DESIGN AND FIRST OPERATION OF THE ELECTROSTATIC STORAGE RING, ELISA

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Abstract

The design of the first ion storage ring using electrostatic deflection and focusing elements was described in [1]. In the present contribution, the design principles will be described, and the first operational experience with the storage ring will be reported. Also, the differences between electrostatic and magnetic storage rings will be emphasised, and the potential in terms of applications will be given. Initially, an old injector was used, and stable beams consisting of 10^7 D_2^+ and N_2^+ ions at an energy of 15 keV were stored. Beam observations have been made with beam-position monitors, either using a chopped beam or a beam bunched with a drift-tube RF system. A bunched-beam lifetime of 0.3 seconds has been observed at an average pressure of $3\ 10^{-10}$ mbar, obtained after the first short bake-out. At present, the pressure in the storage ring is below 10^{-11} mbar. Furthermore a new injector has been built, and higher currents without losses on the first turns are expected. The first beams have already been stored with this new separator.

1 INTRODUCTION

The progress in the field of accelerators, and storage rings, has been intimately related to particle physics. Hence, the frontier has mostly been at the highest attainable energies. Some exceptions have occurred, one being the development starting with the low-energy antiproton storage ring, LEAR, developed at CERN [2]. This has led to the construction of many low- and medium-energy storage rings used in the areas of atomic and nuclear physics [3]. The extremes in terms of low energy and velocity is the 40-m circumference storage ring ASTRID [4], where $^4He^-$ ions at an energy of 5 keV, corresponding to a momentum as low as 4 MeV/c, and a beam of $^{12}C_{70}^-$ at 25 keV with a velocity as small as 0.00025 c have been stored.

The alternative storage device used to confine charged particles for extended periods of time in a small volume of space is the electromagnetic trap [5], where the confinement is provided by static (Penning trap) or varying (Paul trap) electromagnetic fields. In an ion trap, the ions have a vanishing average velocity as opposed to the energetic ions in a straight section of a storage ring.

The development of the electrostatic storage ring, ELISA, to be presented below, can be viewed as a hybrid of these two storage devices. The storage ring ELISA is relatively small and consequently cheap, as a trap, without compromising the advantages of a storage ring, mainly the easy access to both the primary beam and possible decay products.

Initially, we believed that ELISA would be the first electrostatic storage ring to be built, but after an extensive search, it was discovered that an electrostatic storage ring/synchrotron for 1-10 MeV electrons was built and operated successfully at Brookhaven [6]. The ring was built to test the principles of a proton synchrotron before the actual construction of the AGS.

In section 2 we will give a description of ELISA. This will be followed by a presentation of results from the commissioning in section 3. Applications of electro-static storage rings will be discussed in section 4, and some conclusions will end the paper.

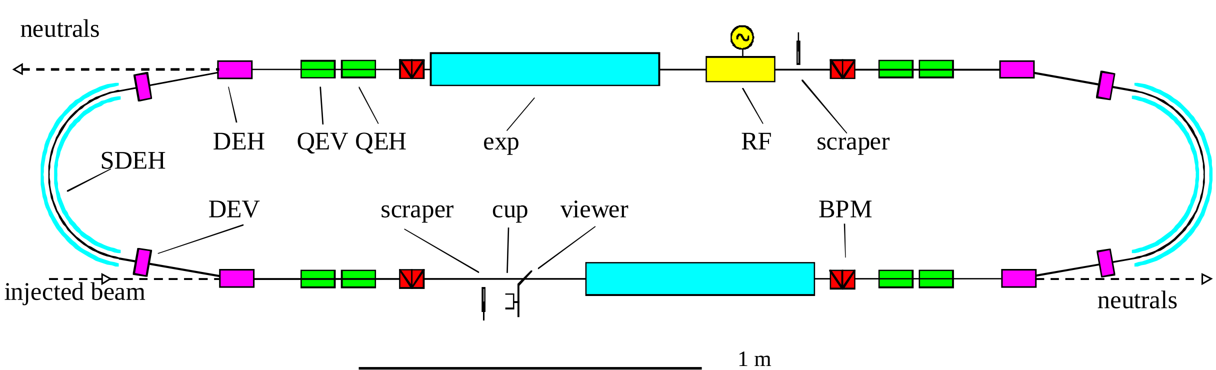

Figure 1: Layout of the ELISA storage ring. The abbreviations are explained in the text.

2 DESIGN OF ELISA

The ELISA machine has been constructed to fulfil the requirements known at the time of the design, but still paying attention to simplicity and practical considerations. Some free space with good access to the beam is required for the experiments, i.e. so-called straight sections, and we chose a lattice with the smallest number of straight sections, namely a racetrack lattice with two straight sections. The layout of the machine is shown in Fig. 1, where the positions and longitudinal extent of the elements are drawn to scale. The abbreviations are explained in the following sub-sections. Clearly, other layouts are possible, as for magnetic storage rings. A list of parameters for ELISA is given in table 1[1].

2.1 The lattice

The lattice is defined by the two 160° spherical electrostatic deflectors (SDEH), each having on each side a 10° parallel-plate electrostatic deflector (DEH) and an electrostatic quadrupole doublet (QEH, QEV). The resulting lattice functions are shown in Fig. 2, as calculated by standard lattice programs.

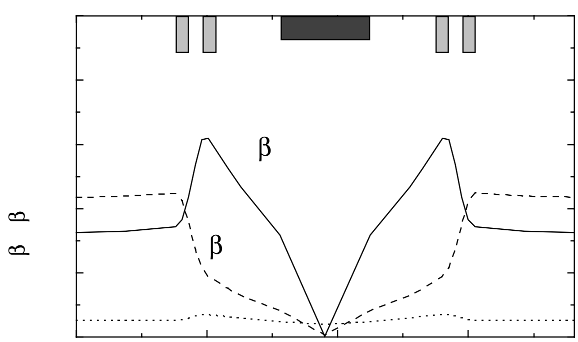

Figure 2: Lattice functions of ELISA for half the circumference.

One of the main differences between magnetic and electrostatic deflection is that the longitudinal energy is not conserved for electrostatic devices. For example, a particle entering an electrostatic deflector off axis will see a longitudinal electric field and hence be ac- or de-celerated. It is also this effect, which leads to the much stronger focusing of electrostatic bends as compared to magnetic. For an electrostatic deflector, equal focusing in the horizontal and vertical plane is obtained for spherical electrodes. This is the main reason for choosing spherical electrodes for the 160° bends. This focusing results in a very strong waist in the middle of the bend with a betatron amplitude of only 0.05 m. The combination of a 160° bend and two parallel-plate 10° bends is chosen because the lattice is unstable for a 180° spherical bend. In addition, the two 10° bends allow observation of neutral atoms created in the straight sections, and they can also be used as spectrometers in connection with detectors for charge- and mass-changing reactions. One of the 10° bends is also used for injection; see section 2.3. The tunes corresponding to the lattice shown in Fig. 2 are 1.25 and 1.42 for the horizontal and vertical planes, respectively, but tunes in the range between 1 and 2 are readily possible.

Closed-orbit correction can be performed with the four vertical correctors (DEV) and the four horizontal 10° bends.

2.2 3D tracking simulations

It was felt that ELISA to some extent was based on new principles, and hence that a simulation of the machine was needed. This simulation should take the actual electrostatic fields including fringe fields into account as accurately as possible. Fortunately, the program SIMION [7] can be used for this purpose. SIMION is an ion-optics simulation program that models ion optics with 3D electrostatic potential arrays determined by solving the Laplace equation outside electrodes. The program operates with a finite number of mesh points, but ELISA is sufficiently small to be accommodated with sufficient accuracy in the program. Ions have been tracked, "flown", through the system for hundreds of turns showing the required stability.

Table 1: Parameters of ELISA

General parameters	
Maximum energy	25 keV
Circumference	7.62 m
Revolution time	3.5 (p), 93 (C_{60}) μs
Betatron tunes Q_H, Q_V	1.25, 1.42
Chromaticities ξ_H, ξ_V	-1.9, -1.4
Momentum compaction α_p	0.41
160° spherical deflectors	
Electrode radii	235 and 265 mm
Nominal voltages	±3.25 kV
10° deflectors	
Plate distance	50 mm
Plate length	100 mm
Nominal voltages	± 2.4 kV
Electrostatic Quadrupoles	
Inscribed radius	26.2 mm
Electrode length	50 mm
Nominal voltages	± 0.37 kV
RF	
Frequency	10-500 kHz
Voltage	< 50 V

[1] Some numbers have changed slightly since [1].

2.3 Injection

A single turn injection is performed by means of a chopper in the injection beamline and one of the 10° deflectors used as a pulsed inflector. The injector is a standard isotope separator with the possibility of easy exchange of ion sources for production of the various ions. A beamline is used for steering and matching the beam to the ELISA lattice, and for differential pumping.

2.4 Rf system

No acceleration is envisaged in ELISA, but a RF system is necessary for bunched-beam observations. Hence, a non-resonant driven drift-tube is used for bunching. However, only a small voltage is needed since 1V peak RF corresponds to a bucket height of $\Delta p/p$ = 0.7 % for harmonic number 1. The drift tube is 20 cm long, and hence a voltage of around 35 V is needed to provide the required 1 V. The required frequency range is 10-500 kHz.

2.5 Diagnostics

In order to ensure a smooth commissioning and daily operation of ELISA several diagnostics devices are mounted in ELISA. The positioning of these is shown in Fig. 1. For steering and focusing into ELISA, a viewer (fluorescent plate and camera) and a Faraday cup will be used.

Figure 3: Picture of the ELISA storage ring.

Four sets of horizontal and vertical beam-position monitors will be used for bunched-beam observations, either with a chopped beam or with a bunched beam. The pick-ups will provide an intensity proportional sum signal (Σ) and a position-proportional difference signal (Δ/Σ). The noise on the amplifier system corresponds to around 10^7 ions stored in ELISA. Hence, signal averaging is useful to obtain good signal-to-noise ratios. Furthermore, new amplifiers with a noise figure reduced by a factor of 10 are being prepared. Analysis of Schottky-noise and bunched-beam current-transformer measurements is also planned. Finally, observations of neutral atoms at the end of the straight sections are very useful. In this connection, we mention that an electrostatic storage ring is mass independent, and hence can be set up with an intense beam before turning to the, possibly weak, interesting beam.

2.6 Vacuum system

The vacuum system has been built from stainless steel, according to usual UHV principles. The only exception is that all electrodes close to the beam, that is all electrodes in the deflectors and quadrupoles and beam position monitors have been gold plated in order to minimise oxide layers and the related patch potentials. A photo of the ELISA storage ring before installation of the injector is shown in Fig. 3.

The vacuum system is equipped with four 300 l/s ion pumps and six 1000 l/s sublimation pumps. The system is baked by means of an easily mountable insulation box and one heating element placed centrally. Two Bayard-Alpert ionisation gauges with modulator and a restgas analyser measure the pressure. At present the pressure is around 6 10^{-12} mbar.

2.7 Predicted intensities and lifetimes

At low energy, the stored currents are usually limited by the space-charge tune-shift. This tune-shift scales as $\Delta Q \propto N/(\beta\gamma\varepsilon)\beta \propto OI/(\beta\gamma\varepsilon)\beta^2$, where N is the number of ions, I the ion current, O the ring circumference, ε the emittance and β and γ the Lorentz factors. Hence we should be able to store currents similar to that in ASTRID, i.e. several μA. From experience in ASTRID, we can store beams with a tune shift up to around 0.2.

Electron-capture or –loss from restgas collisions determines the lifetimes of singly charged ions at low energies. Cross-sections for these processes are slowly varying at low energies, and hence longer lifetimes than in e.g. ASTRID are expected in ELISA, since the traversed target thickness becomes smaller for decreasing velocity. Hence, lifetimes in the 10-1000 seconds range are expected.

Intra-beam scattering can lead to emittance growth, in particular at low energies. As an example, we have calculated using the program ZAP [8] the intra-beam scattering times (1/*e* folding times) for a 25 keV beam of singly charged ions with mass A = 25 AMU, a current of 1 μA (corresponding to around 10^8 particles), a momentum spread of $\Delta p/p$ = 3 10^{-3}, a horizontal emittance of 30 π mm mrad, and a vertical emittance of 15 π mm mrad. The emittances and momentum spread have been chosen to get approximately equal scattering times in the three planes. The resulting scattering times are around 1000 seconds. These scattering times are comparable to or longer than the lifetimes of most beams. Furthermore, we remind the reader that the intra-beam scattering times scale as $\tau \propto T^{3/2}A^2/(Nq^2)$, where *T* is the kinetic energy, *A* and *q* the ion mass (in AMU) and charge, and *N* the number of circulating ions. Hence, heavier and less intense ion beams will have even longer scattering times.

3 RESULTS FROM COMMISSIONING

Initially ELISA was commissioned after only a short bake-out using an old but available isotope separator. The pressure obtained after this bake-out was a few 10^{-10} mbar. In Fig. 4 we show the sum signals from a BPM for a chopped 14 keV D_2^+ beam. It is seen that the beam is chopped to a 50 % filling of the circumference.

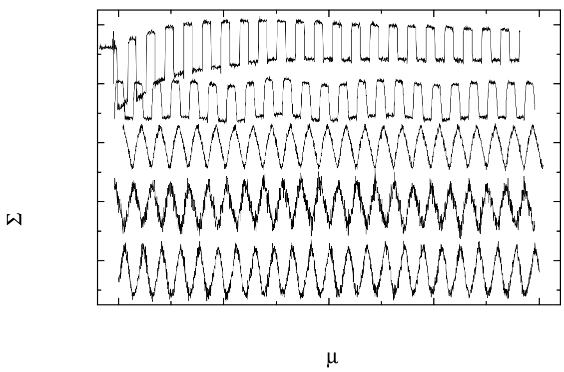

Figure 4: BPM signals from a chopped 15 keV D_2^+ beam. For details, see the text.

The signals are shown (from top) right at injection and furthermore after 1, 5, 15, and 30 mseconds. The delayed signals have been multiplied by a factor of 2, 3, 20, and 100, respectively. Some losses are seen on the first 10-15 turns, since the injected beam was not well matched to the lattice. The debunching resulting from the velocity spread in the beam is clearly seen; the same debunching is also responsible for the decreasing amplitude, as the BPM amplifiers are ac-coupled. We point out that these signals have been averaged many times in order to achieve a good signal-to-noise ratio. The number of circulating ions was initially around 10^7. A similar plot of a 14 keV N_2^+ beam observed immediately at injection, and 1, 5, 15, 30, and 60 msecs. later is shown in Fig. 5. The delayed signals have here been multiplied by a factor of 2, 3, 5, 20, and 100 respectively. The longer revolution time and the slower debunching time is observed directly.

In order to measure the lifetime of the beam, the beam was bunched by the drift-tube rf-system at harmonic 1. The corresponding beam-signal from the BPM amplifier as function of time is shown in Fig. 6, together with a fit resulting in a lifetime of 0.29 seconds. We point out, that this measurement has been made with a rf-system without a phase-loop. This lifetime is, at least qualitatively, in agreement with the expected lifetime from restgas interactions. The lifetime has also been seen to decrease shortly after switching the ion-pumps in the ring off. The extrapolated lifetime at the present pressure would then be more than 10 seconds.

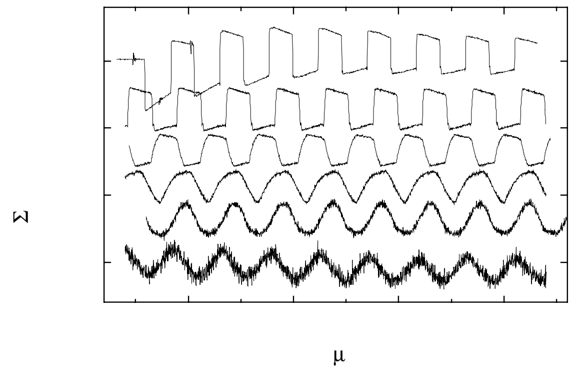

Figure 5: BPM signals from a chopped 15 keV N_2^+ beam. For details, see the text.

Since these initial measurements, a new injector has been built and the system has been baked adequately, resulting in a pressure in ELISA around 6 10^{-12} mbar. At the time of writing, the commissioning with this new injector is in progress. Apart from checking the lattice itself, it will be important to find the space-charge limit of the machine, and demonstrate a pressure limited lifetime at the present low pressure. Also lifetime measurements using a new detector for neutralised ions will be important.

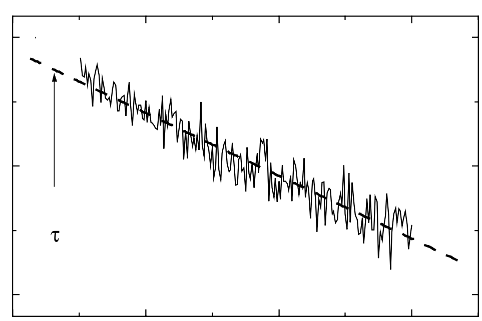

Figure 6: Bunched-beam signal showing a lifetime of 0.3 seconds.

4 PHYSICS APPLICATIONS

The applications of small electrostatic storage rings originate from their ability to store intense ion beams for extended periods of time. The space-charge tune-shift, however, limits the intensity to significantly smaller values than obtainable in a single-pass experiment.

Interactions with the stored ion beam can be with either a photon beam (a laser or synchrotron radiation) or with other particle beams, e.g. an electron beam.

The first group of experiments consists of simple lifetime experiments using metastable ions either created in the metastable state in the ion source itself or after the injection with e.g. a laser. Another class of experiments utilises that initially internally hot ions de-excite spontaneously, and hence may become cold before being studied. Similarly a laser beam may be used to pump the ions into a specific state.

A storage ring is particularly well suited to turn a pulsed beam with low duty-factor into a dc-beam. This could for example be highly charged ion beams from an EBIS source or a positron beam created by a pulsed high-energy electron beam.

One class of experiments that are not directly feasible in ELISA is electron-capture/detachment experiments studied at very low relative velocity as in electron-cooler set-ups. Recombination experiments are, however, possible using a transverse electron beam. Also electrostatic rings for MeV ion beams, needed for the former class of experiments, can be envisaged, and it seems possible to build a storage ring/synchrotron with a maximum energy of 10 MeV with a circumference comparable to the small magnetic storage rings ASTRID, TSR and CRYRING. Furthermore, such accelerators could provide 10-MeV ion beams of arbitrary mass. The absence of magnets would allow very fast ramping.

Storage of very heavy ions would open up the possibility of studying molecules of biological interest, using methods from atomic collision physics.

These general ideas build upon the experience obtained in ASTRID and other storage rings, and some references can be found in [1] and [3].

5 CONCLUSIONS

The design of the first electrostatic storage ring for ions has been described, and some results from the initial commissioning have been given. At a pressure of a few times 10^{-10} mbar, the lifetime of a beam consisting of around 10^7 ions is vacuum-limited.

The applications of electrostatic storage rings for experiments in physics, and hopefully in other areas too, are still to be proven. However, the first applications in physics seem straightforward.

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