Penning mass spectrometry using optical detection with $^{40}Ca^+$ as sensor ion in an unbalanced crystal

Ion Trapping Group

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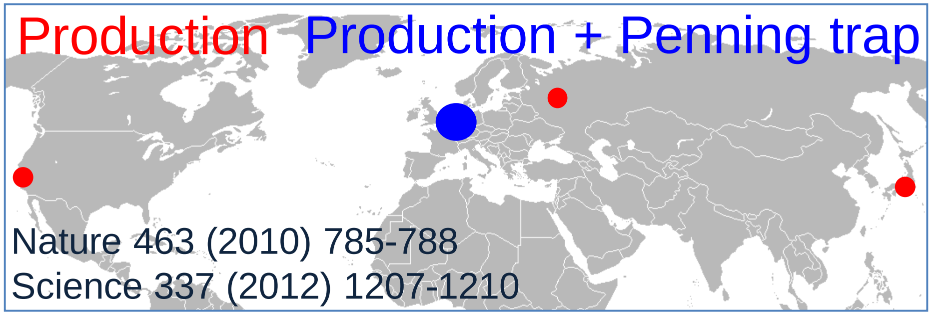
Outline

1. Motivation
2. Mass measurements using optical detection
3. The TRAPSENSOR beamline
4. Preparing the sensor ion: Doppler cooling in 7 tesla
5. Dynamics of the unbalanced crystal (calculations)
6. IIC using a quartz crystal amplifier
7. Conclusions and outlook

Motivation

- Mass measurements of SuperHeavy Elements (SHE)



$$w_c = \frac{q}{m} B$$

Low production rates / Fixed charge states / Half-lives

Single ion sensitivity / Universal technique / Half-lives above 1 second

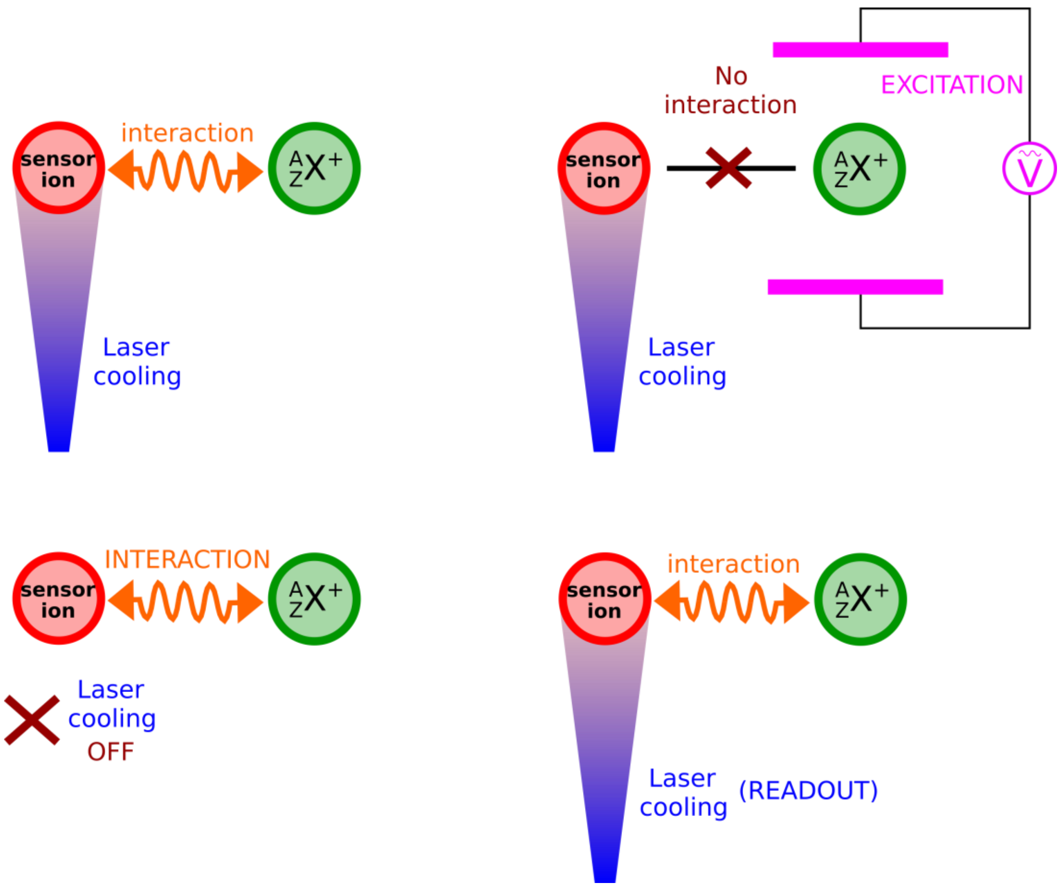
- Techniques in use

  - TOF-ICR: Several tens of ions
  - PI-ICR: About 10 ions and implemented for SHE.
  - IIC: Successfully used in many experiments but not yet implemented for SHE (New approach in collaboration with M. Block's group).

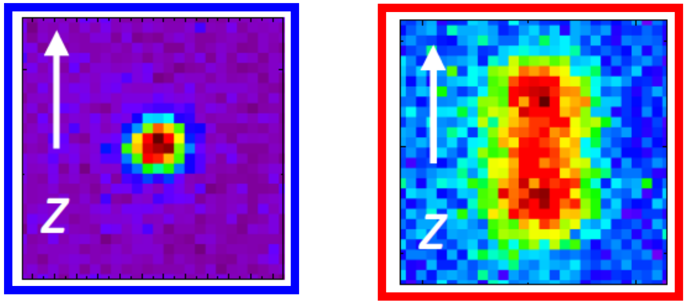
- Mass measurements can be done in Granada.

Mass Meas. Using Optical Detection

- Measurement Scheme



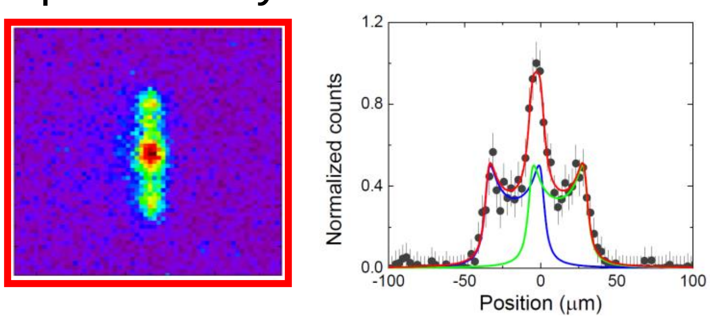
- Optical study of a single ion



Single $^{40}Ca^{+}$ ion *T*~10 mK | Interaction with lasers + RF external field

Sci. Rep. **7**, 8336 (2017)

- Optical study of two-ions



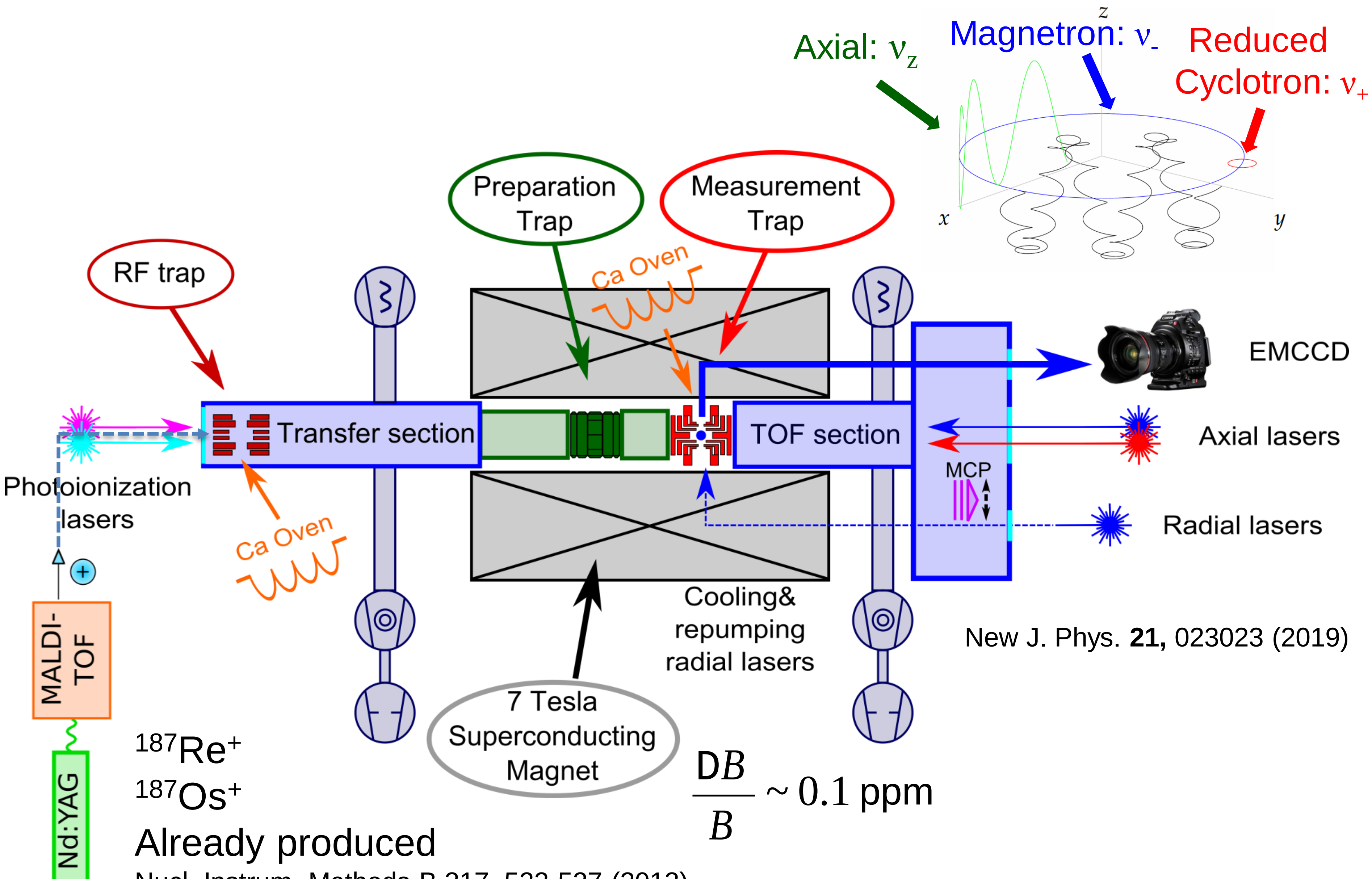
Two $^{40}Ca^{+}$ ion +RF external fields | Two $^{40}Ca^{+}$ ion +RF external fields

J. Mod. Opt. **65** 613-621 (2018)

D.J. Heinzen, D.J. Wineland, Phys. Rev. A 42, 2977 (1990)

Appl. Phys. B **107,** 1031-104 (2012) (for applications in Mass Spect. on SHE and Neutrino Physics)

The TRAPSENSOR Beamline



New J. Phys. **21,** 023023 (2019)

$^{187}Re^{+}$

$^{187}Os^{+}$

Already produced

Nucl. Instrum. Methods B 317, 522-527 (2013)

$$\frac{\Delta B}{B} \sim 0.1 \text{ ppm}$$

The TRAPSENSOR beamline

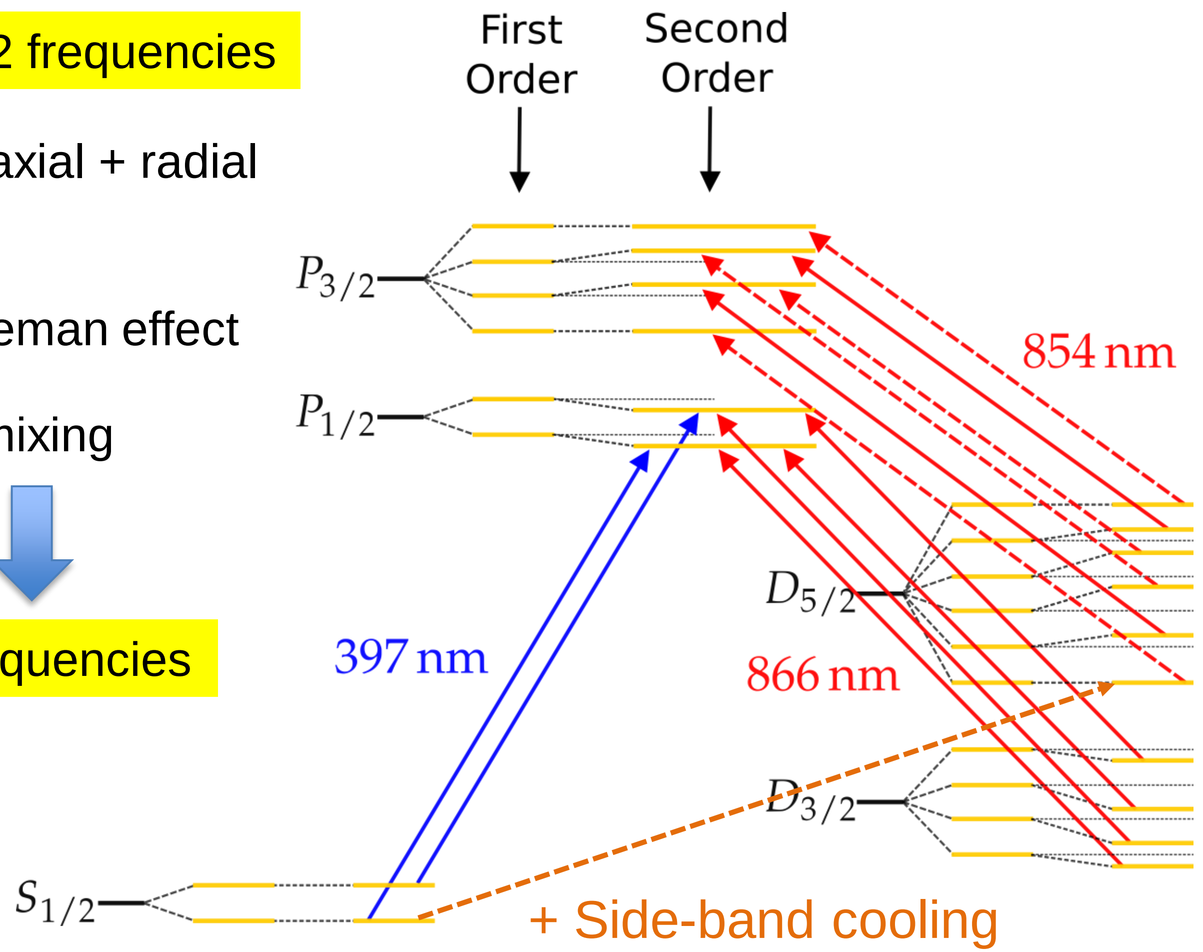
Doppler Cooling in 7 T

- Cooling lasers → 2 frequencies; axial + radial

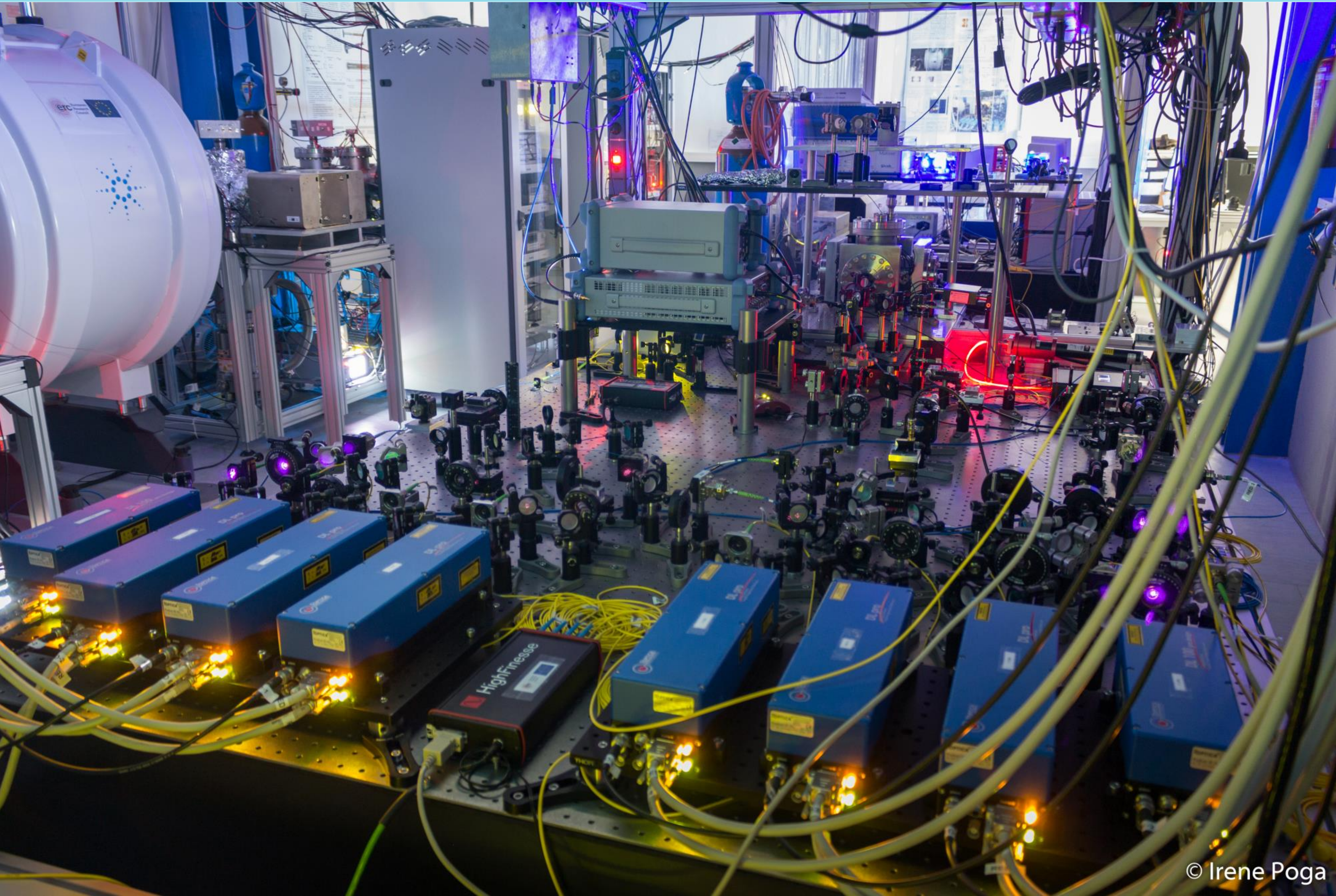
- Repumping lasers
  - Zeeman effect
  - J-mixing

  10 frequencies

- Laser system
  - 397-nm lasers (x2)
  - 866-nm lasers (x4)
  - 854-nm lasers (x2) + EOM
  - Ultra-high accuracy WM

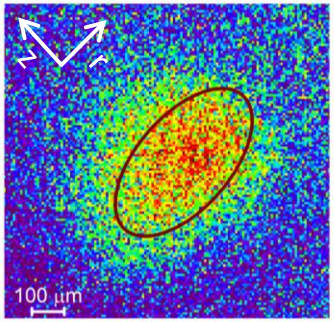


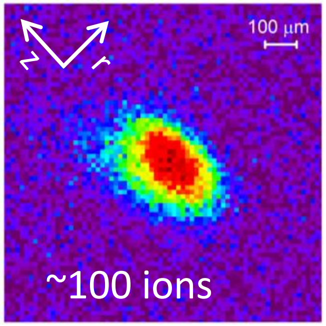
Doppler Cooling in 7 T



Doppler Cooling in 7 T

- Axial cooling
- Radial cooling



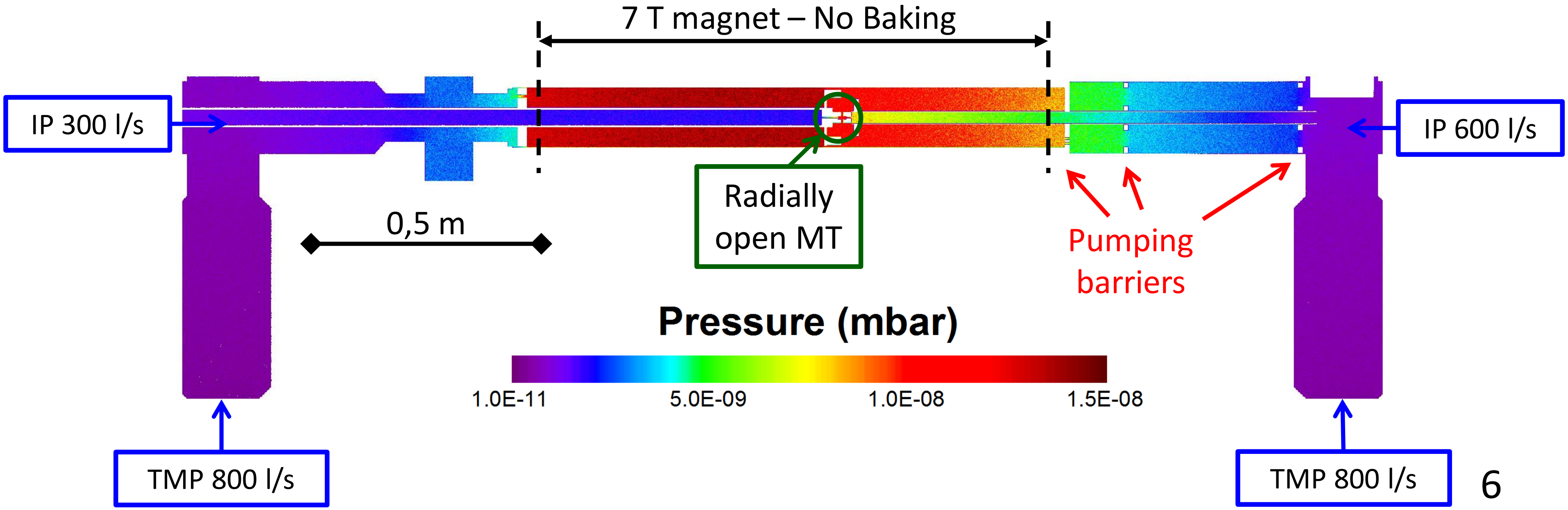


✓ Expected shape

✓ ~10 ions detection limit

✗ ~30 s ion lifetime (in a first experiment)

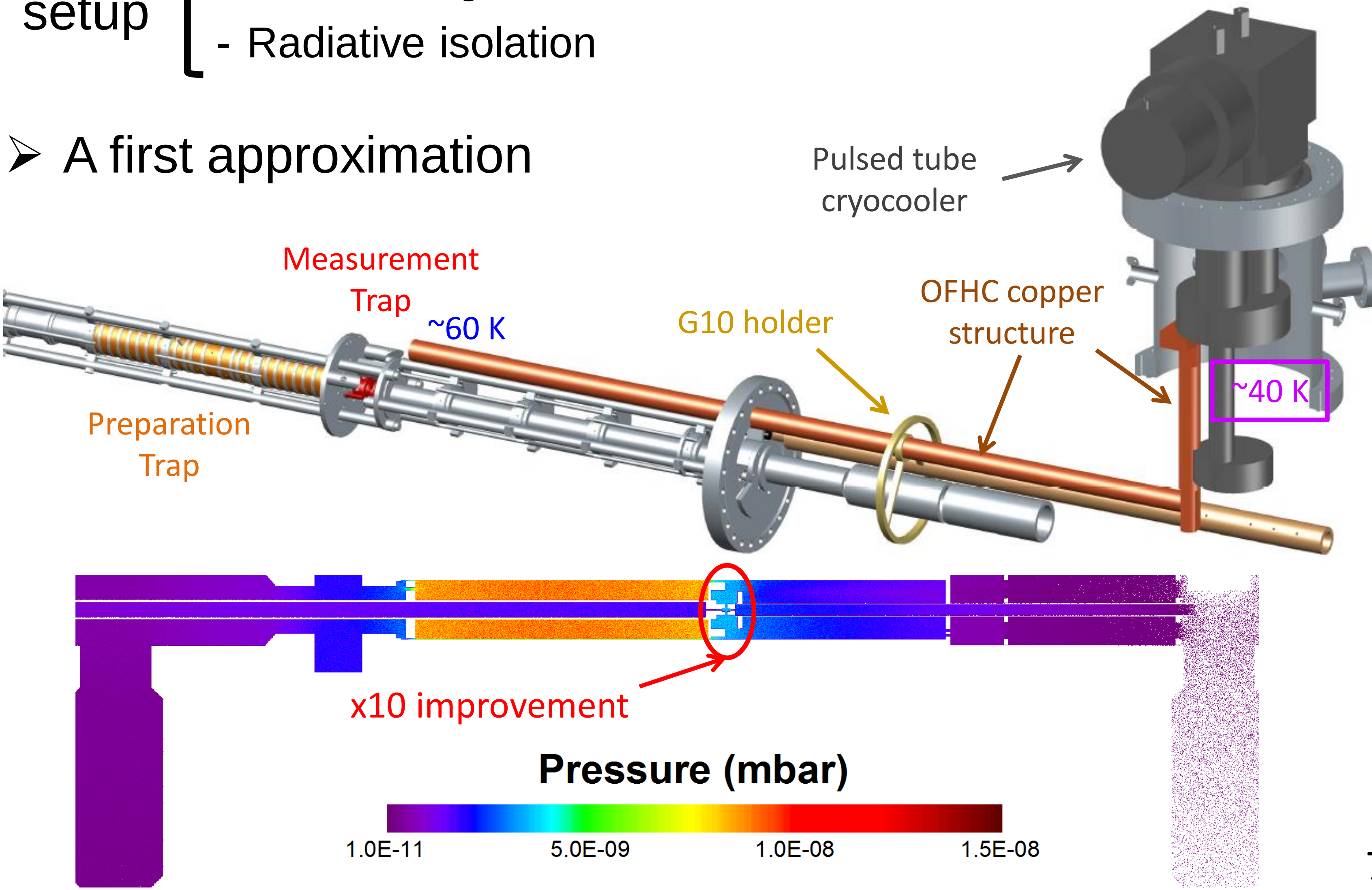
- Vacuum simulations ⟶ Molflow+ (CERN)



Doppler Cooling in 7 T. Cryogenics.

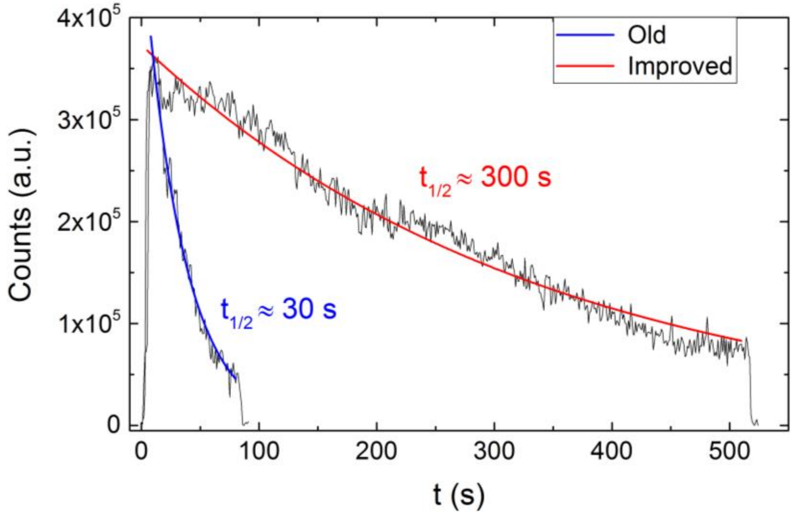
- Final setup
  - Trap can at 4 K ⟶ H_2O, N_2, CO_2, O_2… condensation
  - Surrounding at 40 K ⟶ Conductive + Radiative isolation
  - Radiative isolation

- A first approximation



Doppler Cooling in 7 T. Results

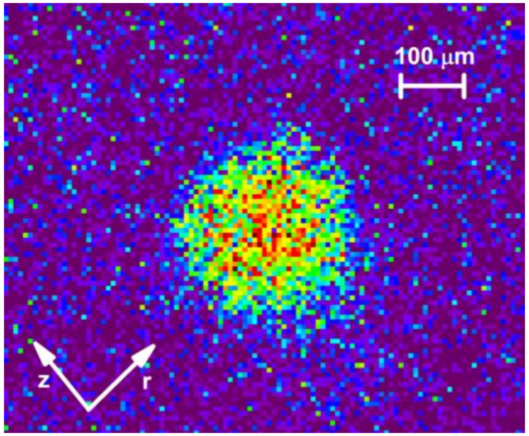
- Lifetime improvement



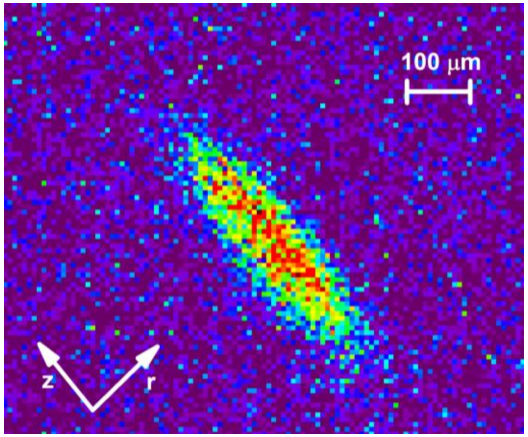
- $p \sim 10^{-9}$ mbar
- ✓ Enough to detect two-ion crystal

- Evidence of axialization

Ax. OFF



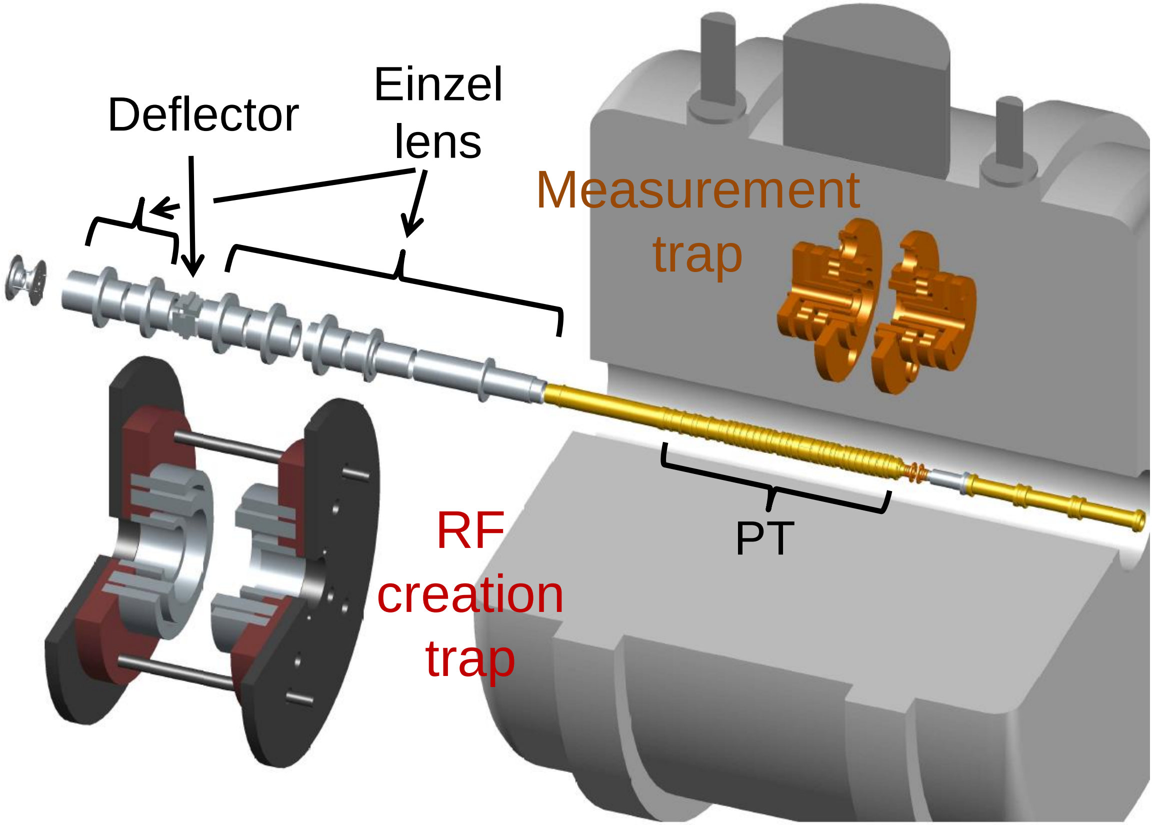
Ax. ON

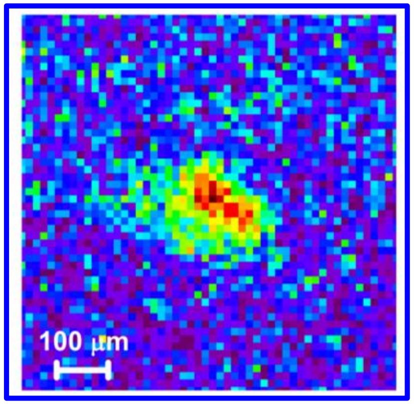


- Cooling lasers: $\Delta \approx -\gamma/2$
- Radial spot: ~100 µm
- Quad. Field: $\nu_c \approx 2.7$ MHz

  $V \approx 300$ mV_{pp}

Doppler Cooling in 7 T. External Production



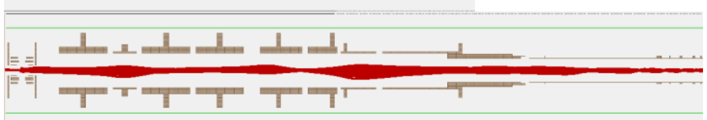


~10 ions

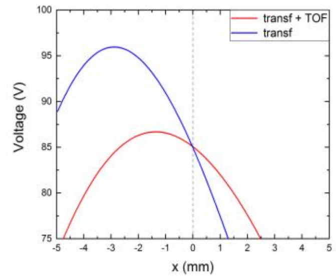
- Simulation work (SIMION)

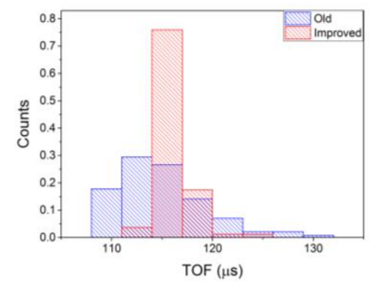
Previous

Optimum



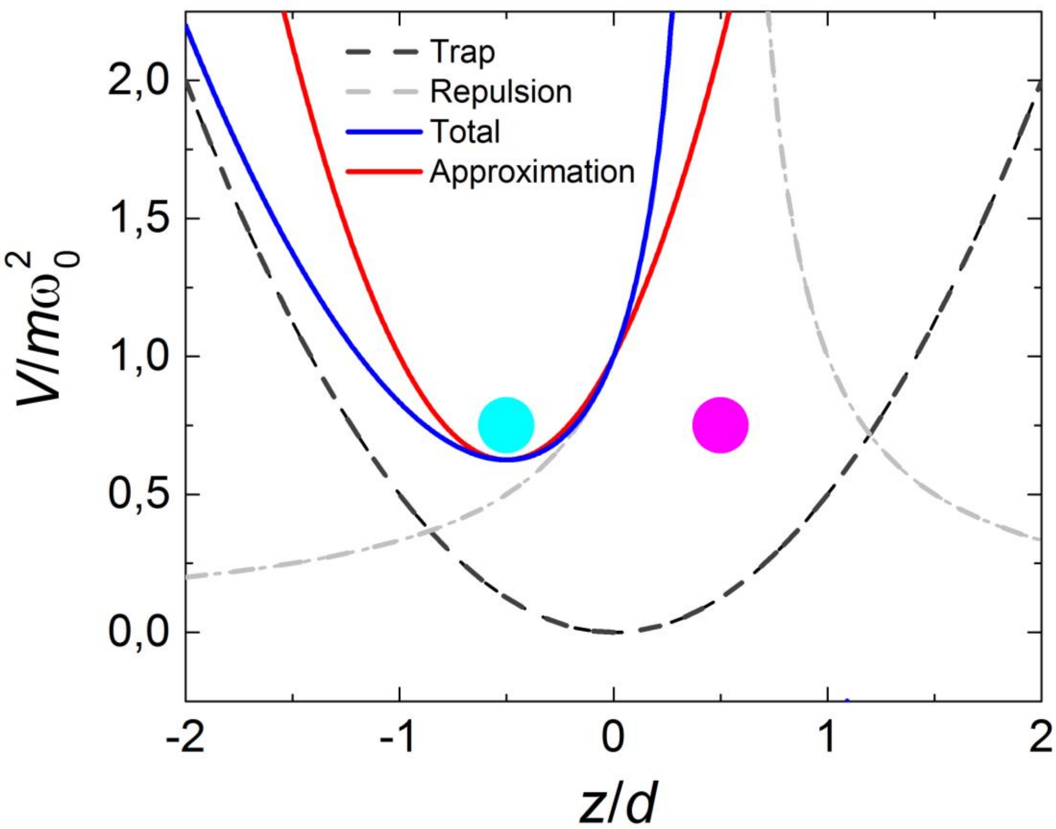
Flatter ext. pulse → Narrower bunch





Dynamics of an Unbalanced Crystal

- Two ions in a harmonic potential



S. Jain et al., arXiv:1812.06755v2,
M.J. Gutiérrez *et al.,* PRA 100, 063415 (2019).

- Crystal alignment on *z* axis

- Nomenclature

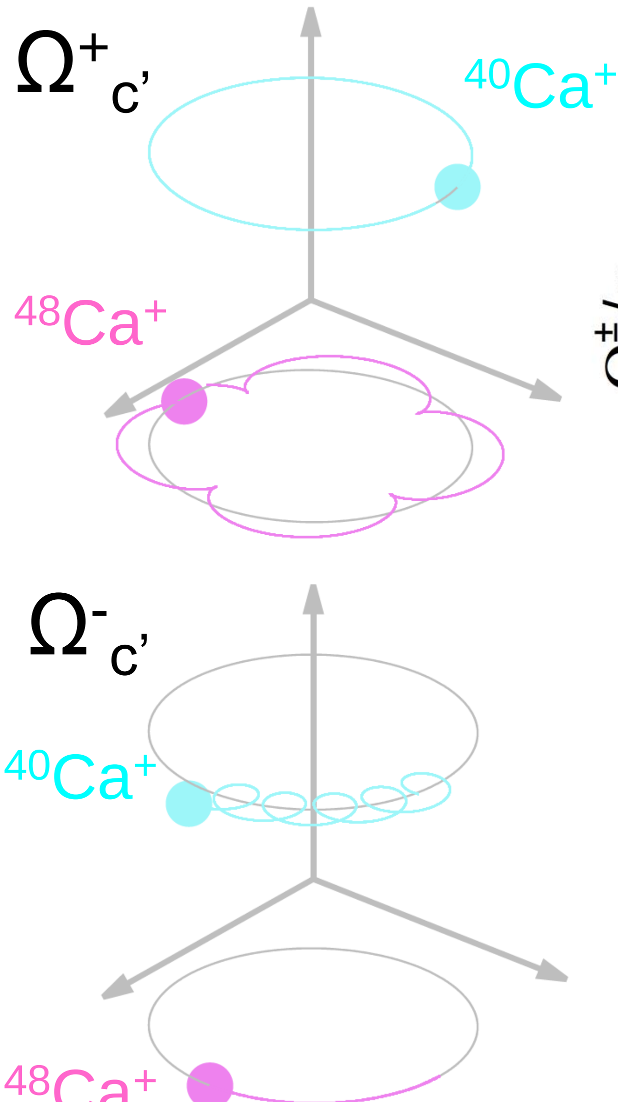
$\Omega^{\pm}_{z/c'/m}$ $\rho^{\pm}_{t/s}$

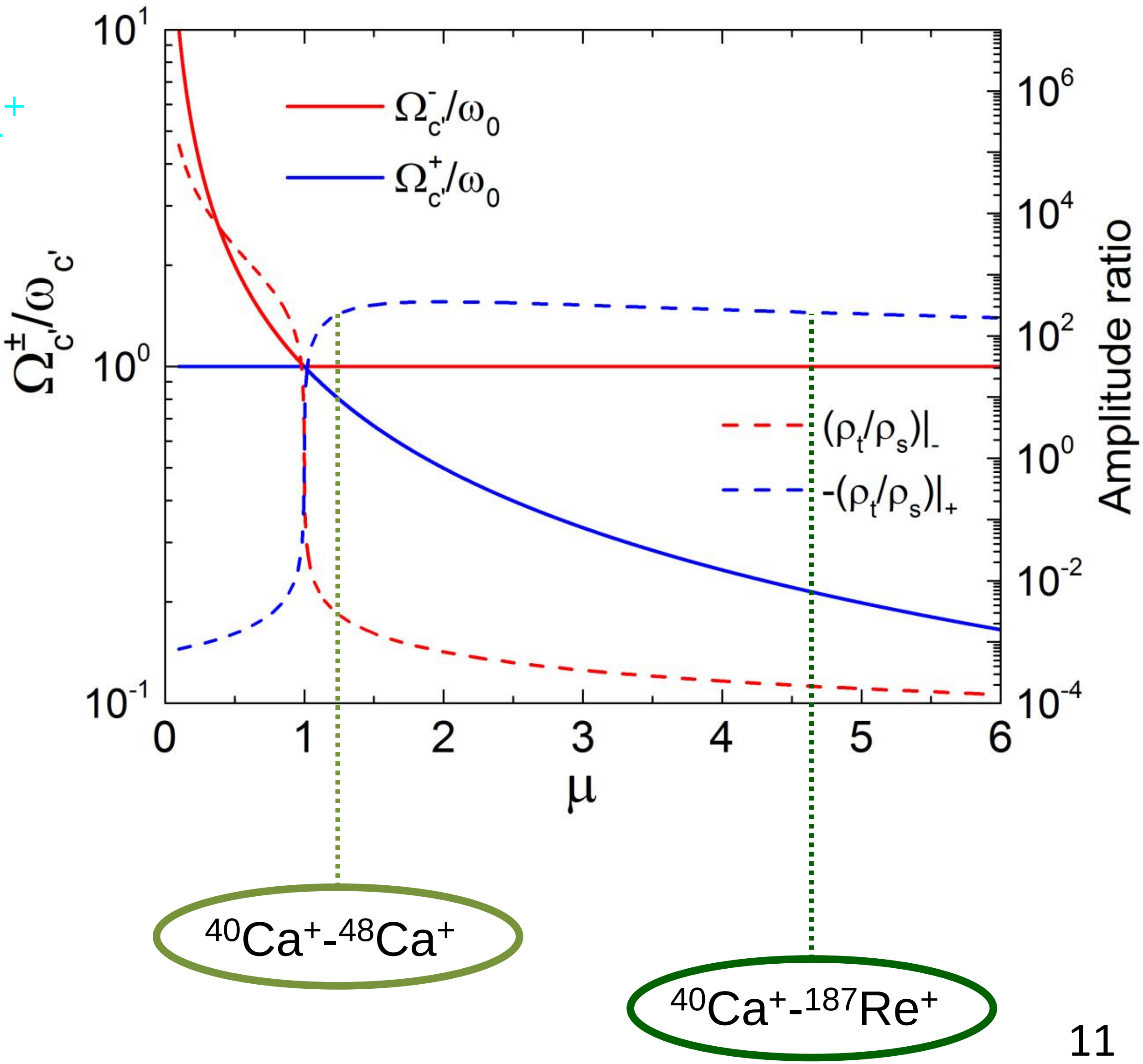
- Axial motion equivalent to Paul trap

Eur. Phys. J. D 13(2), 261-269 (2001), Phys. Rev. Lett. 93 (2004) 243201.

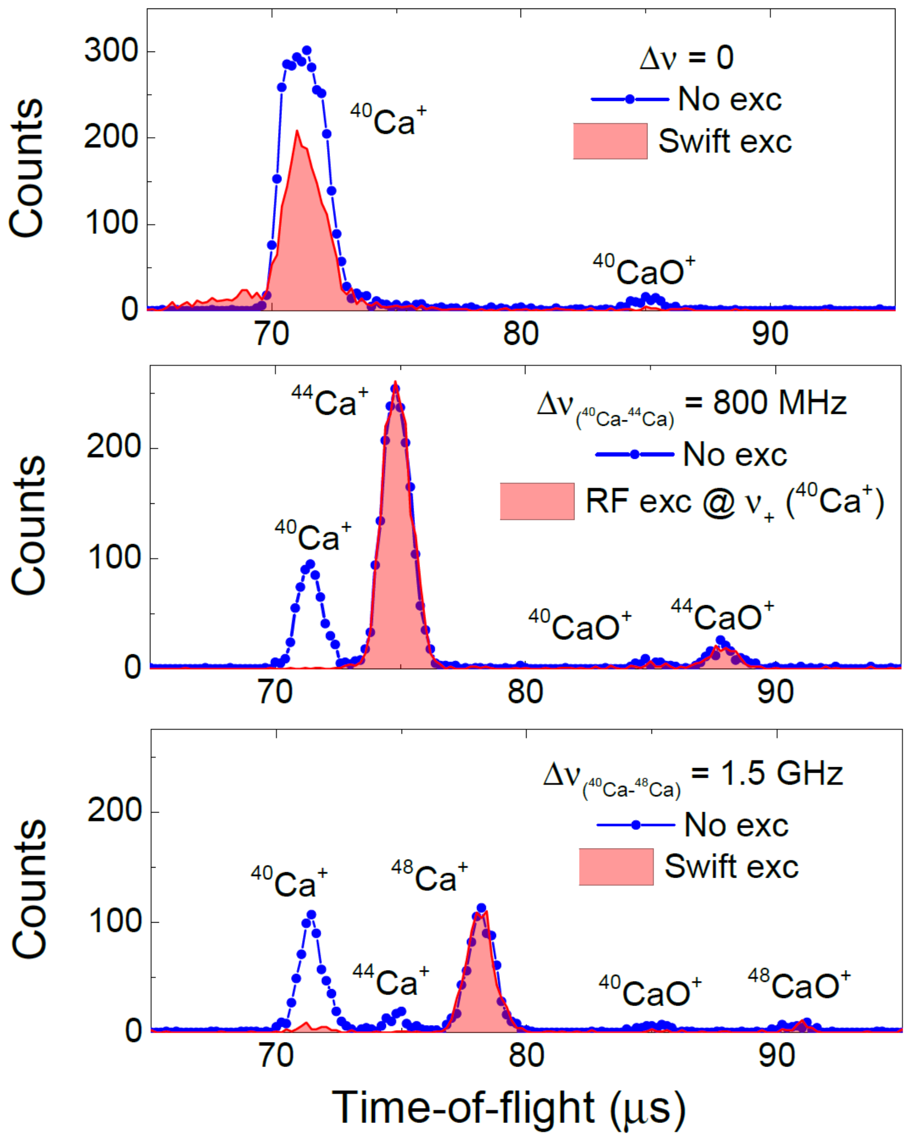
Dynamics of an Unbalanced Crystal

- Radial motion





A Very Close (in Time) Experiment



- Optical detection

Mass measurement → $$\sum_{i=1}^{6} \omega_i^2 = \omega_{cs}^2 + \omega_{ct}^2$$

arXiv:1812.06755v2

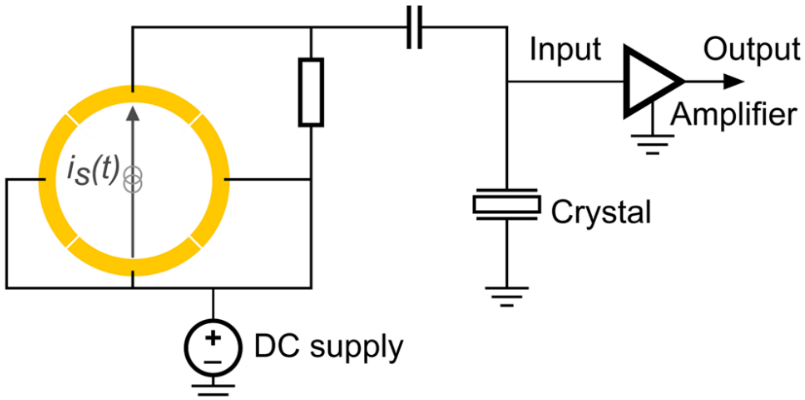
- Frequency shifts

$$\Delta\Omega = \left\{ \text{6 x 6 matrix} \right\} \left[n_{ph} \right]$$

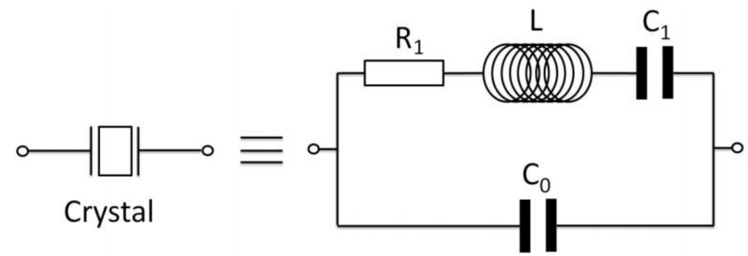
Need still to perform this measurement in a Penning trap

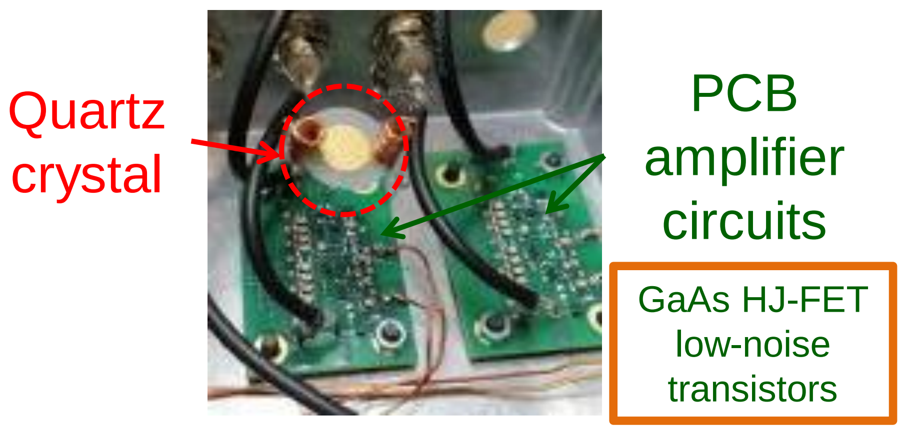
IIC using a quartz amplifier

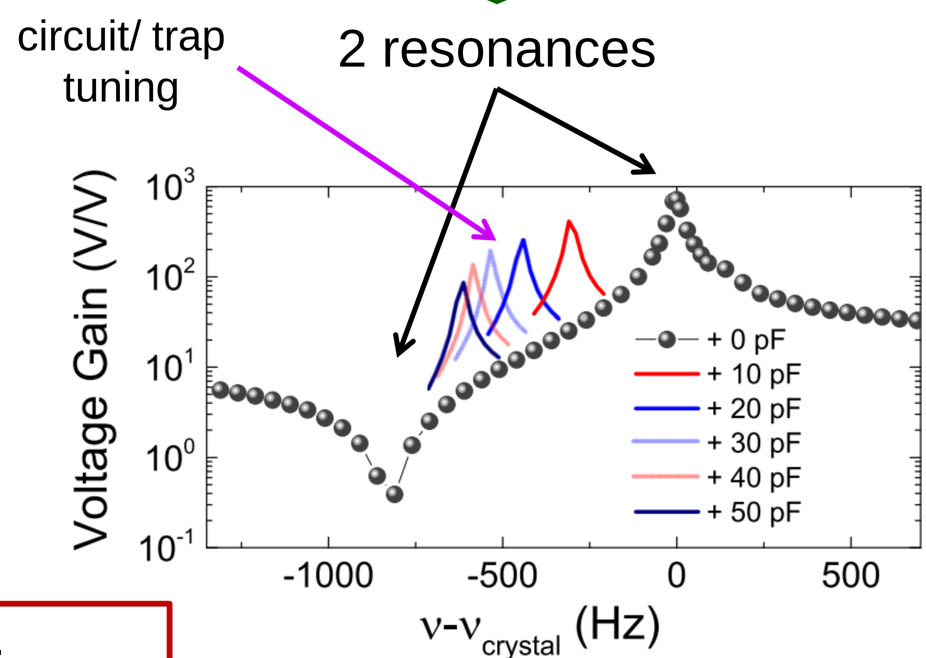
- Detection scheme



- Quartz crystal circuit model



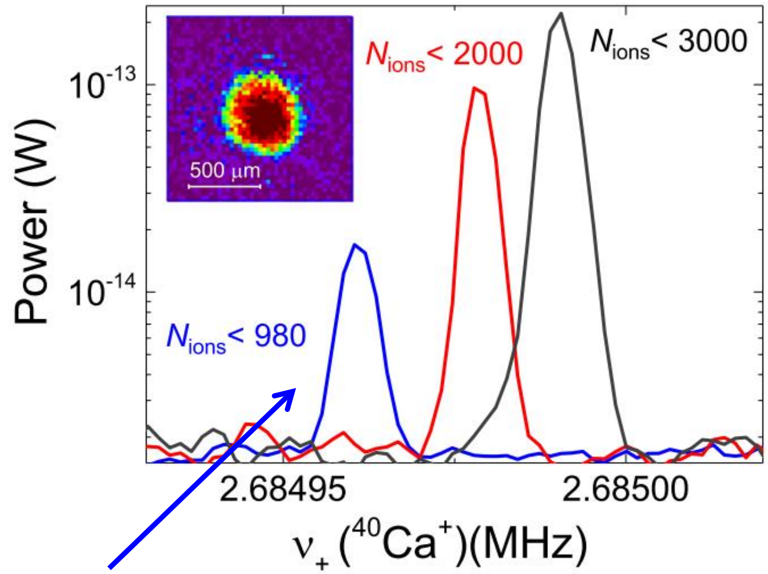




In collaboration with:
- SEVEN Solutions S.L.
- Univ. Mainz (M. Block's group)

IIC using a quartz amplifier

- Broadband results



S/N~9

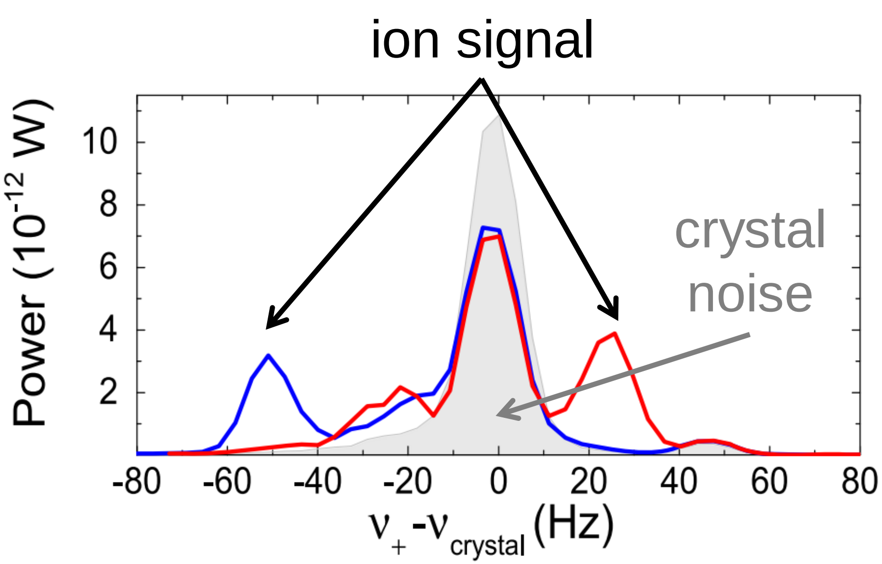
~110 ions lower limit

- Number of photons
- Cloud dimensions

$$n_0 = \frac{2m\epsilon_0\omega_p(\omega_c - \omega_p)}{q^2}$$

✓ Factor of **40** improvement

- Narrowband results



✓ First signal with ions

↓

✓ New results on heavy ions (Mainz)

- cryogenics
- near to trap

Conclusions

- A new Penning-trap mass spectrometry technique based on optical detection under development at the University of Granada.

- Cooling of all the motions of trapped $^{40}Ca^{+}$ ions in a 7-tesla Penning trap has been accomplished (also axialization). Successful cooling of externally injected ions has been carried out.

- The Eigenmodes and frequency shifts of an unbalanced two-ions crystal in a Penning trap have been studied in detail.

- We can also combine optical detection with other techniques: Quartz Crystal Amplifier.

Perspectives

- We still has to reach the single laser-cooled ion. A very first experiment with e.g. $^{40}Ca^{+}$-$^{48}Ca^{+}$ should take place soon.

- Measurements using any other isotopes like $^{187}Re^{+}$ and $^{187}Os^{+}$ (already produced in the system) can be performed using the external injection.

- Performing side-band cooling will be possible since very soon will get the laser equipment to access the clock transition in $^{40}Ca^{+}$. From this moment we will be able to measure precisely our frequencies using a comb.

Thank you for your attention

Joaquín Berrocal (PhD student)
Fran Domínguez (PhD student)
Manuel J. Gutiérrez (PhD student)
Daniel Rodríguez (Group leader)

http://trapsensor.ugr.es

Collaborators:
M. Block's group (JGU, HIM & GSI)
C. Ospelkaus's group (LUH & PTB)
E. Solano's group at UPV & IKERBASQUE

ugr Universidad de Granada

erc European Research Council
Established by the European Commission

TRAP SENSOR

Laboratorios Singulares UGR

CPAN Ingenio 2010

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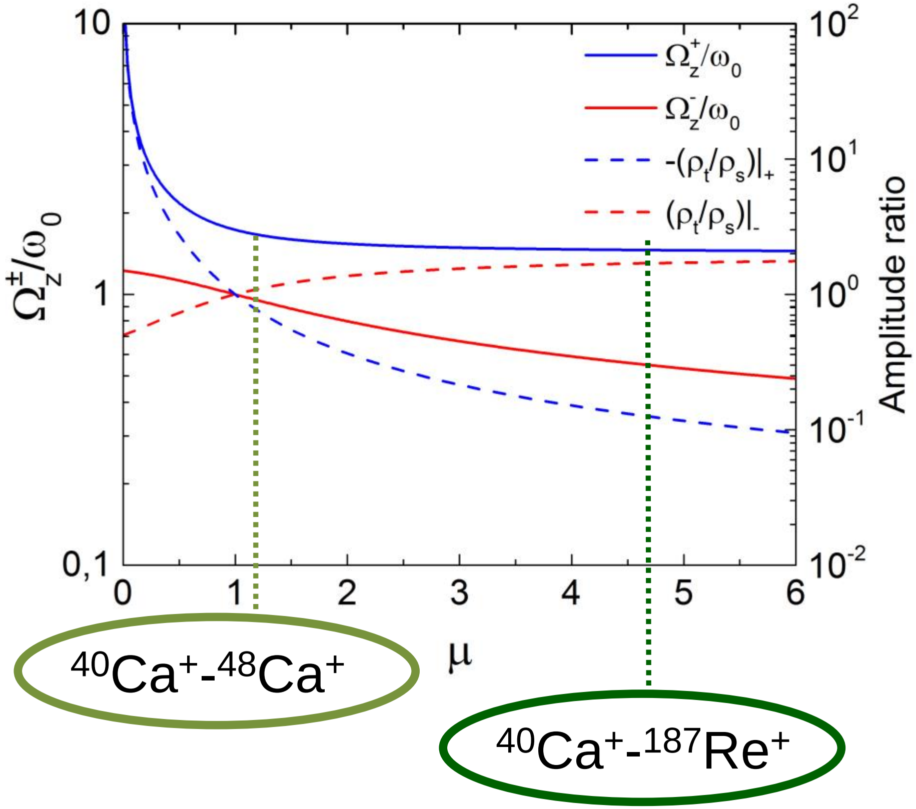
Axial motion

- Axial motion



6x6 matrix

$$\begin{pmatrix} \Delta\Omega_{c'}^{-} \\ \Delta\Omega_{c'}^{+} \\ \Delta\Omega_{m}^{+} \\ \Delta\Omega_{m}^{-} \\ \Delta\Omega_{z}^{-} \\ \Delta\Omega_{z}^{+} \end{pmatrix} = 2\pi \times \begin{pmatrix} 0.0004 & 0.0016 & 0.3967 & 0.0000 & -0.0012 & -0.0162 \\ 0.0016 & 0.0004 & 0.4942 & 0.0000 & -0.0010 & -0.0124 \\ 0.3967 & 0.4942 & -0.4094 & -0.0003 & 2.0643 & -1.2477 \\ 0.0000 & 0.0000 & -0.0003 & -0.0000 & 0.0000 & 0.0000 \\ -0.0012 & -0.0010 & 2.0643 & 0.0000 & -0.0014 & 0.0172 \\ -0.0162 & -0.0124 & -1.2477 & 0.0000 & 0.0172 & 0.0469 \end{pmatrix} \begin{pmatrix} n_{c'}^{-} \\ n_{c'}^{+} \\ n_{m}^{+} \\ n_{m}^{-} \\ n_{z}^{-} \\ n_{z}^{+} \end{pmatrix} \text{Hz}$$