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Status of the Frankfurt low energy electrostatic storage ring (FLSR)

F King, T Kruppi, J Müller, R Dörner, L Ph H Schmidt, H Schmidt-Böcking and K E Stiebing

Institut für Kernphysik der Goethe Universität, Max von Laue Str. 1, D-60438 Frankfurt am Main, Germany

E-mail: king@atom.uni-frankfurt.de

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Abstract

Frankfurt low-energy storage ring (FLSR) is an electrostatic storage ring for low-energy ions up to $q \cdot 80$ keV (q being the ion charge state) at Institut für Kernphysik der Goethe-Universität, Frankfurt am Main, Germany. It has especially been designed to provide a basis for experiments on the dynamics of ionic and molecular collisions in complete kinematics, as well as for high precision and time resolved laser spectroscopy. The ring has 'racetrack' geometry with a circumference of 14.23 m. It comprises four experimental/diagnostic sections with regions of enhanced ion density (interaction regions). First beam has successfully been stored in FLSR in summer 2013. Since then the performance of the ring has continuously been improved and an electron target for experiments on dissociative recombination has been installed in one of the experimental sections.

Keywords: electrostatic, HeH, storage ring

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

Introduction

Electrostatic storage devices have become a valuable tool for atomic- and molecular physics as they allow storage and investigation of atomic and molecular systems with virtually no limit on their masses, opening the window for investigating also very complex bio molecular or astrophysical relevant molecules, which are in the focus of scientific interest. Besides electrostatic traps [1, 2] electrostatic storage rings are particularly suited to investigate the reaction dynamics within these molecules by allowing the study of dynamic collisions under well-defined kinematical conditions. For electrostatic storage devices of sufficient size, the installation of established techniques is possible, like a reaction microscope at an internal gas/electron targets, allowing for kinematical complete experiments of atomic/molecular reactions. Being pioneered by the work at Aarhus at the ELISA-storage ring [3], several such systems are meanwhile installed or under commissioning worldwide [4–10].

At the Frankfurt low-energy storage ring (FLSR) [7] of the accelerator center of the Institut für Kernphysik der Goethe Universität Frankfurt (IKF) first stored beams have been launched in August 2013. Several species of atoms and molecules have been stored in the ring at increasingly improved vacuum conditions. A first experiment on dissociative recombination (DR) of vibrational cool HeH^+ molecules has been started.

Methods

FLSR has been designed for ion-energies of $q \cdot 50$ keV (q being the ion charge state). However, it will be possible to store ions up to $q \cdot 80$ keV without further modification of the existing set up. A two-staged high voltage terminal has been designed and built as a general platform to install appropriate ion sources [11]. It is presently equipped with a penning ion source (PIG).

The injected beam, coming either from the PIG source on the new platform or from the IKF 14 GHz-ECRIS [12], is pulsed in an electrostatic HV *pulsing unit* that allows selecting a suitable injection frequency and bunch length, usually chosen as $\Delta t_b \approx 70\%$ of Δt_r, (Δt_b, being the bunch length and Δt_r, the revolution time of the ions in the ring). This pulsing

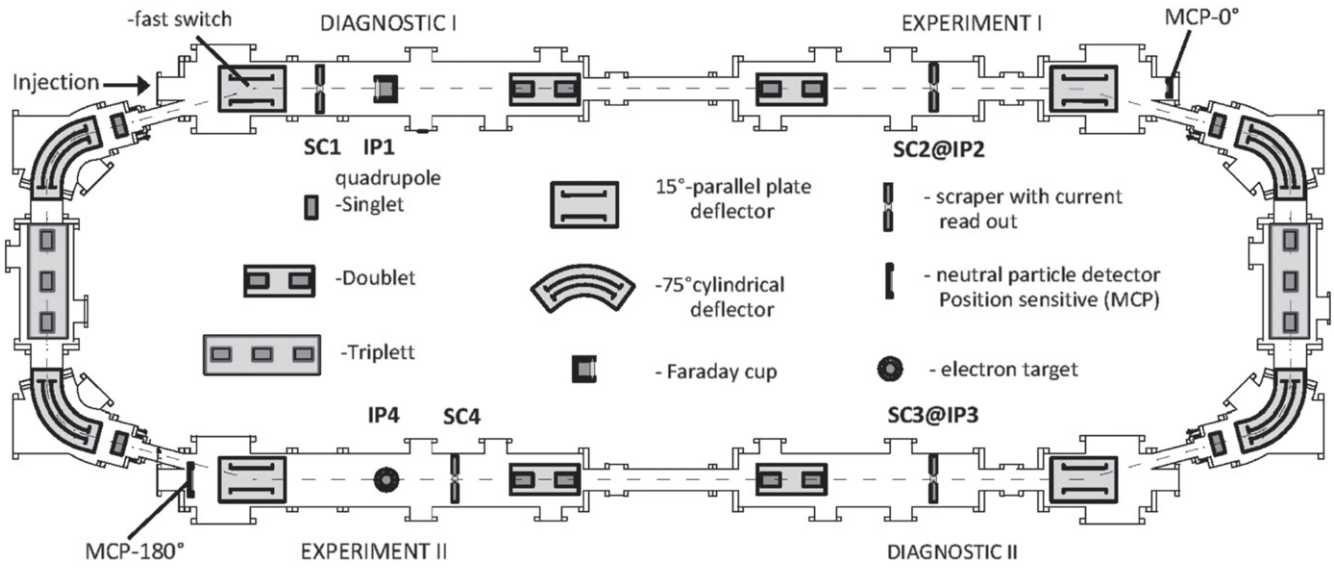

Figure 1. Sketch of the ion optical and beam diagnostic devices in FLSR. The ring has 4-fold super symmetry with four regions of enhanced ion density (IP) with beam spot sizes of 2×3 mm^2 (see [7] for details). The two 'experiment' sections can be separated from the ring vacuum by valves for installation of experiments. Main diagnostic devices are scrapers (close to IP) and two position sensitive particle detector systems at the 0° and 180° ports to monitor neutralized beam particles. An electron target has been installed in experimental section 2.

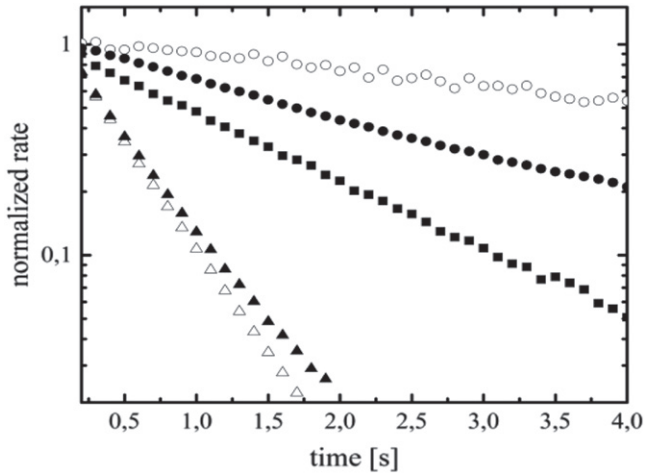

Figure 2. Measured storage times of different ions at 20 keV at 3×10^{-10} hPa. Open triangles: He^+ ($\tau = 0{,}43$ s); full triangles: HeH^+ ($\tau = 0{,}47$ s); full circles: Ar^+ ($\tau = 2{,}0$ s); open circles: Xe^+($\tau = 7{,}1$ s). Closed squares: Ar^+, 10 keV at 7×10^{-10} hPa ($\tau = 0{,}68$ s).

unit is used to trigger the *fast switch* at the entrance to FLSR, which acts on the first ring deflector (15°-parallel plate deflector (PPD)). This deflector is set zero potential during injection and is switched to its design value for stored beam (single turn injection). A sketch of FLSR, its experimental and diagnostic sections, the ion optical elements and the diagnostic devices is displayed in figure 1. Four adjustable *scrapers* (SC1–SC4) are installed near or at the interaction regions (IP) of the ring. In these regions the beam is focused to spot sizes of 2×3 mm^2 as locations for experiments with internal targets or pulsed lasers (see [7] for details). Two *position-sensitive multi-channel-plate-detector systems* (MCP) at the 0°- and 180°- port of the ring serve to detect the neutralized particles generated in the long sections of the ring. A summary of the basic properties of FLSR is given in table 1.

Table 1. Basic properties of FLSR (see also [7]).

General parameters:	
Supersymmetry	4
Design energy	50 keV
Rev. freq. (protons@50 keV)	217 kHz
Circumference	14.23 m
Bake out temperature	$\geqslant$200 °C
Design vacuum (full installation)	$\leqslant 10^{-11}$ hPa
15° deflectors:	
Plate area	200 mm × 200 mm
Plate distance	100 mm
Voltage @ design energy	±6.7 kV
75° deflectors:	
Height	100 mm
Inner/outer radius	230 mm/ 270 mm
Voltage @ design energy	±8.02 kV
Quadrupoles:	
Length of electrodes in singlets	50 mm
Length of electrodes in multiplets	100 mm
Distance between lenses in multiplets	90 mm
Radius of aperture	30 mm
Voltage @ design energy	±3.05 kV

Results and discussion

A collection of figures of merit is shown in figure 2. The storage times are compatible with the neutralization of the beam by charge exchange with the residual-gas in the ring.

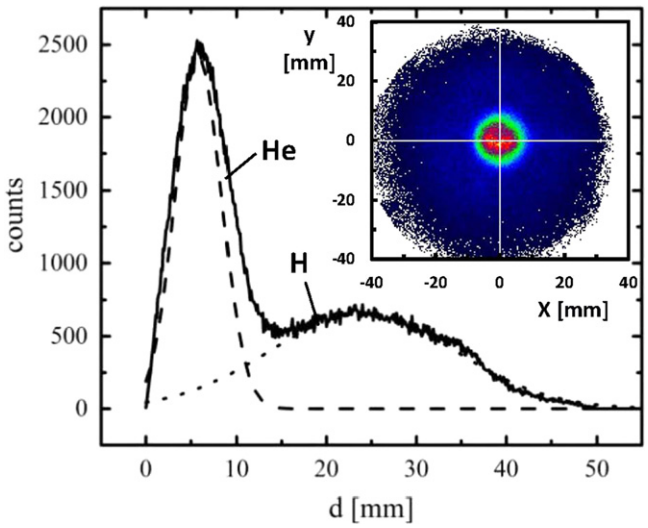

Figure 3. Analysis of double events from the breakup of HeH^+-molecules by residual gas. Inset: 2D plot. Graph: plot as a function of the distance of the events to the cross hair. The data are fitted by two distributions representing the fast (H) and the slow (He) ejectiles (dashed curves).

It should be mentioned that during this phase of commissioning the ring has been baked only up to temperatures of 100°–150° C for comparably short times, safely reaching vacuum values in the lower 10^{-10} hPa range. This yielded storage times sufficient for testing the inserted equipment. Baking the ring at 200 °C we expect the basic vacuum to be better than 10^{-11} hPa with all ion optical and diagnostic devices installed. Such values have already been verified for the empty vacuum chambers at delivery time (2007).

The existence of the waist of 2 mm × 3 mm at the interaction regions (IP) can be verified by closing the scrapers, which are centered at the optical axis of the ring. The alignment of the beam with the optical axis, which is essential for the positioning of experiments in the ring, can be tested by measuring the ion current on the scraper blades as a function of the scraper opening. We found that scrapers 1 and 3 can be closed to their minimum values (2 mm × 2 mm) without cutting significantly into the beam, whereas scrapers 2 and 4 are cutting into the beam already at values of 10 mm × 10 mm. From this experimental result two conclusions can be drawn. First, the interaction points are obviously verified by the result of closing scrapers 1 and 3, because the 4-fold super symmetry does not allow any other conclusion for stored beam. The result of closing scrapers 2 and 4 points to a 'tilting' of the beam axis relative to the optical axis of FLSR. This has been identified to be due to an insufficient compensation of the fringe fields of the 75° cylinder deflectors, which leads to a displaced entrance point of the beam into the 15° PPD deflectors. This has been verified experimentally by monitoring the position of the beam spot on the 180°detector. Meanwhile it was corrected by introducing correction deflectors close to the 15° PPD's.

First experiments on the kinematics of molecular collisions have been performed by measuring the breakup of asymmetric binary molecules by residual gas atoms with the MCP detectors. In the inset of figure 3 the 2D plot of double events from the breakup of HeH^+ by residual gas is shown (in a coincidence window of $\Delta t = 300$ ns, to safely collect all double events from breakup along the 180°- section of the ring). It is evident that the center of the distribution of hydrogen atoms (outer rim) and the center of the distribution of the He atoms (inner rim) coincide very well with the optical axis (white cross hair). The deviation of the MCP center from the optical axis is due a misalignment of the detector in the chamber. In figure 3 these events are analyzed according to their distance relative to the cross hair. These distances d (two for each breakup) depend only on the perpendicular velocity component of the ejectiles $d = l/v_0 \cdot v_\perp$, where l is the distance of the vertex of the breakup from the detector, v_0 the velocity of the molecular ion and $\mathbf{v}_\perp$ the velocity component of the ejectiles perpendicular to the ion velocity. Binary breakup has a 180° angular correlation in the CM frame of reference (molecule) and hence the perpendicular distances for the ejectiles are inversely proportional to their mass ratio $d_{He}/d_H = m_H/m_{He} = 4$, in good agreement with the ratio of the mean values of the two distributions in figure 3.

As a first experiment, the orientation and the kinetic energy release (KER) of the DR of vibrational cool $^4HeH^+$ -molecules by electrons will be measured:

$$HeH^+ + e^- \rightarrow He + H + \Delta E_{KER}.$$

For this purpose, an electron target has been installed in IP4 [13], using the MCP-180° as detector for the neutralized particles. Vibrational cooling of HeH^+ is reached after 100 ms [14]. A resonance behavior is expected for this reaction peaking at impact electron velocities of 18 eV [15] with a narrow KER distribution for vibrational cool molecules (peaking at 5 eV) is expected, whereas the spectrum of vibrational hot molecules consists of a series of resonances [16], resulting in a broad KER spectrum. However, this is a very challenging experiment and strongly depends on the base vacuum in the ring.

A preliminary measurement at a vacuum of 3×10^{-10} hPa did not allow for a separation of breakup events induced by the electron target from those induced by the collisions with the residual gas. The experiments will therefore be repeated at better vacuum. If this was not sufficient, a new set up is planned (internal gas target combined with a reaction microscope). By investigating the reaction

$$HeH^+ + He \rightarrow He + H + He^+ + \Delta E_{KER},$$

an active trigger for reactions with the target gas is then provided by detecting the recoiling He ion [17].

Conclusion

The FLSR has successfully been set into operation and the design values have been verified. First experiments on molecular break- up, using the MCP- 180° detector in combination with a perpendicular electron target (see figure 1) have been started and will be continued at improved levels of

the basic ring vacuum. Presently the implementation of a reaction microscope in connection with an internal gas target is discussed. New experiments with more complex molecules are planned in the frame of the LOEWE initiative of 'Hessisches Ministerium für Wissenschaft und Kunst' (HMWK).

Acknowledgments

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