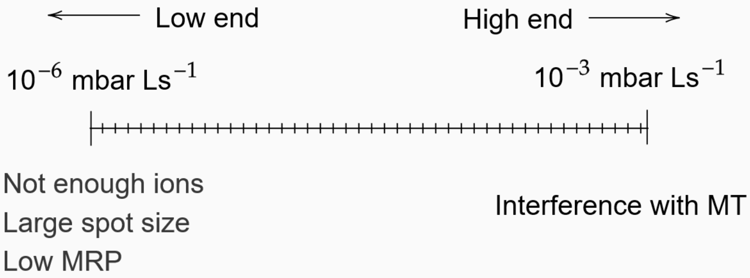
Parameters

1: Helium buffer gas flow

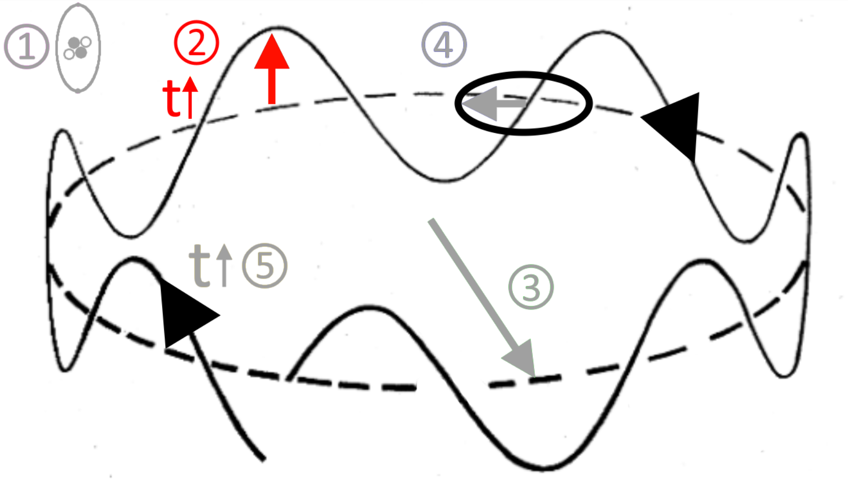


1: Helium buffer gas flow

Energy dissipation through collisions
Pressure in trap determined by gas flow



Axial cooling time



2: Initial axial motion

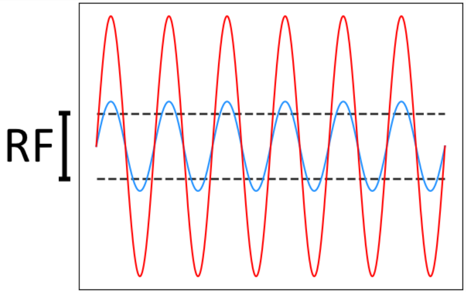
Large axial amplitude

$\Rightarrow$ less time spent in the center of the trap

$\Rightarrow$ less time spent in RF fields

$\Rightarrow$ higher centering amplitude required

$\Rightarrow$ smaller resolving power



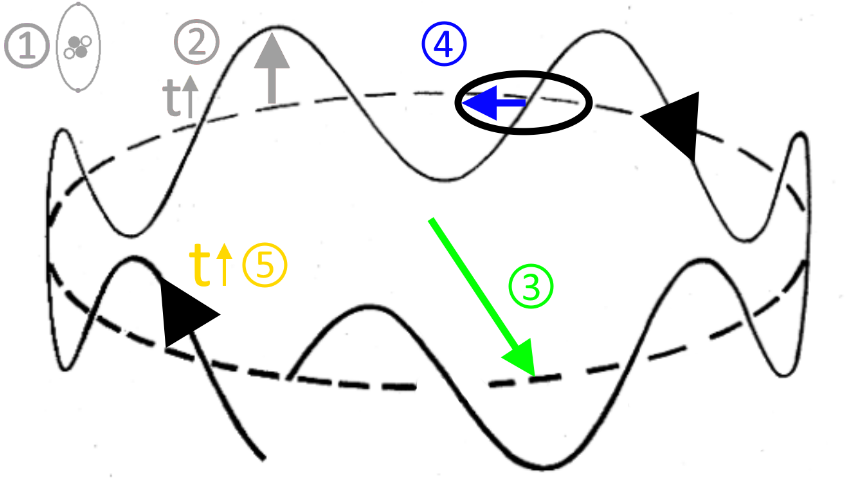
Amplitude diminishes in buffer gas

$\Rightarrow$ reduced effect on MRP/spot size

Initial amplitude depends on injection

$\Rightarrow$ alter injection method to minimize axial amplitude from the start

3, 4, 5: Magnetron driving - amplitude / Cyclotron driving - amplitude & duration



3, 4, 5: Magnetron driving - amplitude / Cyclotron driving - amplitude & duration

Magn. driving amplitude:

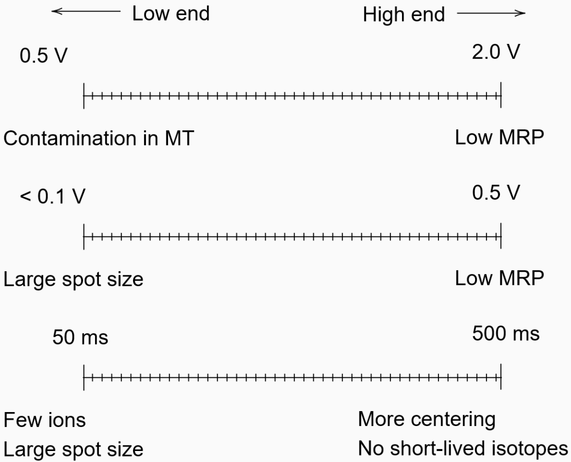
- $\nu_- \neq f(m)$
- All ions driven out

Cycl. driving amplitude:

- Recenter ions of specific mass
- $\nu_c = f(m)$

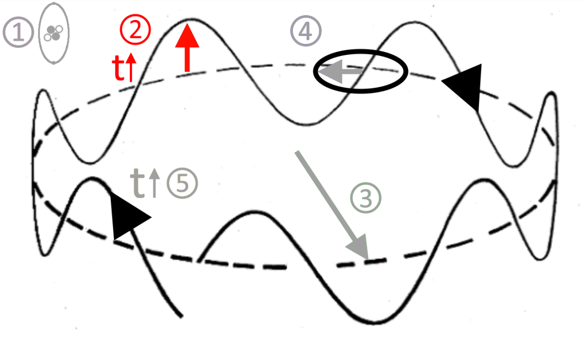
Cycl. driving duration:

- short-lived isotopes
  - $\Rightarrow$ shortest cooling time



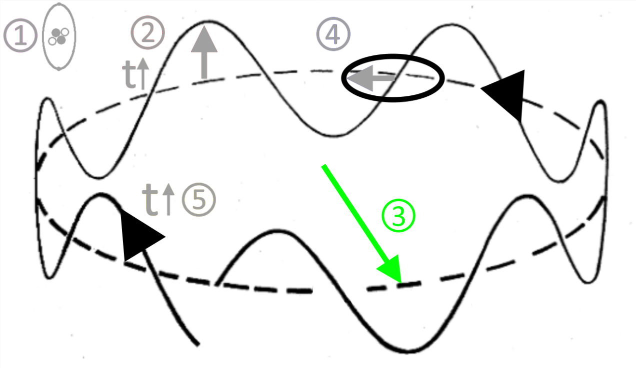
Results

Axial cooling time



Effects are negligible

Magnetron driving - amplitude



0.5 V

Ions not driven out far enough

2.0 V

MRP decreases

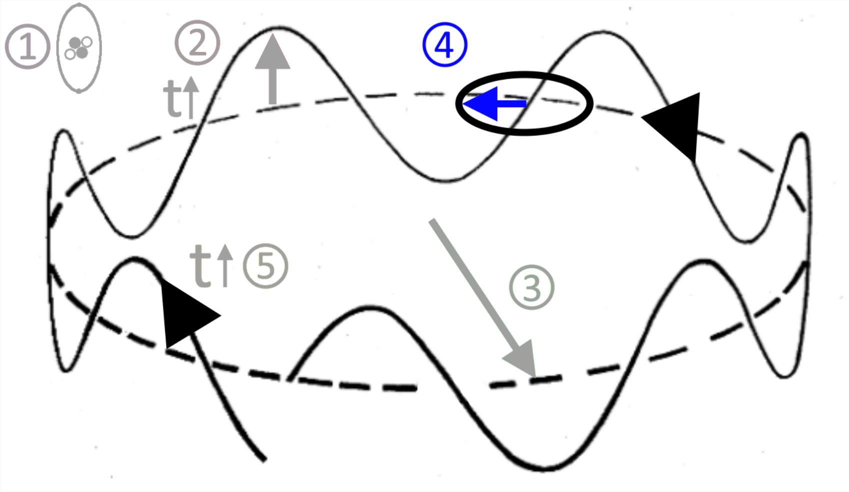
1.0 V

Sufficient

Conclusion:

- Run a scan to optimize
- Calibrate for individual ion sources

Cyclotron driving - amplitude



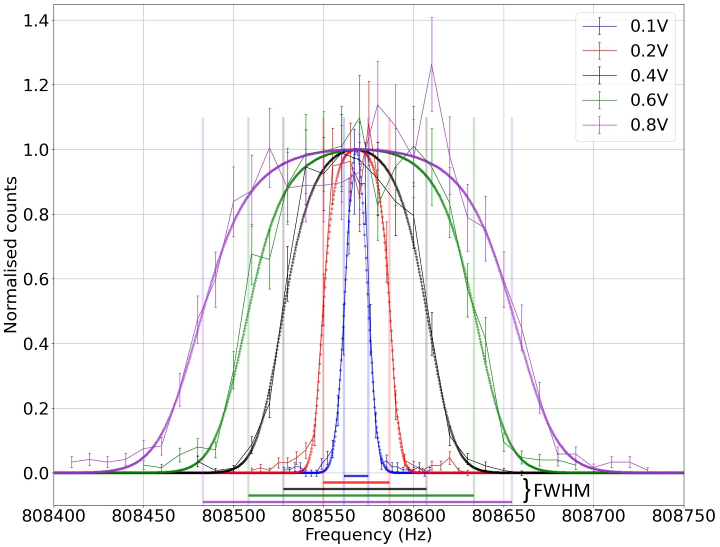
Cyclotron driving - amplitude

Low amplitudes
⇒ small FWHM
⇒ large MRP

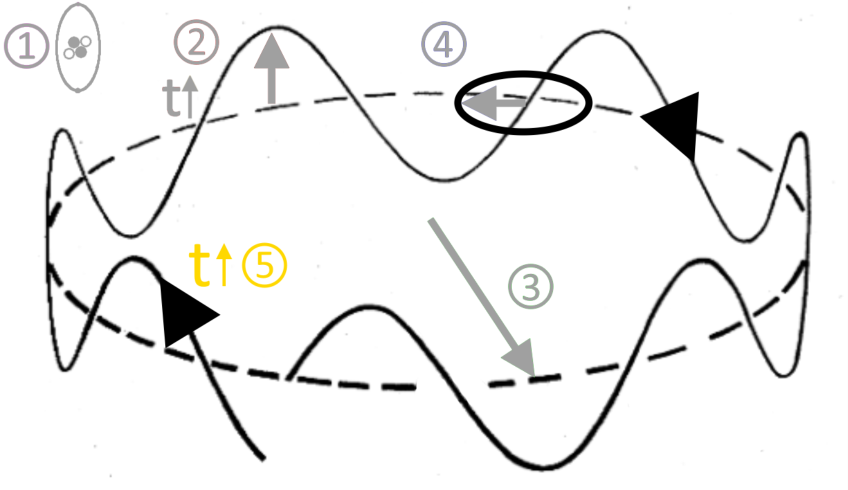
Saturation:
High amplitude
⇒ off-resonance
ions centered

Conclusion:

- Low amplitudes



Cyclotron driving -amplitude & duration



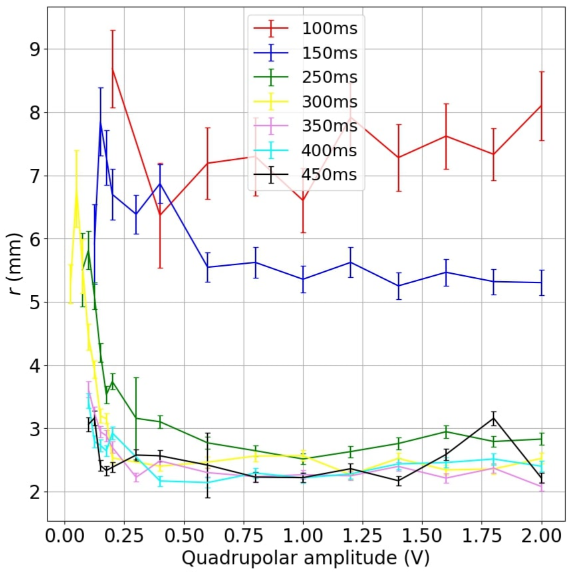
Cyclotron driving - amplitude & duration

Low amplitudes
⇒ less centering
⇒ larger spot size

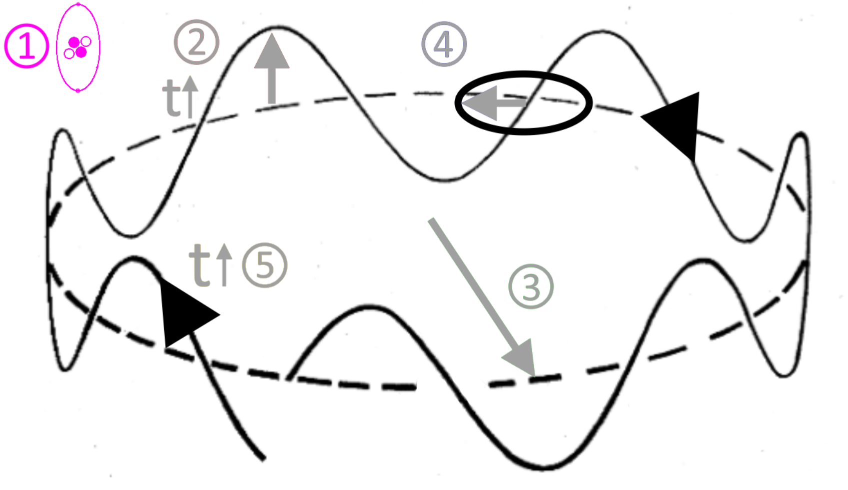
Shorter cyclotron cooling
⇒ not enough energy loss
⇒ larger spot size

Conclusion:

- Longest cooling time
- Lowest cyclotron amplitude possible



Helium gas flow



Helium gas flow

High gas flow:

$\Rightarrow$ lower MRP

Low gas flow:

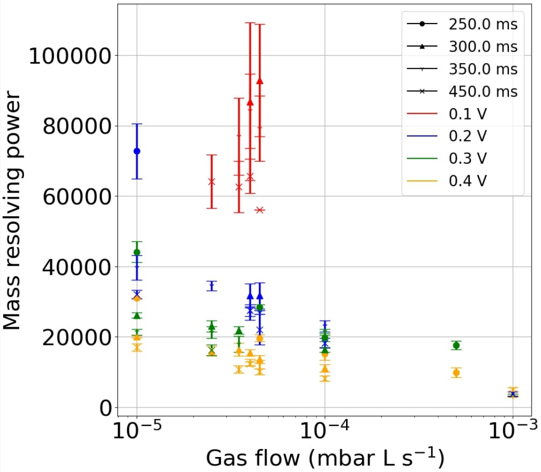
$\Rightarrow$ lower ion count

Efficiency important!

Cyclotron driving more apparent than gas flow

Conclusion:

- Mid-range gas flow



Overview

Competing interests!

Higher cyclotron amplitude:

⇒ smaller spot size

Lower cyclotron amplitude:

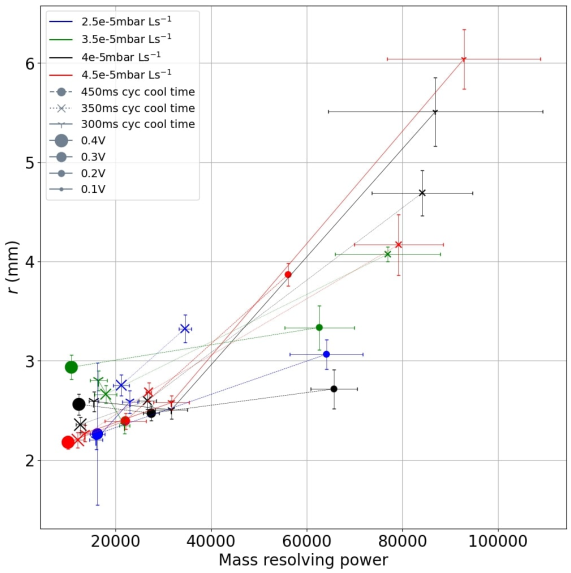
⇒ larger MRP

Longer cooling time:

⇒ smaller spot size

Gas flow:

- trends dominated by other parameters



Conclusion and Outlook

Conclusion

◯ Compromise between spot size and mass resolving power

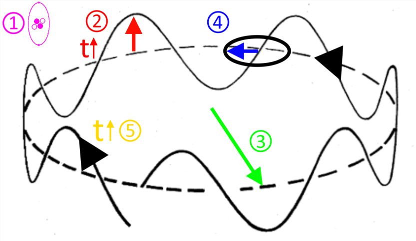
1 Mid-range helium gas flow (more testing)

2 Adjust ion injection to remove initial axial motion

3 Magnetron driving amplitude adjusted per ion source (more testing)

4 Lowest cyclotron driving amplitude

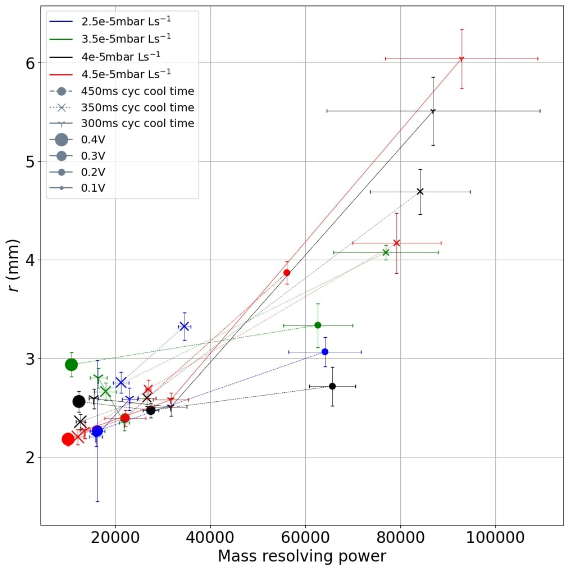
5 Longest cyclotron driving duration



Conclusion

Sufficient for MRP = 56 000
using 450 ms, 0.2 V
for next beam time

More research to reach MRP = 140 000



Axial cooling time

Axial cooling time

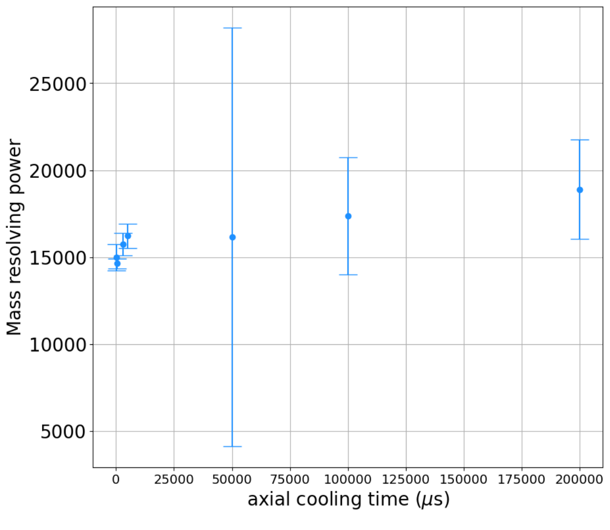
vs

MRP

No apparent correlation

Conclusion:

- Axial motion is damped
- Adjust for each ion source



Axial cooling time

Axial cooling time

vs

Spot size

No apparent correlation

Conclusion:

- Axial motion is damped
- Adjust for each ion source