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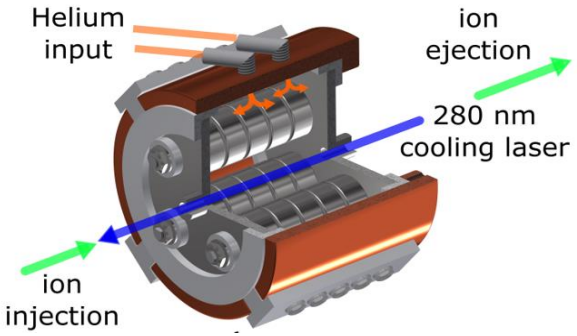
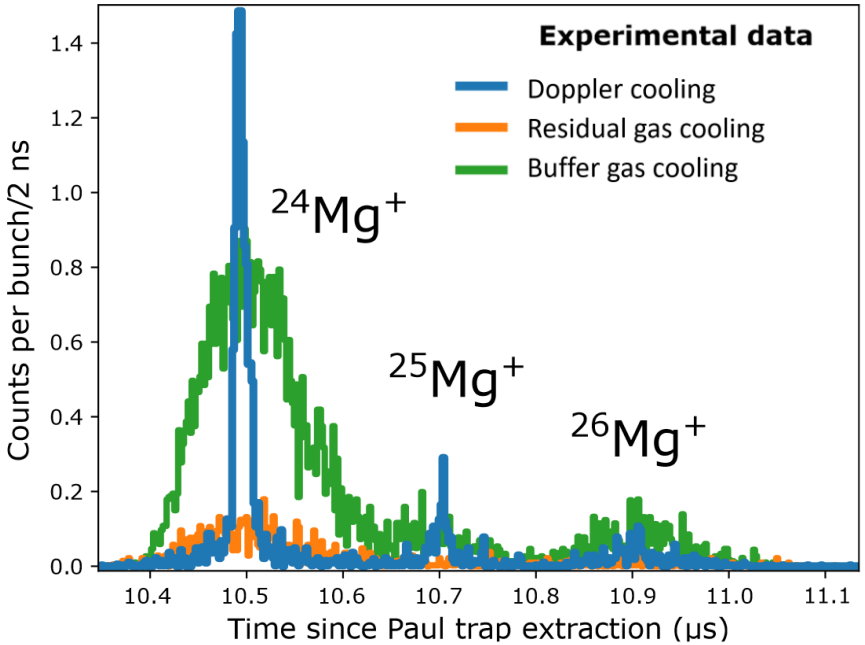
Doppler- and sympathetic cooling for the investigation of short-lived radionuclides

Paul trap:





S.Sels, F.Maier et al, work to be submitted.

MIRACLS

Franziska Maier

CERN PhD Student

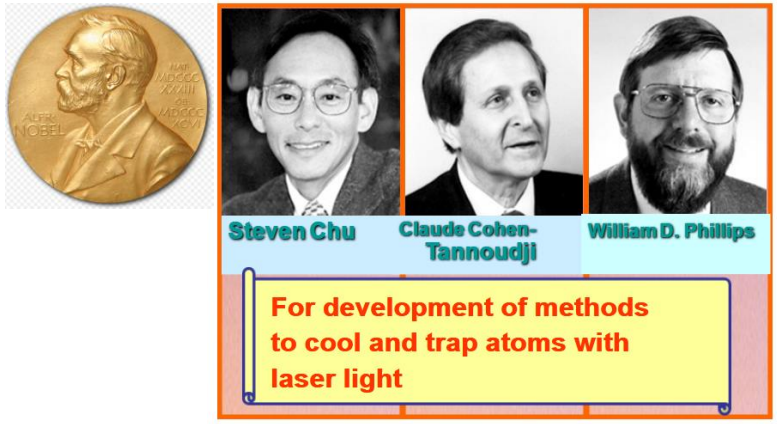
CERN

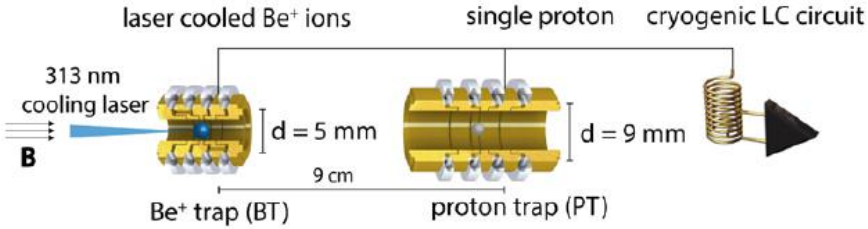
Outline

- Doppler and sympathetic cooling as versatile cooling techniques to deliver high-quality radioactive ion beams to experiments
- Experimental demonstration @ MIRACLS
- Comparison with ion optical simulations & numerical cooling model
- Envisioned applications at RIB facilities

Doppler Cooling

- Powerful technique to reach sub-K atom and ion temperatures [1]
- Standard tool for high-precision measurements: atomic clocks [2], quantum information science [3], physics beyond the standard model [4]





[1] T. Haensch and A. Schawlow, Optics Communications 13, 68 (1975).
D. J. Wineland and W. M. Itano, Phys. Rev. A 20, 1521 (1979).
J. Eschner et al, J. Opt. Soc. Am. B20, 1003 (2003).
[2] D. Ludlow et al, Rev. Mod. Phys. 87, 637 (2015).
[3] C. D. Bruzewicz et al, Applied Physics Reviews 6, 021314 (2019).
[4] M. S. Safronova et al, Rev. Mod. Phys. 90, 025008 (2018).

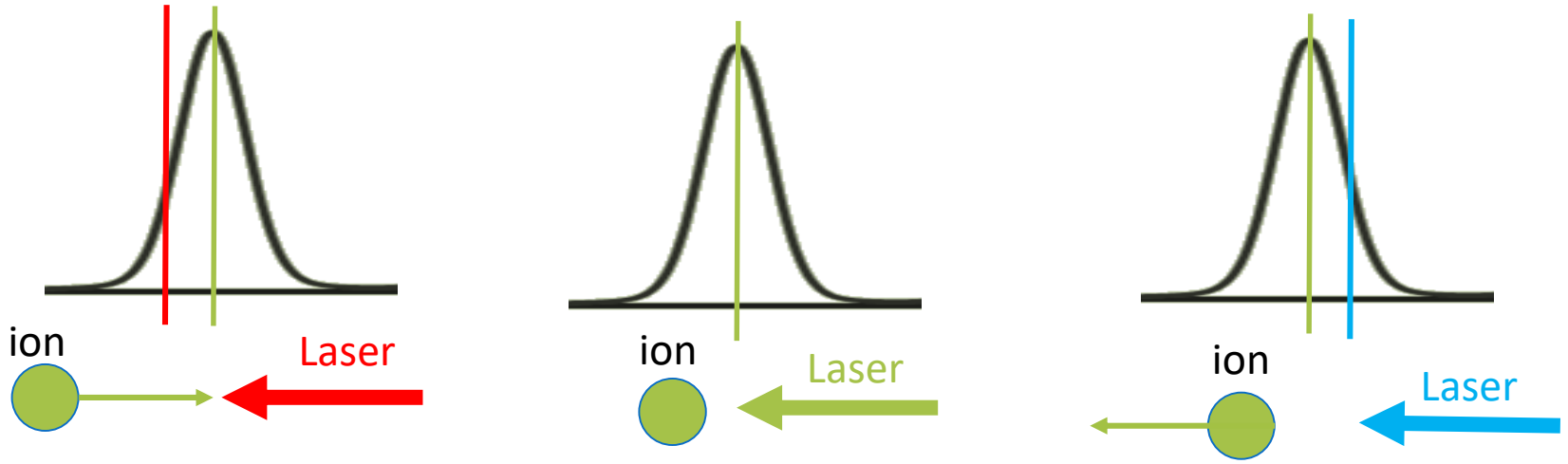
Doppler Cooling at RIB Facilities

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

- 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 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).
M. Trinczek et al., Phys. Rev. Lett. 90, 012501 (2003).
L. B. Wang et al., Phys. Rev. Lett. 93, 142501 (2004).
P. Mueller et al., Phys. Rev. Lett. 99, 252501 (2007).
P. A. Vetter et al., Phys. Rev. C 77, 035502 (2008).
J. R. A. Pitcairn et al., RRC 79, 015501 (2009)
A. Takamine et al., Phys. Rev. Lett. 112, 162502 (2014)
B. Fenker et al., Phys. Rev. Lett. 120, 062502 (2018)

Doppler Cooling principle



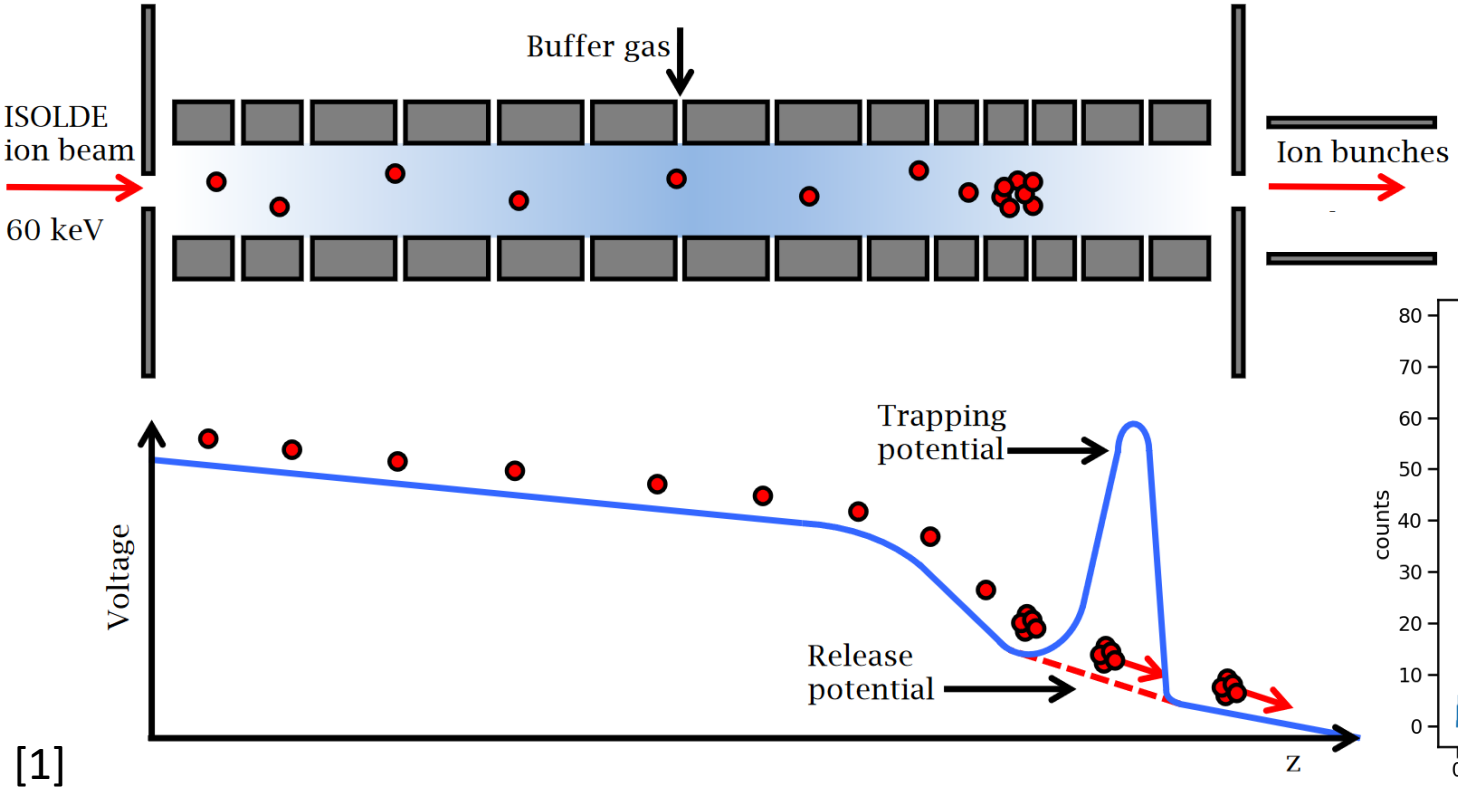
- Moving ions observe Doppler shift in laser frequency
- Absorption of photon in one direction
- Spontaneous emission of photon in random direction
- Net-cooling or heating effect since photon momentum is subtracted from/added to the Mg ion momentum

  Red-detuning: cooling, blue detuning: heating

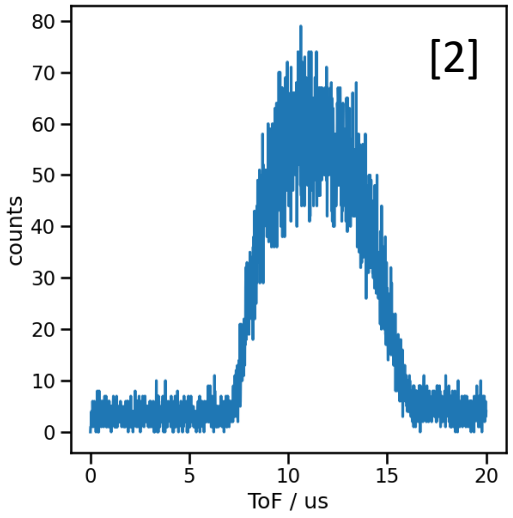
ISCOOL

=RFQ cooler and buncher at ISOLDE, operated at 300 K buffer gas

Cooling limit: 300 K



[1]

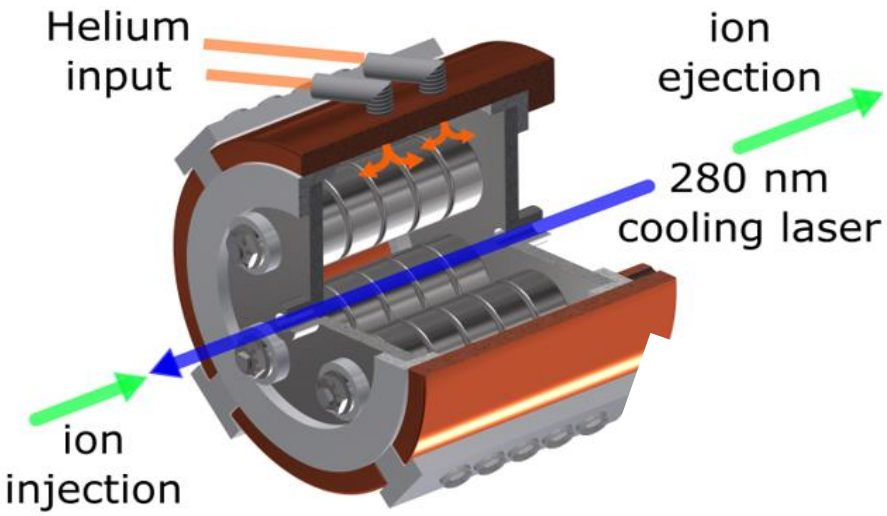


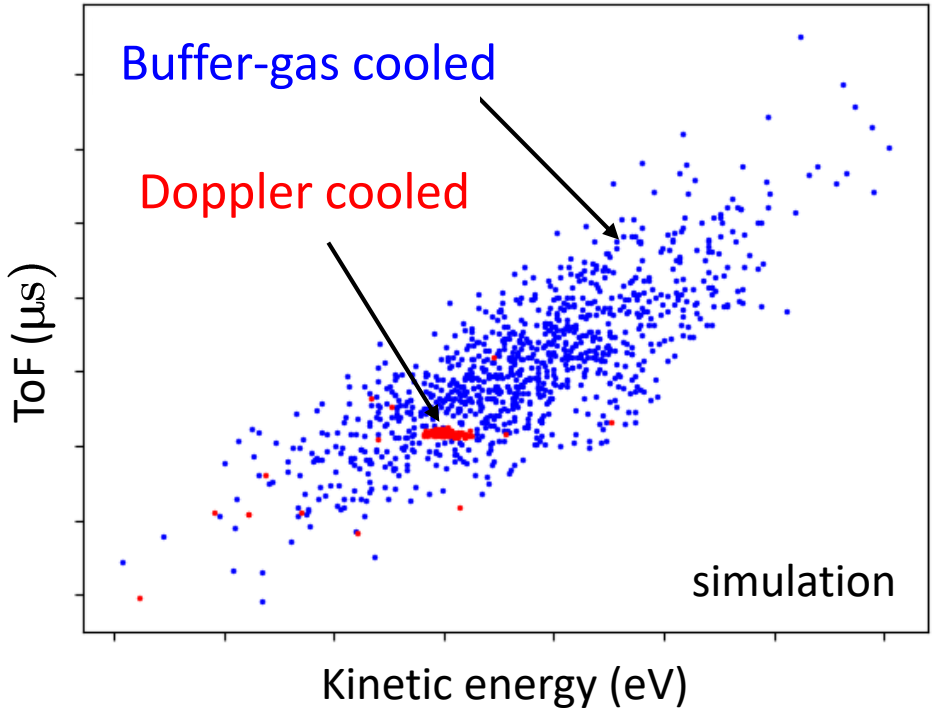
[1] K. Lynch, PhD thesis, University of Manchester, 2013.

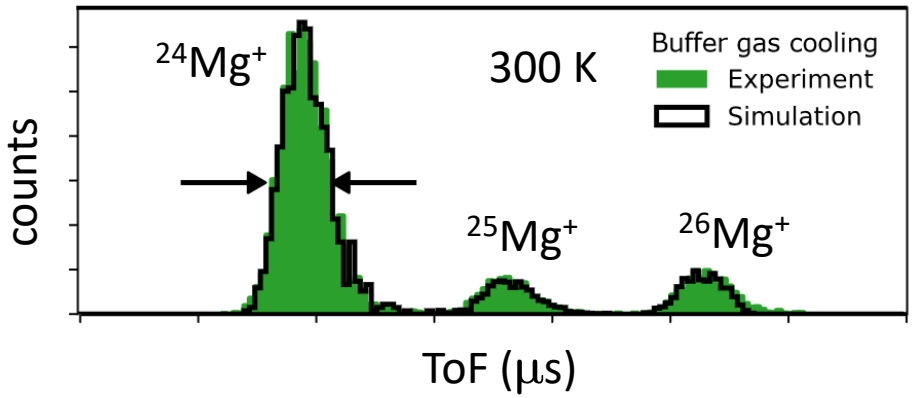
[2] Sb run COLLAPS, 2018.

Experimental Demonstration @MIRACLS

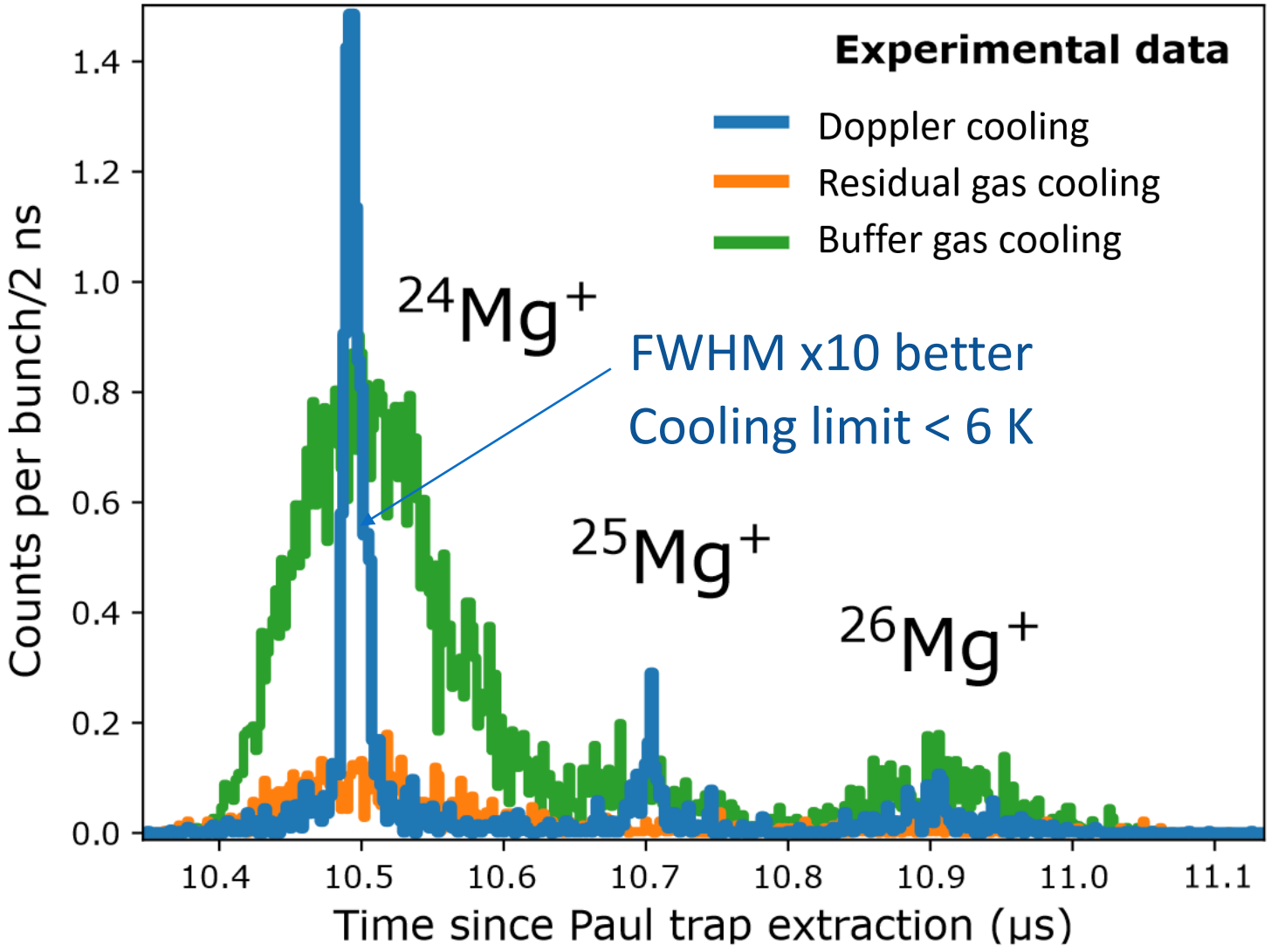
Paul trap:





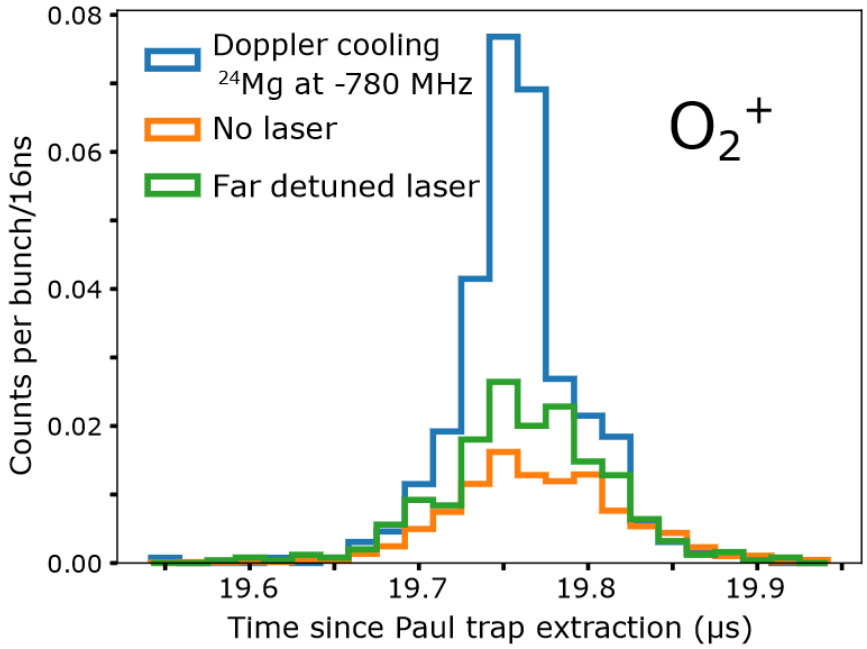


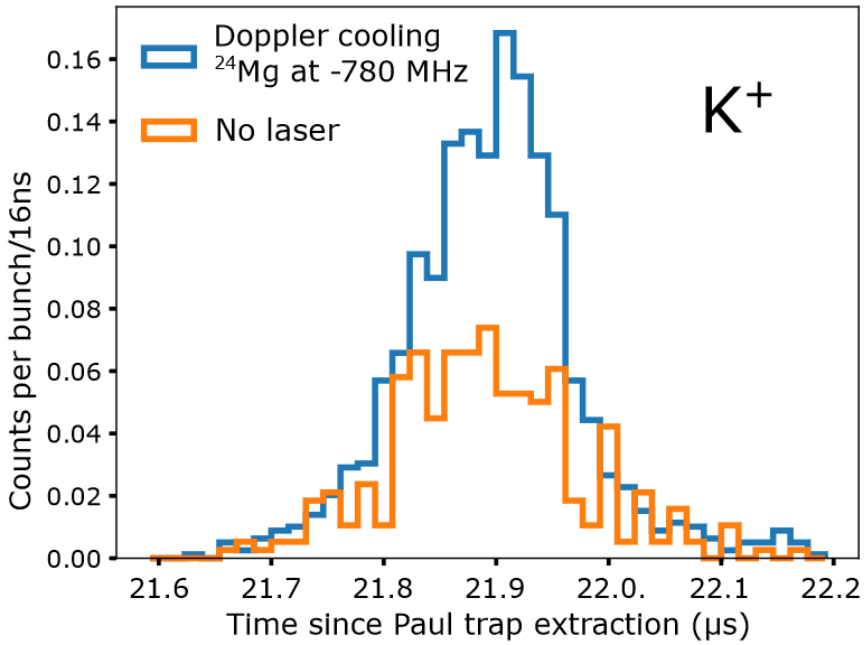
Experimental results



Sympathetic cooling

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





	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]

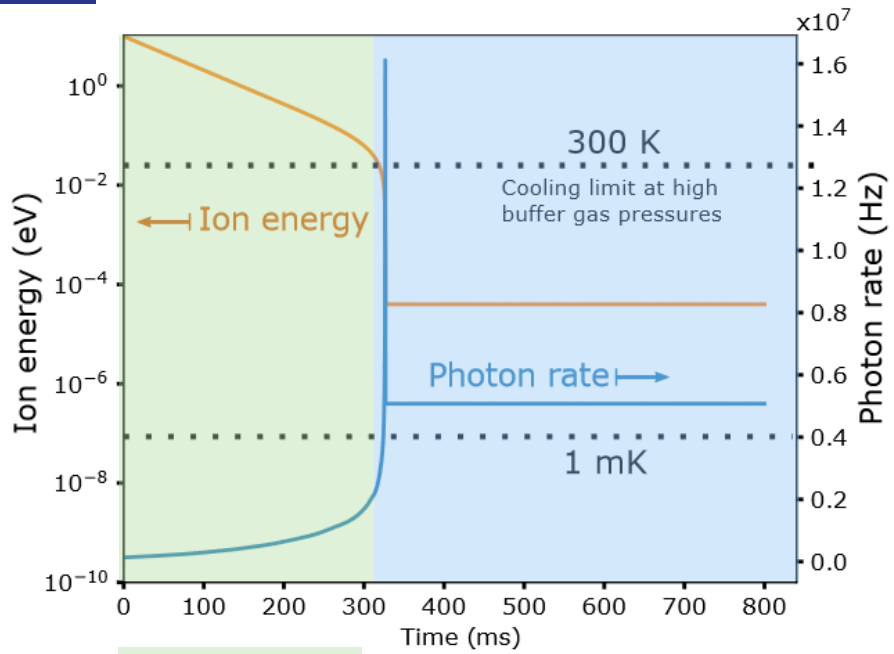
[1] J. Wuebbena et al, Phys. Rev. A 85, 043412,2012.
[2] M. Guggemos. New Journal of Physics 17, 103001, 2015.

Needed cooling time

Experiment:

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

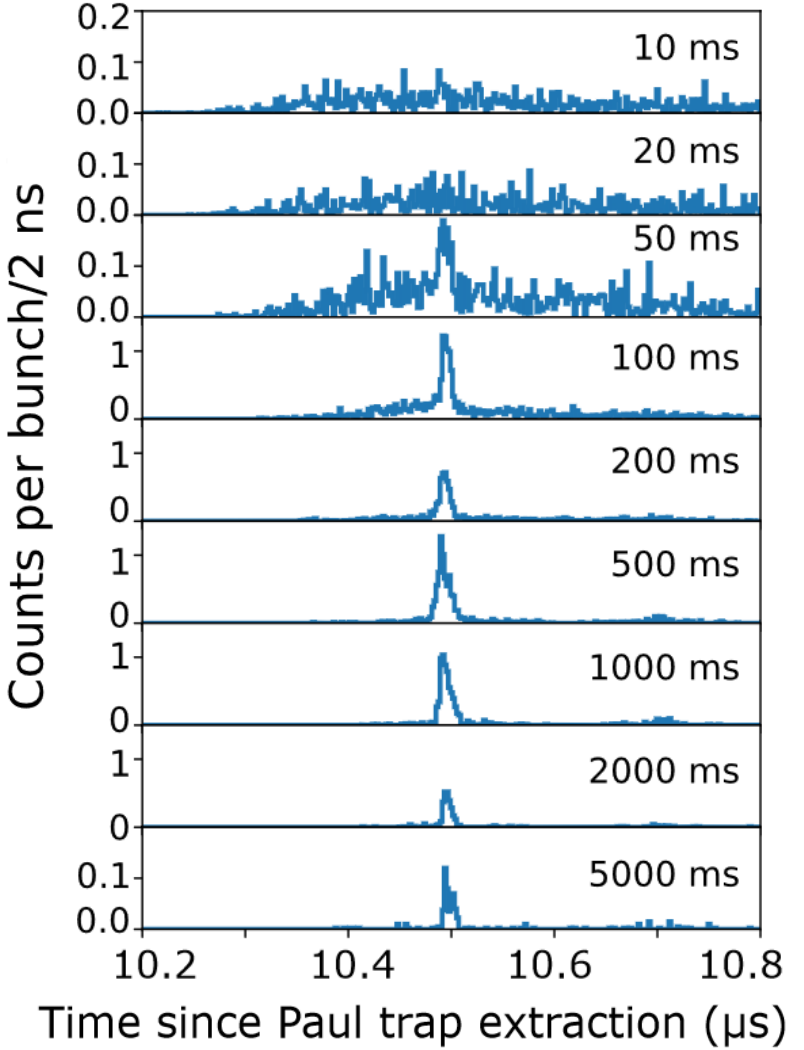
Simulations + numerical model: Presence of buffer gas speeds up the cooling



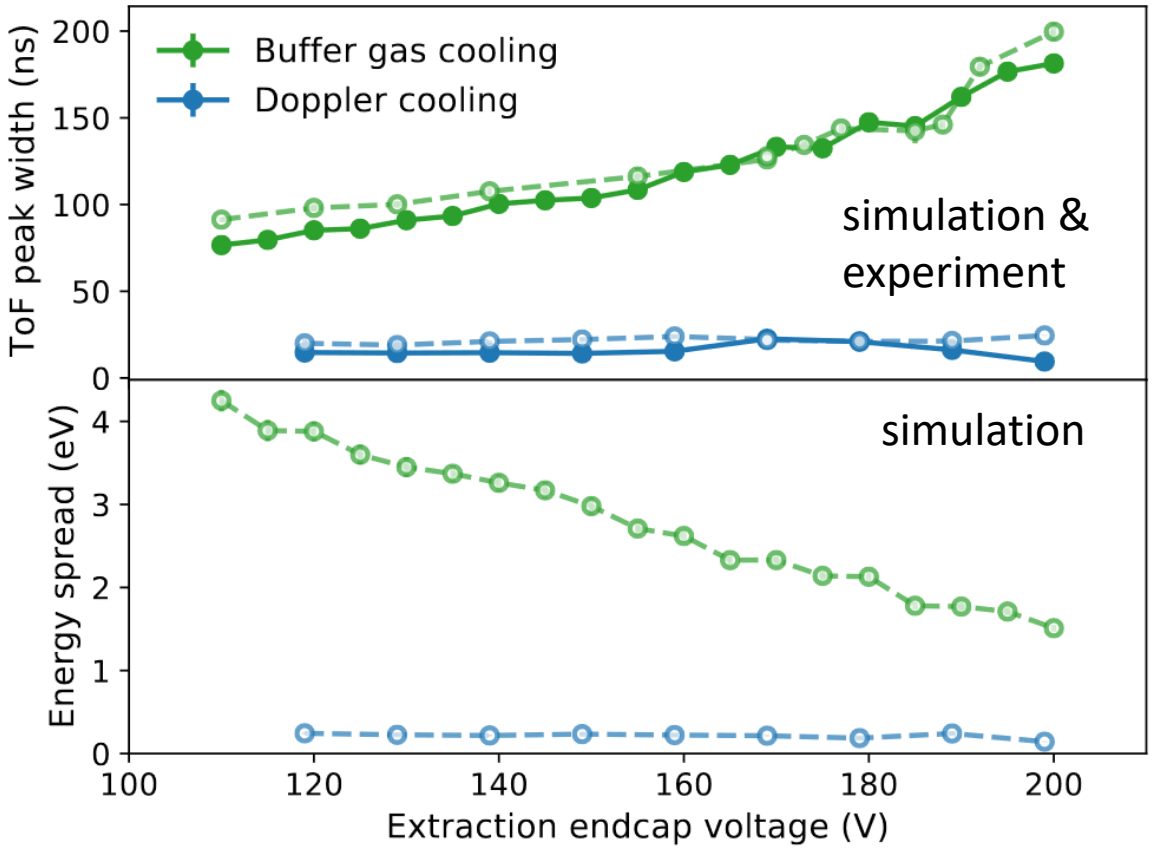
Buffer-gas cooling

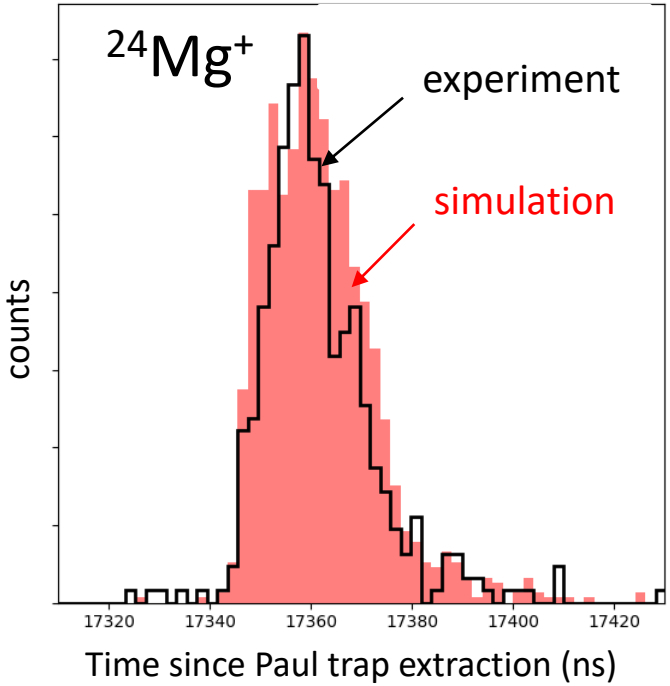
Doppler cooling

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



Applications at RIB facilities





Simultaneously
small Δt & ΔE

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

Improved R in MR-ToF devices

Multiple revolutions in MR-ToF device

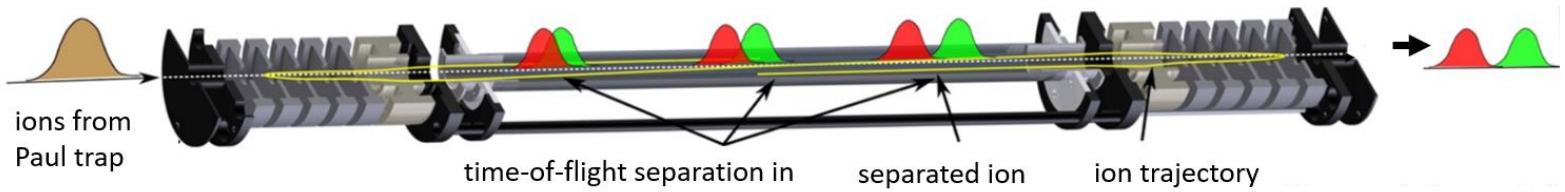
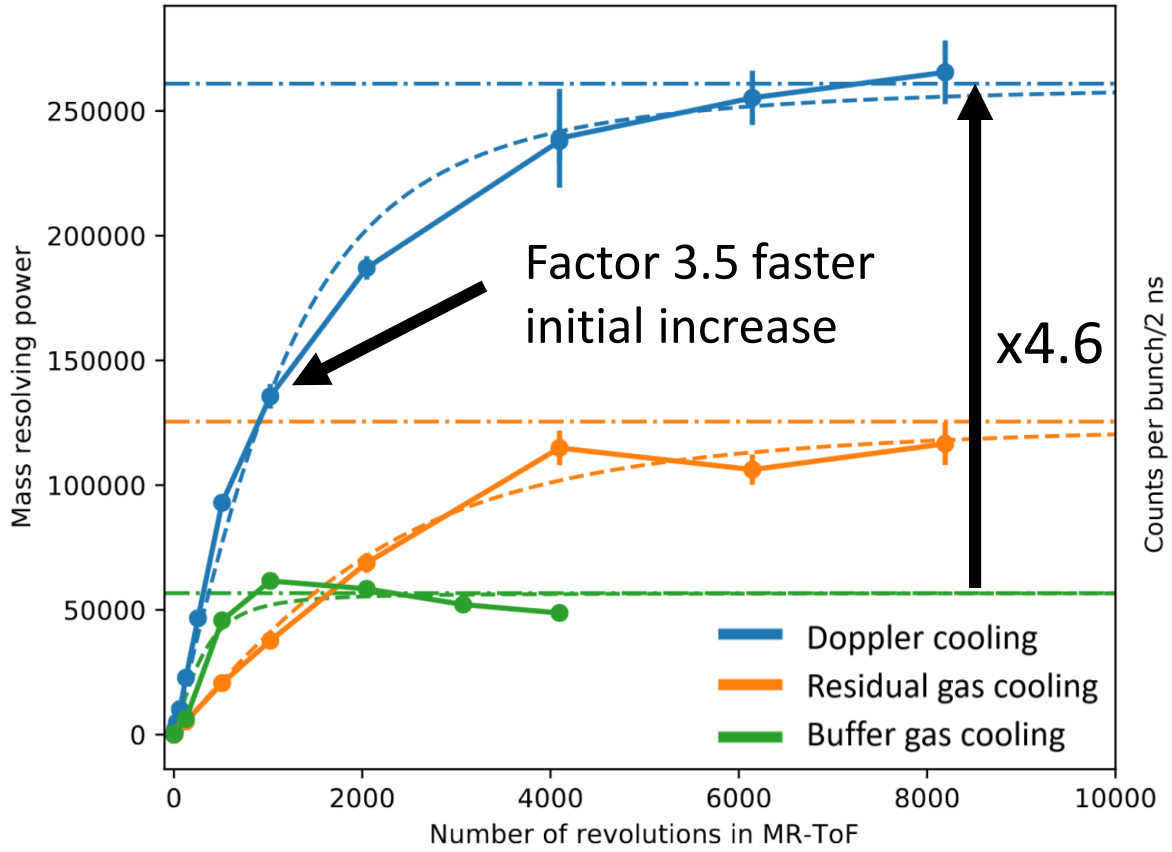
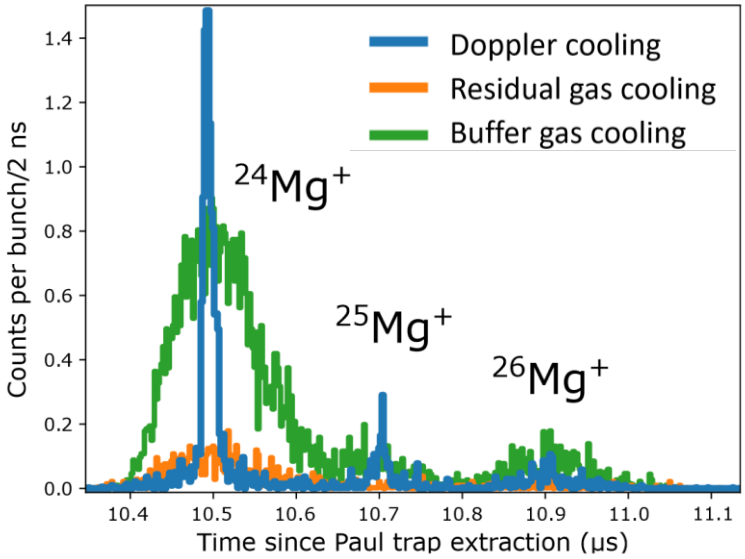


Fig. mod. from R.N. Wolf et al. Int. J. Mass Spectrom., 349-350:123 – 133 (2013).



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



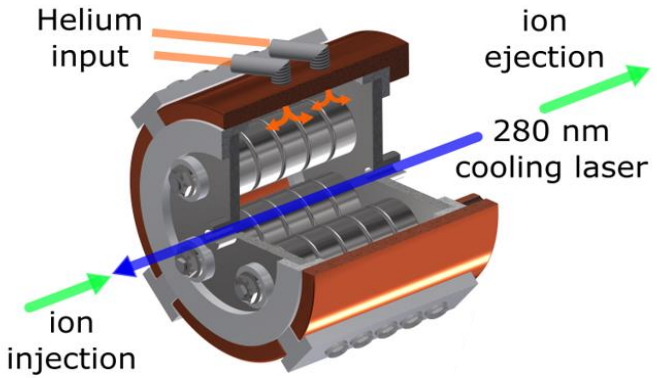
Summary & Outlook

- Demonstration that laser cooling is
  - ... compatible with $T_{1/2}$
  - ... compatible with instrumentation at RIB facilities
  - ... universally applicable (via sympathetic cooling)

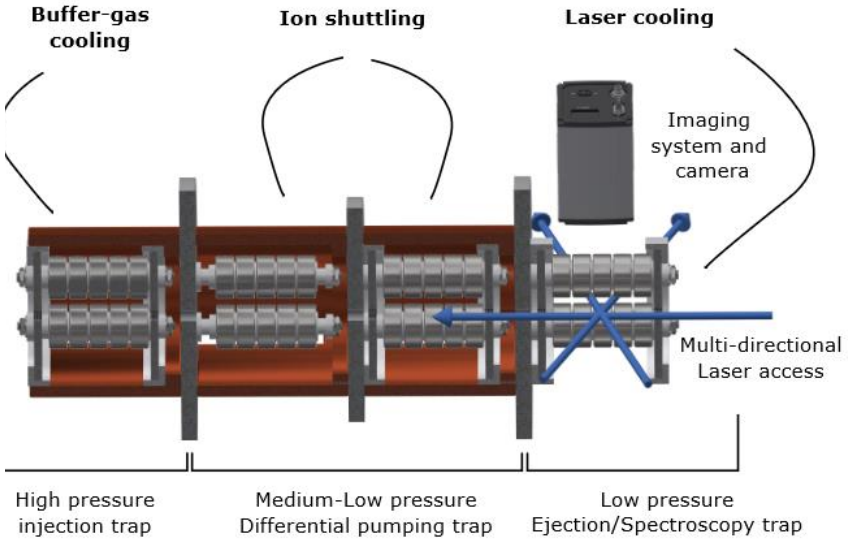
  to deliver low-emittance beams

- 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:



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Thanks!

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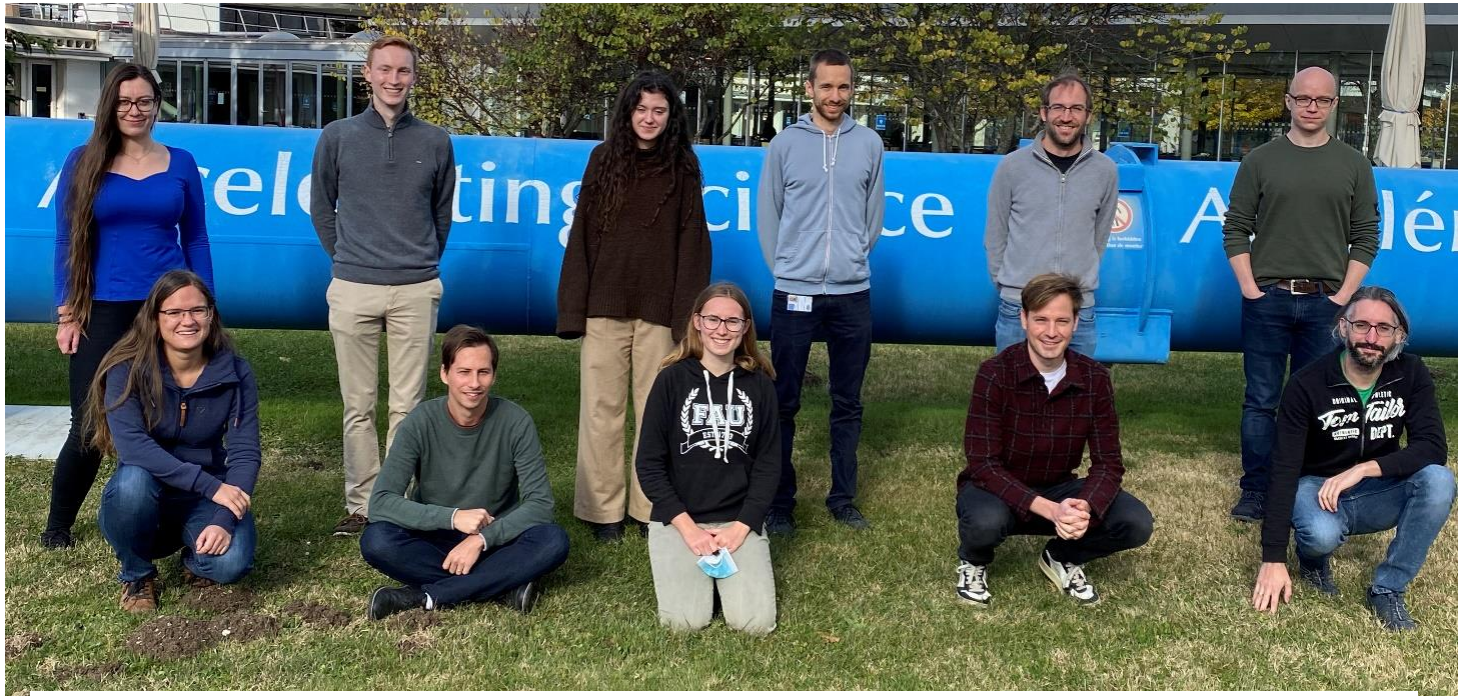
F. Maier, M. Au, P. Fischer, C. Kanitz, V. Lagaki, S. Lechner, E. Leistenschneider, D. Leimbach, E.M. Lykiardopoulou, A.A. Kwiatkowski, T. Manovitz, G. Neyens, P. Plattner, M. Rosenbusch, S. Rothe, L. Schweikhard, S. Sels, M. Vilen, R. Wolf, S. Malbrunot-Ettenauer



New publication: S. Sels, F. Maier et al. *Doppler- and sympathetic ion cooling for the investigation of short-lived radionuclides.* In preparation.