Radio Frequency Plasma Applications for Space Propulsion

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Abstract— **Recent developments in solid-state radio frequency (RF) power technologies allow for the practical consideration of RF heated plasmas for space propulsion. These technologies permit the use of any electrical power source, de-couple the power and propellant sources, and allow for the efficient use of both the propellant mass and power. Efficient use of the propellant is obtained by expelling the rocket exhaust at the highest possible velocity, which can be orders of magnitude higher than those achieved in chemical rockets. Handling the hot plasma exhaust requires the use of magnetic nozzles, and the basic physics of ion detachment from the magnetic field is discussed. The plasma can be generated by RF using helicon waves to heat electrons. Further direct heating of the ions helps to reduce the line radiation losses, and the magnetic geometry is tailored to allow ion cyclotron resonance heating. RF field and ion trajectory calculations are presented to give a reasonably self-consistent picture of the ion acceleration process.** [1]

I. Introduction

Radio frequency (RF) power has been successfully used to heat ions in experimental fusion plasmas for several decades [1]. New advances in solid state RF power supplies, as shown in Fig. 1, now permit RF plasma heating techniques to become space relevant (direct to RF power conversion is already $\lesssim 350$ g/kW and decreasing). New high temperature superconductor (HTSC) technologies can also provide the magnetic elds required for both RF application and exhaust nozzle direction. These RF techniques do not use electrodes, scale over a large power range from ~ 100 to $\gtrsim 10^6$ Watts in fusion applications, and will permit the development of rockets with a wide range of speci c impulse from 2000 s to > 10000 s. These RF technologies show promise for both earth-orbit transfer (EOT) and for high speed interplanetary applications.

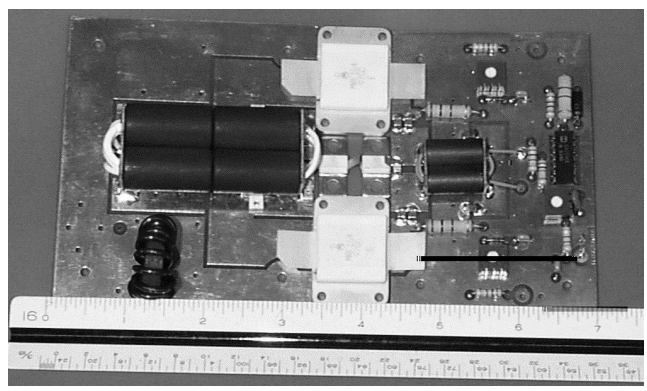

Fig. 1. Solid state amplifiers at 1 KW level now available.

The RF technologies considered here require a magnetic eld, both in the ion source region and in the ion acceleration region. The basic way that the RF rocket functions is illustrated in Fig. 2 in terms of the static magnetic eld along the rocket axis. A helicon plasma source [2] provides a relatively cold plasma stream with ion energies on the order of $5 - 10$ eV. These ions are then heated in the second section where an ion cyclotron resonance transfers wave energy into ion energy. This energy is initially stored in the ion velocity components perpendicular to the static magnetic eld, $E_\perp$, and then converted into directed energy (parallel to the rocket axis) through an adiabatic expansion of the static magnetic eld. Eventually, the magnetic eld becomes weak and bends away rapidly enough that the adiabatic invariance of the ion's magnetic moment is lost, and the ions escape from the magnetic nozzle. Electrons will escape with the ions because of self-consistent magneto-hydrodynamic currents, cross eld (Bohm) diffusion, and other turbulent effects.

The physics of the ion detachment can be estimated by considering the breakdown of the action-angle invariant obtained by averaging over the gyromotion of a

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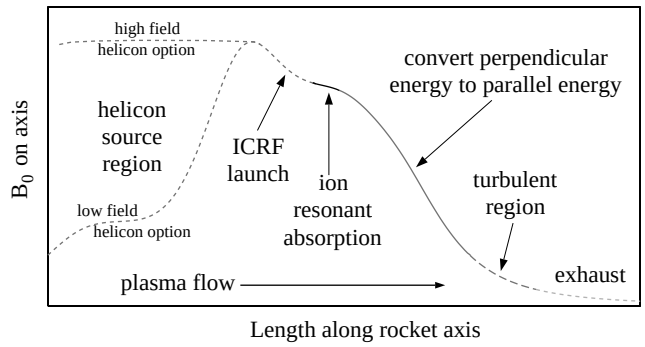

Fig. 2. Magnetic topology of RF heated thruster.

charged particle in a strong magnetic eld, $\mu = E_\perp/B_0$ (magnetic moment), where B_0 is the static magnetic eld strength. A charged particle's μ is a well conserved quantity until the static magnetic eld changes with a scale length comparable to the particle's gyromotion, at which point the orbit effectively becomes unmagnetized.

The action integral used to calculate μ is performed over a gyro-orbit. Therefore, the action invariant (μ) will be destroyed if the orbit becomes very eccentric in a single gyroperiod. De ning ρ to be the average gyro-radius during a gyro-period, and using Δ to denote the change in a quantity after a gyro-period, the orbit becomes unmagnetized when $\Delta\rho \gtrsim \rho$. This relationship can be written as

$$\frac{\Delta\rho}{\rho} = \frac{1}{2}\left[\frac{\Delta\mu}{\mu} - \frac{\Delta\Omega}{\Omega}\right] \approx -\frac{\Delta\Omega}{2\Omega} \gtrsim 1 \qquad (1)$$

where Ω is the gyrofrequency, and the approximation assumes that $\Delta\mu/\mu$ (evaluated at the guiding center location) remains small until the orbit becomes unmagnetized. The quantity $\Delta\Omega/\Omega$ can be estimated using the path of a eld line since the exact orbit roughly spirals around a guiding center orbit until μ is no longer conserved. This approximation allows Eq. 1 to be estimated with knowledge of only geometric quantities and the particle's energy. Along a eld line $\Delta\Omega/\Omega \approx \Delta s\ \hat{b}\cdot\nabla B_0/|B_0|$ where $\hat{b}$ is a unit vector along the eld line, and Δs is the distance traveled along the eld line during a gyroperiod. Assuming that most of the particle's energy has been converted into the parallel direction while μ is still conserved, $\Delta s \approx 2\pi v/\langle\Omega\rangle$, where v is the particle's speed and $\langle\Omega\rangle$ is the average gyrofrequency along the orbit. Thus, the estimate for the spatial location where the orbit becomes unmagnetized is given by

$$\left|\frac{\hat{b}\cdot\nabla B_0}{B_0^2}\right| \gtrsim 2200\frac{Z}{\sqrt{AE}} \qquad (2)$$

where A is the atomic weight, Z is the absolute value of the charge state, E is the particle energy in eV, B_0 is in Tesla, and the gradient scale is in m^{-1}.

The required values of B_0 for good ion heating are determined by the ion cyclotron resonance heating (ICRH) process. ICRH requires that the RF frequency, f, match the cyclotron motion of the ion, $f_i = qB_0/(2\pi m) \approx 15ZB_0/A$ (MHz), where, q is the ion charge and m is the ion mass. The coupling of the RF power tends to improve with increasing f, and a minimal RF coupling resistance is needed to efficiently handle the RF power. Preliminary results indicate that $f \gtrsim 1$ MHz will be required for small thruster systems. Only $Z = 1$ is considered to maintain a low energy cost for ion production and easier ion detachment. Thus, $B_0 \gtrsim 0.1$ T is needed for $A = 1$ (Hydrogen); easily obtainable with present HTSC technology. Constraints on HTSC materials may provide a challenge for applying ICRH acceleration techniques to ions with high A.

In section II, we discuss ion propellant choices based on simpli ed mission requirements. In section III, we discuss RF models used to calculate the RF elds and plasma interactions in RF rocket designs. In section IV, we give our conclusions.

II. Propellant choices

Initial technologies are aimed at low ion mass to ease the magnet and RF design requirements, and thus, have high speci c impulse (I_{sp}) $\equiv v/9.8\mathrm{ms}^{-2}$. Although the thrust is reduced for low ion mass, the resulting high I_{sp} can have signi cant advantages for some applications. First, the high mass propellants are typically rare and expensive noble gases such as Xenon. In addition, maximum practical acceleration energies lead to speci c impulse limits for high mass ions such that a large total propellant mass must be launched to reach high nal payload speeds. High nal payload speeds will be required for practical interplanetary missions, and minimizing the launched propellant mass can lead to lower cost missions or higher delivered payloads.

To demonstrate the advantages of high I_{sp} and low propellant ion mass, consider a simple power balance for a rocket with xed I_{sp}. The total power into the plasma stream, P_t, is the sum of the power required to produce the plasma stream, P_{ion}, plus the power that provides the kinetic energy (and momentum) for the exhaust. To simplify the ion production model, we de ne the average energy required to produce an electron/ion pair, E_{ion}, which includes any radiation or other losses incurred when producing the plasma stream. For an ion with atomic weight, A, $P_{ion} \approx 10^8 E_{ion} m'/A$, where P_{ion} is in Watts, E_{ion} is in electron-Volts (eV), and m' is the mass flow rate in kg/sec. In terms of the rocket thrust, $T \equiv m'v$, the exhaust velocity in the rocket frame can be expressed as

$$v = \frac{P_t}{T}\left(1 + \sqrt{1 - \frac{2\times 10^8 E_{ion}}{A\,(P_t/T)^2}}\right) \qquad (3)$$

where all units are MKS except for E_{ion} which is in eV. Similarly, the thrust is given by $T = 2AvP_t/(Av^2 + 2\times 10^8 E_{ion})$. From Eq. 3, note that for high ratios of P_t/T, the penalty for ionizing the initial plasma stream becomes negligible. Also note that some schemes for recovering part of the ionization energy may be possible if a low ratio of P_t/T is required.

To de ne a metric for determining the advantages of various propellants, consider a simpli ed one-

dimensional mission scenario where an initial mass, M_l, is launched into low earth orbit and is then accelerated by a plasma rocket. We assume that the mission uses a constant exhaust velocity relative to the rocket of v, and expells mass at a constant flow rate, m' until all of the propellant is depleted. The nal payload mass, M_p, is then related to the mass initially launched into low earth orbit, M_l, in terms of v and the change in speed of the nal payload, ΔV, by

$$M_p = M_l \exp\left(-\Delta V/v\right) \tag{4}$$

The time required to complete the velocity increment of ΔV for the nal payload is

$$\Delta t = \frac{M_p}{2P_t}\left(v^2 + 2\times 10^8 E_{ion}/A\right)\left({}^{\Delta V/v} - 1\right) \tag{5}$$

For most missions, it is desirable to maximize the -nal payload without requiring an excessive amount of time or power to achieve the desired orbit. The ratio of M_l/M_p determines the relative cost to launch the initial payload, and $P_t\Delta t/M_p$ determines an effective time per unit payload mass per unit power. Thus, to simultaneously satisfy both goals, we maximize the quantity $(M_p/M_l)/(P_t\Delta t/M_p)$ with respect to v where P_t and M_p are xed parameters. We also assume that tec

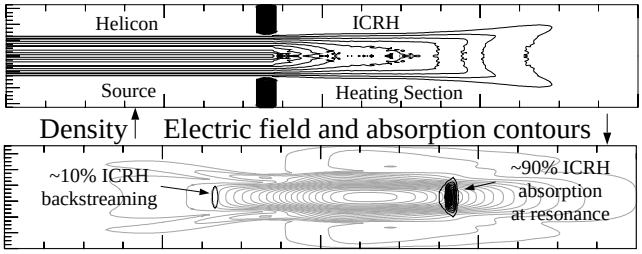

Fig. 4. Converged density and power for EMIR/VASIMR code iteration with con