PHYSICS AND DESIGN OF WIDE-APERTURE BIPOLAR PARTICLE SOURCES

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A review of known designs of bipolar particle sources is presented classifying them by spatial or temporal separation of the oppositely charged particles. Both ion-electron and ion-ion sources are considered. Possibilities of creating bipolar ion-ion source are discussed basing on recent research results from Ecole Polytechnique (France) and from V.N. Karazin Kharkov National University (Ukraine), particularly on comparative study of the sources with magnetic and electrostatic electron filters.

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INTRODUCTION

Wide aperture positive ion sources are in common use for years in different technologies and for electric propulsion in space [1]. In all these applications the neutralization of positive ion beam space charge or current is important task, which is usually solved with use of a neutralizer emitting electrons. The neutralizer is a dedicated device requiring additional power supply and often degrading the overall system reliability due to limited lifetime. Thus the idea of bipolar particle source that is able to emit simultaneously the directed flows of particles of both polarities looks attractive in number of applications.

A few devices are known allowing simultaneous extraction of oppositely charged particles, ions and electrons [2-4] or positive and negative ions [5, 6]. Such devices, namely "bipolar" sources, stand out against different types of ion sources since their unusual design and physical processes allows simultaneous acceleration of oppositely charged particles. Among the methods of bipolar extraction the simultaneous ion-electron extraction is relatively well investigated, and several sources of bipolar ion-electron flow based on different physical principles have been developed and characterized [2-4, 7]. However, the problem of simultaneous extraction of positive and negative ions, or ion-ion extraction, is not extensively studied and currently only pulsed and alternate ion-ion extraction are realized [5, 6]. Thus, investigation of the problem of simultaneous extraction of positive and negative ions is of great interest.

For the first glance, the simultaneous extraction problem can be solved easily since any plasma contains particles of both polarities. However, simultaneous extraction and acceleration of oppositely charged particles is hampered by the obvious fact that in a stationary electric field the oppositely charged particles are accelerated in the opposite directions. The possible solution of the simultaneous extraction problem is spatial or temporal separation of acceleration paths of positive and negative particles.

A conceptual diagram of possible solutions of the bipolar extraction problem is shown in Fig. 1. One can see six possible configurations of bipolar extraction. One of them, namely, parallel ion-electron extraction represents in fact the classical system "positive ion source + neutralizer", while other cases are considered in the present review by examples of existing sources.

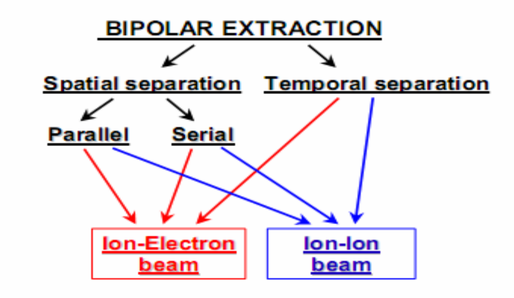

Fig. 1. Conceptual diagram of bipolar extraction

1. ION-ELECTRON SOURCES

One of known ion-electron sources is a combined electron and ion beam system employing a double-chamber inductively coupled plasma (ICP) developed in Lawrence Berkeley National Laboratory, USA for a combined electron and ion beam lithography system [2,8]. The source consists of two independent plasmas with different potentials connected in-series (see Fig. 2). Electrons born in the first plasma and accelerated by an electrode system penetrate trough the second plasma where positive ions are created. At the source output the ions are accelerated while electron beam from the first plasma is decelerated, though keeping significant energy. According to the classification presented in Introduction this source may be treated as a serial source with spatial separation.

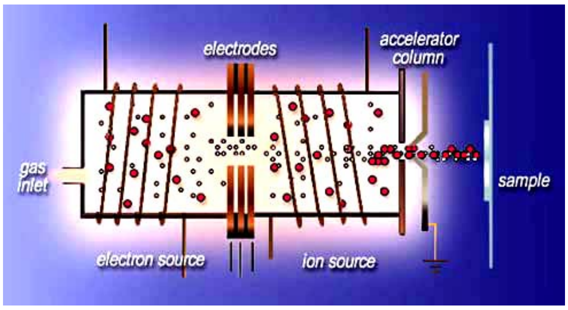

Fig. 2. Scheme of double-chamber ion-electron source [9]

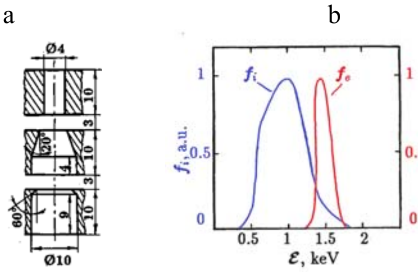

Fig. 3. Multichannel ion-electron source with Penning discharge [3]: a – scheme of single channel; b – electron and ion energy distribution functions

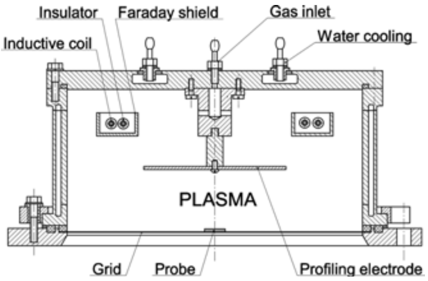

Fig. 5. Internal structure of 250 mm industrial grade ICP-based single-grid ion-electron source [13]

One more example of serial ion-electron source is multichannel source with Penning discharge developed in V.N. Karazin Kharkov National University, Ukraine [3]. Single sell of the source is schematically shown in Fig. 3,a. The device consists of cathode-extractor (lower electrode in Fig. 3,a), anode (middle), and hollow cathode (upper). Gas is fed through the hollow cathode biased negatively with respect to the cathode-extractor. Both cathodes serve also as poles of magnetic system creating magnetic field with strength of 1…1.5 kOe. The source generates coinciding ion and electron beams with energies 0.2…2 keV and current density up to 5 mA/cm^2, with different level of current compensation. Typical electron and ion energy distribution functions (EDF) are shown in Fig. 3,b.

Another kind of ion-electron source, the source with temporal separation, is represented by ICP-based single-grid ion source with RF biasing of the plasma interfacing electrode [10], which is schematically shown in Fig. 4. Due to continuous ion acceleration by stationary part of plasma bias (appears because of self-biasing effect) and pulsed electron extraction in most negative part of RF period of the plasma biasing the source possess the unique ability of quasisimultaneous generation of coinciding flows of positive ions and electrons in contrast to more common two- or three-grid sources [4]. Using the ICP for ionization ensures its durability to reactive gases, and due to the single-grid ion-optical system it is free from disadvantages of multigrid systems. In the paper [11] it was shown that the ion source RF biasing mode of operation is superior since the full ion beam current neutralization is provided for the entire range of ion energy of interest and the extracted ion current is higher than in the DC biasing mode. It should be also mentioned that the RF bias applied to the potential electrode affects not only the ion acceleration but also the plasma as a whole. In fact there is the combined inductive-capacitive discharge studied in the papers [11, 12].

Since the modern industry requires ion sources with hig processing area, in the V.N. Karazin Kharkov National University the number of RF ion sources with beam diameters of 20…250 mm have been developed. In particular, the 250 mm industrial grade ICP-based single-grid ion-electron source is described in [13]. Internal structure of the mentioned source is shown in Fig. 5. The source is able of providing 0.5…5 mA/cm^2 current density in the low ion energy range of 50…250 eV, with possibility of independent current density and energy control. Fig. 6 demonstrates energy distribution function of ion and electron flows emitted by the source as well as etching test result performed using the ion-electron flow. One can see from Fig. 6,a that when the RF bias is applied to the potential electrode, the energy distribution function contains the electron peak and two ion peaks, namely, the high-energy ion beam peak and the peak of slow ions from the ion-beam plasma.

Fig. 6,b shows SEM image of SiO$_2$ film etched by

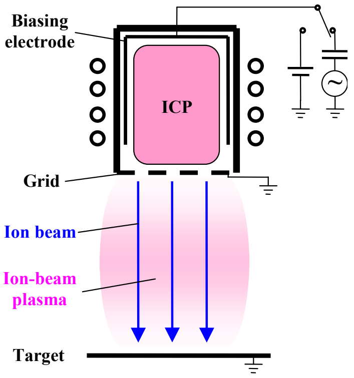

Fig. 4. Schematic diagram of single-grid ion source with RF biasing of the plasma interfacing electrode [10]

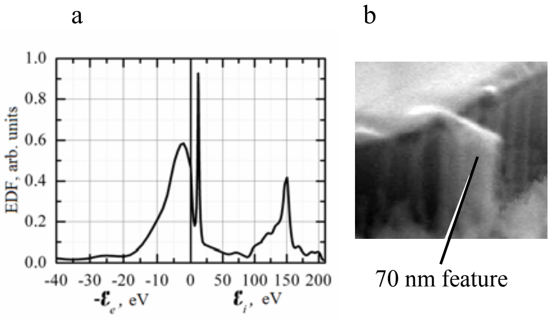

Fig. 6. Energy distribution function of ion and electron flows emitted by the bipolar source [13] (a) as well as etching test result performed using the ion-electron flow (b). The vertical feature is 70 nm thick and 800 nm in height

the bipolar source. Perfect vertical etch profile indicates absence of dielectric surface charging problem. In contrast to reactive ion etching in plasma reactors, utilizing the developed bipolar source provides the possibility of etching under an arbitrary ion incidence angle to the surface.

2. ION-ION SOURCES

In the previous section we have shown that the ion-electron sources are a relatively mature technology with proven efficiency. In contrast, ion-ion sources at the moment are just "breaking new ground".

Recently, it was proposed to use both positive and negative ions for thrust in an electromagnetic space propulsion system [14]. This concept is called PEGASES meaning Plasma Propulsion with Electronegative GASES and has been patented by the Ecole Polytechnique in France in 2007 [15]. The basic idea is to create a stratified plasma with an electron free (ion-ion plasma) region at the periphery of a highly ionized plasma core such that both positive and negative ions can be extracted and accelerated to provide thrust. As the extracted beam is globally neutral there is no need for a downstream neutralizer. The first PEGASES prototype, designed in 2007 in Laboratoire de Physique des Plasmas, Ecole Polytechnique, France, is shown in Fig. 7. The first prototype has two extractors with the extraction surface perpendicular to the cylinder axis and the magnetic field. The two extractors were originally intended for separate extraction of positive and negative ions. One issue with this method is that the accelerated ions have to be brought back to the same potential before being able to recombine. Since the ions originate from the same source the effective acceleration potential will become zero and no net thrust can possibly be achieved [16]. So, we can conclude that in order to realize the parallel type of bipolar extraction (see Introduction) presence in the source of two independent plasmas with different potential is essential.

Taking into account the disadvantages of the first PEGASES prototype, a new prototype is being designed (Fig. 8) with an inductively coupled antenna at 4 MHz and only one extractor surface, allowing alternate extraction and acceleration of positively and negatively charged ions [17, 18].

Fig. 8 illustrates internal structure of PEGASES Prototype II, while the bipolar ion acceleration scheme is shown in Fig. 9,a. This prototype was successfully tested, particularly, the ability of bipolar beam generation has been confirmed. Fig. 9,b shows the bipolar ion energy distribution function.

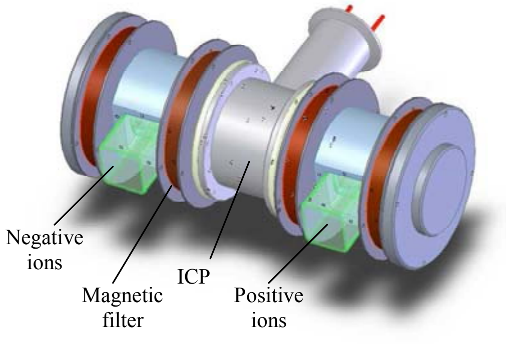

Fig. 7. PEGASES Prototype I

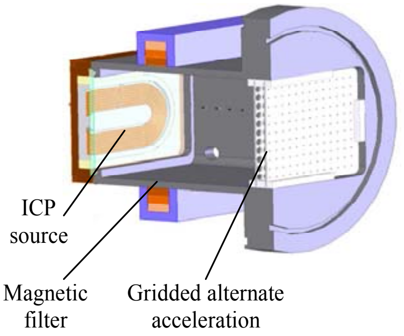

Fig. 8. Internal structure of PEGASES Prototype II

Another approach based on the serial concept is treated in V.N. Karazin Kharkov National University, Ukraine. A double-plasma source capable of the generation of a continuous bipolar ion-ion beam has been developed and tested [19]. According to this concept, in order to generate continuously accelerated coinciding bipolar ion-ion flow with volume production of ions of both polarities the source should contain two plasma regions having different potentials. Taking into account that the usual design of negative ion source with volume ion production includes two plasmas separated by an electron filter [9], such a source may be used as a starting point for the bipolar ion-ion source design. However, in the negative ion source the primary plasma serves only as an electron source for the secondary plasma where the negative ions are created. For generation of the accelerated bipolar ion-ion beam in such a system the primary plasma stage should be a bipolar ion-electron source simultaneously generating accelerated positive ions and cold electrons. Among the mentioned above ion-electron sources the single-grid source [4, 7] is an appropriate choice since low-energy electron emission [21]. As it was shown in the papers [20, 22] the extraction grid of such source can serve not only as ion-optical system but also as the new promising type of nonmagnetic electron filter, namely a grid-type electrostatic filter [20] allowing efficient negative ion generation in the secondary plasma. Initial comparison of the electrostatic and more common magnetic types of the

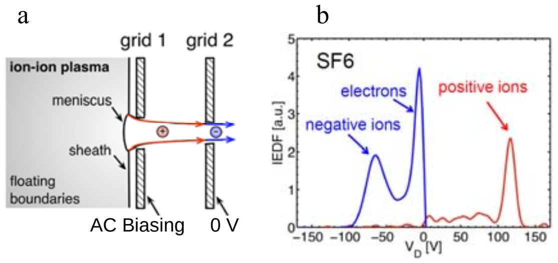

Fig. 9. PEGASES Prototype II: (a) - bipolar ion acceleration scheme; (b) - bipolar ion energy distribution function

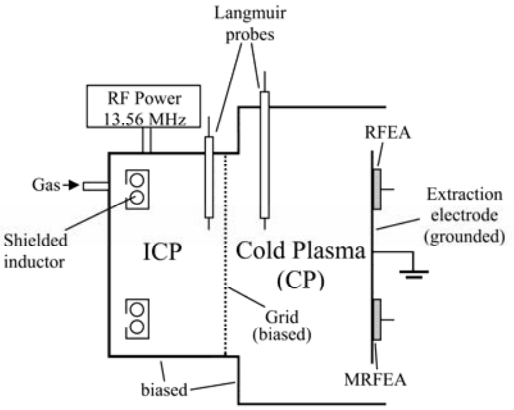

Fig. 10. Design of the double-plasma bipolar ion-ion source [19]

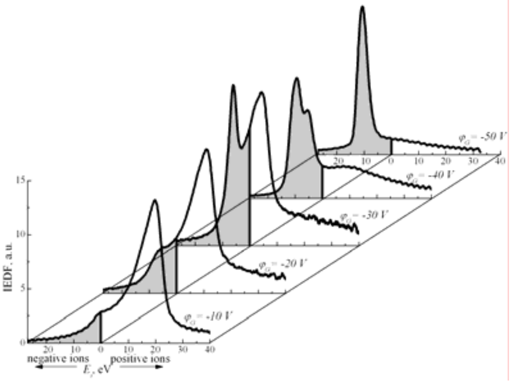

Fig. 12. Positive and negative ion energy distribution functions (IEDF) at different grid potential φ_G. The negative ion distributions are shown to the left of zero energy and positive IEDFs to the right

electron filter is presented in [23], though the question still requires more detailed study. In the paper [20] the broad beam negative ion source based on inductively coupled plasma (ICP) discharge with the grid-type electrostatic filter has been described. It was shown that SF_6 ions are efficiently created beyond the filter and can be easily extracted from the secondary "cold" plasma (CP) since it can be biased negatively with respect to the high-area extraction electrode. The proposed design of the bipolar ion-ion source is schematically shown in the Fig. 10. The system is divided by the grid filter into the two regions: primary inductively coupled plasma and downstream cold plasma.

Ion paths through the system as well as qualitative axial potential distribution along the double-plasma source are shown in the Fig. 11,a. Majority of positive ions are created in the ICP while the negative ions are created mostly in the CP region. The necessary condition for positive ion extraction in the system is the positive ICP potential versus the extraction electrode, while extraction of negative ions created in the CP is possible only with negative plasma potential. These conditions are not in direct contradiction since the system contains two plasmas with different potentials. The compromise solution allowing bipolar ion-ion extraction can be found in the range of relatively low grid biasing, as it is shown in the Fig. 11,b. We can see that the ICP potential in this case is higher than both the CP potential and the extraction electrode potential, hence the positive ions created in the ICP can penetrate through the filter grid holes to the CP region and reach the extraction electrode (here we assume low collisionality of the ions). Negative ions created in the CP can freely move to the more positive extraction electrode.

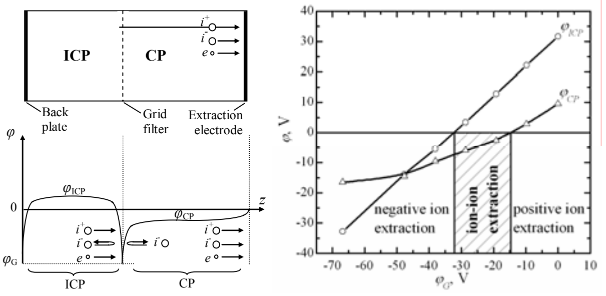

Fig. 11. Qualitative axial potential distribution along the double-plasma source and ion paths through the system (a). CP and ICP potential dependences on the negative grid bias φ_G (b)

Fig. 12 shows the bipolar ion EDFs measured at different filter grid biasing within and near the range of ion-ion extraction. It is seen that almost mono-energetic peaks of both positive and negative ions are present in the distributions, with different amplitudes affected by the grid bias. The increase of negative grid potential leads to suppression of the positive ion peak and growth of the negative ion peak. At the grid potential about -30 V the positive and negative ion peaks are similar and nearly symmetrical versus zero energy, so quasi-neutral ion-ion beam is formed. Total current of each ion species generated by the source to the 250 mm diameter extraction electrode is about 80 mA; the electron current doesn't exceed 30 % of the ion current.

It's worthy to discuss the problem of ion energy control in the bipolar ion-ion beam. In the reported experiments the energies were very low (5…10 eV) due to the limit of the single-grid ion-electron source with DC grid biasing to emit only low energy ions simultaneously with electrons [24]. However, the source with RF grid biasing can generate bipolar ion-electron flow with arbitrary ion energy [4, 7]. Therefore, using the RF grid biasing along with CP potential control would allow independent positive and negative ion energy control in a wide range.

In summary, it can be concluded that despite bipolar particle sources are known for decades their potential is not realized yet. From the presented results, it is believed that the bipolar sources have great prospective in modern technologies and Space applications. In particular, one can expect that due to the high directionality of both positive and negative particle flux the bipolar particle sources can compete with neutral beam sources in such technologies as atomic layer etching [25] and aspect ratio dependent etching removal [26].

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ФИЗИКА И УСТРОЙСТВО ШИРОКОАПЕРТУРНЫХ БИПОЛЯРНЫХ ИСТОЧНИКОВ ЧАСТИЦ

С.В. Дудин

Обзор известных конструкций биполярных источников заряженных частиц проведен с классификацией их по пространственной или временной сепарации противоположно заряженных частиц. Рассмотрены как ион-электронные, так и ион-ионные источники. Возможности создания биполярных ион-ионных источников обсуждаются на основе результатов последних исследований в Ecole Polytechnique (Франция) и в Харьковском национальном университете имени В.Н. Каразина (Украина), в частности, сравнительного изучения магнитных и электростатических электронных фильтров.

ФІЗИКА І БУДОВА ШИРОКОАПЕРТУРНИХ БІПОЛЯРНИХ ДЖЕРЕЛ ЗАРЯДЖЕНИХ ЧАСТИНОК

С.В. Дудін

Огляд відомих конструкцій біполярних джерел заряджених частинок проведено з класифікацією їх по просторовій або часовій сепарації протилежно заряджених частинок. Розглянуто як іон-електронні, так і іон-іонні джерела. Можливості створення біполярних іон-іонних джерел обговорюються на основі результатів останніх досліджень в Ecole Polytechnique (Франція) та в Харківському національному університеті імені В.Н. Каразіна (Україна), зокрема, порівняльного вивчення магнітних і електростатичних електронних фільтрів.