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Publication Date
2001-03-21

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Primary Ion Sources for EBIS*

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Abstract. This paper gives an introduction into the topic of primary ion sources that can be used to feed ions of normally solid elements into EBIS devices. Starting with a set of typical requirements for primary ion sources, some major types of ion generators are discussed first, with emphasis on their working principles rather than trying to give a fully representative listing of used and proposed generators. Beam-transport issues between primary ion source and EBIS are then examined, and generic characteristics of suitable beam-formation and transport systems are explained.

INTRODUCTION

While feeding of gaseous substances into EBIS devices is straightforward, the use of elements with low vapor pressure under normal conditions presents its challenges, due to the unique set of functional requirements for a typical EBIS discharge chamber, with coexisting conditions of ultra-high vacuum, high voltage, high magnetic field, and sharp mechanical alignment tolerances. Use of an external injector–or primary–ion source then becomes a viable and even preferred mode of operation, as opposed to generating the desired free particles inside the EBIS. In combination with a mass separator, the primary ion source can also provide feeds of a single element in a single charge state, drastically reducing the loss of main-beam current in the form of unwanted species. It might further be beneficial for the final product to start the ionization process within the EBIS with already ionized particles for example, to keep the background gas pressure as low as possible, thereby reducing recombination losses.

On the other hand, one should not underestimate the effort needed to efficiently utilize a primary ion source; both the particle generation as well as the primary beam transport issues need to be taken care of when high performance levels are aimed at. These two subjects are discussed in the main part of this paper, after outlining typical conditions towards which they are geared.

*Work supported by the Director, Office of Science, Office of Basic Energy Sciences, of the US Department of Energy under Contr. No. DE-AC03-76SF00098

In the limited space allocated to it, this paper does not make the least attempt of providing an encyclopedic view of the field of primary ion sources for EBIS but rather discusses some fundamental issues of the particle-generation and beam-transport aspects, relying for illustration on a few examples of actually working sources that are or could easily be employed for the purpose under discussion.

BOUNDARY CONDITIONS AND TYPICAL REQUIREMENTS

The issues discussed in this paper concern the generation of ions from normally solid elements, their formation into an ion beam, and its injection into EBIS sources. In most cases, short beam pulses with low duty factor are desired, and singly charged ions are clearly good enough for the purpose because the EBIS itself very efficiently provides further ionization. Multiply charged ions are not harmful either, as long as one does not intend to quantitatively assess the ionization processes occurring in the EBIS in great detail and would prefer clean starting conditions. The injection process of the primary beam has to be compatible with the UHV conditions in the EBIS, and some beam-quality conditions are consistent with best utilizing the primary beam as well as avoiding damage to the internal EBIS components. Having to inject a beam into a steeply rising magnetic field complicates these matters somewhat.

In the following Table 1 of typical requirements, definitive parameter values are listed that serve as a background for the discussion of ion generators and beam-formation issues, just to give a quantitative context. These values do not constitute a consistent description of an actual primary-beam injector; rather, it should be understood that parameters for any specific setup may deviate significantly from the listed numbers.

TABLE 1. Typical Requirements for Primary Ion Beam

Parameter	Value	Unit
Ion current	100	μA
Pulse duration	10	μs
Energy during transfer	30	keV
Emittance limit (4-rms, unnormalized)	100	π mm mrad
EBIS entrance aperture	5	mm
EBIS drift-tube aperture	20	mm

ION GENERATORS

For this paper, the distinction between the ion generator (the ion source proper) on one hand and the beam-formation and -transport system on the other hand is relevant. Ion generators utilize either an electrical discharge to create a plasma, or surface ionization processes that may even directly lead to beam formation. Plasma technology

can be applied to create a large variety of ion species, but in many cases it involves dealing with a mixture of various ions, of different elements as well as in different charge states. Contact ionization, on the other hand, is restricted to a few materials with low work function and therefore offers only very limited choices.

It may be noted that most examples of ion generators discussed in this paper belong to the generic type of high-current ion-sources, in spite of the rather modest current requirements listed in Table 1. This is more due to convenience in assembling material than true functional necessity, although there are certain advantages in working with rather large ion generators, and typically high-current sources have been developed to a high degree of operational reliability as required by their application in industry or large-scale research projects. On the other hand, the beam-forming system of any high-current ion source can and should be scaled down to create just the beam intensity needed for the EBIS injector. The only group of ion generators that might have difficulties delivering 100-μA beam currents is the one utilizing field-ionization.

Plasma Generators for Essentially Pure Elements

Utilization of an electrical discharge to generate ions is a nearly universal method applied in the vast majority of cases because one basic ion-generator model will produce a large variety of different ion species.

Plasma Generators Equipped with Oven

It is desirable in principle to use a pure element as feeding material for the plasma generator. Because of the restriction to solid materials in the context of this paper, this implies taking advantage of the high vapor pressure of a feeding material at elevated temperatures. Occasionally solid bars of material have been introduced into ion generators and heated by the discharge plasma itself, but in most cases the material temperature cannot be controlled well enough to keep the plasma density constant and generate a well-defined and stable ion beam. Therefore, an oven in some form is the obvious solution, and a great variety of designs has been created in the past decades, led by the well-known Freeman source [1, 2], today's industry-standard ion-source for ion implanters.

With an internal oven, incorporated into the vacuum enclosure of the plasma generator, one has to take care to thermally isolate it from the discharge; otherwise, variation of the electrical power coupled into the discharge may easily cause the oven temperature to vary, possibly leading to a runaway effect. An example of a versatile plasma generator where this problem is well solved is shown in Fig. 1. CHORDIS ion sources comprise a family of models that utilize various particle-generation techniques such as internal or external ovens, sputtering, and gas mixtures [3]; they are used in particle accelerators, ion implanters, and stand-alone setups, for example, to create free metal clusters by ion-beam sputtering [4].

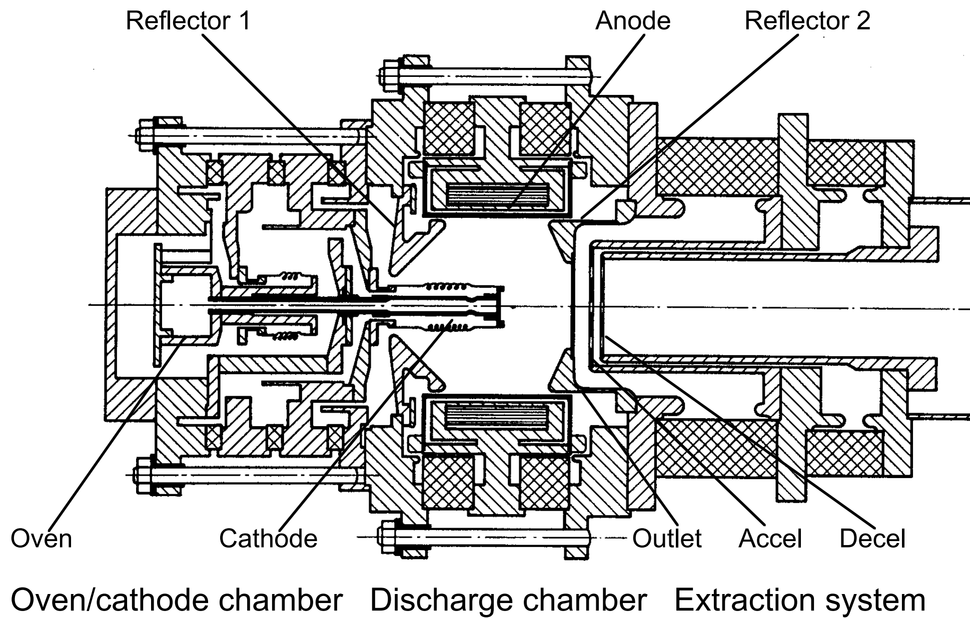

FIGURE 1. CHORDIS multi-cusp, reflex-discharge ion source equipped with internal oven. For simplicity, heat shields surrounding the oven and its filaments are not shown in this illustration.

A useful table of vapor pressures of all elements as a function of temperature is given in Reference [5]. It is worth mentioning that heat shields, made from stacks of thin metal sheets such as tantalum, are very helpful in reducing the electrical heating power that has to be applied to reach operating temperature of the oven. Also, to efficiently utilize the generated particles and avoid clogging and unstable discharge characteristics, one should try to keep the conduit between oven and plasma chamber, as well as the exposed surfaces of the chamber itself, hotter that the oven.

Another problem can occur when evaporated material reaches the nearest extractor electrode. Basically, one has the options of running this electrode hot as well, with the danger of striking a discharge in the extraction gap, or to ensure that the layer of condensed material sticks to the electrode, by cutting a series of concentric grooves into its surface, as shown as a remedy for a similar problem in Figure 3, below. Of course, one could also sacrifice some degree of beam quality and ease of alignment and make the extractor aperture substantially wider than the plasma generator outlet aperture.

Convenient shapes of extraction system electrodes will be discussed in detail below, in the section on beam formation.

In view of the heat capacity of the oven and conduit material, it is often easier to work with an oven at temperatures above a few 100°C where thermal equilibration will be established at reasonably fast rates. For some materials, this poses a problem bec-ause of their low high vapor pressure, but in the case of cesium there exists a practical solution, using cesium chromate mixed with titanium powder as feeding material. Depending on the specific mixture, cesium chromate is reduced to elemental cesium and released as vapor at about 400°C, and the production rate can be well controlled.

One disadvantage of using an oven in a primary ion source is that this technology is compatible with dc operation, at least of the oven itself. For the short beam pulses needed for EBIS injection this means that the process of generating free particles is highly inefficient, and this might be a serious issue, for example, in cases where isotopically pure feeding materials are needed. Keeping the inner surfaces of the plasma generator hot enough with a low-duty-factor discharge is another challenge and might lead to inserting some kind of chopping system in the subsequent beamline to allow operating the generator at higher duty factor. In some cases, when the surface temperature cannot be held high enough, it is advantageous to employ an auxiliary gas to achieve reliable pulse ignition. While by this choice the abundance of metal ions in the plasma is necessarily diluted, the fact that most solid materials have much lower ionization energy thresholds than noble gases will push the particle species distribution towards a favorable share of the desired material.

Vacuum Arc Plasma Generators

Exposing the feed material directly to the discharge plasma is the basic particle-generating mechanism used in vacuum-arc plasma generators such as MEVVA [6]. This source type has proven its usefulness in deposition setups where the integral dose is the most important parameter, and features such as high-current beam generation in short pulses from a large variety of high-melting materials, including refractory metals and lanthanides, could be very attractive for EBIS injectors as well. Unfortunately, the intrinsic nature of a metal-vapor vacuum-arc device involves challenging operational disadvantages.

The discharge is ignited by applying a very short high-voltage pulse which produces a surface spark across the insulator between the metal cathode and a trigger electrode. Metal particles are released from the cathode by a combination of cathode sputtering and evaporation due to rapid heating of the cathode surface which typically develops one or more small craters in the course of operation. A pulsed voltage of several 100 V maintains the plasma for the pulse duration of about 1 ms after ignition. Depending on the thermodynamic properties of the cathode material and its microscopic surface structure, the pulse-to-pulse reproducibility of the main plasma parameters can be quite poor and jeopardize utilization of this ion generator as part of an accelerator system that has to meet high reliability and reproducibility requirements.

Plasma Generators Utilizing Sputtering

Cathode sputtering is a process that can well be utilized for particle generation in primary ion sources for EBIS. Of course, the sputtering action is not limited to the actual cathode of a plasma generator but can be directed towards any negatively biased electrode within the plasma chamber, typically in the vicinity of the outlet electrode. The advantages of this process are that the particle-production rate can be controlled

by a single electrical parameter, independently of the other discharge parameters, and that it can easily be pulsed, providing much higher overall efficiency than found with oven-equipped plasma generators for these purposes. On the other hand, sputtering relies on the utilization of an auxiliary gas, such as argon, and its abundance in the plasma has to be by far higher than that of the material being sputtered to achieve stable discharge conditions. A 15% share of useful particles in the extracted beam is at the upper limit in most practical cases; this makes mass separation in the transport line between primary ion source and EBIS mandatory.

An ion source that actually operates in an EBIS injector [7] and utilizes sputtering for particle generation is the sputter version of CHORDIS [8]. As compared to Fig. 1, the oven is replaced by a simple cathode holder, and a sputtering target is directly mounted on the upstream side of the outlet electrode ('Reflector 2' in Fig. 1). A bias voltage of about 1 kV is applied between these two connected electrodes and 'Reflector 1' which stays on cathode potential, and the ion current drawn from the plasma is limited by a 1-kΩ resistor connected in series.

A quite versatile plasma generator that can easily produce beam intensities in excess of EBIS requirements is the sputter duoplasmatron shown in Fig. 2 [9]. Duoplasmatrons and the similar duopigatron ion sources [10] have been successfully employed in ion-implantation devices [11]. They offer high power- and particle-efficiencies but are somewhat more delicate in their operational characteristics, more subject to memory effects, and less versatile than high-current sources of the multi-cusp type. As with oven-equipped devices, care must be taken to control layers of re-condensed material, especially on outlet and extractor electrodes.

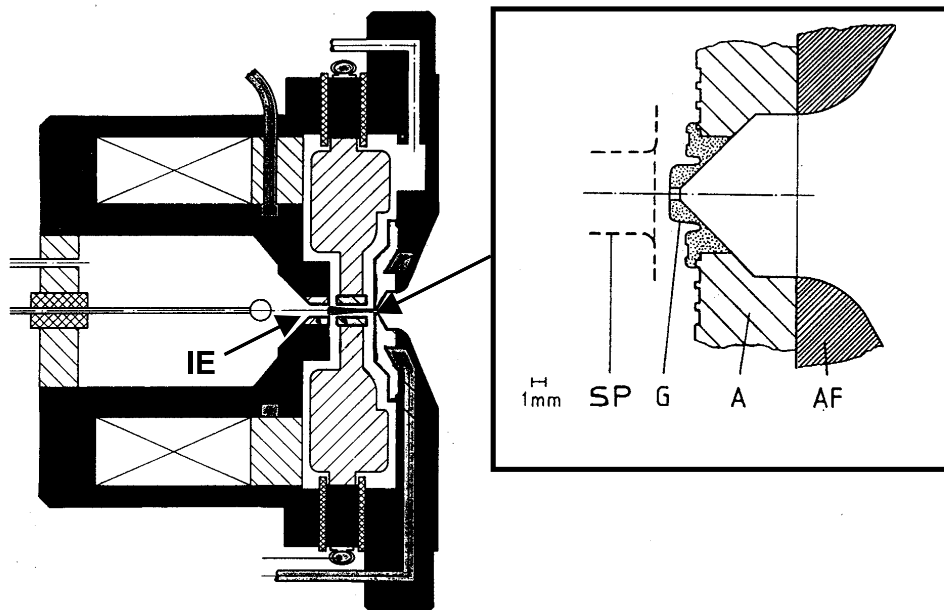

FIGURE 2. Sputter Duoplasmatron with detail of anode shape. The sputter electrode is mounted in the space between intermediate electrode, IE, and anode. Legend for the insert frame: SP, Sputter electrode; G, Graphite insert; A, Anode; AF, Anode flange.

Plasma Generators Utilizing Chemical Compounds

Chemical compounds offer a nearly universal approach for introducing low vapor-pressure elements into plasma generators. A comprehensive list of suitable materials and processing techniques is given in Reference [12]. Most frequently, available compounds in gaseous or liquid form are fed directly into the discharge chamber, but in cases where compounds are not readily available one can use an on-line reaction process, conducting halogen gas across a heated graphite crucible in which the desired solid material is placed. These plasma generators are quite similar to oven-equipped devices, and because of the low vapor pressures of the desired materials care must be taken to avoid excessive condensation on the inner surfaces of the discharge chamber by letting them run hot in operation.

The use of compounds, however, has its own price. First of all, many particle species will be present in the generated ion beam, including a variety of molecular ions. Unfortunately, in electrical discharges many more molecule types can form than under 'cold chemistry' conditions, severely reducing the share of the desired ion species. An even more adverse circumstance is the fact that, by the very nature of their chemical properties, most elements that would be part of a volatile compound are rather aggressive, tend to corrode the discharge vessel walls, and may cause excessive sparking in the extraction gap. Comments on re-condensation and clogging made in the section on oven-equipped plasma generators apply to this group of devices as well.

Ion Generators Utilizing Contact or Field Ionization

Certain materials lend themselves to directly forming ion beams, without creating a plasma first, by applying an extraction high-voltage, utilizing the processes of contact- or field ionization [13]. Contact ionization can be achieved by coating a hot, high-work function metal electrode, such as tungsten, with a desired low-work function metal, mostly from the alkaline or earth-alkaline columns of the periodic table. The second metal can be sprayed on the emitter surface or conducted through a porous sponge or zeolite [14]. A comprehensive list of work functions for all elements is given in Reference [15]. The surface of the emitter can be shaped flat or spherically to give the ions optimum starting conditions across the beam.

Field ionization [16] is the fundamental mechanism used in liquid-metal ion generators. Elements with low vapor pressure at their melting temperature, such as gallium, indium, and bismuth, are ideal feeding substances, and some alloys such as 80% gold with 20% silicon are suitable as well. Depending on the force balance between surface tension on the liquefied metal and the electrostatic force of the directly applied extraction field, a cone with very narrow radius will form at the tip of a metal-covered needle or in front of a narrow metal column that has risen to the end of a capillary. Ions are directly formed at the tip of this cone and accelerated in a beam with rather large

(about 30°) aperture angle. With alloys as feeding material, of course, the beam current will be divided among a mixture of different ion species.

From a purely operational point of view, having the performance of an ion source depend on the stability of a temperature regulation system is always somewhat problematic, but at their best these sources exhibit extremely high beam brightness values at currents reaching beyond 100 µA even with heavy metals. When pushed to excessive current values, the metal cone will release micro-droplets that can cause problems with the extraction system. Liquid-metal sources are mainly being used in lithography setups for integrated-circuit fabrication [17]. For EBIS injectors, they are certainly an attractive option, but limited to a rather narrow selection of useful ion species.

BEAM FORMATION AND TRANSPORT

In view of the rather modest current and emittance requirements listed in Table 1, one might rather undervalue the importance of beam-formation and transport issues, but they still have to be taken care of if one wants to arrive at a functional delivery system. This section is intended to give some background on both issues, listing basic formulas and rules, without any attempt to derive them from fundamental principles.

Beam Formation

The exact shapes of the extraction-system electrodes should nowadays be optimized using beam-modeling codes such as IGUN [18], but there are a few general rules that will enable a newcomer to narrow the choice of major system parameters before starting the actual simulations. The following formulae will be helpful for this purpose; they are derived in detail in Reference [19].

The achievable beam current produced by an extraction system attached to an ion generator depends on two basic quantities, i.e. the ion density in the outlet aperture of the generator and the applied extraction field strength. In analyzing the principal properties of extraction systems, one implicitly assumes that the ion generator is providing just the needed ion density; in this case, the beam formation process is governed by space-charge effects, rather than intrinsic properties of the ion generator.

The highest current I_{max} [mA] within an aperture half-angle of 20 mrad that can be extracted from a single outlet aperture by an extraction system with aspect ratio S is:

$$I_{max} = 1.9\, U^{3/2} S^2 / \{(1 + 1.7\, S^2)\, A^{1/2}\} \tag{1}$$

where U, extraction voltage [kV]; S=r/d, aspect ratio with r , outlet-aperture radius [mm] and d, extraction-gap width [mm]; and A, effective atomic mass number of ions.

The saturation term $1 + 1.7\ S^2$ on the right-hand side reflects the fact that for aspect ratios $S > 1$, there is only minimal gain in beam current with rising S.

The minimum gap width for an extraction system with quantities in the same units is:

$$d = 0.01414\ U^{3/2} \tag{2}$$

The emittance of an ion beam in the plane where it has a waist is in general:

$$\varepsilon = \pi\ \alpha_o\ r_o \tag{3}$$

where α_o, divergence half-angle[mrad] and r_o, beam radius [mm]. Due to geometrical constraints imposed by the size of the outlet aperture, the minimum encompassing emittance (approximately the 4-rms size) [π mm mrad] of a beam extracted by a minimum-gap extraction system is:

$$\varepsilon = 0.1414\ U^{3/2} \tag{4}$$

If minimum emittance is not a high priority one can raise the extraction gap-width somewhat above the lower limit given in Equation (2), increase the outlet aperture in proportion to keep the aspect ratio constant, and thus still obtain the full current given by Equation (1).

The velocity of an ion that has passed through the extractor electrode is, in units of the vacuum light-velocity c:

$$v = 0.00146\ c\ (z\ U/\ A)^{1/2} \tag{5}$$

where z is the actual charge number of the ion in question and A, its actual atomic mass. This latter formula means that in absence of collisions, a 30-keV ion of atomic mass 100 takes 4 μs to travel through a 1-m long EBIS.

Ion Transport to EBIS

Once a beam has been formed, it still has to be transported to and injected into the EBIS. The idea of close-coupling primary ion source and EBIS looks attractive at first, but in reality it has three major disadvantages. First of all, in a close-coupled system there is virtually no possibility of differential pumping, making it hard to meet the extreme vacuum requirements of the EBIS. Secondly, separation of undesired ions from the useful ones is precluded, and parasitic ions will heavily drag on the total charge capacity of the EBIS. Both reasons would limit the choice of ion species quite drastically. Lastly, the persistence of injected ions might be uncomfortably short if they are injected at higher energies around 30 keV, but in order to obtain reasonably high currents at lower extraction voltages, the entire extraction/injection system will have to be made very small. The low-energy beam then has still to pass through the

EBIS cathode before it reaches the ionization chamber, potentially suffering from space-charge blow-up.

An extended Low-Energy Beam-Transport (LEBT) system can address all these issues; it should include differential pumping, beam focusing, and in most cases a mass-separator component. Choice of a double-focusing separator magnet eliminates the need for additional focusing elements such as solenoids or quadrupole multiplets. Discussion of actual beam-transport elements is outside the scope of this paper, and the reader is referred to References [20] on generic transport issues and [21] on beam-line magnets. To obtain sufficient beam current and at the same time facilitate the beam transport, one can accelerate the primary beam to about 30-keV energy and decelerate it upon injection into the EBIS to a few keV; design of such a deceleration system is analogous to extraction-system design.

In a LEBT with magnetic transport elements, space-charge compensation can be provided in principle, reducing the focusing-strength requirements. This transport mode requires an accel/decel (triode) extraction system, as shown in Figure 1, to keep the compensating electrons from being accelerated back into the ion generator. One has to keep in mind, however, the finite build-up time during which the degree of compensation changes from zero to its maximum. For commonly attained beam-line pressures of a few 10^{-6} mbar, these times are comparable to the canonical 100-µs pulse time [22], leading to poor transmission values for these short beam pulses because the focusing strengths cannot be adjusted fast enough.

In cases where the transported beam current suffers too much from this effect one should consider choosing a completely space-charge loaded transport system, consisting of electrostatic einzel lenses, or quadrupoles, and an electrostatic mass separator. These systems require high-vacuum conditions close to UHV which are anyway convenient in view of attachment to the EBIS, and once these basic issues have been taken care of, electrostatic beam transport is no more difficult to achieve than with electromagnetic components. In principle, a magnet-based transport system would work as well under UHV conditions because the beam would be fully space-charge loaded during the pulse duration. The focusing power then required, however, is somewhat harder to achieve by standard magnetic systems.

OUTLOOK

In view of the fact that the requirements on a primary ion-source for a given EBIS may differ substantially from the set of parameters listed in Table 1, the majority of ion generators presented here are versatile enough to satisfy a wide range of actual conditions. Study of the original literature should enable the reader to make an appropriate choice, and in addition to the references quoted above, two comprehensive texts [23, 24] will be useful for this purpose.

There appears to be an historical trend among accelerator facilities to underestimate the effort needed to provide a fully functional, reliable ion source for the main accelerator. EBIS builders have learned by now not to compromise their source

performance by a false sense of economizing, and it is hoped that this paper will help in objectively judging the needs of an adequate ion-generator and beam-transport system.

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