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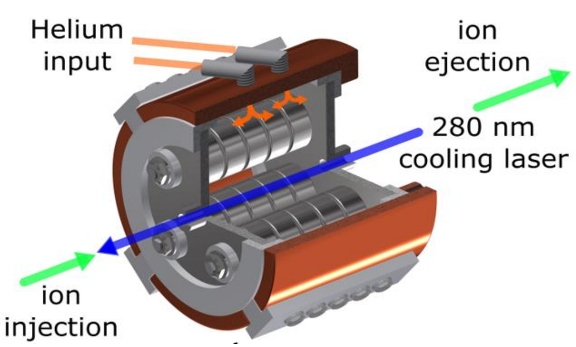
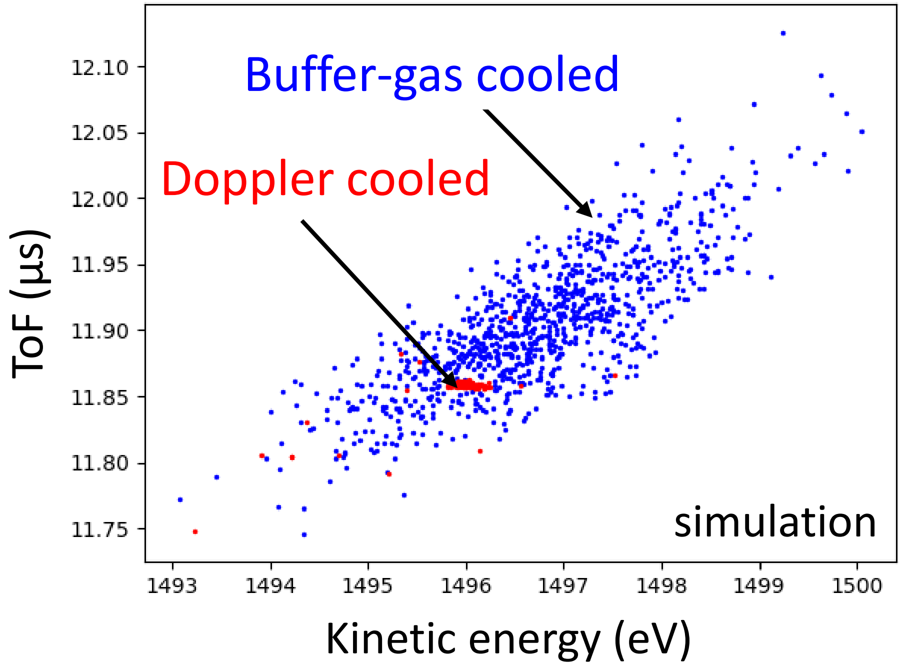
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

# Doppler- and sympathetic cooling for the investigation of short-lived radionuclides

Paul trap:




S.Sels, F.Maier et al. *Doppler- and sympathetic ion cooling for the investigation of short-lived radionuclides.* Accepted in Phys. Rev. Research, 2022.




MIRACLS

## Franziska Maier

CERN PhD Student

CERN

# Radioactive Ion Beam Facilities

Production@ISOLDE:

- ~1000 different isotopes
- ~75 different elements
- Half-life: 1 ms – stable

→ Mass separation, cooling and bunching

→ Mass Spectrometry
Laser Spectroscopy
…

↓

Nuclear ground state properties:

- binding energies
- mass
- nuclear moments
- spin
- charge radii

…

↓

Benchmark for modern nuclear theory

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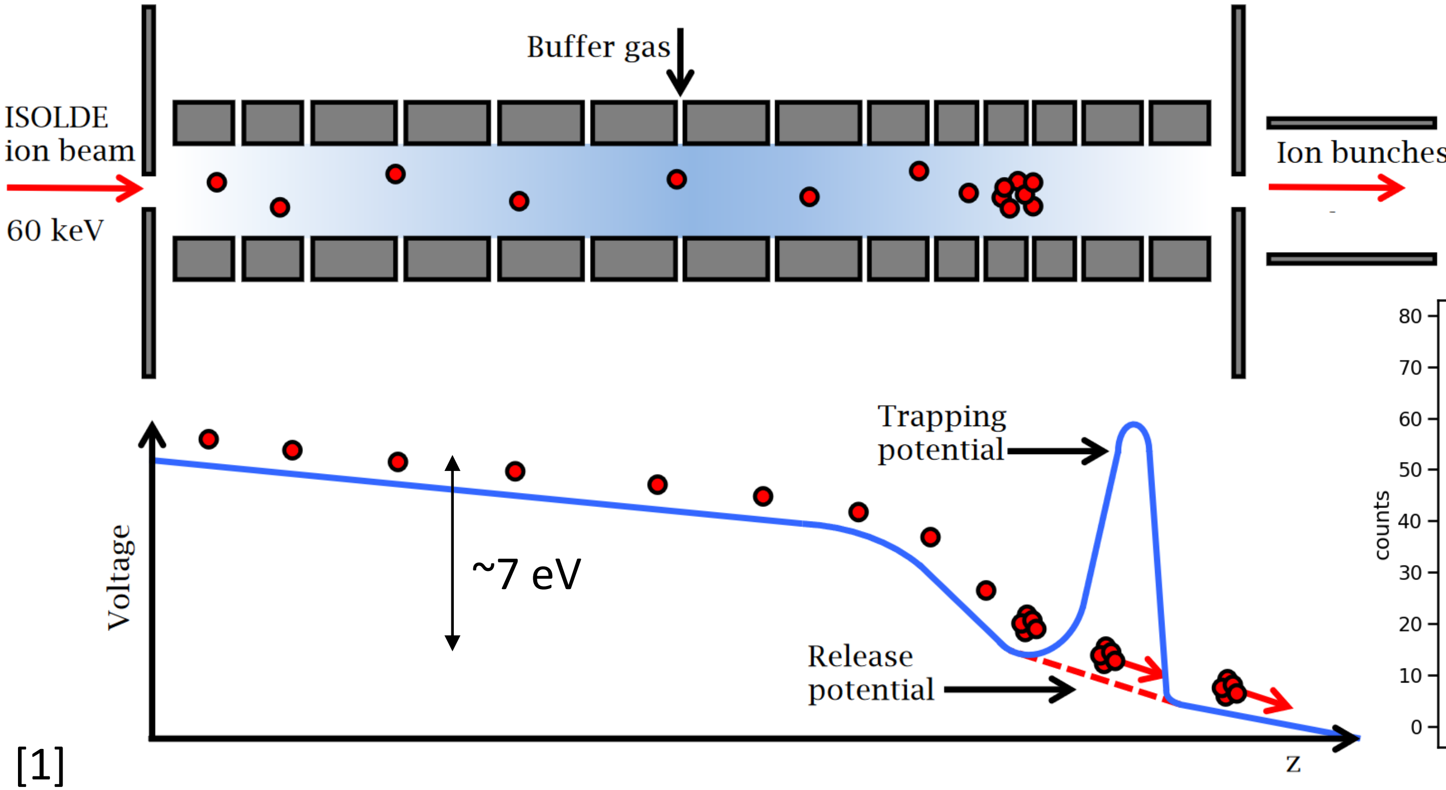
…

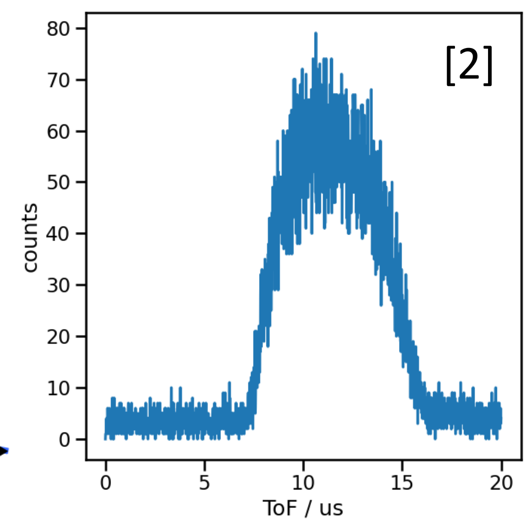
Benchmark for modern nuclear theory

# Buffer-gas filled Paul traps

Commonly operated at 300-K buffer gas → Cooling limit: 300 K



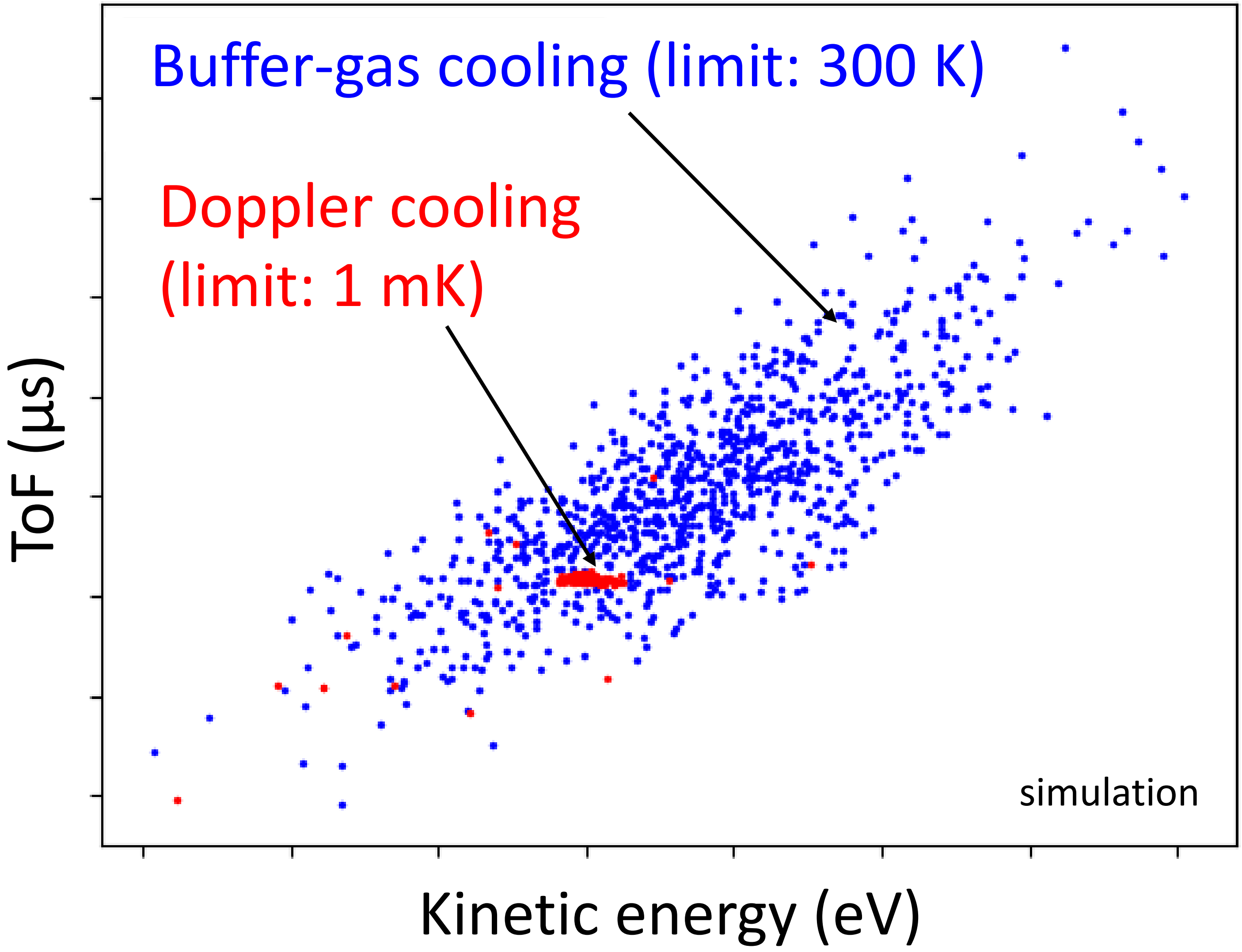

[1]




[1] K. Lynch, PhD thesis, University of Manchester, 2013.

[2] Sb run COLLAPS, 2018.

# Doppler Cooling

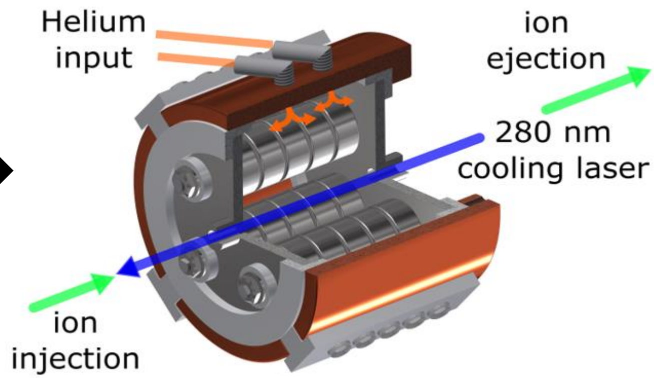


# Doppler Cooling at RIB Facilities

- Specific applications with RIBs [1]
- unexplored as cooling technique to deliver high quality RIBs

External ion source

‘hot’ ions with at least 7eV




Downstream experiments

300 K (up to now)
< 6 K (this work)
< 1 mK (limit)

[1]
G. D. Sprouse and L. A. Orozco, Annu. Rev. Nucl. Part. Sci.. 47, 429 (1997)
J. A. Behr et al., Phys. Rev. Lett. 79, 375 (1997).
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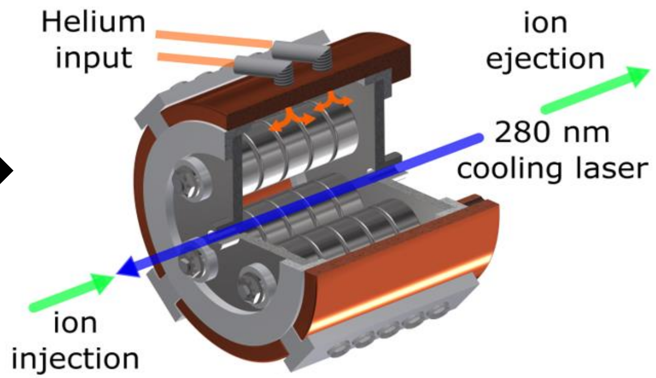


Downstream experiments

300 K (up to now)
< 6 K (this work)
< 1 mK (limit)

- This work: Demonstration that laser cooling is
  - ... compatible with $T_{1/2}$
  - ... compatible with existing instrumentation at RIB facilities
  - ... universally applicable (via sympathetic cooling)
  - ... improving precision and/or sensitivity of various experimental RIB techniques


[1]
G. D. Sprouse and L. A. Orozco, Annu. Rev. Nucl. Part. Sci.. 47, 429 (1997)
J. A. Behr et al., Phys. Rev. Lett. 79, 375 (1997).
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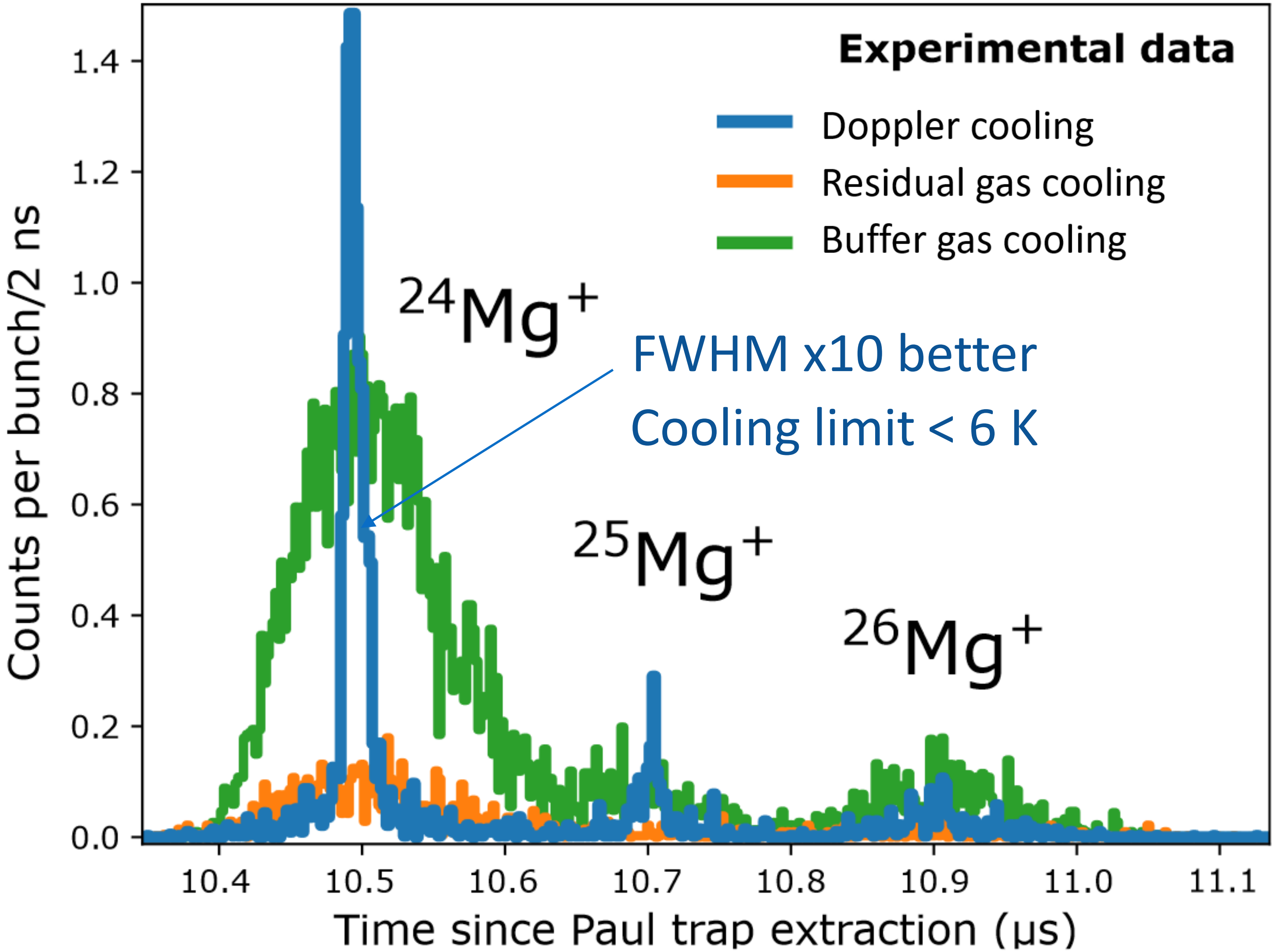
# Experimental results

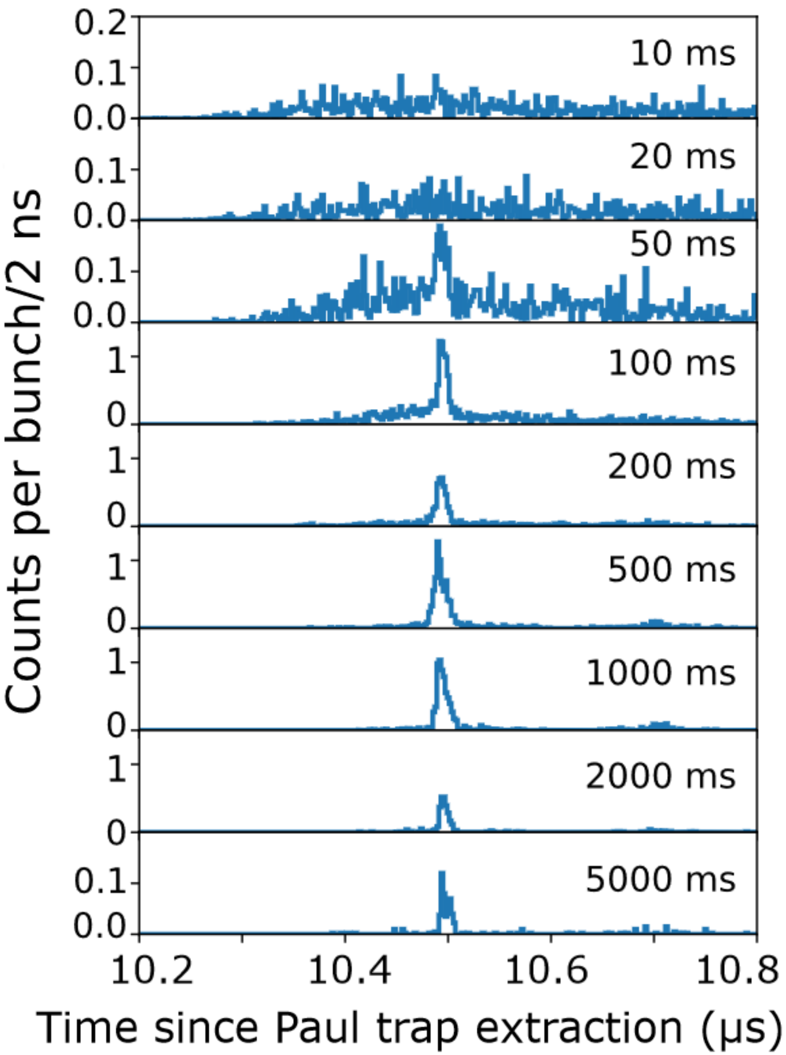


# Needed cooling time is compatible with $T_{1/2}$.

Experiment:

- ➢ 1e-5 to 1e-8 mbar residual gas present within Paul trap
- ➢ cooling time ≈ 100 ms

3 mW & -200 MHz detuning, varying cooling times:



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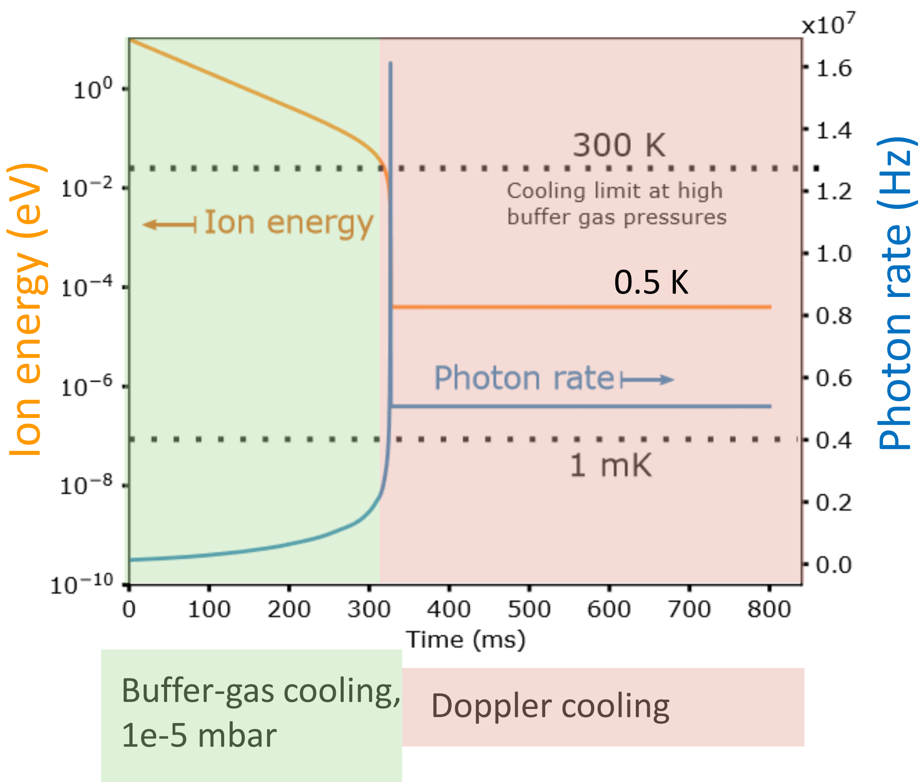
Simulations + numerical model:

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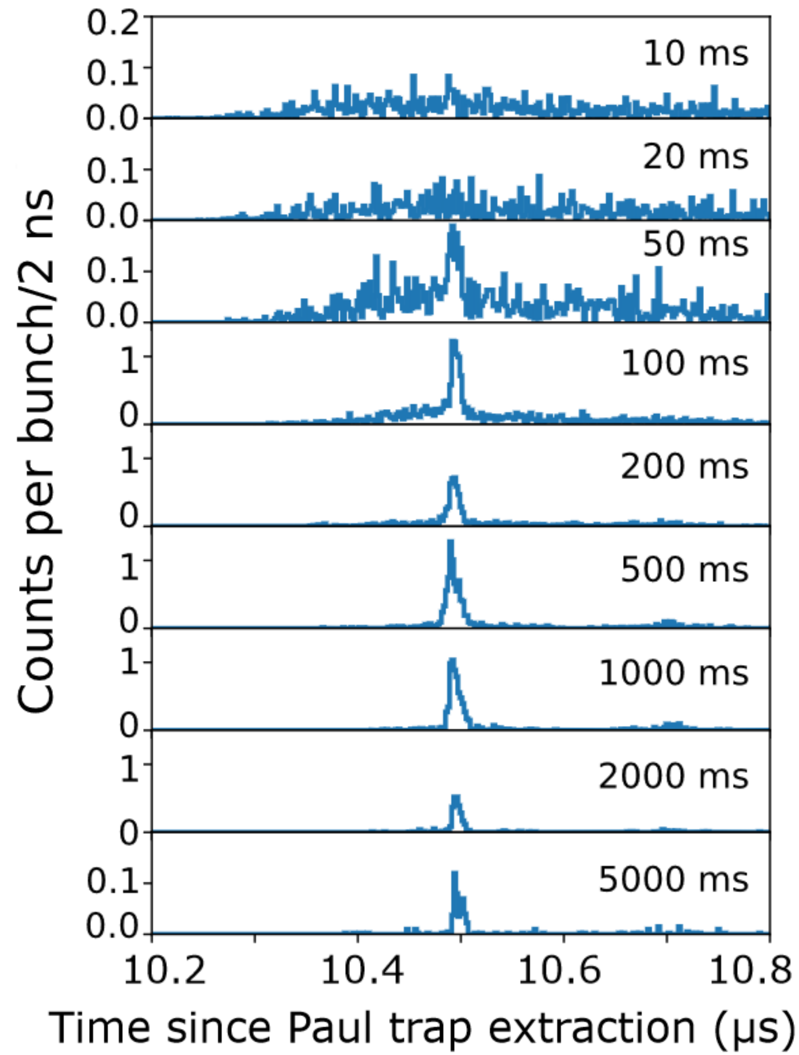


# Needed cooling time is compatible with $T_{1/2}$.

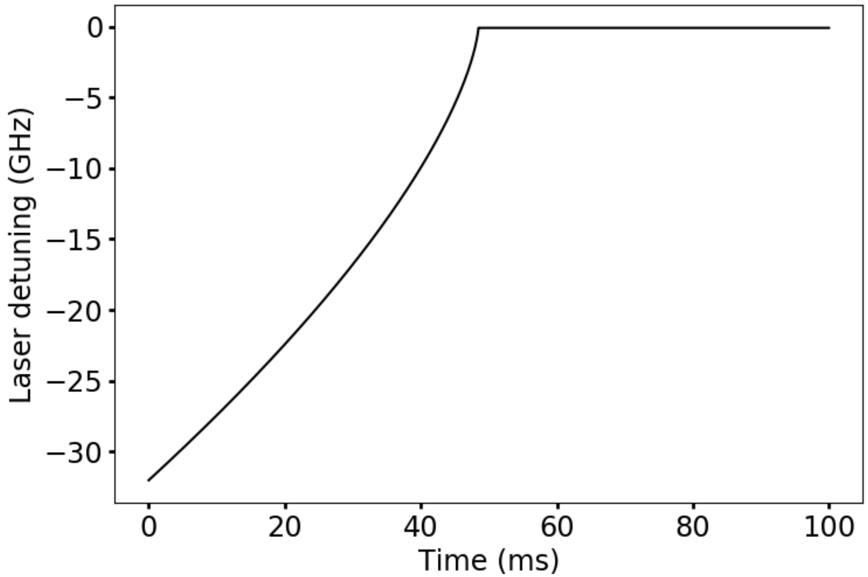
Experiment:

- 1e-5 to 1e-8 mbar buffer gas present within Paul trap
- cooling time ≈ **100 ms** (T < 6 K)

Numerical model:

- No buffer gas present (T ≈ 1 mK)
  - Fixed laser frequency: cooling time **> 100 s**
  - Laser frequency matching to ions' velocity distribution: cooling time **< 50 ms**

*Optimal laser-frequency detuning for cooling down a 10-eV $Mg^+$ ion in absence of a buffer gas*



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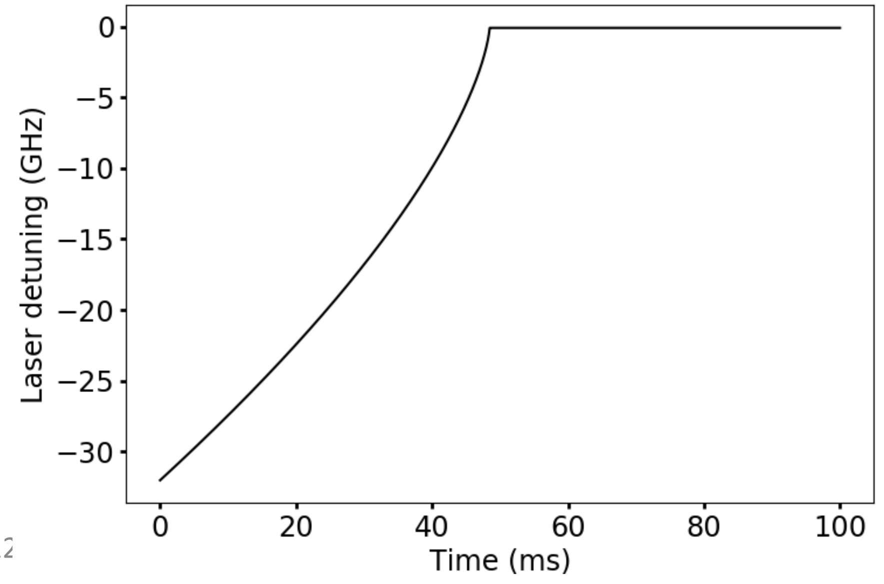
Numerical model:

- No buffer gas present (T ≈ 1 mK)
  - Fixed laser frequency: cooling time **> 100 s**
  - Laser frequency matching to ions' velocity distribution: cooling time **< 50 ms**
- 1e-5 mbar buffer gas present: (T ≈ 0.5 K)
  - Fixed laser frequency: cooling time ≈ **300 ms**

Presence of buffer gas speeds up the cooling, but limits achievable temperature.

⇨ Optimal setup: multi-stage Paul trap

*Optimal laser-frequency detuning for cooling down a 10-eV $Mg^+$ ion in absence of a buffer gas*



# Sympathetic cooling

… extends the availability of cold ion ensembles to ionic systems which cannot be directly laser-cooled.

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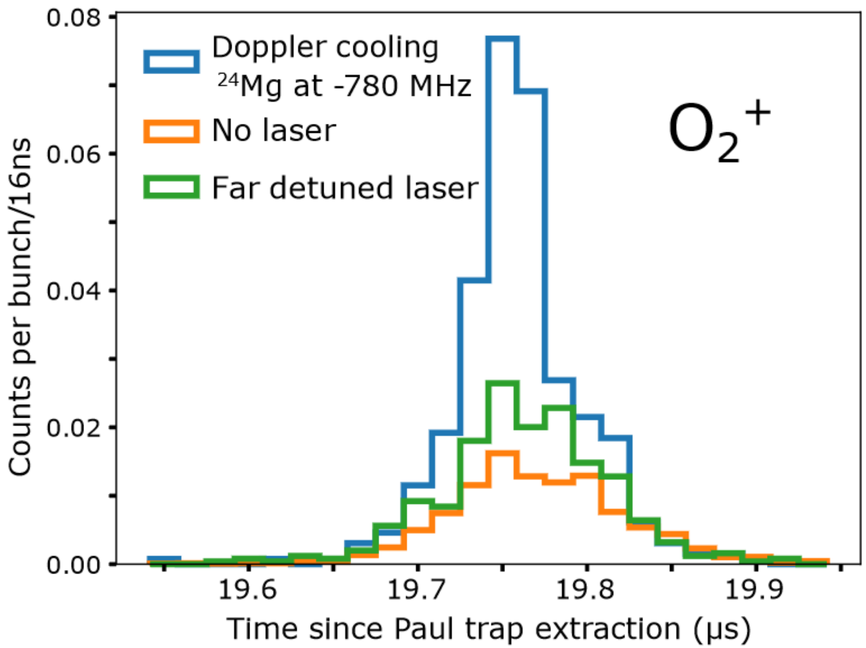
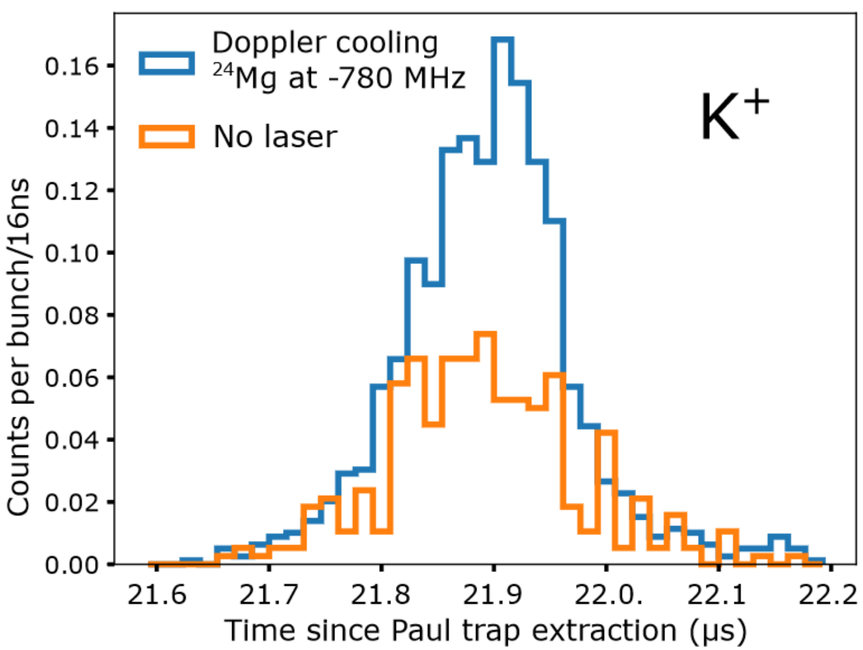


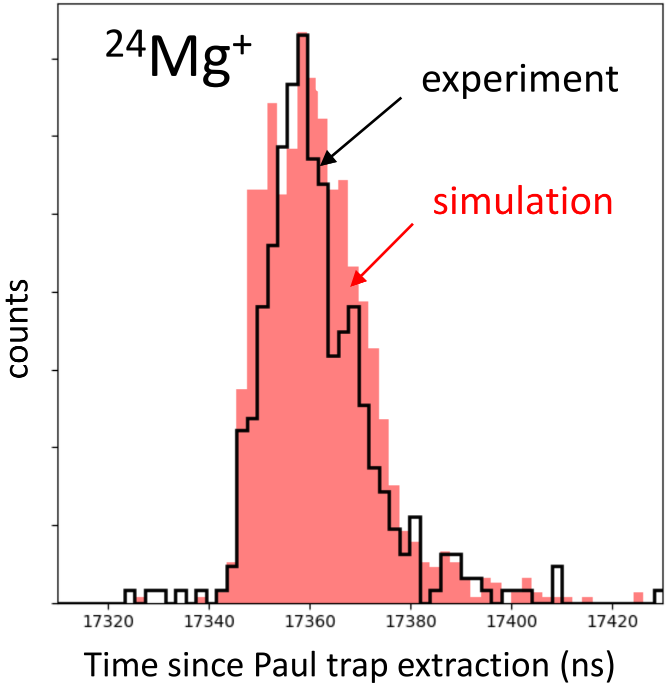

| | $O_2^+$ | $K^+$ |
|---|---|---|
| Peak width residual-gas or buffer-gas cooling | 113(5) ns | 180(13) ns |
| Sympathetic cooling | 58(4) ns | 145(5) ns |
| Improvement in countrate | Factor 2.6 | Factor 2 |

Can be done better analogous to existing work, e.g. [1],[2].


[1] J. Wuebbena et al, Phys. Rev. A 85, 043412,2012.
[2] M. Guggemos. New Journal of Physics 17, 103001, 2015.

# Doppler cooling allows simultaneously small Dt & DE.

Doppler cooling:



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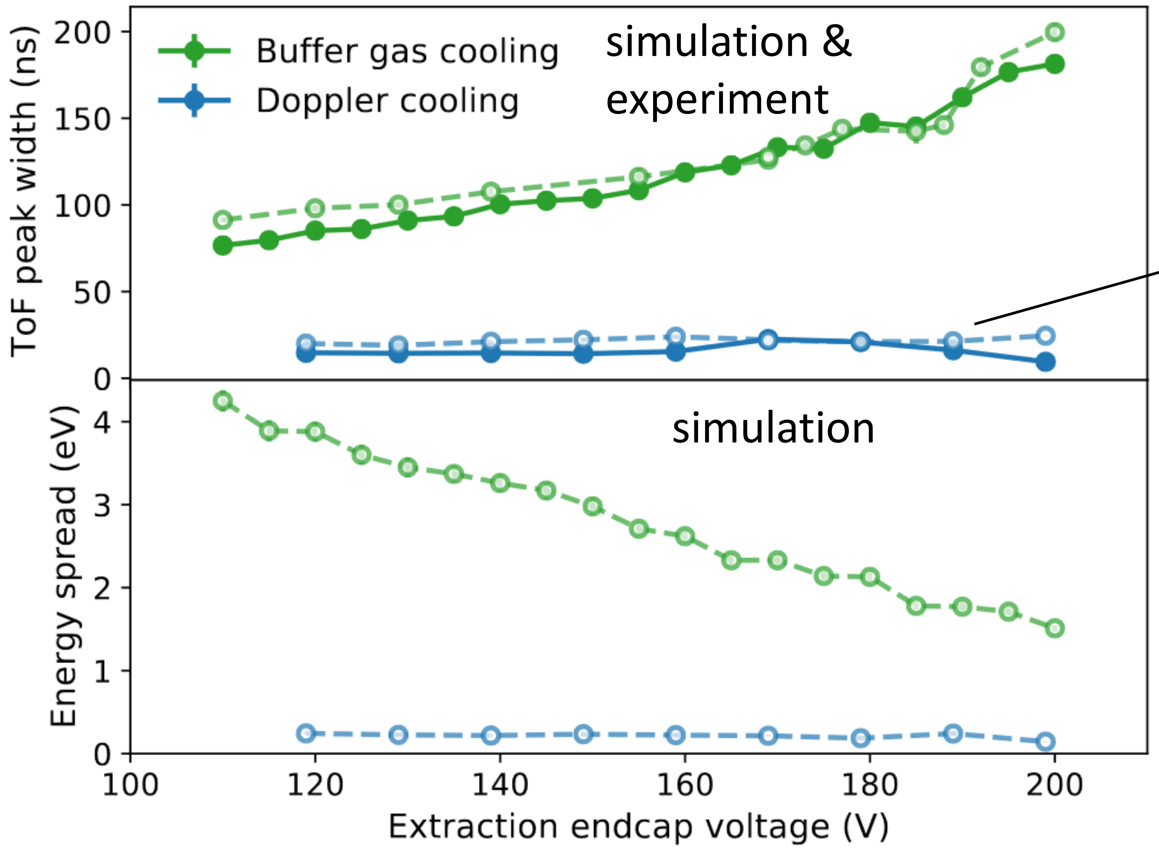
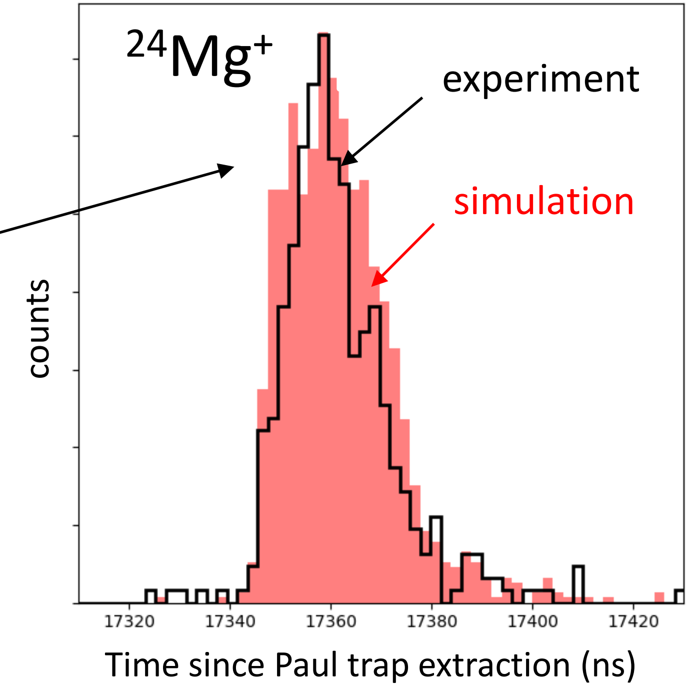



Doppler cooling:



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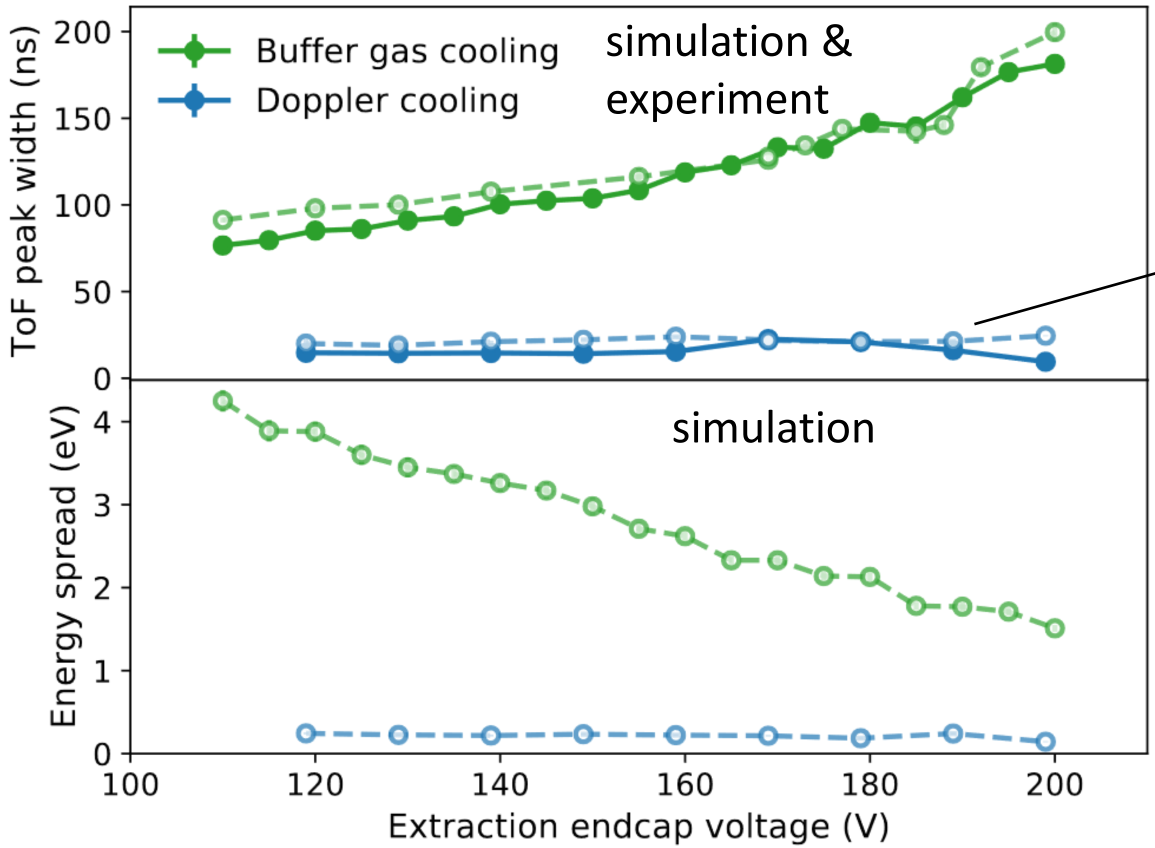


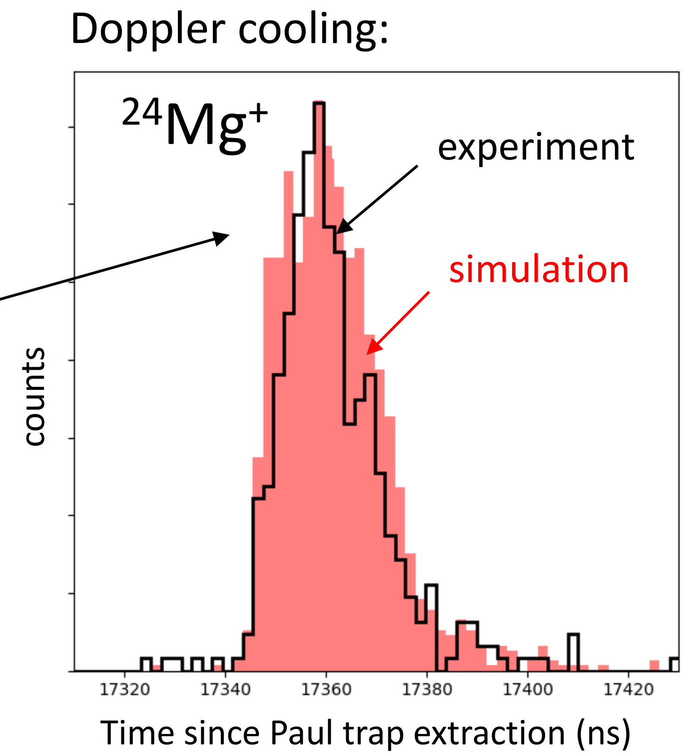


**→ Improvements in precision and/or sensitivity for various experimental techniques such as collinear laser spectroscopy or mass spectrometry**

# Applications at RIB facilities

- Improved mass resolution in MR-ToF devices
- Increased precision for mass measurements in Penning traps
- Increased sensitivity for collinear laser spectroscopy
- Cooling option for radioactive molecules for fundamental physics research
- Preparation step for high precision laser spectroscopy (king plot non-linearities)

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New publication: S. Sels, F. Maier et al. *Doppler- and sympathetic ion cooling for the investigation of short-lived radionuclides.* Accepted in Phys. Rev. Research, 2022.

# Improved R in MR-ToF devices

Multiple revolutions in MR-ToF device

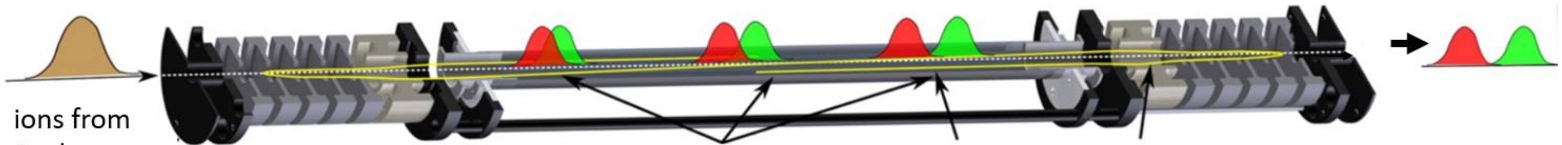
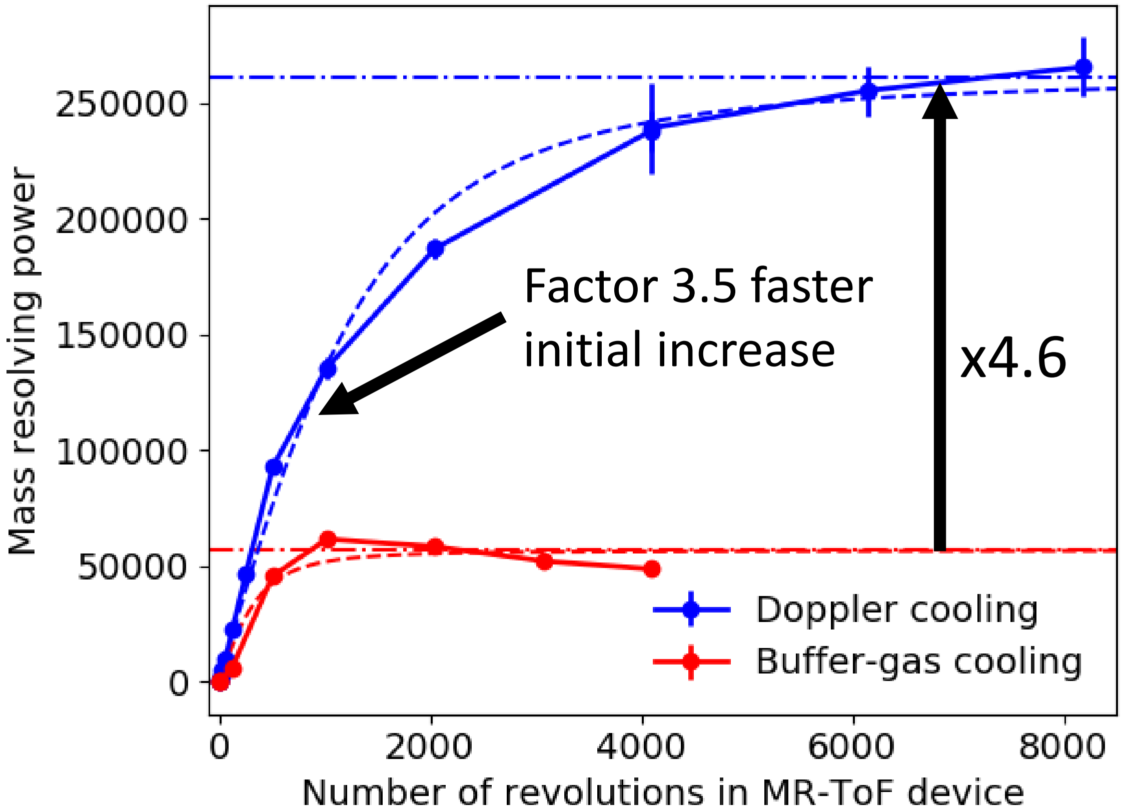
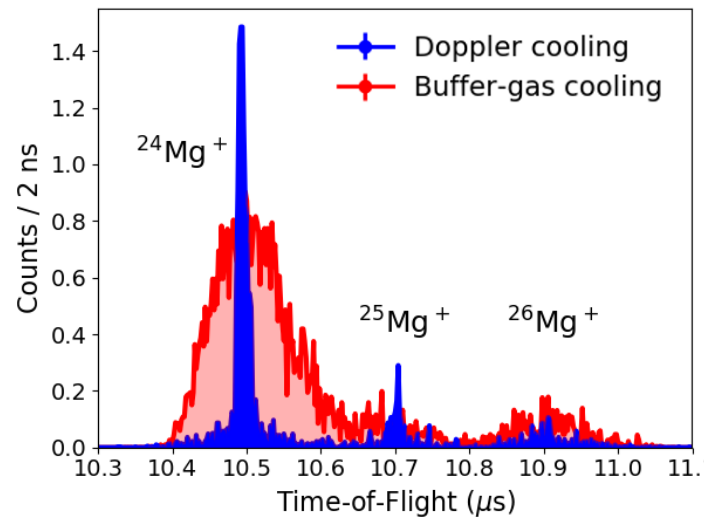



Fig. mod. from R.N. Wolf et al. Int. J. Mass Spectrom., 349-350:123 – 133 (2013).




$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$



# Summary & Outlook

Demonstration that laser cooling is

... compatible with $T_{1/2}$

... compatible with instrumentation at RIB facilities

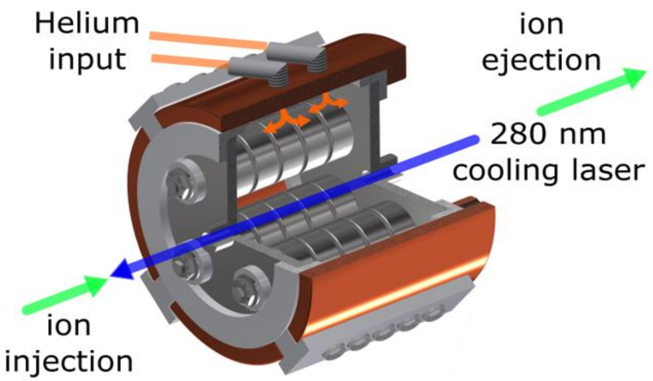
... universally applicable (via sympathetic cooling)

to deliver low-emittance beams

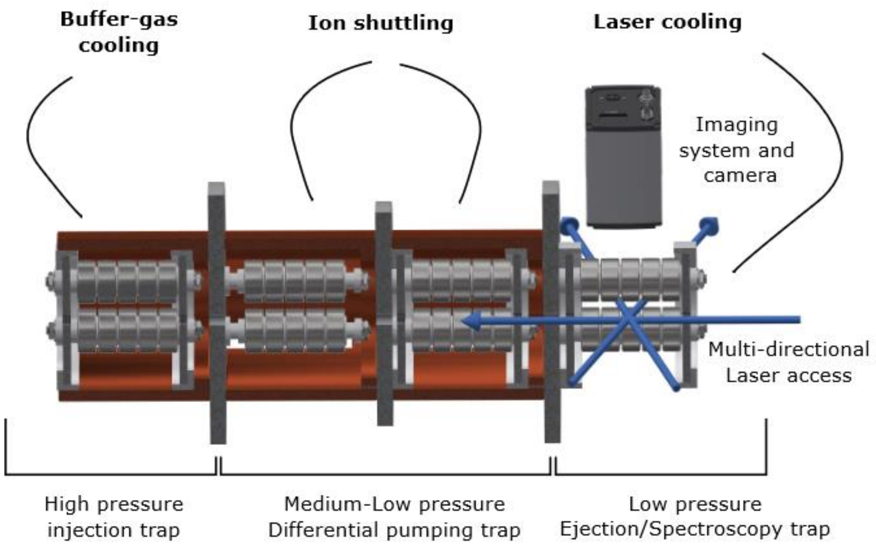
Envisioned applications at RIB facilities:

- Improved mass resolution in MR-ToF devices
- Increased precision for mass measurements in Penning traps
- Increased sensitivity for collinear laser spectroscopy
- Cooling option for radioactive molecules for fundamental physics research
- Preparation step for high precision laser spectroscopy (king plot non-linearities)

Current setup:




improved setup: multi-stage Paul trap:



# Thanks!

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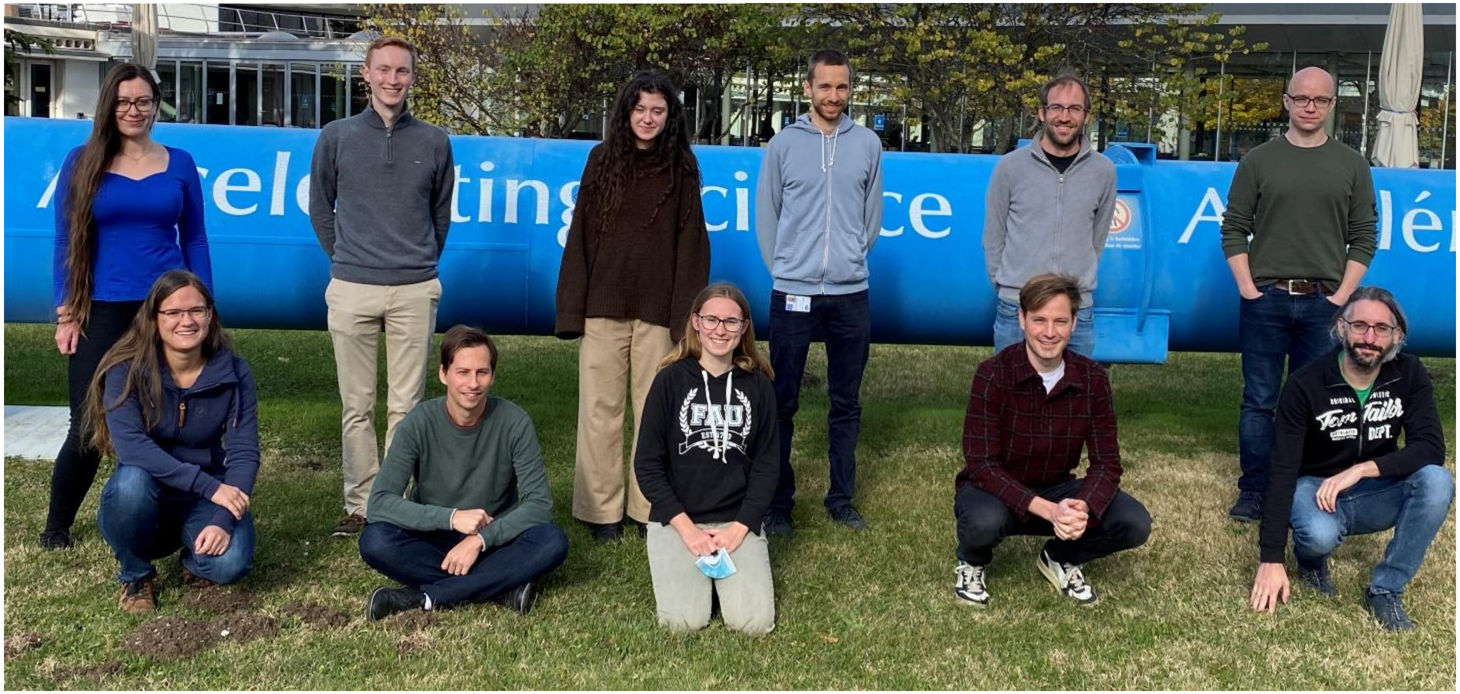
https://miracls.web.cern.ch/

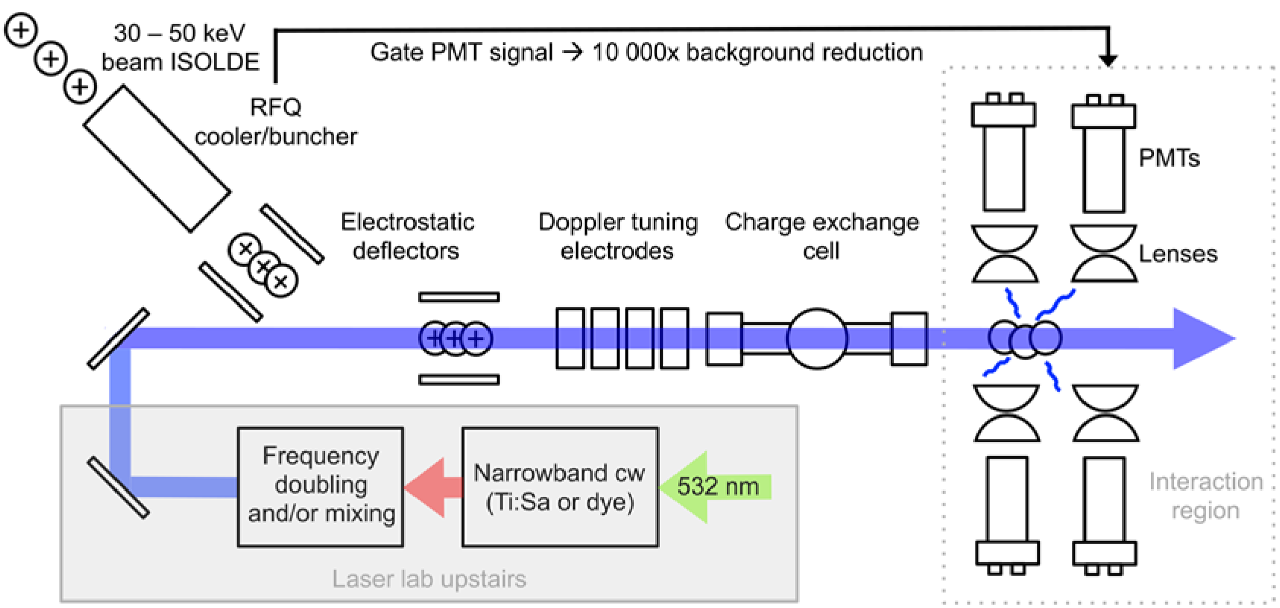
F. Maier, M. Au, P. Fischer, C. Kanitz, V. Lagaki,
S. Lechner, E. Leistenschneider, D. Leimbach,
E.M. Lykiardopoulou, A.A. Kwiatkowski, T. Manovitz,
G. Neyens, P. Plattner, M. Rosenbusch, S. Rothe,
L. Schweikhard, S. Sels, M. Vilen, R. Wolf,
S. Malbrunot-Ettenauer



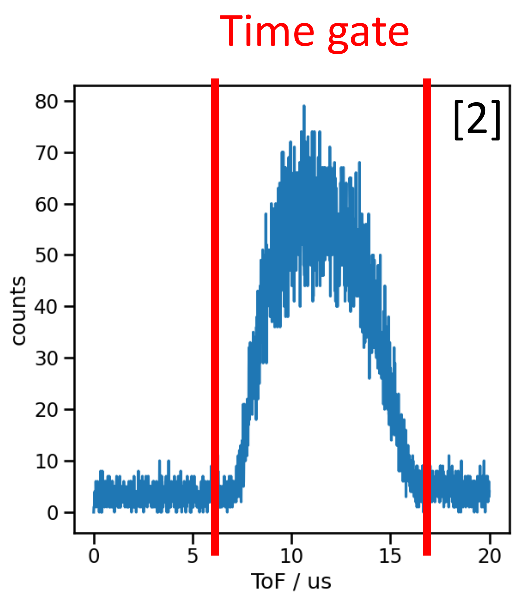
<ins>New publication: </ins>S. Sels, F. Maier et al. *Doppler- and sympathetic ion cooling for the investigation of short-lived radionuclides.* Accepted in Phys. Rev. Research, 2022.

# Increased sensitivity for CLS

- smaller time spread while maintaining a low energy spread allows to choose narrower time gates:
  - currently: time spread ≈ O(μs)
  - laser cooling: ≈ O(ns)
  - ➢ 1000x better sensitivity for several smaller subsequent optical detection regions
- improved transversal emittance if multi-directional laser access is possible
  - ➢ maximizing ion-laser overlap, additional increase in sensitivity




[1]



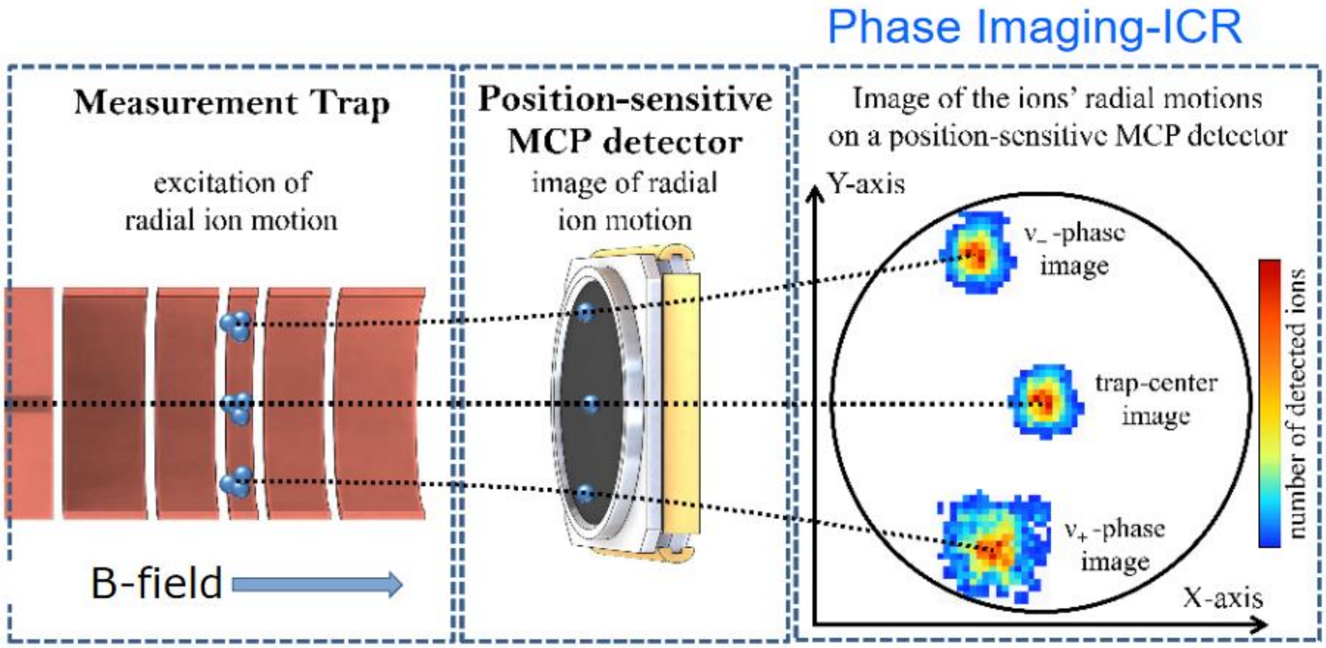


[1] COLLAPS collaboration webpage

[2] Sb run COLLAPS, 2018.

# Increased precision in PI-ICR for Penning traps

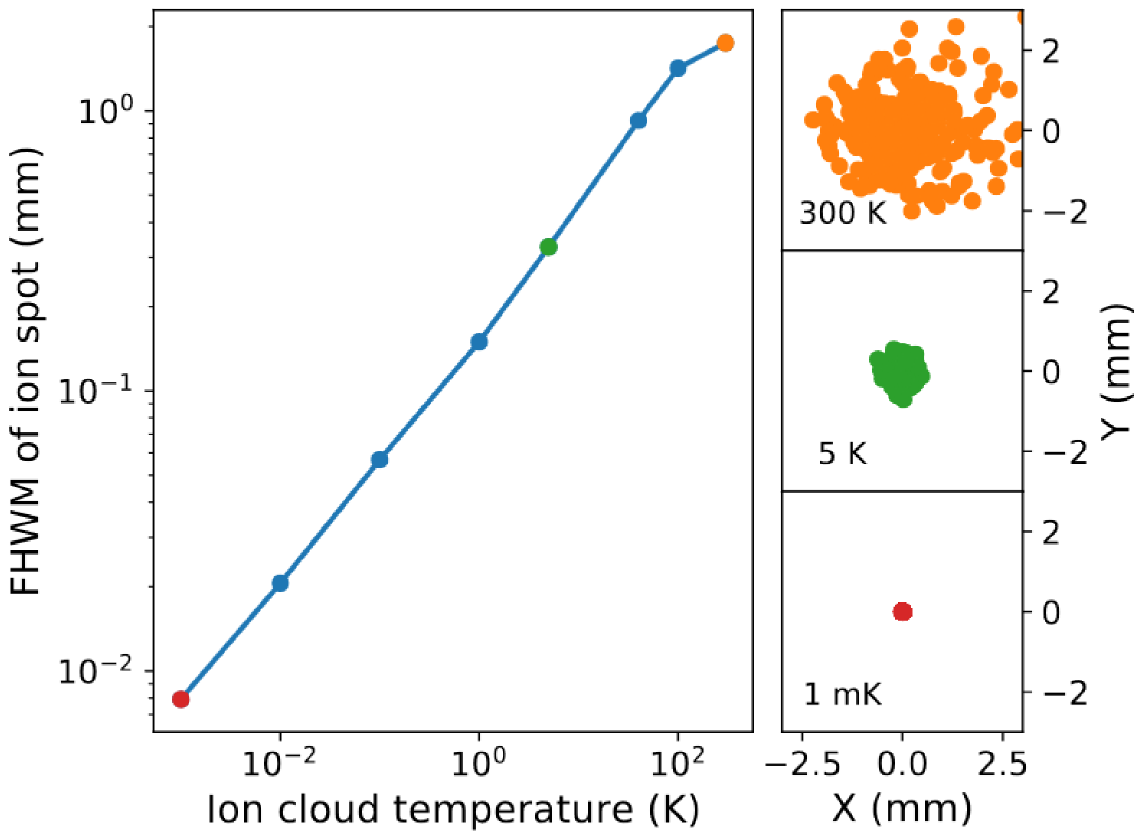
- measurement of cyclotron frequency of an ion confined in a strong and uniform magnetic field
- Phase-Imaging Ion Cyclotron Resonance (PI-ICR) technique: measuring phase evolution of ion's motion inside the Penning trap
- ion is ejected from the trap onto a position-sensitive detector which enables to reconstruct phase of motion and hence its cyclotron frequency




Sergey Eliseev (MPIK)

# Increased precision in PI-ICR for Penning traps

- R is directly proportional to spatial spread of ions hitting detector
- spatial spread is proportional to square root of beam temperature



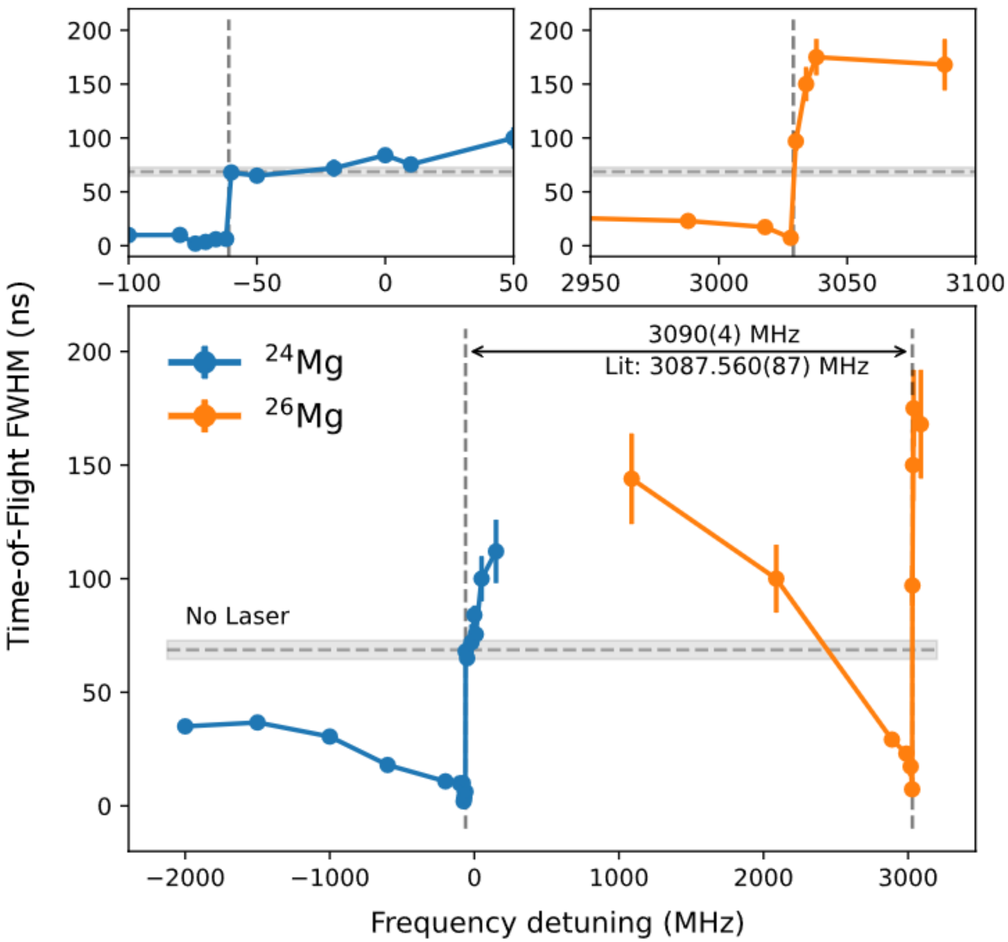

simulation procedure:

- buffer gas cooling in Paul trap
- ions injected into TITAN Penning trap and captured there until release to a detector

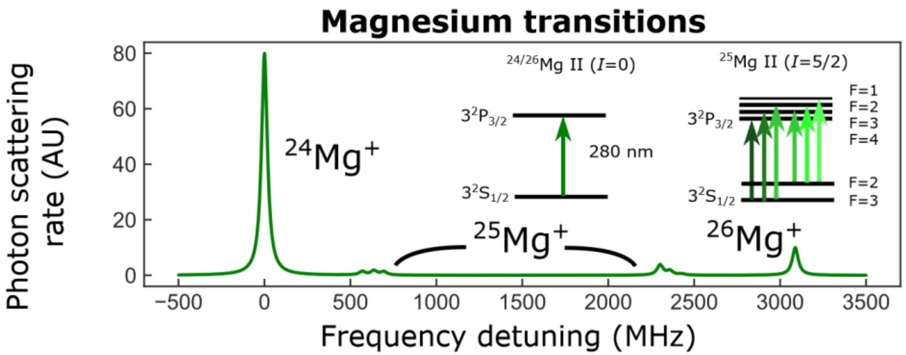
spatial spread reduced by factor 220 between 300 K and 1 mK ion cloud temperature

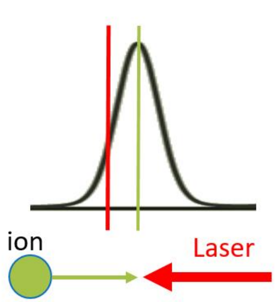
# Isotope shift measurements

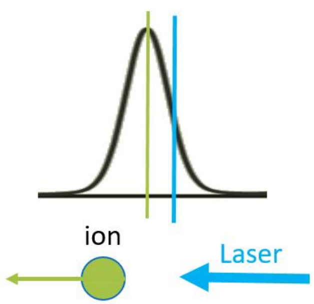
abrupt transition from cooling to heating can be used to determine isotope shift:
no photon detection or extra laser steps for photoionization required

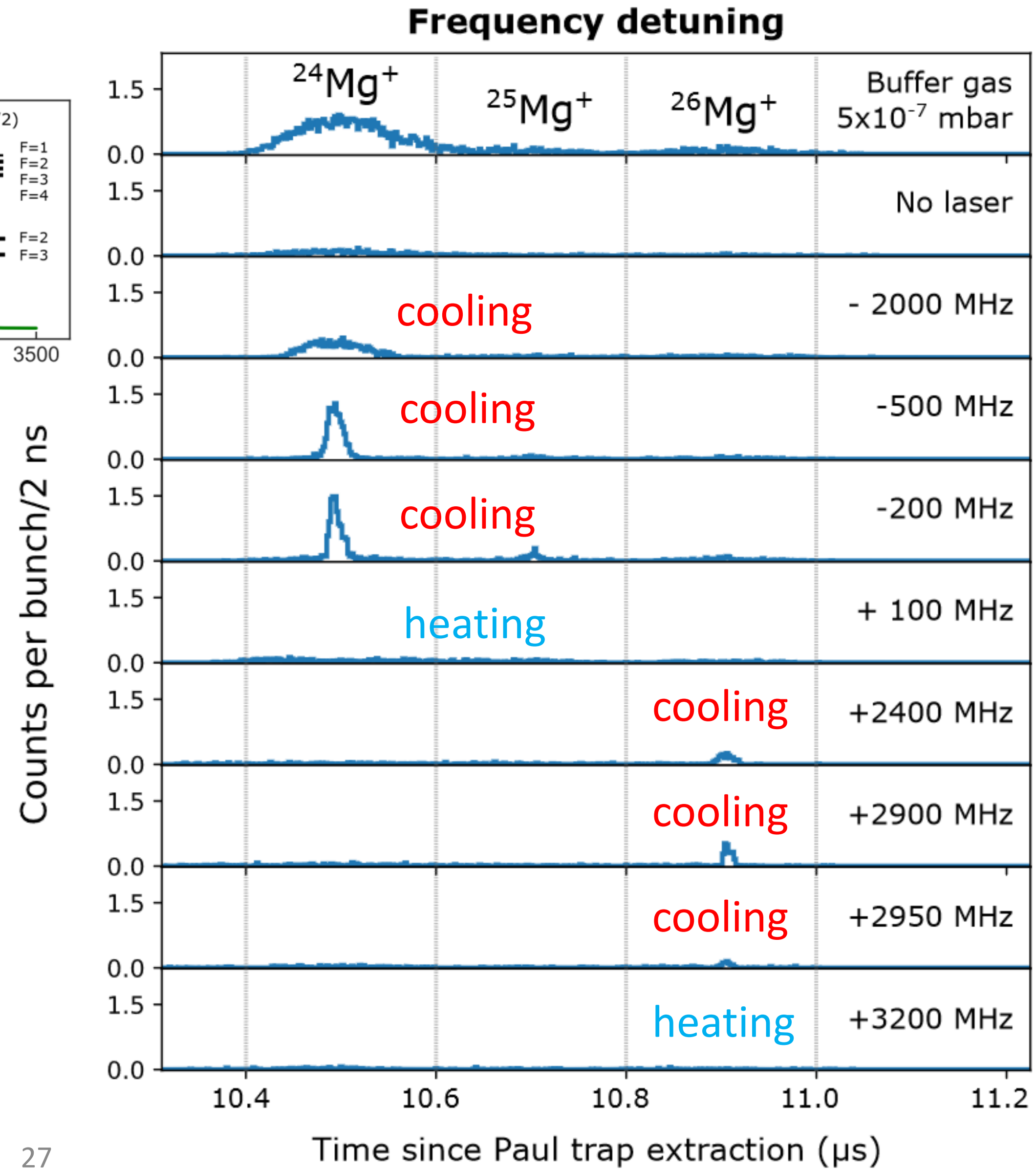


# Cooling Systematics



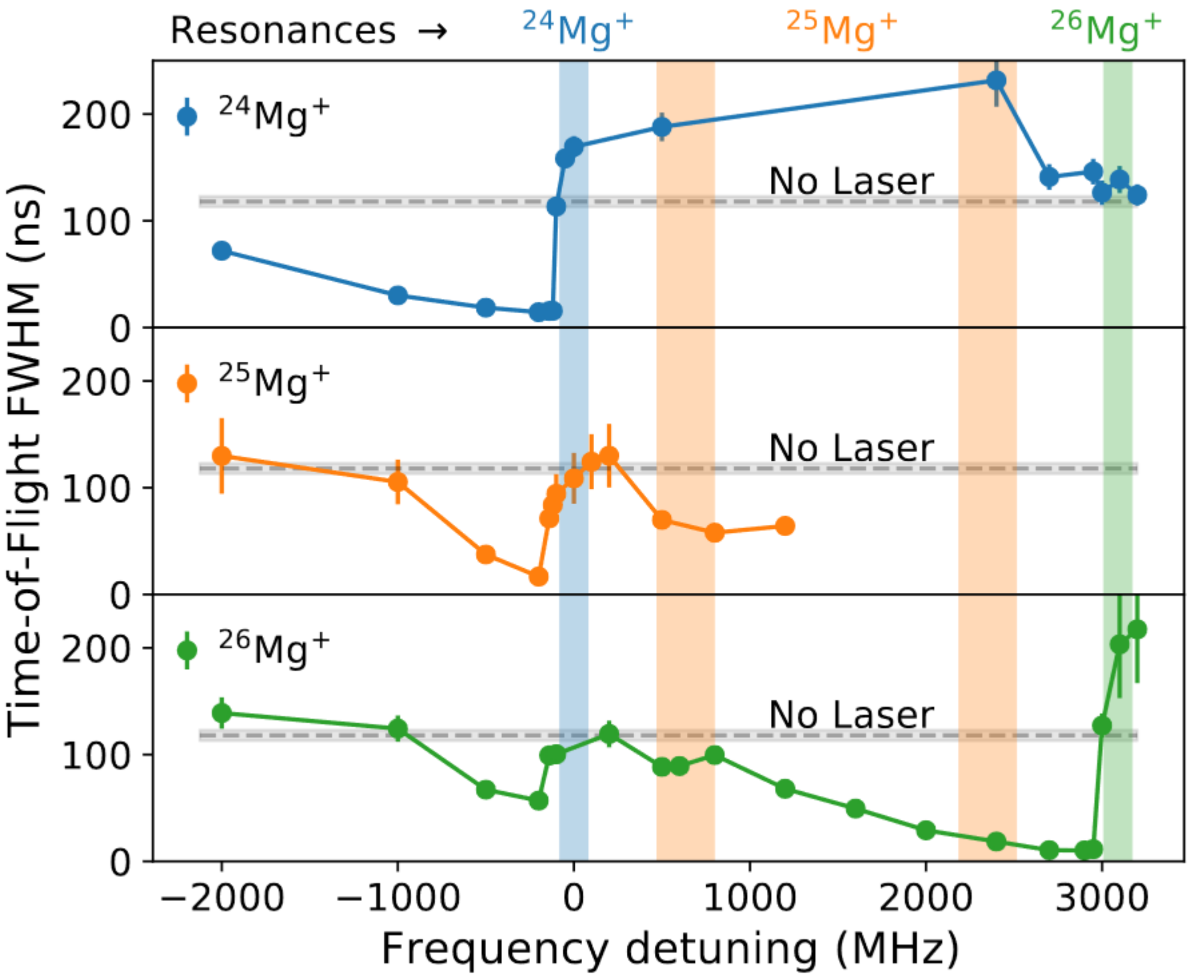



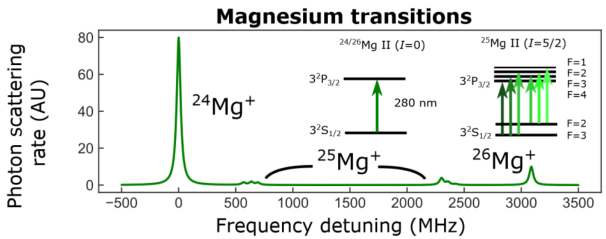




3 mW & 500 ms cooling

# Cooling systematics

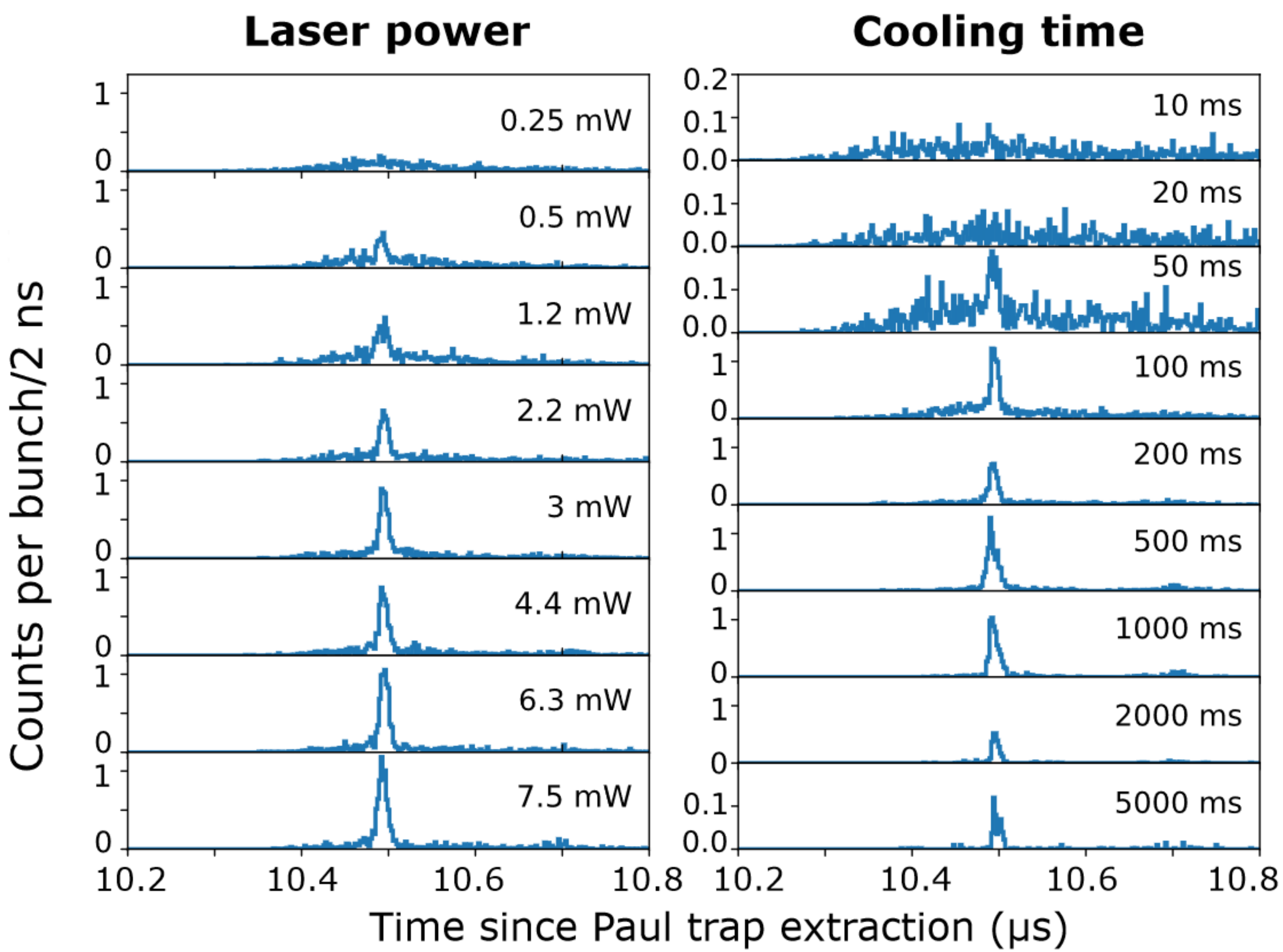


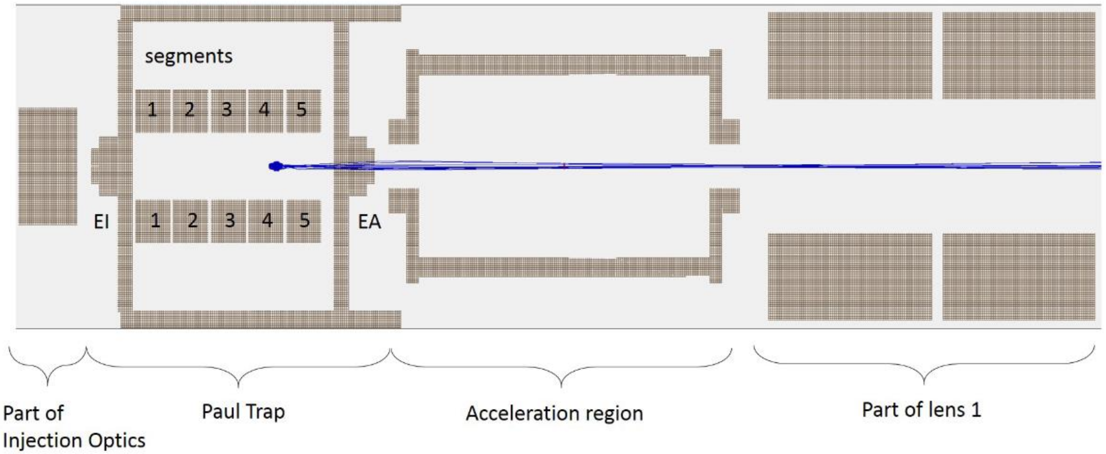
# Cooling Systematics

200 ms cooling and -200 MHz detuning

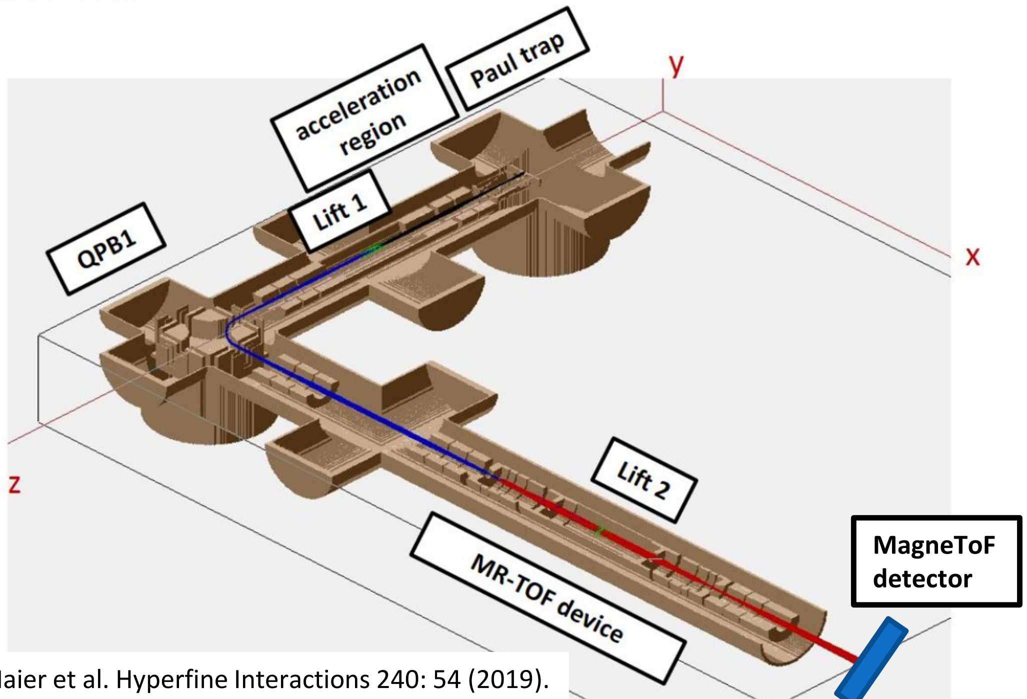
3 mW & -200 MHz detuning



# 3D ion optical simulations




Paul trap simulations + extraction



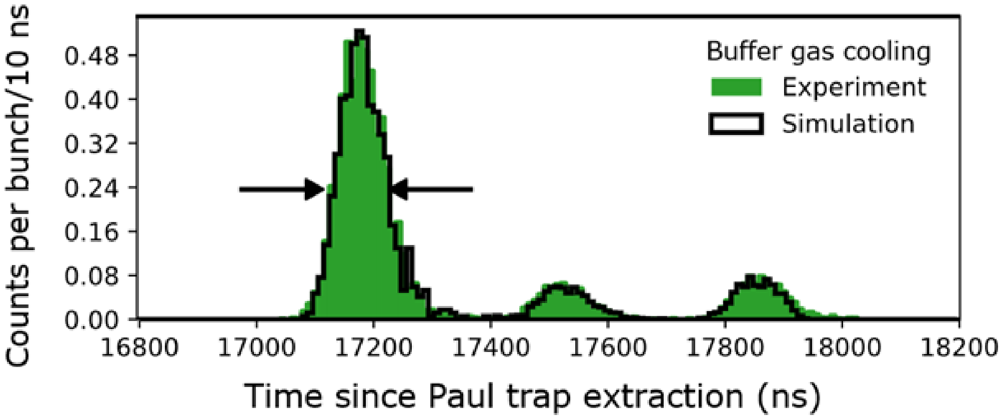

transport simulations to MagneToF detector

recording of ToF and energy distribution at MagneToF detector location

F. Maier et al. Hyperfine Interactions 240: 54 (2019).
F.M. Maier, MSc thesis, JKU, Austria (2019).

# 3D ion optical Paul trap simulations

1st step: 300-K buffer gas cooling of ion ensemble with an energy of 0.03 eV via hard-sphere interactions




same procedure as in
F. Maier et al. Hyperfine Interactions 240: 54 (2019).
F.M. Maier, MSc thesis, JKU, Austria (2019).

2nd step: actual laser cooling

At each time step:

$v_{ion}$ to calculate Doppler shifted frequency detuning + photon scattering rate

→ photon-interaction probability

photon absorption: random number < interaction probability:

in direction of absorption: $p_{\mathrm{ion,\ new}} = p_{\mathrm{ion}} - h/\lambda$

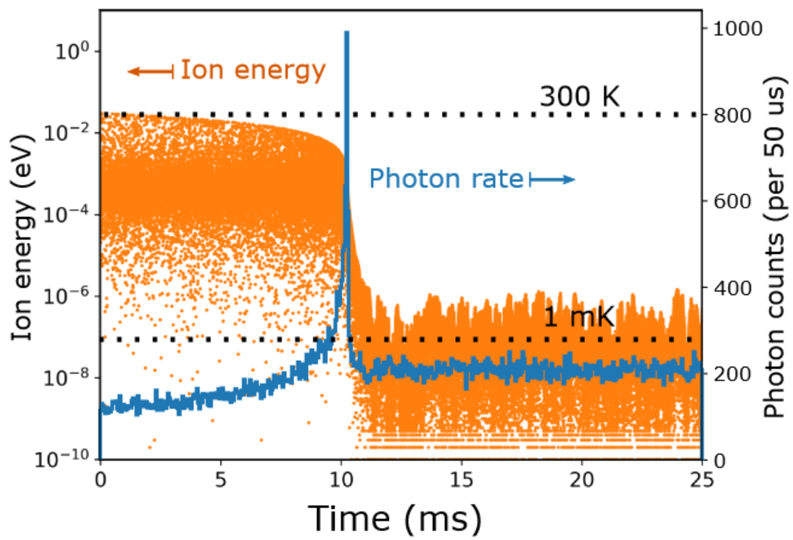
momentum kick due to emission of photon: prompt and in random direction

stimulated emission not taken into account

# Simulations + Numerical model

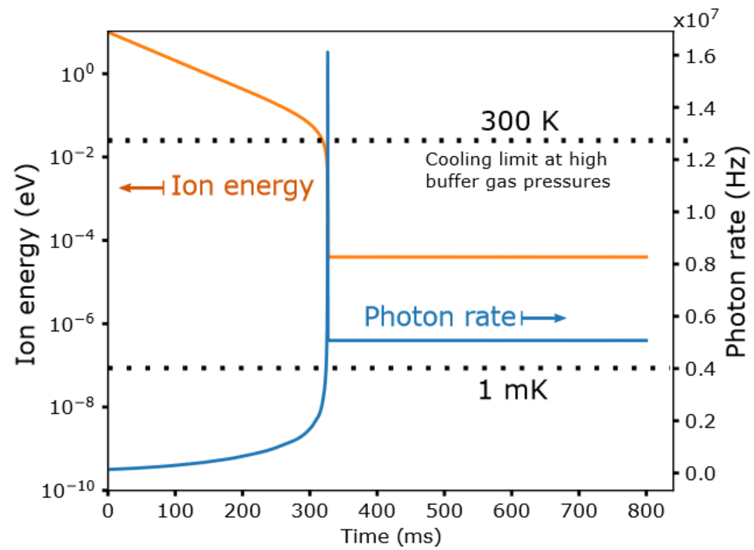
**<u>3 D ion-optical simulations in SIMION:</u>**

- buffer gas cooling via hard-sphere interactions
- First simulation: buffer gas cooling at 300 K
- Second simulation: laser cooling via a semi-classical Monte-Carlo manner




**<u>1 D Numerical cooling model [1]:</u>**

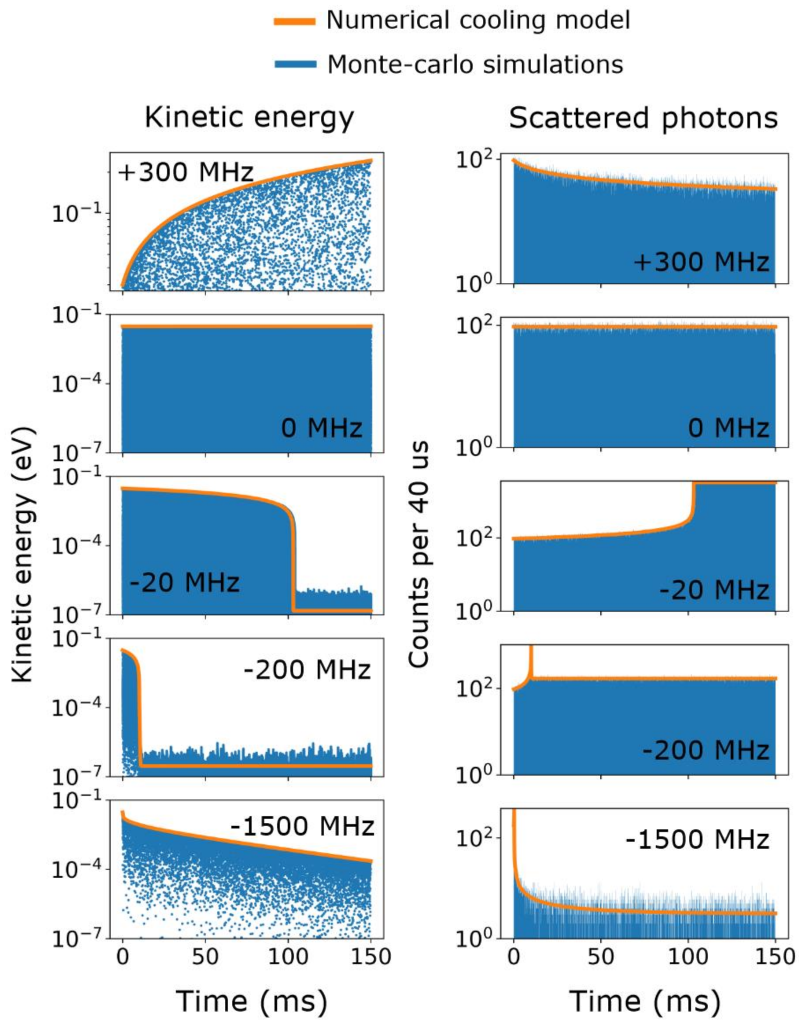
- buffer gas cooling via exponential decay term
- 10 eV initial energy ion being cooled by a 300-K helium buffer gas at 1e-5 mbar + laser cooling




[1] adopted from
J. H. Wesenberg, Phys. Rev. A 76, 053416 (2007).
T. Murboeck et al, Phys. Rev. A 94, 043410 (2016).

# Simulations + Numerical model

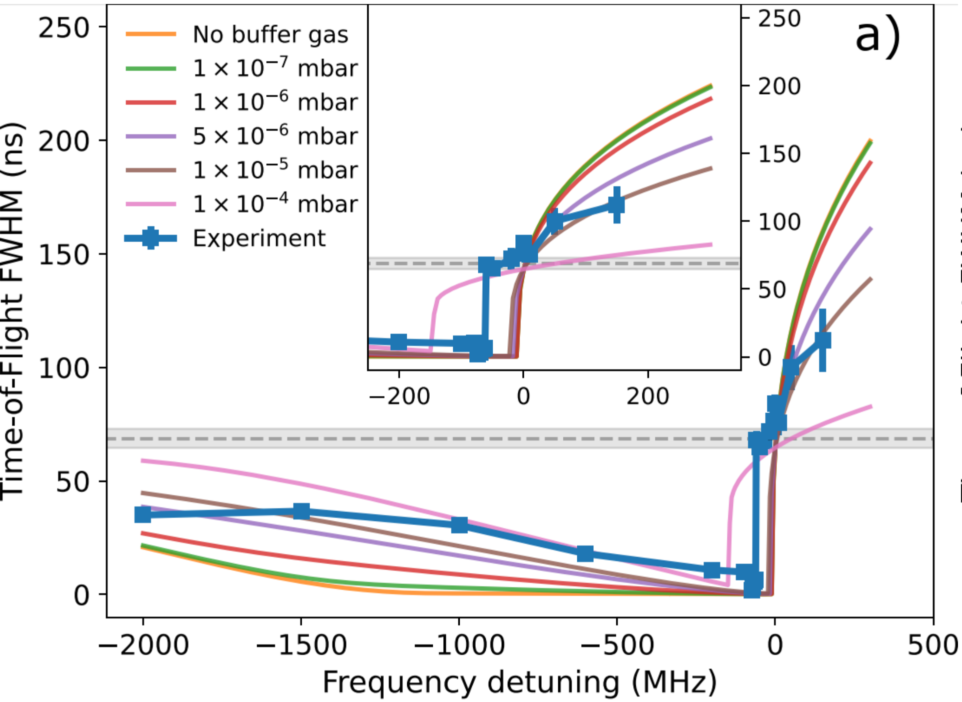
**1 D comparison between simulations and numerical model:**



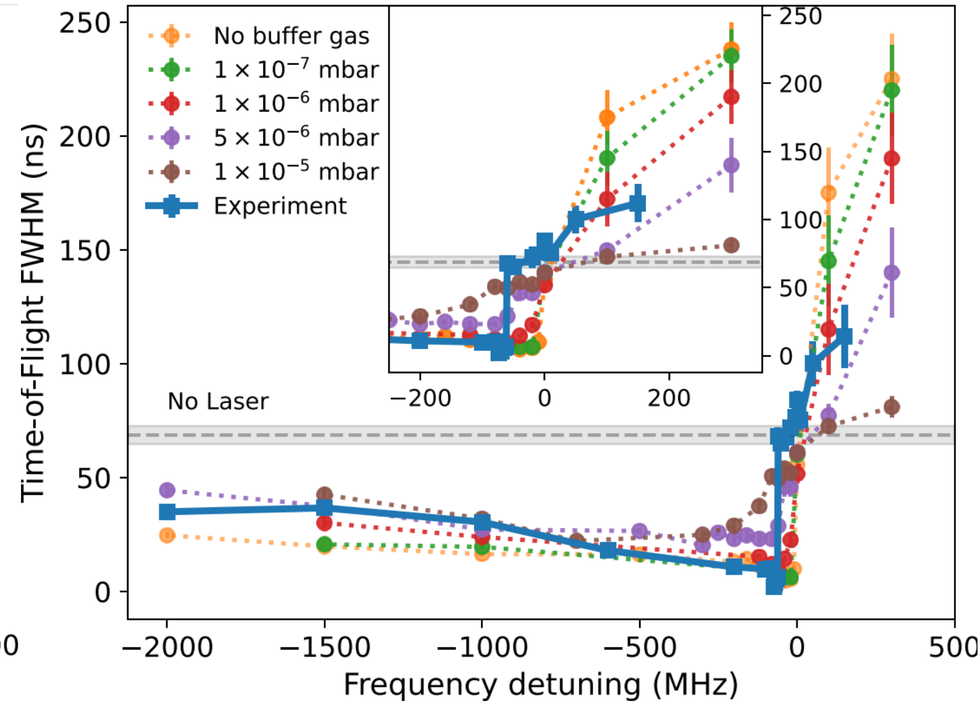
# Simulations + numerical model

**<u>Comparison of both models with experimental data:</u>**

1 D numerical model vs experiment




3D ion-optical simulations vs experiment

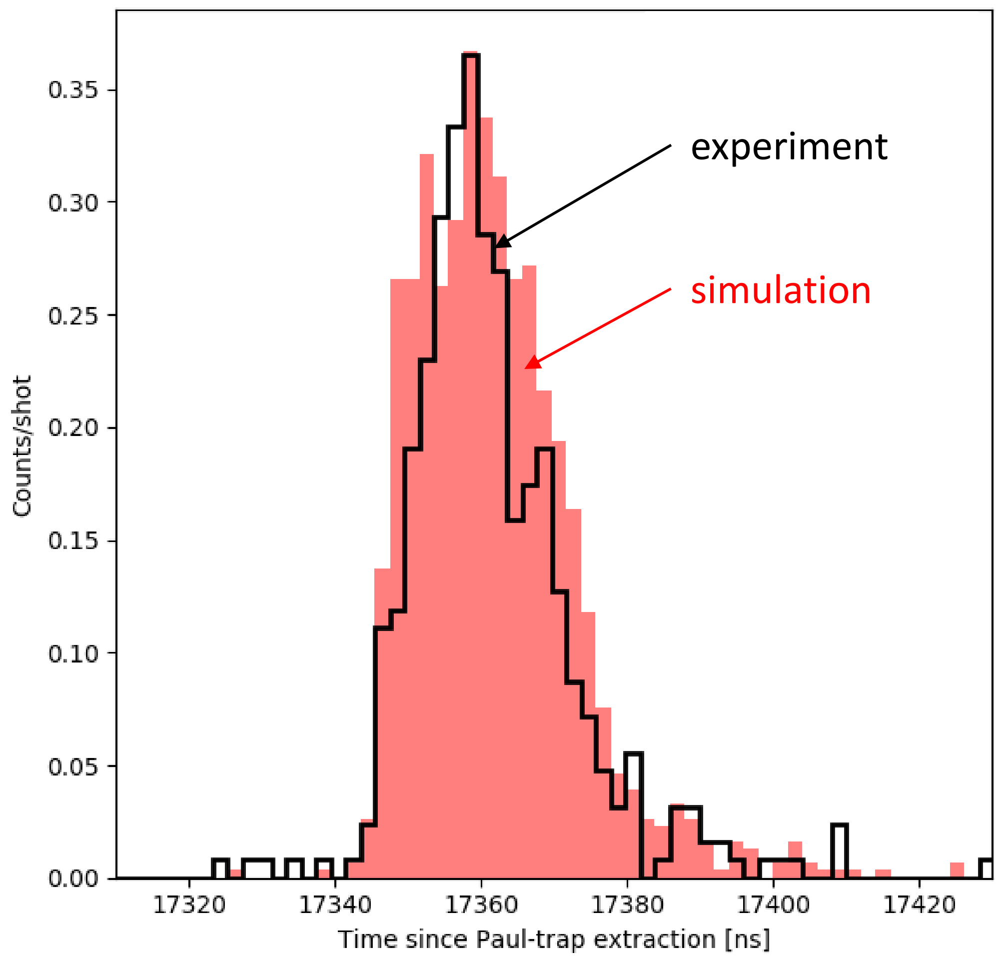



Experiment:

1e-5 to 1e-8 mbar buffer gas present within Paul trap according to MolFlow simulations
cooling time ≈ 100 ms, laser power ≈ 25 mW

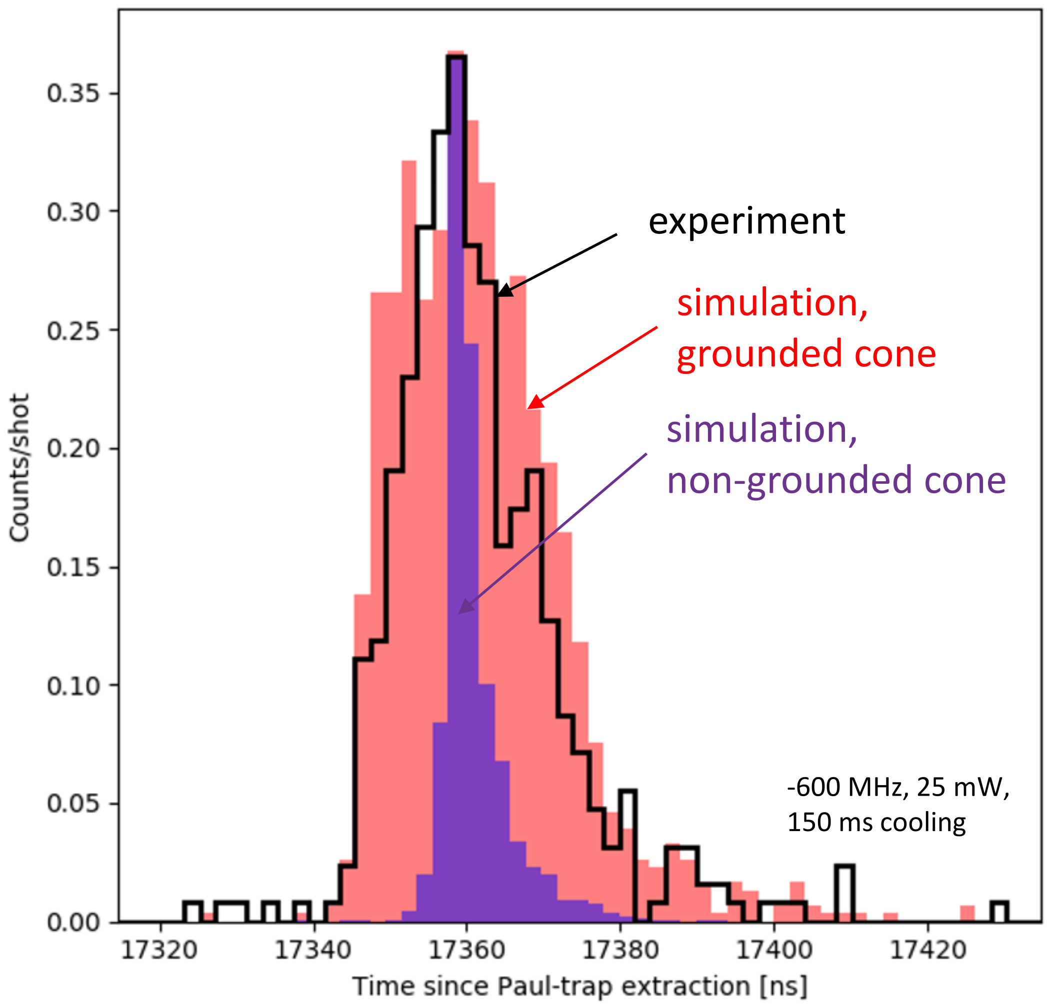
# Simulations vs experiment

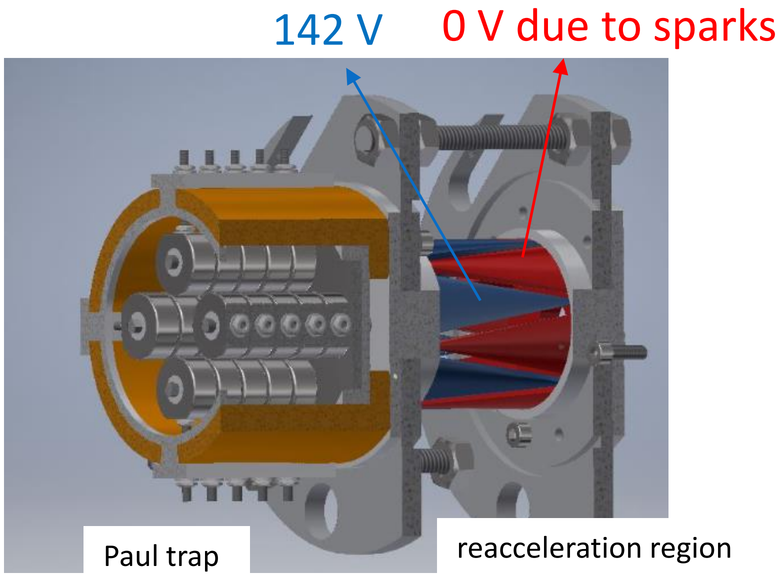
-600 MHz, 25 mW, 150 ms cooling



# Beam temperature revisited

Improved reacceleration optics would give us significantly smaller peak widths for laser cooled ions.

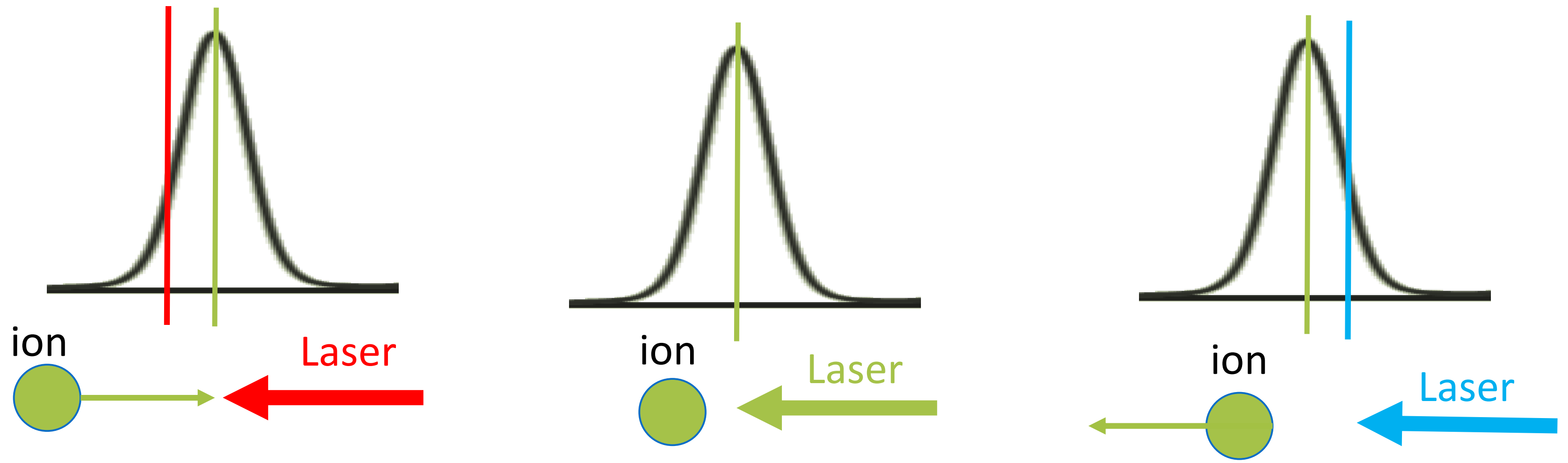



| | Grounded cone | Non-grounded cone |
|---|---|---|
| Laser cooling peak width | 16 ns | 3.6 ns :4 |
| Buffer gas cooling peak width | 102 ns | 106 ns |

3.6 ns peak width corresponds to 0.5 K

# Doppler Cooling principle




- Moving ions observe Doppler shift in laser frequency
- Absorption of photon in one direction
- Spontaneous emission of photon in random direction
- Net-cooling or heating effect since photon momentum is subtracted from/added to the Mg ion momentum

  Red-detuning: cooling, blue detuning: heating