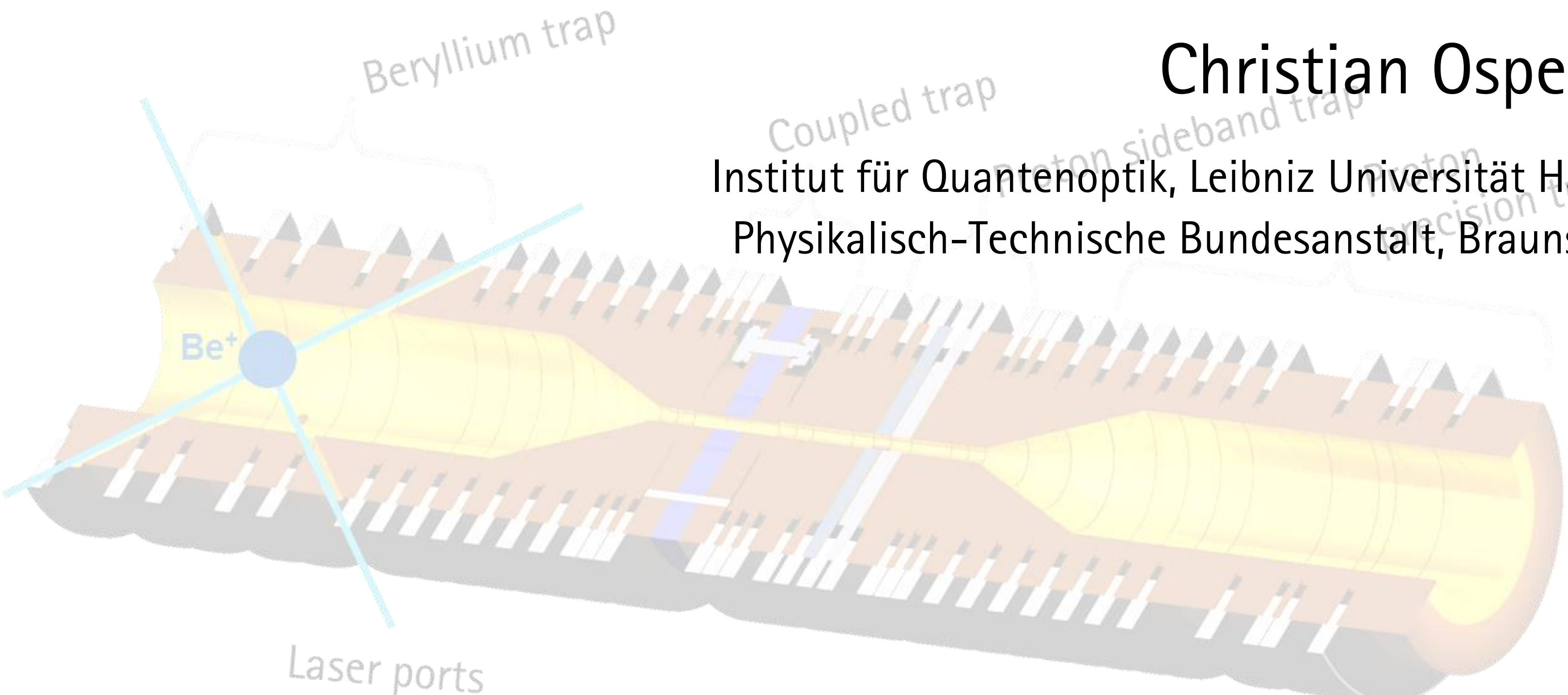
Towards a quantum toolbox for (anti-)proton precision measurements in Penning traps

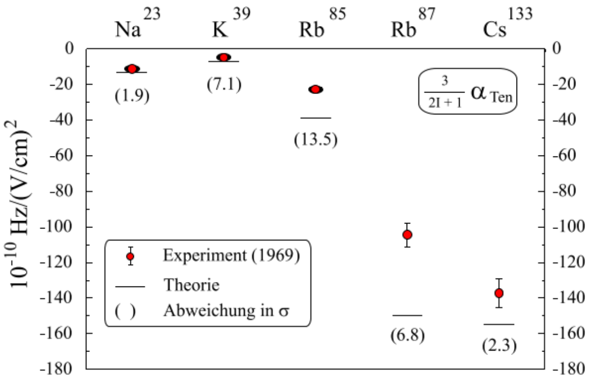
Christian Ospelkaus

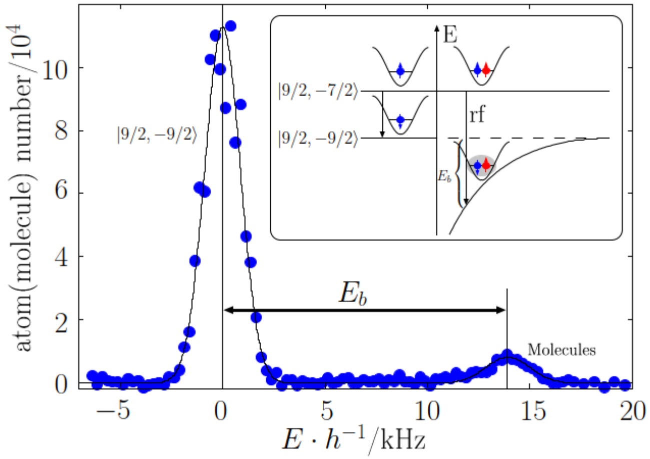
Institut für Quantenoptik, Leibniz Universität Hannover
Physikalisch-Technische Bundesanstalt, Braunschweig



My path in science so far

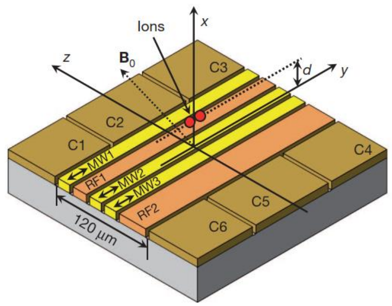
- Studied physics in Bonn (1996-2001)
  - Excursion into plasma physics
  - Numerical mathematics
  - Diploma thesis at Univ. Fribourg with Antoine Weis „Measurement of the forbidden tensor polarizability in ^{133}Cs"
- PhD in Hamburg (with K. Sengstock, 2002-2006)
  - Fermi-Bose mixtures in 3D optical lattices (with Silke Ospelkaus)



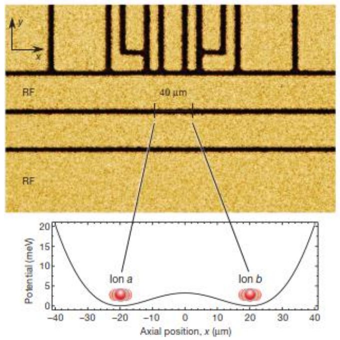


My path in science so far

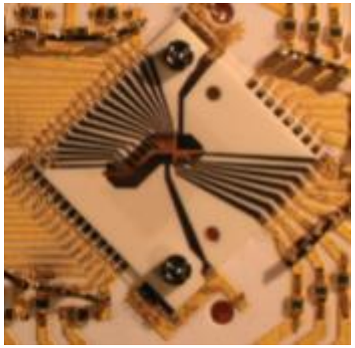
- Postdoc in Boulder (with D.J. Wineland, 2007-2010)
  - Trapped ions, quantum information processing



Integrated microwave gate



Coupled harmonic oscillators

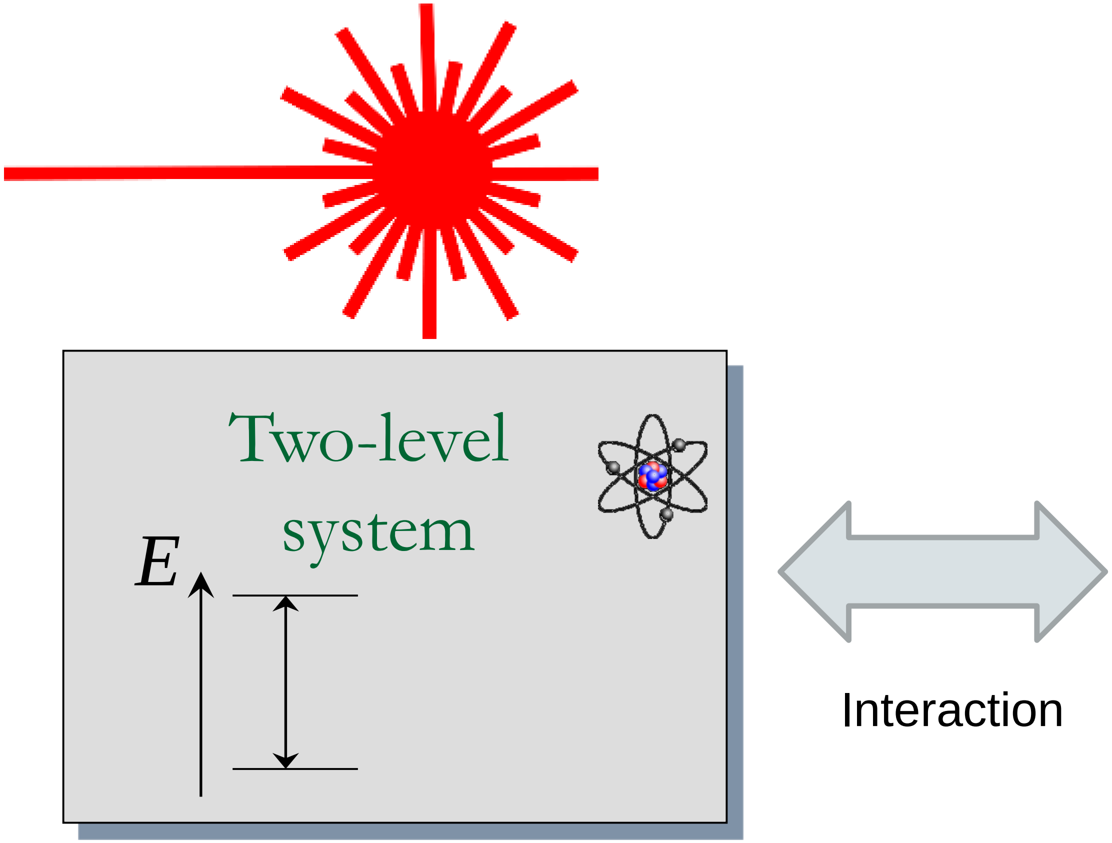


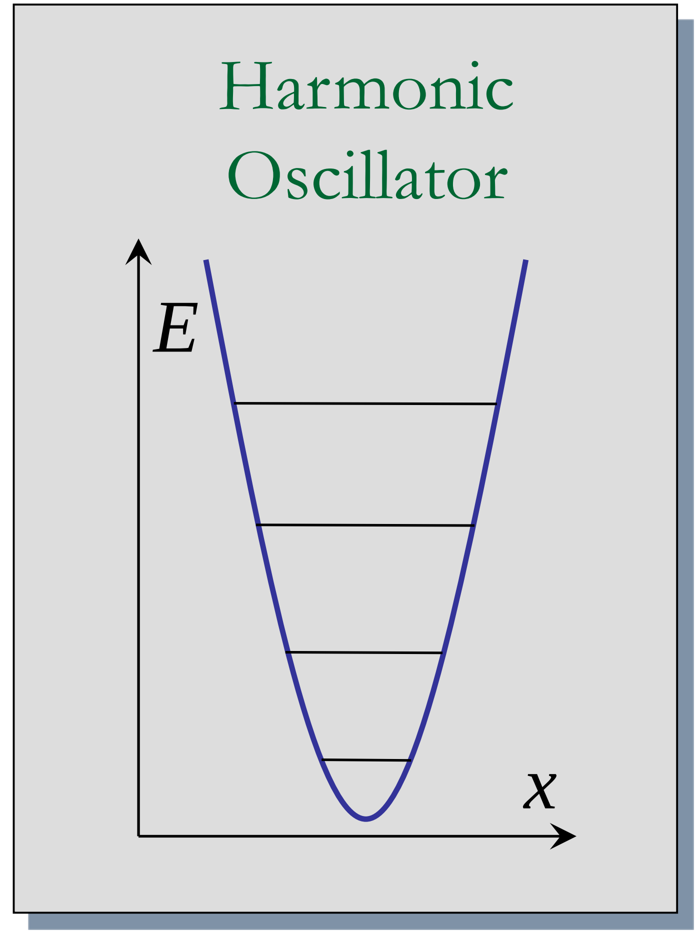
X-junction trap array

Microtraps

- 2010: Assistant professor (tenure track, Stanford)
- 2010: Professor for experimental quantum optics (Hannover/PTB)

Trapped ions in a nutshell

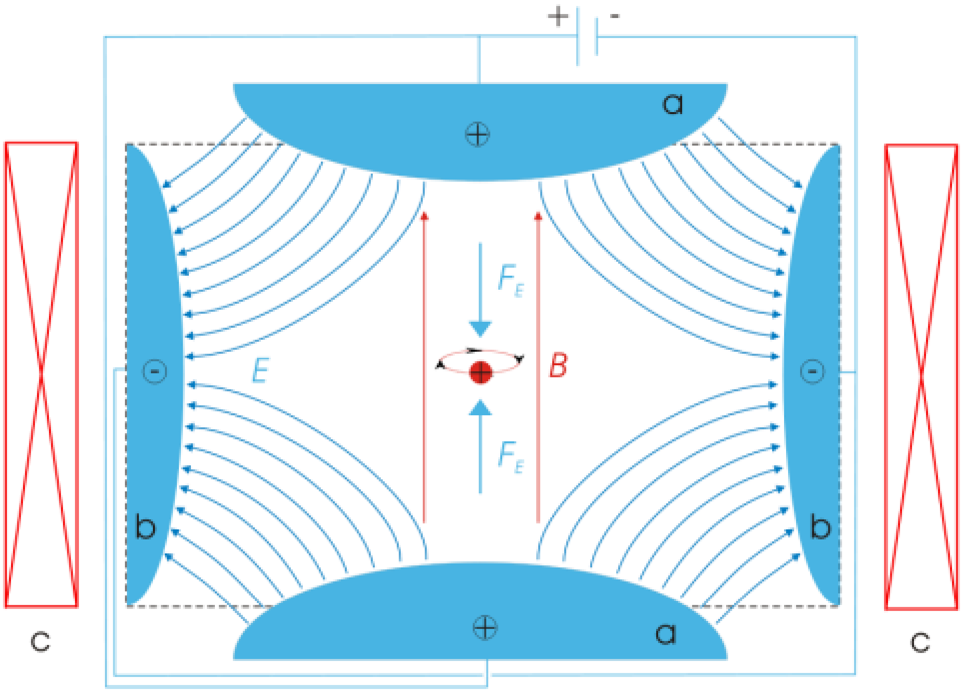




“We never experiment with just one atom or molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences. ”

Erwin Schrödinger, 1952

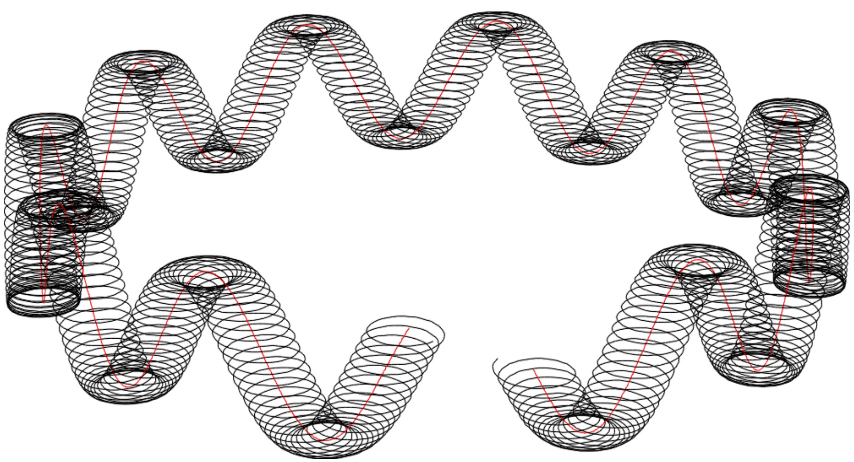
THE PENNING TRAP



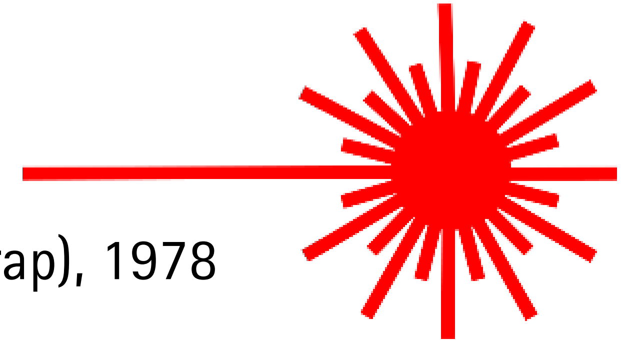
[Wikipedia]

Hans Dehmelt

"Geonium atom"



- Laser cooling, state manipulation and detection are key tools in AMO physics experiments
- Photons carry momentum and spontaneous emission provides irreversibility
- First demonstrations of laser cooling
  - Boulder (Penning trap), Heidelberg (Paul trap), 1978



- Ground state cooling
  - Boulder (1989)
- Key enabling step for qubits and clocks!
- Little use of laser cooling in Penning traps since (compared to Paul traps)!

THE (ANTI-)PROTON

Testing CPT symmetry

Symmetries

mostly symmetric

symmetrized

Symmetries and the Standard Model

~~C~~ ~~P~~ ~~T~~

~~CP~~

CPT ✓

(Lorentz invariant, local QFT with Hermitian Hamiltonian)

Beyond the Standard Model

CPT?

(Lorentz invariance?)

Baryogenesis?

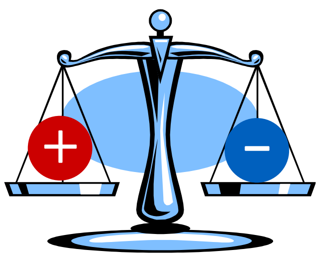
(Matter-Antimatter imbalance in the universe)

Dark matter?

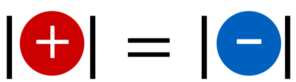
Quantum gravity?

Matter – antimatter comparison

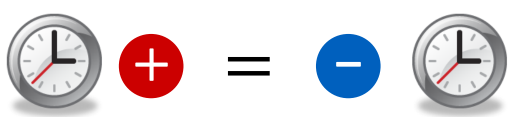
- Particles and antiparticles have:
  - Same mass



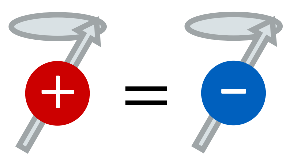
  - Same charge (except for sign)



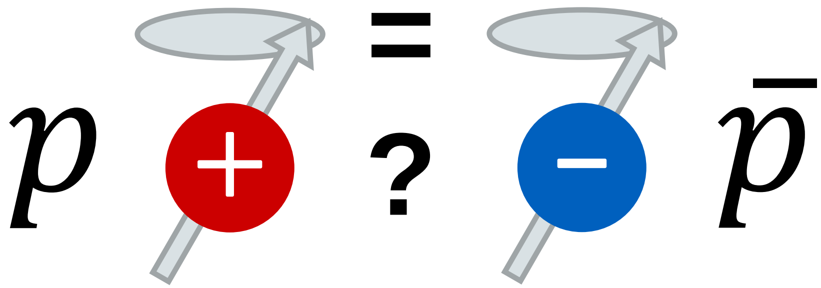
  - Same lifetime



  - Same magnetic moment (g-factor)

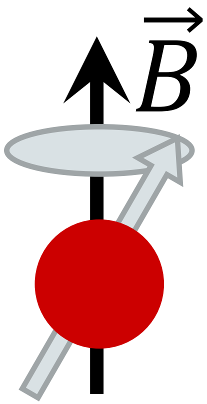


$$\vec{\mu} = g\,\frac{q\hbar}{2m}\,\vec{s}$$



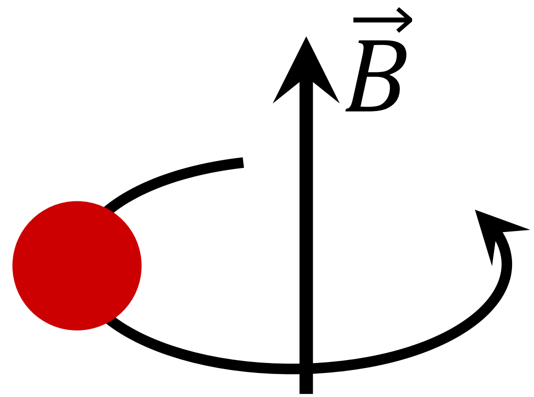
$$\frac{g}{2} = \frac{\omega_L}{\omega_c}$$

It’s a double frequency measurement!



Spin precession

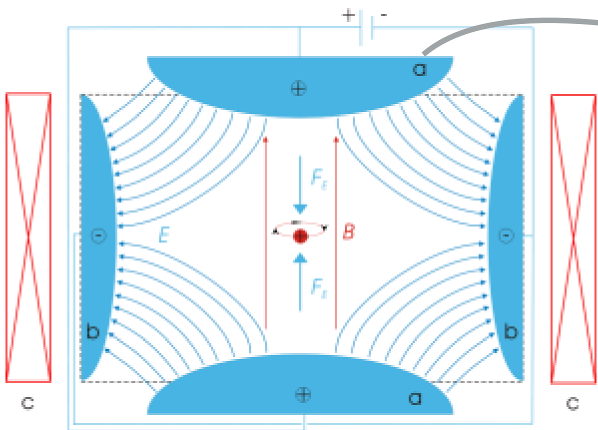
$$\omega_L = g/2 \cdot q/m \cdot B$$



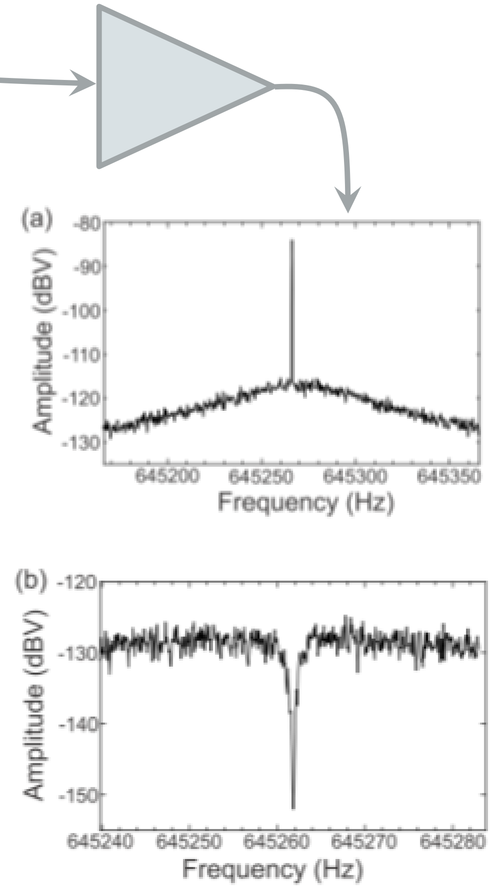
Cyclotron motion

$$\omega_c = q/m \cdot B$$

Measuring motional frequencies



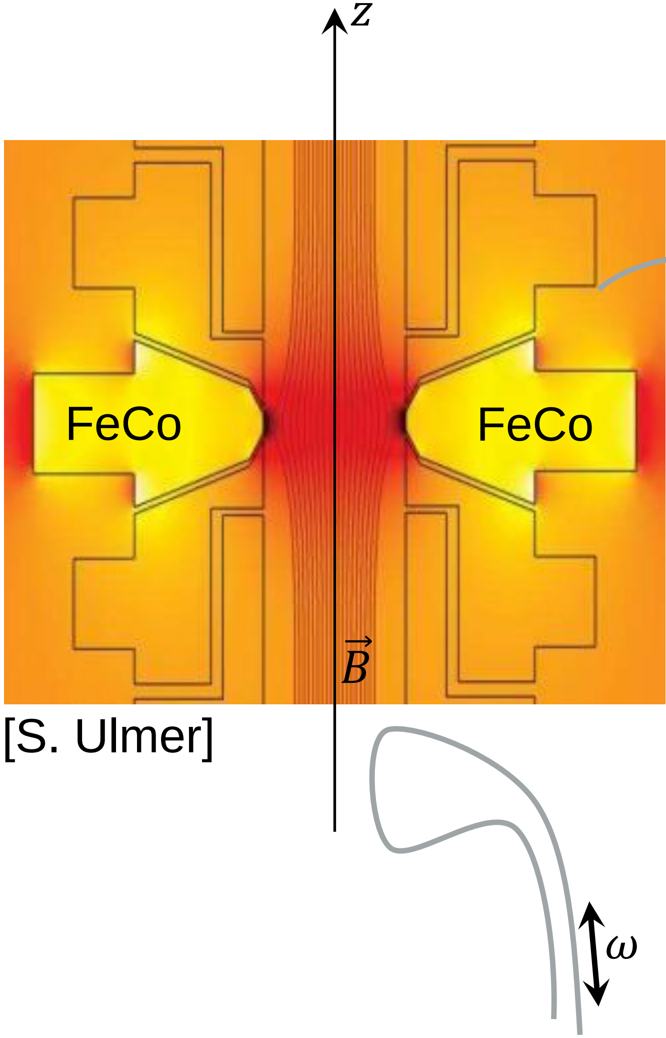
[Wikipedia]



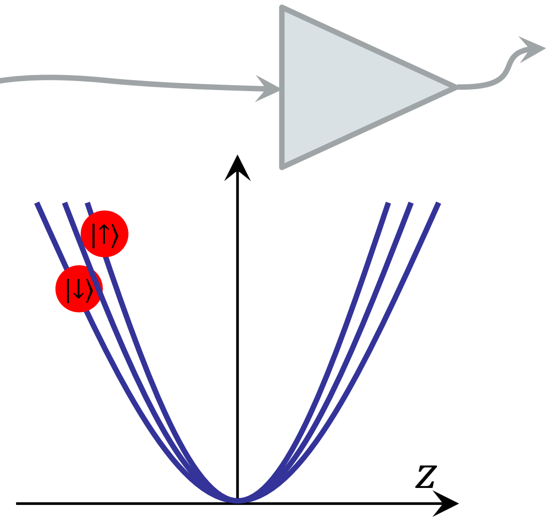
[Plots for the axial movement of an antiproton: Smorra et al., EPJ-ST (2015)]

Hans Dehmelt

Measuring the Larmor frequency

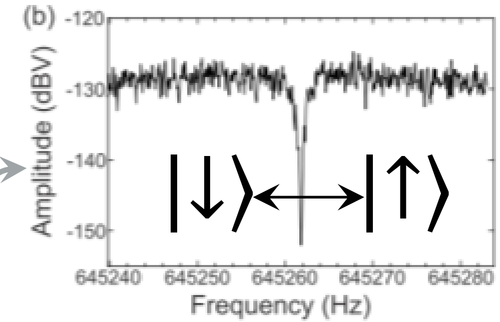


[S. Ulmer]

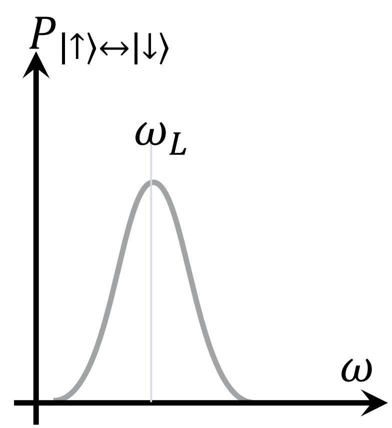


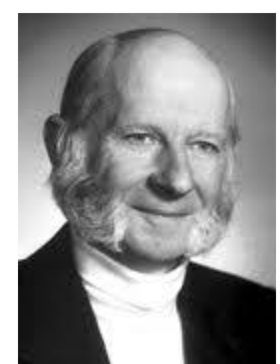
Continuous Stern-Gerlach effect

Measuring the spin state



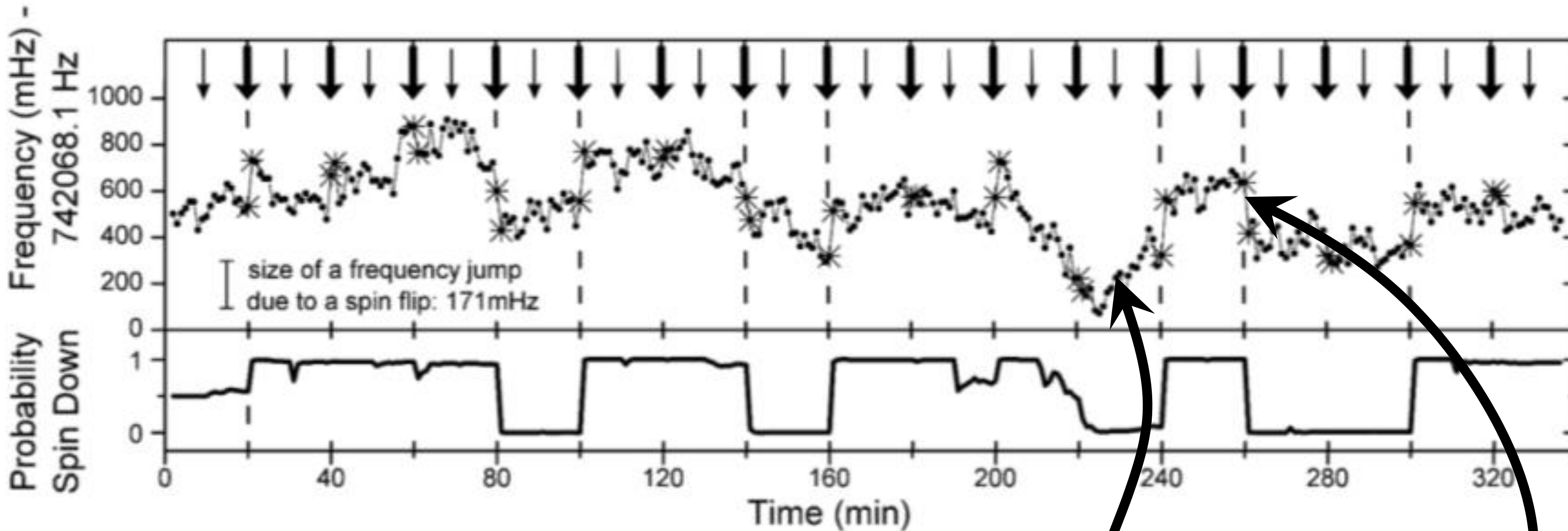
[Plots for the axial movement of an antiproton: Smorra et al., EPJ-ST (2015)]



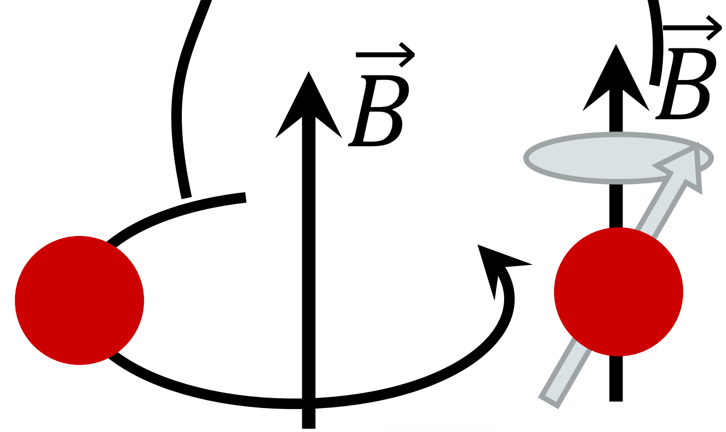


Hans Dehmelt

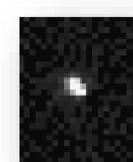
Spin state detection



Mooser et al., PRL **110**, 140405 (2013)

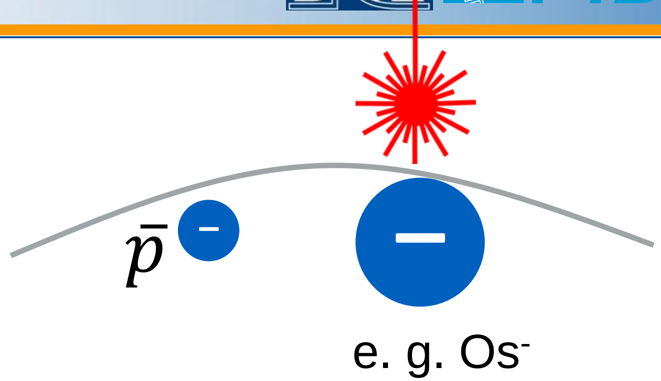


- Tremendous success
- Tremendous effort...
- Laser cool?
- Single Doppler cooled $^9Be^+$ ion at PTB, ~500 µK

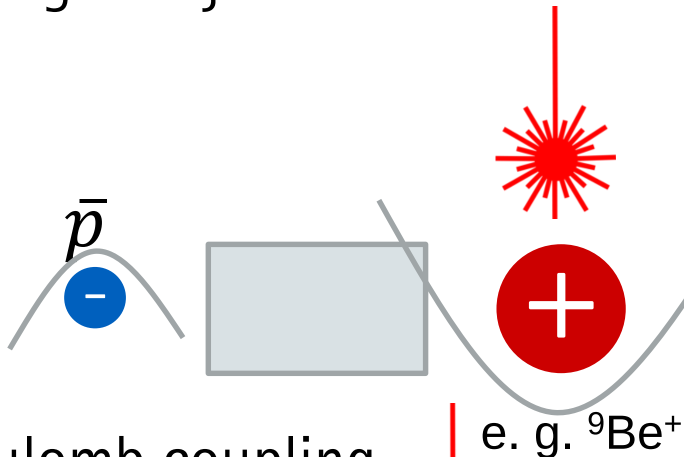


Sympathetic laser cooling of $\overline{p}$

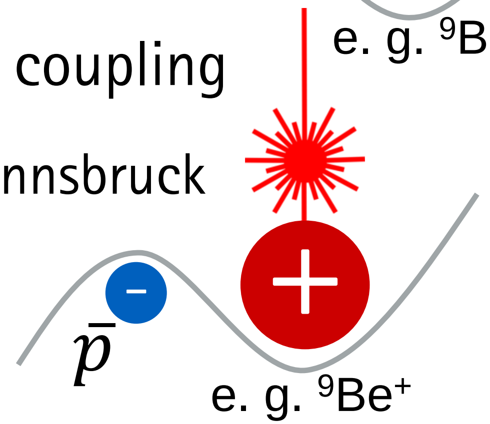
- Negatively charged ions (anions)
  - MPIK



- Interaction with cation through image charges in joint electrode
  - Proposal: Heinzen and Wineland, 1990
  - Experimental work with atomic ions: Hartmut Häffner, Berkeley and Daniel Rodriguez, Univ. Granada, BASE-Mainz

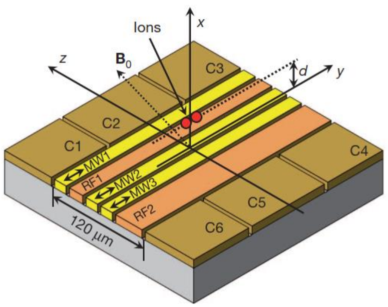


- Interaction with cation through direct Coulomb coupling
  - Experimental work with trapped ions: Boulder, Innsbruck



THE BASE-HANNOVER PENNING TRAP

A hybrid quantum system

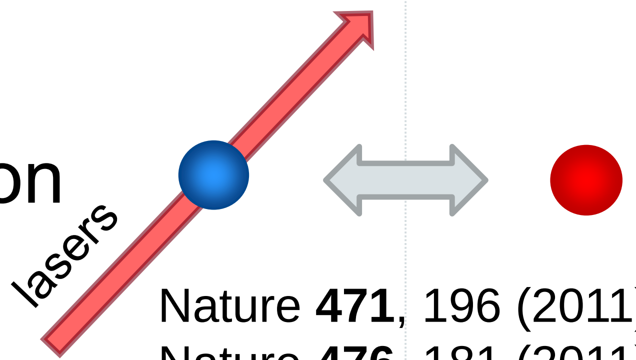


Integrated microwave gate

"Qubit" ion provides

- Sympathetic ground state cooling
- Quantum logic state readout

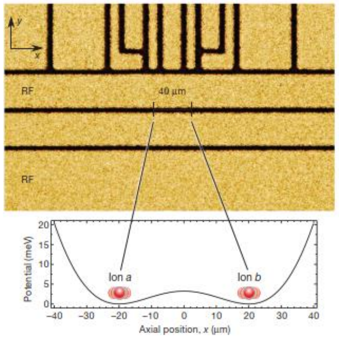
“qubit” ion



(anti-)proton

Nature **471**, 196 (2011)
Nature **476**, 181 (2011)

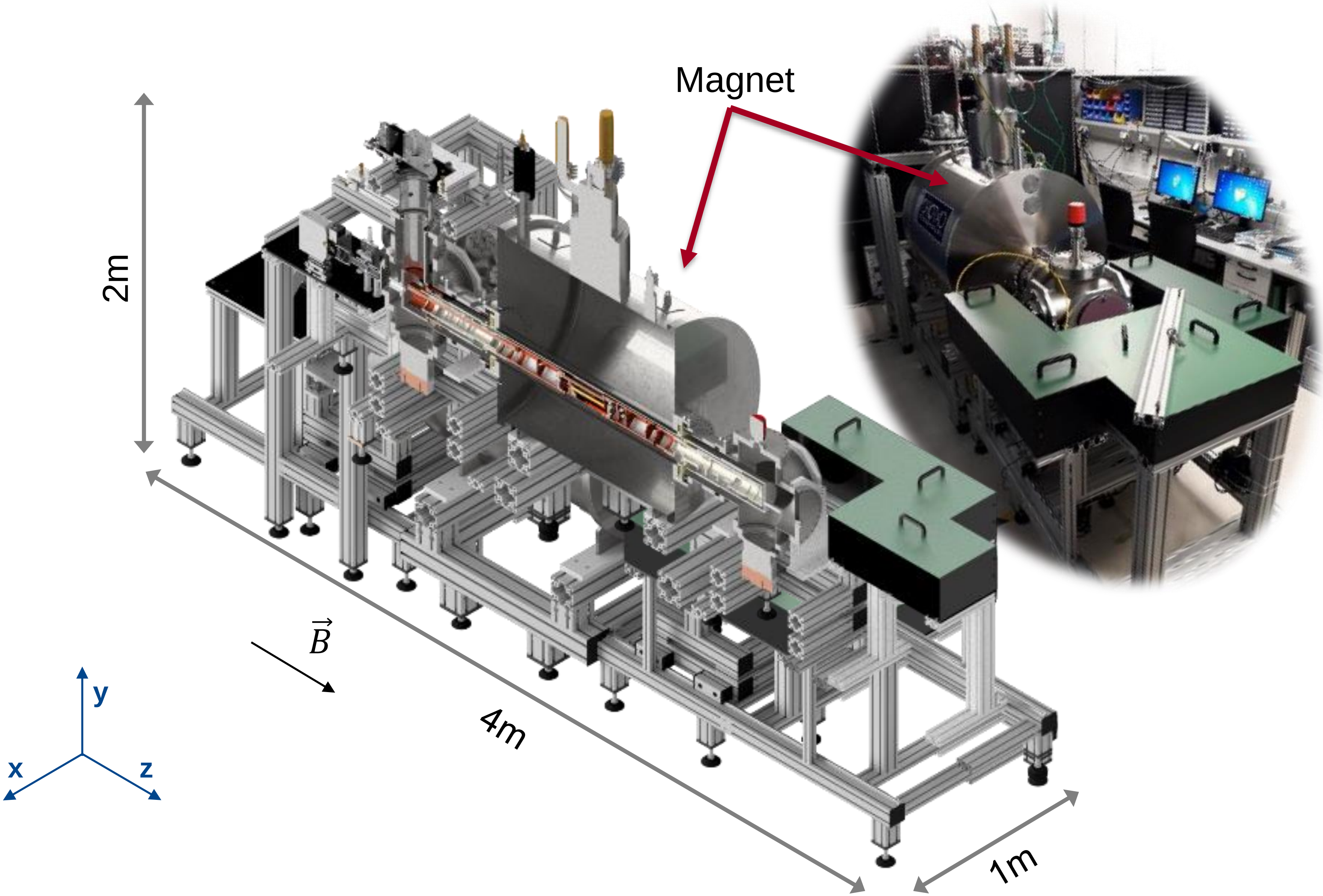
postdoctoral work
(atomic ions)



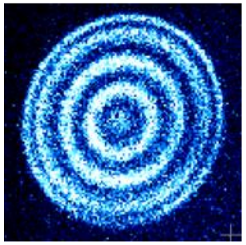
Coupled
harmonic oscillators

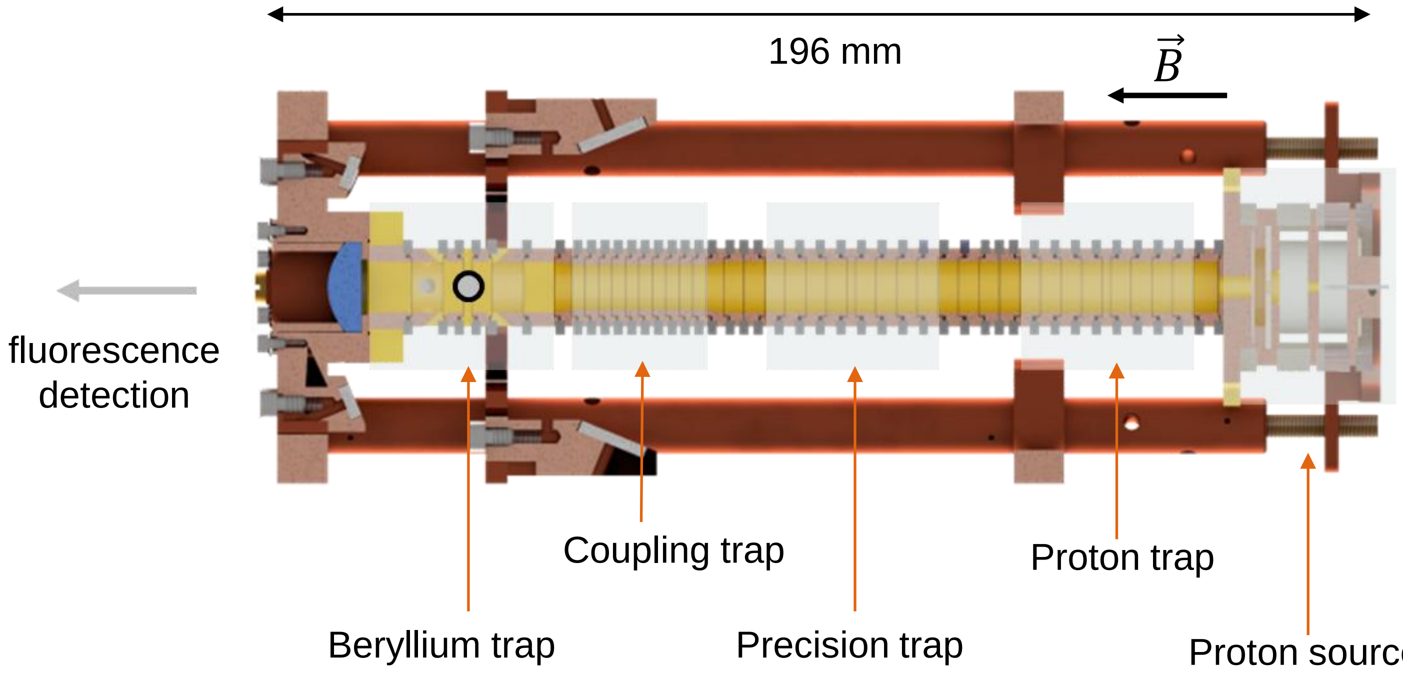
D. J. Wineland *et al.*, J. Res. NIST **103**, 259 (1998)
D. J. Heinzen and D. J. Wineland, PRA **42**, 2977 (1990)

Experimental setup



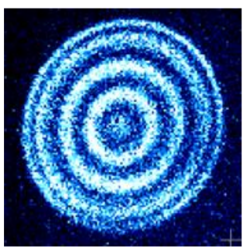
- Step-by-step implementation of the required tools in a cryogenic Penning trap system



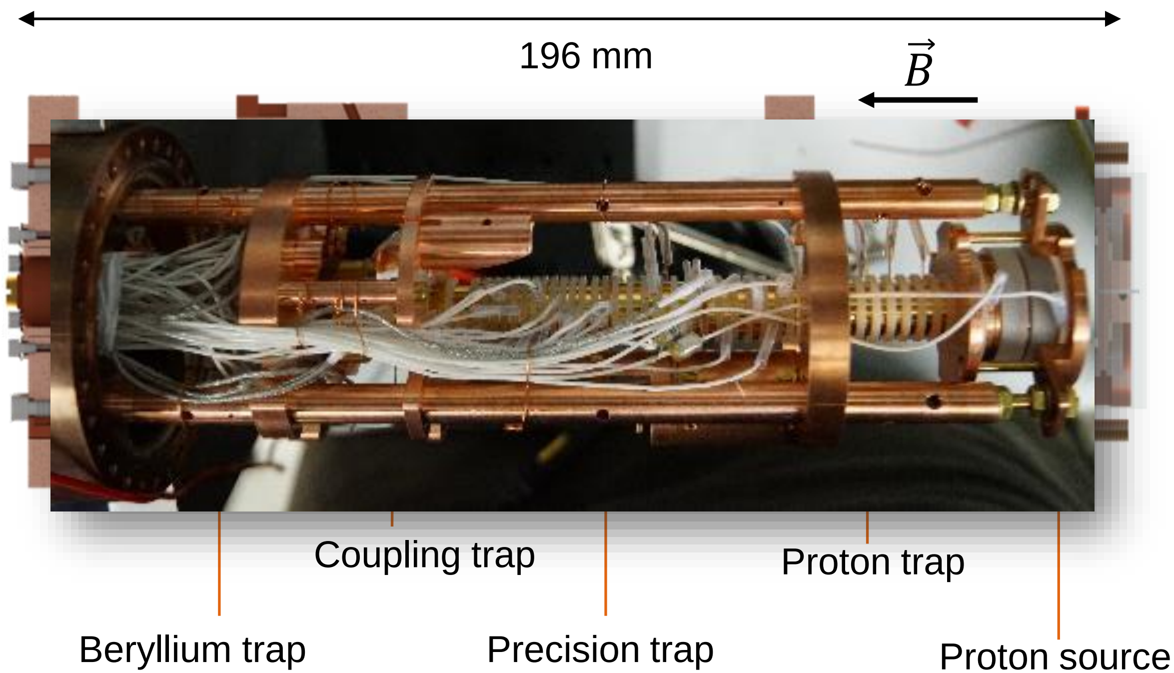


Trap stack

- Step-by-step implementation of the required tools in a cryogenic Penning trap system

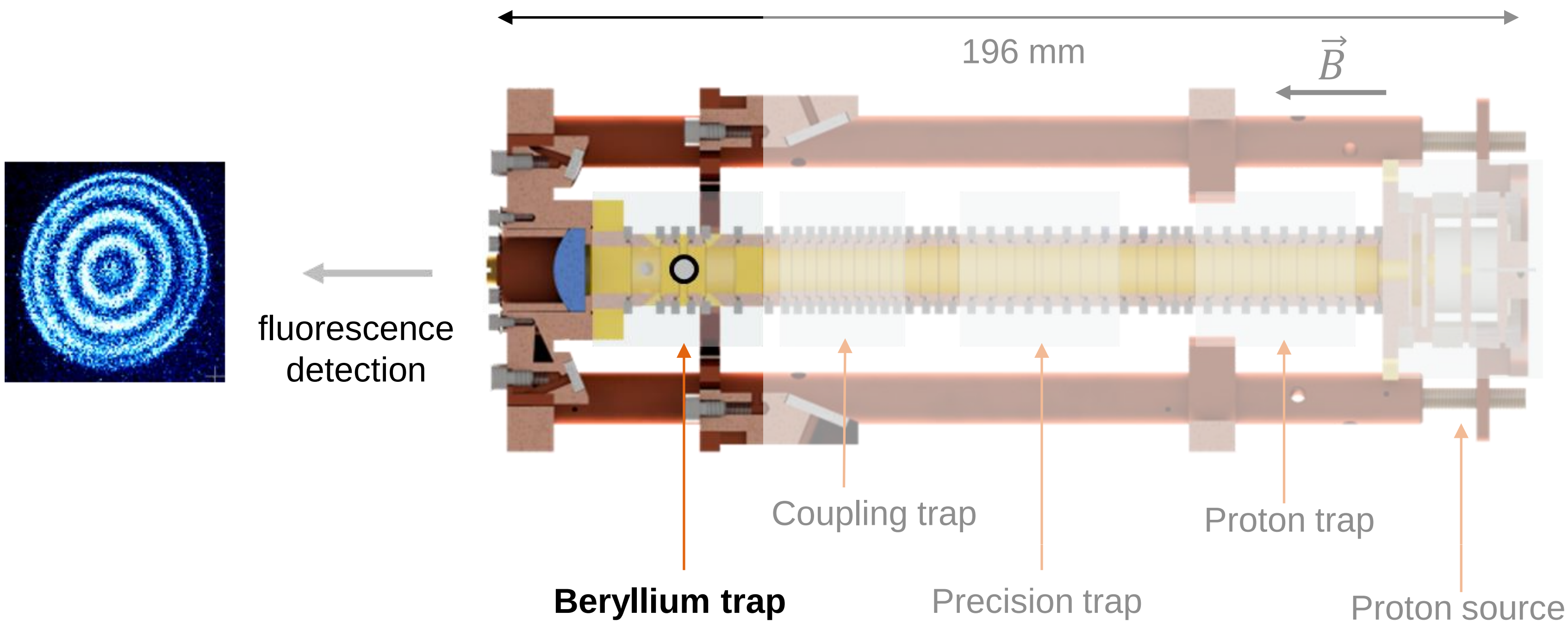


fluorescence detection

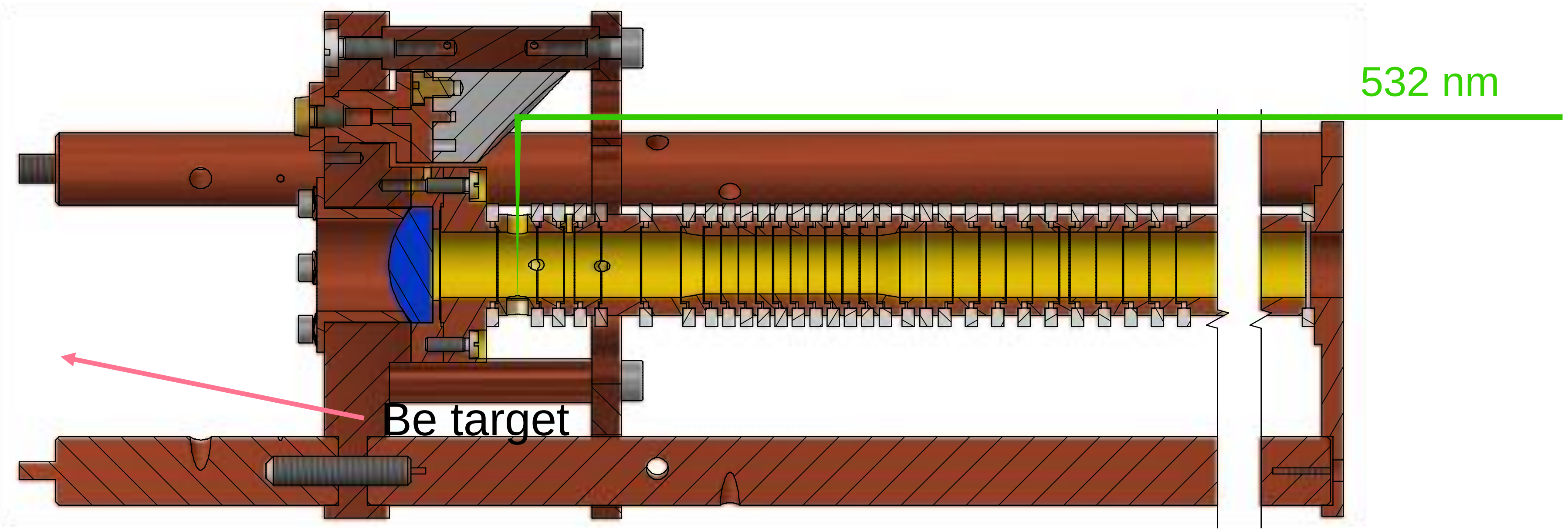


Trap stack

- Step-by-step implementation of the required tools in a cryogenic Penning trap system

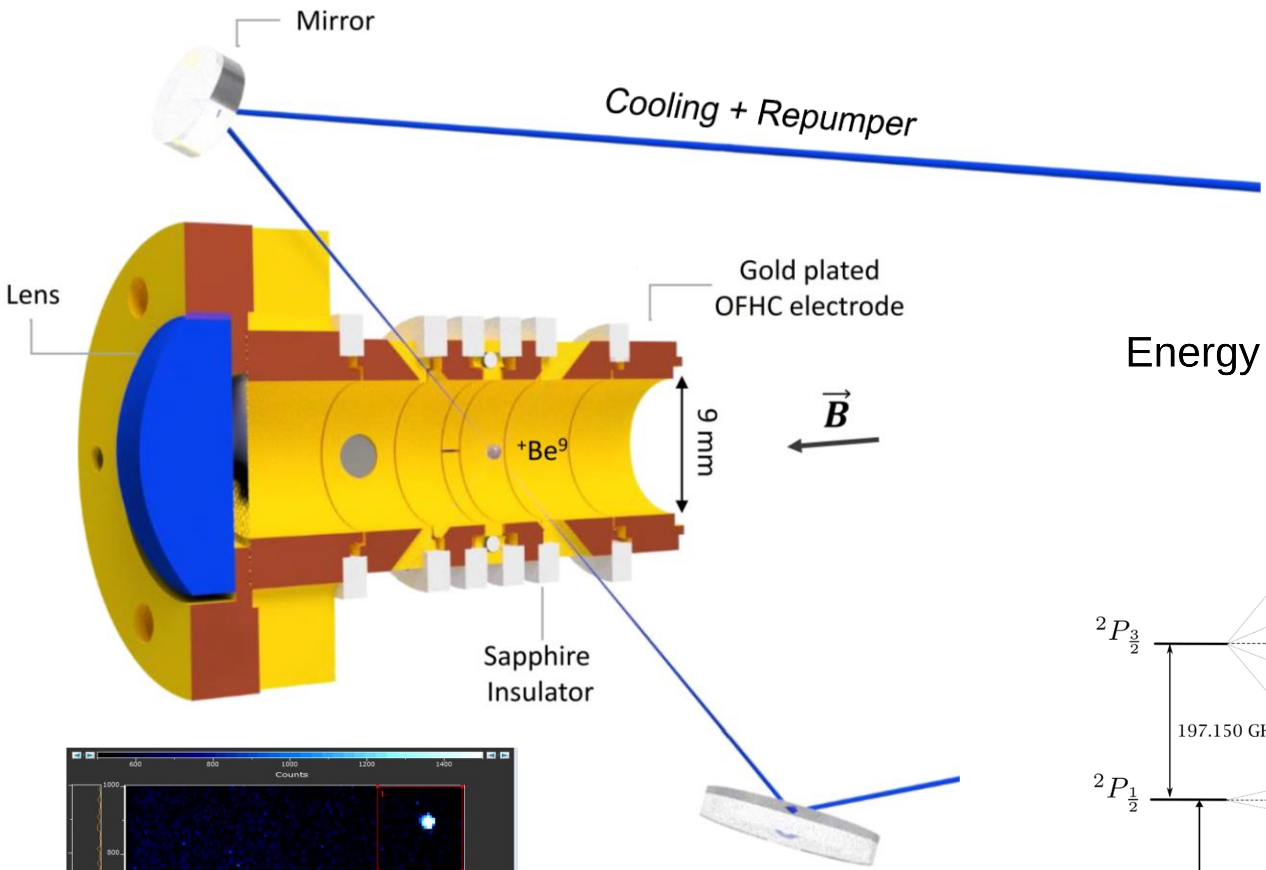


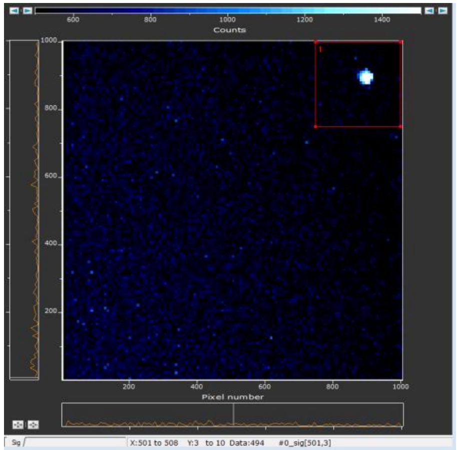
Ion loading



M. Niemann et al., Measurement Science and Technology **31**, 035003 (2019)

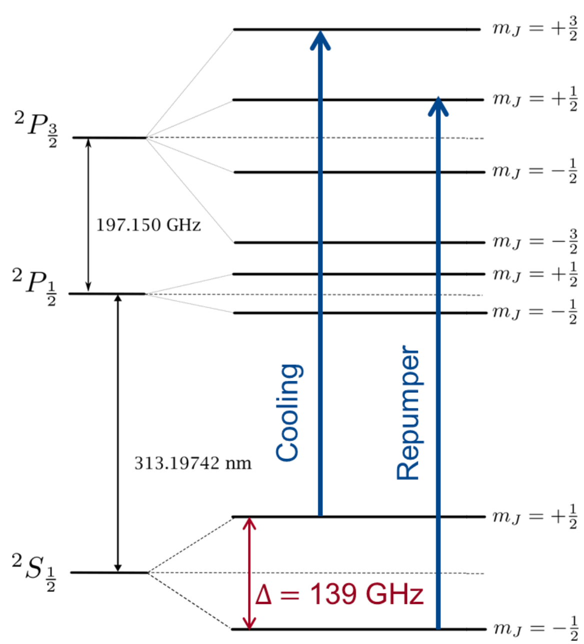
Doppler cooling and detection



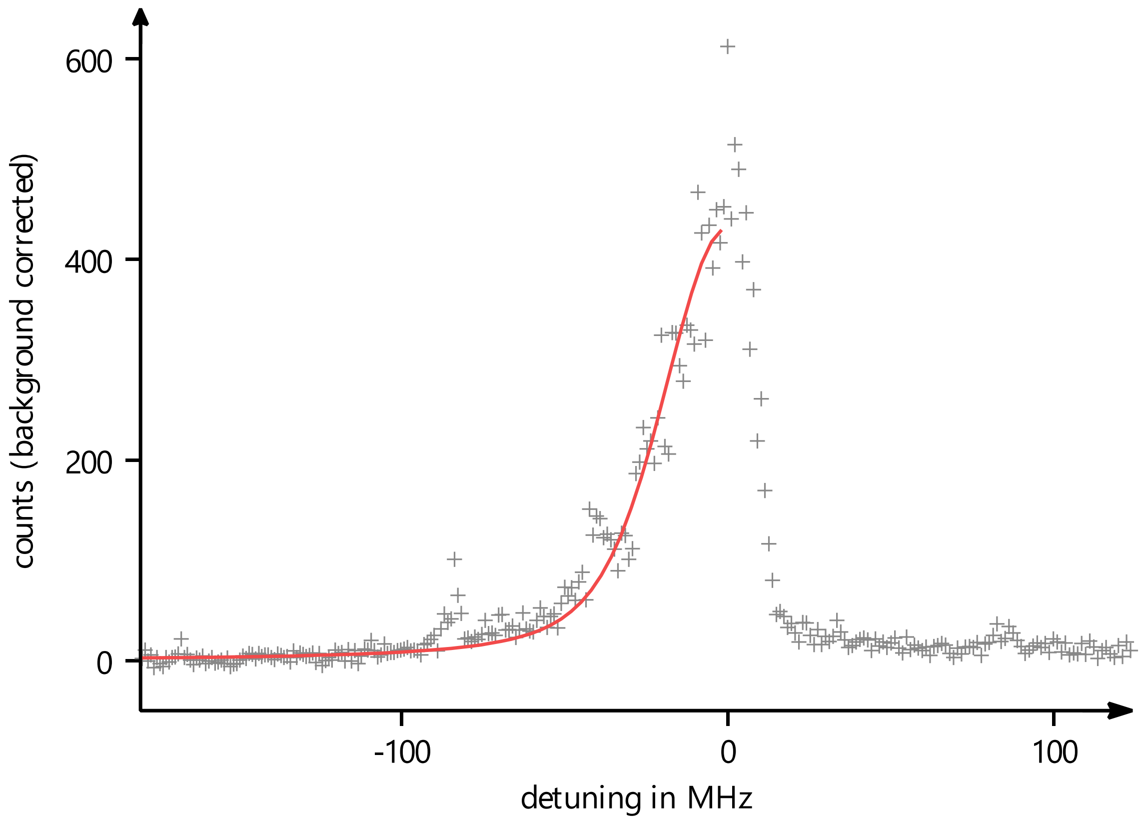


Single $^9Be^+$ ion stored for months

Energy levels of $^9Be^+$ in a 5T magnetic field

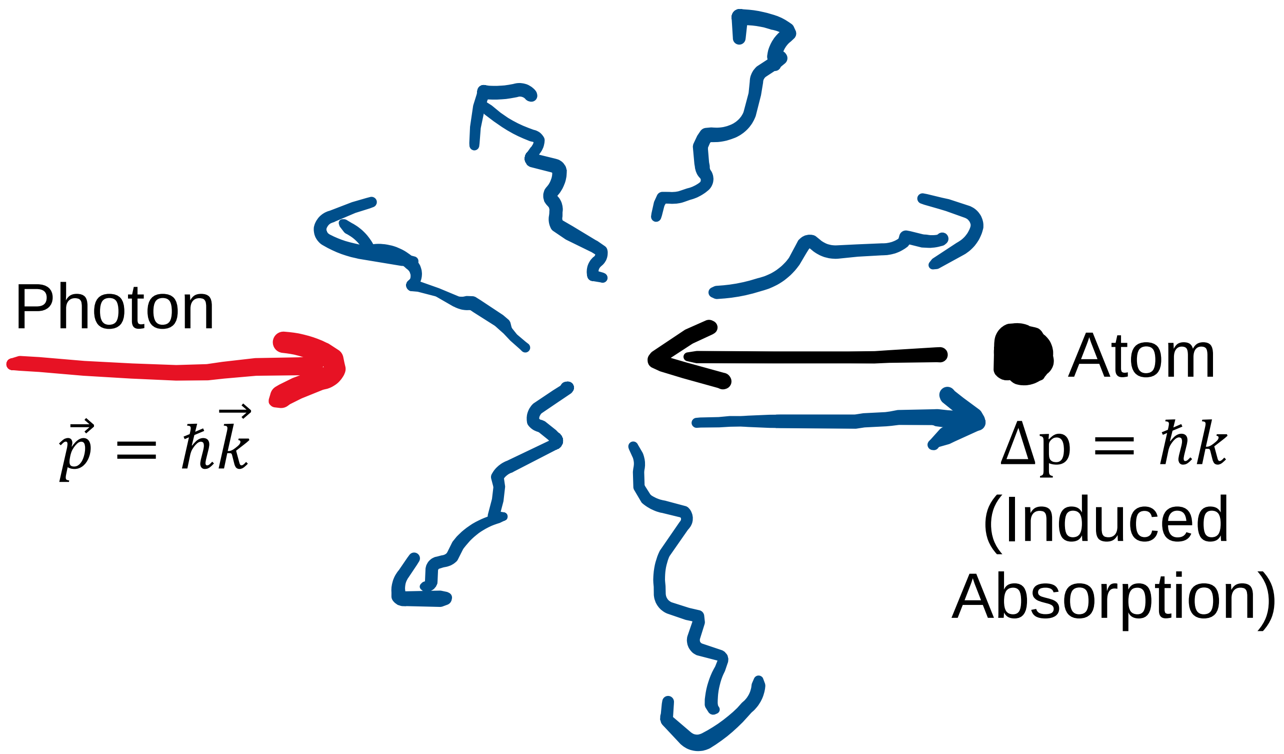


Doppler cooling



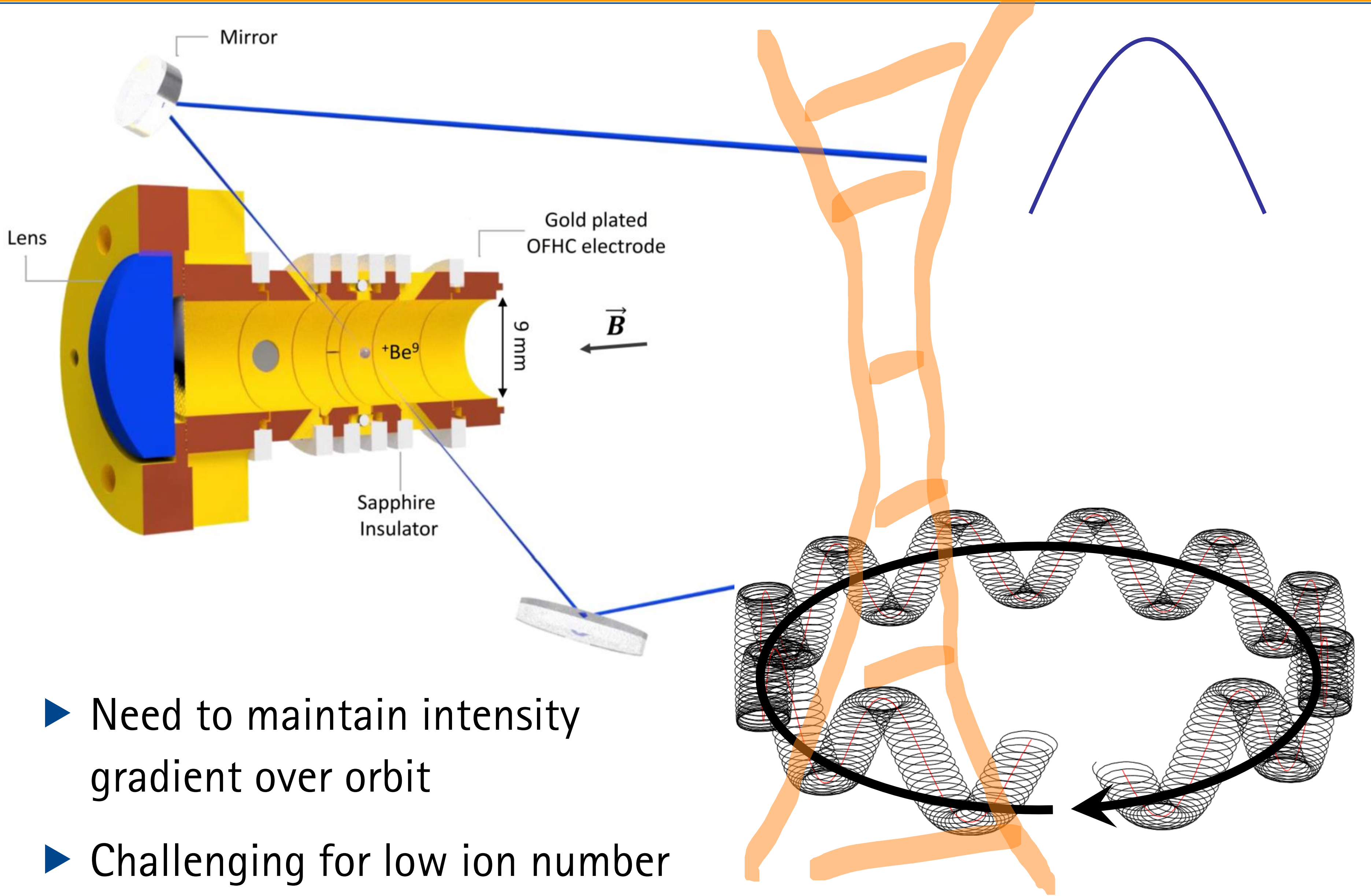
optimised cooling: $\Delta\nu_D = 35.5(10)\ \mathrm{MHz}$

$T = 24.0(7)\ \mathrm{mK}$



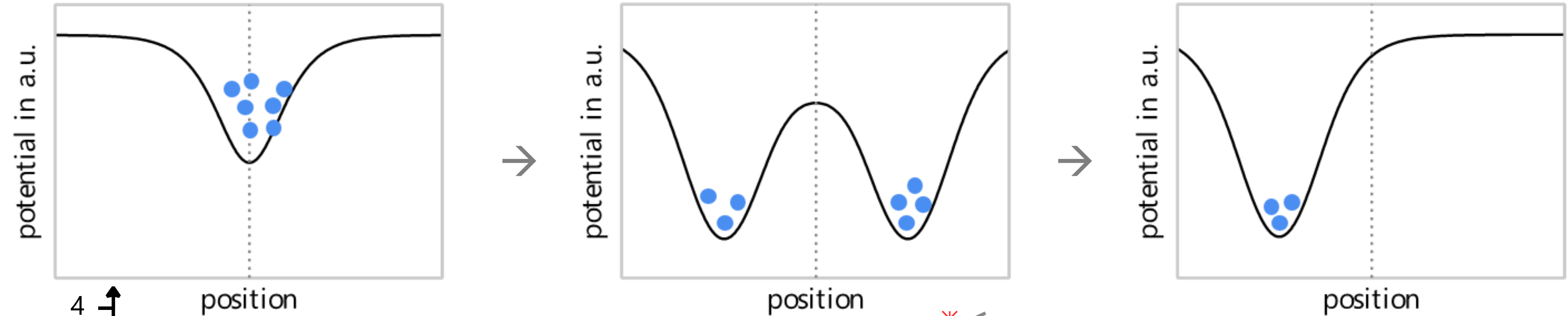
$$T = \frac{h}{k_B}\frac{\Gamma}{2} \approx 500\ \mu\mathrm{K}$$

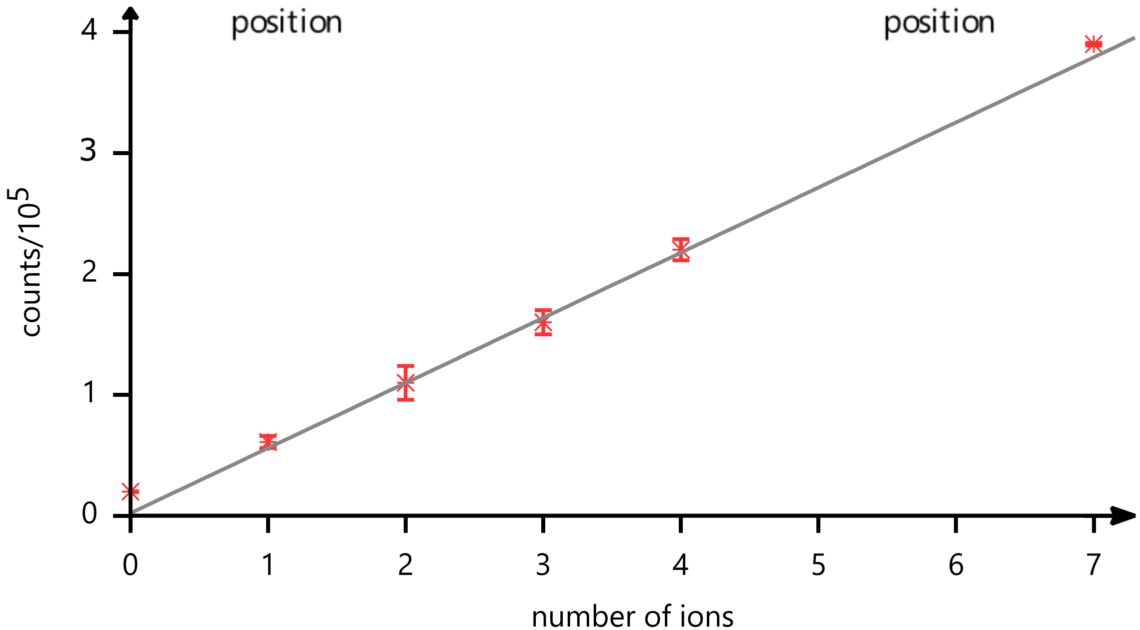
What's difficult about cooling?

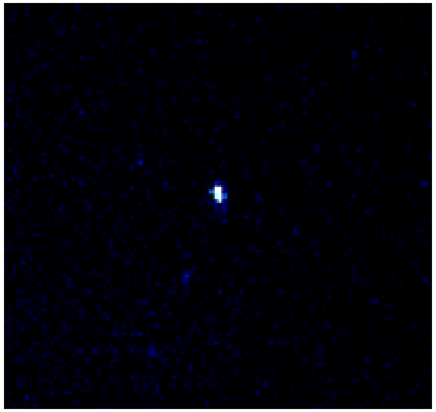


- Need to maintain intensity gradient over orbit
- Challenging for low ion number

Particle number reduction

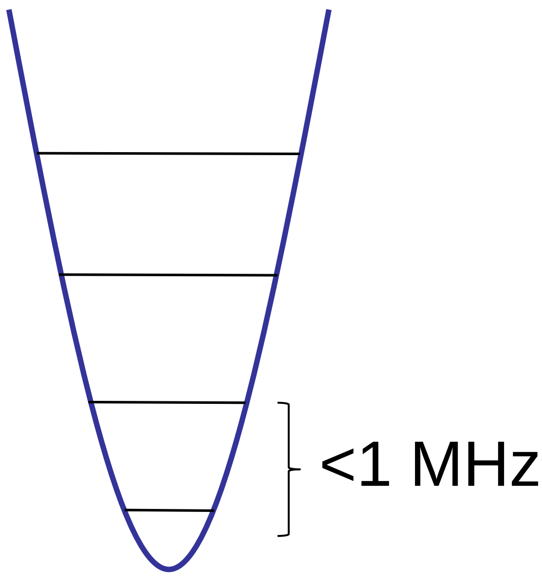






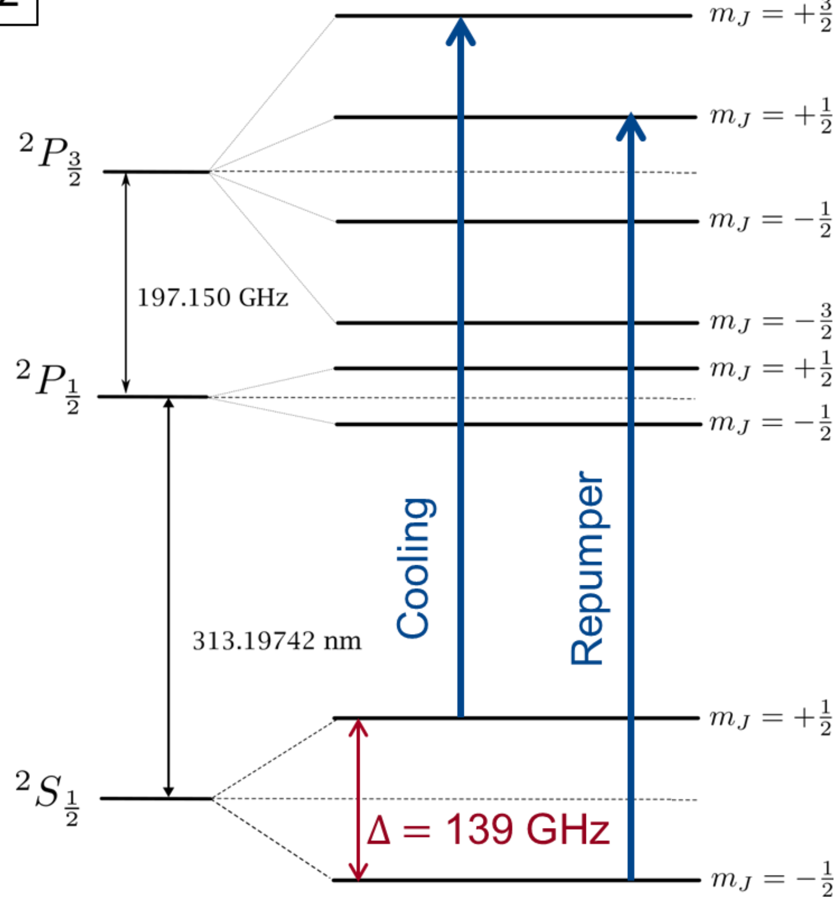
After one month of technical upgrades, lab book entry: *“Today the laser system optimization has been completed. After that, I check the trap and the old ion was still in the trap. “ 08/16/21*

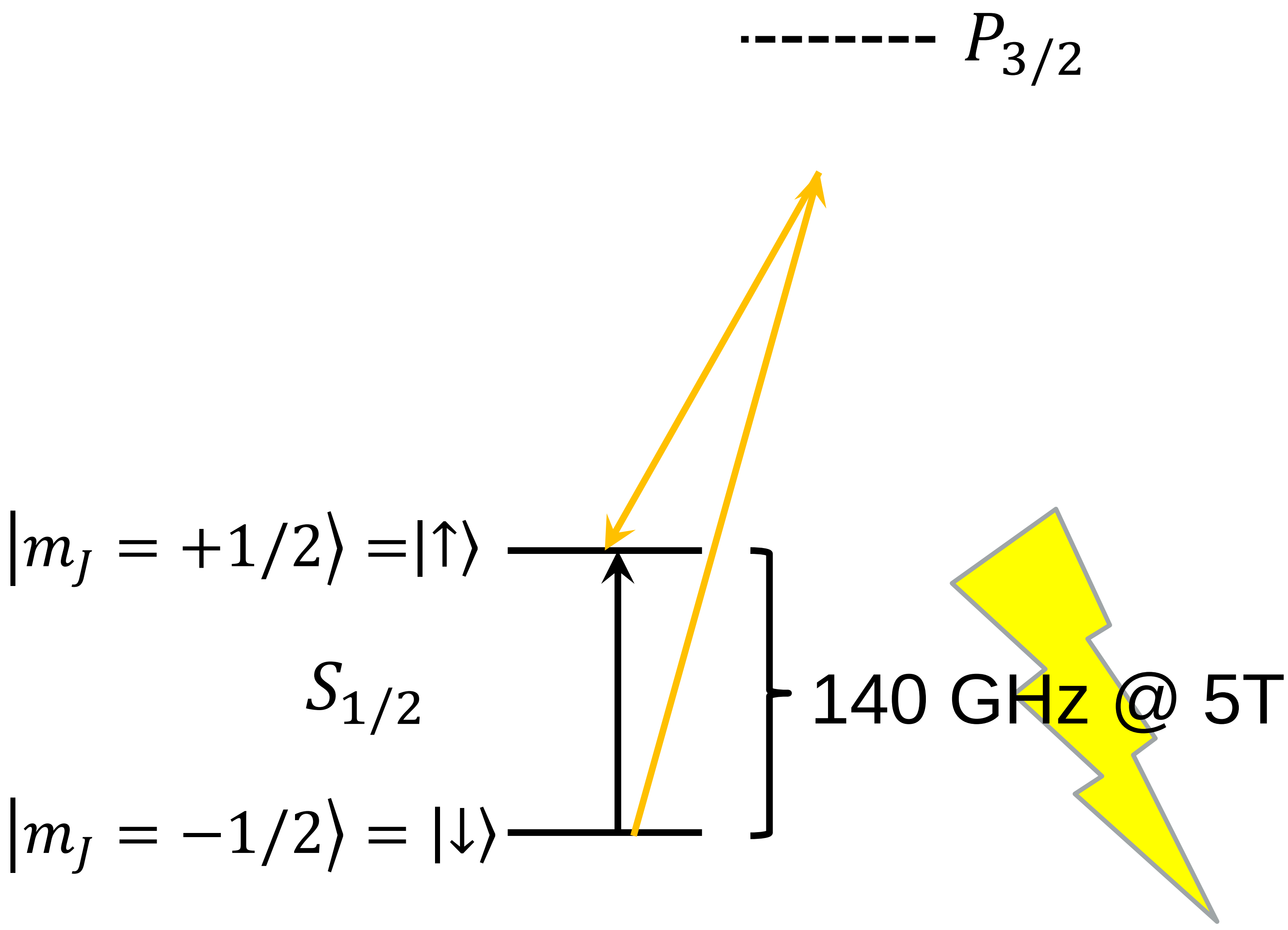
Ground state cooling?



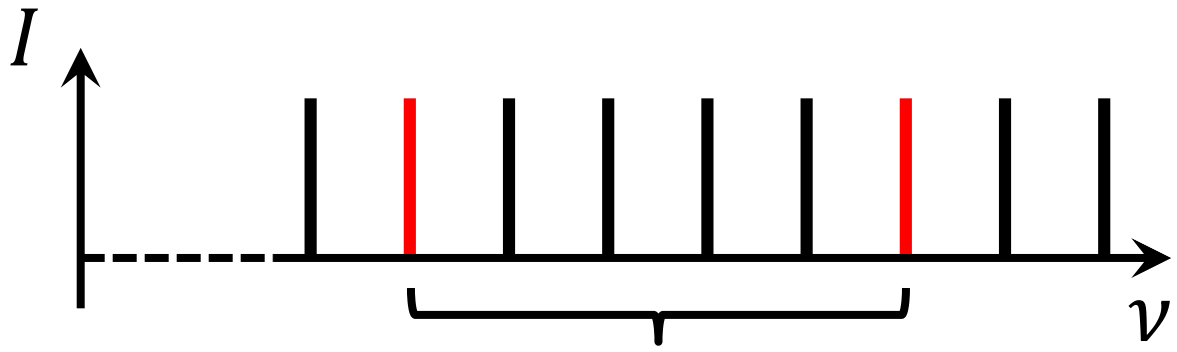
$m_I = +3/2$

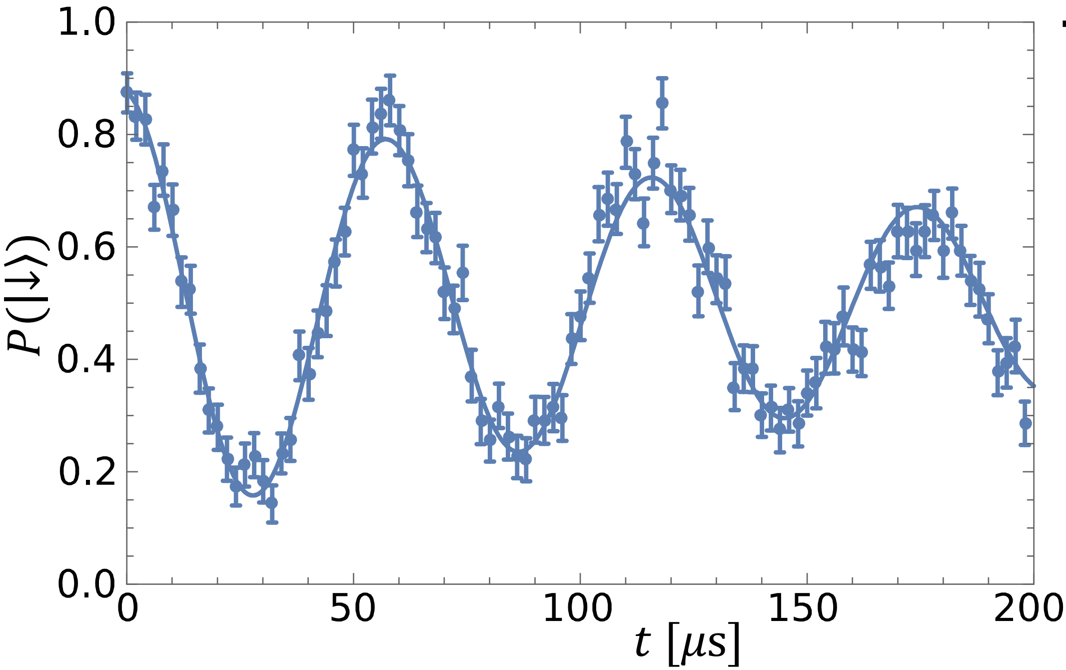
Frequency width
~20 MHz




$P_{3/2}$
$|m_J = +1/2\rangle = |\uparrow\rangle$
$S_{1/2}$
$|m_J = -1/2\rangle = |\downarrow\rangle$
140 GHz @ 5T

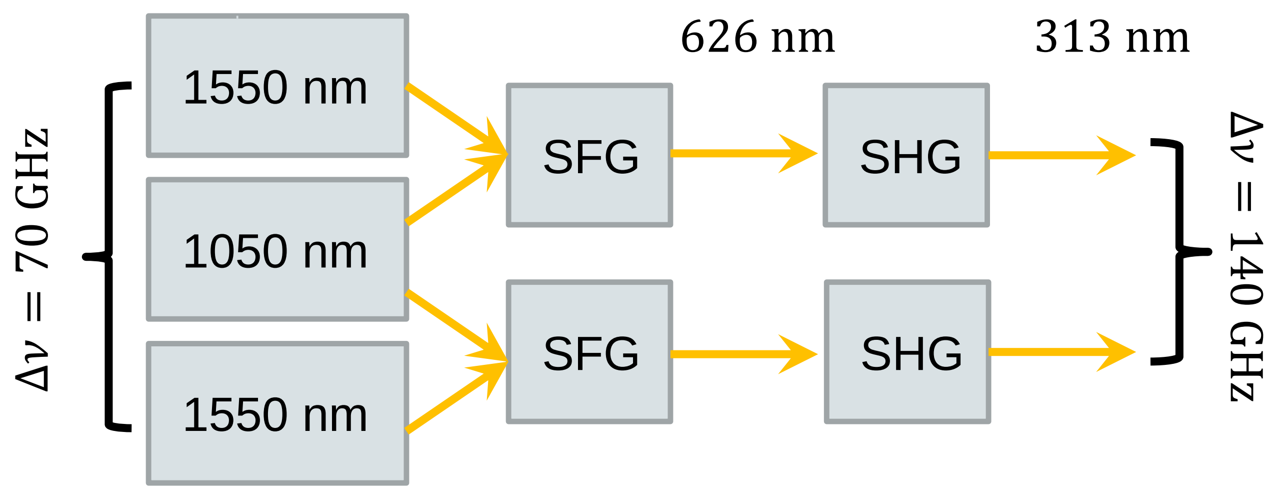
- Femtosecond laser @313 nm

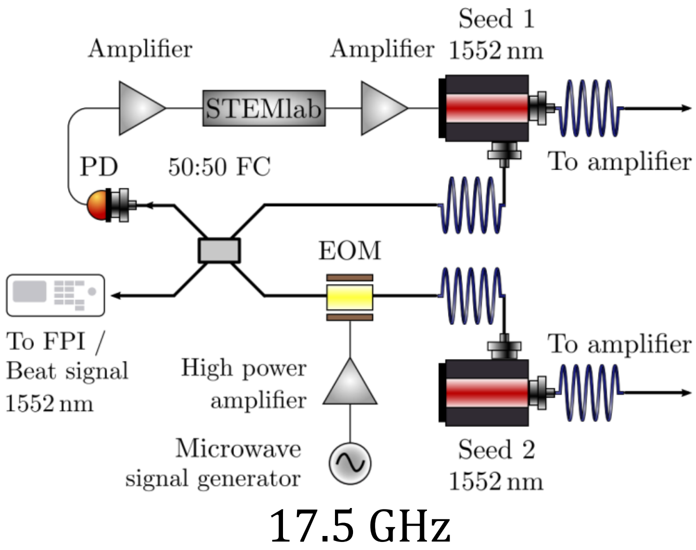




A.-G. Paschke *et al.*, PRL **122**, 123606 (2019)

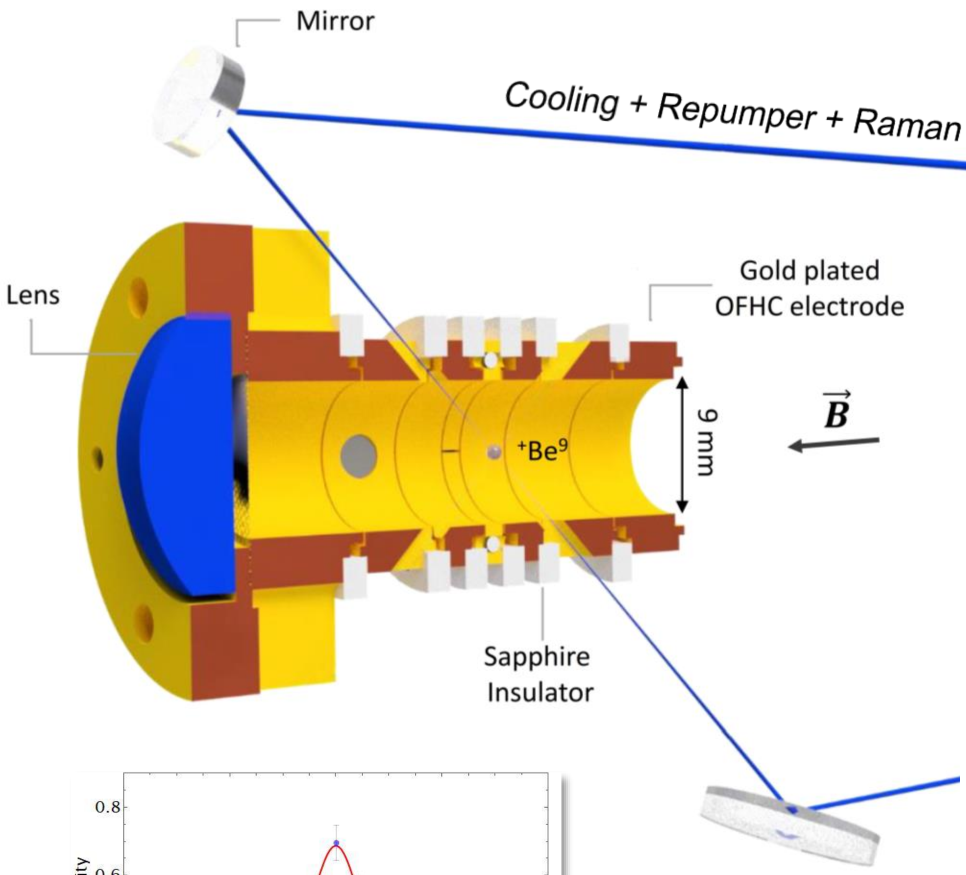
- Collaboration with
  - Menlo Systems
  - G. Cerullo
  - M. Marangoni
  - C. Manzoni
  - U. Morgner

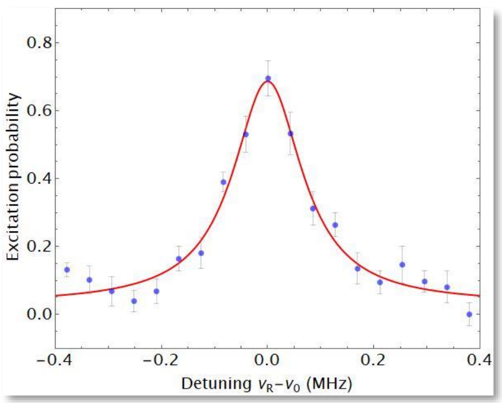




S. Hannig et al., RSI **89**, 013106 (2018)
J. Mielke et al., J. Phy. B: At. Mol. Opt. Phys. **54**, 195402 (2021)

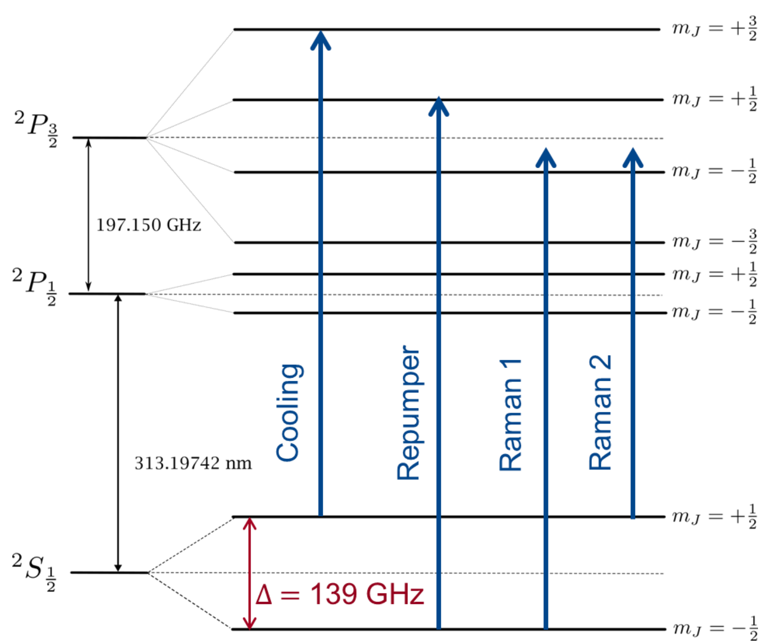
Stimulated-Raman carrier transitions





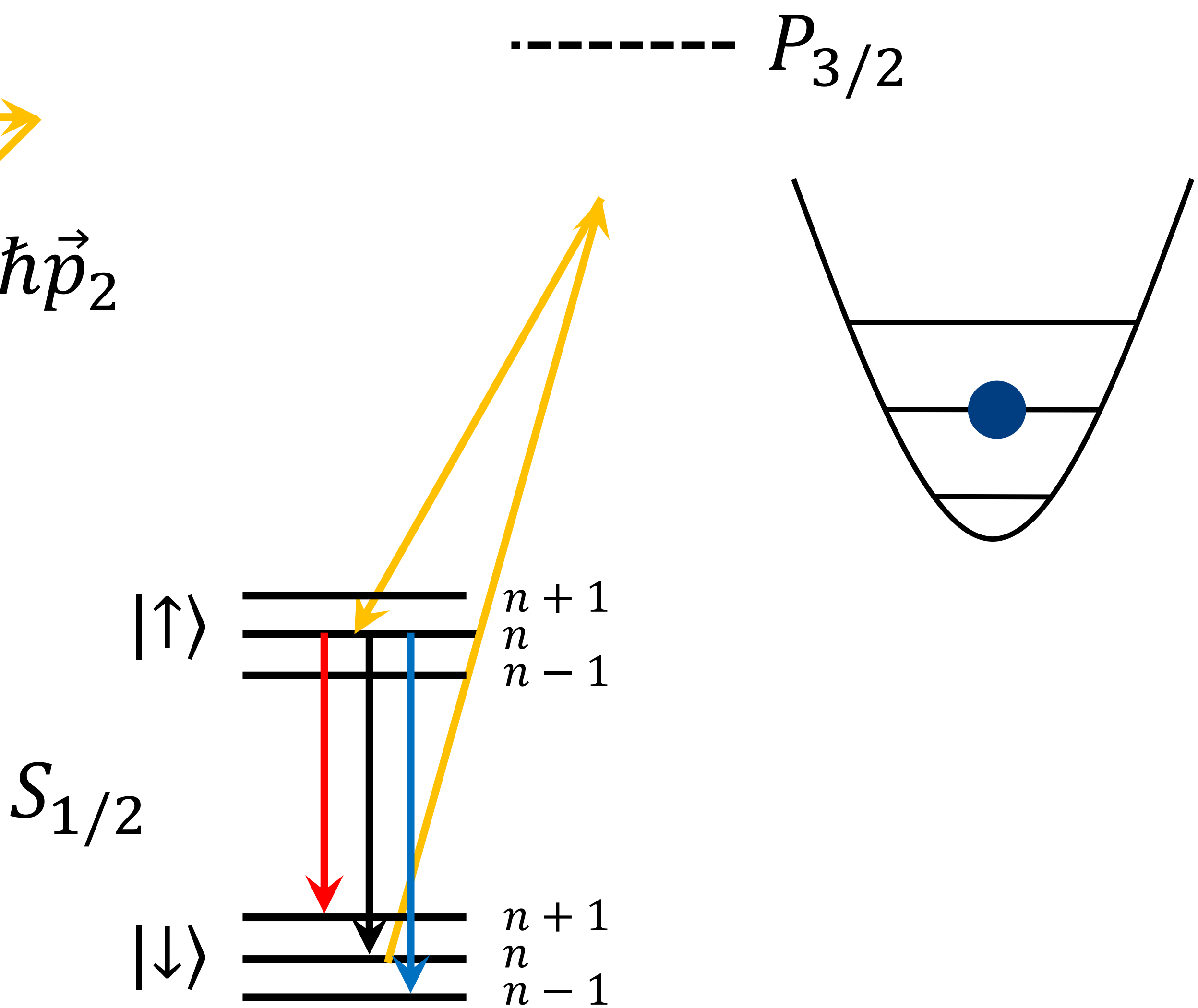
Two photon stimulated Raman transition

Energy levels of $^{9}Be^{+}$ in a 5T magnetic field

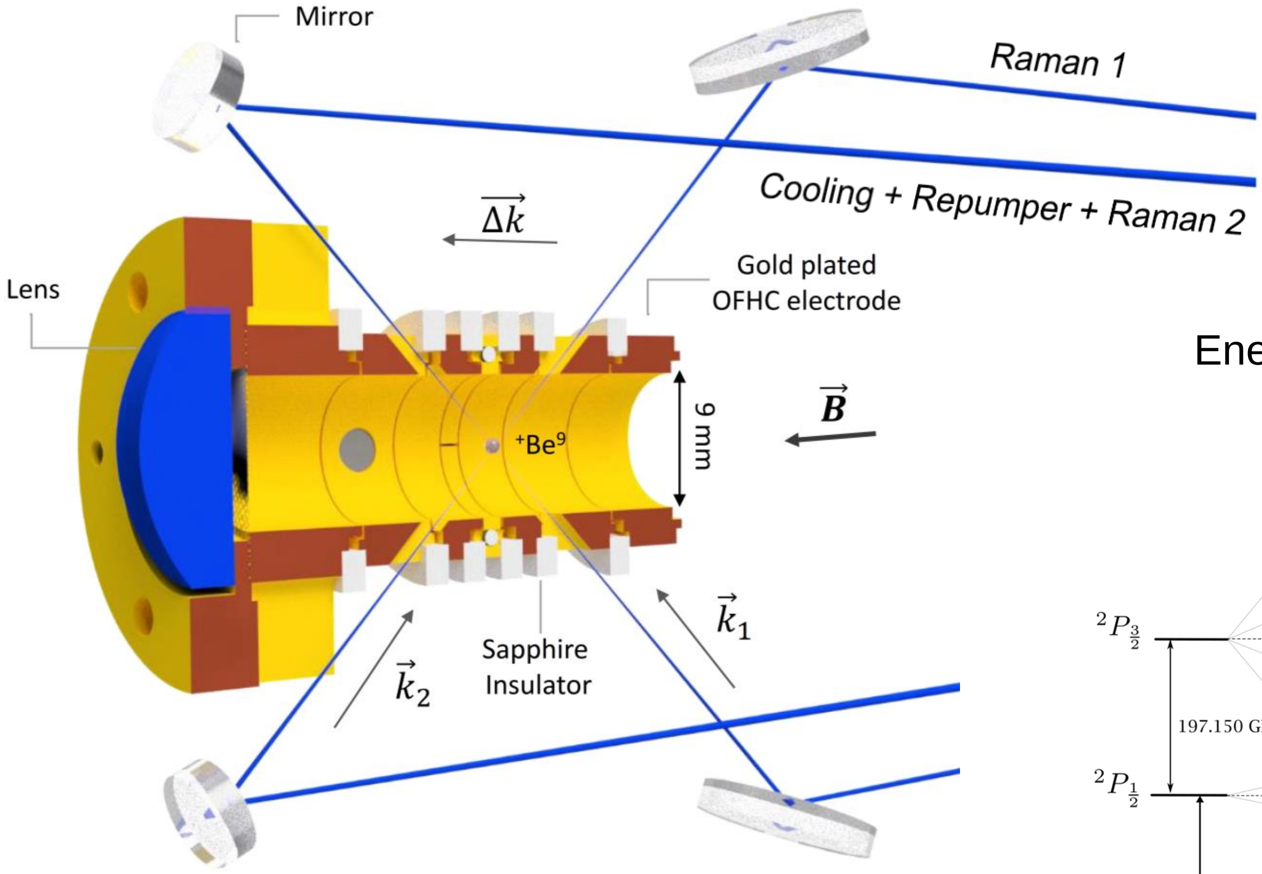


$$\Delta\vec{k} = \hbar\Delta\vec{p}$$

$$\vec{k}_1 = \hbar\vec{p}_1 \quad \vec{k}_2 = \hbar\vec{p}_2$$

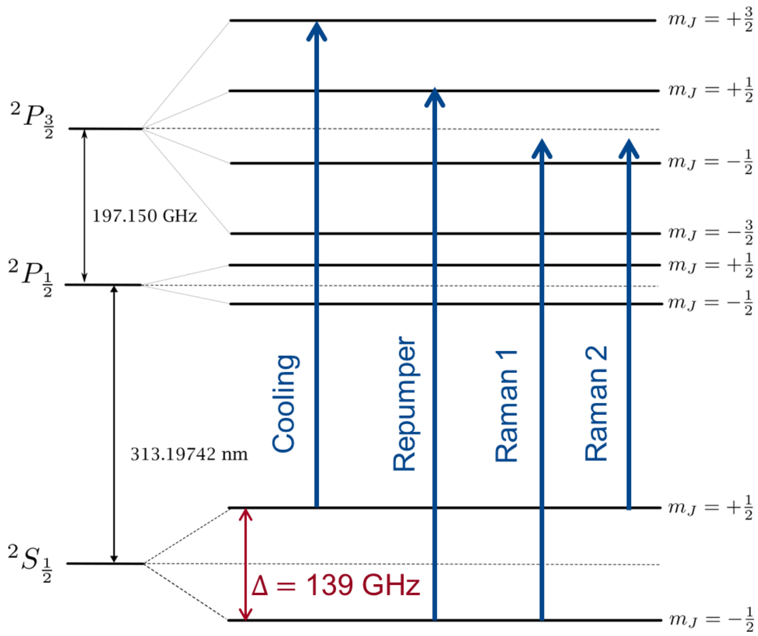


Stimulated-Raman sideband transitions

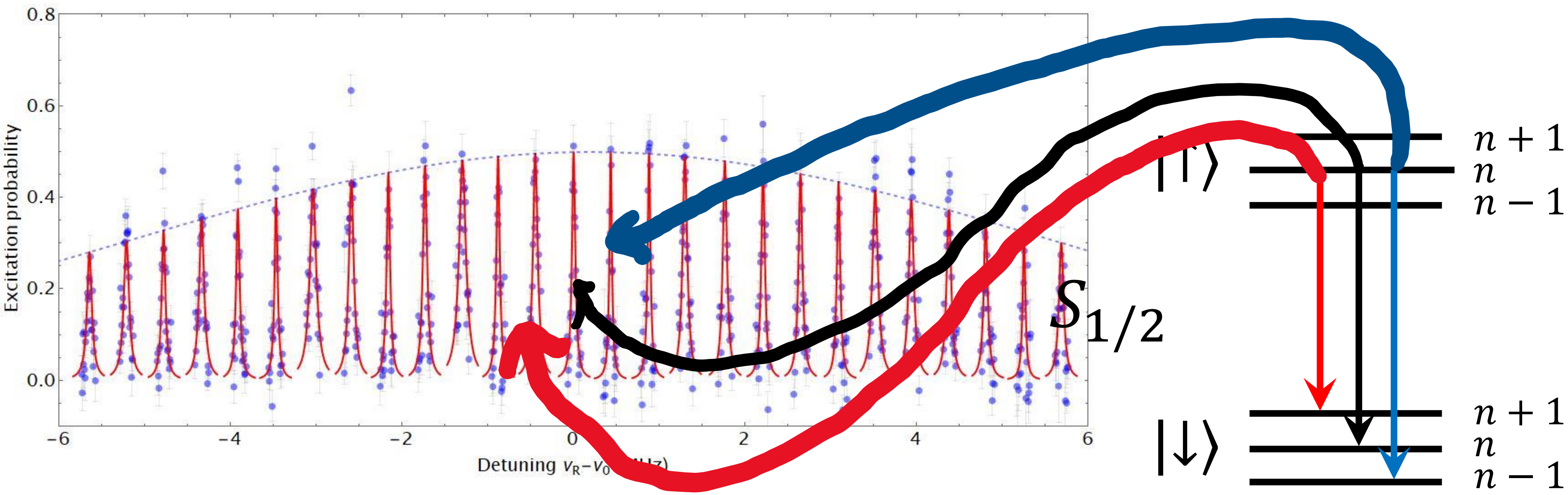


$\vec{k}_2 \nearrow - \vec{k}_1 \nwarrow = \overleftarrow{\overrightarrow{\Delta k_z}}$

Energy levels of $^9Be^+$ in a 5T magnetic field



Resolved sideband spectrum for a
single laser cooled $^9Be^+$ ion @ $\nu_z = 435\ \mathrm{kHz}$



$$T_z = \frac{m\,\lambda^2 \Delta\nu_D^2}{8\,ln2\,k_B} = (3.1\ \pm 0.4)\ \mathrm{mK}$$

$$\bar{n}_z \approx \frac{k_B T_z}{h\nu_z} \approx 150$$

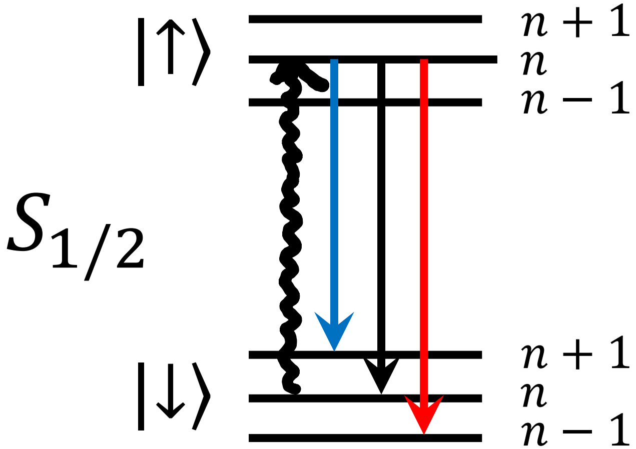
$\longrightarrow$

@ $\nu_z \approx 700\ \mathrm{kHz}$

$$T_z = (2.9\ \pm 0.4)\ \mathrm{mK}$$

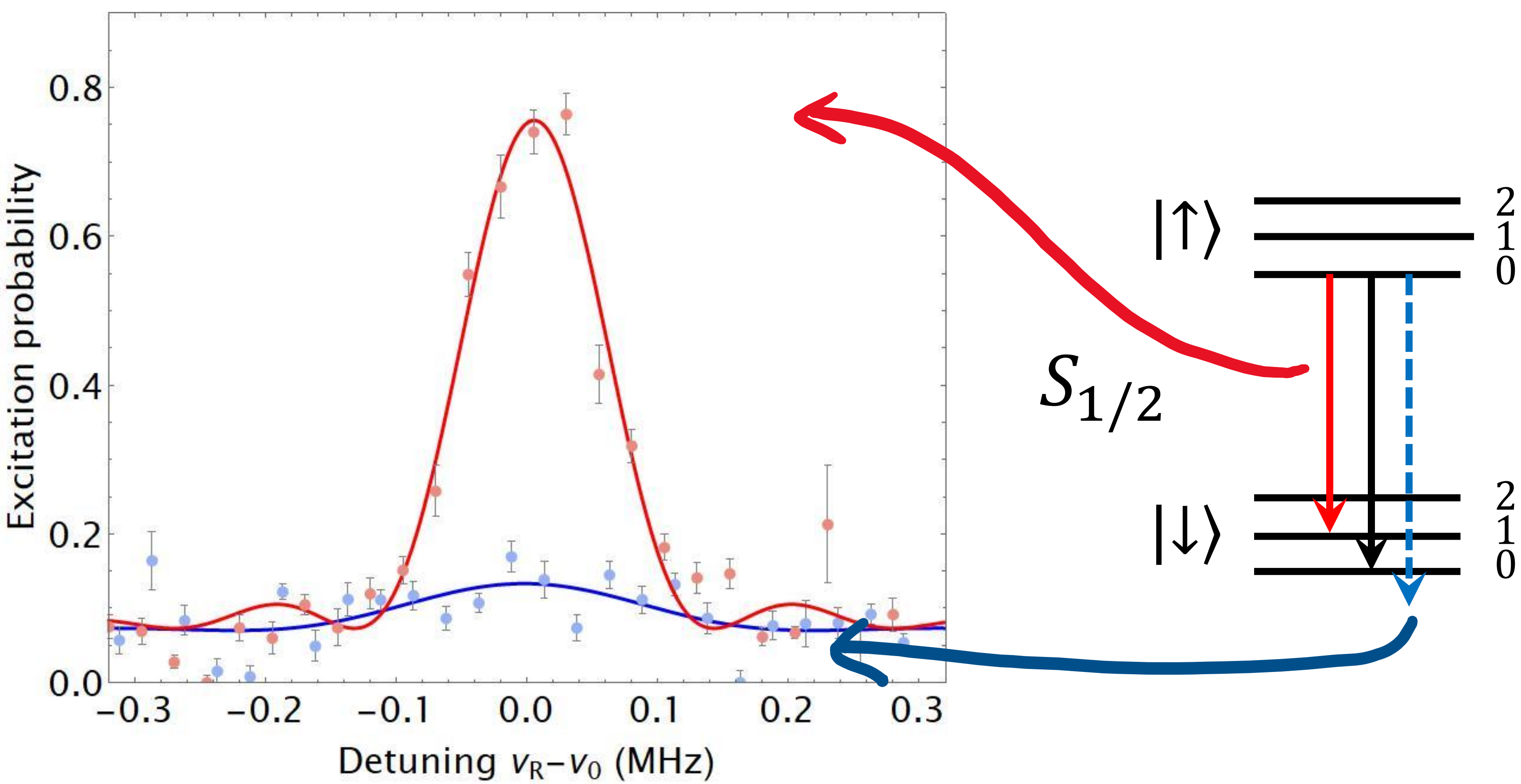
$$\bar{n}_z \approx 80$$

Motional ground state cooling



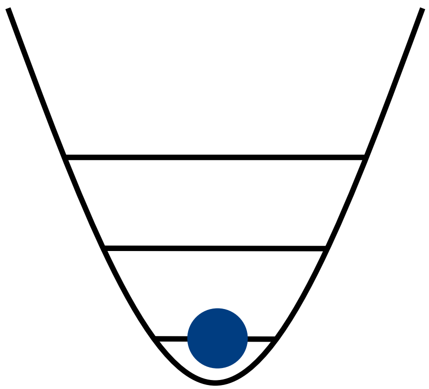
Unpublished

Motional ground state cooling



Unpublished

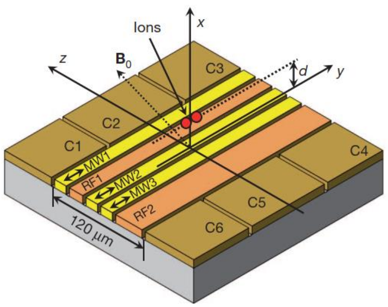
Full quantum control!



This is just the beginning!

(only two experiments worldwide can do this…)

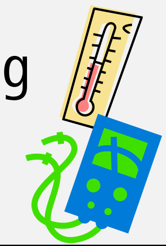
A hybrid quantum system



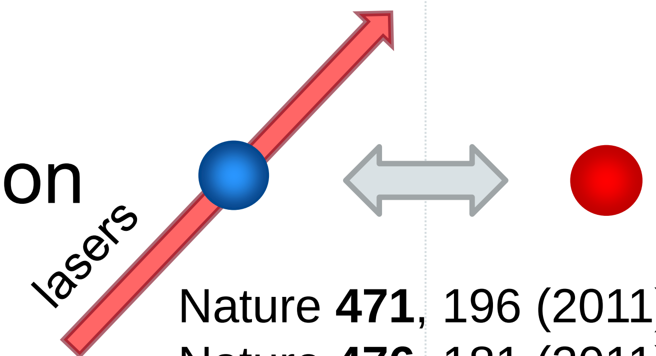
Integrated
microwave gate

"Qubit" ion provides

- Sympathetic ground state cooling
- Quantum logic state readout



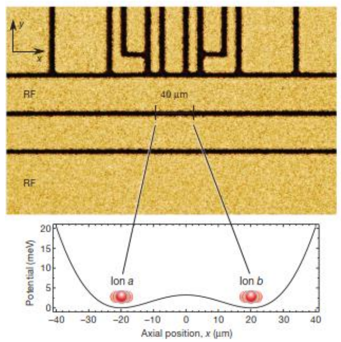
“qubit” ion



(anti-)proton

Nature **471**, 196 (2011)
Nature **476**, 181 (2011)

postdoctoral work
(atomic ions)

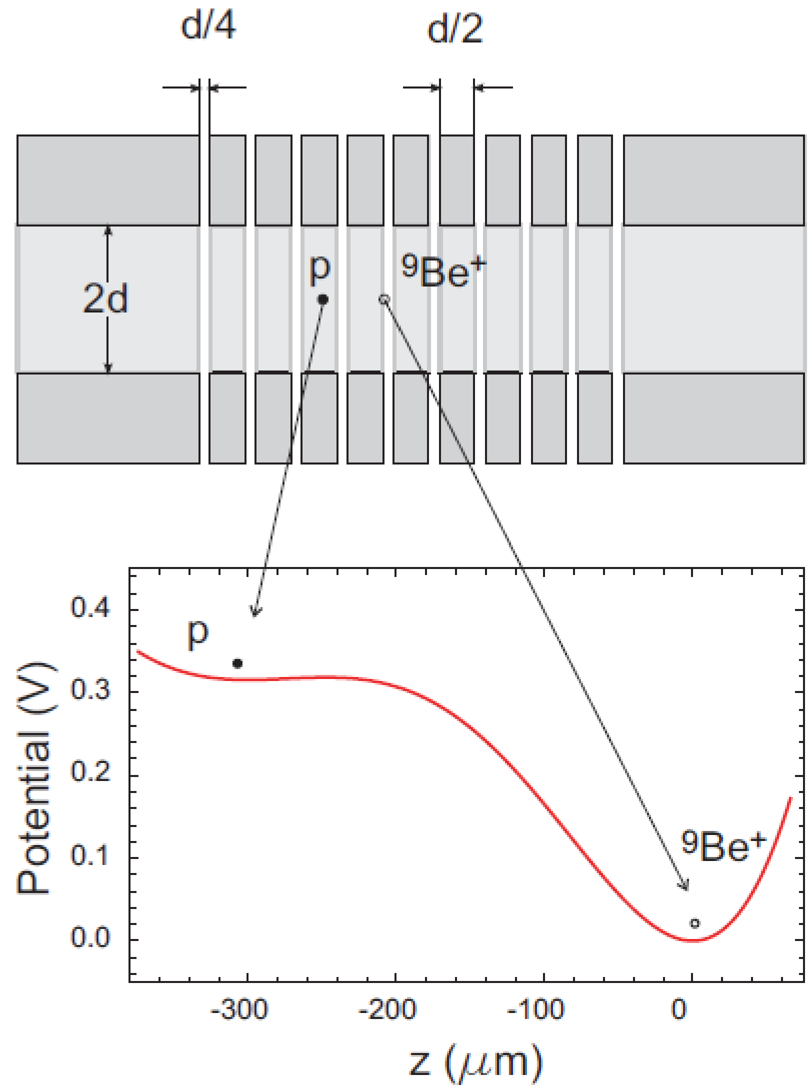


Coupled
harmonic oscillators

D. J. Wineland *et al.*, J. Res. NIST **103**, 259 (1998)
D. J. Heinzen and D. J. Wineland, PRA **42**, 2977 (1990)

Direct Coulomb coupling

- BASE AT geometry:
  $2d = 3.6$ mm
  $\omega = 2\pi \cdot 890$ kHz
  $\tau_{ex} = 76$ ms
  1.35 mm distance
- „Small“ trap:
  $2d = 0.8$ mm
  $\omega = 2\pi \cdot 4$ MHz
  $\tau_{ex} = 3.7$ ms
  0,3 mm distance
- Scaling:
  exchange time $\tau_{ex} \sim d^3$
  heating rate $\sim d^4$
- Bump: 3 meV

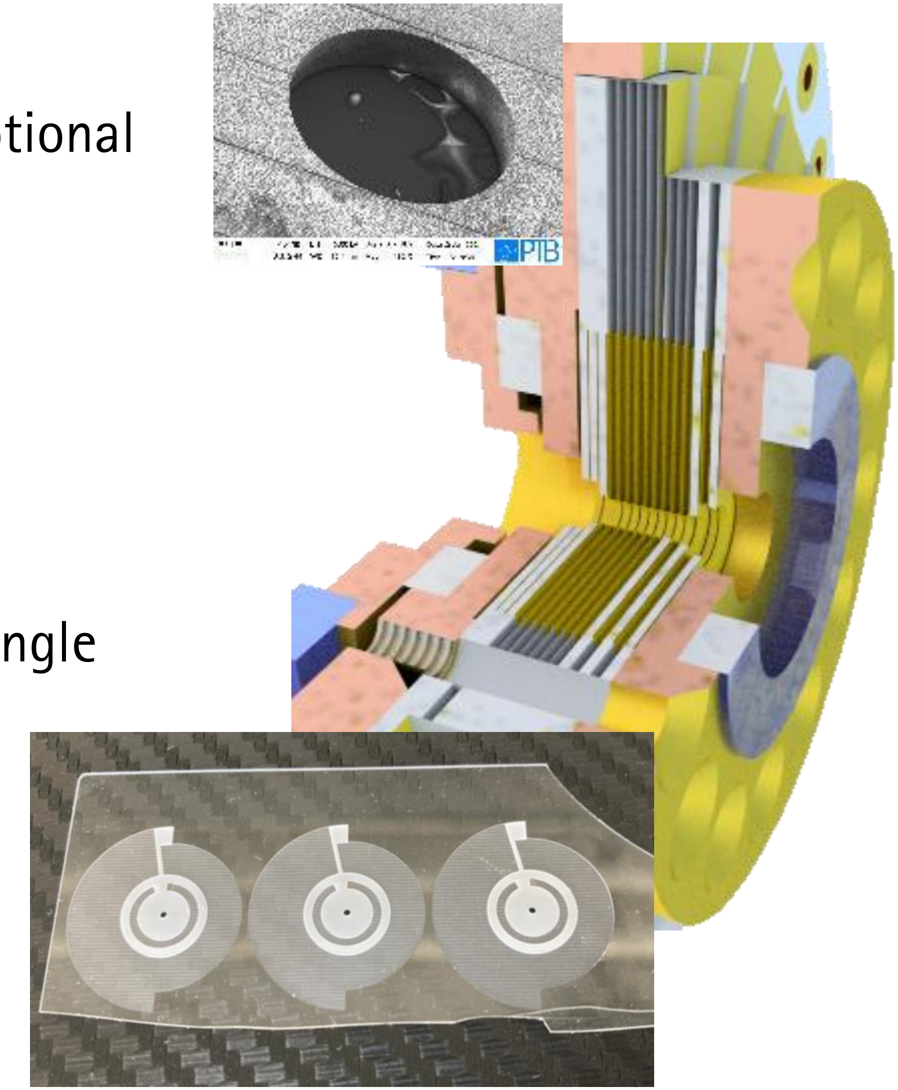


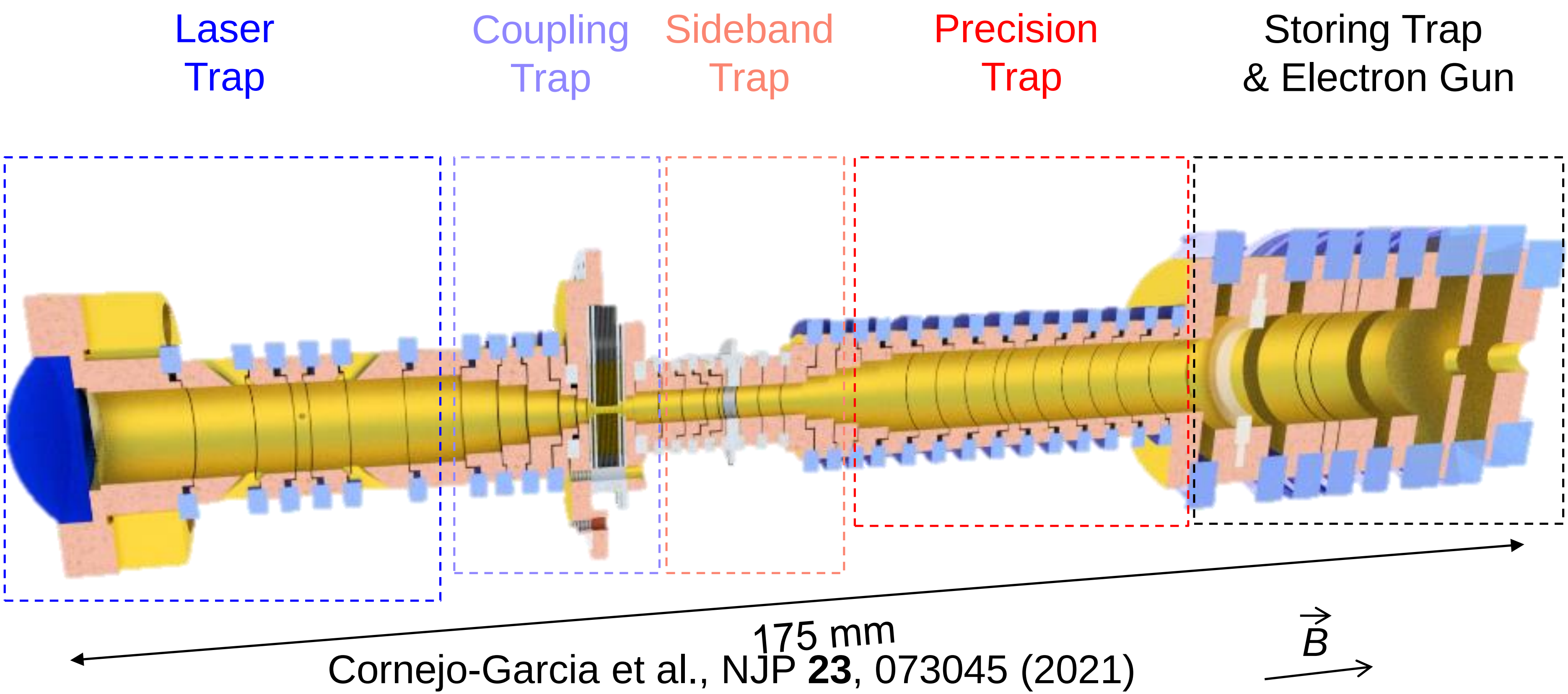
Potential shown for p / $^9Be^+$ combination because it is more challenging

Next steps

- Short-terms goals:
  - adiabatic transport in the motional ground state
  - coupling of two $^{9}Be^{+}$ ions

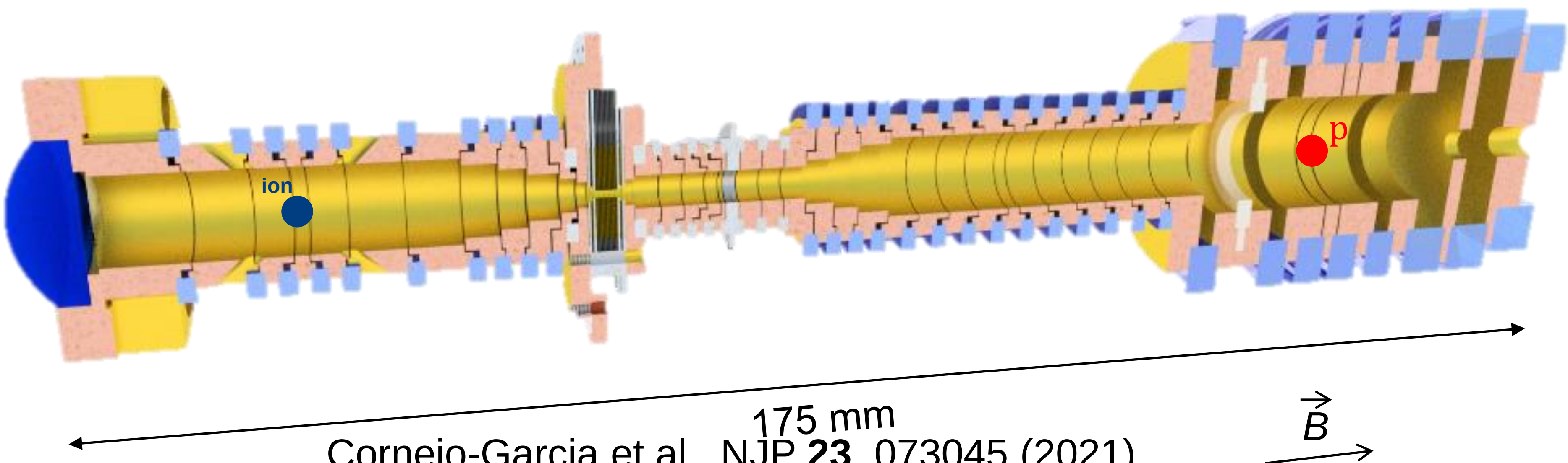
- Mid-terms goals:
  - Coupling of a proton and a single $^{9}Be^{+}$ ion





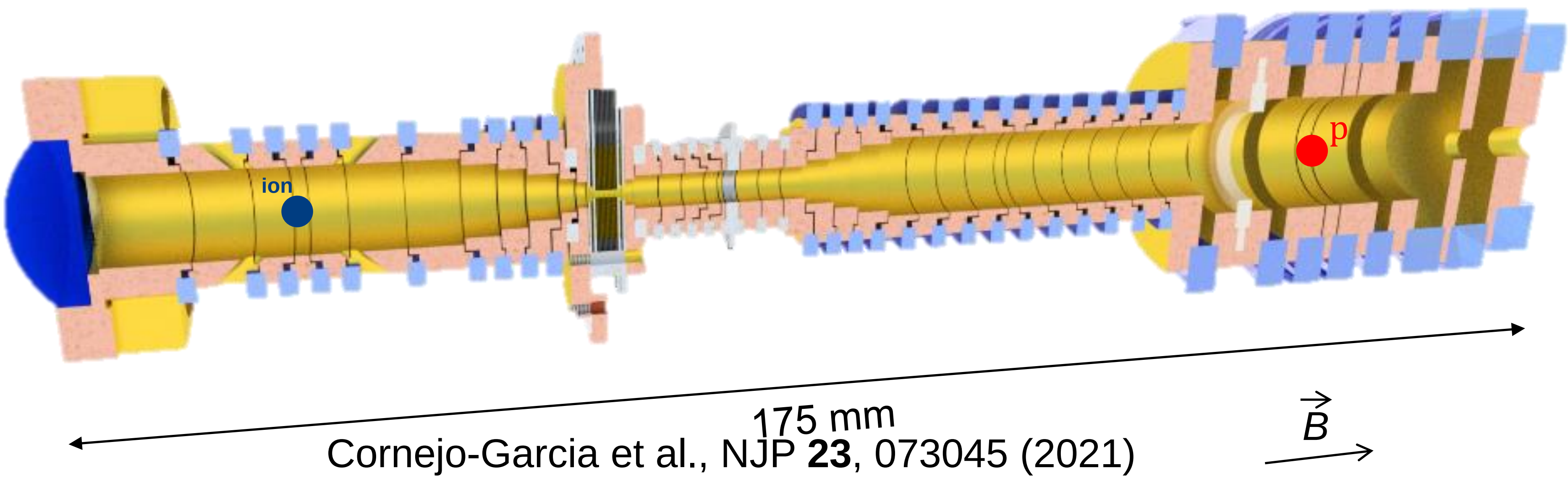
Cornejo-Garcia et al., NJP **23**, 073045 (2021)

Penning trap stack



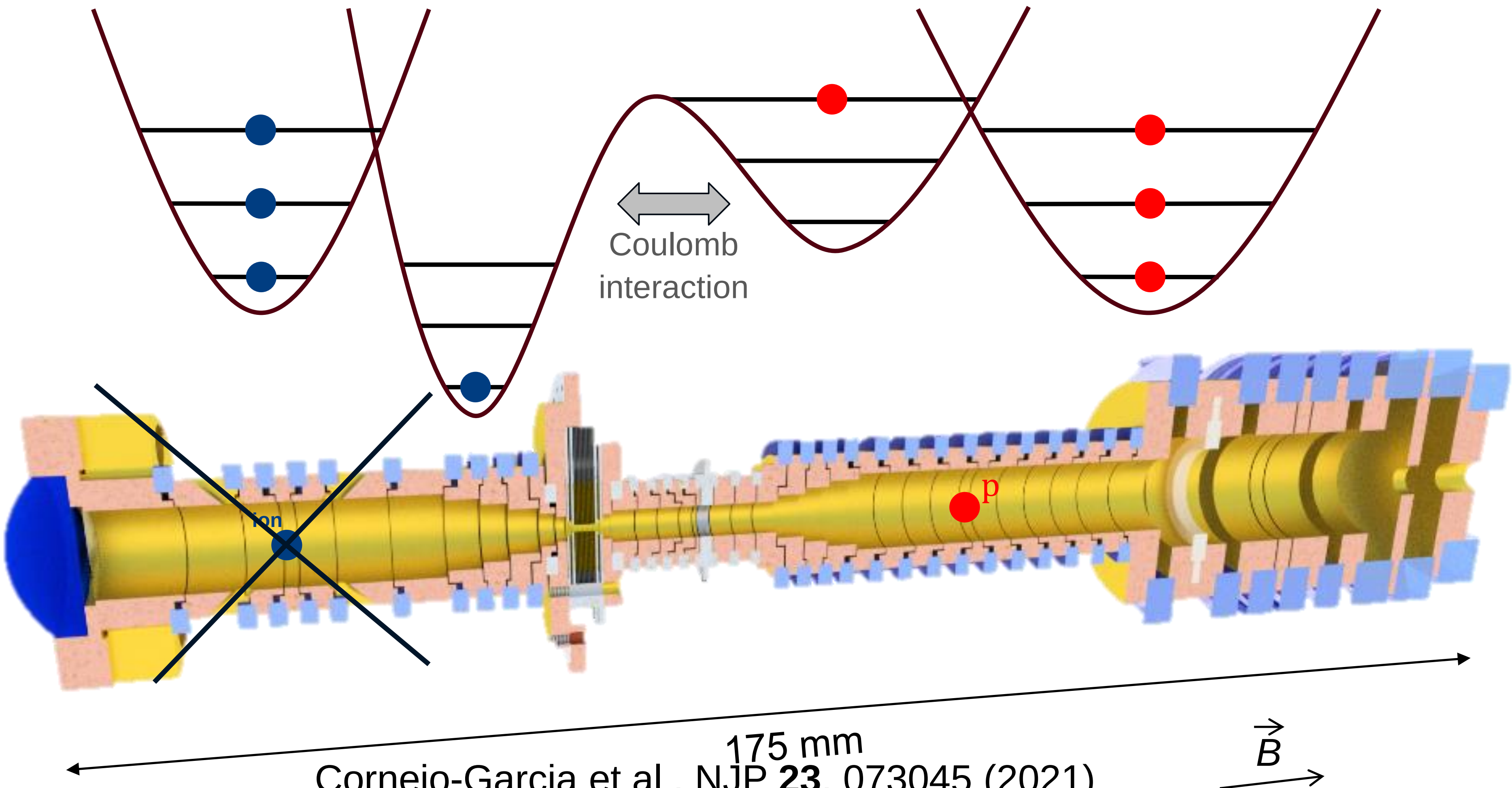
Cornejo-Garcia et al., NJP **23**, 073045 (2021)

Loading ions



Cornejo-Garcia et al., NJP **23**, 073045 (2021)

- Motional ground state cooling

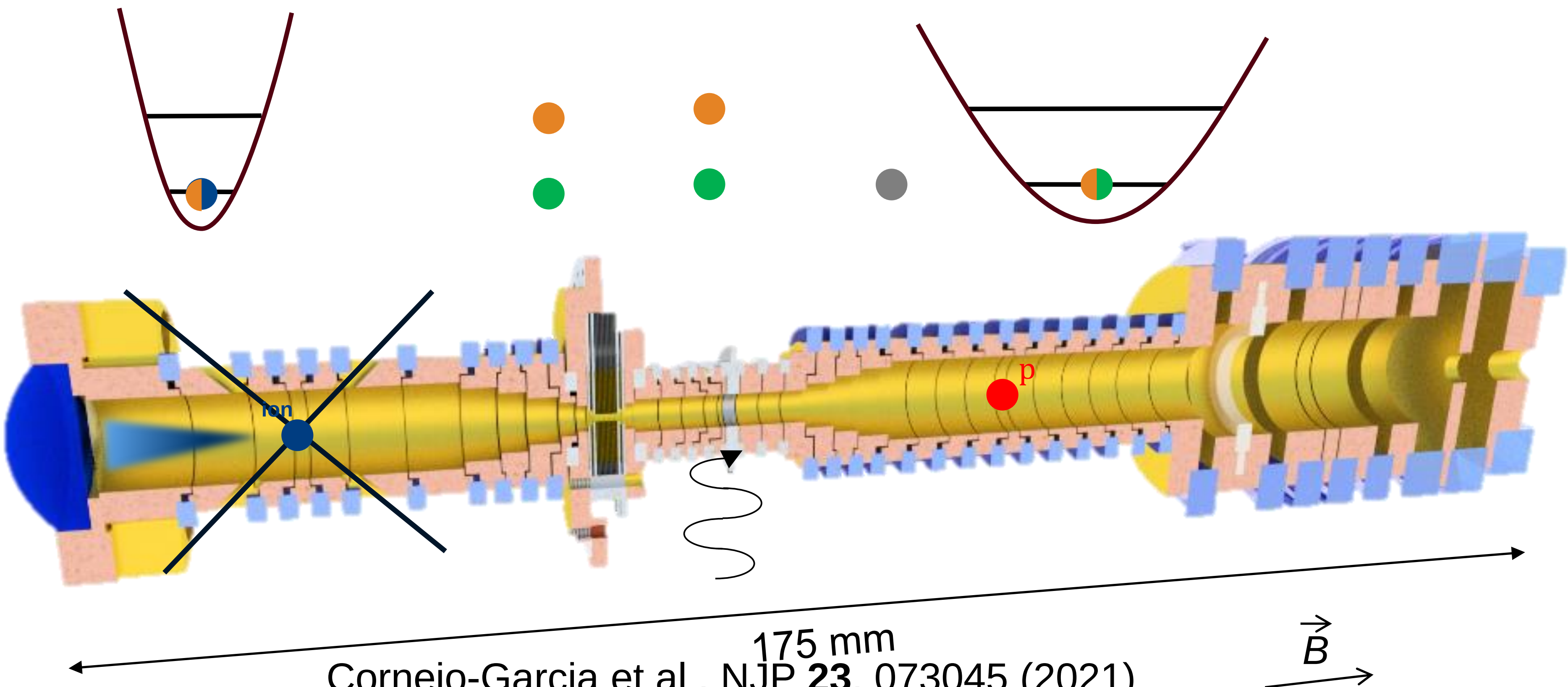


Cornejo-Garcia et al., NJP **23**, 073045 (2021)
Smorra et al., EPJ-ST **224**, 3055 (2015)

Quantum logic spectroscopy

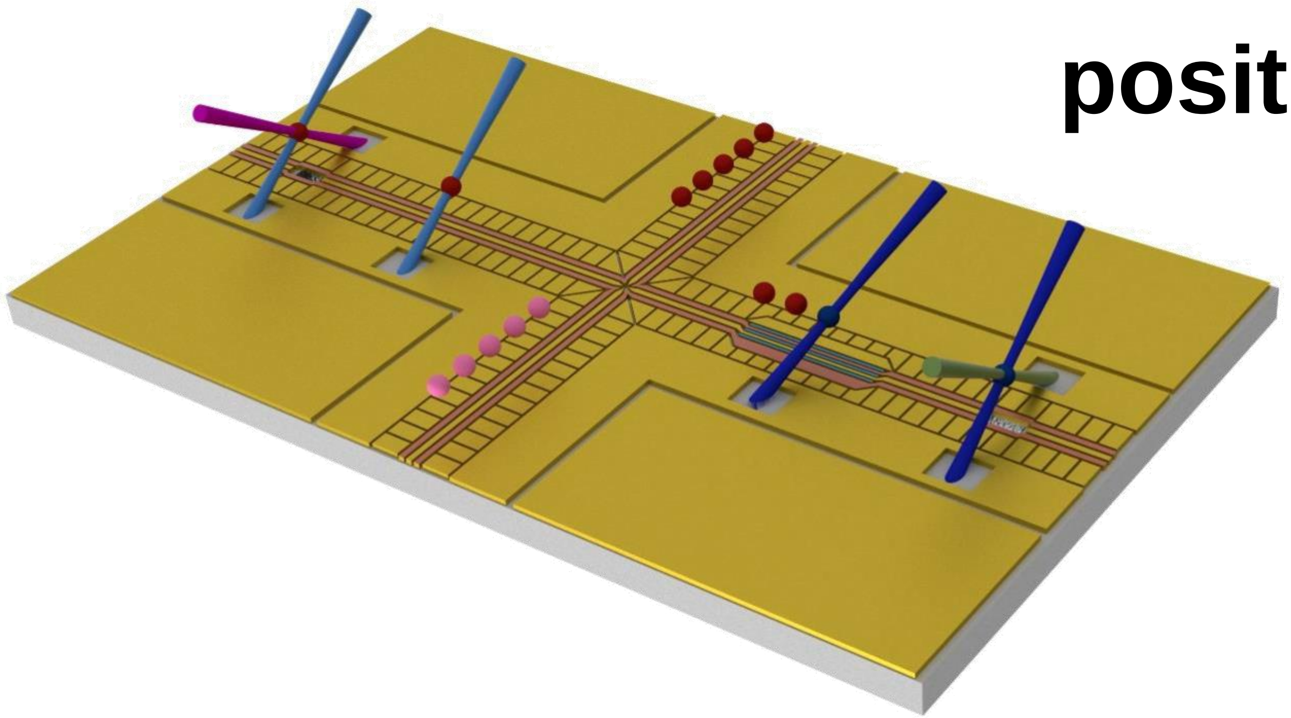
- Quantum logic readout

	ion		ion		p		p
dark ←	$\vert\downarrow\rangle$	←	$\vert 1\rangle$	←	$\vert 1\rangle$	←	$\vert\downarrow\rangle$
bright ←	$\vert\uparrow\rangle$	←	$\vert 0\rangle$	←	$\vert 0\rangle$	←	$\vert\uparrow\rangle$



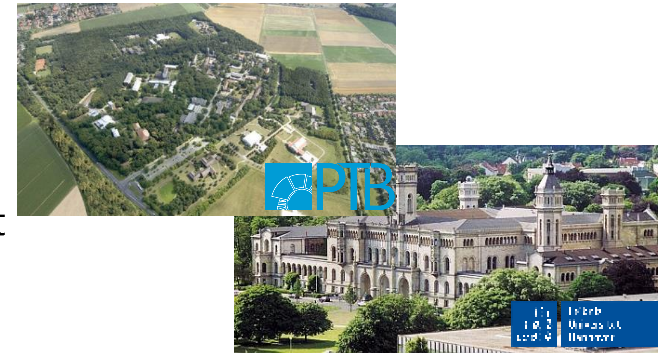
Cornejo-Garcia et al., NJP **23**, 073045 (2021)
Nitzschke et al., Adv. Quant. Techn. **9**, 1900133 (2020)

Open PhD and PD positions



QVLS-Q1, BMBF ATIQ and BMBF MIQRO quantum processor projects

Acknowledgments



PhD students
Chloë Allan-Ede
Julia-Aileen Coenders
Markus Duwe
Sebastian Halama
Eike Iseke
Christian Joohs
Lukas Kilzer
Nila Krishnakumar
Hardik Mendpara
Rodrigo Munoz
Niklas Orlowski
Johannes Mielke
Tobias Pootz
Nicolás Pulido
Florian Ungerechts

Postdocs
Amado Bautista-Salvador
Juan-Manuel Cornejo
Timko Dubielzig
Friederike Giebel
Brigitte Kaune
Niels Kurz
Ludwig Krinner
Teresa Meiners
Celeste Torkzaban

Undergrads
Frederik Schmidt
Emma Vandrey
Yannik Hermann

Alumni
Henning Hahn
Giorgio Zarantonello
Malte Niemann

Staff
Jacob Stupp
Konstantin Thronberens

Humboldt / Mercator fellow
Ralf Lehnert
(Indiana University, Bloomington)

VolkswagenStiftung
Niedersächsisches Ministerium für Wissenschaft und Kultur
GEFÖRDERT VOM Bundesministerium für Bildung und Forschung
QUANTUM FLAGSHIP
microQC
quest
DFG SFB 1227 DQ-*mat*
erc