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Abstract

Nanosatellites have become the most convenient way to approach space. This is due to the ease of manufacturing nanosatellites and the low cost of launching them into space. Due to these favorable factors, nanosatellites are also being used for new technology demonstration in space. We have presented the mechanical and electrical designs for a Micro Pulsed Plasma Thruster which is to be accommodated in the KIIT Student Nanosatellite for technological demonstration. Design related calculations based on physical space limitations, optimal thruster performance and minimal power requirements have been done and presented. Analysis of both the mechanical and electrical system has been done using CAD software.

Keywords	Nanosatellite; Plasma; Electric Propulsion; Thrust; Specific Impulse
Taxonomy	Advanced Space Propulsion, Advanced Space Propulsion Technology, Rocket Propulsion, Electric Propulsion

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DESIGN AND ANALYSIS OF KIIT NANOSATELLITE'S MICROPULSED PLASMA THRUSTER

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Abstract: Nanosatellites have become the most convenient way to approach space. This is due to the ease of manufacturing nanosatellites and the low cost of launching them into space. Due to these favorable factors, nanosatellites are also being used for new technology demonstration in space. We have presented the mechanical and electrical designs for a Micro Pulsed Plasma Thruster which is to be accommodated in the KIIT Student Nanosatellite for technological demonstration. Design related calculations based on physical space limitations, optimal thruster performance and minimal power requirements have been done and presented. Analysis of both the mechanical and electrical system has been done using CAD software.

Keywords: Nanosatellite; Plasma; Electric Propulsion; Thrust; Specific Impulse

1. INTRODUCTION

Pulsed Plasma thruster (PPT) is an electric propulsion system which works on the basis of acceleration of plasma through Lorentz force. The attractiveness of a PPT lies on its ease of operation, effective thruster performance and efficient power usage. In addition to this, a PPT is also highly modifiable as per the requirements of a specific mission. The objective of this paper is to present a micro pulsed plasma thruster which can be accommodated in small satellites for attitude control and drag compensation. For the mission, the plan to use it for technological demonstration in Low Earth Orbit. The critical designs are based on the tight dimensional limitations of a nanosatellite and the mass budget. Application of material research has been considered for enhancing thruster performance. Similarly, for limiting the carbonization and erosion issues choosing better materials for thruster walls is the best solution. Finally, for this ablative PPT; Polytetrafluoroethylene (TEFLON) has been employed as the fuel for this thruster as it is well researched for application in PPT as a fuel. Therefore, the KIIT Nanosatellite is an 8U satellite with the intended purpose of earth mapping and demonstrating the thruster technology. The structure has a mass of 2.2 KG and is 212x212x224 mm in dimensions. The thruster is fixed on the plate adjacent to the single solar panel and is kept at a distance from the center of the satellite in order to create a moment for demonstration when the thruster is fired. The PPT electronics will be installed on a 13X13 cm Printed Circuit Board (PCB).

2. MICRO PULSED PLASMA THRUSTER (μPPT)

- Before calculating the dimensions of the PPT, it is necessary to decide upon certain preset conditions. An Ablative PPT basically has 2 kinds of configuration, Breech Fed and Side Fed. The main distinguishing factor is that in case of Breach Fed there is only a single unit of propellant supply, whereas in case of side fed there can be multiple propellant supply units. Using side fed system, with 2 propellant supply unit is being chosen. The propellant supply unit is to be a rectangular bar, as it is relatively easy to operate upon a rectangular bar and has a simpler design than other kinds of bar such as cylindrical bars.
- Various studies have proven that the ratio of inductance variance (L') to initial inductance (L) are directly linked to the acceleration of plasma [1-10]. Inductance variance can be increased by increasing the aspect ratio, that is the ratio of electrode spacing (H) to electrode width (W) [2, 5, 6, 11, 12] and by mounting the capacitors close to the thrust chamber will ensure reduced initial inductance and therefore maximum thruster performance can be attainted. Inductance Variance can be calculated using [1,8]

$$\boldsymbol{L(x) = \mu\frac{H}{W}x \qquad L' = \mu\frac{H}{W}}$$

  Where $\boldsymbol{\mu}$ is the vacuum permeability. To get an estimated idea of inductance variation with respect to electrode aspect ratio, Kohlberg and Couburn approach can be considered [11].
- Electric Propulsion systems are well known for their drawbacks of contamination and erosion. The erosion can be limited through suitable choice of wall or housing materials, however, there is always a possibility of contamination flyback, which could certainly damage the electronic components of the satellite, and could probably lead to short circuiting. Therefore, a nozzle shaped wall has been introduced here to counter these particular drawbacks [1,13]. Overall thrust also includes a gas dynamic component apart from the electromagnetic one. Therefore, the electrodes were also designed in accordance with the nozzle so as to maximize performance. The electrodes follow a simple design of rectangular ends [2, 8, 14, 15, 16] although other variations like semicircular and tongue shaped end also exist and have their own pros and cons.
- Generally, spark plugs design consists of an electrode which is surrounded by a semiconducting material, and is inserted through an electrode. The same concept also applies to the spark plug of PPT. Shot to shot variation in thruster performance have been reported in such spark based systems [15]. To counter this, it is recommended that the spark plug size should be much smaller than the propellant bar length [17]. Coaxial spark plugs has been considered for this project, which are conventionally used in most PPTs [18], although a rectangular one is relatively easier to manufacture [17].
- Since the purpose of μPPT here is for technological demonstration via tilting the satellite, the least possible angular distance moved can prove the demonstration, which can be detected by an onboard magnetometer. Initially, however the requirements for a 1 km Hohmann Orbit transfer from 800 Km to 801 Km were calculated, although this was never in the mission plan. On calculation, it was computed that such a transfer would require a ΔV of 0.591 m/s. By using the rocket equation [19]

$$\boldsymbol{\frac{\Delta M}{M} = 1 - e^{\frac{-\nabla V}{I_{sp}}}}$$

  it was calculated that with 14 grams ($\boldsymbol{\Delta M}$) of fuel for a 13 Kg ($\boldsymbol{M}$) satellite with specific impulse (I_{sp}) of the thruster being more than 548.51 seconds, the required ΔV can be obtained. The same model for calculations related to propellant size has been considered. However, realistically, the shot energy to exposed area ratio has been found to be of relevance to specific impulse [2,10,13,20]. Therefore, the semi empirical relations as given by other studies should be taken into consideration if the design and nature of the project permits it.

- AVX ceramic capacitors are being used in the electrical system because of their proven high reliability. To prove that required voltages for ablation and acceleration are acquired by the chosen electrical components, the use of 555 Timer has been mentioned here, as the nanosatellite's onboard computer data is beyond the scope of this paper.
- A potential difference of 0.7-5 V (taken from the power subsystems of a given Nano-satellite), is fed to the 555 Timer IC. The 555 timer provides a pulsating input to a XP POWER Q-15, which helps obtain an output of 1500 V. The 1500 V voltage is then redirected to the Bank of capacitors made from AVX ceramic capacitors of 10 nF capacitance.
- Another input of 5 V is taken from the power subsystems and is fed to another 555 Timer IC to produce a pulsating voltage. The pulsating output of the 555 timer is fed to XP POWER Q-60, which helps producing an output of 6 kV. The 6 kV output is in turn fed to a Cockcroft-Walton (CW) generator. This ladder system produces a high voltage spark of nearly equal to 12 kV which ablates the Teflon.

3. DESIGN SPECIFICATIONS OF THE THRUSTER

1.1) MECHANICAL DESIGN OF THRUSTER

· ELECTRODE DESIGN

- An electrode length of 1.5 cm has been considered here. With a longer electrode, the wall friction could slow down the plasma and therefore reduce the Thruster Performance. If the electrodes are too short, then the Plasma would be expulsed when energy is still in the capacitor [3]. It is assessed that the maximum available space in axial direction would be about 2 cm; giving some free space to back wall. For low electrical resistance, high melting point, low thermal expansion and optimal erosion resistance Tungsten-Copper alloy, is being chosen as the material [21]. Other alternatives like thoriated tungsten, tungsten coated copper, pure tungsten or copper could also have been considered [22]. For perfect mechanical and electrical resistance, Electrode thickness of 0.22 cm is being pitched on. Also, for maximum output, flared shaped electrodes have been opted; starting from origin, after 0.5 cm, a divergence of 10° is introduced, followed by 25° divergence after another 0.5 cm. The proper accommodation in the thruster structure as explained in the next sections is also considered for electrode dimensions.
- For optimum performance the electrode aspect ratio can be taken to be 2. If the electrode ratio is too high many non-uniformities could arise which could reduce performance and increase Plasma Resistance. If the ratio is too small, it the system could get uncontrollable [1]. Also, if electrode spacing is increased, there should also be corresponding increase in voltage to keep the electric field optimized. It is critical to choose the correct value for electrode spacing. That is so because a higher value of the space will lead to inefficient discharge when the spark plug is in action. Hence, an electrode spacing of 1.1 cm and corresponding electrode width of 0.55 cm is being settled upon.

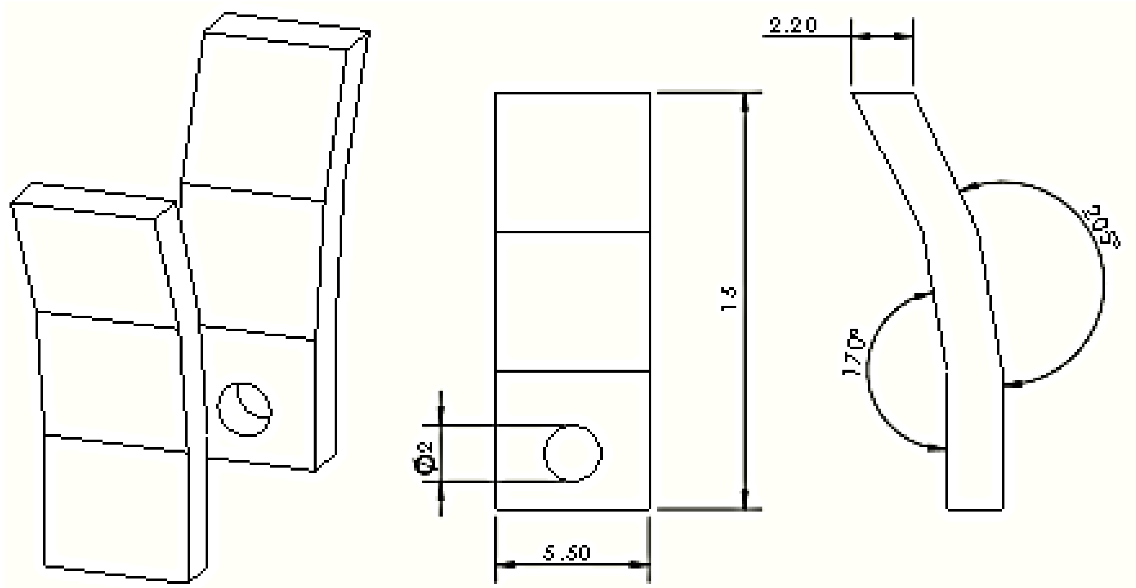


Fig 1: Design and Specifications of Electrodes. (All units in mm).

SOLID FUEL DIMENSIONS

- As per calculations the total mass of Teflon being carried by the nanosatellite should be 14 grams. A propellant height of 1.2 cm has been selected, which is slightly more than the electrode spacing of 1.1 cm. This has been done to avoid getting the propellant bar directly beneath the spark plug which could lead to incomplete ablation. The Teflon bar will be kept linear, and each arm length of the Teflon bar is 5.84 cm. Since the ratio of energy to area is an important factor, the propellant width here is considered as 0.46 cm, giving a small clearance of 0.02 cm on either side of the bar; that is the width of the fuel port is 0.5 cm.

SPARK PLUG DESIGN

- In a coaxial spark plug, there is an inner electrode which is connected to a high voltage supply and is surrounded by a semiconducting material [15, 23, 24, 25]. Tungsten has been selected as the material for inner electrode, and it has a diameter and a length of 1.5 mm and 8 mm respectively. The surrounding semiconducting material is made of TEFLON, and has an interior diameter of 1.5 mm, an exterior diameter of 2 mm and a length of 4.5 mm. The spark plug electrode is fixated at the origin of cathode.

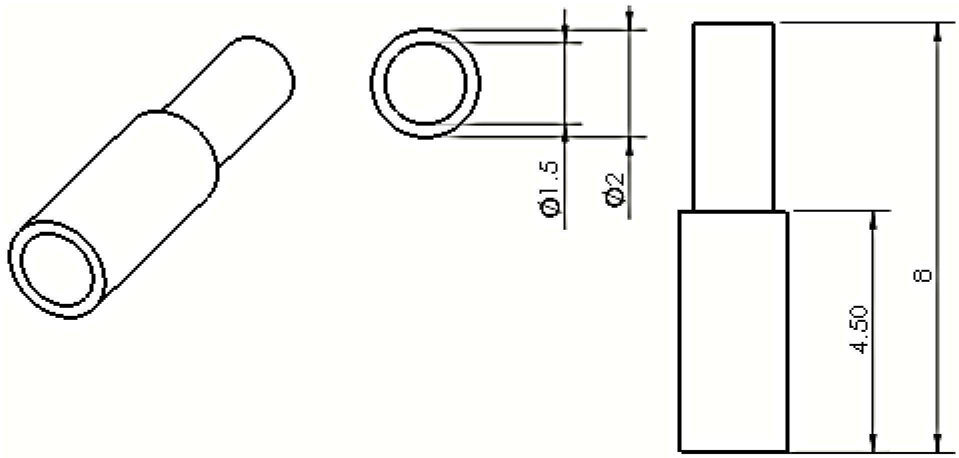
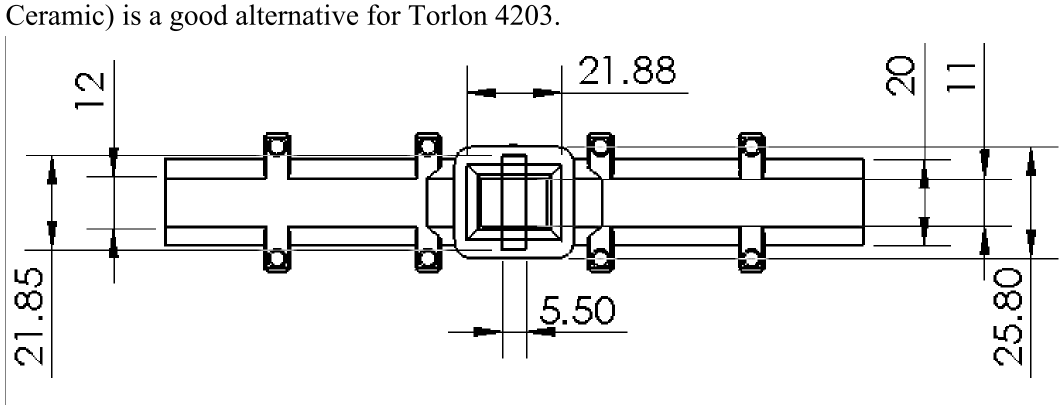


Fig 2: Design and Specifications of Spark Plug (All units in mm).

· µPPT STRUCTURE DESIGN

- Starting from the origin (initial position of the Teflon fuel), after 0.5 cm the Thrust chamber walls begin. To minimize the carbonization [13] of the walls a diverging angle of 10° is introduced. Although, other works have introduced only side wall divergence, in this model the entire middle region has a 10° divergence to limit carbonization to a further extent. After another 0.5 cm, another 25° divergence is introduced. Many authors consider 20° to 30° divergence for optimal performance [26]. To ensure uniform velocity profile, and the plasma sheet being expulsed with synchronization to energy stored in the capacitor, flared electrodes with 25° divergence are accommodated in the nozzle. As it can be assessed, the electrode follows the nozzle shape. A thickness of 0.1-0.3 cm for walls is considered for proper insulation both electrically, thermally and also for surviving static loads. Instead of leaving the design with edges, proper filleting has been done beside the nozzle walls to reduce stress concentrations and to make the structure more rigid against the load brought in by a launch vehicle.
- Due to Carbonization issue, which is highly critical in Pulsed Plasma Thruster, we're considering Torlon 4203™ for manufacturing the final model. ShapalM™ (Machine able Aluminum Nitride Ceramic) is a good alternative for Torlon 4203.



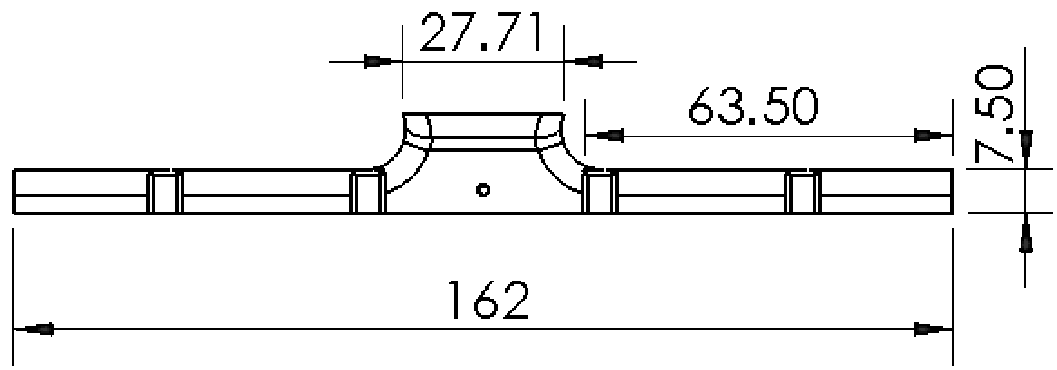


Fig 3: Design and Specifications of μPPT Structure (All units in mm).

NEGATOR SPRING DESIGN

- In order to ensure a constant supply of fuel, a suitable propellant feeding system is necessary to be designed. This can be done by using springs to push the solid fuel towards the spark plug. However, compression springs and torsion springs would not be suitable as when subject to buckling they would not perform the required job properly. Therefore, a constant force spring like a negator spring has to be used [14, 27, 28]. The total length of the negator spring should be more than the length of propellant, so as to ensure the propellant rod is consumed till the end. Commercially available negator springs of the smallest size made of stainless steel by ASRAYMOND has been opted for the thruster. The part number CF012-0037 has been selected for this design.

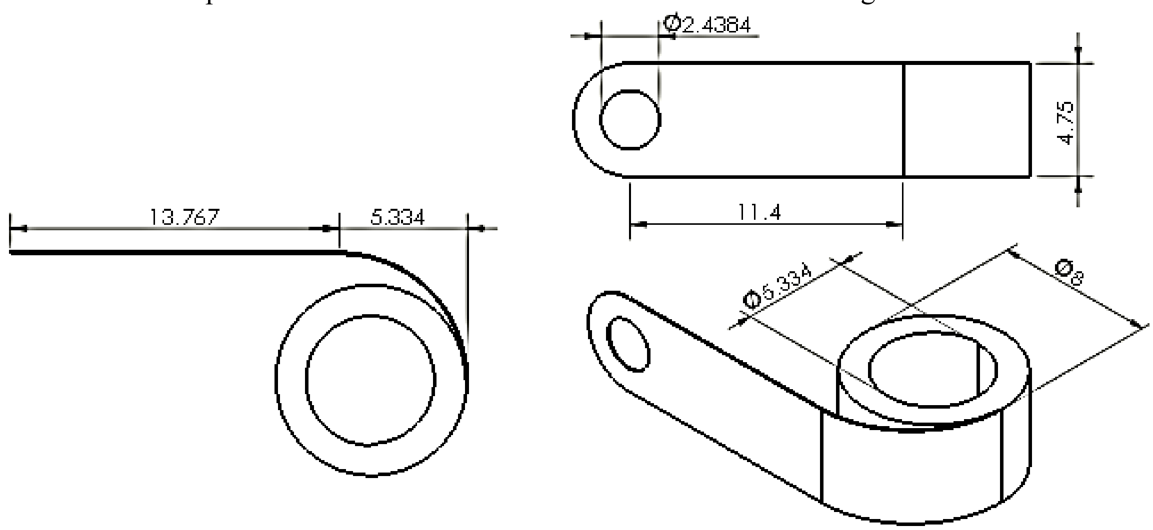


Fig 4: Design and Specifications of Negator Spring (All units in mm).

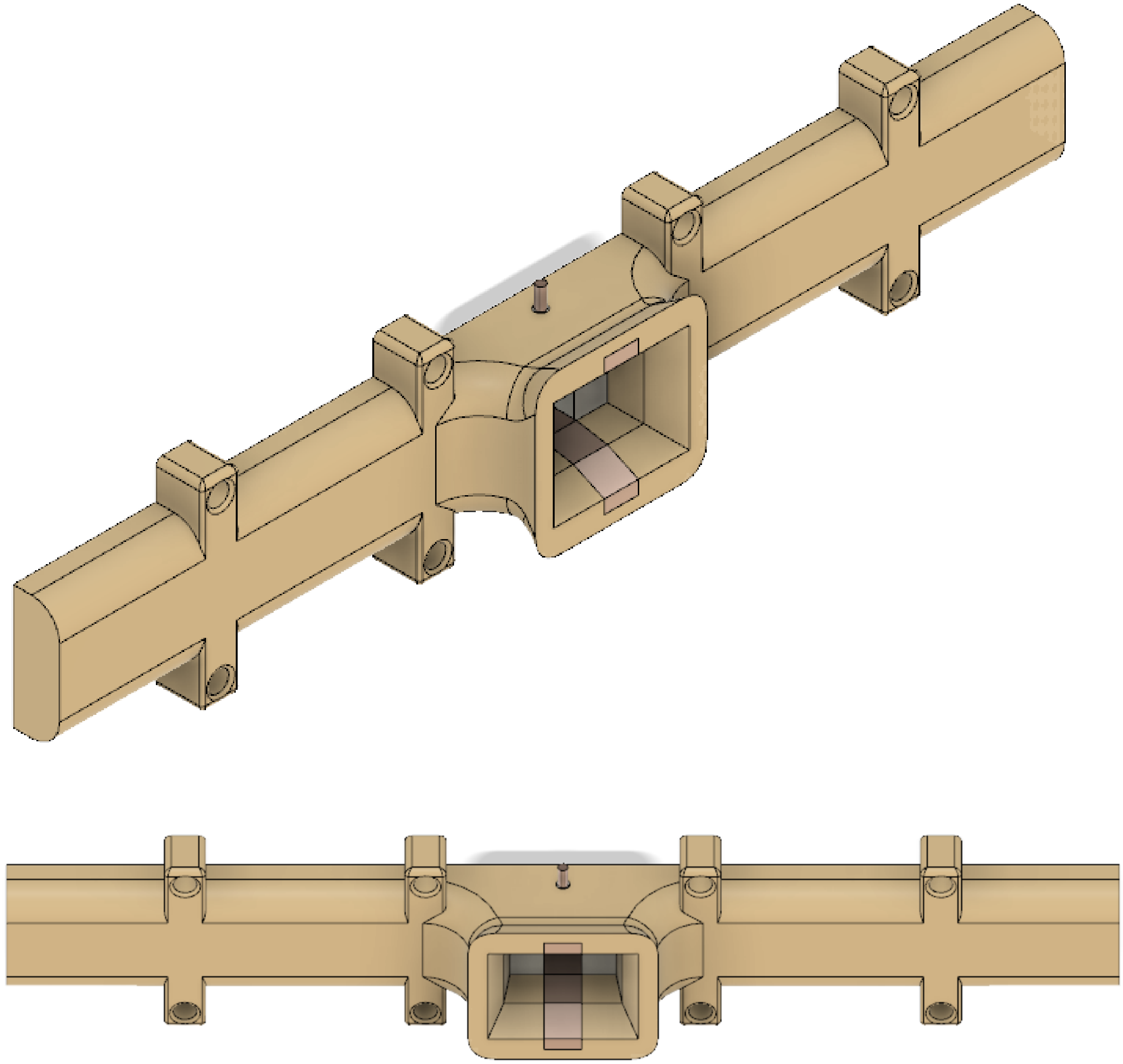


Fig 5: Isometric View of Micro Pulsed Plasma Thruster.

1.2) ELECTRICAL SYSTEM OF THE PULSED PLASMA THRUSTER

- **INITIATION OF SPARK PLUG**

We will apply a pulsed input of 5 V to the 555 Timer connected to fly-back XP POWER Q-60. The pulsating input is boosted to 6000 V which in turn is fed to the CW [29]. We are using the CW of 2 stages in cascade which further boosts the 6 kV to 12 kV. The high voltage of 12 kV is sufficient to produce the high voltage spark at the Teflon surface to initiate its ablation. The ladder comprises of 2 stages in cascade made of 10 nF capacitors and diodes.

Table 1: Specifications of Q-60 fly-back transformer.

Specifications	Value
Input Voltage Range	0.7 V - 5 V
Maximum Output Voltage	6 kV
Maximum Output Current	83 µA
Power	0.5 W
Voltage Isolation	500 V

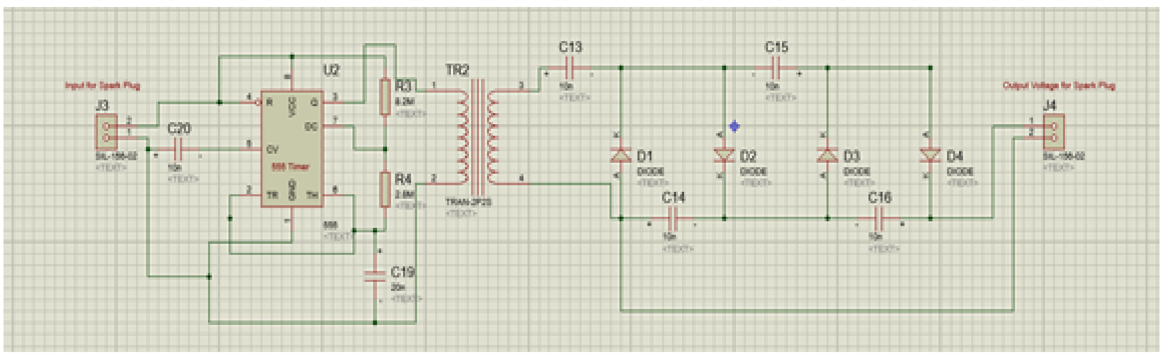


Fig 6: Circuit Diagram for Spark Plug.

The Cock-croft-Walton (CW) generator is manufactured by stacking up of voltage multiplier ladder network comprising of capacitors, diodes to produce a high voltage. Every stage consists of 2 diodes and 2 capacitors. The output voltage can be calculated by using,

$$\boldsymbol{E_{out} = 2 \times n \times 1.4E_{RMS}}$$

Voltage drop under load is calculated as:

$$\boldsymbol{E_{Drop} = \frac{I_1}{f \times C}\left(\frac{2}{3} \times n^3 + \frac{n^2}{2 - \frac{n}{6}}\right)}$$

The ripple voltage in the case where all stage capacitance (C1 through C(2*n)) may be calculated from:

$$\boldsymbol{E_{Ripple} = \frac{I_{Load}}{f \times C}\left(n \times \frac{(n+1)}{2}\right)}$$

Its observed that ripple increases rapidly with increase in the no. of stages (here n is squared).

We will be using 2 stages in cascade in order to produce a voltage nearly equal to 12 kV that would be sufficient enough to produce the high voltage spark from the output of the fly-back Q-60, at the Teflon surface and cause its ablation. So according to our calculations we considered the capacitors of capacitance 1μF and 20 kV rated to be used in the CW. We will be using 2 high voltage diodes and 2 capacitors in a ladder and then each ladder in cascade.

Table 2: Specifications of Diode used in CW.

Specifications	Values
Repetitive-peak in Reversed Voltage	20 kV
average Forward Current	5 mA
Max surge-current	0.51 A
Average Forward-Voltage Drops	44 V
Reversed Recover Time	100 ns
Terminal	Axial Lead

- **INITIATION OF ELECTRODES**

We will apply a pulsed input of amplitude 1.5 kV with Rise Time as 1μs, Fall Time as 1μs and Pulse width as 10 ms. The input is boosted to 1500 V. The boosted output is then fed to the Bank of Capacitors which in turn starts loading the capacitors. The output voltage of 1500 V from the bank is applied across the electrode plates in pulsed form to generate the pulsed plasma thrust.

Table 3: Specifications of Q-15 Fly-back Transformer.

Specifications	Values
Input Voltage Range	0.7 V - 5 V
Maximum Output Voltage	1.5 kV
Maximum Output Current	333 μA
Power	0.5 W
Voltage Isolation	500 V

For the bank of capacitors, we are using a parallel of six, series of two 1µF, 1000 V rated capacitors to form a 3.0 µF as total capacitance of the bank. The capacitor that we are using is of X7R dielectric. When the Q-15 supplies the boosted voltage, the PPT circuit will begin loading capacitors. The main capacitor is loaded to the full output voltage that needs to be applied in pulsating manner between the electrodes plates

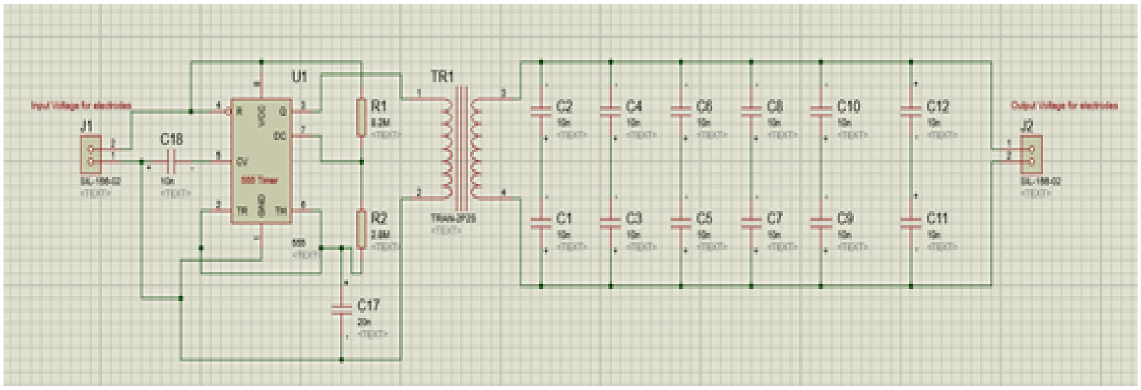


Fig 7: Circuit Diagram for Electrode Charging.

If more than one Thruster is considered a switching mechanism using 4H-SiC IGBT [30] across the output of the CW can be considered

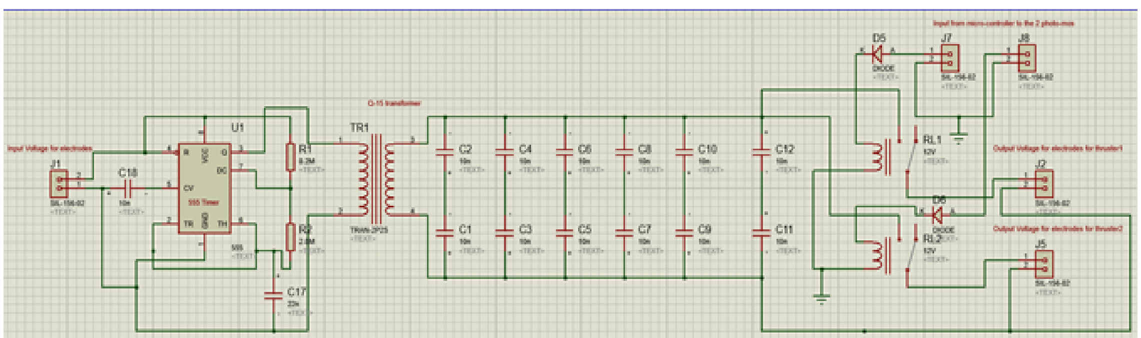


Fig 8: Capacitor bank circuit with IGBT in the end for a 2 system PPT.

- **FINAL CIRCUIT AND PCB DESIGN**

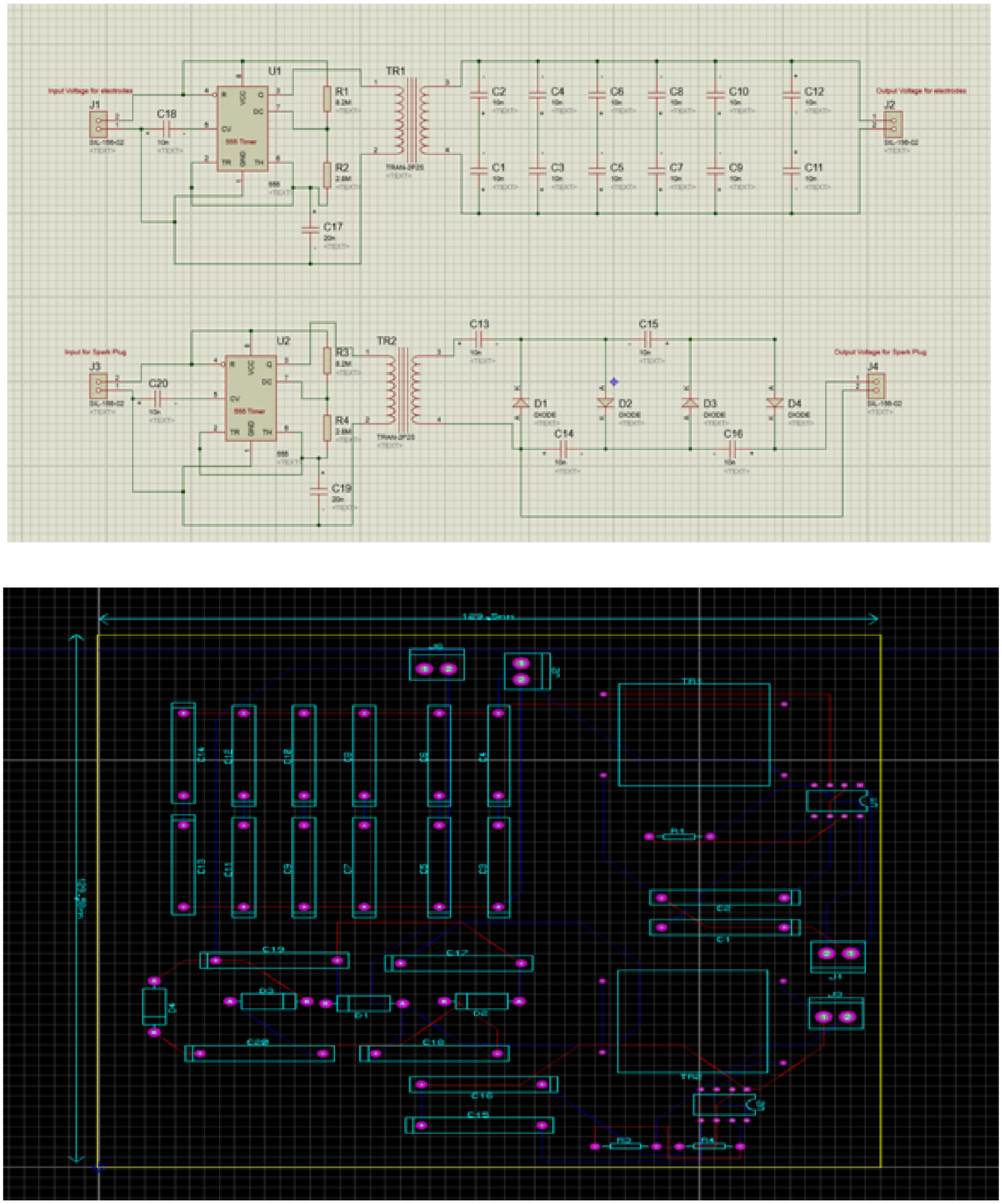


Fig 9: Circuit Diagram and PCB Design of the µPPT electrical System.

4. RESULT AND ANALYSIS

The Tables below show the specifications of components, static load simulations and electrical simulations

Table 4: Specifications of Mechanical Components.

Teflon bar geometry: **Linear**	Electrode Length: **1.5 cm**
Teflon Mass: **14 grams**	Electrode Spacing: **1.1 cm**
Propellant bar Length: **5.84 cm each arm**	Electrode Width: **0.55 cm**
Propellant bar Height: **1.2 cm**	Electrode Thickness: **0.22 cm**
Propellant bar Width: **0.46**	Electrode diversion: **Follows Nozzle**
Nozzle Middle wall divergence: **10°**	Interface to satellite: **Nut and bolts**
Nozzle Outer Wall divergence: **25°**	Spark plug Holder: **1 mm radius**
Spark Plug: **0.75 mm radius, 8 mm long**	Spring Inner Diameter: **5.334 mm**
Spring Width: **4.75 mm**	Working Extension: **228.6 mm**
Spring Hole Diameter: **2.44 mm**	Thruster Casing Mass: **52 grams**

Table 5: Material Considerations of various components

Components	Materials	Composition	Alternative
Electrode	Tungsten Copper Alloy	75%-25% W-Cu	Tungsten Coated Copper
Spark Plug Electrode	Pure Tungsten	99.5% W	Pure Copper
Spark Plug Holder	Teflon	PTFE	ShaplM™
Thruster Casing	Torlon 4203 ™	PAI	ShaplM™
Negator Springs	Steel Wire	Stainless Steel	----

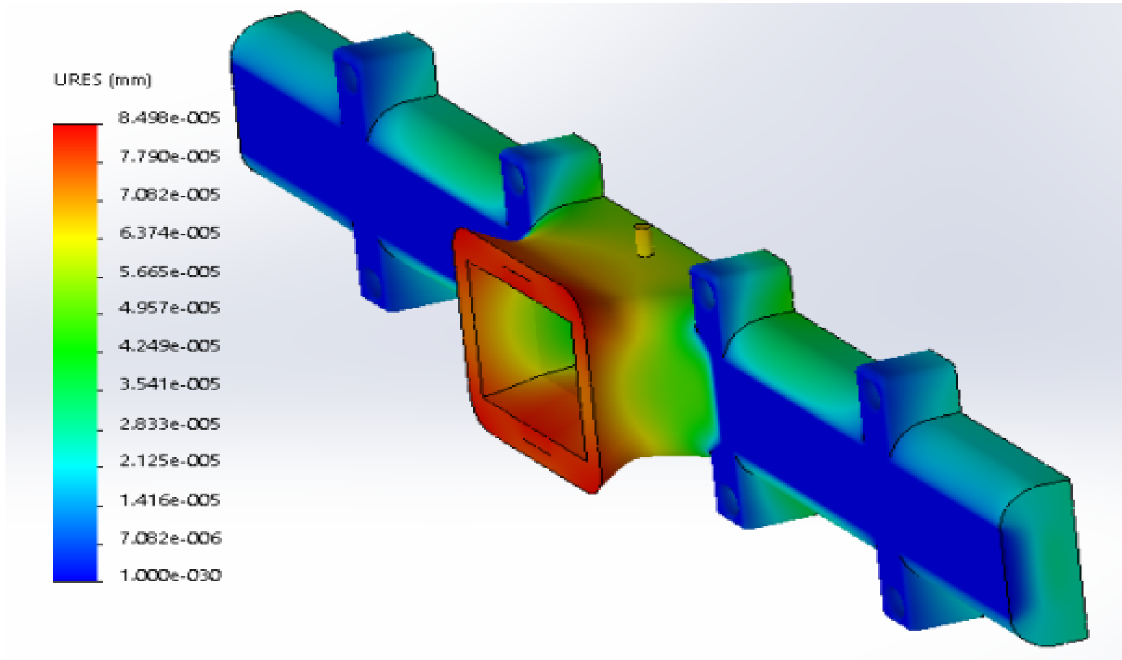
Table 6: Specifications of Electrical Components.

Items	Manufacturer	Quantity	Mass (gm)	Dimensions
Pulse Transformer Q-15	XP POWER	1	4.3	12.7mm L*12.7mm H *12.7mm W
Pulse Transformer Q-60	XP POWER	1	28.3	21.59mm L* 21.59mm H * 21.9mm W
Capacitor (BNC)	AVX	15	1	19.6mm L *18.3mm H *5.08mm T
Diode	HVGT	12	0.45	Φ3mm * 12mm
Capacitor for CW	----	6	2	Φ18 mm
8.2MΩ(for 555 Timer)	JAMECO VALUE PRO	4	1	6.8mm L * 28mm H * Φ2.5mm
2.8MΩ(for 555 Timer)	VISHAY INTER TECHNOLOFY	4	1	6.5mm L * Φ2.5mm
Capacitor-10nF (for 555 Timer)	AVX	4	0.45	3.81 mm L* 2.54 mm W * 3.81 mm H
Capacitor 22nF (for 555 Timer)	AVX	4	0.5	4.83 L * 2.29 W * 4.83 mm H

Total Mass: 130 grams

- **Static load Simulation**

To check whether the system can handle the extreme stresses of a rocket launch, a total load of 15 G is considered for the static load simulation, in addition to gravity acting against the load. Due to the limitations of computational hardware, the simulation has been done without the presence of negator springs. Yield Stress of Torlon is 137 MPa and of Teflon is 7 MPa. As it can be seen in the simulation results below, the maximum stress formed is much less than the yield stress of the considered materials. Therefore, the design is safe for use in space.



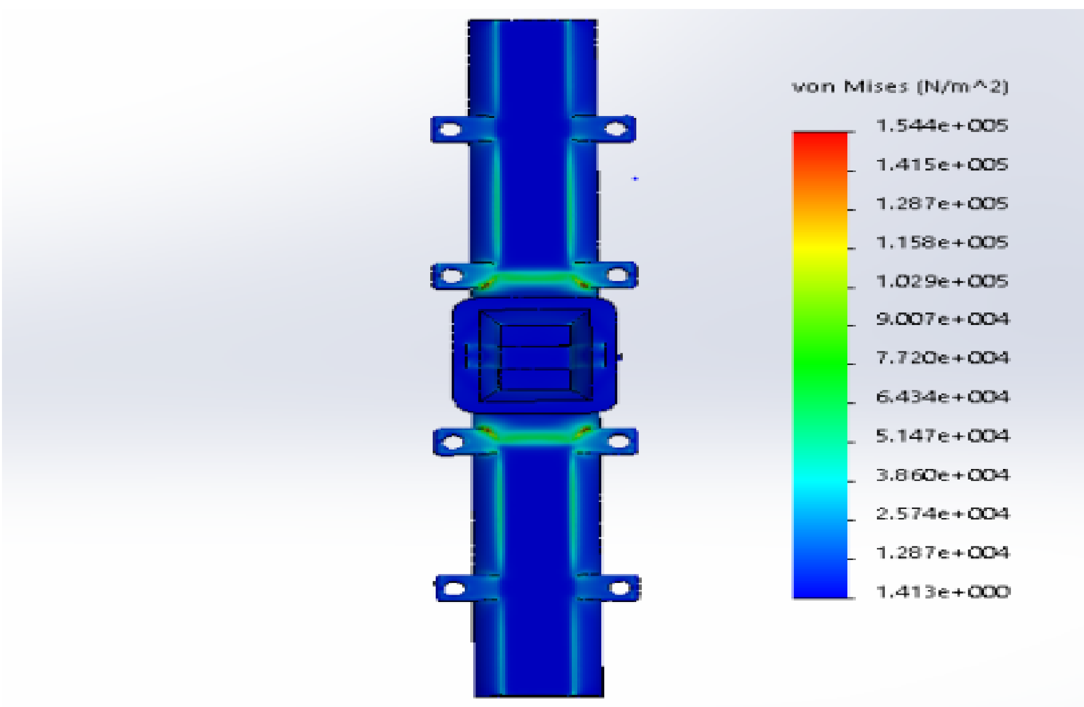


Fig 10: Maximum deformation and Maximum Stress Plot.

- **Simulation of voltage to be applied across the electrodes**

  Amplitude 1.5kV, Rise Time = 1µs

  Fall Time = 1µs, Pulse width = 10ms

  Frequency = 1 Hz, to the Bank of Capacitors. It produced an output voltage of 1500 V.

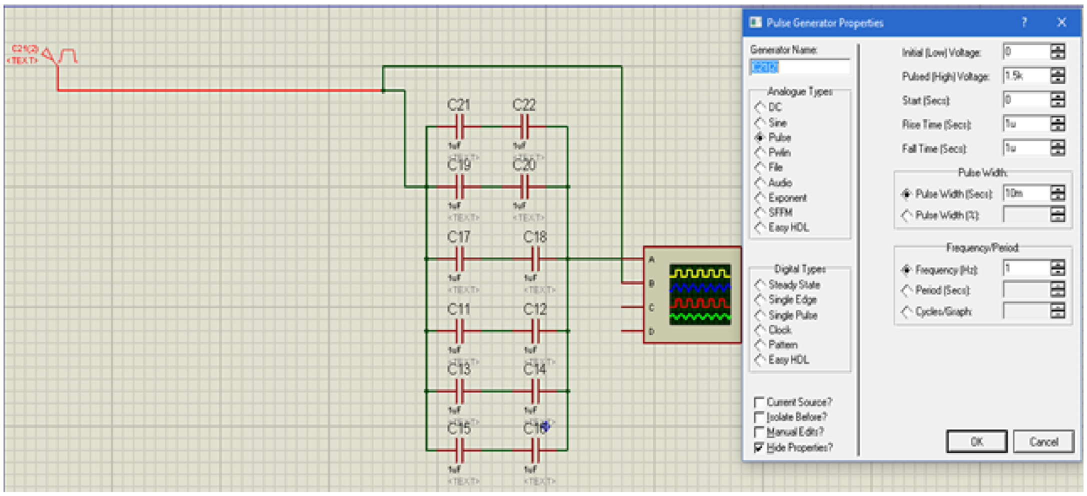


Fig 11: Circuit Diagram and Pulse Generator Properties for Bank of Capacitors.

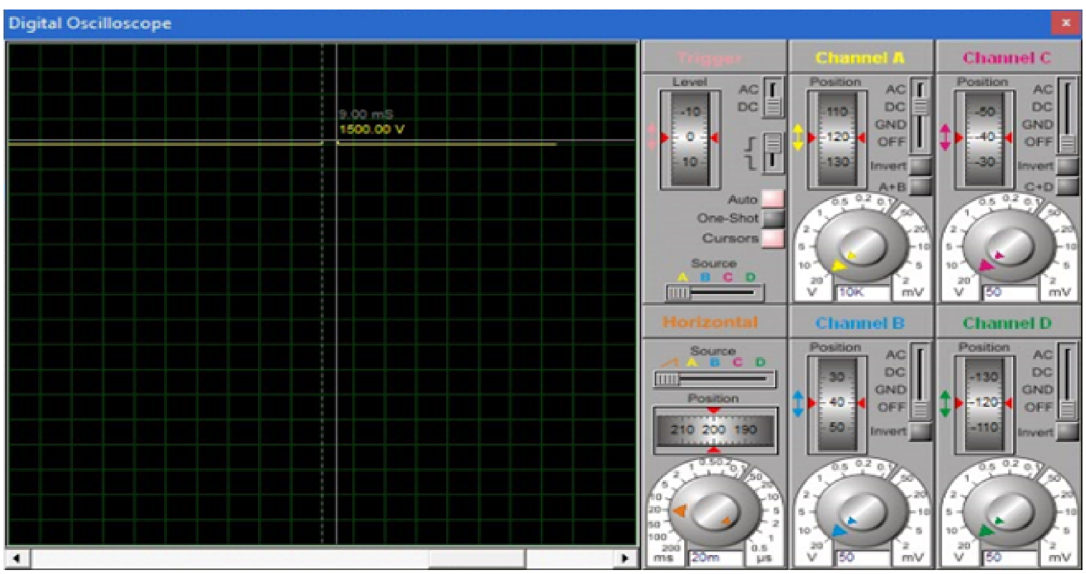


Fig 12: Simulation result produces a voltage of 1500 V as output of bank.

- **Simulation of voltage to be used for the high voltage spark.**

  Amplitude 6.0kV, Rise Time = 1µs

  Fall Time = 1µs, Pulse width = 10ms

Frequency = 1 Hz, to the CW. It produced an output voltage of 12kV.

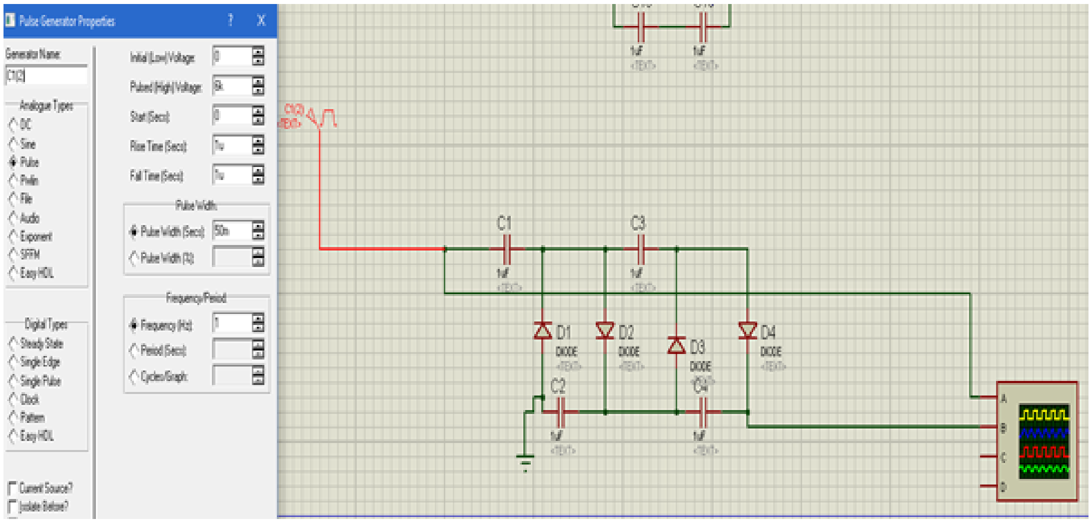


Fig 13: Circuit Diagram and Pulse Generator Properties for CW.

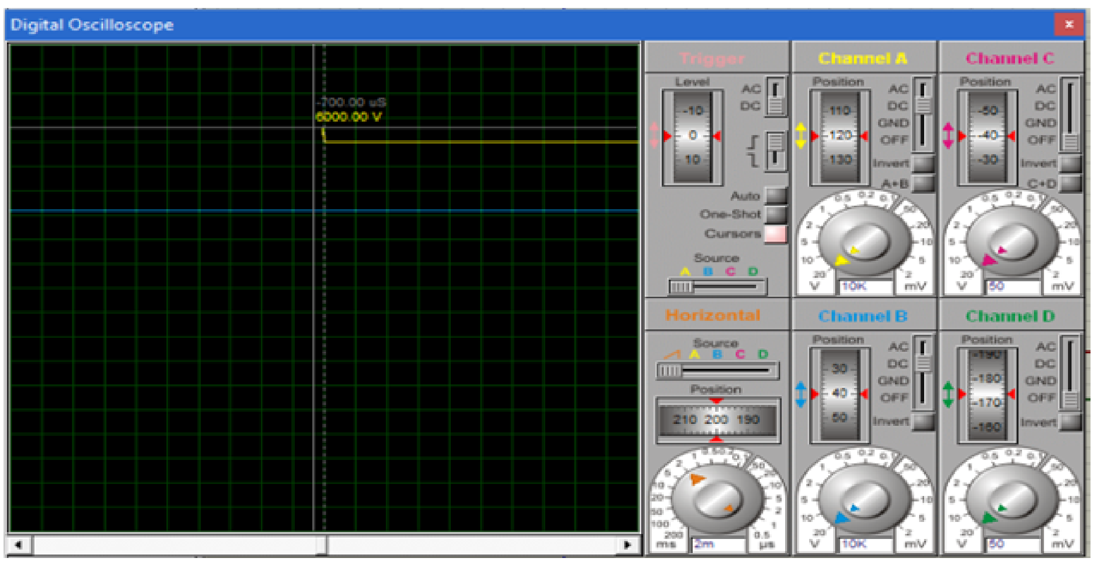


Fig 14: Simulation of the input 6 KV given to CW.

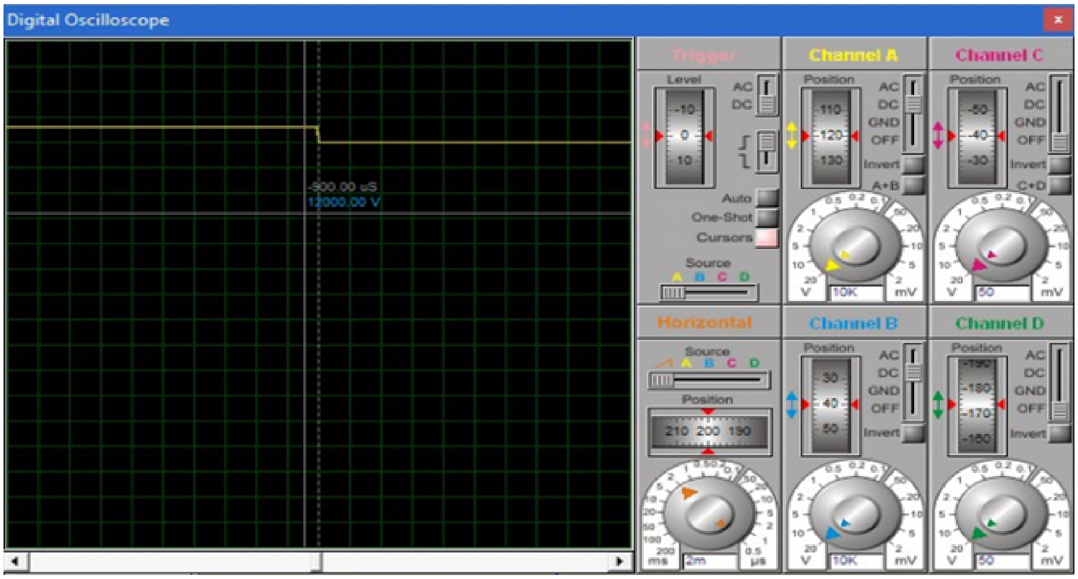


Fig 15: Simulation of the output of High Voltage Spark (12 KV).

- **Thruster Performance Calculation**

Using the Guman Graph [10, 17], the specific impulse of a PPT can be estimated. For that it is necessary to find the value of E/A ratio

$$\boldsymbol{E = 0.5CV^2 = 0.5 \times 3 \times 10^{-6} \times 1500^2 = 3.375\,J}$$

$$\boldsymbol{\frac{E}{A} = \frac{3.375}{(2 \times 1.2 \times 0.46)} = 3.06818\,J/Cm^2}$$

From the reference, it can be estimated that for this thruster system the specific impulse is 600 s.

5. CONCLUSION

The micro pulsed plasma thruster can survive the load which acts on it during launch. A maximum deformation of $8.498e^{-5}$ mm and a maximum stress of $1.544e^{5}$ MPa can be observed in the simulation. The yield stresses of all the components being considered here are much higher than the maximum stress that is being generated, therefore the design is safe. The choice of electrical components also proves that the necessary voltages for electrode charging (1500 V) and spark plug (12 KV) can be attained. Furthermore, the estimated specific impulse of 600 s using semi-empirical relations exceed the necessary specific impulse of 549 s required for a 1 KM Hohmann orbit maneuver, although the current plan is to use this thruster for technological demonstration by firing the thruster long enough to create a tilt which can be detected using the onboard Magnetometer. Experimental study and investigations can verify and compliment to the study done in this paper.

ACKNOWLEDGEMENT

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Declaration of interests

▯ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: