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THE CORNELL ELECTRON BEAM ION SOURCE

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Summary

An electron beam ion source (EBIS) for the production of low energy, multiply charged ion beams to be used in atomic physics experiments has been designed and constructed. An external high perveance electron gun is used to launch the electron beam into a conventional solenoid. Novel features of the design include a distributed sputter ion pump to create the ultrahigh vacuum environment in the ionization region of the source and microprocessor control of the axial trap voltage supplies.

Introduction

Studies of atomic processes involving low energy multiply charged ions have been hampered by the lack of a suitable source of such ions. The EBIS possesses a number of features which make it a particularly fitting source of low energy, multiply charged ions for atomic physics experiments. In an EBIS, a high current density electron beam is launched along the magnetic field axis of a long solenoid. The beam ionizes atoms of an element introduced as a gas or vapor into the ionization region of the source, and highly charged ions are formed by successive ionization by electron impact. The ions formed are contained radially by the attractive potential well due to the negative space charge of the electron beam, and axially by an appropriate potential distribution impressed on a series of cylindrical electrodes concentric with the electron beam and magnetic field axes. After a predetermined containment time, the axial trap potential is modified and the ions are expelled from the source. To avoid space charge neutralization of the electron beam by residual background gas ions, which in turn destroys the radial trapping ability of the beam, the source is operated at a pressure of 10^{-9} torr or better.

The high bombarding electron kinetic energy, typically a few keV, and long ion containment time, 10-100 msec or more, can be used to generate the highest extractable charge states of any source. The low divergence beam and ambient ultrahigh vacuum environment necessary for proper operation of the source greatly simplify beam transport and experimental arrangements.

General Properties of an EBIS Source

The EBIS, which is based on early experiments on electron collisions with trapped positive ions by Baker and Hasted,[1] was first proposed by Donets at Dubna.[2] It has since been under almost continuous development by groups at Dubna and Orsay[3,4] as a source of multiply charged ions for accelerators used in nuclear physics. A number of other groups have constructed an EBIS or one of its variants.[5-7]

Neglecting multiple ionization and electron recombination processes, the ion charge state distribution in an EBIS can be calculated from a simple balance model which describes the change in the density n_i of ions of charge i by the following system of equations:

$$dn_i/dt = (1-\delta_{i,o})Q_{i-1}n_{i-1} - (1-\delta_{i\zeta})Q_i n_i \qquad (1)$$

where δ_{ij} is the Kronecker symbol, $i=0,1,\ldots\zeta$, $Q_i=(j/e)\sigma_i$, j is the electron current density, e the electronic charge, $\sigma_i \equiv \sigma_{i\to i+1}$ the ionization cross section for going from the charge state i to i+1, and ζ the highest charge state obtained under given conditions. The characteristic time τ_i is $e/j\sigma_i$, and for a sequence of ionization steps from charge i to i+1 leading to ζ, $\tau_\zeta=\frac{e}{j}\sum_{i=o}^{\zeta}\frac{1}{\sigma_i}$. The solution $n_i(t)$ can be written as:[8]

$$n_i(t)=N_o\sigma_o\cdots\sigma_{i-1}\sum_{j=o}^{i} e^{-Q_j t} \Big/ \prod_{k=o}^{i}{}'(\sigma_k-\sigma_j) \qquad (2)$$

where the prime on the product sign excludes the term k=j, and N_o is the neutral atom density present at t=0. Finally,

$$\frac{n_\zeta(t)}{N_o} = 1 - \sum_{i=o}^{\zeta-1}\frac{n_i(t)}{N_o} \qquad (3)$$

To investigate the time variation of the $n_i(t)$'s the following approximate cross sections σ_i can be used:[9]

$$\sigma_i = \frac{1.6\times10^{-13}\ln[E/I_{i\to i+1}]}{E/I_{i\to i+1}}\ \text{cm}^2 \qquad (4)$$

where E is the bombarding electron energy in eV, and $I_{i\to i+1}$ the ionization potential of the most easily removed electron in going from charge state i to i+1. For tabulated theoretical values of $I_{i\to i+1}$, see reference 10.

For the background gas ion density to be less than the beam electron density, the pressure P in the ionization region has to be less than:

$$P < \frac{1.92\times10^{-10}}{\sigma(\pi a)^2\tau(\text{sec})\sqrt{E(\text{keV})}}\ \text{torr} \qquad (5)$$

where σ is the cross section in units of π (Bohr radius)^2 for single ionization of the background gas by electrons of energy E, and τ is the confinement time.

To estimate the maximum number n_q of ions of charge q obtained in a pulse after a confinement time τ_q, space charge neutralization of the electron beam by background gas is assumed to be negligible. Equating the ion density to the bombarding electron density gives:

$$n_q=3.3\times10^9 I(\text{amp})\ell(\text{cm})f_q/\sqrt{E(\text{keV})}\sum_{\zeta=o}^{Q}\zeta f_\zeta \qquad (6)$$

where I is the electron beam current in amperes, E the electron energy in keV, ℓ the length of the ionization region in cm, f_ζ the fraction of ions of charge ζ and Q the maximum charge attained. For extraction times short compared to the confinement time τ_q, the number of particles per second N_q is $N_q=n_q/\tau_q$.

To produce appreciable particle currents of highly charged ions, a high bombarding electron current density and long confinement time are required. These conditions are not trivial to obtain. Difficulties encountered in trying to achieve an expected performance of a source fall into the following categories:

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-- Those associated with obtaining a large current density - launching the beam into the magnetic field and aligning the beam with the axial electrode system and magnetic field axes,
-- Those associated with obtaining a sufficiently high vacuum in the ionization region of the source, and
-- Those associated with axial trapping and extraction of ions.

The Cornell EBIS

An EBIS to be used in atomic physics experiments to investigate one and two electron charge transfer to bare, hydrogen and helium-like keV/nucleon ions of carbon, nitrogen and oxygen has been designed and constructed and is currently undergoing tests.

The design of the source draws heavily on established power traveling wave tube technology[11] to which an EBIS bears an uncanny resemblance. Wherever possible, attempts were made to minimize problems in the above categories while keeping the design simple. An overall schematic of the source is shown in Figure 1, and a photograph in Figure 2.

The axial magnetic field is provided by a 50 cm long, 10 cm bore conventional solenoid, continuously wound on a stainless steel bobbin. The solenoid is water cooled and dissipates 10 kW. At full power it generates 4.2 kG, and its magnetic axis is centered to within 0.5 mm of the center line of the bore. It is mounted on ball bushings and can be moved along its axis.

The vacuum housing is 304 stainless steel, uses standard UHV copper sealed flanges and is bakeable to 300°C. To prevent oil contamination of the vacuum system, the chamber is roughed by a sorption pump to the few times 10^{-3} torr range. Two liquid nitrogen trapped 6" diffusion pumps bring the pressure to the 10^{-9} torr range when the gun is not operating.

Difficulties with obtaining an ultrahigh vacuum in the ionization region have plagued all versions of an EBIS. The structure of the ionization region, trap tubes, support elements, etc., and its large length to diameter ratio all lead to very low conductance. Our source uses a distributed sputter-ion pump[12] in a configuration consistent with an axial magnetic field. The distributed pump, shown in Figure 3, encloses completely the ionization region. To increase the lumped conductance of this region, the trap electrodes are made from stainless steel mesh supported by machineable ceramic, Figure 4.

The electron gun electrode structure is that of a Hughes model 112-2B modified Pierce-type convergent gun.[7] The cathode and electrodes are constructed from molybdenum. The structure is simple to assemble, and all elements are easy to align relative to one another. The gun support structure and spacers between elements are machined from boron nitride. The indirectly heated cathode is coated with a Ba/Sr carbonate and converted in vacuum. The gun has a measured perveance of 2.2 microperv. The beam profile has been determined by scanning a 0.15 mm wide slit across the beam, and at 0.7 kV it is 1 mm at the waist. The gun assembly is shown in Figure 5.

The electron beam is launched externally into the magnetic field at fields 2-3 times the Brillouin value:[8]

$$B=0.262\frac{(j(A/cm^2))^{1/2}}{(V(kV))^{1/4}}\ kG \qquad (7)$$

where j is the electron current density inside the magnetic field and V the potential through which the electrons are accelerated. The support holding the electron gun is affixed to bellows and the gun can be adjusted externally by micrometer heads to find the optimum launching position. The magnetic shims are also adjustable externally, and field bucking coils can be placed (from the outside) around the electron gun to reduce the field at the cathode.

The ion extraction region consists of a magnetic shim, an electron collector, and a cylindrical extractor. The magnetic shim defines the extent of the solenoidal field and a small hole in it permits the electron and ion beams to exit. Once the electron beam leaves the field, it starts to spread out under the influence of space charge. The cross sectional shape of the axially symmetric electron collector follows the universal beam spread curve[13] for half of the collector's length and becomes cylindrical for the rest. The collector is made from OFHC copper and all connections are electron beam welded. It is cooled with 4°C water at a flow rate such that its temperature is not expected to rise above 30°C.

A cylindrical extractor is placed immediately after the collector. The extractor and the cylindrical part of the collector form a lens which pulls out and focuses the ion beam.

The axial trap supply voltages will be controlled by a 16 bit microcomputer built around a Motorola MC68000 microprocessor. Programmable control of the 16 axial trap tube voltages will allow us to change these voltages in a trivial fashion and correct for varying conditions during the trapping cycle. Figure 6 shows a schematic drawing of the trap voltage control system. A more detailed description will be published elsewhere.

Acknowledgments

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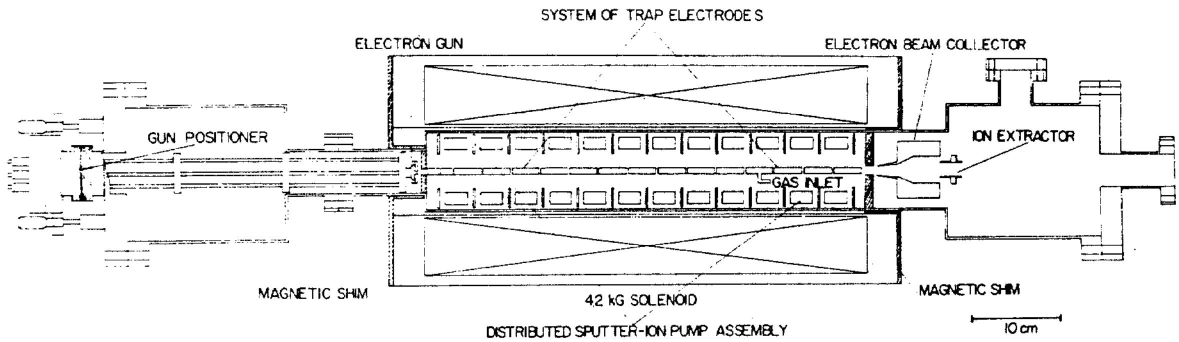

Figure 1. Overall schematic of the Cornell EBIS.

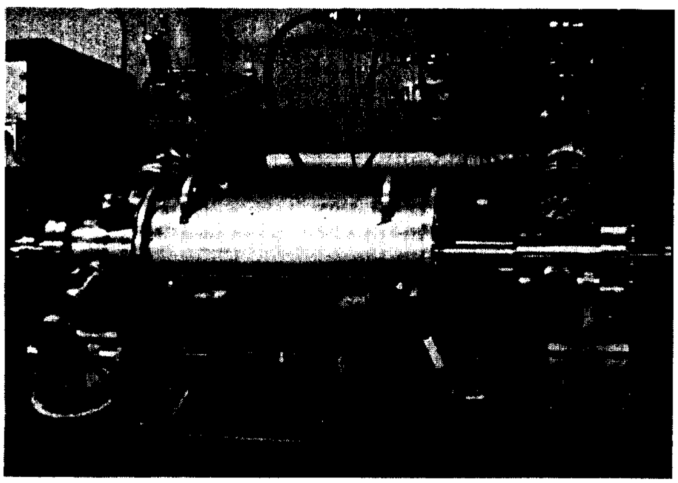

Figure 2. Photograph of the EBIS during construction.

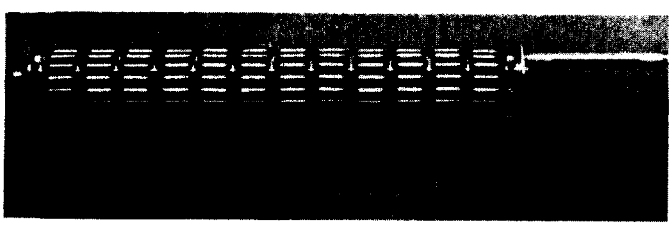

Figure 3. Distributed sputter-ion pump. Cathodes are made from titanium sheet and anodes from thin walled stainless steel tubing. Anode lead is at right.

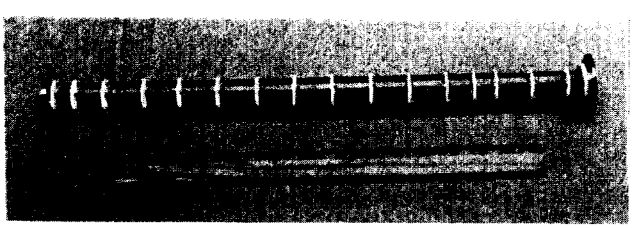

Figure 4. Partially assembled trap electrodes. Electrodes are made from 0.015" stainless steel mesh mounted on machinable ceramic supports.

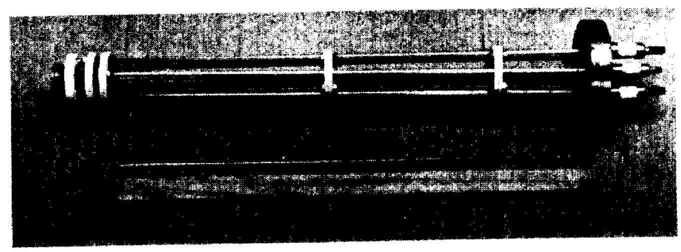

Figure 5. Electron gun assembly. Electrode leads form part of the support structure.

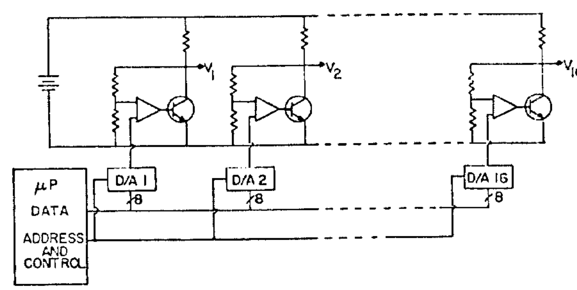

Figure 6. Schematic of the microprocessor controlled trap voltage supplies.