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 decom-
mmissioned. 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
stopped at the ends. Repeated electron impacts
produce mostly stepwise ionization; in principle, any
element could be stripped to bare nuclei. In reality,
negative ion species 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-MOD 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 0.25 nperve 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.

The most important change in the LBL-MOD EBIS
was its 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 continu-
ously, 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 stopping
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 distrib-
ution 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.
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+, N+, 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.

Fig. 4 - Elevation drawing 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 10^7 and uniform within 1 part in 10^9 over the central 80 cm. The beam is launched from a gun using a 1 mm diameter LaB6 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 magnetic field of -80 kV. 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 nonevaporating 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 0-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 in terms of the beam current I [A], beam voltage V [kV], collector voltage V_c [kV], magnetic field B [kG], and cut length L [cm].

The beam area is, assuming perfect Brillouin flow:
$$ A = 6.848 \times 10^{-2} B^{-2} I_e V_e^{-1/2} \text{[cm}^2\text{]} $$

The ions are extracted into the collector into solid angle
$$ \frac{\Omega}{\Omega_0} = 0.753 I_e V_e^{-1/2} V_c^{-1} \text{[sr]} $$

The number of ions per cycle is
$$ N(Q) = 3.327 \times 10^9 f^{-1} I_e V_e^{-1/2} L \text{[ions]} $$

and the confinement time of the cycle is
$$ t_c = 6.848 \times 10^{-2} S(Q) 1^2 B^2 V_e^{1/2} \text{[s]} $$

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

The power carried in the potential energy of the ions per unit area and solid angle is
$$ C(Q) = 1.510 \times 10^{-7} f S(Q) Q^{-1} U(Q) B^4 I_e V_e V_c L \text{[W/cm}^2\text{-sr]} $$

The potential energy power emitted per unit area is
$$ F(Q) = 1.137 \times 10^{-7} f S(Q) Q^{-1} U(Q) B^4 V_e^{1/2} L \text{[W/cm}^2\text{]} $$

The total potential energy power is
$$ P(Q) = 7.785 \times 10^{-9} f S(Q) Q^{-1} U(Q) B^2 I_e L \text{[W]} $$

We adopt the following typical values: I_e = 0.1 A; V_e = 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 x 10^{-7} cm^2/eV); and the total potential energy of the ion U(Q) (taken as 10^{3} eV). From the formula for the beam area A, we obtain A = 3 x 10^{-2} cm^2. This alters I_e from its formula value by 1/A, E by A, 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:

$$ A = 3 \times 10^{-5} \text{[cm}^2\text{]} $$

$$ \frac{\Omega}{\Omega_0} = 1 \times 10^{-4} \text{[sr]} $$

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

$$ t_c = 1 \text{[s]} $$

$$ E = 0.02 \text{[mm-mrad]} $$

$$ C(Q) = 36 \text{[W/cm}^2\text{-sr]} $$

$$ F(Q) = 0.04 \text{[W/cm}^2\text{]} $$

$$ P(Q) = 0.4 \text{[uW]} $$

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 Q * e * V_0, and this equals the ion potential energy when Q * e * V = U(Q), or roughly V = Q * (3 - Z/400) V. For Au+50 ions (Z = 79), this gives V = 1154 V, which is the maximum drift tube voltage if we want the ions to have as much potential energy as their kinetic energy.

References