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Ion engine grids: Function, main parameters, issues, configurations, geometries, materials and fabrication methods

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Abstract Ion optics are crucial components of ion thrusters and the study of the different ion extraction solutions used since the beginning of the electric propulsion era is essential to understand the evolution of ion engines. This work describes ion engine grids' main functions, parameters and issues related to thermal expansion and sputter erosion, and then introduces a review of ion optics used for significant launched and tested ion thrusters since 1970. Configurations, geometries, materials and fabrication methods are analyzed to understand when typical ion thrusters use two or three grids, what are the thicknesses and aperture sizes of the screen, accelerator and decelerator grids, why molybdenum and carbon-based materials such as pyrolytic graphite and carbon–carbon are the best available options for ion optics and what is the manufacturing method for each material.

1. Introduction

The ion thruster, or Gridded Ion Engine (GIE), is a mature electric propulsion technology whose development started in the 1960s[1–4] and has since then been used for commercial satellite propulsion (Boeing 702, Boeing 601HP, etc.) and scientific missions (Deep Space 1, Dawn, etc.).[1–5] Ion propulsion with GIE is a rapidly evolving research field where new directions, such as new propellants,[6–8] and new concepts, such as the annular ion engine,[9–12] are currently under development.

The ion thruster's main feature is that the propellant ionization process and the ion acceleration process are physically separated, contrary to other electric thrusters such as hall thrusters.[1,2] The ionization process takes place in the discharge chamber of the thruster and can be achieved by different principles,[13] namely electron bombardment (Kaufman thruster),[14–16] RadioFrequency waves (RF thruster)[17–19] or

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Electron Cyclotron Resonance (ECR thruster).[20–22] Regardless of the thruster type, the ion acceleration process consists of the extraction of ions from the discharge chamber by means of a multi-aperture grid assembly called ion optics or ion engine grids.[23]

Ion optics play a key role in ion thruster performance, and their erosion is the main life-limiting mechanism of the engine.[1] Since the beginning of the electric propulsion era, many efforts have been made to improve ion engine grids to increase the service life of the thruster. Alongside the plasma generator and the neutralizer, ion engine grids are the components that decide the GIE's geometry,[1] so their study is essential for the scaling of the engine. This work contains an extensive literature review of the available information about ion optics of different sizes, shapes and materials developed by space agencies and companies for significant ion thrusters.

This paper is organized as follows. A brief description of ion engine grids' functions and main parameters is introduced in Section 2. Section 3 summarizes the main challenges faced by ion optics during their service life, focusing on thermal expansion problems and sputter erosion. Section 4 reviews the ion optics used for significant launched and tested ion thrusters from the 1970s to date. Section 5 analyzes the different configurations for ion extraction systems and their potential profile, while Section 6 focuses on the apertures' geometry, optics' thickness and grid-to-grid gap. Section 7 deals with the different candidate materials for ion engine grids and Section 8 describes the fabrication methods used to manufacture ion optics of different shapes and materials. Finally, Section 9 presents conclusions about general features that are common to ion engine grids.

2. Ion optics function and main parameters

Ion thrusters are characterized by the electrostatic acceleration of ions extracted from a plasma source.[24] The ion accelerator consists of electrically biased multi-aperture grids, typically two or three, which are called ion optics. The grid in contact with the plasma in the discharge chamber is called screen grid, the second one is called accelerator (accel) grid, and the third one, used in some engines, is called decelerator (decel) grid. The thruster ion optics assembly serves three main purposes[1]: (A) extract ions from the discharge chamber, (B) accelerate ions to generate thrust and (C) prevent the backstreaming of the electrons from the neutralizer hollow cathode. Fig. 1 shows the main parts of a Kaufman type ion thruster with a two-grid extraction system.

Ion optics are characterized by a series of geometric parameters and electrical parameters (see Fig. 2): grid outer diameter (D), similar to the discharge chamber diameter, grid active diameter or beam diameter (D_{ac}), screen grid thickness (t_s), accel grid thickness (t_a), decel grid thickness (t_d), screen grid aperture diameter (d_s), accel grid aperture diameter (d_a), decel grid aperture diameter (d_d), screen-accel gap (l_{sa}), accel-decel gap (l_{ad}), screen grid potential (V_s), accel grid potential (V_a) and decel grid potential (V_d).

The acceleration length (l_e) is defined as

$$l_e = \sqrt{l_{sa} + t_s + \frac{d_s^2}{4}} \tag{1}$$

For a given grid, open area fraction is the ratio of the aperture array surface (combined area of the holes) to the grid surface and grid transparency (T) is defined as the ratio of the beam current that passes through the grid (I_b) to the total ion current that reaches the grid (I_i):

$$T = \frac{I_b}{I_i} \tag{2}$$

Sections 4–6 focus on the geometric parameters (D, t_s, t_a, t_d, d_s, d_a, d_d, l_{sa}, l_{ad}) of significant ion engine grids and Section 5 refers to the electrical parameters (V_s, V_a, V_d).

There are also some parameters that can be used to assess the quality of the grids, that is, how well they can accomplish their functions:

The Normalized Perveance per Hole(NPH) is the amount of current that a single aperture can extract and focus. It is defined as[25,26]

$$\text{NPH} = \frac{J_b}{V_t^{1.5}}\left(\frac{l_e}{d_s}\right)^2 \tag{3}$$

where J_b is the beam current per hole and V_t is the total voltage applied between the accel and screen grids:

$$V_t = V_s - V_a \tag{4}$$

NPH measures the extraction capability of a given aperture. For the NSTAR ion thruster,[3] NPH decreased with the discharge-to-total voltage ratio (discharge voltage is the discharge cathode potential) from 2.1×10^{-9} A/V$^{1.5}$ to 1.2×10^{-9} A/V$^{1.5}$.

Beam divergence is how much the plasma beam expands after it has been focused (see Fig. 3) and can be characterized by the divergence angle (α) which is defined as[5]

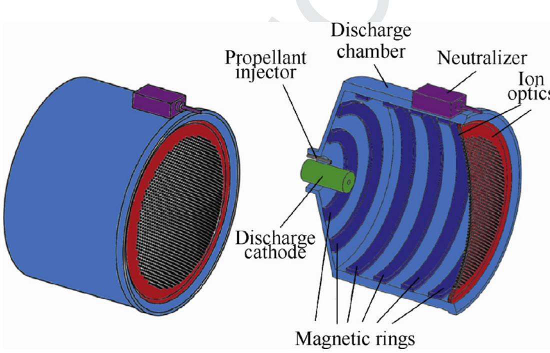

Fig. 1 Kaufman type ion thruster components.

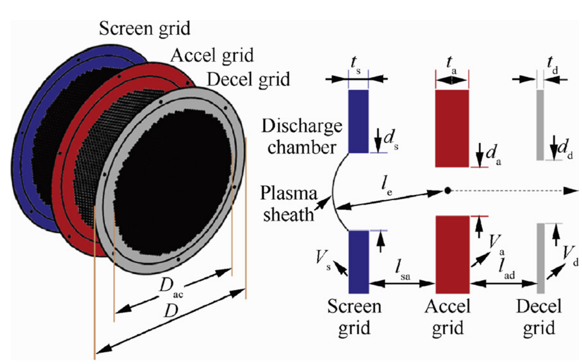

Fig. 2 Ion optics parameters.

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