

# INTERACTION OF STORED IONS WITH ELECTRON TARGET IN LOW ENERGY ELECTROSTATIC RING

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## Abstract

The KEK electrostatic ring has been used for investigations of biomolecular ions. The ion-beam lifetime depends on the electron capture, the stripping and the multiple scattering with the residual gas. The electron target installed in this ring has the same structure as a usual electron cooler. Electron cooling can increase the stored ion lifetime because of compensating for the multiple scattering effect by residual gas atoms and molecules. In the experiments, the proton lifetime of 2 s was increased by a factor of 2 through the electron cooling at the electron beam current of 0.2 mA, proton energy of 20 keV and residual gas pressure of  $4 \cdot 10^{-11}$  Torr. However the electron-ion interaction can decrease the ion lifetime due to excitation of ion transverse coherent oscillations. Actually, in the KEK electrostatic ring the proton lifetime was reduced to 1.7 s at detuning of the electron acceleration voltage by 0.4 V from the nominal cooling voltage. The experimental results and numerical simulations related to the interaction of the stored ions with the electron target in a low energy electrostatic ring are discussed in this report.

## INTRODUCTION

The electrostatic storage rings are used to store ions of different masses when ion kinetic energy and charge state values are the same [1-2]. The biomolecular ions have been stored in the electrostatic storage rings at Aarhus [3] and at KEK [4]. In order to study electron-ion collisions in the KEK electrostatic ring, a merging electron-beam target was designed with adopting the features of an electron cooler [5-7]. The ion lifetime corresponds to 10-50 s in the electrostatic rings at a pressure of  $(3-5) \cdot 10^{-11}$  Torr. The electron target is also used as an electron cooler. The electron cooling compensates the multiple scattering and increases the ion lifetime by several times.

## KEK ELECTROSTATIC RING

The KEK electrostatic ring with a circumference of 8.1 m has been applied to store low-energy ions [2,4]. The maximum ion energy is 30 keV/charge. The ion mass is selected by a mass-analyzing system with a resolving power of 4000. The single-turn injection scheme is used.

The injection current is 50-500 nA. The injection emittance and the initial momentum spread are  $\varepsilon_v/\varepsilon_h = 15 \pi$ -mm-mrad and  $10^{-3}$ , respectively. The ring acceptance is designed to be  $50 \pi$ -mm-mrad.

A micro channel plate installed downstream of the 10-degree electrostatic deflector detects the neutral particles produced through ion collisions with the residual gas and /or the electron target. The neutral particles provide information on the ion lifetimes and the ion-beam size.

The 1/e-lifetimes of ions in the ring are 10-50 s for light partially stripped ions [2] (Fig. 1). Through a comparison of the ion lifetimes obtained in KEK [2] and in TSR [8], it is found that the lifetime is the shortest at ion energy of 10-100 keV/u. The typical lifetimes of biomolecular ions with a mass up to 66000 were 10-20 s [4].

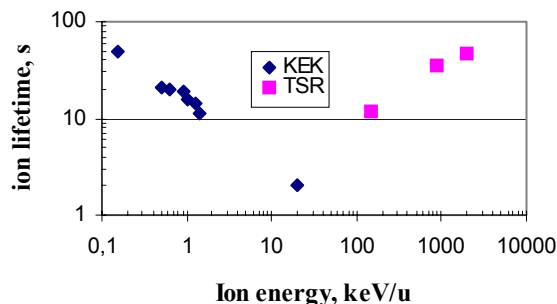


Fig. 1 Dependence of the ion lifetime on the ion energy at a pressure of  $4 \cdot 10^{-11}$  Torr.

The layout of the KEK electron target/cooler has the same structure as an electron cooler with an adiabatically expanded electron beam [5]. The length of the interaction region is 20 cm. The electron target was designed to have the maximum energy of 100 eV and the maximum electron current of 2 mA. Electrons are emitted from a thermo-cathode with a diameter of 3.5 mm in a solenoid field of 1 kG. The gun electrodes can provide a variable beam spot diameter on the cathode in a range of 2-3.5 mm. The electron beam is adiabatically expanded to a diameter of 11-35 mm in a magnetic field of 100-10 G. The transverse electron temperatures are decreased from 0.1 eV to 1-10 meV through the expansion. The longitudinal temperature is high due to low electron energies: 10 meV at the electron energy of 1 eV and 1 meV at 10 eV. The electron energy spread is dominated by the electron beam space-charge because the ion beam size is not small.

## ELECTRON ENERGY

The electron energy is defined as  $E_e/e = V_{cath} - V_0 - kI_e/\sqrt{E_e}$  at the cathode voltage  $V_{cath}$  and electron current  $I_e$  [9-10]. The value  $V_0(I_e)$  is related to the active resistance of the emitter layer, the potential minimum produced near the cathode surface and the work function of the cathode material [9]. The last term on the right side of the above equation corresponds to the electron space-charge. At an electron energy of a few eV and a beam current of tens of  $\mu\text{A}$ ,  $V_0$  is of the same order of magnitude as the other terms. The electron energy corresponds to 2.72 eV at the cathode voltage of 5.2 V and  $V_0 = 1.45$  V. The electron beam space-charge input is 1.03 V at an electron current of 50.6  $\mu\text{A}$ . These constants are determined by using dissociative recombinations (DR) (Fig. 2) of molecular ions [11] in which the neutral-particle production rates have maximum at the zero relative energy between the electron and the ion. For instance, the electron energies at the highest neutral rates are 5.45, 2.72 and 1.82 eV for 20-keV  $\text{H}_2^+$ ,  $\text{D}_2^+$  and  $\text{D}_3^+$ , respectively.

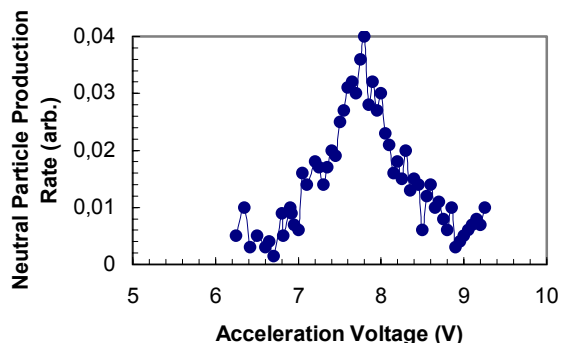


Fig. 2 Dependence of the neutral particle  $\text{H}_2$  production rate on the acceleration voltage [11].

The virtual cathode is formed at a low electron energy and a high acceleration voltage. For instance, the cathode voltage variation from 3 V to 2.1 V gave the electron current reduction from 10  $\mu\text{A}$  to 1  $\mu\text{A}$  at a fixed acceleration voltage of 4 V between the cathode and the anode caused by virtual cathode formation. The electron current is reduced according to the perveance of 10  $\mu\text{A}/\text{V}^{3/2}$  at a decrease of the electron energy.

## ION-ELECTRON COLLISIONS

Two examples of the collisions with electrons and biomolecular ions in the KEK electrostatic ring are presented in Fig. 3 [11]: one concerns arginine (Arg) (MW: 0.17 kDa), which is a kind of amino acid; the other concerns bradykinin (MW: 1.06 kDa), which is a kind of peptide. It consists of 9 amino acid residues and has a one-dimensional structure of Arg-Pro-Pro-Gly-Phe-Ser-Pro-Phe-Arg. Singly protonated arginine or bradykinin

ions are accelerated to 20 keV. The electron current in this experiment is of 12  $\mu\text{A}$  and the electron beam diameter is of 20 mm, which is larger than the ion beam size of around 6 mm. The electron energy is variable between about 1 eV and 100 eV.

As can be seen in Fig. 3, it is slightly but clearly recognized that the rates increase at energies less than 2 eV, which is due to DR at low energies. On the other hand, the rates at high energies are quite different between Arg and bradykinin. The resonant-like peak at 6.5 eV with a shoulder at around 9 eV for bradykinin is deduced to come from electron-ion recombination, resulting in breakage of peptide bonds [12].

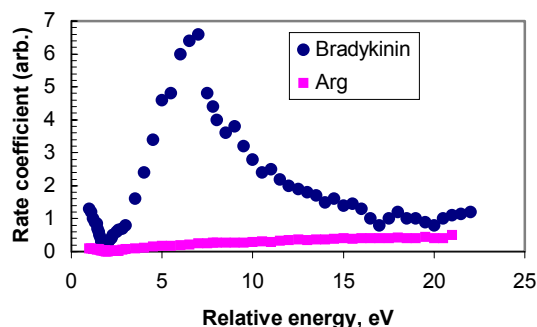


Fig. 3 Neutral particle production rate as a function of relative energy [11].

## ELECTRON COOLING

The electron target is used as an electron cooler [5]. A proton beam with energy of 20 keV is stored and merged with an adiabatically expanded electron beam. The natural proton lifetime without the electron beam is about 2 s under a pressure of  $4 \cdot 10^{-11}$  Torr. The proton lifetime is increased by a factor of around 2 with a velocity-matched electron beam at energy of 10.9 eV, an electron current of 202  $\mu\text{A}$  and an magnetic expansion factor of 33 (Fig. 4) [11]. This clearly indicates that ions are cooled in the transverse direction.

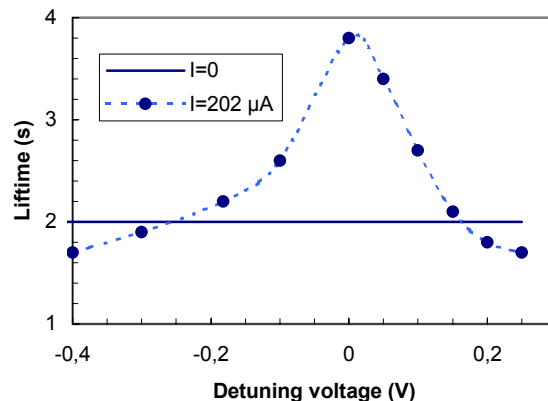


Fig. 4 Dependence of the proton lifetime on the detuning acceleration voltage with and without cooler [11].

The electron-cooling simulations are performed by the BETACOOOL code [13]. According to these simulations the proton lifetime also increases by factor 2 at electron cooling. A reduction of the cathode diameter to 1 mm and the transverse temperature to 1 meV permits a 3-4 times to increase simulated lifetime of ions with an atomic number of  $A/Z \approx 20$ -40 and an ion energy of 20 keV [6-7].

Calculated lifetimes of ions with a mass of 300 and a charge of 2 are 10-20 s as shown in Fig. 5. The electron cooling permits to increase one order of magnitude the ion lifetime (Fig.5).

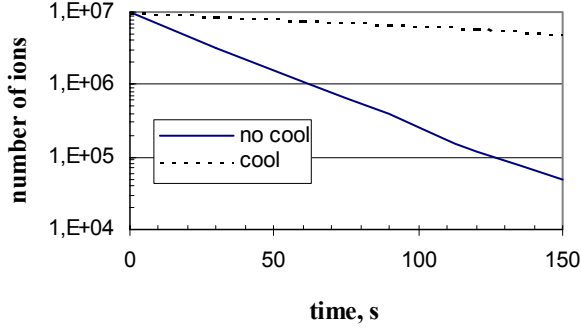


Fig. 5. Dependence of the number of the stored ions ( $A=300$ ,  $Z=2$ ) on the time at  $E_i=40$  keV,  $r_{cath} = 1.5$  mm,  $I_e=100$  nA,  $T_{\perp} = 0.1$  meV.

The crucial point in cooling of these ions is a low transverse electron temperature of 0.1 meV. The photocathode permits reaching an electron temperature of  $T_{\perp} \approx 1$  meV and  $T_{\parallel} \approx 30$  meV [14]. The transverse electron temperature is reduced to 0.1 meV at a magnetic expansion factor of 10.

## SIMULATIONS OF TRANSVERSE COHERENT OSCILLATIONS

The proton lifetime reduction (Fig.4) can be related to excitation of the dipole coherent oscillations produced by ion interaction with the electron target or at the so-called electron heating effect [15-17].

The proper choice of working point reduces the ion-beam losses caused by the excitation of the transverse coherent oscillations. In the KEK electrostatic ring there are 4 stable working points with different amplitude functions and tunes: point *A* ( $Q_x/Q_y=2.68/0.78$ ), point *B* ( $Q_x/Q_y=3.28/0.53$ ), point *C* ( $Q_x/Q_y=2.71/1.38$ ) and point *D* ( $Q_x/Q_y=3.28/1.35$ ) [2]. The interaction of the protons with the electron target is rather weak at working point *C*. The ion lifetime is reduced by about 10-20% at the electron-target interaction (Fig. 2). The simulated cooling and ion coherent-oscillation rates are equal to  $2 \text{ s}^{-1}$  and  $0.5 \text{ s}^{-1}$  for the proton beam at working point *C*.

The increment of the instability has a maximum at a coupling resonance  $Q_x - Q_y = n$ . This resonance is realized in a region around points *A* and *D*. The simulated rate of the transverse coherent oscillations is high by one order

of magnitude for points *A* and *D*, compared with point *C*. The resonance width is of  $\delta Q \approx 0.04$ .

The interaction of the stored ions with a highly intensive electron target also leads to excitation of ion transverse coherent oscillations and ion lifetime reduction. The resonance width of the betatron tune is rather small for the simulated ions in Fig. 6:  $\delta Q \approx 0.015$  at  $I_e = 0.1$  mA and  $\delta Q \approx 0.05$  at  $I_e = 0.5$  mA. The increment of the instability has a maximum at an ion intensity of  $2 \cdot 10^7$  ppp (Fig. 6). It oscillates at a high ion intensity, which is caused by the electron drift resonances.

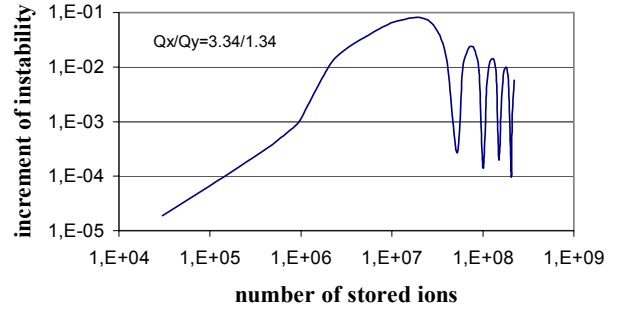


Fig. 6 Dependence of the increment of instability on the number of stored ions at  $I_e=0.5$  mA,  $E_e=40$  eV,  $B=30$  G,  $Z=4$ ,  $A=1200$ ,  $E_i=80$  keV and FWHM=6 mm.

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