ELECTROSTATIC STORAGE RINGS AT THE ULTRA-LOW ENERGIES RANGE

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Abstract

Electrostatic storage rings have proven to be invaluable tools for atomic and molecular physics at the ultra-low energy range from 1 to 100 keV/A. Due to the mass independence of the electrostastic rigidity, these machines are able to store a wide range of different particles, from light ions to heavy singly charged bio-molecules. A so-called "reaction microscope", incorporated into the ring is considered to be a powerful tool to study fundamental effects by multiple crossing of the stored ion beam with an ultrasonic gas jet. To enable the operation of such internal experiment, one needs to provide very short beam pulses in the 1-2 nanosecond range to pave the way for kinematically complete measurements of the collision dynamics of fundamental few-body quantum systems on the level of differential cross sections. However, earlier measurements at some rings showed strong limitations depending on beam intensity, probably linked to non-linear fields that cannot be completely avoided in such machines. In this contribution, we discuss common features of electrostatic storage rings and analyze the performance of such rings.

INTRODUCTION

Magnetic storage rings operates not only in high energy range but also at low energies. In particular, the LEAR ring at CERN was the first machine to store, cool and decelerate antiprotons down to only 5 MeV [1]. $^4He^-$ and $^{12}C_{70}^-$ ions have been stored at energies of 5 and 25 keV respectively in the ASTRID magnetic ring [2].

The first electrostatic ring was built in 1953 to act as an electron analogue of the Brookhaven AGS synchrotron [3]. Ions are stored in electrostatic traps at lowest energies [4,5]. Another type of storage device complinmentary to traps and developed in response to the needs of the astro-, atomic and molecular physics communities, are Electrostatic Storage Rings (ESR) [6]. As opposed to magnetic storage rings, ESR have no lower limit on the beam energy as well as no upper mass limit on the ion mass that can be stored. Due to the mass independence of the electric fields, massive particles such as clusters and bio-molecules can be stored at lowest energies. ESR were already used to study the following problems [4,6,7]:

- Collision phenomena and plasma properties of astrophysical objects i.e.molecular clouds, quasars;
- electron impact rotational and vibrational excitation of cold molecular ions;
- quantum reaction dynamics of cold molecular ions;
- gas-phase spectroscopy of biomolecular ions;
- ultra-cold (2 K) ESR will allow to store molecular ions in their rotational ground state;
- rotational effects in the process of dissociative recombination of molecular ions with low temperature electrons (<10 K);
- molecular dynamics - to achieve Coulomb cristallization for a fast strored beam and study phase transition to a cristalline beam;
- fundamental few body Coulomb problem for single as well as for multiple ionisation;
- measurements of single and multiple ionization cross-sections (total and differential) of antiprotons colliding with atoms of supersonic gas jet;
- ion-impact ionisation to benchmark theoretical predictions;
- anti-hydrogen studies by merging antiprotons with positrons;
- study of the lifetime of metastable atomic states;
- investigations of the single component plasma.

COMMON FEATURES OF ELECTROSTATIC STORAGE RINGS

ESR are in some way complimentary to ion traps and allow reducing the ion energy to almost ground state. In ESR, ions circulate in one direction while in ion traps there is no designated direction of motion. One can outline the following common features of all ES rings:

- ESR can store ions at keV energies and potentially even lower energies;
- Their fields are mass independent, i.e. –a wide range

Table 1. Electrostatic storage rings worldwide

Ring	ELISA [9,10]	ESR [11]	FRR [13]	DESIREE [14]	CSR [18,19,20]	USR [21,22,23]	AD-REC [24]
Location	Aarhus Univ. Danmark	KEK Tsukuba Japan	Frankfurt Univ. Germ	Stockholm Univ. Sweden	MPI Heidelberg Germany	FAIR-GSI Darmstadt Germany	ASACUSA CERN Switz
Ions	A ≤ 100	A ≤ 100	A ≤100	A ≤ 100	A ≤ 100	antiprotons	antiprotons
Energy, keV	(5–25)·Q	20·Q	50	(25-100)·Q	(300-20)·Q	300-20	3-30
Type	Racetrack	Race track	Race track	2 x Race tracks	quadratic	Achromat quadratic	Low beta racetrack
Symmetry	2	2	2	2 x 2	4	4	2
Perimeter, m	7.62	8.14	14.17	9.2 x 9.2	35.2	43	7.9
Revolution time, µs	3.5 (p) 93 (C_{80})	4 (p) 22 (N_2^+)	4.5 (p)	4–60	4–180	5.67–22	10–3
ES Deflectors	160°+10°	160°+10°	75°+15°	160°+10°	39°+6°	37°+8°	90°+90°
Defl.Rad, mm	250	250	250	250	2000+1000	2000+1000	400
Deceleration/ acceleration	Drift tube	Drift tube	--	--	Drift tube 10 V	Drift tube 10 V	Pulsed injector
e-cool, eV	NO	NO	NO	NO	10	10	NO
life time, s	10-30	12-20	--	--	10–100	~10	~20 ms
Operation modes	storage	Storage	D=0 at target	Colliding beams	Cooling storage	Short bunch Slow extr.	Low beta Low Disp.
Vac. mbar	10^{-11}	$5 \cdot 10^{-11}$	10^{-12}	10^{-12} (10°K)	10^{-15} (2°K)	10^{-11}	10^{-10}
Status	operate	operate	tested	Project	manufact.	Design	Manufact.

of particles, from light protons and antiprotons to heavy molecular ions, with positive and negative charge, can be stored;

- no remanent fields and no hysteresis effects;
- Fast acceleration/deceleration can be realized because of the absence of eddy currents

A clear advantage is that in-ring experiments with the circulating ions can be done over many turns, thus multiplying the number of interactions. This is in contrary to single pass experiments realized for example behind the RFQ-D at CERN [8]. Electrostatic rings are compact and relatively cheap with respect their magnetic counterparts. The parameters of some electrostatic storage rings are shown Table 1.

The first electrostatic ring dedicated to atomic physics experiments was built in Aarhus, see Fig.1 [9]. In ELISA, two 160° cylinder deflectors and two 10° parallel plate deflectors, together with four sets of electrostatic quadrupoles form a simple racetrack structure, as seen in Fig.2 [10]. The split deflectors allow for a detection of neutral particles at the end of the straight sections and for simple injection into the machine. Initially, ELISA was equipped with 160° deflectors of spherical shape in order to provide equal focusing in both, the horizontal and vertical plane. The ring performance with spherical deflectors was rather poor. Analytical [11] and computer [12,13] studies indicated that sextupole component of the electric field distribution for the spherical deflector is four times as large as for the cylindrical one and dynamic aperture a few times smaller. Since then ESR operate with deflectors of cylindrical shape. Rings with similar lattice were built at KEK [14] and Tokyo University [15].

In the Frankfurt Storage Ring (FSR) 90° bends are split into 75° deflectors of cylindrical shape and 15° parallel plate deflectors, see Fig.3 [16]. Electrostatic triplets are located in the short sides, between two cylindrical deflectors. Quadrupole doublets in the long straight sections give rise to a low beta-function of $\beta_{x,y}$≈0.2 m at the interaction point. The dispersion function is changing sign at this point and a sharp beam focus of 3x4 mm^2 is available in four locations around the ring.

Figure 1. Photograph of the electrostatic storage ring ELISA **[9].**

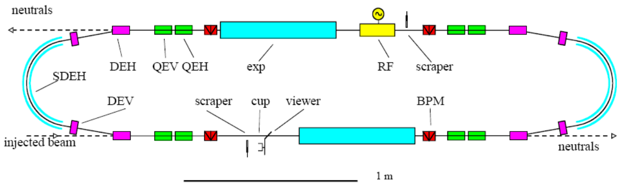

Figure 2. Layout of ELISA storage ring. Neutrals can be detected behind the 10° parallel plate deflectors - DEH [10].

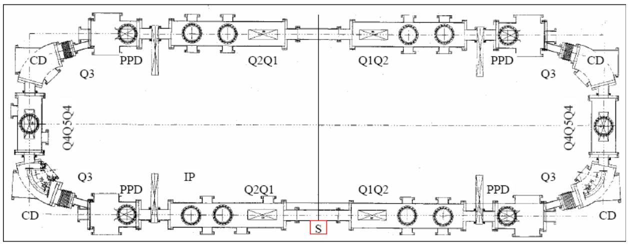

Figure 3. Schematic view of the Frankfurt Storage Ring: CD–75° cylindrical deflector, PPD–15° parallel plate deflector, Q4Q5Q4 – electrostatic triplet [16]

In the DESIREE double ring project, two ESR of the same racetrack type as ELISA were overlapped, to allow for ion-molecular head-on collision studies [17].

CRYOGENIC STORAGE RING (CSR)

The Cryogenic Storage ring (CSR) at the MPI for Nuclear Physics in Heidelberg, Germany is a next-generation low energy storage ring for essentially all ion species – from hydrogen ions up to molecular ions, macro- and biomolecules, clusters, atomic ions at extreme charge states, etc. [18]. The kinetic energy of the stored ions is between 20 and 300 keV. In order to provde unique collision and blackbody radiation-free environment for radiative relaxation of molecular species and for long time storage of keV beams all ring components are cooled down to ~2 K. Vacuum better than 10^{-15} mbar is anticipated [19]. Special attention had to be paid to a precise and stable ion optics alignment under the substantial thermal shrinking and displacement during cool-down of the ring. The ring has a lattice with a four-fold symmetry and accommodates a reaction microscope, electron cooling, injection, and an RF drift tube in its 2.8 m long straight sections, see Fig.4 [20].

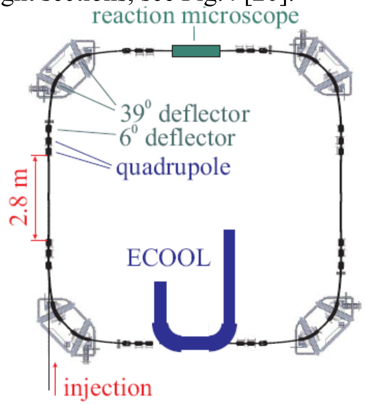

Fig.4.The CSR ring has a 4-fold symmetric lattice, each cell consists of two 39°, two 6° deflectros and two quadrupole doublets [20].

ULTRA-LOW ENERGY STORAGE RING

In the future Facility for Low-energy Antiproton and Ion Research (FLAIR) at FAIR, the USR will provide cooled beams of antiprotons down to energies of 20 keV

[21]. The planned experiments with both, slow and fast extracted, external beams, as well as in-ring experiments with ultra-short bunches in combination with a reaction microscope demand a very flexible ring lattice, see Fig.5 [22]. Four dispersion-free straight sections, each 4 m long, are used for the electron cooler, the decelerating drift tube, the elements for fast/slow extraction, different rf systems for the short bunch operation mode and the reaction microscope [23]. One section is kept free for a possible inclusion of a merged positron ring**.** Five electrostatic quadrupoles, two 8° and two 37° electrostatic deflectors form an achromatic 90° bend.

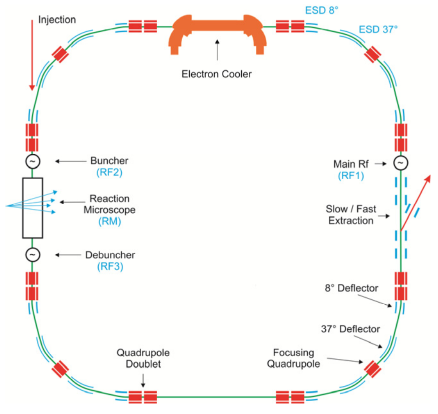

Figure 5. Layout of the Ultra-low energy Storage Ring [22].

ANTIPROTON RECYCLER (AD-REC)

A small recycling ring (AD-REC) in energy range 3 to 30 keV has been designed for use on the Musashi beamline at the CERN-AD [24]. Ring enables differential ionization cross-section measurements by incorporating the reaction microscope, see Fig.6. Four sets of ESQ triplets in the long straight sections are moved as close as possible to each other provide a sharp focus. Dispersion function in the middle of the straight section is reduced to an acceptable low value.

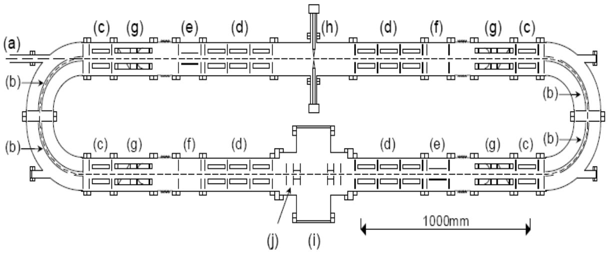

Figure 6. AD-REC cross-section: (a)-injected beam, (b)-90° deflectors, (c,d)-ES quads (e,f,j)-correctors, (g)-beam position monitors, (i)-reaction microscope chamber [24].

ACKNOWLEDGMENTS

The generous support of the Helmholtz Association of National Research Centres (HGF) under Contract no. VH-NG-328 and the GSI Helmholtz Centre for Heavy Ion Research is acknowledged.

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