STATUS OF THE SANDIA EBIS PROGRAM

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Abstract

Since 1983 we have been developing two electron beam ion sources (EBIS), principally for experiments in atomic physics. One, a relatively low-performance device with a warm bore air-core solenoid, has been used for machine development and preliminary experiments using ions up to Xe+38. This machine has completed its program and is now decommissioned. The other EBIS is a state-of-the-art device with a superconducting magnet. It has the capability of producing ions up to U+82. This machine presently is in its final stages of construction and should be producing ions in mid-1989.

Introduction

The electron beam ion source (EBIS) [1] has the capability of producing ions of extremely high charge state while keeping the ion energy very low. It does this by trapping the ions in the potential well of a very intense electron beam electrostatically stoppered at the ends. Repeated electron impacts produce mostly stepwise ionization; in principle, any element could be stripped to bare nuclei. In reality, neutralization by residual gas and other complicating factors limit the ionization, producing an equilibrium charge state distribution.

There are two potential uses for the EBIS: (1) as an injector for heavy ion accelerators, and (2) as a source of ions for atomic physics. Motivated by the second of these, we have for several years been developing an EBIS to produce ions up to U+82. We will first describe some preliminary work with an earlier EBIS and then describe the Sandia Super-EBIS.

The LBL-MOD EBIS

During the early 1980's, Brown and Feinberg at Lawrence Berkeley Laboratory (LBL) built an EBIS test stand [2]. This machine was built around an air-core solenoid assembled from several independent coils stacked in a sandwich. The magnet produces 3 kG on axis. Extensive machine diagnostics showed it behaved as modelled.

The LBL EBIS was designed to evaluate the applicability of an EBIS as an injector for the 88-inch cyclotron. When it was decided to use an ECR source instead, the EBIS was decommissioned. This laboratory was able to obtain this machine and move it to Livermore. Subsequently, major modifications were carried out in an effort to improve the vacuum, high voltage, and beam qualities [3]. A new gun (Litton) having a perveance of 0.26 upervs was installed. The drift tube assembly was completely replaced with one mounted on panels cooled with liquid helium. The extraction and transport optics were modelled extensively and replaced. An electrostatic 90° bend for analyzing ion energy and a 90° dipole charge-separation magnet replaced the time-of-flight spectrometer. Fig. 1 shows the LBL-MOD EBIS after modification.

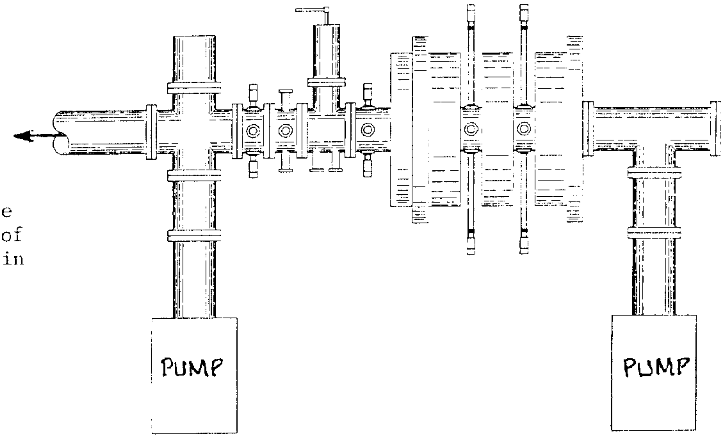

Fig. 1 – The LBL-MOD EBIS. This machine was originally developed at LBL, then moved to Livermore and extensively rebuilt.

The most important change in the LBL-MOD EBIS was it operating mode. Originally Brown and Feinberg operated it pulsed, hoping to obtain high charge states by long confinements. At Sandia, we developed a mode of continuous extraction, called the "leaky" mode [4]. In this mode, the gas to be ionized is bled in continiuously, and the ions are extracted continuously. The stoppering potentials at the ends of the trap are carefully adjusted to achieve a balance between the input of neutral gas and the loss of ions. The ions are lost because they become heated during their relatively long trapping times (up to several seconds). When the ion kinetic energy reaches the axial stoppering potential, they "leak" out the end. If the barrier is set very high, the ions are heated until they reach the edge of the radial potential well produced by the beam, and are lost to the walls. By careful adjustment of the drift tube voltages, often within a few tenths of a volt, the yield of the highest charge states can be optimized, and is surprisingly large.

Fig. 2 shows a typical charge state distribution produced in this leaky mode using xenon gas. Ions up to about Xe+40 were observed. These ions are monoenergetic, which was demonstrated by varying the stoppering potential and measuring the extracted ion kinetic energy. A reasonable analogy is water flowing over a dam--the water rises behind the dam until it reaches the top, then is released in a thin layer, roughly all at the same energy.

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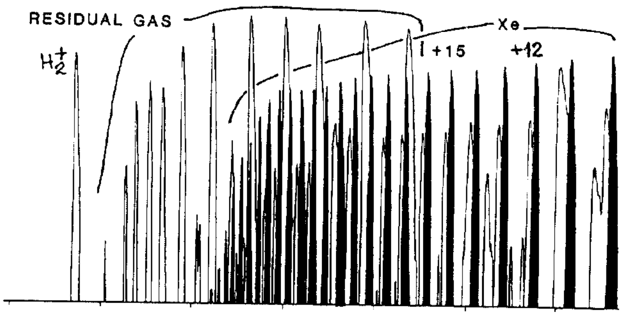

Fig. 2 - Typical ion spectrum observed with the LBL-MOD EBIS operated as a "leaky EBIS," observed with a 90° magnetic analyzer. This spectrum shows ions of the residual gas, including H+, H2+, and ions of C, N, and O, plus the sequence of xenon ions Xe+10 ... Xe+38. The xenon was isotopically enriched: 90% 136-Xe + 10% 134-Xe.

The LBL-MOD EBIS was also operated in a gated mode. The stoppering potentials were kept very high (about 100 V) for varying times, and then dropped to zero, allowing the ions to be extracted axially. Fig. 3 shows typical spectra. It is seen that the residual gas ions quickly reached an equilibrium, but the xenon ions continue to evolve toward higher charge states at very long times.

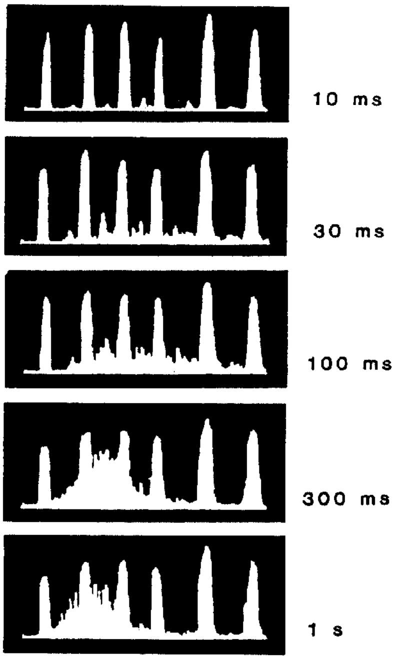

Fig. 3 - Ion spectra from the LBL-MOD EBIS operated in the gated mode. The ions were confined for several times, then released.

The Super-EBIS

Fig. 4 shows an elevation diagram of the Super-EBIS being developed at Sandia, Livermore. Fig. 5 shows a cross section of the device.

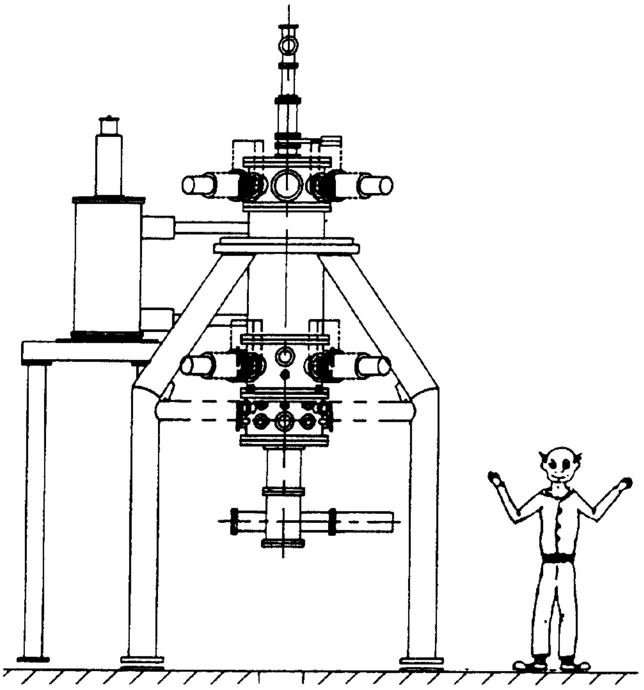

Fig. 4 - Elevation drawing of the Super-EBIS.

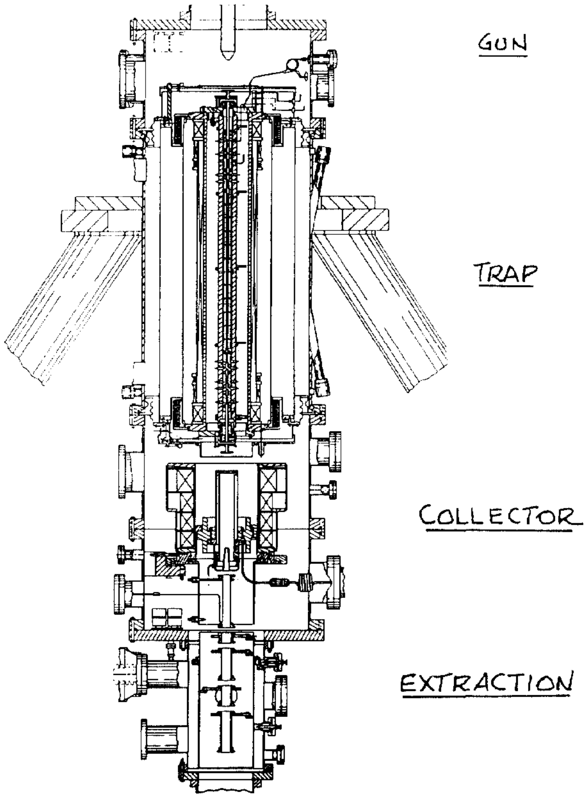

Fig. 5 - Cross sectional drawing of the Super-EBIS.

The Super-EBIS is designed around a superconducting magnet which produces 5 T within its 15 cm-diameter, 1.2-m long cold bore. The field is straight within one part in 10^4 and uniform within 1 part in 10^3 over the central 80 cm. The beam is launched from a gun using a 1 mm diameter LaB_6 cathode biased at -80 kV. Model calculations indicate the beam will achieve a current density approaching 1000 A/cm^2. The beam is collected on a water-cooled surface held about 5 kV positive with respect to the gun. The magnetic field around the collector is nulled by a bucking coil to within 1 G over 20 cm. The ultrahigh vacuum is maintained by four 6-inch cryopumps, several banks of nonevaporable getter pumps (SAES), and several turbomolecular pumps. The stainless steel vacuum chambers and most large parts were vacuum fired prior to fabrication to clear the metal of dissolved hydrogen. The large chambers are sealed together with metal O-rings (Helicoflex).

The Super-EBIS is oriented on a vertical axis to minimize mechanical distortions due to gravity. The ions are extracted through the beam collector and are deflected through 90° by an electrostatic prism. The stray field of the unshielded main solenoid and the Earth's magnetic field are compensated by a set of coils arrayed around the horizontal beam line.

Alignment is accomplished by establishing the cathode-to-collector axis, then aligning the solenoid and all optical components on this axis. The working gas is supplied to the trap through a capillary which is directly heated by passing a current through it.

We estimate the performance of the Super-EBIS as an ion source using the following simple formulas [6] in terms of the beam current I_e[A], beam voltage V_e[kV], collector voltage V_c[kV], magnetic field B[kG], and trap length L[cm].

The beam area is, assuming perfect Brillouin flow:

$$A = 6.848\text{x}10^{-2}\ B^{-2}\ I_e\ V_e^{-1/2} \qquad [\text{cm}^2]$$

The ions are extracted into the collector into solid angle

$$\Omega = 0.753\ I_e\ V_e^{-1/2}\ V_c^{-1} \qquad [\text{sr}]$$

The number of ions per cycle is

$$N(Q) = 3.327\text{x}10^9\ f\ Q^{-1}\ I_e\ V_e^{-1/2}\ L \qquad [\text{ions}]$$

and the confinement time of the cycle is

$$t_c = 6.848\text{x}10^{-2}\ S(Q)^{-1}\ B^{-2}\ V_e^{-1/2} \qquad [\text{s}]$$

The emittance is

$$E = 230.0\ B^{-1}\ I_e\ V_e^{-1/2}\ V_c^{-1/2} \qquad [\text{mm-mrad}]$$

The power carried in the potential energy of the ions per unit area and solid angle is

$$C(Q) = 1.510\text{x}10^{-7}\ f\ S(Q)\ Q^{-1}\ U(Q)\ B^4\ I_e^{-1}\ V_e\ V_c\ L \qquad [\text{W/cm}^2\text{-sr}]$$

The potential energy power emitted per unit area is

$$F(Q) = 1.137\text{x}10^{-7}\ f\ S(Q)\ Q^{-1}\ U(Q)\ B^4\ V_e^{1/2}\ L \qquad [\text{W/cm}^2]$$

The total potential energy power is

$$P(Q) = 7.785\text{x}10^{-9}\ f\ S(Q)\ Q^{-1}\ U(Q)\ B^2\ I_e\ L \qquad [\text{W}]$$

We adopt the following typical values: I_e=0.1 [A]; V_e=V_c=80 [kV]; B=50 [kG]; L=100 [cm]. Other parameters involved in these formulas are the beam fractional neutralization by the ions f (taken as 0.01); the ion charge Q (taken as 50); the ionization factor S(Q), which is related to the ion ionization cross sections (taken as $3\text{x}10^{-5}$ cm^2/C); and the total potential energy of the ion U(Q) (taken as 10^5 eV). From the formula for the beam area A, we obtain $A=3\text{x}10^{-7}$ cm^2. In fact, this probably is too small, since we probably cannot achieve perfect Brillouin flow. Thus, we assume $A=3\text{x}10^{-6}$ cm2. This alters t_c from its formula value by 1/A, E by $A^{1/2}$, C(Q) and F(Q) by $1/A^2$, and P(Q) by 1/A. Using these modifications, we obtain the following estimates for the Super-EBIS:

$A = 3\text{x}10^{-6}$ [cm2]

$\Omega = 1\text{x}10^{-4}$ [sr]

$N(Q) = 7\text{x}10^5$ [ions]

$t_c = 1$ [s]

$E = 0.02$ [mm-mrad]

$C(Q) = 36$ [W/cm2-sr]

$F(Q) = 0.04$ [W/cm2]

$P(Q) = 0.4$ [uW]

We note again that the last three quantities represent the power carried by the total internal potential energy U(Q) of the ions; their kinetic energy is assumed zero. A very rough estimate of U(Q) is Q**(3-Z/400), where Z is the atomic number. The ion potential energy within the drift tubes held at voltage V_0 is QeV_0[V], and this equals the ion potential energy when QeV_0= U(Q), or roughly V_0=Q**(2-Z/400) V. For Au+50 ions (Z=79), this gives V_0=1154 V, which is the maximum drift tube voltage if we want the ions to have as much potential energy as their kinetic energy.

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