# Electromagnetic Thrusters through the Eyes of Accelerator Physicists

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## 1 Introduction

Giacomo Gallina, a PhD student from the University of Padova, gave a seminar on electromagnetic thrusters at one of our Beam Physics meetings. This triggered questions that we try to answer in this note.

Giacomo defined basic requirement for an "ideal" thruster:

1. high fuel efficiency (thrust/mass loss rate);
2. high power efficiency (thrust/electrical power)
3. high instantaneous thrust (a Newton or more);
4. long life-time (much more than 20,000 hours);
5. charge neutrality (expel in space as many positive and negative charges).

These requirements are seemingly cross-related. Let's try to disentangled them.

## 2 General Physics Considerations

Let's consider an electric thruster expelling with a potential difference $U$ a current $I$ of particles with charge $q$ and mass $m$. The momentum carried by each individual particle (in the non-relativistic approximation, and putting aside sign considerations) is:

$$p = \sqrt{2mqU}. \tag{1}$$

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The total trust $T$ is given by:

$$T = \frac{Ip}{q} = I\sqrt{\frac{2mU}{q}}. \tag{2}$$

The fuel efficiency $\eta_m$ can be defined as the instantaneous trust over the rate of mass loss ($m\frac{I}{q}$):

$$\eta_m = \sqrt{\frac{2qU}{m}}. \tag{3}$$

The power efficiency $\eta_e$ can be defined as the instantaneous trust over the used electrical power. Assuming that the electrical power is transfered to the beam without losses, we obtain:

$$\eta_e = \frac{T}{IU} = \sqrt{\frac{2m}{qU}} = \frac{2}{\eta_m} \tag{4}$$

This shows that requirements 1 (high fuel efficiency) and 2 (high power efficiency) are contradictory. High fuel efficiency calls for low mass and large beam energy, while high power efficiency calls for high mass and low beam energy.

To achieve high thrust (requirement 3), given a limited amount of electrical power available on-board, increasing beam current is an efficient option since the thrust scale linear with $I$. Increasing the particle mass works too: both thrust and power efficiency scale like $\sqrt{m}$. Increasing $U$ is the least favored way, since it decreases power efficiency.

## 3 DC Acceleration vs RF Acceleration

We have just shown that high power efficiency calls for low beam energy. Particle accelerators with energy below a few 100 keV are exclusively DC. This likely has to do with their relative simplicity and robustness.

Giacomo put forward a potential advantage of RF acceleration: it allows for alternative ejection of positive and negative charges in the same direction (satisfying requirement 5). We will show in section 6 that this becomes an interesting option only when the negatively charged particles are negative ions and not electrons.

## 4 Type of Ion Source

The long life time (requirement 4) calls for a cathode-free, filament-free and grid-free ion source. Two possible options are: (1) RF plasma sources and (2) self-ionizing alkali ion source (Rubidium or Cesium). Both types of ion source are extensively discussed in the scientific literature. The second one is the most simple/robust/proven technology of the two. This is why for instance our ARIEL test ion source is a Cesium source [1].

## 5 Type of Particles

For practical applications the main limitation of electric thrusters is their relative low thrust and low power efficiency. Fuel efficiency is not a practical limitation: it is already orders of magnitudes better than chemical thrusters (which have ejection energy below 1 eV).

To increase thrust and power efficiency the heavier the particle the better. This is one reason why high-Z atoms like Xenon or Cesium are preferred [2, 3]. One can also use molecules (e.g. hydrazine [4]).

The better solution would seem to use orders of magnitude heavier particles like nano-particles or even “dust” particles (see for instance Ref. [5]).

## 6 Electric Neutrality

The use of RF acceleration to expel alternatively positive and negative charges is one option. Half of the RF power will however be spend in accelerating the negatively charged particles. And if these particles are electrons, the resulting thrust will be negligible. This goes against efficient use of electric power. This issue can be overcome if the negative charges are carried by negatively charged ions.

A potentially simpler option is to use an additional positive electrode around the source body, with a much lower potential, to expel electrons sideways (see fig. 1). This way charge neutrality can be achieved from the same ion source, using only little extra electrical power (because of the low electric potential required).

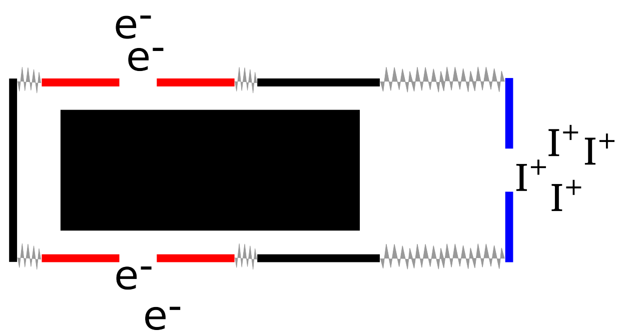


*Figure 1:* Very schematic representation of a proposed way to achieve electric neutrality with a single source body, and using only DC electric fields. The black rectangle represents the ion and electron reservoir: it can be the porous ceramic of a Cesium source, a confined plasma in the case of an RF plasma source, etc. Blue surfaces are set to a large ($\sim$10 kV) negative potential w.r.t. black surfaces. Red surfaces are set to a smaller ($\sim$100 V) positive potential w.r.t. the black surfaces. Grey zigzags represent electrical insulators. A practical design would have its detailed geometry adjusted to balance the flow of positive ions (backwards), and electron (sideways).

## References


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