AN ELECTRON BEAM TARGET/COOLER FOR EXTREMELY LOW-ENERGY ION BEAMS AT THE ELECTROSTATIC STORAGE RING

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Abstract

An electrostatic storage ring for studying atomic and molecular science has been operational at KEK since May 2000. The ring has a circumference of 8 m and can store light-to-heavy ions with an E/q of up to 30 keV. Light ions are produced with an ECR ion source, while bio-molecular ions are produced with an electrospray ion source. The measured 1/e-lifetimes are 10 ~ 50 s for light ions and 12 ~ 20 s for bio-molecular ions. These lifetimes are long enough to cool vibrationally excited molecular ions, and their intensities are tolerable for practical use, like atomic collision experiments. So far, we have stored bio-molecules with a mass of up to 66,000. In order to study electron-ion collisions, an electron beam target was designed. The structure of the target is almost the same as an electron cooler consisting of an adiabatically expanded electron beam; the target can also function as an electron cooler for light-mass ions. The design and construction are presented.

1 INTRODUCTION

Electron coolers have extensively been used to improve the beam quality both transversally and longitudinally in magnetic storage rings, which also allow to stack the beam in transverse direction. Another important function of the cooler is in the electron target for atomic collision experiments. The cooler electron beam is also a dense high-quality electron target with variable velocity in electron-ion collision experiments. These features brought fruitful experimental results in atomic and molecular physics.

On the other hand, electrostatic storage rings can compensate for the disadvantage of the magnetic storage rings that the magnetic rigidity increases with ion mass, because the electrostatic rigidity is independent of ion mass. In fact, the electrostatic storage ring at KEK [1] demonstrated to store bio-molecular ions with a mass of more than 10^4 with sufficiently long lifetimes and moderate intensities [2] as well as light atomic and molecular ions. The lifetimes are long enough to cool vibrationally excited molecular ions. If we introduce an electron target in the ring, the electrostatic storage ring can also be used as a device for the atomic collision research, especially on macromolecular ions. In electron-macromolecular ion collisions, most interesting phenomena occur probably in zero relative energy region like dissociative recombination of light molecular ions. Thus, the electron target needs to cover extremely low energy region where the electron velocity matches the ion velocity. In addition to this, the electron density has to be moderate and the electron temperature should be as low as possible. In order to meet these demands, we adopted an electron cooler consisting of adiabatically expanded electron beam as an electron target. The target can also cool light ion beams under limited conditions.

In this paper, we report on the design and construction of the electron target after describing on the outline of the storage ring.

2 LAYOUT

The layout of the ion sources, the mass spectrometer and the storage ring is shown in Fig. 1.

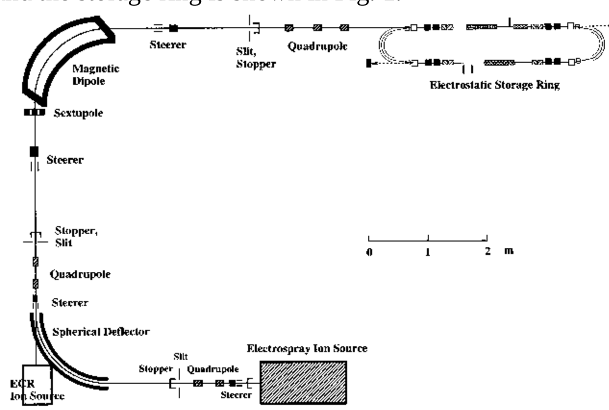

Figure 1: Entire layout of the ion sources, the mass spectrometer and the electrostatic storage ring.

Light atomic and molecular ions are produced in a compact ECR ion source with an acceleration voltage of 20 kV. A momentum-analyzed beam is then injected into the ring through a matching section consisting of an electrostatic quadrupole triplet. These ions have been used to test the characteristics of the ring. On the other hand, bio-molecular ions are produced by an electrospray ion source (ESI) and are accumulated in an octupole ion trap [2]. The ions are then ejected as a bunch and are accelerated up to an energy of 30 keV/charge. After being mass-analyzed, the ions are injected into the ring. The mass spectrometer with a mass resolving power of about 4000 consists of a spherical deflector, a sextupole magnet and a dipole magnet which also serves to analyze the momentum of ion-beams from the ECR source. The ECR and ESI sources can be used alternatively without breaking the vacuum in the merging section. The vacuum pressure at the ion source is high, while it has to be extremely low in the storage ring. A high vacuum was attained by a differential pumping system installed in the beam-transport line between the ion sources and the storage ring. The typical vacuum pressure in the ion source is 1×10^{-6} Torr, while the vacuum in the ring is 1×10^{-10} Torr just after installing the electron target.

3 ELECTROSTATIC STORAGE RING

The layout of the ring is shown in Fig. 2. A race-track lattice consists of two cylindrical-shape 160° deflectors, four 10° deflectors, which allow beam injection and extraction, and four quadrupole doublets [1]. The type of beam injection is single-turn injection. During injection, the high voltage for the first 10° deflector is turned off, and after filling the beam in the ring it is turned on.

A neutral beam produced by collisions with the residual gas is measured by a micro-channel plate with a phosphor anode (32 mm in diameter) installed in a vacuum extension 1.25-m downstream of the 10° deflector, as shown in Fig. 2. The count rate of the neutral beam is proportional to the number of stored ions at a constant residual-gas pressure, which gives exact information about the beam lifetime. Furthermore, a projection of the circulating beam can be observed from the neutral beam profile on the phosphor screen. The position and size of the neutral beam profile are useful for adjusting the ring parameters.

So far, we have stored various atomic and molecular ions at 20 keV. The 1/e lifetimes of the atomic ions were 1 s - 50 s. In order to survey the lifetimes of bio-molecular ions with an energy of 20 keV/charge, a single charge state with the highest intensity was chosen for each ion. The neutral-particle production rate as a function of the storage time was measured for singly and multiply charged positive ions, and also a negative ion. The 1/e lifetimes are 12 s - 20 s [2]. For heavier bio-molecular ions, the charge states become higher and distribute over a wide range. The storage of these ions was confirmed by extracting the beam after storage for about one minute and observing flashing light on the phosphor screen of the neutral beam detector. With this method we observed the storage for protein ions up to a mass of 66,400.

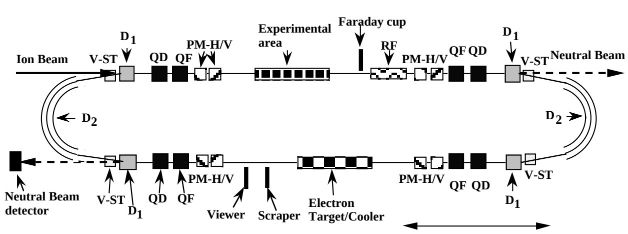

Figure 2: Layout of the electrostatic storage ring. D_1 and D_2 indicate 10° and 160° deflectors, QF and QD the horizontally focusing and defocusing electrostatic quadrupoles, PM-H and PM-V the horizontal and vertical position monitors, RF the drift-tube RF system and V-ST the vertical steerer.

4 AN ELECTRON BEAM TARGET/COOLER

The requirements for the electron beam target are a low electron temperature, a moderate electron density and a variable energy. An electron target which meets the requirements was designed. The device can also function as an electron cooler for light ions. The layout of the device is shown in Fig. 3 and the main design parameters are listed in Table 1. The structure is almost the same as that of the adiabatic-expansion-type electron cooling device [3]. Electrons are emitted from a thermo-cathode with a diameter of 3.5 mm and guided in a uniform solenoid field after acceleration and expansion. The device was installed in one of the straight sections of the ring as shown in Fig. 2. The length of the interaction region is 20 cm, which is 2.5% of the entire circumference of the storage ring. This ratio is almost the same as that for the usual magnetic storage rings. The maximum energy, 100 eV, can almost cover the most interesting energy region for electron-ion collision research. Any orbit deformation of the ion beam at the toroidal field is corrected by electrostatic horizontal and vertical steerers at the entrance and the exit of the electron beam device. The entire length of the device is about 90 cm. In the usual electron gun, the Pierce electrode and the cathode are the same potential. On the other hand, in the present design, the Pierce electrode is electrically isolated from the cathode. This allows a change of emission spot size by applying a negative voltage to the Pierce electrode.

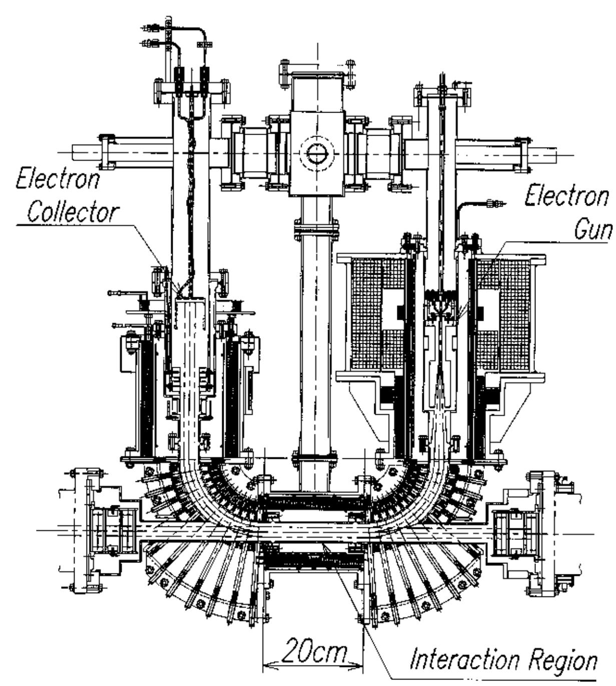

Figure 3: Layout of the electron target/cooler.

Table 1: Electron beam and gun parameter

Length of interaction region	20 cm
Electron energy	0.1~100 eV
Maximum current	2 mA
Cathode diameter	3.5 mm
Emission spot diameter	1~3.5 mm
Gun perveance	2 $\mu A/V^{3/2}$
Beam perveance	1~10 $\mu A/V^{3/2}$
Pierce electrode pot. relative to cathode	-100~+50 V
Anode potential relative to cathode	-20~+250 V
Magnetic field in the gun region B_g	1000 G
Magnetic field in the merging region B_c	10~100 G
Expansion Factor B_g / B_c	10~100
Tansverse temp. in the merging region	1~10 meV
Longitudinal temp. in the merging region	1~50 meV

The electron gun design at an extremely low energy is not easy, because electron-optics programs seem to cover mostly rather high energy region. Although the electron cooling is not main concern for the present design, it gives important information on the electron beam quality if the cooling works. Detailed simulation studies [4] were performed for the present arrangements. At extremely low energies, longitudinal temperature of the electron beam increases. Furthermore, heating through collisions with residual gas is serious. Therefore, the cooling may be observed if the cooling force exceeds the heating force under a good vacuum. The strength of the magnetic field in the interaction region is important for magnetized cooling. The minimum magnetic field where magnetized cooling works was determined by comparing the transverse cooling time in different magnetic fields from 5 G to 30 G [4]. Axial fields higher than 10 G give almost the same and fast cooling times. Thus, the minimum field in the interaction region is determined to be 10 G.

The device was installed in the ring in May 2002 just before EPAC. A photograph of the electron target is shown in Fig. 4. Electron beam current arriving at the collector was measured as a function of electron acceleration voltage. For the voltage higher than about 3 V, the electron current is determined by $I=PV^{3/2}$, where P is about 2 $\mu A/V^{3/2}$. On the other hand, for the voltage less than about 3 V, the electron current was negligibly low. However, if we apply negative voltage to the Pierce electrode, the electron current was recovered, although the perveance decreases. Preliminary results for the maximum electron currents are: ~5 μA at 0.1 V, ~12 μA at 0.5 V, ~30 μA at 1 V and ~250 μA at 10 V. Electron and ion beams merging test has just started. For H_2^+ ion, an increase of neutral beam intensities through collisions with the electron beam was clearly observed.

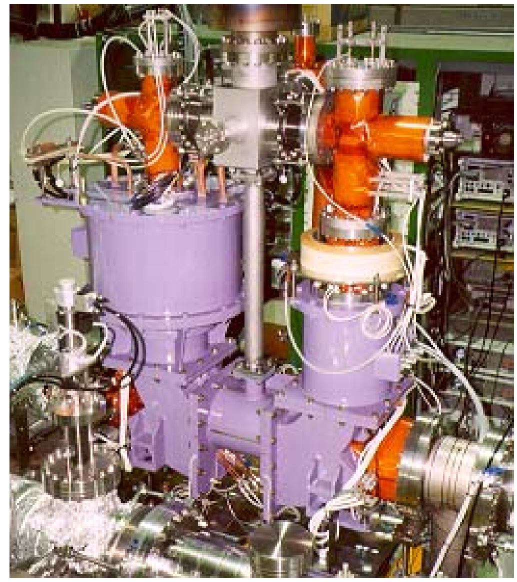

Figure 4: Photograph of the electron beam target.

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