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Investigations of a high current linear aperture radial multichannel pseudospark switch

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In this paper, a high current linear aperture radial multichannel Pseudospark switch (LARM-PSS) is reported which has been analyzed for its high current characteristics. In order to enhance hold-off voltage and support hollow cathode effect for the ignition of the discharge in this configuration, the field penetration analysis through circular and linear apertures of the electrodes has been carried out. The linear apertures in the electrodes increase the current handling capacity than that of circular aperture electrodes without significant compromise of the hold-off capacity. The developed LARM–PSS switch is capable to hold voltage up to 25 kV at gas pressure between 10 and 50 Pa for hydrogen. The switch has been operated using a 800 nF capacitor bank and conducted an effective charge up to 1.5 C with peak switch current ~20 kA at applied voltage 19 kV. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4932966]

I. INTRODUCTION

Pseudospark discharge switches (PSSs) are low pressure (typically 10–100 Pa) plasma switches which are used for various high power applications.[1,2] The PSS can replace commercially available switching devices, such as hot cathode thyratrons, spark gaps, and ignitrons with enhanced capabilities in terms of charge transfer, time jitter, life time, fast current rise, and full current reversal without any negative impact.[3] These can further have high hold-off voltage, high current, and pulse length operation from 10's of nanoseconds to several of microseconds.[2] The major applications include pulsed-power switching, mine blasting, rock fractioning, pulse power modulator, laser, radar, etc.[4–6]

The main property of a pseudospark discharge (PD) is to generate a high current density of the order of 10^4 A/cm^2 in the discharge region of cold cathode.[2] In fact, PSS is also known as a cold-cathode thyratron due to the similarities with regular thyratron but in different operation regimes of the current. The simple structure on account of cold cathode operation than that of regular thyratron adds additional advantages to the PSS. It is well-known that the hot cathode thyratrons, in general, show current quenching above ~10 kA of the discharge current operation[7] and hence are not very much useful for many emerging high current switching applications. On the other hand, the PSS shows current quenching below ~3 kA but one can easily operate it on higher current ratings.[8–10] At present, coaxial multi-channel geometry PSS is considered for moderate current applications[5] but more recently for high current operation of PSS, the radial multi-channel geometries have been worked out.[11,12]

The electrode geometry plays quite important role in reducing electrode erosion which occurs during extremely high coulomb transfer. In fact, in coaxial multi-channel geometry, the discharge channels pinch because of the self-magnetic fields of the discharge current in the individual channels and plasma discharge is confined over a smaller area leading to erosion of the electrodes.[5,13]

On the other hand, in the radial multi-channel geometry, the self-magnetic fields and forces cause the discharge to move upward in axial direction resulting into spreading of the discharge over more surface area.[12] The radial multi-channel PSS can conduct high current and seems advantageous over coaxial channel PSS.

Furthermore, the number of round hole apertures in the radial multi-channel geometry can be increased so as to increase the charge transfer per shot capability of the switch, which can additionally reduce erosion of the electrode material.[14,15] The other way for increasing the current handling capability is to increase the size of the holes in the electrodes. Nevertheless, the increase in the size of holes would certainly lower the voltage holding capability of the PSS and also increasing the number of round hole apertures can limit the simultaneous ignition of the discharge among all the channels.[16] The alternate of this could be to elongate the round holes to linear apertures, i.e., the length greater than the width. It is seen that in coaxial geometry, a long linear aperture can offer the same voltage hold-off as round aperture switch, if the width of the linear aperture is approximately 70% of the round aperture diameter.[16,17] Also, increase in the length of the linear channels can assist in simultaneous triggering of all the channels.[17]

The reported linear aperture radial multichannel Pseudospark switch (LARM-PSS) in this paper alleviates electrode erosion along with the simultaneous triggering of all the channels due to its geometry characteristics. The switching performance has been analyzed experimentally and it has

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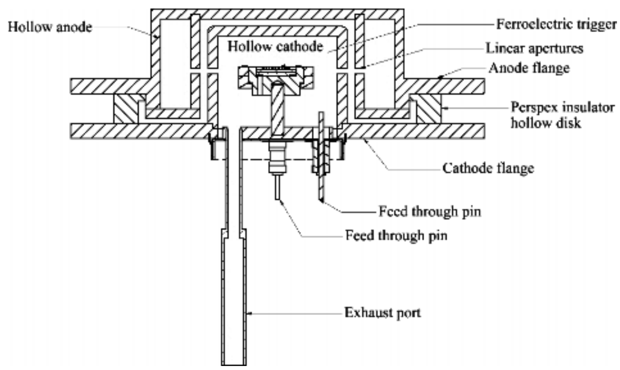

FIG. 1. Schematic view of linear aperture radial multichannel pseudospark switch (LARM-PSS).

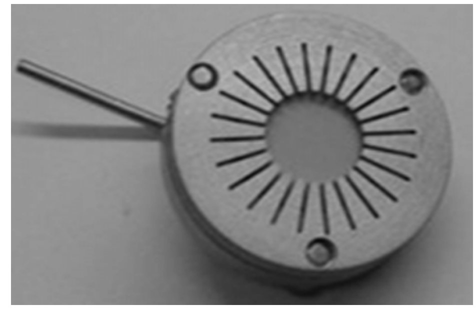

FIG. 2. High dielectric constant trigger unit.

been characterized in terms of various pulse parameters. For the preliminary assessment of the field penetration, the design aspects of this switch have been worked out using electrostatic simulator "OMNI TRACK." The analysis has been performed through circular and linear apertures of the electrodes.

Section II describes the geometry of the switch along with various sub-components while Section III contains the experimental setup for electrical characterization. The results and discussion are presented in Section IV and conclusion is given in Section V.

II. GEOMETRY OF THE SWITCH

A. Electrode geometry design

The schematic drawing of the developed LARM-PSS is shown in Figure 1. The main gap width, thickness of the electrodes, and the aperture width of the linear channels have been taken as 3 mm, 3 mm, and 2.5 mm, respectively. It has a cathode cavity with inner diameter of 48 mm and length of 37 mm to support the hollow cathode effect. The anode cavity has width 12 mm and length 36 mm. The material of the switch electrode is oxygen-free high-thermal conductivity (OFHC) copper. Perspex housing with copper flanges has been used as the switch chamber. The switch hold-off voltage basically depends on the geometrical parameters of the electrode under different gas conditions. There is no exact analytical relation that can determine the breakdown voltage of the switch. However, to approximate the initial breakdown characteristics, an empirical relation for breakdown of hydrogen gas in pseudospark geometry has been used as a feedback.[18]

It is well-known that the metal vapors are evaporated explosively during the high current phase near to the aperture due to plasma sheath contraction and high electric field in it.[19] In our case, the round hole apertures have been elongated to take the form of linear apertures, which leads an increment in the length of the plasma sheath in the linear aperture geometry. This would further lead the density of metal vapor emanating from the aperture area to decrease and hence would be resulting into lesser erosion during the high current phase. Four linear apertures, as shown in Figure 1, have been cut around the radial periphery of the anode and cathode walls. The width, number, and area of linear apertures to switch the high current without affecting the voltage holding capability of the switch have been analyzed and optimized using electrostatic simulations.

B. Trigger unit

There are many trigger schemes available for the initiation of the hollow cathode discharge in pseudospark switches.[20] A high dielectric trigger unit has been used in the present LARM-PSS. It contains barium titanate ($BaTiO_3$) disk of high dielectric constant sandwiched between a finger-contacting electrode and a metal electrode as shown in Figure 2. The trigger device has two wire connections; one for the metal fingers that contact the dielectric disk and another for the metal electrode that holds the dielectric disk. The trigger unit supported by a rod is placed at an optimum position inside the hollow cathode region of the LARM-PSS for minimizing the current quenching and aiding the simultaneous trigger of all the discharge channels. The electrons are generated on applying potential difference of 5 kV between the metal fingers and the base metal electrode. The ground potentials of the trigger unit and developed LARM-PSS geometry are isolated to avoid any interference of the trigger current with the main discharge current.

III. EXPERIMENTAL SETUP FOR ELECTRICAL CHARACTERIZATION

The schematic view of the experimental setup for electrical characterization is shown in Figure 3. First, the

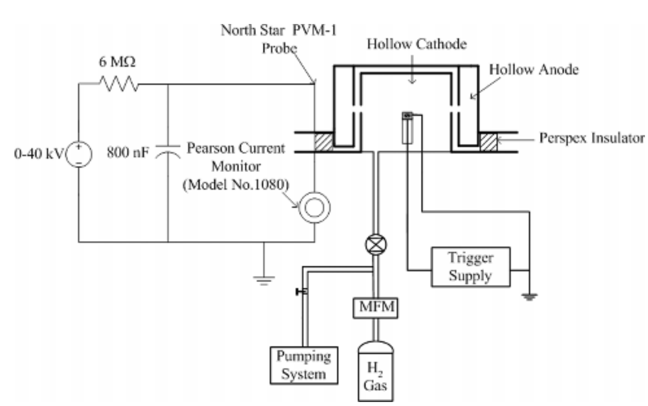

FIG. 3. Circuit diagram for high current testing.

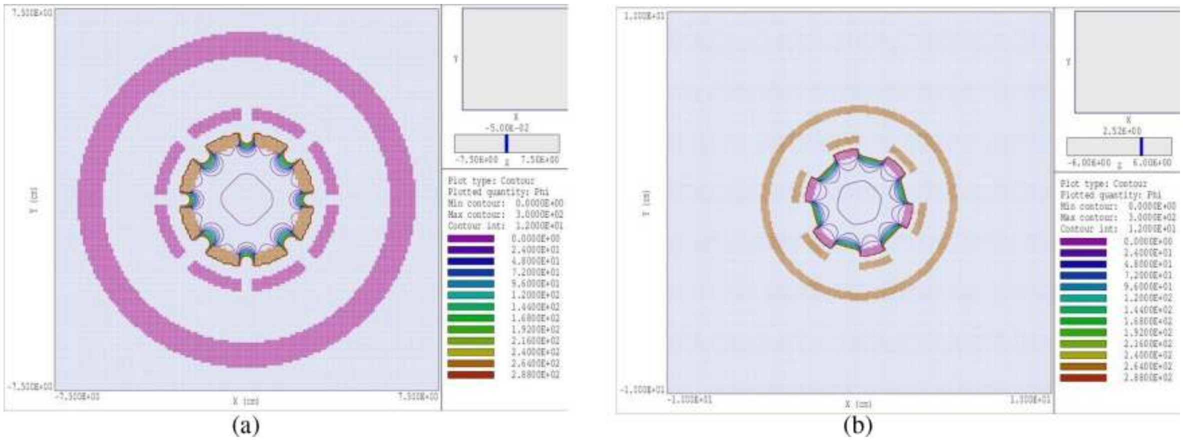

FIG. 4. Voltage penetration through (a) the round hole apertures and (b) the linear apertures in the interfacing electrodes.

LARM-PSS has been evacuated down to base pressure $\sim 10^{-5}$ mbar using rotary and turbo molecular vacuum pumps (TMPs). The virgin switch has been conditioned before experimentations for more than 24 h with high voltage up to 25 kV. Later, hydrogen and argon gases have been used as fill gas in the switch. A variable 40 kV DC power supply along with 800 nF capacitor bank in parallel with the PSS has been used to discharge the stored energy through the switch.

The capacitor is first charged through a large charging resistance and stored energy is dissipated through ground by shorting the LARM-PSS. This helps in minimizing the circuit resistance but the peak discharge current is entirely limited by the discharge circuit inductance. A 1000:1 high voltage probe (North Star PVM-1 probe) has been used to measure the voltage. The discharge current is measured using Pearson's current monitor (Pearson Electronics, Inc., 1080). The cable path length in the current discharge circuit is kept shortest so as to minimize the wire inductances. The breaded copper sheets have also been used as connecting wires for the same reasons. The signals are recorded using a Tektronix Digital Phosphor Oscilloscope (DPO4054B 500 MHz, 4-Ch). To protect the power supply during the conduction, a 6 MΩ resistance is also used in series with the high voltage supply.

IV. RESULTS AND DISCUSSION

To optimize the design of the LARM-PSS, the electrostatic simulations have been carried out using OMNI TRACK[21] keeping same dimensional parameters. A voltage ~30 kV has been applied to the anode with respect to the hollow cathode. The solver creates a grid of cell size 1 mm^3 and then potential within each cell is calculated using Poison's equation and continuity equation. The contour plots have been developed to see the potential distribution inside the geometry. The 2-D cross-sectional views of the geometry with round apertures of diameter 4 mm and linear apertures of width 2.5 mm along with equi-potential lines are shown in Figures 4(a) and 4(b), respectively. The equi-potential lines are parallel to each other in the main gap except for small penetration of the potential through the apertures due to perturbation of the electric field there. The penetrated potential lines in the aperture are clearly shown in the above contour plots whilst high potential parallel lines exist in the main gap but have been omitted to clearly distinguish the contour lines.

It can be inferred from these figures that the linear apertures allow lesser potential penetration inside the hollow cathode region than that of round hole apertures and accordingly provide higher hold-off voltage capabilities. Since the equal areas of both kinds of apertures will provide same current conduction capability, so with the same hold-off voltage, the current handling capabilities would obviously be increased with the linear apertures. Moreover, the equi-potential lines through the linear apertures are distributed more homogeneously inside the hollow cathode region which helps in buildup of the homogeneous and simultaneous discharge. So, the linear apertures are the alternate choice to increase the current handling capability of the switch by increasing the linear length of the apertures without compromising the hold-off voltage capability.

For hydrogen, the maximum probability of impact ionization corresponding to electron energy is around 80 eV.[22] So, ~80 V potential penetrations in the hollow cathode region are good enough to initiate the discharge while the free electrons generated from the trigger unit are available for the ionization of the gas atoms under the influence of penetrated field. This has been clearly illustrated from the simulations in Figures 4(a) and 4(b) where a potential of the order of 300 V has been penetrated through the apertures inside the hollow cathode region. The hollow cathode discharge phase in the PSS is the consequence of pre-discharge which is caused by the free electrons near to the apertures.

To obtain the operating ranges of voltage and pressure for the developed LARM-PSS, its self-breakdown characteristic has been analyzed. The circuit diagram for this analysis is shown in Figure 5. The discharge in the switch has been induced by slowly increasing applied voltage from 1 kV to 20 kV at fixed gas pressure. As the applied voltage is increased, we could observe an abrupt increase in the

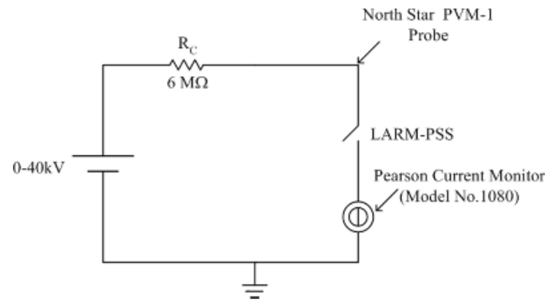

FIG. 5. Circuit diagram to measure self-breakdown characteristic.

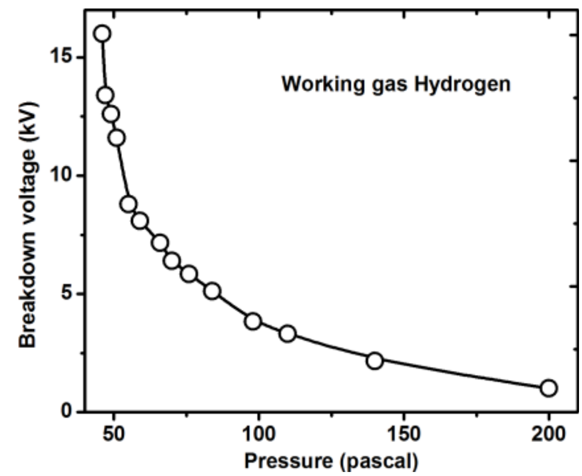

FIG. 6. Pressure voltage characteristics of the switch for hydrogen.

discharge current due to self-breakdown of the gas in all the discharge channels. This voltage has been recorded as self-breakdown voltage at a specific gas pressure and later plotted at different pressures by keeping self-breakdown voltage knowledge. The results are shown in Figure 6 for hydrogen gas.

The self-breakdown voltage follows Paschen's curve and it increases as the working gas pressure decreases in the experimental range under consideration. To obtain the hold-off voltage up to 25 kV, the operating pressure range of the switch has been fixed between 5 and 50 Pa for hydrogen. For about 20 kV hold-off voltage, the switch has been operated at 10 Pa gas pressure. For high-current conduction through the developed LARM-PSS, a 800-nF capacitor bank has been connected in series with the large charging resistance in the charging circuit and also in parallel with the switch in the discharge circuit as shown in Figure 3. The capacitor is initially charged through large charging resistance and stored energy is delivered to the ground by commuting the switch. A typical discharge waveform obtained is shown in Figure 7.

The peak discharge current of 20 kA has been achieved which is significantly observed and has decayed in ~80 μs discharge time. The voltage and current waveform with single current pulse is also shown in Figure 7(b). The full-width-half maximum (FWHM) of the single current pulse is ~2.0 μs. In high current switch, the quenching phenomenon, in general, is unlikely to be observed because the metal vapors released from the cathode spots start contributing to meet the requirements. The waveform, as shown in Figure 7(b), is free from current quenching and also from possible latching. The obtained oscillations in the current waveform are due to discharge circuit inductance, which has been estimated from the obtained frequency of oscillation and discharge path capacitance and is found to be 800 nH. The estimated effective charge transfer from this current waveform is about 1.5 C.

The switch has been operated keeping pulse repetition time 30 s for 100 shots and various parameters related to repeatability have been measured. For operation at high repetition rate, the switch should recover very fast to off-state. From the geometry point of view, the radial channel geometry provides more surface area for charge carrier recombination and thus is helpful in providing fast recovery to switch. However, from the circuit point of view, the repetition rate is limited by the charging of the capacitor bank. We have used low current charging circuit in the present investigations and are restricted to operate the switch at low repetition rate. The estimated jitters in the discharge voltage and current are 88 ns and 50 ns, respectively. The mean delay time from the initiation of the trigger to the breakdown of the voltage is 108 ns. The current rise time is 110 ns and accordingly the rate of current rise achieved is 10^{11} A/s for this switch.

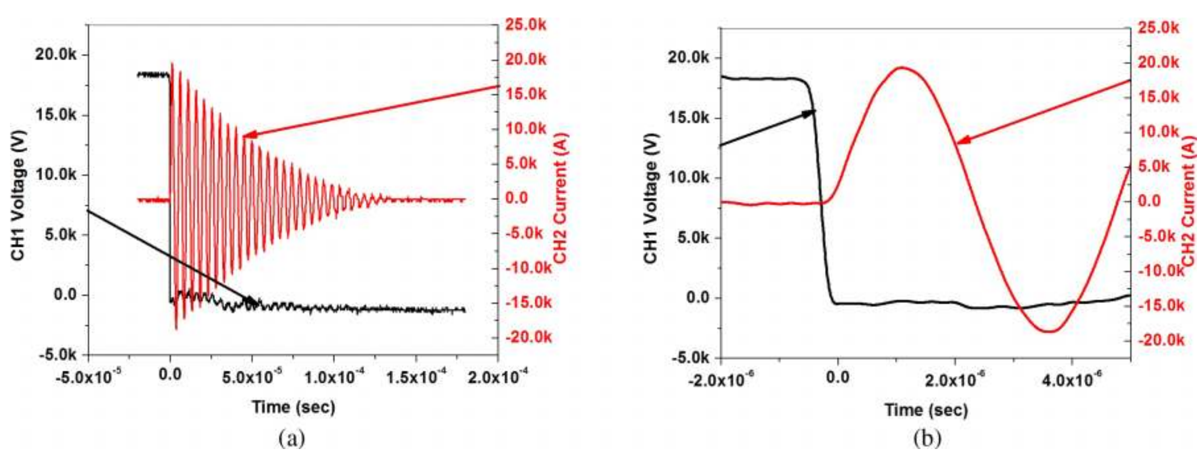

FIG. 7. Voltage and current waveform CH1: discharge current, CH2: voltage across the switch. (a) Full time scale and (b) single current pulse time scale.

V. CONCLUSION

The linear aperture radial multichannel switch has been investigated for high current switching without any tradeoff with the hold-off voltage under pulse operation. The width, length, and number of the linear apertures used in the interfacing electrodes of the cathode and anode sub-assemblies have been optimized. The linear apertures at the place of round hole apertures have helped in increasing the charge transfer capacity of the switch without effecting the surface and hold-off properties. The demountable switch has been operated at optimized hydrogen gas pressure 10 Pa for hold-off voltage 19 kV. The developed LARM-PSS has successfully conducted peak current of 20 kA and charge transfer of 1.5 C per shot. No significant erosion damage has been found near the linear apertures of the electrode walls even after 1000 shots keeping operating parameters intact and pulse repetition time 30 s.

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