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Physique quantique et applications

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MPQ

Sympathetic cooling of a Be^+ ion by a Coulomb crystal of Sr^+ ions: a test bed for taming antimatter ions (GBAR)

Derwell Drapier

Collaboration between LKB and MPQ
LKB : Laurent Hilico, Jean-Phillipe Karr and Albane Douillet
MPQ : Jean-Pierre Likforman and Luca Guidoni

Context & objective

[1] Observation of the effect of gravity on the motion of antimatter. Nature, Vol 621, 2023

Context

CERN : 3 experiments are currently studying the antimatter behavior regarding earth gravity:

- ALPHA-g → $\bar{g}/g=0.75\pm0.29$ [1]
- AegIS
- GBAR

Each experiment has a different approach to measure $\bar{g}$ → Comparison of different measurements

Antiproton Decelerator (AD) and ELENA (Extra Low ENergy Antiproton) produce $\bar{p}$ at 100keV

Create $\bar{H}$ atoms **and cool** them to study the effect of gravity

Context

GBAR : study the free fall of an antihydrogen atom prepared at rest[2].

Need ultra-cold antihydrogen

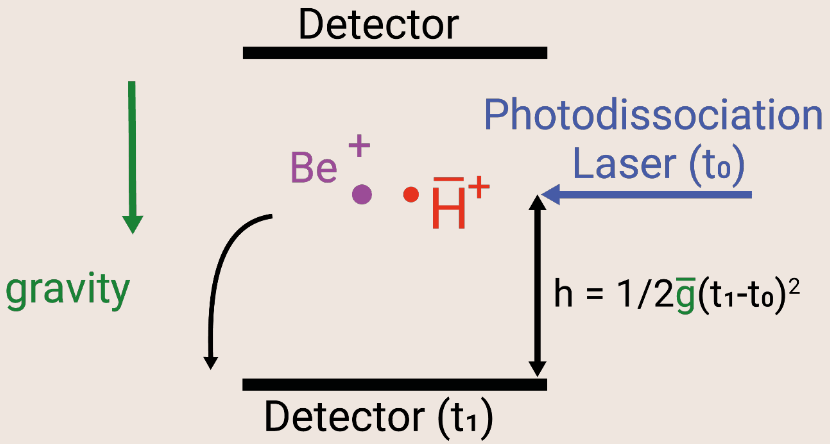
Create a $\overline{H}^+$ ion

$$\bar{p} + Ps \longrightarrow \overline{H} + e^-$$
$$\overline{H} + Ps \longrightarrow \overline{H}^+ + e^-$$

Incident $\overline{H}^+$ with an energy of 1eV (10 000K) in Paul trap

Cooling to 10µK :

- **1st step** : sympathetic cooling using ~1000 laser-cooled Be^+ ions to the Be^+ Doppler limit (mK)
- **2nd step** : Ground-state cooling of the $\overline{H}^+/Be^+$ pair to sub-Doppler limit



[2] P. Perez and Y. Sacquin, Classical and Quantum Gravity, **29** (2012)

Context

1^{st} cooling step:
1eV to 100neV

Sympathetic cooling is obtained by the coupling of the hot species and the cold species via **Coulomb interaction**
The dynamics depends on the mass ratio between the 2 species but the $m_{hot}/m_{cold} << 1$ case is **unfavorable mass ratio**

Modeling 1^{st} cooling step:
→ **N-body problem:** numerical simulations to long to compute

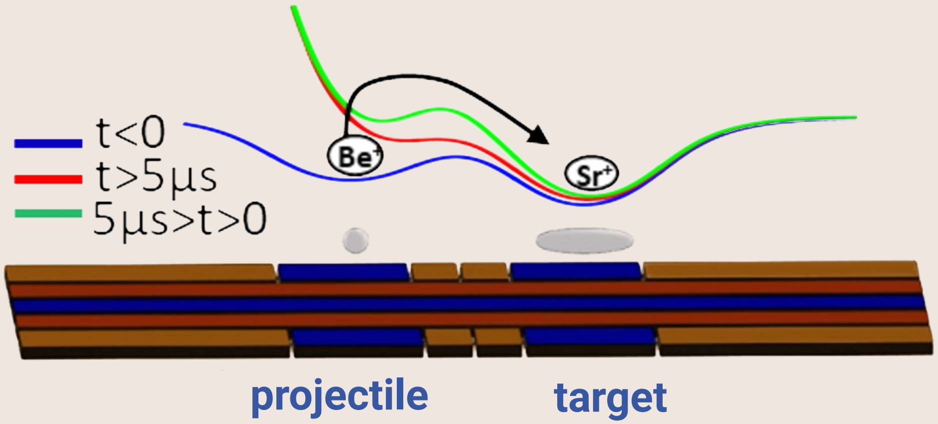
Experimental simulation to get quantitative information about the cooling process

Similar mass ratio

$\overline{H}^+/Be^+$ (1/9) ↔ Be^+/Sr^+ (9/88)

Be^+ laser addressable (cool and measure)

Objective of the experiment



Be^+ initially cooled at Doppler limit in the **projectile trapping zone**

Sr^+ Coulomb crystal load in the **target trapping zone**

Launching of Be^+ with controlled energy (0.1-1eV)

Measure cooling dynamics of Be^+ over 7 orders of magnitude (10 000K→1mK, 1eV→ 100neV)

Outline

I. Experimental setup

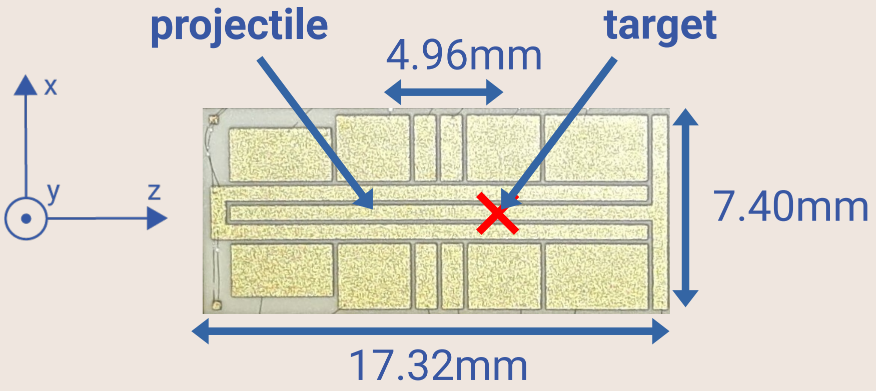
II. Ion launching : approach and simulations

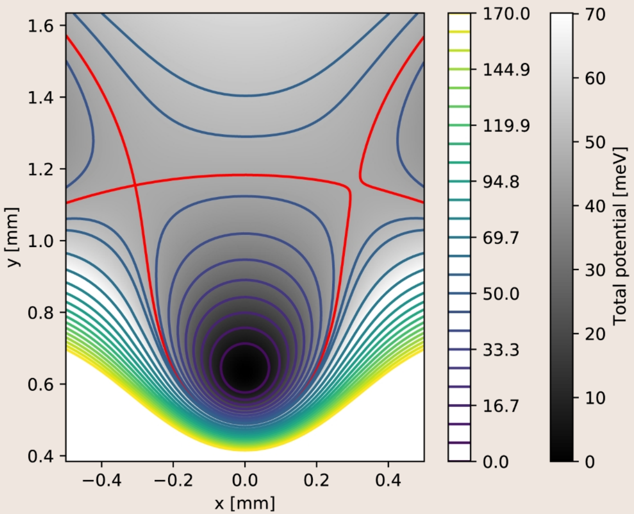
III. Experimental results

IV. Outlook

I- Experimental setup

Ions trap: linear surface trap



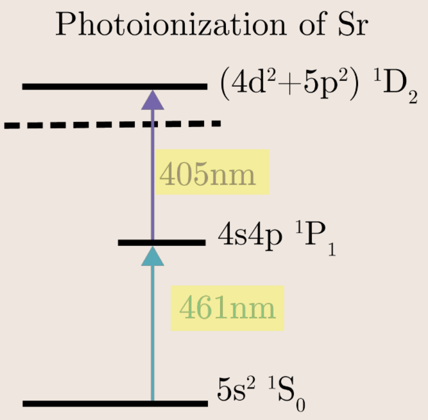


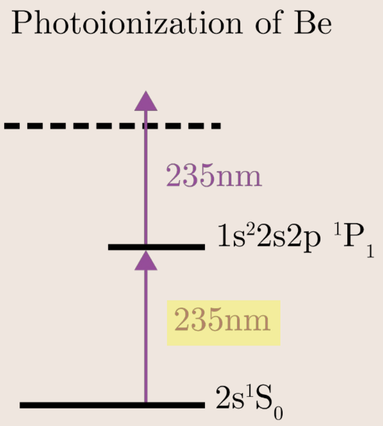
Specifications:

- Subtract: **alumina** (Al_2O_3)
- Electrodes: **gold plated copper** (Au/Cu)
- RF frequency : **14MHz** (up to 20MHz)
- RF amplitude : **500-1000Vpp**
- **Trapping height : 635µm**
- Spacing of the two trapping zones: **4.96mm**
- **Interelectrode** distance : **200µm**
- RF trapping **depth** : **~50meV** for Sr^+
- Radial frequencies : ~350kHz
- Stability parameters: a~0 & q_{Sr+}~0.06

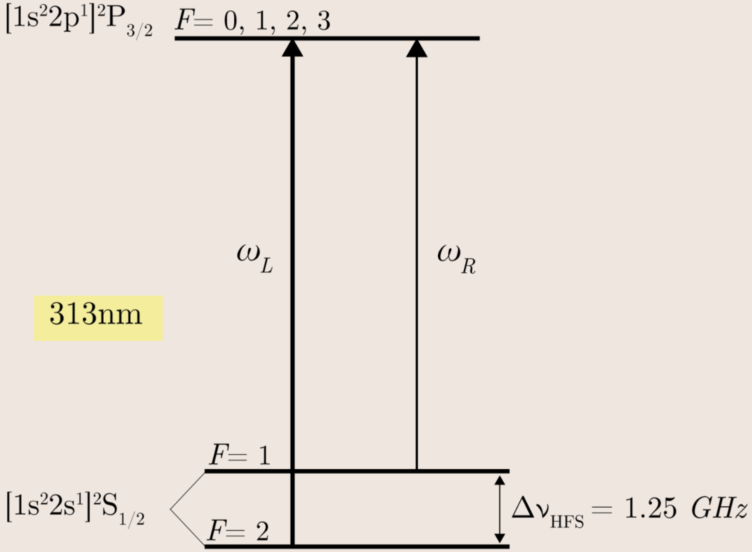
Useful wavelengths

235nm, 313nm, 405nm, 422nm, 461nm,
1003nm, 1033nm and 1092nm

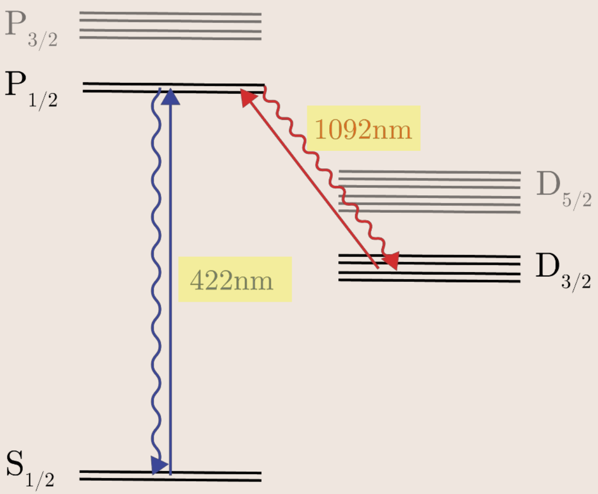




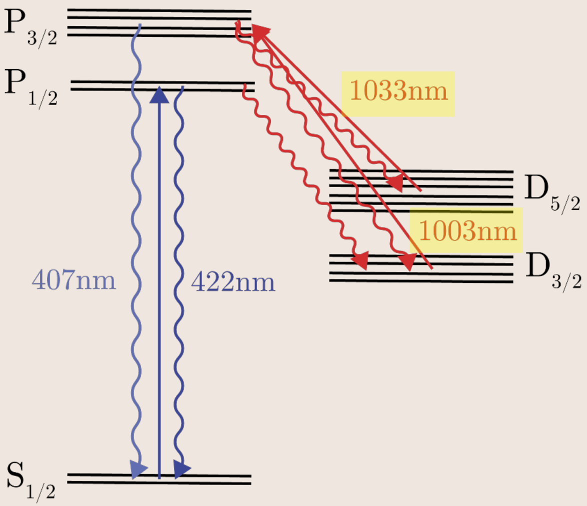
Energy levels diagram of Be⁺ for Doppler cooling



Energy levels diagram of Sr⁺ for Doppler cooling



Coherent repumping scheme

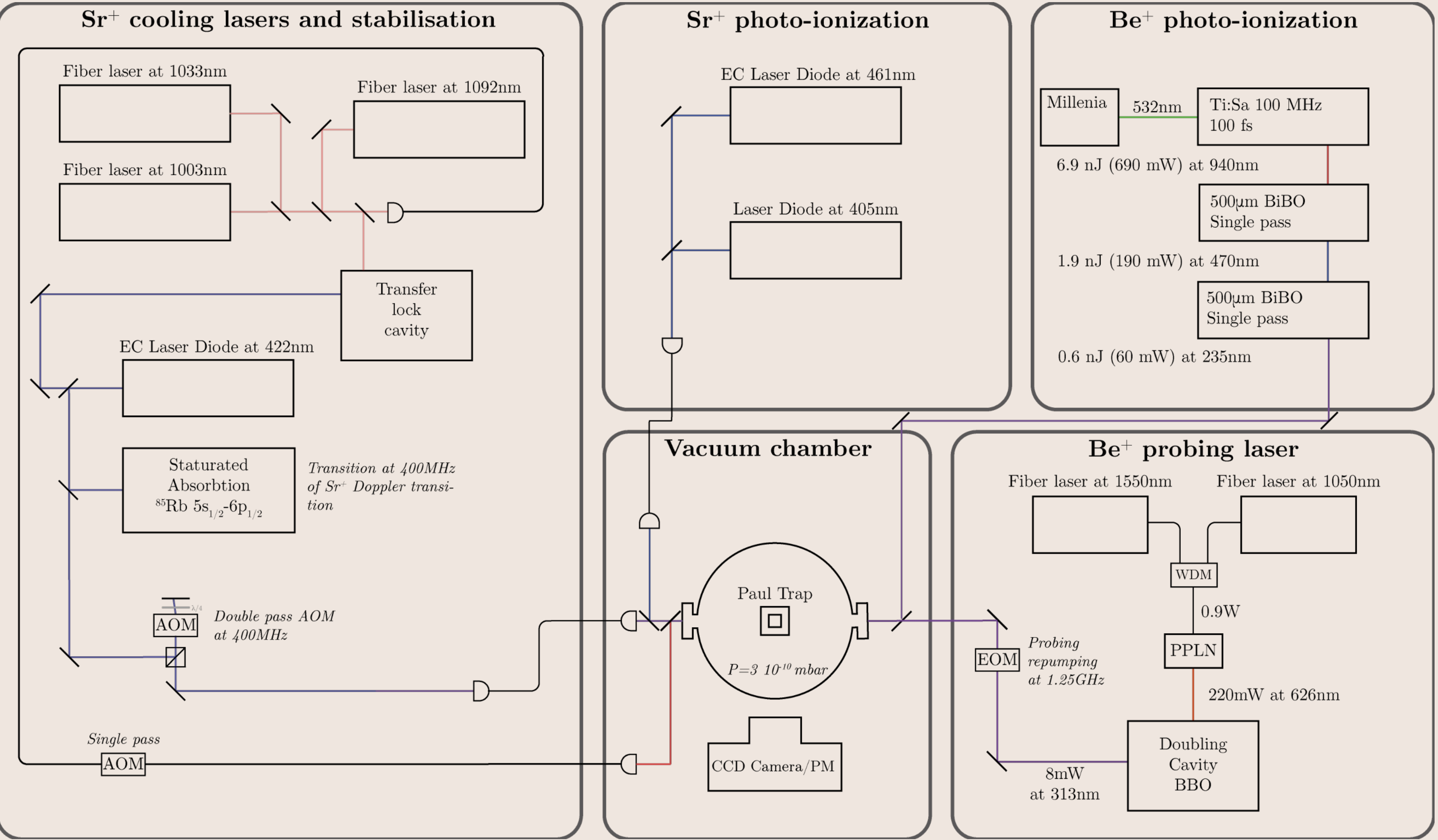


Incoherent repumping scheme

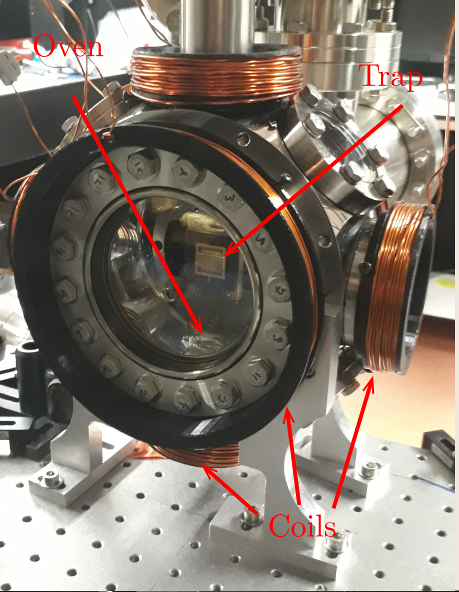
Laser setup :

313nm power:
8mW

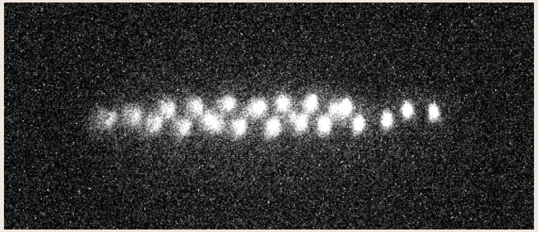
422nm power:
500μW



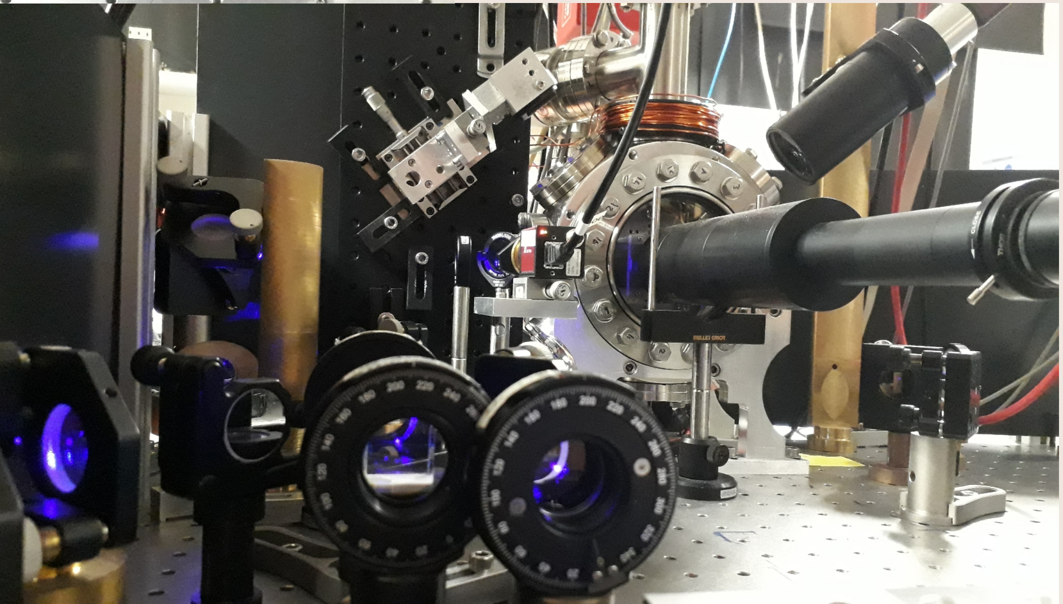
Around the trap

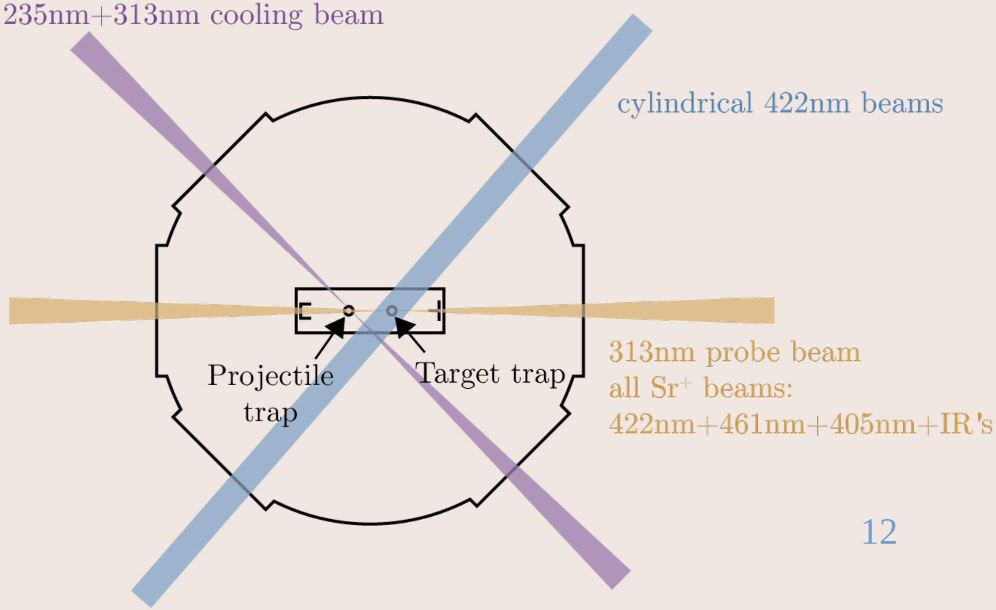


In front of the trap: **camera + PM**



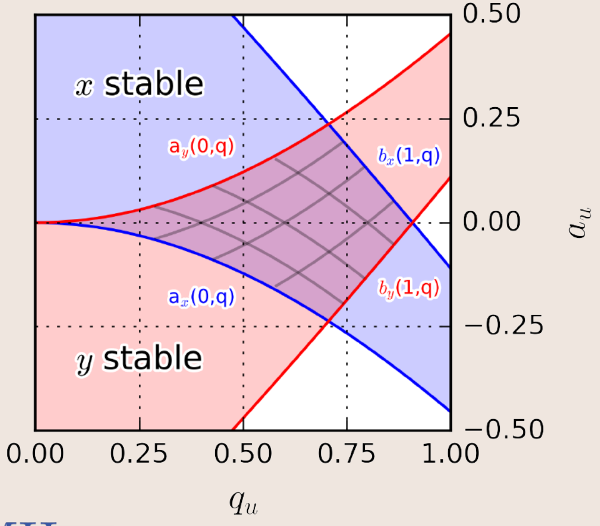
Ultra-high vacuum chamber (2.5 10^{-10}mbar)





Trapping stability

Equations of motion of an ion in the trap → Mathieu equation
Oscillating or divergent solution depending on stability parameters (a and q)



$$q \propto \frac{V_{RF}}{m\Omega^2} \qquad q_{Be} = \frac{m_{Sr}}{m_{Be}} q_{Sr}$$

Ω	3.60MHz	5.17MHz	7.26MHz	11.4MHz	14.15MHz
V_{RF}	533Vpp	780Vpp	809Vpp	630Vpp	510Vpp
q	0.561	0.561	0.295	0.0933	0.0615

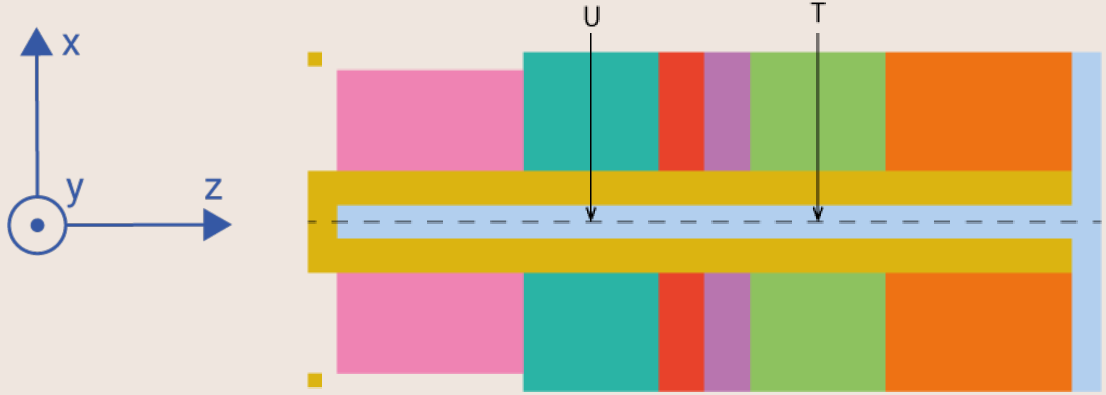
q_{Sr}max = 0.561 → we need to work at q_{Sr}~0.057
Ω_{RF} : [14MHz : 20MHz]

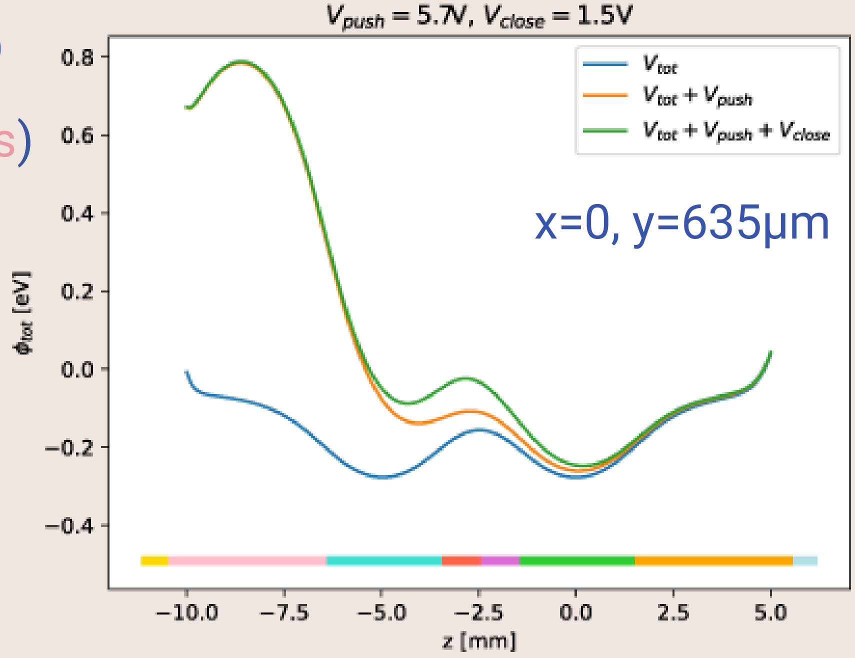
II- Ion launching: approach & simulations

Approach for ion launching

Objective : control the launching energy

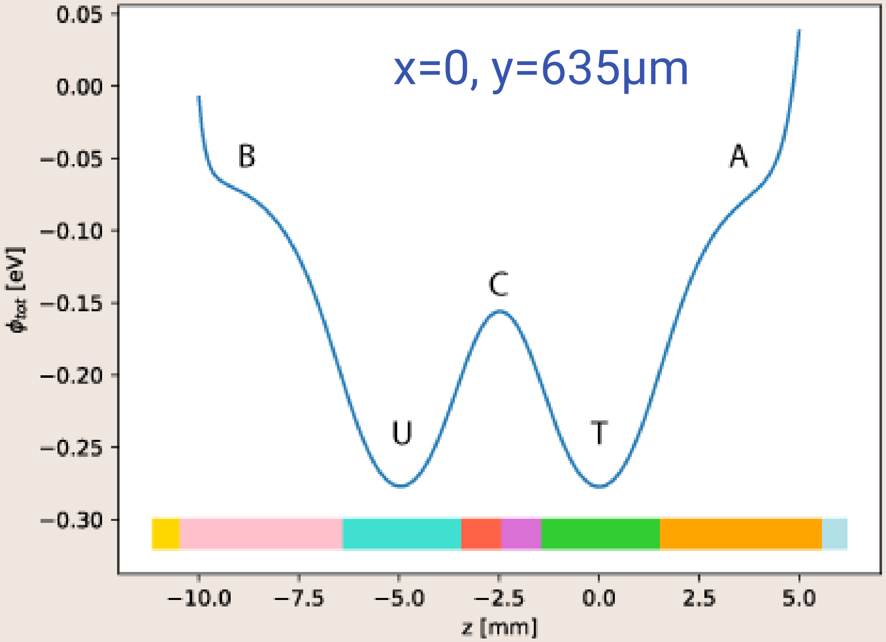
- Cooling Be^+ ($E_c \approx 0$eV) in the projectile trapping zone (U)
- Add voltage V_{push} at the end electrodes (pink electrodes)
- Add V_{close} between the two trapping zone (red electrodes) Δt later when the ion arrives in the target trapping zone



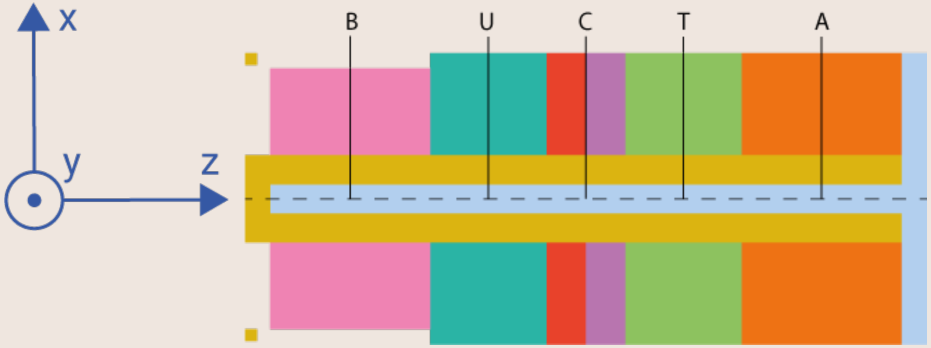


Calculation of the initial DC voltages

A : end of trap
T : center of the target trap
C : middle of the trap
U : center of the projectile trap
B : end of trap

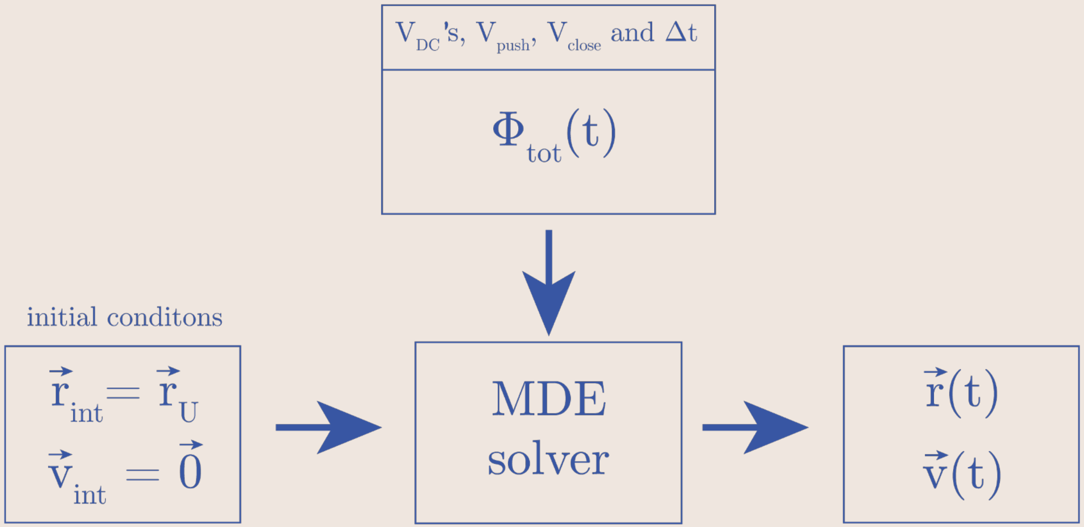


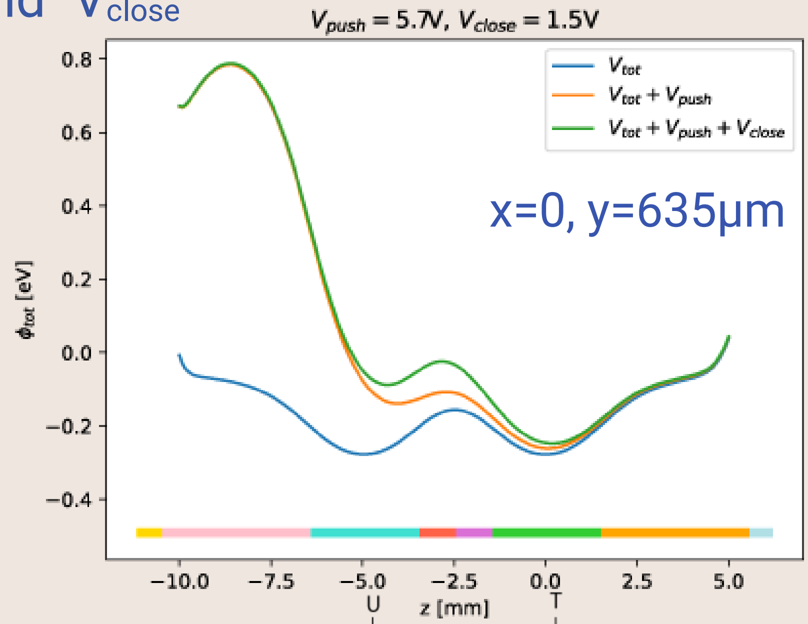
We want a potential whose **central barrier is lower** than those on the sides



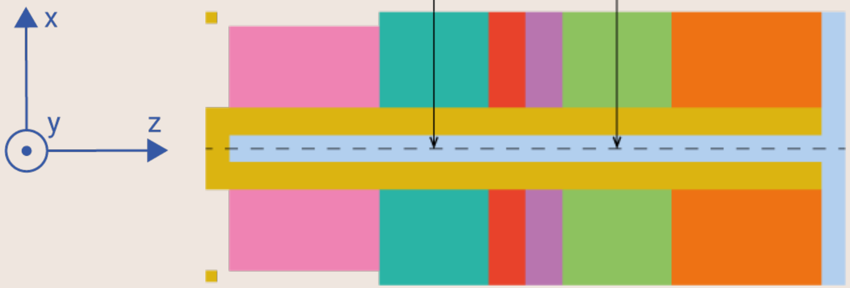
Launching simulation

Objective : find the launching parameters V_{push}, Δt and V_{close}





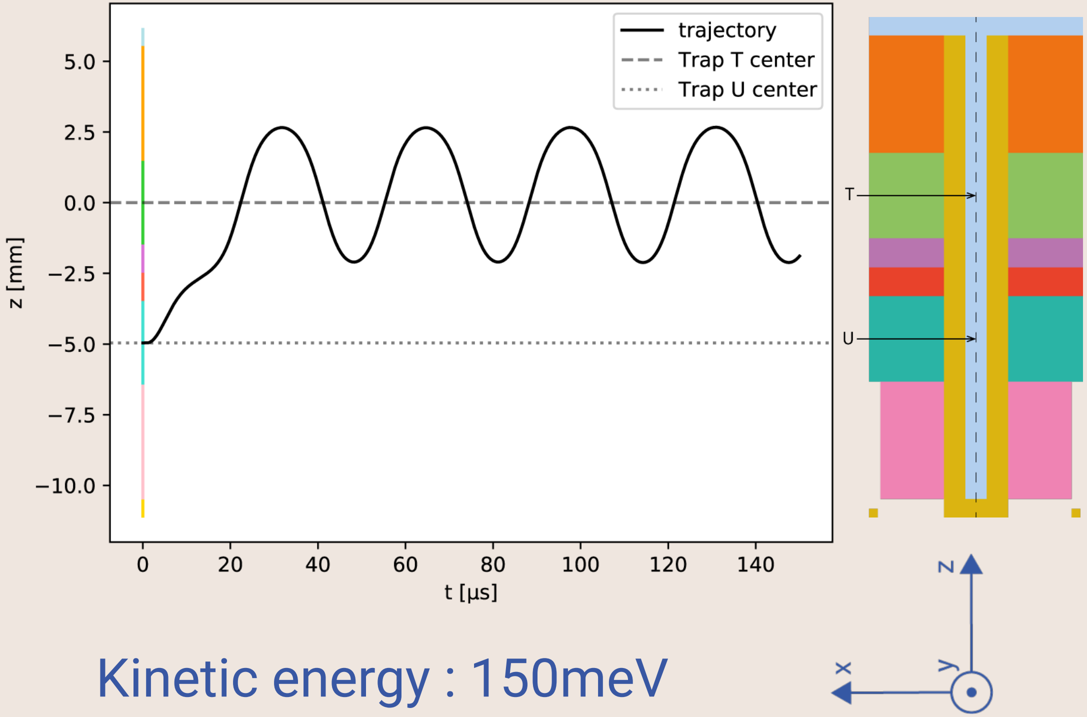
1) Find V_{push} to enter the target trap
2) Find Δt (in simulation)
3) Finaly find V_{close}



III- Experimental results

Simulation and experimental results

V_{push}=5.7V, V_{close}=1.5V and Δt=35μs



Kinetic energy : 150meV

Simulation and experimental results

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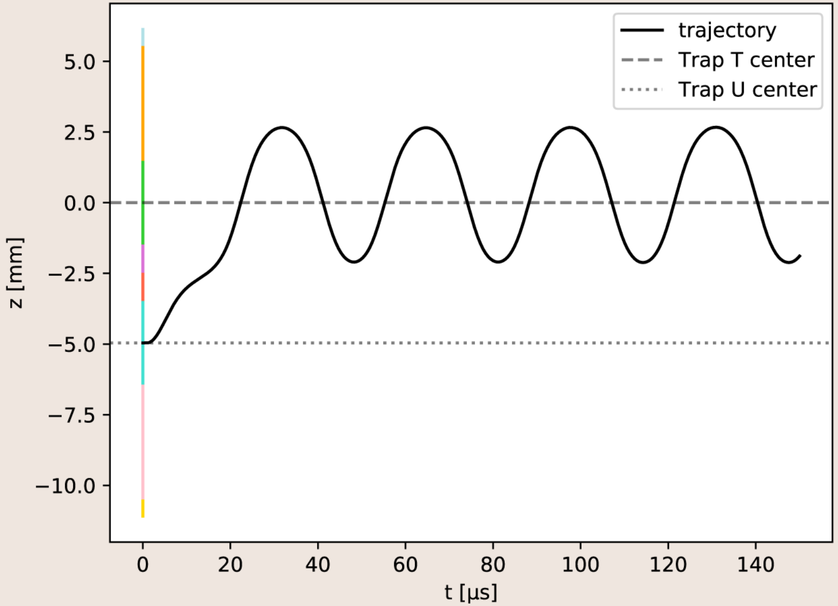
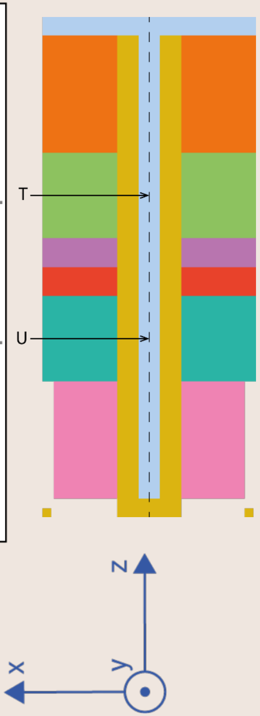
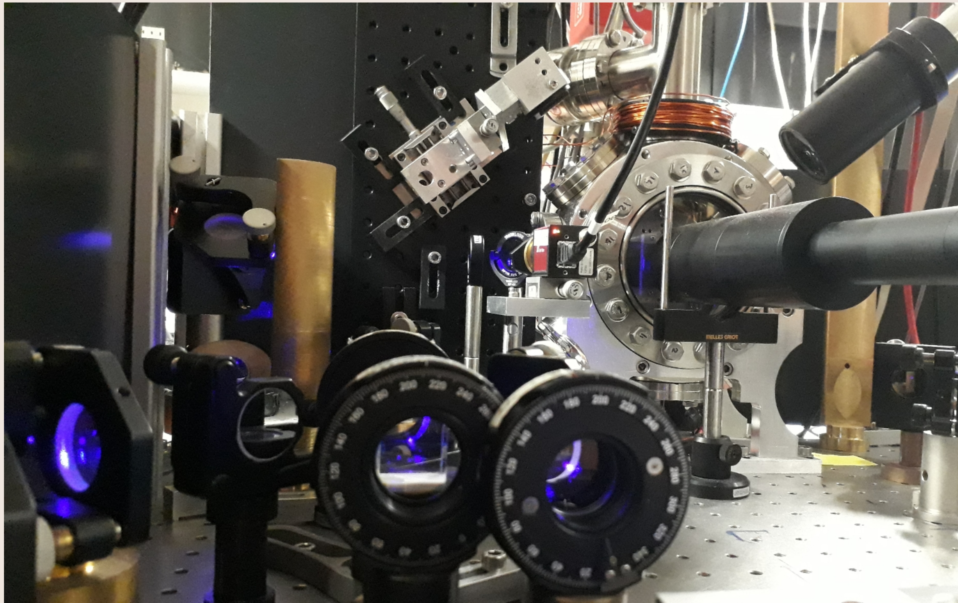




Kinetic energy : 150meV

Launching of Sr^+ ions achieved with a success rate of up to 95%



Characterization of Sr^+ energy

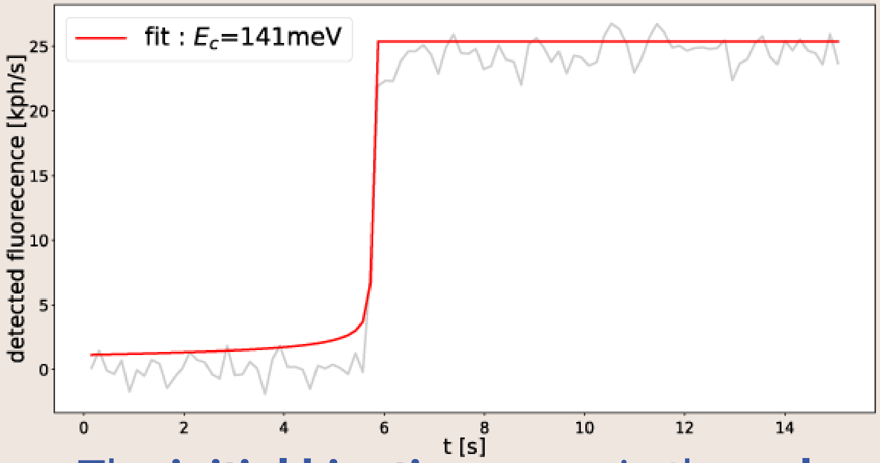
Objective : Measure Sr^+ initial energy

Method : Doppler recooling technique[4]

- Depending on the initial kinetic energy of the ion, the fluorescence will rise more or less late.
- Knowing the **saturation parameter** and the **detuning** of the laser it is possible to **fit the fluorescence** dynamics after launching to **obtain the initial energy** of the ion.

The model considers a constant laser intensity

The laser intensity depends on the position of the ion
→ **We need a new model**



The **initial kinetic energy** is the **only adjustable parameter** of this fit

Cooling time: $t_r \approx -\dfrac{4\sqrt{r}\varepsilon_0^{3/2}}{3\delta}$

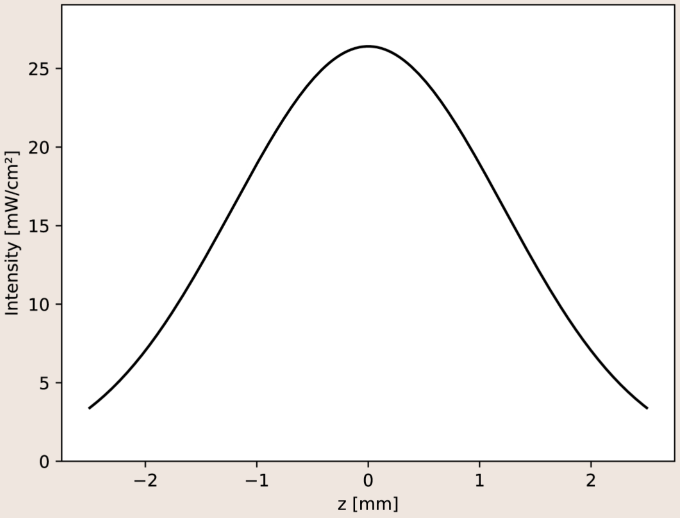
r : normalized recoil energy

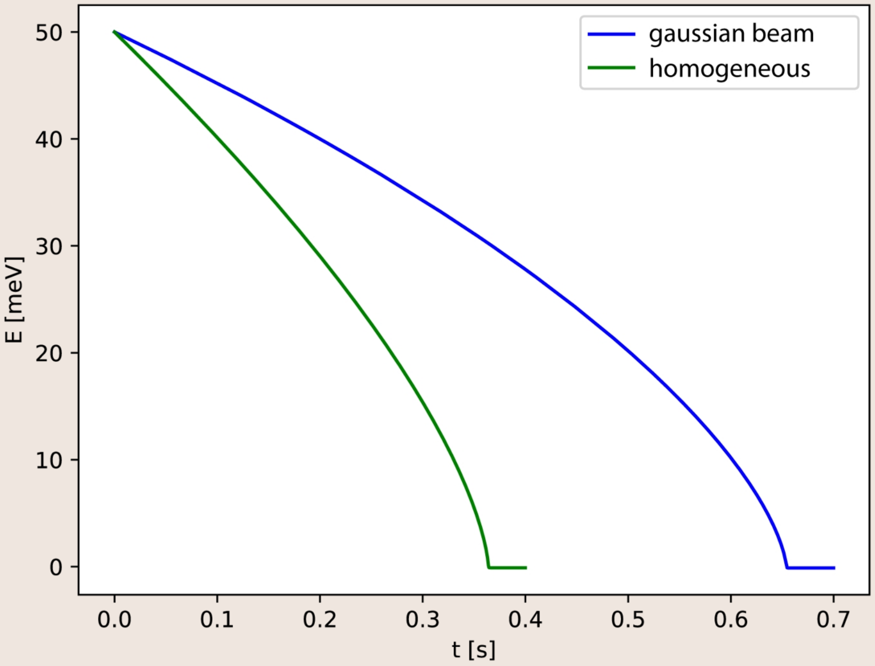
ϵ_0 : normalized initial energy

δ : normalized laser detuning

[4] Wesenberg *et al*. *Phys. Rev. A*, 76 :053416, 2007.

New model





- Potential simplification : polynomial fit
- Doppler cooling : dissipative force of a Gaussian beam $\vec{F}(\vec{v}, I(\vec{r}))$

$$\vec{F}_{dissip} = \hbar \vec{k_L} \frac{\Gamma}{2} \frac{\Omega_R^2/2}{(\delta_L - \vec{k_L} \cdot \vec{v})^2 + \Omega_R^2/2 + \Gamma^2/4}$$

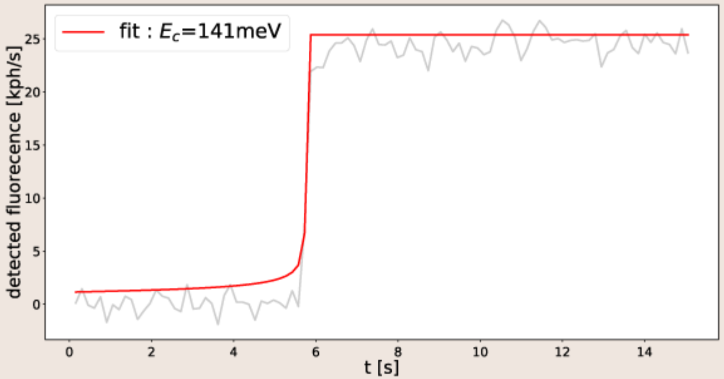
- Initial conditions:

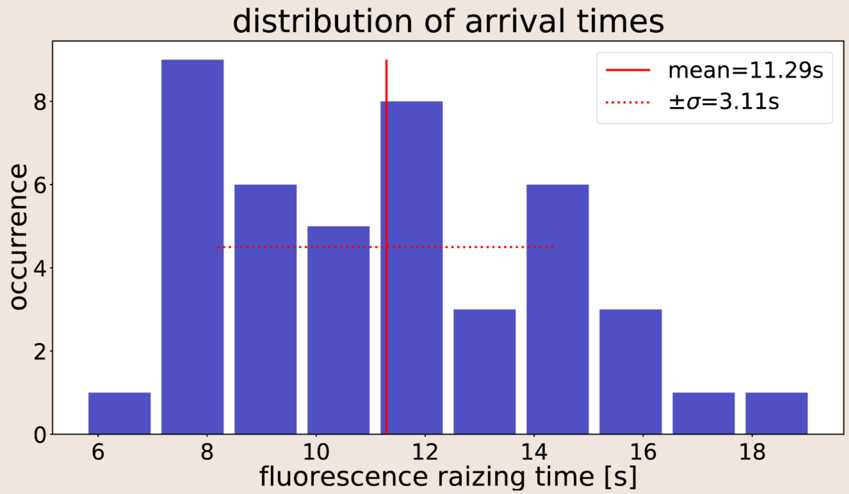
$$\vec{r} = (x_{0,T}, y_{0,T}, z_{0,T})$$

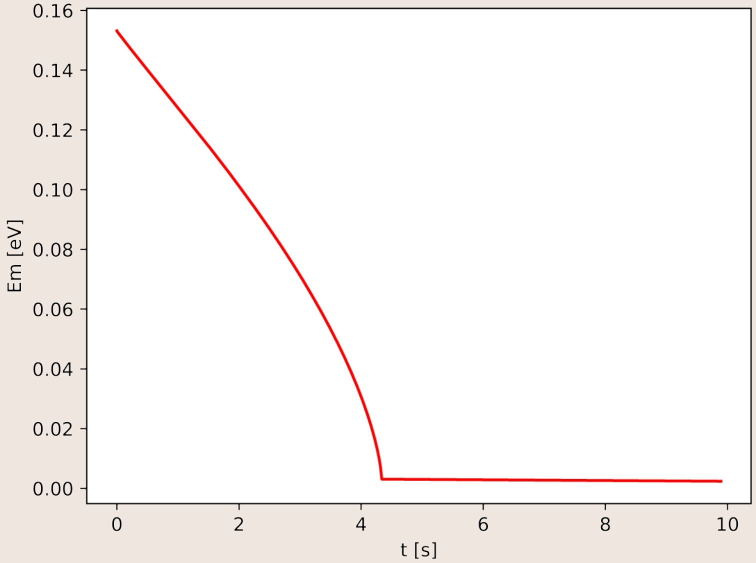
$$\vec{v} = (0, 0, \sqrt{2E_c/m})$$

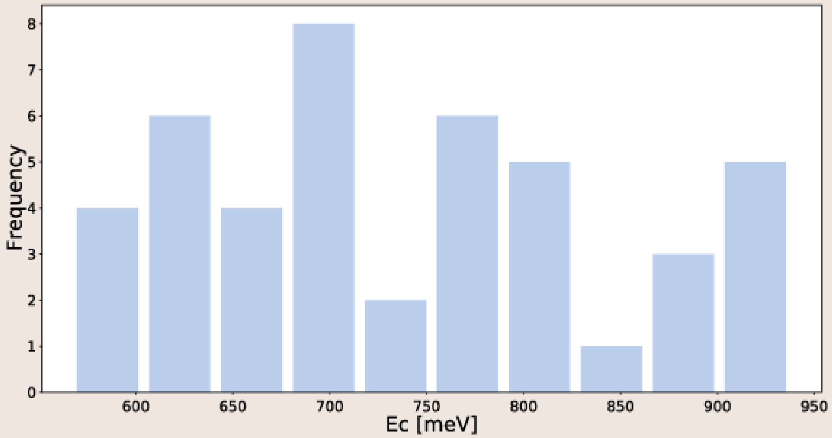
Cooling time:
Homogeneous: 360ms
Gaussian beam: 650ms

Work in progress







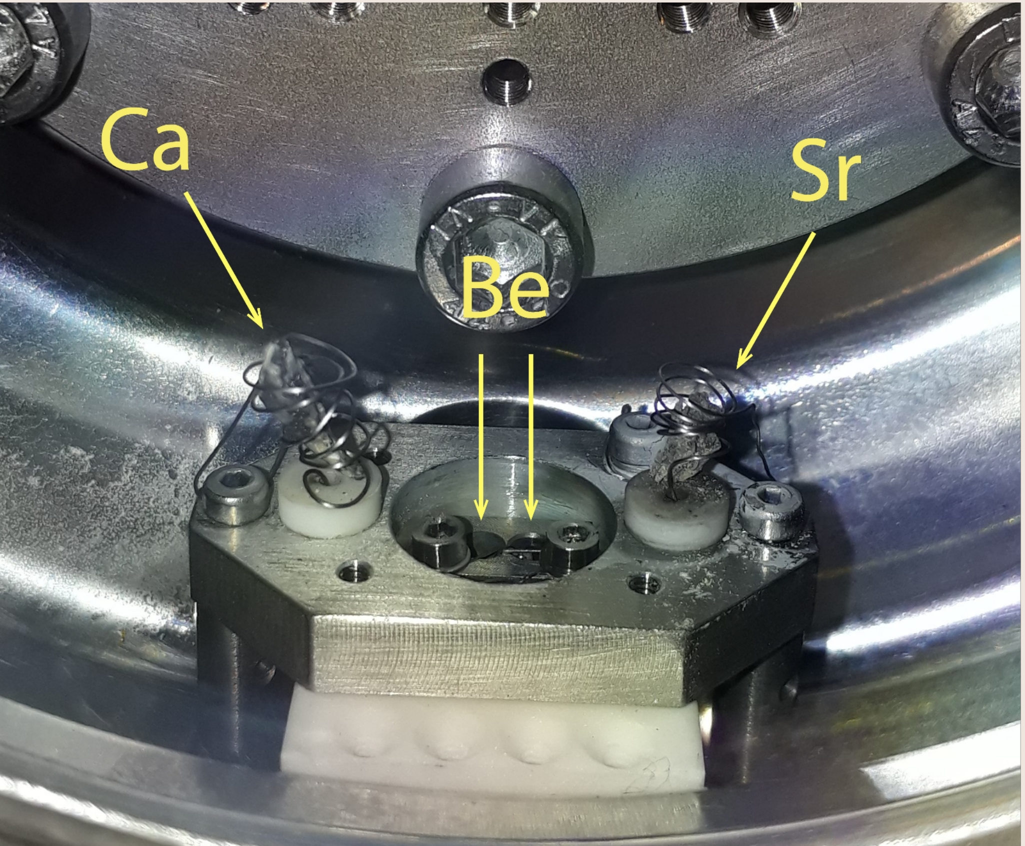


Outlook

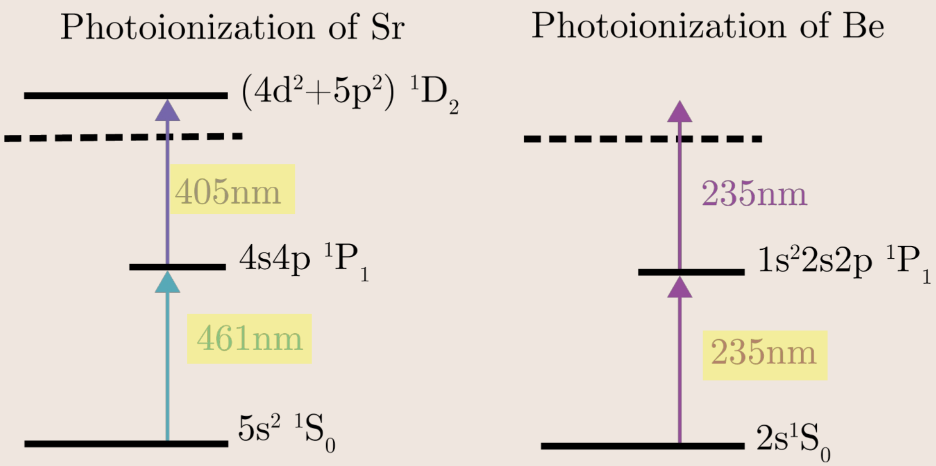
- Finishing the characterization of the launching energy of Sr^+ ions
- Be^+ trapping and cooling
- Trapping both Be^+ and Sr^+
- Launching Be^+ in Sr^+ Coulomb crystal
- Ground state cooling of the Be^+/Sr^+ pair

Thank you for your attention

Ion creation



Two step photoionization



Matrix Method

Potential of a rectangular electrode[3] :

Position (x,y,z)
Rectangle (x_1,x_2,z_1,z_2)

$$\phi(x,y,z) = \frac{V}{\pi}\Bigg\{ \arctan\left[\frac{(x_2-x)(z_2-z)}{y\sqrt{y^2+(x_2-x)^2+(z_2-z)^2}}\right] - \arctan\left[\frac{(x_1-x)(z_2-z)}{y\sqrt{y^2+(x_1-x)^2+(z_2-z)^2}}\right] - \arctan\left[\frac{(x_2-x)(z_1-z)}{y\sqrt{y^2+(x_2-x)^2+(z_1-z)^2}}\right] + \arctan\left[\frac{(x_1-x)(z_1-z)}{y\sqrt{y^2+(x_1-x)^2+(z_1-z)^2}}\right]\Bigg\}.$$

Taylor development for electrode i :

$$\frac{\phi_i(x,y,z)}{V_i} \simeq \alpha_{x,i}x^2 + \alpha_{y,i}y^2 + \alpha_{z,i}z^2 + \gamma xy + \beta_{x,i}x + \beta_{y,i}y + \beta_{z,i}z + cste$$

[3] M. G. House. *Physical Review A*, 78, 2008.

Matrix Method

$$\frac{\phi_i(x,y,z)}{V_i} \simeq \alpha_{x,i}x^2 + \alpha_{y,i}y^2 + \alpha_{z,i}z^2 + \gamma xy + \beta_{x,i}x + \beta_{y,i}y + \beta_{z,i}z + cste$$

$$\phi_{DC}(x,y,z) \simeq \sum_{i=elec} \phi_i(x,y,z) = \alpha_x x^2 + \alpha_y y^2 + \alpha_z z^2 + \gamma xy + \beta_x x + \beta_y y + \beta_z z$$

$$\begin{pmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \\ \gamma \\ \beta_x \\ \beta_y \\ \beta_z \end{pmatrix} = \begin{pmatrix} \alpha_{x,1} & \alpha_{x,2} & \alpha_{x,3} & \alpha_{x,4} & \alpha_{x,5} & \alpha_{x,6} & \alpha_{x,7} \\ \alpha_{y,1} & \alpha_{y,2} & \alpha_{y,3} & \alpha_{y,4} & \alpha_{y,5} & \alpha_{y,6} & \alpha_{y,7} \\ \alpha_{z,1} & \alpha_{z,2} & \alpha_{z,3} & \alpha_{z,5} & \alpha_{z,5} & \alpha_{z,6} & \alpha_{z,7} \\ \gamma_1 & \gamma_2 & \gamma_3 & \gamma_4 & \gamma_5 & \gamma_6 & \gamma_7 \\ \beta_{x,1} & \beta_{x,2} & \beta_{x,3} & \beta_{x,4} & \beta_{x,5} & \beta_{x,6} & \beta_{x,7} \\ \beta_{y,1} & \beta_{y,2} & \beta_{y,3} & \beta_{y,4} & \beta_{y,5} & \beta_{y,6} & \beta_{,7} \\ \beta_{z,1} & \beta_{z,2} & \beta_{z,3} & \beta_{z,4} & \beta_{z,5} & \beta_{z,6} & \beta_{z,7} \end{pmatrix} \times \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{pmatrix}$$

Pseudo-inverse

$$C = M \times V$$

$$V = M^{-1}C$$

Matrix Method : Generalization for N trapping zone

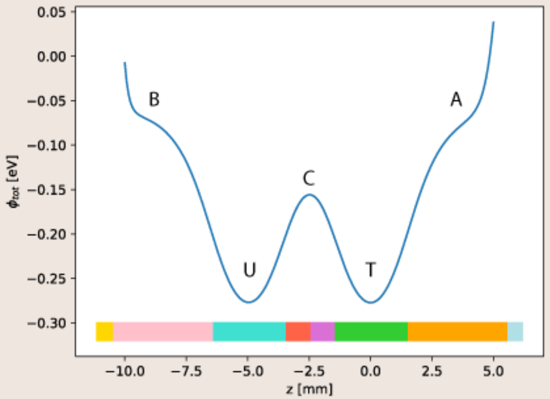
$$
\begin{pmatrix}
\begin{bmatrix} C_{1,zone1} \\ \vdots \\ C_{m_1,zone1} \end{bmatrix} \\
\vdots \\
\begin{bmatrix} C_{1,zoneN} \\ \vdots \\ C_{m_N,zoneN} \end{bmatrix}
\end{pmatrix}
=
\begin{pmatrix}
\begin{bmatrix} C_{1,E_1} & \cdots & C_{1,E_n} \\ \vdots & \ddots & \vdots \\ C_{n,E_1} & \cdots & C_{n,E_{n_{DC}}} \end{bmatrix}_{(x_1,y_1,z_1)} \\
\vdots \\
\begin{bmatrix} C_{1,E_1} & \cdots & C_{1,E_n} \\ \vdots & \ddots & \vdots \\ C_{n,E_1} & \cdots & C_{n,E_n} \end{bmatrix}_{(x_N,y_N,z_N)}
\end{pmatrix}
\begin{pmatrix} V_1 \\ \vdots \\ V_n \end{pmatrix}
$$

Matrix Method in our case

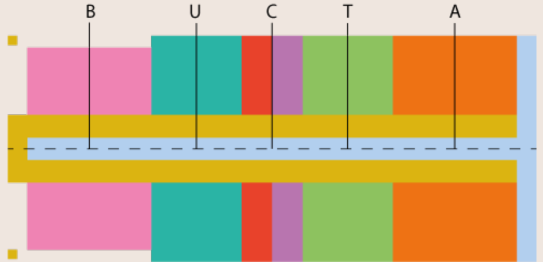
N=2	Target in T	Loading in U	Number of imposed conditions
Position	$(\beta_x, \beta_y, \beta_z)_T = (0,0,0)$	$(\beta_x, \beta_y, \beta_z)_U = (0,0,0)$	6
Anisotropy	$(\alpha_y - \alpha_x)_T = a_T$	$(\alpha_y - \alpha_x)_U = a_U$	2
Tilt	$(\gamma_{xy})_T = t_T$	$(\gamma_{xy})_U = t_U$	2

depth	d_A=d_B>d_C d_A=d_B=200meV d_C=150meV	$d_A = \phi_A - \phi_T$ $d_B = \phi_B - \phi_U$ $d_C = \phi_C - \phi_T$	3

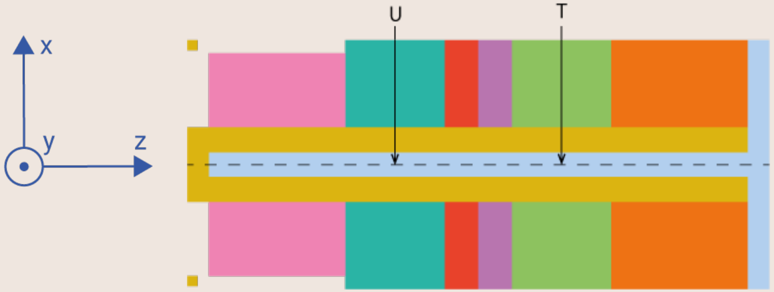
A : end of trap
T : center of the target trap
C : middle of the trap
U : center of the projectile trap
B : end of trap



Total : 13
≤ number of DC electrodes (13)



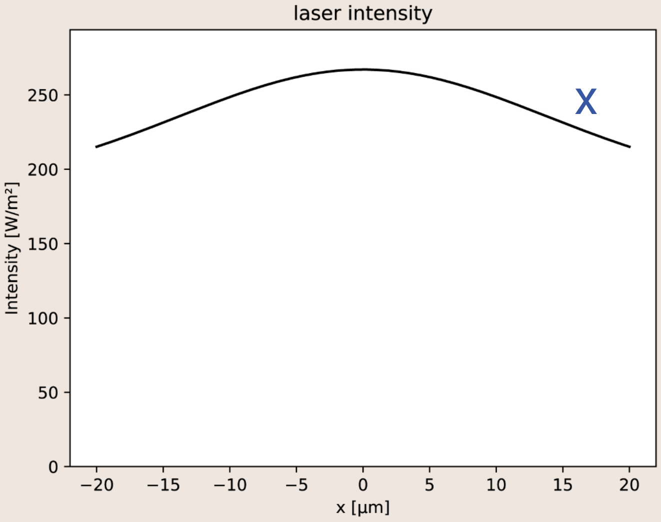
Model limitation

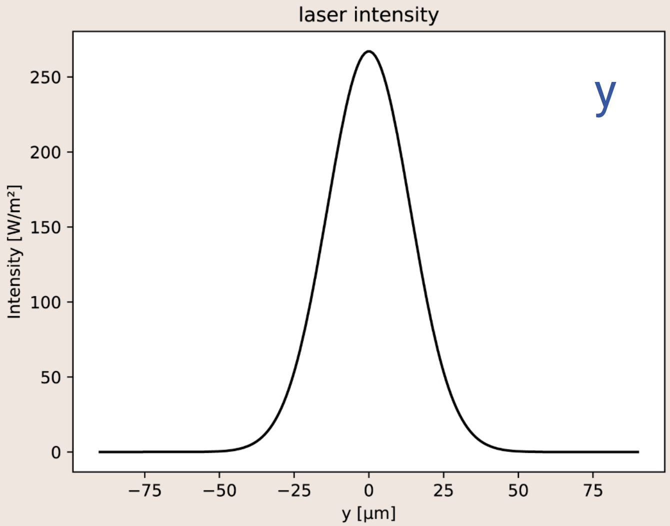


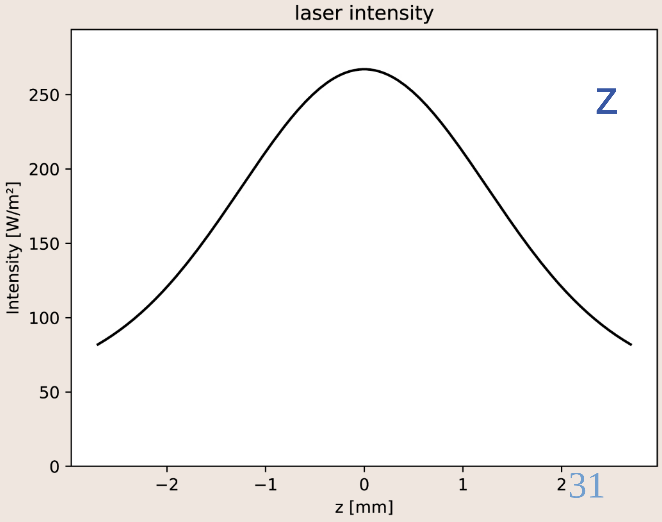
Cooling beam profile with respect to the ion's motion

The laser intensity depends on the position of the ion

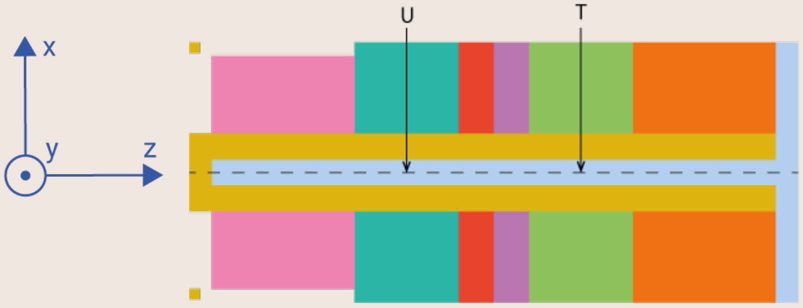
We need a new model







Mapping des charges parasite



The minimum of the DC potential must match the minimum of the RF potential, otherwise the ions undergo a forced motion of pulsation Ω_{RF}.

Thanks to the matrix method, we can apply linear fields along the different axes of the trap. This allows us to correct the mismatch.

To correct the position of the ions

Radial direction :

- the ions can be brought back to their position when the RF voltage is high.
- Check correlations between photon's arrival time and RF zero (0 correlation = ion on a node).

Longitudinal direction :

- Change potential stiffness along z.

Identify any parasitic charges (and take them into account in simulation)

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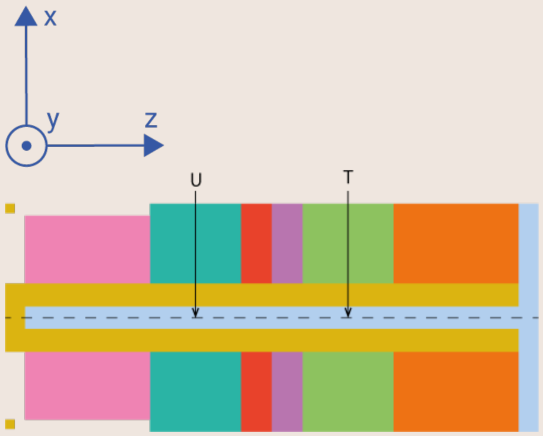
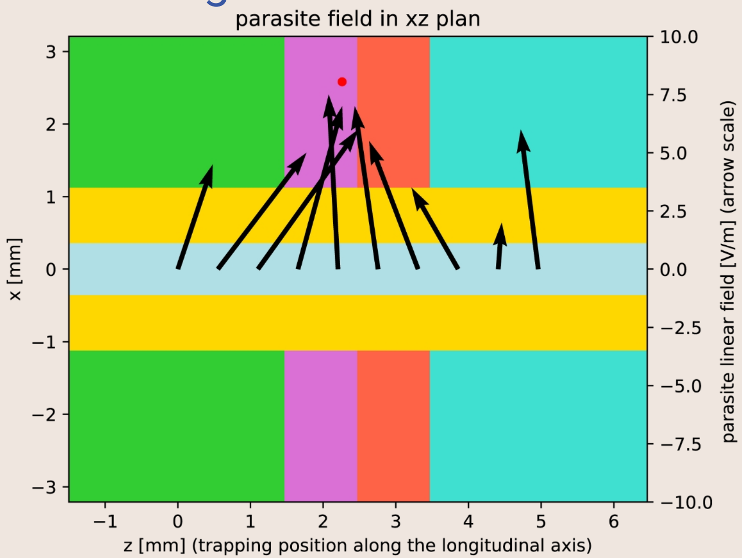
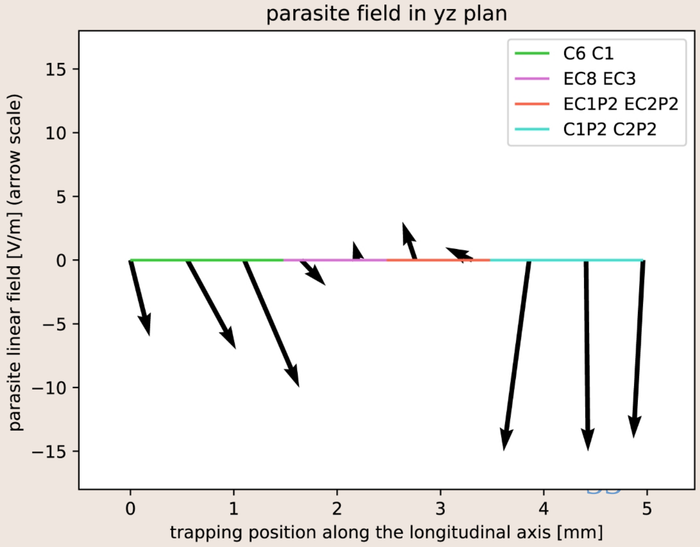






Equivalence between axial frequency and barrier height

$$U(z) = az^2 + bz^4$$

$$a < 0$$
$$b > 0$$

$$z = \pm\sqrt{\frac{-a}{2b}}$$

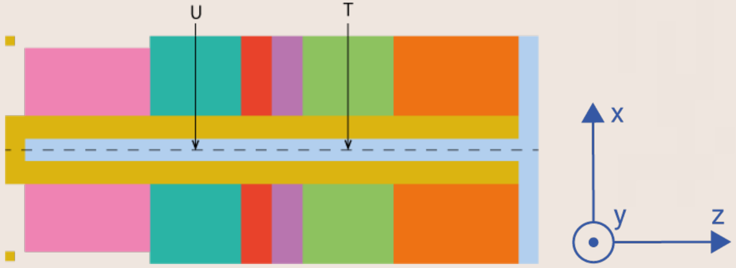
The minimums position in fixed, therefore a/b=c is constant

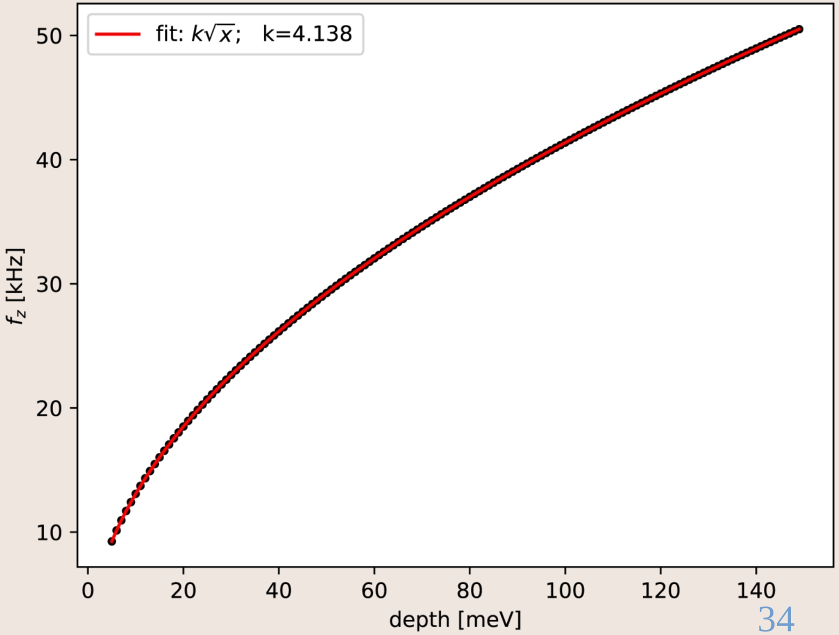
$$U\left(\pm\sqrt{\frac{-a}{2b}}\right) = \frac{-a^2}{4b}$$

Barrier height :

$$d = \frac{a^2}{4b} = \frac{ac}{4}$$

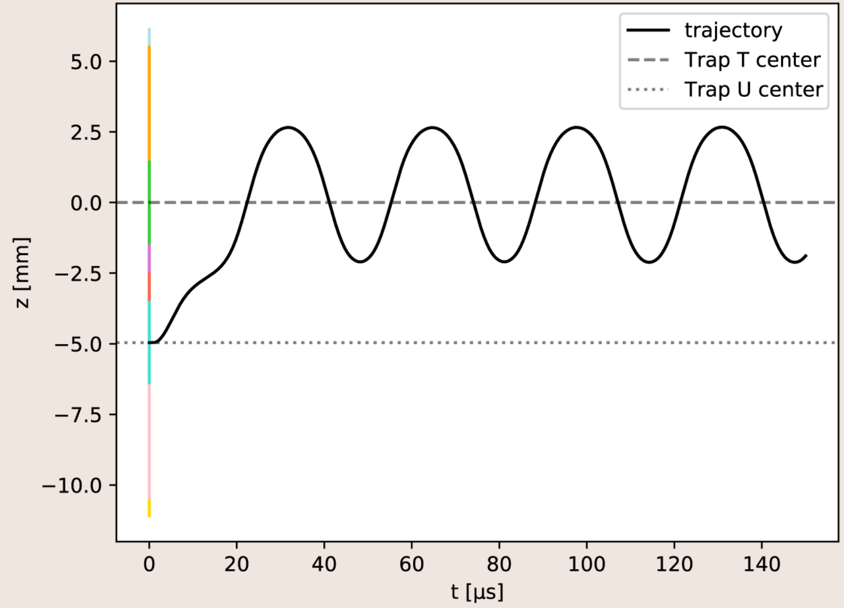
$$f_z = \frac{1}{2\pi}\sqrt{\frac{e}{m}\frac{d^2U(z)}{dz^2}_{z_{1,2}}}$$
$$= \frac{1}{2\pi}\sqrt{\frac{e}{m}(-4a)}$$
$$= \frac{2}{\pi}\sqrt{\frac{e}{m}(-\frac{1}{c})d}$$
$$\propto k\sqrt{d}$$

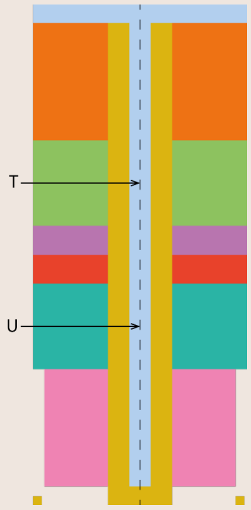


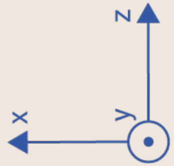


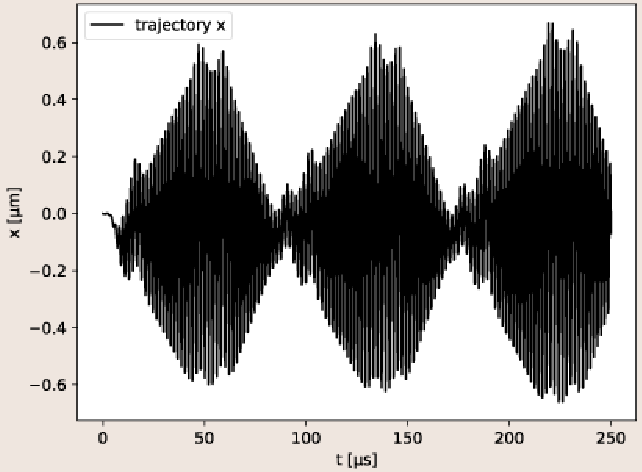
Simulation result

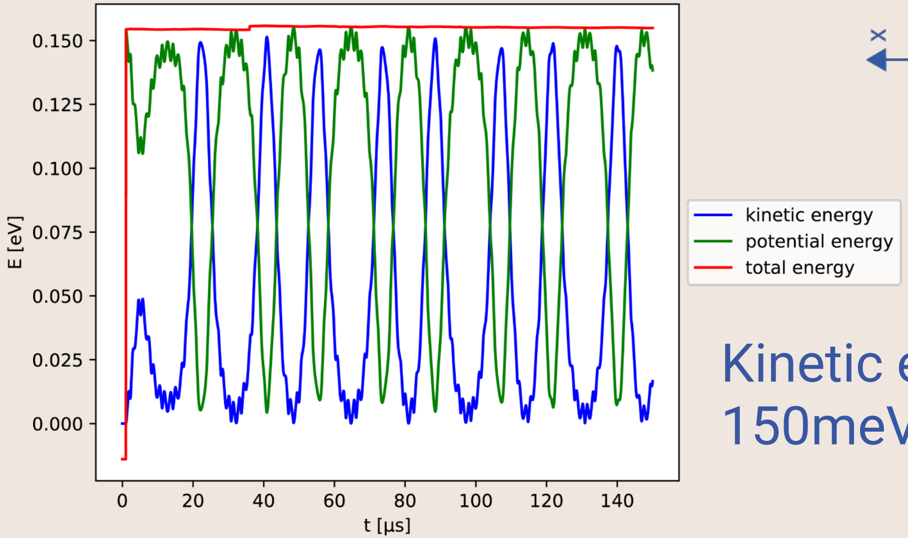
V_{push}=5.7V, V_{close}=1.5V and Δt=35μs



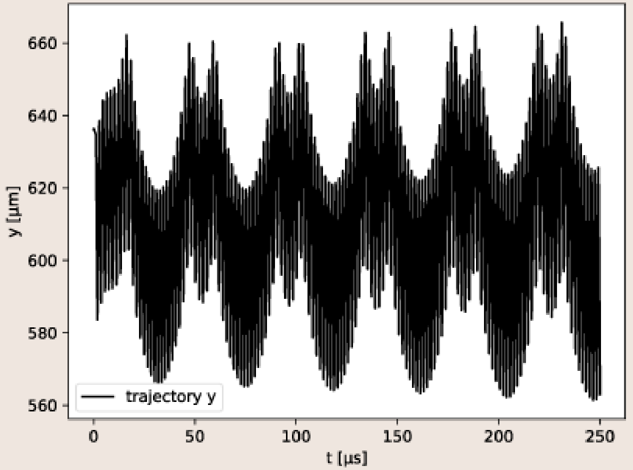






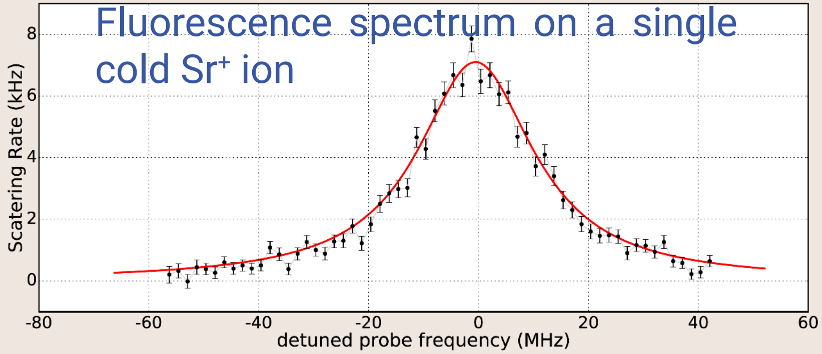


Kinetic energy : 150meV



Spectrum problem

Objective : extract the saturation parameter at the center of the trap



Spectrum at low laser intensity :
Width = 27.3MHz
(natural Sr^+ width : 21.54MHz)
Broad spectrum at low intensity + no concordance between height and width

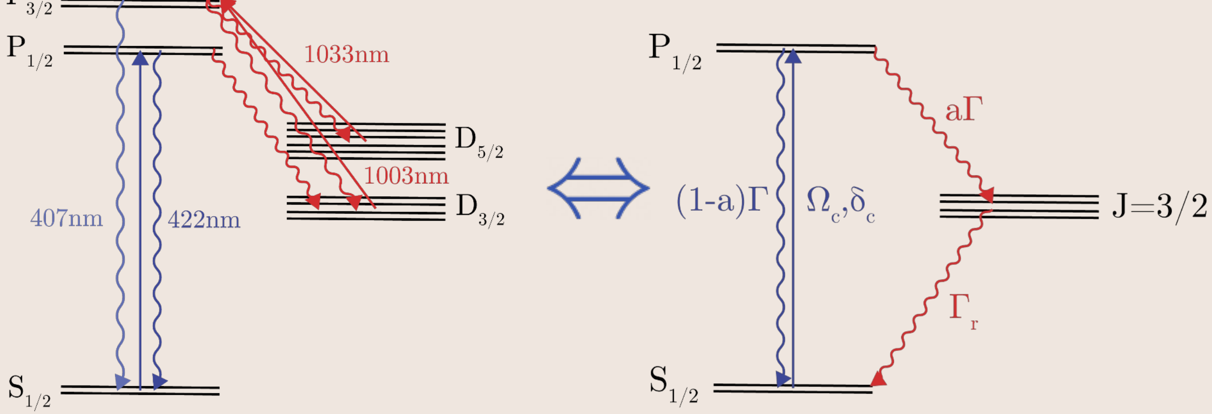
$$\frac{dN}{dt} = \frac{\Gamma}{2} \frac{s}{1+s} \frac{1}{1+\Delta^2/\gamma_{eff}^2}$$

$$\gamma_{eff} = \gamma\sqrt{1+s}$$

Magnetic field compensation :
spectrum width = 24MHz at low intensity

Repumping rate :
Increase power density of the repumping beam
Check the repumping saturation

[5] thesis of Vincent Tugayé



2 level system approximation: $\frac{a\Gamma}{\Gamma_r} \ll 1$

Fluorescence spectrum measurement