A thruster using magnetic reconnection to create a high-speed plasma jet

IEPC-2019-940

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: High speed plasma jets are observed in the solar corona and in laboratory experiments where magnetic reconnection heats and accelerates plasma to Alfven speeds. Two designs of electrodeless plasma thrusters that exploit this phenomenon were constructed. The first design employed concentric split cylindrical conductors with equal pulsed currents of varying duration flowing circumferentially in the inner and outer cylinders. Those currents created magnetic fields that cancelled in the annulus between the cylinders. A second rectangular thruster was constructed with spaced parallel plate conductors carrying similar parallel currents that produced a magnetic field cancellation in the space between the plates. Both thrusters were operated in argon plasma at pressures between 5 x 10^{-5} and 1 x 10^{-3} Torr. High speed ions and electrons were detected with a Langmuir probe. An SCR was used to initiate a current pulse from a capacitor bank and a time delay with microsecond resolution was used to connect a second SCR as a shorting link to control the duration of the current pulse. The energy delivered to the thrusters was determined by the capacitor bank voltage. The velocity of the ions was measured by the sequential arrival time of accelerated plasma at two Langmuir probes, one 40mm behind the other, both facing the outlet of the thruster. The parallel plate thruster produced significantly larger ion outputs compared with the concentric cylinder thruster for the same energy input. Evidence for magnetic reconnection was threefold: (1) The detection of an initial flux with electron energy in excess of 150 eV that resembles the outflow observed in astrophysical objects; (2) The electron current coincided with the rising magnetic field and was followed by a large ion current, again similar to astrophysical observations; (3) In accordance with known physics of magnetic reconnection, the ion currents were found to increase as the plasma became less collisional. The measured speed of the out-flowing ions in plasma with a density of 1.6 x 10^{17} /m^3 was 1316 ± 575 m/s corresponding to an Isp of 134 ± 58 s.

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Nomenclature

B	=	magnetic flux density
B_x	=	upstream magnetic flux density
c	=	speed of light
c_{Ae}	=	electron Alfven speed
dt	=	time step
δ_ε	=	electron skin depth
δ_ι	=	ion skin depth
E	=	electric field strength
e	=	electron charge
η	=	resistivity
η_t	=	thrust efficiency
J	=	current density
L_e	=	current sheet length
ℓ	=	current sheet width
m_e	=	electron mass
m_i	=	ion mass
n_e	=	electron number density
n	=	plasma number density
Ω_i	=	ion cyclotron frequency
$\mathbf{P_e}$	=	electron pressure tensor
ρ_s	=	effective ion Larmor radius
T_e	=	electron temperature
v	=	fluid (ion) velocity
μ_0	=	permeability of free space
ω_{pi}	=	ion plasma frequency
ω_{pe}	=	electron plasma frequency

I. Introduction

MAGNETIC reconnection occurs when domains of anti-parallel magnetic field lines that are frozen into plasma meet. The interaction releases magnetic energy and creates new domains together with an accelerated outflow of heated plasma that is produced in a current sheet or diffusion layer that arises at the boundaries of the original domains. The process results in a rough equi-partition of the energy in the magnetic fields into the thermal and kinetic energy of the accelerated particles. Magnetic reconnection was first proposed by Giovanelli[1] in 1946 as an accelerating mechanism for the hot, high speed outflows that were observed in the solar atmosphere. Subsequently, Dungey[2], a student of Fred Hoyle, proposed that “lines of force can be broken and re-joined” and developed an MHD theory where reconnection occurs at magnetic nulls and the magnetic energy is converted to that of hot, high speed particles. Following that work, Sweet and Parker produced a model where the breaking and reconnection of field lines occurs in a current sheet and where the out-flowing plasma is accelerated to a speed comparable to the Alfven speed of the inflowing plasma[3,4]. In the Sweet–Parker model of reconnection the plasma resistivity η provides the dissipation required to break magnetic field lines and the tension associated with newly reconnected magnetic field lines drives plasma away from the X-line at the Alfvén speed c_A[5]. The model describes reconnection as a stationary resistive MHD process that occurs with the conservation of mass and flux (Fig. 1[6]).

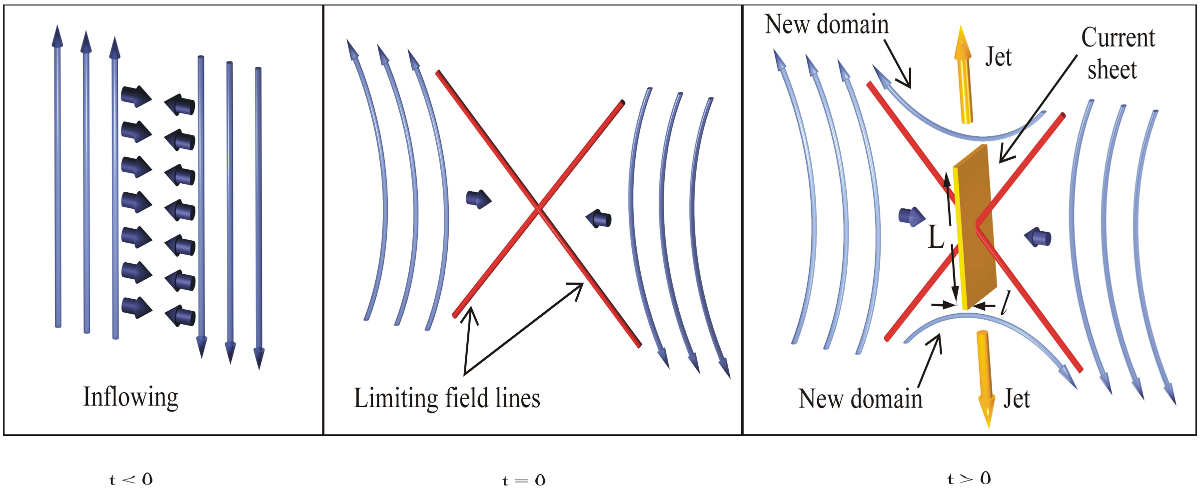

Figure 1. The Sweet-Parker model of reconnection proposes that collisions between two separate magnetic domains in plasma produce plasma jets by reconnection of magnetic field lines in a current sheet or diffusion region that forms between the domains. At t < 0 inflowing plasma with embedded magnetic flux initiates the process. At t = 0 an X-type magnetic null is produced by the interaction of opposing magnetic field lines. The limiting field lines are known as separatrices and form an "X" from which the term "X" type null point is derived. At t > 0 a current sheet of length L and thickness l forms a diffusion region, jets of heated plasma are ejected from the current sheet, lines of force are broken and rejoined and four separate magnetic domains are created6.

The Sweet-Parker model is accepted as a limited description of the basic mechanism of magnetic reconnection, calculations based on the model underestimate the rate at which reconnection occurs in the limit of low resistivity – such as in the solar corona - by several orders of magnitude. In order to resolve this difficulty, Petschek[7] proposed a different steady state model in which reconnection is forced to occur at an X point. In contrast with the Sweet-Parker model, Petschek's model yields reconnection rates that are near-Alfvenic, with a weak logarithmic dependence on η[8]. Later work demonstrated that reconnection depends upon kinetic effects that occur on scale lengths where MHD breaks down.

The evolution of the magnetic field in a plasma with resistivity η is governed by the magnetic induction equation (based on Faraday's, Ampere's and Ohm's Laws) which describes the motion of magnetic field lines in a plasma that is described as a conductive fluid:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B} \tag{1}$$

This equation states that the magnetic field changes partly because of the transport of the plasma (the first term on the right hand side) and partly because of the diffusion of the magnetic field through the plasma (the second term on the right hand side). In most regions of the universe the magnetic field is frozen into the plasma and the diffusion term is negligible as when $\eta = 0$, i.e. the plasma is a perfect conductor and the field lines move with the plasma. The simplified resistive MHD Ohm's law equation where resistivity breaks the frozen-in condition is given by:

$$\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} = \eta \mathbf{J} \tag{2}$$

In this approximation time derivative terms are not included which means that the Hall currents, electron pressure and electron inertia that operate at small scale lengths make no contribution. In high temperature plasmas the width of the diffusion region becomes comparable to kinetic scales so terms incorporating these effects must be included. The more complete generalized Ohm's law is given by:

$$\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} = \eta \mathbf{J} + \frac{\mathbf{J} \times \mathbf{B}}{e n_e c} - \frac{\nabla \cdot \mathbf{P_e}}{e n_e c} + \frac{m_e}{n_e e^2} \frac{d\mathbf{J}}{dt} \tag{3}$$

The additional terms introduce respectively dispersive whistler waves, kinetic Alfven waves through electron pressure and electron inertia into the system. All these effects have associated scale lengths viz. the ion skin depth, $\delta_i = c / \omega_{pi}$, the effective ion Larmor radius $\rho_s = \sqrt{T_e / m_i} / \Omega_i$ and the electron skin depth (also known as electron inertia) $\delta_e = c / \omega_{pe}$ respectively. When the resistive scale length of the diffusion region is comparable to or larger than these scale lengths then the resistive MHD theory is valid. Otherwise the appropriate terms must be incorporated in the calculations[9].

At small scales the field lines are frozen into the electron fluid, the motion of the electrons and ions decouple and when the transverse scale length of the diffusion region, ℓ, is smaller than the ion skin depth δ_i , then the $\mathbf{J} \times \mathbf{B}$ term must be incorporated in Ohm's Law. The effect of this inclusion is to bring the dynamics of whistler waves into the equation. Simulations reveal that whistler waves play a central role in driving electrons away from the magnetic X-line where the outflow is propelled by the Hall electric and magnetic fields. In these simulations when the width of the diffusion layer is equal to the electron skin depth, δ_e, the magnitude of the electron outflow speed driven by the whistler is equivalent to the electron Alfven speed[10].

$$c_{A_e} = B_x / \sqrt{4\pi m_e n} \tag{4}$$

Fast reconnection requires either the coupling to dispersive waves at small scales or a mechanism for anomalous resistivity. A basic analysis shows that during reconnection approximately 50% of the energy in the magnetic field is converted into heat and kinetic energy of the particles[11]. In a thruster those particles may then be further accelerated with a magnetic nozzle[12]. In a simple thruster design, particles are symmetrically expelled from the current sheet that is aligned with the axis of the device so that a magnetic mirror at one end may be required to maximize the thrust. Other proposals, such as a longitudinal density gradient of propellant inside the thruster, could be used to produce the required asymmetric outflow12.

II. Methods

Measurements were made in a purpose-built vacuum chamber to which was attached a plasma source that consisted of a 200mm diameter quartz tube supporting a helicon antenna that was fed through a matching network with 250 watts of 13.56MHz RF energy (fig. 2). The thrusters that were insulated from the plasma were connected to a 4.5 x10-3 F capacitor bank that was charged to voltages between 30V and 120V. A Labview program initiated the discharge of the capacitor bank into the thrusters through an interface to an 800A silicon controlled rectifier. In order to investigate the effect of varying durations of driving current pulses, a device with a 10µS resolution that could limit the time that current was delivered to the thruster was constructed. The driving current supplied to the thruster was measured with a Rowgowski coil and the resulting electron and ion outflow current from the thruster was detected with a Langmuir probe. That current was measured with a differential amplifier whose inputs were connected to the Langmuir probe. Data from experiments were collected by a Tektronix model 2014 digital storage oscilloscope operating under the control of the Labview program.

In a typical experiment, the plasma density was first measured with a Langmuir probe. The equipment was then re-configured to measure electron and ion currents produced by the thruster in the same plasma. Twenty five pulses of driving current were fed to the thruster and the electron and ion currents produced by the thruster were averaged. The ion current produced by the thrusters was found to be directly proportional to the duration of the driving current pulse.

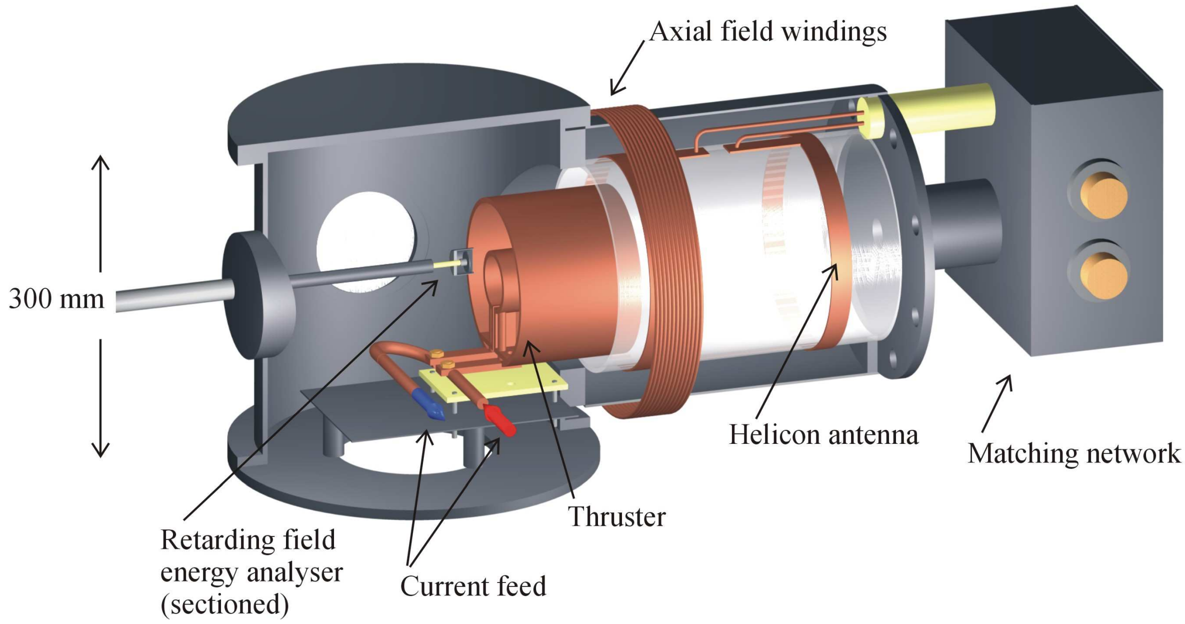

Figure 2. Sectioned schematic of the magnetic reconnection experimental apparatus showing the installation of the cylindrical thruster tubes inside a vacuum chamber. The thruster tubes were normally covered with Teflon insulation that is not shown in order to expose the structure of the thruster. Plasma was produced in argon by a helicon antenna outside a quartz tube that was fed with radio frequency energy through a matching network at 13.56MHz. A Langmuir probe, part of a retarding field energy analyzer, either facing the annulus between the thruster tubes or the center of the tubes, detected ions and electrons accelerated by a current pulse injected into the thruster tubes6.

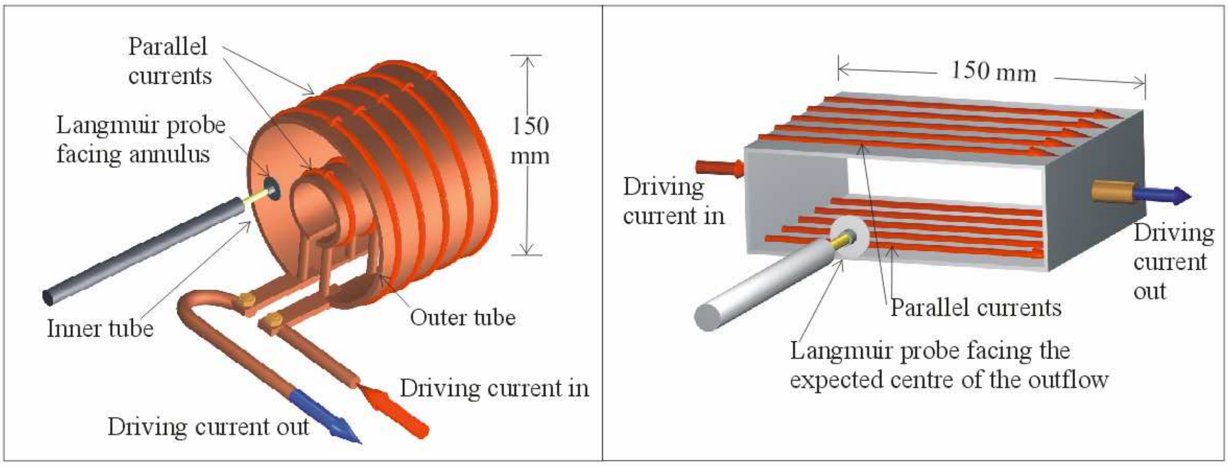

Figure 3. Schematic of the cylindrical (LHS) and the rectangular (RHS) thrusters. The cylindrical thruster was constructed from copper tubes while the rectangular thruster was constructed from sheet aluminium. Both thrusters were insulated from the plasma in which they were immersed with enclosures of Teflon that are not shown in order to make the illustrations clearer. Parallel currents flowing in the conductors created magnetic fields that cancelled in the region between the cylinders and plates respectively. Magnetic reconnection in those regions produced a measured outflow of high speed electrons and ions.

III. Results

Measurements of ion and electron currents produced by the cylindrical and rectangular thrusters were made. In all experiments the Langmuir probe was kept at a voltage of -150V in order to repel electrons. Ion currents from the thrusters were observed to increase in synchrony with the rise of the driving current pulse. A threshold effect was evident and a driving current of at least several hundred amps was required to produce an ion current from the thrusters. The magnitude of the resulting ion current produced by the rectangular thruster (fig. 5) was, for a similar driving current and plasma density, approximately five times as great as that produced by the cylindrical thruster (fig. 4).

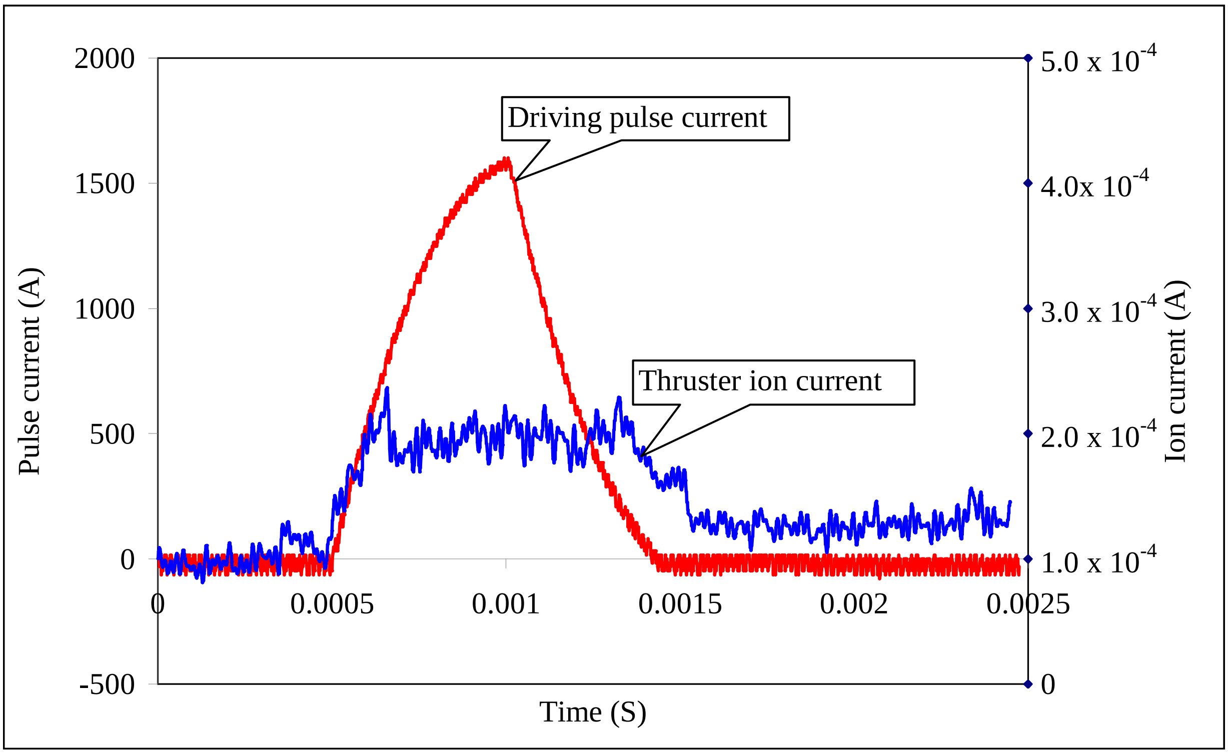

Figure 4. Measured ion currents collected by a 15mm diameter Langmuir probe produced by the tubular thruster when driven by a 500μS current pulse.

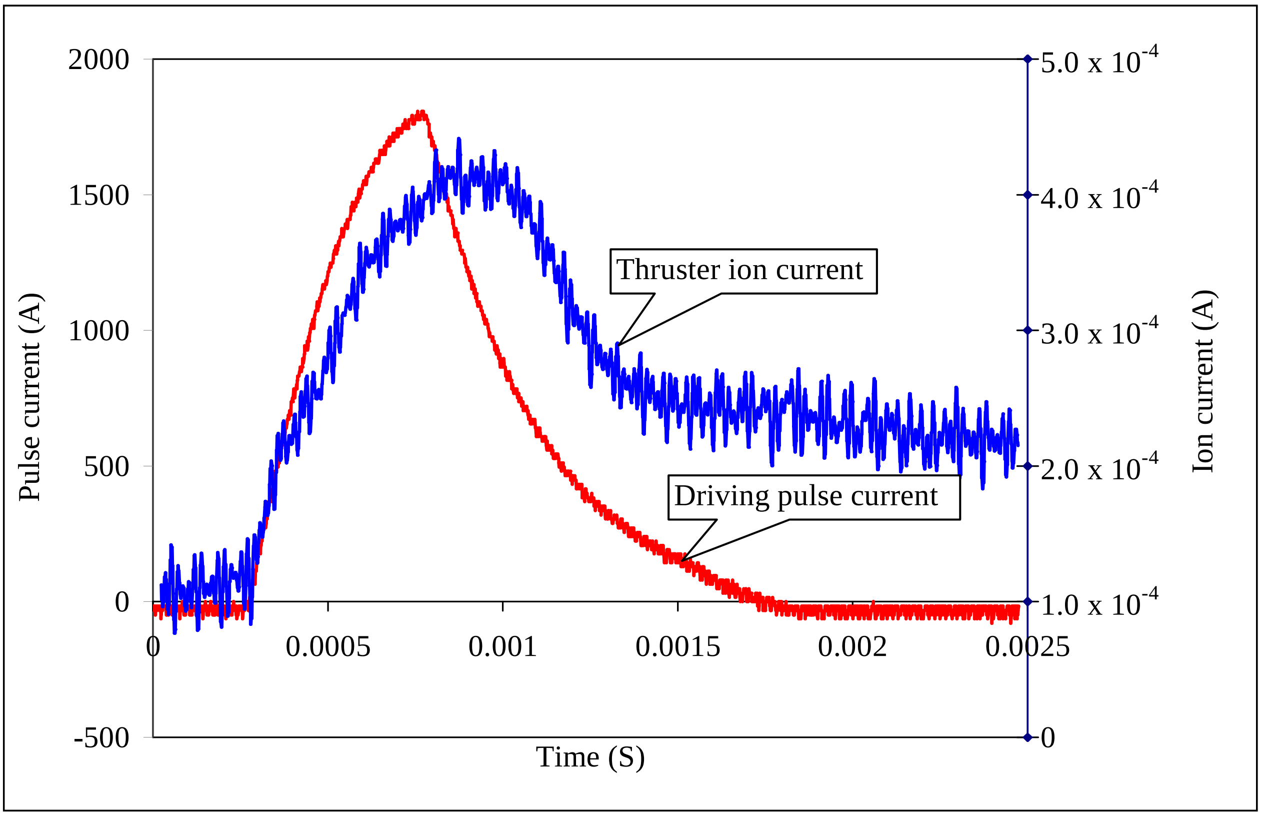

Figure 5. Measured ion currents collected by a 15mm diameter Langmuir probe produced by the rectangular thruster when driven by a 500μS current pulse.

The effect of varying lengths of driving current pulses supplied to the rectangular thruster was investigated. A clear correlation between the length of driving current pulse and the quantity of accelerated charges produced by the thruster was found (fig. 6).

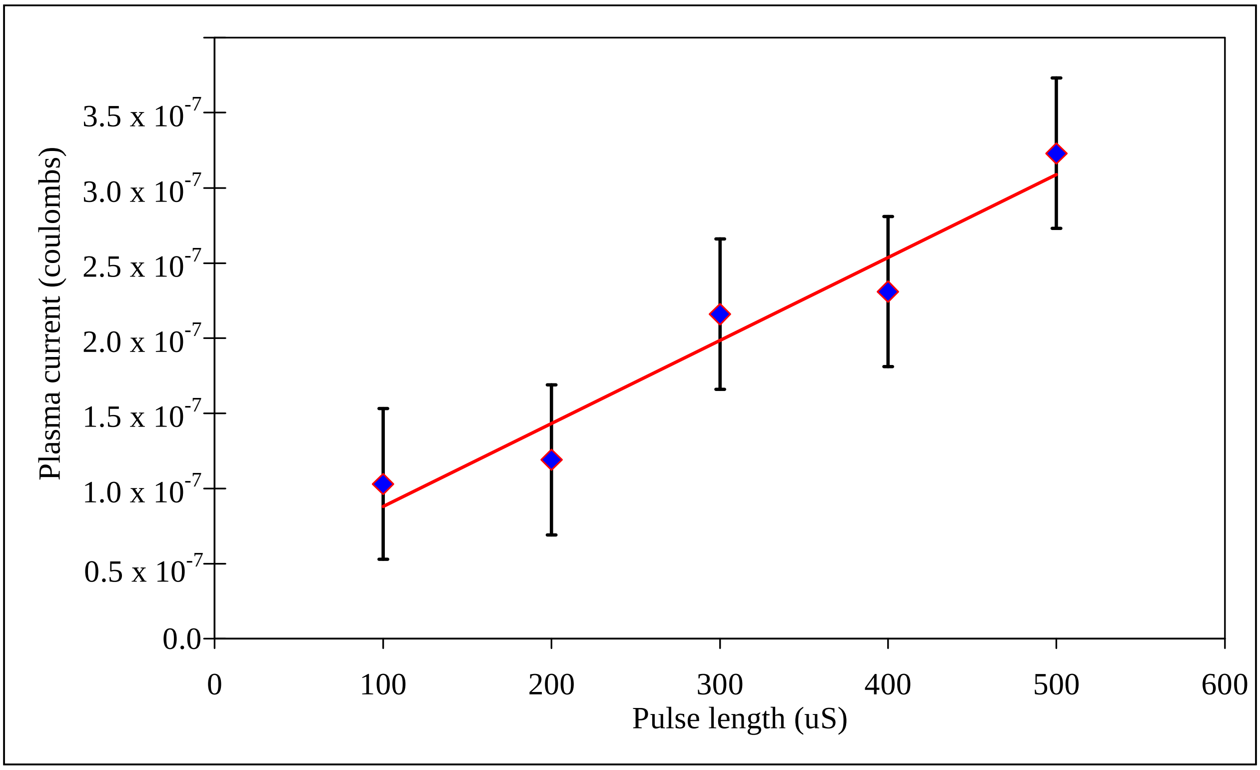

Figure 6. Measured ion currents collected by a 15mm diameter Langmuir probe were produced by the rectangular thruster as a function of the driving current pulse duration. The ion currents produced by the thruster increased in proportion to the length of the driving current pulse

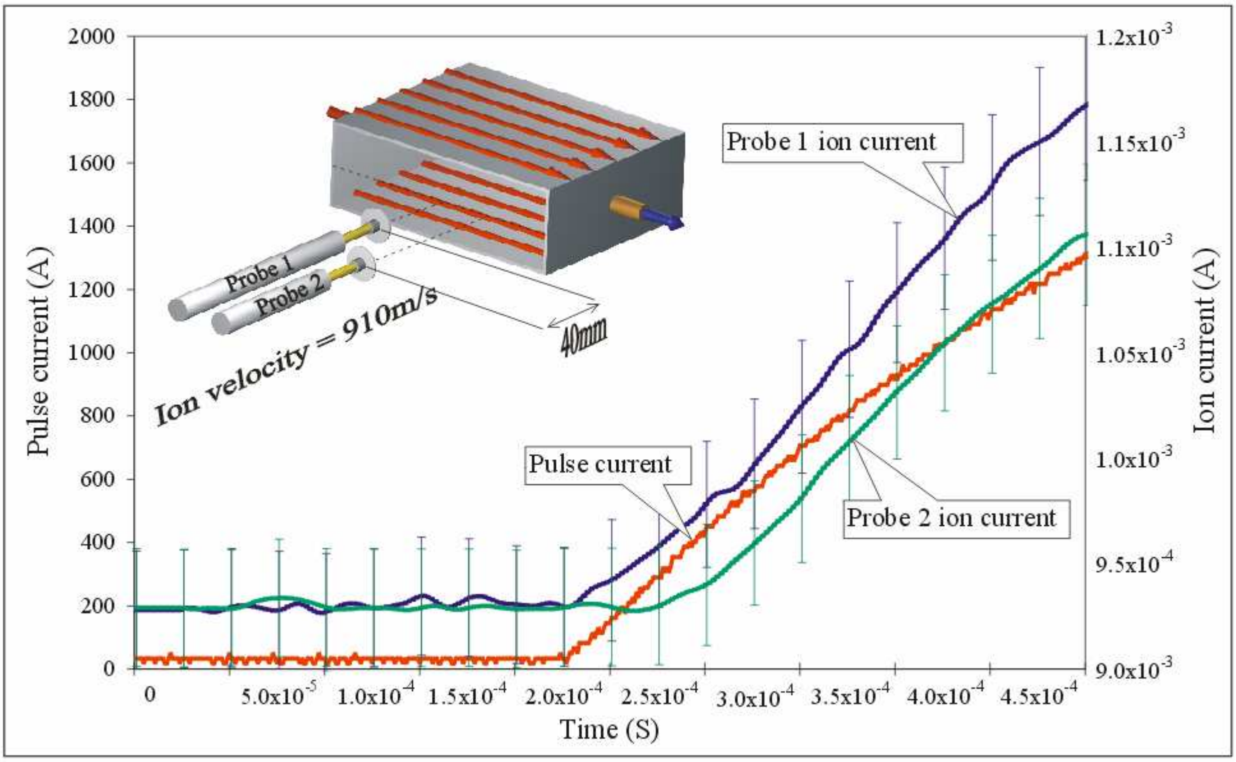

Figure 7. Measuring ion velocity using two Langmuir probes aligned with the axis of the rectangular thruster with the second probe located 40mm behind the first probe. The consecutive arrival times of the accelerated plasma at the probes were used to determine the ion velocity. 25 samples were taken and then averaged to produce a velocity figure. The average ion velocity was 1316 ± 575 m/s corresponding to an Isp of 134 ± 58 s.

Conclusions

The purpose of this investigation was to determine if the phenomena of magnetic reconnection could be used as a means of accelerating plasma in a thruster suitable for spacecraft. We have demonstrated that magnetic connection can be used as a mechanism in a simple electrodeless plasma thruster to produce a significant ion current at a high velocity. The experimental results strongly support the occurrence of magnetic reconnection in these devices. Although the average measured ion velocity (1316 ± 575 m/s**)** was much less than the calculated Alfven velocity, (21,800 m/s) the relatively high pressure that the velocity measurements were made at (1 x 10^{-3} Torr) meant that the plasma was collisional and the high-energy electron flux associated with reconnection at lower pressures (5 x 10^{-5} Torr) where the plasma is collisionless was not observed.

The physics of magnetic reconnection indicate that the inherent thrust efficiency η_t of an optimized thruster would be approximately 50%, the result of the conversion of the magnetic energy into a rough equipartition between the thermal and kinetic energies of the accelerated particles. The thrust efficiency would be increased by the effect of the magnetic nozzle formed by the diverging magnetic field produced by the currents in the thruster.

Equation (1) shows that the ion velocity is proportional to the rate of change of the magnetic field. An increase in the rate of change in the magnetic field – which is a practical proposition - would lead to increase the ion velocity.

We have shown that comparing cylindrical and rectangular devices, the production of accelerated plasma is enhanced when the thruster geometry produces a magnetic null between domains of equivalent field strength since the magnetic field strength on the exterior of the inner tube is much less than the field strength inside the outer tube.

Acknowledgments

- The financial support of the Australian Research Council for this project is acknowledged. The Australian Government is acknowledged for the provision of an Australian Postgraduate Award.
- Professor Iver H. Cairns and the ARC Industrial Transformation Training Centre for CubeSats, UAVs, and Their Applications (CUAVA) are acknowledged for their support.
- Professor Marcela Bilek is gratefully acknowledged for her support.
- Professor David McKenzie is gratefully acknowledged for his support.

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