HIGH-CURRENT ION SOURCES

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Introduction

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

This paper presents a variety of high-current ion sources suitable for linear accelerators and emphasizes their common aspects, concentrating on plasma sources for positive ions.

Individual Source Types

Duopigatron

The source with which most of the pioneer work has been done is the duopigatron[1]. Essentially, it bases on a two-stage discharge between a hot cathode, an intermediate electrode, and an anode, see fig. 1. The plasma is guided by a carefully tailored axial magnetic field through the rather wide anode channel into a third chamber, at the end of which the electrons are reflected back towards the intermediate electrode. With more sophisticated models[2], additional electrodes are applied to controll 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.

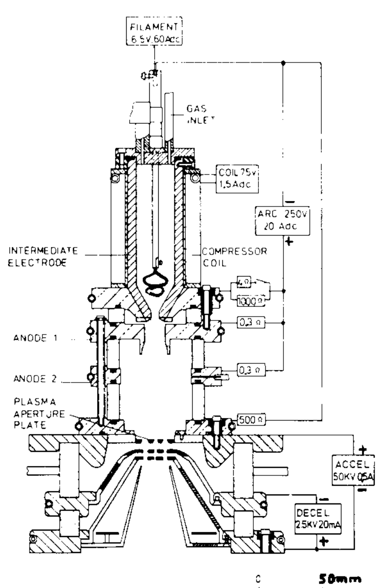

Fig. 1. Duopigatron ion source[3].

Ehlers Source

In a quite rugged source, the discharge is stroken between cathode filaments positioned near the wall of a cylindrical chamber and a thick anode piece on the source axis[4]. This discharge produces a quiet plasma of large width, but the gas efficiency of the source seems to be quite poor.

"Penning" Source

An efficient as well as simple source[5] 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 the difference that 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.

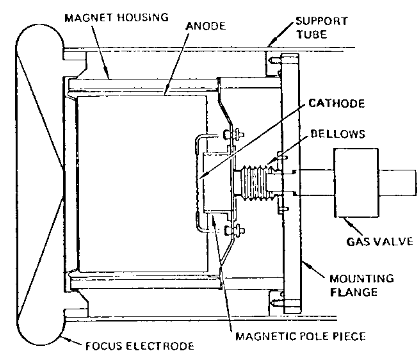

Fig. 2. "Penning" high-current ion source.

Multicusp Sources

With the availability of strong permanent magnets, multicusp discharges are more and more 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 which yields a stable plasma confinement over many decades of plasma density[6]. The rear source side may be protected by magnets, see fig. 3, or biased[8], 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 other features like gas- and power efficiency or ionization degree are of minor importance.

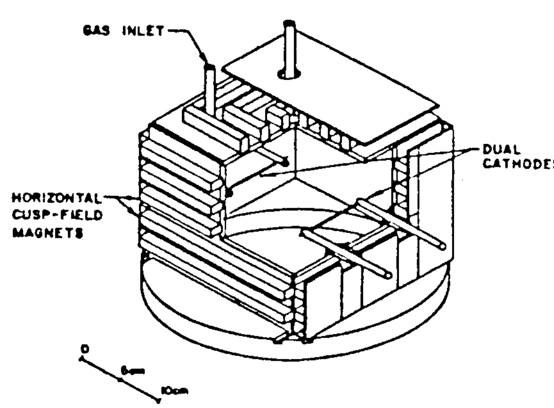

Fig. 3. Multicusp ion source[7]. Ions are extracted towards the bottom.

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[9], see fig. 4. This results in excellent gas efficiency since the plasma losses are very low, but somewhat limits the useful plasma cross section near the outlet electrode, due to the radial variation of the plasma density.

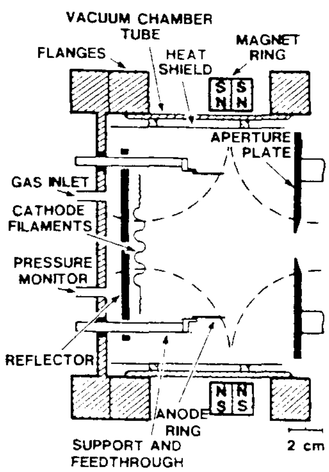

Fig. 4. Monocusp ion source. Broken: magnetic field lines.

High-Frequency Sources

Sources using discharges between polarized electrodes always suffer from erosion, mostly of the cathodes. HF-discharges are free of this defect, but it must be individually examined if this advantage pays for the more complicated equipment envolved. The used frequencies generally range from several hundred kHz to some ten GHz. The plasma vessels can be made from insulators or metal; in the latter case they are often formed as a resonator. Axial 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[10], equipped with a magnetic multicusp field, is shown in fig. 5.

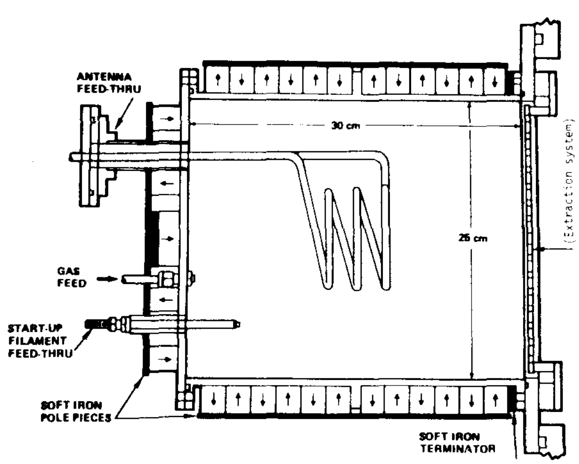

Fig. 5. High-frequency ion source (2MHz) with multicusp.

Contact Ionization Sources

Not in all cases is it necessary to extract ions out of a plasma: if a material with low ionization potential is disposed on the surface of another material with high work function positive ions of the first species can be directly extracted by applying a high electrical field. In one of such sources the material (Cs) is sprayed on an iridium plate[11], while another one makes use of the high mobility of molten metal within a zeolite sheath[12]. The advantage lies in the possibility to shape the emitting surface according to the ion optical requirements; the technique is restricted, however, to quite few ion species.

Common Features of High-Current Sources

Extraction Systems

All the 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 since the spacing between the apertures has to be added to the beamlet waist sizes[13]. Commonly, accel/decel extraction systems are applied, see fig. 6, in order to avoid that compensating electrons are accelerated back into the source, destroying its rear side and leaving the ion beam uncompensated.

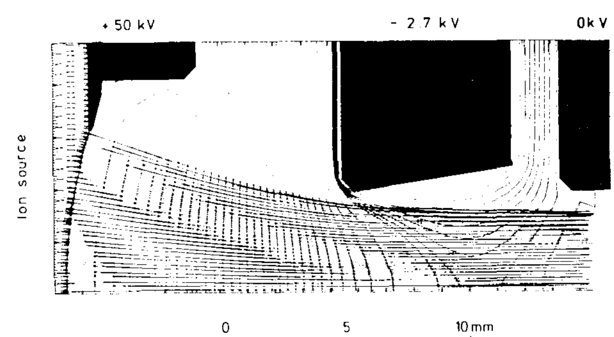

Fig. 6. Accel/decel extraction system[14] (half section, computer simulation of ion trajectories).

The most important aspect 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 avoided, considering 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 in dividing the extraction gap into two gaps, see fig. 7. Thus the total width can be shortened, allowing higher fields to be applied, due to the non-linear relation between necessary gap width and voltage, see below. The major benefit, however, is to be seen in the possibility to use 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 only for single-aperture systems.

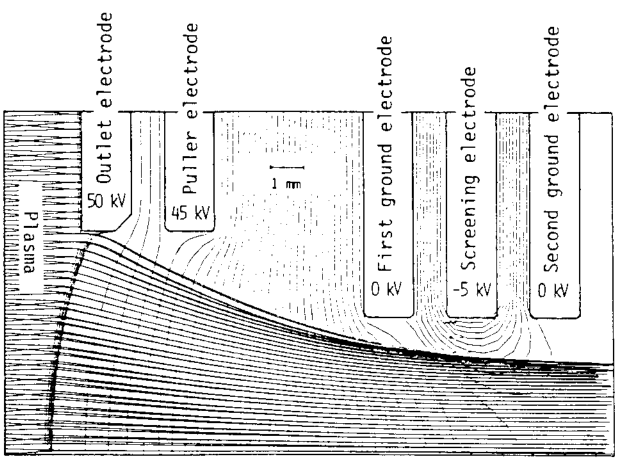

Fig. 7. Two-gap extraction system[13]. Here the screening electrode is enclosed between two ground electrodes to improve the system reliability[7].

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

Plasma oscillations, especially in the 100 kHz range, must be avoided in order not to destroy the space-charge compensation of the beam. To yield optimum beam quality the transverse ion energy (temperature) must be low, typically some tenths of eV.

These quiet, cold plasmas (or the metal layer of a contact ionization source) are not at all suited to produce highly charged ions, but considerable fractions of doubly charged ions have been found[15,16,17] in some cases. Multicusp sources with their large regime of operation parameters can quite easily be tuned to produce doubly and higher charged ions since they can be stably burnt 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, higher charge states can be extracted from a high-current source with about one third, maximum, of the current obtained with exclusively singly charged ions.

Ions from Solids

While the generation of ions from gases is simple enough and mostly exhibits life-time problems, solids open up 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 among the different ion species, including ionic molecules; the compound usually contains an aggressive component, like halogens, which reduces the source life-time; and the free atoms of the solid element are likely to condense on the cold source walls, this may lead to problems with the extraction system.

A better solution is the design of a hot source, see fig. 8, as many solids have suitable vapour pressure curves to be processed in an oven. If the inner source walls, including the outlet plate, are kept hotter than the oven no re-condensation 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.

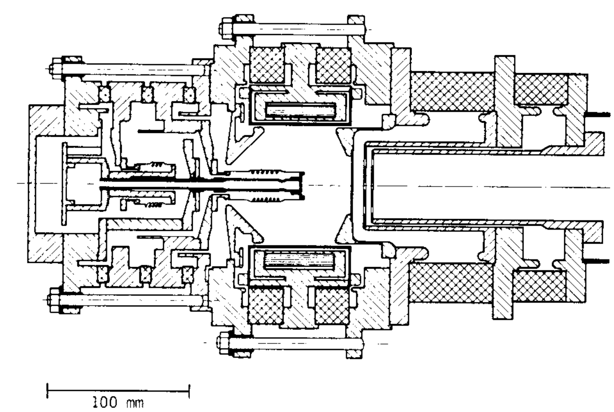

Fig. 8. Hot running multicusp ion source[17], for use with non-volatile elements.

In another approach[18], 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.

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

Scaling Rules for High-Brightness Ion Beams

The quality of an ion beam is commonly judged by its brightness value, as defined below. With this quantity, frequently some misunderstanding occurs: 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 that the maximum normalized brightness of an ion source was 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;
$I_n = I \times (A/\zeta)^{1/2}$: 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.

$\varepsilon = A_E/\pi$: measured emittance (here called absolute emittance), with A_E: area of the emittance figure; $\varepsilon_n = \beta\times\gamma\times\varepsilon$: 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: $\beta = (\zeta\times U/A)^{1/2} \times 1.46\times10^{-3}$.

The common definition for the brightness of a cylindrical beam reads: $B = I / \varepsilon_n^2$. It seems indicated, however, to distinguish between this quantity, better named $B_{\varepsilon n}$, "emittance-normalized" brightness, and a newly introduced "current-normalized" brightness B_{cn}, defined as: $B_{cn} = I_n / \varepsilon^2$ using the quantities normalized current and absolute emittance.

Voltage Dependence of Beam Parameters

The following discussion is intended for conventional plasma ion sources, not the contact-ionization sources, and only one round aperture is considered.

In a thorough experimental study of a duopigatron[19], it was found that the actually transported ion currents, with low divergence half angle, scale as
$I_{tr,n} = P^*\times S^2/(1+a\times S^2)\times U^{3/2}$, see fig. 9a, rather than $I \propto S^2\times U^{3/2}$ as suggested by the Child/Langmuir law[20] 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, but also upon the chosen extraction electrode geometry. The quoted study states $a \approx 3$. For a more refined two-gap extraction system[13], $a = 1.7$ and $P^* = 6\times10^{-8}$ [$A/V^{3/2}$] give the best fit to the current values measured within $\alpha_0 = 20$ mrad, see fig. 9b.

The existence of a saturation limit for the transportable current with increasing aspect ratio S, strongly recommends to maintain $S \approx 0.5$, when designing extraction systems, as the spilled beam part extracted out of larger openings causes quite unfavorable effects. Only sophisticated geometries[14], see fig.6, or two-gap systems permit the application of values $S \approx 1$ without loosing too much in reliability of the extraction system.

Taking the values P^* and a of the above quoted two-gap system[13] as reference and allowing for S = 1, one can at once conclude that the maximum normalized current to be gained out of one round aperture and transported within 20 mrad divergence half-angle is a function of the voltage only and (in convenient units) amounts to:

$$I_{tr,n} = 7.03\times10^{-4}\times U^{3/2} \quad [A/kV^{3/2}].$$

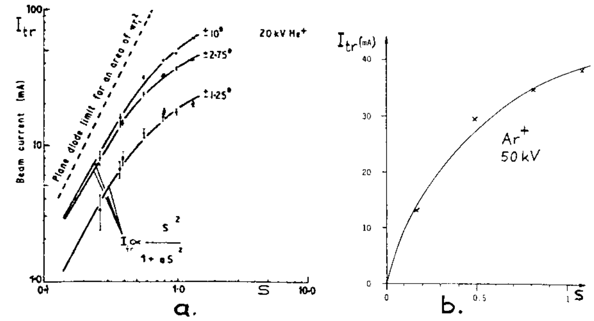

Fig. 9a,b. Transported ion currents I_{tr} versus aspect ratio S of extraction system. a: triode[19], b: pentode[13].

In the usual case that 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 $\varepsilon = \alpha_0 \times r_{max}$, where α_0 is the maximum angle of the trajectories crossing the beam axis in this plane. It has often been found, and been confirmed for the two-gap system[13] by computer simulations and emittance measurements, that for cylindrical high-brightness beams the waist has one half of 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 (= d) and amounts to $\varepsilon = 0.5\times r\times 20 = 10\times d$ [mrad].

Regarding the minimum d-value, collected data of many existing high-current sources[21] show that the implicit Kilpatrick law[22] marks a close lower limit for the gap widths through two decades of voltages, see fig. 10, and that a reasonably cautious empirical limit is given by the explicit formula:

$$d = 0.01414\times U^{3/2} \quad [mm/kV^{3/2}],$$

permitting 50 kV for a 5 mm gap.

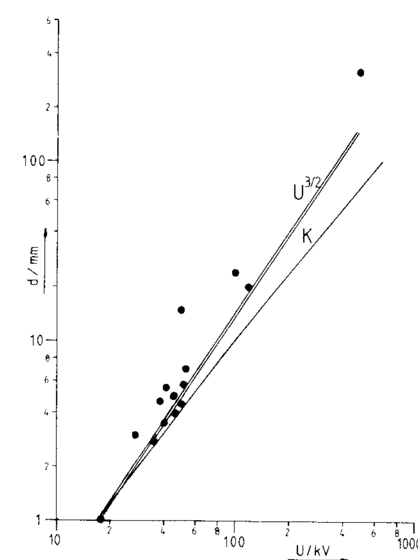

Fig. 10. Breakdown limits for extraction gaps. K: Kilpatrick law; $U^{3/2}$: empirical limit.

Taking an optimized system with S = 1 then yields $r = d = 0.01414 \times U^{3/2}$ $[mm/kV^{3/2}]$ and in consequence for the absolute emittance:

$$\varepsilon = 0.1414 \times U^{3/2} \quad [mm \times mrad/kV^{3/2}].$$

For the normalized emittance directly follows:

$$\varepsilon_n = 2.06 \times 10^{-4} \times (A/\zeta)^{-1/2} \times U^2 \quad [mm \times mrad/kV^2].$$

The conclusion to be drawn for the dependence of the brightness values from the extraction voltage looks quite unfamiliar: it results that the emittance-normalized (commonly used) as well as the newly introduced current-normalized brightness quantities strongly decrease with increasing voltage, see fig. 11:

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

and:

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

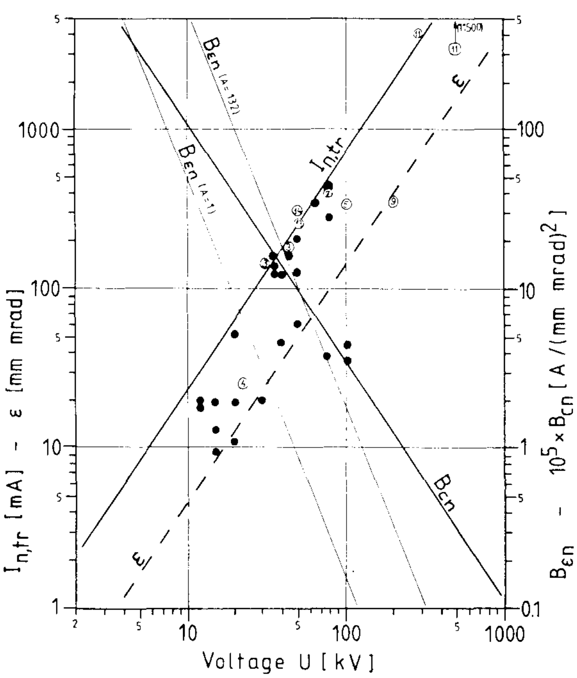

Fig. 11. Voltage dependence of normalized transported current $I_{n,tr}$, absolute emittance ε, emittance-normalized brightness $B_{\varepsilon n}$, and current-normalized brightness B_{cn}, calculated according to the formulae derived above.
The points mark the $I_{n,tr}$-values of actual sources, calculated for one emitting aperture only. Sources quoted in this paper are represented by their reference numbers.
Current values which lie significantly below the marked limit mostly belong to neutral injection experiments, where other conditions than maximum transported current are dominant.

This scheme does not mean, of course, that the derived numerical factors were absolute natural constants. Especially the brightness values may still be improved somewhat; but the validity of the here developed tendencies for individual sources appears well confirmed, and, much more important, over thirty different collected source data fit closely into the scheme, including two contact ionization sources for which the reasoning does not apply at all.

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

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