AUG 07 1985

CONF-8505164-2

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--85-1626

DE85 015690

TITLE: HIGH-BRIGHTNESS, HIGH-CURRENT ION SOURCES

AUTHOR(S): Roderich Keller

SUBMITTED TO: Workshop on "High-Current, High-Brightness, and High-Duty
Factor Injectors" San Diego, California (May 21-23, 1985)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or 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 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. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

2

HIGH-BRIGHTNESS, HIGH-CURRENT ION SOURCES*

Roderich Keller,[†] MS H816
Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

Several existing high-current dc ion sources are presented that yield positive ions and are based on gas discharges. Their common features are then outlined: extraction systems, required plasma qualities, and the production of ions from solid materials. Finally, from well-established laws, scaling rules for high-brightness ion beams are derived taking one specific case to determine the numerical constants. These rules predict that the current values of transportable beams scale proportionally to the $3/2$ power of the extraction voltage, whereas the brightness strongly decreases with rising voltage.

INTRODUCTION

The definition of high ion current is linked to space-charge phenomena, but there is no sharp threshold where these phenomena begin. The effects depend on current density, beam energy, and also on the beam quality involved. Nevertheless, many sources delivering beams between some milliamperes and tens of amperes ion current can be grouped together as high-current sources because they exhibit several common features.

This paper presents a variety of dc high-current ion sources suitable for linear accelerators and emphasizes their common aspects, concentrating on plasma sources for positive ions. Scaling rules for brightness dependence on extraction voltage are derived from several well-established laws, independently of any particular source type. The numerical factors in these rules, however, are based on the performance of one existing source only. A comparison of current values actually obtained by many other sources with the current scaling law here proposed seems to justify this derivation.

INDIVIDUAL SOURCE TYPES

Duopigatron

The source with which most of the pioneering work has been accomplished is the duopigatron.¹ Essentially, it is based on a two-stage discharge between a hot cathode, an intermediate electrode, and an anode, see Fig. 1. The plasma is guided by a

*Work done at Darmstadt.

[†]Visiting scientist from GSI, Darmstadt, West Germany.

carefully tailored axial magnetic field through the anode channel into a third chamber, at the end of which the electrons are reflected back toward the intermediate electrode. With more sophisticated models,² additional electrodes are applied to control the expanding plasma. The duopigatron offers good gas and power efficiencies, but the discharge suffers from strong oscillations if the electrode geometry is not optimized or the optimum operation conditions are not applied.

Fig. 1. Duopigatron ion source.²

"Penning" Source

As efficient as well as simple source⁴ of the Penning type--not to be mistaken for a Pig source of highly charged ions--effectively resembles the second half of a duopigatron, with one difference: the electrons sustaining the discharge are directly emitted by a filament, without need for a first discharge stage, see Fig. 2. The axial magnetic field is generated by permanent magnets placed around the cylindrical anode and expands from the cathode plane towards the outlet electrode (called "focus electrode" in Fig. 2).

Fig. 2. "Penning" high-current ion source.⁴

Multicusp Sources

With the availability of strong permanent magnets, multicusp discharges are more and more being used to create the plasma needed for high-current sources. The discharge vessel is surrounded by magnets with alternating polarity, creating a minimum-B configuration that yields a stable plasma confinement over many decades of plasma density.⁶ The rear source side may be protected by magnets (Fig. 3) or biased,⁷ depending mostly on technical considerations. The multicusp sources, in general, offer the highest versatility whenever a wide range of ion species, beam intensity, and beam quality is to be provided by one basic source type and when other features like gas- and power-efficiency or ionization degree are of minor importance.

Fig. 3. Multicusp ion source.* Ions are extracted towards the bottom.

Monocusp Source

A rather new source type* combines the qualities of the "Penning" and cusp sources, using a single, ring-shaped magnet around the discharge vessel (Fig. 4). This source design results in excellent gas efficiency because plasma losses are very low, but the design somewhat limits the useful plasma cross section near the outlet electrode because of the radial variation of the plasma density.

High-Frequency Sources

Sources using discharges between polarized electrodes always suffer from erosion, mostly of the cathodes. High-frequency discharge sources are free of this defect, but one must consider whether or not this advantage pays for the more complicated equipment involved. The frequencies used generally range from several hundreds of kilohertz to some tens of gigahertz. The plasma vessels can be made from insulators or metal; in the latter case, they are often formed as a resonator. Magnetic fields can be used to confine the discharge or, in the case of microwaves, to produce electron cyclotron resonance (ECR) effects. An example of such sources,* equipped with a magnetic multicusp field, is shown in Fig. 5.

Fig. 4. Monocusp ion source.* Broken: magnetic field lines.

Fig. 5. High-frequency ion source (2 MHz) with multicusp.*

COMMON FEATURES OF HIGH-CURRENT SOURCES

Extraction Systems

All source types presented above are equipped with large-area outlet apertures; most of them can be used with single- or

multiple-aperture extraction systems. With the latter, the total beam current simply multiplies by the number of apertures (as compared to a single-aperture system) but the overall emittance may increase drastically because the spacing between the apertures has to be added to the beamlet waist sizes.¹⁰ Commonly, accel/decel extraction systems are applied, see Fig. 6, to avoid compensating electrons being accelerated back into the source, thus destroying its rear side and leaving the ion beam uncompensated.

Fig. 6. Accel/decel extraction system¹¹ (half section, computer simulation of ion trajectories).

The most important feature of an extraction system is the contour of the outlet aperture. The point is to form the equipotentials in the extraction gap in a way that aberrations are reduced, taking into account also the space-charge action of the resulting beam. This aperture shaping must always be paid for in terms of extraction field strength. As a general rule, it is convenient to reduce the thickness of the outlet electrode near its aperture rim as much as the cooling requirements permit. The outer contour then should be bell-shaped, but no further general hint can be given, the individual needs being too different from one another.

A quite promising technique consists of dividing the extraction gap into two gaps (Fig. 7). Thus, the total width can be shortened, allowing higher fields to be applied, because of the nonlinear relation between necessary gap width and voltage, see below. The major benefit, however, is the possibility of using the voltage applied to the inserted electrode as an additional free parameter to influence the shape of the equipotentials. This technique seems to be convenient at extraction voltages above 50 kV, but in general for single-aperture systems only.

Plasma Qualities

The first condition imposed on an ion source plasma is that its density must match the applied extraction field to yield a low-divergence beam. Uniform ion emission is required across the

Fig. 7. Two-gap extraction system.¹⁰ Here the screening electrode is enclosed between two ground electrodes to improve the system reliability, following Ref. 6.

whole outlet area, even if only one aperture is used. In the case of plasma sources, this requirement implies that the plasma column must be much wider than the outlet aperture.

Plasma oscillations, especially in the 100-kHz range, must be minimized to avoid destroying the space-charge compensation of the beam. To yield optimum beam quality, the transverse ion energy must be low, typically some tenths of electron volts.

These quiet, cold plasmas usually are not suited for producing highly charged ions, but considerable fractions of doubly charged ions have been found,¹² in some cases. Multicusp sources with their large regime of operation parameters can quite easily be tuned to produce doubly and higher charged ions because they can operate stably with relatively high voltage and low gas pressure, the most suited conditions for this purpose. It must be noted, however, that there always exists a distribution over different ion charge states. In consequence, individual higher charge states can be extracted from a high-current source with less than one-third the current obtained when producing singly charged ions only.

Ions from Solids

Although the generation of ions from gases is simple enough and mostly exhibits lifetime problems, solids address quite another class of difficulties in source development and operation. The use of volatile compounds with conventional sources brings three disadvantages: the total extracted ion current must be shared between the different ion species, including ionic molecules; the compound usually contains an aggressive component, like halogens, which reduces the source's lifetime; and the free atoms of the

solid element are likely to condense on the cold source walls, which may lead to problems with the extraction system.

A better solution is the design of a hot source (Fig. 8) because many solids have suitable vapor-pressure curves that they can be processed in an oven. If the inner source walls, including the outlet plate, are kept hotter than the oven, no recondensation of the feeding material can occur. Thus, the solid material can be used like a gas, with the oven temperature replacing the gas pressure as an independent source-operation parameter. In another approach,¹² a metal supply is introduced into the plasma expansion chamber of a duopigatron. An auxiliary gas maintains the discharge; the plasma heats the supply to provide free atoms and ionizes the atoms.

Fig. 8. Hot running multicusp ion source,¹² for use with nonvolatile elements.

With such sources, solid material will always be deposited on the relatively cold extraction electrodes. This layer cannot be re-evaporated because a discharge would arise in the extraction gap; thus, larger gaps than those used with gas sources must be applied, allowing less ion current to be drawn out of the source.

SCALING RULES FOR HIGH-BRIGHTNESS BEAMS

The quality of an ion beam is commonly judged by its brightness value, as defined in the following paragraph. Frequently some misunderstanding occurs concerning this quantity.

In the accelerator community, people are familiar with the Liouville theorem which, when applicable, states that for a given beam the normalized emittance remains constant. This rule sometimes induces one to expect the maximum normalized brightness of an ion source to be a constant, but that is completely wrong.

Beam-Quality Definitions

In this paper, the following definitions will be used: I , ion current emitted by the ion source; I_{tr} , transported part of the total current; $I_n = I (A/\zeta)^{1/2}$, normalized current (proton equivalent of any ion beam of atomic mass A and charge ζ); U , effective extraction voltage, defining the beam energy; $P = I_n/U^{3/2}$, perveance; d , extraction gap width; r , outlet aperture radius; $S = r/d$, aspect ratio of the system; r_{max} , beam-waist radius.

The measured emittance is $\epsilon = A_E/\pi$ (here called absolute emittance), with A_E , area of the emittance figure; $\epsilon_n = \beta\gamma\epsilon$, normalized emittance; β and γ , usual relativistic parameters. For ion sources and low-energy beams, $\gamma = 1$ is always fulfilled, and the velocity can be evaluated from $\beta = 1.46 \times 10^{-3} (\zeta U/A)^{1/2}$.

A common definition for the brightness of a cylindrical beam reads: $B = I_{tr}/\epsilon_n^2$. It seems indicated, however, to distinguish between this quantity (better named B_{en} , "emittance-normalized" brightness) and a newly introduced "current-normalized" brightness B_{cn} , defined as $B_{cn} = I_{tr,n}/\epsilon^2$, using the quantities normalized current and absolute emittance.

Voltage Dependence of Beam Parameters

The following discussion is intended for conventional plasma ion sources, and only one round aperture is considered.

In a thorough experimental study of a duopigatron,¹⁴ it was found that the actually transported ion currents, with low divergence half-angle, scale as $I_{tr,n} = P^* S^2 U^{3/2} / (1 + aS^2)$, see Fig. 9a, rather than $I \propto S^2 U^{3/2}$ as suggested by the Child/Langmuir law¹⁵ for the total extracted currents. The factors a (aberration factor) and P^* (low- S perveance) depend upon the divergence half-angle α_0 accepted by the transport system, and also upon the chosen extraction electrode geometry. The quoted study states $a \approx 3$. For a more refined two-gap extraction system,¹⁰ $a = 1.7$ and $P^* = 6 \times 10^{-8} (A/V^{3/2})$ give the best fit to the current values measured with $\alpha_0 = 20$ mrad, see Fig. 9b.

Fig. 9. Transported ion currents I_{tr} versus aspect ratio S of extraction system: (a) triode¹⁴ (log-log plot), (b) pentode¹⁰ (linear plot).

The existence of a saturation limit for the transportable current with increasing aspect ratio S strongly recommends maintaining $S \approx 0.5$, when designing extraction systems, because the spilled-beam part extracted out of larger openings causes quite unfavorable effects. Only sophisticated geometries,¹¹ (Fig. 6) or two-gap systems permit the application of values $S \approx 1$ without losing too much in reliability of the extraction system.

Taking the values P^* and a of the above-quoted two-gap system¹⁰ as reference and allowing for $S = 1$, one can conclude at once that the maximum normalized current to be obtained from one round aperture and transported within 20-mrad divergence half-angle is a function of the voltage only and (in convenient units) amounts to

$$I_{tr,n} = 7.03 \times 10^{-4} U^{3/2} \text{ (A/kV}^{3/2}\text{)} \text{ (see Fig. 10) .}$$

In the usual case where the emittance figure of a beam is contained within an ellipse, the beam emittance in the plane of its waist is given by the product $\epsilon = \alpha_0 r_{max}$, where α_0 is the maximum angle of the trajectories crossing the beam axis in this plane. It has often been found (and confirmed for the two-gap system¹⁰ by computer simulations and emittance measurements) that for cylindrical high-brightness beams, the waist has one-half the extraction aperture width: $r_{max} = r/2$. Considering that 20 mrad was the acceptance half-angle for the system under discussion, it results that now the absolute emittance of the transported beam is only a function of r (which is equal to d) and amounts to $\epsilon = 0.5 \times 20 r = 10 d$ (mrad).

Fig. 10. Voltage dependence of normalized transported current $I_{n,tr}$. The points mark the $I_{n,tr}$ -values of actual sources, calculated for one emitting aperture only. Current values that lie significantly below the marked limit mostly belong to neutral injection experiments, where conditions other than maximum transported current are dominant.

Regarding the minimum d -value, collected data of many existing high-current sources¹⁶ show that the implicit Kilpatrick law¹⁷ marks a close lower limit for the gap widths through two decades of voltages (Fig. 11) and that a reasonably cautious empirical limit is given by the explicit formula

$$d = 0.01414 U^{3/2} \text{ (mm/kV}^{3/2}\text{)}, \text{ permitting 50 kV for a 5-mm gap.}$$

Taking an optimized system with $S = 1$ then yields

$$r = d = 0.01414 U^{3/2} \text{ (mm/kV}^{3/2}\text{)} \text{ and, in consequence, for the absolute emittance } \epsilon = 0.1414 U^{3/2} \text{ (mm mrad/kV}^{3/2}\text{)}.$$

Fig. 11. Breakdown limits for extraction gaps. K, Kilpatrick law, $U^{3/2}$, empirical limit.

For the normalized emittance, it directly follows that

$$\epsilon_n = 2.06 \times 10^{-4} (A/\zeta)^{-1/2} U^2 \text{ (mm mrad/kV}^2\text{)}.$$

The conclusion to be drawn for the dependence of the brightness values from the extraction voltage looks quite unfamiliar; the emittance-normalized (commonly used) as well as the newly introduced current-normalized brightness quantities strongly decrease with increasing voltage (Fig. 12):

Fig. 12. Voltage dependence of absolute emittance ϵ , emittance-normalized brightness $B_{\epsilon n}$, and current-normalized brightness B_{cn} , calculated according to the formulae derived in the text.

$$B_{\epsilon n} = 1.65 \times 10^4 (A/\zeta)^{1/2} U^{-5/2} [A \text{ kV}^{5/2}/(\text{mm mrad})^2]$$

and

$$B_{cn} = 3.52 \times 10^{-2} U^{-3/2} [A \text{ kV}^{3/2}/(\text{mm mrad})^2] .$$

Of course this scheme does not mean that the derived numerical factors were absolute constants. The absolute brightness values may vary considerably, depending on the emittance definition (fraction, rms value), the measurement technique, and also on the assumed acceptance half-angle; however, the validity of the tendencies here developed for individual sources appears to be well confirmed, and (much more importantly) over 30 different collected source data fit closely into the ion-current scheme (Fig. 10), including a contact-ionization source for which the above discussion does not apply at all.

The proposed scaling rules may therefore be regarded at least as a standard reference to which any high-current ion source can be compared, to judge its performance.

ACKNOWLEDGMENTS

Thanks are due to Los Alamos National Laboratory, particularly to S. Schriber, L. Taylor, and P. Allison, for critically examining and editing this manuscript, and to E. Vigil and D. Martinez for their excellent work in redrawing the illustrations.

REFERENCES

1. R. A. Demirkhanov, H. Fröhlich, V. V. Kursanov, T. I. Gutkin, Brookhaven National Laboratory report BNL-767, 224 (1962).
2. R. C. Davis, O. B. Morgan, L. D. Stewart, W. L. Stirling, Rev. Sci. Instr. 43, 278 (1972).
3. M. R. Shubaly, Inst. Phys. Conf., Ser. 54, Bristol, p. 333 (1980).
4. R. P. Vahrenkamp, R. L. Seliger, IEEE Trans. Nucl. Sci. 26, 3101 (1979).
5. K. N. Leung, N. Hershkowitz, K. R. MacKenzie, Phys. Fluids 19, 1045 (1976).
6. J. D. Schneider, H. L. Rutkowski, E. A. Meyer, D.D. Armstrong, B. A. Sherwood, L. L. Catlin, Brookhaven National Laboratory report BNL-51134, 457 (1979).
7. R. Keller, F. Nöhmayer, P. Spädtke, M. H. Schönenberg, Vacuum 34, 31 (1984).
8. J. P. Brainard, J. P. O'Hagan, Rev. Sci. Instr., 54, 1497 (1983).
9. V. V. Fosnight, W. F. Di Vergilio, report EDB 700205, TRW, Redondo Beach, California, USA (1983).
10. R. Keller, P. Spädtke, K. Hofmann, Springer Ser. Electrophys. 11, Heidelberg, p. 69 (1983).
11. B. Piosczyk, Los Alamos National Laboratory report LA-9234-C (February 1982).
12. R. Keller, P. Spädtke, F. Nöhmayer, Int. Ion Engin. Congr., Kyoto, p. 25 (1983) and K. N. Leung and R. V. Pyle, submitted to IEEE Int. Conf. on Plasma Sci., Pittsburg (1985).
13. P. G. Weber, Rev. Sci. Instr., 54, 1506 (1983).
14. J. R. Coupland, T. S. Green, D. P. Hammond, A. C. Riviere, Rev. Sci. Instr., 44, 1258 (1973).

15. C. D. Child, Phys. Rev., 32, 492 (1921).
16. R. Keller, Gesellschaft für Schwerionenforschung report GSI-82-8, Darmstadt, p. 87 (1992).
17. W. D. Kilpatrick, Rev. Sci. Instrum., 2, 824 (1957).