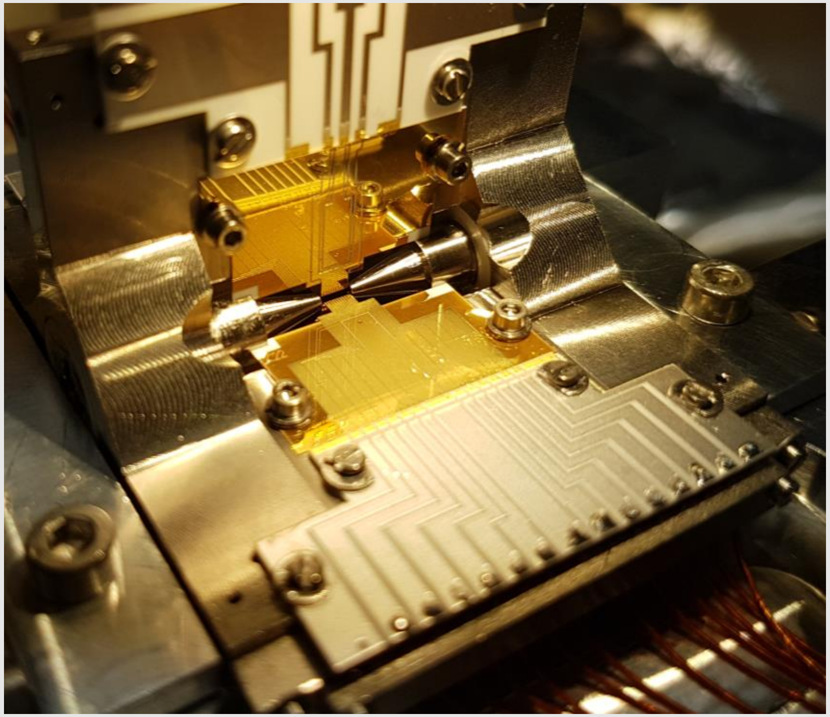
www.quantenbit.de

gbar.web.cern.ch

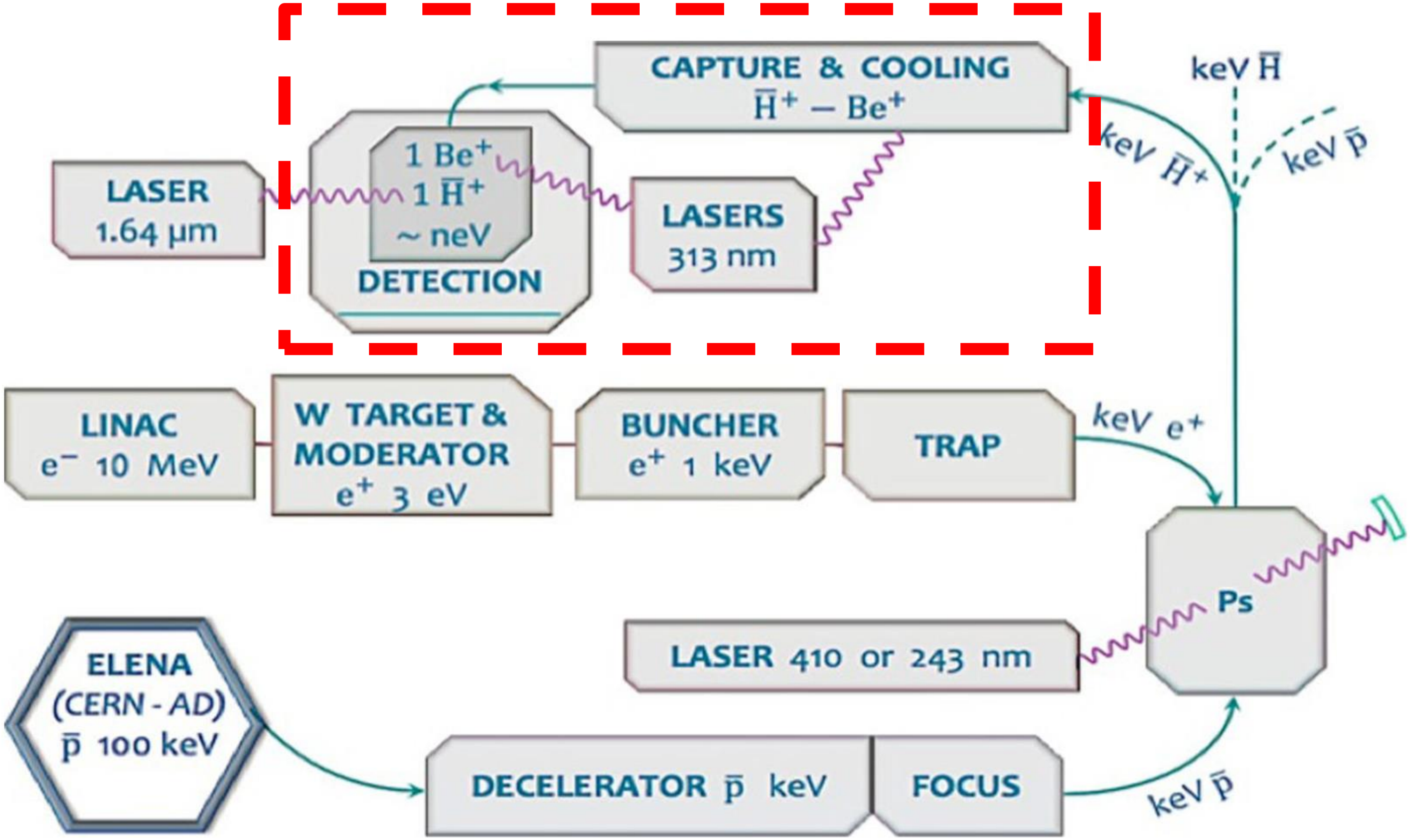
Sympathetic ground-state cooling studies for GBAR



- Outline of GBAR experiment
- Alternative capture trap design
- Be^+ laser system and photo-ionization
- Precision trap
- Ground-State cooling of mixed crystals

Sebastian Wolf and Ferdinand Schmidt-Kaler
QUANTUM, Johannes Gutenberg-University Mainz, Germany

GBAR experimental scheme



P. Perez and Y. Sacquin,
Class. Quantum Grav. **29**, 184008 (2012).

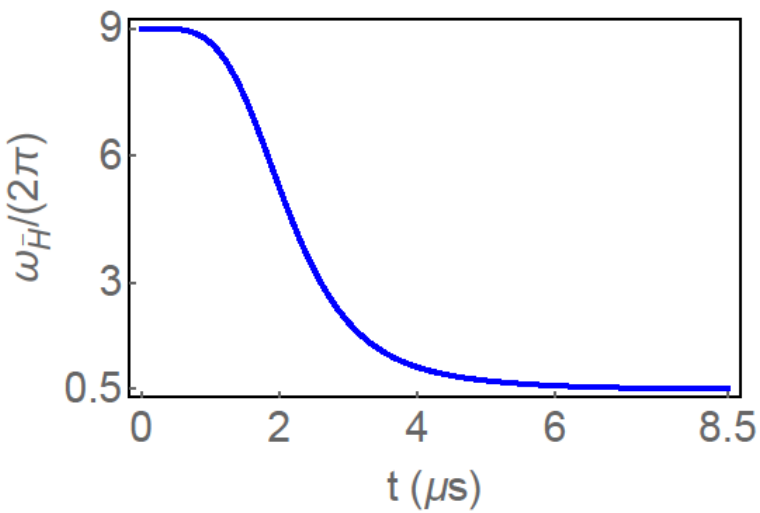
Adiabatic wavepacket expansion

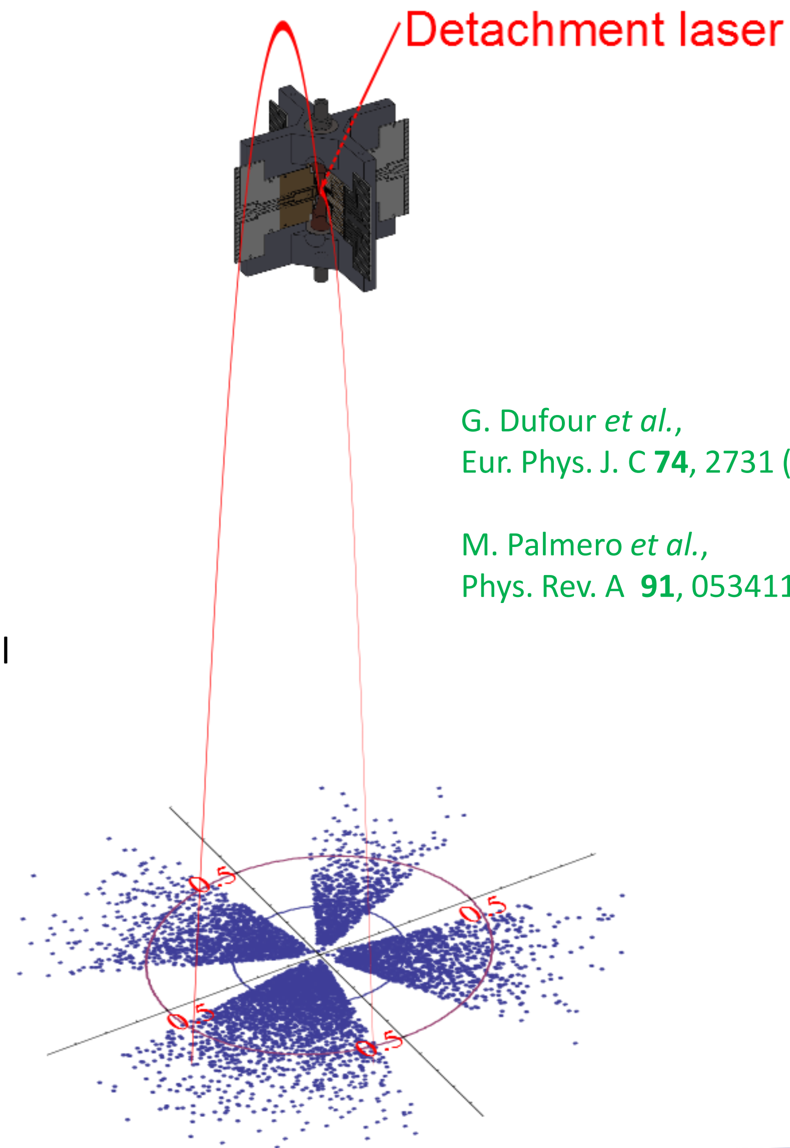
Heisenberg limited ground state

$$\frac{\Delta \bar{g}}{\bar{g}} = \sqrt{\left(\frac{\Delta x}{2\,h}\right)^2 + \left(\frac{\hbar}{2\,m\,\sqrt{2\bar{g}\,h\,\Delta x}}\right)^2}$$

Optimal trap frequency
→ $\omega_{ax} = 2\pi\ 1\ Hz;\ \Delta x_{min} = 88\mu m$

Solution:
Vertical trap and adiabatic expansion of axial potential





G. Dufour *et al.*,
Eur. Phys. J. C **74**, 2731 (2014).

M. Palmero *et al.*,
Phys. Rev. A **91**, 053411 (2015).

GBAR accuracy target

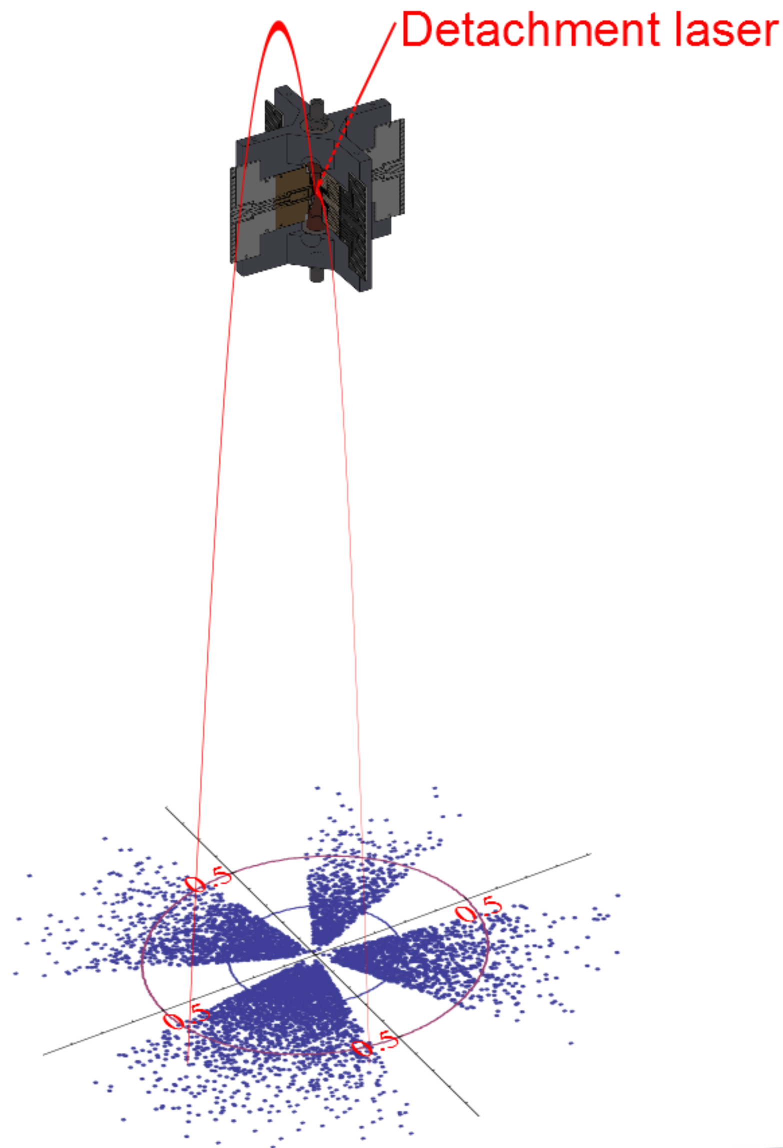
Only experimental limits by ALPHA collaboration

$$-65 < \bar{g} \,/\, g < 110$$

ALPHA collaboration,
Nature Comm. **4**, 1785 (2013).

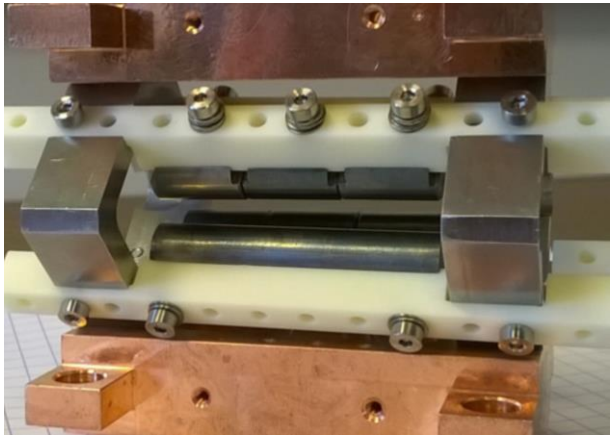
GBAR accuracy goal:

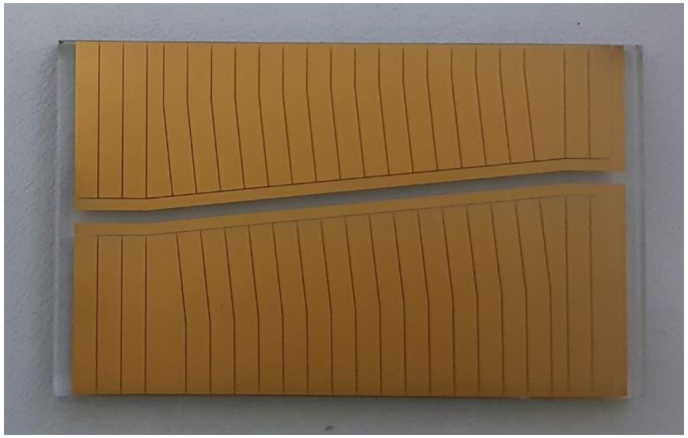
$$\frac{\Delta\bar{g}}{\bar{g}} < 1\ \%$$



Capture trap prerequisits

- 10^6 Be^+ ions
- axial laser cooling → conflict with incoming ion beam
- switching of trap potentials
- isolate $\overline{\mathrm{H}}^+$ from Be^+ reliably





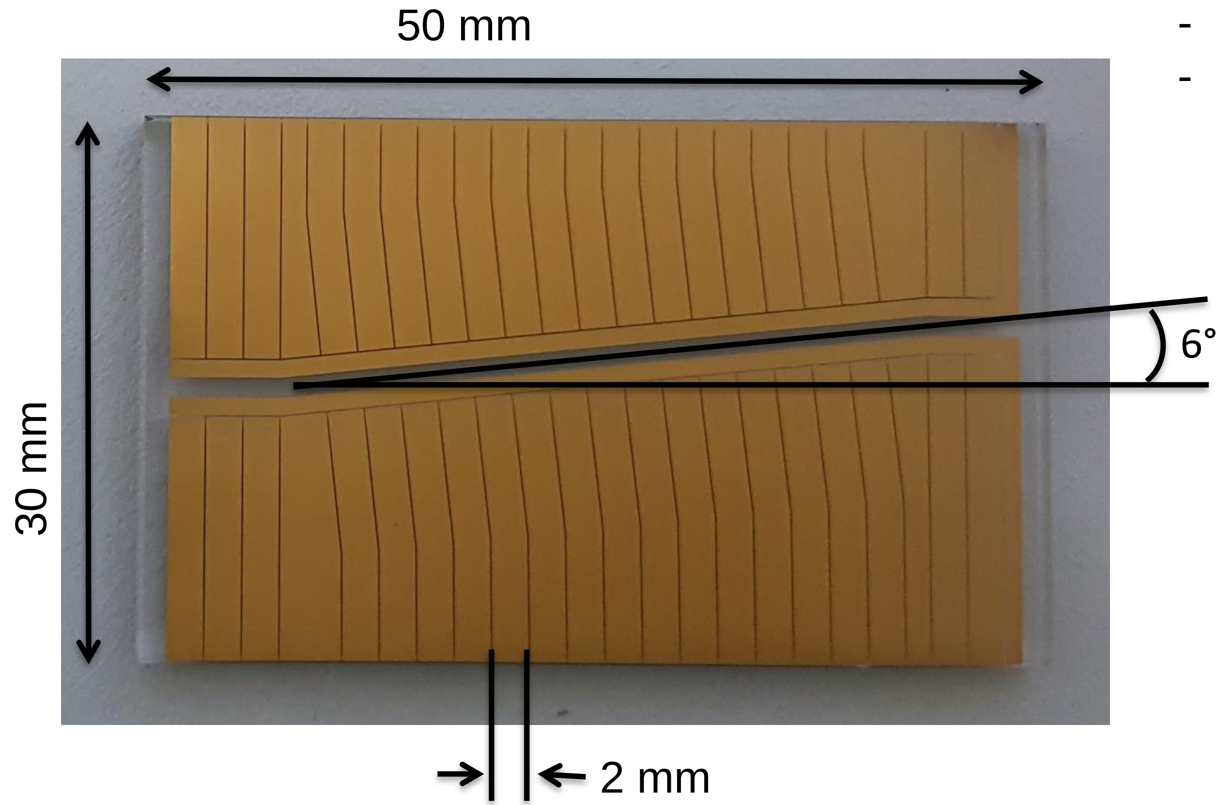
pros

- big trapping region
- works with HV

pros

- high resolution potentials
- separation of ion beam and cooling laser

Alternative design for capture trap



- quartz substrate
- Indium-tin-oxide (ITO) coated
- 2 µm thick gold wires
- ion imaging through chip

fabricated by Ron Folman, Ben-Gurion Univ., Be'er Sheva, ISRAEL

Capture trap: next steps

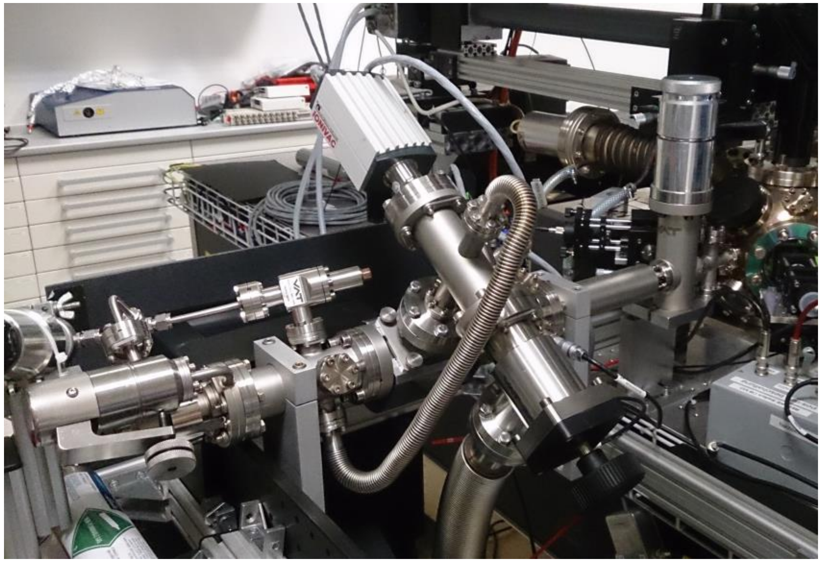
crucial part for GBAR

next steps: inject p^+, H_2^+, HD^+, D_2^+ into capture trap filled with Be^+

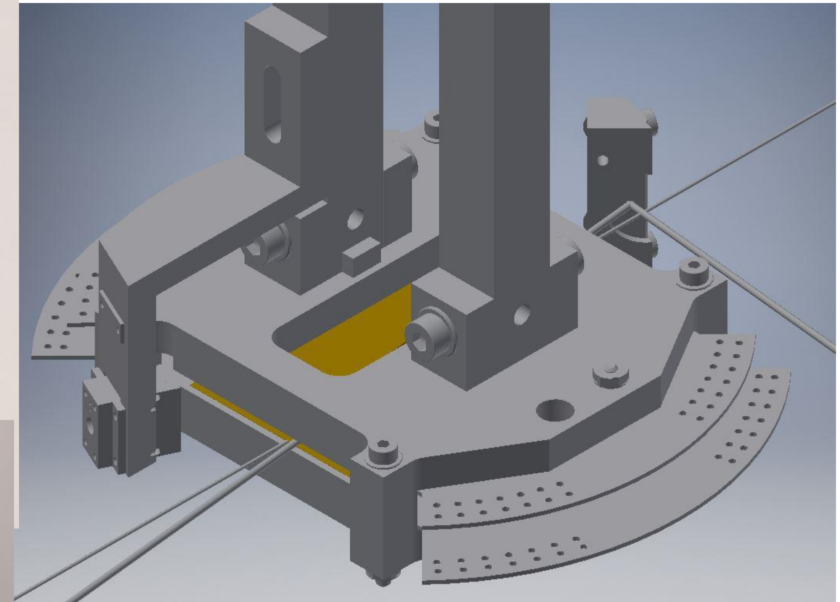
- investigate & optimize trapping & sympathetic cooling offline
- transport to Precision trap

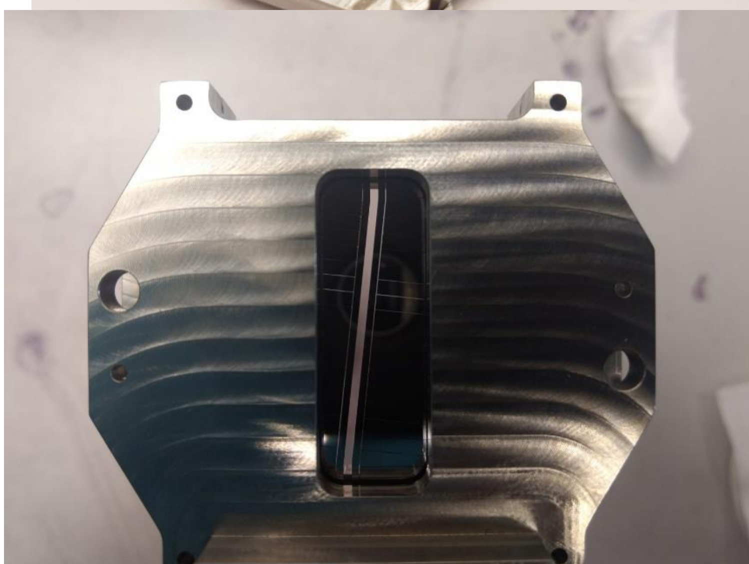
trapping of wide mass spectrum already realized in ion implantation setup by switching of axial trapping voltages:

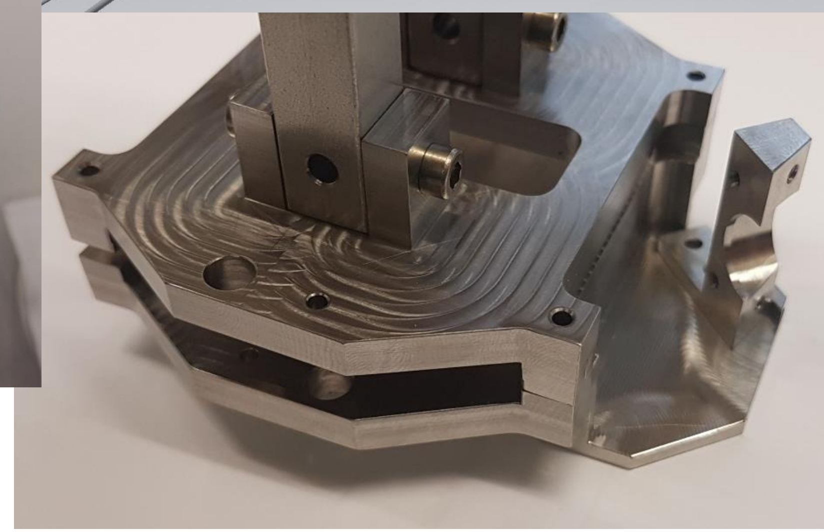
$^{28}N_2$, ^{40}Ca, ^{40}Ar, ^{128}Xe, ^{129}Xe, ^{140}Ce, ^{141}Pr



Holder for ITO trap







design together with
L. Hilico and J. Heinrich, LKB

Be^+ laser system prerequisits

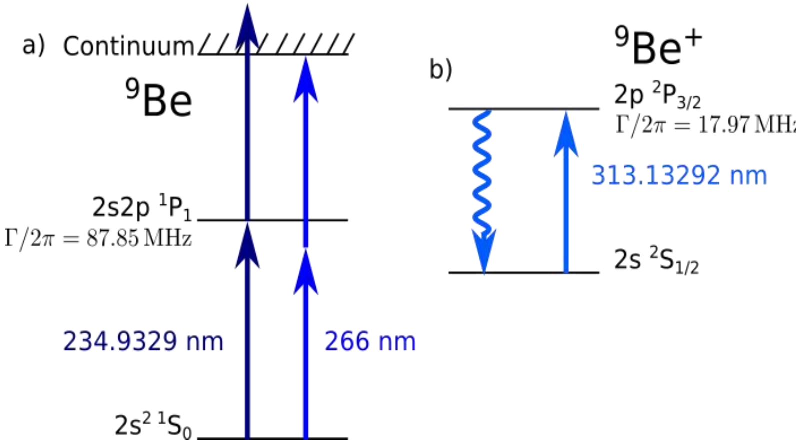
- stable laser system in noisy enviroment
- efficient loading of Be+
- reliable Doppler cooling

Efficient and robust loading of beryllium

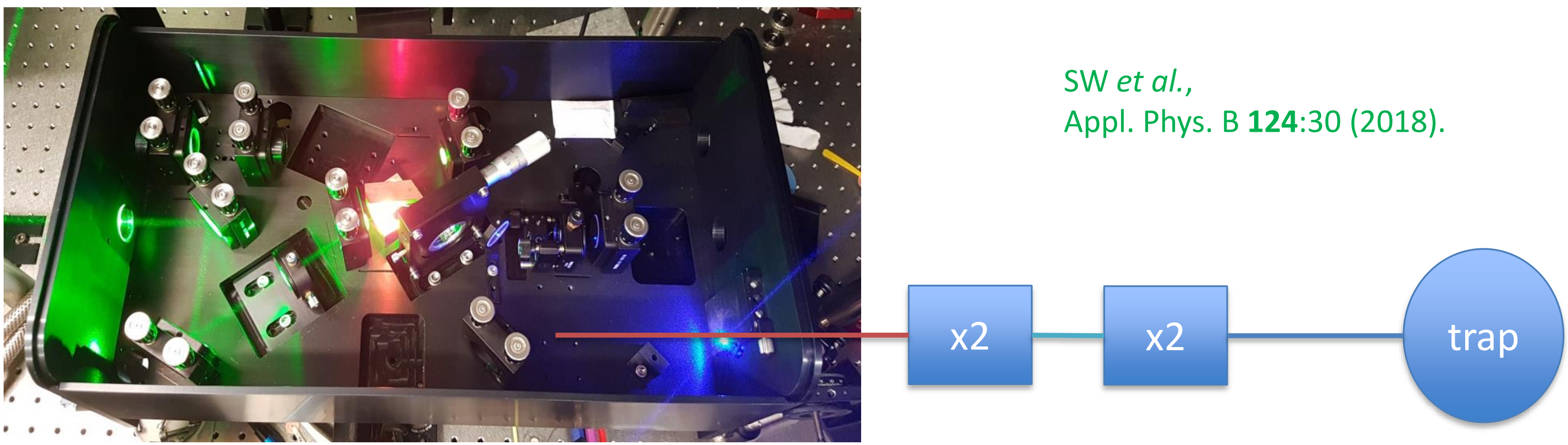
Other loading methods:

- e^- bomboardement
- cw photo-ionisation

H.-Y. Lo *et al.*,
Appl. Phys. B **114**, 17 (2014).

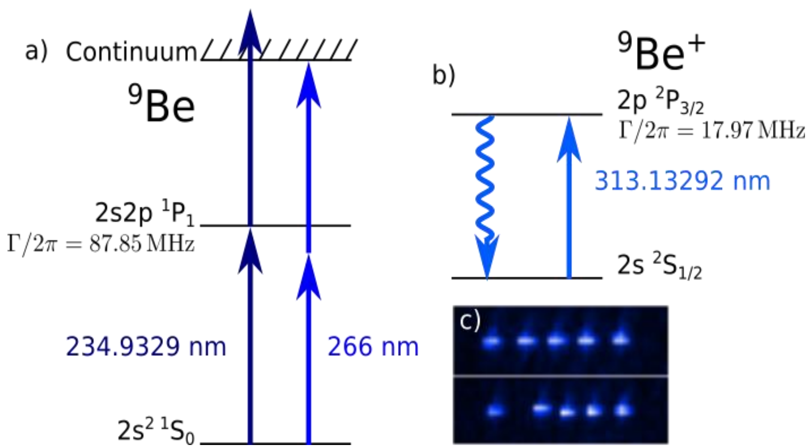


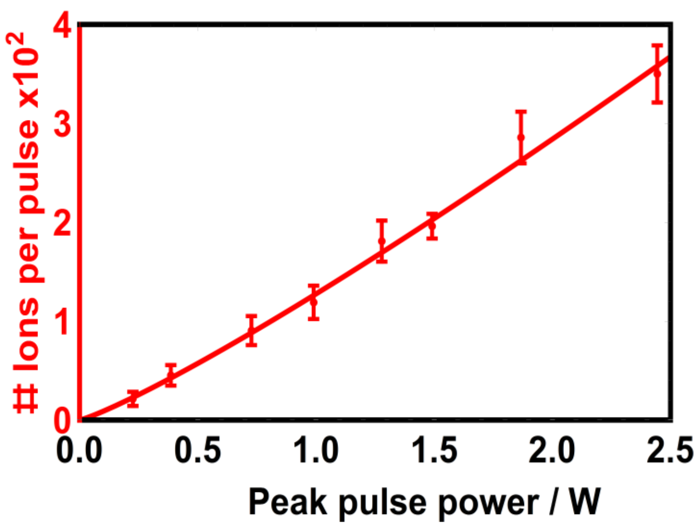
SW *et al.*,
Appl. Phys. B **124**:30 (2018).

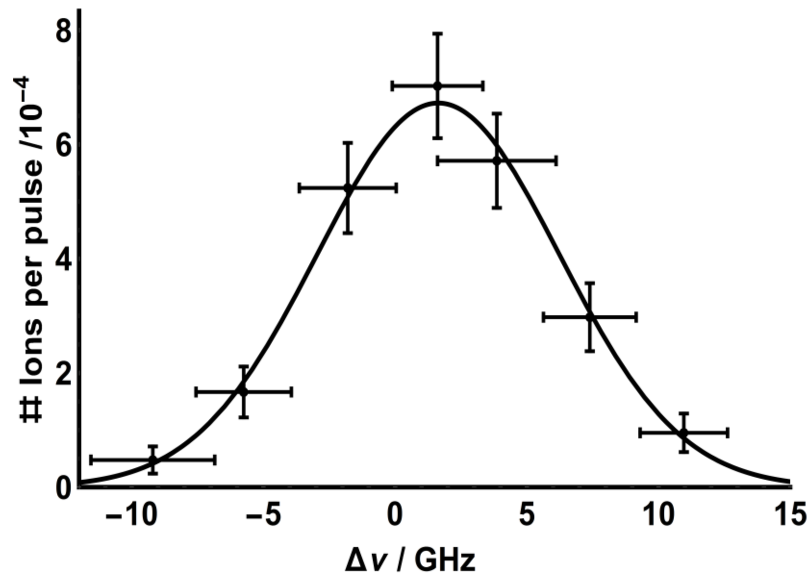


Ti:Sapph laser with 50 ns pulses

Resonant pulsed ionisation with Ti:sapphire

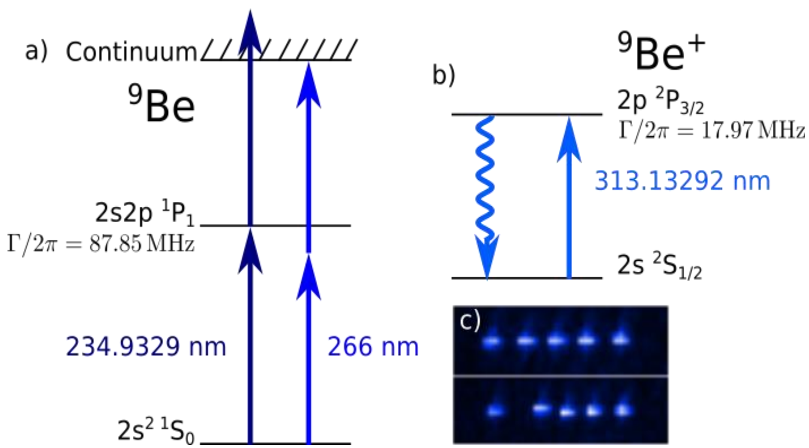


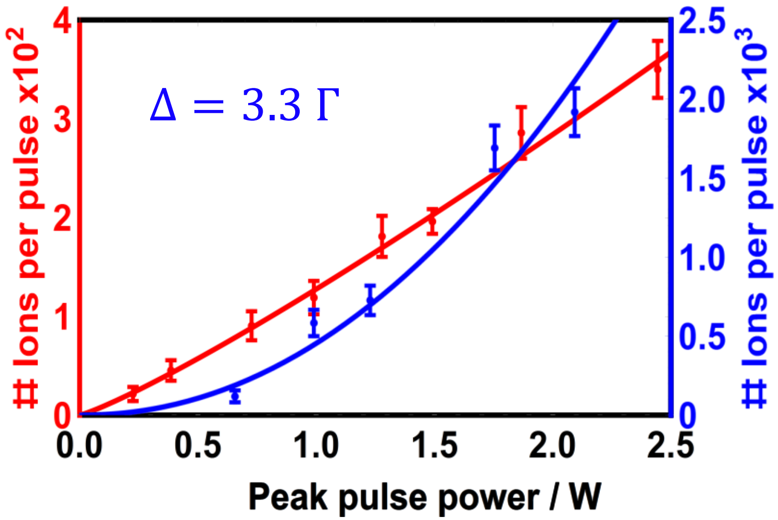


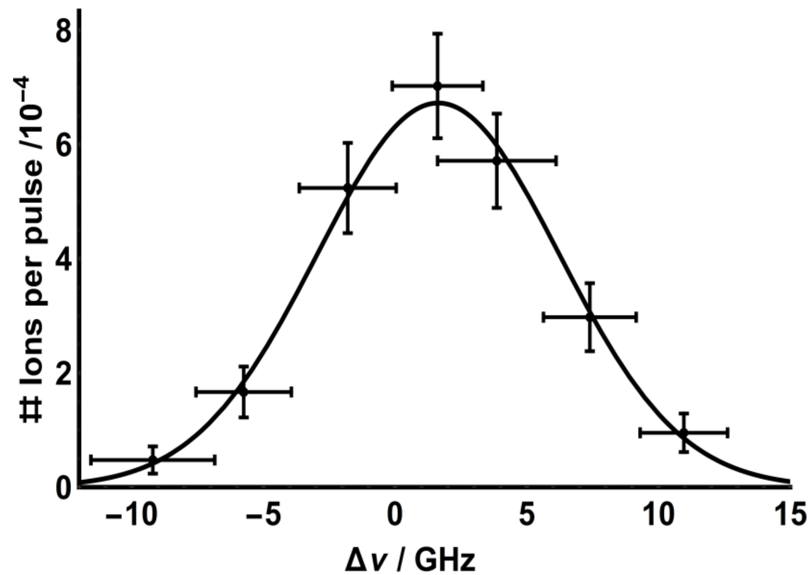


S → P transition in neutral beryllium
Natural linewidth: 88 MHz
Fully dominated by laser linewidth

Resonant pulsed ionisation with Ti:sapphire







S → P transition in neutral beryllium
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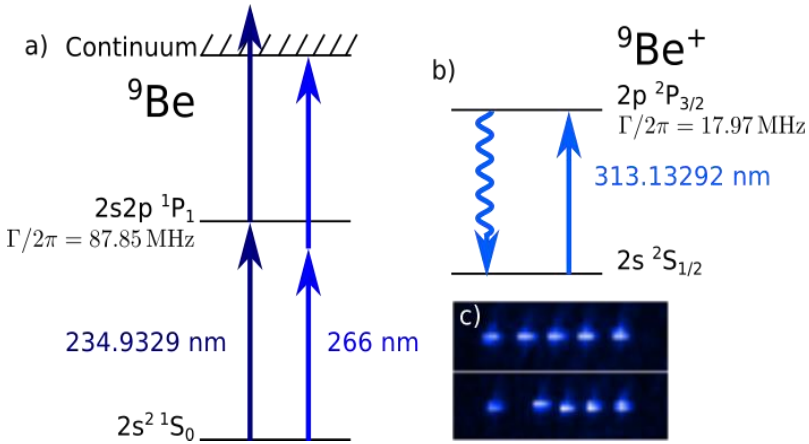
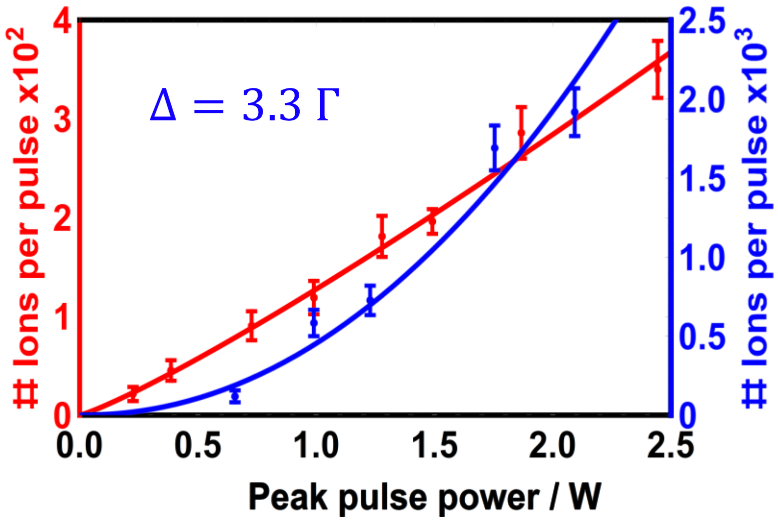
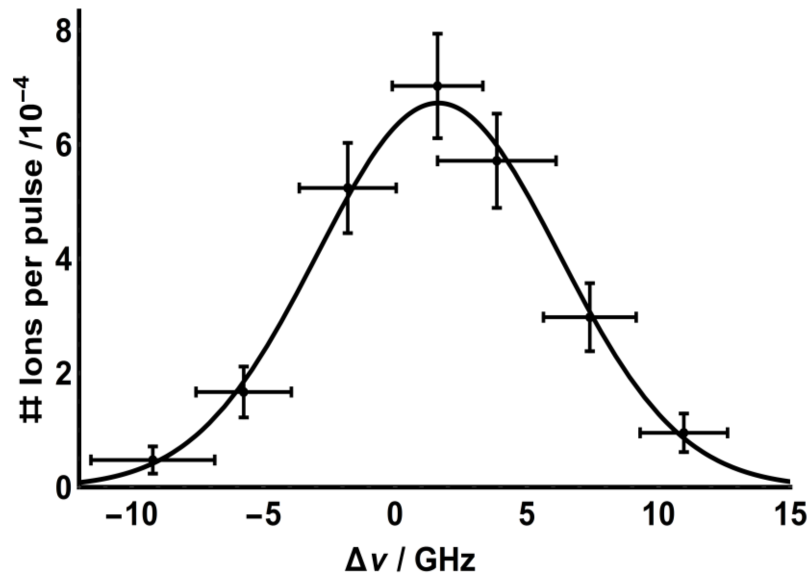


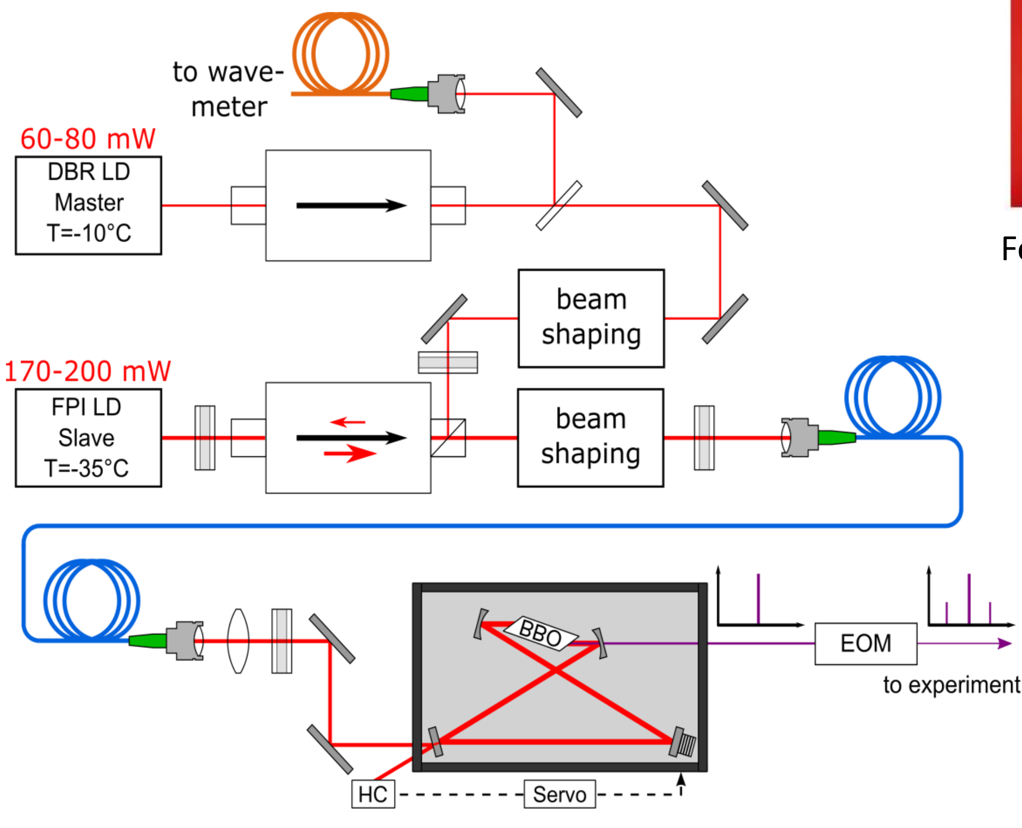




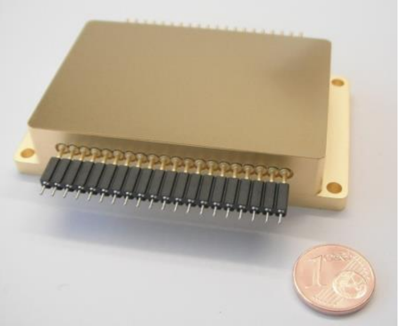
S → P transition in neutral beryllium
Natural linewidth: 88 MHz
Fully dominated by laser linewidth

Matches Doppler width
with high peak power
→ Saturation of first transition

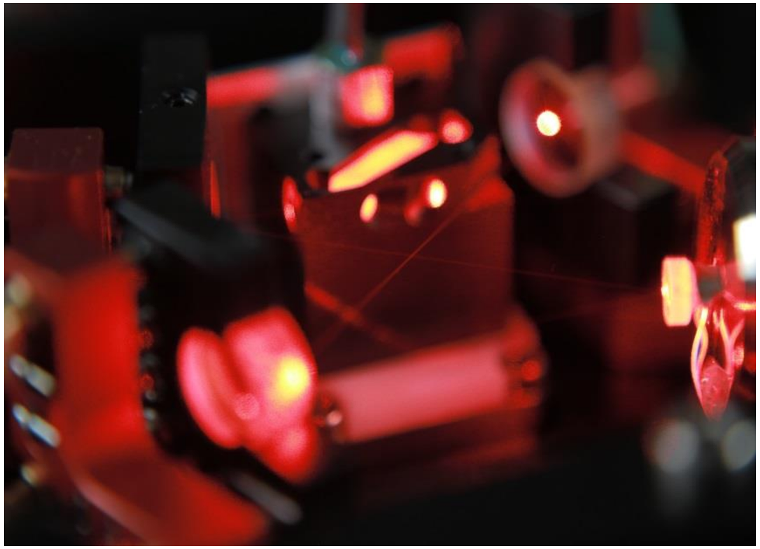
Beryllium cooling laser setup



Ferdinand-Braun-Institute
Berlin



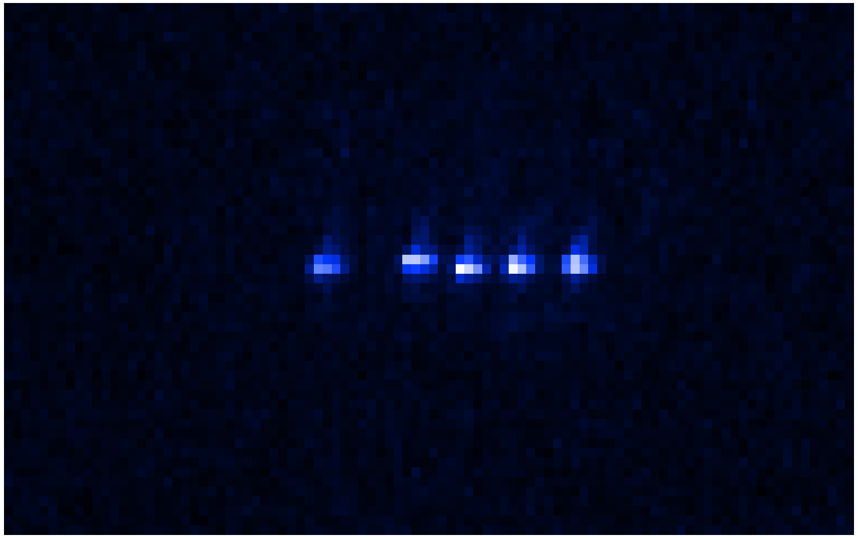
new integrated module
available



~300 μW of 313 nm light

Ion crystals

Be^+ crystals



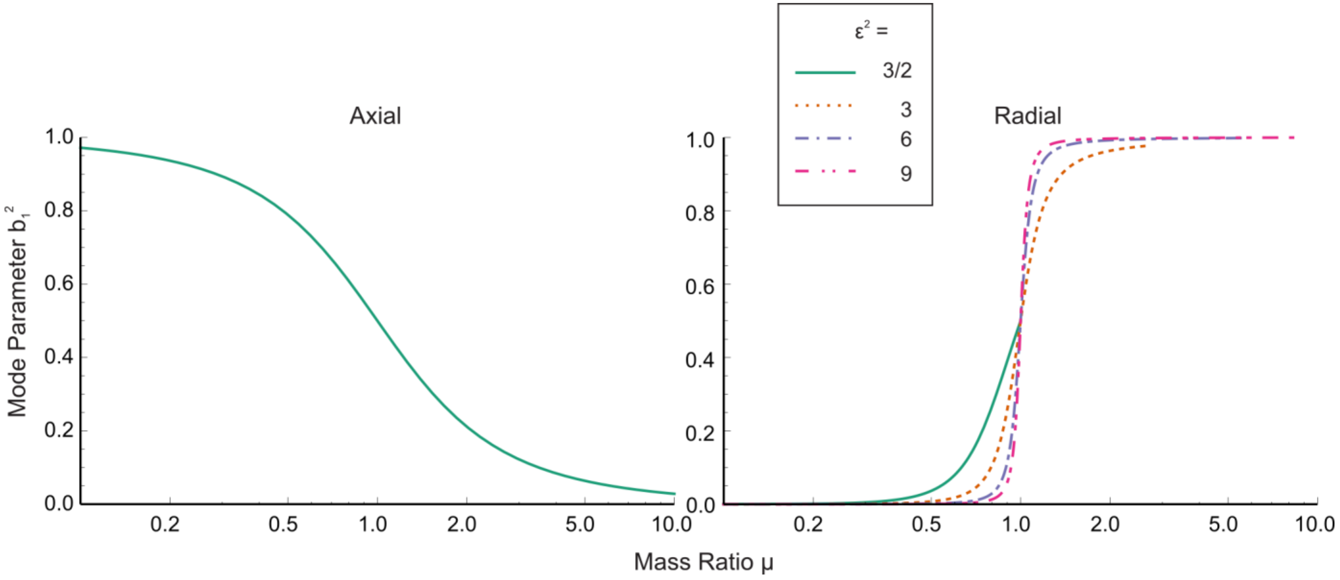
Ca^+ crystal with dark Be^+ ion

Precision trap prerequisits

- ground-state cooling
- adiabatic expansion of axial mode
  → low heating rates for low trap frequencies
- handling of high mass ratio mixed crystals
- side-band spectroscopy to determine temperature

Ca^+-Be^+ ion pairs

- methods optimized mass ratio of $m_{Ca}/m_{Be}=40/9=4.4$
- later address even larger ratio of $m_{Be}/m_H=9/1$



J.B. Wübbena et al.,
Phys. Rev. A 85, 043412 (2012).

Sideband spectroscopy

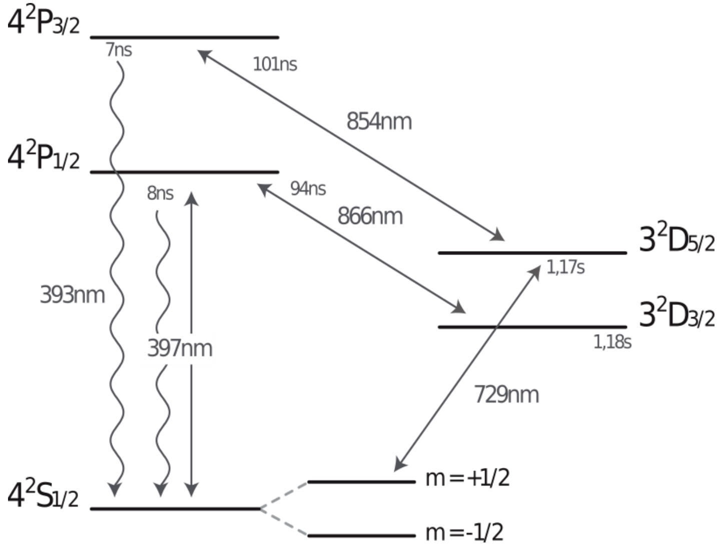
Lamb-Dicke Parameter

$$\eta_{j,\alpha} = \sqrt{\frac{\hbar}{2m_j\omega_\alpha}}\ \boldsymbol{k}\cdot\boldsymbol{e}_{j,\alpha}$$, for ion j and mode α

Lamb-Dicke regime:

$$\eta(2\bar{n}+1) \ll 1$$

J. Home,
Advances In Atomic, Molecular, and Optical Physics. Vol. **62**, 231-277 (2013).



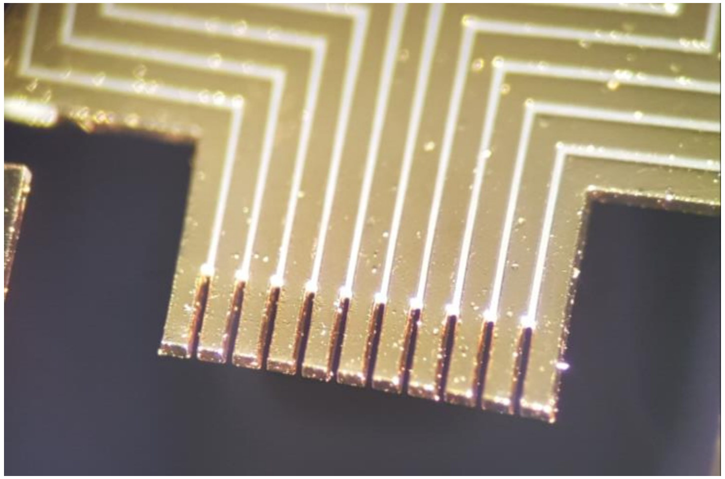
Thermal state:

$$P_n(\bar{n}) = \frac{1}{\bar{n}+1}\left(\frac{\bar{n}}{\bar{n}+1}\right)^n$$

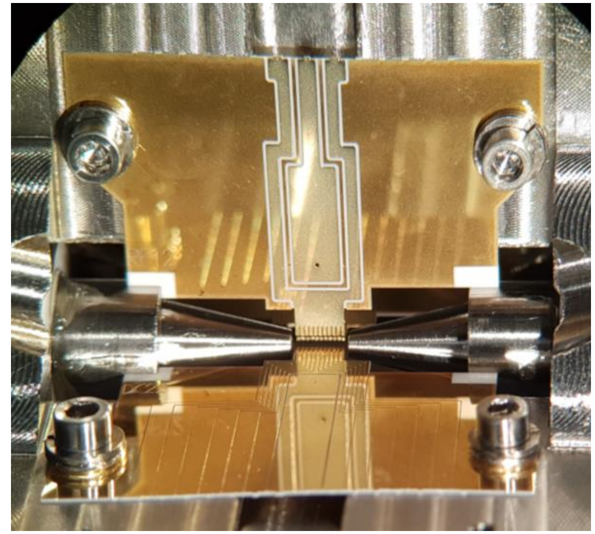
Rabi frequencies:

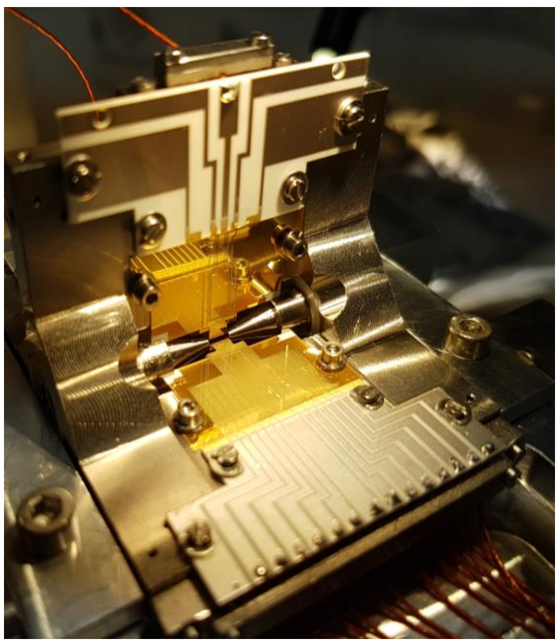
$$\Omega_{carr} = (1-\eta^2\bar{n})\ \Omega_0 + \mathcal{O}(\eta^4)$$
$$\Omega_{rsb} = \eta\sqrt{\bar{n}}\,\Omega_0 + \mathcal{O}(\eta^2)$$
$$\Omega_{bsb} = \eta\sqrt{\bar{n}+1}\,\Omega_0 + \mathcal{O}(\eta^2)$$

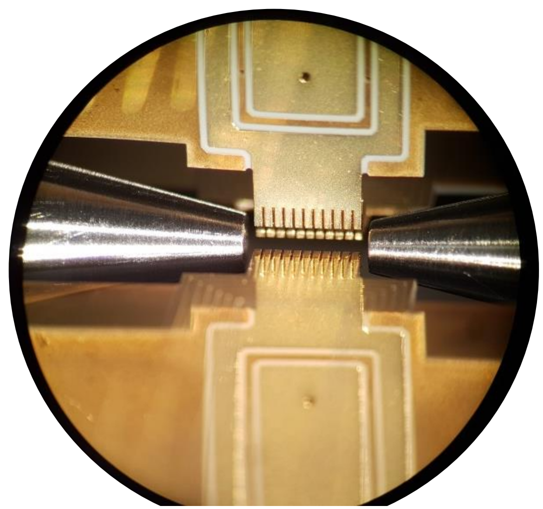
New electroplated trap

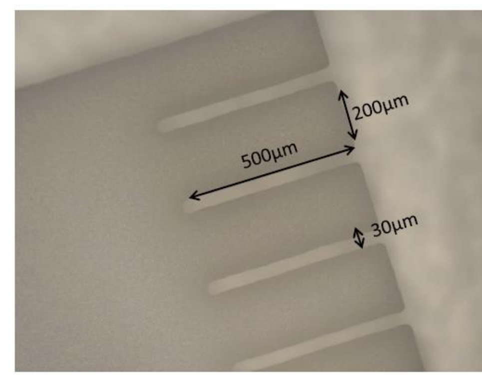


10 µm gold plated on electrodes

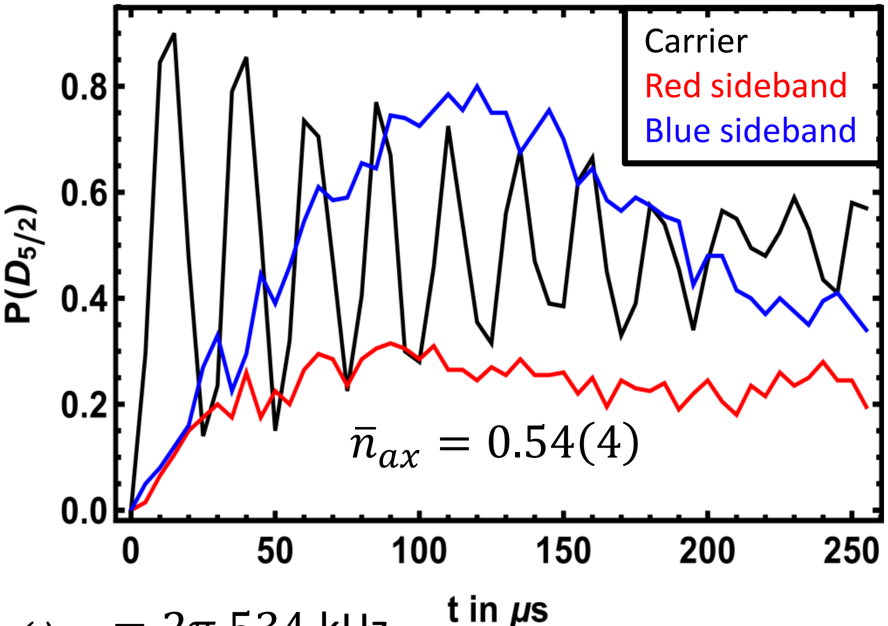


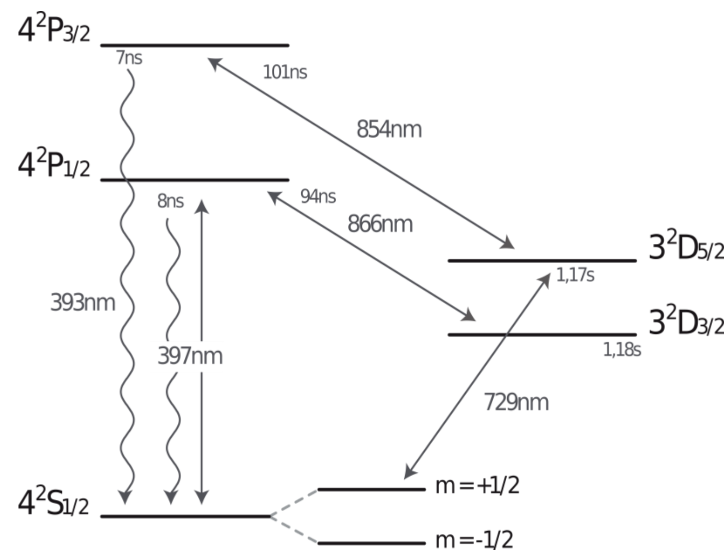




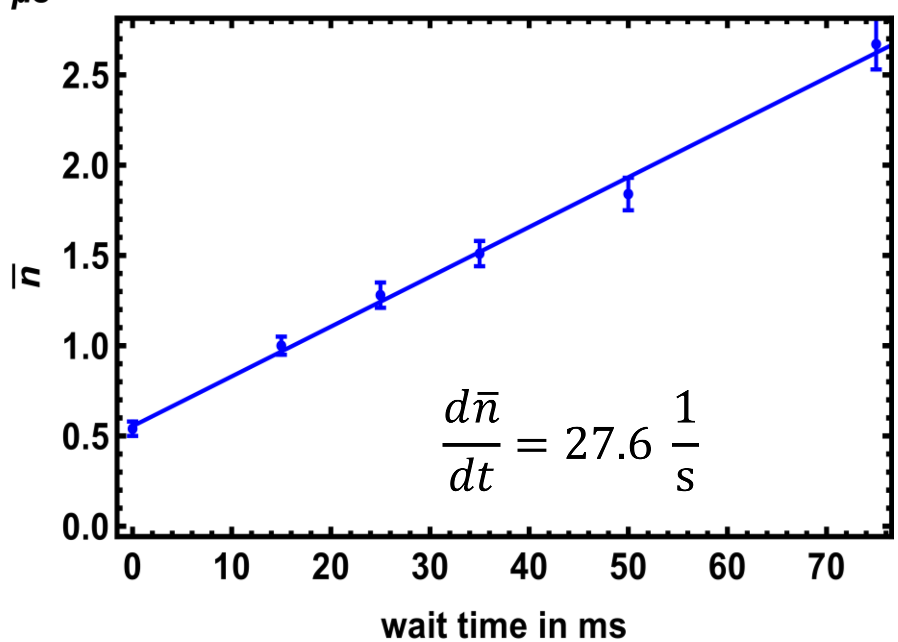


Ground-state cooling of Ca⁺ and heating-rate measurement





$\omega_{ax} = 2\pi$ 534 kHz

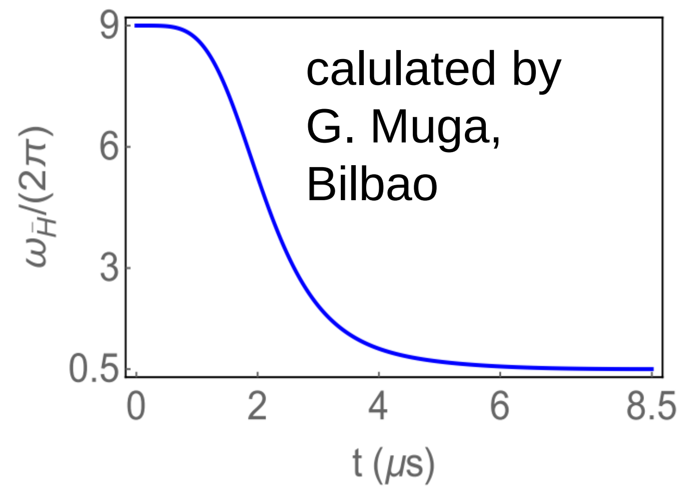


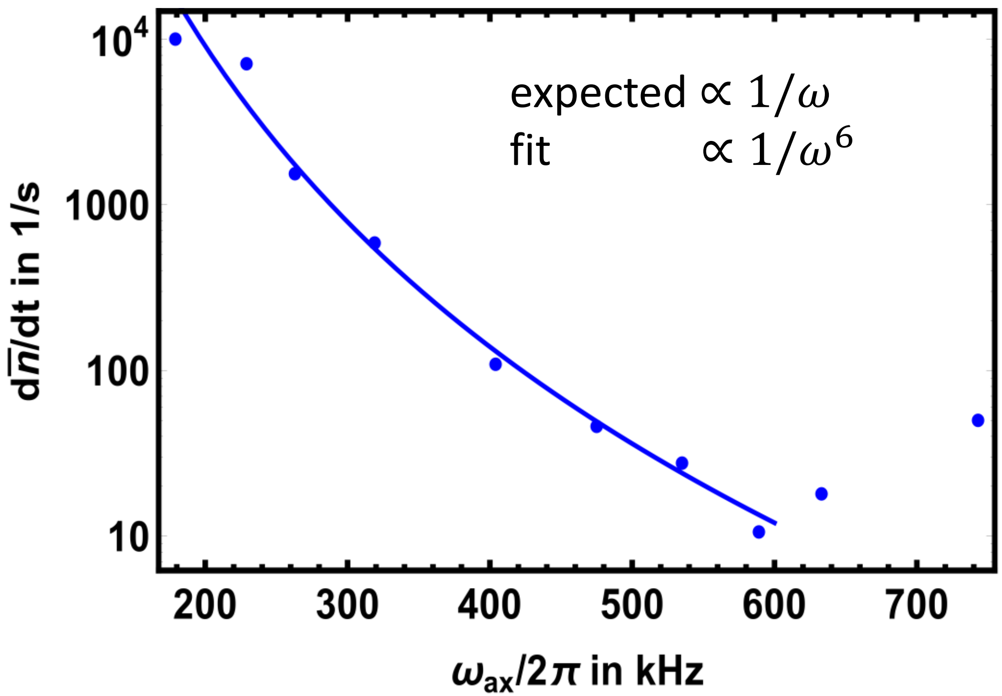
Heating rate against trap frequency

adiabatically lower trap frequency

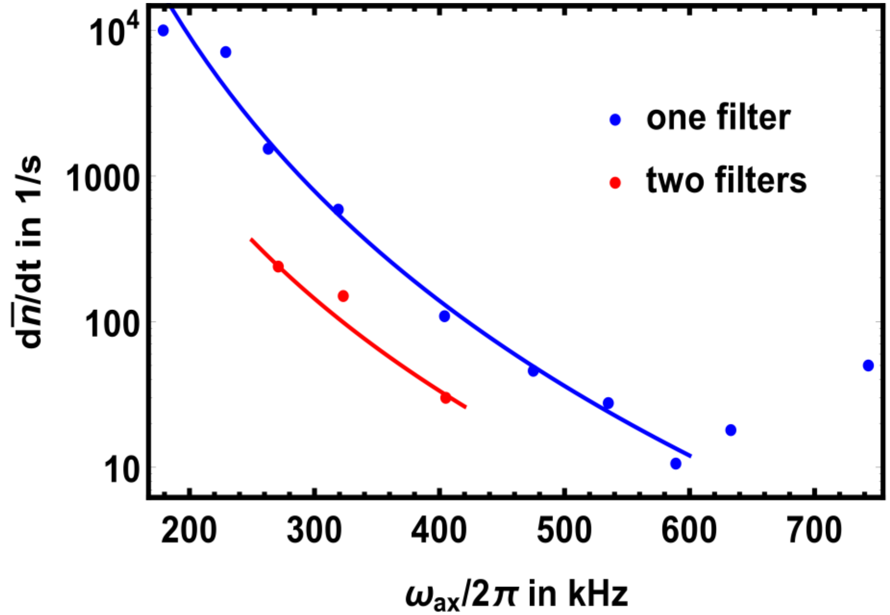
$\omega_{ax}(Ca) = 2\pi$ 500 kHz → 50 kHz

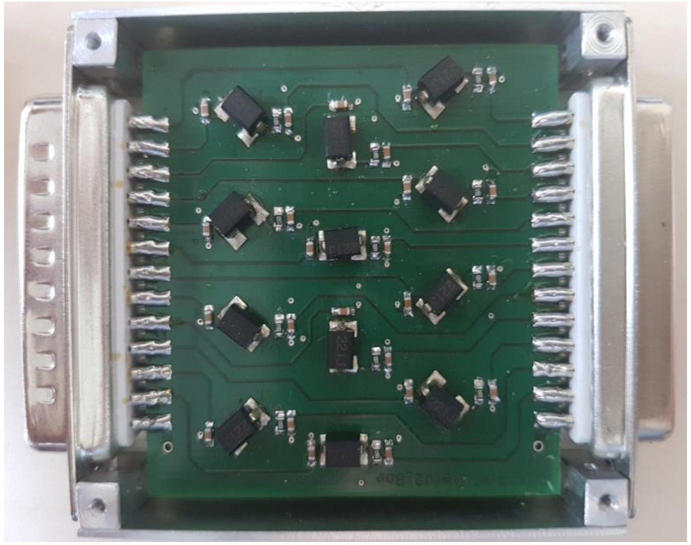
$\sigma_v(\bar{H}) = 1.3$ m/s → 0.4 m/s



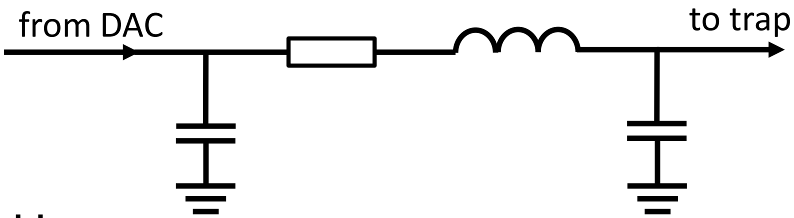


Heating rate against trap frequency



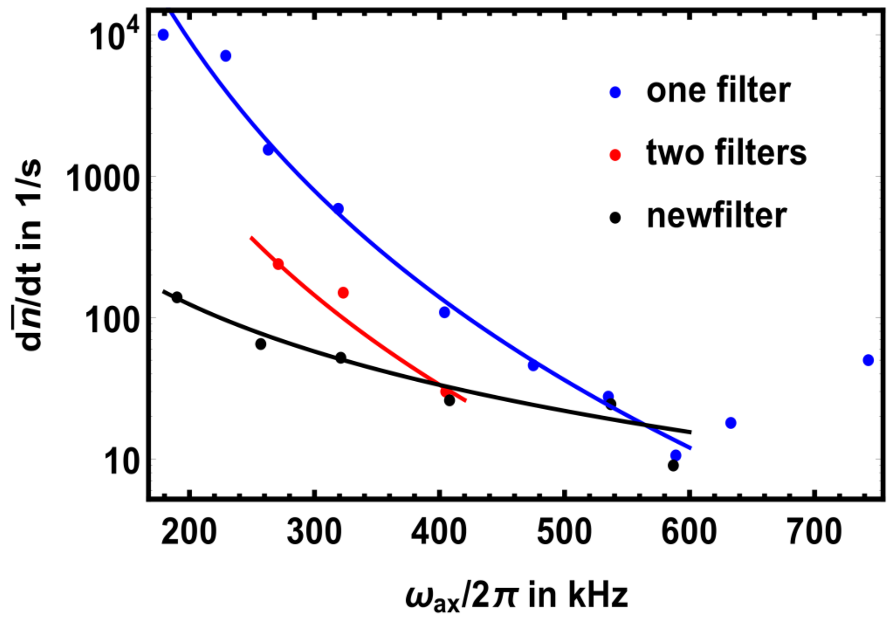


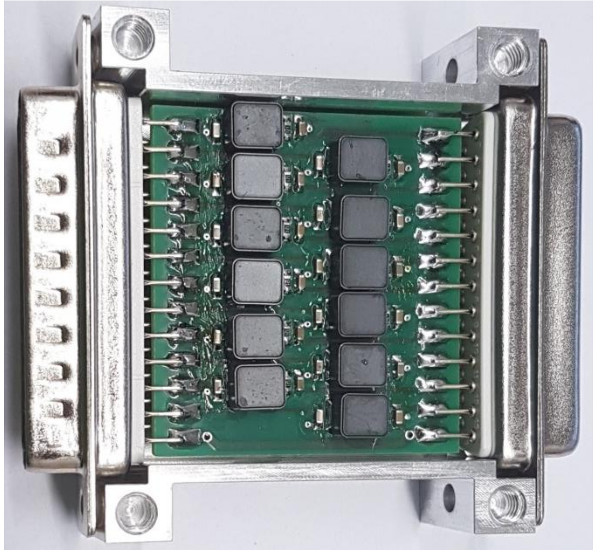
DC-lowpass, CRLC-type, cut-off: 50 kHz



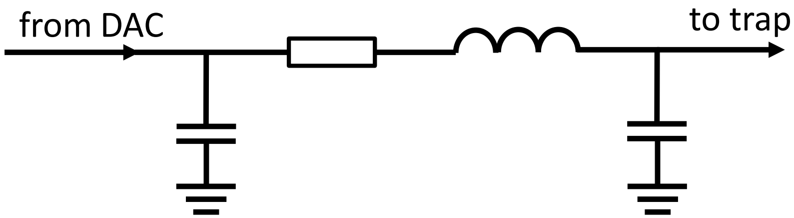
→Design of new filter with cut-off 1kHz

Heating rate against trap frequency



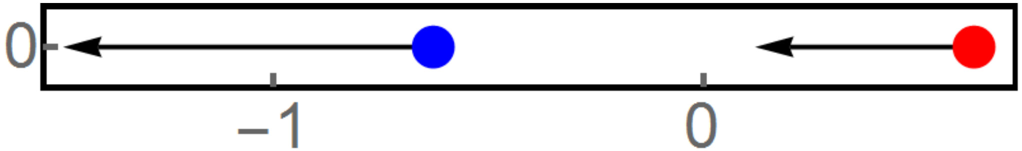


DC-lowpass, CRLC-type,
cut-off: 7 kHz

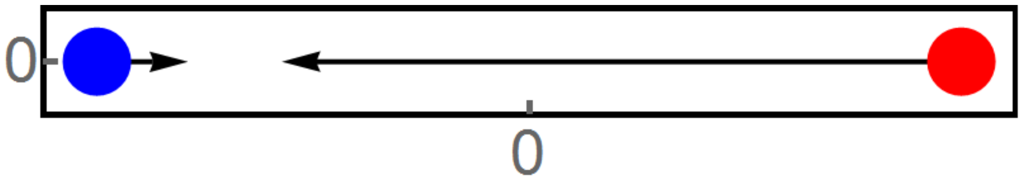


Ca^+-Be^+-ion pair modes

COM $\omega = 2\pi$ 625 kHz



Breathing $\omega = 2\pi$ 1623 kHz

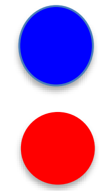


Ca trap frequencies:

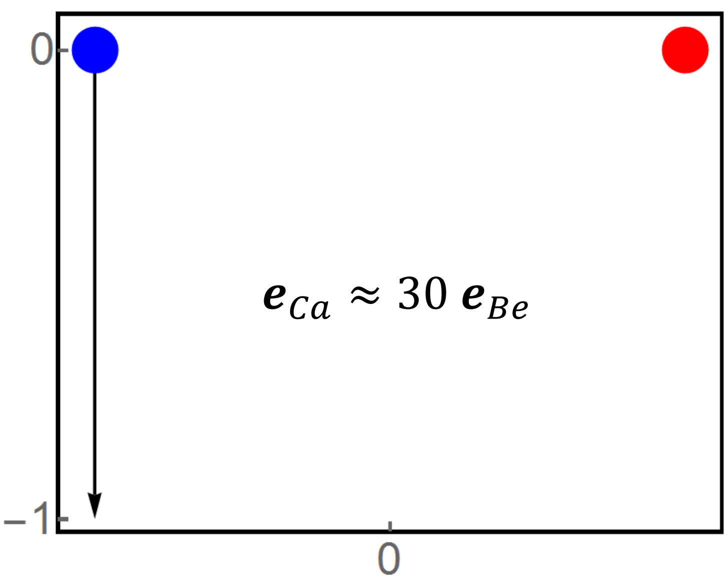
$\omega_{ax} = 2\pi$ 528 kHz

$\omega_{xRad} = 2\pi$ 801 kHz

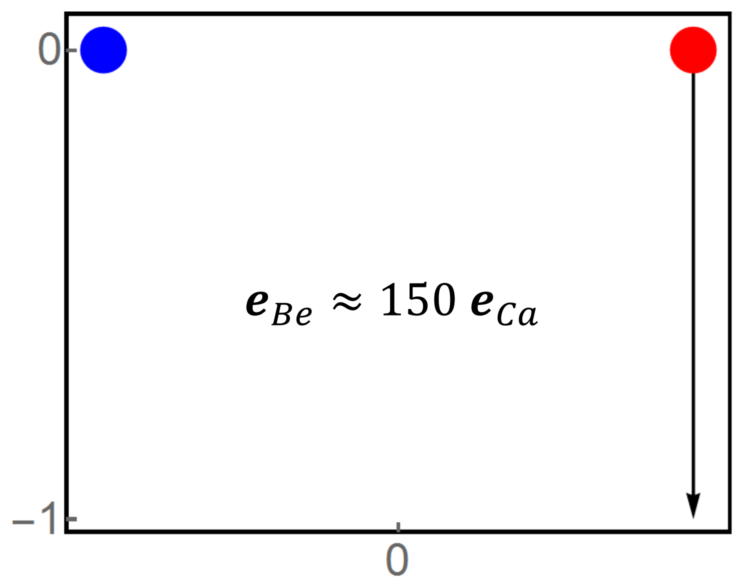
$\omega_{yRad} = 2\pi$ 1017 kHz



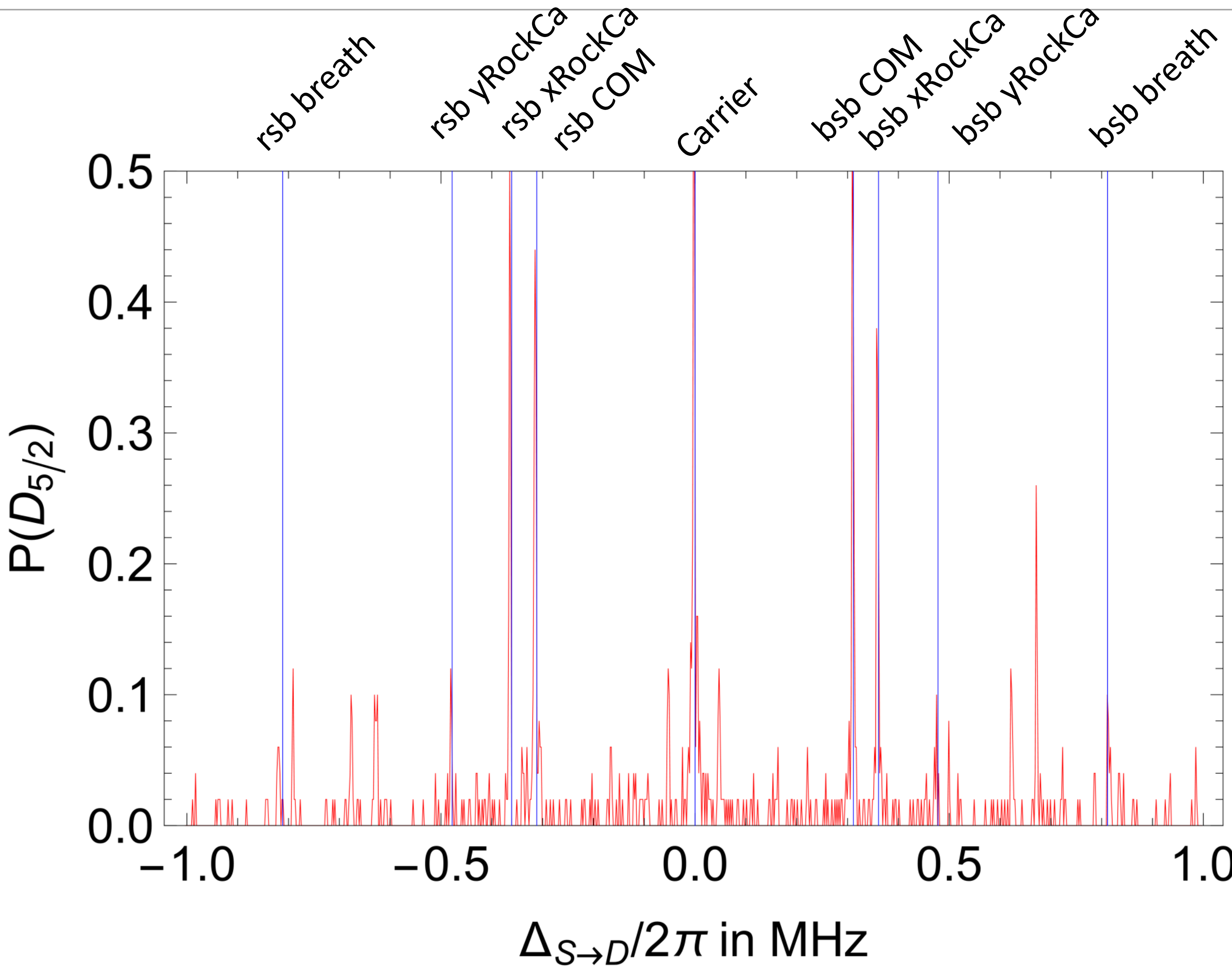
x-/y-RockCa $\omega_x = 2\pi$ 722 kHz, $\omega_y = 2\pi$ 956 kHz



x-/y-RockBe $\omega_x = 2\pi$ 4202 kHz, $\omega_y = 2\pi$ 5328 kHz



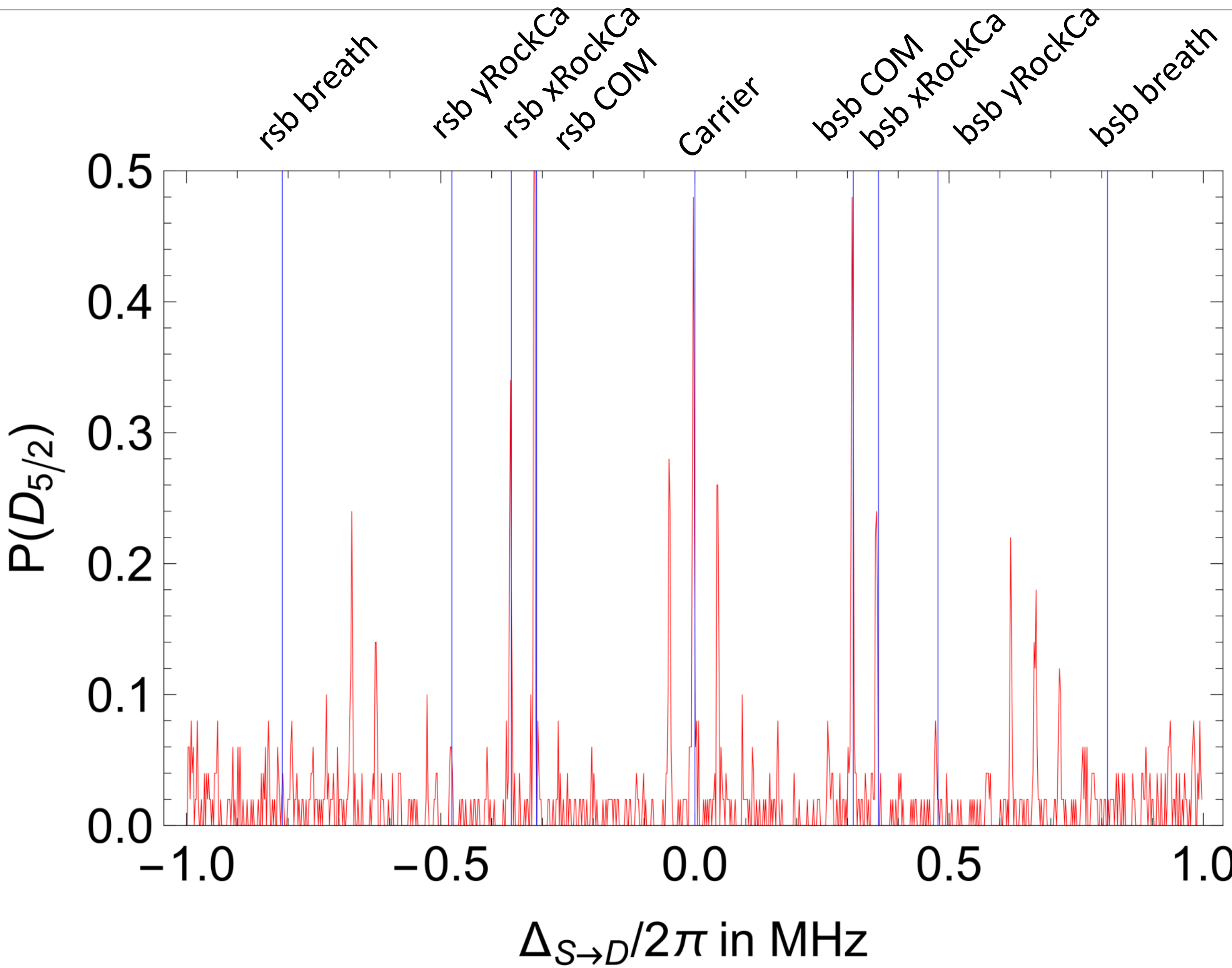
Ionpair spectrum



Ca
doppler cooled

Be
doppler cooled
far detuned

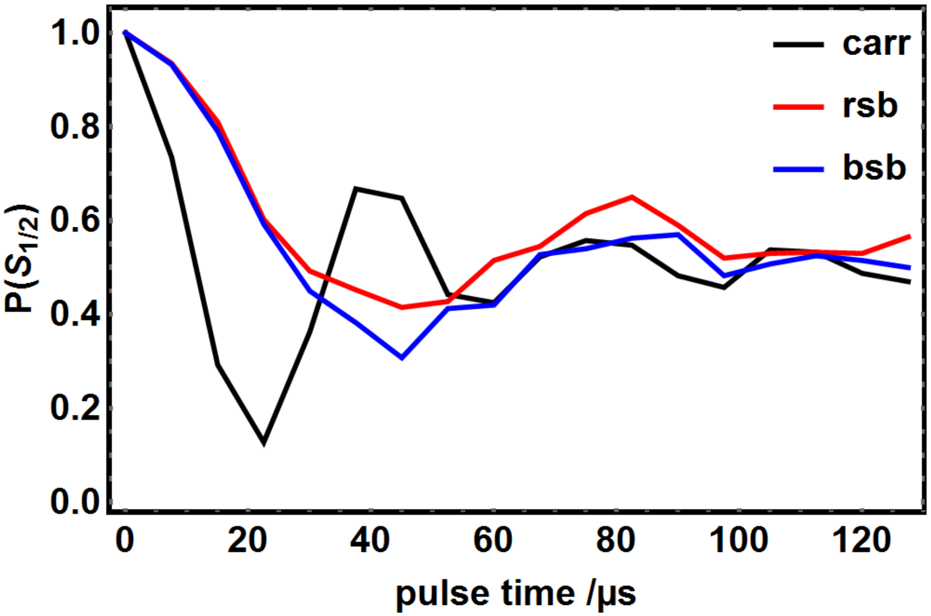
Ionpair spectrum



Ca
doppler off

Be
doppler cooled
optimal
detuning

Mixed crystal temperatures: COM mode



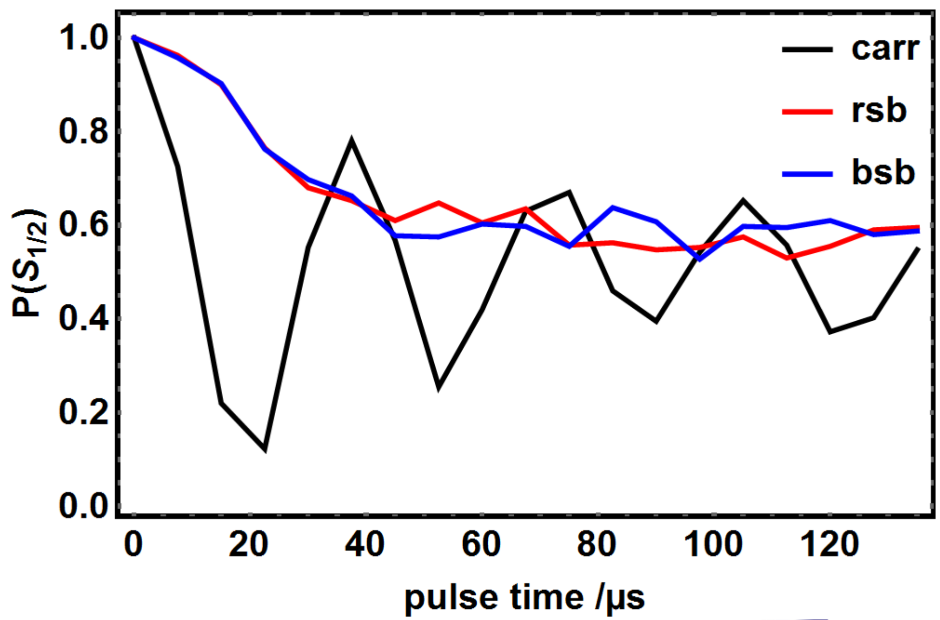
Doppler cooled with on Ca

$$\bar{n} = (35.8 \pm 1.4)$$

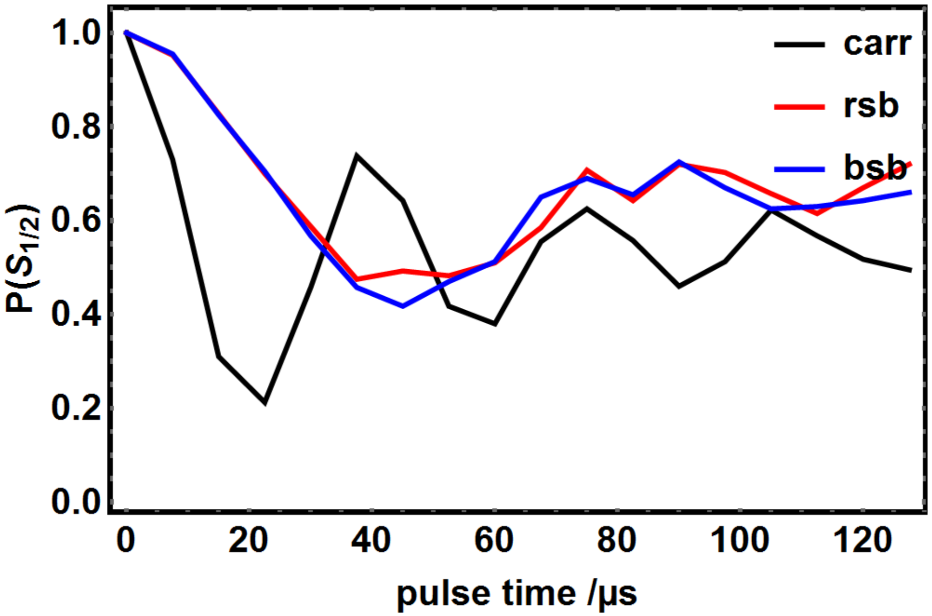
$$\eta = 0.0744$$

SB cooled with 50 pulses
on red sideband

$$\bar{n} = (6.00 \pm 0.45)$$



Mixed crystal temperatures: xRockCa mode



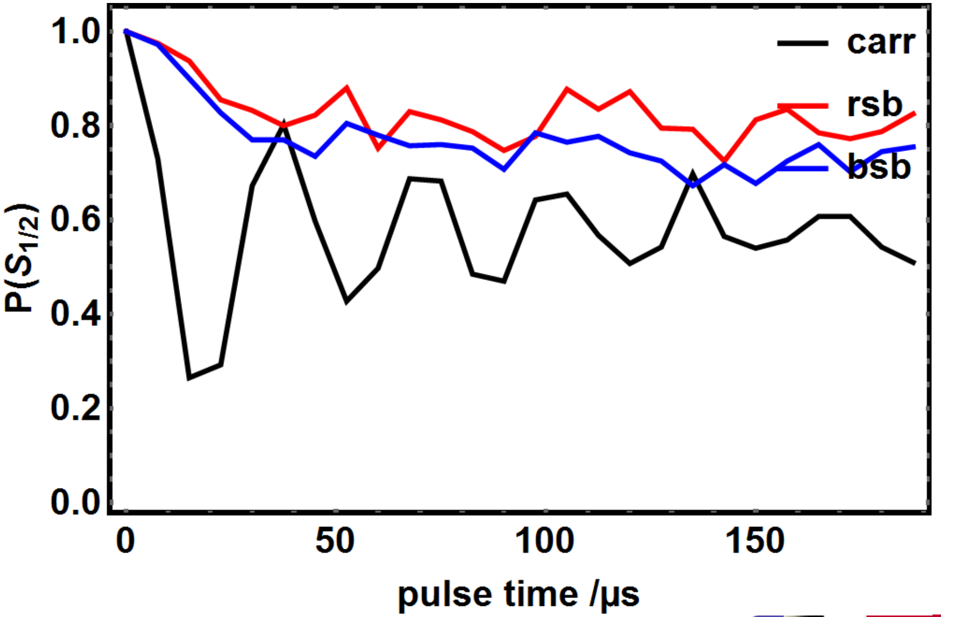
Doppler cooled with on Ca

$\bar{n} = (53.1 \pm 2.3)$

$\eta = 0.0569$

SB cooled with 50 pulses on red sideband

$\bar{n} = (1.23 \pm 0.08)$



Outlook

- optimize mixed crystal spectroscopy and cooling
- optimize adiabatic opening with
  - single ion
  - two ions
  - mixed crystal
- setup capture trap
- inject p^+, H_2^+, HD^+, D_2^+ into capture trap filled with Be^+
  - ➢ investigate & optimize trapping & sympathetic cooling offline