The Aarhus Storage Ring for Ions and Electrons ASTRID

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Abstract

ASTRID is a storage ring/synchrotron for ions and electrons. Results from the first 3 years of commissioning and running will be presented. A wide range of both positive and negative ions (both atomic and molecular) varying in mass from $_3$He to C_{70} (Buckminsterfullerene) have been stored in the ring. The physics has been centered around laser-cooling, lifetime measurements of metastable ions and electron recombination. The ring is 2×3 months a year operational as a 580 MeV synchrotron radiation source (λ_c = 35 Å), with stored currents (presently) around 150 mA. Initially beam-loading problems in the rf-cavity hindered large currents, but a fast feedback loop has circumvented this problem. Presently the current is limited by the injection rate at 100 MeV and the lifetime of the beam, at high currents influenced by ions trapped in the beam.

I. THE FACILITY

ASTRID is the first facility which combines a storage ring for ions with a synchrotron-radiation source [1-3]. The motivation for this was to make a relative expensive piece of equipment available to a wider user community.

The layout of the storage ring with injectors is shown in fig. 1. The electron injector is placed in a separate well-shielded cave. There is no radiation shielding around the storage ring; hence the ring hall is evacuated during filling of the ring. Scrapers in the ring are left close to the electron beam to give a well-defined beam dump.

A. The injectors

Ions are preaccelerated in an isotope separator using a very stable (RMS<1 V) 200 kV high-voltage supply. A variety of ion sources for both positive and negative ions can be used with the separator to produce singly-charged ions and molecules of almost any type. A charge exchange cell has been installed after the separator magnet to produce negative ions by electron capture in a Na, K or Cs vapour. Differential pumping in the injection beamline separates the high-pressure ion source (10^{-2}torr) from the ring vacuum (10^{-12}torr).

A pulsed (10 Hz) race-track microtron has been built to produce the 100 MeV electrons for the storage ring. The RF system is operating at 3 GHz. The resonant energy gain is 5.3 MeV corresponding to 19 turns.

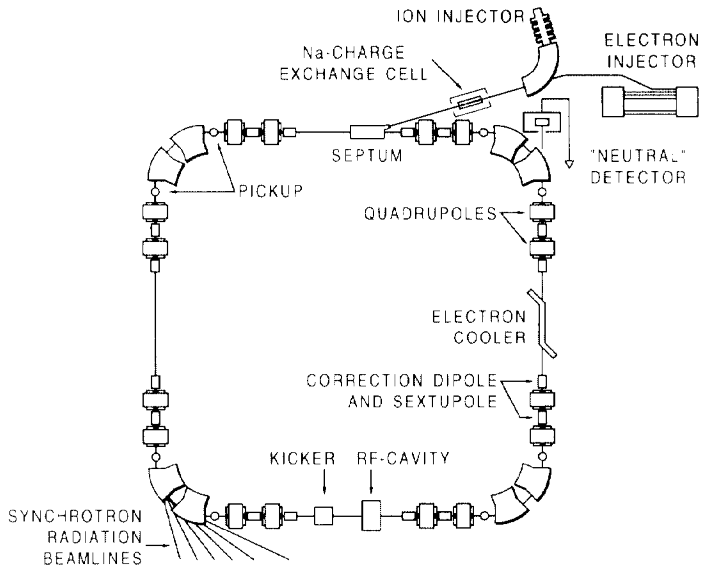

Figure 1. Layout of the storage ring with injectors.

B. The storage ring

The "ring" is a square as formed by two 45° bending magnets, excited by a common coil, in each corner. The lattice functions for ASTRID are shown in fig. 2. The quadrupoles are grouped in four families, so that the dispersion in two opposite straight sections can be varied continously between 0 and 6 m without change of the tunes. In fig. 2 is shown the dispersion in ASTRID with four superperiods, and with two superperiods giving two dispersion-free straight sections.

Two families of 8 sextupoles are available for chromaticity corrections. Superimposed on the air-cored sextupoles are 8 horizontal and 8 vertical correction dipoles. Furthermore 4 horizontal correctors are available as back-leg windings on the main dipoles.

The vacuum system is designed for the 10^{-12} torr region, as required for long storage times of the ions. Hence the system has been vacuum fired and is prepared for a 300° C in-situ bake-out. There is installed a total of 20 ion pumps and 24 sublimation pumps in the ring. Presently the system has only been baked to 150° C, resulting in an average pressure around 10^{-11}torr.

Two different RF systems are used. For the ions, a

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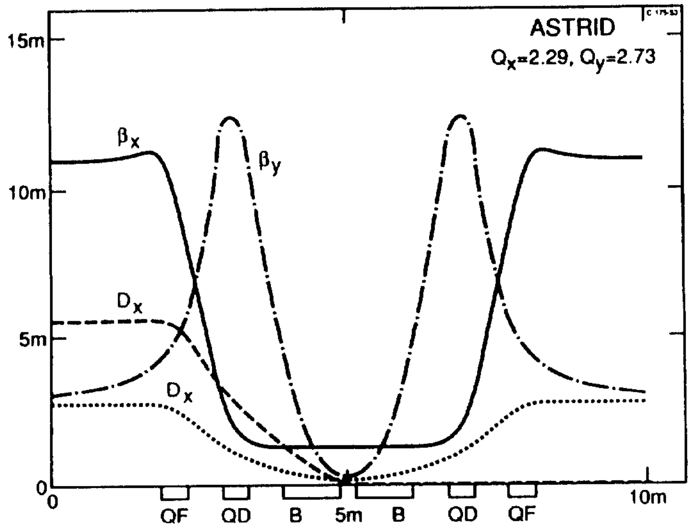

Figure 2. Lattice functions of ASTRID.

ferrite-loaded cavity operating in the 0.5-3.3 MHz region is available, giving a maximum voltage of 2 kV. For the electrons, a capacitively loaded coaxial TEM cavity operating at 104.9 MHz is used. This cavity was fabricated in steel, which was then copper plated. The obtained Q is around 9000.

Table 1
Parameters of ASTRID

Magnetic rigidity		1.87 Tm
Circumference		40 m
Ions		
Injection energy		<200 kV
Hor., vert. tune	2.29	2.73
Hor., vert. chromaticity	-3.4	-7.5
Momentum compaction		0.053
RF system	0.5-3.3 MHz	2 kV
Injected currents		1 pA - 10 μA
electrons		
Injection energy		100 MeV
Hor., vert. tune	2.208	2.640
Hor., vert. chromaticity	-4.3	-7.1
Momentum compaction		0.068
Design current		200 mA
Electron energy		580 MeV
Horizontal emittance		0.14 mm mrad
Critical energy, wavelength	0.36 keV	35Å
Energy loss/turn		8.3 keV
Beam lifetime (Touschek)		16 hours
Number of bunches		14
RF system	105 MHz	125 kV

Ions and electrons are injected with a magnetic septum (dc) and a kicker placed diametrically opposite. For the ions, the electrostatic kicker excited by a square pulse injects one turn. For the electrons, a magnetic kicker excited by a half-sine pulse is used to accumulate electrons. The dc septum has a maximum bending power of 1.3 Tm and an effective thickness of 11 mm. This rigidity allows injection of heavy ions and also extraction of a low-intensity 580-MeV electron beam.

The kicker and RF-system are the only components being exchanged when swapping between electron and ion operation.

Clearing electrodes covering around half the circumference are installed in the ring to reduce ion-trapping effects.

A variety of diagnostics is installed, including 10 horizontal and vertical position pick-ups, scintillation screens, Schottky pick-ups, beam-current transformer, beam scrapers and synchrotron-radiation detectors.

The control system is based on a NORD main computer with PC's as consoles. Autonomous function generators are used for all dynamical parameters for acceleration and similar operations.

II. RUNNING ASTRID WITH IONS

Since the start up of the facility many different ions have been stored in the ring; a list is given in table 2.

Table 2
Atomic and molecular ions stored in ASTRID

$^{4}He^{+}$	$^{6}Li^{+}$	$^{7}Li^{+}$	$^{16}O^{+}$	$^{20}Ne^{+}$	$^{40}Ar^{++}$
$^{151}Eu^{+}$	$^{166}Er^{+}$				
H_2^{+}	$^{13}CO^{+}$	$^{12}CO^{++}$	$^{13}CO^{++}$	C_{60}^{+}	C_{60}^{++}
C_{70}^{+}					
$^{3}He^{-}$	$^{4}He^{-}$	$^{9}Be^{-}$	$^{12}C^{-}$	$^{16}O^{-}$	$^{19}F^{-}$
$^{35}Cl^{-}$	$^{40}Ca^{-}$	$^{56}Fe^{-}$			
$^{4}He_2^{-}$	$^{12}C_2^{-}$	OH^{-}	C_{60}^{-}	C_{70}^{-}	

The stored ion beams had rigidities between 7 MeV/c for 6 keV $^{4}He^{-}$ and 260 MeV/c for 50 keV $^{12}C_{60}^{-}$.

The lifetime at injection energy of stored beams of positive ions was limited by the vacuum, typically a few 10^{-11} torr, giving lifetimes around ten seconds. Injected currents for the positive ion beams were in the 1-10 μA range. A large fraction of the runs with positive ions have been for laser cooling experiments [4] with Li^{+} and Er^{+}.

The lifetime of a negative ion beam is determined by rest gas stripping, intrabeam stripping and field stripping (in the bending magnets) [5,6]. A new stripping mechanism has been identified for loosely bound ions. Black-body radiation can ionize ions with small electron affinities like Ca^{-} and He^{-}[7]. Furthermore some ions are metastable and autoionize on timescales around a msec. In fig. 3 is shown the decay of a stable and a metastable beam. The slow components are due to restgas interactions. The energy of the stable beam has been chosen so that the two beams have the same rigidities, to avoid adjustments of the ring magnets between the two measurements. A storage ring, acting as a very long beamline, is ideal

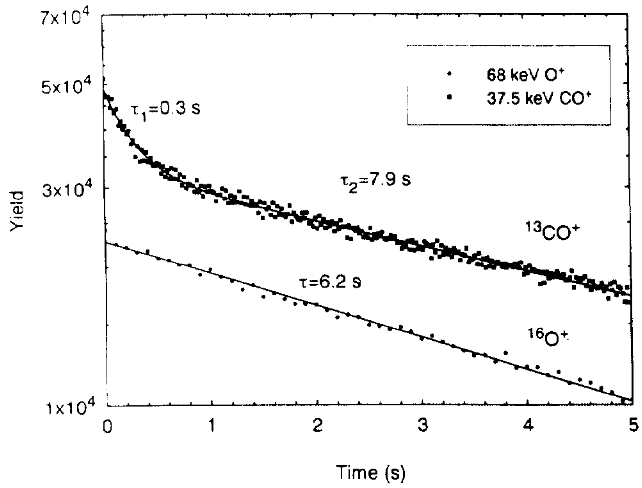

Figure 3. Decay of a stable and an unstable beam.

for such fundamental lifetime measurements.

Most negative ions can only be produced in small quantities, leading to currents in the pA-nA range. Hence they can only be observed with 'neutral' detectors monitoring the decay of the stored beam by counting neutralized ions at the end of the straight sections. An electron multiplier, a semiconductor and a microchannel-plate detector (as in fig. 3) have been used in ASTRID for this purpose.

The first electron cooling/recombination experiments have started. The electron beam has an energy of 0.5-2 keV, requiring ion energies above 1 MeV/amu. Ions can now be accelerated from 0.15 MeV up to 6 MeV in one cycle, whereas higher energies requires change of harmonic number and two acceleration cycles.

III. RUNNING ASTRID WITH ELECTRONS

The 100-MeV race-track microtron routinely delivers 10-15 mA pulses of 1 μsec width. This 3 GHz beam is injected into the ring and captured by the 105 MHz RF system. The current captured per injection is around 1-5 mA, and the optimal injection frequency is around 0.2 Hz, to be compared to transverse damping times of 4 secs. This rather low injection frequency is caused by the rather thick septum used. During the early commissioning it was realized, that beam loading in the rf-system [8] limited the maximum accumulated current to 1-2 mA per bunch for rf-voltages around 8 kV. In our case this limitation can not be cured by running with a higher rf power, since a good accumulation efficiency is needed owing to the low injection frequency. A rf power of less than 10 kV is needed to keep the bucket height smaller than the ring acceptance (1%). Hence an amplifier feedback system was built, which reduce the effective cavity impedance as seen by the beam [8]. This feedback system has raised the beam-loading threshold to 20 mA per bunch. The largest current accumulated to date is 210 mA, well below this threshold.

Up to 160 mA can be accelerated to 580 MeV during 1 min. without significant losses. Above this current, large losses occur. The reason for these losses is currently being investigated. The lifetime at high current at 580 MeV is around 80 minutes, determined by the high pressure (few 10^{-8} torr.). No decrease in this pressure has been observed after a conditioning of the vacuum system to 12 A hours. Coupled bunch oscilllations are observed at high energy with large circulating currents. The beam size has been measured using the optical part of the synchrotron radiation at 580 MeV. The horizontal and vertical beam size at the entrance to the dipole have been measured to 0.73×0.10 mm^2(RMS). From this we deduce a coupling of 1.4 %, and an increase in the horisontal beam size of around 60 % owing to the bunch oscillations.

IV. FUTURE PLANS

The coming laser cooling experiments will be performed on Mg^+, which can be cooled in the ground state using UV photons. A wide program with negative ions and molecular ions is planned. One program is a continuation of the lifetime measurements. Another is electron recombination/detachment studies using positive/negative ions and molecules. Also photo-excitation experiments are planned.

Two synchrotron-radiation beamlines are currently in use, i.e. a x-ray microscope and a PGM monochromator (SX-700) for the 11-2300 eV range for surface physics. The third beamline, a large acceptance (20 mrad) high-resolution SGM monochromator for the 30-600 eV region is presently being commissioned.

Several longer term improvements are being discussed, among others we mention installation of insertion devices (wiggler/undulator) in the ring combined with new monochromators, new ion sources and an induction accelerator.

V. REFERENCES

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