INNOVATIONS IN ION SOURCES AND INJECTORS

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Abstract

Current trends in the development of high-intensity positive-ion sources for linear accelerators are discussed with regard to particle production, ionization principle, and extraction system. A few sources are presented and their most recent beam data given.

The performance of injection systems under the influence of strong space-charge action is demonstrated in an example. The design of a compound system where the beam is extracted, focused, and accelerated to injection energy in a single structure with reduced aberration is explained in the following. In connection with this system the concept of beam emittance is critically examined and a new interpretation of fractional emittances derived.

Introduction

The status of high-current positive-ion sources for linear accelerators has not changed drastically since the last conference of this series,[1] but improvements have been achieved regarding the processing of chemically aggressive or high-melting materials. Especially the progress made in developing MEVVA, a metal-vapour vacuum-arc ion source,[2] should be mentioned in this regard. The availability of high-current ion beams with quite different species and intensities, however, creates new difficulties for the layout of acceleration gaps that rise the beam energy to injection values and have to match a wide range of space-charge conditions.[3] An integrated extraction- and acceleration structure, the so-called compound system, helps to overcome these problems without incurring in brightness losses.

The optimization of extraction systems as well as investigations of beam transport problems first of all need a suitable beam quality criterion. While for bunched beams there seems to be no substitution for the approach using statistical (rms) emittances[4,5] the situation with continuous beams is more favourable and allows a detailed description of the beam quality by the minimum-ellipse method.[6] This method can be applied optimizing extraction systems or beam transport lines to obtain either highest currents or highest brightness values or least beam halos.

The choice of subjects for this review is obviously quite arbitrary and, with the exception of M. Shubaly's oxygen source, determined by the author's direct participation in the activities mentioned in the following. This selection does not at all imply that there were not many other development efforts going on in this area that are equally or even better suited for such a presentation.

Plasma Generators

One of the most difficult substances to be processed in ion sources is, undoubtedly, oxygen. No hot filament lasts long enough in a pure oxygen atmosphere to allow for reasonable operation times above 10 h. The best choice in that case would be a source without filaments, that is an RF or microwave driven plasma generator, but up to now there appears no such source to be actually working at accelerators and delivering high ion currents of 10 mA or more. In this situation, the DUOPIGATRON offers a major advantage over other sources because it has two discharge chambers and the one where the filament is situated can be run in a noble gas environment, feeding the oxygen only to the expansion chamber behind the anode,[7] see Fig. 1. Excellent results are obtained using this method: 230 mA beam current at 52 kV extraction voltage, within an absolute emittance (area divided by π) of 550 mm mrad. The maximum share of atomic O^+ ions reaches 61 %.

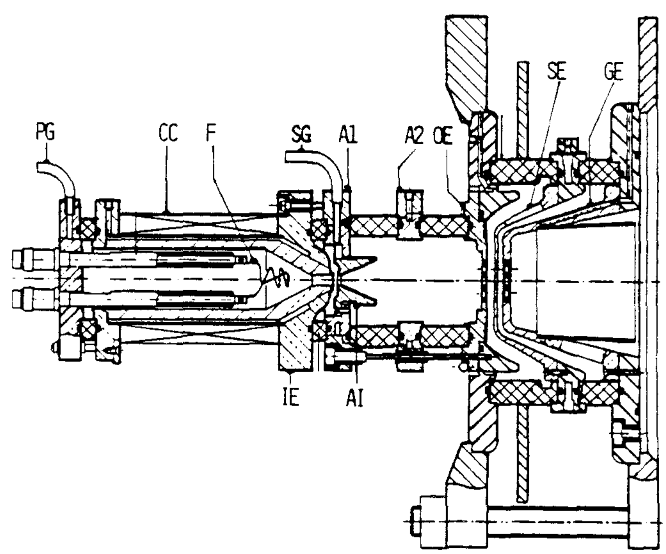

Fig. 1. DUOPIGATRON ion source for oxygen, after Ref. 7. PG, primary gas inlet (argon). CC, compressor coil. F, cathode filament made from rhenium wire. IE, intermediate electrode. SG, secondary gas inlet (oxygen). A1, first anode. AI, anode insert. A2, second anode. OE, outlet electrode. SE, screening electrode. GE, ground electrode. These last three electrodes form a multi-aperture triode (accel/decel) extraction system.

For elements with high vapour pressure like iodine, a modification of the hot-running multi-cusp/reflex source CHORDIS has now been presented.[8] Instead of the usual vacuum oven, the source is equipped with an external bottle that is directly connected to the cathode holder tube inside the source, see Fig. 2.

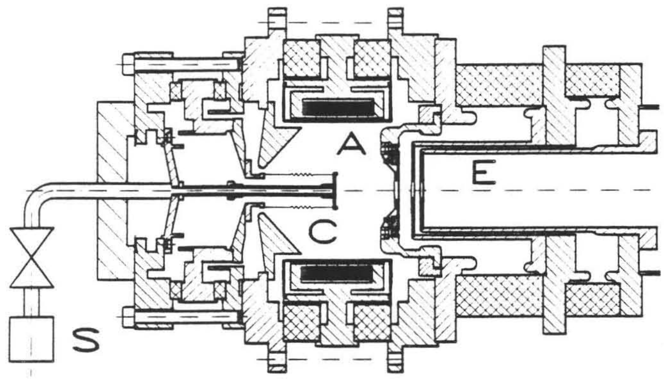

Fig. 2. Hot-running ion source of the CHORDIS type[8] with external supply bottle. A, anode: the inner tube runs hot; the outer, cold wall is lined with 18 permanent magnets producing a linear multi-cusp field for stable plasma confinement. The electrodes that axially enclose the discharge chamber are usually connected to the negative cathode leg. C, cathode made from six tantalum filaments. E, extraction system; single- or multi-aperture triode or pentode. S, vapour supply bottle.

The discharge burns in a pure vapour atmosphere, and 28 mA I^+ ions are so far extracted at 31 kV within 150 mm mrad absolute emittance. The same source type can also be run in a sputtering mode by biasing the outlet reflector to about -150 V and leaving out the supply bottle. In a pilot experiment with aluminum, a 20 % share of metal could be reached within the beam, amounting to 2.4 mA Al^+ at 20 kV within 75 mm mrad.

A major progress was made by further developing the metal-vapour vacuum arc source MEVVA,[9] see Fig. 3.

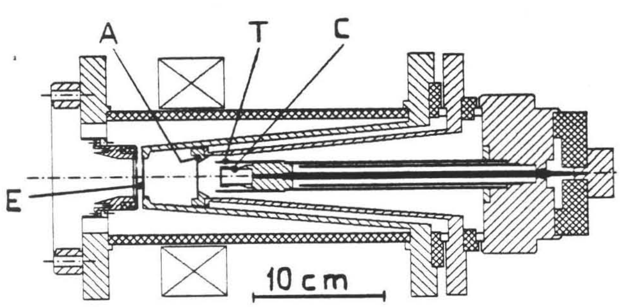

Fig. 3. Metal vapour ion source MEVVA.[2] C, solid cathode made from the material yielding the desired ion species. T, triggering electrode. A, ring anode. E, triode extraction system.

This source is capable of delivering high-current beams of multiply charged ions up to 1 A of virtually any metal.[2] The discharge is initiated by a triggering spark and then maintained for typically 1 ms by a pulse-forming network. The plasma expands through the hollow anode of the source and reaches the outlet electrode where a beam can be formed by adding an accel/decel extraction system. For the experiments reported in Ref. 9, the open area of the extraction system was reduced so as to yield ion beam currents in the 100-mA range. For example, 77 mA of Ti^{2+} were obtained at 40 kV within 400 mm mrad absolute emittance using a 163-hole extraction system, and 29 mA of U^{4+} at 38 kV within 200 mm mrad using a 7-hole system.

There are, however, two disadvantages associated with the MEVVA source in its present development state: one is the low duty factor of typically 0.1 % which is unsufficient for many linac applications; the other one concerns the unsatisfactory pulse-to-pulse reproducibility. This latter feature was improved when only the central part of the plasma expansion chamber was employed for beam production,[10] but still the average deviation between the intensities of consecutive beam pulses amounts to 10 %, and about every tenth pulse will entirely be missing.

Extraction- and Injection Systems

General guide lines for designing extraction systems as well as scaling rules for the beam parameters to be expected have been published in the last conference of this series.[1] In a recent study of an accel/decel system,[8] shaping of the screening electrode aperture, too, was applied additionally to the usual shaping of the outlet contour, see Figs. 4 and 5. This procedure seems to further reduce the amount of beam halo, especially when relatively wide screening- and ground electrode apertures are used, as shown in Figs. 4 b and 5 b.

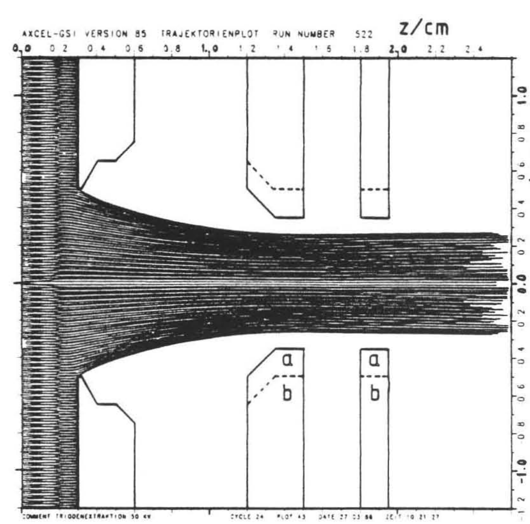

Fig. 4. High-brightness extraction system, designed with the aid of the simulation code AXCEL-GSI.[11] The two cases show electrode shapes optimized for either highest beam current within 20 mrad divergence half-angle (a) or for lowest divergence (b). The extraction voltages of +50 kV and -4 kV (screening voltage) are well tolerated by the 6-mm gap[1].

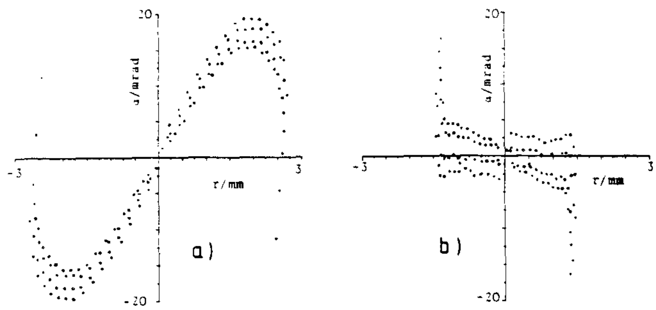

Fig. 5 a and b. Calculated emittance patterns for the extraction systems in Fig. 3 a and b. System (a) is optimized for highest current within 20 mrad half angle, amounting to 283 mA (proton equivalent). With system (b), the aberrations are considerably reduced in intensity. The beam core still contains 100 mA, within 5 mrad half angle. In terms of brightness B, system (b) is better by a factor of 19 than system (a), according to the formula $B = I/\varepsilon^2$, when the encompassing ellipses are taken to determine the emittance values ε. System (b) yields 220 mA within 20 mrad at matched current density.

Even the best extraction system would be useless, however, if the beam quality could not be maintained during the next acceleration step, usually needed to reach injection energies of RF structures. While there may be satisfactory solutions for direct extraction systems in cases where ion species and current are constant, with heavy ion accelerators these two parameters are frequently changed according to the users' requirements and the maximum currents available. In addition, the injection energy varies proportionally to the mass-over-charge ratio of the ions. For a given arrangement of extraction system, drift space, and acceleration gap then there exists an optimum ratio of extraction- over acceleration voltage yielding the highest transported beam currents.[3] This phenomenon is illustrated by measurements using the MEVVA source,[9] see Fig. 6.

Using the emittance-normalized brightness definition[1]

$$B_{\varepsilon n} = I/\varepsilon_n^2$$

with: I, ion current and ε_n, normalized emittance (area divided by π), in the best case during these measurements a value of $B_{\varepsilon n} = 1.4$ A/(mm mrad)^2 was measured at 158 keV energy for the core of the beam, containing about 80 % of the total of 40 mA current. The entire beam emittance pattern exhibited substantial aberration wings.

Such aberration problems can quite easily be overcome by using a so-called compound system,[3] a structure that basically consists of extraction, electrostatic einzel lens, acceleration gap, and screening electrode. Such a system had been proposed some time ago,[12] but only recently a computer-optimized design was actually built and tested on the MEVVA source,[10] see Fig. 7.

A uranium ion beam current of 15 mA was delivered by this system at 159 keV energy within an absolute emittance of 12.3 mm mrad, that is, with 21 A/(mm mrad)^2 emittance-normalized brightness. The core of this beam contains 2.8 mA as derived by integration of the measured profile, see Fig. 8, within 2.5 mm mrad. This means an extraordinarily high emittance-normalized brightness value of 78 A/(mm mrad)^2.

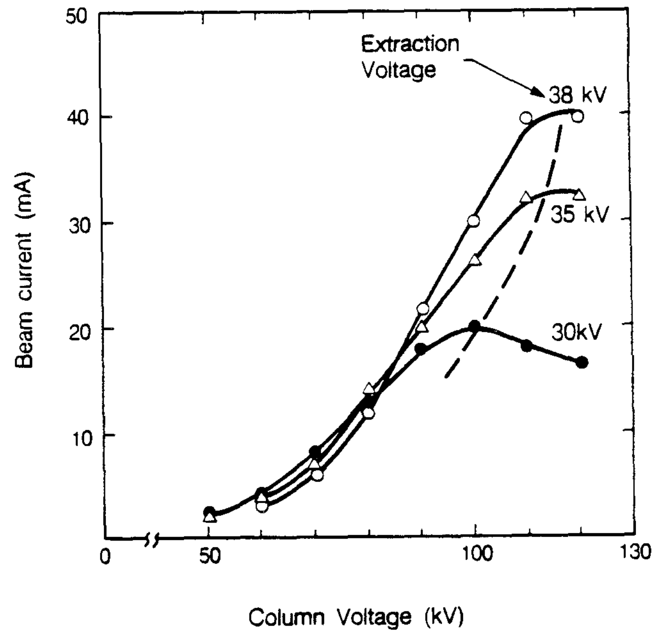

Fig. 6. Beam current measured at the ground side of a high-voltage gap versus gap voltage, with extraction voltage as parameter. The broken line indicates matched conditions that yield maximum transported current for every extraction voltage. The beam consists of 58 % U 4+, 29 % U 3+, and minor shares of other uranium charge states. From Ref. 9.

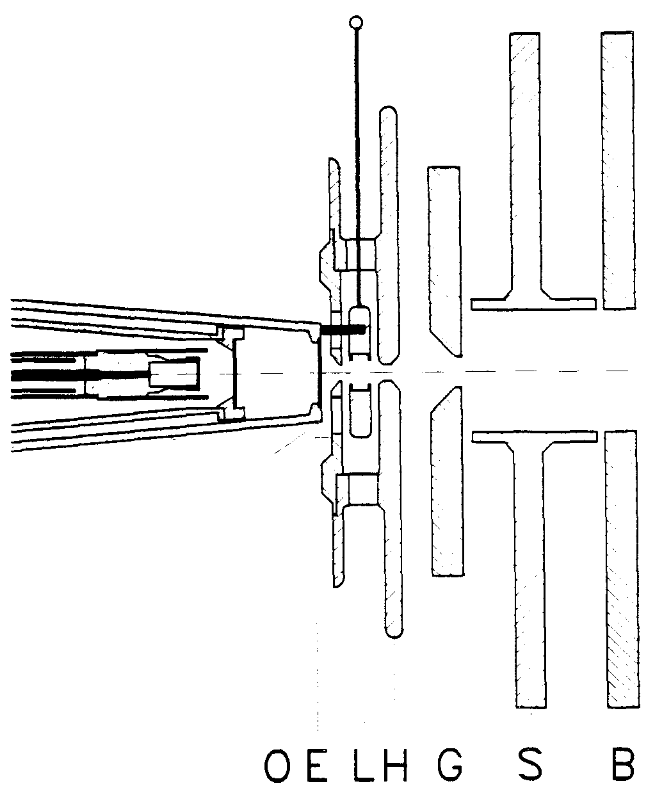

Fig. 7. Compound extraction system for MEVVA.[10] O, outlet electrode, on 159 kV potential. E, extractor electrode, 125 kV. L, einzel lens, 154 kV. H, high-potential gap electrode, 125 kV. G, grounded gap electrode, 0 kV. S, screening electrode, -1.5 kV. B, beam potential electrode, 0 kV.

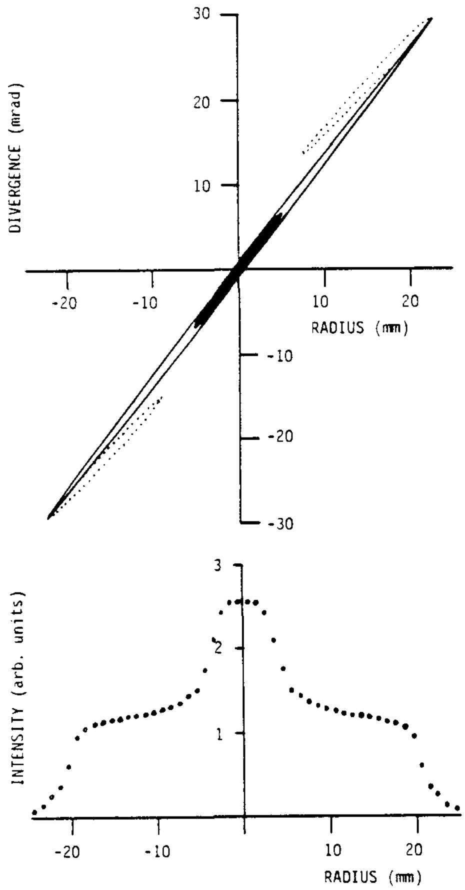

Fig. 8. Emittance pattern and profile of a 15-mA, 159 keV uranium beam extracted from MEVVA by a compound system.[10] The intensity in the dotted wings is less than about 1 % of the total intensity. The emittance is measured using a radial pepper-pot measurement technique. To obtain the beam profile, a kapton foil was exposed to the entire beam for several minutes and the radial density distribution photometrically evaluated. The core of the emittance pattern as determined by the profile measurement is shown in full black within the emittance diagram.

Quantification of Emittances

At a first glance, it might be surprising to notice how much the measured brightness values differ for one single source, even considering the fact that the square of the emittance value is entered into the brightness formula. The data given above for MEVVA, however, spread so much because of two reasons. The first one is of purely physical nature: the compound system is designed so as to minimize aberrations that are produced when extracting and accelerating a beam in a conventional way by two separate structures. The much higher brightness value obtained by the compound system then just proves that this goal has in fact been reached. The second effect bases on the arbitrary choice which part of the beam actually to take into account with its emittance- and current values, in order to achieve a very high brightness result.

This latter point should explain why it is desirable to have an objective criterion with which to quantify and judge beam emittances. So far, the rms concept[4,5] is widely used in the accelerator community for this purpose, but it has one decisive disadvantage: for a beam with large halo even the 4rms emittance ellipse of size:

$$\varepsilon_{4rms} = 4\cdot\varepsilon_{rms} = 4\cdot[\overline{x^2}\cdot\overline{x'^2} - \overline{(x\cdot x')}^2]^{1/2}$$

(with: x, transverse position and x', transverse angle of every trajectory of the measured beam) does not encompass the entire emittance pattern but cuts off the aberration wings and, on the other hand, extends too far along the main axis, see Fig. 9. The existence of such problems has already been acknowledged in Ref. 5.

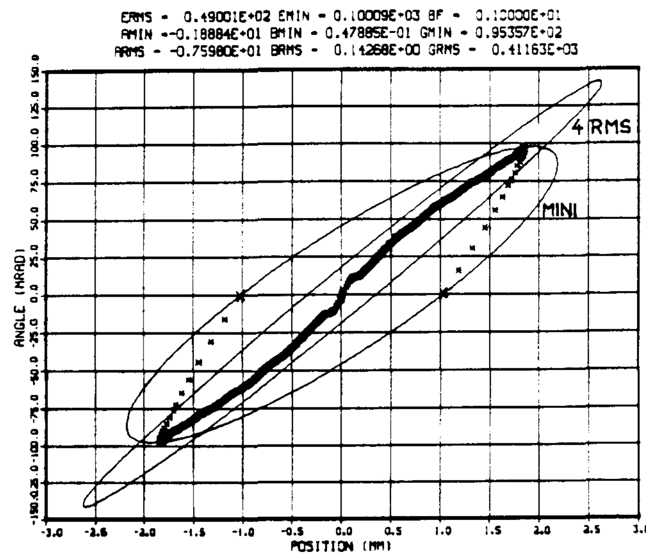

Fig. 9. Emittance pattern of a simulated beam near the extraction plane, with 4rms- and minimum-ellipse contours. After Ref. 6.

During a study on this subject,[6] a new algorithm was created that permits to calculate encompassing ellipses of minimum size for arbitrary emittance patterns. At the same time, the algorithm yields an objective criterion to decide which of the individual points of the distribution is the one that determines the actual size of such a minimum-ellipse. Consequently, this one point is eliminated and a new minimum-ellipse drawn around the remaining fraction of the distribution. By repeating this procedure the distribution is gradually reduced, and a plot of beam intensity versus size of the encompassing ellipse then clearly shows the particularities of the distribution, especially the halo and the core, see fig. 10.

The great advantage of the minimum-ellipse method consists in the fact that for every beam fraction a closely fitting shape is known that encompasses all this fraction. Thus, by providing an equivalent acceptance, one is absolutely shure which amount of beam current can be transported. (The minimum-ellipse method as well as the rms method both yield the ellipse orientation and excentricity, too, not only the size as discussed here.) Also for studies of emittance growth effects, the new method seems appropriate because it enables to distinguish between significant growth and cases where only a tiny fraction of the halo spreads away and leads to much increased 100 % emittance contours.

It should be underlined that plotting emittance sizes versus beam fractions is not at all a new procedure. But usually intensity thresholds are taken to determine the contours of fractional emittances.[14] This way, however, suffers from two disadvantages: simulated emittances very often do not have large enough trajectory numbers to allow the definition of reasonably smooth density distributions, and, even for measured distributions, density contours generally have complicated shapes with partially concave border lines. The minimum-ellipse approach, on the contrary, automatically leads to completely convex shapes and does not even use any definition of trajectory density. For measured emittances, the current density is taken into account as a statistical weight for every occupied area element of the phase plane.

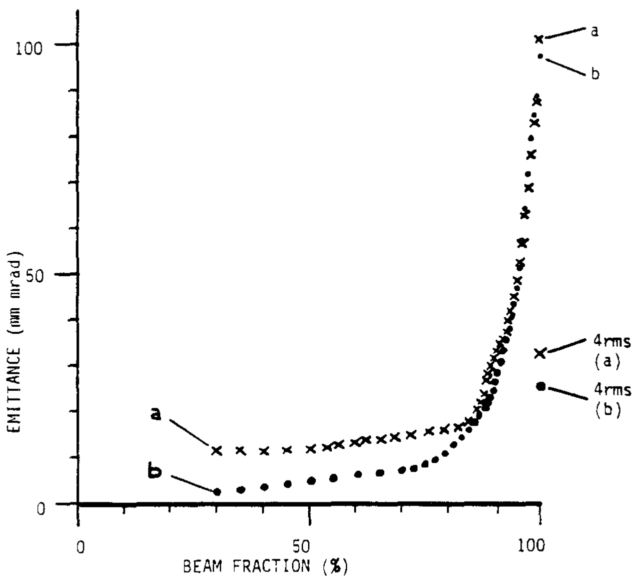

Fig. 10. Beam fraction versus minimum-ellipse size for two different beams simulated by using the code SNOW.[13] The plot shows that case (b) is much more favourable than case (a) because for 75 % and lower beam fractions the emittance values of (b) are only half as large as those of (a), even if both values for the 100 % fractions are nearly identical. On the other hand, the 4rms values of the entire distributions differ by only 20 %. After Ref.6.

In conclusion, the minimum-ellipse method is helpful whenever a detailed, quantitative judgement of given emittances is needed, whether they are measured or result from simulations. A user of this method anyway has the freedom to choose the goal of an optimization or matching process: either highest current within a given acceptance or highest brightness or least losses, to avoid excessive power loads under high-intensity, high-duty factor conditions.

Acknowledgements

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