The Two-Stage Pulsed Plasma Thruster

IEPC 2009-250

31st International Electric Propulsion Conference, Ann Arbor, Michigan,USA
September 20-24, 2009

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ABSTRACT

Pulsed Plasma Thrusters (PPTs) are long standing electric propulsion thrusters. One of the main issues with the PPT is its poor utilization of the propellant and low efficiency. Typically only 40-60% of the propellant contributes to the production of significant impulse and the efficiency is typically less than 15%. The cause of the PPT's poor propellant utilization is the late time ablation (LTA), which has a major impact on the efficiency. LTA is the sublimation of propellant that takes place after the main discharge, due to the propellant, usually Polytetrafluoroethylene, being at a temperature above its sublimation point during the cooling, after the electric discharge. The LTA produces a very low speed gas and solid particles that do not contribute significantly to the impulse. This work presents a way of accelerating the late time ablation. A new thruster, called the two-stage pulsed plasma thruster (TS-PPT) was envisioned and employs an additional discharge after the main discharge, in a separate pair of electrodes. The TS-PPT uses a new approach for the thrust generation in the PPT, divided in two phases: propellant dosing and propellant acceleration. Evidences were found that a pair of electrodes placed downstream, further from the propellant surface is able to discharge in the late ablation portion of the propellant and can impart extra energy into the exhaust and improve propellant utilization. A simple analytic model was developed to predict trends. A prototype of a TS-PPT was designed and built. A vacuum facility was modified, adapted, partially designed and built. An average mass bit consumption test was carried out. Several current measurements were performed and the total electrical resistance, total inductance, electromagnetic impulse bit, specific impulse, efficiency, and other parameters were calculated based on experimental data. Experimental results indicated that improvements in the specific impulse and efficiency are possible by utilizing a two-stage PPT. Specific impulses as high as 4000s were calculated based on experimental results, indicating that a TS-PPT has a better propellant utilization than a regular PPT.

1. Introduction and Background

Ablation-fed Pulsed Plasma Thrusters – or PPTs – are electric propulsion devices that can be categorized as electromagnetic thrusters, although thermal expansion is also responsible for part of the thrust produced. The PPT utilises a solid propellant, most commonly PTFE – Polytetrafluoroethylene –, a synthetic fluoropolymer.

A typical PPT operation cycle is comprised of a capacitive electric discharge initiated by electrons emitted by a spark plug mounted on the cathode, close to the propellant surface. During the discharge the propellant is heated and sublimated. The electric discharge then takes place in the generated gas that becomes ionised, forming the plasma. The plasma is subsequently accelerated by a combination of a self induced magnetic field (**B**), generated by the discharge current, and the current density (**J**). This resulting force, known as the Lorentz force, produces the thrust, jointly with gas dynamic forces, also known as pressure forces. Figure Figure 1 shows a schematic diagram of a PPT.

After the main discharge is finished the temperature of the propellant is still above its sublimation point (~260 °C) and a significant portion of propellant sublimates without being electromagnetically accelerated. This portion of mass that ablates after the main discharge and is ejected at very low speed is known as *late ablation* [1] or late time ablation (LTA) and account for around 40% of the total ejected mass [2].

Practically since its inception the PPT has been widely known for three main characteristics: simplicity, robustness and low efficiency, typically less than 15% [1]. After numerous studies on how to increase the efficiency of the PPT, many

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of them identified the late ablation as a main contributor to the low efficiency of the PPT and several subsequent works studied ways to minimise the production of the late ablation.

In this work a new approach to the PPT thrust production was carried out. The production of the thrust in the PPT was divided in two phases: i) ablation and ii) acceleration. Each of these phases is carried out by two physical stages: first and second. The first stage is mainly responsible for dosing the total amount of propellant that will participate in the pulse cycle. The second stage is responsible for accelerating the propellant. Both stages' main role are non-exclusive, as the first stage also accelerates the propellant and radiation from the second stage could contribute to a very small increase in ablation. This new thruster was given the name of two-stage pulsed plasma thruster –TS-PPT.

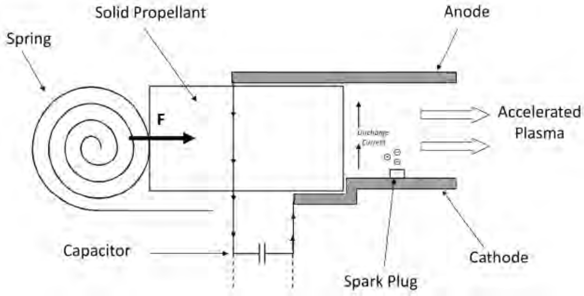

Figure 1: Schematic diagram of the PPT.

2. The Two-Stage Pulsed Plasma Thruster (TS-PPT)

The TS-PPT has been investigated previously in a derivate configuration, called the high frequency burst PPT (HFB-PPT) [3] and its regimens of operation were analysed [4]. The TS-PPT is the general concept of using two stages in a PPT to accelerate the LTA. A prototype presented in this work is a Double Discharge Pulsed Plasma Thruster (DD-PPT), also a derivate of the TS-PPT, but is simpler and more robust than the HFB-PPT and therefore is closer to the original PPT philosophy than the HFB-PPT. Another DD-PPT is also being developed at the University of Southampton and at the Brazilian National Institute for Space Research – INPE - to fly on the UniSat-5 satellite [5]. Nevertheless, the HFB-PPT is still a valid line of investigation for increasing the PPT efficiency.

The TS-PPT presents two pairs of electrodes, while a regular PPT employs one pair. In the TS-PPT, the first pair is in contact with the propellant, like in a conventional PPT, and the second pair is placed downstream, relatively far from the propellant surface.

The DD-PPT employs a single secondary discharge - while the HFB-PPT employs several high-frequency discharges - and is modulated by the first discharge and by the late ablation. The secondary discharge current is dynamically modulated by the electrical impedance of the products of the first discharge when they reach the secondary electrodes and are influenced by varying the initial voltage of the secondary discharge capacitor and its capacitance. In this particular analysis no switch is used and the secondary discharge capacitor is always connected to the secondary electrodes. Nevertheless, a switch can be employed on the second discharge, depending on the specific thruster details. During the main discharge – and therefore before the late ablation – the current flowing in the plasma due to the first discharge is expected to induce currents in the secondary electrodes. This is due to time variation in the magnetic field - in this case caused by the varying current in the first pair of electrodes - inducing an electric field. The induced electric field is responsible for the expected modulation of the current. Figure 2 illustrates the mentioned induction.

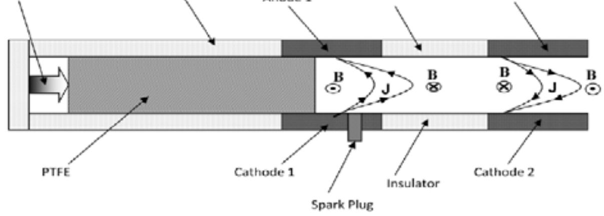

Figure 2 – Schematics of a TS-PPT.

The production of the thrust in the TS-PPT has been divided in two stages, corresponding to the two pairs of electrodes. The first stage is responsible for dosing the propellant and therefore ablating the propellant and providing it with an initial acceleration. The second stage provides the main acceleration force to the propellant ablated during the first stage discharge and, very importantly, it provides acceleration to the late time ablation.

By adding the second stage of the TS-PPT it is possible to impart further energy to the exhaust without increasing the total mass ablated, as Δm does not depend on the second discharge, as observed from:

$$\Delta m(\varepsilon_1, T_P) = \alpha_1 \varepsilon_1 + \beta {T_P}^{\sigma} = \tau_E + \tau_G \tag{1}$$

where Δm is the total mass lost during a single discharge cycle, ε_1 is the discharge energy of the primary discharge, T_P is the steady state temperature of the propellant immediately before the discharge, α_1, β and σ are constants obtained experimentally, τ_E is the mass that is accelerated electromagnetically during the discharge and τ_G is the mass of the gas-dynamically accelerated propellant.

The impulse bit of the first stage (or primary discharge) is:

$$I_{bit_1}(\varepsilon_1, T_P) = \int_0^{t_2} F_P \, dt = \int_0^{t_1} F_{P_1} \, dt + \int_0^{t_2} F_{P_2} \, dt \tag{2}$$

where I_{bit_1} is the impulse bit solely due to the first discharge, F_P is the total force exerted by the exhausting products of the first discharge, t_1 is the time in which the primary capacitor, connected to the primary electrodes, is fully discharged, t_2 is the total time during which the propellant is sublimating[4], F_{P_1} is the force due to the electromagnetically accelerated particles and F_{P_2} is the force due to the gas dynamically accelerated mass, intrinsic in the first discharge. Part of this gas dynamically accelerated mass will come after the discharge as late ablation and part will be produced during the discharge as not necessarily all propellant is ionized and electromagnetically accelerated during the discharge.

The impulse bit of the second stage (or secondary discharge) can be calculated as:

$$I_{bit_2}(\varepsilon_2, \Delta m) = \int_{t_3}^{t_5} F_S \, dt = \int_{t_3}^{t_4} F_{S_1} \, dt + \int_{t_3}^{t_5} F_{S_2} \, dt = \int_{t_3}^{t_5} \left(F_{S_1} + F_{S_2}\right) dt \tag{3}$$

Where ε_2 is the energy of the secondary discharge, F_S is the total force due to the secondary discharge, t_3 is the instant where the secondary discharge starts, t_4 is the time where the secondary discharge ends, t_5 is the time where no more gas dynamic forces are produced, F_{S_1} is the thrust force due to the electromagnetically accelerated species in the secondary discharge and F_{S_2} is the thrust force due to the gas dynamically accelerated particles in the secondary discharge. It should be noted that there is no late ablation production due to the secondary discharge. Both electromagnetic thrust and gas dynamic thrust are produced during the secondary discharge.

For convenience, we can now define the total mass accelerated electromagnetically and the total mass accelerated gas-dynamically and electromagnetically:

$$m_E = \phi \Delta m \tag{4}$$

$$m_G = (1 - \phi) \Delta m \tag{5}$$

where ϕ is the portion of the mass accelerated electromagnetically.

The thrust efficiency of the two stages of the TS-PPT can be calculated by:

$$\eta_{2A} = \frac{\sum_{i=1}^{EP} m_{ep_i} {v_{ep_i}}^2 + \sum_{j=1}^{GP} m_{gp_j} {v_{gp_j}}^2 + \sum_{k=1}^{ES} m_{es_k} {v_{es_k}}^2 + \sum_{o=1}^{GS} m_{gs_o} {v_{gs_o}}^2}{2(\varepsilon_1 + \varepsilon_2)} \tag{6}$$

where m_{ep_i} and v_{ep_i} are the mass and velocity, respectively, of the specie i that was electromagnetically accelerated in the primary discharge and m_{gp_j} and v_{gp_j} are the mass and velocity, respectively, of the particle j that was gas dynamically accelerated in the first discharge and EP and GP are the number of electromagnetically accelerated species and the number of gas dynamically accelerated particles, respectively, in the primary discharge. m_{es_k} and v_{es_k} are the mass and velocity, respectively, of the specie k that was electromagnetically accelerated in the secondary discharge and m_{gs_o} and v_{gp_o} are the mass and velocity of the particle o that was gas dynamically accelerated in the secondary discharge and ES and GS are the number of electromagnetically accelerated species and the number of gas dynamically accelerated particles, respectively, in the secondary discharge and ε_1 and ε_2 are the energies of the primary and secondary discharges, respectively.

Also, from the principle of conservation of mass, in a pulse:

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[4] The propellant sublimates during and after the discharge, so $t_2 > t_1$.

$$\sum_{i=1}^{EP} m_{ep_i} + \sum_{j=1}^{GP} m_{gp_j} = \sum_{k=1}^{ES} m_{es_k} + \sum_{o=1}^{GS} m_{gs_o} = m_E + m_G = \phi\Delta m + (1-\phi)\Delta m = \Delta m \tag{7}$$

It is then possible to define the specific impulse for the TS-PPT:

$$I_{s_{TS}} = \frac{I_{bit_1} + I_{bit_2}}{g_0 \int_0^{t_5} \dot{m}\, dt} \tag{8}$$

As the source of propellant is only due to the first discharge, $\int_0^{t_5} \dot{m}\, dt = \int_0^{t_2} \dot{m}\, dt$, since $\dot{m}(t) = 0$ for $t > t_2$ in a single discharge cycle. It is important to note that, although the times described are sequentially numbered, $t_1,\ t_2,\ t_3$, etc, they do overlap. For example, t_2 is greater than t_3. This nomenclature was chosen to simplify the notation. Figure 3 shows a time diagram of the discharge cycle of the TS-PPT. This diagrams shows a generic case where $t_5 > t_4$. Ideally $t_5 = t_4 = t_2$ and therefore the secondary discharge accelerates all the sublimating propellant.

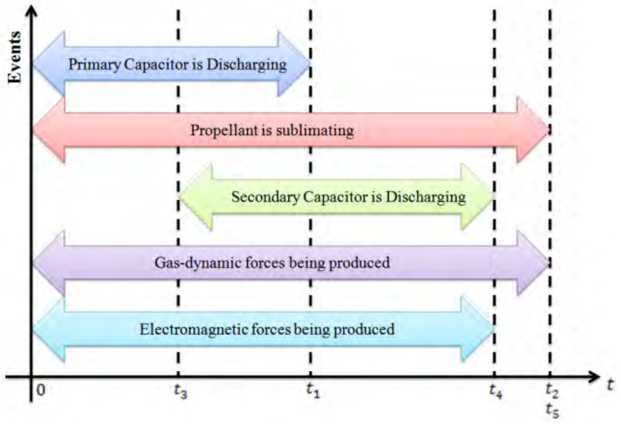

Figure 3: Time diagram of a discharge cycle of the two-stage PPT.

It is then possible to write the specific impulse for the TS-PPT as:

$$I_{s_{TS}} = \frac{I_{bit_1} + I_{bit_2}}{g_0 \int_0^{t_2} \dot{m}\, dt} \tag{9}$$

But as $\int_0^{t2} \dot{m}\, dt \overset{\text{def}}{=} \Delta m$, then

$$I_{s_{TS}} = \frac{I_{bit_1} + I_{bit_2}}{g_0 \Delta m} = \frac{\int_0^{t_1} F_{P_1}\, dt + \int_0^{t_2} F_{P_2}\, dt + \int_{t3}^{t_4} F_{S_1}\, dt + \int_{t_3}^{t_5} F_{S_2}\, dt}{g_0 \Delta m} \tag{10}$$

And the efficiency of the TS-PPT can be written as:

$$\eta_{2B} = \frac{1}{2} g_0 I_{s_{TS}} \left(\frac{I_{bit_1} + I_{bit_2}}{\varepsilon_1 + \varepsilon_2} \right) \tag{11}$$

It is also interesting to analyse to behaviour of the secondary discharge current. The current in the secondary electrodes should have the form of:

$$I_s = I_{MF}(t) + \frac{V_{0_2}}{R_{P2}} e^{-t/_{R_{P2}C_2}} \tag{12}$$

where $I_{MF}(t)$ is the secondary discharge current due to the induction from the primary discharge, as mentioned above, V_{0_2} is the initial voltage of the secondary capacitor, R_{P2} is the total electrical equivalent resistance between the electrodes of the secondary discharge, C_2 is the capacitance of the secondary discharge capacitor and t is the secondary discharge time. Figure 4 illustrates the expected behaviour of the Two-Stage PPT operating without a switch as a double discharge PPT, also called dual stage PPT or DS-PPT. The primary discharge is shown in blue and modulates the current on the secondary electrodes, shown in red. After the end of the first discharge the secondary discharge behaves similar to a capacitor discharging circuit. The time scales and current magnitudes shown serve as an example only, but are consistent with the experiments observed in this work. Despite of the fact that the secondary discharge induction on the first set of electrodes is not being analysed in the present work, it shall be object of future investigation, as in some regimens of operation indications of mutual induction were observed.

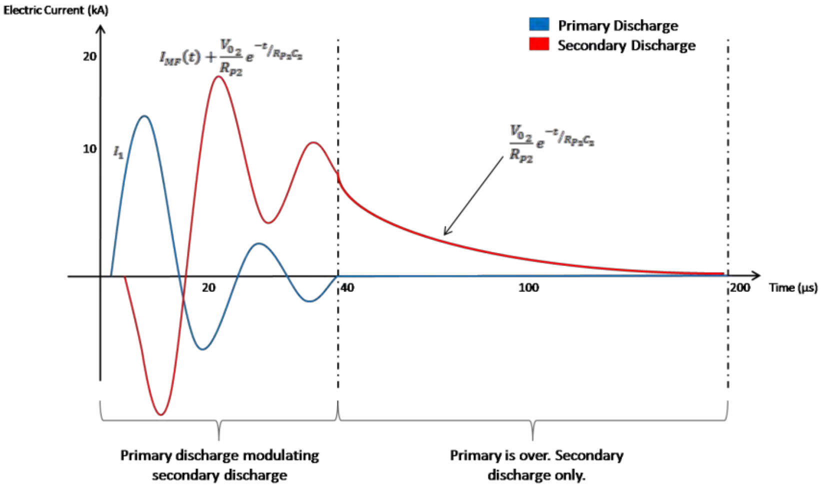

Figure 4: Expected discharge currents when using Double Discharge Method.

3. Experimental Results

Tests with a laboratory DD-PPT were carried out at the Astronautics Research Group at the University of Southampton [6]. This laboratory DD-PPT was built at the Combustion and Propulsion Laboratory (LCP) of the Brazilian National Institute for Space Research (INPE). To make it possible to visualize the plume between the two pairs of electrodes this thruster had glass walls. Figure 5 shows the DD-PPT during tests. It is convenient to note that this thruster was used as a prototype of a HFB-PPT before.

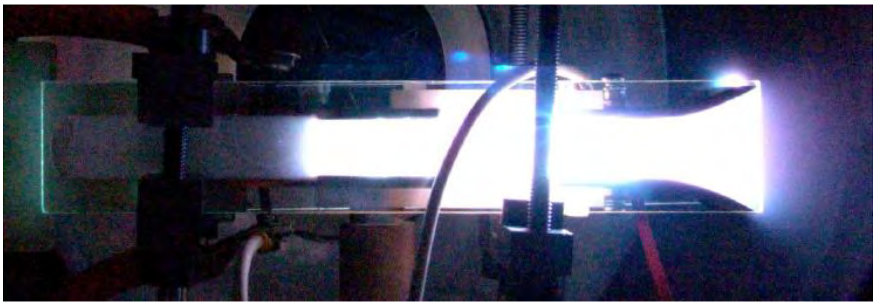

Figure 5: Laboratory DD-PPT plume.

The electromagnetic impulse bit was calculated using electric current measurements made with a Rogowski coil PEM CWT300, 0.1mV/A, 16MHz bandwidth. The accuracy of this equipment is $\pm 1.05\%$. A total uncertainty of $\pm 5\%$ was used for the values calculated from the current measurements and comprises the uncertainty of the Rogowsky coil, oscilloscope, voltmeters and power supplies metering. Figures 6-8 shows the results of the current measurements for three different conditions, with primary discharge energy at 1kV(55J), 1.5kV(123J) and 2kV (220J) and secondary discharge at 300V (211J). In these graphs it is possible to see that the secondary discharge is indeed modulated by the primary discharge and subsequently behaves similarly to a capacitor discharging circuit.

In order to have an overview of the behaviour of the DD-PPT, it is convenient to calculate the total resistance and total inductance for the first stage and for the second stage for 39 electric current discharges measurements, with varying primary and secondary discharge voltages. Figures 9-11 show these results.

The discharge currents of the TS-PPT give us a great indication on the performance of the thruster. The impulse bit of the first discharge due to the electromagnetic acceleration of the propellant in a TS-PPT can be estimated as:

$$I_{EM_1} = \frac{1}{2} L_1' \int I_1^2 dt = \frac{1}{2} L_1' \frac{\varepsilon_1}{R_{total_1}} \tag{13}$$

where I_{EM_1} is the impulse due to electromagnetic acceleration in the first stage, L_1' is the inductance gradient in the first stage (in μH/m), I_1 is the electric discharge current of the first stage, ε_1 is the total initial energy stored in the primary discharge capacitor and R_{total_1} is the equivalent total resistance of the primary discharge circuit.

Assuming a similar behaviour for the secondary discharge, its electromagnetic impulse can be then written as:

$$I_{EM\,2} = \frac{1}{2} L_2{}' \int I_2{}^2 dt = \frac{1}{2} L_2{}' \frac{\varepsilon_2}{R_{total\,2}} \tag{14}$$

where $I_{EM\,2}$ is the impulse due to electromagnetic acceleration in the second stage, $L_2{}'$ is the inductance gradient in the second stage (in μH/m), I_2 is the electric discharge current of the second stage, ε_2 is the total initial energy stored in the secondary capacitor and $R_{total\,2}$ is the equivalent total resistance of the secondary discharge circuit. For this DD-PPT prototype, $L_1^{'} = L_2^{'} = L^{'} = 0.485\ \frac{\mu H}{m}$. Figures 12-14 show the results of the calculated electromagnetic impulse bit.

Also of interest is the specific impulse due to the electromagnetic acceleration, $I_{sp\,(MAG)}$. In this calculation it was used the electromagnetic impulse bit, here called $I_{bit\,(MAG)}$, and the total mass lost during a discharge, Δm:

$$I_{sp\,(MAG)} = \frac{I_{bit\,(MAG)}}{g_0 \Delta m} \tag{15}$$

The calculated specific impulse is shown in Figures 15-17.

The efficiency of the DD-PPT for the electromagnetic impulse can be calculated as:

$$\eta_{(MAG)} = \frac{1}{2} g_0 I_{sp\,(MAG)} \left(\frac{I_{bit\,(MAG)}}{\varepsilon_1 + \varepsilon_2} \right) \tag{16}$$

Figures 18-20 show the efficiency $\eta_{(MAG)}$ for 39 tested cases.

4. Discussion and Conclusion

In this work a new approach to the PPT thrust production was carried out. The production of the thrust in the PPT was divided in two phases: i) ablation and ii) acceleration. Each of these phases is carried out by two physical stages: first and second. The first stage is mainly responsible to dosing the total amount of propellant that will participate in the pulse cycle. The second stage is responsible for accelerating the propellant. Both stages' main role are non-exclusive, as the first stage also accelerates the propellant and radiation from the second stage could contribute to a very small increase in ablation. This new thruster was given the name of two-stage pulsed plasma thruster –TS-PPT.

A simple analytic model was developed to show the advantages of adding a second stage to the conventional PPT.

A DD-PPT was introduced as a particular case of the TS-PPT, where a single secondary discharge is used. A prototype of a DD-PPT was designed and built. The DD-PPT prototype built had a rectangular geometry and four electrodes and a spark plug. The first two electrodes were placed in contact with the propellant surface and were mainly responsible for the ablation process. To allow the discharge initiation, a spark plug was placed in the cathode of the first stage. The second two electrodes were placed downstream to avoid generating more late ablation. Glass walls ware used to enable visualization of the discharges. The DD-PPT was controlled by a computer attached to a power system that used Insulated Gate bipolar Transistors (IGBT) as a high voltage, high current, high speed switch. The DD-PPT had a $110\mu F$ capacitor for the primary discharge and a $4700\mu F$ capacitor for the secondary discharge, operating at a maximum of 2kV and 300V, respectively.

The average mass ablated in one pulse, Δm, was measured and found to be $0.32\frac{\mu g}{J}$, a relatively low value when compared to other PPTs, and attributed to an unexpectedly higher propellant area discharge due to discharges on the side of the propellant and also to the long duration of the primary discharge. However, for the goals of this research this was not considered a problem.

Simple time-of-flight measurements for the first stage, using the second stage as probe, indicated that the fastest portion of the plasma that was able to break down the secondary discharge was travelling at approximately $14.28\frac{km}{s} \pm 4.65\frac{km}{s}$.

Several measurements of current were taken for both the first and the second stage, while the primary discharge energy and the secondary discharge energy was varying. These measurements allowed insights on the electromagnetic impulse of the DD-PPT for both the first stage and the second stage. Based on the current discharges it was possible to calculate the equivalent total resistance and total inductance of the primary and secondary circuits for all cases measured.

It was not observed a significant change in the total resistance and in the total inductance of the primary discharge when the secondary discharge energy was increased, indicating a good decoupling of the two stages. This relative decoupling of the first stage, at this point, is seen as a positive aspect, as the first stage can be treated as an isolated regular PPT.

Analysis of the impulse bit indicated that it is possible to increase the total impulse bit when adding the second stage, as expected.

The electromagnetic specific impulse bit of the second stage was rather lower than expected, and this low performance was attributed to a non-optimised design and to the utilisation of low voltages for the second discharge - due to limitations of our power supplies – yielding lower currents that yield lower impulse bits. For the demonstration of the mechanism this was not considered a problem, but a good indicator for future implementations.

One of the main objectives was to increase the specific impulse of the PPT. Based on the calculations the specific impulse was greatly improved by adding the second stage, especially when the energy of the second stage was higher than the energy of the first stage. At 55J primary discharge and 50J secondary discharge (total 105J) a specific impulse of around 2000s was calculated based on the current discharges, while the first stage alone had a specific impulse of around 1500s. Specific impulses as high as 4000s were obtained.

Calculations of the efficiency were also carried out and indicated that it was possible to increase the efficiency of the PPT by adding the second stage. Increases of efficiency as high as 60% over the single stage were obtained, but even higher values are expected when the second stage operates at higher voltages and with an optimised design. Similar to findings of the specific impulse, higher efficiencies were found for $\varepsilon_2 > \varepsilon_1$.

These evidences found indicate that it is possible to accelerate the late ablation, increase the specific impulse and potentially increase the efficiency of the PPT by using the two-stage technology.

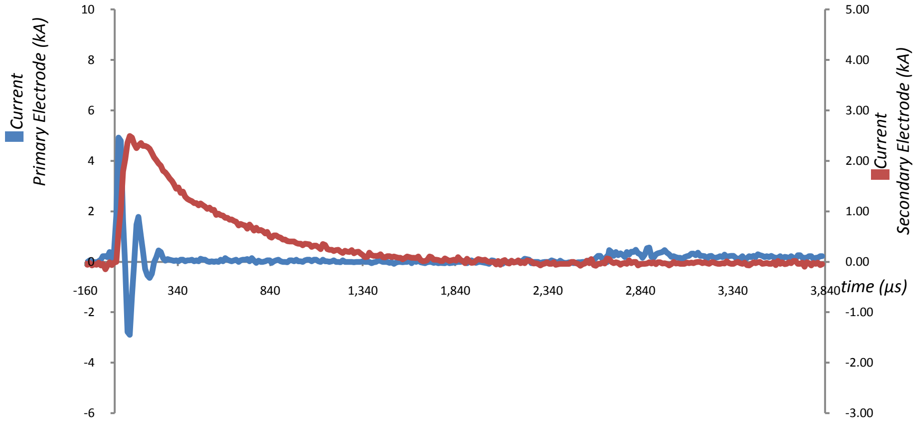

Figure 6: TS-PPT discharge 1kV (55J) Primary Discharge and 300V (211J) Secondary Discharge.

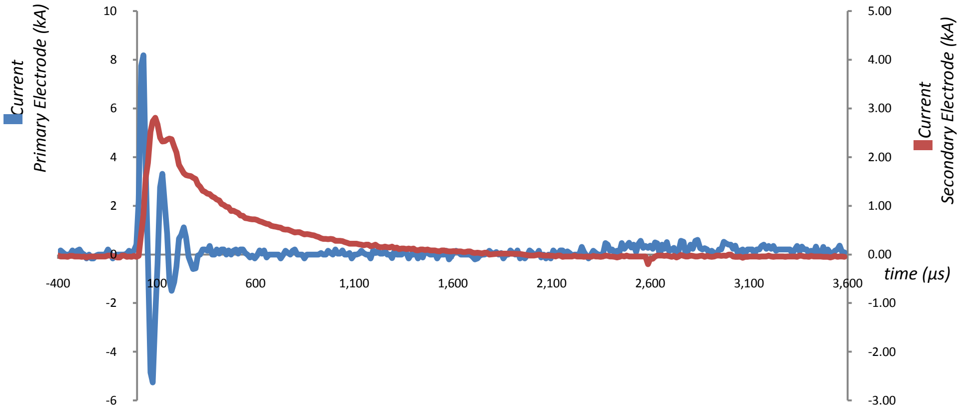

Figure 7: TS-PPT discharge 1.5kV (123J) Primary Discharge and 300V (211J) Secondary Discharge.

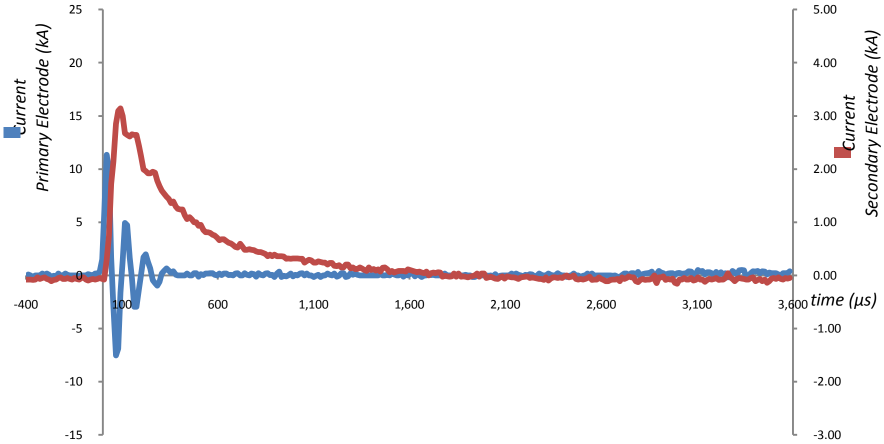

Figure 8: TS-PPT discharge 2kV (220J) Primary Discharge and 300V (211J) Secondary Discharge.

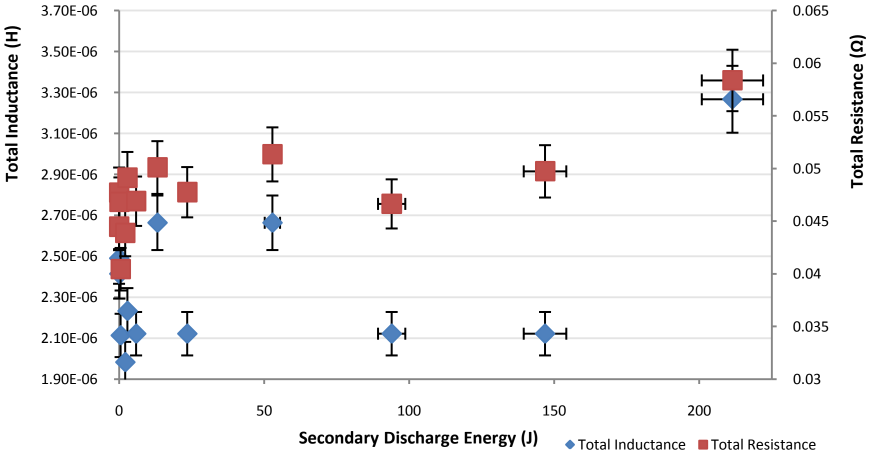

Figure 9: Total inductance and total electric resistance as a function of the secondary discharge energy for 1kV, 55J primary discharge.

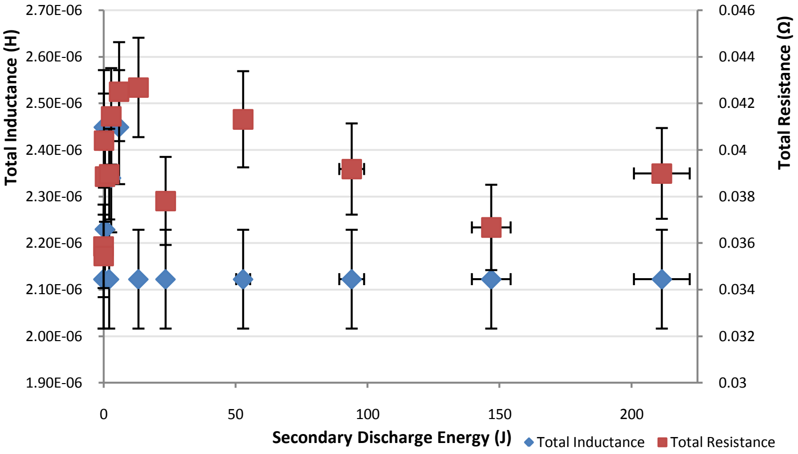

Figure 10: Total inductance and total electric resistance as a function of the secondary discharge energy for 1.5kV, 123J primary Discharge.

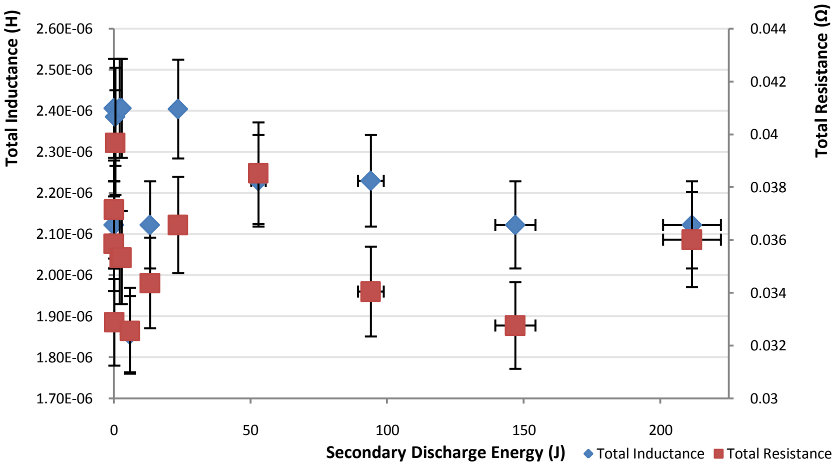

Figure 11: Total inductance and total electric resistance as a function of the secondary discharge energy for 2kV, 220J primary Discharge.

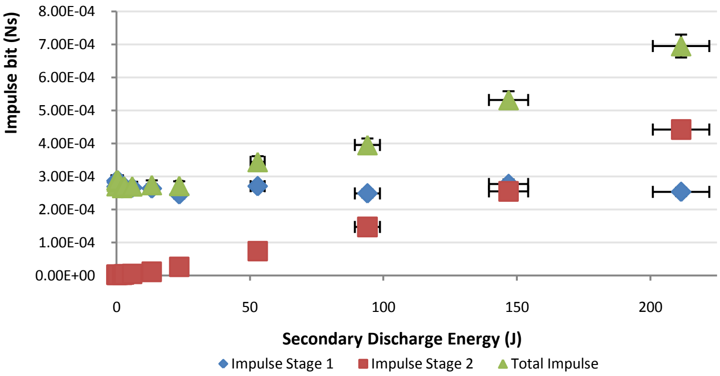

Figure 12: Electromagnetic impulse bit of stage one, stage two and the total electromagnetic impulse bit as a function of the secondary discharge energy for 1kV, 55J primary discharge.

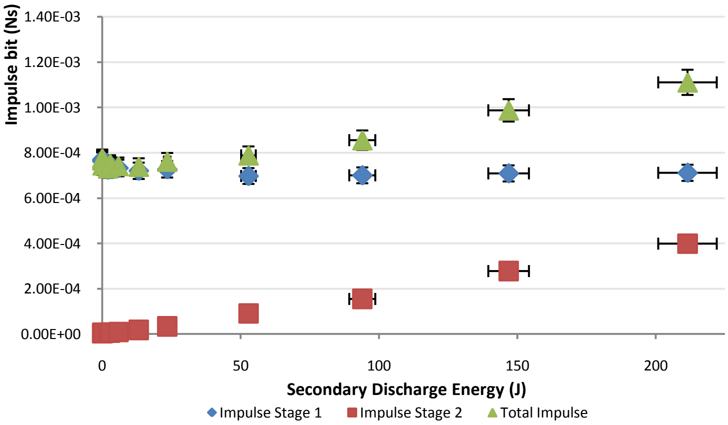

Figure 13: Electromagnetic Impulse Bit of stage one, stage two and the total electromagnetic impulse bit as a function of the secondary discharge energy for 1.5kV, 123J primary discharge.

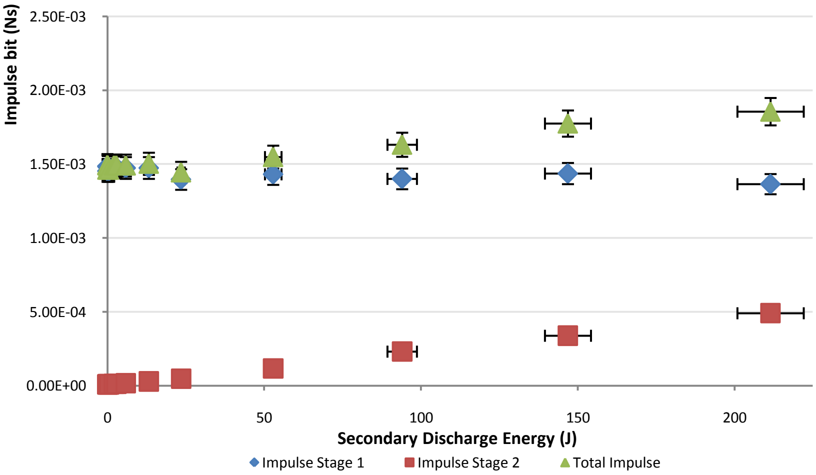

Figure 14: Electromagnetic Impulse Bit of stage one, stage two and the total electromagnetic impulse bit as a function of the secondary discharge energy for 2kV, 220J primary discharge.

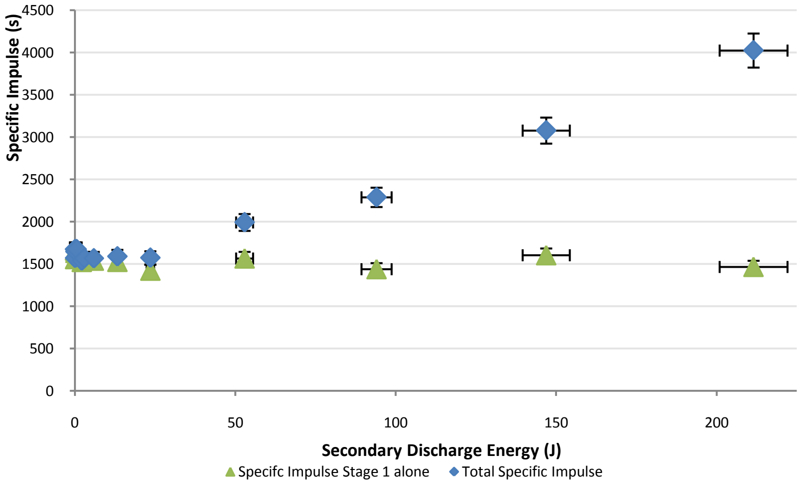

Figure 15: Specific Impulse for the electromagnetic impulse bits of the first stage alone and for both stages as a function of the secondary discharge energy for 1kV 55J primary discharge.

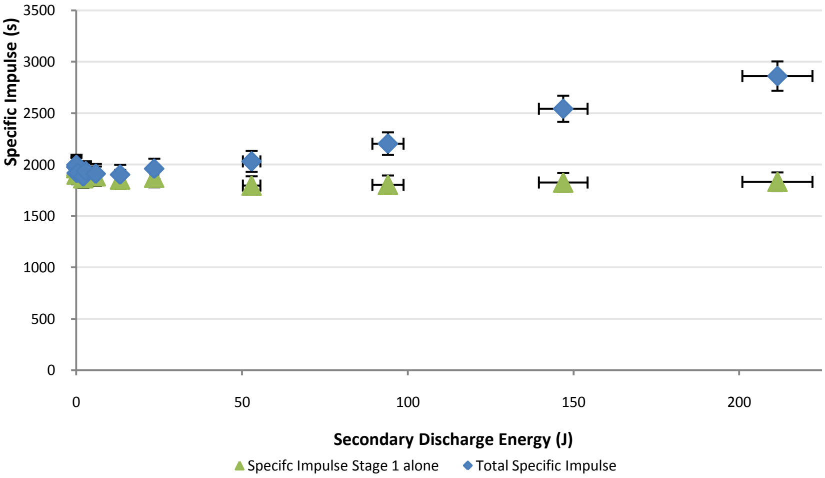

Figure 16: Specific Impulse for the electromagnetic impulse bits of the first stage alone and for both stages as a function of the secondary discharge energy for 1.5kV 123J primary discharge.

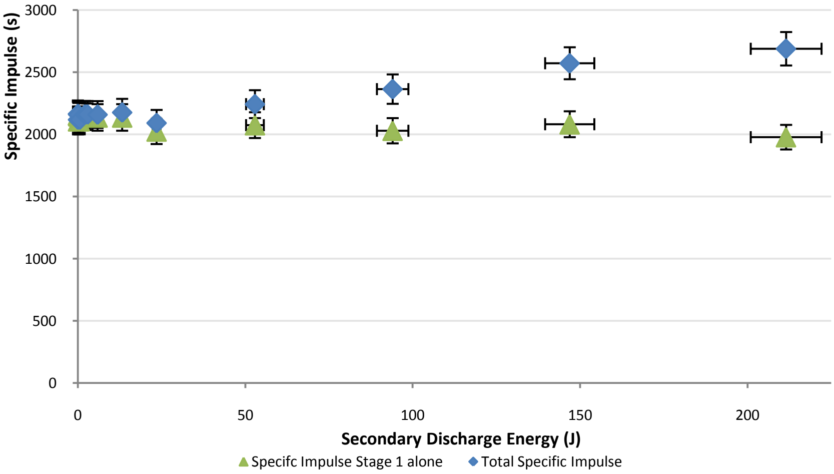

Figure 17: Specific Impulse for the electromagnetic impulse bits of the first stage alone and for both stages as a function of the secondary discharge energy for 2kV 220J primary discharge.

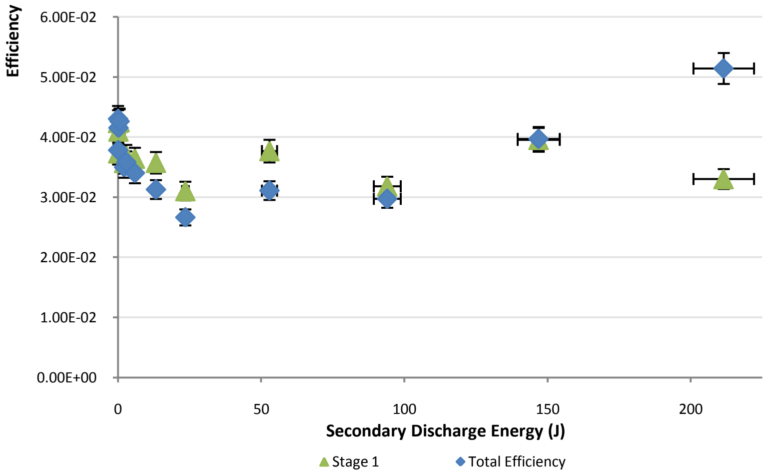

Figure 18: Efficiency of the stage one and the total efficiency as a function of the secondary discharge energy for 1kV 55J primary discharge.

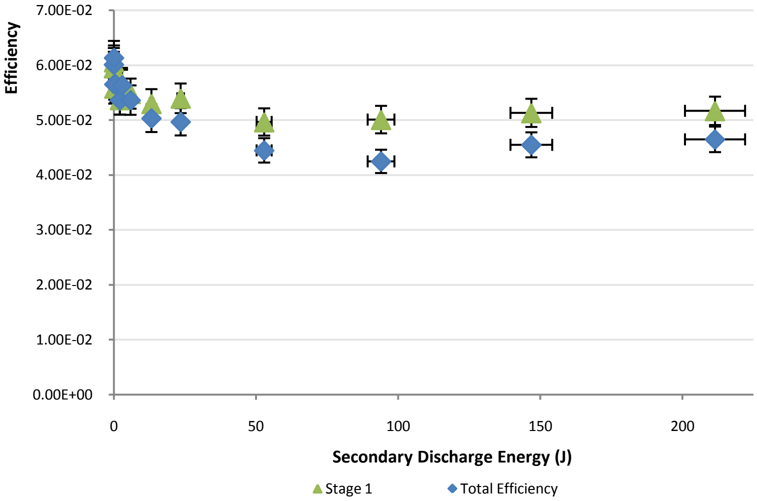

Figure 19: Efficiency of the stage one and the total efficiency as a function of the secondary discharge energy for 1.5kV 123J primary discharge.

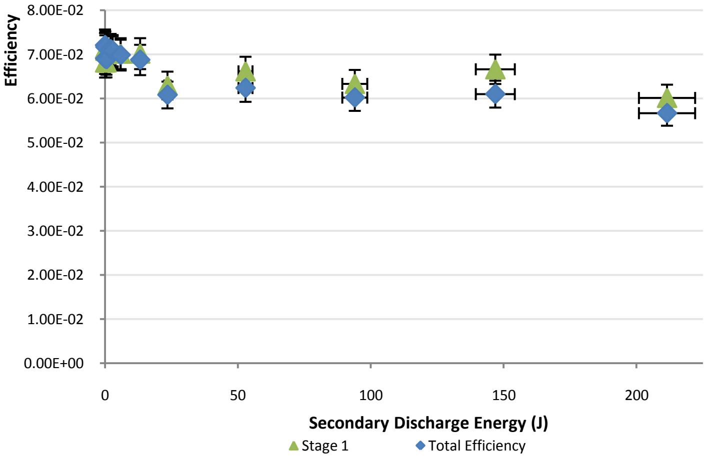

Figure 20: Efficiency of the stage one and the total efficiency as a function of the secondary discharge energy for 2kV 220J primary discharge.

5. References

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