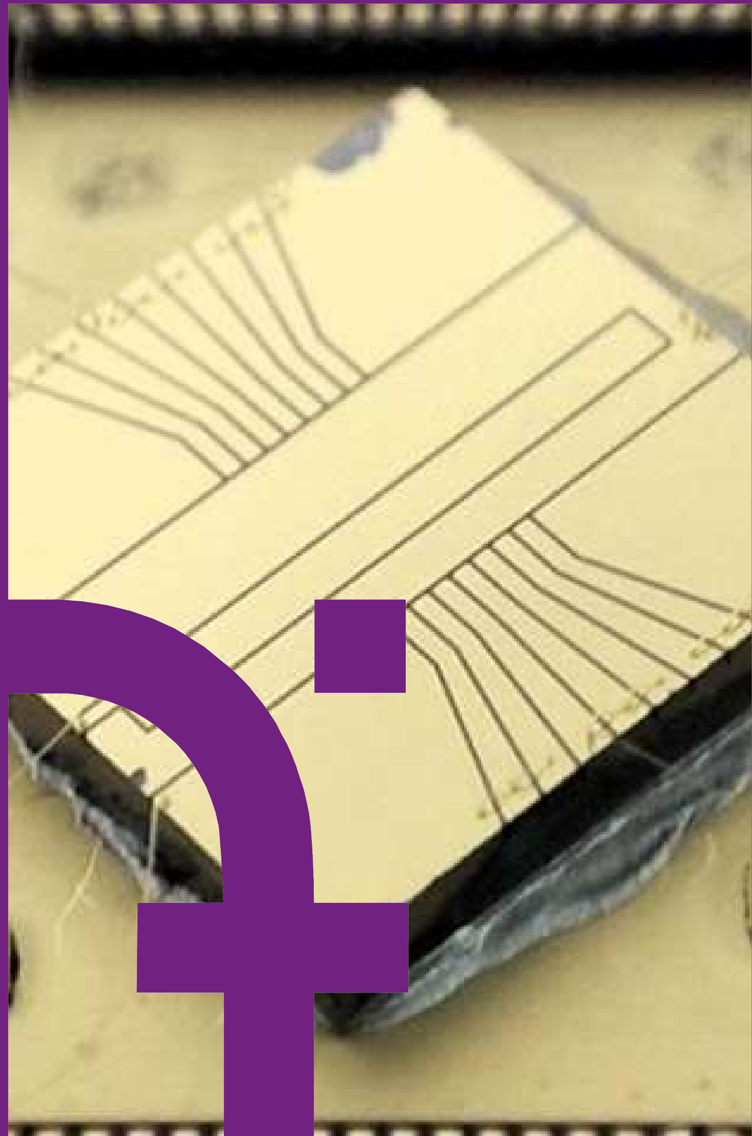
COMPACT YB^+ CLOCK

Alan Boudrias, Valérie Soumann, Moustafa Abdel-Hafiz, Clément Lacroûte – 8 octobre 2025

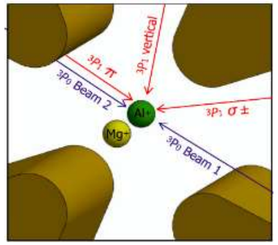


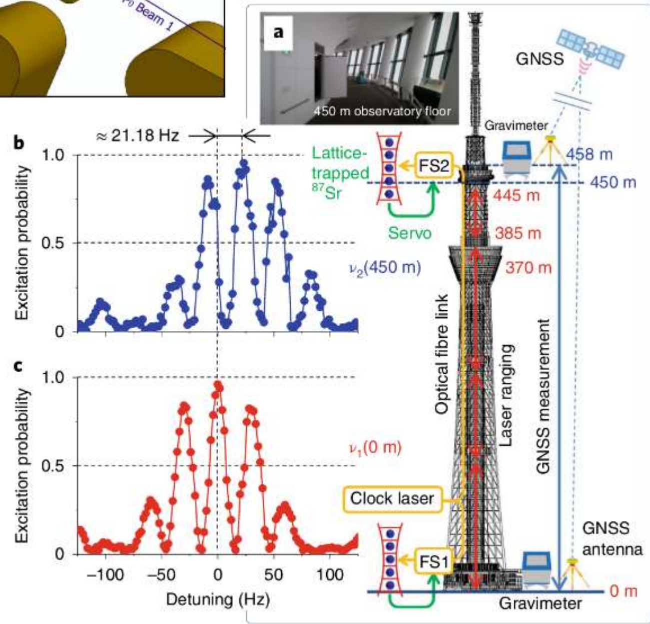
SINGLE-ION YB$^+$ OPTICAL CLOCK

Optical clocks reach fractional frequency stabilities of ~10^{-15} $\tau^{-1/2}$ for single-ion clocks to <10^{-16} $\tau^{-1/2}$ for optical lattice clocks, and fractional **accuracies of 10^{-18}** and below [1].

- BIPM has defined a roadmap for the redefinition of the SI second;
- several proposals consider a multi-species definition;
- relativistic effects have been tested with 18-digits precision, and **height measurements** reach the cm level [2].

⇒ Several calls and projects aim at the implementation of continental **optical clocks network** [3,4].
⇒ Future optical timescales will require flywheel oscillators, equivalent to H-Masers.
⇒ Robust, continuous-operation clocks must be built.





[1] Brewer *et al.*, PRL 123, 033201 (2019)
[2] Takamoto *et al.*, Nat. Phot. 14, 411-415 (2020)
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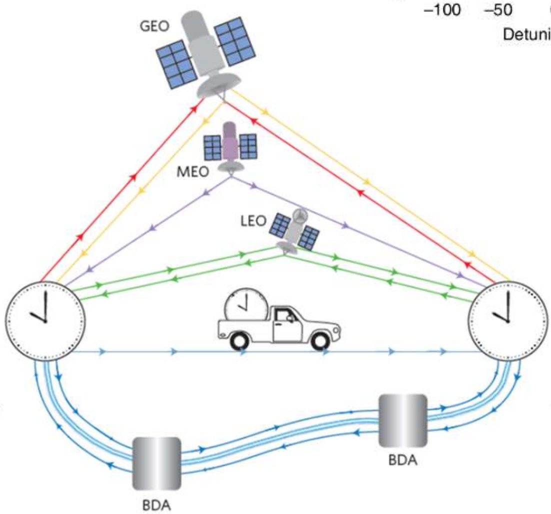

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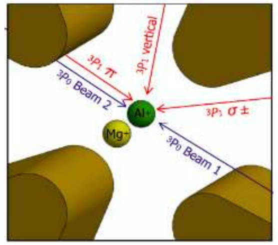
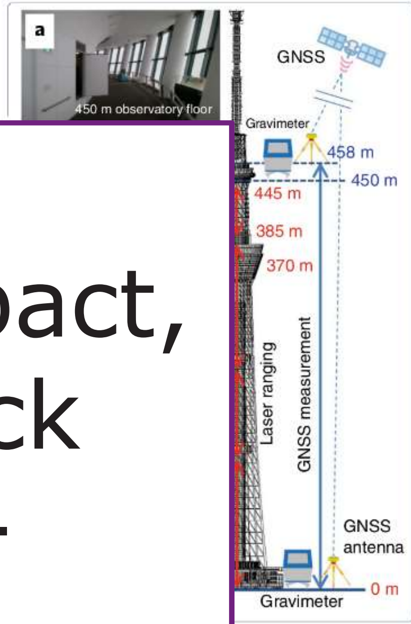
⇒ Several calls and continental **optical**

⇒ Future optical time equivalent to H-Ma

⇒ Robust, continuous





We are building a compact, single-ion optical clock based on a surface-electrode trap

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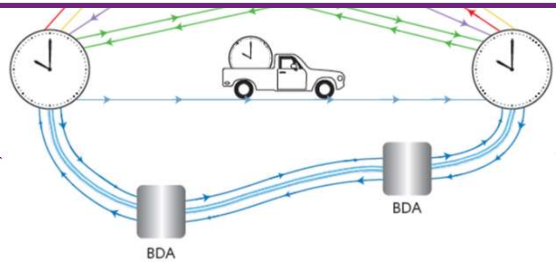
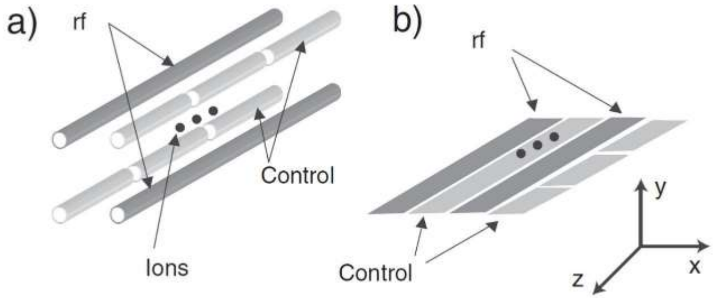


SURFACE-ELECTRODES ION TRAPS

Optical single-ion clocks are usually based on 3D electrodes geometries (linear Paul traps, ring traps, endcap traps…), either machined or micro-fabricated.



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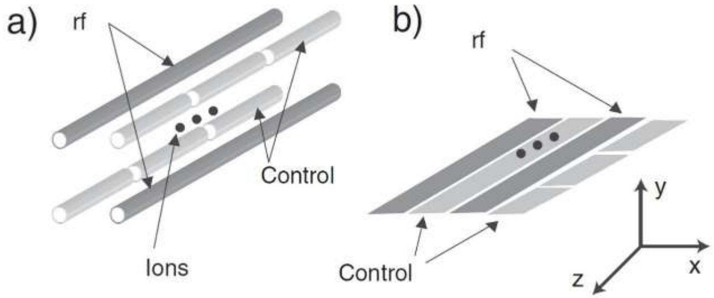
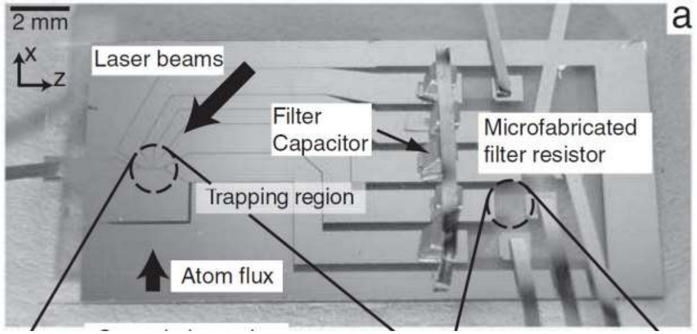
Since their demonstration in 2006, Surface-electrode geometries have been widely used within the QIP community, allowing the fast and coherent control of single-ions and the integration of additional functions to the trap (integrated beam couplers, detection, microwave lines…)





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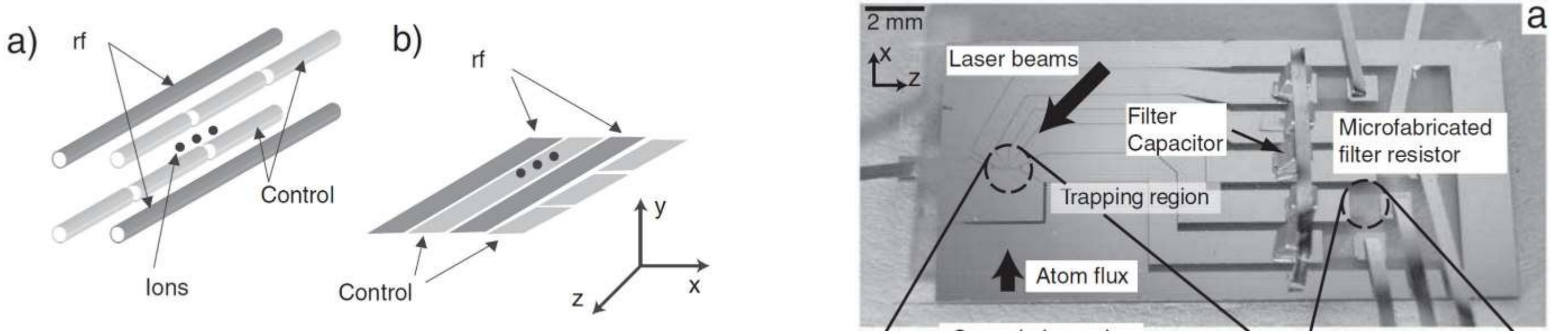

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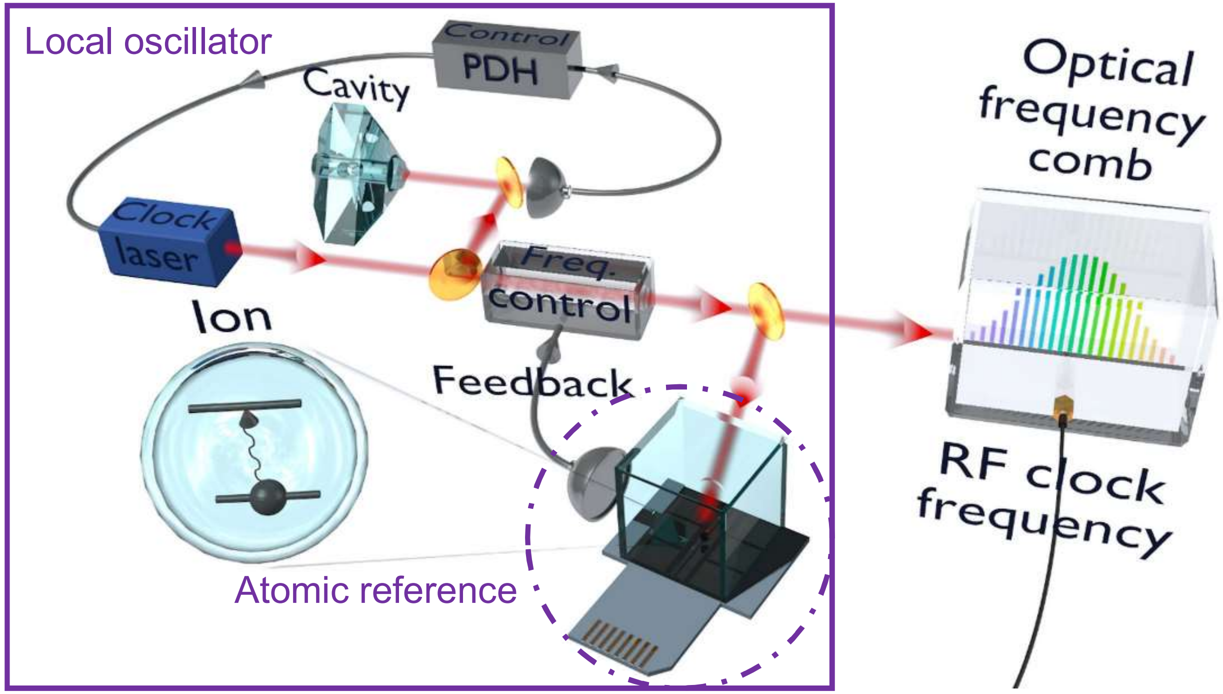
- Simple geometries;
- versatility;
- easy fabrication with trad. clean-room processes;
- good control of surface quality and tolerances.

- Anomalous heating;
- low breakdown voltages;
- shallower traps;
- shorter lifetimes.

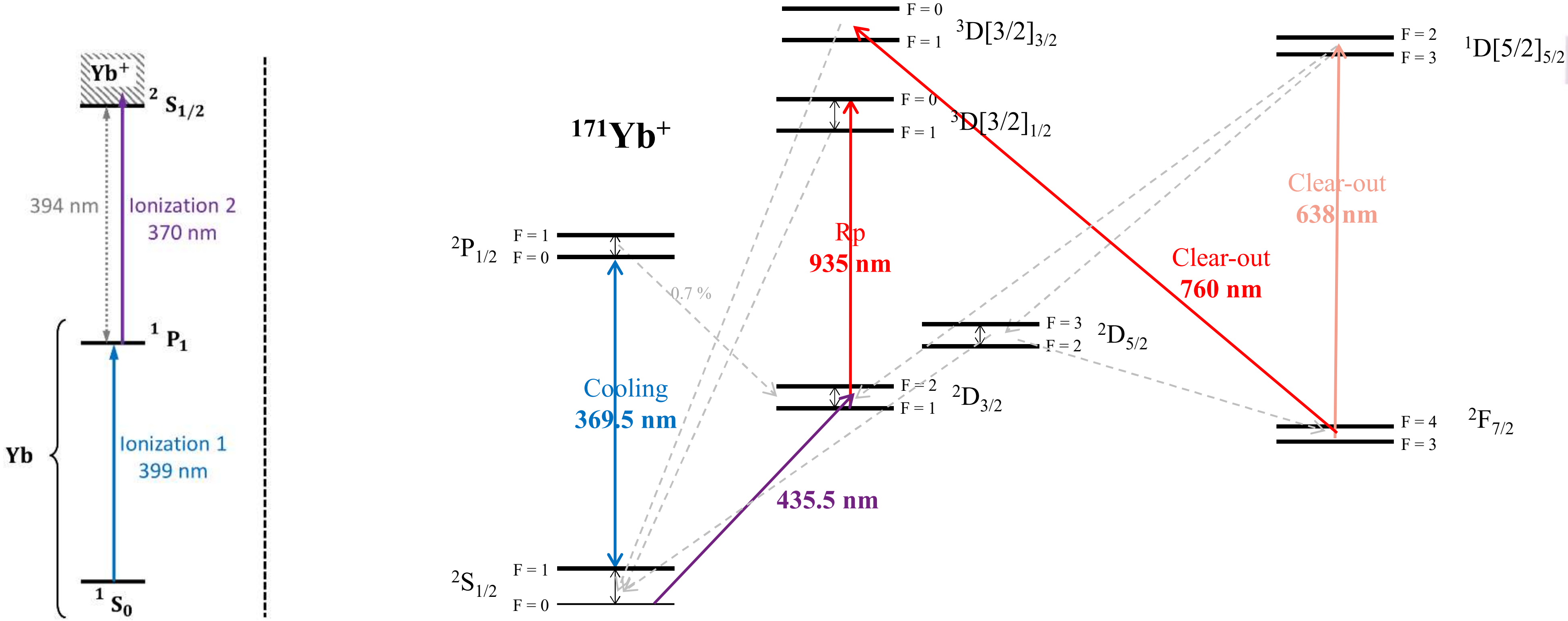
OBJECTIVES

We are building a compact optical clock based on a surface-electrode trap for $^{171}Yb^{+}$, with target volume and fractional frequency stability of <500 L and $10^{-14}\tau^{-1/2}$.

We are working on the E2 transition at 435.5 nm.



YB+ STRUCTURE



SURFACE-ELECTRODES ION CLOCK

- Operate in the **Lamb-Dicke regime** (Doppler effect rejection), *ie* high trapping frequencies.
- **Low micromotion** (2^d order Doppler effect rejection).
- **Long lifetime** (avoid deadtimes linked to ion loading).
- **Low heating rate** (avoid decoherence), *ie* high trapping distance.

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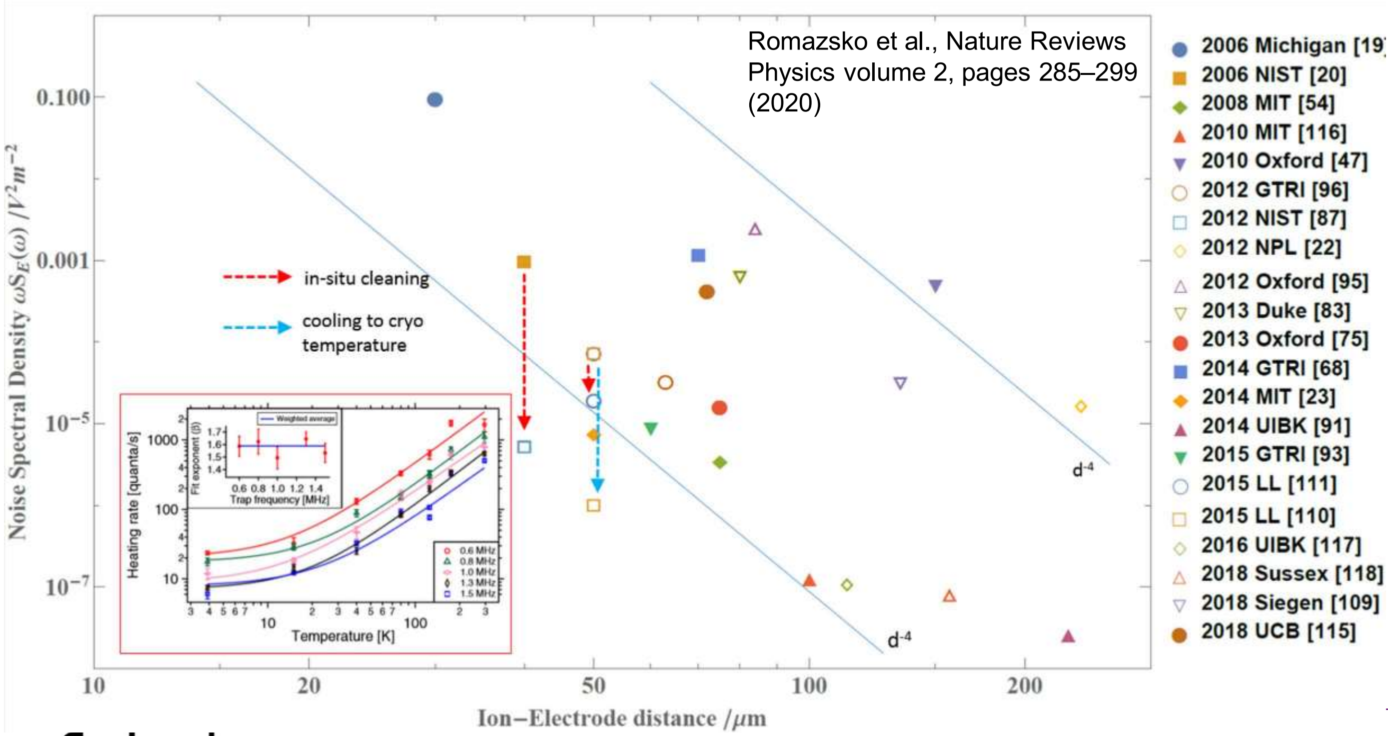
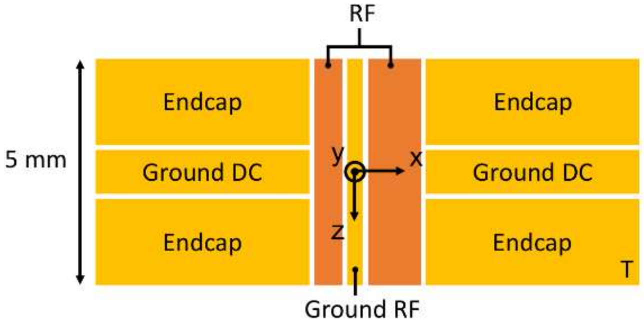
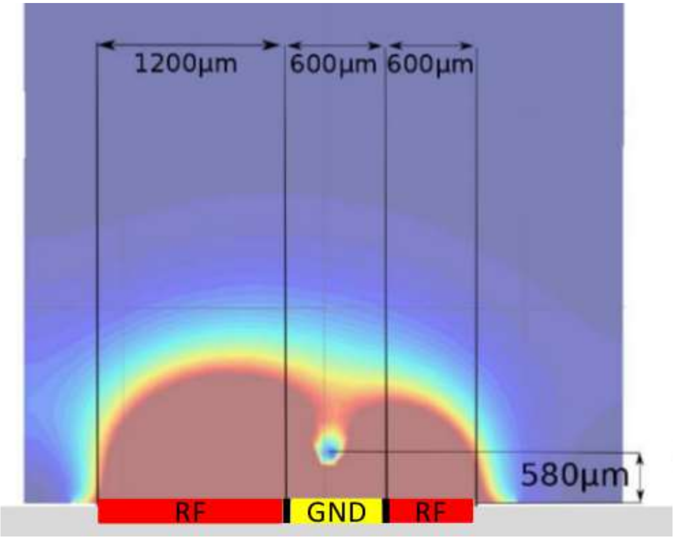


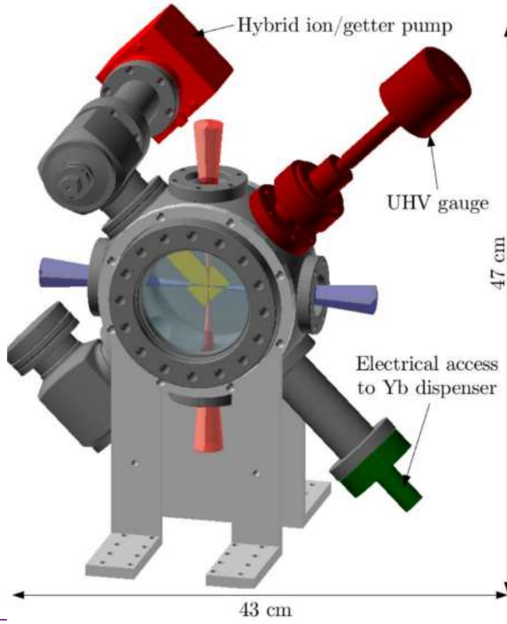
TRAP DESIGN – 5-WIRE GEOMETRY





- RF electrodes widths: 600 µm and 1200 µm
- Trapping distance: ~500 µm

- $\Omega_{RF}/(2\pi)$~3 to 6 MHz, V_{RF}=75-150 V
  $\omega_{ax}/(2\pi)$~85 kHz
  $\omega_{rad}/(2\pi)$~350 kHz



PROTOTYPE TRAP

Prototype chip trap:

- 9 gold-plated copper electrodes on FR4 PCB
  (not high-vaccum graded)
- RF electrodes widths: 600 μm and 1200 μm
- Trapping distance: ~500 μm

- $\Omega_{RF}/(2\pi)$~5.7 MHz, V_{RF}=150 V
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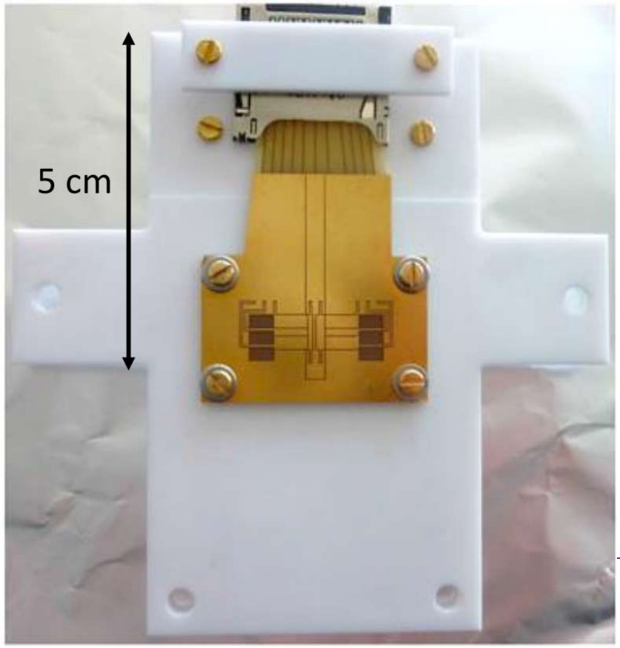

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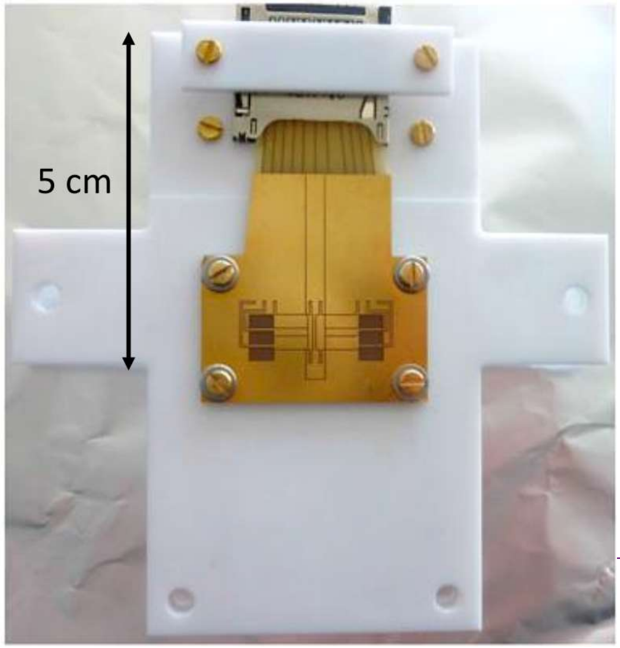

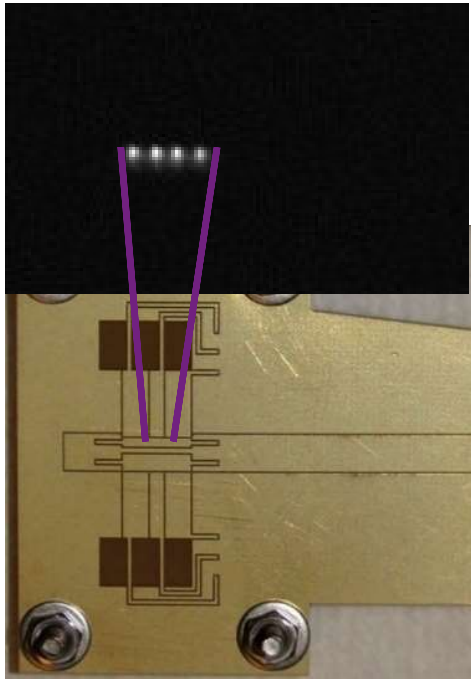

Starting with $^{176}Yb^{+}$ for simplicity

⇒ Fluorescence detection using a high NA optics, a CCD camera for spatial resolution (magnification ~x6) and/or a PMT for detection efficiency (collection efficiency 2.1%) and good SNR

⇒ Detection axis = perpendicular to the chip

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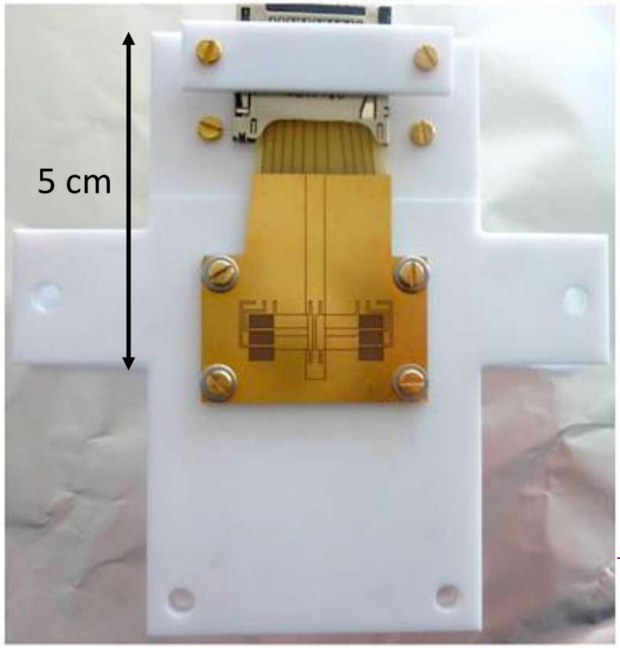

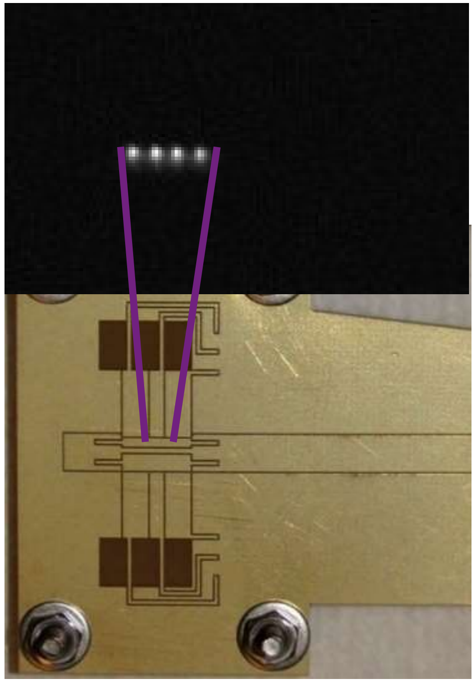

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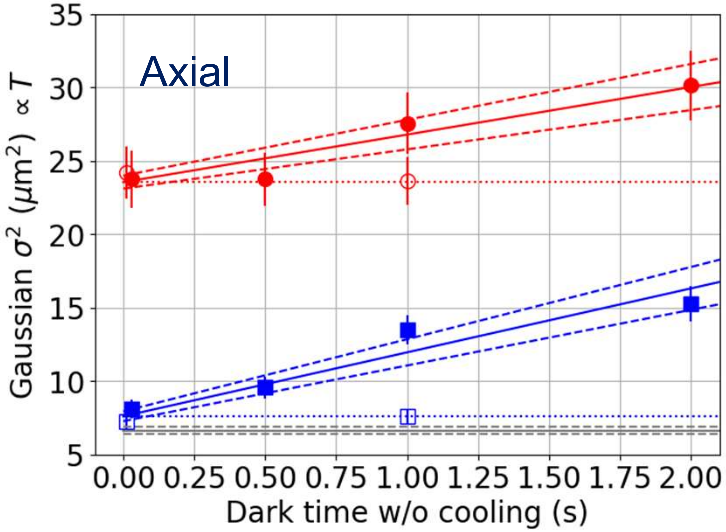
Trap lifetime ~1500 s
Trapping frequencies from 250 to 350 kHz
Heating rate ~8000 phonons/s



arXiv:2206.08215 / App. Phys. B 129, 37 (2023)

PROTOTYPE CHIP – EXPECTED PERFORMANCES

<u>Heating rate</u>
8 10^3 phonons/s
Trapping frequencies 350 kHz

<u>Micromotion</u>
Compensated using AM modulation of the RF voltage

Stark: calculation from exp. measurements;
Quadrupole: estimated from literature.

Clock operation:

Reduction of probing duration to a **few ms only** (vs $\tau_{D_{3/2}}$~53 ms)

$\Rightarrow \sigma_y \sim 5\ 10^{-14}\ \tau^{-1/2}$

Shift	Prototype trap	Prototype trap advanced	State-of-the-art materials
2^{d} order Doppler	3.1×10^{-17}	3.1×10^{-17}	$\approx 10^{-18}$ [50]
Stark	3.6×10^{-17}	1.2×10^{-17}	$\approx 10^{-18}$ [51]
Quadrupole	10^{-15}	10^{-16}	$\approx 10^{-17}$ [51]

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PROTOTYPE CHIP – EXPECTED PERFORMANCES

Heating rate
8 10^3 phonons/s
Trapping frequencies 350 kHz

Micromotion
Compensated using AM modulation of the RF voltage

Short lifetime

Heating rate
Should be improved

Micromotion
⇒ use photo-correlation at trap secular frequencies to implement 3D optimization with a single beam

Lifetime
Use UHV-compatible materials for the chip

Shift	Prototype trap	Prototype trap advanced	State-of-the-art materials
2^{d} order Doppler	3.1×10^{-17}	3.1×10^{-17}	$\approx 10^{-18}$ [50]
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MICRO-FABRICATED TRAP

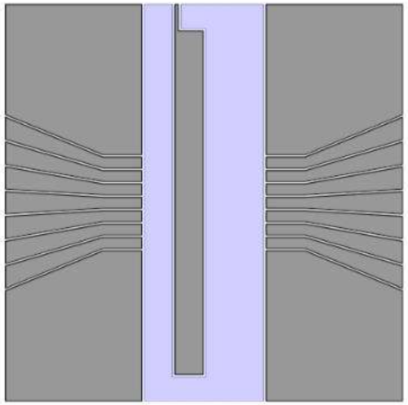
<u>New chip</u>

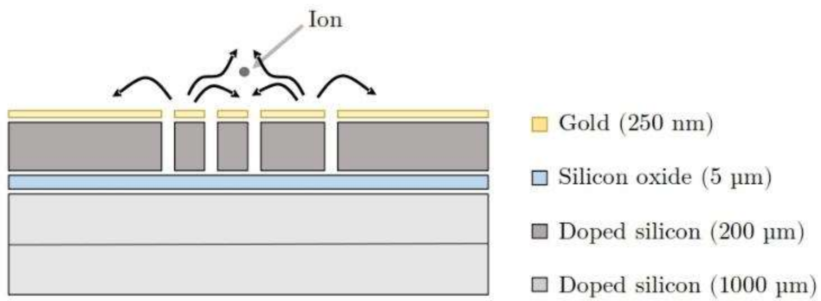
✓Designed and produced locally in clean room

- SOI electrodes
- Gold plated
- Much smaller dielectric interspacings
- Cleaned by plasma

Trapping parameters

- Trapping frequencies of 250 kHz or more
  - Increase V_{RF}
  - Lower Ω_{RF}





Better materials

⇒ better vacuum

⇒ lower heating rate

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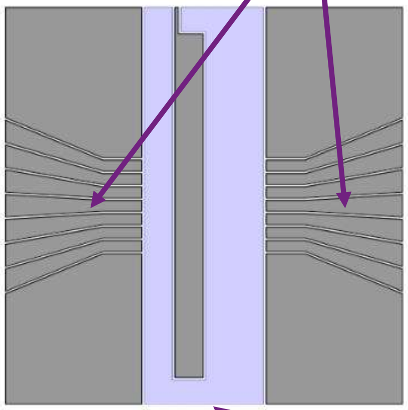
Additional control electrodes

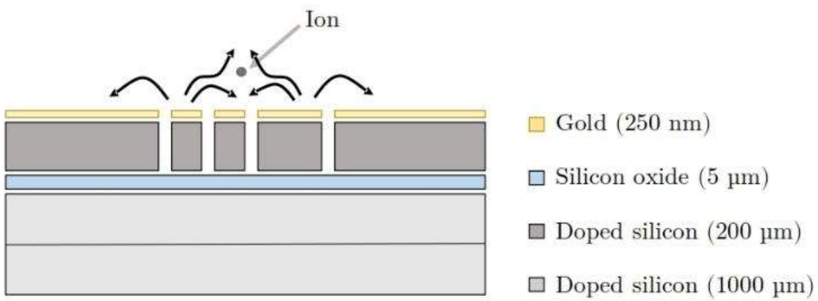
⇒ EMM compensation

⇒ Possible to use multiple trapping locations



Center electrodes width identical to prototype

Inter-electrodes spacing=20 μm



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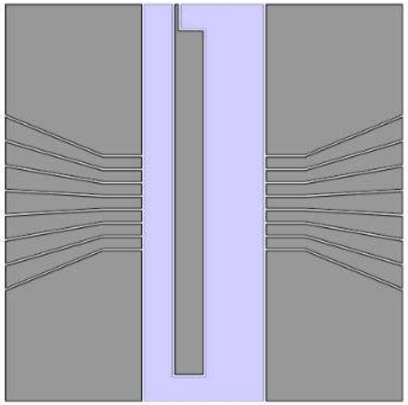

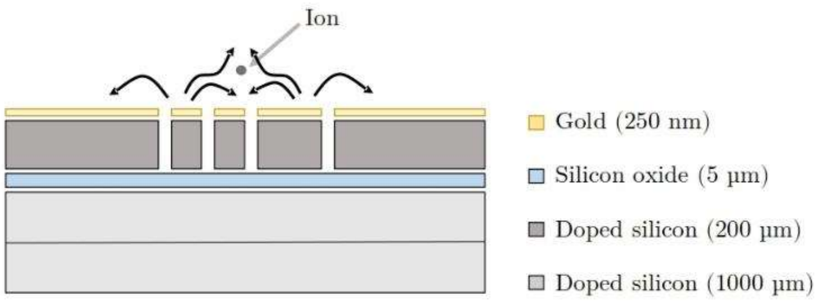

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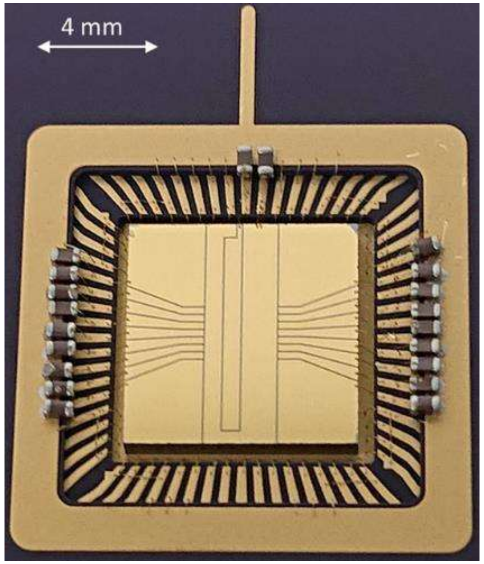

Commercial ceramic chip-carrier

Filtering capacitors on all DC electrodes

Trapping parameters

- Trapping frequencies of 250 kHz or more
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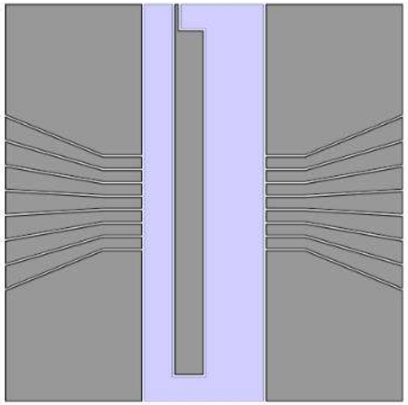

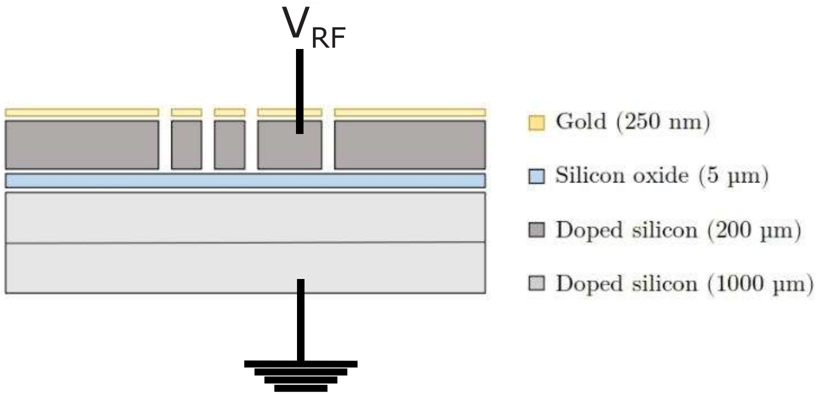

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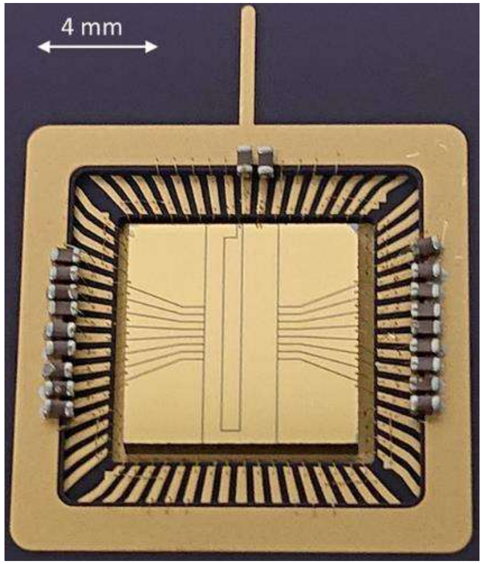

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Better materials

⇒ better vacuum

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Initial goal: 500 Vpp (or more!)

MICRO-FABRICATED TRAP: BREAKDOWN TESTS

<u>Dedicated chamber</u>

- UHV
- RF supply
- Optical access

Detect breakdown through

- Imaging
- Voltage monitoring
- Pressure monitoring

⇒ Very random results…

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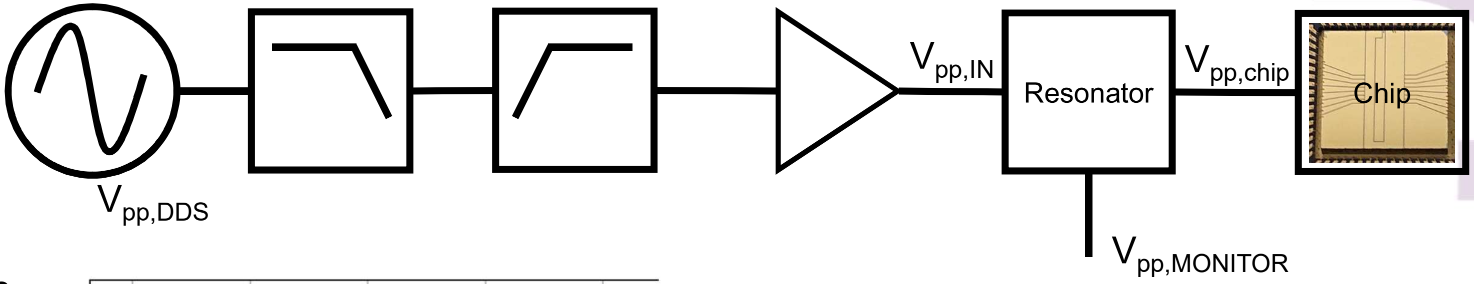

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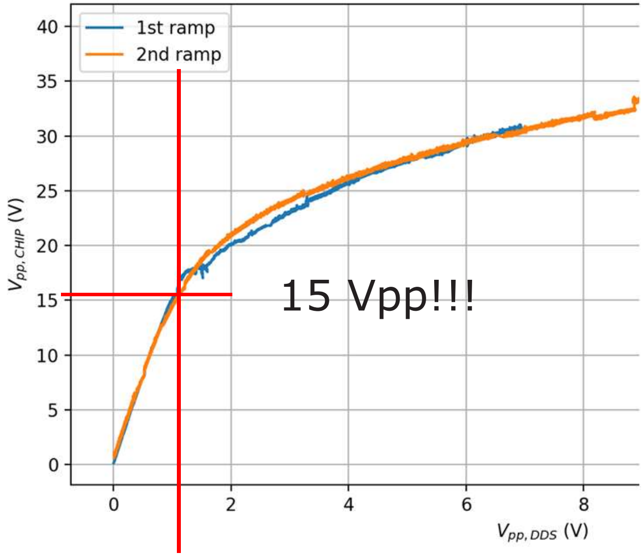

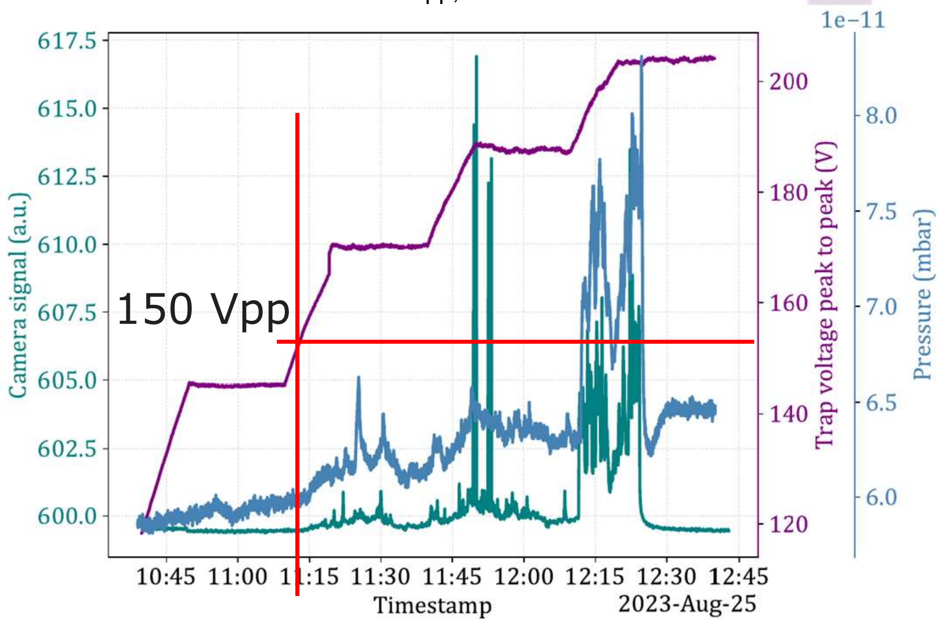

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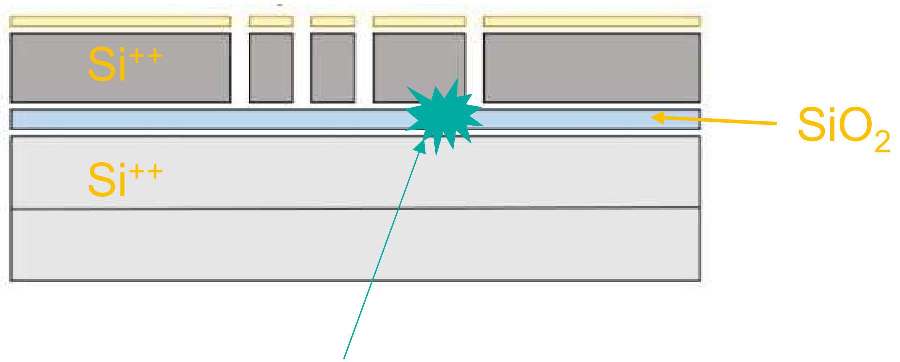

Most likely breakdown point; matches observations.

BUT: 5 µm of SiO2 should handle at least 200-300 V.

TSP tests reveal non-linear behavior of random electrodes (junction-like)

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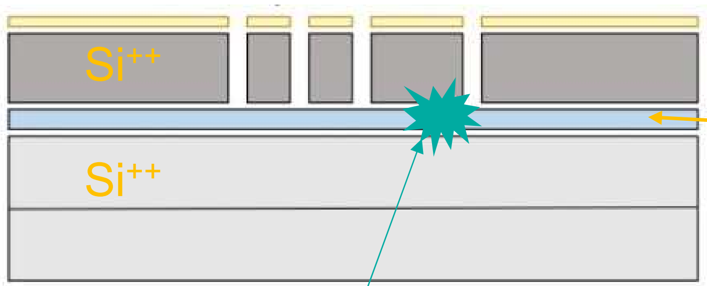

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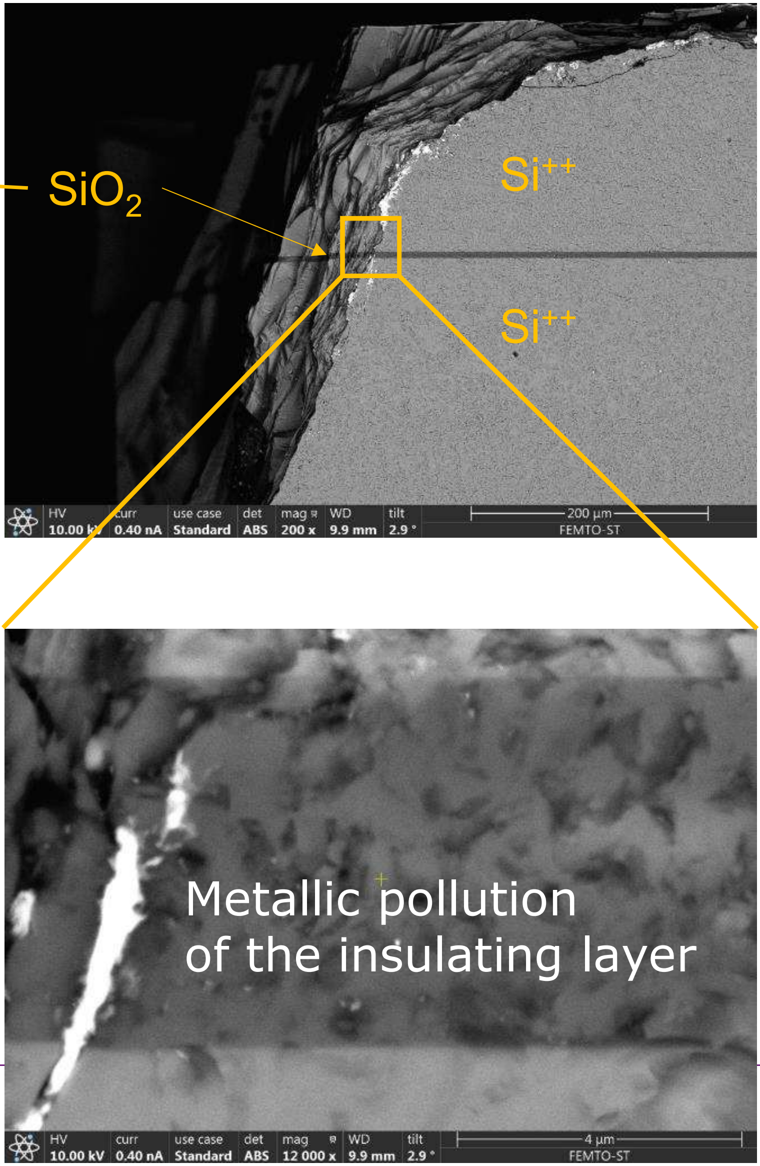

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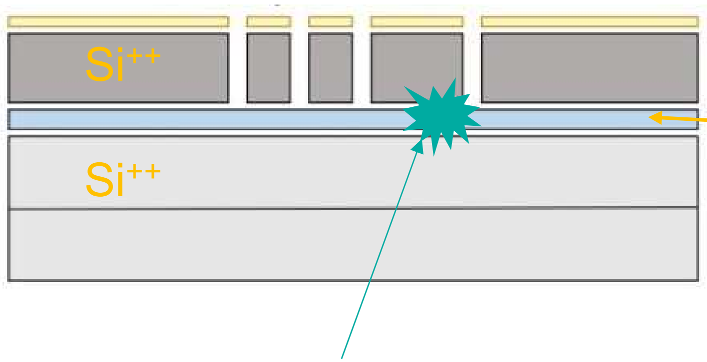

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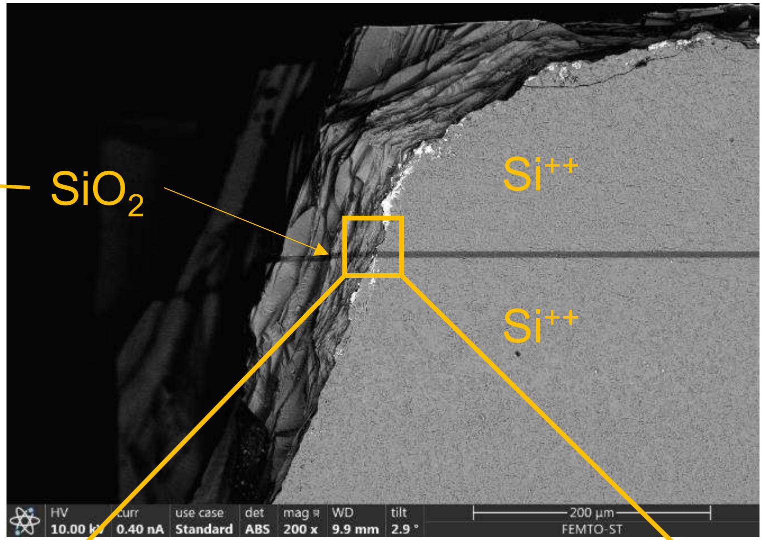

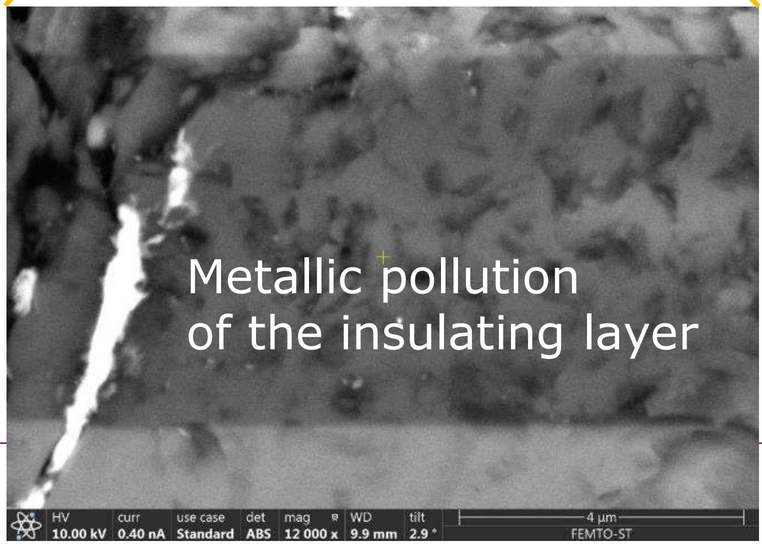

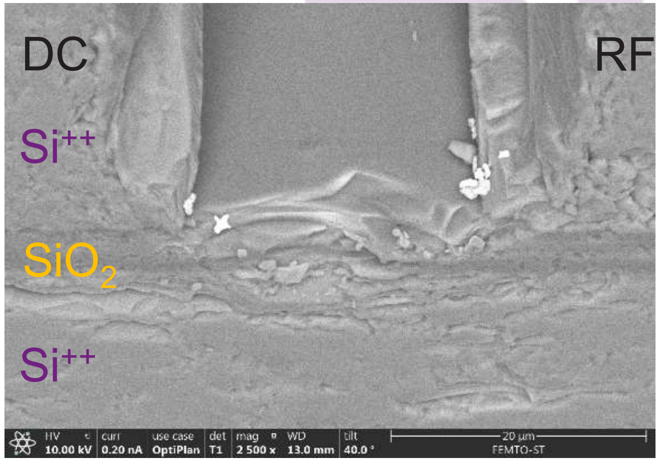

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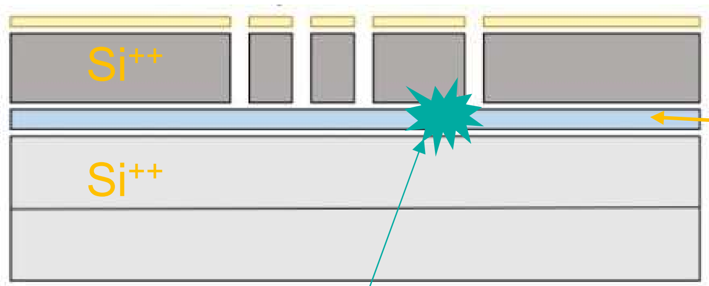

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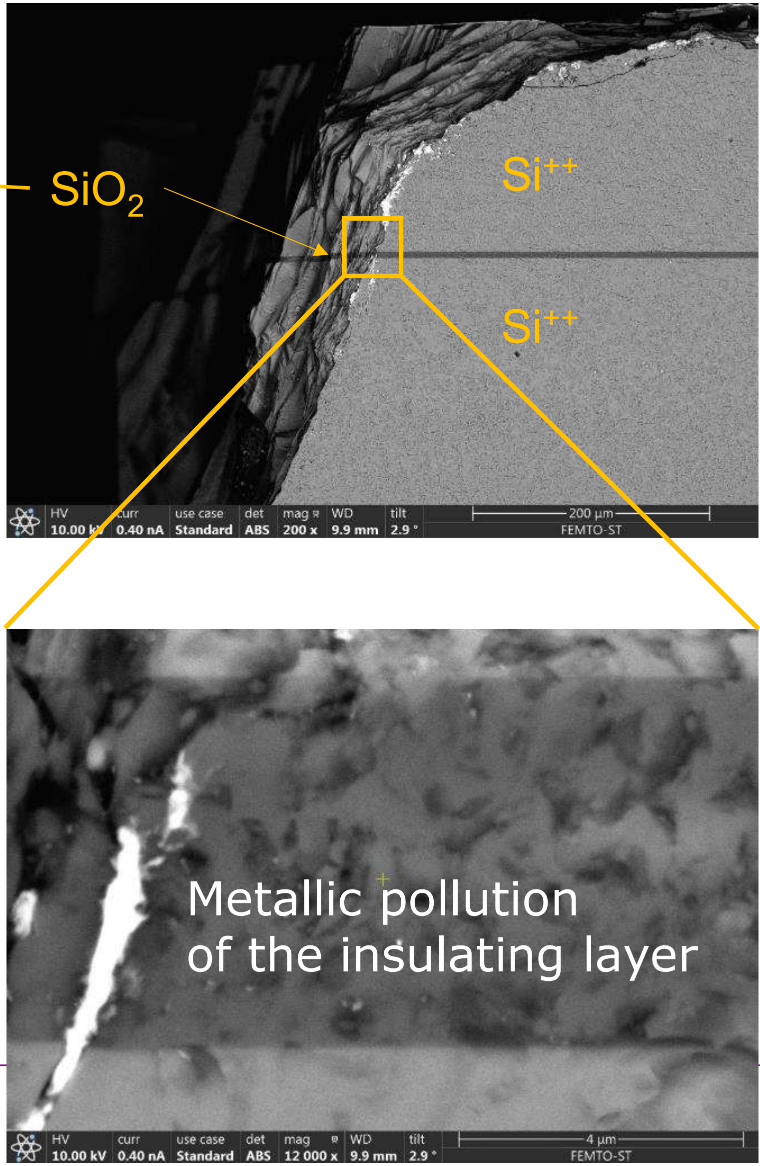
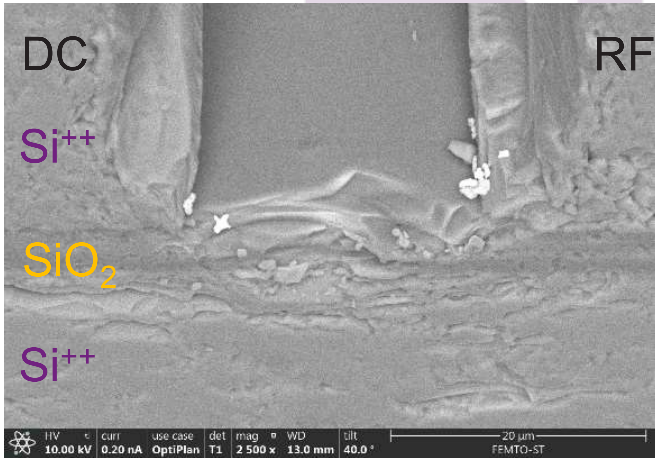




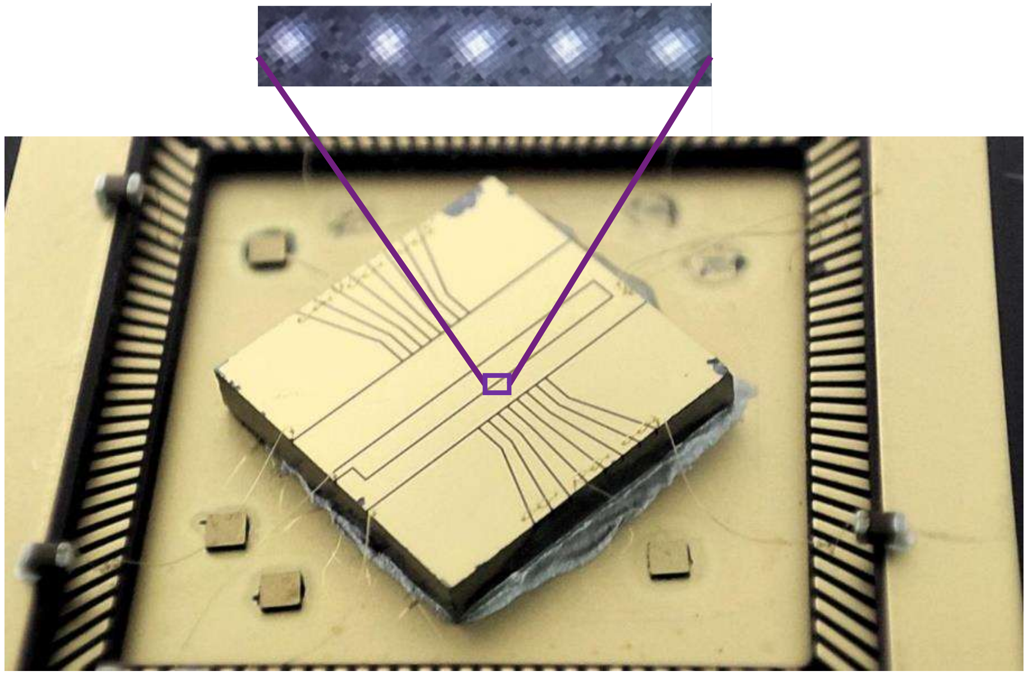
Random behavior due to random contamination of the chip flanks.

Metallic pollution came from wafer dicing!

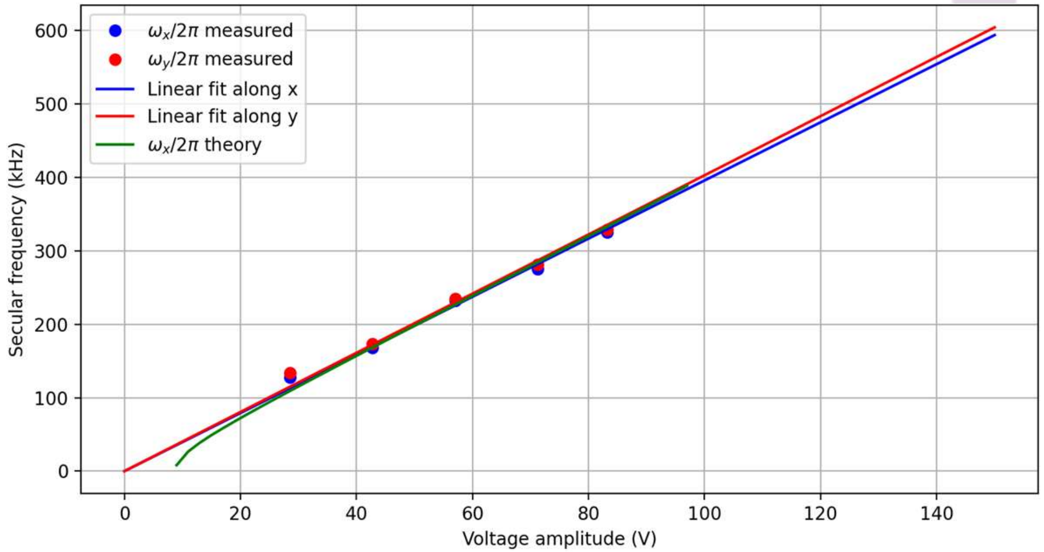
⇒ **Easy fix; chip v2 underway**

⇒ **Possible to find non-polluted chips.**

MICROFABRICATED TRAP: SR+ (PARIS) IONS

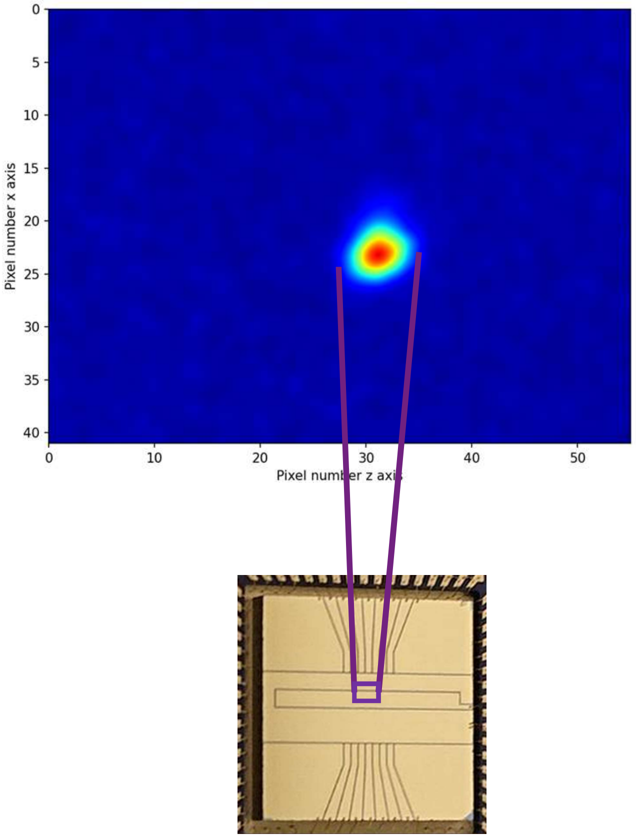


$^{88}Sr^{+}$ ions trapping at MPQ
w/ L. Guidoni & J.P. Likforman
April 2024



Secular frequencies evolution in the radiale plan (x,y)
as a function of the RF voltage
@Ω_{RF}=4,62 MHz

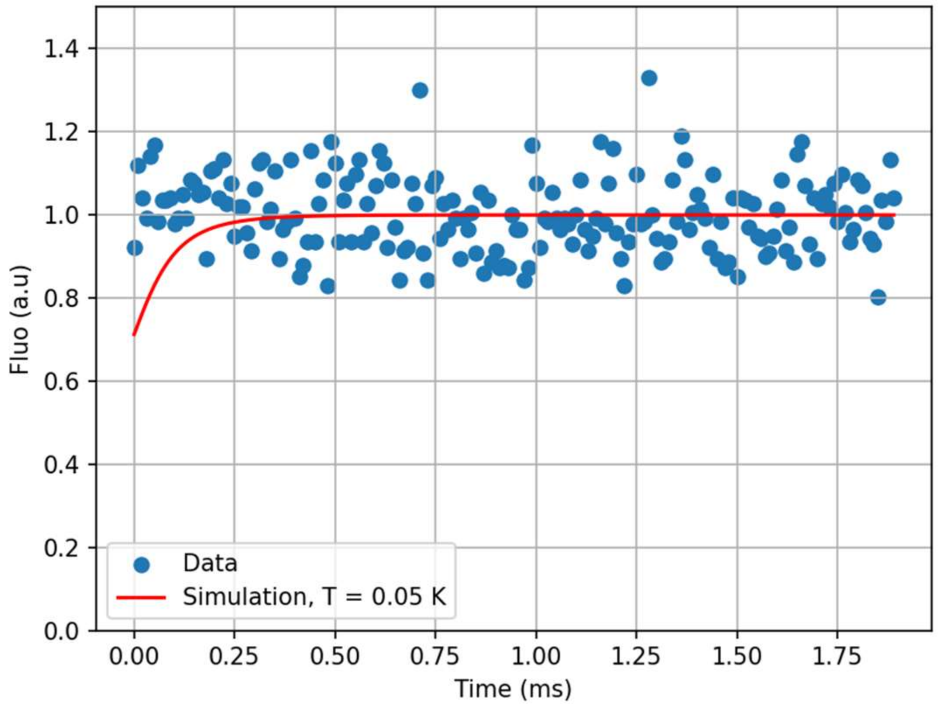
MICROFABRICATED TRAP: YB$^+$ (BESANÇON) IONS



- Applied voltages:
  - RF frequency : 3,77 MHz
  - RF voltage : 200 Vpp
  - DC voltages : Between $\pm$ 10 V
- Trap:
  - Trap frequencies 80 kHz, 209 kHz and 223 kHz
  - Lifetime 6000 s without clear-out laser, many hours with clear-out laser
  - **Measurement runs > 12 hours regularly**
- Vacuum:
  - Measured 7×10^{-11} mbars
  - Estimated collision rate 8/hour

MICROFABRICATED TRAP: YB⁺ (BESANÇON) IONS

- Heating rate:



Heating rate estimation based on the analysis of the temporal dynamics of a several Doppler cooling cycle [1].

Upper bound estimated **< 1000 phonons/s.**

Heating rate improved by a **factor 10.**

[1] Wesenberg, J. H., et al. *"Fluorescence during Doppler cooling of a single trapped atom." Physical Review A—Atomic, Molecular, and Optical Physics 76.5 (2007): 053416.*

CONCLUSION

- Succesfull design and fabrication of a Surface-electrode for TF metrology.
- Improvement of trap lifetime and heating rate.
- Clock laser installed, clock transition spectroscopy asap.

- 2.0 chip in fabrication, with improved process.
- Should enable higher operating voltages.

- Collaboration with MPQ on trap design, perspective of optical waveguides integration.

ION TRAPPING TEAM

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