THE LBL EBIS PROGRAM

Brown, I.

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I. Brown and B. Feinberg

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

I. Introduction

It has been decided to increase the energy range of the LBL 88-Inch Cyclotron by constructing an advanced ion source for installation on the existing axial injection system. The type of advanced ion source chosen is the Electron Beam Ion Source. The energy range will be increased to 40 MeV/nucleon for the lighter heavy ions and with development to over 20 MeV/nucleon at mass 100. Besides the 88-Inch Cyclotron, present accelerators at LBL include the SuperHILAC, with beam energy up to 8.5 MeV/A, and the Bevalac, which will provide beams from 40 MeV/A to 2 GeV/A at all masses upon completion of the current Uranium Beams line item.(1) The cyclotron energy vs. mass specification is shown in Figure 1, at present and after the addition of the EBIS source. The new energy

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range provided will span the region between the SuperHILAC and the Bevalac. Further, the low energy highly charged ions available directly from EBIS will be extraordinarily valuable for research in atomic physics as well as in such applied fields as fusion reactor development. The properties of fusion reactor plasmas are significantly affected by the presence of highly stripped impurity ions such as C, O, Si, Ti, Fe.(2) For example, these ions can interfere with the heating of a plasma by means of injected neutral H or D atoms. It is, therefore, very important to measure the cross sections for electron exchange between highly stripped ions and neutral atoms. There are many other unknown atomic cross sections for low energy collisions of highly ionized (impurity) atoms with other ions, atoms, and electrons that must be known or estimated for use in fusion plasma transport calculations. An EBIS is the only known way to produce most of these ions under suitable laboratory conditions, and a demonstration of this capability will perhaps provide the basis for construction of a similar device for fusion related experiments.

II. Present EBIS Research and Development at LBL

In order to confidently design a full-scale device, we deemed it wise to first embark upon a small research and development program. This involves the construction of a test stand - a small EBIS device, BEBIS(3), with less ambitious goals than the full scale device by means of which we can gain experience. Experience to be gained on the test stand includes such important points as what is critical to proper and reliable operation and what is not critical -

e.g., degree of field error, gun-to-field matching, field strength on the gun cathode. We wish to investigate the conditions that lead to a neutralized-beam collapse, while avoiding recombination and instability. Our test stand enables us to look at new approaches to EBIS operation with a minimum of time, expense and difficulty, and to determine what is essential to the full-scale device. For these various reasons, we believe that this small R and D effort, though taking a little time and costing a small amount initially, will result in an overall more efficient path to the final product in terms of time, money, and device parameters.

Our aim has been to build a test-stand in a short time and at a low cost, while incorporating those features which will allow for a reasonably complete survey of EBIS operation. Thus, we have made use of much equipment previously available at the laboratory, or that we could borrow or obtain cheaply. This approach has led us to a number of innovations which will be brought out in the following description of our test-stand.

A schematic of the device is shown in Figure 2 and a photograph taken during assembly in Figure 3. The magnetic field, of strength up to 10 kG dc, is established by using three 16" I.D. coils wound with 1/2" x 1/2" cross section copper conductor and powered by a 360 kW motor-generator set. The field "quality" - homogeneity, straightness of axis - produced by these coils is inadequate for our purposes, and we have made a structure of iron rings, very precisely machined and positioned (approximately 0.001 inch tolerance), which is located inside the solenoid and outside the vacuum vessel. One can then think of the solenoid as energizing the iron ring structure, and the field shape is then determined by the iron rather than by the copper.(4) The resultant field is straight to ± 40 μ over a 60 cm axial distance, which should be more than adequate for good EBIS operation.

The vacuum vessel is made of type 310 stainless steel (25% Cr, 20% Ni) - a type not at all commonly available but which has superior magnetic qualities (very low susceptibility) - and all-metal gaskets are used. The vessel is baked to 200°C for several days and is pumped by two 500 l/sec ion pumps. Base pressure is in the 10^{-9} - 10^{-10} Torr range.

We have obtained an electron gun for use on this test stand from Texas A and M University(5) at considerable savings of time and money. This gun, made by Hughes Electron Dynamics Division, produces a 1 Amp beam at 6 kV and has an electrostatic area compression of 66. The gun is mounted in a well-shielded region ($B < 0.2G$) within the 3" thick iron pole-piece and the beam is injected into the steeply rising magnetic field through a 4 mm diameter aperture in the iron.

An important feature of our device is the ability to precisely adjust ($\sim 10^{-3}$ cm tolerance), from the outside and while at high vacuum, the axial position, transverse position and tilt of the gun, and the transverse position and tilt of the drift tube structure. Also, we can measure the beam current that may be striking the drift tubes, during operation.

We plan on trying to inject material into the electron beam - the ion feed material - by using a metal vapor atomic oven. We will construct a modified drift tube, to be located at the injection location, incorporating a small (about 1 mm x 1 mm cross section x 5 cm long) alkali metal dispenser(6) which will inject a metalic atomic jet across the electron beam. The dispenser heater current may be pulsed. Note that the unionized material which will plate the drift tubes in the vicinity of the oven forms a getter surface; this surface will pump the background gas. In this way we hope to produce Li, Na, K, Rb and Cs ion species simply, and to avoid cryopumping.

Diagnostic tools, such as probes and detectors have been constructed to measure magnetic field quality, electron beam trajectory, and current profile. We will monitor X-ray, microwave and r.f. emission, and of course the ion charge state spectrum. These measurements will provide informaton on conditions leading to beam collapse, on the gas requirements needed to avoid recombination or contamination, and the conditions necessary for beam stability.

III. Proposed Full-Scale Device

The design of our full-scale device is based upon the French CRYEBIS.(7,8,9) This device has produced an output ion beam of quality very nearly adequate for our purposes. The principal improvements over the French device that we need to obtain are an increased duty cycle and improved reliability and reproducibility. We anticipate no great difficulty in stretching the output pulse widths; this can be accomplished by employing the proper electronics - raising the ion trapping potential well sufficiently slowly. The pulse repetition rate will be raised by the electronics and by ensuring adequate cooling capacity to handle the increased mean power, principally cooling of the electron beam collector. Reliability will be increased significantly by incorporating into the device a number of critical alignment adjustments that can be made externally and simply.

We are starting from an enormously advantageous position by virtue of the wealth of experience gained by the French group. Their device is quite similar to our proposed device, and we have benefited greatly from their program. It is clear what kinds of modifications need to be made to obtain more reliable operation, and our device will incorporate these modifications. A schematic outline of the device, as presently conceived, is shown in Fig. 4.

We will use a gun to be purchased from either Hughes or Varian. These firms have developed great expertise in electron gun design and construction through their involvement in the Klystron and traveling wave tube industry. We have had interaction with Hughes and it is clear that the gun we need is well within their capability. The gun design will be done either by us or jointly by them and us. The gun construction should be done predominantly by them, so as to take advantage of their long involvement in and technological know-how of gun manufacturing. The gun will produce a 2 Amp beam at 10 kV accelerating voltage. The supply for the accelerating voltage is a 20 kV, 2 Amp supply, with switching allowing for a rise-and fall-time of 1μsec and a pulsewidth of from a few microseconds to d. c. Protection circuitry will be built in.

We will employ a magnetic field of peak magnitude 30 kG, produced by a superconducting solenoid approximately 1.5 m long. This laboratory is well experienced in superconducting magnet design and fabrication, and we have considerable expertise at our disposal. The superconducting solenoid will be flanked on both ends with shorter and lower field strength normal coils, coupled with field homogenizing iron rings of the type previously described. (Such iron rings are useful only for field strengths not too great compared to the saturation field, say $B \leq 15$ kG). These short solenoid sections will allow for flexibility in matching the gun to the field, and in tailoring the field shape in the extraction region.

Gas is to be injected within the drift-tube structure, close to the gun end. The drift tube diameter will be ~ 0.5 cm. For a 2 Amp beam of nominal 10 kV energy, the number of beam electrons within the trapping region at any time is ~ 3 x 10^{11}, and so also is the number positive charges that the beam can support at full neutralization. Thus the trap capacity is ~ 1.5 x 10^{10} Ar^{18+} or ~ 0.7 x 10^{10} Xe^{44+}. The drift tubes will be supported upon a rigid "bench", and the axis of the drift tubes must be straight to within $\leq$ 0.1 mm. Furthermore, this axis must be colinear with the magnetic axis to this same tolerance. This will be achieved in a manner similar to that used on our test-stand, so that the drift tube structure can be aligned relative to the magnetic field axis externally while at cryogenic temperature and at high vacuum. Linearly following the drift tubes are the electron beam collector, ion extractor, beam steering plates, and einzel lens. The collector will be designed using techniques similar to those used in the gun design. The ion beam output from the final set of steering plates will then be injected either into a time-of-flight charge state analyzer or into the cyclotron.

As with our EBIS test-stand, the full-scale device will be constructed from type 310 stainless steel and will be fully bakeable. We anticipate that cryogenic cooling of the drift tube structure will be necessary, and that gas injection will be done in the "normal" way (e.g., as for CRYEBIS). However, final design decisions regarding cryopumping and gas injection will be made after we have fully investigated the alkali metal injection that will be tried on the EBIS Test-Stand.

IV. Theoretical and Computational Support

Support is available to us at a number of levels. We are fortunate in being able to call upon the considerable expertise of Dr. Klaus Halbach in magnetic field design. This interaction has already resulted in the design of our magnetic field homogenizer and the consequent field straightness of ± 40 μ over the 60 cm axial distance. Further, there is an abundance of expertise at LBL in superconducting magnet design. We thus are fully confident in our ability to design and construct high quality magnetic fields. A number of the LBL theoretical scientific staff has taken interest in EBIS design and operation. The relevance of collective effects within the beam has been pointed out, and it has been shown that the equilibrium of the neutralized beam is complex and stability is not guaranteed.(10) Scaling studies suggest that raising the beam voltage may be the easiest way to increase both the ionization rate and particle intensity, and consideration of radial ion confinement in the space charge of the beam suggests that neutralized beam collapse to high current density may be dependent on the highest charge state which is energetically accessible.(10) Calculations have been made(11) of the trajectory of the beam envelope, ignoring axial forces. Fig. 5 shows such a trajectory, indicating the beam compression by neutralization of the electron space charge. Calculations of this type indicate the importance of gun-to-field matching and small field at the cathode in obtaining significant compression by space charge neutralization.

V. Schedule

Design of our test-stand commenced in January 1980. Construction is now 95% complete; the drift tubes and extraction optics are presently being installed. We have fully investigated the magnetic field quality and the electron beam properties. We anticipate producing and measuring ions from the background gas by mid-year, and this should be followed shortly by metal vapor ions using our atomic oven. We thus envisage that BEBIS will be fully assembled and functioning by about July or so, allowing us then to carry out EBIS research. The final decision to proceed with the full-scale, cryogenic EBIS is awaiting results from the test-stand. Only after the test-stand is operational will we commit ourselves to a major construction program.

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* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

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Figure Captions

Fig. 1. 88-Inch Cyclotron external beam energies with target intensities (particles/sec) as indicated.

Fig. 2. Schematic outline of LBL EBIS Test Stand.

Fig. 3. Photograph of EBIS Test Stand during assembly. The electron gun is located on the left hand side of the picture, extraction on the right.

Fig. 4. Proposed cryogenic EBIS for the 88-Inch Cyclotron.

Fig. 5. Envelope of the electron beam. The beam is initially compressed to the Brillouin radius by the magnetic field and is then further compressed by 99% space charge neutralization due to the trapped ions.

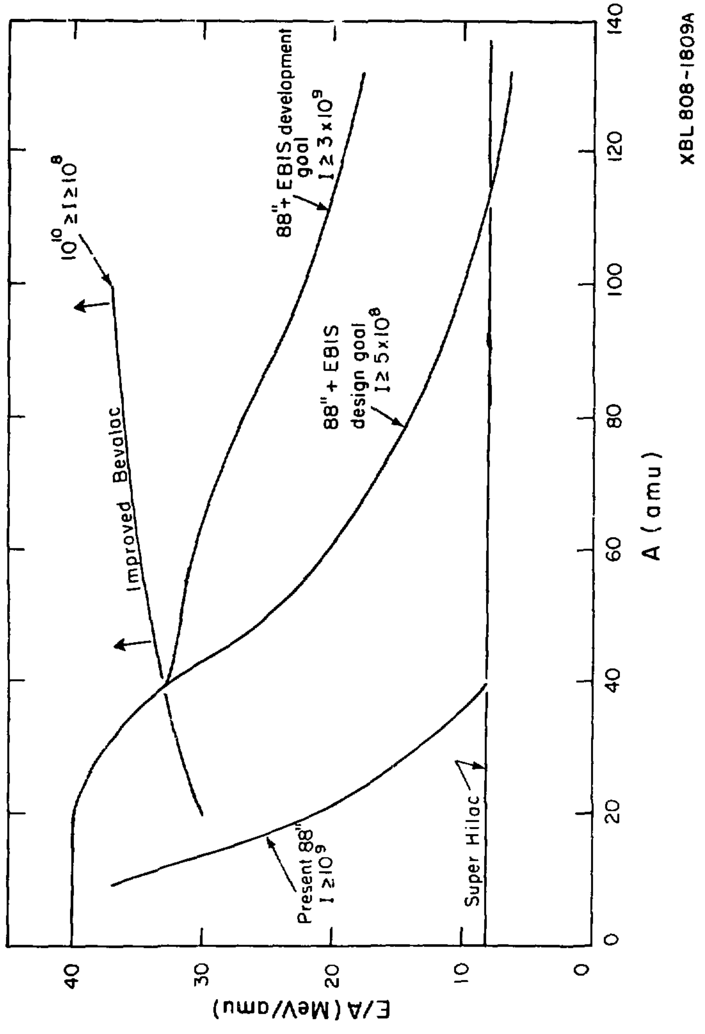
E/A (MeV/amu)
40
30
20
10
0
A (amu)
0
20
40
60
80
100
120
140
Improved Bevalac
$10^{10} \geq I \geq 10^8$
88" + EBIS development goal $I \geq 3 \times 10^9$
88" + EBIS design goal $I \geq 5 \times 10^8$
Present 88" $I \geq 10^9$
Super Hilac
XBL 808-1809A

Figure 1

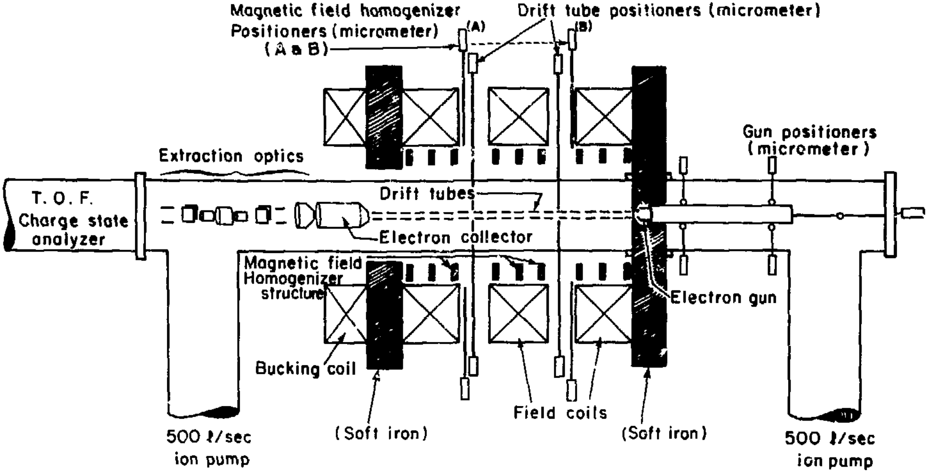

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Figure 2

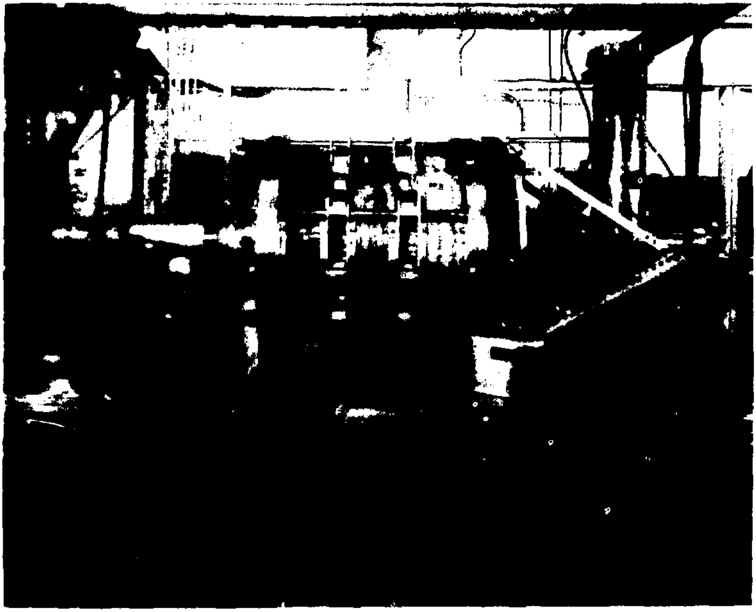

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Figure 3

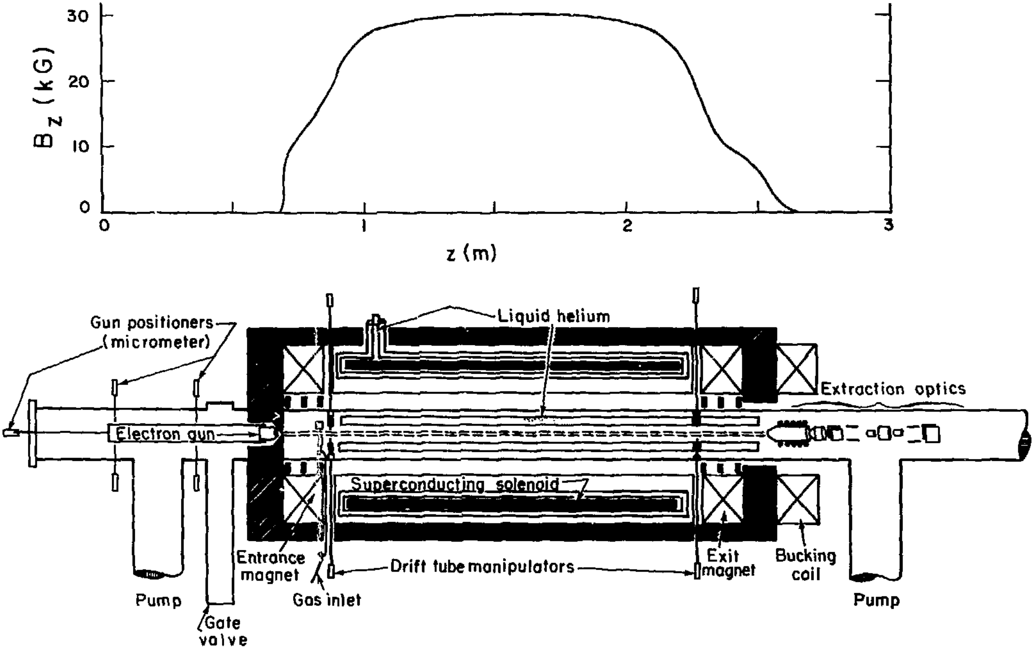

Figure 4

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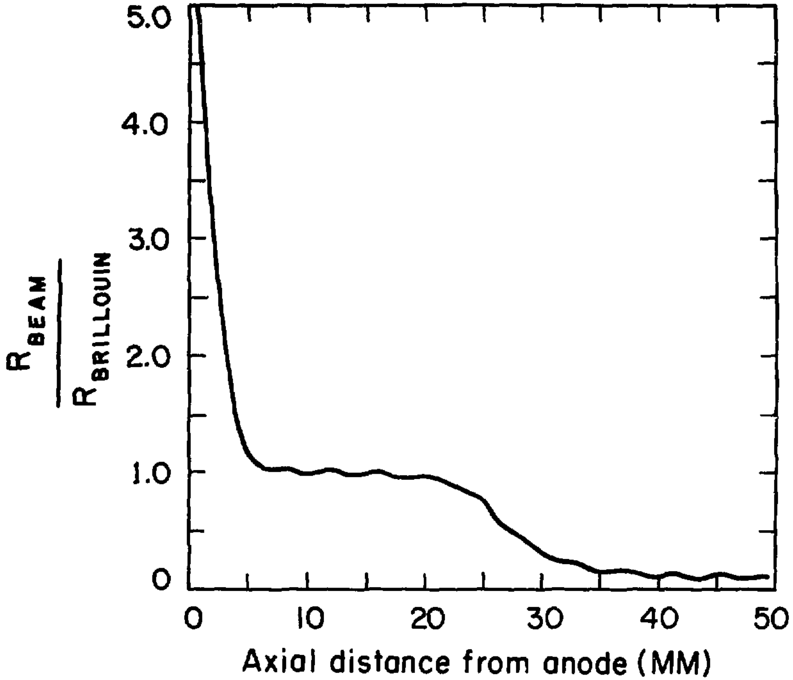

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Figure 5