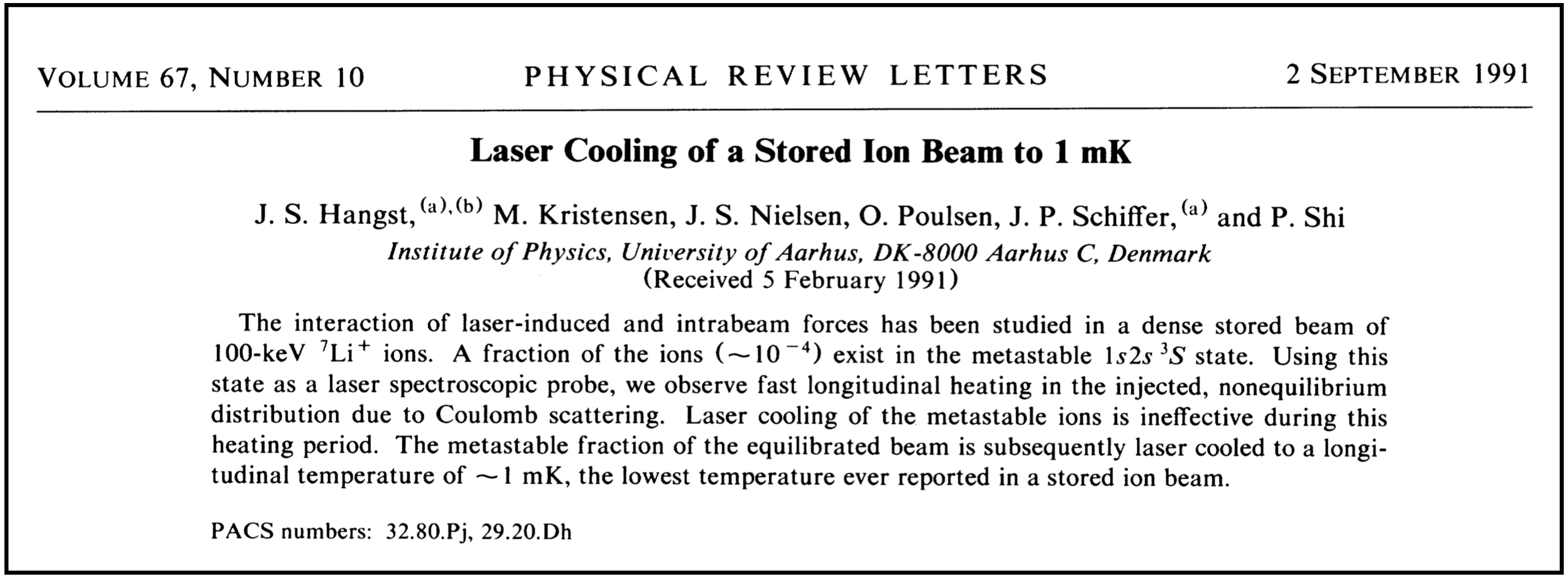
By special request from Sergei

Beam vacuum in ASTRID

ASTRID beam vacuum



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Laser Cooling of a Stored Ion Beam to 1 mK

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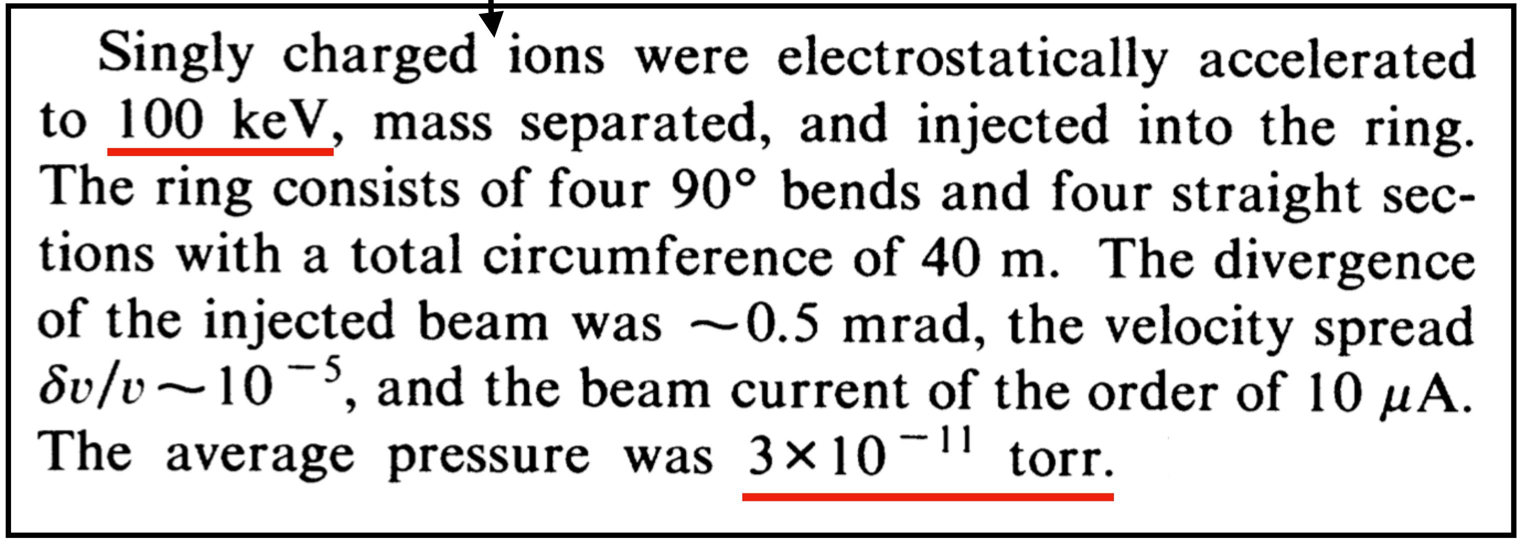
(Received 5 February 1991)

The interaction of laser-induced and intrabeam forces has been studied in a dense stored beam of 100-keV $^7\mathrm{Li}^+$ ions. A fraction of the ions ($\sim 10^{-4}$) exist in the metastable $1s2s\,^3S$ state. Using this state as a laser spectroscopic probe, we observe fast longitudinal heating in the injected, nonequilibrium distribution due to Coulomb scattering. Laser cooling of the metastable ions is ineffective during this heating period. The metastable fraction of the equilibrated beam is subsequently laser cooled to a longitudinal temperature of ~1 mK, the lowest temperature ever reported in a stored ion beam.

PACS numbers: 32.80.Pj, 29.20.Dh

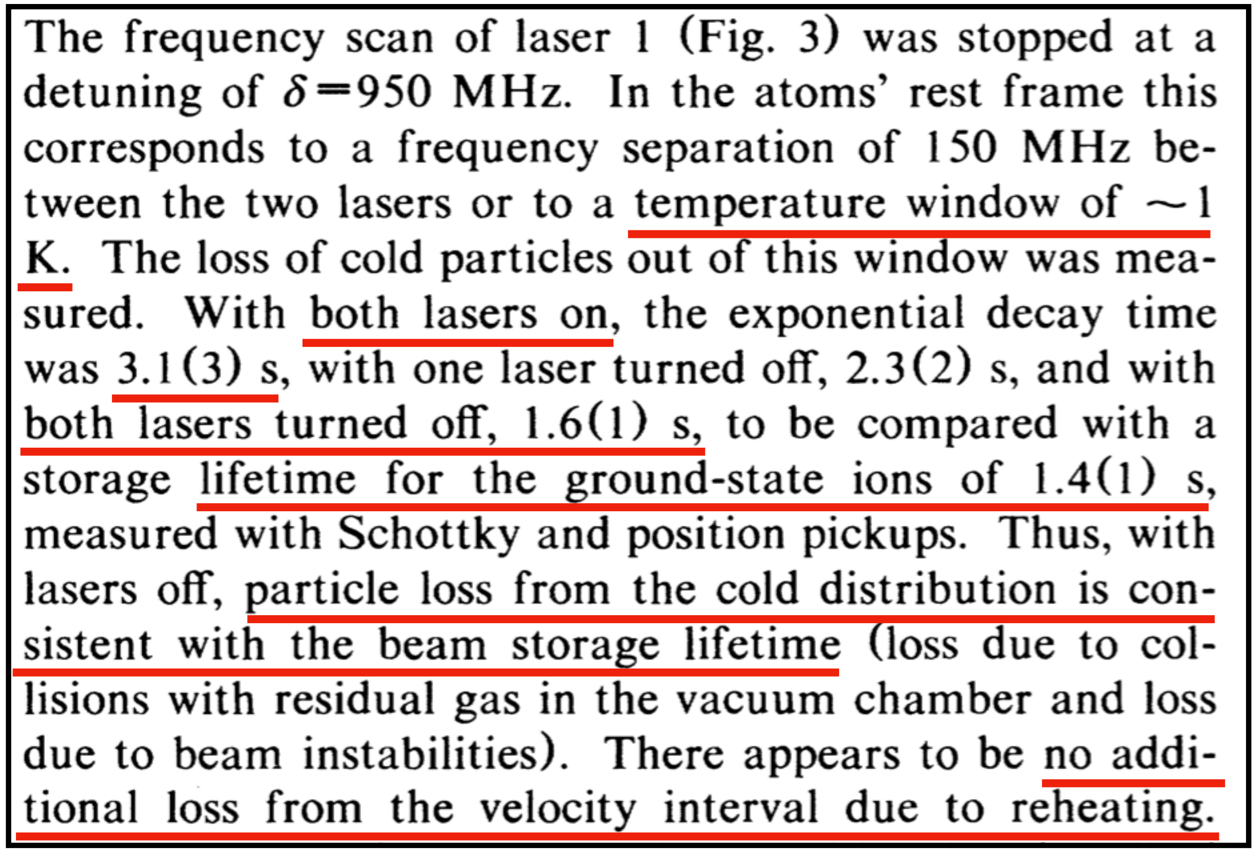
Li



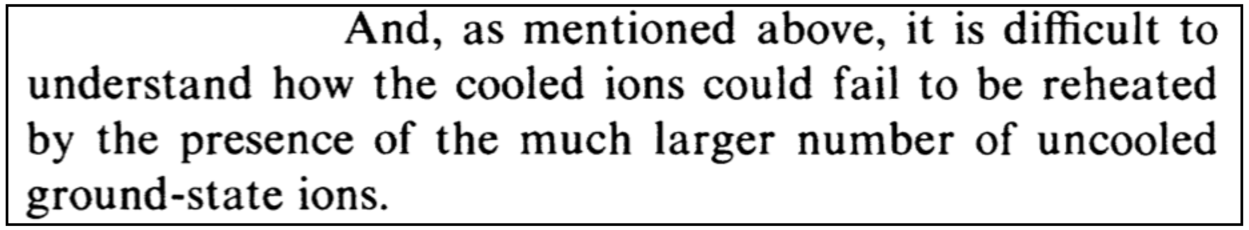
Singly charged ions were electrostatically accelerated to 100 keV, mass separated, and injected into the ring. The ring consists of four 90° bends and four straight sections with a total circumference of 40 m. The divergence of the injected beam was ~0.5 mrad, the velocity spread $\delta v/v \sim 10^{-5}$, and the beam current of the order of 10 μA. The average pressure was 3×10^{-11} torr.

$\sim 4 \cdot 10^{-11}$ mbar

ASTRID beam lifetime



The frequency scan of laser 1 (Fig. 3) was stopped at a detuning of $\delta = 950$ MHz. In the atoms' rest frame this corresponds to a frequency separation of 150 MHz between the two lasers or to a temperature window of ~ 1 K. The loss of cold particles out of this window was measured. With both lasers on, the exponential decay time was 3.1(3) s, with one laser turned off, 2.3(2) s, and with both lasers turned off, 1.6(1) s, to be compared with a storage lifetime for the ground-state ions of 1.4(1) s, measured with Schottky and position pickups. Thus, with lasers off, particle loss from the cold distribution is consistent with the beam storage lifetime (loss due to collisions with residual gas in the vacuum chamber and loss due to beam instabilities). There appears to be no additional loss from the velocity interval due to reheating.

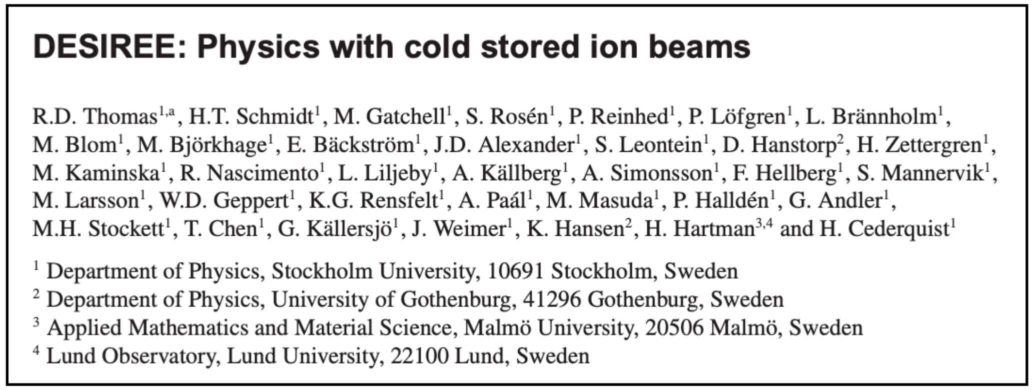


And, as mentioned above, it is difficult to understand how the cooled ions could fail to be reheated by the presence of the much larger number of uncooled ground-state ions.

Applications of *classical* cold / crystalline ion beams

A browse through existing literature
and some brainstorming

Cold chemistry at DESIREE



DESIREE: Physics with cold stored ion beams

R.D. Thomas[1,a], H.T. Schmidt[1], M. Gatchell[1], S. Rosén[1], P. Reinhed[1], P. Löfgren[1], L. Brännholm[1], M. Blom[1], M. Björkhage[1], E. Bäckström[1], J.D. Alexander[1], S. Leontein[1], D. Hanstorp[2], H. Zettergren[1], M. Kaminska[1], R. Nascimento[1], L. Liljeby[1], A. Källberg[1], A. Simonsson[1], F. Hellberg[1], S. Mannervik[1], M. Larsson[1], W.D. Geppert[1], K.G. Rensfelt[1], A. Paál[1], M. Masuda[1], P. Halldén[1], G. Andler[1], M.H. Stockett[1], T. Chen[1], G. Källersjö[1], J. Weimer[1], K. Hansen[2], H. Hartman[3,4] and H. Cederquist[1]

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DESIREE as a new tool for interstellar ion chemistry

Henning T. Schmidt[1], Henrik A.B. Johansson[1], Richard D. Thomas[1], Wolf D. Geppert[1], Nicole Haag[1], Peter Reinhed[1], Stefan Rosén[1], Mats Larsson[1], Håkan Danared[2], K.-G. Rensfelt[2], Leif Liljeby[2], Lars Bagge[2], Mikael Björkhage[2], Mikael Blom[2], Patrik Löfgren[2], Anders Källberg[2], Ansgar Simonsson[2], Andras Paál[2], Henning Zettergren[3] and Henrik Cederquist[1]

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The possibility to perform merged-beams experiments with positive and negative ions that are stored and cooled to low temperatures by temperature equilibrium with the surroundings is the most clearly unique feature of DESIREE. Consider the simplest mutual neutralization (MN) process between small atomic cations and anions: $A^+ + B^- \rightarrow A + B + E_R$.

By storage for extended periods of time (seconds or even minutes), infrared active molecular ions, which may be hot after production in the ion sources, will relax and eventually reach thermal equilibrium with the temperature of the surrounding vacuum walls. To take further advantage of this and at the same time achieve a very low background pressure, the electrodes and inner vacuum chamber walls will be cooled to cryogenic temperatures (10–20 K).

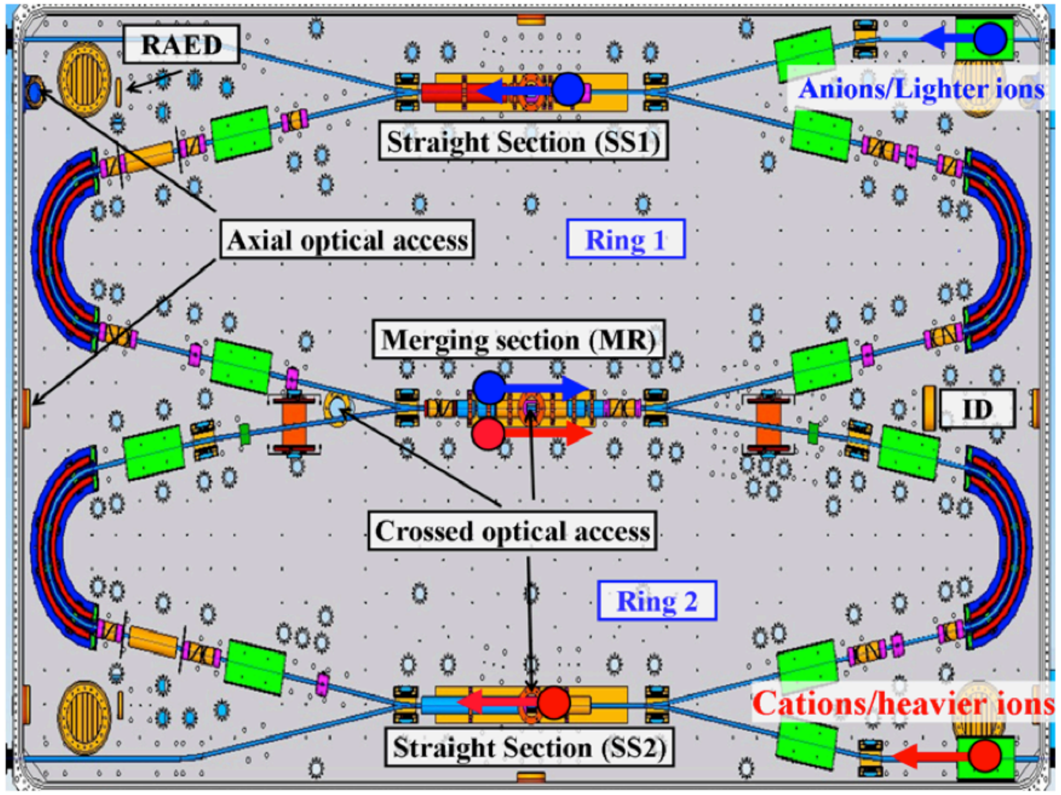

Figure 2. A rough schematic of the heart of the DESIREE facility showing: the two rings, the two straight sections in each ring (SS1,SS2) and the common straight section – the merging section MR. The position of several of the available particle detectors: the imaging detector (ID) and a resistive anode encoder (RAED), are noted, as are viewports for laser access allowing co-axial and crossed laser-ion beam interactions.

Cold chemistry at CSR

Astrochemical studies at the Cryogenic Storage Ring

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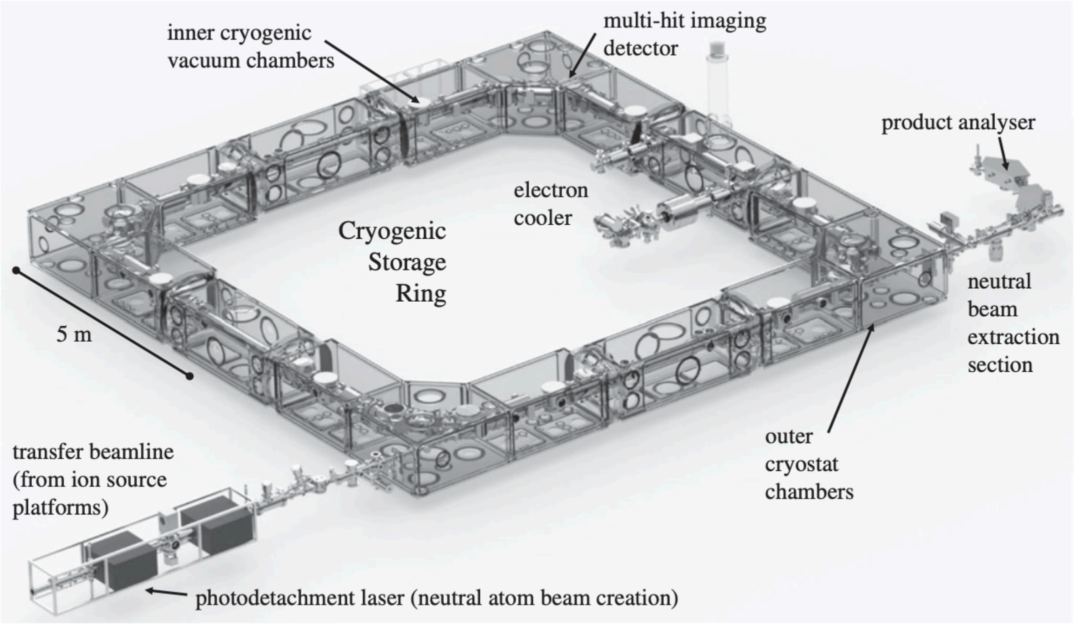
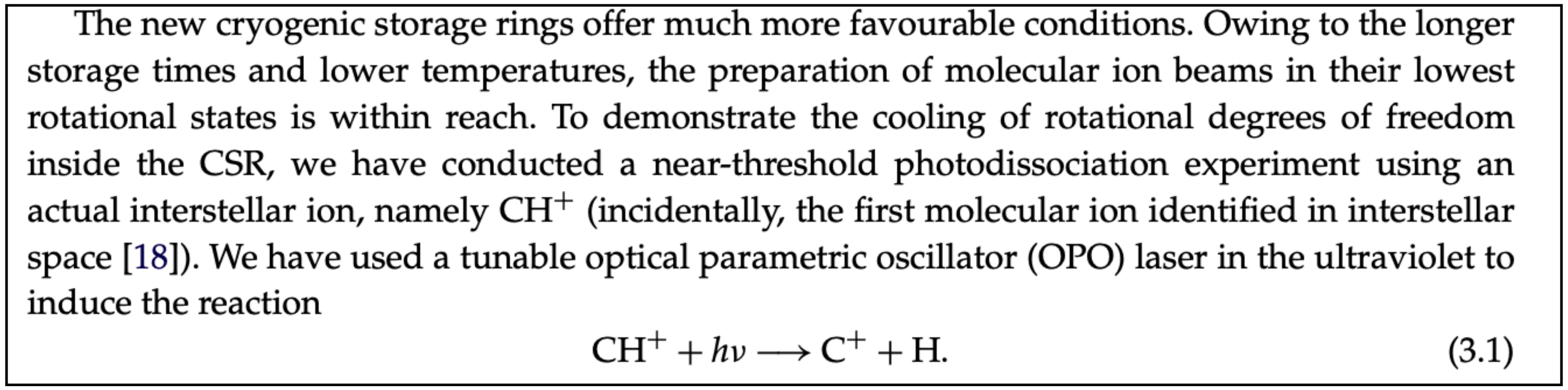


Figure 1. Overview of the CSR. The experimental set-ups relevant for astrochemical studies are labelled in the insets. The image includes the new low-energy electron cooler as well as the photodetachment section for the neutral beam creation in the injection beamline, the neutral beam extraction and some of the corresponding detector units.



The new cryogenic storage rings offer much more favourable conditions. Owing to the longer storage times and lower temperatures, the preparation of molecular ion beams in their lowest rotational states is within reach. To demonstrate the cooling of rotational degrees of freedom inside the CSR, we have conducted a near-threshold photodissociation experiment using an actual interstellar ion, namely CH^+ (incidentally, the first molecular ion identified in interstellar space [18]). We have used a tunable optical parametric oscillator (OPO) laser in the ultraviolet to induce the reaction

$$CH^+ + h\nu \longrightarrow C^+ + H. \quad (3.1)$$

Cryogenic rings can only cool infrared-active molecules …
is there a market for experiments with cold atomic ions?

Something “crazy” …

ARIES topical workshop on

Storage Rings &
Gravitational Waves
SRGW2021

Chairs:

G. Franchetti	GSI
M. Zanetti	UNIPD
F. Zimmermann	CERN

International Committee

William	Barletta	MIT
Pisin	Chen	NTU
Raffaele-Tito	D’Agnolo	IPHT
Raffaele	Flaminio	LAPP
Shyh-Yuan	Lee	Indiana U
Katsunobu	Oide	CERN & KEK
Qin	Qing	ESRF
Jörg	Wenninger	CERN

Virtual workshop

https://indico.cern.ch/event/982987/

[proceedings]

Detecting gravitational waves with storage rings

Several proposals discussed at this workshop

(I can’t claim to have understood all the details!)

Basic idea: compare *geodesic of stored particles* with *geodesic of stationary clock* in the lab frame

E.g. particles confined longitudinally in harmonic (RF) potential, measure variations in orbital period → highest sensitivity when in resonance

Detecting gravitational waves with storage rings

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E.g. particles confined longitudinally in harmonic (RF) potential, measure variations in orbital period → highest sensitivity when in resonance

Synchrotron frequency

$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

Longitudinal damping time

Frequency of gravitational wave

$$f(\omega_g, t) \simeq h \times L \times \cos(\omega_g t + \phi)$$

Strain

Circumference

Detecting gravitational waves with storage rings

When in resonance:

Orbital period

$$h \gtrsim 10^{-13} \left(\frac{2\pi \times 10\ \mathrm{Hz}}{\omega_l}\right) \left(\frac{10\ \mathrm{hours}}{\tau_l}\right) \left(\frac{\Delta T/T}{10^{-7}}\right)$$

Strain sensitivity

Synchrotron frequency

Damping time

(For LHC beam parameters: sensitivity 7 orders of magnitude too low for known astrophysical sources)

Need:

- Large orbital period $T \sim \omega_g^{-1}$ → low energy beam
- Good time tagging, i.e. small ΔT
- Large damping time τ_l
  - Need quiet beam that is stable over long time periods
- Don’t want to increase ω_l
  - smaller astrophysical GW amplitude at higher frequencies

Detecting gravitational waves with storage rings

When in resonance:

Orbital period

$$h \gtrsim 10^{-13} \left(\frac{2\pi \times 10\ \mathrm{Hz}}{\omega_l} \right) \left(\frac{10\ \mathrm{hours}}{\tau_l} \right) \left(\frac{\Delta T / T}{10^{-7}} \right)$$

Strain sensitivity

Synchrotron frequency

Damping time

(For LHC beam parameters: sensitivity 7 orders of magnitude too low for known astrophysical sources)

IOTA:

- $T \sim 0.2\,\mathrm{ms}$ (for $L = 40\,\mathrm{m}$), $\Delta T \sim ??$
  - How to time-tag the passing ions? BCT? Fluorescence too slow?
  - Can assume 10ps single-photon time resolution
- $\tau_l = ??$
- 40 turns with 5V barrier bucket and 50eV beam energy spread: $2\pi\omega_l \sim 150\,\mathrm{Hz}$

(I think a cold beam is a *prerequisite* for this simple treatment to apply)

Detecting gravitational waves with storage rings

When in resonance:

Orbital period

$$h \gtrsim 10^{-13} \left(\frac{2\pi \times 10\ \mathrm{Hz}}{\omega_l} \right) \left(\frac{10\ \mathrm{hours}}{\tau_l} \right) \left(\frac{\Delta T/T}{10^{-7}} \right)$$

Strain sensitivity

Synchrotron frequency

Damping time

(For LHC beam parameters: sensitivity 7 orders of magnitude too low for known astrophysical sources)

For a crystal beam and weak longitudinal confinement,
ω_l could also be the plasma frequency of the beam
(Quantum beam: entanglement between internal state of crystal and centre-of-mass motion [ref])

But: RF noise! → Use longitudinally free ion crystal?

GW detection with coasting beam

Need to time-tag individual crystal ions on a turn-by-turn basis

Slow, cold beam of heavy ions plays in our favor

Need precise, nondestructive ion time tagging

(???)

Need precise external time reference

(Optical atomic clocks: 1e-19 seconds)

Need sufficiently long beam lifetime

(Concept could provide sensitivity for mHz GWs from supermassive black-hole mergers
→ need several hours beam lifetimes!)

Not easy! Mais c'est la vie …

Minutes of [discussion session]