Electrostatic storage rings for atomic and molecular physics

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Abstract

A significant number of electrostatic ion-storage rings have been built since the late 1990s or are currently in their construction or commissioning phases. In this short contribution, we attempt to supply an overview of these different facilities, while we also mention a selection of the electrostatic ion-beam traps that has been developed through the same time period and by some of the same research groups.

Keywords: electrostatic storage ring, molecular ions, negative ions

(Some figures may appear in colour only in the online journal)

1. Introduction

Since the first electrostatic ion storage ring, (ELISA) [1], was inaugurated in 1999 there has been a growing interest in developing the field of research utilizing electrostatic storage rings and traps. This is mainly driven by the need for possibilities to investigate molecular and atomic ions over extended periods of time without having to go to the larger scale of magnetic confinement ion-storage rings. Many ground-breaking experiments performed with magnetic-confinement storage rings made use of the ability to store ions at MeV energies [2] and the thereof following convenient few keV electron energies of velocity-matched electron cooler[3]/target[4, 5] beams. However, some very interesting experimental results obtained with magnetic-confinement storage rings relied solely on the possibility to store ion beams for extended periods of time. An early example of such a measurement concerned the determination of the lifetime of the He− (1s2s2p 3P 5 2) state that decays through a forbidden autodetachment process to the helium ground state and a free electron. Andersen et al [6] determined this lifetime in the ASTRID magnetic confinement storage ring in Aarhus, Denmark by storing an ion bunch of He− and recording the rate of neutrals after a straight section as a function of time after the injection. While this experiment was a big step forward at the time, the accuracy was limited by two systematic effects: the strong magnetic fields of the dipole magnets mixed the longest-lived fine structure component of interest with the other fine structure levels, reducing the effective lifetime, and the effect of photodetachment of the loosely bound (77 meV) ‘extra’ electron by photons of the room temperature blackbody radiation. Many other experiments using only the storage and/or the possibility for laser interaction with the stored ions were performed in Aarhus, and in this situation the idea of more compact, less complex and more economical ion-beam storage in form of an electrostatic storage ring was developed [1]. Furthermore there are advantages in using electrostatic rather than magnetic confinement: electric-field confinement is inherently mass-independent allowing for storage of heavier species and while magnetic-field effects are sometimes found to influence the results of the measurements (see the He− example mentioned above [6]) equivalent effects of electric fields are insignificant. A qualitative explanation for the different effects of electric and magnetic fields on the stored ions lie in the basic fact that the force on a charged particle is proportional to the velocity of the particle for magnetic fields while it is velocity independent for an electric field. The keV ions under consideration in the present context have laboratory velocities that are slow compared to the electron velocities in the ionic bound states. In order to achieve a sufficiently strong magnetic field to confine the ion beam one therefore inevitably exposes the bound electrons to forces...
that are considerably stronger than those required to confine the relatively slow-moving singly charged ion. Obviously the equivalent enhancement of the force on the bound electrons is not present in the case of electrostatic storage.

2. Early electrostatic storage rings

2.1. ELISA

The first electrostatic ion-storage ring was the ELISA [1]. There the general layout of a closed orbit consisting of two cylindrical $160^\circ$ bends and four $10^\circ$ deflectors was introduced, which has been used in several of ELISA’s followers. At ELISA, intense research programmes have been undertaken for more than fifteen years and here we can only give a few examples. One example concerns the aforementioned He$^−$ lifetime. When this measurement was performed in ELISA [7] one of the sources of systematic error mentioned above was in fact eliminated as the ring had no dipole magnets to mix the fine structure levels. Furthermore the ring was cooled down to about $225 \, \text{K}$ to limit the influence of the blackbody radiation. Another important early ELISA experiment was a study of the active chromophore of the green fluorescent protein [8]. The absorption spectrum of the chromophore ion was determined by action spectroscopy, where the absorption of a photon by a complex molecular system is followed by a fragmentation process leading to one or more neutral fragment(s) that are easily detected in the storage ring. This technique has been extensively used in ELISA for the studies of the properties of isolated ions of biological importance. A highly remarkable series of investigations at ELISA concerned the fact that when a bunch of complex molecules or clusters are stored in the storage ring the signal of neutrals produced in spontaneous decay/fragmentation processes does not follow the well-known exponential law characteristic of a constant decay rate common for all the ions. Rather it is observed that the signal of neutral particle detection follows a power-law as observed for silver cluster anions in [9]. The reason for the deviation from the simpler exponential law is that the ions are formed with a broad distribution of internal energies and those that are most highly excited therefore decay earlier depleting the ion ensemble in such a way that the average internal energy of the remaining ions decreases with time [9].

2.2. The Tsukuba electrostatic storage ring

Quite soon after ELISA a storage ring with a similar electrode lay-out was built in Tsukuba, Japan. The unique feature of this ring is that it is equipped with a merged electron beam making it possible to study interactions between free electrons and complex molecular ions if only for relative energies in excess of $1 \, \text{eV}$ (see [10]).

2.3. The Tokyo Metropolitan University (TMU) electrostatic storage ring

Continuing chronologically, the next electrostatic ion storage ring was also built in Japan. At TMU another racetrack shaped storage ring rather similar to ELISA was built. There are, however, some essential differences. This ring can be cooled in part to liquid nitrogen temperature. Also the mass selection before ion injection is performed by time-of-flight, thereby eliminating also the injection-line dipole magnet otherwise used for this purpose [11]. As at ELISA, the TMU ring is used extensively for studies of complex molecules and their interaction with laser light, and detailed information is extracted by varying both the laser wavelength and the time after injection at which the laser is applied. A recent example is a comparative study of the very different cooling rates of $C_6^+$ and $C_6H^+$. The former is an open-shell system with a small HOMO-LUMO gap. This makes the inverse internal conversion cooling mechanism effective. Here energy initially distributed over many degrees of freedom is transferred to an electronic excitation and thereby effectively radiated away. For the latter closed-shell system the HOMO-LUMO gap is too large for this mechanism to be effective and as a result $C_6H^+$ cools very much slower than $C_6^+$ [12].

3. Electrostatic ion-beam traps

3.1. The Zajfman trap

In parallel with the development of the larger electrostatic storage rings there has been a development of much smaller and compact devices in the form of electrostatic ion-beam traps (EIBTs). The first EIBTs were developed simultaneously and with no mutual communication between the groups at the Weizmann Institute [13] and at Berkeley [14]. Such traps that consist of two separate focusing electrostatic mirrors much like an optical cavity are now often referred to as Zajfman traps, and several laboratories have now developed their own versions of this—generally room-temperature operated—device. One of many such traps is the one built at Queen’s University, Belfast [15]. Also the so called multi-reflection time-of-flight mass spectrometer can be viewed as an EIBT with strong similarity to the Zajfman trap [16]. There has been many interesting results from the Israel group using the Zajfman trap. A relatively early example is their measurement of the He$^−$ lifetime. Just like in the case of the measurement with ELISA [6], the problem of magnetic-field mixing did not exist, but the measurement was performed at room temperature making the final result dependent upon modeling of the effect of black-body radiation thus affecting the final uncertainty of the result [17]. A more recent example concerns the rapid cooling through inverse internal conversion of $C_6^+$ [18].

3.2. ConeTrap

A simpler EIBT is the ConeTrap, which was developed at Stockholm University around 2000 [19]. This EIBT consists
of only three electrodes. Two conical electrodes facing each other and separated by a cylindrical electrode that typically is grounded. This geometry yields equipotential surfaces inside the cones that are curved and form focusing mirrors for ions of the proper kinetic energy. This device was later installed inside a cryogenic vacuum chamber and operated at 12 K for a high-precision measurement of the lifetime of the metastable He$^-$ ion [20]. In this experiment both systematic limitations mentioned for the original ASTRID experiment [6] were eliminated. Since the device is electrostatic there is no magnetic-field induced mixing and the role of blackbody radiation is completely negligible at such a low temperature. Interestingly, the result, 359.0 ± 0.7 μs, lies between the less accurate results of the ELISA [7] and the Zajfman trap [17] measurements, off by 2 σ from both according to their respective error estimates. So the ‘who is right’ battle was a draw in the end. Currently a new ConeTrap is installed in a collision experiment [21]. Complex ions formed in electrospray ionization collide with noble gases at center of mass energies in the 100 eV range, whereupon mass-selected fragments are stored in ConeTrap to investigate their stability against further fragmentation.

3.3. The miniring

A recent very interesting development is the table-top electrostatic ion storage ring, miniring, in Lyon [22]. For this instrument two conical electrodes similar to those found in ConeTrap are used as 160° bends. In 2013 the Lyon group used this ‘trap-sized ring’ to demonstrate very rapid cooling of ions of the polycyclic aromatic hydrocarbon, anthracene after heating by laser irradiation [23].

3.4. CTF, cold test facility

As part of the ambitious cryogenic storage ring (CSR) project in Heidelberg to be discussed below, an enlarged Zajfman trap has been installed in a cryogenic chamber and storage lifetimes of several minutes have been demonstrated [24]. This large cold EIBT is a very interesting device, and it is clear that many of the advantages of cryogenic electrostatic storage rings are found with equal validity for this apparatus. Besides being a test setup for CSR, the CTF has also been used for research. Cryogenic storage of SF$_6^-$ shows that radiative cooling can be observed at the longer time-scales now made available due to the much improved vacuum conditions over those found in room-temperature devices [25].

4. New electrostatic ion-storage rings and projects

4.1. Room temperature electrostatic rings

A larger electrostatic storage ring with a rather different ion-optical layout has been constructed at Frankfurt University [26]. The first beam was stored in this ring in 2013 and storage lifetimes in the order of several seconds have been demonstrated. First experiments with electron interactions are in progress. In Aarhus, where it all started, Henrik Pedersen and Lars Andersen have built a 4 m circumference room-temperature electrostatic ring in a 1 × 1 m square shape for optimised access for laser interaction and have demonstrated a stored beam [27]. Furthermore, a new electrostatic ring is being set up at King Abdulaziz City for Science and Technology in Riyadh, Saudi Arabia [28].

4.2. RICE, Riken cryogenic e-ring

At RIKEN in Japan a 3.0 m circumference electrostatic storage ring has very recently been constructed and has already been operated at cryogenic conditions (5 K in this case), storing beams of positive ions with very long storage lifetimes. In fact the residual-gas density is so low that no neutral particles formed in charged transfer were detected [29].

4.3. CSR

At the Max-Planck Institute for Nuclear Physics in Heidelberg, a very ambitious project is close to its realization: a 35 m circumference single cryogenic electrostatic ion-storage ring (CSR) has been constructed [30]. Beams have been stored at room temperature and at the time of writing of this proceedings contribution the entire system is for the first time being cooled down, a process estimated to take 2–3 weeks [31]. In its final form CSR will be equipped with an internal gas-jet target, an ion-neutral merging section, and an electron cooler/target device [30].
4.4. DESIREE, double electrostatic ion-ring experiment

The DESIREE facility [32, 33] consists of two electrostatic ion-storage rings enclosed in a common cryogenic vacuum chamber. Each of the two rings are race-track shaped and the layout is rather similar to that of ELISA [1] except that additional steerers in one of the rings are necessary in order to make it possible to have two ion beams of opposite charges overlap along their common straight section. To enable studies of mutual neutralization in merged beams of positive and negative ions is the primary motivation for choosing a double-ring structure. At the same time, this is also the most challenging aspect of the project and it is therefore perhaps not surprising that the first results were obtained in single-ring operation mode. In the commissioning paper beam-storage for up to 7 min (for 10 keV operation mode. In the commissioning paper beam-storage for up to 7 min (for 10 keV operation mode. In the commissioning paper beam-storage for up to 7 min (for 10 keV operation mode. In the commissioning paper beam-storage for up to 7 min (for 10 keV operation mode. In the commissioning paper beam-storage for up to 7 min (for 10 keV operation mode. In the commissioning paper beam-storage for up to 7 min (for 10 keV operation mode.

In this paper we show the hitherto longest storage lifetime of an ion beam in DESIREE. Te+ was stored at 10 keV and with optimum vacuum conditions at a temperature of 12 K. With these conditions the rate of neutrals formed in residual-gas collisions was too low to provide a useful signal. Instead we applied a photodetaching laser pulse once every 30 s and recorded the yield of neutrals from this process (while keeping the laser power sufficiently low that the laser photodetachment itself was not a significant loss process). The decay of the beam lead to an exponentially decreasing signal with a characteristic (1/e) lifetime of 30 min determined by the presumably still collision-limited lifetime of the stored ion beam. This is to the best of our knowledge the longest storage lifetime measured for a beam of negative atomic or molecular ions, while for MeV positive ion beams in magnetic confinement storage rings, much longer lifetimes can be achieved without extremely high vacuum as the cross section for the dominating loss mechanism, electron transfer ion-neutral collisions, decreases rapidly with energy for velocities well above the Bohr velocity [36]. The very long Te+-lifetime found here gives ground for optimism concerning the future plans for this facility and other cryogenic electrostatic storage devices as the ability to store the ions longer will expand the range of physics problems to be addressed.

5. Conclusions and outlook

In this contribution, I have tried to give a short overview of the status of the many electrostatic ion storage rings (and some of the traps) that are in operation, under construction or in the planning phase. If any projects have been excluded from this presentation, this is due only to the ignorance of the author rather than any bad will. Obviously very many experiments performed at the rings and traps mentioned here are not treated in this presentation. The choices made are mostly based on an attempt to tell a coherent story of this development from the ELISA all the way to the cryogenic devices ConeTrap, CTF, DESIREE, RICE and CSR. The first 15 years of physics with electrostatic storage rings and traps have given us many interesting results and with the many new emerging projects, whether cryogenic or room temperature, there is good hope that the next 15 years will yield an even more impressive scientific output from the maturing field of science with electrostatic storage devices.

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