TOWARD A REALISTIC AND TRACTABLE MODEL FOR NEGATIVE ION EXTRACTION FROM VOLUME SOURCES

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Abstract

The physics of negative ion formation is fundamentally different than that for positive ion formation. For example, with negatively biased plasma electrodes, relative to the plasma, it can be shown that the Bohm sheath stability criteria is not generally satisfied and that, in addition, the potential structure near the extraction region is a saddle point. Traditional modeling of volume negative ion sources treats them in a manner similar to positive ions with a monatomic downhill run of the negative ions from source plasma to extraction and acceleration. This method (for positive ions) consists of finding self consistent solutions to a multidimensional Poisson Equation, with the plasma electrons represented as a Boltzmann Distribution, and ions as a Vlasov Equation simulated by a suitably large number of trajectories with space charge embeddings. Ideally for negative ions, one would like to model the positive and negative ions and the electrons everywhere in a Vlasov description. However, so far this is an untractable formulation since a stable convergence scheme has yet to be developed of this extremely nonlinear problem. The tractability of an alternate formulation that will be explored consists of: (1) a Vlasov treatment for the positive ions in the conventional manner, (2) a Boltzmann treatment for the electrons on the plasma side on the extraction sheath, (3) a Vlasov formulation of negative ions formed in the plasma volume, and (4) a Vlasov treatment of electrons. A self-consistent treatment of the above scheme will produce the entire potential structure in the presheath and extraction region. The Boltzmann electron component is expected to be a key ingredient in establishing a convergent scheme while at the same time modeling much of the salient and nontrivial features of the negative ion extraction from volume sources with a negatively biased plasma electrode.

1 POSITIVE IONS

Extraction modeling for positive ion sources has been shown to be a very effective tool for predicting and optimizing the performance of position ion sources [1]. This success has obtained even though the models used are very nonlinear and several dimensional [2]. One of the reasons for this success is that the physical formulation is apparently rather accurate; it consists of a self-consistent solution of a Poisson Equation with source terms for the plasma ions obtained directly through a solution of the kinetic ion-Vlasov Equation and the plasma electrons represented by a Boltzmann equilibrium distribution. Boundary conditions consist typically of a quasineutral plasma with a negatively biased plasma electrode (to electrostatically contain the plasma electrons). This plasma electrode has a hole in it that reveals applied ion extraction and acceleration fields, as shown in Fig. 1.

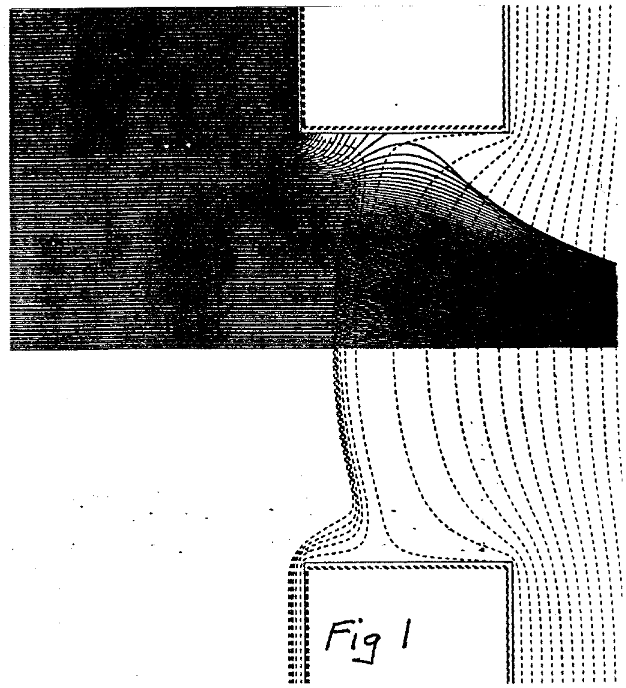


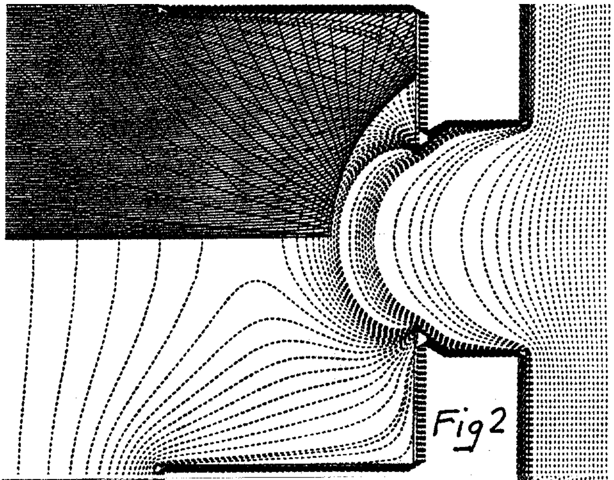
Fig 1

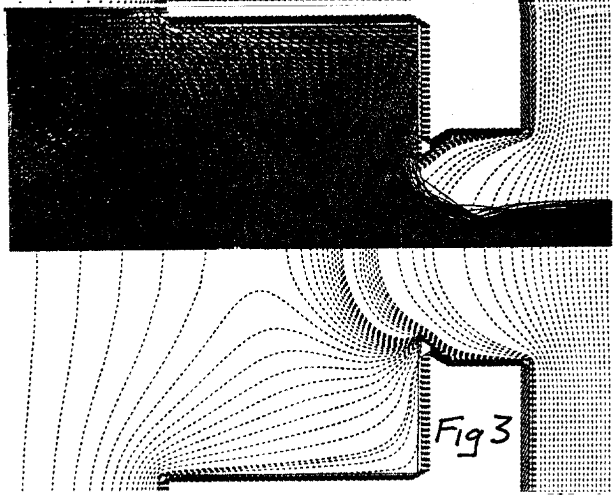
With this formulation and suitable boundary conditions, a self-consistent Debye-length scale sheath results for the transition between the neutralized plasma and the non-neutralized ion beam. The geometric configuration of this sheath has a large effect on the ion optics and RMS beam emittance (see Fig. 1). That there is apparent agreement between experiment and modeling results [1] suggests that this nonlinear sheath is correctly arrived at.

2 NEGATIVE IONS

For negative ion extraction, the usual ploy is to assume perfect symmetry using the same model with the fields reversed [3]. There were some hints that this perfectly symmetric model was not capable of predicting negative ion extraction optics or optimum presence correctly. A single heuristic alteration to the basic positive ion model showed some prospects of correlating with experimental data [4].

However, the actual asymmetries which exist between positive ion extraction and negative ion extraction suggest that a more serious treatment is called for to obtain a reliable tool for predicting and optimizing the beam formation process. The first, and most obvious asymmetry, is that the charge compensation in the negative ion source plasma is obtained by the space charge of the positive ions instead of the equilibrium electrons, as is the case for positive ion sources. However, these positive ions are far from equilibrium — in fact, a collisionless one shot pass at the extraction sheath and subsequent reflection appears to be a more accurate picture.





A second, and most considered asymmetry [3], is the extraction of electrons along with the negative ions. In the presence of magnetic fields, these electrons can have a significantly different beam distribution than the ions which must be accounted for to predict power loading on electrode surfaces. Of perhaps equal importance is the fact that the electrons affect the sheath geometry and, thus affect the ion motion. In the presence of magnetic fields, the electrons, due to their $E \times B$ drifts, produce an oblique sheath that cause nonlinear space charge effects to occur throughout the extracted beam, even if the ions were generated uniformly [3].

A third asymmetry, that may be no less important but which appears to be totally ignored up to this point, is that the plasma electrode is not biased in a symmetric way with respect to the plasma potential. For positive ion sources, the plasma electrode is biased negative relative to the plasma potential in order to electrostatically contain the highly mobile plasma electrons. The symmetric situation would be that the plasma electrode is biased positive relative to the plasma for negative ion sources. However, the reason for biasing the plasma electrode negative is unchanged for negative ion sources since confinement of the plasma electrons is still a priority. The consequence of this in the pre-extraction region is significant: a monatomic downhill run of positive ions from the center of the source plasma to the accelerated beam occurs for both positive and negative ion sources. There is therefore a saddle point in the pre-extraction region for volume negative ion sources with negative ions that might be created near the center of the plasma being repelled by the plasma electrode. Only those negative ions created near the extraction region, on the down stream side of the electrostatic potential ridge passing through the saddle point are attracted to the extraction region.

3 A MULTIPLE VLASOV NEGATIVE ION MODEL

For application requiring minimum negative ion emittance or halo, such as those in colliding beam high energy physics or spallation neutron sources, attention to detail in the extraction of negative ions could be important. Therefore, a more comprehensive multi-Vlasov model is proposed. In addition to considering just positive ions kinetically and Boltzmann electrons (or for the symmetric model — negative ions kinetically and Boltzmann positive ions), we will also consider volume produced negative ions in a kinetic (Vlasov) description.

Results of this model for low densities are shown in Figs. 2-3. As example, Fig. 2 illustrates the positive ion trajectories from the center of the source plasma being reflected by the extraction sheath. It also illustrates the saddle point in the potential. Figure 3 illustrates the volume produced negative ions, some of which are extracted and the rest of which go back into the ion source plasma. At higher plasma densities, we see the compression of the saddle point region toward the extraction sheath as shown in Figs. 4 and 5.

Three features of this physical circumstance tends to produce ion time scale instabilities in the extraction presheath. First, the Bohm sheath criteria is not generally satisfied, as evidenced by the presence of ion acoustic frequency arc noise [5]. Second, the presence of additional negative space charge, due to the presence of volume produced negative ions, could add to the extent the Bohm sheath criteria is violated. Third, reflected positive ions from the sheath could produce a two stream instability with the outgoing stream of positive ions. Figure 4 shows a hint of these two stream instabilities, although a resolution of these and other ion acoustic instabilities has only been done for positive ion extraction [5]. The present study only involves steady state considerations. Figure 5 shows the trajectories of volume produced negative ions.

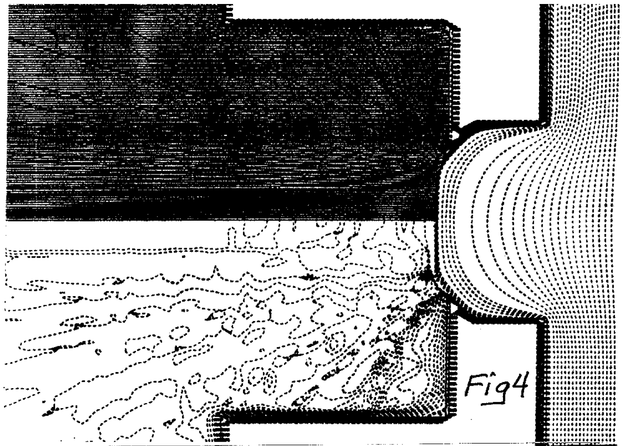


Fig4

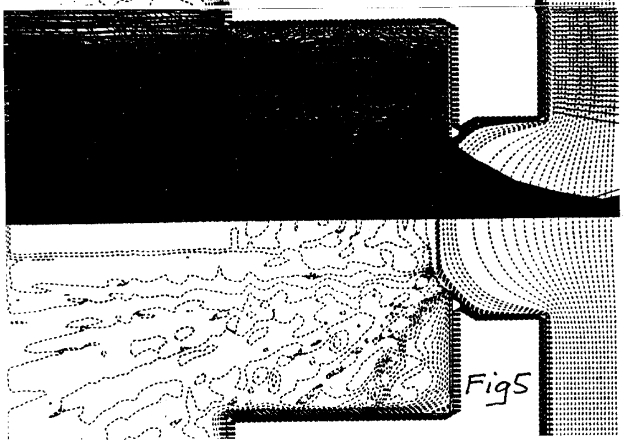


Fig5

The opportunities afforded by exploitation of this model appear to be significant since not only can beam emittance be minimized, but the extractable current itself.

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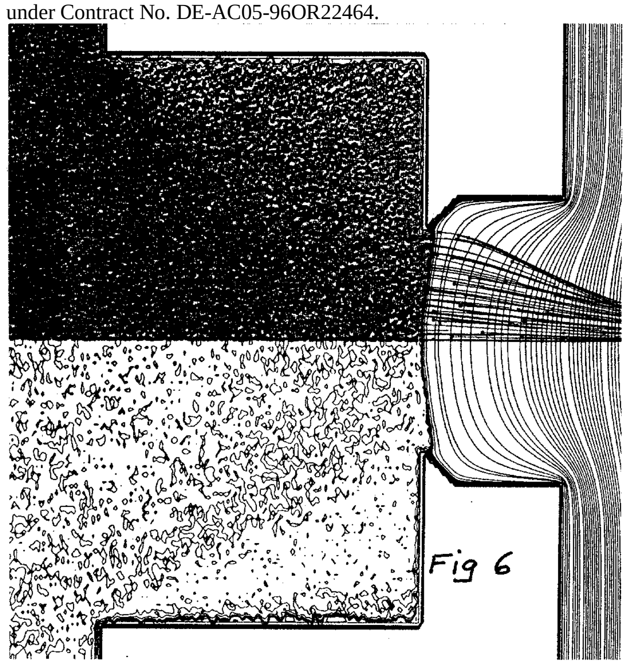

Fig 6