Experimental Setup for the Development of a Traveling Magnetic Field Plasma Accelerator

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This paper describes the experimental setup developed to study a traveling magnetic field plasma accelerator. This system represents the second stage of a dual-stage electrodeless propulsion system in which the plasma produced by a primary ionization source is accelerated by means of a traveling magnetic field. Previous 1D Particle-In-Cell simulations showed that the electron dynamics is directly affected by the propagating magnetic field; under certain conditions this interaction generates a space charge and an electric field at the magnetic front that accelerates ions. A proof-of-concept system has been designed and built based on an array of time-delayed pulsed discharges to produce the traveling magnetic field and it has been tested coupled with independent helicon or microwave plasma sources. The experimental setup includes current probes, magnetic field probes and a time-of-flight probe in order to capture possible plasma-traveling magnetic field interactions.

Nomenclature

PIT	= Pulsed Inductive Thruster
I_{sp}	= Specific impulse
$MOSFET$	= Metal Oxide Semiconductor Field Effect Transistor
z	= Axial Direction
DC	= Direct Current
f	= Frequency
R	= Resistance
L	= Inductance
C	= Capacitance
ζ	= Damping Coefficient
RF	= Radio Frequency

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I. Introduction

In standard electric propulsion systems one of the main lifetime-limiting process originates from the erosion of the acceleration grids or electrodes, whose surfaces are exposed to energetic particles and are subject to high temperature conditions. For this reason, a lot of emphasis has been put in developing electrodeless propulsion systems. Not relying on electrodes to accelerate the propellant can boost significantly the lifetime of a thruster; an added bonus to this technology is the neutrality of the exhaust flow, which avoids the use of an additional neutralizer.

An example of an electrodeless thruster is the PIT.[2] It mainly consists of a flat spiral coil, with a pulsed current flowing through it; the current is typically generated by discharging a bank of capacitors. Gas is injected in the thruster in pulses synchronized with the current pulses through the coil. The increasing current generates a strong azimuthal electric field that ionizes the gas and induces an azimuthal current in the plasma itself. The current in the plasma and that one in the coil flow in opposite directions, creating a repulsive force that blows the plasma out of the thruster. I_{sp} over 2000 s and efficiencies around 50% have been obtained.

Other alternative solutions have been proposed, such as an electrodeless thruster based on a rotating electric field.[3] In this case the superposition of a rotating electric field and a magnetic field (both axial and radial) is exploited to accelerate the propellant. The plasma produced in a source stage is injected into the thruster and gets an induced rotational motion due to the applied rotating electric field and axial magnetic field; this rotating motion generates an azimuthal current in the plasma, which interacts with the radial component of the magnetic field to push the propellant flow downstream.

Another proposed concept is an electrodeless thruster based on an axially traveling magnetic field.[1,4,5,6,7] This technology is typically arranged in a dual-stage configuration in which a traveling magnetic field accelerates the plasma generated by a primary ionization source. However, in some studies the electric field associated to the time-varying magnetic field was strong enough to ionize the neutral propellant, embedding ionization and acceleration in a single stage. The acceleration mechanism has been previously investigated implementing a particle-in-cell model.[1] The simulations highlight the role of electrons as carriers of the acceleration; indeed the traveling magnetic field directly acts on electron dynamics creating a space charge at the magnetic front and inducing an electric field which accelerates also the ions (indirect effect on the ion dynamics). The typical hardware configuration is made of coils with phase shifted currents to generate a magnetic field that propagates downstream in the axial direction. Multiple studies were carried out in the '60s and '70s about accelerating plasma with a propagating magnetic field and demonstrated the effectiveness of the acceleration concept. Most studies however relied on huge amounts of power to produce a high enough level of current in the coils to generate a strong magnetic field in the accelerator channel.

The goal of this work is to design a traveling magnetic field accelerator that operates in the low power range. A design guideline is the limitation of wall losses increasing the aspect ratio diameter/length of the accelerator cylindrical channel in comparison with previous prototypes[1]. The accelerator is based on time-delayed capacitor discharges in RLC circuits which are able to produce a traveling magnetic field with velocities up to 30,000 m/s and strengths up to 150 G. The developed system is able to work in constant velocity mode or can provide an increase of the traveling velocity along the accelerator channel.

II. Paper Outline

This paper is organized as follows. First, a general description of the setup is presented along with the key parameters of the system and its operational features. Then, after a brief description of the diagnostics, we present and discuss some preliminary results obtained in different configurations, and we conclude with ideas that could be applied in the future to carry on and improve the work.

III. Accelerator Characteristics

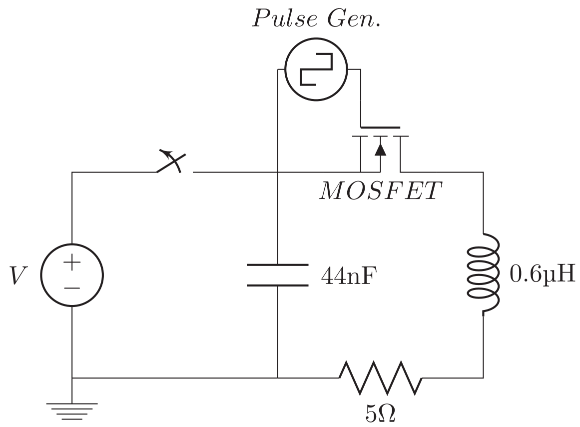
The accelerator has been designed and built for pulsed mode operation. It consists of 7 independent RLC circuits that generate time-delayed current pulses to achieve an overall traveling magnetic pulse; the internal diameter of the accelerator is 2.5 cm and the total length is 3.5 cm. Each coil is made of 4 windings of 2 mm diameter copper wire arranged in 2 layers with 2 turns each, with an inductance of 0.6 µH. The current pulses are produced by discharging two 22 nF capacitors in parallel, equivalent to 44 nF for each circuit. To damp the oscillations and produce a single current pulse, a 5 Ω resistor has been introduced in series to the other components. These parameters have been selected following a design phase based on the classical equations describing the physics of RLC circuits. In particular:

$$2\pi f = \frac{1}{\sqrt{LC}} \tag{1}$$

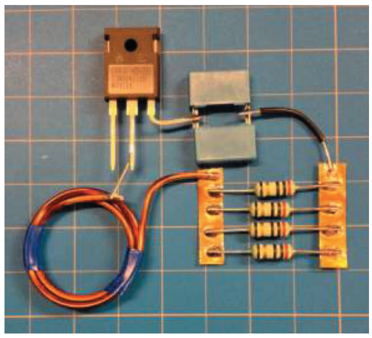
$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}} = 4\pi f L \tag{2}$$

where f is the natural oscillation frequency and ζ the damping coefficient. The design phase includes a trade-off analysis to satisfy the requirements on: 1) magnetic field strength; 2) traveling velocity range; 3) pulse width; 4) accelerator channel geometry (in terms of aspect ratio); 5) energy/pulse ratio and repetition rate of the pulses (giving the power consumption). Such a process has been carried out with the support of Matlab and Simulink models. The developed single circuits present a natural frequency of 1 MHz and a damping coefficient $\zeta = 0.83$.

MOSFETs have been embedded in the circuits to control the charge and discharge of the capacitors, whereas solid state relays are used to open and close the connection between the capacitors and the power supply. A simple schematic of a circuit is represented in Fig. 1a, while Fig. 1b shows the arrangement of the components within the circuit.



(a) Single circuit schematic.


(b) Picture of a single circuit.

A. Pulsed Mode Operation

The capacitors are charged by a 10 mA high voltage DC power supply at a maximum voltage of 800 V, giving a pulse energy of 0.014 J for single circuit or 0.098 J overall; a power level of 9.8 W is obtained at a repetition rate of 100 Hz. Solid state relays are incorporated between the power supply and the capacitors and are controlled by a Stanford Research System DG535 pulse generator (A) which opens and closes the line at a set frequency (i.e. the traveling magnetic pulse repetition frequency). The same pulse generator triggers two additional pulse generators (B and C) which operate the MOSFETs, allowing to close the RLC circuits only when the power supply has been disconnected; this operational sequence is needed to avoid any influence of the power supply on the current pulses generated by discharging the capacitors through the coils. Each pulse generator (B and C) may pilot up to four MOSFETs, closing each circuit at the proper time-delay from the trigger. The velocity of the traveling magnetic pulse is directly dependent on the time delay between the activations of the MOSFETs embedded in two consecutive circuits; the possibility to set the time-delays on the pulse generators allows a flexible determination of the magnetic field propagating velocity. The upper boundary for the velocity is 30,000 m/s, however the accelerator has been operated mostly at a magnetic pulse velocity of about 13,000 m/s, with some tests done at different velocities ranging from 5,000 m/s to 25,000 m/s. The tests have been conducted at different repetition rates, however we mainly operate at 5 Hz in order to allow the power supply to fully charge the capacitors before discharging them. Two different primary ionization stages have been employed in the experiments: one is a helicon source, continuously operated in a power range from 3 to 35 W on argon; the second source is a 2.45 GHz Evanson microwave cavity operated at 40 W, again on argon. The system consists of a quartz tube with two expansion regions: the tube diameter presents two step-changes from 1.25 cm to 2.5 cm and from 2.5 cm to 5 cm. The plasma sources require a diameter of 1.25 cm, the accelerator is located around the 2.5 cm region, and finally the tube is connected to the vacuum chamber through a 5 cm port. The tube is mounted outside the vacuum chamber, with the accelerator placed about 2 cm after the first expansion. The vacuum chamber is a 0.6 m diameter, 1.2 m length stainless steel chamber, pumped down to a base pressure level of 10^{-6} Torr when any mass flow is not injected, or $10^{-4} - 10^{-5}$ Torr during the thruster operation; these pressure levels are achieved by a single 50 cm diameter cryopump; the initial rough vacuum is obtained through a mechanical pump and a blower. Pictures of the setup are presented in Fig. 3.

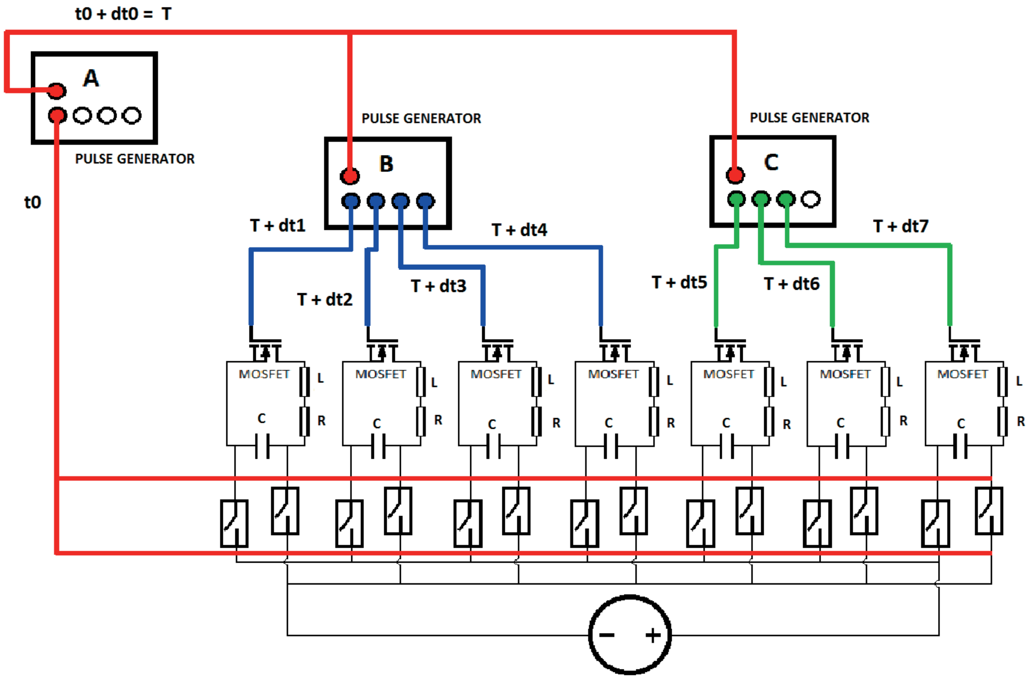


Figure 2: Simplified system schematic.

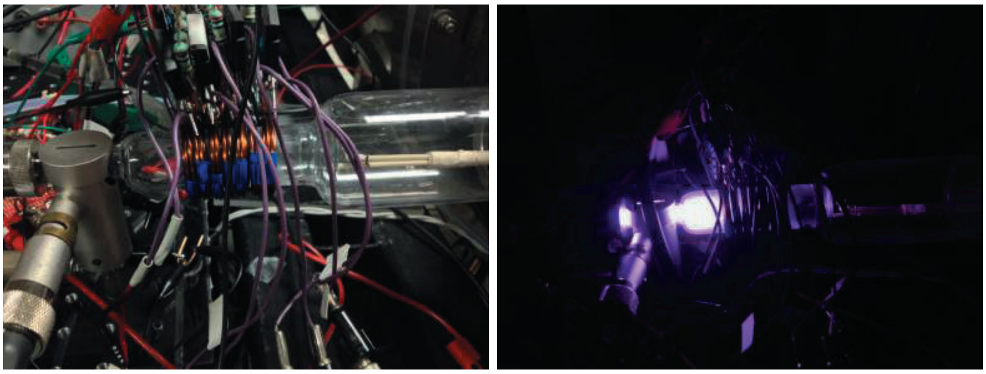


Figure 3: Pictures of the setup with the microwave plasma source.

B. Diagnostics

In order to determine the presence of a traveling magnetic pulse within the accelerator, two B-dot probes have been built. Each one consists of a single layer of 30 turns of 32 AWG wire, with an inner diameter of 1.2 mm; both have been calibrated with the uniform magnetic field of a solenoid, applying a similar approach as that presented in Ref. 8. The two probes have been placed at a known distance inside the accelerator channel in absence of plasma; the magnetic pulse velocity is then calculated by determining the time delay between the peaks measured by the two probes. Finally, time-resolved measurements of the magnetic field at multiple distances (every 3 mm along the length of the accelerator) allow the reconstruction of the magnetic field spatial evolution.

Pearson probes have been used to measure the current flowing through the first and last circuits to check the coherence of the time delays with the settings on the pulse generators; all circuits have also been tested before and after the assembly in the final array to verify their capability of generating the expected current pulses.

A time-of-flight probe has been used in order to detect any interaction between the traveling magnetic pulse and the plasma. The probe consists of two copper conductors placed 1.46 cm apart; the purpose is estimating the velocity of the plasma flow simply by detecting the time delay of the current peaks at the conductors spaced by a known distance. The probe includes also a third conductor shielded from the plasma flow by means of a ceramic case in order to detect whether the signals produced by the unshielded conductors come from a real interaction with the plasma sheet or just from electromagnetic interference. Measurements have been performed at different time scales, in order to detect both the effect of a single burst and the effect of multiple magnetic pulses discharged at the set frequency. The effect of different voltage levels (i.e. of the energy per pulse in each single circuit) has been also explored.

IV. Preliminary Experimental Investigation

The first measured parameter has been the current through the coils in order to verify its agreement, both in terms of intensity and pulse width, with the design profile and the capability of the system to properly time-delay subsequent pulses. The results obtained from these measurements have been used as input parameters for numerical simulations of the magnetic field produced within the accelerator; we have then compared the measured values of the field with the simulated ones to demonstrate the agreement between the predicted magnetic field and that generated by the experimental setup.

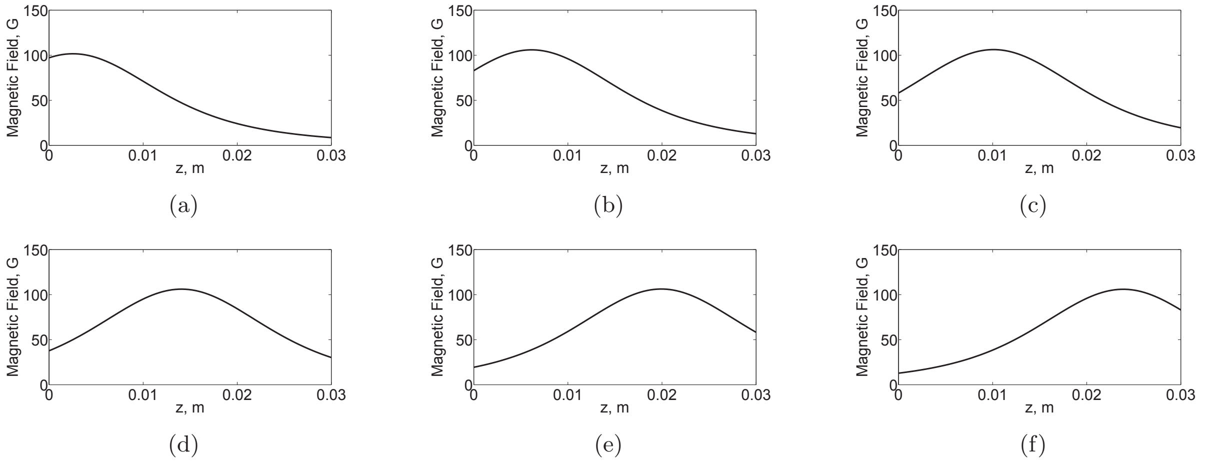


Figure 4: 1D magnetic field simulation at different time instants: a) t_0 µs, b) $t_0 + 0.5$ µs, c) $t_0 + 1$ µs, d) $t_0 + 1.5$ µs, e) $t_0 + 2.2$ µs, f) $t_0 + 2.5$ µs.

The following step involves capturing the time-evolution of the magnetic field at ten different locations inside the accelerator; this set of measurements provides enough resolution to reconstruct the spatial distribution of the magnetic field at different times. Fig. 4 and 5 show the measured field is in agreement with that obtained through the numerical simulations. The measurements demonstrate the accelerator effectively

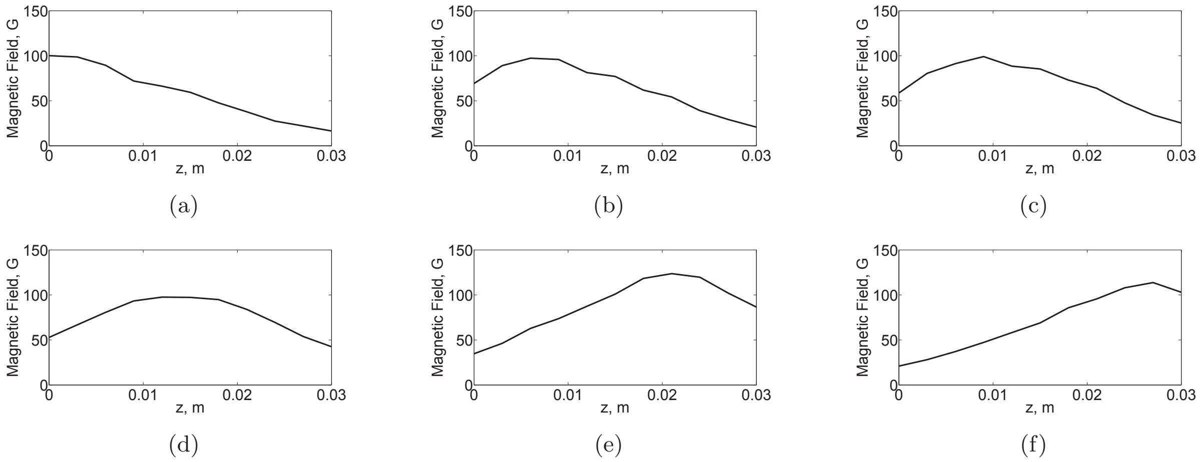


Figure 5: 1D magnetic field measurement at different time instants: a) t_0, b) $t_0 + 1.3$ µs, c) $t_0 + 1.5$ µs, d) $t_0 + 1.9$ µs, e) $t_0 + 2.5$ µs, f) $t_0 + 2.9$ µs.

produces a magnetic pulse traveling along its length.

Additional tests have been performed to verify the coherence of the generated magnetic field velocity with the settings of the accelerator; we have tested different velocities (see Fig. 6) and we have determined that the measured velocities differ from the theoretical ones by less than 11%, an acceptable discrepancy for our purposes which has roots in the errors on the position of the magnetic probe as well as some fluctuations of the delay between two consecutive current pulses.

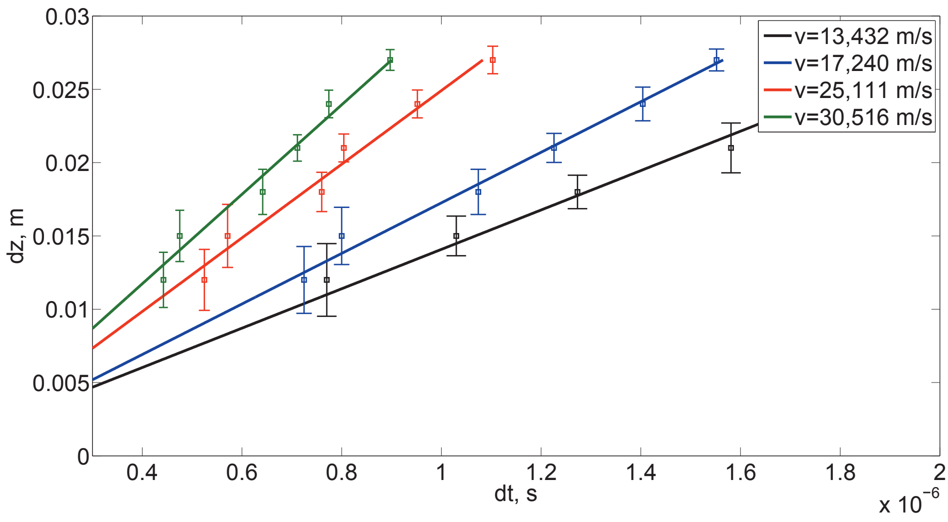
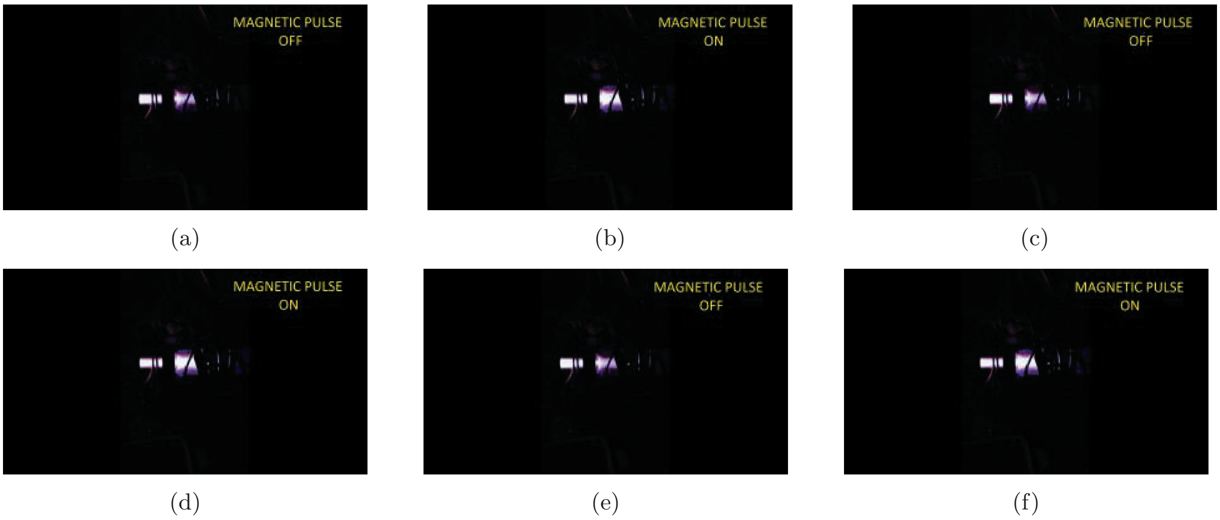


Figure 6: Magnetic field at different velocities.

After all these tests were conducted in absence of plasma, the investigation then focused on the interaction between the generated magnetic field and a plasma flow. Time-of-flight probe measurements have been carried out in various configurations and data have been collected with both the plasma and the accelerator operating, only the plasma operating, and only the accelerator operating. This procedure is aimed to isolate the signal generated by plasma-field interactions from electromagnetic noise. In particular, we aim to: 1) detect a plasma-field interaction, 2) discriminate the signal originated by a propagating plasma sheet from electromagentic noise, 3) understand the nature of the plasma field interaction (if present) seeking evidence of a "magnetic piston" effect.

During the tests, an effect of the pulsed magnetic field can be witnessed visually by looking at the plasma flow, which appears pulsating as soon as the accelerator is turned on, whereas it appears quiescent when the accelerator is not operating. After capturing a video of the experiment, we have analyzed the different frames and indeed we can observe bursts of more intense plasma synchronized with the repetition rate of the discharges in the accelerator (in the case of Fig. 7 the repetition rate is 5 Hz).



(a) (b) (c)

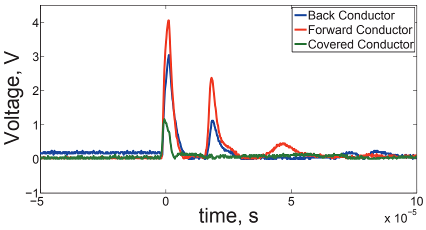
(d) (e) (f)

Figure 7: Magnetic field at different time instants: a) t_0, b) $t_0 + 0.1$ s, c) $t_0 + 0.2$ s, d) $t_0 + 0.3$ s, e) $t_0 + 0.4$ s, f) $t_0 + 0.5$ s.

Fig. 8 and 9 illustrate the time-of-flight traces using the helicon source and the microwave cavity as the primary ionization stage, respectively. The time-of-flight probe is located inside the quartz tube, at a distance of about 4 cm from the end of the accelerator. From the collected data we can outline some key aspects: although some electromagnetic interference is present (the signal without plasma shows such phenomenon), it is much weaker than the signal obtained with plasma operating. As expected, the electromagnetic interference produced by the accelerator in absence of plasma is observed by all the electrodes, including the encased one. Its intensity decreases as the distance from the accelerator end increases, independently by the electrode being encased or exposed. On the other hand, when the plasma is injected, the strength of the peaks observed by the uncovered electrodes is much stronger in comparison with that detected by the encased electrode. This observation suggests that such an effect is not merely an increase of the electromagnetic interference due to the plasma-circuit coupling, but there is an overlapping plasma contribution. Moreover, the analysis of the time-of-flight profiles under certain operating conditions highlights the presence of multiple peaks on the exposed electrodes traces that are completely absent on the encased electrode trace (Fig. 8). Also, recall that these effects take place only when the plasma source is operating. These characteristics demonstrate an interaction of the traveling magnetic field with the plasma, however the observed multiple features and the measured delay-times between peaks are unexpected and in contrast with the theoretical predictions; as a consequence, the experimental results do not allow to provide a final assessment on the nature of the interaction, that may not be an effective magnetic piston (an alternative mechanism may be a fluctuation in the plasma source induced by the magnetic pulse). Additional experiments with different probes and different operating conditions (energy/pulse, propellant mass, plasma sources with enhanced ionization), along with theoretical studies, are needed to demonstrate the proposed acceleration concept.

V. Conclusions and Future Work

In this paper we present the development of a compact, low power traveling magnetic field accelerator. The system is intended to be used as the plasma accelerator in a dual stage electrodeless propulsion system to accelerate the plasma produced by a primary ionization source. We show the results of the design phase and how the performance of the built system is in agreement with that simulated. In particular, the developed system is able to satisfy the design requirements in terms of: magnetic field strength, magnetic pulse width



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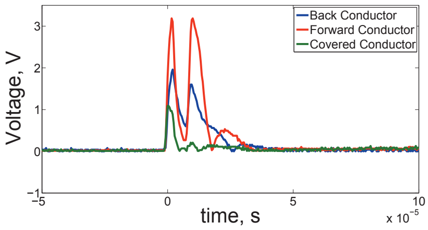

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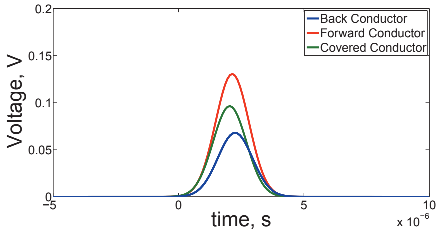
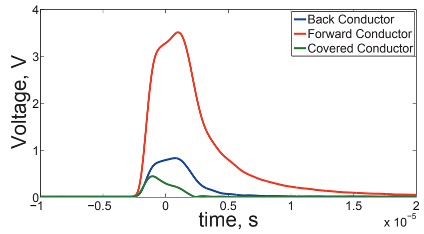


(c)

Figure 8: Time-of-flight probe data using the helicon source as the primary ionization stage: a) 0.05 mTorr 10 W, b) 0.05 mTorr 15 W, c) no plasma.



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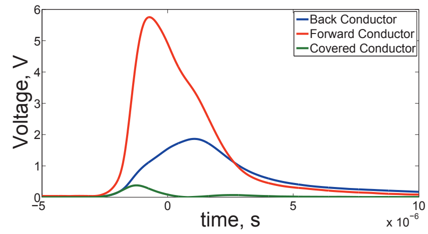

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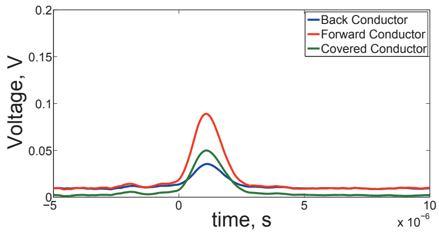

(c)

Figure 9: Time-of-flight probe data using the microwave source as the primary ionization stage: a) 0.2 mTorr 30W, b) 0.4 mTorr 10W, c) no plasma.

and traveling velocity, geometry (in terms of system aspect ratio), power consumption. The system consists of an array of coils with progressively delayed currents to generate an axially-propagating pulsed magnetic field. Current probes and B-dot probes are used to characterized the time and space evolution of the magnetic field profile at different propagating velocities.

We have started a preliminary experimental campaign, aiming to detect an interaction between the accelerator and a plasma flow. A microwave source or a helicon source are used as the primary ionization stage. We observe an interaction between the generated pulsed magnetic field and the plasma, however the collected measurements do not allow to asses such interaction is the result of a magnetic piston effect.

Future investigations will explore different operating conditions, different primary ionization stages and the use of different diagnostics systems (magnetic probes inside the plasma flow, energy analyzers, Faraday probe).

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