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Design and simulations of a linear Paul trap for single-ion spectroscopy

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ODYSSEUS
Top science in Flanders

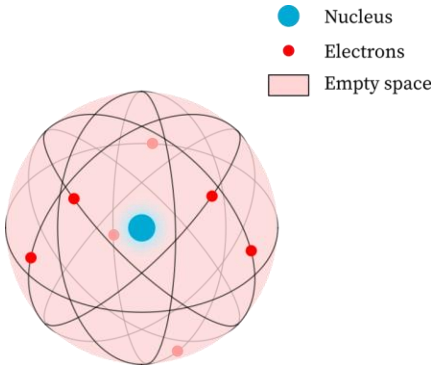
Motivation

Key question in nuclear physics today:

How can we accurately describe the Strong Nuclear force in the nuclear level

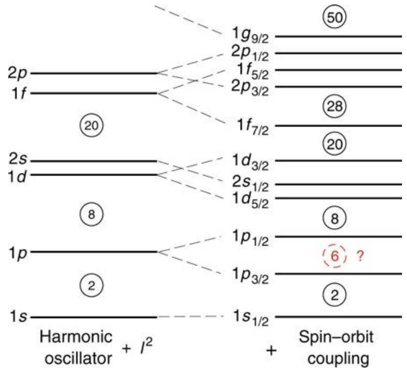
Atomic model

1911



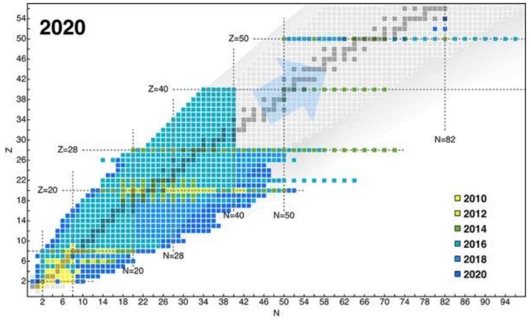
Nuclear Shell model

1955



Ab-initio

Today



Motivation

Ab-initio nuclear theories:

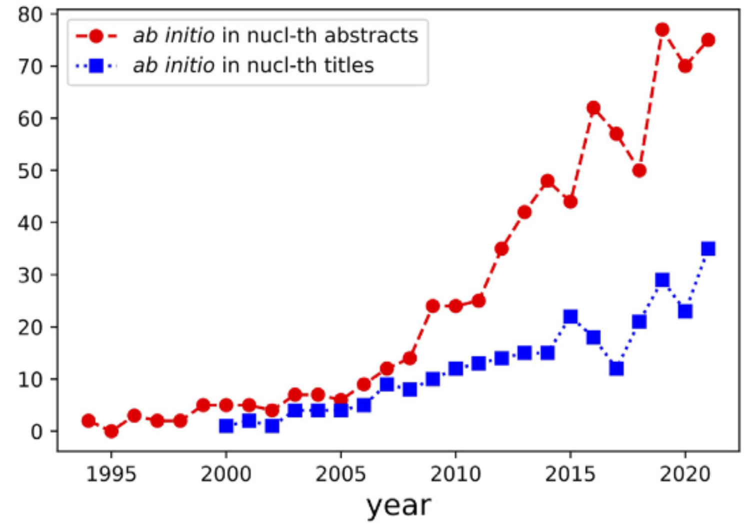
Remarkable in predicting experimental results, based only on very light systems

However:

Require experimental input for benchmarking

Input includes:

- B(E2) obtained from lifetime measurements
- Binding energies obtained from precision mass spectroscopy etc.



A particularly successful technique is **laser spectroscopy**, which gives access to 4 complementary quantities in a **theory-independent** way:

Magnetic dipole moment (μ)

Nuclear spin (I)

Electric quadrupole moment (Q_s)

Nuclear charge radius ($\delta\langle r^2\rangle$)

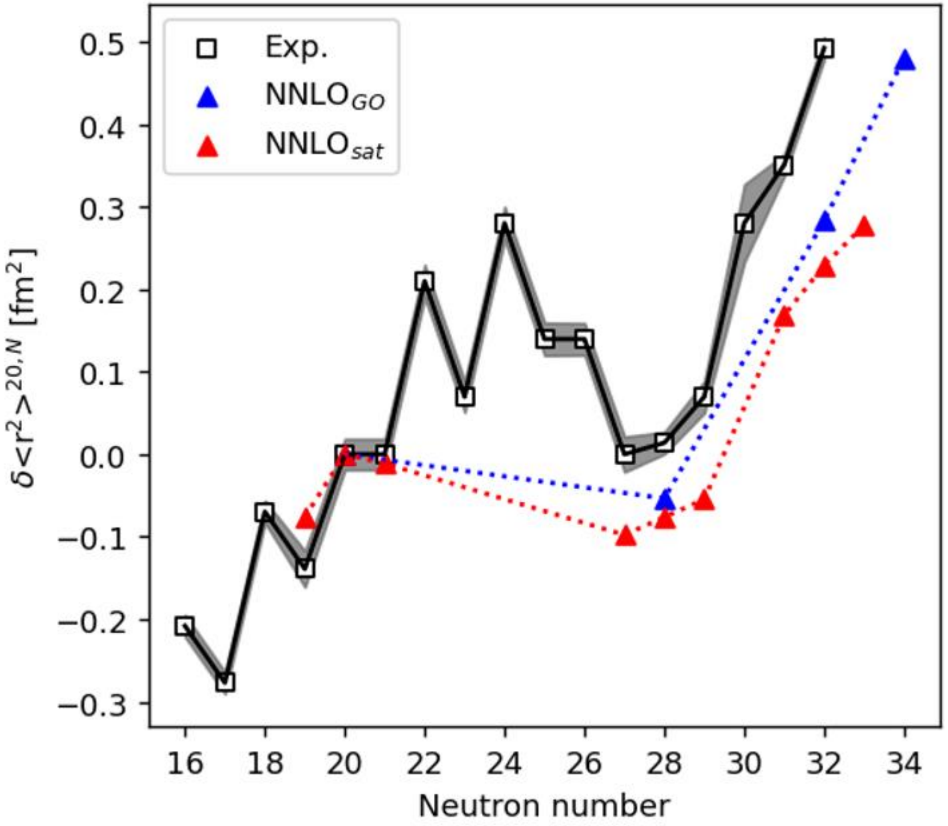
A. Ekstrom et al. Frontiers in Physics 11 (2023) 29094

Motivation

Laser spectroscopy:

- Successfully applied to around 1/3 of the 3000 nuclei produced at RIB facilities[1]
- However, accessing the exotic region, known for revealing new patterns of the Strong force, suffers from limited sensitivity

e.g. Ca isotope chain



[1]R. F. G. Ruiz et al. Nature Physics 12 (2016) 594-598

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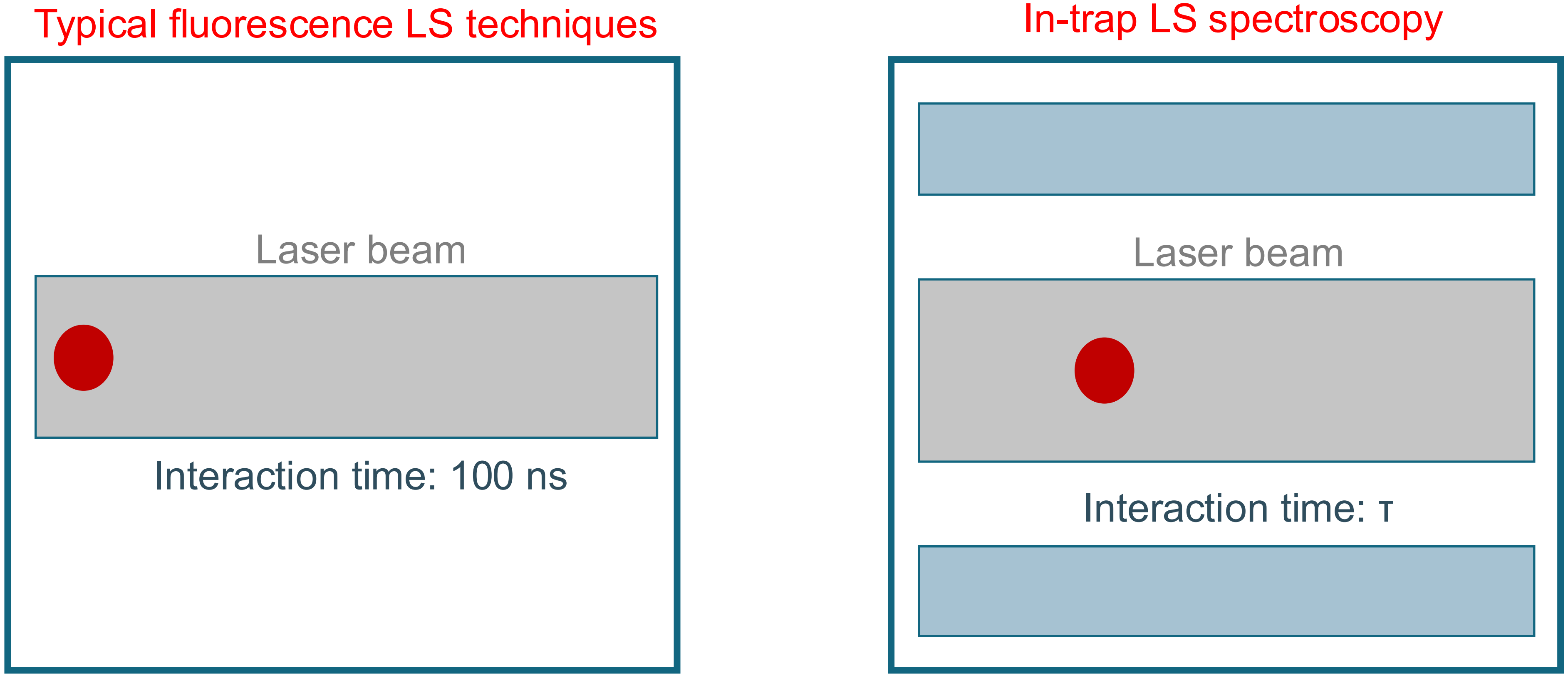
[1]X. Yang et al. Progress in Particle and Nuclear Physics 129 (2023) 104005

Motivation

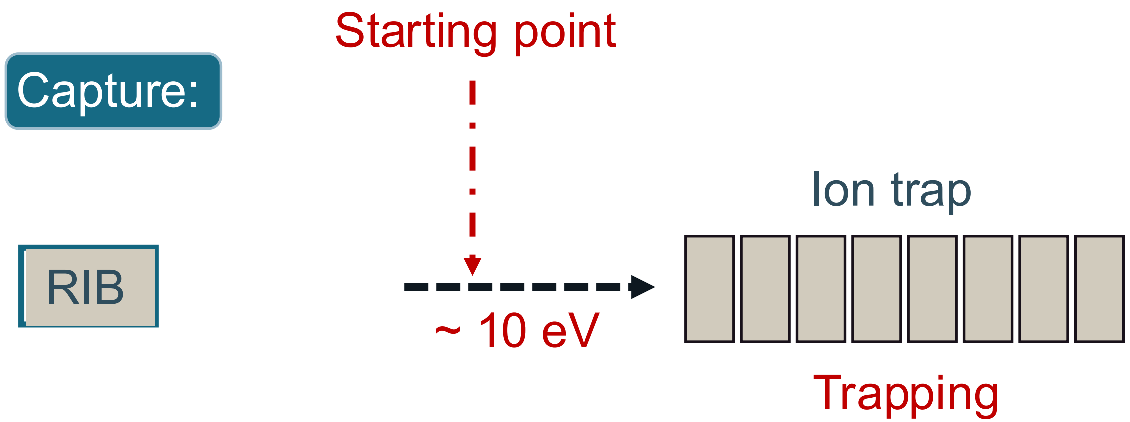
Mitigation:

Perform laser spectroscopy on trapped ions -> Higher sensitivity



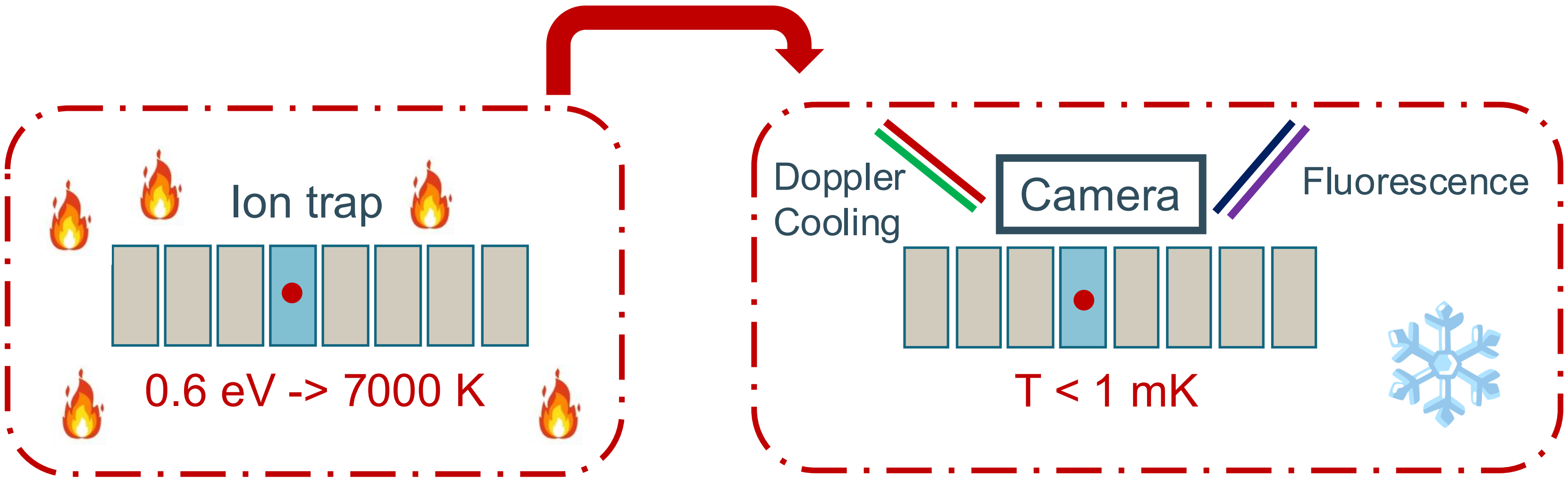
Plan

Capture:



Parameter	Value	Units
KE	10	eV
KE spread	0.5	eV
ToF	10	µs
ToF spread	1	µs
Emittance	$\sim 3\pi$	mm·mrad

Cooling:



Trapping

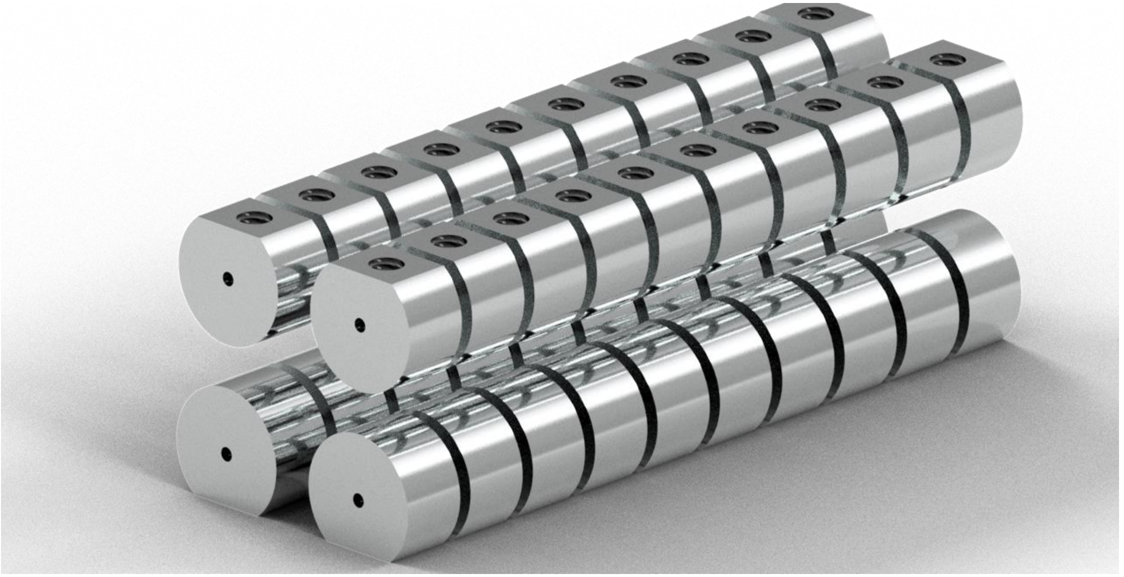
The trap

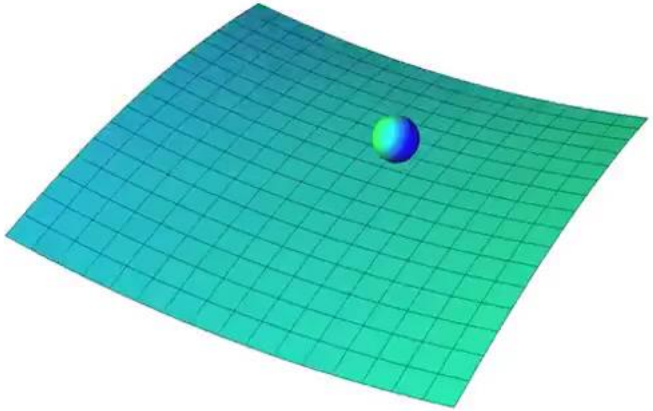
Consists of:

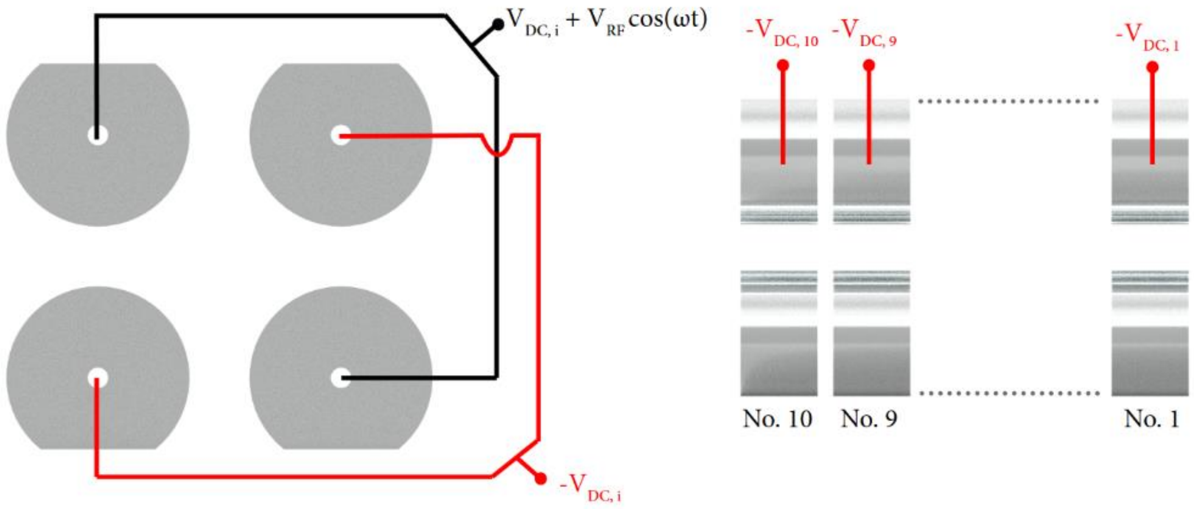
40 segmented round electrodes with:

- length of 5 mm
- Inner-electrode half distance $r_0 = 4$ mm
- Electrode radius $r_{rod} = 4.592$ mm

separated by 1 mm



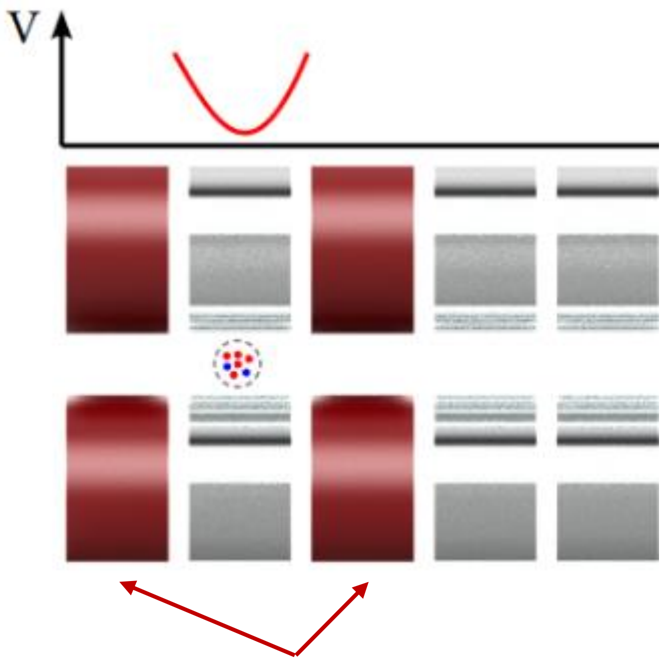




Capture

Axial stability:

- To ensure total confinement of the ions, we need to use additional DC potentials to restrict them in the axial direction.
- To find the optimal setup, **three different** voltage configurations were investigated.
- The parameters responsible for the radial stability, as well as the trap dimensions were left the same.

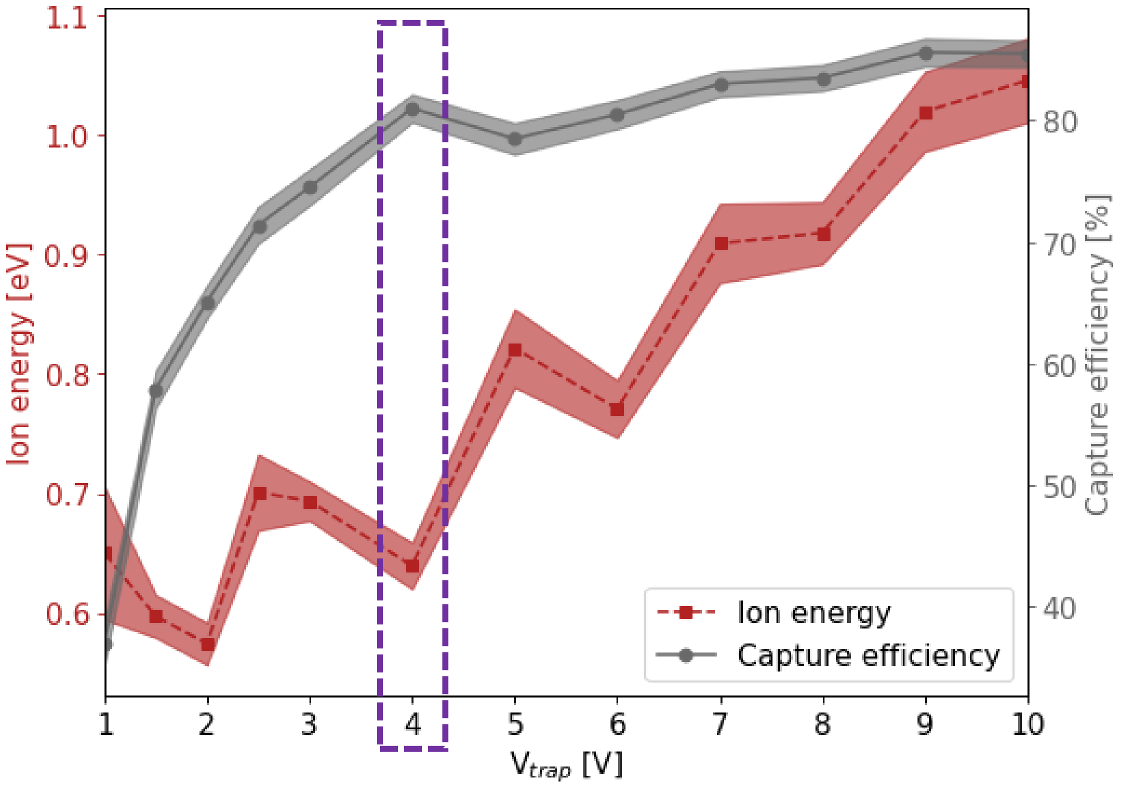


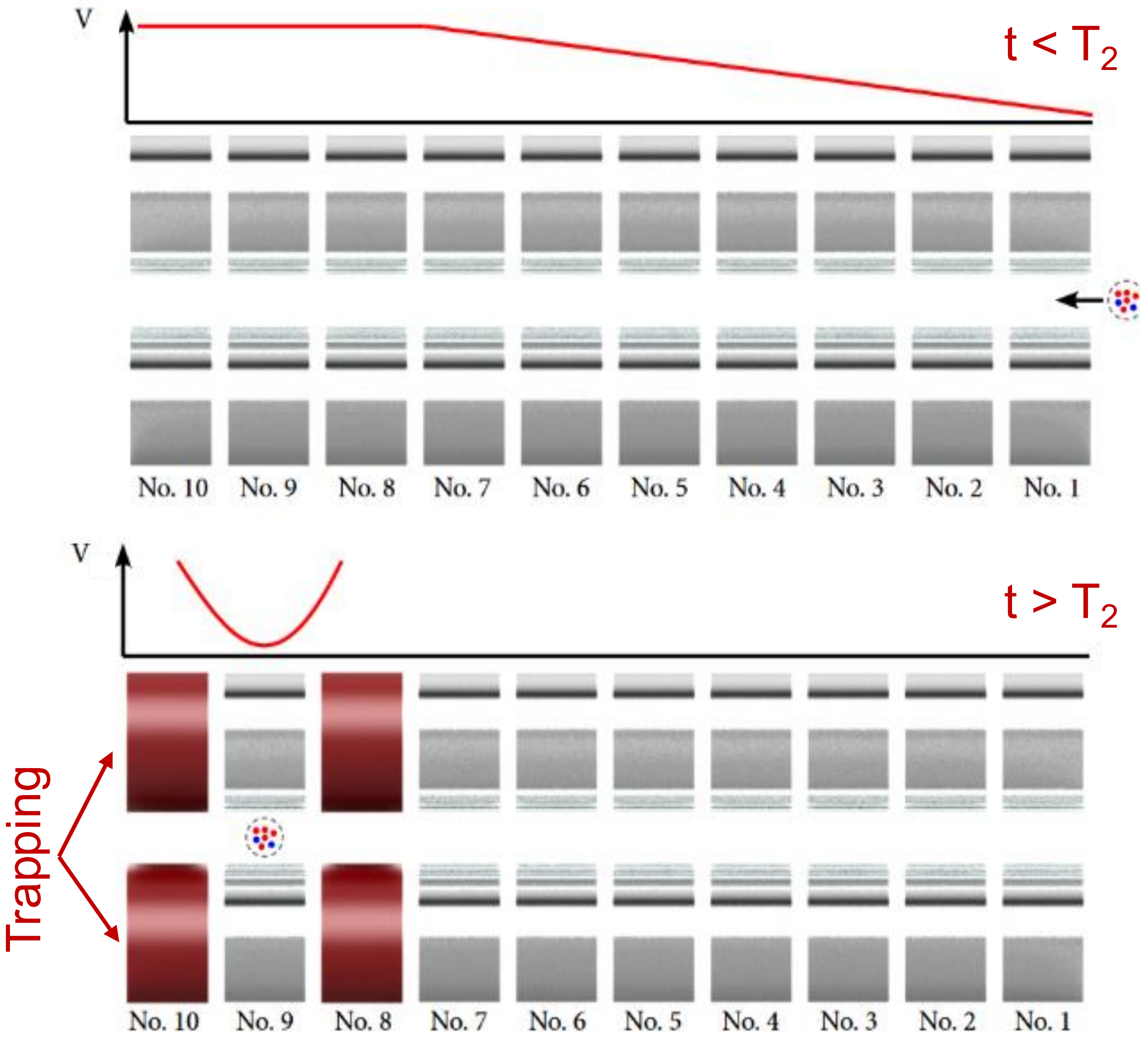
Trapping potentials

Capture scheme: Step potential

Axial stability:

Ion energy: 0.65 eV
Capture efficiency: 85 %





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Cooling

Doppler laser cooling

Principle:

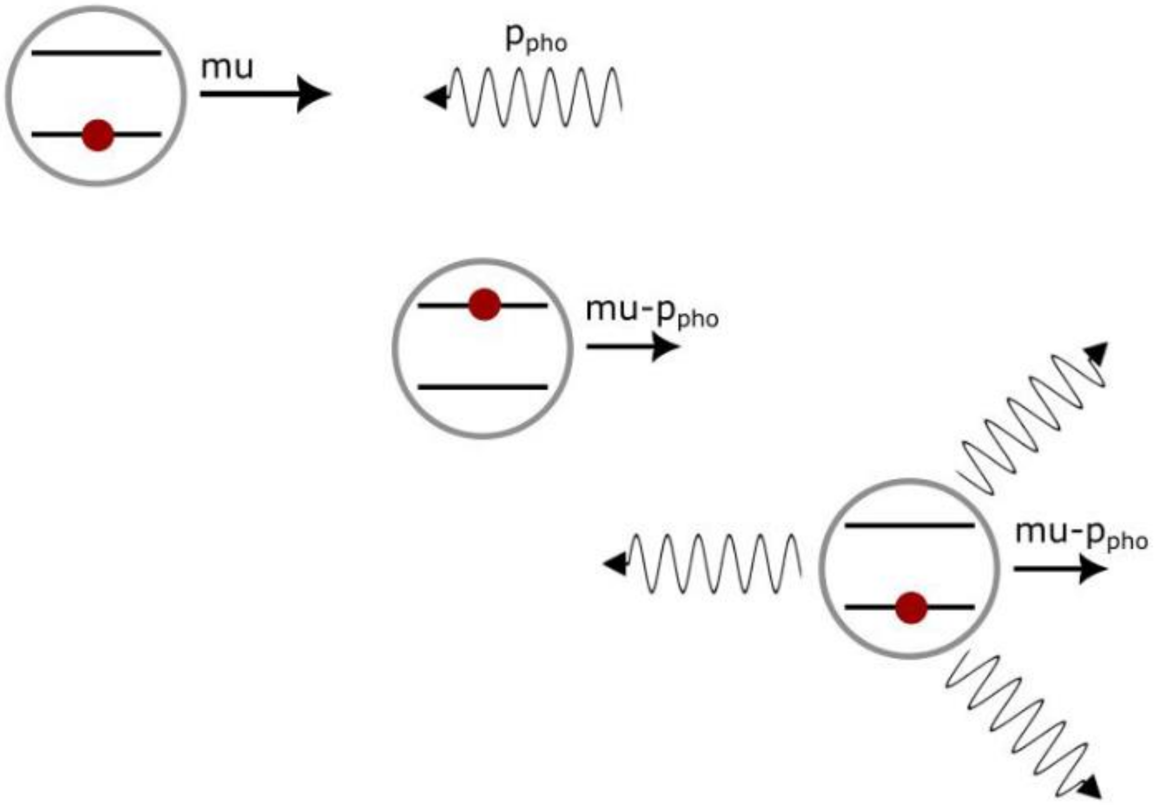
Use radiation pressure to remove energy from an ion, by red-tuning the laser below its resonance by **δ**. The photon scattering rate will be:

$$R_{\mathrm{scatt}}(\delta) = \frac{\Gamma}{2} \frac{I/I_{\mathrm{sat}}}{1 + I/I_{\mathrm{sat}} + 4\delta^2/\Gamma^2}$$

where Γ is the linewidth, I the laser intensity and I_{sat} the saturation intensity.

There is a limit to the lowest temperature obtained using Doppler cooling, namely:

$$T_D = \frac{\hbar\Gamma}{2k_B}$$



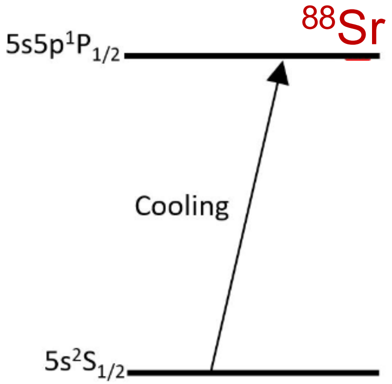
C. J. Foot, Atomic Physics, Oxford University Press, USA, 2005

Cooling scheme: Realistic case

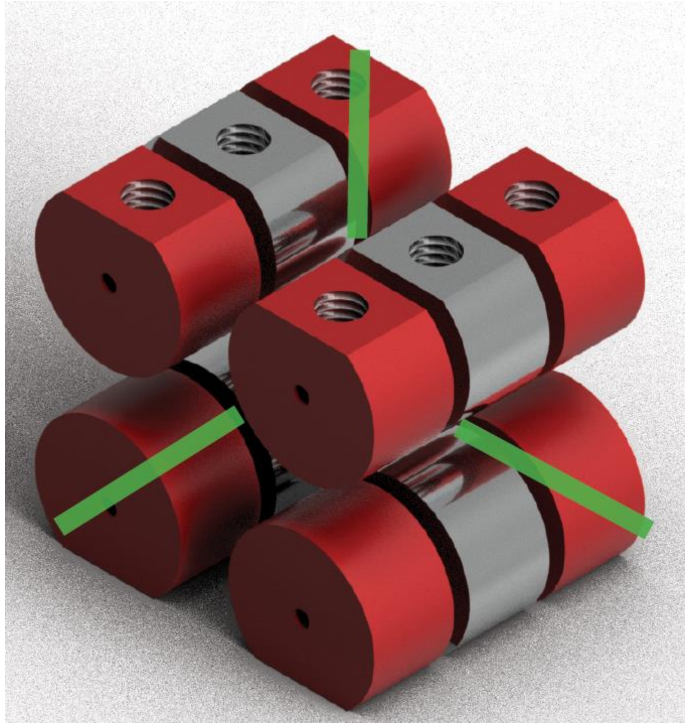
Capture:

We send a 10 eV beam (100 amu) inside the trap, capture it using the best capture scheme and start the cooling process 100 µs after capture.

Cooling transition:



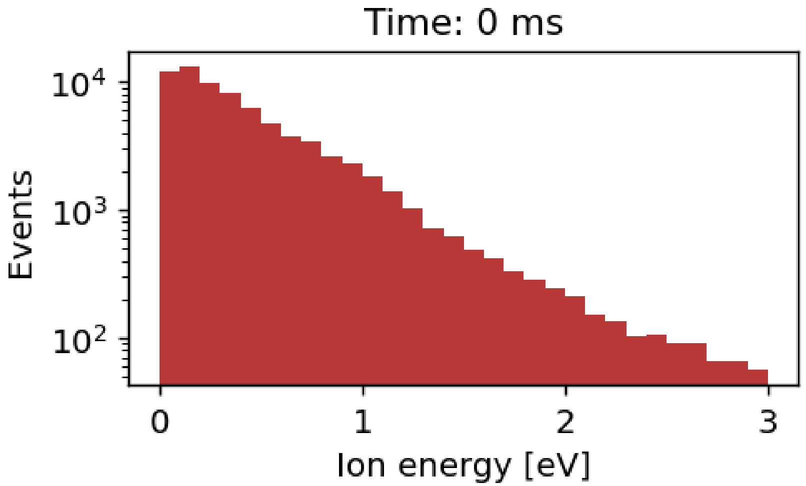
For this D1 transition with a linewidth of 135 MHz, the Doppler limit is 0.52 mK.



Cooling scheme: Realistic case

Results:

- Set the frequency detuning **$\delta = -\Gamma/2$, after investigating the ion's velocity**
- Cooling close to the Doppler limit can be achieved in **a few 100 ms**.
- After 500 ms of cooling time, **99 %** of the ions are within the first bin of the ion energy distributions.
- Even the more energetic ions (few eV) are slowly being cooled.



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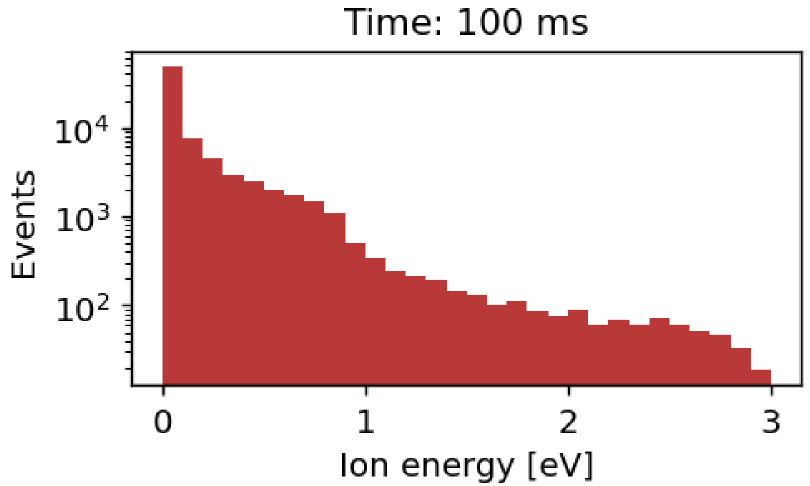

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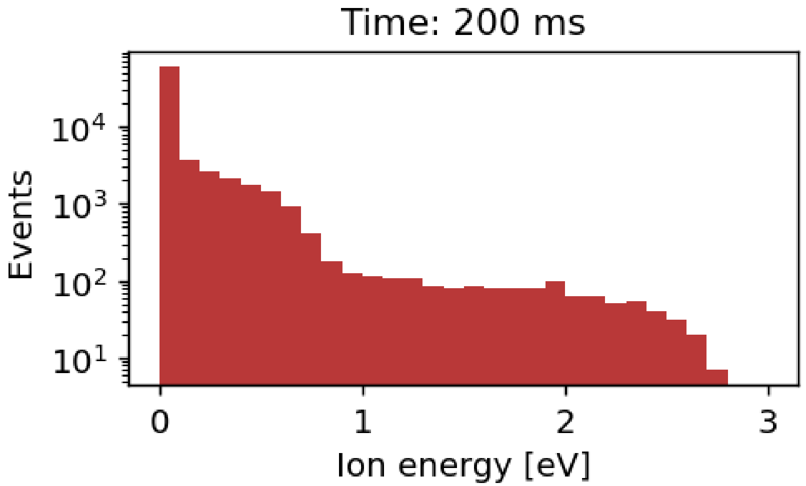

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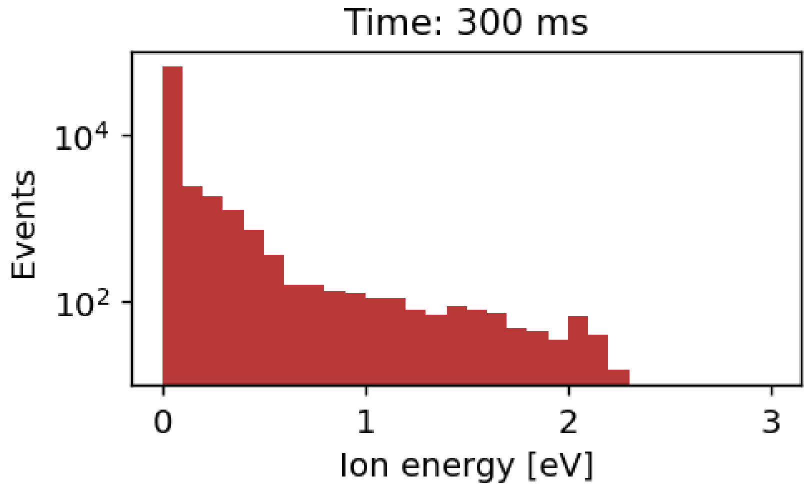

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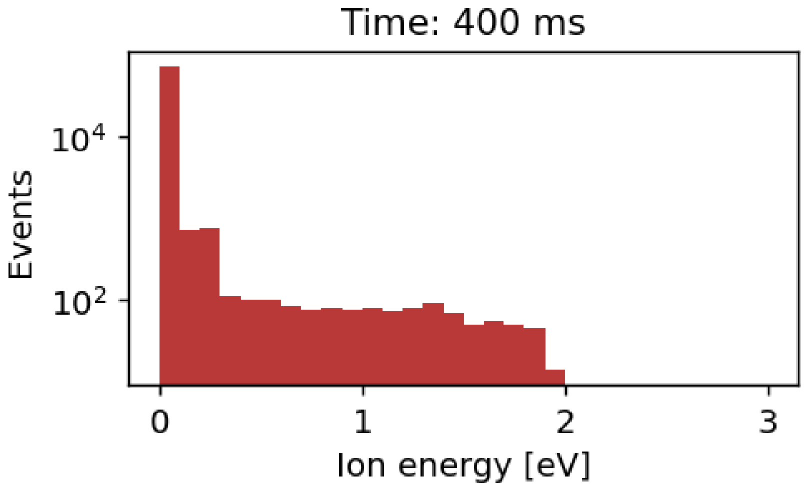

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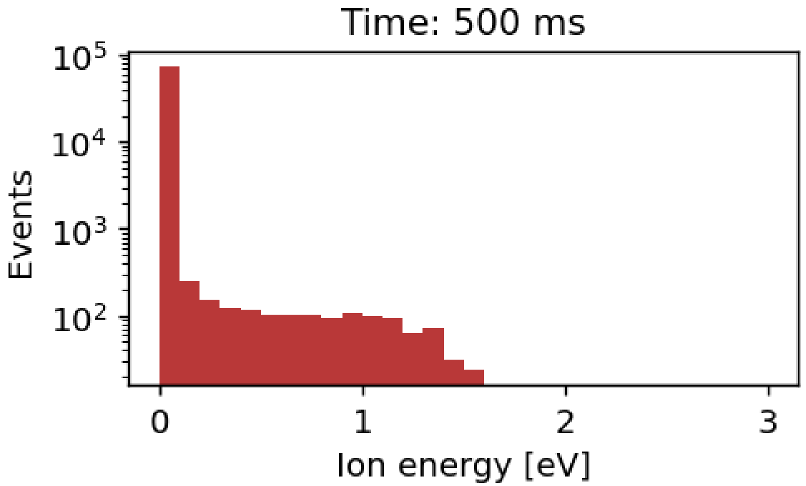

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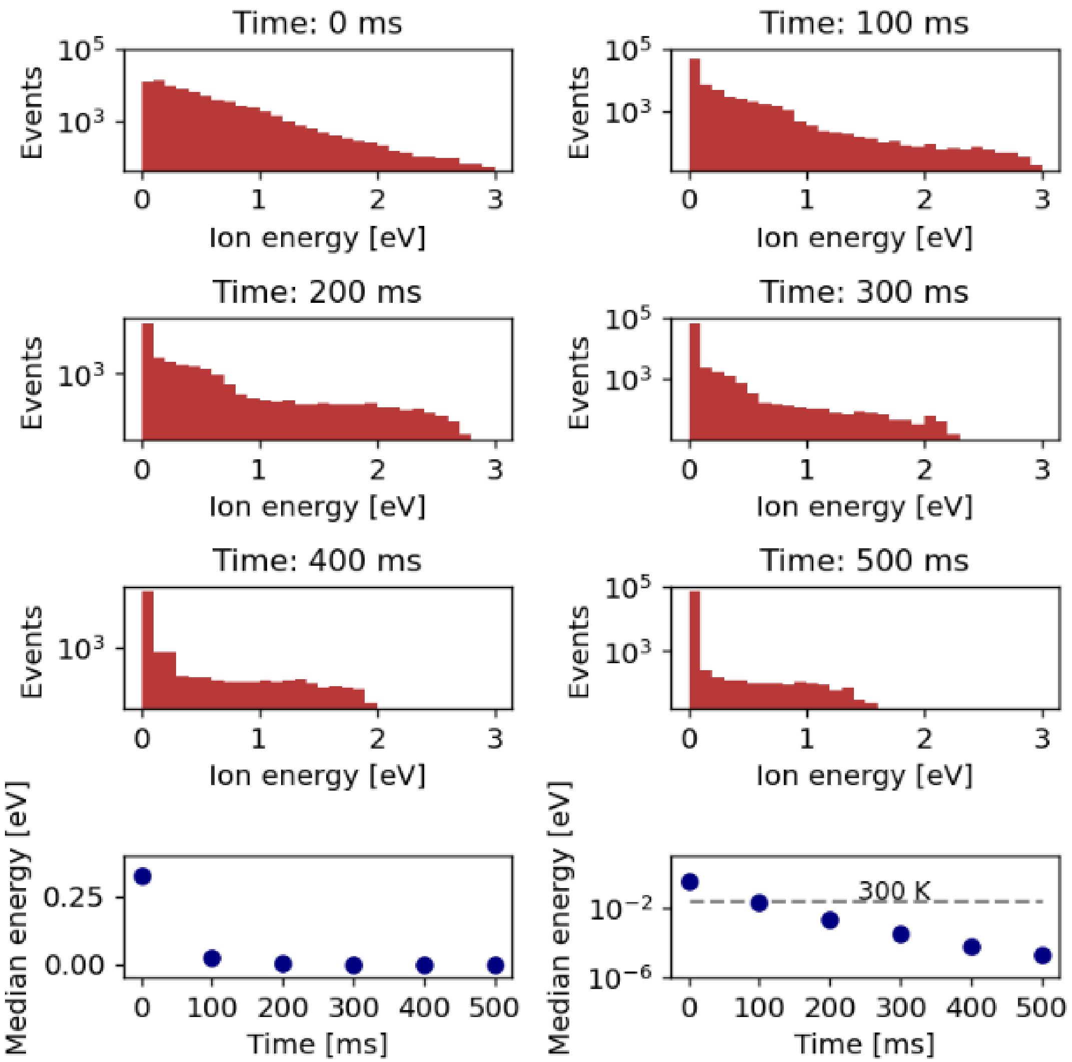
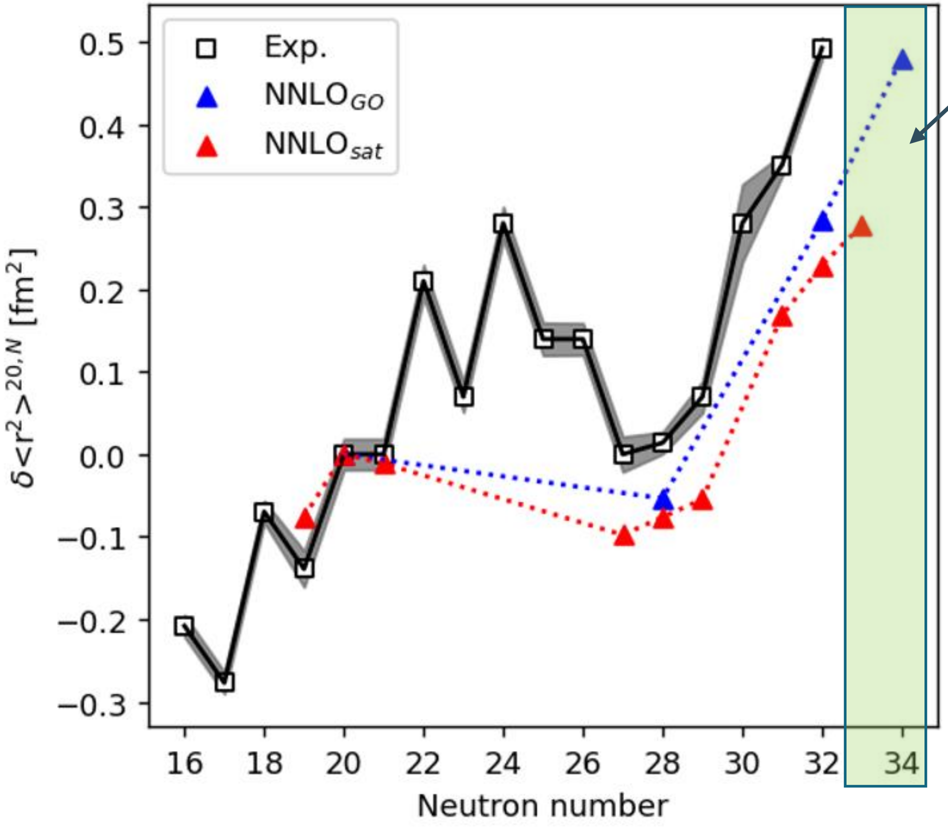


Rewind

Laser spectroscopy:



Ca isotope chain

^{53}Ca	^{54}Ca
461 ms	107 ms

- This method should allow measurements on ^{53,54}Ca
- The proposed method can also work on the rest of alkaline-earth, without modification

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[1] X. Yang et al. Progress in Particle and Nuclear Physics 129 (2023) 104005

Conclusions

Capture

Three configurations were used, all of which had:

- Capture efficiency > 50 %
- Ion energy < 1 eV

The one using a step potential was the optimal for fastest Doppler cooling.

Cooling

The cooling code was successfully benchmarked with literature.

Laser cooling a realistic beam was done in a few 100 ms.

Future plans

Sympathetic cooling is expected to be faster, as indicated in [1].

The construction of this designed trap is expected to start from this fall, aiming at studying ^{53,54}Ca.

[1] S. Sels et al. Phys. Rev. Res. 4 (2022) 033299

Thank you for your attention

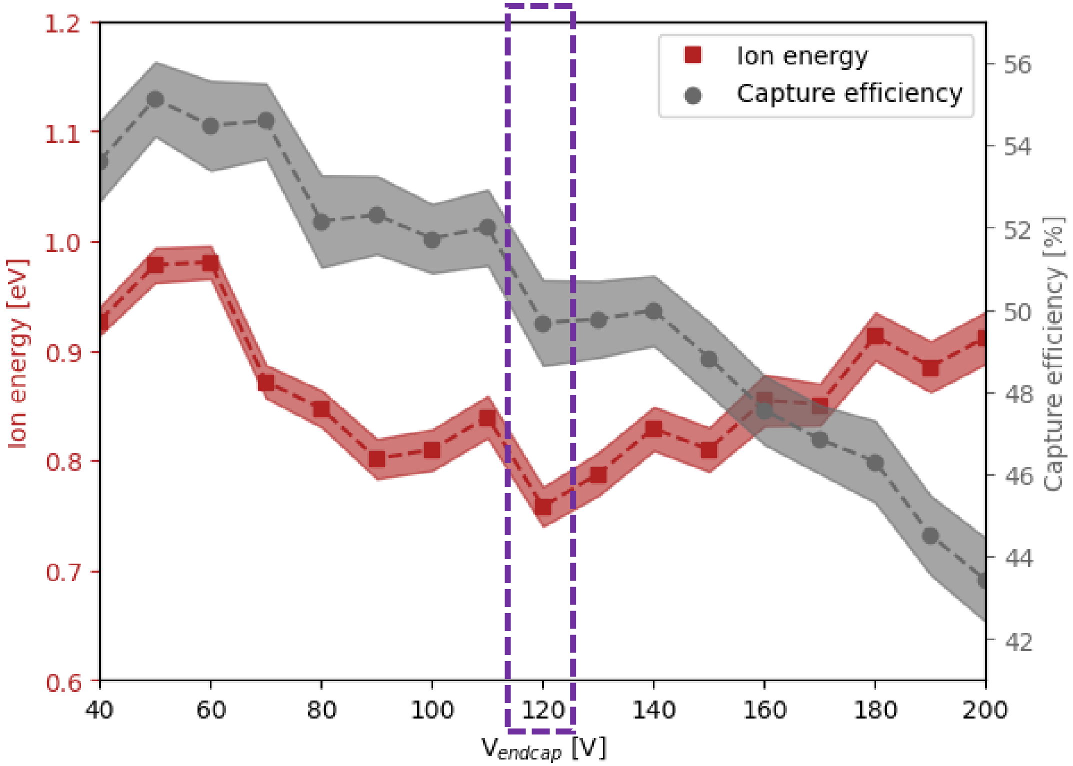
Supplementary Material

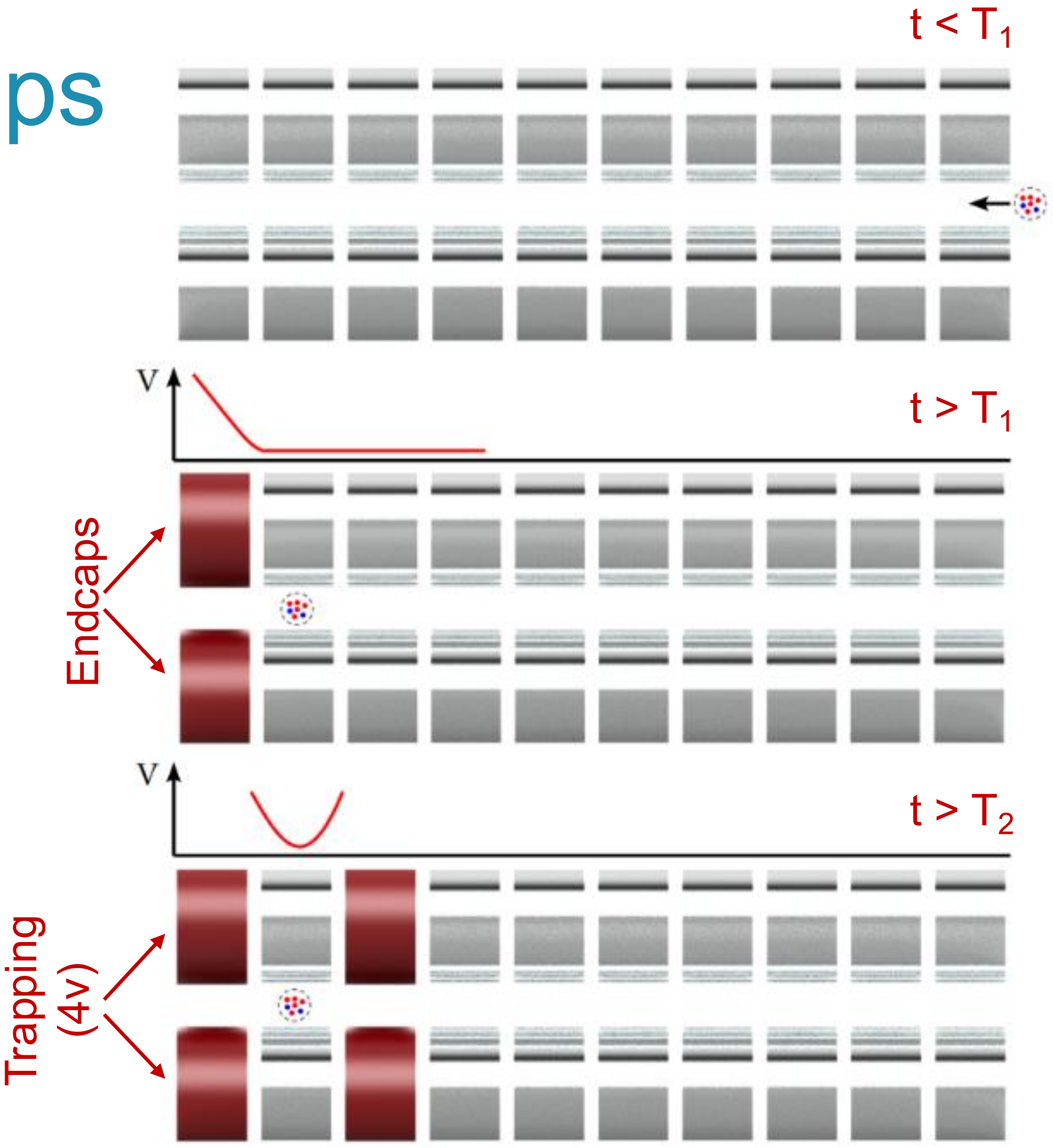
Rest of capture schemes
Details

Capture scheme 1: Endcaps

Axial stability:

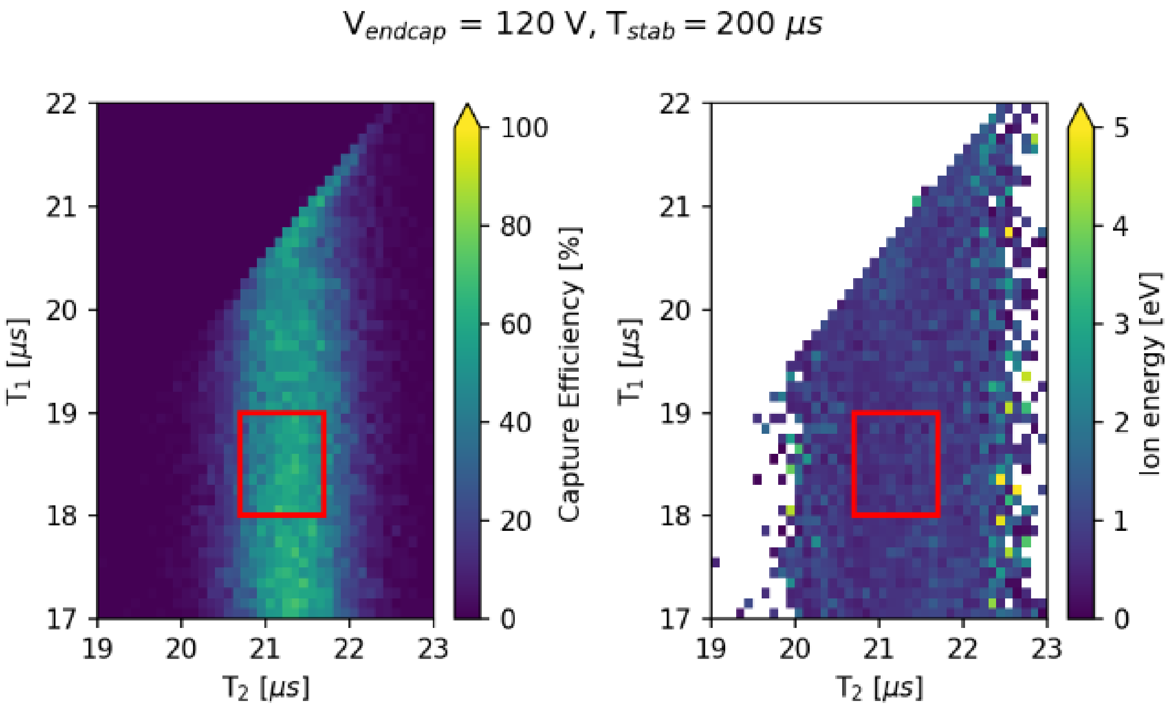
T_1 є (17,22) μs
T_2 є (19,23) μs





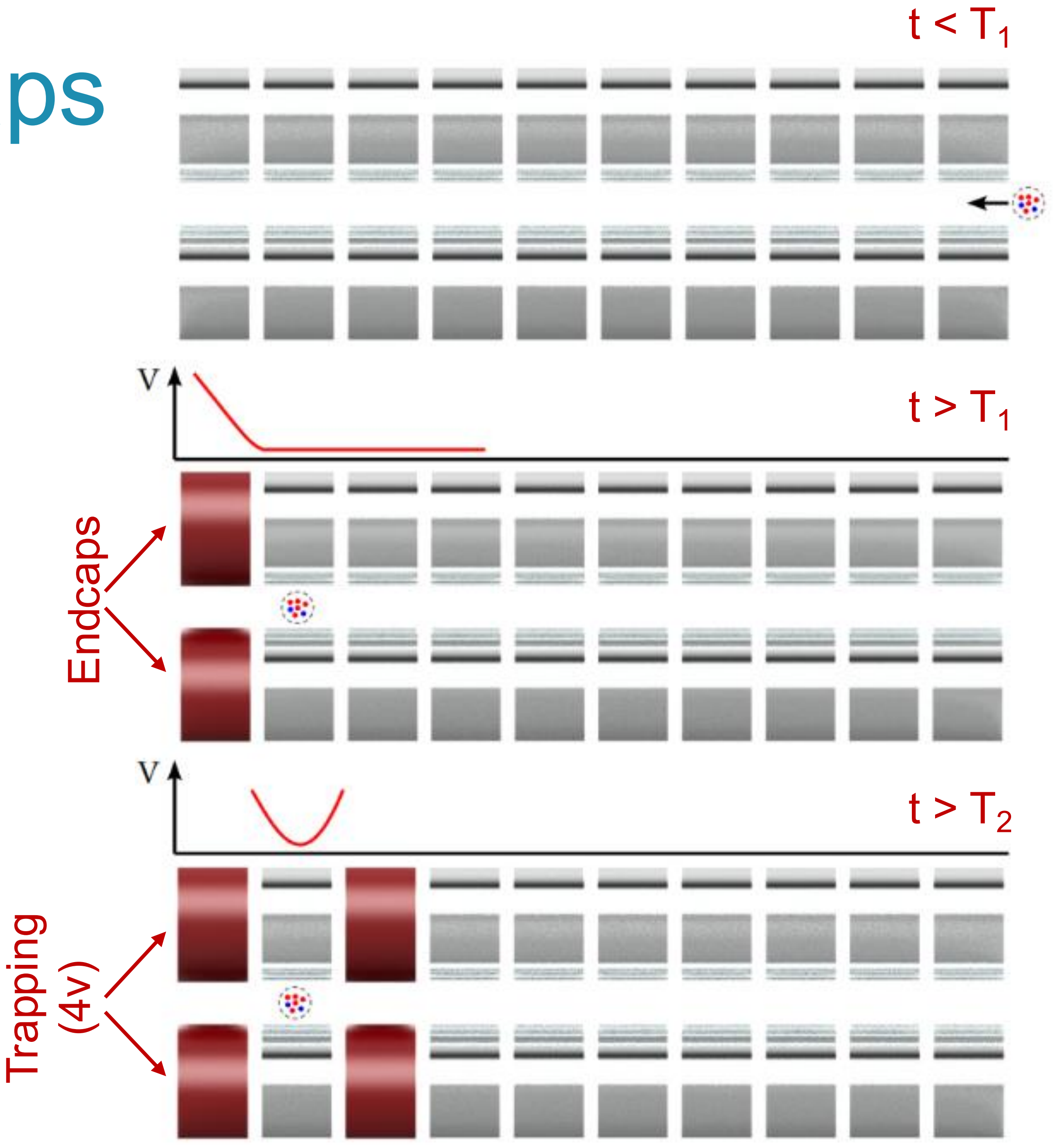
Capture scheme 1: Endcaps

Axial stability:


$V_{endcap} = 120$ V, $T_{stab} = 200$ μs

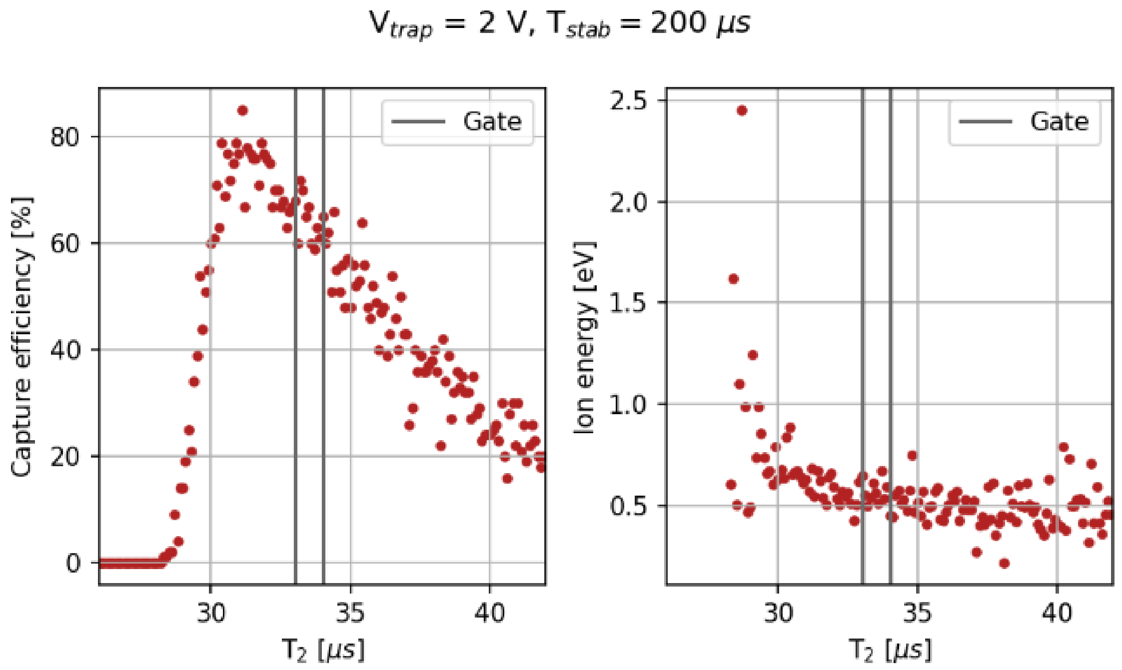
Capture efficiency: 49.68 +/- 1.0 %

Ion energy: 0.76 +/- 0.02 eV



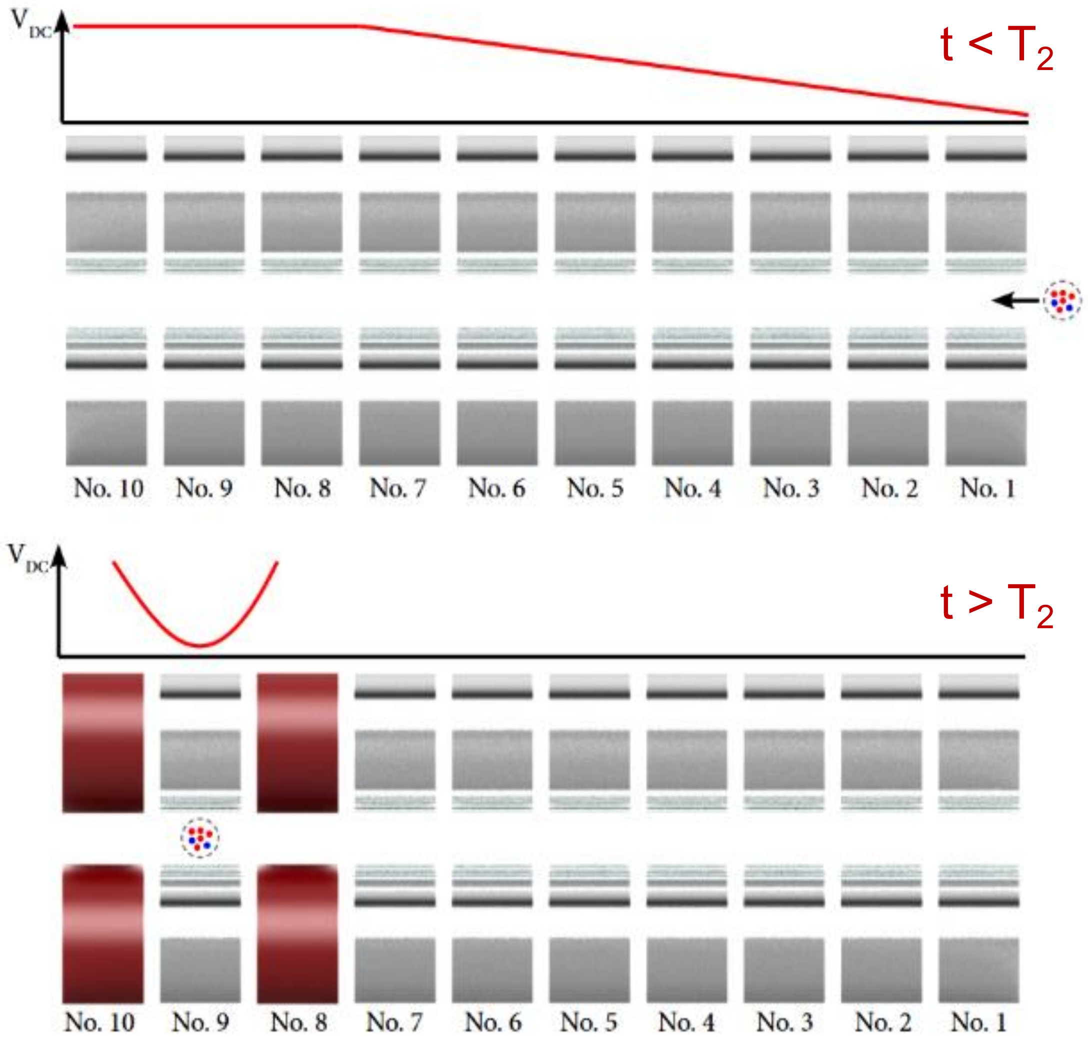
Capture scheme 2: Step potential

Axial stability:



Capture efficiency: 65.1 +/- 1.3 %

Ion energy: 0.57 +/- 0.02 eV

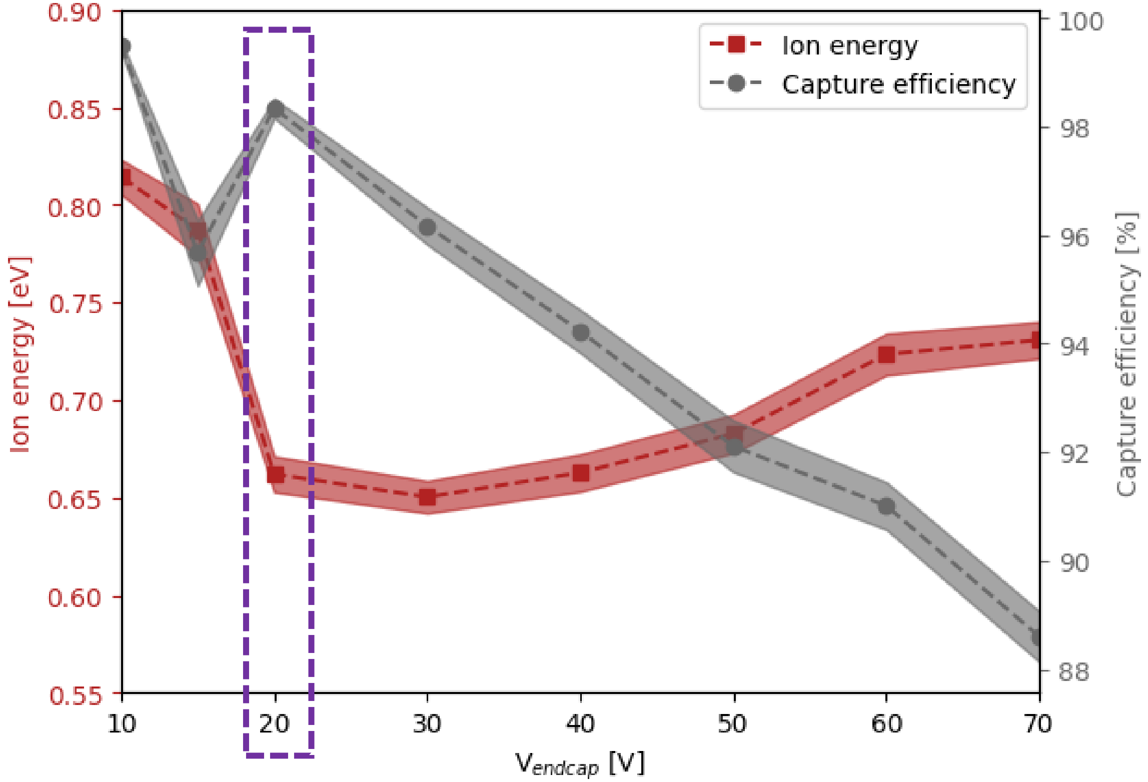


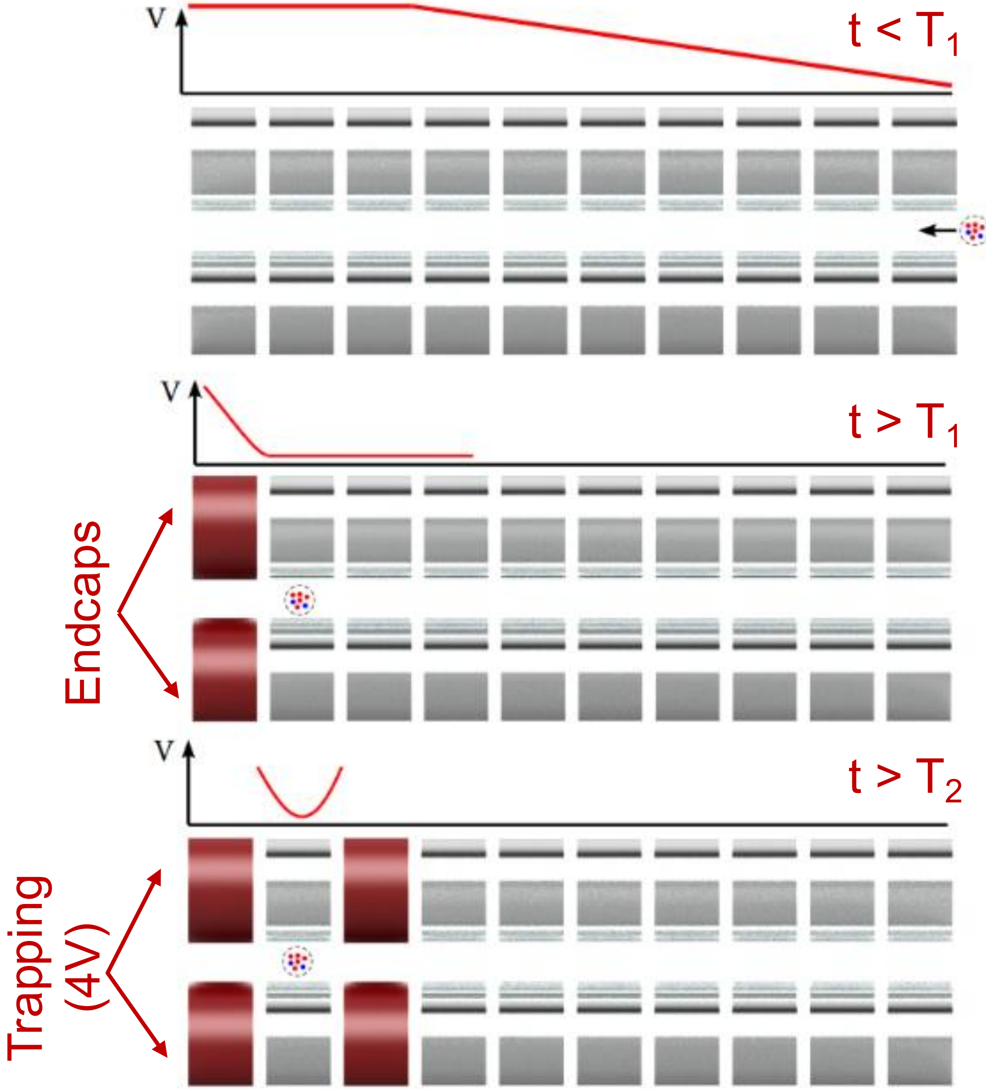
Capture scheme 3: Combination

Axial stability:

$T_1 \in (23,27)$ μs

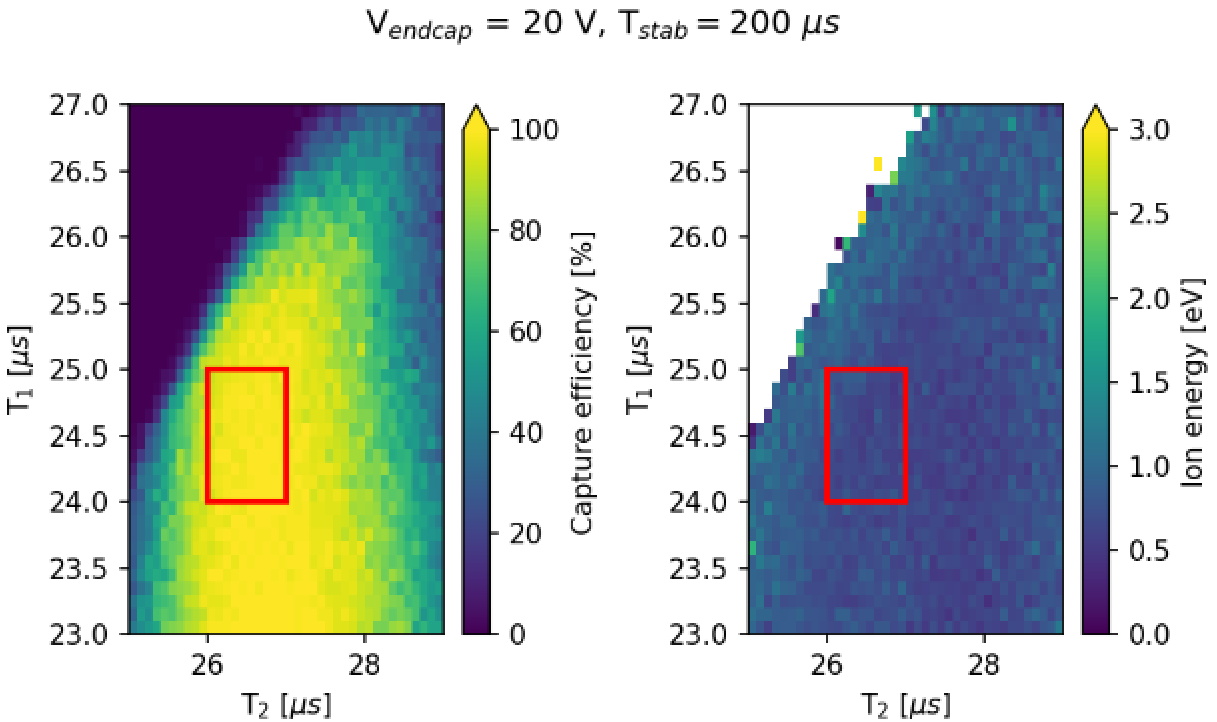
$T_2 \in (25,29)$ μs





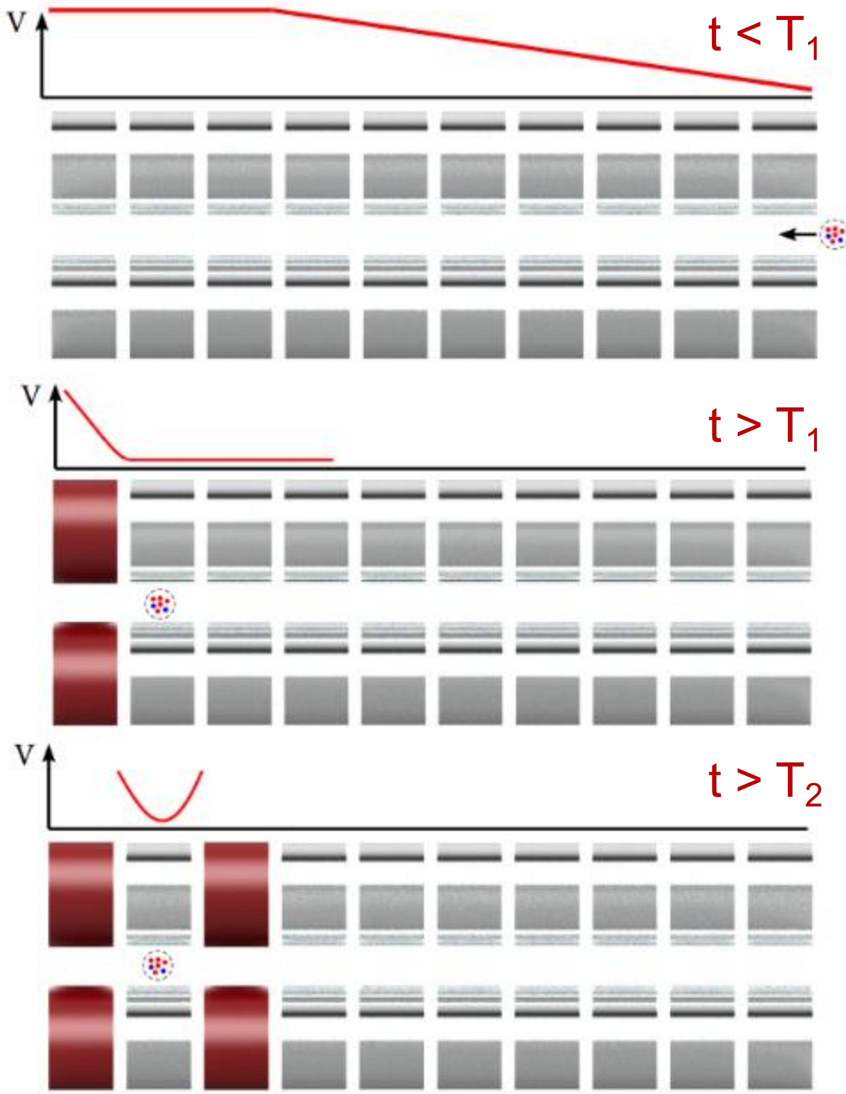
Capture scheme 3: Combination

Axial stability:



Capture efficiency: 98.34 +/- 0.2 %

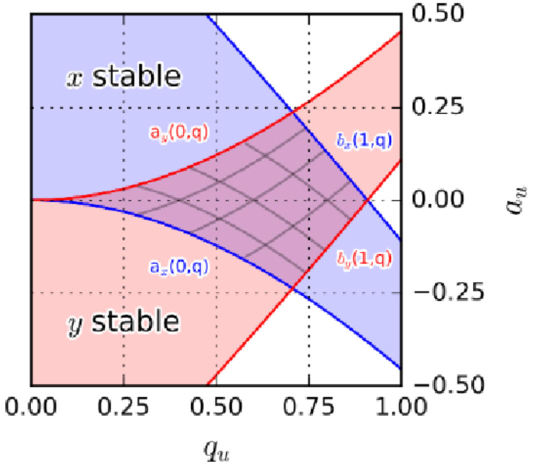
Ion energy: 0.66 +/- 0.01 eV



Capture

Operating parameters:

- RF frequency of 1.1 MHz
- Ions with 100 amu/e



Radial stability:

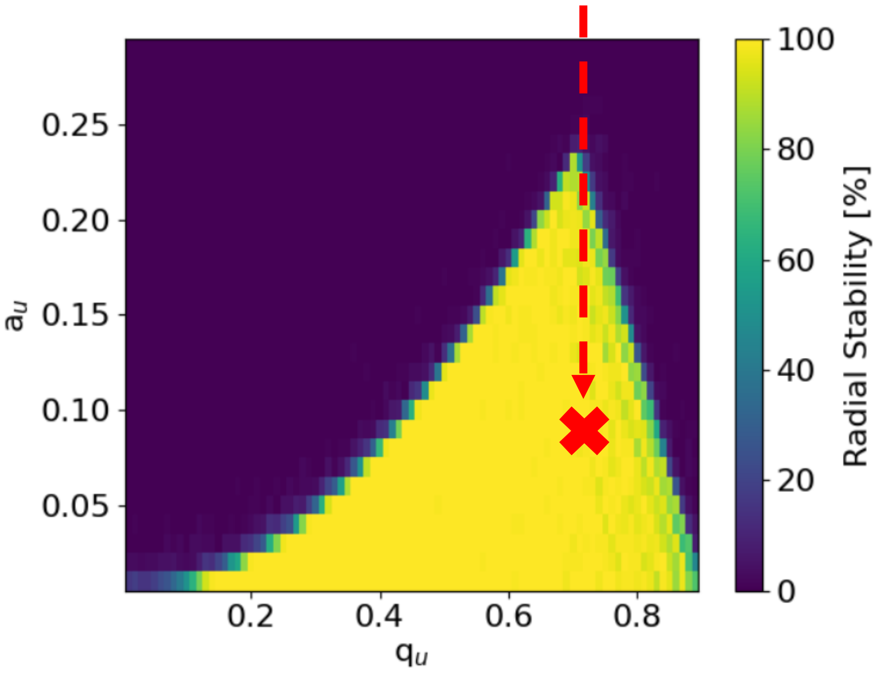
Using the previous operating parameters, we optimize the Mathieu stability parameters:

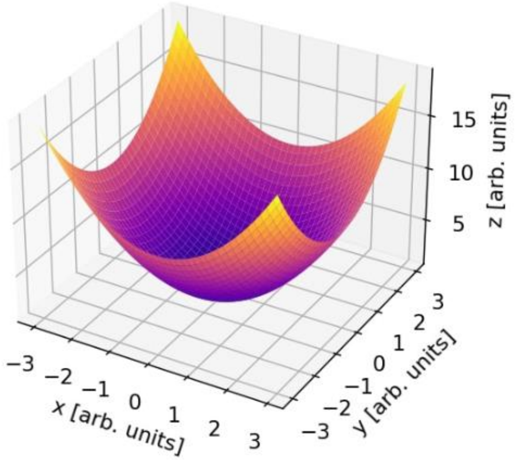
$$a_u = \frac{8eVDC}{m\omega^2 {r_0}^2} \qquad q_u = \frac{2eVRF}{m\omega^2 {r_0}^2}$$

and we get 100% radial stability. The resulting voltages have:

- A DC amplitude of 12.1 V
- A RF amplitude of 246 V

$a_u = 0.122$ and $q_u = 0.62$





Capture schemes: Summary

Endcap potentials:

Ion energy: 0.75 eV
Capture efficiency: 50 %

→

- Low complexity
- No segmentation needed

Step potential:

Ion energy: 0.55 eV
Capture efficiency: 65 %

→

- Medium complexity
- **Best for fastest cooling**

Combination:

Ion energy: 0.66 eV
Capture efficiency: 98 %

→

- High complexity
- **Best for wider acceptable parameter space**

Capture schemes: Limitations

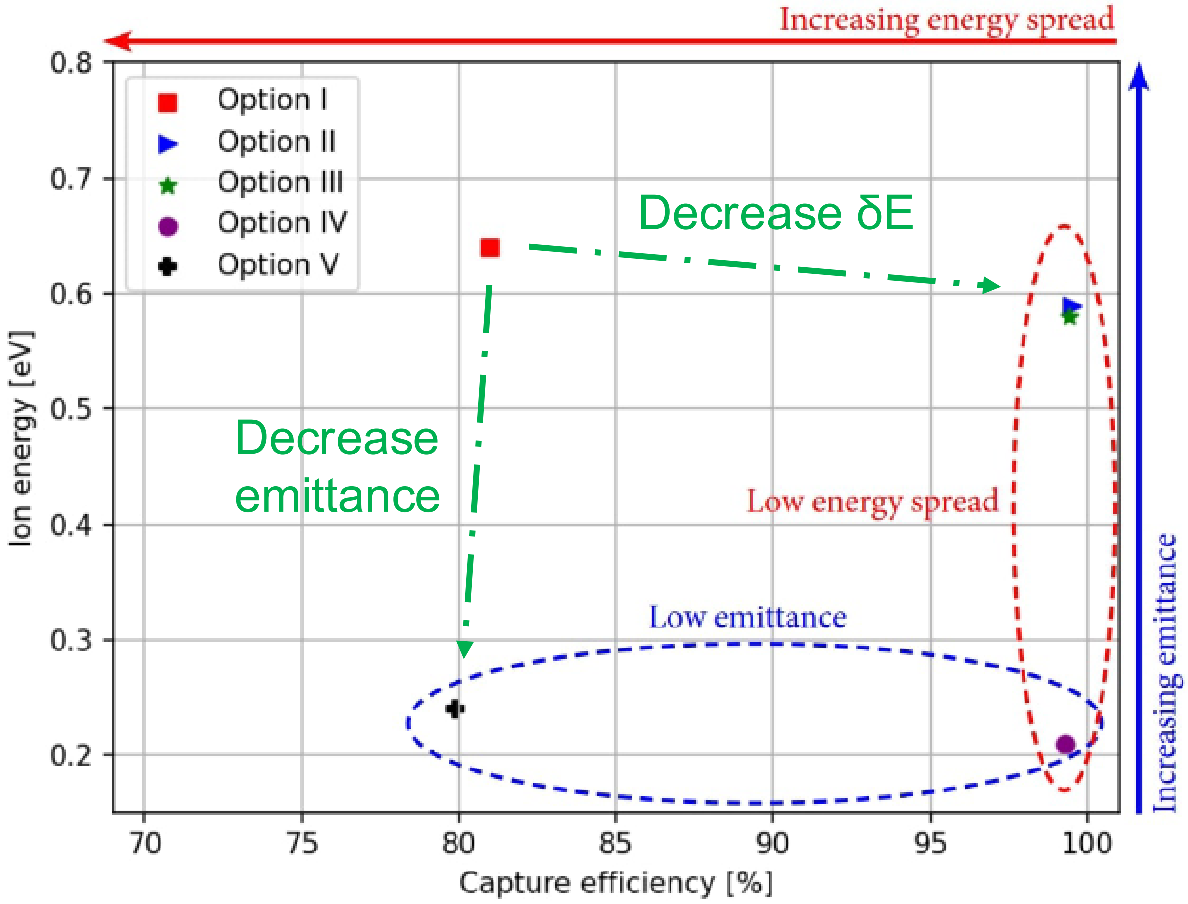
Question:

Is there a better trap configuration or is the beam quality the limiting factor?

Investigation:

Take the capture scheme 2 for V_{trap} = 4 V and explore the beam characteristics.

	δE [eV]	δToF [μs]	emittance [mm · mrad]
Option I	0.5	1	3π
Option II	0.2	1	3π
Option III	0.2	0.1	3π
Option IV	0.2	0.1	1
Option V	0.5	1	1

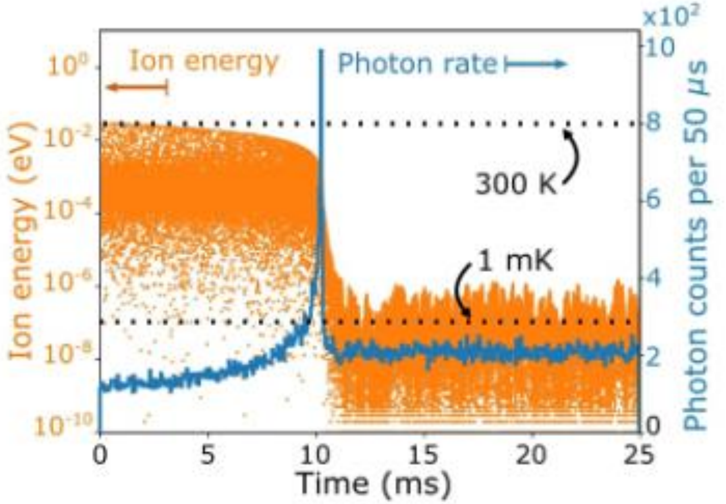


Cooling schemes: Details

Cooling scheme: Benchmarking

Recent publication[1]:

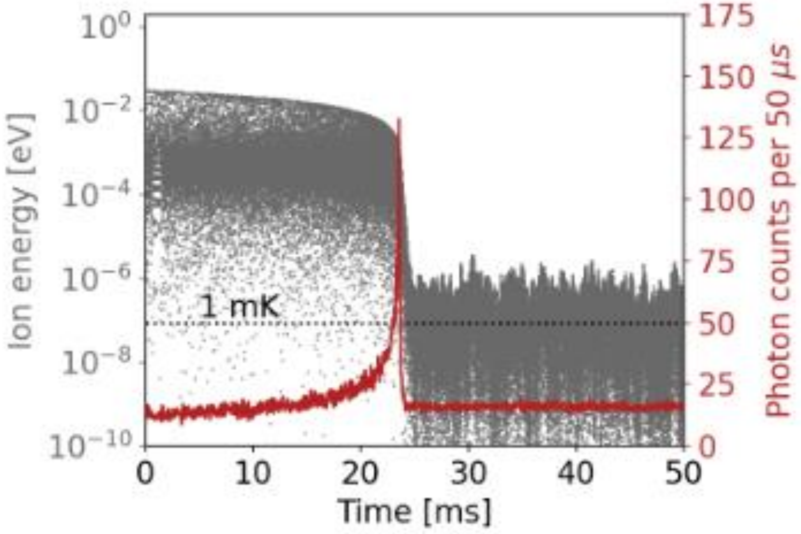
Take a ^{24}Mg^{+} ensemble and leave it to thermalize in a room temperature (0.03 eV) buffer gas. Then pick one random ion and cool it using a 25 mW (2mm) laser red-tuned by – 200 MHz from the D2: $3s^2P_{3/2}$ -> $2s^2S_{1/2}$ transition



My case:

Initialize a 0.03 eV ^{24}Mg^{+} ion directly into the trap, assume 1D and cool it with the same transition.

The difference in cooling time is due to the 1D approximation, where cooling the z-axis is more time-consuming due to an imperfect trapping potential.



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[1] S. Sels et al. Phys. Rev. Res. 4 (2022) 033299

Cooling scheme: Realistic case

Laser detuning:

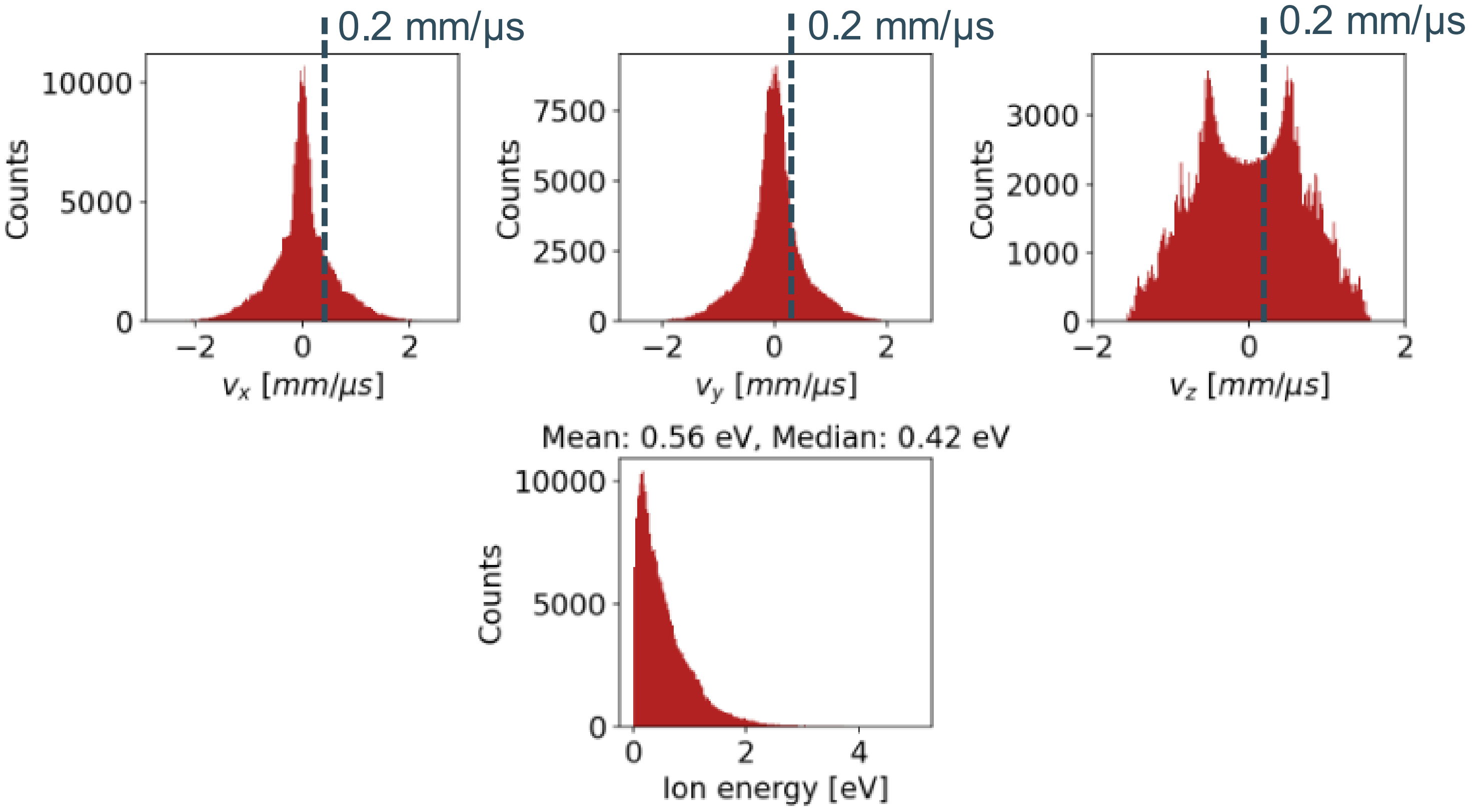
To determine the ideal laser frequency detuning from resonance **δ**, we need the velocity distributions of the trapped ions.

We then choose the Doppler shifted frequency detuning to match the ions velocities close to 0 mm/μs.

This guarantees:

- High chance that the ions will have these velocities initially
- Increasing chance for laser cooling, as the cooling progresses

Results of 100 uncorrelated ions

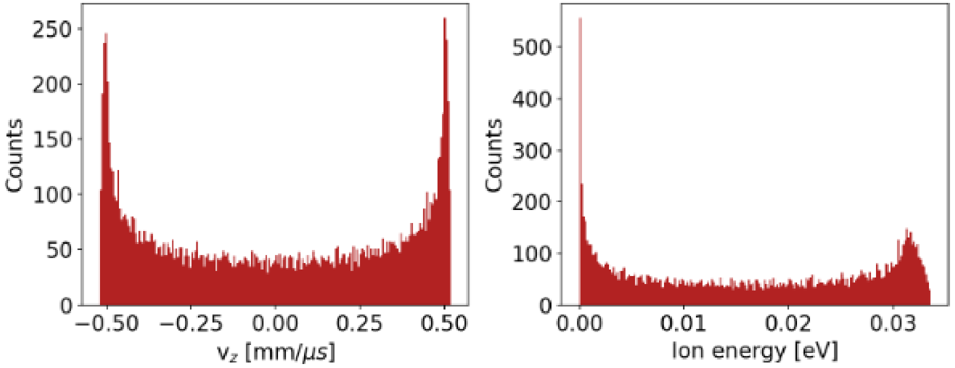


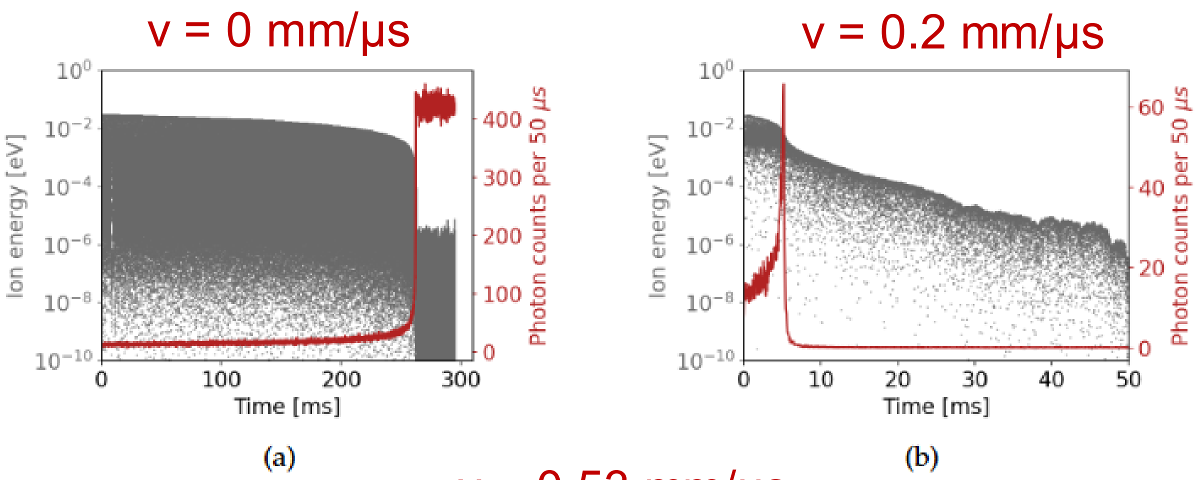
Optimizing δ

Literature:

The spike in the Doppler cooling occurs for δ = - Γ/2 tuned for half the width of the velocity distribution.

Let's look at the simpler case of a single ^{24}Mg^{+} ion.

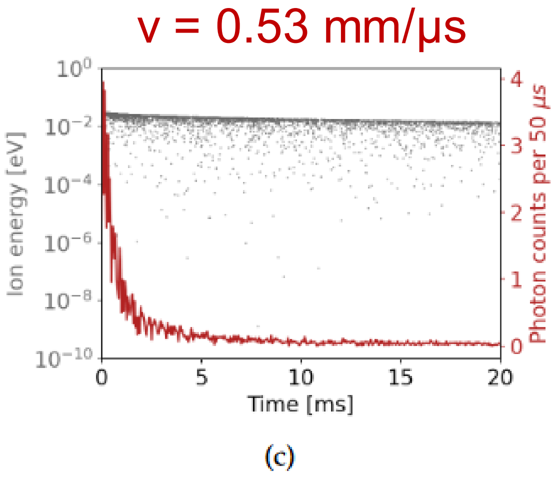



v = 0 mm/µs

v = 0.2 mm/µs

(a)

(b)


v = 0.53 mm/µs

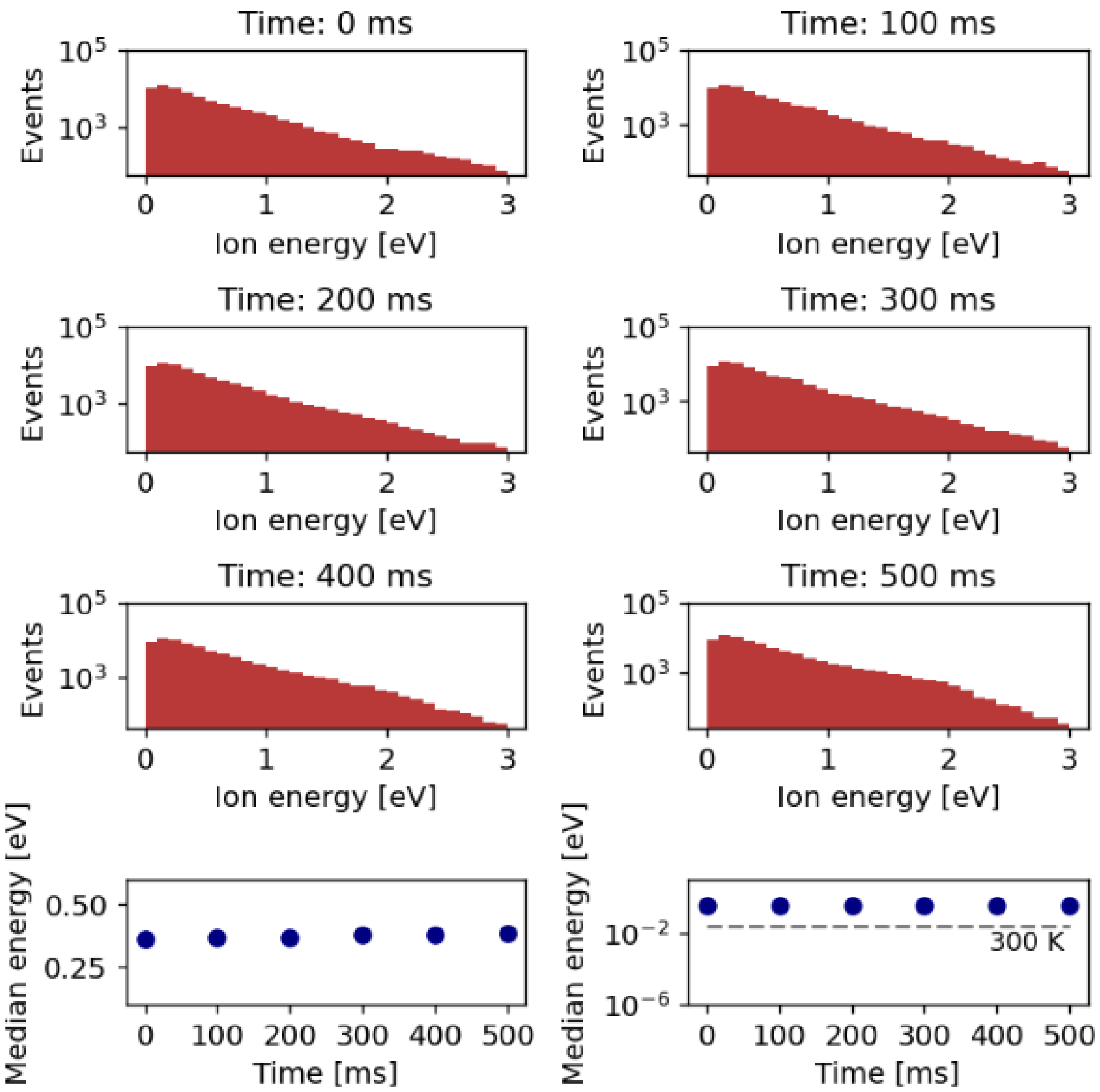
(c)

Optimizing δ

Literature:

Applying this to the realistic 3D case doesn't work.

A slight heating effect is also visible, probably due to the imperfect shape of the trapping well.

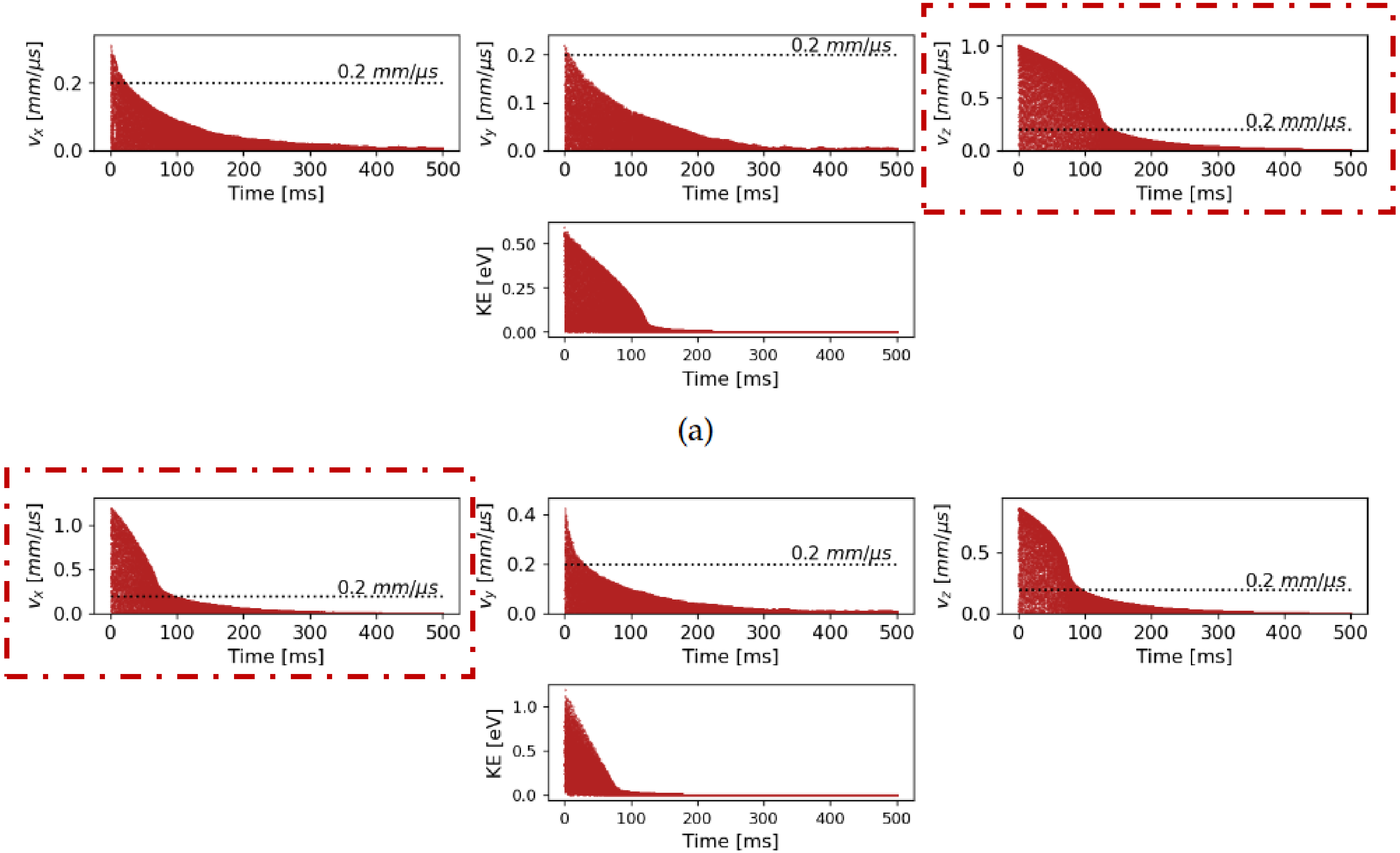


Cooling scheme: Realistic case

Results:

Cooling the z-axis is more time-consuming, due to the imperfect trapping well.

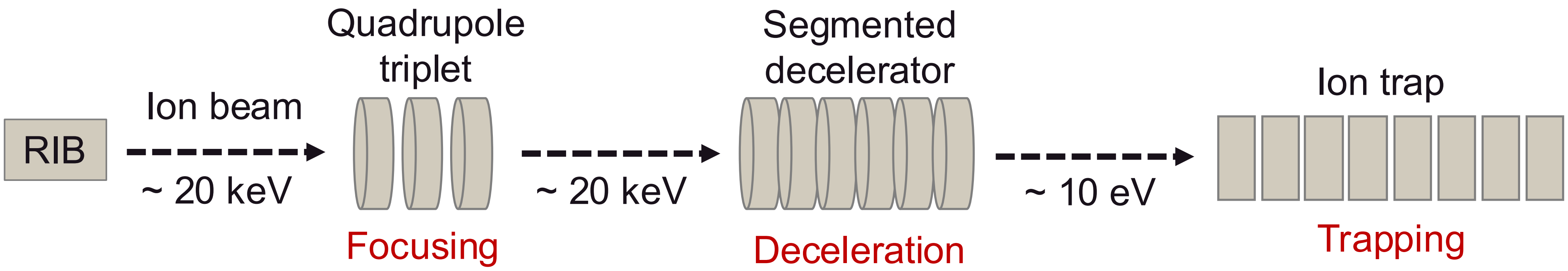
One could restrict the fluorescence measurements on the xy-plane, whose modes are cooled faster.



(a)

Full plan

Plan



Quadrupole triplet

Segmented decelerator

Ion trap

RIB

Ion beam

~ 20 keV

~ 20 keV

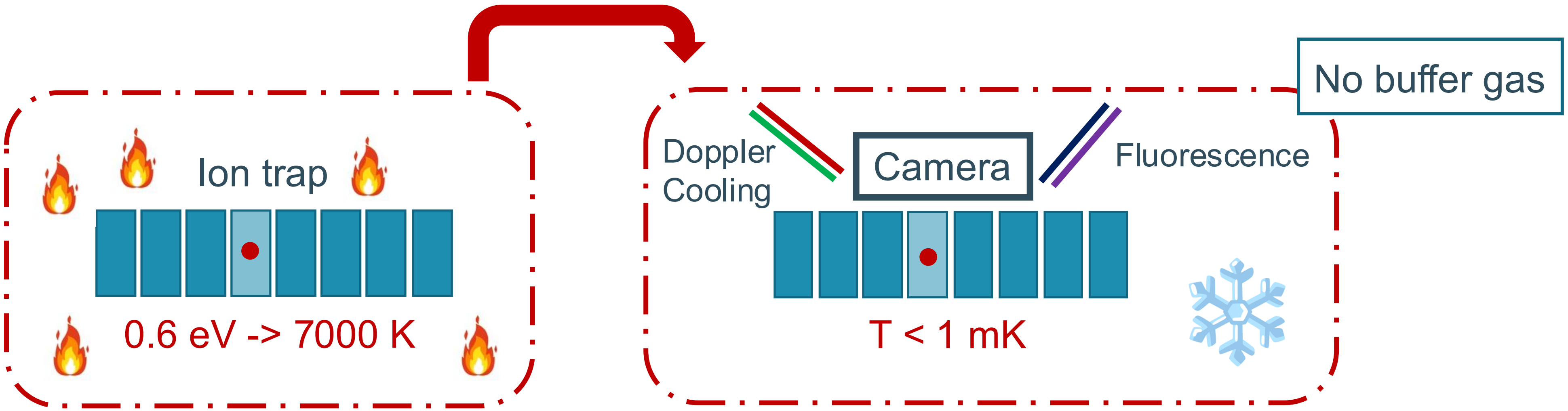
~ 10 eV

Focusing

Deceleration

Trapping

Cooling:



Ion trap

0.6 eV -> 7000 K

Doppler Cooling

Camera

Fluorescence

T < 1 mK

No buffer gas

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[1] G. Lospalluto MSc thesis, University of Manchester (2020)

Doppler broadening

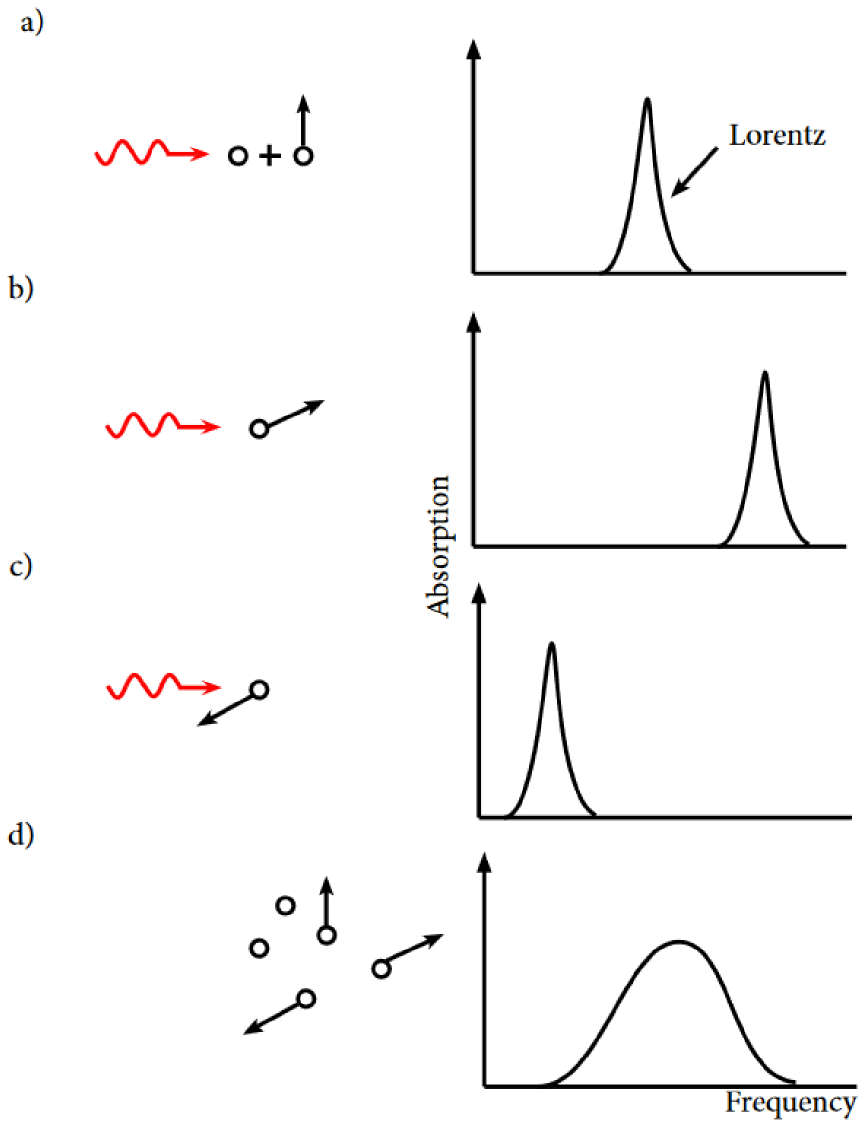
Principle:

This Doppler broadening is:

- Proportional to the frequency
- Scales with temperature

Performing precision measurements requires a Doppler broadening smaller than the natural linewidth. This mean **cold**!

e.g. For a 10^{15} Hz transition (UV) of an ion with 10 amu mass, getting a 10 MHz Doppler shift requires T ~ 1 mK.



C. J. Foot, Atomic Physics, Oxford University Press, USA, 2005