ISOTYPE SEPARATION

Axisymmetric Plasma-Optic Mass Separators
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Abstract—A systematic description is given of the principles of operation of axisymmetric plasma-optic mass separators with azimuthators that are compatible with stationary plasma thrusters with closed electron drift. Two schemes of plasma-optic separators (with electrostatic and with magnetic ion focusing) are considered. Results are presented from calculations of the parameters of model devices for separating ions whose masses are on the order of those of xenon ions. © 2005 Pleiades Publishing, Inc.

1. INTRODUCTION

Industrial-scale mass separators are now used for different purposes, e.g., for obtaining superpure materials for medicine and scientific investigations, for creating isotopically pure engineering materials for atomic industry, for processing nuclear wastes, and so on. There are many mass separation schemes: centrifugal, diffusive, laser-based, ion resonant, etc. Among these schemes, the electromagnetic isotope separation method [1] is notable for its conceptual simplicity, its single-stage design, and its “panoramic” mode of operation—the ability to simultaneously separate many isotopes with different masses. This method is illustrated graphically in Fig. 1. The mass separator system consists of three blocks. The natural substance (an isotopic mixture) is fed into an ion source, where it is ionized to produce ions and electrons, which are accelerated and formed into a high-quality quasineutral electron–ion beam. This beam moves into a separator, where it becomes subject to a uniform magnetic field oriented perpendicular to its path. In the strong magnetic field of the separator, the beam ions revolve along their Larmor semicircles, while the beam electrons, which neutralize the ion space charge, are essentially immobile. The gyroradius of a singly charged ion depends on its mass,

\[
\rho_i = \frac{V_i}{\omega_{hi}} = \frac{M e}{e H_0} \frac{2 e U_a}{M} \propto \frac{M}{\sqrt{e}},
\]

where \( U_a \) is the accelerating voltage, \( H_0 \) is the magnetic field in the separator, and \( M \) and \( e \) are the mass and charge of an ion. Finally, the ions are deposited on collectors.

Figure 1 and formula (1) demonstrate that it is, in principle, possible to create a single-stage separator capable of operating in a “panoramic” mode (i.e., over a broad range of ion masses). However, the electromagnetic separator fabricated in the 1940s has a fundamental drawback: a very low productivity. The characteristic ion currents are \( J_i \leq 0.01–0.1 \) A. The charge per gram atom is equal to \( 10^5 \) C; consequently, even with a current of \( J_i = 0.1 \) A, the processing of this amount of matter will require about 15 days. It is clear that the productivity should be increased by at least three to four orders of magnitude.

The low productivity of the classical electromagnetic separators stems from the fact that there are only ions in the acceleration gap of the ion source. The electric field of these ions restricts the current density by the so-called 3/2 law:

\[
j = \frac{g}{9 \pi N} \frac{2 e U_a^{3/2}}{M^{1/2} d^2},
\]

where \( d \) is the distance between the electrodes and \( g = 1 \) is a geometrical factor. Attempts to increase the current density in such sources led to an increase in the accelerating voltage and, consequently, in the energy expenditure; in this way, however, it is unrealistic to expect

\[
\rho_i = \frac{V_i}{\omega_{hi}} = \frac{M e}{e H_0} \frac{2 e U_a}{M} \propto \frac{M}{\sqrt{e}}.
\]
that the current could be increased by several orders of magnitude.

Classical electromagnetic separators began to be built in the mid-1940s; 20 years later (in the 1960s), plasma accelerators were developed in which the acceleration region contained a quasineutral plasma. These developments were stimulated by the need for space electrojet engines. The devices most suitable for solving the separation problem in question are stationary plasma thrusters (SPTs) [2] and anode-sheath thrusters (ASTs) [3]. These are axisymmetric systems with ring-shaped acceleration channels with a quasi-radial magnetic field (Fig. 2). Deep in the acceleration channel, there is an anode in the vicinity of which the working gas is fed into the channel. A hollow cathode is positioned outside the channel near its exit end. The potential difference applied between the anode and the cathode creates an electric field in the channel. When the \( E \) and \( H \) fields are switched on and the working gas is injected, the electrons emitted from the heated cathode enter the channel and ionize the gas particles. At the same time, they begin to drift in the azimuthal direction in the crossed \( E \) and \( H \) fields and to diffuse slowly toward the anode. The ionization-produced ions are accelerated in the \( E \) field. By the time they arrive at the exit end of the channel, they acquire an energy of

\[ \varepsilon = e\phi, \]  

where \( \phi \) is the potential at the point at which the gas particle was ionized. The cathode potential is assumed to be zero. The magnetic field strength in the channel is chosen so as to magnetize the electrons and not to magnetize the ions to any significant extent, the corresponding condition being

\[ \rho_e \ll L \ll \rho_i, \]  

where \( L \) is the channel length and \( \rho_e, \rho_i \) are the electron and ion gyroradii.

The magnitude of the ion current at the exit from the channel is determined primarily by the flow rate of the working gas injected into the channel. In a well-optimized model channel, the degree of gas ionization is close to 95%. Consequently, for singly charged ions, we have

\[ J_i = \frac{m_e}{M} \]  

Hence, there is no restriction on the magnitude of the ion current density because the plasma in the channel is quasineutral. In stationary thrusters, the factor that restricts the current density is simply the heating of the channel. The typical current density values are about 0.1–0.2 A/cm\(^2\). For a channel with a cross-sectional area of \( \sim 20 \) cm\(^2\), the total ion current is about 3–4 A.