Pseudospark Switch Development for Pulse Power Modulators

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ABSTRACT. The Pseudospark switch is able to control high voltage and high current discharges and operates at low pressure like thyatron but much simpler in construction and does not suffer in electrodes wear. This switch is bipolar and has 100 % reverse current capability, much faster than thyatron and has applications in pulse power modulators, linear accelerators, laser systems etc. Such switch has been developed at CEERI Pilani and tested in a demountable setup. Switching behavior has been observed at 22 kV and 7 kA in hydrogen atmosphere (13 Pa). Electrodes shaping and high voltage gap has been simulated in ESTAT and designed accordingly. For this switch, as a cold cathode, a ferroelectric trigger source has also been developed and characterized. High dielectric material has been opted for such a source. The hold off voltage can be doubled if the gap of the electrodes is stacked to two single stage gaps. Such stack of two single stage switches has also been fabricated in a demountable setup. Switching behavior has been observed up to 40 kV and 2.9 kA. High voltage conditioning and characterization is still in progress. In this paper design of the electrodes, ferroelectric source, description of the demountable set up, fabrication, processing of the Pseudospark switch and switching behavior have been presented and discussed.

1. Introduction
Developments in pulsed power technology, especially in the field of high power Excimer laser etc., often exceed the capabilities of the commercially available switches such as Thyatron or Spark Gaps. Therefore over two decades, considerable interest has been generated in low pressure switching device with a cold cathode. Such device is known as Pseudospark switch (PSS)\(^1,2\). The pseudo-spark is a low-pressure gas discharge on the left branch of the Paschen breakdown curve. This device is mercury free, unlike Ignitron, high pressure Spark gaps for its limited life, and alternative to Thyatron with the advantage of fast rise time and low jitter. Principally the switch is like cold cathode Thyatron with a grounded grid. This device is simple in construction and free from electrodes erosion and comprises, hollow cold cathode and anode.

Most of the investigations have been done in the literature in the demountable setup. There is now some progress of such device in sealed off state in which the operating pressure is maintained due to attached Hydrogen reservoir\(^3\).

The switch has applications in pulse power generators, producing intense pulsed electron beam for material processing, medical techniques, discharge heated copper vapour laser, and soft x-ray source. Owing to the symmetric design of the electrodes, 100 % reverse current capability is possible without any failure of Pseudospark switch.
The hold off capability of a single gap Pseudo-spark switch is limited by surface flashover and field emission. Scaling the switch into multi-gap switch configuration can perform improvement of hold off voltage.

The pseudospark is defined as a high voltage discharge which employs a discharge-gap and pressure such that the pd product is smaller than pd\textsubscript{min} of the Paschen’s curve, but larger than the pd value of a vacuum discharge. To increase the hold off voltage, Hydrogen, Helium, Deuterium and other inert gases are filled\(^4\).

The PSS’s essential feature is its closed hollow cathode geometry. The electrons are multiplied very rapidly because of the hollow cathode effect. The multiplication in any other part is considerably low. Therefore PSS’s are usually triggered by electron or plasma injection into the hollow-cathode. The high dielectric trigger unit furnishes all the qualities of a good trigger system\(^5\).

Ferroelectric cathodes are attractive cold electron emission sources, allowing the generation of high electron emission current density up to 100 A/cm\(^2\). The cathodes can be handled and operated in poor vacuum conditions and do not require heating or activation process before operation.

In the present work, a Pseudospark switch for 25 kV hold off voltage and 5 kA peak current, has been designed, fabricated and has been evaluated for their performance in a demountable setup. Single gap PSS has been upgraded to double gap switch to increase hold off voltage capability from 25 kV to 40 kV. An electrostatic simulator ESTAT has been used to study electric fields penetration and shape various electrodes.

### 2. General Operating Principle of Pseudospark Switch

The general operating principle of the switch is shown in the figure 1. The electrode system of the switch consists of a hollow anode and a hollow cathode whose cavity communicates with the main gap through the main axial hole or several holes. In the cavity of one of the electrodes (typically, the cathode), the trigger unit is placed intended to initiate breakdown in the main gap. The main gap spacing is comparable to the bore hole diameter for the high current discharge so that high current hollow cathode discharge can take place.

![Figure 1. General picture of Pseudospark Switch,1](image)

**Figure 1.** General picture of Pseudospark Switch,1

- Insulator, 2 Hollow Cathode, 3 Hollow Anode

### 3. Design Features of Electrodes Elements

At CEERI Pilani we have taken the technologies development programme of PSS with the specifications: hold off voltages of 25 kV and 40 kV, peak current of 5 kA, 500 PRR, current rise time of 1kA/microsecond.

#### 3.1 Hollow cathode

Pseudo-spark switch is a gas–discharge device. The PSS’s essential feature is its closed hollow cathode geometry. The hollow cathode, being filled with plasma, works like a virtual cathode for the electron extraction from the cathode backspace. The electrons are accelerated by the high electric field across the electrode gap 2 to 5 mm. Charge carrier multiplication takes place in the hollow cathode,
triggering of the discharge can be easily achieved by making the charge carriers available in this region.

3.2 High Dielectric trigger source
The electrons are multiplied very rapidly because of the hollow cathode effect. The multiplication in any other part of PSS is considerably low. Therefore PSS’s are usually triggered by electron or plasma injection into the hollow-cathode. If one wants to replace Thyratron by Pseudospark switch, current quenching is a major problem. Although quenching was reduced to a good extent by facilitating the availability of additional charges by increasing the gas pressure inside the tube, optimizing electrode geometry and by the addition of heavier gases in the switch. The current quenching in PSS has been found to be suppressed by the use of long pulse trigger⁶. Hence in our case, for reliable operation of PSS, about $10^9$ to $10^{10}$ electrons are injected inside the hollow cathode by using a triggering device. There are various methods of triggering PSS such as Charge Injection, Surface Discharge, Optical, Flash Lamp and Optical Fibre. High dielectric trigger source has been employed in our PSS development. APC-850 dielectric material from APC International with dielectric constant of 1900 has been used.

High dielectric triggers are surface discharge type trigger units, wherein the bottom of metal fingers of a refractory material are in contact with a metalized high dielectric disc, which is mounted on a metal holder as shown in figure 2. There is a microscopic vacuum/gas gap between the bottom of metal fingers and dielectric disc making a triple point junction between dielectric, metal finger and vacuum/gas as depicted in figure 3. A high voltage pulse, when applied to metal fingers with respect to metal holder, causes very high electric field at the triple point and explosive electron emission takes place forming surface discharge plasma spread on the dielectric. The electrons from this plasma are extracted for entry into the hollow cathode of PSS.
Pseudospark switches triggered by charge carrier injections are well suited for operation at hold off voltages of up to 40 kV and peak currents of up to 25 kA at a very high current reversal⁷.
3.3 Hold off voltage, currents
Hold off voltage is a voltage that a device can stand. This can be obtained for the desired Pseudospark switch either through simulation using computational electrostatic methods or experimentally. It has been reported in the literature that an average value of electric field equal to $10^5$ V/cm for low pressure H$_2$/D$_2$ gas gap of 0.1 torr-cm is a safe value$^1$. A simple PSS with hollow cathode and hollow anode separated by a bore hole of 2-5 mm dia with similar gap length, can be operated at potentials of 35 kV and handle currents of 10 kA with rates of current rise of $4 \times 10^{11}$ amps/second at 0.1 – 1 mbar gas pressure.

3.4 Electrodes shaping
Design of vacuum electronic devices can be carried out effectively using computer simulations. There are several PC based computer codes which are capable of computing electrostatic, magnetostatic and electromagnetic fields for devices employing complicated electrode shapes. Given the physical and electrical parameters as input, they give potential, fields and charge distributions. For required values of these devices can be tailored. OMNITRAK including ESTAT software has been employed to shape established the gas gap of electrodes. The size shape and number of apertures are decided with the current carrying capacities. The shapes are either circular holes or kidney shaped slots. The corners and collars were chamfered accordingly with fields’ penetration studies.

![Figure 4. Electric field along X-axis voltage range](image1)
![Figure 5. Electric Field in Gap](image2)

3.5 Current Quenching
Current quenching is a major problem. In PSS current quenching takes place due to depletion of charge carriers due to interaction of plasma and cathode surface during the high current conduction phase$^8$. This quenching is reduced to a good extent by facilitating the availability of additional charges by increasing the gas pressure inside the tube, optimizing the electrodes geometry and by the addition of heavier gases in the switch. It could be suppressed by using long pulse trigger also.

3.6 Multiple gap PSS
High power, high repetition rate modulation and pulsed power systems require fast switches capable of operating at high currents and high voltages$^5$. PSS can be used as a fas, long life high voltage switch, overcome hold off limit, led to the development of multiple gap structure. Hence for our application of 40 kV and 5 kA switch, two gap PSS has been developed.

3.7 Multi-channel PSS
In multi channel PSS device, discharged plasma is allowed to accelerate away from the discharge channels which are distributed radially around a common hollow cathode. Multi channel also reduces
erosions of the electrodes. Thus we have employed multi channel cathode and anode discs in our single and two gap PSS. This type of switch is also suitable for high current and high repetition rate.10.

4. Fabrication

4.1 Demountable setup

The Pseudospark switch mainly consists of a hollow cathode, a hollow anode with axially symmetric radial slots and a trigger source of PLZT material. The electrodes are made of nickel plated 304 stainless steel material. The Pseudospark switch is housed in a Ceramic cylinder which serves as an insulator between cathode and anode. The assembly has been assembled on conflate flange in a demountable format. The complete demountable PSS consists of a hollow anode, hollow cathode, reservoir, header, ceramic flange and trigger unit assembly. Hollow anode and hollow cathode assemblies are fabricated of SS components by brazing techniques. The gap between the main electrodes is 2.5 mm and the gaps between the auxiliary electrodes is 2-5 mm. Ultra pure hydrogen is filled of known quantity for the pre calibrated hydrogen reservoir.

Reservoir is a critical component of the device. When heated to around 500°C - 700°C, the reservoir maintains equilibrium of gas pressure inside the PSS. Ceramic insulator is brazed with conflate flange.
4.2 Processing
For the proper operation of the switch, the device after fabrication is mounted on the vacuum pump station. The tube is thoroughly degassed at 450°C for 18 hours. The ultimate vacuum attained this pressure was under $10^{-7}$ mbar. Subsequent to the vacuum processing, ultra pure hydrogen gas of known amount is loaded to the reservoir mounted inside the PSS. The reservoir has been pre-calibrated with pressure and filament power.

4.3 High voltage conditioning
A finished switch assembly needs to be conditioned before starting the performance evaluation, to achieve the desired operating characteristics. The first parameter, which is taken into consideration, is Hold-off Voltage. The conditioning process smoothen the high voltage electrode surfaces inside the Pseudospark switch by self/forced discharges in the tube at low current. Such smoothness on the electrode surface cannot be obtained to desired order (up to 1 micron level and below) by machining. Therefore, conditioning is a process, preceding any Switch testing process.

5. Pseudospark Switch Characterisation
Figure 8 shows the test circuit diagram of the switch.

![Figure 10. Test Circuit](image)

Pseudospark devices are operated in a pulsed mode. A capacitor bank is charged for every pulse, prior to discharge. Then the discharge is triggered, draining the capacitors, where after they are recharged. In general there are two methods of controlling the timing of the discharge. One is to apply a voltage just below the breakdown voltage and to use a trigger of some kind, either optical (by shooting a laser pulse through the discharge), or electrical to initiate the discharge. Another method to initiate the discharge is to apply a voltage greater than that required for spontaneous discharge and to use an electrical inhibitor. The inhibitor increases the voltage required for breakdown. The discharge is then initiated by releasing the inhibitor. Each cycle can be broken down in a number of different phases.

6. Experimental results
The fabricated and processed demountable Pseudospark switches with single and double gap have been experimentally characterized for its switching behaviour at various hydrogen pressures and charging capacitors. For single gap, designed for 25 kV/5kA switching, we have observed switching at 22 kV/7 kA at 0.12 mbar hydrogen pressures as in figure 11. 100% current reversal has also been observed. In double gap PSS, designed for 40 kV/5 kA switching performance at 0.3 mbar hydrogen pressure has been attained as shown in figure 12. In this case 100 % current reversibility and 5kA peak current are not visible. This may be attributed to the non inductive load used in the circuit and insufficient charging capacitance.

In both the cases the rate of current rise has been obtained more than in the specifications laid down, i.e. in single gap it over 6 kA/microsecond and in double gap PSS it is 1.3 kA/microsecond.
7. Conclusion
Pseudospark switches developed in demountable setup with single and double gaps for 25 kV and 40 kV hold off voltages and 5 kA peak currents respectively, have the capability to switch at designed specifications.

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