Building a single-ion optical clock

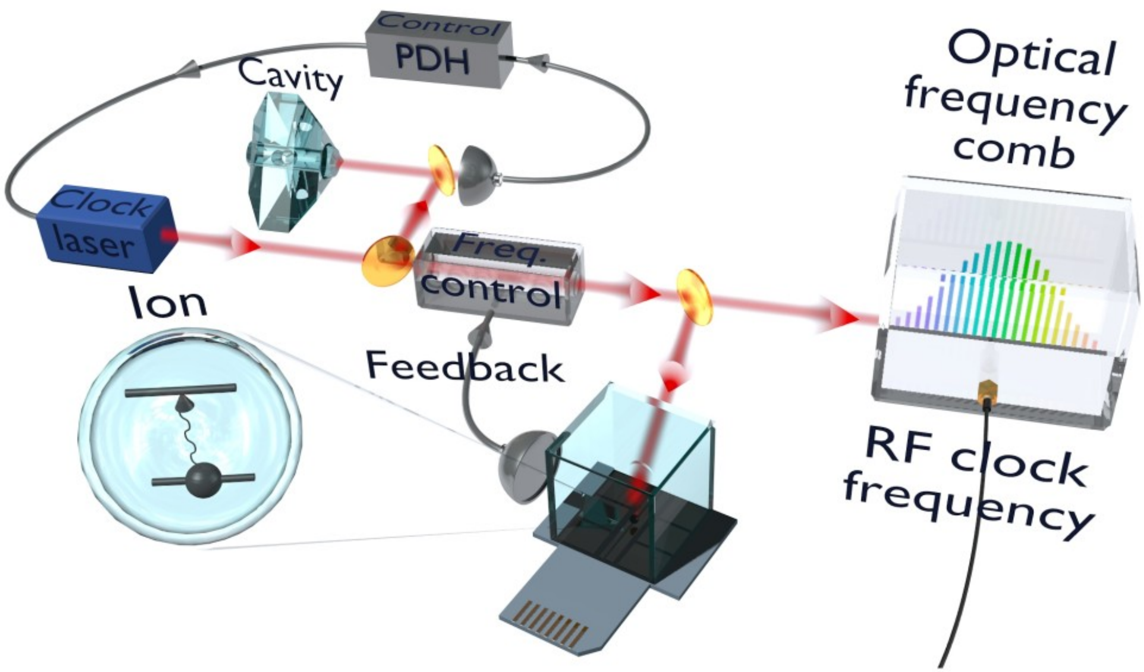
Bachir ACHI, Thomas LAUPRÊTRE, Lucas GROULT, Yann KERSALÉ, Marion DELEHAYE, Moustafa ABDEL HAFIZ and Clément LACROÛTE

SUMMARY

- General introduction
  - Building a compact optical clock
  - Ion trap setup
- Heating rate
  - Heating rate sources
  - Heating rate measurement
- Results
  - Ion spot width
  - Doppler recooling
- Conclusion and outlook

General introduction

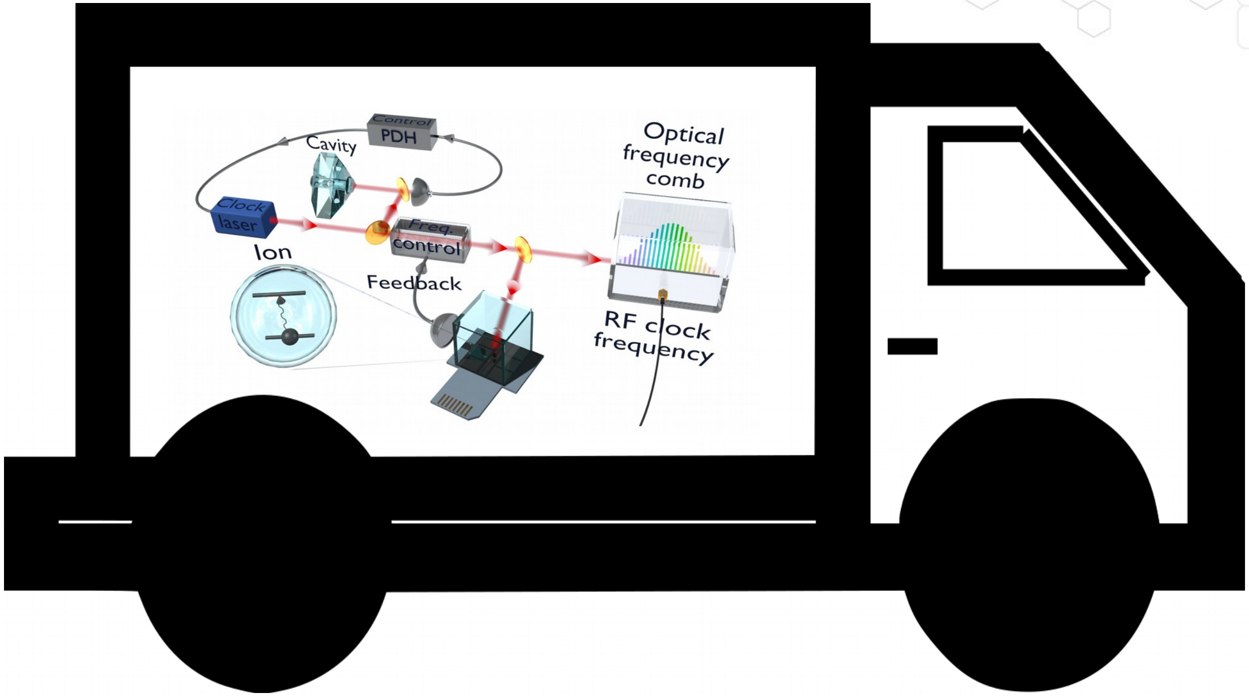
BUILDING A COMPACT OPTICAL CLOCK



From [1]

[1] M. Delehaye and C. Lacroûte, “Single-ion, transportable optical atomic clocks.“ Journal of Modern Optics, 65:5-6, 622-639 (2018)

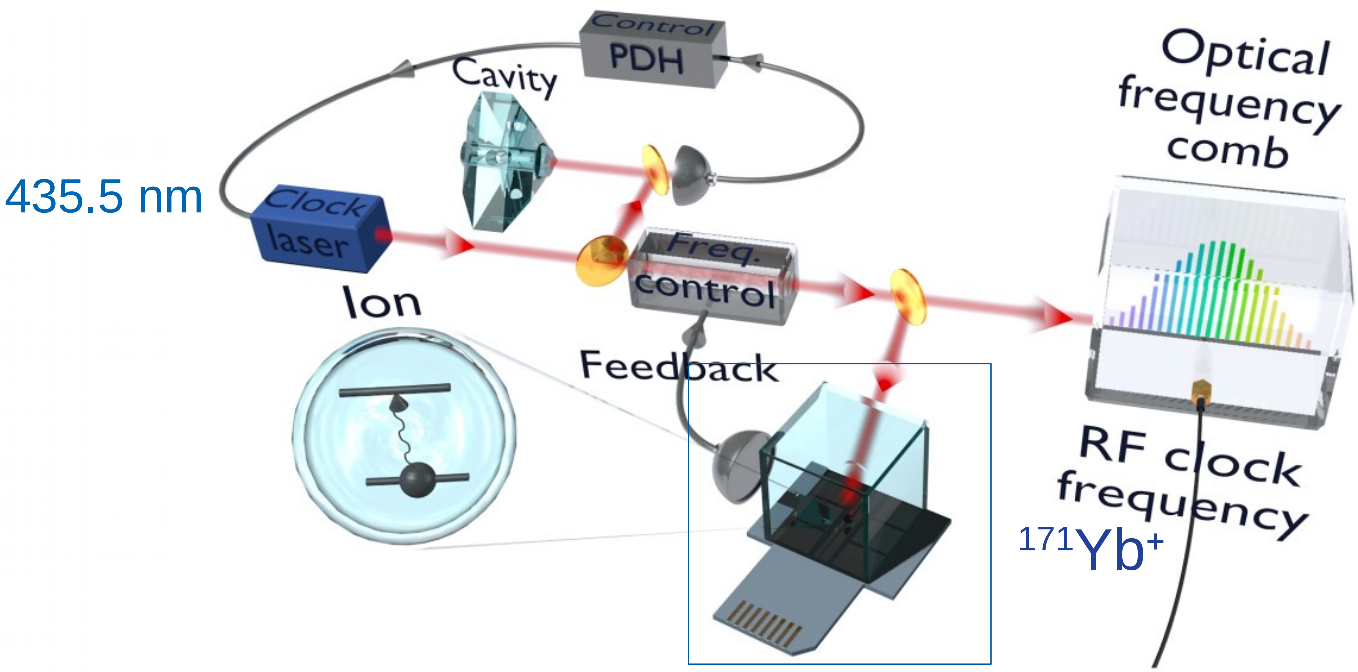
BUILDING A COMPACT OPTICAL CLOCK



→ transportable clock
→ Total Volume < 500 L
→ $\sigma_y \approx 10^{-14} \tau^{-1/2}$

→ Applications : geodesy, fundamental physics, internet of clocks

BUILDING A COMPACT OPTICAL CLOCK



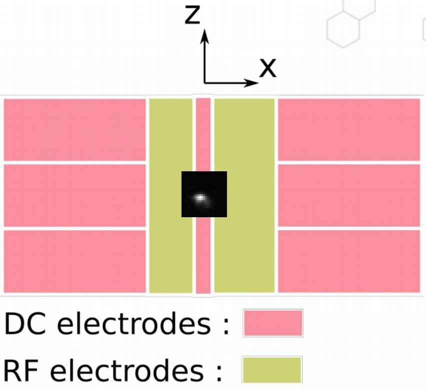
→ Single $^{171}Yb^+$:
Quadrupole clock transition :
$^2S_{1/2}(F = 0) - {}^2D_{3/2}(F = 2)$

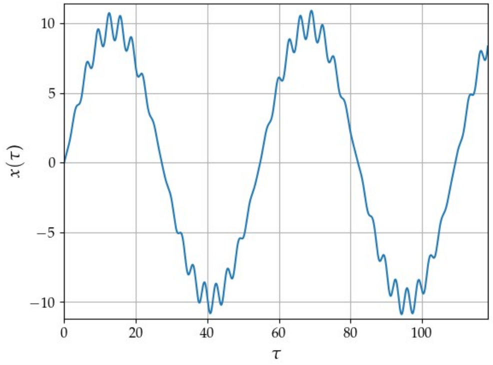
ION TRAP SETUP

Single $^{171}Yb^{+}$:

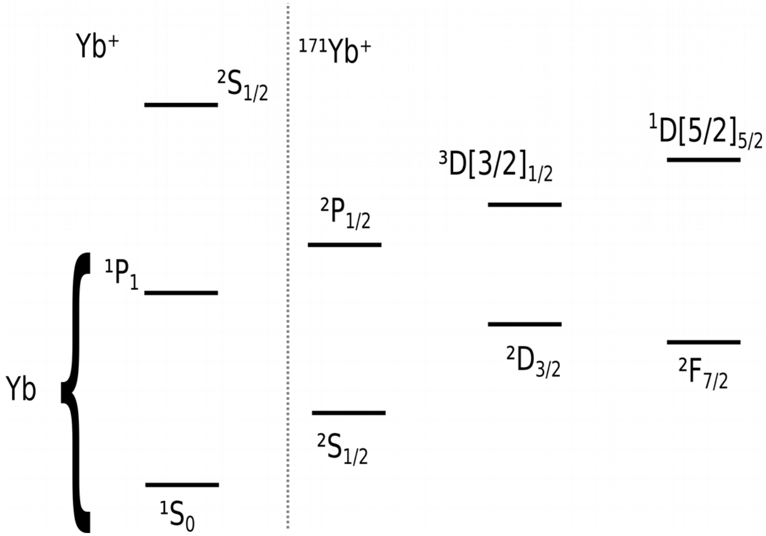
→ Planar Paul trap :

- $d_{ion\text{-}electrodes} \approx 500$ µm
- $f_{trap} = 5.7$ MHz
- $V_{RF} = 270\ V_{pp}$





→ 5 lasers :



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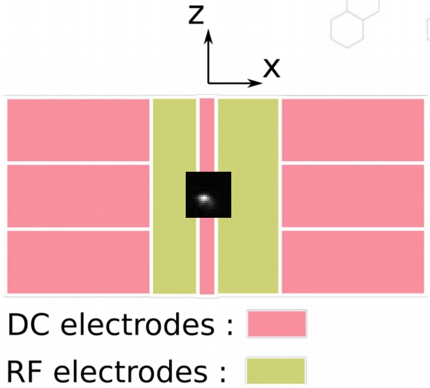
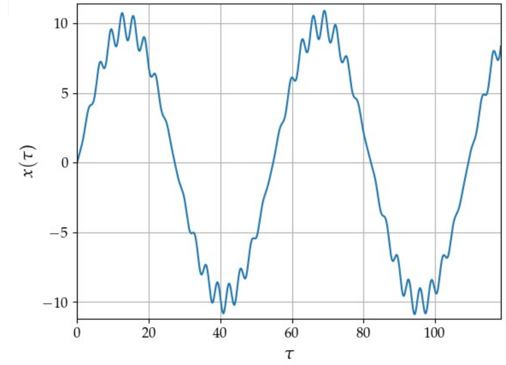
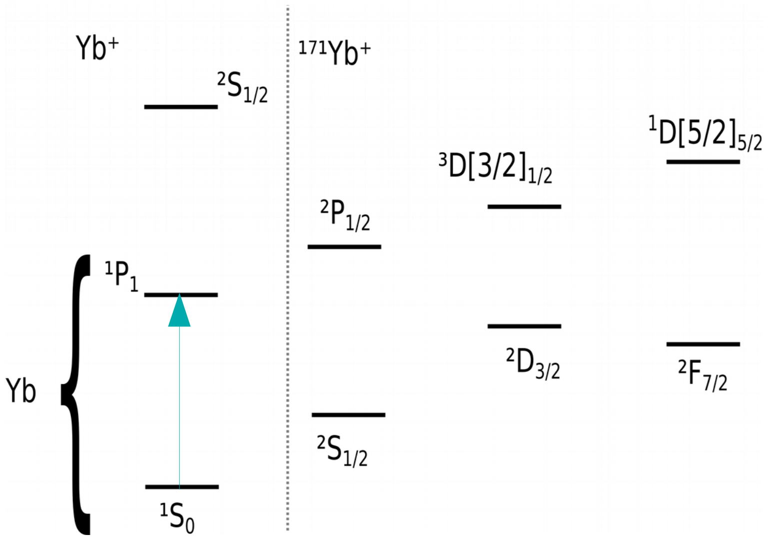




→ 5 lasers :

- Ionisation laser : 398 nm



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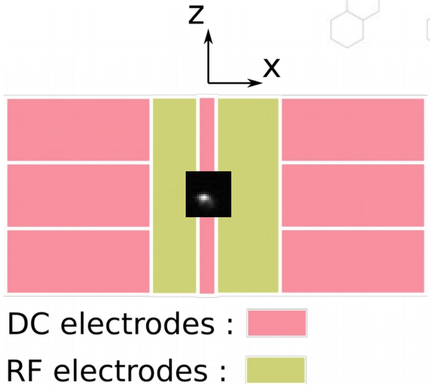
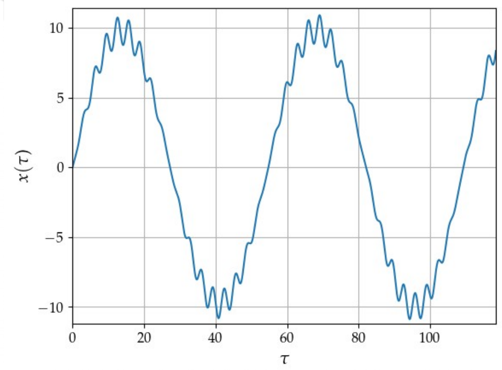
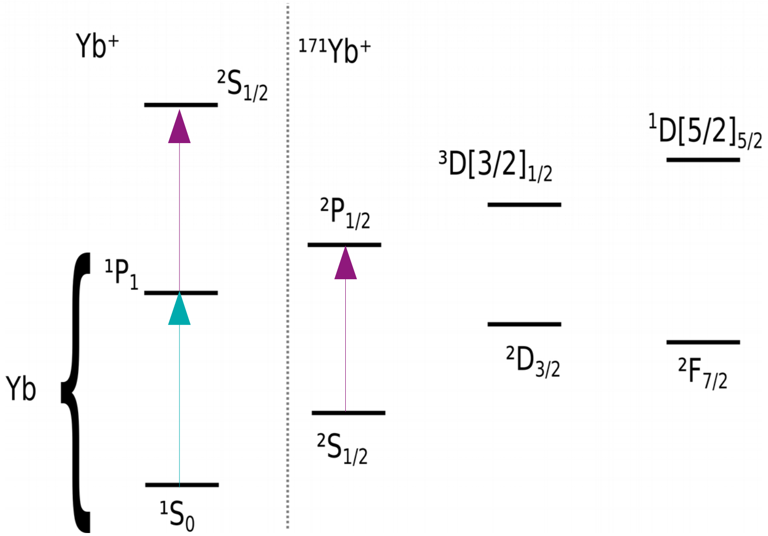




→ 5 lasers :

- Ionisation laser : 398 nm
- Cooling laser : 370 nm



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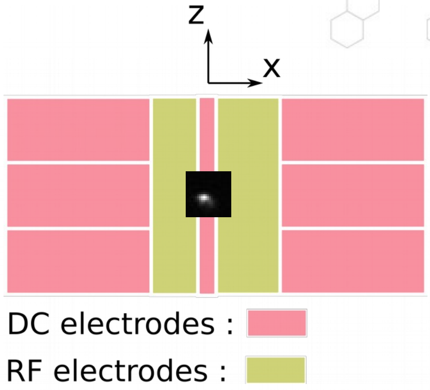
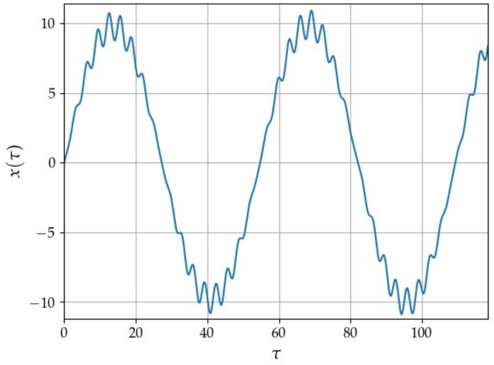
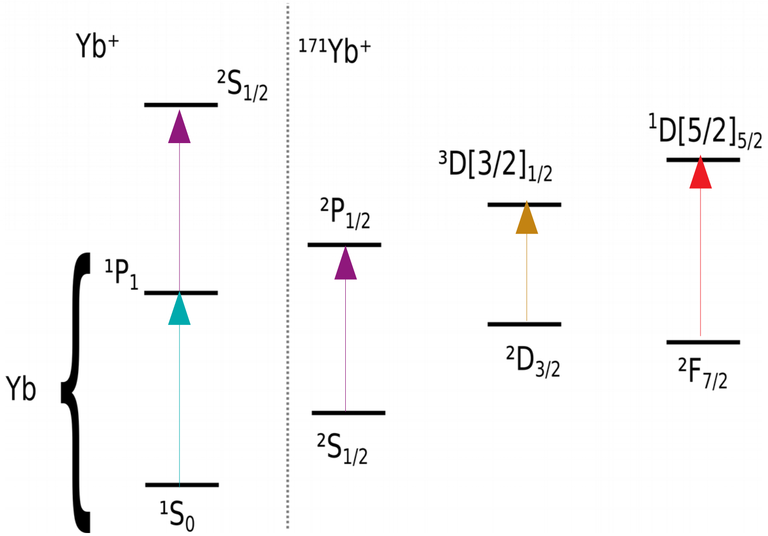




→ 5 lasers :

- Ionisation laser : 398 nm
- Cooling laser : 370 nm
- Repumping lasers : 935 nm & 638 nm



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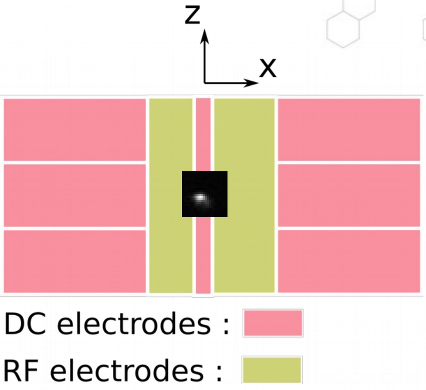
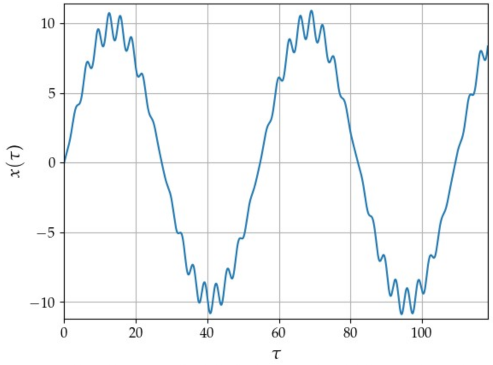
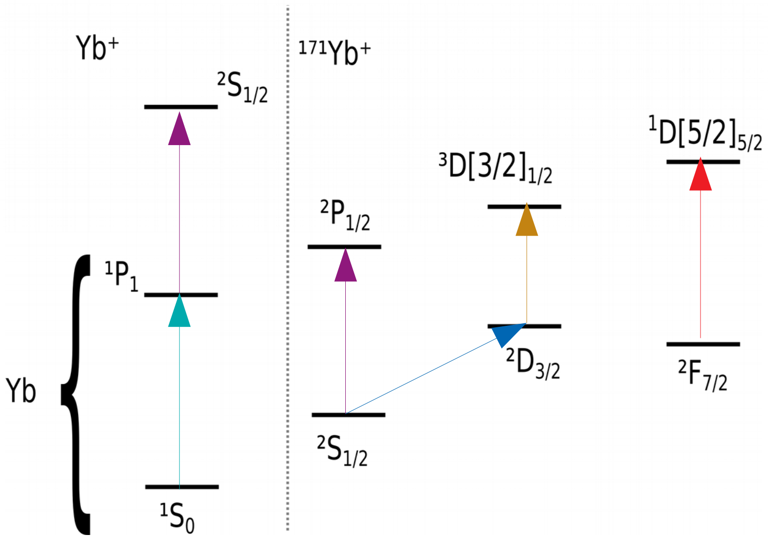




→ 5 lasers :

- Ionisation laser : 398 nm
- Cooling laser : 370 nm
- Repumping lasers : 935 nm & 638 nm
- Clock laser : 435 nm



ION TRAP SETUP

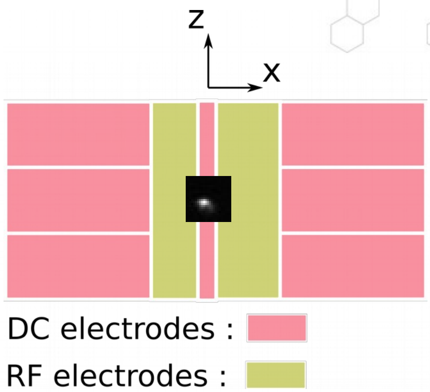
Single $^{171}Yb^{+}$:

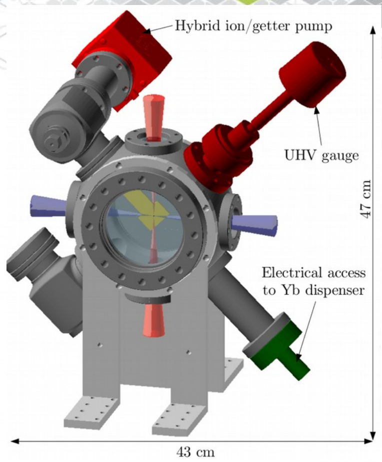
→ Planar Paul trap :

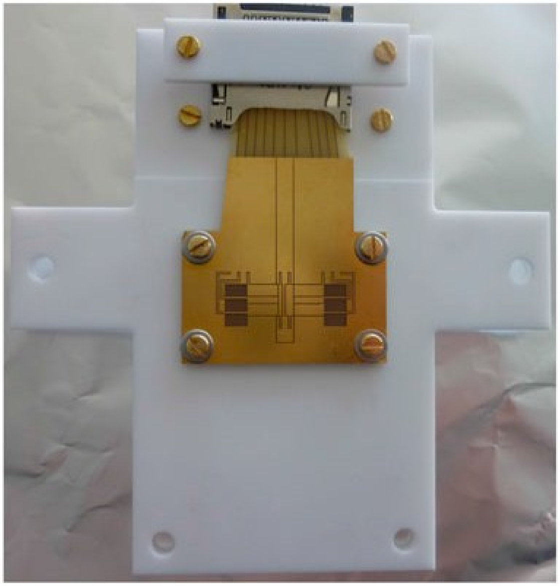
Prototype

pressure : ~10^{-10} mbar

ion lifetime : τ = 1550 s







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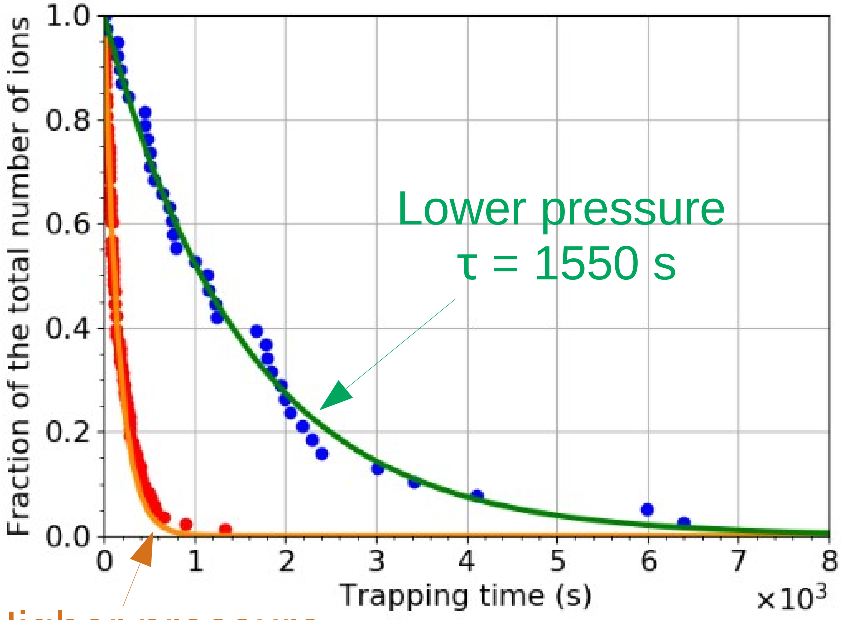

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[2] T. Lauprêtre *et. al*., Article in preparation.

femto-st SCIENCES & TECHNOLOGIES

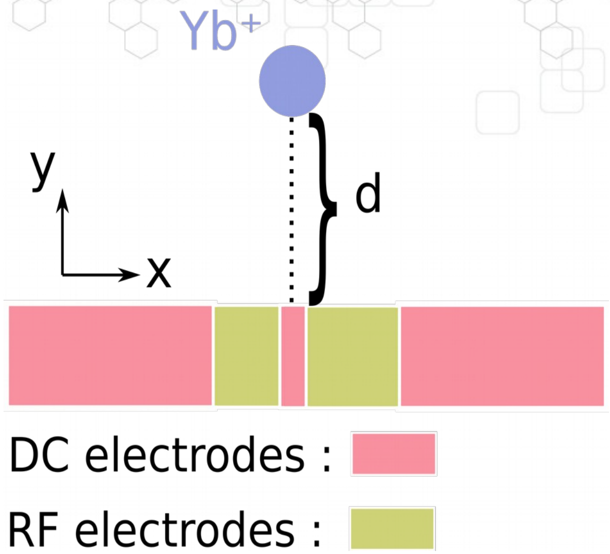
Heating rate

HEATING RATE SOURCES

→ Planar Paul Trap are mainly used in Quantum Information Processing

- Easier manufacturing & reproduction
- Possibility of integration
- Better optical access

→ We use such a trap to make a clock!



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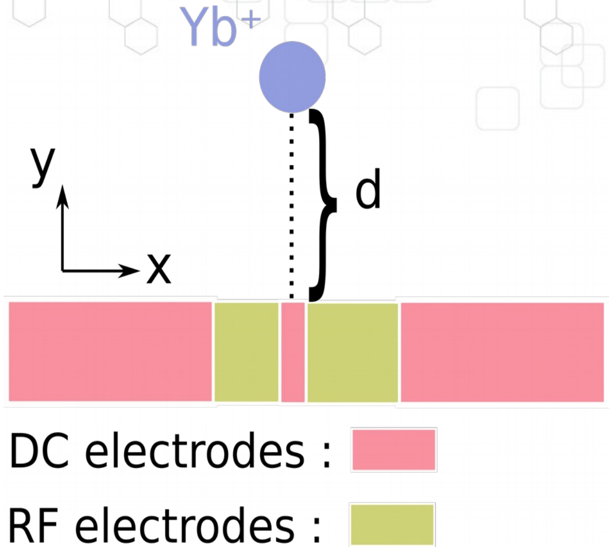
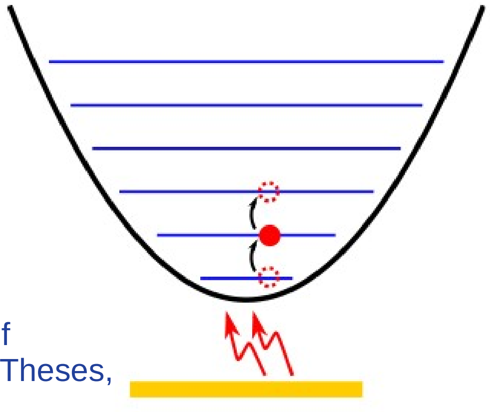
→ Heating rate :

- Due to electrical noise
- « normal » $\propto d^{-2}$
- **« anomalous »** $\propto d^{-4}$, $\propto \omega_u^{-\alpha}$ [3]

  ω_u : the secular frequency along the ***u*** direction

  $\alpha > 1$





From [4]

[3] Q. A. Turchette *et al*., "Heating of trapped ions from the quantum ground state," Phys. Rev. A 61, 063418 (2000).

[4] B. Szymanski, "Trapping and cooling of strontium ions in a micro-fabricated trap." Theses, 2013.

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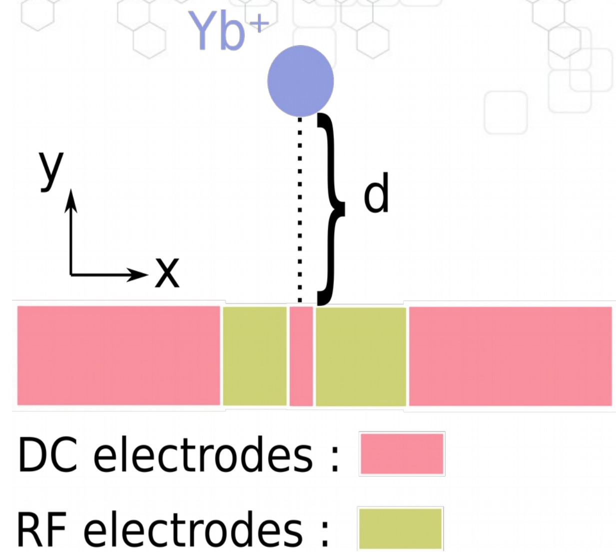
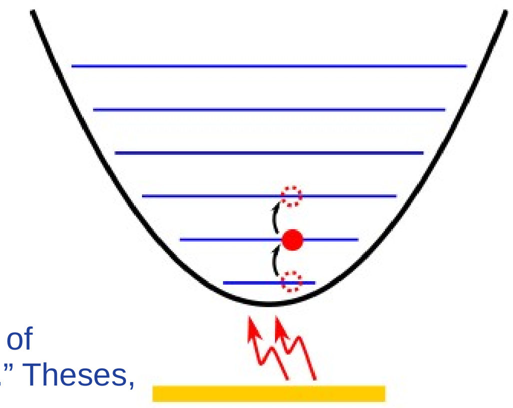


→ $d \approx 500$ µm

→ $\omega_{radial} \approx 350$ kHz ; $\omega_{axial} \approx 85$ kHz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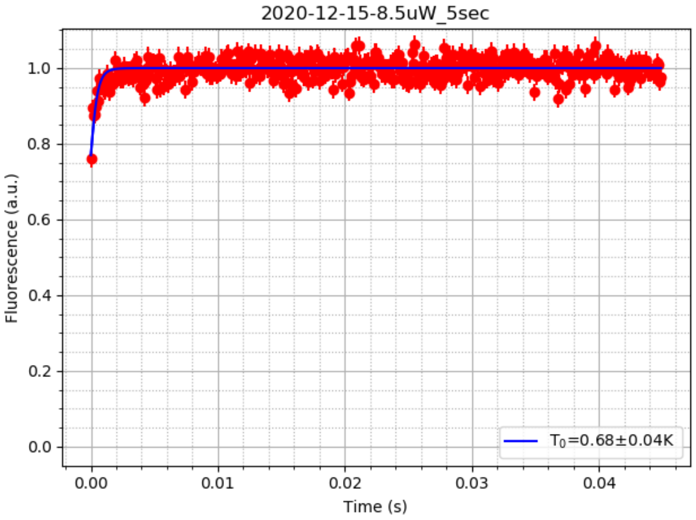
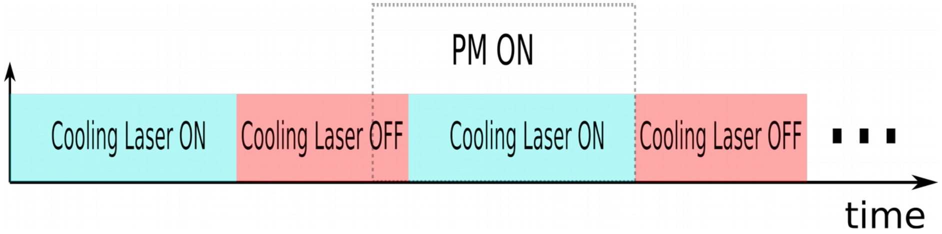
HEATING RATE MEASUREMENT

→ Doppler recooling [5] :

- Record the fluorescence signal after heating the ion
- Fit the fluorescence dynamics in order to extract the temperature



- Easy to implement

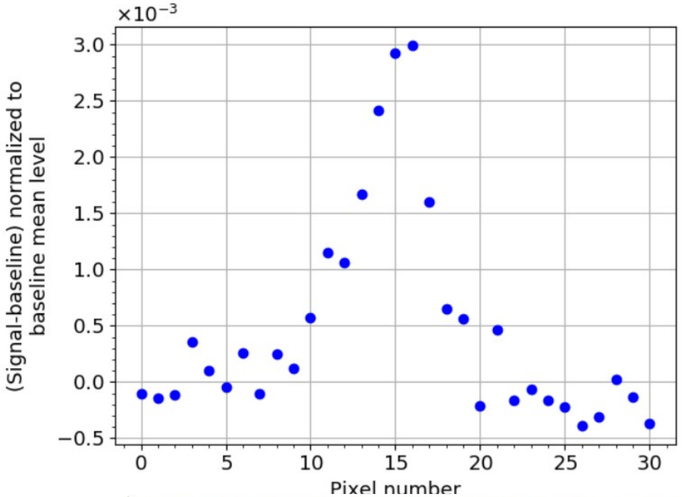


- Very model dependent
- 1D assumption

[5] J.H. Wesenberg *et al.* ,"Fluorescence during doppler cooling of a single trapped atom," Phys. Rev. A 76, 053416 (2007).

HEATING RATE MEASUREMENT

From [2]



→ Ion spot picture analysis [6] :

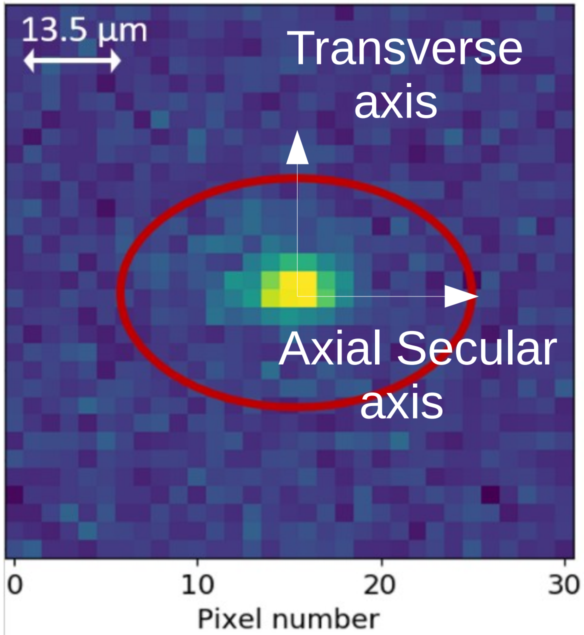
- The RMS Gaussian distribution of the ion is given by :

$$\sigma_u = \sqrt{\frac{k_B T_u}{M \omega_u^2}}$$

- The heating rate can be extracted from 2 pictures of the ion at 2 different temperatures :

$$\Delta T = T_2 - T_1 = \frac{M\omega_u^2}{k_B}\left(\sigma_{im.,2}^2 - \sigma_{im.,1}^2\right)$$

- Our imaging resolution : 2.7 µm.pixel^{-1}
- Need an EMCCD (Andor Model)



[2] T. Lauprêtre *et. al*., Article in preparation.

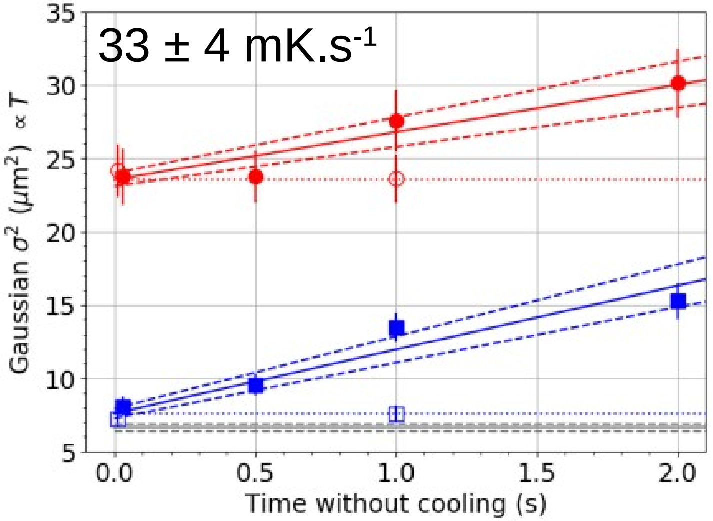
[6] B. Srivathsan *et al*., "Measuring the temperature and heating rate of a single ion by imaging", New J. Phys 21, 113014 (2019).

Results

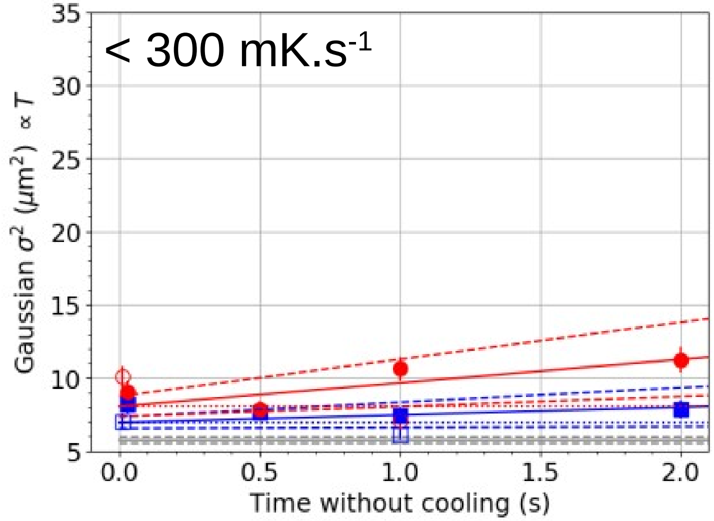
ION SPOT WIDTH

→ Variance of the 2D gaussian as a function of the time without cooling the ion

Secular axial direction



Transverse direction



→ Full blue squares are the measurements of the ion picture width after the time without cooling

→ Straight blue line is a fit of these data

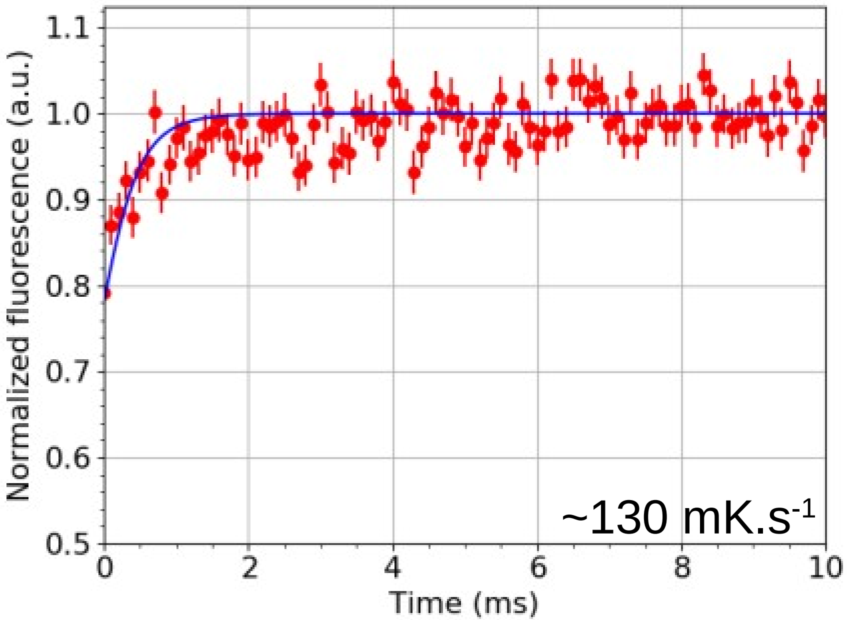
→ Full red circles are the measurements of the ion picture width after the time without cooling and artificialy warmed up at the end of the cooling cylcle

→ Straight red line is a fit of these data

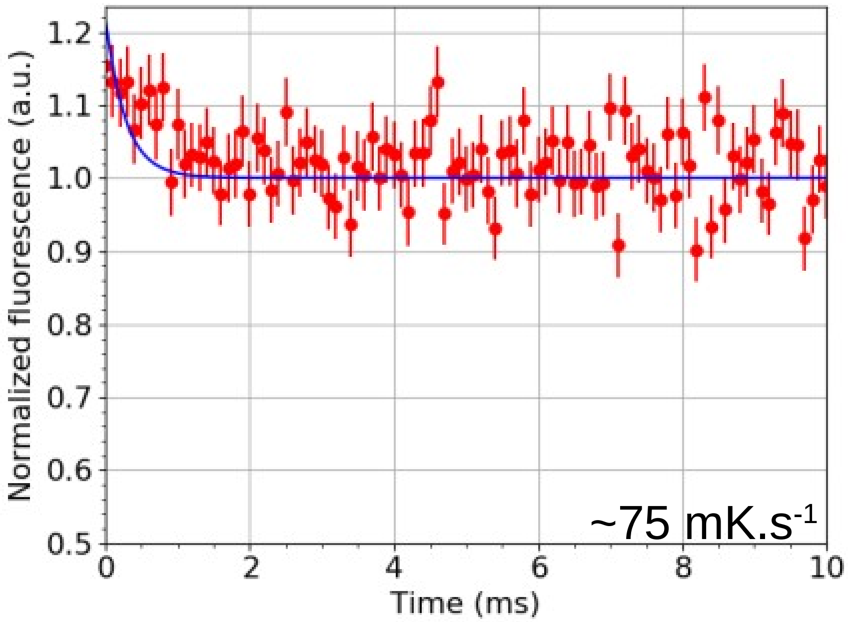
DOPPLER RECOOLING

→ Normalized fluorescence as a function of the time without cooling the ion

$I = I_{sat}/2$ $\Delta = -5$ MHz



$I = I_{sat}/2$ $\Delta = -20$ MHz



→ With I the laser intensity and Δ the detuning of the laser frequency from the resonance.

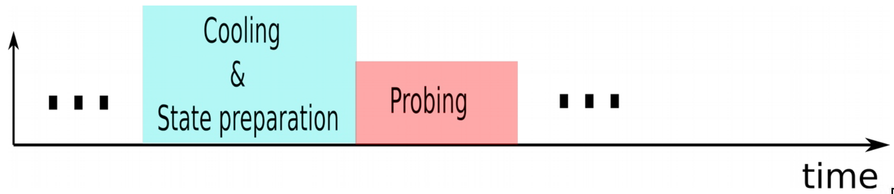
→ « Dark time » of 5 s.

RESULTS

→ in terms of phonons : $\dot{\bar{n}}$ ~ 8000 phonons.s^{-1} in both directions

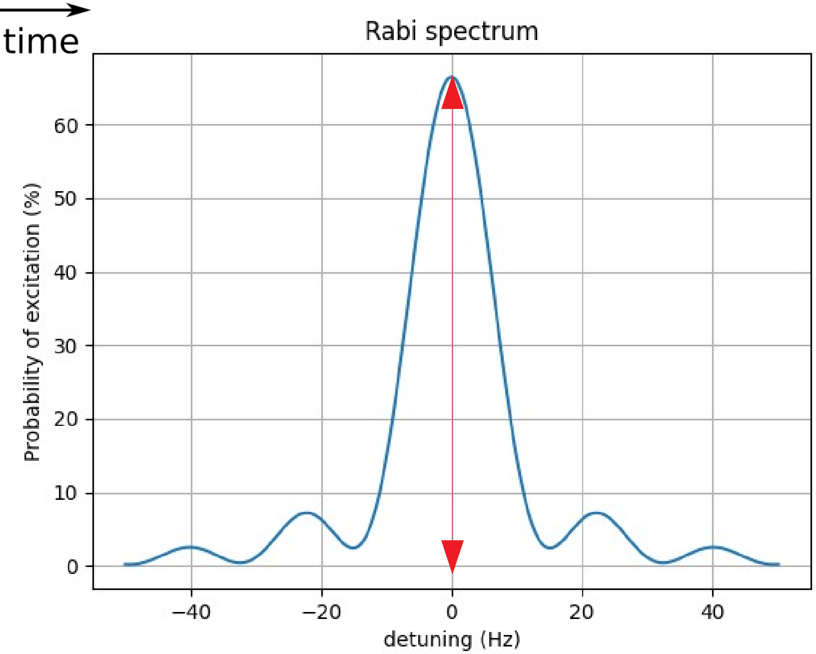
→ impact of the heating rate on the clock ?

Example :



Probing step : Rabi interrogation
Probing step : no cooling!

$$\sigma(\tau) \propto \frac{1}{SNR} \frac{\Delta\nu}{\nu_0} \sqrt{\frac{t_s}{\tau}}$$



We need $\dot{\bar{n}}$ < 1000 phonons.s^{-1} in the transverse direction !

CONCLUSION

CONCLUSION AND OUTLOOK

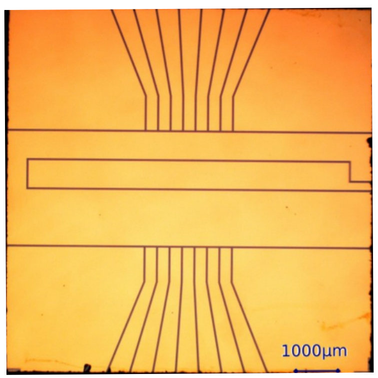
→ Doppler recooling and ion spot width measurement are complementary

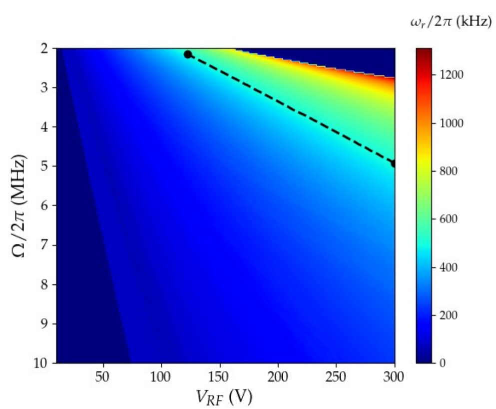
→ heating rate : ~33 mK.s^{-1} in the axial direction
< 130 mK.s^{-1} in the transverse direction

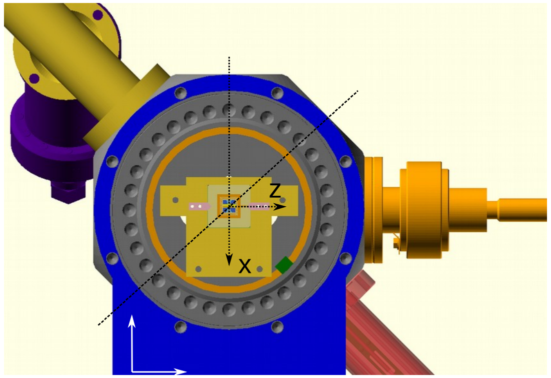
→ in terms of phonons : ~ 8000 phonons.s^{-1} in both directions

→ Investigate an absolute thermometry of the ion [7]

→ Change the chip (UHV compatible) [8]







→ The clock laser beam will be in along a secular direction

[7] Vincent Tugayé *et al.*, Phys. Rev. A 99, 023412, 2019.

[8] L. Groult, “Conception d’un piège de Paul microfabriqué pour le développement d’une horloge optique compacte, à ion piégé Yb^{+}” Theses, 2021.

Thank you for your attention