Characteristics of the beam line at the Tokyo electron beam ion trap

Hiroshi Shimizu[a)]
Cold Trapped Ions Project, ICORP, Japan Science and Technology Co. (JST), Chofu, Tokyo 182-0024, Japan

Frederick J. Currell,[b)] Shunsuke Ohtani,[b)] Emma J. Sokell, and Chikashi Yamada[b)]
University of Electro-Communications, Chofu, Tokyo 182-8585, Japan

Takato Hirayama
Faculty of Science, Gakushuin University, Toshima, Tokyo 171-8588, Japan

Makoto Sakurai
Department of Physics, Kobe University, Kobe 657-8501, Japan

(Presented on 6 September 1999)

A new beam line has been constructed to make various experiments with highly charged ions produced in an electron beam ion trap. The characteristics of the beam line are reported. Ions are extracted upward into the beam line and are deflected horizontally and analyzed for the charge states by a double-focusing magnet. To obtain sufficient intensity, several electrostatic lenses are located. A quadrupole lens is used to correct the distorted beam shape before an entrance slit of the magnet. Ions are accelerated during the passing of the analyzing magnet to obtain the higher mass resolution. Trajectories were calculated by a ray-tracing program and matrix multiplication for lens actions. Preliminary results are shown here for investigation of characteristics of extracted ions. *© 2000 American Institute of Physics.* [S0034-6748(00)56402-8]

I. INTRODUCTION

An electron beam ion trap (Tokyo-EBIT) had been constructed in the Institute for Laser Science, University of Electro-Communications. Highly charged ions produced with the EBIT cannot be investigated only for spectroscopic studies but are also used as projectiles for collision experiments. An extraction beam line has been desired and constructed to perform a variety of atomic collision experiments. Here we describe the design of the beam line and show some recent results for investigation of extracted ions.

II. DESIGN OF THE BEAM LINE

A. EBIT

The details of the Tokyo-EBIT can be found elsewhere.[1,2] Briefly the trap which corresponds to the ion source consists essentially of three cylindrical tubes, through which an intense electron beam travels. The electron beam ionizes existing gas atoms or ions which are injected into the drift tubes. These ions are trapped in the radial direction by the space charge of the electron beam and in the axial direction by potentials applied to the drift tubes, forming an electrostatic well. Highly charged ions are produced by successive electron impact ionization. The electrons are produced from a Pierce-type gun, injected axially into a strong magnetic field (2–4.5 T) produced by a Helmholtz coils, and then compressed adiabatically forming a high current density beam. The potential of the cathode in the electron gun corresponds approximately to the accelerating voltage of the electron beam, which determines the charge-state distribution of the trapped ions produced at a fixed current of the beam. The potential of the top drift tube corresponds to the accelerating voltage for extracted ions, which is usually 3 kV. The combination of a positive potential on the electron collector with respect to the cathode potential and a magnetic field that cancels the fringing field from the Helmholtz coils forces all of the electrons to be collected at the collector. Due to the complicated shapes of the electrostatic and magnetic fields around the ion source area: from the drift tube to the collector, we disregard the motion of the primary ions in this area, and consider that ions are emitted from the center of the collector. A schematic view of the beam line is depicted in Fig. 1. Trajectories in the beam line were simulated by a ray-tracing program SIMION 3D.

B. Electrostatic lens

Several cylindrical electrostatic lenses and a quadrupole lens are located along the beam line. First, three lenses are einzel lenses and the fourth lens is used as an einzel or an acceleration lens. Before an analyzing magnet the quadrupole lens is used. To decelerate ions a cylindrical lens is located after the magnet. Dimensions of the cylindrical lenses were determined from the data in the book written by Harting and Read.[3] Schematic drawings of the einzel and the cylindrical lens are shown in Fig. 2. To reduce spherical aberration, diameters of these lenses are designed as large as possible. Each einzel lens is operated with positive voltage on the middle electrode.

The quadrupole lenses are used to modify the beam shape in order to penetrate well through the entrance slit of the magnet. The dimensions, the focal lengths, and the mag-

[a)]Electronic mail: shimizu@hci.jst.go.jp
[b)]Also at: Cold Trapped Ions Project, ICORP, JST.

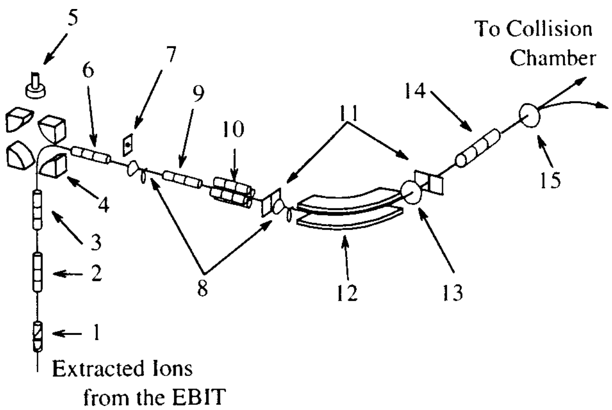

FIG. 1. Schematic diagram of the beam line. The EBIT is located below the deflector: (1) deflector, (2) einzel lens 1, (3) einzel lens 2, (4) bender, (5) metal vapor vacuum arc ion source, (6) einzel lens 3, (7) movable aperture, (8) movable secondary electron multiplier, (9) acceleration lens, (10) quadrupole lens, (11) two-jaw slit, (12) analyzing magnet, (13) movable micro-channel plate (MCP) /w PSD, (14) deceleration lens, (15) movable MCP.

nifications were calculated using a matrix multiplication method. Through these calculations, the lens parameters for each quadrupole lens were determined to minimize the distortion of the image on the focal plane.

C. Bender and deflector

The electrostatic bender which is shown in Fig. 3 consists of four rods whose cross section is a quadrant.[4,5] Each diagonal pair is connected and the same voltage is applied to those pairs so that ions pass along the trajectory shown in Fig. 3. This bender has four ports, two of which are used for ion injection from the external ion source and alignment of the beam line. Two correction plates are located near the entrance and the exit ports to suppress the fringing fields.[6]

For small angle steering of the extracted ions, electrostatic deflectors are used which are made from pairs of obliquely cut cylindrical electrodes with inner diameters of 40 mm similar to those used in the NIST EBIT.[7]

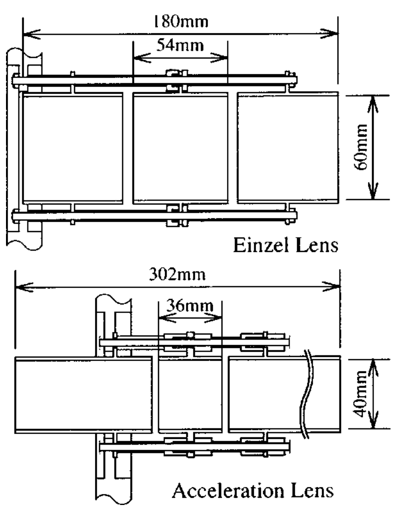

FIG. 2. Schematic diagram of the einzel and the cylindrical lens.

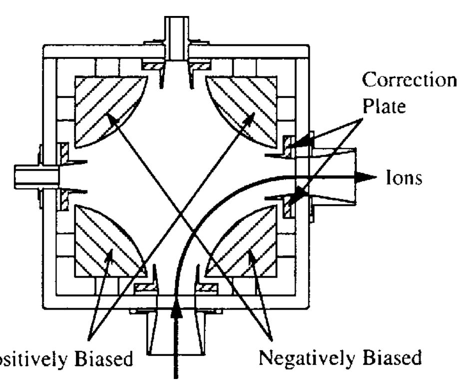

FIG. 3. Schematic diagram of the bender. The trajectory of the ion is also indicated.

D. Analyzing magnet

The ion beam containing various charge states of all ion extracted is transported along the beam line. The analyzing magnet is used to separate ions with desired charge to mass ratio and to transport them to the other vacuum chamber for the collision experiments. The magnet was designed to be a double-focusing type in order to obtain the high intensity of the ions analyzed. To obtain the sufficient resolution in the charge state analysis, the mean radius of the trajectory in the magnet is chosen to be 300 mm. In addition, ions are accelerated before the magnet by the acceleration lens. The distance between the entrance (exit) slit and the edge of the magnet is fixed at 680 mm. The angle of the beam axis to the edge plane of the magnet is chosen to be 118.5° so that the ion beam is double focused at the exit slit on the focal plane. The mass-resolution $\Delta M/M$ was estimated to be 8.3×10^{-3} when it was supposed that widths of the slits were 1 mm and that the extraction voltage and the variation were 10 kV and 100 V, respectively.

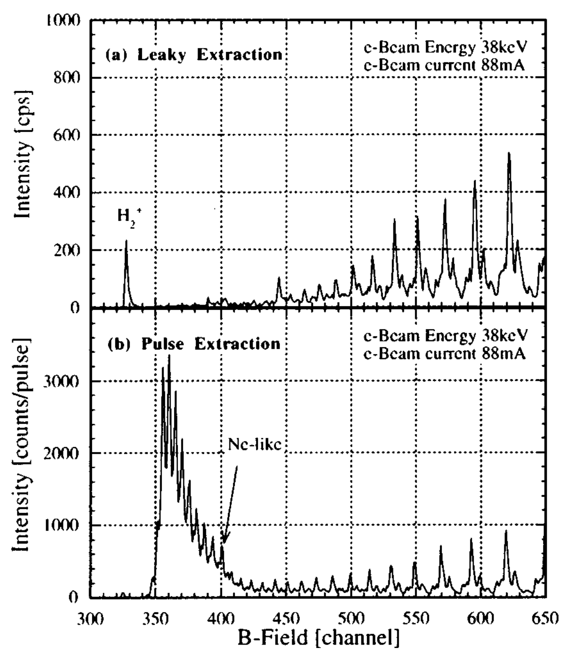

FIG. 4. Charge-state distribution of extracted Kr ions: (a) in leaky mode, (b) in pulse mode.

TABLE I. Typical operating parameters in the EBIT for extraction of ions.

Element	Typical values
Electron gun	−35 kV
Electron beam current	88 mA
Drift tube 1	+3.2 kV
Drift tube 2	+2.9 kV
Drift tube 3	+3.0 kV
Extraction time (ramped)[a]	100 ms
Repetition rate of extraction[a]	3 Hz

[a]In pulse mode.

III. RESULTS

There are two modes for ion extraction, leaky (dc) and pulse extraction mode. In leaky mode ions escape a trap potential when their kinetic energy exceeds the potential barrier. Pulse mode forcefully releases all ions in the trap by raising the potential on the center drift tube up to the same on the top drift tube. Figure 4(a) shows a charge-state spectrum of continuously extracted Kr ions obtained with scanning magnetic field at 3 kV extraction. The parameters of the electron beam are shown in Table I. It can be seen that the population of the extracted ions with charge states lower than 26 (Ne-like) is dominant. On the contrary, as is shown in Fig. 4(b) for the pulse mode, ions with charge states higher than 26 are detected. If it is supposed that the ion temperature of different charge-state ion is the same, higher charge-state ion is bound more tightly in the fixed trap potential, while the ions with lower charge states evaporate out of the trap. Measurement of the energy distributions of the extracted ions is important to determine the energy of projectiles for very slow collision experiments. The distributions for the ions with several charge states were analyzed by a retarding field analyzer. Energy distributions of Kr^{34+} (pulse mode) and Kr^{15+} (leaky mode) are shown in Fig. 5, where

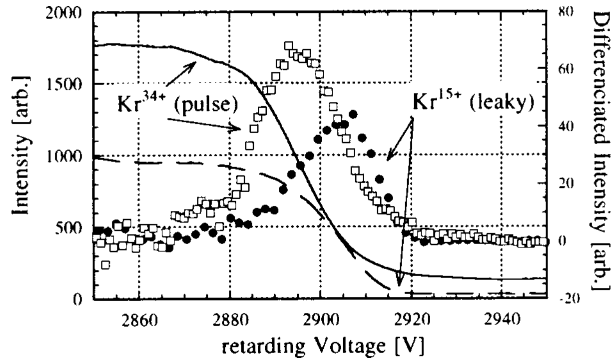

FIG. 5. Detected numbers by the analyzer with scanning retarding voltage. Differenciated intensities are also indicated.

the parameters of the electron beam are the same in both measurements. Energy widths [full width at half maximum (FWHM)] were approximately the same 20 V for those ions in spite of different extraction mode and the charge state. The difference of the voltage between the ion source potential of 3 kV and the peak value of the ion beam energy profile might be ascribed to the space charge of the electron beam and to the other effects. It is interesting to see the difference of the peak value in the energy distributions for Kr^{15+} (leaky) and Kr^{34+} (pulse) ions. Variations of the characteristics of the electron beam which interacts with the ions might have a strong influence on both the mean energy and the energy spread of the extracted ions. Further investigations are needed.

[1]F. Currell *et al.*, J. Phys. Soc. Jpn. **65**, 3186 (1996).
[2]H. Watanabe *et al.*, J. Phys. Soc. Jpn. **66**, 3795 (1997).
[3]E. Harting and F. H. Read, in *Electrostatic Lenses* (Elsevier, Amsterdam, 1976).
[4]H. D. Zeman, Rev. Sci. Instrum. **48**, 1079 (1977).
[5]J. W. Farley, Rev. Sci. Instrum. **56**, 1834 (1985).
[6]P. R. Mahaffy and K. Lai, J. Vac. Sci. Technol. A **8**, 3244 (1990).
[7]A. I. Pikin *et al.*, Rev. Sci. Instrum. **67**, 2528 (1996).