ELISA - AN ELECTROSTATIC STORAGE RING FOR ATOMIC PHYSICS

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Abstract

The design of a new type of storage ring (synchrotron) for heavy ions using electrostatic deflection and focusing devices is described. Such a storage ring will be attractive for many atomic-physics experiments, and also for basic research in neighboring fields such as chemistry and biology.

1 INTRODUCTION

Storage rings were initially developed for storage of high-energy particles in particle-physics laboratories. In the last decade, storage rings have also been introduced in atomic-physics and intermediate-energy physics laboratories with great success, see [1]. These low- and medium-energy storage rings were modelled after the storage rings in the high-energy laboratories, in particular LEAR [2], using magnetic bending and focusing devices (e.g. magnets and quadrupoles) and only using electrostatic devices in special cases, e.g. electrostatic septa. These low-energy storage rings have stored particles of very low momentum and velocity. As extreme examples, ASTRID [3] has stored $^{4}He^{-}$ ions at an energy of 5 keV, corresponding to a momentum of 4 MeV/c and a beam of $^{12}C_{70}^{-}$ at 25 keV with a velocity of 0.00025 c.

The new development [4] summarized in the present paper is a design of a storage ring for low, but yet finite, energy particles using electrostatic devices, in particular electrostatic deflectors and quadrupoles. The device is called ELISA for ELectrostatic Ion Storage ring, Aarhus. Although the energy is limited to rather low values, this is not an issue for several experiments.

The advantages of such a ring as compared to a magnetic storage ring are both technical and fundamental. Examples of more technical advantages are no remanent fields, no hysteresis and no cooling water. A more fundamental advantage is the absence of magnetic fields, which may e.g. induce transitions between the hyperfine levels of the circulating ions. Such an electrostatic ring can also be made much smaller than a magnetic one, which in itself can be advantageous, but it also means that heating and cooling of the vacuum chambers surrounding the beam is easy. In this way lower pressures can be envisaged by cooling.

ELISA-type rings are thought to be storage devices, but electrostatic rings could just as well be operated in synchrotron mode. Actually, much faster acceleration than in magnetic rings is possible due to the absence of eddy currents.

The other storage device used to confine charged particles for extended periods in a small volume is the electromagnetic trap. Comparing with an electromagnetic trap, the electrostatic storage ring allows easy access to the ion beam. Furthermore, electrons and atomic/molecular fragments created either spontaneously or by the interaction with an electron- or laser-beam can easily be detected. In particular neutral fragments will be easily detected at the end of straight sections. This issue, although seemingly trivial, is actually a very important feature of storage rings used for atomic-physics experiments [4].

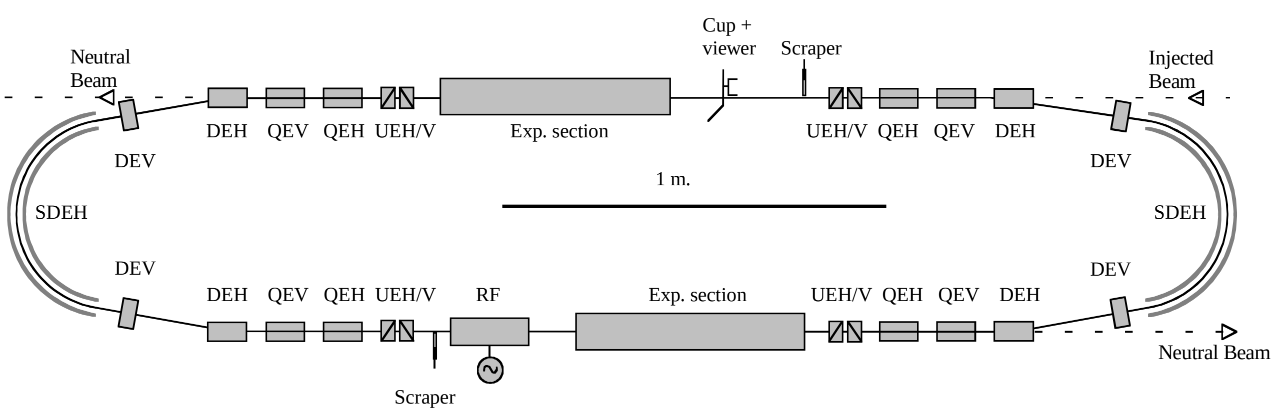

Figure 1 Layout of the ELISA storage ring.

There is one fundamental difference between a ring based on electrostatic and magnetic elements: The longitudinal energy is conserved in the magnetic case, but this is not the case for an electrostatic device. Clearly, an ion traversing an electrostatic deflector off-axis will meet a longitudinal component of the deflecting field and will be accelerated or decelerated at the entrance and exit of the device. This means that there will be an inherent coupling between the longitudinal and transverse directions. It also means that the focusing in a deflector will be different for the electrostatic and the magnetic case.

Initially, we believed that ELISA would be the first electrostatic storage ring. An electrostatic storage ring/synchrotron was, however, built and tested successfully in the mid 50'es, before starting the construction of the AGS at Brookhaven [5]. This ring was built to test the principles of alternating-gradient focusing and transition crossing, and was as such very succesful. The ring was designed for 1-10 MeV electrons and had a circumference of 43 m. This so-called "electron analog" is to the authors knowledge the only electrostatic synchrotron/storage ring ever built, and one might speculate why this is so. One reason is undoubtedly that the low-energy rings are descendants of the high-energy rings where magnetic devices are beneficial.

2 TECHNICAL DESCRIPTION

The electrostatic storage ring presently being built has a race-track shape as shown in fig. 1. This is the most simple lattice with straight sections, but clearly different lattice configurations are possible as for magnetic storage rings. In the following, we shall briefly outline some details. Comparisons with a magnetic storage ring will be made, and here ASTRID [3], familiar to the author, has been chosen.

2.1 Optics - the lattice

The lattice is defined by two 160° spherical electrostatic deflectors (SDEH), four 10° parallel plate deflectors (DEH) and four pairs of electrostatic quadrupoles (QEV, QEH) in the two straight sections.

The resulting lattice functions are shown in fig. 2 corresponding to tunes of Q_H = 1.21 and Q_V = 1.44. The strong focusing from the 160° deflectors is seen to result in a very narrow waist in the middle of the deflectors. Furthermore, an almost round beam is obtained in the straight sections. The lattice is quite flexible, and straight section lengths between 0.6 m (as indicated in fig. 1) and 1.2 m can easily be accomodated. The horizontal and vertical tunes can be adjusted between 1 and 2. For closed-orbit correction, four vertical ± 1° steerers (DEV) are arranged as shown in the fig. 1. Horizontally, the two 160 ° and the four 10° deflectors will be used for closed-orbit corrections.

The injection system consists of a chopper in the injection beamline and one of the 10° deflectors used as a pulsed inflector giving a single-turn injection. Injection will initially be made from an isotope separator.

All electrodes close to the beam will be gold-plated in order to avoid oxide layers and the potentials across such insulating layers. The required voltages, apertures and other relevant numbers are given in the table.

2.2 3D tracking simulation

The optics has first been designed using linear transfer matrices for hard-edged elements in ordinary lattice programs. In this way, fig. 2 was produced.

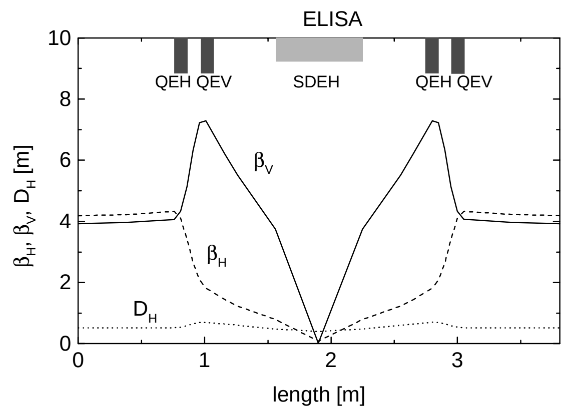

Figure 2 Lattice functions for half the circumference.

Secondly, the program SIMION [6] has been used for inclusion of fringe fields etc. SIMION is an ion optics simulation program that models ion optics with 3D electrostatic potential arrays determined by solving the Laplace equation outside electrodes. Ions has been traced (flown) through the machine for many turns, and stability has been verified for hundreds of turns for not too large starting amplitudes.

2.3 Radio Frequency System and Diagnostics

Although no acceleration is envisaged in ELISA, bunching of the beam will be useful for bunched-beam observations. Hence a driven drift tube rf-system of 20 cm length will be installed. 30 V on the drift tube will give 1 V peak rf corresponding to $\Delta p/p = 0.7\,\%$ for harmonic number 1. This can be achieved with a rf-signal generator and a small amplifier. The required frequency range is 10 kHz - 500 kHz.

The diagnostics for ELISA will consist of a viewer, a Faraday cup, four sets of horizontal and vertical pick-ups for bunched beam observation, Schottky noise detection, two sets of horizontal and vertical scrapers, and a current transformer.

Finally, observations of the neutral beam emerging from the two straight sections will be very useful.

GENERAL PARAMETERS	
Injection energy	25 keV
Circumference	7.62 m
Revolution time	3.5μs (p), 93μs (C_{60})
Betatron tunes (Q_H, Q_V)	1.21, 1.44
Chromaticities (ξ_H,ξ_V)	-1.7, -1.3
Momentum compaction (α_p)	0.42
160° spherical deflectors	
Electrode radii	235 and 265 mm
Nominal voltages	± 4.0 kV
10° deflectors	
Plate distance	50 mm
Plate length	100 mm
Nominal voltages	± 2.2 kV
Electrostatic quadrupoles	
Inscribed radius	26.2 mm
Electrode length	50 mm
Nominal voltages	± 0.43 kV
Chopper and inflector	
rise/fall time	< 200 nsec.

2.4 Intensities and lifetimes

The maximum current that can be stored is usually limited at low energy by the space-charge tune shift. Hence, we should be able to store currents comparable to that in ASTRID, up to around 10 μA corresponding to some 10^8 particles.

The lifetime of a beam of singly-charged ions at low energy is determined by interactions with the residual gas, either electron-capture or electron-loss. Cross sections for these processes are approximately velocity-independent at small velocities, and hence a longer life-time is expected at low velocities, since the traversed target thickness becomes smaller. Furthermore, it is easier to obtain a low pressure in a small ring than in a large one. We design for a pressure around 10^{-11} mbar, which should give lifetimes in the 10-1000 sec. region. The short lifetimes apply to loosely bound negative ions.

Intra-beam scattering is the scattering between beam particles, which can lead to emittance growth. As an example, we have calculated the intra-beam scattering times (1/e folding times) for a 25 keV beam of singly-charged ions with mass M = 24, a current of 10 μA, momentum spread $\Delta p/p = 3\ 10^{-3}$, horizontal emittance of $\varepsilon_H = 30\ \pi$ mm mrad, vertical emittance $\varepsilon_V = 15\ \pi$ mm mrad using the program ZAP [7]. We get a longitudinal scattering time of τ_L = 36 sec., a horizontal scattering time of τ_H = 162 sec. and a vertical scattering time τ_V = 65 sec. The emittances and momentum spread have been chosen to get roughly equal scattering times in all three planes. These scattering times are comparable to the lifetimes of positive particles. We note here, that intra-beam scattering times scale as $\tau \propto T^{3/2} A^2/(N q^2)$, 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 ions will have significantly larger scattering times.

3 POTENTIAL PHYSICS EXPERIMENTS

The applications of ELISA-type storage rings exploits the specific properties such as simplicity, use of electric fields and absence of magnetic fields, low residual gas pressure and easy access to beam particles and decay products. In particular, storage of ions with <u>any</u> mass is possible at the design energy of 25 keV [8], including fullerenes, proteins and macro-molecules. We refer to [4] for further speculations about possible experiments.

The limitation for the actual ELISA ring is the rather low storage energy, which however is not a principal constraint for this type of storage ring, and one can envisage electrostatic storage rings with energies up to tens of MeV's with circumferences below 100 m.

4 CONCLUSIONS AND OUTLOOK

A new general type of storage device for charged particles has been described.

At the time of the present conference the ELISA storage ring is being assembled at our institute, and the commissioning will start this summer.

5 ACKNOWLEDGEMENTS

Several persons have contributed to the design and concept of ELISA. In particular, V. Toft has converted the ideas to engineering constructions and L.H. Andersen has brought the physics ideas and potential experiments into the design.

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[8] Actually for very heavy ions, the beam will sag in the straight sections owing to gravity, eventually limiting the mass to a finite value. This effect was realized by J.S. Nielsen.