Status and planning of the Borealis project

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08.05.2024

Outline

Background

- General idea and goal of the Borealis project

Current state and ongoing activities

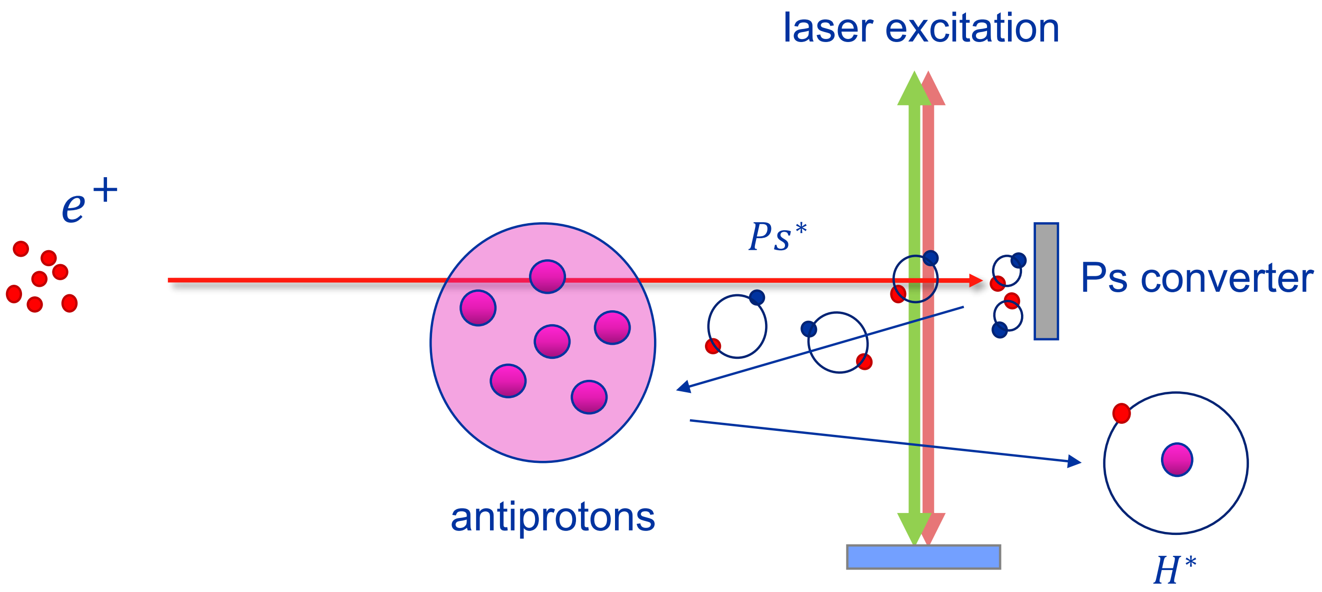
- Challenges: Ion number and ion lifetime
- Theory: Simulation of a pulsed drift tube decelerator (project of Sneha Jos)
- Experiment: Optimization of beam transport (project of Frederik Zielke)

Future plans

- Collinear ion-beam spectroscopy of C_2^- at DESIREE facility in Stockholm

H̄ formation at AEgIS

- e^+ implanted into a nano-channeled silicon target
  → Ps formation
- Rydberg excitation of Ps
  → Ps*
- Charge exchange between Ps* and p̄:
  Ps* + p̄ ⟶ H̄ + e^-



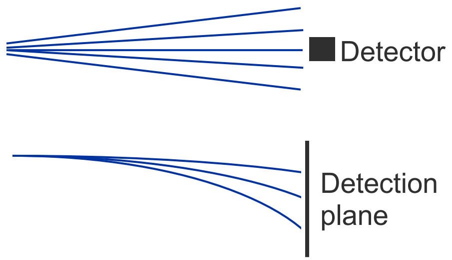
➔ H̄ temperature dominated by temperature of p̄ precursor.

➔ Cooling p̄ results in colder H̄.

Importance of $\bar{H}$ temperature

Colder $\bar{H}$ leads to

- Reduced transversal velocity of $\bar{H}$ beam
  ➔ Increased flux of $\bar{H}$ reaching the detector
- Reduced axial velocity spread
  ➔ Enhanced precision for $\bar{g}$ measurement.



Gravity measurement

- Reduced Doppler broadening.
  ➔ Enhanced precision in spectroscopy measurements.
- Increased $\bar{H}$ density.
  ➔ Enhanced formation rates for more complex antiprotonic bound systems.

More exotic prospects…

Doppler laser cooling

The tool box of AOM physics offers a time-tested method for cooling atoms close to absolute zero temperature:

- Irradiate atoms with laser light just slightly tuned below resonance with an atomic transition (for an atom at rest).
- Atoms moving counter-propagating to the laser “see” a Doppler-shifted laser beam.
  ➔ laser radiation comes in resonance with atom
- Atom absorbs a photon from the laser beam.
- Momentum of photon is transferred to atom.
  ➔ atom gets kicked against its direction of travel.
- Continuous repetition of this cooling cycle slows down – i.e., cools – the atoms.

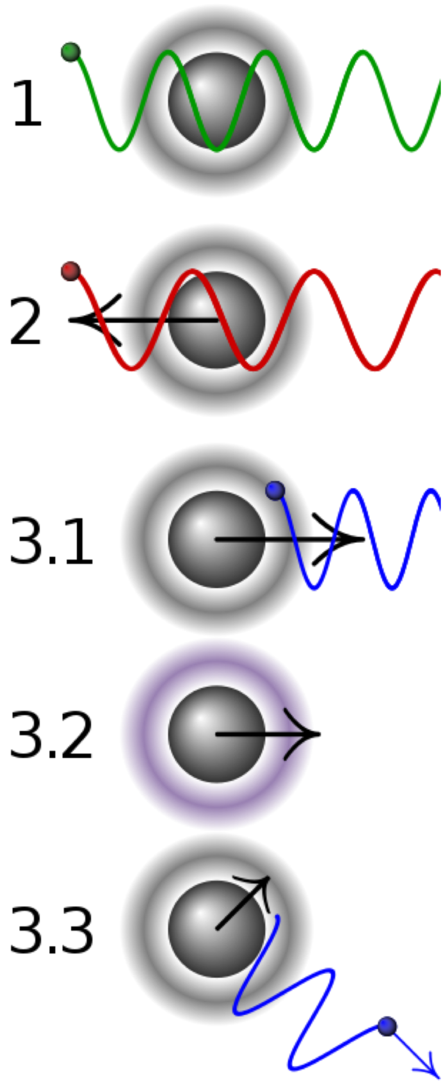


Figure: wikipedia.org

How to apply that to $\bar{p}$?

Problem

- Antiprotons do not have excited states!
- Direct laser cooling not applicable.

Solution

- **Sympathetic cooling** – another trick from the AOM toolbox.

Sympathetic cooling

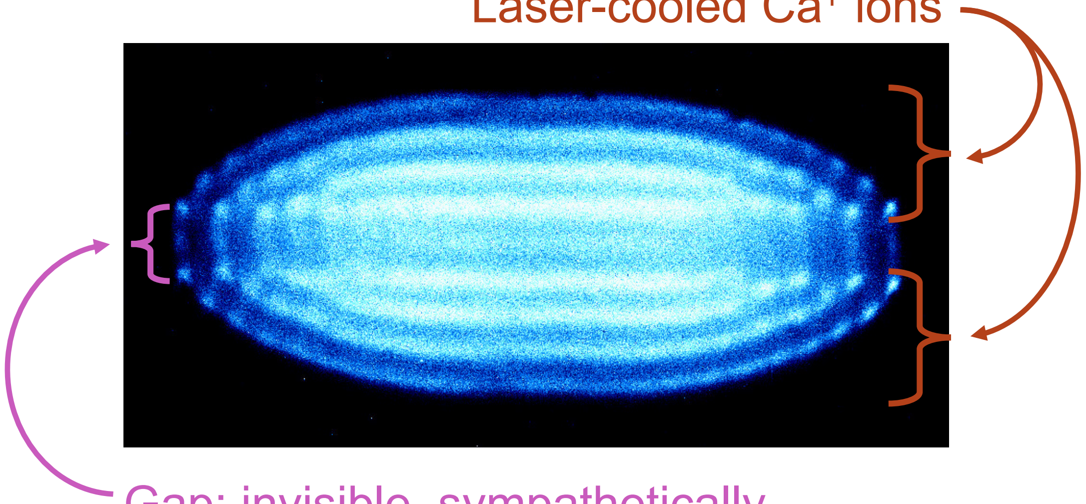
Idea

- Trap two species of charged particles in the same trap:
  a) particle of interest to be cooled (atomic ion, molecular ion, $\bar{p}$, etc.)
  b) an ion that can be laser cooled.
- Laser cool the ion b).
- Energy is exchanged between a) and b) through their Coulomb interaction.

➔ Species a) gets cooled indirectly – "sympathetically" cooled.

Example from my PhD work

Laser-cooled Ca^+ ions



Gap: invisible, sympathetically cooled N_2^+ ions

Temperatures
$T(Ca^+) \approx 18$ mK
$T(N_2^+) \approx 20$ mK

Sympathetic $\bar{p}$ cooling

Problem

- $\bar{p}$ is negatively charged.
- Needs laser-cooled negative ion as a coolant.
- So far, no anion has ever been Doppler laser cooled.

- Reason: Most anions do not have strong spectroscopic transitions.

  Excited states have most often (*) same parity as ground state
  ➔ transition (electric-dipole) forbidden.

(* Known exceptions: La^-, Os^-, Ce^-, Th^-, U^-)

Sympathetic $\bar{p}$ cooling

Possible solution

- Use molecular ion!
  (instead of atomic ion)

PRL **114**, 213001 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

Laser Cooling of Molecular Anions

Pauline Yzombard,[1] Mehdi Hamamda,[1] Sebastian Gerber,[2] Michael Doser,[2] and Daniel Comparat[1]
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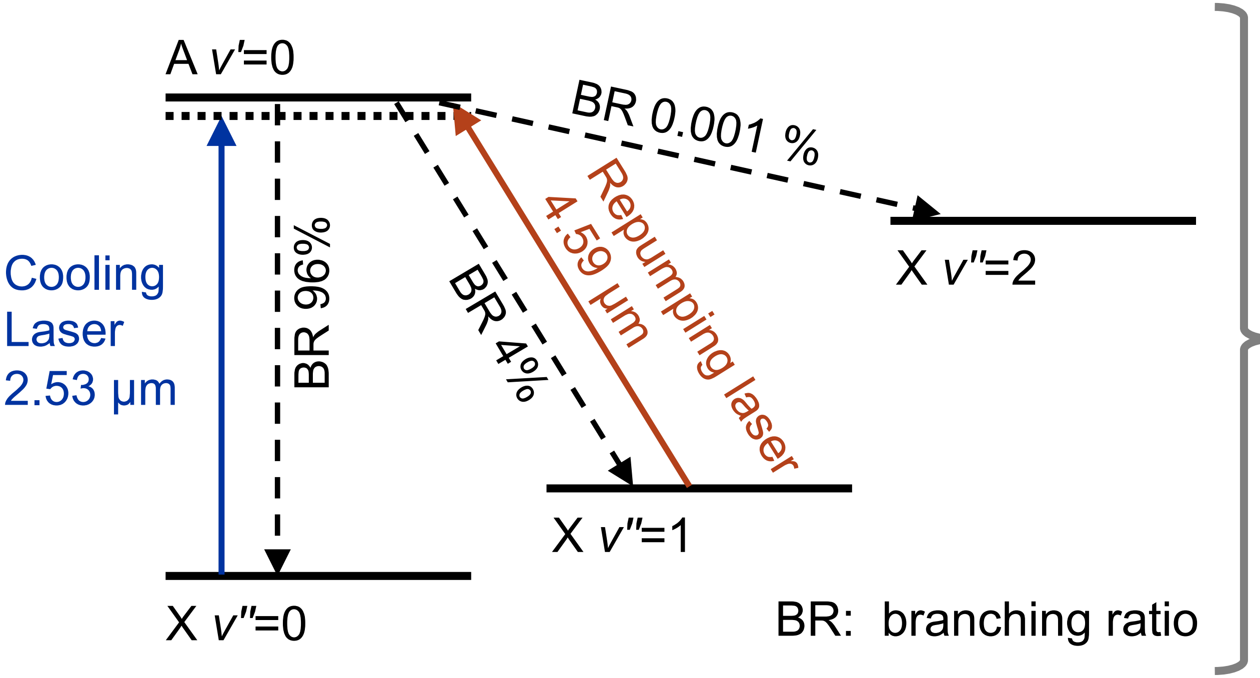
(Received 27 November 2014; published 27 May 2015)

We propose a scheme for laser cooling of negatively charged molecules. We briefly summarize the requirements for such laser cooling and we identify a number of potential candidates. A detailed computation study with C_2^-, the most studied molecular anion, is carried out. Simulations of 3D laser cooling in a gas phase show that this molecule could be cooled down to below 1 mK in only a few tens of milliseconds, using standard lasers. Sisyphus cooling, where no photodetachment process is present, as well as Doppler laser cooling of trapped C_2^-, are also simulated. This cooling scheme has an impact on the study of cold molecules, molecular anions, charged particle sources, and antimatter physics.

DOI: 10.1103/PhysRevLett.114.213001 PACS numbers: 37.10.Mn, 37.10.Rs

➔ **Goal of “Borealis” experiment:
Demonstrate laser cooling of C_2^- anions.**

Doppler cooling on X-A system



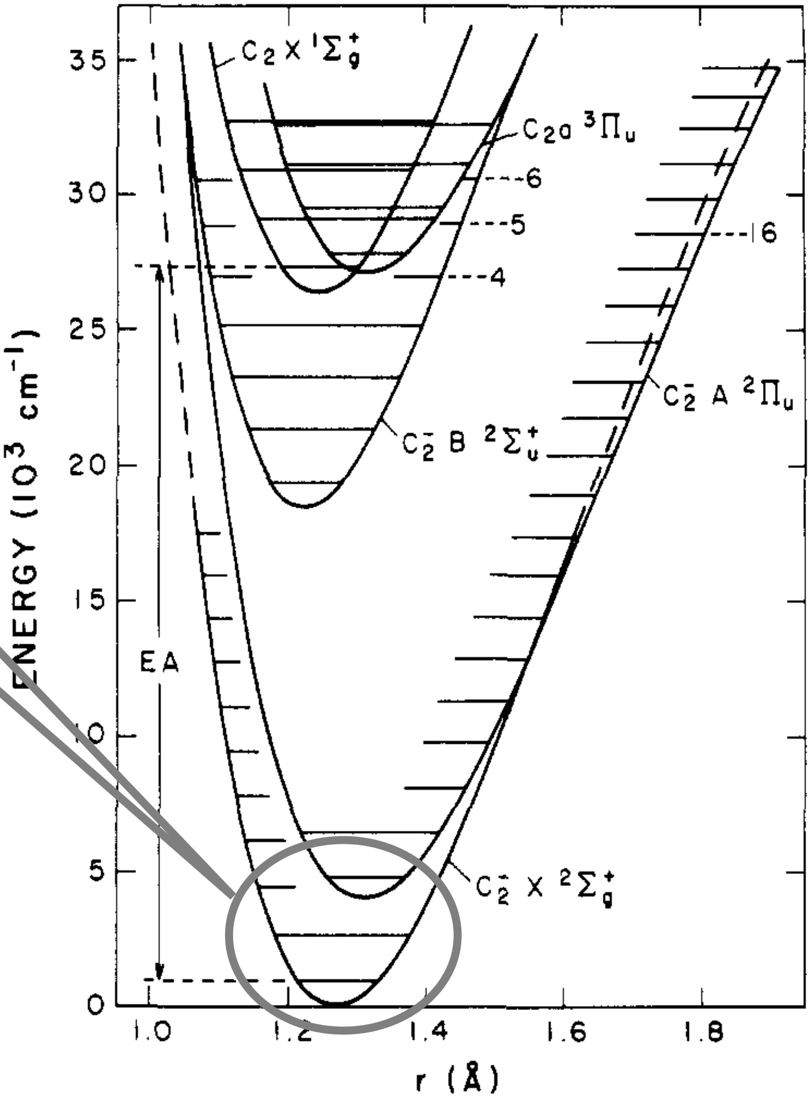
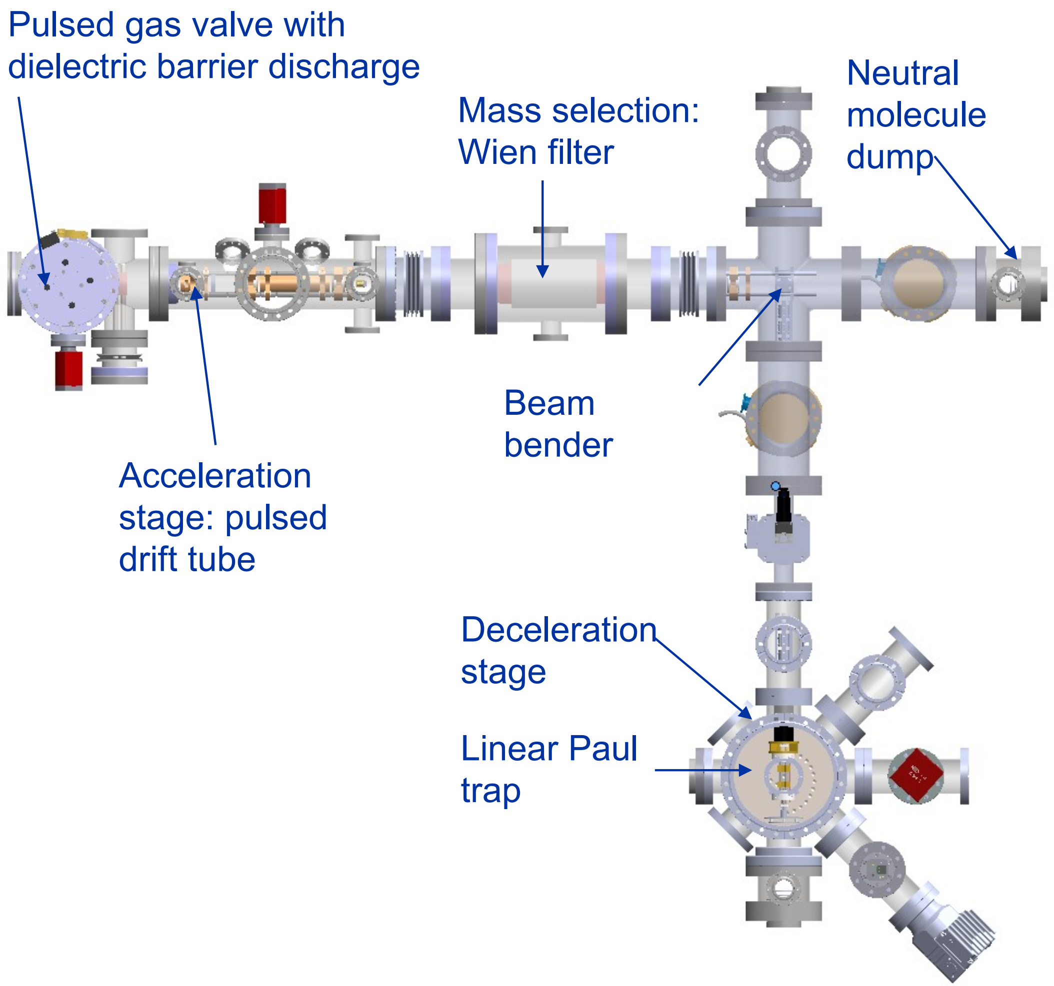
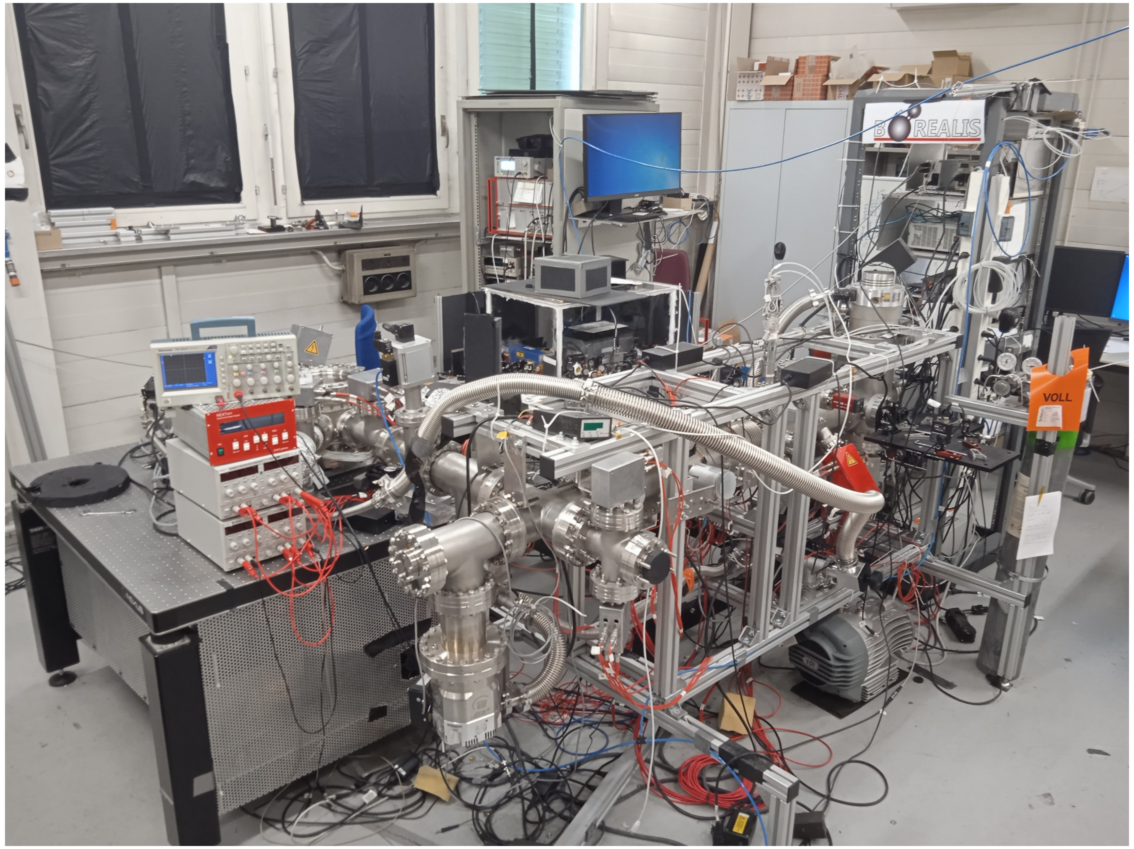


Figure: K. M. Ervin and W. C. Lineberger, J. Phys. Chem. 95, 1167 (1991).

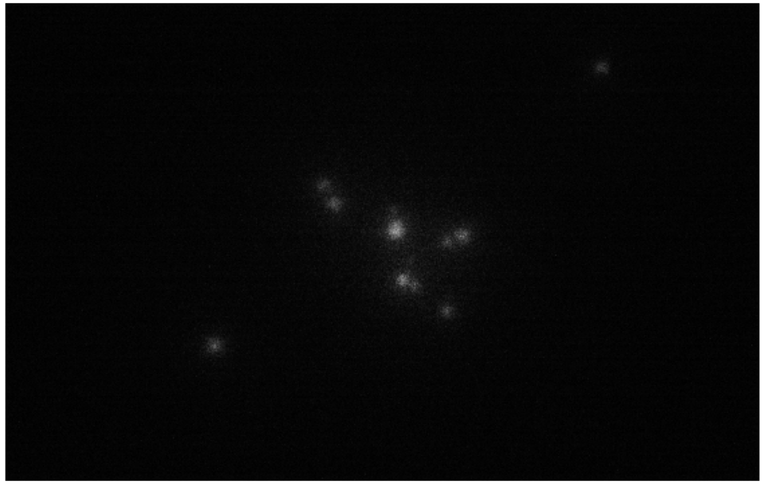
- **Nearly closed cycle**
  Repumping only v''=1 population:
  Scattering of ~50000 photons when accepting 50% population loss.
- **Line width**
  Γ(A v'=0 – X v''=0) = 2π × 5.8 kHz
  T_{Doppler} = 1.4 µK

Borealis setup





Current state and current issues



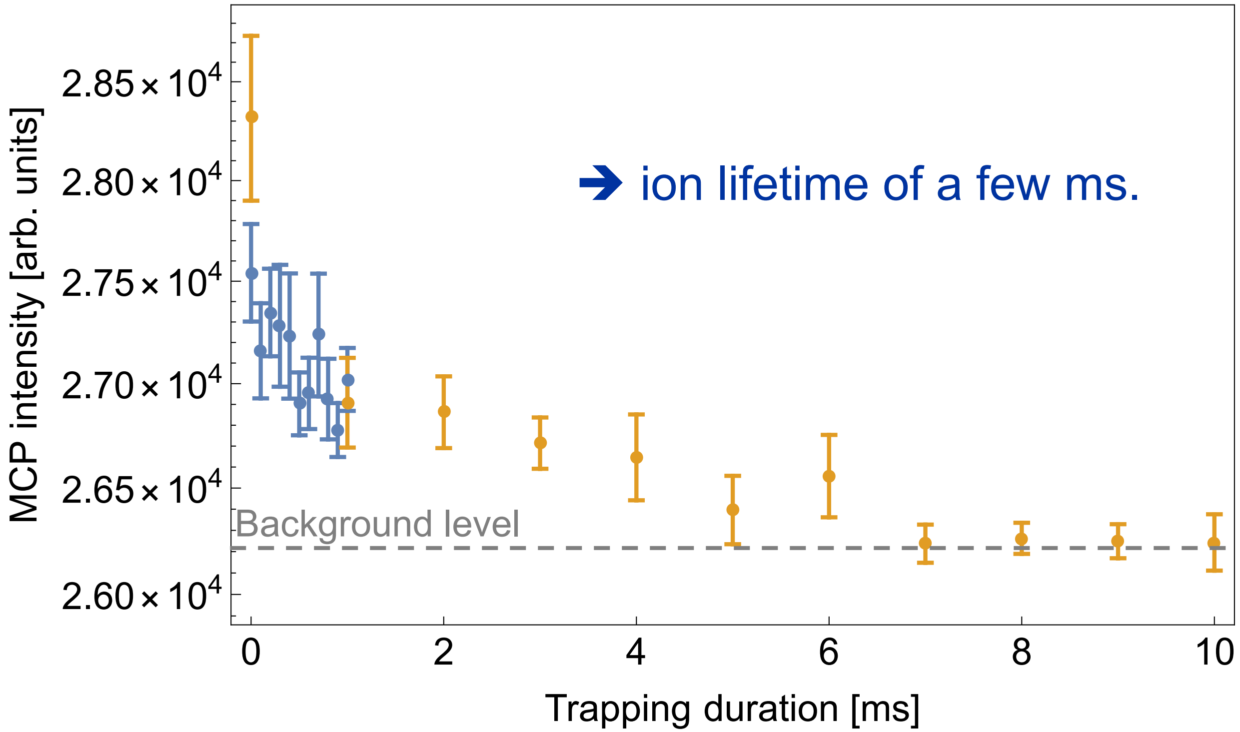
Number of ions

- Currently, only a handful of ions are trapped.
- Deceleration of ion beam and loading into trap should be improved.

Lifetime of ions

- Currently limited to a few ms.

➔ **Current effort: Increase number of trapped ions.**



Bottleneck: Deceleration stage

our case. The counted number of distinguishable dots from the MCP images corresponds to approximately 100 trapped anions. In [9, 25] about 10^7 anionic molecules were produced per valve shot by using the same valve in a similar experiment with 5% ammonia gas in He. Assuming similar discharge conditions in our valve setup, we estimate that $\sim 10^5$ C_2^- are accelerated per valve shot where the most losses occur during the deceleration of the anion beam. This effect could be reproduced from

A. Hinterberger et al. J. Phys. B 52, 225003 (2019).

➔ **We only trap 1 in 1000 ions. (At best!)**

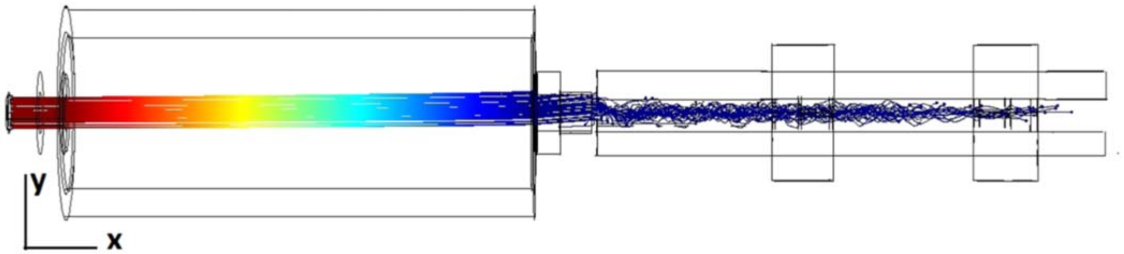
Deceleration stage

Several iterations of the deceleration stage have been tried before.

Current implementation

- Glass tube with high-resistive coating
- One side grounded: ion entrance
- Other side: at -1.8 kV (same potential as trap)

➔ Decelerating electrostatic potential.



A. Hinterberger et al. J. Phys. B 52, 225003 (2019).

Limitations

- Trap must be held at floating potential (-1.8 kV).
- Kinetic energy distribution of ion beam is not affected by deceleration: ions with too high/too low kinetic energy are not trapped.

Pulsed drift tube deceleration

Literature search

Pulsed drift tube for deceleration of an ion beam and loading into Paul trap.

Advantages

- Drift tube pulsed to 0V while ions are inside
  ➔ trap can be at ground potential.
- Potential gradient over extension of tube
  ➔ compression of kinetic energy distribution.
  (pulsed operation: not limited by Liouville's theorem!)

REVIEW OF SCIENTIFIC INSTRUMENTS **86**, 103111 (2015)

Deceleration, precooling, and multi-pass stopping of highly charged ions in Be^+ Coulomb crystals

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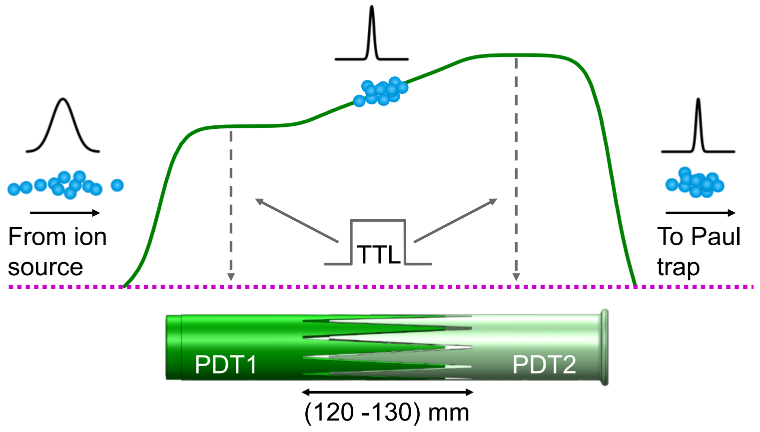
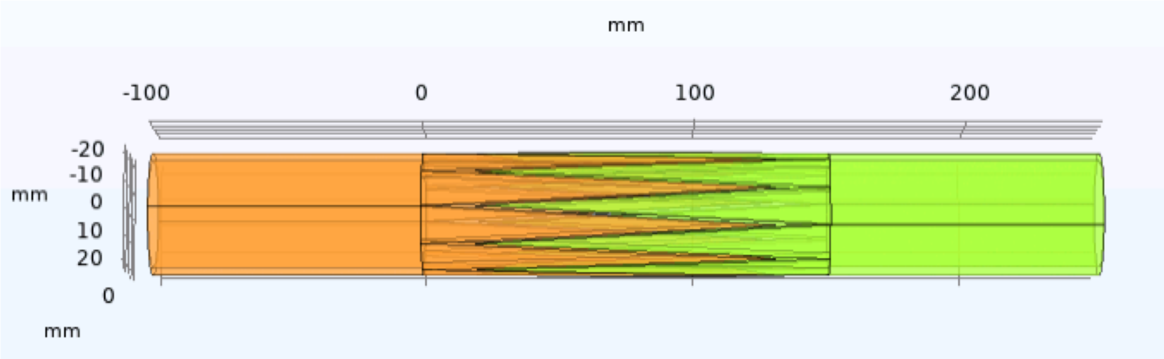
(Received 15 July 2015; accepted 8 October 2015; published online 26 October 2015)

Preparing highly charged ions (HCIs) in a cold and strongly localized state is of particular interest for frequency metrology and tests of possible spatial and temporal variations of the fine structure constant. Our versatile preparation technique is based on the generic modular combination of a pulsed ion source with a cryogenic linear Paul trap. Both instruments are connected by a compact beamline with deceleration and precooling properties. We present its design and commissioning experiments regarding these two functionalities. A pulsed buncher tube allows for the deceleration and longitudinal phase-space compression of the ion pulses. External injection of slow HCIs, specifically Ar^{13+}, into the linear Paul trap and their subsequent retrapping in the absence of sympathetic cooling is demonstrated. The latter proved to be a necessary prerequisite for the multi-pass stopping of HCIs in continuously laser-cooled Be^+ Coulomb crystals. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4934245]

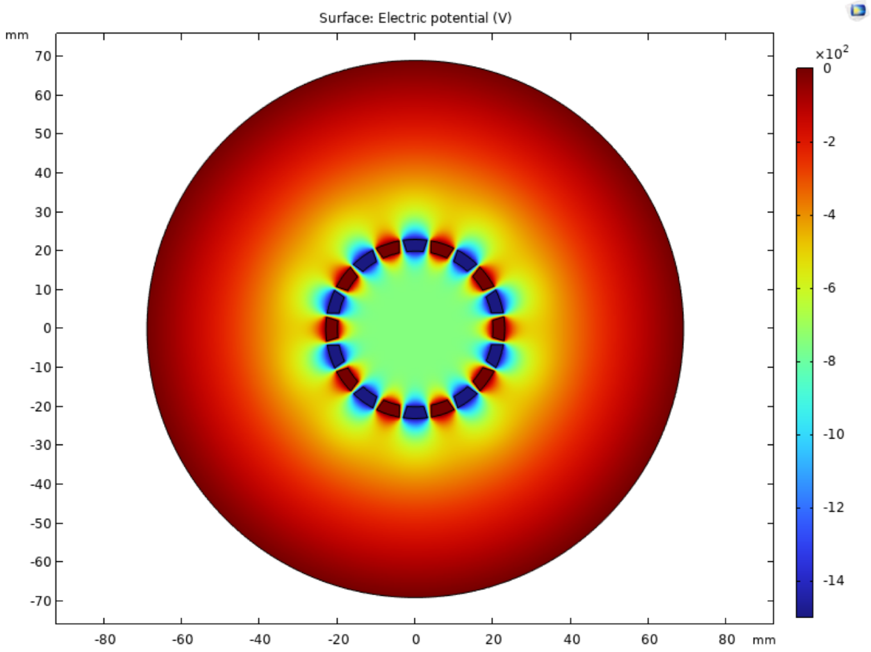


Simulation for implementation at Borealis

Project of Sneha Jos
(Boston University "Study Abroad Program")



Electrode configuration modeled in COMSOL.
➔ Serrated structure gives rise to linearly increasing potential along symmetry axis while requiring only two electrodes.

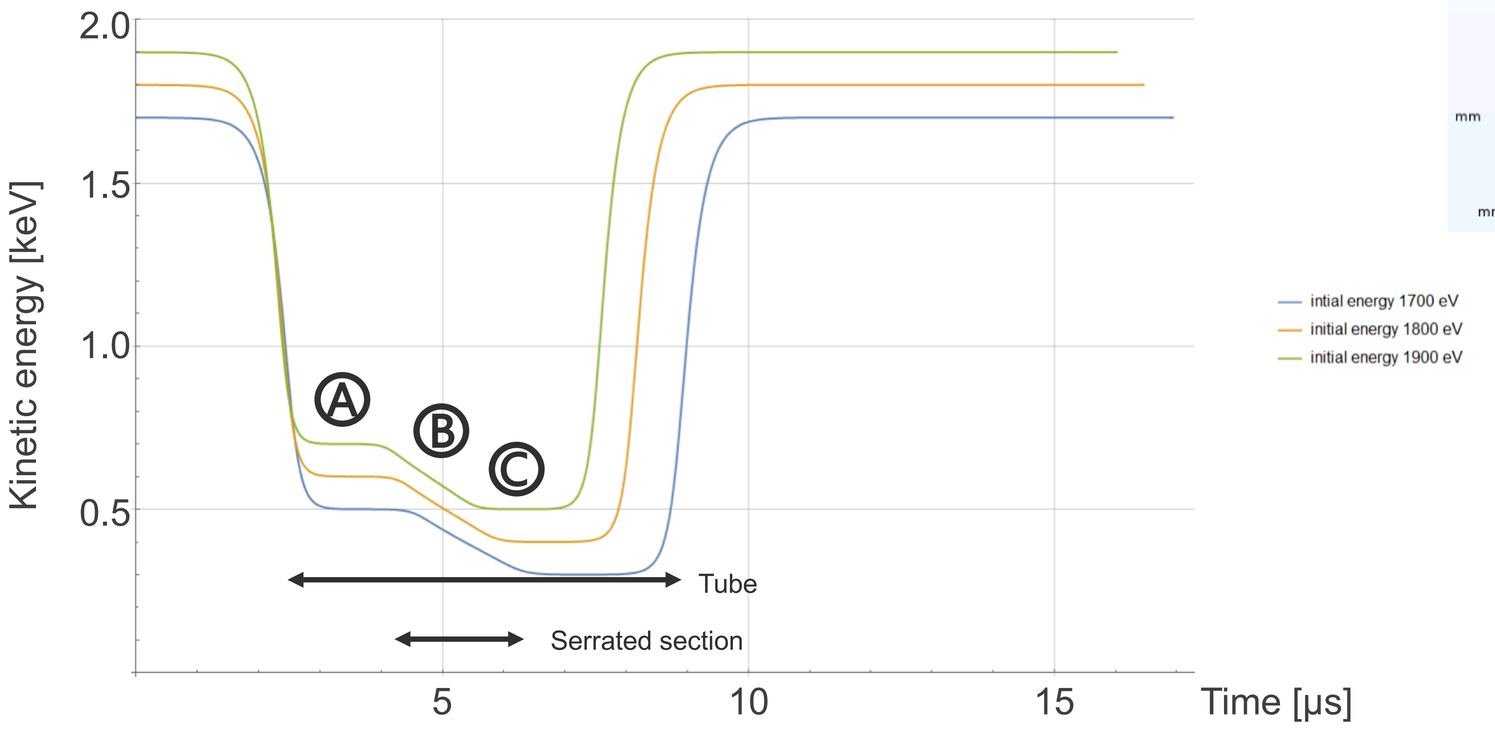


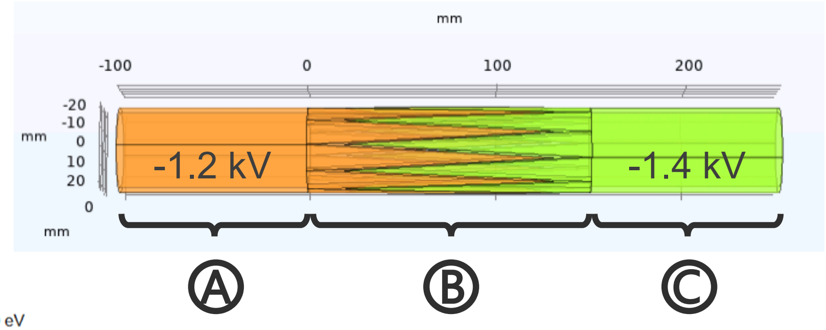
Electric potential in a cut-plane along the section with serrated electrodes.

Simulation for implementation at Borealis

C_2^- ions passing through decelerator: Kinetic energy as a function of time.

Static electric potential: decelerator not pulsed.



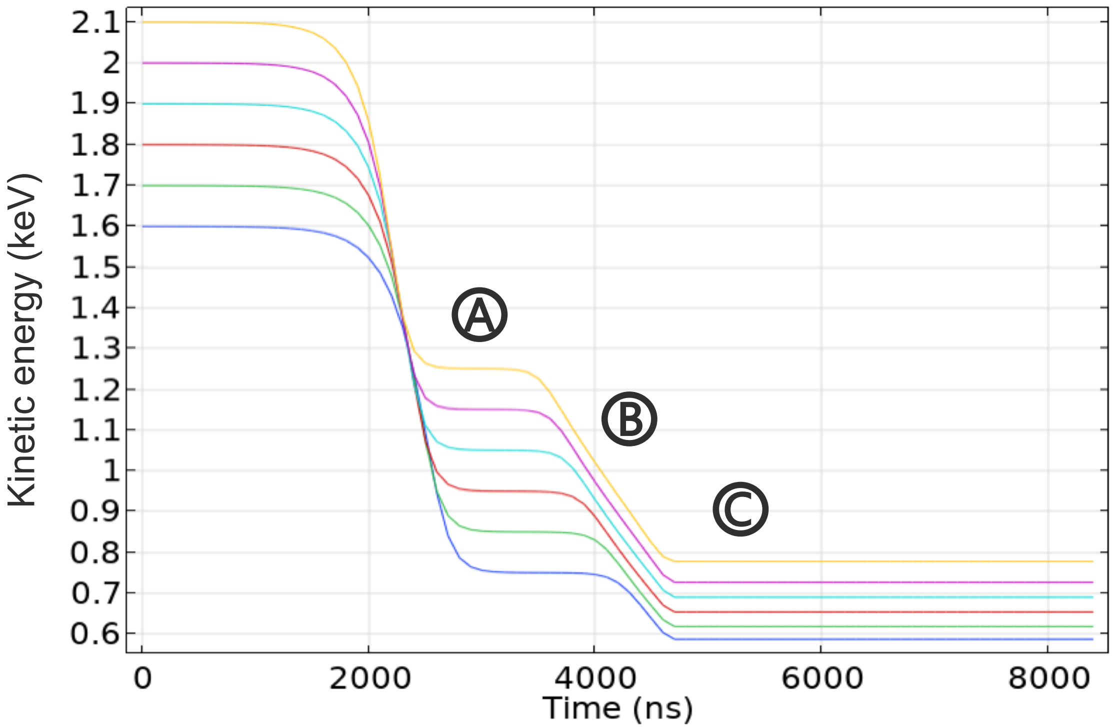


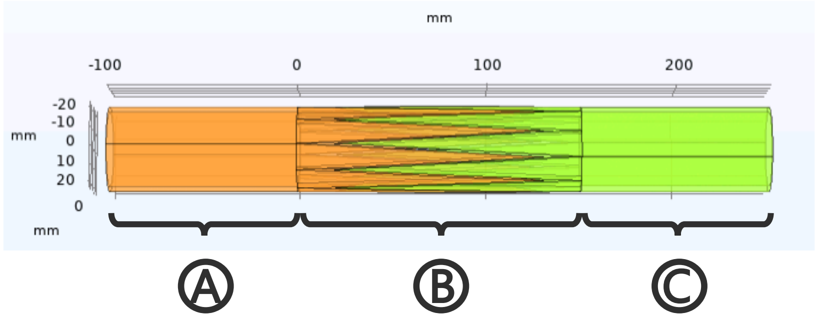
Simulation for implementation at Borealis

C_2^- ions passing through decelerator: Kinetic energy as a function of time.

Decelerator pulsed to 0V while ions are within serrated section.

5 ions, kinetic energy spread: 500 eV



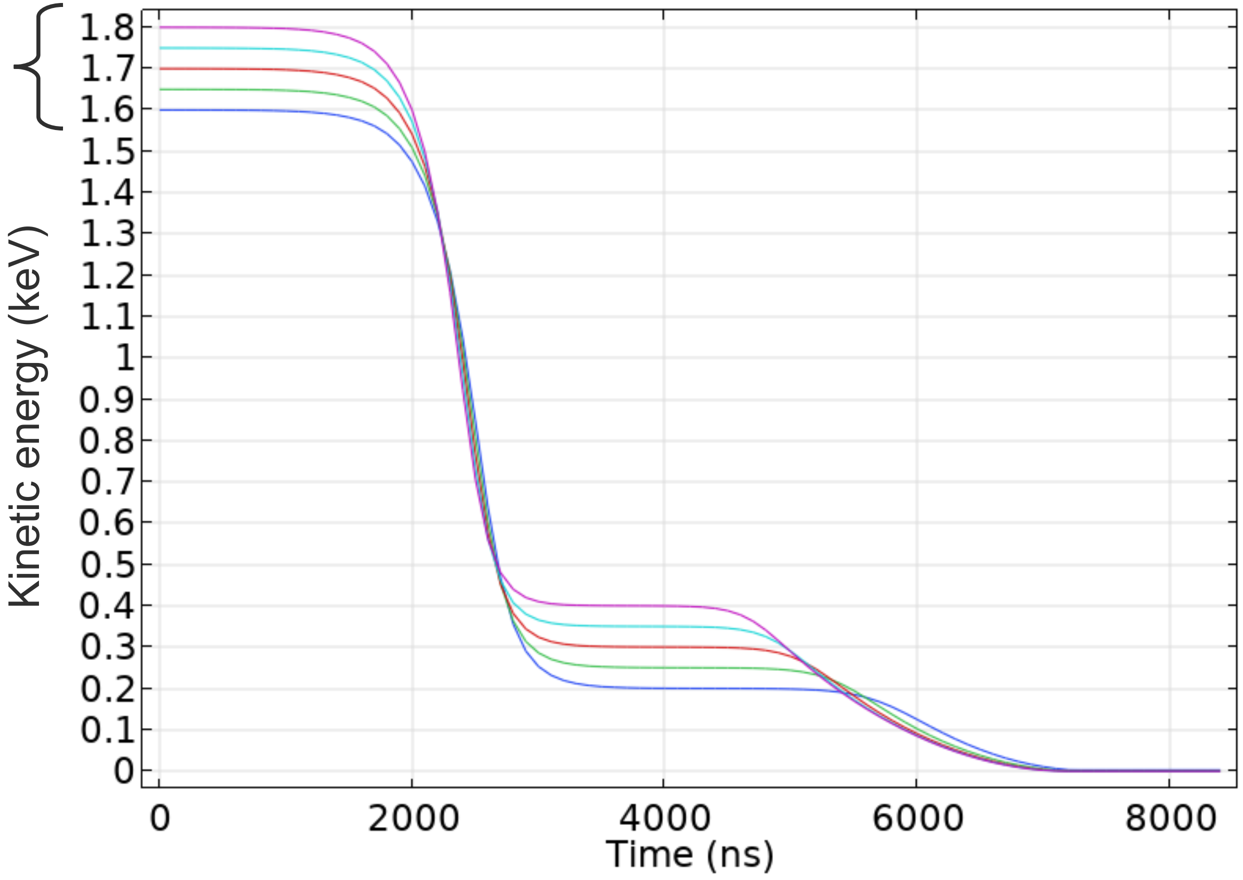


Kinetic energy spread: 200 eV

Simulation for implementation at Borealis

Deceleration to stand-still.

Kinetic energy spread: 200 eV



Kinetic energy spread in the eV range.

Pulsed drift tube decelerator: Conclusion

A pulsed drift tube decelerator might be a viable alternative to the current electrostatic deceleration for use at Borealis.

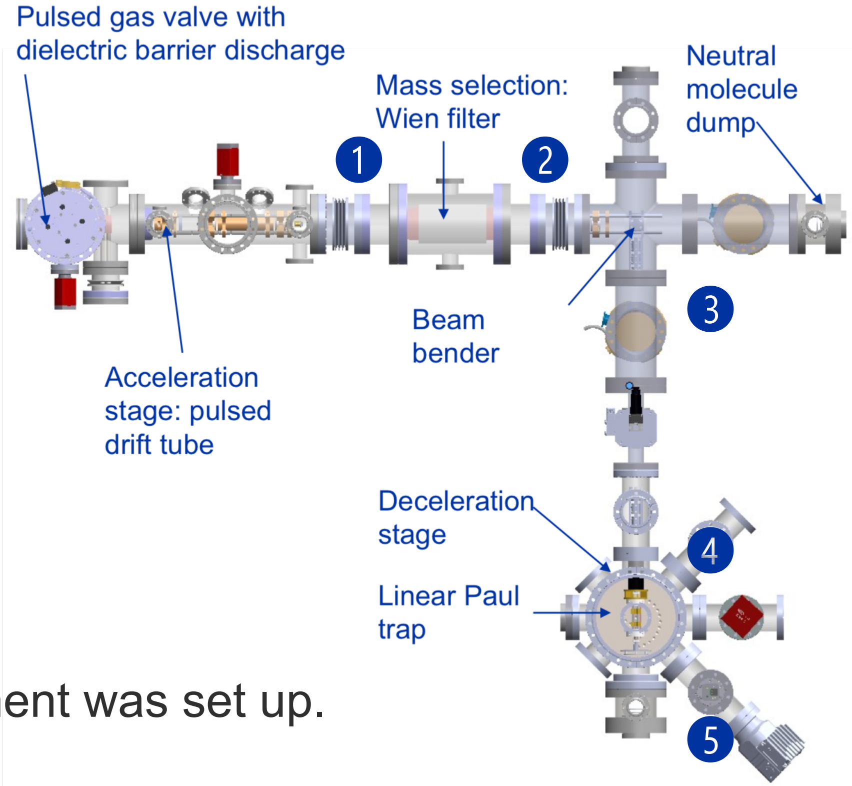
With more detailed simulations, we will study the performance and limitations of this type of decelerator.

Experiment: Improvement of beam transport

Plan

- Measure beam current at different stages along beam line with Faraday cup (❶, ❷, ❸, ❹, ❺).
- Localize bottle necks.

➔ We opened the beam line to realize this plan.



Challenges

- Access to beam is very limited.
- Different stages have been added sequentially when the experiment was set up.
- After adding elements, access has been blocked: Vacuum flanges not accessible, Faraday cup cannot be inserted.

➔ Systematic beam diagnostic / tracing of ion current hardly possible with reasonable effort.

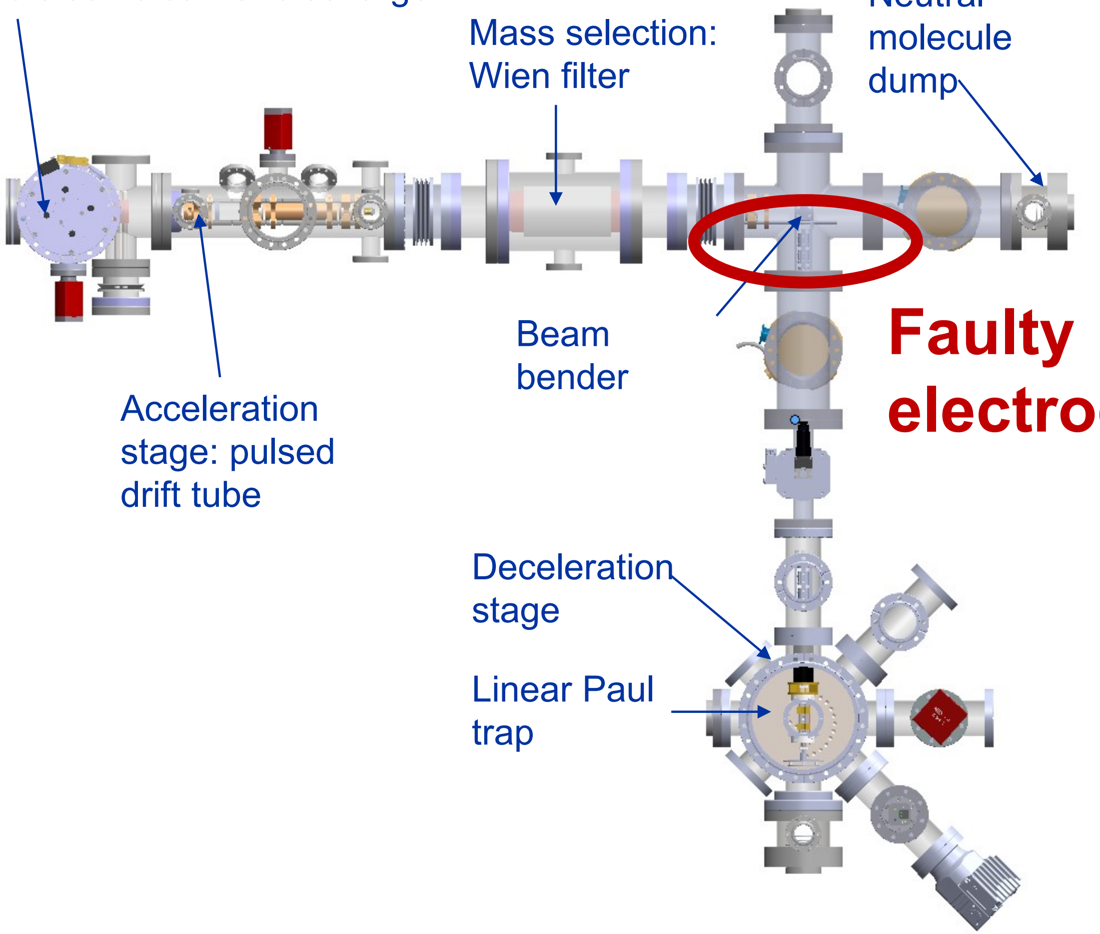
Experiment: Improvement of beam transport

One problem localized

- Correction electrode after beam bender was not connected (wrong wiring).

Actions

- Wiring corrected.
- Unfortunately HV feedthrough broken.
- Feedthrough replaced.



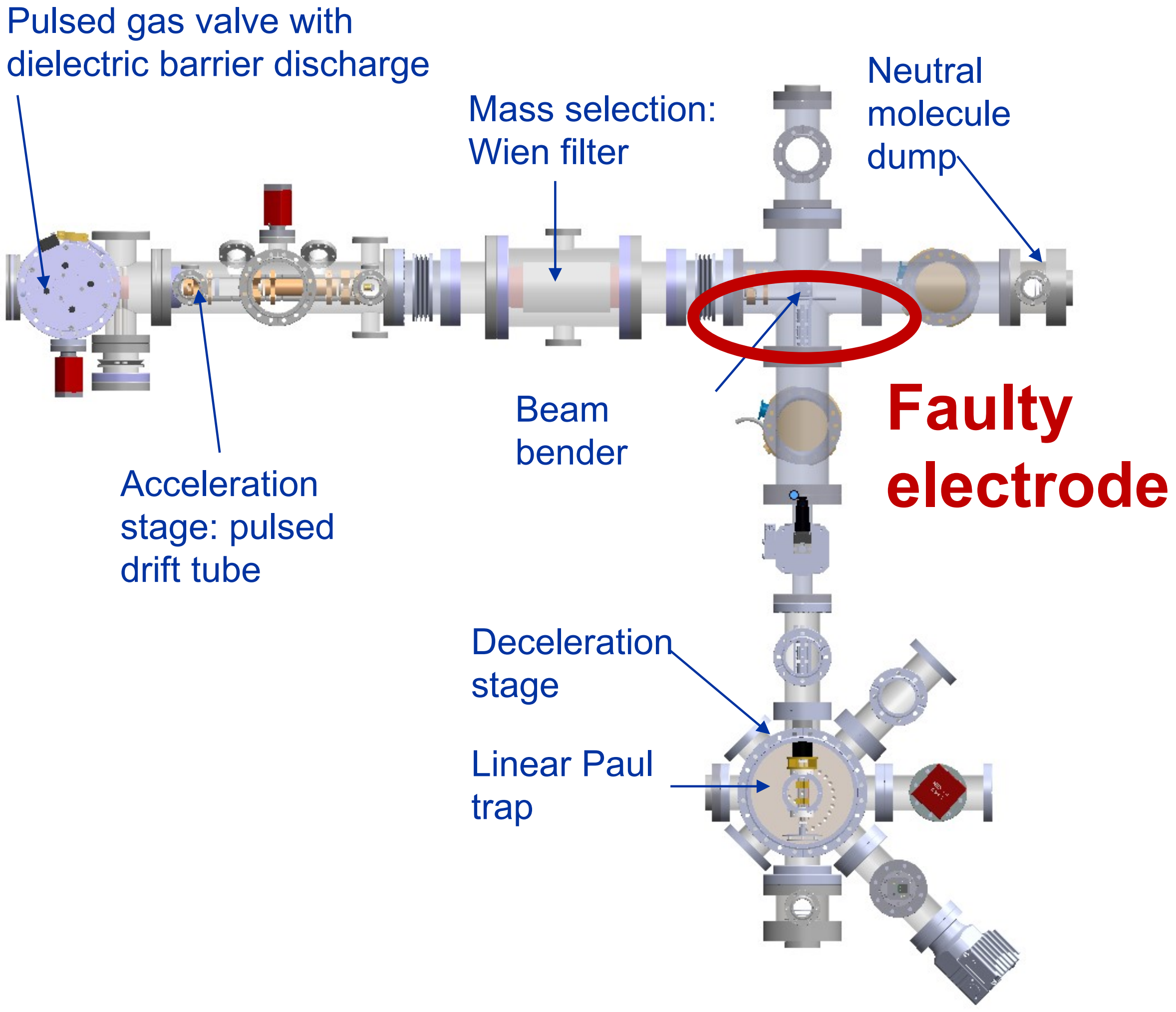
Experiment: Improvement of beam transport

Current situation

- Experiment evacuated again.
- Up and running again since last week.
- Beam transport is currently being optimized.

Bachelor thesis project

- Frederik Zielke from TU Dortmund is doing his Bachelor thesis on beam characterization and beam manipulation (beam transport optimization) at Borealis.
- Helpful discussions and ideas for potential optimization.
- Very helpful support in the practical lab work.



Improvement of beam transport: Conclusions

Any beam diagnostic and improvement of beam transport at Borealis is challenging because of the way the experiment has been setup.

**We could localize and correct one substantial problem:
unconnected electrode.**

We will soon know how much of an improvement will result from this.

Based on that, we will decide on the next steps to be taken.

Upcoming measurement: Collinear ion-beam spectroscopy of C_2^-

Prerequisite for laser cooling

- Precise knowledge of C_2^- rovibronic energy level structure
- Characterization of rovibrational population distribution of C_2^- ions produced in our source.

Method

- Photodetachment spectroscopy of C_2^- in the ion beam
- Previous attempt:
  spectroscopy with **CW laser crossing ion beam perpendicularly**,
  effective laser power increased with enhancement cavity
  → not successful: **cavity could not be locked to laser**.
- Alternative:
  collinear spectroscopy of C_2^- with pulsed laser, **detection of neutral C_2 molecules** formed in photodetachment
  → high instantaneous laser power
  → very sensitive detection

Measurement at DESIREE facility in Stockholm

Collinear spectroscopy at Borealis

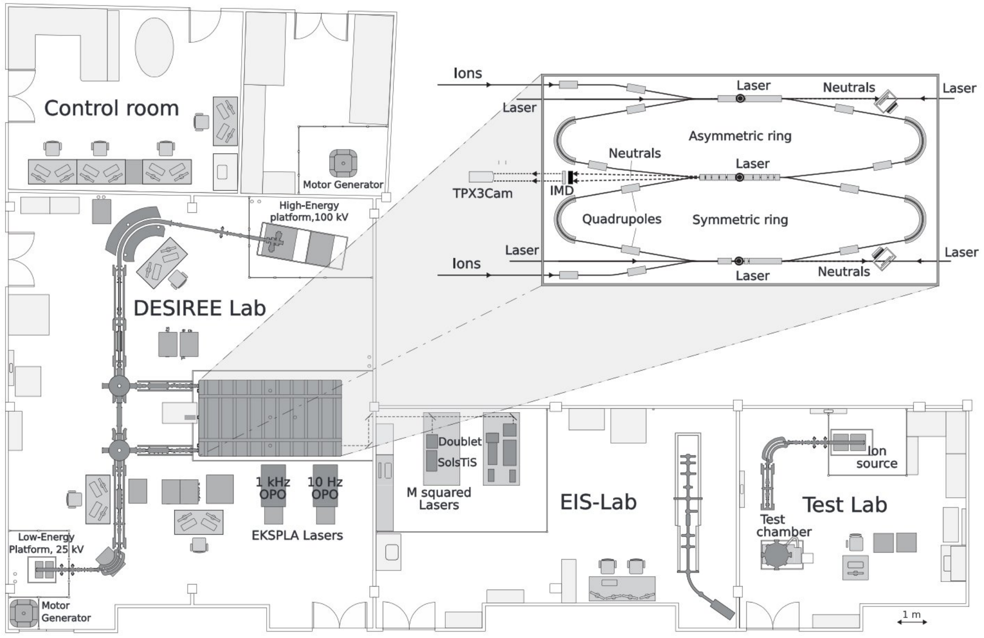
Rather involved modification of setup needed.

Alternative

Use existing user-facility:
DESIREE lab at Stockholm University.

DESIREE

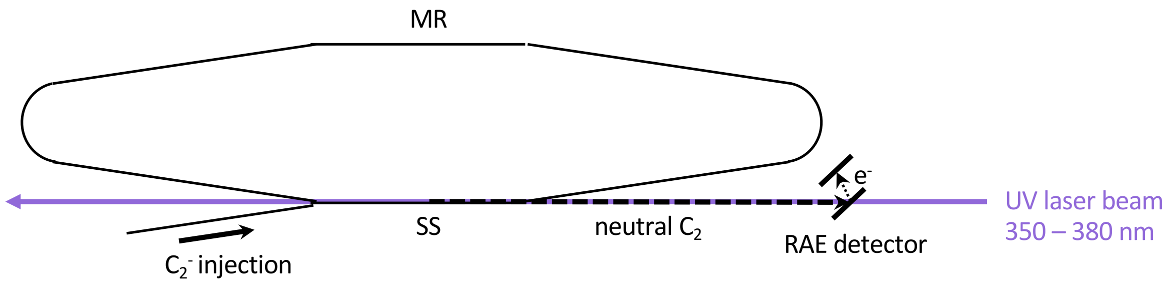
- “Double ElectroStatic Ion Ring ExpEriment”:
  ion storage ring for spectroscopy and reaction experiments with cold atomic and molecular ions.
- International user facility
- Access to external users:
  beam time of usually 1 week, 30 weeks per year
  (I have been there as a user in 2022 and 2023 for an HD^+ spectroscopy project.)



C_2^- photodetachment spectroscopy at DESIREE

Planned experiment

- Attach our C_2^- source (Even-Lavie valve with dielectric barrier discharge) to one of the source platforms at DESIREE.
- Produce and mass-select C_2^- with high-resolution sector magnet.
- Store a beam of C_2^- ions at ~10 keV in one of the DESIREE rings.
- Overlap ion beam with collinear laser beam for photodetachment.
- Detect neutral C_2 molecules formed in photodetachment.



C_2^- photodetachment spectroscopy at DESIREE

Planned measurements

a) Survey spectrum

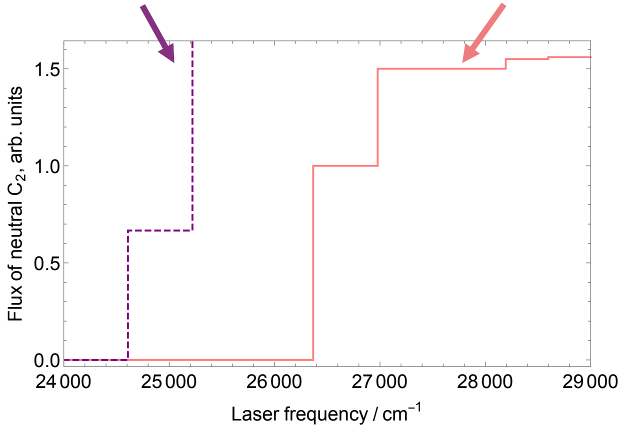
- low resolution
- localization of thresholds corresponding to transitions between different rovibrational levels of the C_2^- anion and the neutral C_2 molecule.
- determine rovibrational population distribution.

b) High-resolution spectrum

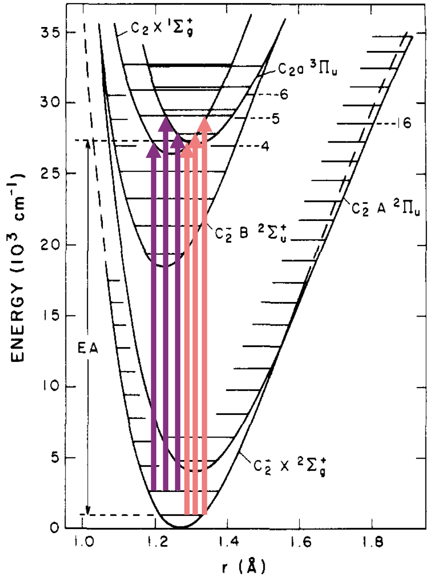
- Accurate measurement of the transition between rovibrational ground states.
- Accurate measurement of the electron affinity of C_2.
- Interest: electron configuration interaction effects in *ab initio* calculations.

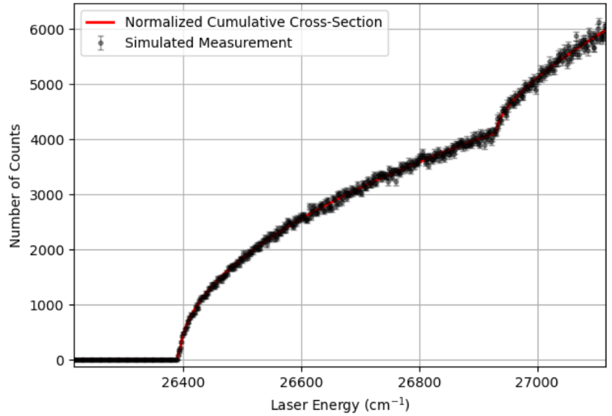
C_2^-.in first vibrational excited state (v''=1)

C_2^-.in vibrational ground state (v''=0)



Idealized photodetachment spectra of C_2^-.





Simulated photodetachment spectrum for C_2^- in vib. GS.

Conclusion

Two serious challenges at Borealis:

- Number of C_2^- ions trapped.
- Lifetime of ions

These issues need to be addressed for successful spectroscopy and cooling of C_2^-.

Ion beam spectroscopy of C_2^-

- Applied for beam time at DESIREE for the autumn 2024 experiment period (August to December)
- Goals:
  Determine rovibrational state distribution
  Characterize rovibronic level structure: accurate EA

Acknowledgements

- AEgIS team at CERN for support.
- Project students:
  Sneha Jos and Frederik Zielke
- Dag Hanstorp (ISOLDE, Gothenburg University) for input and support for collinear spectroscopy

Marie Skłodowska-Curie Actions