Ion sources for electrostatic accelerators

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1 Introduction

Maybe the most important part of an electrostatic accelerator system, and also often the most tricky part is the ion source. There has been a rapid growth in activity in ion-source research and development during the last two to three decades. Some of these developments have also been of benefit to electrostatic accelerator users.

In this report some of the different types of ion sources used in electrostatic accelerators are described. The list is not complete but more an overview of some of the more commonly used sources. The description is divided into two groups; positive ion sources for single stage electrostatic accelerators and negative ion sources for two stages (*i.e.* tandem) accelerators.

2 Positive ion sources to be used at single stage electrostatic accelerators

Positive ion sources to be used in electrostatic accelerators are in many cases identical or similar to sources used at other types of accelerators. The limited beam current possible to transport through the tube of course means that only low current sources with rather limited emittance are used. The most used source during the years has been the rf-source but also the duoplasmatron has in many cases been used.

2.1 The radio frequent (rf) source

The breakdown of a gas by an rf field provides a simple and often convenient method of plasma formation that can be utilised in an ion source. The rf is usually in the range from around 1 MHz to a few tens of MHz. This kind of source can be extremely simple, consisting of a glass container for the gas/plasma, some kind of extraction aperture and a coupling loop surrounding the vessel to couple inductively into the plasma. A power of a few tens of watts and up to 150 W can be adequate, which together with a lifetime of several thousand hours makes it a suitable source to be placed in a high voltage terminal of a single stage electrostatic accelerator. This type of source can only be used for gaseous materials. Maximum current can be up to 1 mA. However, usually only up to 100 μA can be used in an electrostatic accelerator. This type of source is in use in the 3MV single stage accelerator in Lund.

2.2 Duoplasmatron

The most important pioneer work in the development of high current ion-sources was performed with duoplasmatrons. In this source, used for gaseous materials, a discharge is maintained at relatively high pressure (about 10^{-1} mbar) and low voltage (a few tens of volts) between a thermionic cathode and an intermediate electrode, acting as a primary anode. The plasma is then guided by a strong axial magnetic field through an aperture within the intermediate electrode into the second discharge chamber. In this chamber the discharge runs at much lower pressure (about 10^{-3} mbar) and higher voltage (about 100 volts), between the intermediate electrode, now acting as cathode, and the main anode. The plasma created in the second stage flows out through a small aperture in the anode and expands into a third chamber, the so-called expansion cup. Currents of up to 10 mA are possible. The disadvantage of having this source in the high voltage terminal of a single stage electrostatic accelerator is the need of higher power compared to the rf-source and the limited lifetime of the filament.

2.3 PIG ion source

The *PIG (Penning Ionisation Gauge)* source has been used as a source of multiple charged gaseous ions for over three decades. PIGs operate immersed in a magnetic field, which serves also to separate the charged ion species, with currents of multiple stripped ions up to mA. The PIG source derives its name from the vacuum gauge invented by Penning. This kind of source has been extensively used in injectors for particle accelerators like cyclotrons, synchrotrons and linacs, but is also used in single stage accelerators especially if they are designed for heavy ion production. This type of source is used in the neutron generator in Lund.

2.4 Nielsen source

This type of source can be used with solid (and gaseous) materials. It was developed around 1960 at the Niels Bohr Institute by Karl Ove Nielsen as a source for electromagnetic isotope separators, *i.e.* small accelerators up to a few hundred kilovolts. The source can produce ions from solid materials with not too high melting point. A Nielsen source built at our laboratory has been used together with a charge exchange cell, see 3.1 below.

2.5 Liquid metal

The liquid metal ion source consists of a liquid metal coating on a needle substrate. Application of a potential of several kilovolts in a vacuum of better than 10^{-7} mbar to a nearby extractor electrode distorts the liquid metal at the needle apex to form a conical shape. At the apex of the stabilised liquid cone the electric field is sufficiently high to produce ions at currents in the range of 1-100 μA. The liquid metal ion source is unique among all ion sources because of its extraordinary high brightness which can exceed 10^{+6} A/cm^{2}sr. It is this property, coupled with a reasonably small energy spread of less than 10 eV that makes this ion source attractive for use in applications for extreme small beam sizes with current densities of 1 to 10 A/cm^2. Example of applications is scanning microscopy. It should be possible to use it in a single stage accelerator for producing a beam to be used as a nuclear microprobe. The lifetime of the source, limited to some hundred hours, is of course a severe limiting factor.

2.6 ECR source

Electron Cyclotron Resonance (ECR) ion sources are today in widespread use for the production of high-quality multiple charged ions for accelerators, atomic physics experiments and industrial applications. An ECR source, originally a large, power-consuming complex apparatus, is today a compact, simple, efficient high-performance source for producing high charge state ions. ECR sources are maybe not so often discussed in connection with electrostatic accelerators. However, at the VICSI accelerator complex at the Hahn-Meitner institute in Berlin an ECR source has been installed in the high voltage terminal of a single stage accelerator (HVEC type CN). This accelerator is used as an injector for the sector focusing syncrocyclotron.

3 Negative ion sources to be used at tandem electrostatic accelerators

Sources of negative ions for electrostatic accelerators fall in two main groups. The first group consists of those which produce a primary beam of positive ions which by double charge exchange processes in an electron donor vapour target result in a fraction, generally a few percent being converted to negative ions (type 3.1 below). The second group consists of those producing negative ions direct from the ionised substance. For the latter type two possibilities are available. The ions can be produced by collisions between electrons and molecules in a discharge plasma (type 3.2 below) or the ions can be produced by particle collisions with low work function surfaces (type 3.3 below).

3.1 Sources using positive ions and an electron donor vapour target

A positive source followed by an electron donor vapour target, *i.e.* a charge exchange cell, for recharging the positive ions to negative is today mostly used for He^- production (as was mentioned above in fact the only possibility to produce negative helium ions!). This type of source was originally the only way to obtain negative ions. The charge exchange method has also shown to be particularly suited for production of beams of elemental negative ions with low electron affinity (*i.e.* ions from the "left" part of the periodic system). For such ions generally absolute beam currents, in excess of those achieved with the best of the existing negative ion sources are obtained.

The positive ion source

Generally a modest positive ion source is required. For example the rf source supplying about 1 mA of beam from most gases. The Penning source or the duoplasmatron can also be used.

The charge exchange cell

The positive beam, after passing through the charge exchange cell, becomes mainly neutral but contains some positive and negative ions. The negative ion formation is by collisional attachment. Under optimum conditions the negative component is for helium around 1%, but can for heavy ions be several tens of percent of the positive beam. The material in the cell can be a gas, like H_2, or a vapour of an alkali metal (Li, Na, K, Rb and Cs) [1]. Such a cell has been developed at the Pelletron.

3.2 Duoplasmatron

The duoplasmatron for producing negative ions is same type of source as used for positive ions, however, with a slightly different geometry. Around 1965 it was observed that a slight misalignment of the intermediate electrode compared to the anode can give a considerable negative beam component. The explanation is that the outer part of the plasma contains a higher amount of negative ions compared to the inner part. This type of source can be used to produce negative beam currents of up to 100 μA. This type of source is used at our Pelletron, mostly for producing H^-, and (today very seldom) D^-, but was in the initial stage the only source at our tandem and was therefore used for different ions like C^- and O^- (from CO_2 gas), CN^- (from CO_2 and N_2 gases), F^- and S^- (from SF_6 gas) etc.

3.3 Sputtering sources

The starting point of development of caesium sputtering negative ion sources was the discovery by Krohn [2] that when a surface is sputtered by Cs^+-ions a surprisingly large fraction of the sputtered particles are negative. Krohn further showed that this fraction can be significantly increased by overlaying the sputter surface with neutral caesium. The caesium sputtering source has been used to generate a wide variety of elemental and molecular ions. Positive caesium ions from a surface ionisation source are used to sputter a target. Negative ions formed are extracted out of an aperture. The positive caesium ions have an energy of 3-30 keV and a current of up to 1 mA. Negative ion current is up to 10 μA or for a few cases up to 100 μA. Different types of sputtering sources for producing negative ions from solid materials have been developed during the last 25 years. Negative ion species can be changed rapidly, requiring only replacement of the sputtering cathode through an interlock system.

The ANIS source. One type of sputtering source uses a Penning discharge geometry, has radial extraction and use caesium vapour. An ANIS sputtering source [3] has been in use at the Pelletron during 15 years. A Penning discharge generates a plasma of caesium (and sometimes also of an added gas). The function of the caesium is twofold. To act as a sputtering agent and to lower the work function of the target surface and in this way enhance the negative ion formation. The plasma forms a sheath in front of the spherical surface of the sputter cathode, which is at a negative potential of 3-4 kV. Positive ions are accelerated from the plasma across the sheath and impinge on the surface of the cathode. Negative ions formed on the cathode surface are accelerated back across the plasma boundary towards the exit aperture.

The cylindrical geometry source. A versatile high intensity negative ion source was presented by Middleton in 1983 [4]. For producing Cs^+-ions it has a cylindrical ioniser of tantalum. The source emittance for 70% of the beam is reported to be very low, 1.6π mmmrad$(MeV)^{1/2}$.

The spherical geometry source. One year after the introduction of the cylindrical source mentioned above Middleton reported about a new version in which the cylindrical ioniser was replaced by a spherical one and the caesium vapour was conveyed to it by a direct spray [5]. This arrangement eliminates the need for cesium vapour containment. Several sources of this model have been built around the world and it became also commercially available from General Ionex Corp. (their model no. 846). Middleton has presented an extensive handbook [6] with test results of this source for most ions in the periodic table. For many ions he obtained tens of μA and for some ion types several hundred μA.

The reflected beam source. The first simple model of a sputter source was demonstrated by Middleton in the beginning of the 1970's. It was later on modified with the caesium beam steered through an off axis molybdenum cone, reflected by the negative ion extraction electrode and sharply focused on a pill of target material located on the back of the molybdenum cone [7]. This design improves the emittance of the negative ion beam and eliminates two disadvantages with the original version, the complicated form of the target and ioniser damage from back streaming negative ions.

3.4 Sources of polarised ions

In the study of nuclear reactions, situations often arise where even very accurate cross-section measurements are not sufficient to determine the reaction amplitudes uniquely. One way to solve this is to produce and accelerate polarised ions. Some big tandem accelerators (5-10 MV) were during the 60s and beginning of the 70s supplied with polarised sources. As time went on the energy range of these accelerators become too low for modern nuclear physics experiments and very few installations still exist.

3.5 Ion source in the high voltage terminal of a tandem

In some cases it has been found necessary for some specific use to place an ion source in the high voltage terminal of a tandem. One example is an rf-source placed in a FN tandem for producing a high intensity

beam of ^3He [8]. It consists of the source, an isolator containing an extractor electrode and an einzel lens, a double focusing permanent dipole magnet, a steerer and a Faraday cup. During operation of the source the gradient of the first part of the high energy accelerator tube is reduced to limit the problem of the too strong lens effect for this low energy beam.

3.6 Negative ion sources for accelerator mass spectrometry (AMS)

The requirements for negative ion sources to be used for AMS partly differ from requirements for other types of uses [9]. The main reason is that a typical AMS sample contains only 10^5-10^8 atoms of the radioisotope to be measured. Therefore a high beam current is needed to obtain a sufficient statistical precision of the ratio between the rare isotope and the much more abundant species. Furthermore the current needs to be stable and in that way reduce systematic errors when the beam of the rare and the abundant species are compared sequentially. As the samples often are very small (1 mg or even less) a high efficiency is required: *i.e.* a high fraction of the atoms sputtered from the sample should be converted into negative ions with trajectories within an emittance that can be transferred through the accelerator. A multiple sample holder is needed to permit on-line sample changing without disrupting the operation of the source. As several samples are mounted together in the source it is important that the source has a low memory effect. Different types of sputtering sources have been modified for AMS use, mainly by including a multiple sample holder, by optimising the beam current and reducing the memory effect. To reduce the number of steps in the carbon sample preparation procedure some sources for gaseous samples have been constructed. National Electrostatic Corp. has designed and built a multiple gas feed cathode negative ion source [10].

3.7 Radioactive ion beams

For new types of investigations in nuclear physics and astrophysics it was suggested about ten years ago to construct systems to accelerate radioactive ion beams. An example of a system that has recently been developed is the tandem-cyclotron system in Oak Ridge. In this system intense light ion beams from the isochronous cyclotron (ORIC) is used to produce radioactive atoms in a thick target ion source mounted on a high-voltage platform serving as an injector for the 25 MV tandem Pelletron [11]. (This tandem was originally designed as an injector for the cyclotron!) Since the tandem requires negative ions the positive radioactive ion beam is converted in a charge exchange cell. As the positive source for radioactive ions the high temperature version of the CERN ISOLDE source has been chosen because of its low emittance, relative high ionisation efficiency and the capability for producing a broad range of radioactive species.

3.8 Microbeam negative ion sources (combination of AMS and SIMS)

AMS with tandem accelerators was originally developed for measurements of rare isotopes, particularly cosmogenic isotopes. The method has been further developed as an extension of secondary ion mass spectrometry (SIMS) for detection of ultra traces where extreme sensitivity is necessary. The method is further enhanced when micro-beams are used for scanning the ion source sample. Such systems have been demonstrated for application in semi-conductor [12], geological materials analysis [13], mineral exploration [14] and for biomedical applications [15]. Below two such systems are briefly described.

Mineral exploration. A system has been designed at North Ryde, Sydney to enable *in situ* microanalysis of geological samples for ultra-traces and for isotronic data for minerals exploration research. The negative ions are produced by sputtering with a micro-beam of Cs^+. A standard Cs-gun combined with auxiliary cylindrical lenses produces the primary micro-beam. The Cs-beam bombards the sample and the negative ions are analysed in an AMS accelerator system.

Biomedical investigations. A new method for imaging ^{14}C-labelled tracers in sections of biological tissue was presented a few years ago. A highly focused beam of gallium ions bombards the tissue. This is sputtered into constituent atoms, molecules and secondary ions. The ^{14}C-ions are detected after transport through the AMS system. The specimen is scanned pixel by pixel ($1\times2\ \mu m^2$), generating an image in a manner analogous to scanning electron microscopy [15].

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