Low energy surface flashover for initiation of electric propulsion devices

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Abstract
An approach to modify a classic surface flashover by reducing the energy of the individual flashover event in order to reliably operate the same flashover assembly for large number of triggering events has been demonstrated. This modified surface flashover is referred to as Low Energy Surface Flashover (LESF). LESF is intended to trigger the discharge in electric propulsion systems throughout the entire operational lifetime. LESF differs from the conventional surface flashover in reducing the duration of high-current stage of the flashover to below \(< 100–200 \text{ ns}\). This minimizes the damage to the LESF assembly and allows successful operation of the same assembly for \(> 1.5 \cdot 10^6\) consecutive flashovers without failure. The amount of the seed plasma created in the individual LESF event was demonstrated to be sufficient to trigger a moderate current arc which models a discharge in an electric propulsion system.

1. Introduction
Recently there has been a rapid increase of interest in small satellites, such as CubeSats, which are usually launched as secondary payloads and are useful as instruments of targeted investigations to augment the capabilities of large space missions and enable new kinds of measurements [1]. With an on-board propulsion system, CubeSats are able to achieve orbital maneuvers, formation flying, constellation maintenance and precise attitude control [1]. Chemical propulsion as one candidate for propelling smaller spacecraft into outer space has the advantage of large thrust but presents severe concerns due to its requirement for large propellant mass, high temperature and pressure, and a threat to the main payloads posed by the reactive propellant materials. Electric propulsion, in comparison, has very high exhaust velocity and fuel efficiency. Depending on the mechanism of acceleration, traditional electric propulsion systems are generally divided into three categories: [2, 3] electrothermal [1, 5], electrostatic [6, 7], and electromagnetic [8–10]. While R&D of the electric propulsion for CubeSats currently involves multiple technologies including pulsed plasma thruster (PPT) [1], miniature Xenon ion thruster [1, 11], electrospray [1–15] and vacuum arc thruster (VAT) [1–25], these propulsion systems are still at their infancy and mostly remain \(< 7\) in the Technology Readiness Level scale used by NASA [1].

One of the central part of electrical propulsion systems are ignitor subsystems, which are required for the discharge initiation. Generally, there are many different methods to ignite a discharge in vacuum, among which are initiation using gas injection, high voltage breakdown, mechanical actuators for drawn arcs, and fuse wire explosion [20–28], etc. Other methods such as the triggerless method use vaporization of conductive coating between the anode and cathode [29]. Ignitor plugs in a PPT use point ablation of semiconductor layers to create highly ionized seed plasma [30–32]. All these triggering mechanisms operate by providing seed plasma required to bridge the electrodes and initiate the discharge.

A robust and compact ignitor that can reliably trigger the discharge in the electrical propulsion system throughout the entire operational lifetime is still challenging and under research as detailed below. This is due to the fact that while the triggering methods considered above are capable of discharge initiation, they still have their respective drawbacks from the prospective of propulsion applications. Indeed, the necessity to carry a gas storage tank for the gas injection triggering methods [26], and the need to utilize a high voltage source in high voltage breakdown techniques [20, 28] are adding to weight and complexity of the ignitor. Use of the fuse wire
explosion for the discharge ignition is highly unreliable if multiple ignitions are sought \[28\]. The triggerless method requires relatively high current (\(~200\) A) and long duration (\(~5\) ms) for reliable re-deposition of the conducting film on the insulating electrode separator and operation up to \(10^6\) pulses \[29\]. In application to micropulsion systems, arc currents and durations are significantly smaller (in the range of \(10\) s of Amperes and \(100\) s of microseconds, respectively), thus no reliable re-deposition was obtained and finally assembly suffered from electrode/film assembly damage after relatively low number (60,000) of triggering events \[33\]. Very recently, failure of micro-Cathode Arc Thruster (\(\mu\)CAT) operation after about 10,000–100,000 pulses was reported when conductive carbon paint was used over inter-electrode separators with surface area of \(\geq 10\) mm\(^2\) made of boron nitride and alumina ceramics, respectively \[34\]. Another very recent publication shows that an Inline-Screw-Feeding Vacuum-Arc-Thruster (ISF-VAT) design and the choice of Titanium as cathode material enables the VAT to achieve 700,000–1,000,000 pulses \[35, 36\]. In the case of the PPT ignitor plugs, encrustation on the ignitor plug face limits the thruster life time (2,000,000) \[31\] and the energy conversion efficiency is generally low (\(<10\%\)) \[32, 37\].

One particular type of vacuum discharge triggering is a surface flashover. In the surface flashover, two electrodes are separated by an insulating layer and the breakdown over the insulating surface is initiated at application of high voltage that exceeds the breakdown threshold \(V_b\). Studies of the surface flashover of insulators have been mainly driven by the high voltage vacuum devices’ applications. High voltage holdoff capability is desired for these devices, and surface flashover and subsequent breakdown are undesirable effects. Thus, surface flashover was studied from the perspective of the ultimate goal to reduce the probability of the said events and increase the holdoff voltage capability of the device. It has been shown that the surface flashover voltage of insulators in vacuum depends upon many parameters, such as material, geometry, processing history of the insulator, the applied voltage waveform and its duration, and on the number of previous flashovers \[38, 39\]. The breakdown voltage of insulators was found to be independent of pressure in the ranges of \(5,10^{-3} - 10^{-2}\) Torr \[40\]. Typically, surface flashover can be broken down in a three-stage process \[41\]. It starts with stage 1 lasting for about 10 ns when electrons are emitted from Cathode Triple Junction (CTJ). Stage 2 (100–400 ns) is associated with Secondary Electron Emission Avalanche (SEEA) development since some electrons emitted from the CTJ impact the surface of the insulator and produce secondary electrons. On the stage 3 (>100–400 ns) desorption of gases from the insulator surface at SEEA development occurs, Townsend breakdown develops in these desorbed gases and high current arcs develop in the assembly \[41–46\].

Therefore, surface flashover was studied thoroughly by the high voltage vacuum devices’ community. This classic flashover is associated with overheating of the flashover electrode assembly and permanent damage to the assembly after relatively low number (<\(10^3\)) of flashover events due to high current arcs developing in the assembly on the stage 3 of the flashover event \[47–50\]. In contrast, surface flashover at higher pressure (about 0.4 Torr of hydrogen) has been demonstrated for successful ignition of a pseudospark high-power switch up to 4 million pulses \[51\].

A possibility to limit the energy of the surface flashover in order to shorten/remove the high-current stage 3 of the flashover event with an ultimate goal to reduce/remove the damage to the flashover electrode assembly and use it as an ignitor for the discharge in propulsion system is a novel and original approach that was not studied earlier. In this work we have studied the novel approach to modify classic surface flashover by significant reduction of the energy of the individual flashover event in order to achieve large number of flashovers with the same electrode assembly without significant damage or degradation to the assembly and demonstrated potential of using this approach for ignition of electric propulsion systems such as micro thrusters. The proposed approach is referred to as Low Energy Surface Flashover (LESF) in the following description.

2. Experimental details

The experiments were conducted in high vacuum setup pumped down to \(5.10^{-6} - 3.10^{-5}\) Torr. Electrode assembly shown in figure 1 was utilized in the experiments. It consists of a 0.635 mm thick non-porous alumina ceramic sheet clamped between the two 10 mm x 10 mm x 0.5 mm copper electrodes bonded to the ceramic sheet with a low vapor pressure epoxy. The electrodes were sanded with 600 grit sandpaper and the side on which the surface flashover events occur was additionally sanded using 514 grit diamond wheel.

This study has been intended to initiate the breakdown at potentially lower voltages. To this end, alumina ceramics was chosen as an insulator material since it is characterized by the relatively low surface flashover breakdown voltages about 5–10 kV mm\(^{-1}\) \[52\]. In addition, the insulator thickness was significantly reduced (down to <1 mm) in comparison to that normally used in surface flashover studies (>1 cm). While surface flashover in vacuum may require high voltages to discharge, this study was focused on attempts to limit the \(V_b\) to the range of around 10–15 kV.
Two high voltage power supplies have been used to initiate the surface flashover in the experiments, namely Eagle Harbor Nanosecond Pulser model NSP-3300–20-F (<110 ns, <20 kV) and Bertan Series 225–20 R DC power supply (<20 kV, <1 mA). DC power supply Sorenson X60–28 (<60 V, <28 A) was used to support a main discharge triggered by the flashover (see details below). Electric characteristics of the discharges were measured by Tektronix P6015A passive high voltage probe, Pearson 2100 and Bergoz FCT-028–0.5-WB current monitors. Fast photographing of the surface flashover was captured by Princeton Instruments PI-MAX4 ICCD camera.

3. Experimental results and discussions

Figure 2 shows evolution of the voltage required to breakdown the flashover electrode assembly ($V_{br}$) in $>1.5 \cdot 10^6$ flashover events ($N$). The flashover assembly shown in figure 1 was used in these experiments. Eagle Harbor pulser was utilized with pulse amplitudes up to 15 kV and pulse duration of 110 ns in order to limit the duration of the high-current stage 3 of the flashover associated with high-current arcing [38, 39]. These short flashover events with duration $\tau_f \leq 100$–200 ns are referred to as Low Energy Surface Flashover (LESF). Schematics of the utilized electrical circuit are shown in the insert of figure 2. For the first 500 initial pulses the pulser was operated at single pulse mode, and then the pulse repetition rate was gradually increased from 1 to 200 Hz.

One can see from figure 2 that the breakdown voltage increased rapidly from 2.9 kV during the first hundred pulses and eventually approached a nearly saturation region in the range of 9–15 kV for $N > 1000$, as indicated by the red shaded area in figure 2. The initial increase of $V_{br}$ is a well-known effect of conditioning of the
insulator surface which is associated with removal of surface gas, removal of surface contaminants, or removal of emission sites\(^{38,39}\). One can see that in the nearly saturation region, the \(V_{br}\) is still highly variable within 50\% due to natural variability of the different flashover events. All experimental results presented below were obtained with fully conditioned electrode assemblies which are associated with the nearly saturation region indicated by the red shaded area on the figure 2.

It is important to note, that the data presented in the figure 2 was obtained using the same electrode assembly which was run without failure or significant damage to the electrodes/insulator for more than 1,500,000 pulses. For confirmation purpose, another 1 million pulses test was conducted on a different assembly using same other experimental conditions. It is important to note, that both assemblies remained fully operational after conducting the 1.5 and 1 million pulse tests. Both tests were carried with the initial energy stored in the flashover/leads assembly prior to the event \(E_0 = \frac{Q_0^2}{2} \gtrsim 0.73 \text{ mJ}\) which will be shown below to be sufficient to initiate moderate-current vacuum arc used to model the discharge in an electric propulsion system. The photograph shown in figure 1 demonstrates the assembly after conducting \(>1.5 \cdot 10^7\) flashover events. Only minor ablation of the electrode assembly can be visually observed at the electrode-insulator interface. This finding confirms that the approach of limiting the duration/energy of individual surface flashover event has great potential for very long operational lifetime of the same electrode assembly. In addition, visual observations of the LESF events confirm that ignition was randomly occurring over the entire insulator surface (total surface area = 6.35 mm\(^2\)) and was not attached to any particular location.

An individual flashover event of a fully-conditioned assembly was studied in detail using the circuit shown schematically in figure 3(a). In this case, DC high voltage was applied to the electrodes through a current limiting resistor \(R_{lim}=100 \text{ k}\Omega\) connected in series to the electrodes using Bertan 225–20 R DC power supply. Duration of the surface flashover (\(t_f\)) was a free parameter in these experiments, and it is governed by the amount of the energy available in the capacitive circuit formed by the flashover assembly and the leads indicated by the dashed area in the figure 3(a) (see details below). Simultaneous measurements of the electrical parameters of the flashover along with the series of photographs (3 ns exposure time) taken by the ICCD camera are presented in figure 3(b)–(d).

One can see in figure 3(b) that initiation of the flashover was indicated by an instant drop of voltage (near \(t \approx 0\)) and start of high frequency current oscillations. These current oscillations are associated with the resonant ringing in the \(L\)-circuit formed by the flashover assembly shortened by the plasma column (see dashed area in figure 3(a) behind the current limiting resistor). Indeed, prior to the flashover the electrode assembly is equivalent to a capacitor \((C)\) charged to the voltage \((V_{br})\) as shown in figure 3(c). This capacitance

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**Figure 3.** Simultaneous measurements of the electric parameters and fast photographing of the surface flashover. (a) Schematics of the electric circuitry used in the experiments. (b) Voltage and current waveforms during the flashover event. Moments of time \(t_1–t_4\) correspond to the images shown in figure 3(d). (c) Equivalent circuits of the LESF assembly and leads without and with plasma. (d) Photographs of the LESF event taken in the moments of time \(t_1–t_4\) taken by the ICCD camera (exposure time = 3 ns).
was measured prior to the experiment to be 7 pF and thus resulting in total energy stored in the capacitor:
\[ CV_0^2 = 0.35 \text{ mJ}. \] Creation of the plasma in the flashover event causes immediate short of one side of the assembly by plasmas, while the other side of the assembly is nearly opened (see figure 3(c)), since current replenishment through the large 100 kΩ resistor on the short flashover timescale \( \tau_R \) is negligible \( (R_{\text{lin}} C \gg \tau_R) \). Thus, total energy stored in the capacitor is oscillating between the open-ended capacitive side of the assembly and shortened by the plasmas inductive side of the assembly. The inductance of the shortened assembly is governed by the inductance of the leads and it was measured prior to experiments to be \( L_w = 0.5 \mu \text{H} \). One can see in the figure 3(b) that period of the current oscillations was about 15 ns, which is consistent with the theoretical estimation for the resonant oscillation period in the LC-circuit: \( 2\pi \sqrt{L_w C} = 12 \text{ ns} \). Note, we do not present the evolution of the discharge voltage after the flashover start in figure 3(b), since these measurements are far beyond frequency bandwidth of the Tektronix P6015A probe (75 MHz) used in the experiments.

Oscillations of the discharge current were peaked at around 40 A around \( t \approx 0 \) and decayed on the time scale of about 50 ns according to figure 3(b). This decay time provides an estimate of flashover duration time \( \tau_F \) as follows from the experimental results. Indeed, \( \tau_F \) was directly evaluated by means of fast photographing conducted by ICCD camera as shown in figure 3(d). These visual observations indicate that flashover decays on the approximately same time scale of about 50 ns. Note, even though driven by the DC high voltage source, the duration of the flashover presented in the figure 3 was short \( \tau_F < 100 \text{ ns} \) and thus, it operated in the LESF mode.

Duration of the flashover event \( \tau_F \) driven by the circuitry shown in the figure 3(a) can be controlled by adjusting the amount of initial energy stored in the flashover/leads assembly prior to the event \( E_0 = \frac{CV_0^2}{2} \) (see dashed area in the figure 3(a)). Specifically, \( \tau_F \) can be increased if larger energy \( E_0 \) is used. To demonstrate this, an additional capacitor was inserted in parallel to the LESF assembly to increase the capacitance and energy stored in the circuit prior to the flashover event. The tests were conducted with two capacitances \( C = 7 \) and 100 pF and the corresponding initial energies stored in the assemblies were \( E_0 = 0.35 \) and 5 mJ, respectively \( (V_{fr} \text{ was about } 10 \text{ kV in both cases}) \). Current waveforms for \( E_0 = 0.35 \) and 5 mJ are presented in figure 4. One can see that flashover duration \( \tau_F \) increased from about 50 ns to about 200 ns when initial energy \( E_0 \) increased from 0.35 to 5 mJ. In addition, the increase of capacitance to \( C = 100 \text{ pF} \) led to the corresponding increase of the oscillations’ period to about 50 ns which is in agreement with the theoretical estimation \( 2\pi \sqrt{L_w C} = 44 \text{ ns} \).

An extreme case of large capacitance \( C = 4 \text{ nF} \) (referred to as ‘high energy regime’) was examined in order to demonstrate quick damage to the electrode assembly. It was found that after less than 200 flashover events, the sample operation became unstable and ignition happened less than once in three trials. Figure 5 presents photographs of the assembly before and after the high energy flashover tests. There were observable gaps between the insulator and the electrodes due to the erosion of the insulator. Furthermore, both the insulator and electrodes surface had multiple traces of damage. Visual comparison of figures 5 and 1 indicate that flashover operation in a ‘high energy regime’ for 200 pulses was more detrimental to the assembly than operation in LESF mode for over \( 1.5 \cdot 10^6 \) flashover events.
In the following description we have evaluated whether the proposed approach can satisfy the purpose of triggering the discharge in the electric propulsion system. To this end, the LESF assembly was tested as an igniter for a moderate current vacuum arc and influence of initial energy $E_0$ on the ignition success was determined. Vacuum arc was used to model the discharge in the electric propulsion system in these experiments. An additional anode was placed at the distance $d$ from the LESF assembly as shown in figure 6(b). The anode was biased to a voltage of $+60$ VDC with respect to cathode of the flashover assembly as shown in figure 6(a). The initial energy $E_0$ supplied to the flashover was varied by reducing the capacitance of the flashover/leads assembly.

For $d = 4$ cm, a successful ignition of the arc discharge was observed with the initial energy $E_0 = 0.73$ mJ in 16 out of 20 trials, while $E_0 = 0.39$ mJ failed to ignite the arc. The successful initiation of the arc discharge is demonstrated by the arc current pulse of about $I_{arc} = 5$ A lasting for about 8 $\mu$s as shown in figure 7(a). For $d = 2$ cm, a successful ignition of the arc discharge was observed in every try with the initial energy $E_0 = 0.73$ mJ, while $E_0 = 0.39$ mJ led to the ignition of 4 out of 20 tries. It can be inferred that seed plasma created by the LESF considered in this work is sufficient to trigger the arc discharge used to model the discharge in electric propulsion system. In addition, closer proximity of the arc anode to the flashover assembly enhances the ignition due to higher density of the seed plasma in the gap.

Let us now describe the potential applications of Low Energy Surface Flashover demonstrated and tested in this work. LESF can be used to initiate discharge in Cathodic Arc Thrusters (CAT), Pulsed Plasma Thrusters (PPT) or other systems that may require reliable trigger. If LESF is used with CAT, there are two potential ways to prevent the LESF assembly failure due to the deposition by the cathode spots. First, the attempts will be made to shield the LESF assembly from the direct exposure to the metallic ions produced by the arc [20, 51]. This would allow controlling the amount of the deposition on the LESF insulator at the desired level by adjusting the extent to which the assembly is shielded from the cathode spots. In vacuum arcs, the cathode side facing the anode is
typically eroded and consumed; therefore, LESF assembly can be attached to the non-eroding side of the CAT cathode to minimize the direct exposure to the metallic ions [20]. In addition, magnetic field on the CAT cathode can be used to direct cathode spots away from the LESF assembly using ‘acute angle opening’ principle [20]. Second possible solution might be ‘self-cleaning’ of the LESF assembly from the metallic deposition originated from the cathode spots. Specifically, deposited LESF insulator can potentially be ‘self-cleaned’ due to overheating and evaporation of the deposited film when electric current is sent through the film, similar to that in fuse wire explosion mechanism [20, 27]. Of course, possible damage to the LESF assembly will have to be considered in this case. Particular operation regime of the LESF will be determined based on practical application. It has to be noted that, LESF assembly can be used for triggering of miniature pulsed plasma accelerators utilizing gas propellant [3].

Another aspect of application of LESF for the micropropulsion systems is necessity to generate HV pulse and mitigation of EMI. HV pulse generation can be accomplished on the spacecraft by utilizing a compact flyback transformer that requires low driving voltages of about 20–30 V, thus eliminating the need for bulky HV capacitors [53, 54]. EMI mitigation can be achieved using shielding [30, 55] or EMI filters [17]. In addition, reducing the insulator gap to <100 μm can be a possible solution to reduce breakdown voltage to <2–3 kV range according to the data available in the literature [48, 52]. This would also significantly reduce the amplitude of electromagnetic noise generated by the HV pulse. Tests of the LESF ignitor as part of a complete propulsion system are subject of the separate future work.

4. Conclusions

Proposed here approach is paving the way for utilization of Low Energy Surface Flashover for triggering the electric propulsion systems. We have demonstrated that LESF electrode assembly can withstand extended operation for >1.5 · 10⁸ breakdowns without significant damage to the electrode assembly. The amount of seed plasma produced in the single flashover event is sufficient to trigger a moderate current arc which was used to model a discharge in the electric propulsion system.

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