

Article

Basic Design Guidelines for Pseudo-Spark Switches Based on Literature Review

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Abstract

Pseudo-Spark Switches (PSSs) are characterised by high-voltage withstand, high-current conduction capabilities, and an extended lifetime compared to alternative gas discharge switches. Despite numerous studies investigating PSS characteristics across different geometries, construction materials, and triggering methods, a generalised design methodology is still lacking. This work addresses this gap by establishing foundational design guidelines synthesised from the available literature data. By analysing diverse electrode geometries, gas pressure configurations, and trigger mechanisms, the core operational boundaries of the electrical parameters, as well as the lifetime, are mapped. Furthermore, the practical significance of these guidelines is demonstrated through a complete design example of a PSS tailored for a Marx generator used in Pulsed-Power Geo-Drilling (PPGD). The resulting framework provides a systematic roadmap that reduces trial-and-error in PSS development for high-power applications.

Keywords: pseudo-spark switch; low-pressure gas discharge; Marx generator; high-voltage switches

1. Introduction

Pseudo-Spark Switches (PSS) are closing switches used in pulsed-power applications, first suggested by [1], who observed that discharge phenomena used to create intense electron beams could be exploited to develop a high-voltage, high-current closing switch. PSSs present high blocking voltage capability, high peak current handling, and a relatively long lifetime compared to other gas closing switches, such as high-pressure spark gaps and thyratrons. Additionally, unlike thyratrons, PSSs do not require continuous power to maintain a heated cathode, which not only reduces power consumption but also mitigates electrode erosion, extending the switch's operational lifetime. Such characteristics make PSSs suitable for demanding applications that require high-voltage and/or high-current pulsed generators such as X-ray equipment, particle accelerators, and medical treatments.

One particularly challenging application for pulsed-power systems is Pulsed-Power Geo-Drilling (PPGD), a promising technology that employs high-voltage pulse discharges to fracture rock, offering a potential alternative to conventional drilling methods [2]. This approach could reduce drilling costs and facilitate access to deep underground resources, such as geothermal energy [3]. PPGD requires a compact pulsed-power generator capable of delivering high-voltage pulses of several hundreds of kV [4], fitting inside a drilling hole with a diameter of approximately 30 cm, and withstanding temperatures of around 200 °C or more, as encountered at depths of approximately 10 km.



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Furthermore, the total number of pulses required to drill a borehole is on the order of 1×10^9 , assuming a drilling efficiency of 200 J cm^{-3} [5] and a pulsed-power generator delivering 200 J per pulse.

These combined constraints—high voltage, compactness, high temperature, and life-time—restrict the range of suitable components to design a pulse generator for PPGD. A compact Marx generator is a strong candidate to meet PPGD requirements [5], with the closing switch being one of its most critical components. High-pressure spark gaps, despite their simplicity and high blocking voltage capability, present high erosion rates that limit operational lifetime, making them unsuitable for downhole drilling. Solid-state switches, in turn, are limited by their relatively low blocking voltage capability and insufficient current rise rate, on the order of $100 \text{ kA } \mu\text{s}^{-1}$, required by the pulsed operation. The PSS therefore stands out as the most suitable candidate, combining compactness, high blocking voltage, high-current capability, and a relatively long lifetime.

Despite more than four decades since their initial conception, PSSs are still not widely available on the market. Although several PSS designs have been published, comprehensive design guidelines are not available.

In this context, this paper presents the guidelines for designing a PSS, as well as an example targeting the requirements imposed by PPGD. The assumed key parameters of the proposed switch are summarised in Table 1, in which the requirements come from the Marx generator described in Section 6. PSSs in a similar range have been designed for other applications [6–9], but they are neither available in the market nor are the design details available. In addition, the design procedure details what critical design aspects, such as electrode geometry, trigger mechanisms, and gas pressure maintenance, are presented in this paper.

Table 1. System parameters derived from a Marx generator operation.

Parameter	Value
Marx generator output voltage	360 kV
Energy per pulse	200 J
PSS blocking voltage	30 kV
Peak current	10 kA
Operating frequency	20 Hz
Lifetime	7×10^8 pulses
Charge transfer per pulse	1.9 mC

It is worth noting that while this paper aims to establish practical design guidelines, its current scope is focused on the theoretical and conceptual synthesis of the methodology. Due to the limited available literature on PSSs, the existing experimental data were fully utilised to construct and calibrate these guidelines.

The remainder of this paper is organised as follows: Section 2 outlines the operating principles of the PSS. Section 3 presents the key design considerations for the geometry of the electrodes. Section 4 shows the different methods for triggering the PSS. Section 5 details a step-by-step design methodology derived from these considerations. In Section 6, a conceptual design of a PSS for a Marx generator, for which the parameters are listed in Table 1, is presented. Finally, Section 7 summarises the main outcomes of this work.

2. Pseudo-Spark Switch Operation

The PSS is a high-voltage, high-current switch that operates at relatively low pressures compared to conventional spark gaps. A common basic structure is shown in Figure 1. The main feature of the PSS is the hollow cathode with one or more holes in the electrode

at the main gap, as seen in Figure 1c. The hollow cathode is essential to initiate the discharge process. In many configurations, the PSS also includes a hollow anode to allow current reversal without destructive electrical arcs—a solution similar to the one used in thyratrons [10].

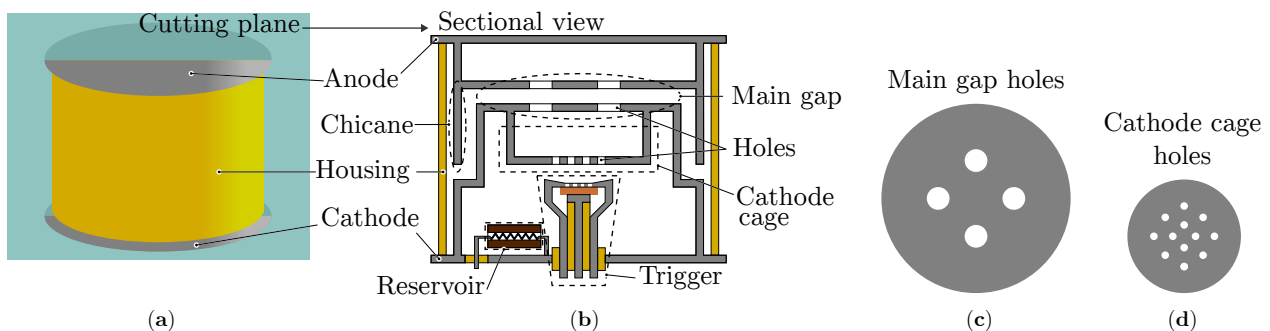


Figure 1. Detailed PSS structure. (a) Cylindrical structure of a PSS. (b) Sectional view of a PSS with the description of the main elements. (c) Holes of the main gap electrodes. (d) Holes in the cathode cage to allow electrons coming from the trigger to enter inside the cage.

A gas reservoir is integrated to control the internal pressure of the switch, and in some applications, the pressure can be externally regulated through a gas pump connected to the inlet and outlet ports.

The trigger provides the initial electrons required by the cathode for the transition from the blocking state to the conducting state. The electrons access the cathode cage via holes, as shown in Figure 1d. Additionally, a chicane is used as a barrier to prevent metal vapour from depositing on the housing insulators during the discharge.

The discharge evolution during the triggering of a PSS is shown in Figure 2. The voltage potentials inside the switch are represented by red lines. The trigger structure is represented by a box for simplicity. Figure 2h shows typical waveforms during the transition process. The discharge evolution can be divided into seven phases, as described below.

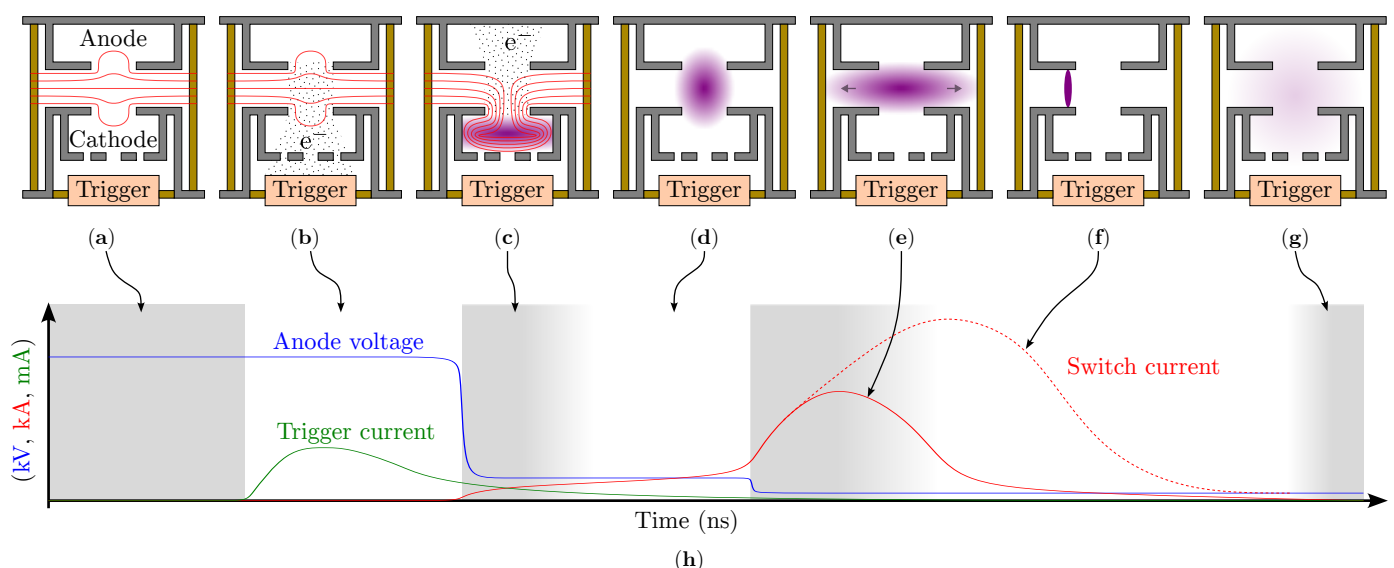


Figure 2. Phases of PSS discharge: (a) blocking; (b) triggering; (c) hollow cathode; (d) borehole; (e) high current; (f) arc; (g) recombination; and (h) sketched voltage and current waveforms. Adapted from [11,12].

1. Blocking phase, Figure 2a: A DC voltage is applied between the anode and cathode. The presence of holes in the anode and cathode within the main gap region allows equipotential lines to penetrate the hollow anode and cathode.
2. Triggering phase, Figure 2b: The trigger must provide around 10^{10} electrons inside the cathode for effective triggering [13]. The relatively low pressure and low electric field at the cathode cage benefit the ionisation of the gas in this region [14] (p. 511).
3. Hollow cathode phase, Figure 2c: The ionisation of the gas produces a plasma that grows in volume and particle density inside the cathode cage. The plasma allows the further penetration of the equipotential lines at the cathode cage, which forms a virtual anode. In this phase, a limited electron current is emitted to the anode, and the voltage across the switch collapses to a few hundred volts. As the plasma grows, more electrons are extracted from inside the cathode. It is believed that the electrons are extracted via field-enhanced thermionic emission [15].
4. Borehole phase, Figure 2d: The emission of electrons from the hollow cathode phase ionises the gas of the main gap, forming an anode plasma [12] in the main gap. At the end of this phase, the voltage presents another sharp collapse [16].
5. High-current phase, Figure 2e: The plasma expands in the main gap, allowing high currents to flow. The current is mainly limited by the external circuit of the switch.
6. Arc phase, Figure 2f: The plasma shrinks, forming an electrical arc, which contains metal vapour. This condition only occurs for very high currents [11].
7. Recombination phase, Figure 2g: The current is extinguished by the external circuit in this phase, and the ionised gas atoms recombine with free electrons, and the PSS recovers its blocking capability.

The geometry of the electrodes, gas type and pressure, the trigger type, as well as the materials used in the PSS influence all the closing dynamics, such as the delay time and maximum blocking voltage. The design of these parameters is discussed in the following sections.

3. Gas Selection and Main Gap Geometry

The gas type and its properties, together with the main gap geometry of the PSS, define its maximum blocking voltage capability. The physical phenomena that limit this maximum voltage are gas breakdown and/or vacuum breakdown.

Figure 3 illustrates the dependence of the maximum blocking voltage of a PSS on the distance between tungsten electrodes in the main gap for hydrogen at 50 Pa, which lies within a typical operating pressure range for the PSS [12]. The presence of a hole in the PSS electrodes, which introduces a non-uniform electric field, reduces the region of the maximum blocking voltage compared to flat electrodes that produce uniform fields, as shown in Figure 3.

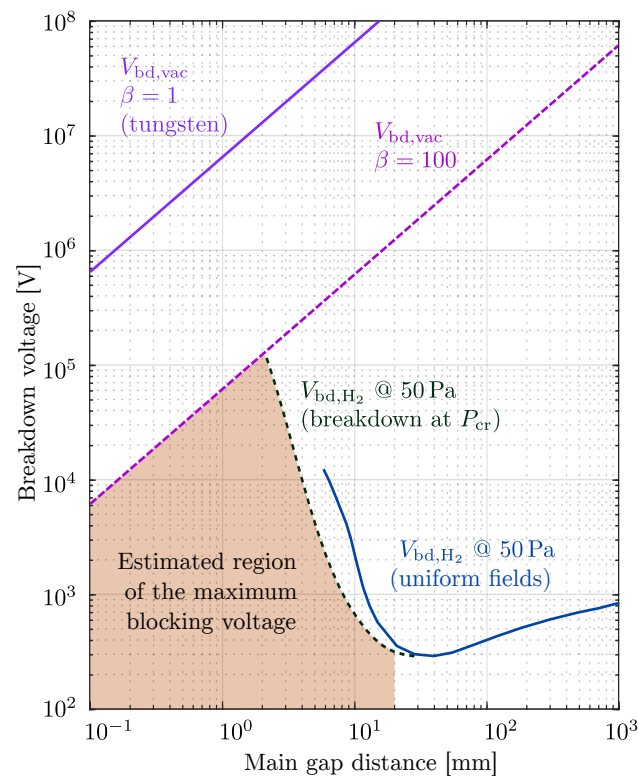


Figure 3. Breakdown voltage at low pressure. The solid lines show the breakdown voltage for uniform fields in a vacuum for tungsten [14] and for hydrogen [17] at 50 Pa, which were obtained by experimental results. The parameter β represents the electric field enhancement factor. The dashed lines represent the limits of the operating region due to the hollow geometry. The dashed lines are for illustration purposes only and do not represent actual values.

3.1. Gas Breakdown

Gas breakdown occurs when the criterion given in Equation (1) is satisfied, also known as Townsend's ignition [18,19]. This criterion represents the condition under which a self-sustained multiplication of electrons occurs in the presence of an electric field, where α is the ionisation coefficient, E is the electric field, r is the position of the path, γ is the feedback coefficient, and P is the electron path from the cathode to the anode.

$$\int_P \alpha[E(r)] dr \stackrel{\text{def}}{\geq} \ln \left(1 + \frac{1}{\gamma} \right) \quad (1)$$

The coefficient α depends on the modulus of the electric field $E(r)$, gas type, and gas density, and can be computed for weakly ionised gases using modern Boltzmann equation solvers, such as Bolsig+ [20]. The feedback coefficient γ is obtained experimentally, and accounts for multiple effects, including photoionisation, cathode photoemission, ion feedback emission, and metastable molecules [18].

The hollow electrodes of the PSS produce non-uniform electric fields around the hole, creating additional electron trajectories between the anode and the cathode, as shown in Figure 4. The path P_{cr} represents the critical breakdown trajectory, which requires the lowest voltage to satisfy condition Equation (1), and thus defines the self-breakdown voltage $V_{br,gas}$ of the PSS.

The pressure of the gas also defines the region of the operating voltage of the PSS. In uniform fields, the voltage breakdown curve in gases can be shifted horizontally by changing the pressure due to its dependence on the product of pressure and distance (see Paschen's curve [18]). Similarly, in non-uniform fields, the operational blocking voltage region is expanded when the pressure is reduced. However, lower pressure reduces the

number of neutral particles in the PSS, which are required for the formation of the virtual anode during the hollow cathode phase (see Figure 2c).

The critical gas density required to enable the hollow cathode phase is given by Equation (2) [21], where m_e is the mass of the electron, and M is the mass of the neutral gas molecule. The term $\bar{\sigma}_i$ is the averaged ionisation cross-section of the gas, defined in Equation (3) by integrating the ionisation cross-section across the main gap region at the centre of the hole. Here, $V(r)$ is the electric potential at position r [22]. Equation (2) was experimentally validated in the references cited in [21].

$$n_{\min} = \frac{1}{\bar{\sigma}_i h_g} \sqrt{\frac{3m_e}{M}} \quad (2)$$

$$\bar{\sigma}_i = \frac{1}{h_g} \int_0^{h_g} \sigma_i[eV(r)] dr \quad (3)$$

The minimum pressure, derived from Equation (2), is given in Equation (4), where k_B is Boltzmann's constant and T is the temperature.

$$p_{\min} = \frac{k_B T}{\bar{\sigma}_i h_g} \sqrt{\frac{3m_e}{M}} \quad (4)$$

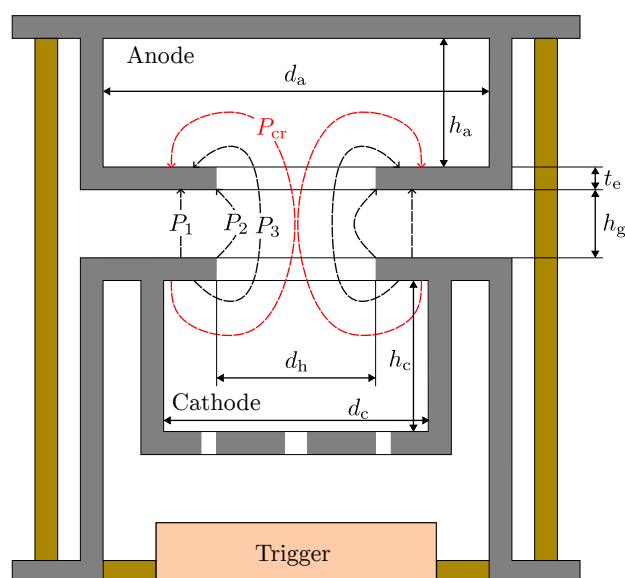


Figure 4. Sketch of different trajectories of electrons in a PSS. The parameter h_g is the main gap length, d_h is the hole diameter, d_c is the cathode cage diameter, h_c is the cathode cage height, d_a is the anode cage diameter, h_a is the anode cage height, and t_e is the electrode thickness. The different electron paths are represented by the trajectories P .

3.2. Vacuum Breakdown

Vacuum breakdown occurs in the presence of high electric fields that can directly extract electrons from the cathode surface. The values for the critical electric field E_{cr} are summarised in Table 2 for different electrode materials. The corresponding breakdown voltage for the vacuum mechanism, $V_{bd,vac}$, is given by Equation (5), where β is the field enhancement factor.

$$V_{bd,vac} = \frac{E_{cr} h_g}{\beta} \quad (5)$$

The enhancement factor β is a result of the geometry and the macroscopic protrusions at the surface. Therefore, β is determined experimentally by measuring the field-emission current in uniform fields [14] using the Fowler–Nordheim equation [23,24], given

in Equation (6). Here, J is the current density (A m^{-2}), E is the electric field (V m^{-1}), e is the electron charge, m_e is the electron mass, $\hbar$ is the reduced Planck constant, ϵ_0 is the vacuum permittivity, ϕ is the work function of the metal, and β is the electric field enhancement factor.

$$J = A \frac{(\beta E)^2}{\phi t^2(y)} \exp \left[-B \frac{\phi^{3/2} v(y)}{\beta E} \right] \quad (6)$$

$$t(y) = \sqrt{\frac{1-y^2}{1-y}} = \sqrt{1+y} \quad (7)$$

$$v(y) = (1-y) \sqrt{1-y^2} \quad (8)$$

$$y = \sqrt{\frac{e^3 \beta E}{4\pi \epsilon_0 \phi^2}} \quad (9)$$

$$A \approx \frac{e^3}{16\pi \hbar} \quad (10)$$

$$B \approx \frac{4\sqrt{2}m_e}{3e\hbar} \quad (11)$$

With a controlled voltage applied between the electrodes, the emitted current is measured, allowing β to be determined.

While the parameter β could be experimentally obtained, such an approach has not been reported in the literature as a design step to determine the vacuum breakdown limits for PSSs. The design is mainly based on the limits of the gas breakdown curve.

Table 2. Critical electric fields for different materials obtained experimentally. Adapted from [14].

Material	E_{cr} (MV mm ⁻¹)
Chromium	5.32 ± 0.1
Molybdenum	5.4 ± 1.0
Stainless steel	5.9 ± 1.4
Gold	6.36 ± 0.63
Tungsten	6.5 ± 1.0
Copper	6.9 ± 1.0
Nickel	10.4 ± 1.3

3.3. Design Approach

After the review of the breakdown mechanisms of the PSS, the question of how to select the parameters and dimensions of the main gap remains. A priori, basically any gas composition can be used to implement a PSS switch, where the main challenge is to maintain the internal pressure approximately constant over time.

One approach is the use of a pumping system to stabilise the internal pressure. However, this increases the complexity and size of the system, which may be undesirable in many applications.

An alternative to a pumping system is using a sealed-off switch. A drawback of this approach is the gradual reduction in internal pressure over time due to gas molecules being trapped in the solid surfaces of the switch [25]. To compensate for this pressure drop, a gas reservoir must be included inside the switch. Hydrogen and deuterium are particularly suitable for such a concept, as they can be stored in compact and well-controllable reservoirs (see Figure 1).

The reservoir is typically made of a metal alloy that stores gas on its surface through a reversible chemical reaction. When heated, the reservoir releases gas, and when cooled, it absorbs it. At a constant temperature, the pressure inside the PSS remains approx-

imately stable. Adjusting the alloy temperature therefore allows the regulation of the internal pressure.

To enable thermal control, a resistive coil is embedded in the alloy, providing joule heating when an electric current is applied. Consequently, controlling the current in the coil directly controls the PSS pressure [6]. The reservoir is integrated into the switch, as shown in Figure 1.

Some PSS employ a Selective Reversible Hydrogen Leakage (SRHL) membrane to eliminate the need for continuous power consumption by the reservoir's resistive coil [26,27]. The SRHL membrane acts as a valve, so that the reservoir is heated only during the initial filling of the gas switch. The reservoir and membrane are activated again only after a relatively long interval to compensate for pressure loss, since gas decay inside the switch occurs at a slow rate [26].

As the goal of a PSS is to pursue high blocking voltages, deuterium is a preferred option due to its higher withstand voltage compared to hydrogen in sealed-off switches [8]. Once the gas composition is defined, the last step is to choose the appropriate pressure. The minimum pressure is defined by Equation (4), and the maximum pressure is limited by the self-breakdown voltage ($V_{bd@P_{cr}}$).

The optimum pressure is typically determined experimentally, representing a trade-off between the delay time and blocking voltage, as shown in [6]. Although higher pressure reduces the delay time and jitter, it simultaneously decreases the self-breakdown voltage. Therefore, selecting a pressure such that the operational voltage is approximately 60% of the PSS self-breakdown voltage provides a good balance between operating voltage and timing performance.

Regarding the geometry, there are no general rules for choosing appropriate dimensions, which leads to an initial design based on reported experiments available in the literature. Some design aspects have been investigated for different designs:

- Hole diameter: Measurement results in [16] show that the hole diameter d_h influences the switching losses of the PSS. The optimal diameter for the given setup was 3 mm in the tested range of 2 to 4 mm.
- Number of holes: Increasing the number of holes helps reduce the current rise time [28].
- Hole shape: Non-circular holes, such as kidney-shaped apertures [29] and ring gaps [30], have been used to reduce electrode erosion by lowering the current density compared to a single circular hole.
- Chicanes: Chicanes are added in [6,29,30] to prevent the deposition of metal vapour on the housing during the high-current phase (see Figure 2e), caused by plasma expansion in the main gap.
- Radial distribution of the holes: Implemented in [31,32] to improve the homogeneity of the plasma distribution across the main gap.
- Cathode dimensions: Influence of cathode dimensions and gas pressure on the breakdown voltage of a nitrogen PSS [33,34].

In summary, the limits that define PSS breakdown voltage result from its geometry, gas type, gas density, as well as the macroscopic field enhancement. The dashed curves in Figure 3 cannot be obtained analytically, since the parameters α , γ , $\sigma[eV(z)]$, and β are not known. Hence, the operation region of the PSS is obtained through measurements after the construction of the switch. For a PSS filled with nitrogen, an empirical expression for the breakdown voltage was obtained in [33] as a function of h_g , t_e , d_h , h_c (refer to Figure 4), and the operating pressure. Unfortunately, no similar approach has been reported for other gases.

In the absence of exact breakdown-voltage curves for PSSs according to their gas parameters and geometry, the breakdown curves of gases and a vacuum under uniform electric fields can be used as an initial estimate with an appropriate safety margin, i.e., by shifting Paschen's curve and selecting a value for β .

An example of the shift applied to Paschen's curve is shown in Figure 5, which compares different PSS structures using hydrogen as the working gas.

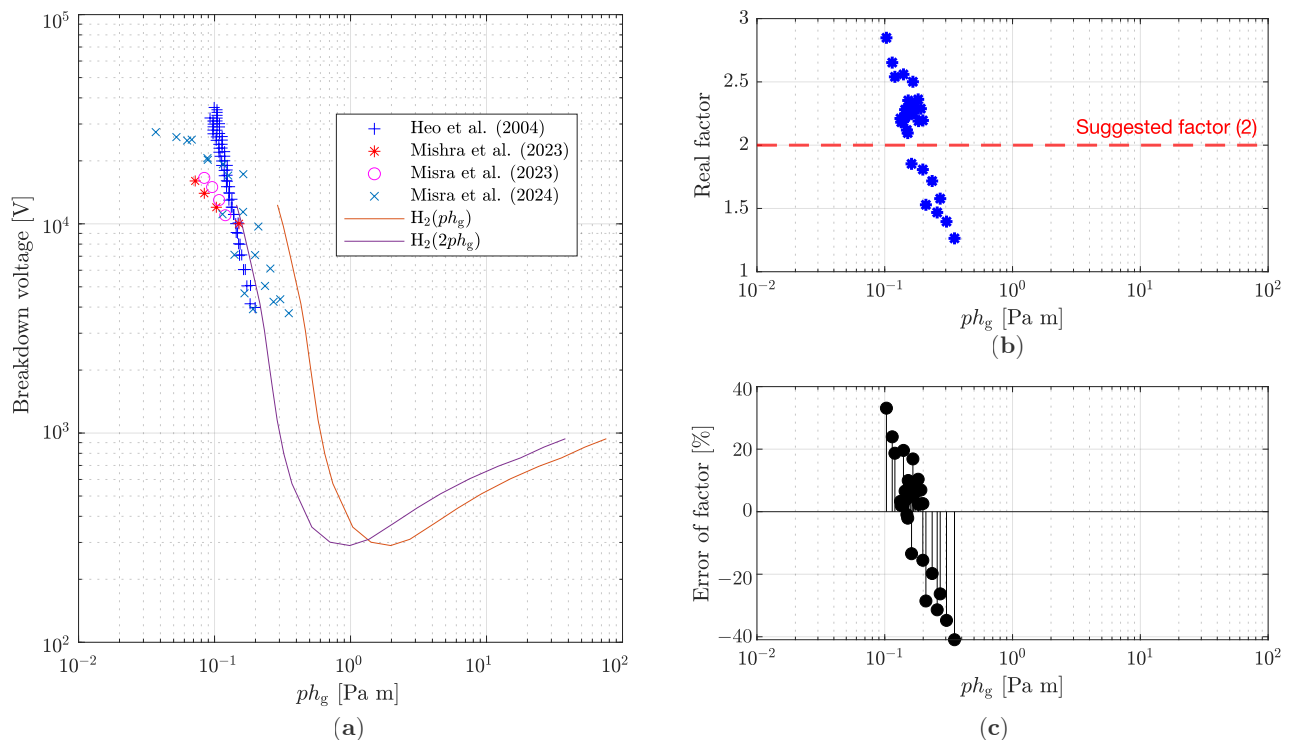


Figure 5. Comparison between Paschen's curve and measurement data of the PSS. (a) Adapted measured breakdown-voltage data of hydrogen PSSs with various geometries from [29,35–37], and the measured Paschen's curve for hydrogen ($H_2(ph_g)$) from [17]. The curve $H_2(2ph_g)$ corresponds to a shifted hydrogen breakdown-voltage curve, where p is the pressure and h_g is the gap distance. (b) Real factor compared to suggested factor. (c) Error of the suggested factor.

Based on Figure 5a, an initial voltage estimation is given in Equation (12), where the gas breakdown curve is shifted to the left side. Figure 5b,c show the error associated with the assumption in Equation (12).

$$V_{bd,PSS}(ph_g) \approx V_{bd,gas}(2ph_g) \quad (12)$$

Here, p is the pressure and h_g is the gap distance. The voltage $V_{bd,PSS}$ is the approximated breakdown voltage for the PSS, based on the gas breakdown voltage $V_{bd,gas}$, using a scaling factor of two on the horizontal axis. It should be noted here that the actual breakdown voltage of a PSS is influenced by many other factors, such as the thickness of the electrode and dimensions of the cathode cage. Also, the comparison assumes that the only mechanism of breakdown is gas discharge, where, in reality, the breakdown could be initiated by vacuum breakdown, as described earlier. Therefore, the approximation suggested in Equation (12) and exemplified in Figure 5a should be used as an initial guess for the operational voltage of the PSS.

The estimation of β can be obtained from the geometric electric field enhancement β_{geo} , which can be determined using FEM simulations, and from the surface finish electric field enhancement β_{sur} . The resulting value of β is given in Equation (13).

$$\beta = \beta_{\text{geo}}\beta_{\text{sur}} \quad (13)$$

If the shape and size of the surface protrusions are known, β_{sur} can be estimated as presented in [38]:

$$\beta_{\text{sur}} = \frac{ah_p}{r_p} + 1 \quad \text{for an ellipsoid,} \quad (14)$$

$$\beta_{\text{sur}} = \frac{h_p}{r_p} + 2 \quad \text{for a cylinder, and} \quad (15)$$

$$\beta_{\text{sur}} = \frac{h_p}{2r_p} + 5 \quad \text{for a cone.} \quad (16)$$

Here, a is a constant approximately equal to one, h_p is the height of the protrusion, and r_p is the radius of the protrusion tip (assumed to be hemispherical). The relations in Equations (14)–(16) can result in values in the range from 7 to 3000 [38]. As electrodes used in high-voltage applications are typically subjected to surface conditioning (mechanical, chemical, and/or electrical) to reduce the surface protrusions, the values of β_{sur} are more likely to be close to the lower limit. Thus, a reasonable initial estimate for β_{sur} as a safety factor lies in the range from 10 to 50.

3.4. Multi-Gap PSSs

The maximum voltage of a single-gap PSS typically falls within the range of 35 to 40 kV, as reported in [8,39], due to the limitations imposed by the region of the maximum blocking voltage shown in Figure 3.

When applications require voltages higher than 40 kV, a multi-gap switch should be employed [8]. A multi-gap PSS consists of two or more main gaps, as shown in Figure 6, in which the total blocking voltage is distributed among the corresponding pairs of electrodes. Representative designs can be found in [8,9,40].

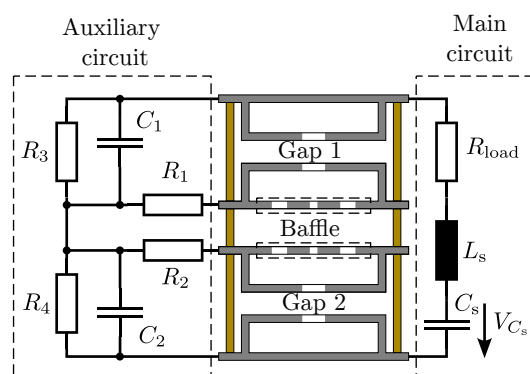


Figure 6. Multi-gap PSS with an external circuit. The components C_1 , C_2 , R_3 , and R_4 are used for equal voltage distribution between gaps. The resistors R_1 and R_2 are placed to reduce the delay time of the closing stage [41]. The elements R_{load} , C_s , and L_s compose the main circuit for the pulsed discharge.

To ensure proper voltage distribution across the gaps, auxiliary circuits based on resistive-capacitive dividers are added to the PSS, as shown in Figure 6. These auxiliary circuits also help reduce the delay time [41]. The baffle electrodes act as a barrier that reduces the probability of electrons travelling directly between the gaps, thereby decreasing the likelihood of gas ionisation during the blocking phase.

3.5. Materials

The main electrodes are most commonly fabricated from molybdenum [7] and tungsten [42]. Some prototypes have also employed brass [28,43], copper [6,44], and stainless steel [45] in experimental setups.

The material selected influences not only the vacuum breakdown voltage, as presented earlier, but also the erosion of the switch. A good practice is to choose materials with a high “resistance to erosion” [14], which is given by $T_m \sqrt{\rho_e \lambda_e c_e}$, where T_m is the melting temperature, ρ_e is the density, λ_e is the thermal conductivity, and c_e is the thermal capacity of the material. Values of the resistance to erosion of some metals are given in Table 3.

Table 3. Resistance to erosion for electrode materials calculated based on data from [46,47].

Metal	$T_m \sqrt{\rho_e \lambda_e c_e} \text{ (J m}^{-2} \text{ s}^{-0.5}\text{)}$
Tungsten	7.76×10^7
Graphite	5.79×10^7
Copper	5.05×10^7
Molybdenum	4.35×10^7
Silver	4.01×10^7
Tantalum	3.78×10^7
Gold	3.76×10^7
Nickel	3.27×10^7
Iron	3.05×10^7
Niobium	3.04×10^7
Platinum	2.92×10^7
Aluminium	2.24×10^7
Titanium	1.40×10^7
Neodymium	6.04×10^6

The parameters of the pulsed discharge also contribute to the erosion. Table 4 presents a comparison of erosion measurements for two different pulse parameters. The high erosion observed in [48] could be explained by the transition to the arc phase (see Figure 2f). A surprisingly low erosion rate was obtained with graphite in [48] for high charge transfer pulses, as seen in Table 4, but no qualitative analysis of this result is given.

Table 4. Measured erosion rates of materials at different pulse parameters.

Category	Parameter	Felsner et al. [49]	Tkotch et al. [48]
Operational conditions	Charge transfer	11 mC	1.9 C
	Peak current	9 kA	120 kA
	Reverse current	10%	90%
	Blocking voltage	10 kV	30 kV
Erosion rate ($\mu\text{g C}^{-1}$)	Ta	43	-
	W-Re (97%–3%)	15	150
	Mo	16	450
	Ni	14	-
	Cu	8	-
	Ti	-	3800
	Cr-Cu	-	1400
	C (graphite)	-	20
	W	-	110

The mass eroded per pulse can also be related to the charge transfer per pulse, as shown in Figure 7. A similar erosion profile was observed in high-pressure spark gaps in

the study conducted in [50]. The fitting curves obtained from the experimentally measured data in Figure 7 for tungsten–rhenium and molybdenum are, respectively:

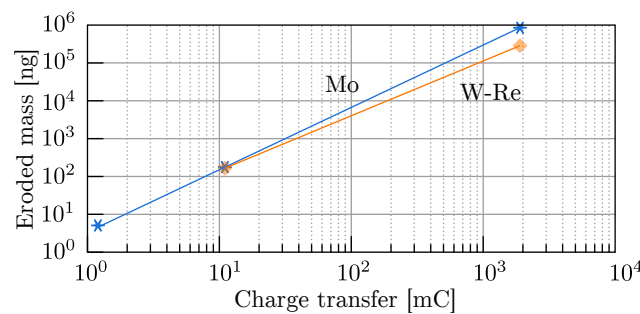


Figure 7. Average eroded mass per pulse for tungsten–rhenium (97%–3%) and molybdenum electrodes as a function of the total charge transferred per pulse. The lines represent fitted curves expressed in Equations (17) and (18). Experimental data are from [48,49,51].

$$\eta_{W-Re} = 112.59 Q_T^{1.44686}, \text{ and} \quad (17)$$

$$\eta_{Mo} = 129.724 Q_T^{1.64766}, \quad (18)$$

where η is the mass erosion in μg for a pulse with a charge transfer Q_T in C. Such empirical fitting equations can be utilised to estimate the total erosion per pulse based on the total charge transfer. However, several limitations and uncertainties arise when extrapolating these models to predict long-term switch lifetimes. Firstly, the available experimental dataset covers a limited range of charge transfer values, introducing uncertainty when predicting behaviour outside these bounds. Secondly, these equations assume a uniform erosion rate throughout the operational lifetime of the switch. In practice, cumulative erosion alters the electrode geometry and surface topography over time, which inevitably affects the discharge dynamics and erosion rate of subsequent pulses. Consequently, these predictions should be interpreted as idealised baseline estimates rather than absolute life cycle values.

The housing of the PSS should present high dielectric strength due to the presence of a high electric field near the main gap. Some test setups used glass [43], epoxy [52], and perspex [32]. The preferred material is aluminium oxide (Al_2O_3), widely used in other high-voltage insulators [19], due to the maturity of metal–ceramic technology.

4. Trigger

The trigger in a PSS is responsible for injecting the initial electrons into the cathode cavity. Its design directly affects the delay and jitter of the switch and is also one of the main factors limiting the switch lifetime. Figure 8 shows different types of triggers discussed in the following subsections.

4.1. Pulsed Glow Discharge

A pulsed glow discharge trigger is illustrated in Figure 8a. During the blocking stage of the PSS, a stable low-current glow discharge occurs between electrodes E2 and E3. A positive voltage is applied to electrode E1 to prevent electrons from entering the cathode cage during this stage.

Triggering is achieved by applying a negative voltage to electrode E3 while grounding electrode E1. The negative potential at electrode E3 drives electrons into the cathode cage, initiating the formation of the virtual anode. An example of the time evolution of the trigger voltages is shown in Figure 9. This method was first reported in [43], where the switch was demonstrated to operate at frequencies up to 100 kHz.

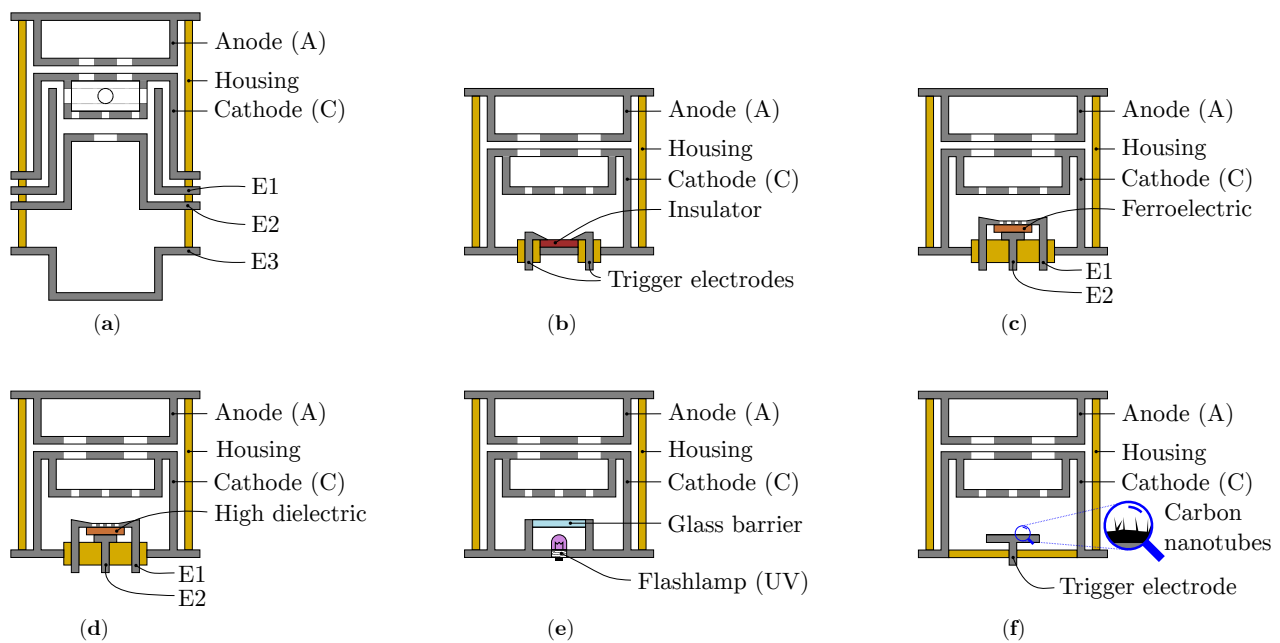


Figure 8. Methods for triggering Pseudo-Spark Switches: (a) pulsed glow discharge; (b) surface discharge; (c) ferroelectric emission; (d) high dielectric; (e) UV light; and (f) carbon nanotubes.

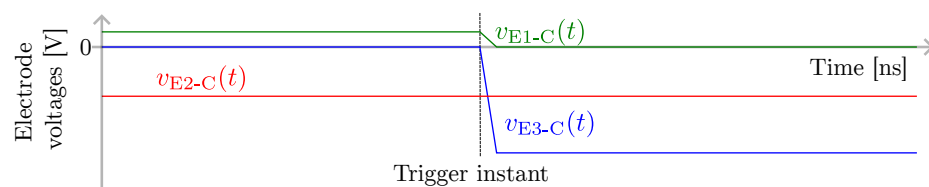


Figure 9. Sketched voltages at electrodes in a pulsed glow triggering method according to the description in [43].

4.2. Surface Discharge

In surface discharge triggers, two-point electrodes are placed on a surface made of an insulator material, such as Mylar or Al_2O_3 [52], as shown in Figure 8b. When a high voltage is applied to the electrodes, an arc discharge develops across the surface. The arc releases charge carriers and photons, which initiate the formation of the virtual anode (see Figure 2c).

The surface discharge trigger can be positioned either at the back side of the cathode or within the main gap. In the latter case, the charges are injected directly into the hollow cavity. Examples of PSSs employing surface discharge triggers can be found in [52,53].

4.3. Ferroelectric Emission

The ferroelectric emission was first reported at CERN [54]. When a ferroelectric material undergoes rapid electric field polarisation, electrons are ejected from its surface. The application of the ferroelectric emission phenomenon in PSSs was introduced in [55].

Figure 8c illustrates the ferroelectric emission trigger in a PSS. A fast-rising negative voltage is applied to electrode E2, with E1 being connected to the cathode. The pulsed voltage causes the release of electrons on the opposite side, i.e., near the fingers of electrode E1.

4.4. High Dielectric

The mechanical design of a high-dielectric trigger is similar to that of the ferroelectric emission trigger, as shown in Figure 8d. The main difference is that a negative pulse is applied to electrode E1, while E2 is connected to the cathode. The electric field is enhanced near the fingers due to both the high-dielectric material and the finger geometry [56]. This

strong electric field produces a corona discharge that releases electrons, which, in turn, ionise the surrounding gas. The negative voltage at electrode E1 also drives the electrons toward the cathode cage.

The high-dielectric trigger exhibits a shorter delay compared to the ferroelectric emission trigger, as reported in [8,57].

4.5. UV Light

PSSs employing this type of trigger are also referred to as Back-Light Thyratrons (BLT switches). In this configuration, an ionising light source is placed at the back of the cathode, as shown in Figure 8e. The light source can be a flashlamp or a laser. It is also possible to use a fibre optic cable to guide the UV light to the inside of the cathode cage [58].

A disadvantage of this trigger type is that the lifetime of UV light triggers is limited by metallisation at the interface between the light source and the cathode, as well as by the lifetime of the light source itself.

4.6. Carbon Nanotubes

The application of carbon nanotubes (CNTs) in PSSs was first reported in [59]. Electrons are injected at the back side of the cathode through field emission from the sharp tips of the nanotubes, as illustrated in Figure 8e.

However, some of the ions generated in the trigger region are accelerated toward the CNT surface. The collision of the ions with the surface damages the sharp nanotubes, reducing their efficacy to emit electrons. In laboratory tests, CNTs exhibited a lifetime of approximately only 10^5 pulses [59].

4.7. Comparison of Triggers

A summary of the different trigger types is presented in Table 5, highlighting the delay and jitter times, as well as the expected lifetime based on data reported in the literature. It is important to note that the delay and jitter times depend on the number of initial electrons released in the cathode cage [60]. Consequently, they are influenced not only by the trigger type, but also by the PSS geometry, which can promote or hinder the injection of electrons into the cathode cage during the triggering phase.

Table 5. Comparison of triggering methods from experimentally measured data.

Trigger Type	Delay	Jitter	Lifetime (Pulses)	Data From
Pulsed Glow Discharge	200 ns	1 ns	$>10^{10}$	[43,61]
Surface Discharge	40 ns	1 ns	$<10^5$	[61]
Ferroelectric Emission	100 ns	1 ns	$>10^8$	[6]
High Dielectric	165 ns	20 ns	$>10^8$	[57]
UV Light	100 ns	7 ns	$<10^5$	[62]
Carbon Nanotubes	270 ns	15 ns	$<10^5$	[57]

Although Table 5 summarises the lifetimes associated with each trigger technology, it is crucial to note that these values are highly dependent on specific operational conditions and design configurations, limiting a direct baseline comparison. For instance, the lifetime of a UV light trigger is primarily governed by the degradation of the UV source and window fouling caused by the deposition of vaporised electrode material. Consequently, the switch geometry plays a critical role in either mitigating or accelerating this metal vapour deposition on the optical interface. Similarly, for surface discharge triggers, the degradation rate of the dielectric material where the discharge occurs directly dictates the component lifetime. Nevertheless, it should be considered that the designs reported in

the literature deliberately employed optimisation strategies to maximise or, at the very least, preserve switch longevity. Therefore, despite different experimental conditions, these values serve as a reliable first-order estimate for benchmarking similar PSS designs.

Among the trigger types considered, the pulsed glow discharge trigger stands out due to its high lifetime. The main drawback of this trigger is its large mechanical size and complex configuration, which requires three different voltage potentials. For some applications, the associated delay time can also be prohibitive.

Following this, the ferroelectric emission and high-dielectric triggers exhibit increased lifetime and reduced delay time compared to the pulsed glow discharge trigger, making them suitable alternatives for systems where both durability and fast response are required, which is the case for sealed-off switches.

On the other hand, triggers based on surface discharge, UV light, and carbon nanotubes present the lowest lifetime values. The surface discharge trigger offers the advantage of a low delay time, which can be beneficial in specific applications. However, a major drawback is the evaporation of the dielectric surface material [52], a non-reversible process that modifies the gas composition in sealed-off PSSs.

The UV light trigger, when implemented using fibre optic cables, presents an advantage in systems requiring the simultaneous triggering of multiple switches, as it provides inherent electrical insulation. The carbon nanotube trigger, however, does not show any significant advantage compared to other triggering methods.

5. Design Procedure of a Pseudo-Spark Switch

For designing PSSs, the design flowchart shown in Figure 10 is proposed. It starts with the PSS specifications, in which the requirements of the final application are collected and analysed.

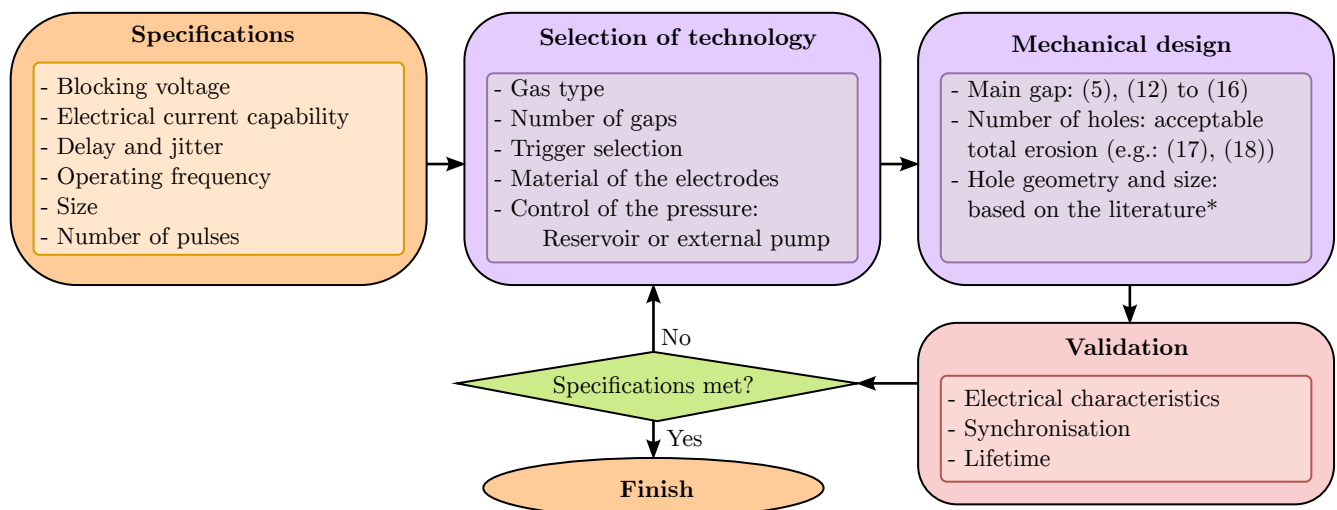


Figure 10. Flowchart of the PSS design procedure. The specification phase defines the operating parameters, followed by component selection according to the application. The mechanical design phase defines the geometry to meet the required operating voltage, and the final phase verifies compliance through prototype testing. * E.g., [16,28–30].

The second step “technology selection” corresponds to the preliminary design phase and involves identifying possible parameter combinations that can meet the specification goals based on the data available in the literature.

The third step is the mechanical design of the switch. As discussed in Section 3, it is not possible to precisely define the operational voltage region (see Figure 3). An estimated breakdown-voltage region can be constructed based in Equations (5) and (12)–(16).

Multiple holes are selected to reduce erosion, since each hole will experience a lower total charge transfer. The total erosion is estimated using the fit functions as shown in Equations (17) and (18). The hole size is estimated from the literature data of similar designs.

In the validation phase, the switch is fabricated, and the design specifications are experimentally verified. At this stage, the only adjustable parameters are the gas pressure or the gas type. For sealed-off switches, the choice of gases is limited to hydrogen and deuterium, as these are the only gases that can be stored in an integrated gas reservoir.

If the experimental results do not satisfy the design requirements, a redesign is required, where different materials, geometries, or trigger types may be selected to optimise performance.

6. Compact PSS Design for Marx Generator

This section describes a design example of a PSS for a 12-stage Marx generator used in the considered drilling application. The topology of the Marx generator employing PSSs is shown in Figure 11. The stage capacitors C_s are charged in parallel by a DC voltage source V_{ch} , where each stage is separated by the charging inductors L_{ch} . After the capacitors are fully charged, all the stage PSSs S_s are triggered, connecting the capacitors in series, creating a high-voltage pulse across the load.

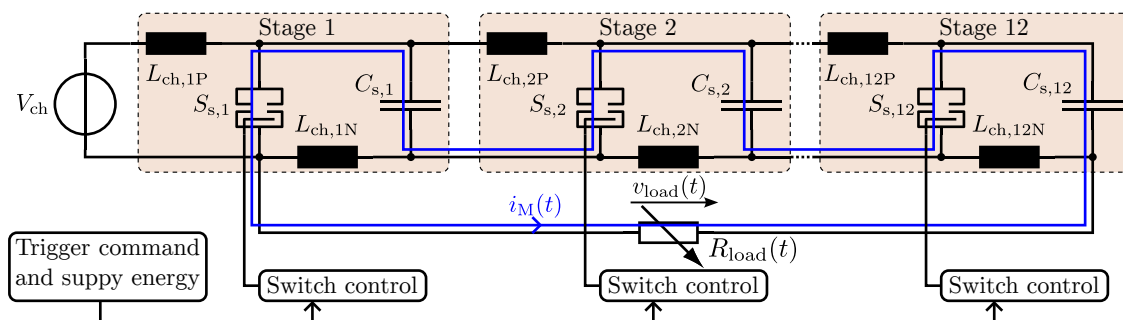


Figure 11. Twelve-stage Marx generator circuit using Pseudo-Spark Switches. C_s are the Marx stage capacitances, L_{ch} are the charging inductors, V_{ch} is the source voltage, S_s is the stage switch, R_{load} is the output load, $i_M(t)$ is the current in the erected mode, and $v_{load}(t)$ is the voltage across the load.

In this application, each stage of the Marx generator shown in Figure 11 is defined to operate at 30 kV, resulting in a total pulse amplitude of 360 kV. A variable resistor R_{load} represents the resistance of the plasma channel formed inside the rock during the pulse, based on the non-linear load model described in [63] as

$$R_{load}(t) = \frac{Al_{ch}}{\Delta + \sqrt{\int_0^t i_M^2(\tau) d\tau}}, \quad (19)$$

where A is a constant depending on the type of rock, l_{ch} is the distance between the electrodes in contact with the rock, and Δ is the parameter that gives the initial resistance of the rock.

The expected current waveform of the circuit and the corresponding load voltage are obtained through simulation, as shown in Figure 12. The simulation uses a stage capacitance C_s of 37 nF and a total stray inductance of 1 μ H for the Marx generator. The total capacitance charged to 30 kV per stage results in a 200 J pulse. The parameters used for the load are $A = 618 \text{ V s}^{0.5} \text{ m}^{-1}$, $l_{ch} = 0.046 \text{ m}$, and $\Delta = 2.56 \times 10^{-4} \text{ V s}^{0.5} \Omega^{-1}$.

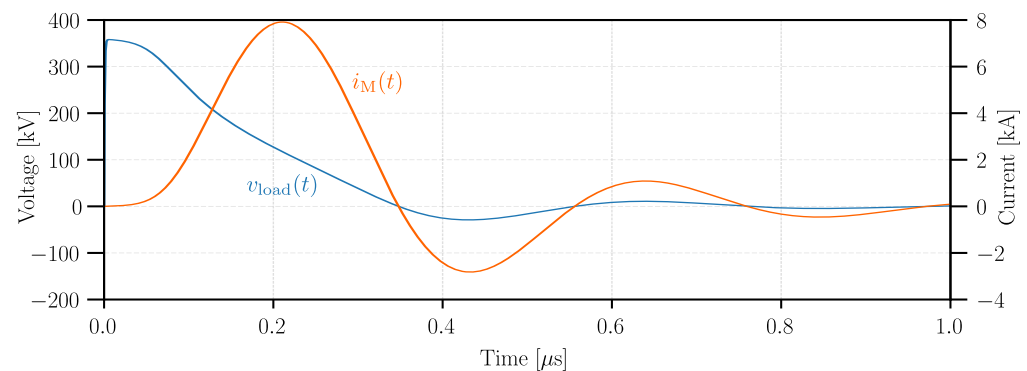


Figure 12. Simulated current $i_M(t)$ and load voltage $v_{load}(t)$ for the Marx circuit used in PPGD. The total charge transfer is approximately 1.9 mC per shot. The PSS switches have been considered ideal switches for simplicity, which results in a negligible voltage rise time at the load.

To generate the pulse, all PSSs are triggered simultaneously by a centralised control unit. The maximum duration between the first and the last PSS to close is in the order of a few nanoseconds to minimise the voltage rise time at the load in order to meet the solid–liquid interface breakdown conditions [2].

Achieving nanosecond-level synchronisation across the multiple PSS in the proposed Marx generator involves managing both intrinsic switch physics and external circuit propagation. PSS devices characteristically exhibit a relatively long commutation delay but a remarkably low jitter, often in the ns range. Since identical PSS geometries are employed throughout the Marx stages, similar baseline delay and jitter profiles are anticipated across all switches.

To achieve precise synchronisation feasibility, two main control strategies are considered:

- **Pressure-Based Jitter and Delay Control:** The intrinsic delay and jitter of each PSS can be actively tuned by adjusting the internal gas pressure. This is practically achieved by modulating the filament current of the gas reservoir, allowing for fine-tuning of the operating pressure (p) to synchronise the breakdown characteristics.
- **Electronic Delay Compensation:** Beyond the switch itself, total system delay dispersion includes trigger circuit propagation and signal transit times through the cabling. To ensure simultaneous triggering, programmable electronic delay lines can be integrated into the triggering circuit of each individual stage. This allows for post-assembly calibration to compensate for any structural or geometric path differences.

Consequently, while the absolute delay of a PSS is inherently large, its low jitter combined with active pressure regulation and external electronic compensation confirms the feasibility of ns-level synchronisation for the Marx generator.

The total charge transfer of 1.9 mC per pulse is obtained from the time integral of the current $i_M(t)$, as shown in Figure 12.

Proposed PSS Design

The proposed PSS design is presented in Figure 13. Starting with the specification phase (refer to Figure 10), the PSS specifications are obtained from the Marx generator simulation and the estimated number of pulses required for drilling. The specifications are summarised in Table 1.

In the selection of the technology phase, tungsten is selected as the material for the electrodes at the main gap due to its low erosion rate. Although the mass erosion rate of copper is lower than that of the tungsten–rhenium (W-Re) alloy [49], as shown in Table 4, the density of tungsten is 2.15 times higher than that of copper, meaning that the volume erosion is similar. Moreover, tungsten has both a higher melting point and a greater resistance to erosion than copper (see Table 3). The high erosion resistance makes tungsten

the most suitable choice in case the PSS reaches the arc phase (see Figure 2f), which can occur when breakdown in the rock does not take place, resulting in long-lasting oscillatory current in the Marx generator due to the lower damping.

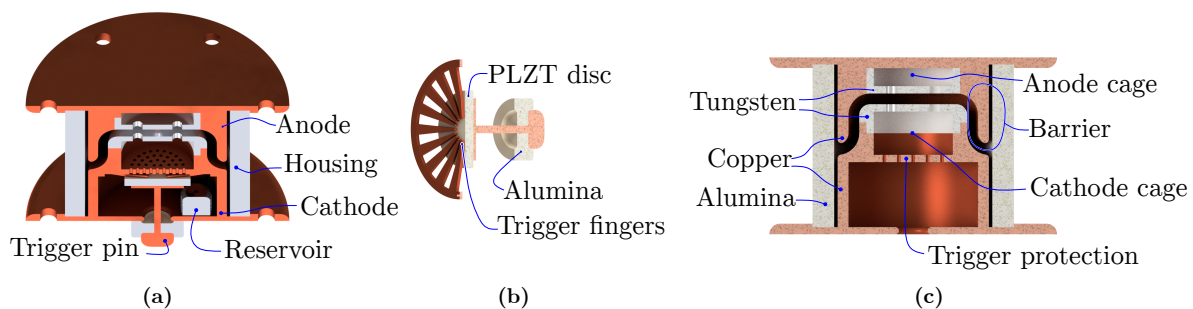


Figure 13. Structure of the Pseudo-Spark Switch for a compact Marx generator: (a) Section view of the PSS. (b) Detail of trigger electrode structure. (c) Section view of the PSS with detailed materials and regions.

Outside the main gap, copper is selected for the remaining parts of the electrodes. In addition, copper is cheaper than tungsten and easier to machine compared to tungsten. Copper also has good resistance to erosion, as shown in Table 3.

A ferroelectric emission trigger is selected because it can achieve the desired lifetime of 7×10^8 pulses. Other trigger types capable of meeting this lifetime requirement include the pulsed glow discharge trigger and the high-dielectric trigger. The pulsed glow discharge trigger is discarded due to its additional height, which increases the total length of the Marx generator and, consequently, its total impedance. The ferroelectric emission trigger is preferred because, with this trigger, electrode E1 can be grounded (see Figure 8c), simplifying the insulation design of electrode E2.

Hydrogen is chosen as the working gas to enable a sealed-off design. Although deuterium could also be used, hydrogen is preferred because it is easier to obtain and can meet the blocking voltage requirements.

To conclude the technology selection design phase, a single-gap PSS configuration is chosen for simplicity, which should be possible to achieve for the stage voltage of the Marx generator (30 kV).

At the mechanical design phase, the main geometry is defined. At this stage, FEM simulations are used to compute the electric field distribution. Rounded edges (fillets) in the geometry reduce the local electric field enhancement. The resulting electric field distribution is shown in Figure 14. The electric field distribution was obtained under a current-free assumption, meaning the profile was governed solely by the geometry and the permittivity distribution of the media. Additionally, axial symmetry is used for the calculation.

The estimated operating region of the designed PSS is shown in Figure 15. The gas breakdown limit is defined by the shifted Paschen's curve of hydrogen. The main gap distance h_g is 3 mm, so that based on the approximation given in Equation (12), Paschen's curve is plotted for an effective h_g of 6 mm.

The vacuum breakdown limits are determined by the maximum electric field on tungsten or copper surfaces, which occur near the electrode holes or close to the housing, as shown in Figure 14.

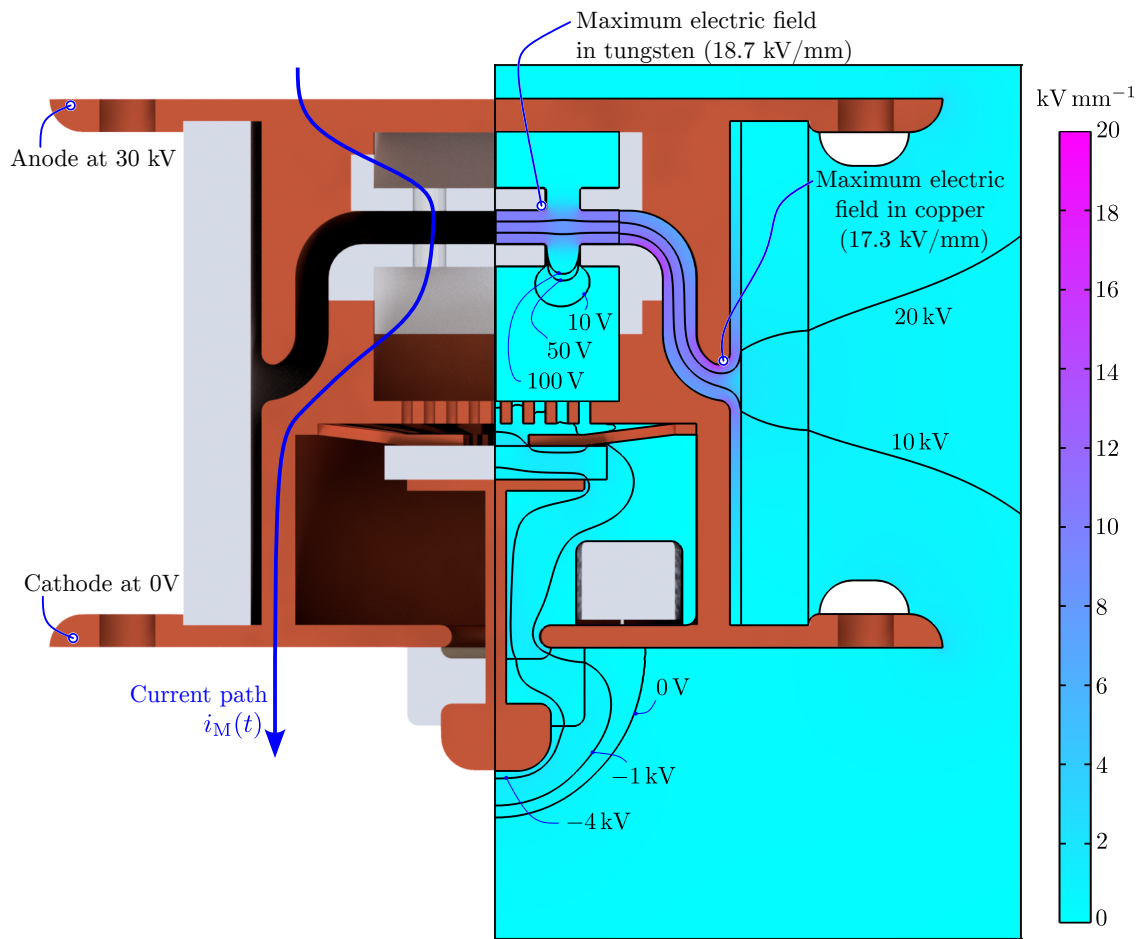


Figure 14. Electric field distribution inside the Pseudo-Spark Switch obtained through FEM simulation.

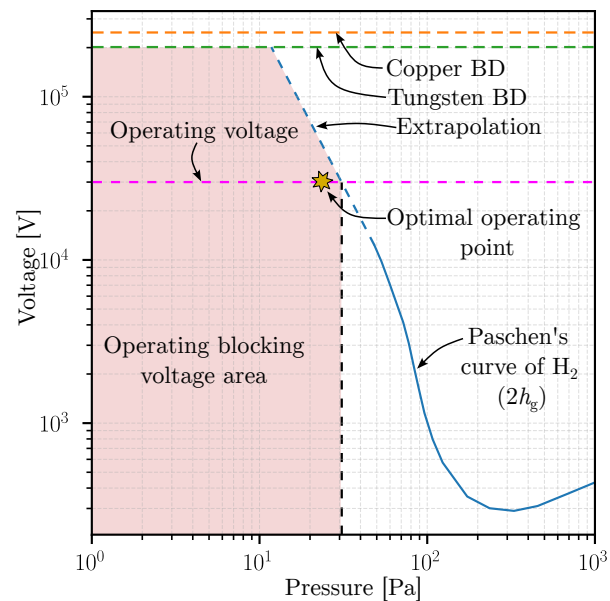


Figure 15. Estimated operating voltage region of the designed PSS. Scaled Paschen's curve of H_2 from the measurement data in [17].

The maximum geometric electric field enhancement is obtained from:

$$\beta_{\text{geo,Cu}} = \frac{E_{\text{Cu,max}} h_g}{V_{\text{ch}}} = 1.73, \text{ and} \quad (20)$$

$$\beta_{\text{geo,W}} = \frac{E_{\text{W,max}} h_g}{V_{\text{ch}}} = 1.87. \quad (21)$$

The points of maximum electric fields $E_{\text{Cu,max}} = 17.3 \text{ kV mm}^{-1}$ and $E_{\text{W,max}} = 18.7 \text{ kV mm}^{-1}$ are shown in Figure 14. A safety factor for the surface enhancement is assumed as $\beta_{\text{sur}} = 50$, as discussed in Section 3. Finally, the vacuum breakdown voltages for copper and tungsten shown in Figure 15 are obtained using Equations (5) and (13).

The optimal operating point shown in Figure 15 lies at the maximum pressure for which the operating voltage is 60% of the self-breakdown voltage. The pressure at this point is approximately 22 Pa. If the self-breakdown voltage is lower than the estimated values due to the hollow electrodes, as discussed in Section 3, the pressure can be further reduced to compensate for the hollow effect in the validation phase.

The PSS is designed with four channels to reduce the charge transfer per channel, thereby helping to minimise erosion. Using Equation (17), the total erosion is estimated to be 4.91 g after 7×10^8 pulses, which corresponds to approximately 17% of the cathode surface mass. The initial total size of the considered cathode has a diameter of 2.6 cm and a thickness of 3 mm, excluding the volume of the four channels.

The chicanes are added to prevent the eroded metal from being deposited at the housing during the high-current phase (see Figure 13c).

Aluminium oxide was selected as the insulating material for both the housing and the trigger due to its high dielectric and mechanical strength [19], as well as its ability to withstand high temperatures. The maximum electric fields in the aluminium oxide components are 2.05 kV mm^{-1} at the housing and 1.78 kV mm^{-1} at the trigger support, which are below the maximum dielectric strength of aluminium oxide, 13.4 kV mm^{-1} [64].

A protection barrier consisting of several holes is added to the cathode cage structure, allowing the electrons emitted from the trigger to penetrate into the cathode cage, as shown in Figure 13a. This barrier protects the trigger during the hollow cathode phase (see Figure 2c), thereby extending the trigger lifetime.

The trigger is designed for an input pulsed voltage of -5 kV , with a minimum duration of approximately 200 ns, which is expected to be sufficient. A PSS with the same type of trigger has been successfully triggered at approximately -3 kV , as reported in [65]. In the Marx generator shown in Figure 11, the trigger voltage of each stage must be isolated.

Finally, in the mechanical design phase, the reservoir shown in Figure 13a, which controls the pressure, is implemented using a commercial getter. The selected model is ST 172 HI/9.5-7 from SAES [66]. The criterion for selecting this specific model is based on the device geometry. The capability of maintaining the desired pressure in the designed PSS is verified in a subsequent testing phase.

During Pulsed-Power Geo-Drilling (PPGD) operations, the ambient temperature within the Marx generator enclosure is expected to reach up to 200°C . Such elevated thermal conditions inevitably influence the switching performance of the PSS, primarily by altering the gas density and pressure profiles, which, in turn, shift the operational breakdown voltage. To counteract these thermal effects and maintain gas pressure stability, the heating current of the reservoir filament can be dynamically or pre-emptively adjusted. The precise correlation between the ambient temperature, required filament current, and optimal internal pressure can be experimentally calibrated beforehand, isolated from the primary Marx generator setup. This pre-calibration ensures that the PSS triggers reliably and maintains stable commutation characteristics even under the harsh thermal constraints of the geo-drilling environment.

The design is concluded after the validation phase, which is not presented here. For the Marx generator shown in Figure 11 to be used in PPGD applications, the main objectives of the PSS are durability and precise synchronisation between switches. Durability can be

verified through continuous testing of a single switch, while synchronisation is achieved when multiple switches exhibit the same delay time, i.e., when no time difference exists between them. This synchronisation can be adjusted by controlling the internal pressure of each switch through the reservoir current.

7. Conclusions

This paper presents a comprehensive review of the design process of Pseudo-Spark Switches (PSSs) and introduces a compact design tailored for Pulsed-Power Geo-Drilling (PPGD) applications. A structured set of design guidelines is presented, based on a literature review of the individual components of the PSS, enabling estimation of the breakdown voltage, operating pressure, and the approximate total electrode erosion prior to the fabrication of the initial prototype.

The proposed switch design aims to withstand 7×10^8 pulses with a charge transfer of 1.9 mC per pulse and a blocking voltage of 30 kV. Key design features, including a multi-channel configuration and a heated gas reservoir, ensure stable operation and minimise electrode erosion over time.

While the design demonstrates significant improvements in durability and performance compared to other high-voltage switches, such as spark gaps used in pulsed-power generators, careful control of internal gas pressure and precise mechanical tolerances remain critical for reliable operation.

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Abbreviations

The following abbreviations are used in this manuscript:

BLT	Back-Light Thyatron
CERN	Conseil Européen pour la Recherche Nucléaire
CNT	Carbon Nanotube
FEM	Finite Element Method
PPGD	Pulsed-Power Geo-Drilling
PSS	Pseudo-Spark Switch

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