A Lunar-Based Spacecraft Propulsion Concept – The Ion Beam Sail

Ian G. Brown[a], John E. Lane[b,*], and Robert C. Youngquist[c]

[a]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720*

[b]*ASRC Aerospace Corp., P.O. Box 21087, Kennedy Space Center, FL 32815*

[c]*National Aeronautics and Space Administration (NASA), Kennedy Space Center, FL 32899*

Abstract

We describe a concept for spacecraft propulsion by means of an energetic ion beam, with the ion source fixed at the spacecraft starting point (e.g., a lunar-based ion beam generator) and not onboard the vessel. This approach avoids the substantial mass penalty associated with the onboard ion source and power supply hardware, and vastly more energetic ion beam systems can be entertained. We estimate the ion beam parameters required for various scenarios, and consider some of the constraints limiting the concept. We find that the "ion beam sail" approach can be viable and attractive for journey distances not too great, for example within the Earth-Moon system, and could potentially provide support for journeys to the inner planets.

Keywords: Spacecraft propulsion; ion beam thruster; ion propulsion; interplanetary travel

* Corresponding author. Tel. 1-321-867-6939. E-mail address: John.Lane-1@ksc.nasa.gov

1. Introduction

It is well recognized that chemically-based spacecraft propulsion systems are inherently limited and that exploration of the solar system and beyond will require non-chemical approaches to propulsion technology. A number of alternative propulsion concepts have been proposed and studied, and ion beam propulsion systems have been used in practice with considerable success [1–4]. Ion propulsion systems that have been brought into practice use an onboard ion source to form an energetic ion beam, typically Xe^+ ions, as the propellant. Such systems have been used for steering and correction of telecommunication satellites and as the main thruster for the Deep Space 1 demonstration mission [2,3]. Other propulsion techniques that have been explored conceptually include plasma systems that make use of energetic plasma flows (as distinct from ion beams), fission-based systems in which a reactor is used to heat the propellant, solar sails in which a large area collector is used to harness the solar photon pressure, and more.

An ion beam propulsion system based onboard the spacecraft requires an onboard electric power supply system, the combined mass of which increases with required ion beam thrust, a circumstance that tends to mitigate the value of the ion thruster concept. An alternative approach that avoids this dilemma has been proposed [5] in which the high power ion source is located at a fixed position, e.g., on the surface of the moon, and the energetic ion beam is directed at the spacecraft so as to provide propulsion by momentum transfer from the beam striking the craft. This concept has been called the "ion beam sail".

The primary concerns that determine whether or not the concept is viable have to do with the ion beam parameters required, beam collimation and integrity over large distances, and interaction of the beam with the interplanetary magnetic field and particles (solar wind), among other issues. We point out that even if only relatively short range beams are feasible due to limitations of this nature, the ion beam sail concept may still be effective for moving objects from say the moon's orbit to a nearby LaGrange point between the earth and moon and for other more "specialized" application.

Here we outline a preliminary and simplified analysis of some features of the ion beam sail concept, including a rough estimate of the ion beam parameters required for various space mission scenarios and the kind of ion source that would be needed to form the required beam. In this context we briefly describe the present status of large, high power, ion source technology, and we find that the kind of ion source required for ion beam sail propulsion is only a relatively modest scale-up from the present technology. The critical feature of ion beam divergence is discussed, and some approaches that could be taken to minimize the effects of diminishing ion beam current density with distance described. A number of other considerations that may play a role are described, such as effects due to the interplanetary magnetic field, background gas, and the solar wind plasma. We conclude that the ion beam sail concept could provide a feasible route to space propulsion in some cases.

2. Beam Parameters

We can make an order-of-magnitude estimate of the ion beam parameters required via a highly simplified approach to the propulsion kinetics. Consider an ion beam (subscript *i*) bombarding a spacecraft (subscript *s*) in vacuum. Assume that all the beam ions are collected – ions are brought to rest within the spacecraft mass; (we describe a refinement of this assumption later, in which selective beam reflection is used for spacecraft steering). Assume also that the ion velocity v_i is much greater than the spacecraft velocity v_s, $v_i >> v_s$. We neglect effects due to the solar gravitational potential well.

The momentum transferred from the ion beam to the spacecraft in time dt is

$$dp_i = v_i dm_i = (Am_u I_c v_i/eQ)dt \tag{1}$$

where dm_i is the ion beam mass collected by the spacecraft in time dt, $dm_i = m_i I_c dt/eQ$, m_i is the ion mass, also written as Am_u where A is the atomic weight of the ion and m_u is the mass of 1 amu, I_c is the ion current collected by the spacecraft, e is the unit electronic charge, and Q is the ion charge state ($Q = 1, 2, 3, \ldots$; typically $Q = 1$). This also equals dp_s, and the force on the spacecraft due to the beam is given by

$$F_s = \frac{dp_s}{dt} = \frac{Am_u I_c v_i}{eQ}, \tag{2}$$

It is convenient to relate the ion velocity v_i to the ion source extraction/acceleration voltage, V_a, since this is a designer-controlled parameter:

$$v_i = \sqrt{\frac{2eQV_a}{Am_u}} \tag{3}$$

and thus the force on the spacecraft due to the ion beam can be written as

$$F_s = \left(\frac{2Am_u V_a}{eQ}\right)^{\frac{1}{2}} I_c \tag{4}$$

Inserting numerical values for e and m_u, and putting $V_a = 10^6 V_a'$, where V_a' is the ion source extraction/acceleration voltage in MV, then

$$F_s = 0.14\left(\frac{AV_a'}{Q}\right)^{\frac{1}{2}} I_c \qquad \text{(Newtons)} \tag{5}$$

Thus for maximum thrust we want heavy ions that are singly-charged and high ion beam energy. Here we take Ar^+ ions, Q = 1 and A = 40. In the present technology, a maximum realistic ion source extraction/acceleration voltage is 1 MV [6], and we take $V_a' = 1$. We obtain finally a very simple expression for the ion beam thrust,

$$F_s = 0.9\, I_c, \tag{6}$$

where F_s is expressed in Newtons and I_c in Amps. We remark in passing that the seemingly incongruent call for singly-charged ions rather than higher charge state ions follows from the fact that we measure the beam current I in electrical current I_{elec} rather than particle current I_{part}, and $I_{\text{elec}} = QI_{\text{part}}$. For constant electrical beam current I_{elec}, highest beam momentum is delivered for Q = 1.

The ion thrust becomes more meaningful if we relate it to spacecraft flight-time for a nominal mission. For purposes of comparison and further discussion, we take a journey length of 385,000 km, the Earth-Moon distance. In the spirit of our highly-simplified approach, we ignore concern for spacecraft slow-down and estimate the very approximate flight-time t_F from $s = ½at_F^2$, where s is the flight path distance (3.85×10^8 m) and a is the acceleration F_s/m_s, to obtain

$$t'_F = 11\sqrt{\frac{m'_s}{I_c}} \quad \text{(days)} \tag{7}$$

where t'_F is the flight time in days and m'_s is the spacecraft mass in metric tons (1 metric ton = 1 tonne = 1000 kg). This simple expression is plotted in Fig. 1. These results indicate that the ion beam parameters required, in order that the flight time be reasonable and attractive, are in principle feasible. First-approximation beam parameters are: ion energy ~1 MeV, beam current ~10–1000 A, singly charged, heavy ions (e.g., Ar^+). A critical assumption is that all of the ion beam flux is collected by the spacecraft collector throughout the entire voyage; we return to this point later.

3. Ion Source

Having made a preliminary estimate of the ion beam parameters required, we review the state-of-the-art of ion source physics to consider what technology is available and/or what degree of scale-up from present technology might be called for. We can also estimate the power requirements for the propulsion system.

Firstly we make a few observations of the parametric variation of flight time with some of the primary beam and source variables. Parameters affecting the flight time that are more-or-less readily controllable are the ion mass A, the ion beam current I_c, and the ion energy V_a.

• The flight time varies inversely as the fourth root of ion mass, $t_F \sim A^{-1/4}$; thus high mass ions are preferred, but the gain in using Xe over Ar, for example, is only $(54/40)^{1/4} = 1.08$, or 8%.

• The flight time varies inversely as the root of beam current. Clearly and unsurprisingly, very high collected beam current is needed, of order hundreds of amperes.

• The flight time varies inversely as the fourth root of ion energy, $t_F \sim V_a^{-1/4}$. Thus high ion energy is preferred. However, increasing the ion extraction voltage from 1 MV to 10 MV would decrease the flight time by a factor of 1.8, and going from 1 MV to 100 MV by a factor of 3. The gains are not large, while the cost and effort to achieve these huge extraction voltages is immense.

We point out that for the high beam current required it is not feasible to use particle accelerators to achieve high energy. All of the ion energy must be produced by the ion source extraction system – ions are accelerated by the ion source extractor electrodes directly by their fall through a large potential drop, as per Eq. (3). In present-day ion source technology the upper limit to ion source extractor voltage is of order 1 MV.

Ion sources can be classified in many different ways, for example according to their application, beam species, beam size, beam current, etc. For the present purposes we wish to consider that kind of source, or that established field of application, that will take us to the highest beam currents possible. This leads us directly and unequivocally to the large ion sources that have been developed at a number of locations around the world in recent decades for application to the controlled nuclear fusion research program – neutral beam injection (NBI) ion sources. In this context, the term "neutral beam" implies a beam composed of neutral atoms. Very high power neutral beams have been developed and are used for fueling and heating the reacting plasma in experimental controlled fusion devices, typically tokamaks; the particle beams need to be neutral, as opposed to ion beams, so that they can penetrate the intense magnetic field confining the plasma. An NBI device consists of a large ion beam source followed by a charge exchange region in which charge exchange collisions between energetic ions and cold neutrals produces a beam of energetic neutral atoms. For our present purposes we are interested in only the ion source part of the NBI system. These sources have been described in a recent review by Takeiri [6]. Photographs of the 35 cm×145 cm cross section arc chamber of the giant ion source used in the 180 keV NBI system of the LHD fusion machine (Japan) are shown in Fig. 2 [7,8]. An illustration of the 500 kV giant negative-ion source used in the JT60U-NBI system (Japan) is shown in Fig. 3 [9].

The relevant critical parameters of the large NBI ion sources can be summarized as follows:

- The ion beam energy is high, up to 500 keV at present and 2 MeV in the near future.
- For fusion application the ion species used is typically deuterium, and frequently negative ions are employed; negative ions are preferred at high energy because of their large charge exchange cross section compared to positive ions. However these are not inherent features of the ion source, and beams of heavy positive ions can be formed with moderate source reconfiguration.
- Beam current is typically several tens of amperes for negative-ion-based NBI systems. When reconfigured for positive ions, a large, present-technology NBI ion source could deliver an Ar^+ ion beam current of several hundred amperes.

• The sources are highly engineered, and machined to very tight specifications. This is essential in order that the very high internal power densities are not dissipated destructively, and so that the extracted ion beam has minimum possible beam divergence.

• For high extraction voltage, ~1 MV, most of the ion source power input goes into accelerating the beam, with a relatively minor power fraction going into the plasma discharge. Thus the overall power efficiency (beam power out to total electrical power in) can be high, say of order 50% or more.

• Low divergence of the extracted beam is critically important for fusion application, and great effort has gone into minimizing beam divergence. Typical values are about 10 mrad (1/*e* half-angle).

Thus the ion source technology that has been developed for the worldwide controlled fusion research program offers by far the largest, highest power, ion sources that have been made or contemplated. This is without doubt the kind of source that would serve as a model for the ion beam sail propulsion system. Ion sources that have actually been made have ion energies up to 0.5 MeV and ion currents (Ar^+ equivalent) in the range 100 – 500 A. Thus the source development required beyond the present technology is modest, or for some ion beam sail applications – nil. The total electrical power called for, say for a 300 A beam at 1 MeV (300 MW beam power), would be about 0.5 – 1 GW.

4. Beam Divergence and Self-Pinching

The effect of beam divergence is critical to the concept. Here we discuss the origins of ion beam divergence, estimate the effect on the ion beam sail propulsion concept of real-world beam divergence, and consider beam self-pinching as a tool for mitigating the deleterious beam divergence effects.

The divergence of an ion beam is defined as the beam-spread half-angle as indicated in Fig. 4. For example a $1/e$ half-angle divergence is common; meaning that angle at which the beam radial profile of current density decreases to a level that is $1/e$ of the peak (on-axis) ion current density. Implicit in this definition is that the beam profile remains unchanged (self-similar) with distance. In the absence of any exterior forces acting on the beam, the beam profile will tend to Gaussian over a fairly short propagation distance and remain Gaussian thereafter. Importantly, note that the initial or inherent (at the ion source extractor) beam divergence is separate from and unrelated to any subsequent divergence effects that might occur, for example due to space charge blowup of the beam.

There are two independent causes for inherent beam divergence:

- Transverse ion temperature of the plasma within the ion source.
- Beam extraction considerations including not only physical limitations to the mechanical precision of the extractor electrodes but also limitations to the uniformity of the plasma presented to the extractor.

4.1. Transverse ion temperature of the ion source plasma

Ions are "extracted" from the plasma to form the ion beam. More precisely, ions fall through the sheath that forms the plasma boundary, and (when they are no longer part of the bulk plasma) are accelerated by the electric field established by the extractor electrodes. Ions within the plasma have a non-zero thermal energy spread (the plasma ion temperature, T_i), that can be considered to be composed of a longitudinal component of temperature, $T_{i//}$, and a transverse component of temperature, $T_{i\perp}$, (referred always to the direction of beam extraction as the longitudinal direction). The ion temperature in typical ion source plasmas is usually around 1 eV. In the beam formation process, longitudinal energy is added to the ions by the extractor electric fields – the ions gain longitudinal energy; this is the ion energy of the beam. However, the transverse ion temperature is unaffected by the beam formation process, and the transverse energy spread (temperature) of ions in the pre-extraction plasma is maintained in the extracted, energetic ion beam. Thus if the transverse ion temperature in the plasma is 1 eV, so is the transverse energy of the beam ions. The beam divergence is given by the ion velocity ratio

$$\theta = \frac{v_{i\perp}}{v_{i//}}, \tag{8}$$

where $v_{i//}$ is the longitudinal velocity of the energetic beam ions, and $v_{i\perp}$ is the transverse velocity of the beam ions which is the same as the transverse velocity of the plasma ions. In terms of temperatures,

$$\theta = \sqrt{\frac{T_{i\perp}}{E_{i//}}}, \tag{9}$$

where $E_{i//}$ is the (longitudinal) ion beam energy. We can estimate the divergence for a 1 MeV Ar^+ ion beam, as considered above, assuming that the ion source plasma has a temperature of 1 eV. Then $\theta = (1/10^6)^{1/2} = 10^{-3}$ rad, or 1 mrad.

4.2. Extraction considerations

Another source of inherent beam divergence is imperfections in the ion extraction optics. This includes at least two primary effects:

(a). The electrode system design is properly done using highly sophisticated computer simulation programs [10], following which the electrode system must be manufactured. There are often some difficult constraints, especially in high power systems. For example the electrode structure must be internally oil- or water-cooled, necessitating hollow grid structures. This clearly puts constraints on the shape and size of the electrodes, and it may not be possible to produce in the real world the computer-demanded electrode structures. Quite apart from the difficulty of manufacture, there is also the difficulty of holding the electrodes immobile even though they may consist of large open area plates (in effect) that are subject to substantial electrostatic forces. The grids may move.

(b). The plasma presented to the large-area extractor is never perfectly uniform in density and temperature over the whole extractor area. In fact, not only is the plasma imperfectly uniform on the macroscopic length and time scales, but also the plasma suffers inherent microscopic plasma fluctuations. This is a fundamental characteristic of plasma – the particles suffer random small-scale fluctuations in density and energy, as does any gas. Thus the extraction optics, which is dependent not only on the physical shape of the electrodes but also on the plasma parameters, suffers and so also the divergence of the extracted beam.

The NBI ion sources [6–9] that have been developed for the controlled fusion research effort worldwide constitute the best comparison for the ion beam sail space propulsion concept, not only from the point of view of the high beam energy and current but also because these sources have been developed with a primary goal of minimizing beam divergence (in order that the beam be able to enter the fusion chamber and reacting plasma with minimal disturbance to the vacuum enclosure ports). A huge scientific effort has gone into understanding the origins of beam divergence and in creating extractor systems that result in a divergence as low as is possible to obtain. The minimum beam divergence actually obtained is about 10 mrad, and we can take this value as the best divergence possible for large ion sources of the kind under consideration.

4.3. Effect of beam divergence

As the beam spreads due to its non-zero divergence, the ion current density decreases as z^2, where z is the distance from ion source to spacecraft, and the collector radius, r_c, will at a certain critical distance from the ion source, z_{crit}, become smaller than the ion beam radius, r_b, at that distance. Thereafter, a progressively lower fraction of beam current will be intercepted by the ion beam sail. For example, for a beam divergence of 10 mrad and a sail/collector radius of 10 km, the critical distance is just 10^3 km; further, the fraction of ion beam collected at a distance $z > z_{crit}$ is $r_c^2/\theta^2 z^2$, and falls to 1% for a distance $z = 10^4$ km. Clearly the effect of beam divergence on the propulsion concept is severe. Thus we consider next the use the beam's self magnetic field as a means for confining the beam expansion.

4.4. Beam confinement by its self magnetic field

An ion beam establishes its own magnetic field that is azimuthal to the beam propagation direction and can thus provide a confining force on the beam. The effect is well known in the context of plasma confinement mechanisms for controlled fusion [11], where it is known as the pinch effect, or the Bennett pinch after its discoverer [12]. The pinch effect can be used to advantage in the ion beam sail concept as a means for limiting beam divergence.

Ignoring contributions to the beam magnetic field by electron flow within the beam, the azimuthal magnetic field B_θ due to the ion current is given by $B_\theta = \mu_o I_i/2\pi r_b$, where I_i is the ion current in the beam and r_b is the radius of the ion beam. We can calculate the magnetic field required to balance the outward expansion/divergence of the beam by equating the inward magnetic pressure to the outward kinetic pressure of the beam particles. The magnetic pressure generated by a magnetic field of strength (flux density) B is given by $P_{mag} = B^2/2\mu_o$. Combining these two equations we obtain $P_{mag} = 1.5 \times 10^{-8}\, I^2/r^2$. The radial kinetic pressure due to the beam is determined by the transverse temperature of the ions and electrons, $P_\perp = P_{i\perp} + P_{e\perp} = n_i kT_{i\perp} + n_e kT_{e\perp}$, where the ion density n_i is given by $I_i = \pi r^2 n_i eQv_{i//}$ and the longitudinal ion velocity $v_{i//}$ by $\frac{1}{2} m_i v_{i//}^2 = eQV_a$, and we can take, roughly, $T_{e\perp} = T_{i\perp} = T$ and

$n_e = n_i$. Combining these equations, taking Ar^+ ions (A = 40, Q = 1), and equating the magnetic pressure P_{mag} to the kinetic pressure $P_\perp$, a condition for pressure balance is obtained,

$$I \;=\; 1\times 10^{23}\frac{kT_\perp}{V_a^{\frac{1}{2}}}. \tag{10}$$

This is the beam current that balances the outward kinetic pressure of the beam due to transverse temperature of the ions and electrons in the beam. Note the current is independent of beam radius. This derivation assumed a sharp boundary between beam and magnetic field, which in reality will not be so; a Gaussian radial distribution of ion density and a magnetic field that penetrates the plasma will prevail. Even so, however, a more detailed analysis yields precisely the same result. Eq. (10) remains valid in general.

Taking $T_\perp$ = 1 eV (both for ions and for electrons) and $V_a = 10^6$ V, we obtain $I \approx 20$ A. A beam current greater than this will compress the beam until the transverse temperature rises so as to balance the increased magnetic field. We conclude that the beam current required to balance the outward ion flow (due to thermal energy spread) is feasible and well within the range we are considering. Thus the spacecraft collector (sail) size can remain relatively modest. We consider some caveats with respect to beam confinement and possible instabilities below.

5. Space Charge Neutralization

In a simple scenario, an ion beam is composed only of streaming, energetic ions, usually positive ions as considered here. As the ion particle density increases as the ion current is increased, so also does the positive beam potential due to the ion charge; this is referred to as the space charge of the beam. The effect of the positive space charge is that the beam ions experience a repulsive force, with the result that the beam expands in size as it propagates.

The increase in beam size that occurs because of the positive space charge of the beam is called "space charge blowup". This is a well known effect in ion beam physics that must be considered here. All beams except for the lowest current cases may suffer blowup, and the effect is significant for the high beam currents considered here. The effect can be so severe that the beam is reflected by its own space charge potential; in this case the beam stalls and the ions reverse direction. Thus it is common that ion beams are space charge neutralized, or space charge compensated, so as to reduce to near-zero the internal potential of the beam and so to minimize or nullify the electric forces that drive the blowup. This is accomplished by adding cold electrons to the beam. The picture is then of an energetic beam of ions streaming through a background sea of cold electrons that are drawn by uncompensated electric fields to flow precisely where they are needed in order to neutralize the positive space charge. In fact in most laboratory situations it is difficult to remove the electrons – it is usual that the beam is space charge neutralized more-or-less incidentally to the ion beam formation. Cold electrons are formed in the ion beam as "scrape-off electrons" from bombardment of the metal electrodes of the extractor grids by energetic ions, by ionization of the background gas by energetic ions, and by bombardment of the ion beam target by energetic ions. In space clearly this picture changes, and it is usual that (in small ion thruster application, for example) supplementary electron sources, such as simple thermally-emitting filaments, are used to provide the space charge neutralizing electrons.

We note parenthetically that a "space-charge neutralized beam" is quite different from a "neutral beam". In a neutral beam the energetic particles are atoms, not ions. Whereas in an ion beam, space charge neutralized or not, the ions are independent particles and can be affected by electric and magnetic fields, in a neutral beam the energetic particles are charge-neutral atoms that are unaffected by electric or magnetic fields. A neutral beam is of course fully neutralized also, since there are exactly as many positive charges as electrons, simply in a bound, atomic state. Importantly, note that once the neutral beam has been formed, it can no longer be manipulated in by electric or magnetic fields, since the particles are neutral atoms. The ion beam sail concept envisages a space-charge-neutralized ion beam, not a neutral atom beam.

5.1. Magnitude of space charge blowup

Ion beam space charge blowup has been treated analytically by a number of authors [13,14]. A convenient approach is that described by Holmes [13], who calculates a universal curve for the normalized beam radius as a function of normalized axial distance. For a 1 MeV beam of Ar^+ ions, we obtain an expression for the axial distance z for the beam radius to double,

$$\frac{z}{a} = \frac{30}{I^{\frac{1}{2}}(1-h)^{\frac{1}{2}}}, \tag{11}$$

where I is the ion beam current, a the initial beam radius, and h the degree of space charge neutralization (fraction of positive ion charge that is neutralized by electrons). The factor $(1 - h)$ can be called the neutralization deficiency. If we take an initial beam radius of 1 m, we can plot Eq. (11) as in Fig. 5. Clearly a very high degree of space charge neutralization is required for the beam to propagate without space charge blowup. Note however that if the space charge deficiency is not too great, it may well be possible to confine the beam against radial expansion due to space charge forces by the beam's self-magnetic field, as discussed in section 4.4.

6. Steering

The spacecraft is driven by a fixed, distant ion source that provides thrust to the spacecraft by a powerful ion beam that propagates through space to transfer momentum to the spacecraft via ion collisions with it. In this first-order scenario the thrust vector lies in the same direction as the ion beam and remains fixed radially away from the ion source, without the possibility of a transverse component of thrust to provide steering to the spacecraft motion. In this section we discuss some approaches that can be incorporated into the concept to provide steering.

In the analysis presented up to now we have considered the ion beam to bombard a large-area sail mounted on the spacecraft. Beam ions strike the collector surface and are implanted in the sail material. A computer simulation using the SRIM (Stopping and Range of Ions in Matter) code [15] shows that 1 MeV Ar^+ ions are brought to rest within a 1 μm surface layer of material. That is, momentum exchange collisions between ions and the spacecraft are inelastic, and since the post-collision ions have no transverse momentum component, so also the spacecraft can gain no transverse momentum. The solution is to allow for elastic collisions between the ion beam and the spacecraft, in which the beam ions are deflected from their initial purely-axial direction (with respect to the initial ion beam direction). Then the post-collision ions have transverse momentum and the spacecraft gains the same (equal and opposite) transverse momentum.

The ions can be deflected electrostatically, and a simplified way of viewing the configuration is to consider the spacecraft as surrounded by a number of individually-mounted spheres or plates that can be charged to desired voltages; see Fig. 6. A large-area collector may be segmented to achieve essentially this kind of configuration. In the configuration shown, the sail consists of a number k of spheres biased to voltages V_k. The total thrust on the system is $\boldsymbol{T} = \Sigma \boldsymbol{F}_k$, where $\boldsymbol{F}_k$ is the vector force on the k^{th} sphere due to the beam. The directions of vectors $\boldsymbol{F}_k$ can be controlled by the potentials V_k to which the segments are charged, and the deflected ion beam direction can in principle be varied from $\varphi \approx 0$ (glancing) to π (reflection of the beam upon itself), allowing tacking of the spacecraft across the beam.

At the same time, the rotational moments on the spacecraft must cancel in order to prevent unwanted rotation and to provide attitude stability and control, $\boldsymbol{M} = \Sigma\, \boldsymbol{r}_k \times \boldsymbol{F}_k = 0$, where $\boldsymbol{r}_k$ is the position vector from the k^{th} sail component center of force to the system center of mass.

As the spacecraft tacks transverse to the beam, the beam must also move, ideally in such a manner that the spacecraft remain always centered on beam axis. This may not be easily accomplished, but it is nevertheless feasible in principle. We envision feedback between the sail-segment potentials that determine the tacking and a beam-recognition system that detects the location (in the transverse plane) of the spacecraft with respect to the Gaussian ion beam profile. Other approaches might include small conventional thrusters using compressed gas or chemical propellant, or small conventional onboard ion engines. Beam movement, controlled by the ground-based ion source, must necessarily be done quite slowly, since the time required for a 1 MeV Ar^+ ion to travel a distance 10^5 km, say, is about 50 sec.

We point out that in the simple scenario described, the high voltages applied to the collector segments could have adverse effects due to the associated electron flow to these positive elements, in two possible ways. Firstly, to the extent that electrons are drawn from the cold electron sea that provides space-charge-neutralization to the ion beam, the beam will suffer space-charge-blowup. The beam radius will increase and the collected ion current will diminish. Secondly, electrons that are energetically attracted to and bombarded into the positive metallic target will generate high energy x-rays, which could present a safety hazard to the spacecraft crew, if the vessel is manned. However, it may be possible to shield against such effects by the addition of grounded or suitably biased metallic grids, with mesh size of order the Debye length or less, in front of the positively biased sail components so as to isolate the low energy electron flux but not the energetic positive ion flux from the electrostatic influence of the biased sail.

7. Other Considerations

We consider some other factors that may influence the concept, including the ambient magnetic field, the solar wind plasma, possible beam instabilities, a further look at beam neutralization, and the effect of entrained electron current.

7.1. Effect of ambient magnetic field

A particle of charge eQ moving at velocity $\boldsymbol{v}$ in a magnetic field of strength $\boldsymbol{B}$ experiences a force given by $\boldsymbol{F} = eQ\boldsymbol{v} \times \boldsymbol{B}$, called the Lorentz force. The general net charged particle motion in a uniform, homogenous magnetic field is a helical trajectory, with the radius, ρ, of the circular orbit in the transverse plane called the cyclotron radius or gryoradius and given by

$$\rho = \frac{mv_\perp}{eQB} \qquad (12)$$

where m is the particle mass and $v_\perp$ is the particle velocity in the direction normal to the magnetic field direction. For ions with energy $E_i = ½mv^2$, the ion gyroradius can be written as

$$\rho_i \approx 10^{-4}\frac{\sqrt{AE_i}}{QB} \quad \text{(m)} \qquad (13)$$

where A is the ion atomic weight (amu), E_i the ion energy in eV, Q the ion charge state, and B the magnetic field (flux density) in Tesla. Similarly the electron gryoradius can be written as $\rho_e \approx 4 \times 10^{-4}\sqrt{T_e}/B$, where T_e is the electron temperature in eV.

The primary component of the interplanetary magnetic field is the solar magnetic field, transported outward from the sun by the solar wind. In the plane of the ecliptic the field is spiral in shape with an angle of about 45° to the radial direction (at about 1 AU from the sun) and of magnitude of order 10 nT. Taking $B = 10^{-8}$ T, and $E_i = 1$ MeV, $Q = 1$, $A = 40$ for the beam ions, and $T_e = 1$ eV for the beam (neutralization) electrons, we obtain $\rho_i \sim 10^5$ km and $\rho_e \sim 100$ km. Thus both the ion gyroradius and the electron gyroradius are small compared to the distances involved. This implies that both the ion beam and its neutralization electrons are perturbed by the magnetic field.

If the ion beam were "low current", meaning that no space charge neutralization were needed to keep the beam intact, then the consequence of the ion gyroradius being small would be that the beam is bent; because the direction of the solar magnetic field is complex, the trajectory would be a distorted helix. In the present case where cold electrons provide beam neutralization, the neutralization will be perturbed to some extent – electrons will be hindered from flowing to where they are needed in the beam. It is difficult to predict the magnitude of this effect, and because the electron gyroradius is many orders of magnitude greater than the beam diameter it is possible that the effect will be insignificant. Importantly, beam confinement by its self magnetic field as described in section 4.4 could help to counter the tendency to beam expansion due to this effect of the interplanetary magnetic field.

7.2. Effect of interplanetary gas and plasma (solar wind)

Beam ions suffer collisions with background particles in the medium through which the beam propagates, including both neutral atoms and background plasma, for which the collision mean-free-path λ is given by $\lambda = 1/n\sigma$, where n is the density of the background particles and σ is the cross section for the particular kind of collisions considered at the relevant ion energy. If the mean free path is small compared to the scale lengths involved then the scattering will be severe and cannot be neglected. A particle beam of initial current I_o suffers an attenuation (*if* the collisions effectively remove particle from the beam) at a rate given by $I = I_o e^{-n\sigma z}$, and the distance L_{exp} for the beam to attenuate (or otherwise change its properties, according to the kind of collision) by a factor of $e = 2.718$ is given by $L_{exp} = 1/n\sigma$, which is the mean free path λ.

A number of different kinds of collisions should be considered for the case of an energetic heavy ion beam propagating for great distances through the interplanetary or earth-moon medium. These include (but are not be limited to):

- Electron-capture collisions. Beam ions may capture electrons via charge-exchange collisions with ambient gas, converting Ar^+ ions into neutral Ar atoms that are then lost from the beam.
- Ionization (of the ambient gas) collisions. Energetic Ar^+ ions will suffer collisions with the neutral background gas, most of which is H or H_2, to form H^+ or H_2^+ ions. These low mass ions may then remain trapped within the beam, slowly replacing Ar^+ ions with H^+ ions, to arrive at a new equilibrium Ar^+:H^+ beam mixture.
- Scattering collisions. Energetic Ar^+ ions will be scattered out of the ion beam by collisions with neutral gas, slowly reducing the beam current.

We can make an order-of-magnitude estimate of the mean free paths involved based on cross-sections known for "comparable" processes. The electron capture cross section for O^+ ions in H and H_2 at an energy of 1 MeV is [16] $\sigma_{ec} \sim 0.6 \times 10^{-16}$ cm^2 (in H) and $\sim 1.2 \times 10^{-16}$ cm^2 (in H_2). The ionization cross section can be roughly estimated via a Firsov approximation [17] to obtain $\sigma_{ioniz} \sim 10^{-16}$ cm^2. If we thus assume a typical cross-section $\sim 10^{-16}$ cm^2, and take the density of the interplanetary gas as ~10 particles/cm^3 and the Ar^+ beam ion velocity as 2.2×10^6 m/s, we obtain that the mean-free-path $\lambda \sim 10^{10}$ km, orders of magnitude greater than the scale-lengths of our conceptual journey. We provisionally conclude that collisions of beam ions with ambient gas and plasma do not adversely influence the ion beam sail concept.

7.3. Possible beam instabilities

Plasma instabilities are legion. Instabilities can be either macroscopic, in which the bulk plasma configuration is grossly distorted, or microscopic, in which individual particles of the plasma acquire energy in destructive motion. The present plasma scenario is that of an energetic ion beam moving through its self-contained sea of cold (neutralizing) electrons, and through the drifting solar wind plasma. Some of the kinds of instabilities that might occur are: beam-plasma instabilities, due to the energetic beam passing through cold background plasma; the Buneman instability, due to the ions having directed energy much greater than their thermal energy; the ion cyclotron instability, due to the ions, in a magnetic field, having directed energy much greater than their thermal energy; and more. Detailed analysis is needed to reveal whether or not the conditions for instability onset are met, and, most importantly, the growth rates of any instabilities that can occur (compared to the total beam length and duration).

Another kind of instability that must considered is the pinch instability [18]. In a plasma discharge, the Bennett pinch is basically unstable; as soon as it is brought into effect, the plasma rapidly moves away from its simple configuration, and is lost. There are two basic instability modes (as well as higher order modes and mixtures of modes): the sausage instability (m = 0) and the kink instability (m = 1). The origin of these instabilities is that any small departure from equilibrium causes the magnetic field to increase so as to drive the current-carrying column further into the instability – the essence of instability. Although these instabilities are observed in laboratory plasmas, they may or may not occur in the present situation. It is possible, perhaps probable, that the "stiffness" of the energetic ions may provide resistance to the growth of the modes.

7.4. Possibility of current neutralization by electron entrainment in the beam

Inherent to the ion beam sail concept is the notion that the adverse effect of ion beam divergence can be avoided by a counter-effect in which the energetic ion beam is confined radially by its self magnetic field. In this scenario, the beam azimuthal magnetic field is established by the ion beam current, and it fortuitously emerges that the strength of this field is of the appropriate order to provide confinement against beam expansion due to transverse ion temperature ("inherent beam divergence"). One must, however, also consider possible effects due to the space-charge-neutralization electrons within the beam. If the electrons have no streaming or drift energy (only their thermal energy), they do not constitute a net electron current and they will not contribute to the beam magnetic field. However, the beam electrons will tend to be accelerated by the streaming ions with which they coexist – the beam ions and the influence of collisions will provide a force that will slowly accelerate the electrons so that they also stream in the same direction as the ions. This electron current will establish a magnetic field component that is in the opposite direction to the field formed by the positive ion current. Thus the self-confining magnetic field will be reduced; the limiting case, when the ion current equals the electron current and the beam self magnetic field is zero, is referred to as "current neutralization". Minimizing this effect is that the electron current may remain at just a small fraction of the ion current, but a detailed theoretical analysis is required in order to assess what the equilibrium total $(I_i - I_e)$ beam current is.

8. Discussion and Conclusion

The ion beam sail propulsion concept appears to be a viable approach at the level of analysis described here and within some constraints. The ion beam and ion source parameters required are entirely feasible, and in fact only modestly beyond the present NBI (neutral beam injector) ion source technology as developed within the controlled fusion community.

Approximate beam parameters are ion energy ~1 MeV, beam current ~10–1000 A, singly-charged heavy ions (e.g., Ar^+). The total system electric power called for, say for a 1 MeV, 500 A beam, is roughly twice the beam power, ~1 GW.

A critical assumption is that all or most of the ion beam flux is intercepted by the spacecraft collector (the sail) throughout all or most of the voyage. Thus the concern of beam divergence is critical. Beam divergence for the giant NBI sources is about 10 mrad, and because of the extreme importance of this parameter to the controlled fusion application and the vast amount of scientific and engineering effort that has gone into minimizing divergence, we can take this value as about the best that is possible. The effect of beam divergence on the propulsion concept is severe. However, it may be possible to nullify the adverse effect of beam divergence by self-confinement of the ion beam by its own azimuthal magnetic field (the "pinch effect"). This may require judicious selection of other beam parameters (beam size, energy). Space charge neutralization of the positive ion beam by a cold electron background within the beam is vitally important. Beam blowup due to uncompensated space charge forces will tend to occur unless the neutralization can be made essentially complete. However, we point out that magnetic self-confinement of the beam by its own magnetic field, as described above and in the main text, could help in containing the beam not only against expansion from inherent divergence due to transverse ion temperature but also against expansion due to incomplete space charge neutralization. Thus the concern of beam blowup may be minimized in this way.

The interplanetary magnetic field (~10 nT) will perturb both the beam ions and the neutralization electrons. The ion gyroradius for 1 MeV Ar^+ in a 10 nT field is about 100,000 km, and the electron gyroradius is of order 100 km for 1 eV electrons. These orbit sizes are not large compared to typical journey scale lengths (which for simplicity we take as a lunar distance of 385,000 km), and the effect of the field will be to bend the beam path into (a section of) a distorted helical trajectory and to inhibit the space charge neutralization of the beam. The effect of the interplanetary magnetic field can be reduced if it is possible to align the ion beam trajectory as much as possible along (parallel to) the magnetic field direction. Further, beam confinement by its self magnetic field as described in the preceding may also play a role in preserving beam integrity in the presence of the interplanetary magnetic field.

As the beam propagates through the interplanetary gas and plasma, collisions could slowly change the beam properties in a number of ways, including beam attenuation as energetic particles are scattered out of the beam and also neutralized by electron capture collisions, replacement of Ar^+ ion by H^+ ions as the ambient gas is ionized and trapped, and other kinds of collisions. However this effect is minimal, with an estimated beam attenuation length due to collisions that is several orders of magnitude greater than the lunar distance.

The ion beam sail concept that we've outlined can provide a viable approach to spacecraft propulsion for the case when the journey distance is not too great. The limiting factor is beam integrity against divergence, disruption, and distortion due to a number of different effects, a precise quantitative determination of which awaits detailed analysis.

Acknowledgements

We are grateful to the NASA Exploration Systems Research and Technology (ESR&T) Program for support of this work.

References

[1] J. Brophy, Advanced ion propulsion systems for affordable deep-space missions, Acta Astronautica 52 (2003) 309–316.

[2] M.D. Rayman, The Deep Space 1 extended mission: challenges in preparing for an encounter with Comet Borrelly, Acta Astronautica 51 (2002) 507–516.

[3] J.R. Brophy, NASA's Deep Space 1 ion engine, Rev. Sci. Instrum. 73 (2002) 1071–1078.

[4] J.R. Beattie and J. Matossian, Xenon ion source for space applications, Rev. Sci. Instrum. 61 (1990) 348–353.

[5] R. Youngquist, P. Metzger and J. Lane, Particle beam propulsion: Simulations of an electrostatic sail concept, Research and Technology 2004 Annual Report, John F. Kennedy Space Center, 6–7 (2004); see http://rtreport.ksc.nasa.gov/techreports/2004report/RTrpt04.pdf

[6] Y. Takeiri, "Giant Ion Sources for Neutral Beams", in *The Physics and Technology of Ion Sources*, 2nd Revised Edition, edited by I.G. Brown (Wiley, N.Y., 2004), pp. 341–371.

[7] Y. Takeiri, M. Osakabe, K. Tsumori, Y. Oka, O. Kaneko, E. Asano, T. Kawamoto, R. Akiyama, and M. Tanaka, Development of a high-current hydrogen negative ion source for the LHD-NBI system, J. Plasma Fusion Res. 74 (1998)1434-1443.

[8] O. Kaneko, Y. Takeiri, K. Tsumori, Y. Oka, M. Osakabe , *et al.,* Experiments on NBI plasmas in LHD, *Proceedings of the 16th International Conference on Fusion Energy,* Montreal, 1996 (International Atomic Energy Agency, Vienna, 1997), Vol. 3, p. 539.

[9] M. Kuriyama, N. Akino, T. Aoyagi, M. Araki, N. Ebisawa, et al, Negative-ion based NBI system for JT-60U, *Proceedings of the 16th IEEE/NPSS Symposium on Fusion Engineering*, Illinois, 1995 (IEEE, 1995), Vol. 1, pp. 491-496.

[10] See, for instance, P. Spaedtke, "Computer Simulation of Extraction", in *The Physics and Technology of Ion Sources*, 2nd Revised Edition, edited by I.G. Brown (Wiley, N.Y., 2004), pp. 41–60.

[11] S. Glasstone and R.H. Loveberg, *Controlled Thermonuclear Reactions* (Van Nostrand, Princeton, 1960), p. 225.

[12] W. H. Bennett, Magnetically self-focussing streams, Phys. Rev. 45 (1934) 890–897.

[13] A.J.T. Holmes, "Beam Transport", in *The Physics and Technology of Ion Sources*, (First Edition), edited by I.G. Brown (Wiley, New York, 1989), pp. 75–81.

[14] A.T. Forrester, *Large Ion Beams*, (Wiley, New York, 1988), p. 33–44.

[15] J. Ziegler. See the website http://www.srim.org/

[16] *Physics Vade Mecum*, 2nd Edition, edited by H. L. Anderson (American Institute of Physics, N.Y., 1981) p. 87.

[17] Ibid, p. 90.

[18] S. Glasstone and R.H. Loveberg, *Controlled Thermonuclear Reactions* (Van Nostrand, Princeton, 1960), pp. 234-241.

Figure Captions

Fig. 1 Flight duration (days) as a function of ion beam current (Amps), with spacecraft mass (metric tons) as a parameter, for a journey equal to the Earth-Moon distance. (1 MeV Ar^+ ions).

Fig. 2 Photographs of the giant ion source in the NBI system of the LHD fusion machine (Japan). Beam energy and current are 180 keV and 30 A, respectively. The arc chamber has dimensions of 35 cm$\times$145 cm in cross section and 21 cm in depth. [7,8]

Fig. 3 Illustration of the 500 keV giant negative-ion source used in the JT60U-NBI system. From Kuriyama *et al.* [15]

Fig. 4 Beam divergence is the half-angle of beam spread.

Fig. 5 Beam propagation distance for the beam radius to double under the influence of space-charge-blowup, as a function of space-charge neutralization deficiency, for ion beam currents of 10, 100, 1000 A. (1 MeV Ar^+, initial beam radius 1 m)

Fig. 6 Conceptual electrostatic ion sail, segmented so as to allow deflection of the ion beam in chosen directions by electrically biased beam deflectors, and hence spacecraft steering.

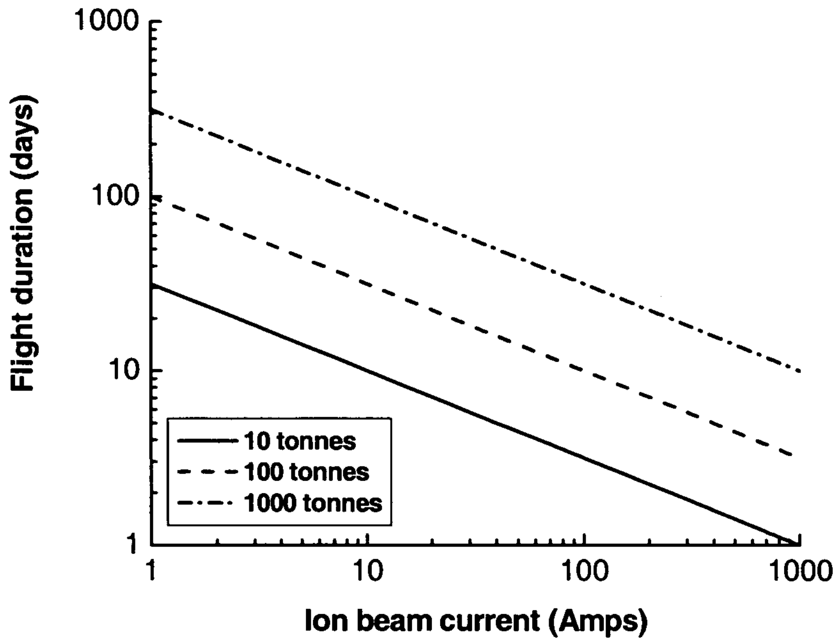
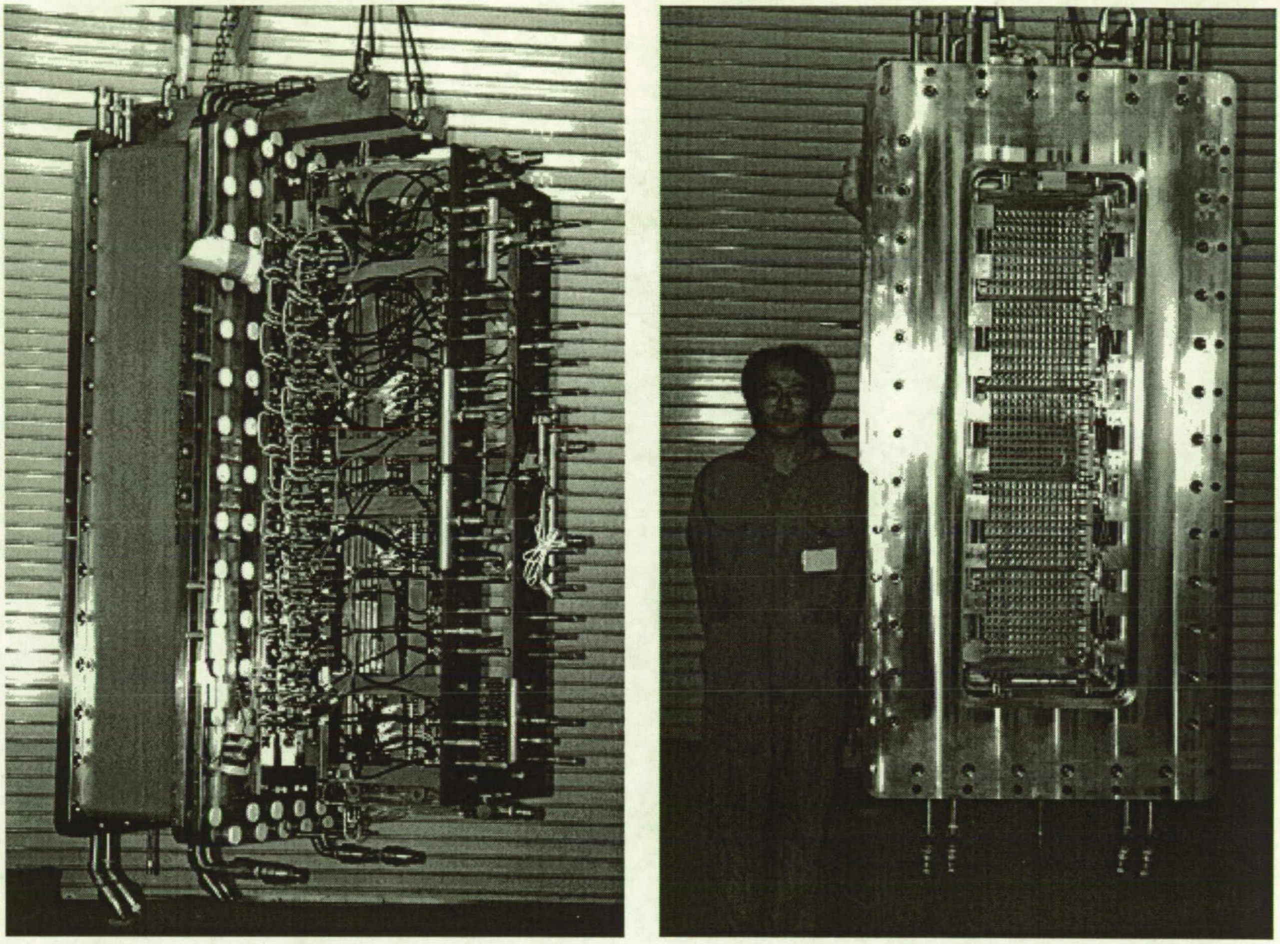

1000
100
10
1
1
10
100
1000
Flight duration (days)
Ion beam current (Amps)
10 tonnes
100 tonnes
1000 tonnes

Fig. 1



(a) (b)

Fig. 2

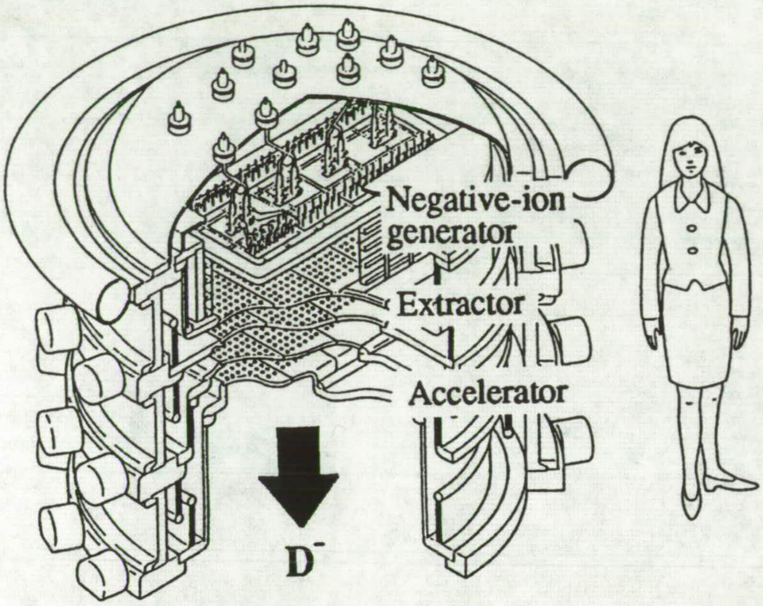


Fig. 3

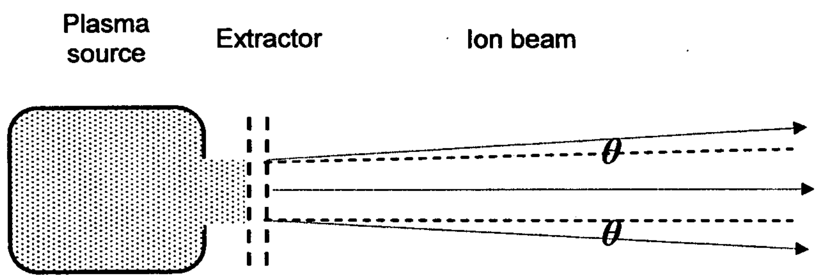


Fig. 4

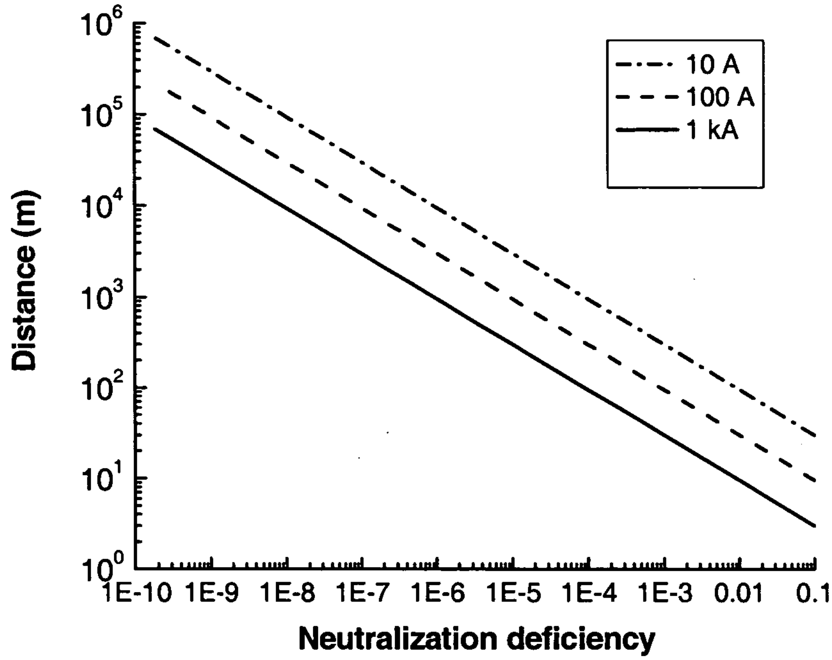
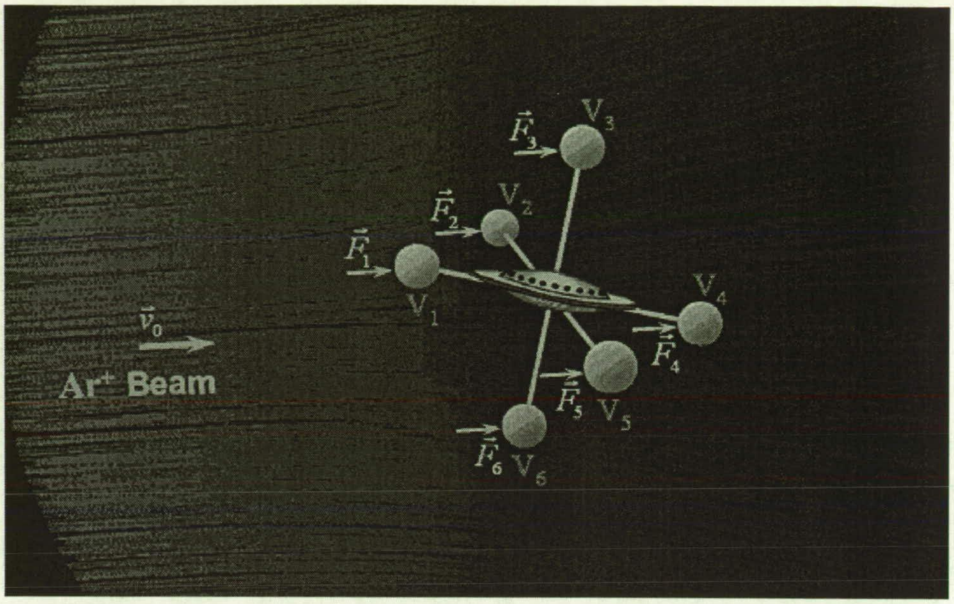

10 A
100 A
1 kA
Distance (m)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
1E-10 1E-9 1E-8 1E-7 1E-6 1E-5 1E-4 1E-3 0.01 0.1
Neutralization deficiency

Fig. 5



$\vec{F}_3$
V₃
$\vec{F}_2$
V₂
$\vec{F}_1$
V₁
V₄
$\vec{F}_4$
$\vec{v}_0$
Ar⁺ Beam
$\vec{F}_5$
V₅
$\vec{F}_6$
V₆

Fig. 6