Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Submitted to Nuclear Instruments and Methods

PHYSICS OF THE HIGH CURRENT DENSITY ELECTRON
BEAM ION SOURCE (EBIS)

M.C. Vella

February 1980

LAWRENCE
BERKELEY LABORATORY

MAR 3 1981

LIBRARY AND
DOCUMENTS SECTION

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 6782.*

LBL-10611C.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

PHYSICS OF THE HIGH CURRENT DENSITY
ELECTRON BEAM ION SOURCE (EBIS)*

M. C. Vella

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

February 19, 1980

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

Contents

Abstract	v
I. Introduction.	1
II. Basic Requirements.	3
III. Fundamental Relationships	8
IV. Beam Equilibrium.	12
V. Beam Stability.	17
VI. Scaling CRYEBIS Performance	20
VII. Conclusions	25
Acknowledgements	26
References	27

PHYSICS OF THE HIGH CURRENT DENSITY
ELECTRON BEAM ION SOURCE (EBIS)

ABSTRACT

Interest in upgrading present heavy particle accelerators has led to study of EBIS as a possible source of high Z ions, e.g., Ar^{+18} . The present work has been motivated primarily by the results reported by CRYEBIS, which indicate that a space charge neutralized, external electron gun can achieve current densities of 10^5 A/cm^2 . Scaling relationships are developed as a basis for understanding CRYEBIS operation. The relevance of collective effects to beam equilibrium and stability is pointed out. Single electron impact ionization scaling and beam neutralization scaling indicate that higher beam voltage may be the easiest way of increasing both ionization rate and particle intensity. Consideration of radial ion confinement suggests that beam collapse to high current density may be related to the highest charge state which is energetically accessible.

I. INTRODUCTION

The possibility of upgrading present heavy particle accelerators has led to general interest in the development of high Z ion sources. One type which has demonstrated great success is the Electron Beam Ion Source (EBIS), a concept which originated with Donets.¹ A version particularly attractive for broad application is the CRYEBIS of Arianer,² which has produced high Z ions, Ar^{+18} , Kr^{+34} and Xe^{+44} , in 5 msec. This device uses an external electron gun, in which the cathode has near zero magnetic flux. The observed ionization rates indicate that the neutralized electron beam achieves a high current density, $\sim 10^5 \text{ A/cm}^2$, approximately two orders of magnitude above that of the un-neutralized beam. This paper gives an overview of the basic physics governing the operation and scaling of a high current density EBIS.⁺

The components of an EBIS are relatively well understood: (i) a high quality vacuum; (ii) a straight magnetic solenoid with minimum field error; and (iii) an electron beam of maximum current density. The ions are radially confined by the space charge of the beam. If no axial confinement is used, relatively low charge states are produced, but operation can be dc.³ Higher charge states may be obtained with axial ion confinement; this is accomplished by creating an axial potential well between positively biased drift tubes, in which case operation is pulsed. For application to a high duty factor accelerator, e.g., a cyclotron, a pulsed EBIS should have both high rep rate and high particle intensity. Unfortunately, high current density operation has been difficult to reproduce, and limited diagnostic information is

available from CRYEBIS. Except for alignment problems related to the beam, operating and scaling limitations are only vaguely understood at present.

The organization of this paper is as follows. The basic requirements for high Z EBIS operation are discussed in Section II. Some fundamental relationships which will be used throughout are presented in Section III. A special feature of CRYEBIS is the use of an external electron gun,¹ i.e., magnetic flux on the cathode is nulled to $\pm 1G$. This appears essential to CRYEBIS performance, since conservation of the canonical angular momentum associated with flux on the cathode would otherwise severely limit neutralized beam current density. The subject of beam equilibrium is developed in Section IV by comparison of CRYEBIS operation with an ideal model, Brillouin flow. Beam stability is discussed briefly in Section V from the point of view of collective instabilities. The possibilities and limitations of EBIS development are explored in Section VI. In addition, the suggestion is made that, in pulsed operation, the maximum current density may be related to the highest charge state which is energetically accessible.

II. BASIC REQUIREMENTS

The time, τ_Z , required to produce an ion of final charge Z may be approximated^{1,2} as the time required for single electron ionization from the ground state of charge $Z-1$. For a monoenergetic beam, this is,

$$\tau_Z(\text{sec}) = (\sigma_Z v_b n_b)^{-1} = 1.6 \times 10^{-19} / [\sigma_Z(\text{cm}^2) J(\text{A/cm}^2)], \quad (1)$$

where σ_Z is the appropriate cross section, v_b the beam velocity, n_b the beam electron density, and J the current density. A hybrid system of units is chosen for convenience. Basic physical quantities are in cgs, except for particle energies, which are keV, and engineering quantities which are mks (e.g., kV and amps). A semiempirical formula of Lotz⁴ is used to estimate the cross section for single electron impact ionization from the ground state of $Z-1$,

$$\sigma_Z(\text{cm}^2) \approx 4.5 \times 10^{-20} \frac{\ln(V_b/I_Z)}{V_b I_Z}, \quad (2)$$

where V_b is the beam voltage (kV), and I_Z the ionization potential⁵ (keV). Recently, using a semi-immersed cathode to produce a beam of known current density, Donets⁶ has verified the relevance of this cross section within a factor of two. For CRYEBIS ions, the Lotz formula gives $\sigma_Z \approx 2 \times 10^{-22} \text{ cm}^2$. From (1), this implies that, $J \tau_Z \approx 10^3 (\text{A sec/cm}^2)$. Without confinement, thermal ions would drift a machine length ($\sim 100 \text{ cm}$) in 1 msec, in which case, J would have to be $\sim 10^6 \text{ A/cm}^2$. This requirement on J can be eased by forming an axial

potential well for ion confinement by means of positively biased drift tubes. CRYEBIS parameters are reproduced in Table 1. The cross sections and observed ionization times suggest, $J \leq 80 \times 10^3 \text{ A/cm}^2$. The implications of this for beam equilibrium are discussed in Section IV.

After ionization to high Z, recombination and charge exchange can be a problem, which requires control of neutrals and cold electrons. One way of understanding vacuum quality is to ask that the total number of background neutrals captured by the beam during a pulse be less than the total number of high Z ions. In CRYEBIS, nominal current is 1A and current density 10^5 A/cm^2 . For a beam 100 cm long, this gives a beam surface area of 1 cm^2 . The maximum tolerable neutral density can be estimated from the random neutral flux. If every incident neutral were captured, the vacuum requirement would be,

$$\frac{n_0 v_0}{4} A_b \tau_Z \leq N_Z, \quad (3)$$

where the beam area is A_b , n_0 the neutral density and v_0 the average neutral velocity. For CRYEBIS, the pulse length is $\tau_Z = 5 \times 10^{-3} \text{ sec}$, and the number of high Z ions is $N_Z \approx 2 \times 10^8$. For a neutral of atomic mass 84, this would correspond to a room temperature gas density of $7 \times 10^6 \text{ cm}^{-3}$, or 10^{-10} Torr . If the dominant neutral species were hydrogen, the vacuum requirements would be more severe, $8 \times 10^5 \text{ cm}^{-3}$, or 10^{-11} Torr . With a semi-immersed gun, like Donets,⁶ the current density is reduced to 150 A/cm^2 , with a corresponding increase in pulse length; this also means an equivalent improvement in vacuum quality is required. The criterion used here may

be too severe, since the mean free path for ionization or charge exchange probably exceeds the beam width. On the other hand, impurities could neutralize a significant fraction of the electron beam space charge, an effect proportional to the charge of the impurity.

An alternative criterion for vacuum quality can be obtained by using a model for electron capture by fully stripped ions from background neutrals. Following Laslett⁷, ionization and charge exchange rate balance gives,

$$\frac{dn_Z}{dt} = \sigma_{Z-1,Z} v_b n_{eb} n_{Z-1} - \langle \sigma_{Z,Z-1} v_Z \rangle n_0 n_Z . \quad (4)$$

At equilibrium, this gives,

$$n_0 = \frac{\sigma_{Z-1,Z} v_e n_{eb}}{\langle \sigma_{Z,Z-1} v_Z \rangle} \frac{n_{Z-1}}{n_Z} . \quad (5)$$

The crosssection for ionization of the last electron may be approximated by,⁸

$$\sigma_{Z-1,Z} = 1.4 \times 10^{-19} Z^{-2.2} . \quad (6)$$

The electron capture crosssection for low energy ions is approximately,⁹

$$\sigma_{Z-1,Z} = \frac{\pi}{4} a_0^2 Z^2 = 2.2 \times 10^{-17} Z^2, \quad (7)$$

where a_0 is the bohr radius. If v_b , n_{eb} , and v_Z are taken from Eqs. (9), (10a), and (32), Eq. (5) becomes,

$$n_0 = 5.3 \times 10^9 J \left(\frac{A}{PV_b} \right)^{1/2} \frac{n_{Z-1}}{n_Z} Z^{-4.2}, \quad (8)$$

where A is the atomic weight and P (μ pervs) the beam perveance.

Following (32), the ion energy has been estimated above as,

$\delta\phi$ (ev) $\approx 30 PV_b$. For $P = 2 \mu$ pervs and $V_b = 5$ kv, this gives,
 N_0 (cm^{-3}) $\approx 6 \times 10^7 n_{Z-1}/n_Z$, for Ar^{+18} and $J = 10^3 \text{ A/cm}^2$,

which is a less severe vacuum requirement than the previous estimate.

If the beam collapses to high current density, $\sim 10^5 \text{ A/cm}^2$, then Ar^{+18} could be produced with a reasonable vacuum, $\sim 6 \times 10^9$, or 10^{-7} Torr.

Cold electron recombination poses a potential problem in any high Z ion source. Although not yet observed, recombination is a major uncertainty in any extrapolation of CRYEBIS results. Disposal of ionization secondary electrons is not understood. Coupling of the beam energy to cold electrons is dominated by small angle collisions,¹⁰ with the heating rate approximately equal to the rate of momentum transfer. This suggests that ionization secondaries may be lost axially to the beam dump, but this is unverified. On the other hand, wall secondaries from the beam dump could conceivably become a problem. In any case, the Spitzer heating rate dominates the two body recombination rate¹¹ for parameters of interest. Outside the beam, the most likely

place for cold electron accumulation is the region of the positive potential barriers used for ion confinement; this could be studied¹² by monitoring the currents collected by these drift tubes. Because of the strong magnetic field, trapped electrons can escape only by crossfield diffusion, and associated currents should be small.

III. FUNDAMENTAL RELATIONSHIPS

Fundamental relationships between electron beam parameters are presented; this also serves to develop a general perspective about an EBIS beam.

The velocity, v_b of a nonrelativistic electron beam, of voltage, V_b , is, $v_b = (2V_b/m_e)^{1/2}$, or,

$$v_b \text{ (cm/s)} = 1.88 \times 10^9 V_b^{1/2} \text{ (kV)}. \quad (9)$$

Beam velocity, current density, J , and particle density are related by,

$$n_{eb} = J/ev_b, \quad (10)$$

which gives,

$$n_{eb}(\text{cm}^{-3}) = 3.33 \times 10^9 J(\text{A/cm}^2) V_b^{-1/2} \text{ (kV)}. \quad (10a)$$

The electron beam is designed on the basis of single particle beam optics. However, it is useful to be aware of conditions under which collective effects become relevant. The collective scale length, or Debye length, is

$$\lambda_D = (T/4\pi n e^2)^{1/2}, \quad (11)$$

which becomes,

$$\lambda_D(\text{cm}) = 2.35 \times 10^4 [T(\text{keV})/n(\text{cm}^{-3})]^{1/2}, \quad (11a)$$

where T is the temperature. From Eq.(10a), λ_D may be written in terms of machine parameters,

$$\lambda_D(\text{cm}) = 0.408 T^{1/2}(\text{keV}) V_b^{1/4} (\text{kV}) J^{-1/2}(\text{A/cm}^2). \quad (12)$$

Typically, J is 10^2 - 10^5 A/cm^2 , which means the Debye length is much shorter than the machine. Since the beam particles move through the device, another figure of merit is the number of natural oscillation periods in a transit time. The electron plasma frequency is defined as,

$$\omega_{pe} = (4\pi n_e^2/m_e)^{1/2}, \quad (13)$$

which becomes,

$$\omega_{pe}(\text{rd/sec}) = 5.64 \times 10^4 n_e^{1/2} (\text{cm}^{-3}), \quad (13a)$$

or, from Eq. (10a)

$$\omega_{pe} = 3.25 \times 10^9 J^{1/2}(\text{A/cm}^2) V_b^{-1/4} (\text{kV}). \quad (13b)$$

From Eq. (g), the number of collective oscillations which beam electrons can experience in a transit time is approximately,

$$\frac{\omega_{pe}}{2\pi} \frac{L}{v_{eb}} = 0.276 J^{1/2} L V_b^{-3/4}. \quad (14)$$

For typical parameters, this corresponds to 10^2 - 10^3 oscillations, and suggests that collective effects can be relevant. The possibility of instability will be discussed in Section V.

The relevance of collective effects across the beam is less clear. The ratio of the beam radius, $r_b = \sqrt{I/\pi J}$, to the Debye length is,

$$\frac{r_b}{\lambda_D} = 1.38 I^{1/2} T_{eb}^{-1/2} V_b^{-1/4}, \quad (15)$$

where I denotes the beam current. The current density has dropped out, but the beam temperature, which is unknown, now appears. The condition $r_b/\lambda_D \leq 1$ must be fulfilled in order to neglect Debye shielding across the beam. Some insight can be gained by rewriting Eq. (15) in terms of T_{eb}/V_b . Squaring and dividing by V_b , Debye shielding can be neglected for,

$$T_{eb}/V_b \geq 1.91 I/V_b^{3/2} = 0.06 P, \quad (16)$$

where P is the beam perveance in μpervs . This suggests that a substantial beam temperature, ~ 0.3 keV, would be required to neglect radial Debye effects in CRYEBIS.

The magnetic field introduces another scale length, the electron gyroradius, $\rho_e = v_e/\Omega_{ce}$, where $v_e = (2T_e/m_e)^{1/2}$ and $\Omega_{ce} = eB/mc$ (cgs units). This may be compared with the Debye length, which yields an algebraic identity,

$$\frac{\rho_e}{\lambda_D} = \frac{v_e}{\Omega_{ce}} \left(\frac{4\pi n_b e^2}{T_e} \right)^{1/2} = \sqrt{2} \frac{\omega_{pe}}{\Omega_{ce}}. \quad (17)$$

This may be rewritten in terms of beam parameters,

$$\frac{\rho_e}{\lambda_D} = \frac{0.0261}{B} \frac{J^{1/2}(\text{A/cm}^2)}{V_b^{1/4}} \quad (17a)$$

Since this scaling depends on the current density, the implications for beam equilibrium are discussed in Section IV.

The condition $\rho_e/\lambda_D > 1$ corresponds to electrons being on "free" particle orbits, i.e., unmagnetized, on the collective scale length.

The azimuthal field associated with the beam current is given by, $B_\theta(\text{T}) = 10^{-4} I(\text{A})/5 r_b(\text{cm})$. This may be rewritten in terms of the current density and compared with the axial field,

$$\frac{B_\theta}{B_z} = 3.54 \times 10^{-5} I^{1/2}(\text{A}) J^{1/2}(\text{A/cm}^2) B_z^{-1}(\text{T}). \quad (18)$$

Using un-neutralized CRYEBIS parameters, $I = 2\text{A}$, $J = 10^3 \text{ A/cm}^2$, this gives $B_\theta/B_z = 10^{-3}$. However, if $J \rightarrow 10^5 \text{ A/cm}^2$, the field ratio becomes $\sim 10^{-2}$, which is much larger than the design field error. The effect of the self-field on stability is discussed in Section V.

IV. BEAM EQUILIBRIUM

External electron beams, like that used on CRYEBIS, have been developed over several decades, and are relatively well understood.¹³ An external electron beam consists of a Pierce gun, which electrostatically compresses the beam in a region free of magnetic field, matched to a magnetic solenoid with a strong gradient, which further compresses the beam. Typically, such beams are designed on the basis of single particle beam optics. They were originally developed for microwave generators, and intended to operate with negligible ion effects. For ion-free operation, external beams are well diagnosed and understood. However, little attention has been given to the effect of substantial ion neutralization on beam equilibrium and stability, and diagnostic information is scarce. From Section II, CRYEBIS results indicate that the ions are associated with a two order of magnitude increase in beam current density, a fact which has been noted for sometime.²

Beam equilibrium can be understood in terms of an ideal model called Brillouin flow. The measured current density of the un-neutralized CRYEBIS electron beam, J_C , is compared with the un-neutralized Brillouin current density, J_{B0} . The Brillouin scaling is then used to extrapolate J_C for the operating parameters of the ionization experiments. This extrapolated current density, J_{Cx} is compared with J_{B0} , and also with the experimental current density obtained from the ionization rates, J_i . The Brillouin flow model is useful because it is simple, relevant to the un-neutralized beam, and easily extended to include the effect of neutralization. Since convenience does not

guarantee correctness, alternative equilibria for the neutralized beam are mentioned.

The radial equation of motion for an electron encircling the axis of a magnetic field, B_z , is given by,¹⁴

$$\frac{m_e v_\theta^2}{r} = e E_r + e v_\theta B_z / c, \quad (19)$$

where the radial electric field is obtained from the net charge density $\vec{\nabla} \cdot \vec{E} = -4\pi en(r)$. If a square density profile assumed, $n(r) = (1-f)n_b$, for $0 \leq r \leq r_b$, the radial field is given by, $E_r = -2\pi e(1-f)n_b r$. For present purposes, the neutralization fraction, f , is assumed to represent the total ion charge density divided by the total beam electron charge density, and f is assumed constant across the beam radius. Since no information is available, cold electrons are neglected. Substituting $v_\theta(r) = \omega r$, an algebraic solution for Eq. (19) is found,

$$\omega = \frac{1}{2} \Omega_{ce} \left\{ 1 \pm [1 - 2(1-f) \omega_{pe}^2 / \Omega_{ce}^2]^{1/2} \right\}. \quad (20)$$

The highest beam density for which an equilibrium exists is called Brillouin flow, and corresponds to the condition, $\omega_{pe}^2 / \Omega_{ce}^2 = 1/2(1-f)$. From Section II the Brillouin beam density is given by,

$$[n_{eb}(\text{cm}^{-3})]_B = 4.86 \times 10^{12} B^2(T) / (1-f). \quad (21)$$

From Eq. (10a), the Brillouin current density is given by,

$$\begin{aligned}
 J_B(\text{A/cm}^2) &= 1.46 \times 10^3 B^2(T) V_b^{1/2}(\text{kV}) / (1-f) \\
 &= J_{B0} / (1-f)
 \end{aligned}
 \tag{22}$$

This naive derivation has assumed a very simple profile, but is useful as a model against which the neutralized beam can be compared.

Two experimental measurements have been reported for the CRYEBIS gun; $J_C = 63 \text{ A/cm}^2$ at 0.5T, and 1020 A/cm^2 at 1.5T, both at 10 kV and 2A. These measurements were made in a high vacuum pulsed mode, specifically to avoid ion effects (i.e., $f = 0$). The scaling of Eq. (22) can now be used to extrapolate the experimental data for the operating parameters of the un-neutralized beam used in the CRYEBIS ionization experiments (Ref. Table 1),

$$\begin{aligned}
 J_{Cx} &= J_C \cdot (V_b/10)^{1/2}. \\
 \longrightarrow & 1020 \text{ A/cm}^2 \cdot [V_b(\text{kV})/10]^{1/2}.
 \end{aligned}
 \tag{23}$$

This extrapolation assumes that the beam quality is preserved.

Comparison of J_{Cx} with J_{B0} (i.e., J_B with $f = 0$) provides a useful indicator of gun performance, which is presented in Table 2. The CRYEBIS gun performs reasonable well, producing an unneutralized current density approximately ten percent of the ideal.¹³

Using the observed ionization times, from Table 1, the experimental beam current density, J_i can be estimated from Eqs. (1) and (2). The results are also listed in Table 2. For the high Z ions, J_i exceeds J_{Cx} by a factor of 35-110, and exceeds J_{Bo} by 3.5-11. A graphical comparison is shown in Fig. 1. As mentioned previously, Donets⁶ has recently confirmed the relevance of the Lotz cross section within a factor of two, which supports the experimental estimate of the beam current density. Neglecting secondaries, the required neutralization fraction is approximately,

$$f = 1 - J_i/J_{Cx} \quad (24)$$

from Table 2, this suggests nearly complete neutralization of the beam.

This discussion has neglected several complicating features. The CRYEBIS cathode has a small hole in the center;² this might result in a slightly hollow beam with peak current densities in the un-neutralized beam higher than the average.¹³ Also, the natural scalloping of a beam which is not in Brillouin flow could locally enhance the effective ionization current density.¹⁵ Both of these effects have the attraction of preserving the single particle basis of the equilibrium, but, without neutralization, appear insufficient to account for a two order of magnitude increase in current density. In addition, thermal effects, which lower the maximum possible un-neutralized beam density,¹⁶ have been neglected.

The ideal model which has been used for this evaluation of the beam equilibrium, Brillouin flow, has the attraction of simplicity.

Self-consistent effects are implicitly neglected. However, from Eq. (16), the relevance of this model is not guaranteed. A larger class of self-consistent equilibria exists, called rigid-rotor,¹⁴ which also have uniform angular velocity. In general, rigid-rotors have a bell shaped density profile with $r_b \leq \lambda_D$, but the maximum density is still given by Eq. (21), or Eq. (22). Thus, the Brillouin beam density is a useful benchmark, although more complex equilibria are possible. At present, no experimental information is available concerning the structure of the neutralized beam in CRYEBIS.

V. BEAM STABILITY

The possibility of collective instabilities in an EBIS is now considered, although little experimental evidence is available. This discussion is preliminary, pending completion of a more detailed theoretical analysis.¹⁷ Results are used from linear plasma theory for an infinite homogeneous plasma. The relevance of collective effects was mentioned in Section III. Two basic types of instability are considered briefly: (i) electrostatic two stream; and (ii) electromagnetic kink.

The electrostatic two-stream instability¹⁸ can occur when one charge distribution has sufficient motion relative to another. An EBIS, with an electron beam passing through a stationary ion background, represents an obvious candidate. The two-stream instability can lead to charge bunching (i.e., beam modulation), or particle heating on a collective time scale. If γ represents the growth rate, and δt the period available for growth, a practical stability criterion is, $\gamma \cdot \delta t \leq 3$. The less dangerous form of instability is convective growth.¹⁸ In this case, the phase velocity is on the order of the beam velocity, and stability requires $\gamma L/v_b \leq 3$. Using Eq.(14) this can be rewritten,

$$\gamma/\omega_{pe} \leq 1.73 L^{-1} J^{-1/2} V_b^{3/4}. \quad (25)$$

For CRYEBIS parameters, $L = 150$ cm, $V_b = 5$ kV and $J = 10^3$ (10^5) A/cm², convective stability requires $\gamma/\omega_{pe} \leq 10^{-3}$ (10^{-4}). For $\vec{k} \parallel \vec{B}$, the magnetic field may be neglected, and the usual field free result applies. From linear plasma theory,¹⁹ maximum growth is found to occur for $k v_b \approx \omega_{pe}$ (in the frame of the beam), with

$$\begin{aligned}
(\gamma/\omega_{pe})_{\max} &= \frac{\sqrt{3}}{2} \left(\frac{\omega_{pi}}{2\omega_{pe}} \right)^{2/3} \\
&\longrightarrow 0.0707 (Z/A)^{1/3},
\end{aligned} \tag{26}$$

where ω_{pi} is the ion plasma frequency and $n_e \approx Zn_i$. For ^{40}Ar , maximum growth gives $\gamma/\omega_{pe} \approx 0.021$ for $Z = 1$, and 0.054 for $Z = 18$. By the convective criterion used here, Eq. (25), the high current density CRYEBIS would be two-stream unstable. However, a number of stabilizing effects have been neglected in the present estimate, e.g., finite beam radius and finite gyroradius. A more sophisticated calculation is presently in progress.²⁷

Electromagnetic instabilities can result in large scale perturbation of the beam, and even disruption. Geometrically, the beam current gives a slight twist to the net field line. Although finite beam radius makes comparison with plasma devices uncertain, a system with an axial current and an axial field is generically called a stabilized pinch. A simple criterion for stability against a magnetic kink is given by the Kruskal-Shafranov limit,²⁰

$$q = 2\pi \frac{r_b B_Z}{L B} \geq 1. \tag{27}$$

In effect, this says that a full twist of the field line must require a distance longer than the length of the device ($m = 1$); q is called the safety factor. Substituting for r_b and B , this becomes,

$$q = \frac{10^5 B_Z (\text{T})}{J (\text{A/cm}^2) L (\text{cm})}. \tag{28}$$

For CRYEBIS parameters, 1.5 T and 150 cm, this gives $q = 10^3/J$, which means $q = 1$ for the un-neutralized beam, and $q \ll 1$ for the neutralized beam. A tendency of the neutralized beam toward kink instability should be detectable with magnetic probes, since large scale perturbations develop at the relatively slow Alfvén speed. However, a considerable number of assumptions used in the derivation of Eq. (27) do not apply to CRYEBIS, particularly the fact that the electron gyro radius is comparable to the beam radius. In addition, more general, stable equilibria exist for pinches with finite particle pressure. All of which suggests that further study of electromagnetic stability is needed.

VI. SCALING CRYEBIS PERFORMANCE

At present, just reproducing CRYEBIS performance represents a significant technical task. However, consideration of possible improvements and limitations is still worthwhile. In this section, a potential advantage in optimizing V_b/I_Z is noted, and a simple estimate is given for scaling particle intensity. In addition, the possibility that beam collapse is Z -dependent is pointed out. In comparison with other sources suitable for accelerators, EBIS appears to have an intrinsically high ratio of energetic to cold electron density. As mentioned in Section II, recombination has not been a problem, and, due to Spitzer heating, this may be an intrinsic property of such devices.

As in Section II, the hypothesis is that single electron impact ionization from the ground state of $Z-1$ to Z is representative of the rate at which Z is produced. In all cases considered here, this corresponds to removal of the last electron in a subshell. If the Lotz cross section is used, from Eqs. (1) and (2), a significant reduction in the CRYEBIS ionization times appear possible. Equation (2) can be rewritten in terms of the form factor, $\ln(x)/\sqrt{x}$, where $x = V_b/I_Z$. This function has a maximum of $2/e$ at e^2 . The normalized form factor is plotted in Fig. 2, along with the CRYEBIS operating points. For Ar, Kr and Xe, a reduction of τ_Z by a factor of $1/2$ to $1/4$ appears possible at higher V_b/I_Z .

In a high density EBIS, the ions are un-magnetized and must be radially confined by the net negative space charge of the beam (i.e., in CRYEBIS, the ion gyroradius would exceed the neutralized beam radius).

The total charge of the electron beam is now used to estimate the maximum number of ions which can be trapped during one pulse. In a beam with current I , length L , and voltage V_b , the total number of electrons may be approximated by, $N_b = IL/ev_b$. Using Eq. (9), this can be rewritten in terms of the perveance as,

$$N_b = 1.05 \times 10^8 P V_b L \quad (29)$$

For nominal CRYEBIS parameters, 1 μ perv, 5 kV and 150 cm, this gives N_b as 8×10^{10} . The maximum number of ions of charge Z is, $N_Z = N_b/Z$. If the pulse rate is ν and the efficiency of extracting ions is ϵ_Z , the expected particle intensity (particles per second) is,

$$\dot{N}_Z = 1.05 \times 10^8 \nu \epsilon_Z P V_b L/Z. \quad (30)$$

From Table 1, for CRYEBIS ϵ_Z was from 0.1 to 0.25 for the heavy ions; the pulse rate was 1 per second. For many accelerator applications, higher intensities are desired. Increases in perveance, P , and length, L , are likely to be small and technically difficult. Therefore, higher intensity is most likely to be gained by increasing the voltage, rep rate, or efficiency. Efficiency and rep rate are determined by factors not presently understood, but some improvement should be possible.

With an external gun, radial ion confinement²¹ in the space charge of the beam has some surprising implications for the evolution of the charge states and the beam density. If the field is given by, $E_r = -\partial_r \phi(r)$ and a flat density profile is assumed, Poisson's

Equation gives,

$$\phi(r) = e(1-f)n_b\pi r^2, \quad (31)$$

where $0 \leq r \leq r_b$. Neglecting the initial particle energy and the ion recoil energy associated with ionization, the total energy, ϵ_Z , of an ion created with charge Z at radius r would be,

$$\begin{aligned} \epsilon_Z(\text{eV}) &= Ze\phi(r) \\ &= 15.1 Z(1-f)PV_b X^2, \end{aligned} \quad (32)$$

where $X = r/r_b$, P is in μpervs and V_b in kV . This suggests that, at fixed voltage, the energy of confined ions is determined by Z, f , and r/r_b . Some implications of Eq. (32) are now examined.

From Eq. (32), the maximum energy of an ion trapped at $Z = 1$ and $f = 0$ is $\epsilon_0(\text{eV}) = 15.1 PV_b$. If the first ionization occurred at $r_1 \leq r_b$, neglecting the initial neutral particle thermal energy, the total confined energy is, $\epsilon_1 = \epsilon_0 (1-f) X_1^2$, where $X_1 = r_1/r_b$. For the flat density profile which has been assumed, the radial trapped ion motion is harmonic, with the bounce rate much greater than the ionization rate. If subsequent ionization to charge 2, 3, ... Z occurs at position $X_Z \leq \dots \leq X_2 \leq X_1$, the total energy of a confined ion can be written,

$$\epsilon_Z = \epsilon_0 Z(1-f) \bar{X}_Z^2, \quad (33)$$

where, for constant f , $\bar{x}_Z$ would be given by,

$$\bar{x}_Z^2 = (x_1^2 + x_2^2 + \dots + x_Z^2)/Z. \text{ In general, some}$$

ionization events will occur within the turning points, which implies that $x_Z < x_1 \leq 1$. If a significant fraction of the confined ions have undergone multiple ionization, focusing due to stepwise ionization would tend to shift the radial ion distribution inward. Since the ion particle motion is roughly harmonic, the ions spend most of their time at the turning points, which would make the neutralization fraction peak at large relative radius. Thus, the effort of stepwise ionization would be to smooth out the neutralization fraction.

Consider an ion of charge Z , confined with neutral ionization f and turning point $x < 1$. If the charge becomes $Z' > Z$ as the system evolves to $f' > f$, and an ion remains confined provided $\epsilon_{Z'} \geq \epsilon_Z$, or,

$$Z'(1-f') x_{Z'}^2 \geq Z(1-f) x_Z^2. \quad (34)$$

If the mean distribution of relative radii is not drastically changed, the maximum current density to which the beam equilibrium will evolve can be related to the maximum charge state by,

$$\frac{J'}{J} = \frac{1}{1-f'} \leq \frac{Z'}{Z(1-f)} \quad (35)$$

For an ion initially trapped with $Z = 1$ and $f = 0$, this means that,

$(J/J_0)_{\max} \leq (Z_{\max})$. From Table II, this estimate agrees qualitatively with CRYEBIS results, with worst agreement for N^{+7} .

These arguments are suggestive, and indicate the need for a dynamical simulation of ionization and beam collapse. There is obviously some trade-off in the effect of neutralization, which increases current density but weakens ion confinement. Neglect of secondary electrons in the beam equilibrium is potentially troublesome, but they may be left behind, on field lines outside of the collapsed beam.

VII. CONCLUSIONS

An overview has been presented of basic physical phenomena relevant to operation of an EBIS as a high current density, high Z ion source. This work was stimulated by the remarkable results of CRYEBIS,² in which the observed ionization rates indicate electron beam current densities $\sim 10^5$ A/cm². Since this performance has been difficult to reproduce, limited data are available, and, in this respect, the present study is preliminary. Some repetition of previous understanding has been necessary, e.g., the un-neutralized beam equilibrium has been studied for decades, and the enhanced current densities were inferred by Arianer. A specialist might prefer more sophisticated models, e.g., for atomic physics, but such detail would necessarily limit the scope. The models chosen have been adequate to develop useful scaling relationships as a basis for extrapolation. The relevance of collective effects has been pointed out; this has led to the suggestion that the equilibrium of the neutralized beam can be more complicated than has been assumed, and that stability is not guaranteed. Scaling suggests that raising the beam voltage may be the easiest way of increasing both the ionization rate and particle intensity, although higher rep rates should be possible. Consideration of radial ion confinement in the space charge of the beam led to the suggestion that neutralized beam collapse to high current density may be dependent on the highest charge state which is energetically accessible. The one area of present concern which has not been discussed is cold electron recombination, about which little information is available.

ACKNOWLEDGEMENTS

The author is please to acknowledge the contributions of his colleagues. Interest at the Lawrence Berkeley Laboratory in EBIS was motivated by David Clark, Hermann Grunder, and Andrew Sessler, and the author has benefitted from their technical knowledge. Many of the ideas presented here have also been developed in conversation with Ian Brown, Ben Feinberg and Wulf Kunkel. Harold West of the Lawrence Livermore Laboratory has been particularly helpful; the present work owes much to his in-depth critique of an earlier manuscript.

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

REFERENCES

- ⁺An excellent, pre-CRYEBIS, summary of EBIS development is contained in the thesis of R. W. Hamm, Los Alamos Scientific Laboratory Report, LA-7077-T (1977, unpublished).
1. E. D. Donets, IEEE NS-23, 897 (1976).
 2. J. Arianer, A. Cabrespine, and Ch. Goldstein, IEEE NS-26, 3713 (1979).
 3. M. Kleinod, R. Becker, H. Klein, and W. Schmidt, IEEE NS-23, 1023 (1976).
 4. W. Lotz, Astrophys. J. Suppl. 14, 207 (1967).
 5. T. A. Carlson, C. W. Nestor, N. Wasserman, and J. P. McDowell, At. Data 2, 63 (1970).
 6. E. D. Donets, V. P. Ovsyannikov, and V. G. Dudnikov, Comm. of the Joint Institute for Nuclear Research, Dubna, USSR, P7-12905.
 7. D. Keefe, L.J. Laslett, M. Michel, J.M. Peterson, and R.W. Schmieder, Electron Ring Ion Trap and Spectroscopic Instrumentation for Basic Studies Related to Production of High Charge State Ions and the Physics of Highly Ionized Atoms (unpublished LBL Report, ERAN-250, 1974).
 8. A. Salop, Phys. Rev. A 8, 3032 (1973).
 9. V.S. Nikolaev, Sov. Phys. USPEKHI 8, 269 (1965).
 10. L. Spitzer, Physics of Fully Ionized Gases, Chapter 5, Interscience Publishers, John Wiley & Sons (1962).
 11. R. W. P. McWhirter, Plasma Diagnostic Techniques, Chapter 5 (R. H. Huddleston and S. L. Leonard, Ed.), Academic Press (1965).

12. This is being investigated by I. G. Brown and B. Feinberg on the LBL EBIS teststand.
13. A. Ashkin, J. of Appl. Phys. 29, 1594 (1958); G. R. Brewer, J. of Appl. Phys. 30, 1022 (1959); R. D. Frost, O. T. Purl, and H. R. Johnson, Proc. of the IRE 50, 1800 (1962); and K. Amboss, IEEE ED-16, 897 (1969).
14. R. C. Davidson, Theory of Nonneutral Plasma, Chapters 1 and 2, W. A. Benjamin (1974).
15. Suggested by H. Kim, (private communication).
16. G. Hermann, J. Appl. Physics 29, 127 (1958).
17. C. Litwin, M. C. Vella, and A. M. Sessler (in progress).
18. F. E. Cap, Handbook on Plasma Instabilities, Chapter 10, Academic Press (1976).
19. N. A. Krall and A. W. Trivelpiece, Principles of Plasma Physics, Chapter 9, McGraw-Hill (1973).
20. B. B. Kadomstev, Reviews of Plasma Physics, Vol. 2, p. 179 (M. A. Leontovich, Ed.).
21. The author was first motivated to consider ion confinement by H. I. West, who was concerned about the limitations on compression due to ion temperature.

Table I. ORSAY CRYEBIS parameters.²

Electron beam					
Voltage (kV)	3.8	4.3	6.5	4.8	4.8
Current (A)	0.19	0.25	0.60	0.33	0.33
Maximum Charge State	N ⁺⁷	Ne ⁺¹⁰	Ar ⁺¹⁸	Kr ⁺³⁴	Xe ⁺⁴⁴
Ionization period (ms)	6	7	8	5	5
Spectrum Abundance*	100 percent	100 percent	70 percent	70 percent	10 percent
Particles per pulse	5x10 ⁹	3x10 ⁹	2x10 ⁸	2x10 ⁸	3x10 ⁷

*Does not include impurity ions, e.g., H⁺.

Table II. Comparison of current densities for CRYEBIS data (Ref. Table 1).

	$I_Z(\text{keV})^9$	$J_{CX}(\text{A/cm}^2)$	J_{Bo}	J_i	J_{Bo}/J_{CX}	J_i/J_{CX}	J_i/J_{Bo}
N^{+7}	0.643	0.63	6.5	0.83	10	1.3	0.13
Ne^{+10}	1.296	0.67	6.9	2.4	10	3.6	0.35
Ar^{+18}	4.254	0.82	8.4	29.0	10	35.0	3.50
Kr^{+34}	4.021	0.71	7.3	79.0	10	110.0	11.00
Xe^{+44}	3.386	0.71	7.3	34.0	10	48.0	4.70

FIGURE CAPTIONS

Fig. 1. Beam current densities relevant to CRYEBIS. The measured current density of the un-neutralized beam ($\blacksquare$) is compared with: (o) the un-neutralized density expected at the chosen operating voltage; the ideal Brillouin current density, J_B , at $f = 0$ and 5 kV; and ($\blacktriangle$) the current density required to account for the observed ionization rate.

Fig. 2. The normalized form factor for the Lotz ionization rate, σ_Z $v_b \propto (e/2) \ln X/\sqrt{X}$ is shown; CRYEBIS operating points are indicated.

XBL 808-1792

FIG. 1

XBL 8010-4444

FIG. 2