THEORY OF ION EXTRACTION FROM PLASMA BY AN EXTERNAL ELECTRIC FIELD IN SYSTEMS OF LASER ISOTOPE SEPARATION

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Abstract

A refined model of processes taking place in electrostatic extractors is proposed. The model is based on the analysis of the present-day state of theoretical studies in this field and takes into account both the Langmuir and Bohm mechanisms of ion transport, calculations of initial profile of ionic current to the cathode, and the integrated contribution of ionic current to the anode. The Bohm mechanism is shown to make the dominant contribution to ion extraction for typical values of initial ionic density \( n_i \geq 10^{10} \) cm\(^{-3} \). Under these conditions, this mechanism not only causes a considerable (by more than an order of magnitude) decrease in plasma relaxation time \( \tau_R \) in comparison with the values determined by the usual Langmuir mechanism, but also substantially modifies the main structural dependences of the relaxation time, which are found to be now in good agreement with the experimental power dependences. The new results obtained in the work favor the view that electrostatic (nonmagnetic) ion extraction systems provide a rather high efficiency at an increased \( (n_i \sim 10^{11} \) cm\(^{-3} \) plasma density and, correspondingly, at a high power density.

1. Introduction

In the past 20 years, extensive studies aimed at the development of atomic vapor laser isotope separation (AVLIS), which promises high efficiency, have been undertaken [1].

The method is based on the concept of two- or three-stage selective photoionization with pulsed laser radiation \( (\tau_I \sim 20\) ns \) of atoms of the isotopes being separated out. This duration is typical for copper-vapor lasers extensively used in systems of laser isotope separation. Photoionization is carried out under conditions of a free molecular flow of vapors of the corresponding chemical element. The desired ions are extracted from a plasma by an external electric field formed in the spacing between two plane electrodes. In this case, the ionization of foreign isotopes under the action of laser radiation during the course of the pulse and in subsequent plasma relaxation processes must be absent.

As for the latter processes, selective charge exchange of ions of the desired isotopes at atoms of the high-abundance isotope and the ionization of these atoms by electron impact present the most problems. It should be noted that for the high-abundance isotope, the concentration of atoms in a flow is generally higher (by an order of magnitude or more) than for the desired isotope. These foreign ions are also extracted, which deteriorates the separation coefficient.

Of considerable importance is also the scattering of neutral atoms in the process of interatomic collisions. These scattered atoms may be deposited on ion collector plates. The intensity of this process is proportional to the concentration of atoms squared. The corresponding flux density must necessarily be lower than the ion flux density for the desired isotope.
The above requirements set the upper limit for the density of atoms in the flow and the ion concentration in the plasma. For typical values of electrode spacing in the range \( d = 2 - 5 \) cm, these parameters must satisfy the conditions

\[
\begin{align*}
n_a & \leq 10^{12} - 10^{13} \text{ cm}^{-3} ; \\
n_i & \leq 10^{10} - 10^{11} \text{ cm}^{-3} .
\end{align*}
\]

(1)

It should be noted that the electron temperature of the plasma \( T_e \) must not certainly exceed the ionization threshold for atoms of the working gas, which lies, as a rule, in the range 5–10 eV.

Plasma with such parameters is commonly referred to as a strongly rarefied (collisionless) low-temperature plasma. However, the main property of a plasma, its quasi-neutrality \( (n_e \approx n_i) \), is fulfilled under these conditions with a high accuracy. Moreover, this plasma density is too high for extraction processes, i.e., for plasma resolution in spacing between two electrodes. As a result, space charge effects cause a considerable increase (by up to two orders of magnitude) in the ion extraction time \( \tau_R \) in comparison with the usual transit time.

Thus, the natural problem of increasing the system yields (with overall dimensions held constant) by way of increasing concentrations \( n_a \) and \( n_i \) is in obvious conflict with the potentialities of systems used for ion extraction in an electric field. That is why the improvement of the efficiency of ion extraction systems is a problem of primary importance.

The aim of this work is to study theoretically the physical processes involved in ion extraction by an electric field under strong limiting conditions imposed by the space charge. The theoretical results are compared with currently available experimental data, and the ways of increasing efficiency of extraction systems are analyzed.

2. Previous Research and Formulation of the Problem

Physical processes taking place in electrostatic plasma extractors have been much studied, both theoretically and experimentally [2–9]. In theoretical publications based on relatively simple calculations, which began with the pioneering work by Chen [2] (see also [3]), primary attention has been given to a separate analysis of the effect of various mechanisms on the time of plasma extraction, but a detailed study of the joint action of these mechanisms is absent. In paper [4], which presents the results of a more complicated numerical model with a nonstationary (hydrodynamic) description of ion motion, all these mechanisms are coupled, but it gives only one variant of calculations for one of the extractor operating regimes. As a result, presently available theoretical studies do not give a clear idea of the effect produced by one or another mechanism on extraction characteristics and do not give any clue to increasing the efficiency of such systems.

On the other hand, the empirical power law found in [5–8] by processing experimental results obtained there and plotted on the logarithmic scale gives the dependence of the plasma extraction time \( \tau_R \) on the main extractor parameters, namely, the voltage \( U_0 \), the spacing between the plates \( d \), and the plasma concentration \( n_i \). The law is valid in a rather wide range of parameters and has the form

\[
\frac{\tau_R}{\tau_0} = \left( \frac{U_0}{10^3} \right)^{\alpha} \left( \frac{d}{5} \right)^{\beta} \left( \frac{n_i}{10^9} \right)^{\gamma} ,
\]

(2)

where \( \tau_0 \) is the time \( \tau_R \) for the main (reference) variant with \( U_0 = 10^3 \) V, \( d = 5 \) cm, and \( n_i = 10^9 \) cm\(^{-3} \).

For the simplest variant of extractor design (cathode–anode system), the exponents in expression (2) are equal to –0.81, 1.4, and 0.56, respectively, [6].

Nearly the same dependences were obtained for improved systems with two-side ion extraction: a system with a periodic change in potential polarity [7], and a system in which both plates have the cathode potential,