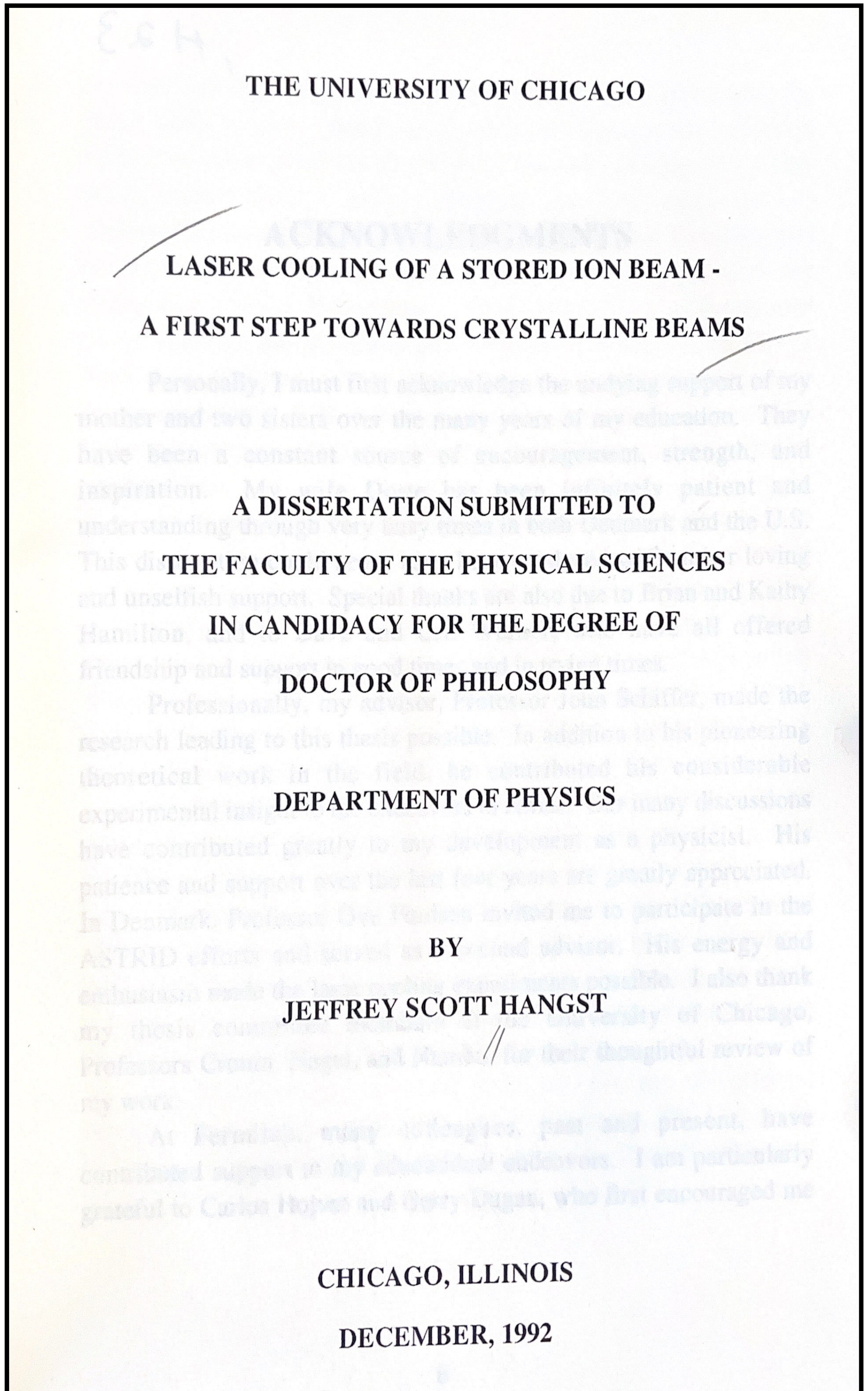
Reading Jeff's thesis

A few points that might be important for us

Metadata


THE UNIVERSITY OF CHICAGO

LASER COOLING OF A STORED ION BEAM -

A FIRST STEP TOWARDS CRYSTALLINE BEAMS

A DISSERTATION SUBMITTED TO

THE FACULTY OF THE PHYSICAL SCIENCES

IN CANDIDACY FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICS

BY

JEFFREY SCOTT HANGST

CHICAGO, ILLINOIS

DECEMBER, 1992

Some follow-up publications:

- “Laser cooling of a stored ion beam to 1 mK”, [link]
- “Laser cooling in storage rings”, [link]
- “Laser cooling of a bunched beam in a synchrotron storage ring”, [link]

ASTRID

Injection energy:
100keV

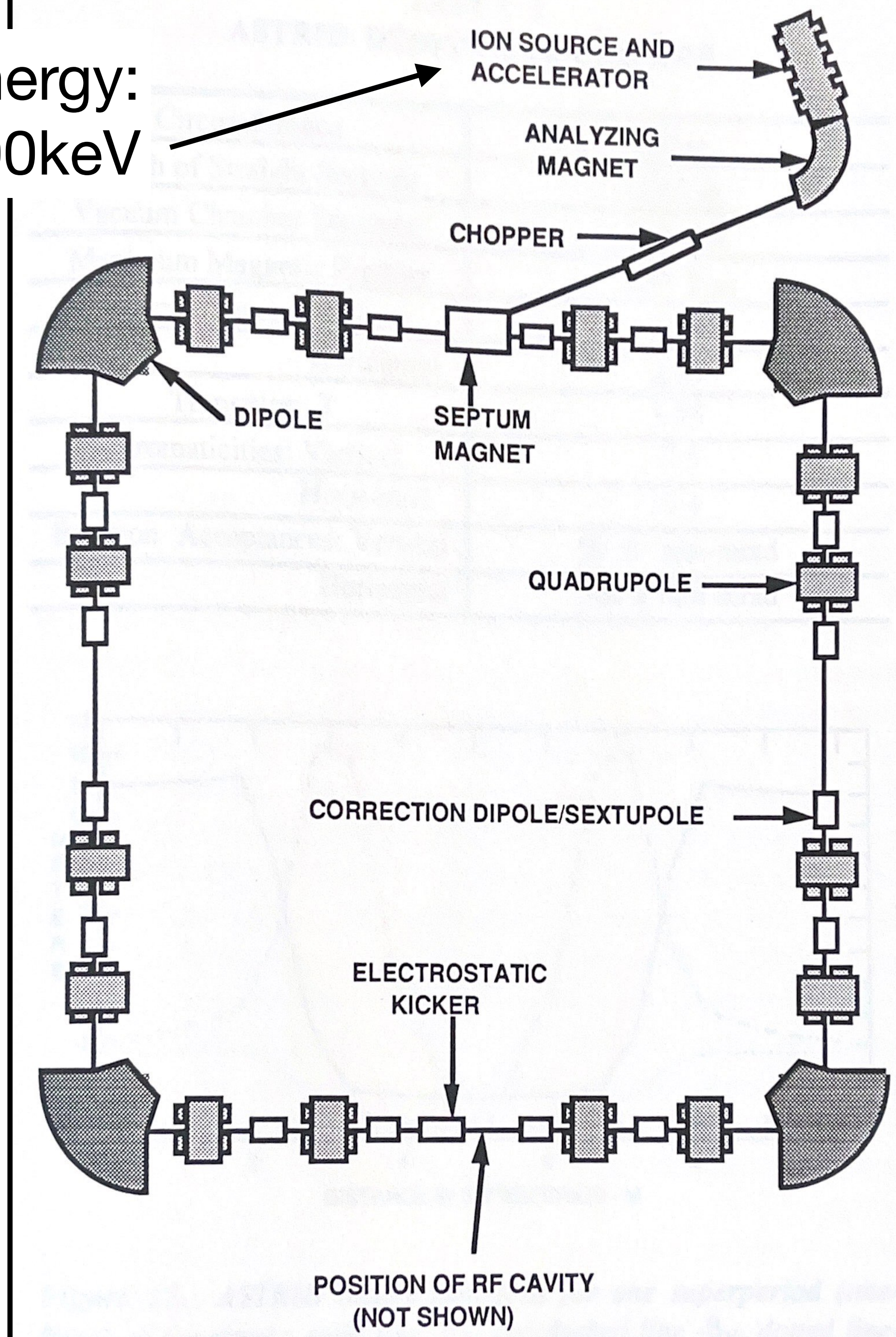


***Figure 14.** The storage ring ASTRID*

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TABLE 1
ASTRID DESIGN PARAMETERS

Circumference	40 m
Length of Straight Sections	7.83 m
Vacuum Chamber Diameter	100 mm
Maximum Magnetic Rigidity	1.87 T-m
Betatron Tunes: Vertical	2.73
Horizontal	2.29
Transition γ	4.58
Chromaticities: Vertical	-7.5
Horizontal	-3.4
Betatron Acceptances: Vertical	60 π mm-mrad
Horizontal	320 π mm-mrad

ASTRID ion source

Section 5.2 The Ion Source and Injector

A variety of ion sources can be used in ASTRID. The present experiments utilized a hot filament plasma ion source to produce the singly charged ions $^{7}Li^{+}$ and $^{166}Er^{+}$. This source is chosen to provide a low emittance beam with divergence less than 1 mrad, corresponding to an initial transverse temperature of a few hundred K. The beam is accelerated electrostatically by a precision high voltage accelerator. Stability of the acceleration voltage is < 1 V (RMS) at 100 kV. The accelerator can operate at energies from 10 to 150 keV; the bulk of the current work was carried out using ions with kinetic energy 100 keV. Initial energy spread of the beam was thus of order $\delta E/E < 10^{-5}$. The ions are mass-separated in a 45 degree analyzing magnet and then pass through the injection beam line. Two sets of electrostatic quadrupoles in this beam line serve to match the source to the ring, thereby minimizing the emittance dilution in the storage ring. Magnetic correction dipoles provide horizontal and vertical fine control over the beam position and angle at injection. A fast electrostatic chopper is used to select the desired length of beam to inject. The chopper has a rise or fall-time of about 200 ns; this may be compared to revolution periods of about 24 µs and 118 µs for $^{7}Li^{+}$ and $^{166}Er^{+}$ ions, respectively. The minimum chopper duration is ~3.8 µs; thus the number of ions injected, and the initial length of the injected pulse, can be controlled over a wide range.

An electrostatic kicker, located diametrically opposite to the septum, kicks the beam onto the closed orbit. Both kicker and septum operate in the horizontal plane. The first 1/2-turn in the ring thus has large horizontal position oscillations. The injection devices use triggers which are synchronized to the 50 hz line frequency in order to minimize pulse-to-pulse variations in beam position at injection. The minimum time between injections is thus about 20 ms. The injection system may also be operated in a DC mode, providing a continuous stream of particles which makes about two and one half turns before hitting the vacuum chamber wall. This mode is useful for initial setup of laser frequency and optimization of the spatial overlap between the laser and ion beams. Figure 14 also indicates the position of a radio frequency (RF) cavity which can be used for bunching or acceleration of the ions. This device did not play a role in the experiments described here.

(Could mains frequency coupling into the beam be an additional heating mechanism?)

(Beam current used in experiments: 1-20µA)

ASTRID ion source (?)

Is this what they are using?

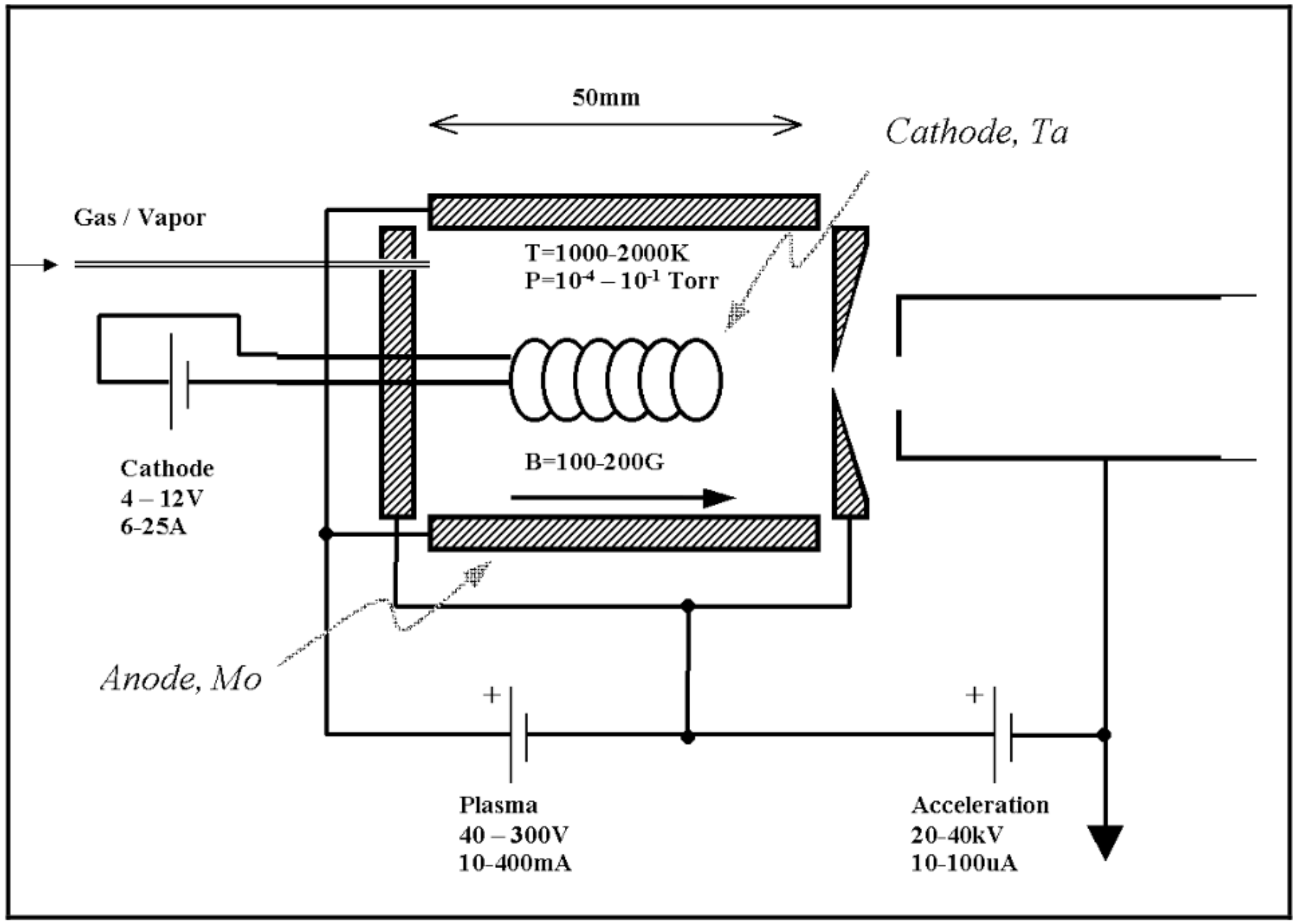

Figure 1: The “normal” hot filament ion source.

EXTENDING THE USE OF THE CRYRING STORAGE RING

G. Andler, L. Bagge , M. Björkhage, H. Danared, A. Källberg, L. Liljeby, A. Lundqvist, P. Löfgren, F. Österdahl, A. Paál, K-G. Rensfelt, A. Simonsson, M. af Ugglas,
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ASTRID laser cooling

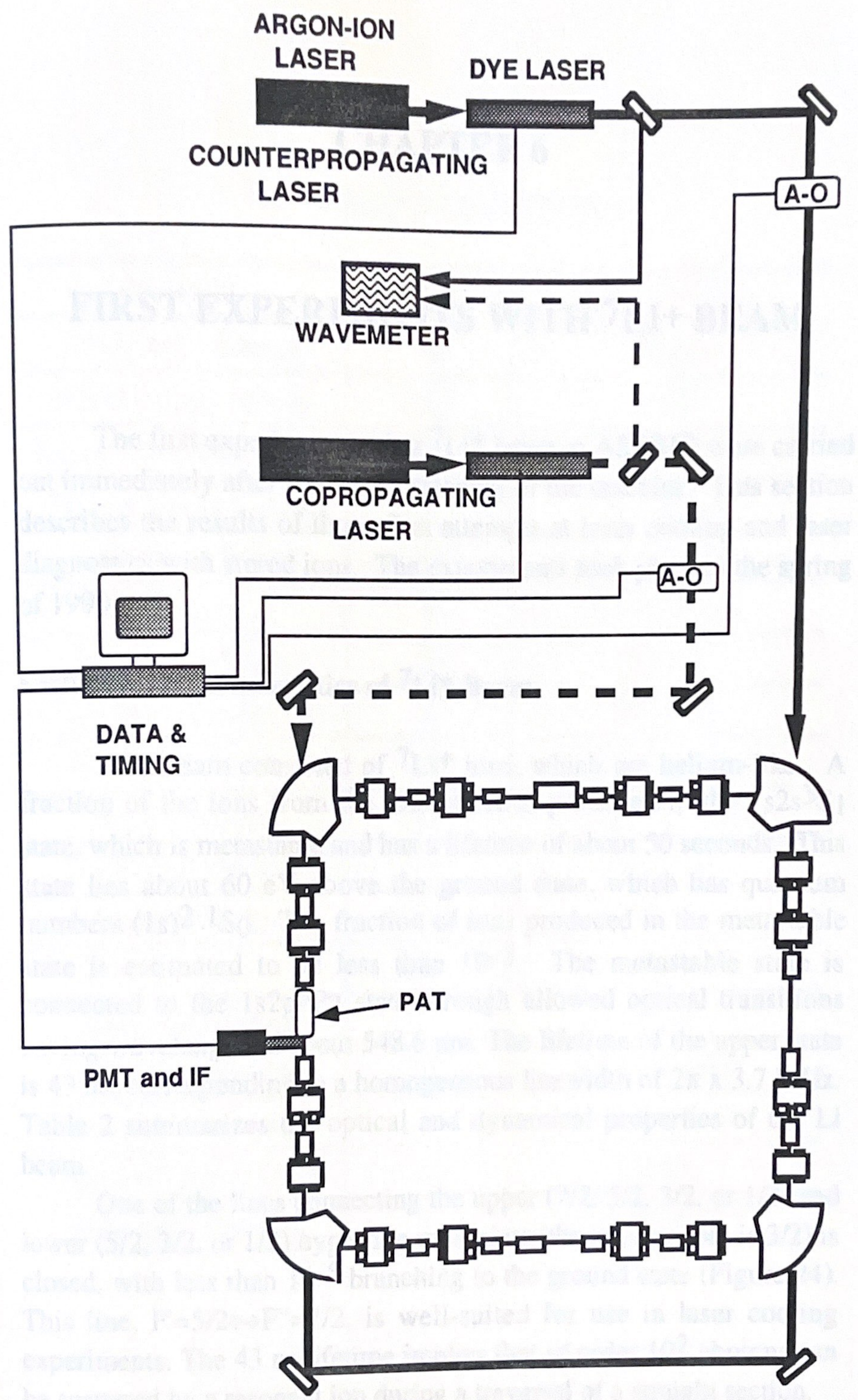

Figure 23. ASTRID laser systems

The lasers employed are tunable ring-dye lasers, pumped by argon-ion lasers. The wavelengths of interest are optical, in the range 540 to 550 nm. Using the dye rhodamine 110, the lasers typically produce several hundred mW of light when pumped with 5 to 6 W of argon-ion laser light. For cooling experiments, two lasers, one copropagating with the ion beam, the other counterpropagating, are used. For probing of the longitudinal velocity distribution, one laser is sufficient. The lasers operate CW and are switched by acousto-optic modulators (A-O), which divert the beams into stops. Wavelength measurement is performed by a phase locked Michelson wavemeter, which has a resolution of 0.0005 Å

The cooling process begins at injection with the co- and counterpropagating lasers detuned about 1 Ghz red of the resonance frequency (in the beam frame) of the central beam velocity. The copropagating laser is in resonance with the slowest particles, the counterpropagating with the fastest. Note by comparison to Figure 25 that the lasers, spaced 2 GHz apart, "surround" the initial velocity distribution (FWHM of ~300 MHz) of the injected ions. Beginning at injection, the counterpropagating laser was swept to higher frequency at a constant rate of about 625 MHz/s. The faster ions are thus decelerated by the scanned laser until they come into resonance with the fixed-frequency laser. The scanned laser should pile up particles in front of it, forming a very narrow velocity distribution just before the laser frequencies cross. After the laser frequencies cross, the cooling force becomes a heating force and the ions are accelerated away.

Why do they need tunable lasers?

Laser cooling $^7Li^+$

TABLE 2
$^7Li^+$ BEAM PARAMETERS

Ion Mass	M	1.15×10^{-26} kg
Ion Kinetic Energy	E	100 keV
Initial Energy Spread	$\delta E/E$	$< 10^{-5}$
Initial Transverse Temp.	$T_\perp$	~ 1000 K
Typical Source Current	I	1 - 20 μA
Conversion Factor	stored beam	1 μA ≡ 1.5×10^8 ions
Velocity	v	1.67×10^6 m/s
Relativistic Factor	β	0.0056
Transition Wavelength	λ	548.6 nm
Photon Momentum	p_γ	2.25 eV/c
Ion Momentum	p_i	3.6×10^7 eV/c
Ion Recoil Velocity	v_r	0.105 m/s
Doppler Shifts	Δλ	3.0 nm
	Δν	3.1×10^{12} Hz
Transition Lifetime	τ	43 ns
Natural Linewidth	Γ	2π x 3.7 MHz
Saturation Intensity		8.8 mW/cm²
Doppler Cooling Limit	T_D	62 μK
Metastable Fraction	f	$10^{-5} < f < 10^{-3}$

$\delta v/v \sim 5 \cdot 10^{-6}$ (Initial Energy Spread)

$\delta v \sim 8\,\mathrm{m/s}$ (Velocity)

Doppler broadening due to initial longitudinal energy spread:

$$\delta f \sim \frac{\delta v}{\lambda} \sim 15\,\mathrm{MHz} \ll \Gamma$$

Laser cooling $^7Li^+$

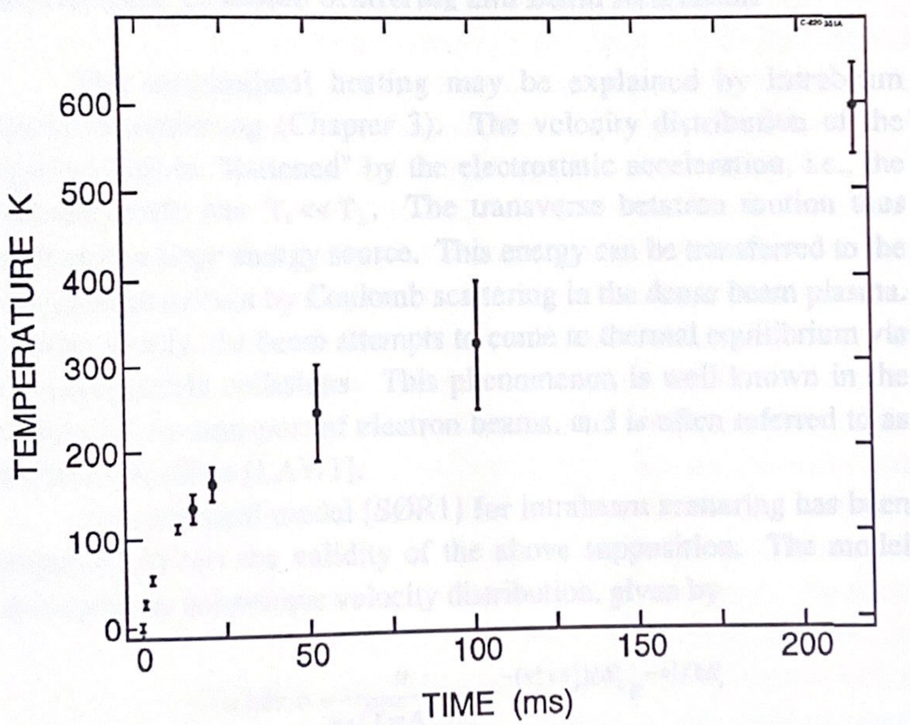

Figure 26. Longitudinal beam temperature in the co-moving frame versus time after injection for 100 KeV $^7Li^+$ beam,

Transverse temperature ~ 1000K couples into longitudinal motion

For T ~ 1000K, get $\delta v/v \sim 6 \cdot 10^{-4}$, i.e. 2 orders of magnitude than at injection

$$\delta f \sim \frac{\delta v}{\lambda} \sim 1.5\,\mathrm{GHz}$$

The cooling process begins at injection with the co- and counterpropagating lasers detuned about 1 Ghz red of the resonance frequency (in the beam frame) of the central beam velocity. The

TABLE 5

INITIAL AND EQUILIBRIUM BEAM PARAMETERS

Parameter	Value	Method
initial number of ions	up to 3x10⁹	Faraday Cup
maximum stored ions	1x10⁹	Faraday Cup, Neutral Det.
initial longitudinal temp.	100 mK	laser fluorescence
equil. longitudinal temp.	3000 K	Schottky pickup
initial transverse temp.	500 K	laser fluorescence
equil. transverse temp.	6000 K	laser fluor., scraper

Can we start cooling right after injection before the beam can heat up?

(They were suffering from some beam instabilities.)

Or do we need tunable lasers?

Applications of *classical* cold / crystalline ion beams

A browse through existing literature
and some brainstorming

Cold chemistry

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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[3] Applied Mathematics and Material Science, Malmö University, 20506 Malmö, Sweden
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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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[3]*Department of Physics, Århus University, DK8000 Århus C, Denmark*

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).

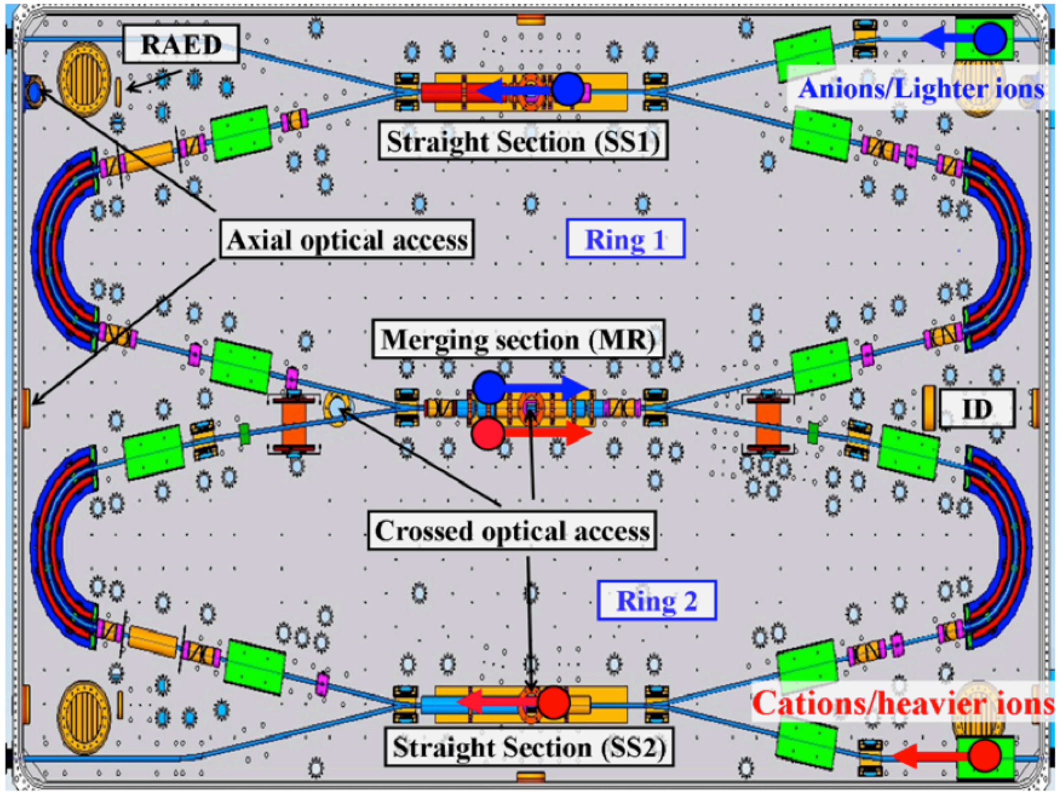


Figure 2. A rough schematic of the heart of the DESIREE facility showing: the two rings, the two straight sections in each ring (SS1,SS2) and the common straight section – the merging section MR. The position of several of the available particle detectors: the imaging detector (ID) and a resistive anode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

Is there a need for (actively cooled) beams like ours?

Focused ion beam tomography

Focused Ion-Beam Tomography

A.J. KUBIS, G.J. SHIFLET, D.N. DUNN, and R. HULL

The focused ion beam (FIB) has become an important tool in materials science for studying and modifying materials systems at the micro and nanometer levels. The technique, due to its ability to perform precision *in-situ* milling, has been extended to studying three-dimensional structural and chemical relationships. With the help of computer algorithms for processing data and graphics packages for display, three-dimensional systems can easily be reconstructed and the structure interrogated to obtain both qualitative and quantitative information. It is possible to study features at spatial resolutions at the tens-of-nanometers level and volumes with dimensions of up to tens of microns. This allows the reconstruction of many systems in the size range important to nanotechnology. Practical aspects of FIB tomography will be presented, emphasizing data collection, image processing, creating three-dimensional volumes, and extracting quantitative information.

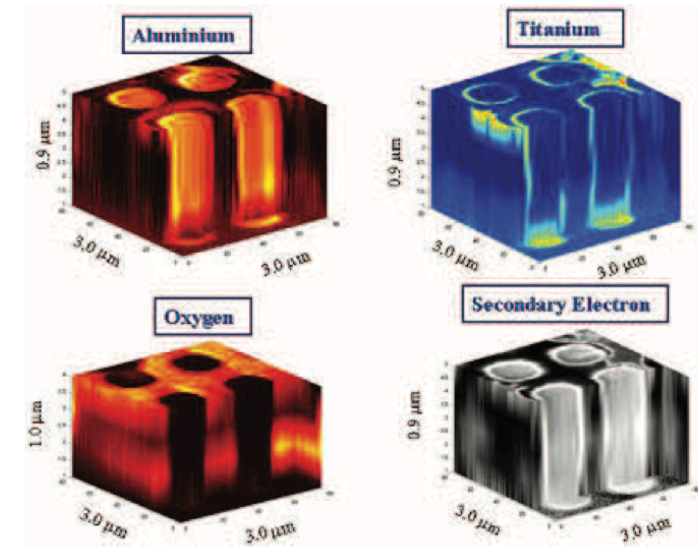
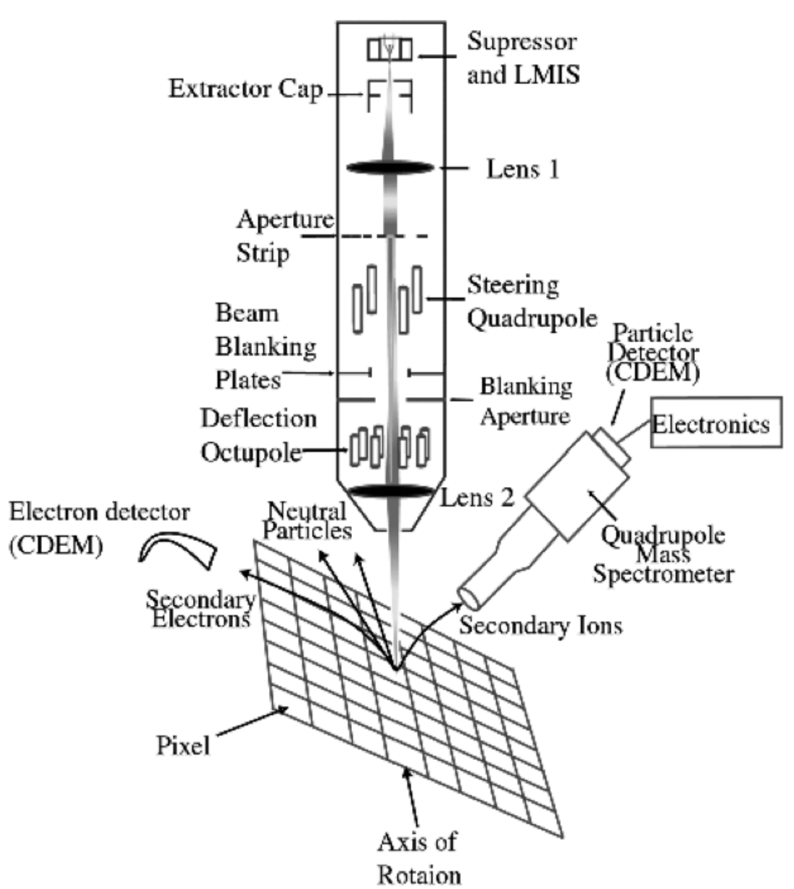


Fig. 6—A comparison of secondary electron and Al, Ti, and O elemental volume reconstructions of microelectronic *via* structures using the linear interpolation method.



For a primary ion beam with a diameter of 10 nm and a beam energy of 30 keV, a practical minimum spatial resolution of *ca.* 20 to 30 nm can, thus, be expected for most inorganic materials. This is true for dimensions both parallel and perpendicular to the imaging plane.

Table I. Projected Range and Spread of 30 keV Ga+ Ions in Several Metals Calculated Using the Linhard, Scharff, and Schoitt Method

Target Material	Projected Range (nm)	Lateral Spread (nm)
Aluminum	17	7
Titanium	14	7
Silicon	20	3

Could this profit from a colder, parallel, beam?

How low can the beam intensity go?

Something crazy at the end …

[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

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

Synchrotron frequency (ω_l)

Longitudinal damping time (τ_l)

Frequency of gravitational wave (ω_g)

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

Strain (h)

Circumference (L)

Detecting gravitational waves with storage rings

When in resonance:

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

Strain sensitivity (h)

Synchrotron frequency (ω_l)

Damping time (τ_l)

Orbital period (T)

(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
- Weak longitudinal confinement ($\omega_l \to 0$) and large damping time τ_l
  - Need quiet beam that is stable over long time periods

Some of this sounds vaguely related to our situation; worth investigating more?