REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 71, NUMBER 2 FEBRUARY 2000

Electron beam ion sources and traps (invited)

Reinhard Becker[a)]
Institut für Angewandte Physik, Johann Wolfgang Goethe-Universität, Frankfurt, Germany

(Presented on 7 September 1999)

The electron beam method of stepwise ionization to highest charge states has found applications in electron beam ion sources (EBISs) for accelerators and atomic physics collision experiments as well as in electron beam ion traps (EBITs) for x-ray and mass spectroscopy. A dense and almost monoenergetic electron beam provides a unique tool for ionization, because radiative recombination by slow electrons is negligible and charge exchange is almost avoided in ultrahigh vacua. These are essential differences to electron cyclotron resonance ion sources with inevitable low energy electrons and comparatively high gas pressure. The distinction between EBIS and EBIT as genuine devices has become meaningless, because EBISs may work as traps and almost all EBITs are feeding beamlines for external experiments. More interesting is to note the diversification of these devices, which demonstrates that a matured technology is finding dedicated answers for different applications. At present we may distinguish six major lines of development and application: high current EBISs for upcoming hadron colliders, super EBITs in the energy range above 300 keV for quantum electrondynamics tests, inexpensive and small EBISTs for atomic physics studies, a highly efficient EBIS with oscillating electrons, MEDEBIS for tumor therapy with C^{6+}, and charge breeding in facilities for exotic radioactive beams.
[S0034-6748(00)50902-2]

I. STEPWISE IONIZATION

The production of highly charged ions by electron impact occurs most probably via many successive inelastic electron collisions, resulting in a stepwise ionization, which needs time for evolution, as seen in Fig. 1 for the example of ionizing argon to a bare nucleus with 8 keV electrons (upper panel). Ar^{8+} has a maximum abundance for $j\tau = 1$ Cb/cm^2, which means 1 s at 1 A/cm^2 or 1 ms at 1000 A/cm^2. The abundance of Ar^{8+} reaches about 35%, because the two neighboring charge states exist to about 25% at the same time. This is different for Ar^{16+}, which is He-like and due to the great step in ionization energy to Ar^{17+} the abundance may grow as high as 70%. Finally Ar^{18+} grows to full abundance after 1 s at 1000 A/cm^2. In the lower panel of Fig. 1 the electron energy is set to 3 keV, which is not enough to perform the ionization to Ar^{17+}, therefore all ions finally reach the charge state 16, resulting in full abundance for this charge state! In Fig. 2 the steady influx of neutral argon atoms is simulated, in contrast to Fig. 1, where a full batch of atoms has been exposed to the electron beam at the same time. By the constant influx, all charge states grow to a stationary value of abundance, which directly reflects the cross sections of production. Additionally, by compensation at a certain value of $j\tau$ the typical charge spectrum of electron beam ion trap (EBIT) operation is obtained, showing a final charge state distribution, which is also determined by the choice of this compensation time (upper panel 100 Cb/cm^2, lower panel 1000 Cb/cm^2). In experiments the time is set by the partial pressure of argon, if there are no heavier atoms in higher charge states in the trap, which—by cooling themselves—may kick out argon.

II. ION YIELD OF AN EBIST

Besides a single report[1] it has been found in experiments so far that the ionic charge density in the trap volume of an electron beam ion source trap (EBIST) cannot exceed the charge density of the electron beam

$$\sum_{i=1}^{q} \rho_i \leq \rho_e \tag{1}$$

which can be related to currents by

$$I = j\pi r^2 = \rho v \pi r^2 \tag{2}$$

resulting in

$$\sum_{i=1}^{q} \frac{I_i}{v_i} \leq \frac{I_e}{v_e}. \tag{3}$$

The electron velocity v_e is well defined by the potential difference U between cathode and ionization region, while the ion velocity may be either something ‘‘real’’ in the case of dc operation with ionization during time-of-flight or somewhat artificial in the case of pulsed extraction with confinement. In order to obtain a certain charge state i, the ions have to travel through the length l of the trap for the time τ_i, required for stepwise ionization, either in one single pass (dc) or in many axial oscillations (pulsed), hence we define

$$v_e = \sqrt{\frac{2e}{m} U} \quad \text{and} \quad v_i = \frac{l}{\tau_i}$$

[a)] Electronic mail: rbecker@physik.uni-frankfurt.de

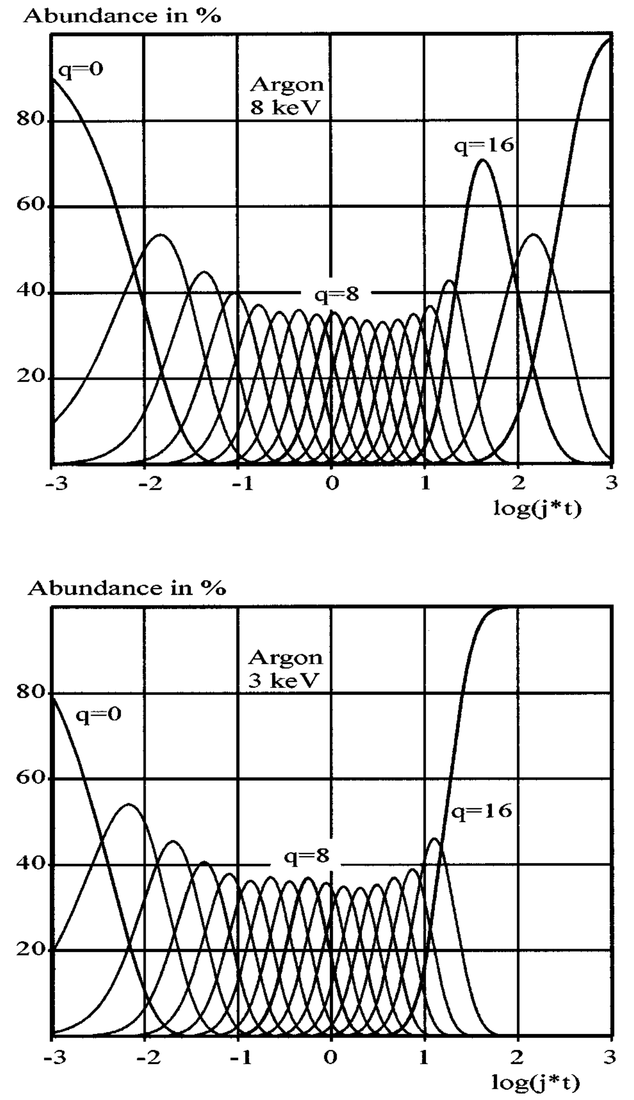

FIG. 1. Time evolution of argon charge states by stepwise ionization with feed of neutral atoms only in the beginning (EBIS). Upper (lower) panel: Electron energy 8 (3) keV.

and get from Eq. (3)

$$\sum_{i=1}^{q} I_i\tau_i=\frac{I_e l}{\sqrt{\frac{2e}{m}U}}, \tag{4}$$

which may be related to the current I_i in the desired charge state i by introducing an abundance factor f_i, describing the relative abundance of charge state i in the charge spectrum

$$f_i=\frac{I_i\tau_i}{\sum_{j=1}^{q} I_j\tau_j}, \tag{5}$$

giving

$$I_i\leqslant\frac{f_i}{\tau_i}\,\frac{I_e l}{\sqrt{\frac{2e}{m}U}}. \tag{6}$$

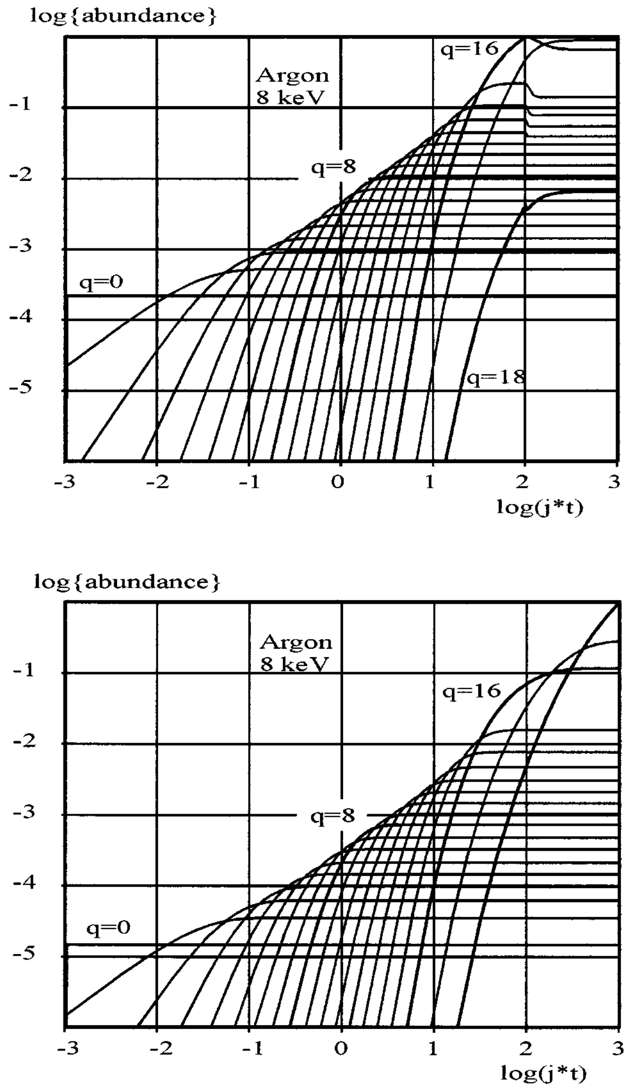

FIG. 2. Time evolution of argon charge states by stepwise ionization with continuous feed of neutral atoms (EBIT). Upper (lower) panel: Compensation at $j\tau=100(1000)$ Cb/cm^2.

Now we use the perveance for the electron beam $P=I_e/U^{3/2}$ and the relation of the ionization time τ_i with electron current density j_e and cross section σ_i for stepwise ionization

$$\tau_i=\frac{e}{j_e\sigma_i} \tag{7}$$

to rewrite Eq. (6) in the following way:

$$I_i\leqslant\frac{1}{e\sqrt{\frac{2e}{m}}}f_iPUlj_e\sigma_i=1.05\times10^{13}f_iPUlj_e\sigma_i, \tag{8}$$

which, using

$$N_i=\frac{I_i}{ei}\tau_i \tag{9}$$

and Eq. (7) may be turned into the more common expression for the number of ions, extractable after time τ_i in pulsed mode

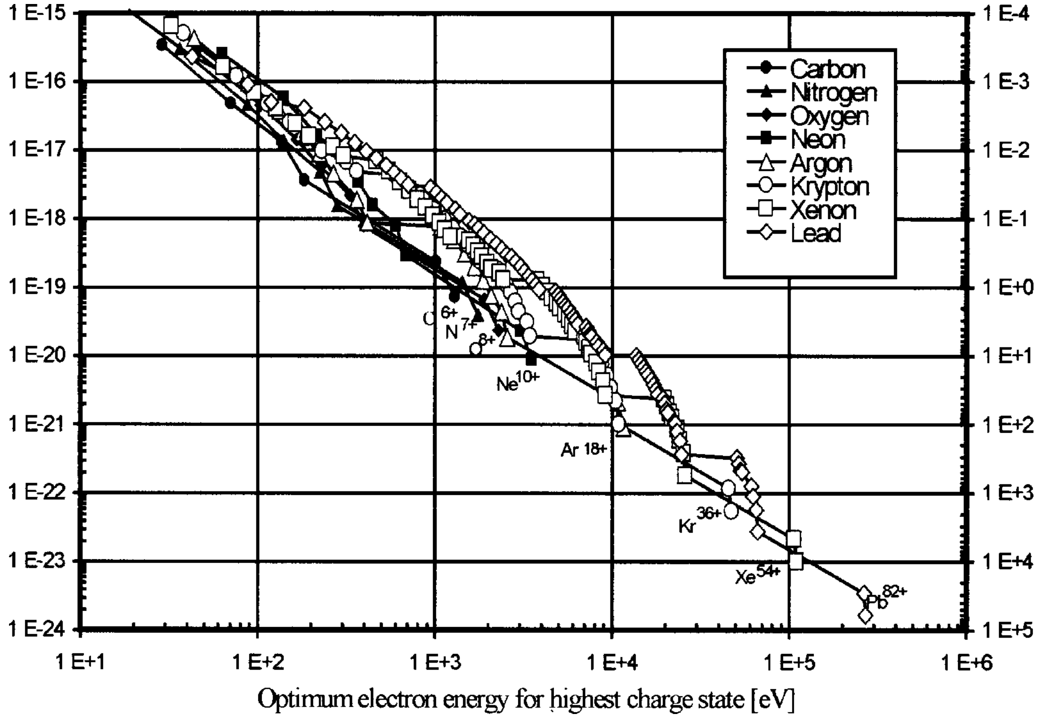

FIG. 3. Stepwise ionization of C, N, O, Ne, Ar, Kr, Xe, and Pb. (Left scale) cross sections in cm^2, (right scale) ionization time in s at 0.62 A/cm^2.

$$N_i \leqslant 1.05 \times 10^{13} \frac{f_i}{i} PUl. \tag{10}$$

By applying a linear axial electrostatic gradient during ion extraction over the entire length of the trap volume, this number of ions may be extracted from the source within 10–50 μs, but by the induced velocity modulation—first ions have lower velocity than last ions—this amount of ions may be bunched at the entrance of the next acceleration device (RFQ) to even shorter pulses (1.5 μs demonstrated for MEDEBIS[2] or 10 μs expected for RHIC[3]). For synchrotron injection an EBIS may produce in this way ion currents in the mA range in short enough times for single turn injection, being beneficial for the simplicity of operation and low emittance, resulting in higher luminosity for a hadron collider (RHIC).

Analyzing Eqs. (8) and (10), we may ask ourselves about the limits to the electron beam parameters involved, namely the perveance P, the beam voltage U, the length l of the trap, and the electron beam current density j_e. Clearly, the length is defined for practical reasons: 10 cm can be made longer easily, 1 m is more or less standard, and 10 m seems to be a difficult task. In order to align all electrodes properly to the magnetic axis, a flux straightness of 10^{-4} is needed for thin beams and 0.1 mm radial accuracy is at the limit for a length of more than 1 m. The voltage should be taken high enough for an efficient ionization (e times the ionization threshold) and limited with respect to the beam power involved, which increases by $I*U = P*U^{5/2}$. Therefore the voltage will be also set with consideration of the perveance. The beam perveance P may reach a maximum of 32.4 μA/V$^{3/2}$, if the beam is perfectly enclosed by a tube. Since this is impossible in practice, the maximum perveance will depend on the ratio of tube to beam radii, reasonably well approximated by the expression[4]

$$P_{\lim} \approx \frac{32.4}{1 + 2.4 \times \ln \dfrac{r_t}{r_b}} \left(\frac{\mu\mathrm{A}}{\mathrm{V}^{3/2}} \right), \tag{11}$$

resulting in $P_{\lim} = 10.1$, 5.0, 2.7, 1.8, and 1.4 μA/V$^{3/2}$ for $r_t / r_b = 2.5$, 10, 100, 1000, and 10 000. We may conclude that for beams of some mm diameter the perveance may reach 10 μA/V$^{3/2}$, but only reach 2 μA/V$^{3/2}$ for thin high density beams. It is worth noting that almost all EBIS devices are recuperating most of the beam energy by a depressed collector design (which is also essential to allow axial ion extraction) and that the gun perveance may be much less than the beam perveance by an appropriate deceleration of the electron beam between the gun anode and the trap electrodes.

Finally, we will investigate the limits to the current density: The maximum current density is given by Brillouin focusing, which is not useful for EBISTs, because the beam will react immediately with its radius on the change of compensation, which occurs slowly during stepwise ionization and almost abruptly during ion extraction. Instead a more robust kind of focusing called immersed flow will be needed, where electrons seem to be attached to magnetic flux lines. The upper limit to immersed flow, however, is also given by the Brillouin limit. For highly compressed beams this Brillouin limit becomes reduced by thermal initial velocities of the electrons at the cathode and almost independent of the magnetic field at the cathode[5]

$$j_{\lim} < \frac{e}{m} \frac{B_z I}{\pi r_c v_t} \times 10^{-4} \left(\frac{\mathrm{A}}{\mathrm{cm}^2} \right). \tag{12}$$

The dc ion current [Eq. (8)] also depends on the electron current density j_e, as given by Eq. (12), and the total cross section σ_i for stepwise ionization (see Fig. 2). For example, 1A at 5 T from a cathode of 1 mm radius and 2000 K will result in $j_{\mathrm{lim}} < 10^5$ A/cm^2 and with an ionization cross section of 10^{-20} cm^2, which is the maximum value for Ne^{10+} and Ar^{16+} at 3–5 keV (compare Fig. 3) we calculate an upper limit to the possible dc current according to Eq. (8) of 100 μA (electrical). This allows us to provide interesting ion currents of highly charged ions at moderate charge states, as proposed for a so called TOFEBIS,[6,7] which is operating dc and provides stepwise ionization during the time-of-flight of ions through the length of the source. By raising the electron current density to its possible limits in high magnetic fields, demonstrated with the NIST EBIT,[8] where at 5000 A/cm^2, 10 keV, 2 cm length, dc currents of some pA of Xe^{44+} ions were obtained, which however is still far below theoretical limits. This may probably be more conveniently accessible by the reflex mode of the operation of REFEBIS:[9] The power increase caused by an increase of U is almost insignificant and high perveances may be reached simultaneously with high current densities at low voltages. In addition, dc operation does not need individual drift tubes with the adverse chance of rf generation provided by axially oscillating electrons, but can be operated with only one single tube.

In the past, EBISTs have been used for atomic physics experiments with either low perveance electron beams at high voltage (Kryon-II and all EBITs) or medium perveances at low voltages, as may be seen from Table 11.1 of Ref. 10. At present we are seeing a move to high perveances at medium voltages and moderate current densities at MSL, Stockholm as well as at BNL, Brookhaven, and IAP, Frankfurt. Making EBISTs work with megawatt electron beams as used in high power klystrons, will provide pulses of 10^{10} ions/s, essentially useful for single turn injection into synchrotrons.

III. ESSENTIALS OF EBIST TECHNOLOGY

Besides providing the electron current density needed to create a desired charge state in required time, which is a straightforward engineering task, care must be taken to obtain the necessary vacuum level in the 10^{-10}–10^{-12} mbar range for classical pulsed operation with an ion confinement of a fraction of a second, or in the 10^{-8}–10^{-10} mbar range for dc operation. Vacuum is either spoiled by insufficient differential pumping between the trap region and gun and collector or by small electron losses in the μA range in the trap region, which will cause generation of soft x-rays with subsequent desorption from a large surface, even under cryogenic conditions.

The cathode material is chosen according to specific requirements. Proven long lifetimes (up to 10 yr for TWTs in space communication systems) may be expected from dispenser cathodes at a relatively low cathode loading of less than 0.2 A/cm^2. This low current density at the cathode will need a considerable electrostatic and magnetic compression to reach interesting current densities, with an according increase of the transverse beam temperature, giving rise to Gaussian-like beam profiles. Higher emission current densities from monocrystalline LaB$_6$ (Ref. 11) and IrCe (Ref. 12) alloy materials will reduce the transverse beam temperature, even at twice the operating temperature, however with some reduction of the lifetime, which is not acceptable for all applications.

Other construction materials must be chosen with respect to their cryogenic and vacuum behavior, also with respect to differential thermal expansion across interfaces like electrical or thermal conductor versus insulator.

IV. CONCLUSIONS

EBISs have been successfully used for heavy ion acceleration in a synchrotron and future application may be for C^{6+} cancer therapy and for upcoming hadron colliders like RHIC at BNL, NY.

EBITs became well established tools for—mostly spectroscopic—atomic physics studies on highly charged low energy ions. Super EBITs in the energy range above 300 keV are in progress in several places and thorough QED tests will become possible, if ions like U^{92+} are available by reproducible production and extraction.

Inexpensive and small EBISTs for atomic physics studies have been developed, which may produce interesting quantities of highly charged ions like: Ba^{46+}, Xe^{44+}, or Ar^{18+}. In the case of an eventual industrial application of creating craters of nm size on insulators by the impact of highly charged ions, these smart EBISTs will be preferable.

A highly efficient EBIS using axially oscillating electrons is promising to enhance the number of extractable charges at only a modest decrease of the average electron density and may become a direct competitor to ECRs.

In facilities for exotic radioactive beams, an EBIS may serve as a charge breeder with a special feature to selectively accumulate heavy ions by evaporative ion cooling.

[1] J. Arianer and C. Goldstein, *The Orsay Electron Beam Ion Source*, Proceedings Proc. IEEE **NS-23**, 1976, p. 979.

[2] R. Becker, H. Hoeltermann, M. Kleinod, A. Schempp, and B. Zipfel, *The EBIS Option for Hadron Therapy*, Proceedings of the 6th European Particle Accelerator Conference, Stockholm, Sweden, June 22–26, 1998 (Institute of Physics, Bristol, 1998), p. 2345.

[3] E. Beebe, J. Alessi, S. Bellavia, A. Heshcovitch, A. Kponou, R. Lockey, A. Pikin, K. Prelec, G. Kuznetsov, and M. Tiunov, *Results of Beam Tests on a High Current EBIS Test Stand*, Proc. PAC-99, New York, 1999.

[4] R. Becker, *Numerical Simulations in the Vicinity of the Virtual Cathode Regime*, Proc. SCHEF-99, Dubna, 1999 (in press).

[5] K. Amboss, *Verification and Use of Herrmanns Optical Theory of Thermal Velocoity Effects in Electron Beams in the Low Perveance Region*, Proceedings, Proc. IEEE **ED-11**, 1964, p. 479.

[6] R. Becker, *Successive Ionisation during Time of Flight*, Proceedings ICIS 2, Wien, Germany, Sept. 11–15, 1972, p. 640.

[7] M. Kleinod, R. Becker, H. Klein, and W. Schmidt, *The Time-of-Flight EBIS with Unusual Cathode Operation*, Proceedings, Proc. IEEE **NS-23**, 1976, p. 1023.

[8] L. P. Ratliff, E. W. Bell, D. C. Parks, A. I. Pikin, and J. D. Gillaspy, Rev. Sci. Instrum. **68**, 1998 (1997).

[9] E. D. Donets, Rev. Sci. Instrum. (these proceedings).

[10] *Handbook of Ion Sources*, edited by B. Wolf (Chemical Rubber Corp., Bocca Raton, FL, 1995), p. 180.

[11] FEI Beam Company, www.feic.com/main.htm

[12] O. Kultashev, Phys. Scr. **T71**, 127 (1997).