Closing Switches

Fall, 2018

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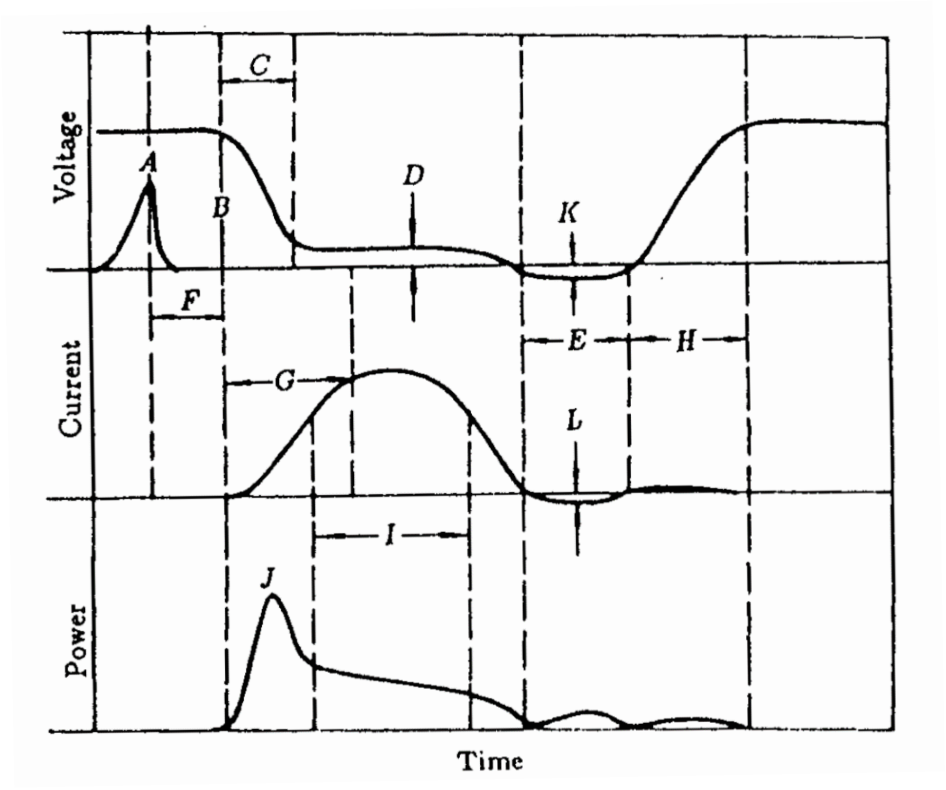
Switch fundamentals

- The importance of switches in pulsed power systems
  - In high power pulse applications, switches capable of handling tera-watt power and having jitter time in the nanosecond range are frequently needed.
  - The rise time, shape, and amplitude of the generator output pulse depend strongly on the properties of the switches.
  - The basic principle of switching is simple: at a proper time, change the property of the switch medium from that of an insulator to that of a conductor or the reverse.
  - To achieve this effectively and precisely, however, is rather a complex and difficult task. It involves not only the parameters of the switch and circuit but also many physical and chemical processes.

Switch fundamentals

- Design of a switch requires knowledge in many areas.
- The property of the medium employed between the switch electrodes is the most important factor that determines the performance of the switch.
- Classification
  - Medium: gas switch, liquid switch, solid switch
  - Triggering mechanism: self-breakdown or externally triggered switches
  - Charging mode: Statically charged or pulse charged switches
  - No. of conducting channels: single channel or multi-channel switches
  - Discharge property: volume discharge or surface discharge switches

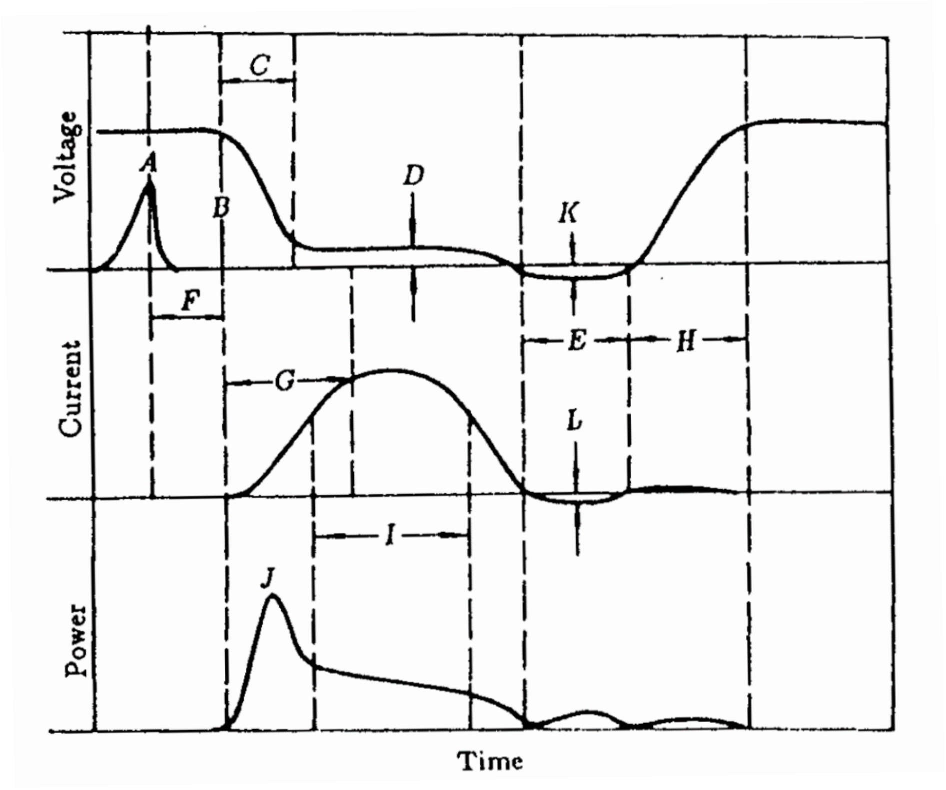
Characteristics of typical switches



A. Trigger pulse: a fast pulse supplied externally to initiate the action of switching, the nature of which may be voltage, laser beam or charged particle beam.

B. Hold-off voltage: the maximum static voltage V_s that can be applied to the switch before breakdown between the main electrodes occurs. If the switch is pulse charged, the hold-off voltage can be greater than V_s and its magnitude depends on the risetime of the applied voltage pulse.

Characteristics of typical switches

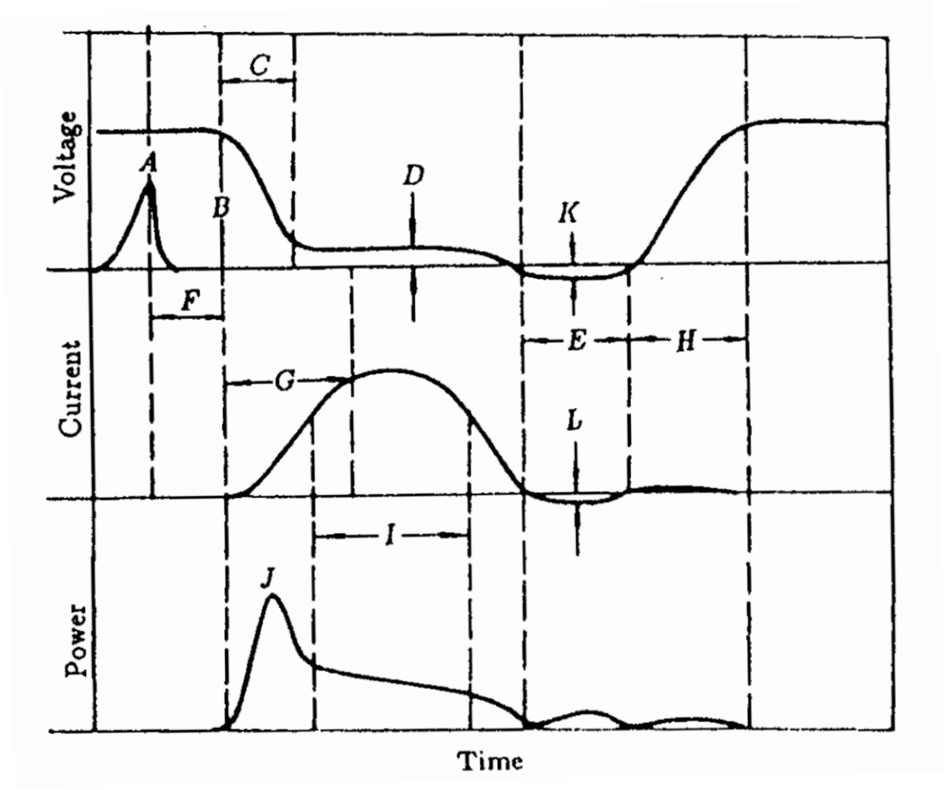


C. Voltage fall time: after breakdown is initiated, the time interval during which the voltage drops from the value of hold-off to that of the conduction drop. For gas switches, this roughly corresponds to the resistive phase during closure.

D. Conduction drop: the voltage drop across the switch impedance during conduction.

E. Recover time: the time interval during which the voltage reverses its polarity.

Characteristics of typical switches

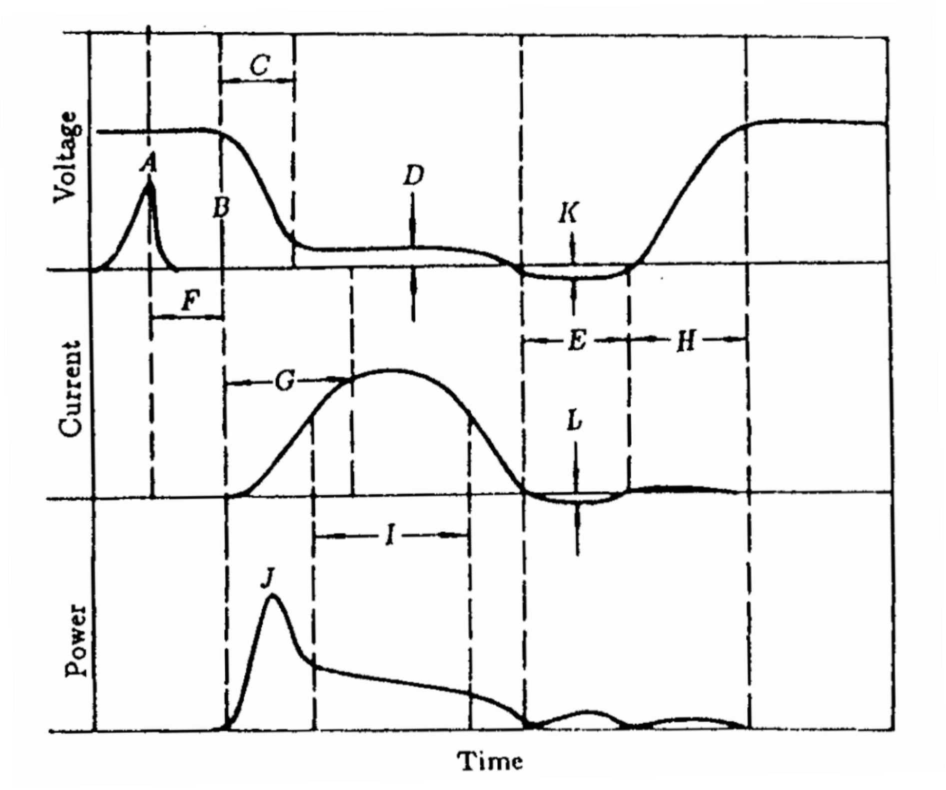


F. Delay time: the time interval between the time the trigger pulse is at its peak value and the point at which switch starts to close or open.

G. Current rise time: the time interval required for the current to rise from the 10% to 90% of its peak value.

H. Recharge time: the time interval between the end of the recover time and the point at which the voltage recovers to the hold-off value.

Characteristics of typical switches

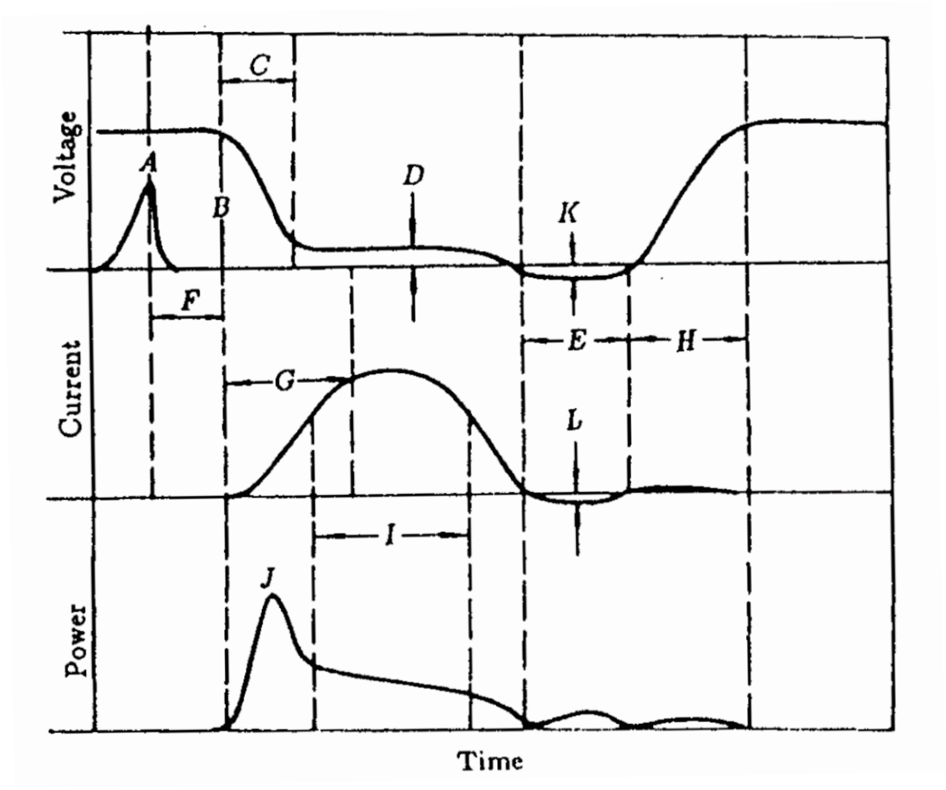


I. Current pulse width: the time duration corresponds to the full width at half maximum of the current pulse.

J. Peak power: the maximum value of the product of voltage and current which occur at the same time (alternatively it is also defined as the product of the peak current and the hold-off voltage which are not necessarily occurring at the same time).

K. Peak reverse voltage: the maximum value of the reverse voltage.

Characteristics of typical switches



L. Peak reversed current: the maximum value of the reversed current.

M. Energy transferred: the time integral of the product of voltage and current.

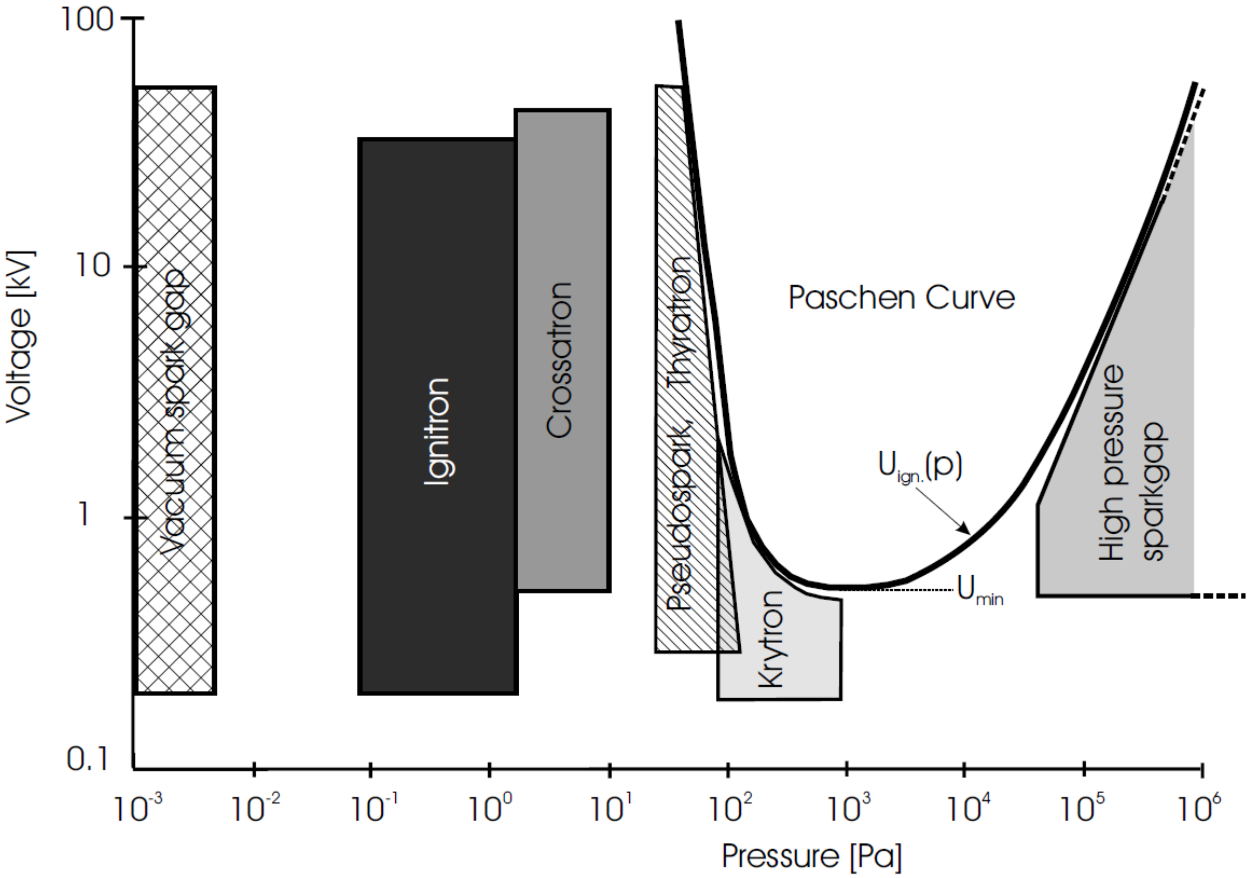
N. Life time: under normal operating conditions, the total number of switching operations beyond which the switch can no longer function properly.

O. Total charge transferred: the accumulated total charge that has passed through the switch during its life time.

Gas switches are commonly used

- Range of gas pressures and operating voltages

Paschen curve: air with 3 mm gap

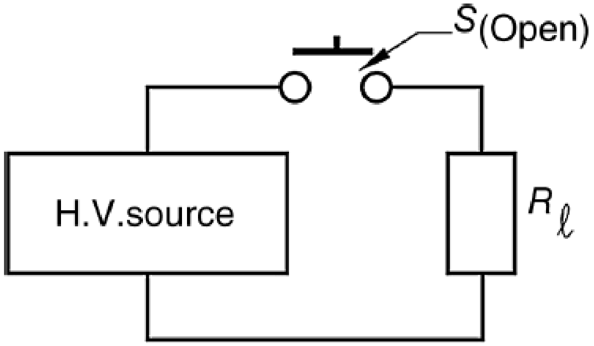


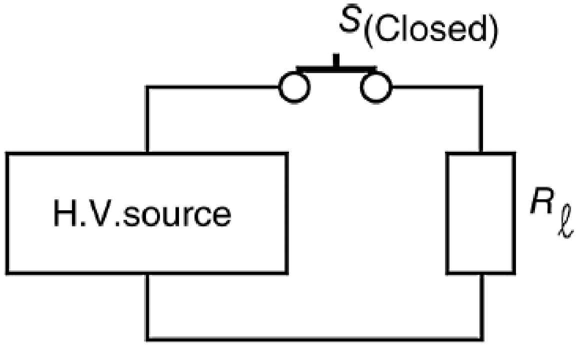
Spark gap switches

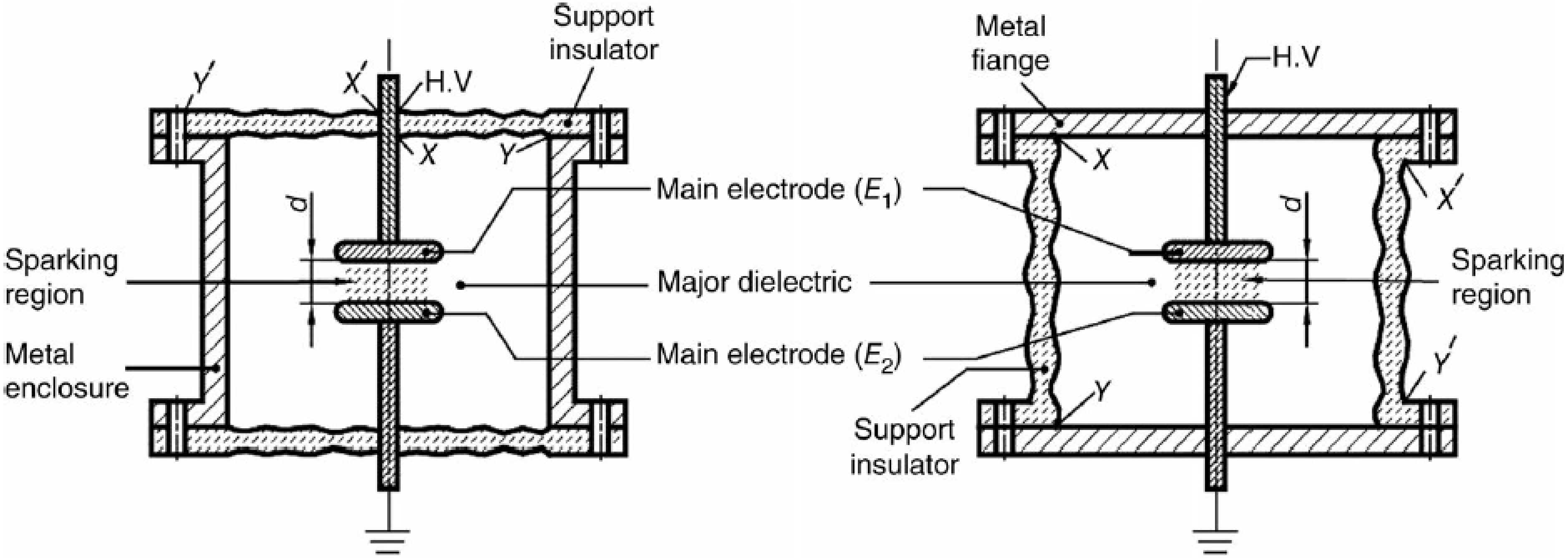
- Characteristics of spark gap switches

  - ◆ Trigger: - Self-breakdown
    - External trigger by electric pulse, laser, plasma, ptl. beam
  - ◆ Important design parameters:
    - ✓ The self-breakdown (hold-off) voltage
    - ✓ The variance of breakdown voltage (probability of pre-breakdown)
    - ✓ The operation range with reliability
    - ✓ The jitter (time variance of ignition)
    - ✓ The switching time (decay of impedance)
    - ✓ The pre-breakdown inductance and capacitance
    - ✓ The repetition rate capability
    - ✓ The lifetime and cost

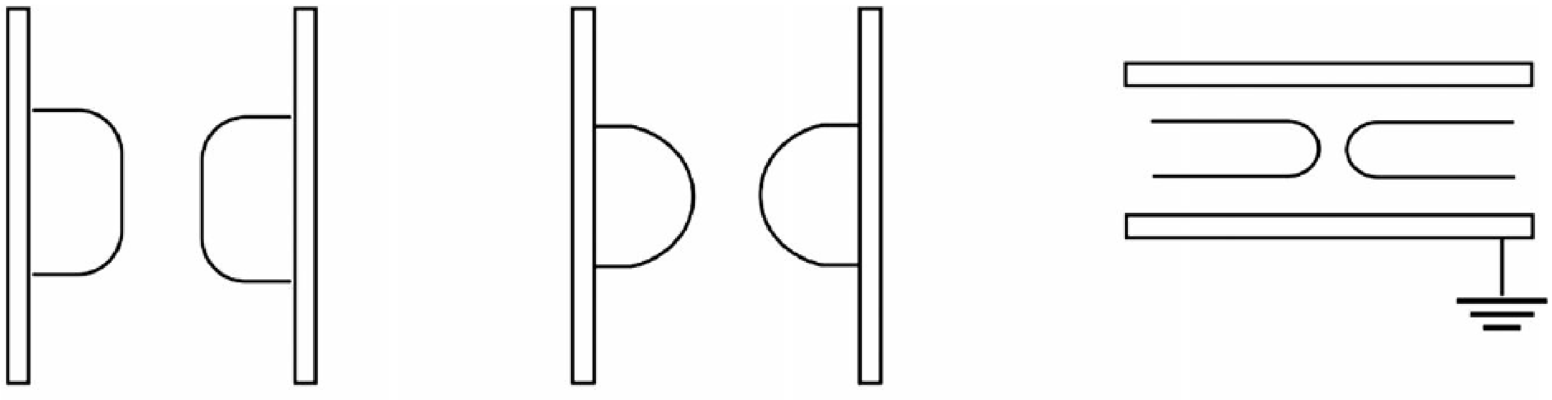
Typical configuration





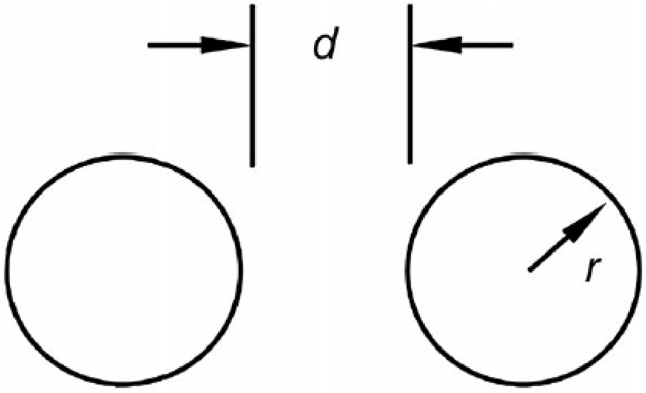


Electrode geometry



- Field enhancement factor (FEF)
  - Spheres

$$FEF = \frac{E_{max}}{E_{avg}} \approx \frac{d}{2r} \quad for\ \frac{d}{r} \gg 1$$

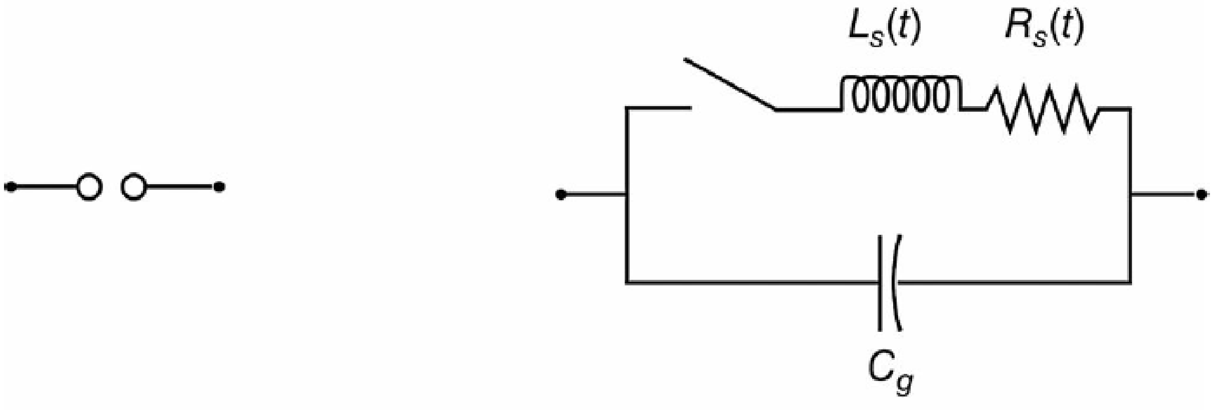


  - Parallel cylinders

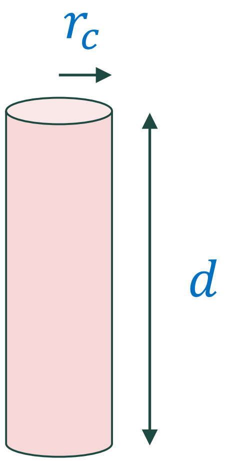
$$FEF = \frac{E_{max}}{E_{avg}} \approx \frac{d}{2r\ln\left(\frac{d}{r}\right)} \quad for\ \frac{d}{r} \gg 4$$

Equivalent circuit

- When the switch is open, the spark gap acts as a capacitor. When the spark gap fires, the switch closes and the self-capacitance of the spark gap is shunted by the series combination of spark channel resistance $R_s(t)$ and spark channel inductance $L_s(t)$ representing the arc.



- Capacitance of the gap



$$C_g = \frac{Q}{V} = \frac{\epsilon \oint \boldsymbol{E} \cdot d\boldsymbol{A}}{\int \boldsymbol{E} \cdot d\boldsymbol{l}} \approx \epsilon \frac{A}{d}$$

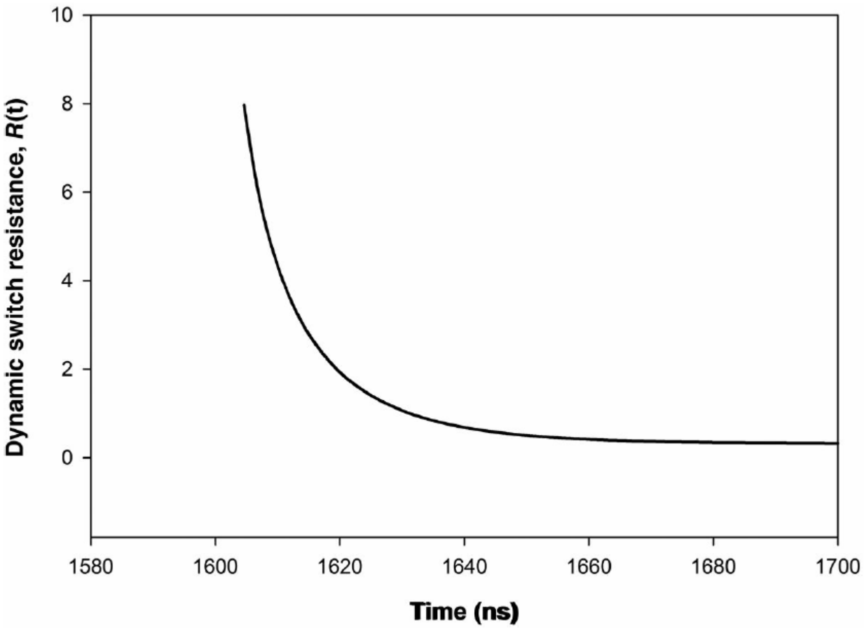
- Inductance of the arc channel (ideal cylinder)

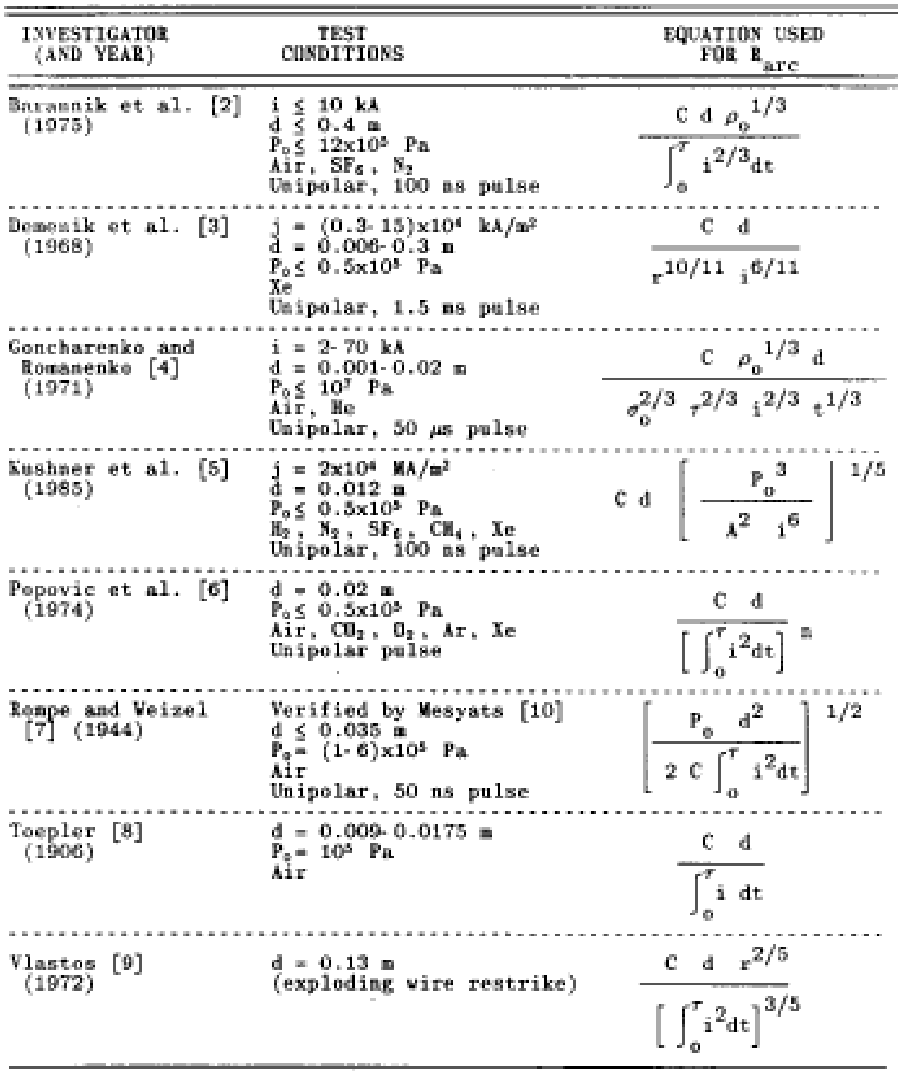
$$L_s(t) = \frac{\mu_0 d}{2\pi}\left[\ln\left(\frac{2d}{r_c(t)}\right) - \frac{3}{4}\right]$$

Equivalent circuit

- Resistance of the arc channel

$$R_s(t) = \frac{d}{\sigma(\rho,T)\cdot\pi r_c^2(t)}$$



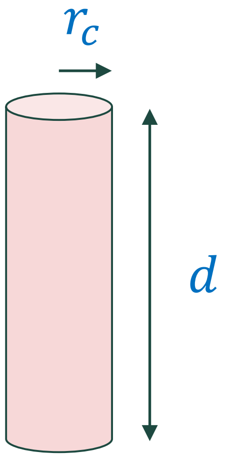


INVESTIGATOR (AND YEAR)	TEST CONDITIONS	EQUATION USED FOR R_{arc}
Barannik et al. [2] (1975)	$i \le 10$ kA $d \le 0.4$ m $P_o \le 12\times10^5$ Pa Air, SF_6, N_2 Unipolar, 100 ns pulse	$\dfrac{C\ d\ \rho_o^{1/3}}{\int_o^\tau i^{2/3}dt}$
Domenik et al. [3] (1968)	$j = (0.3\text{-}15)\times10^4$ kA/m^2 $d = 0.006\text{-}0.3$ m $P_o \le 0.5\times10^5$ Pa Xe Unipolar, 1.5 ms pulse	$\dfrac{C\ d}{r^{10/11}\ i^{6/11}}$
Goncharenko and Romanenko [4] (1971)	$i = 2\text{-}70$ kA $d = 0.001\text{-}0.02$ m $P_o \le 10^7$ Pa Air, He Unipolar, 50 μs pulse	$\dfrac{C\ \rho_o^{1/3}\ d}{\sigma_o^{2/3}\ r^{2/3}\ i^{2/3}\ t^{1/3}}$
Kushner et al. [5] (1985)	$j = 2\times10^4$ MA/m^2 $d = 0.012$ m $P_o \le 0.5\times10^5$ Pa H_2, N_2, SF_6, CH_4, Xe Unipolar, 100 ns pulse	$C\ d\left[\dfrac{P_o^{3}}{A^2\ i^6}\right]^{1/5}$
Popovic et al. [6] (1974)	$d = 0.02$ m $P_o \le 0.5\times10^5$ Pa Air, CO_2, O_2, Ar, Xe Unipolar pulse	$\dfrac{C\ d}{\left[\int_o^\tau i^2dt\right]^{n}}$
Rompe and Weizel [7] (1944)	Verified by Mesyats [10] $d \le 0.035$ m $P_o = (1\text{-}6)\times10^5$ Pa Air Unipolar, 50 ns pulse	$\left[\dfrac{P_o\ d^2}{2\ C\int_o^\tau i^2dt}\right]^{1/2}$
Toepler [8] (1906)	$d = 0.009\text{-}0.0175$ m $P_o = 10^5$ Pa Air	$\dfrac{C\ d}{\int_o^\tau i\ dt}$
Vlastos [9] (1972)	$d = 0.13$ m (exploding wire restrike)	$\dfrac{C\ d\ r^{2/5}}{\left[\int_o^\tau i^2dt\right]^{3/5}}$

Toepler's spark law

- It is assumed that a weakly conducting column exists and its conductivity is increased by collisional ionization.

$$dn_e = n_e \alpha dx = n_e \alpha u_e dt = n_e \alpha \mu_e E dt$$



- The mean electron density in the spark channel

$$n_e(t) = \frac{\alpha}{e}\int_0^t j dt \qquad (j = n_e e \mu_e E)$$

- The spark resistance

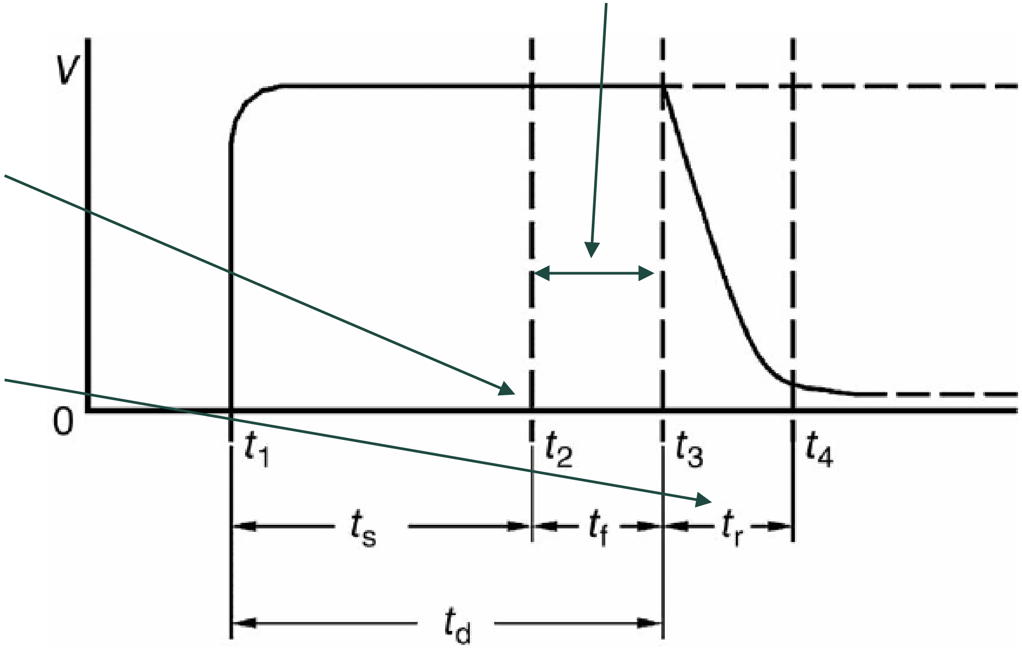
$$R_c(t) = \frac{V}{I} = \frac{Ed}{n_e(t) e \mu_e E \cdot \pi r_c^2} = \frac{d}{\alpha \mu_e \int_0^t I(t) dt}$$

→ Expansion of the spark channel due to Joule heating is not considered.

Delay time

- The delay time to breakdown, also called the time lag, is a measurement of the temporal development of the arc upon application of a voltage. The delay time is a fundamental metric in the development and evaluation of spark gaps.
- The switch jitter is the standard deviation of the delay time.
- The switching time or time lag t_d is generally considered to be separable into two components: the statistical time lag t_s and the formative time lag t_f.

$$t_d = t_s + t_f$$



Ionization growth and channel formation

An electron appears to initiate the breakdown process

Rise time: high Z → low Z

Rise time

- The rise time of interest is the time for the current to rise between 10 and 90% of its peak value.

$$t_r = 2.2\tau_{tot} = 2.2\sqrt{\tau_R^2 + \tau_L^2}$$

- Resistive phase time constant (τ_R): The initial reduction of impedance of the gap is due to the increase in the temperature of plasma from 5,000 to 100,000 K. Further reduction of the gap impedance takes place by an increase in the cross section of the arc channel. Martin proposed the following formula:

$$\tau_R = \frac{88}{Z^{1/3}E^{4/3}}\sqrt{\frac{\rho}{\rho_0}} \quad ns$$

Z is the impedance of the source driving the channel in ohms,
E is the field in units of 10 kV/cm,
ρ is the density of the gas, and
ρ_0 is the density of air at STP.

- Inductive phase time constant (τ_R): As the current builds up during the resistive phase, the resistance of the spark channel is gradually lowered. It is at this stage that inductance starts playing a dominant role. When the spark inductance is small, the electrode inductance must also be considered.

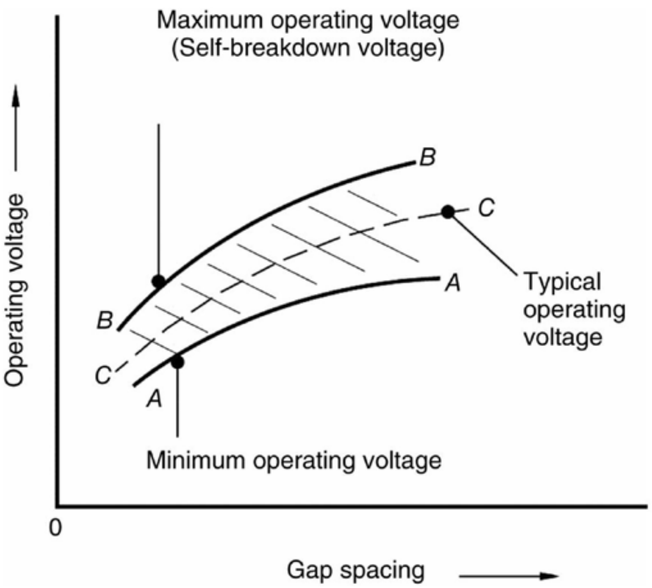
$$\tau_L = \frac{L}{Z} = \frac{L_{arc} + L_{electrode}}{Z}$$

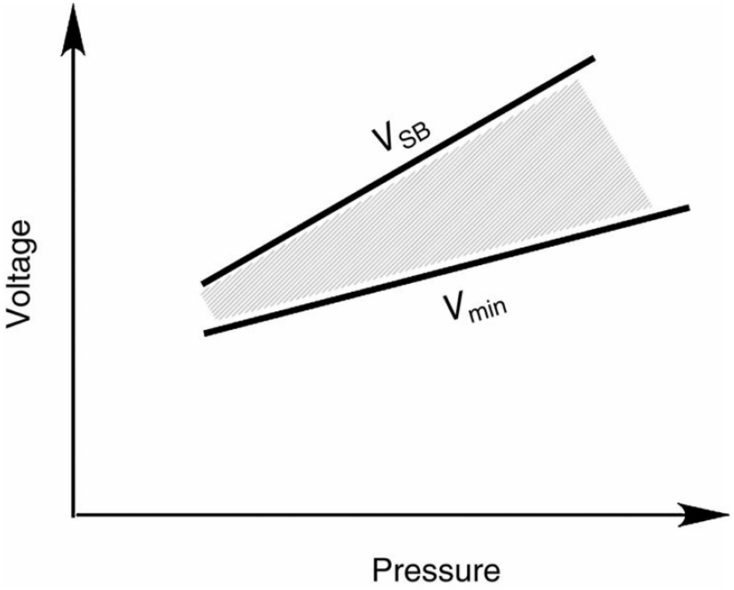
Current sharing

- In some instances, it is desirable to split the circuit current into a number of channels. This may be achieved by sharing the current by using several spark gaps switches in parallel or by designing a single switch to produce multiple channels.
- There are three dominant reasons for provoking current sharing: (i) lifetime extension, (ii) inductance reduction, and (iii) uniform injection of energy from one energy storage stage to another.
- Parallel operation
- Multichannel operation
  - When an impulse voltage of sufficient amplitude is applied to a spark gap, a spark channel is formed at the weakest point and collapses the voltage at that point to a very low voltage. Once formed, the spark channel prevents the formation of other channels across the area of the electrodes. → voltage collapse wave
  - The probability of multichanneling increases with high electric fields, high rates of voltage application(dV/dt), long electrode lengths, and large time isolation (high dielectric constant insulators). The parameters that produce multichanneling in spark gaps also result in low switching jitter.

Triggered spark gap switch

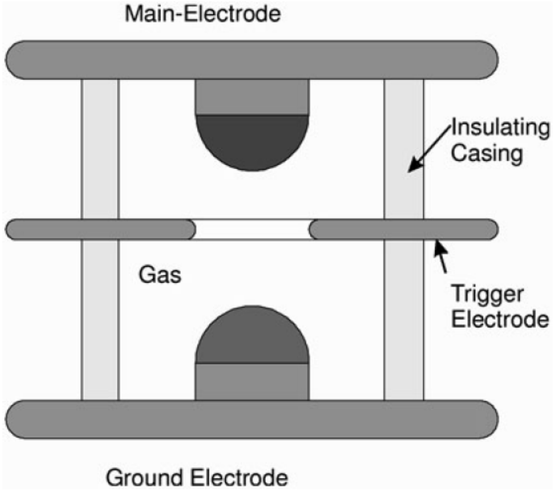
- Triggered switches are capable of producing sub-nanosecond jitter and can greatly affect the capability and reliability of a device.
- Triggered switches have a minimum operating voltage below which the switch does not fire upon application of a command trigger. The spread of voltages lying between the limits of minimum operating voltage and the self-breakdown voltage.





- Types
  - Trigatron
  - Three-electrode field distortion spark gap
  - Laser-triggered spark gap

Three-electrode field distortion spark gap



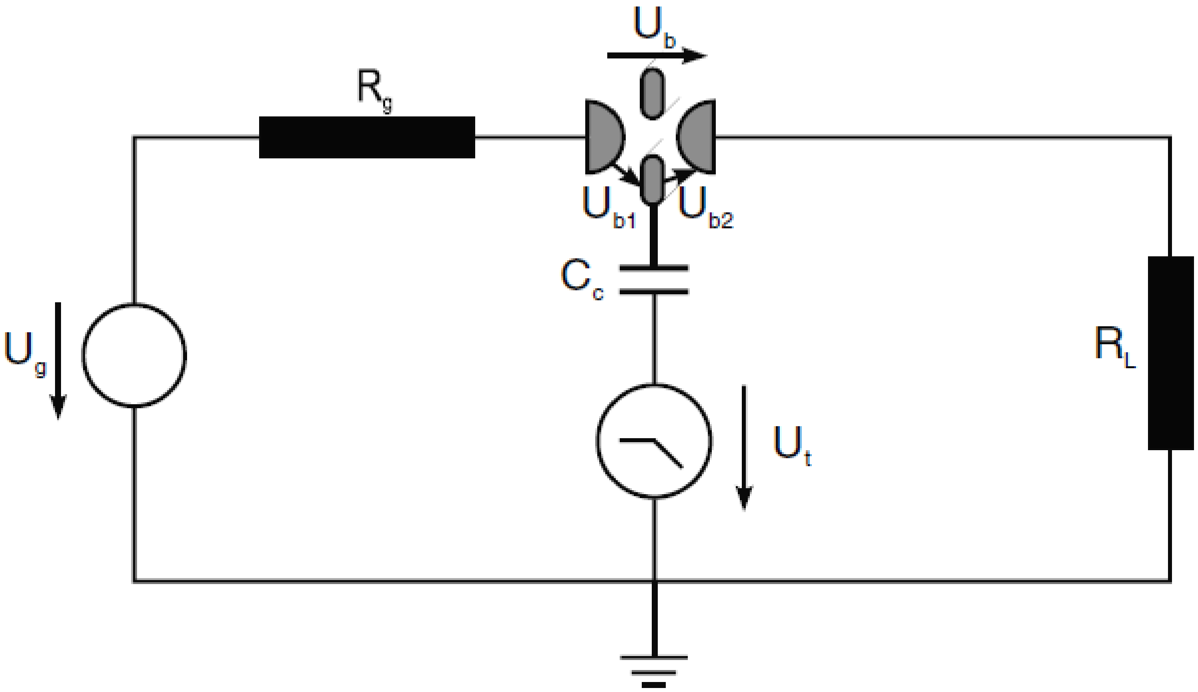
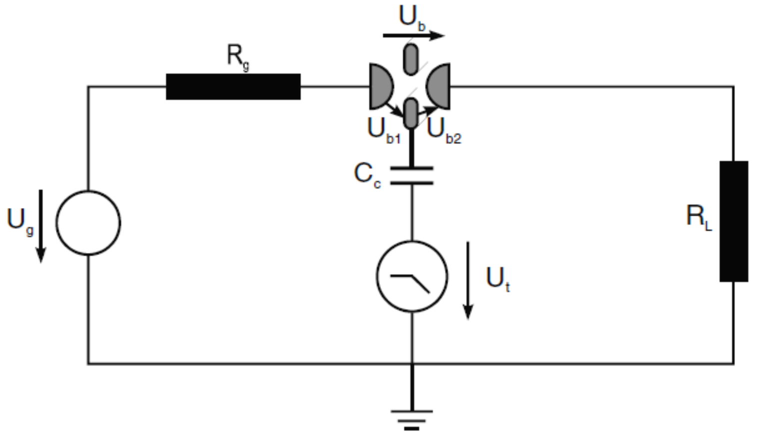
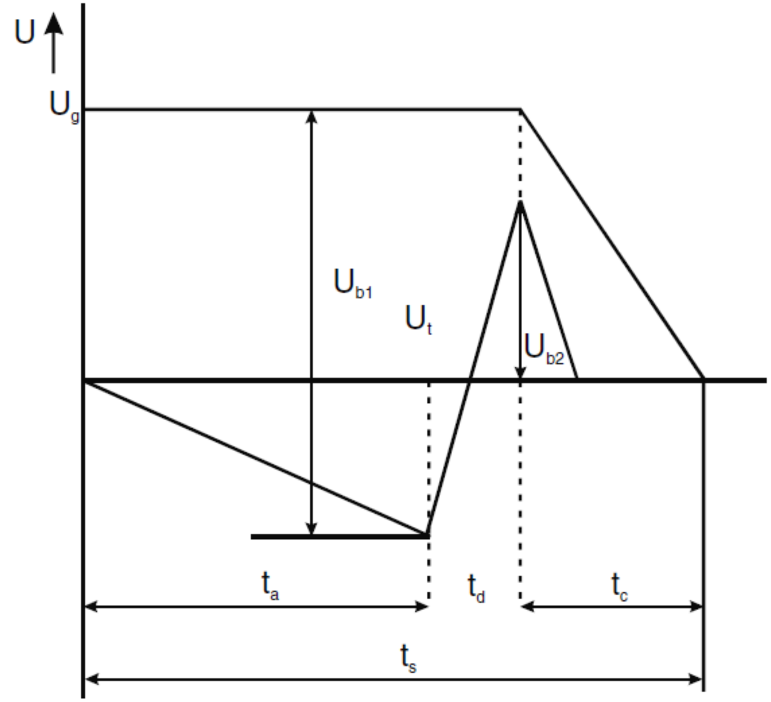
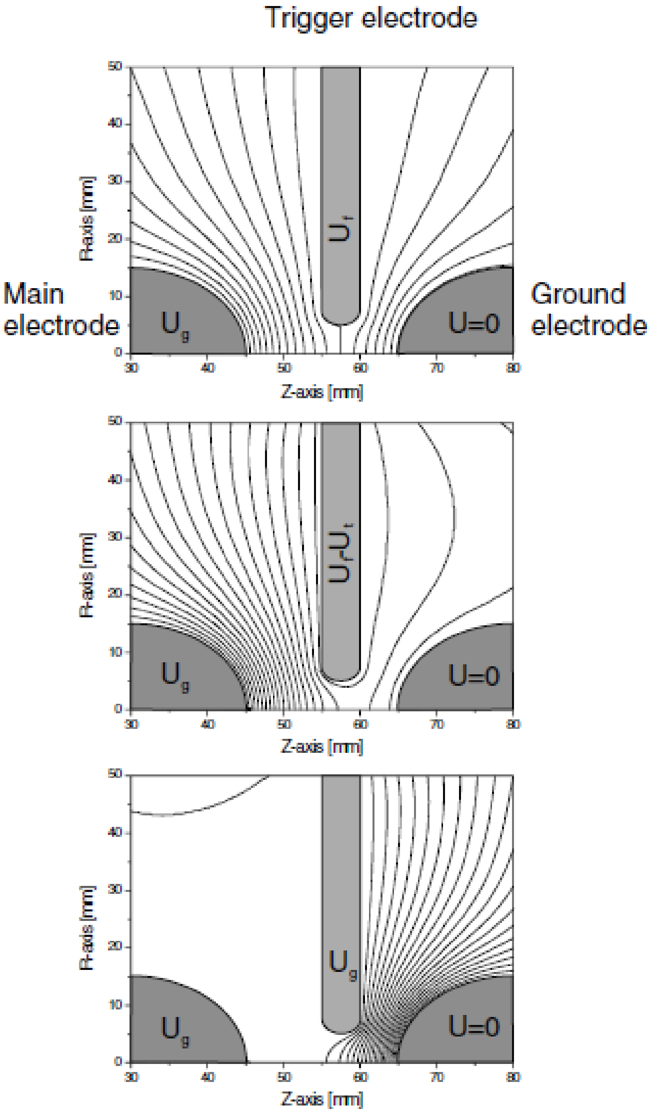


Fig. 4.4. Wiring diagram of a three-electrode spark gap (U_{g} = generator voltage, U_{t} = trigger voltage, U_{b} = breakdown voltage, U_{b1}, U_{b2} = breakdown voltages of the partial gaps, R_{g} = generator impedance, R_{L} = load impedance, C_{c} = coupling capacitor)

Operating principle of three-electrode spark gap







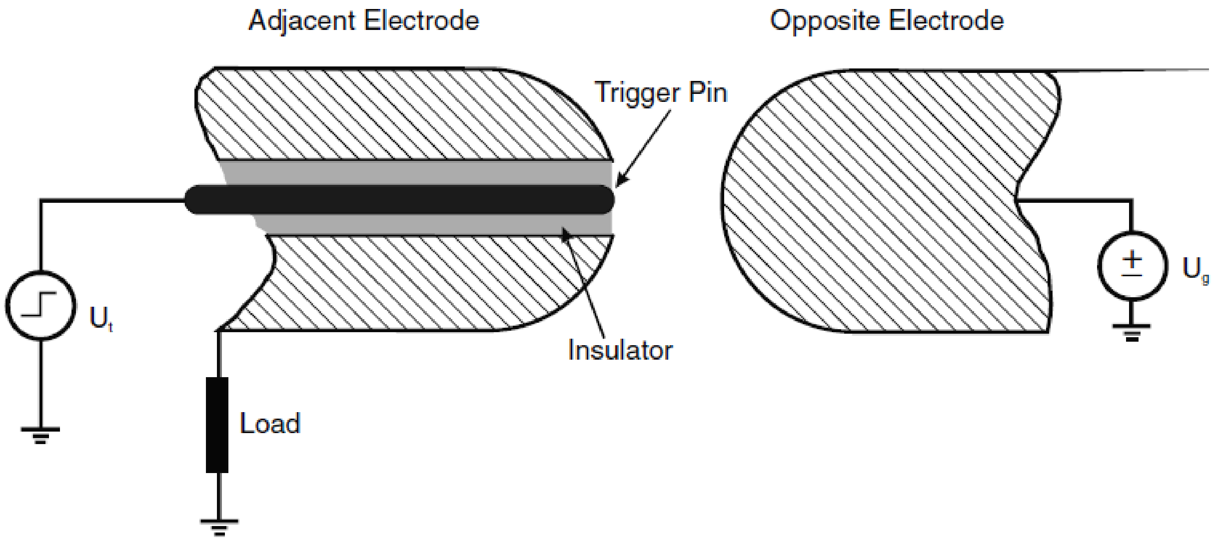
Before ignition

After trigger signal

After breakdown of the first gap

Trigatron spark gap

- Basic principle



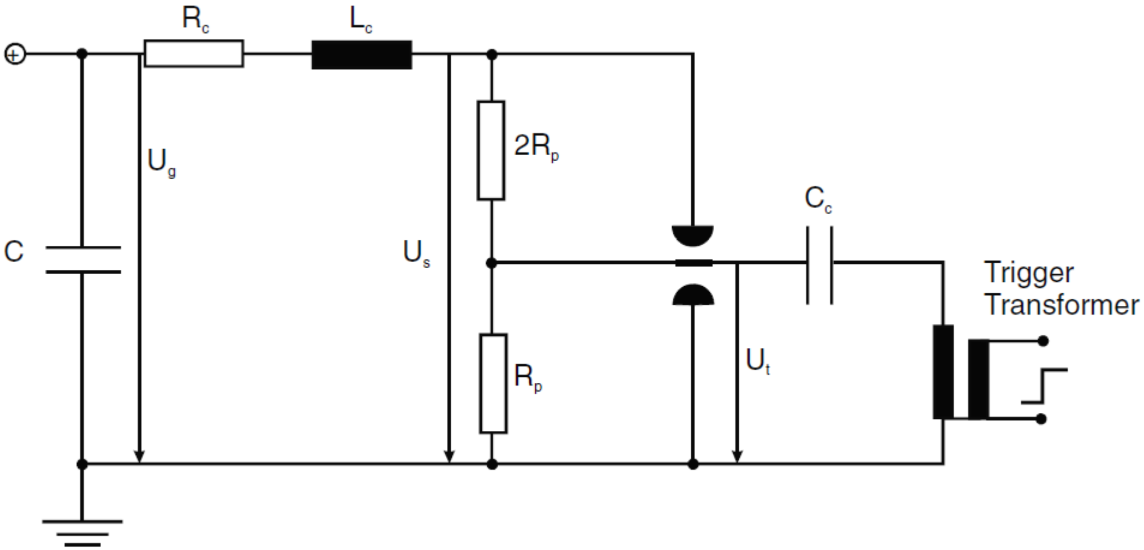
- Upon arrival of the trigger pulse, streamers begin to grow in the vicinity of the trigger pin tip and propagate across the main gap.
- After the streamer has reached the opposite electrode, the applied field causes the ionization density in the channel to grow.
- The gap between the trigger pin and the adjacent main electrode also undergoes a streamer breakdown process.

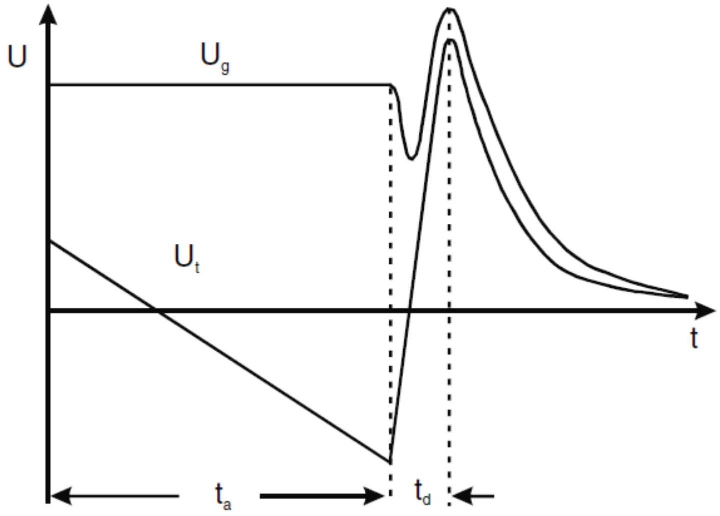
Trigatron switch

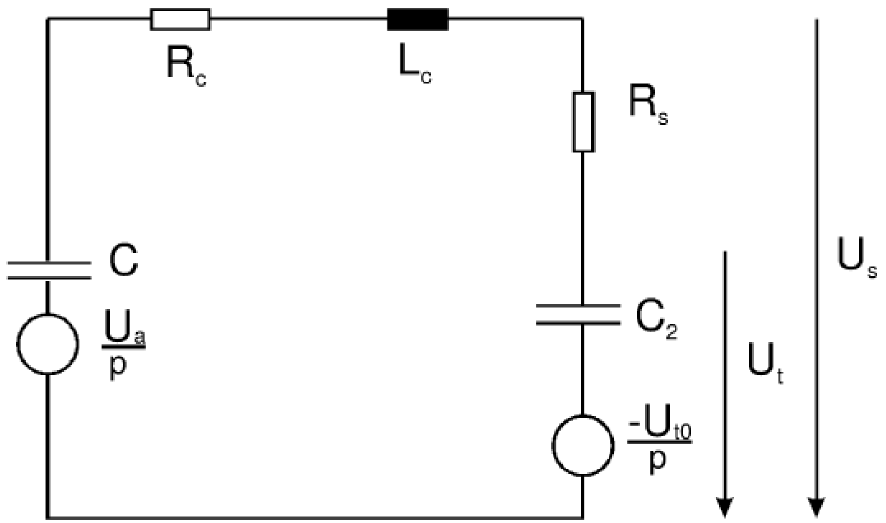
- Characteristics

  - Advantages:
    - ✓ Wide triggering range: the main gap can be readily triggered at charging voltages as low as 25% of the static hold-off voltage.
    - ✓ Good triggering ability: it produces relatively short delay and jitter.
    - ✓ Simple structure: it has a relatively simple structure.
  - Disadvantages:
    - ✓ Trigger generator requirement: it requires a powerful enough generator to produce a fast rising, voltage pulse of magnitude comparable to the main charging voltage.
    - ✓ Electrical isolation of trigger: the trigger circuit is not isolated from the main gap circuit.
    - ✓ Trigger electrode erosion: in high current operations, erosion of the tip of the trigger electrode affects the performance of the triggering.

Analysis of trigger circuit





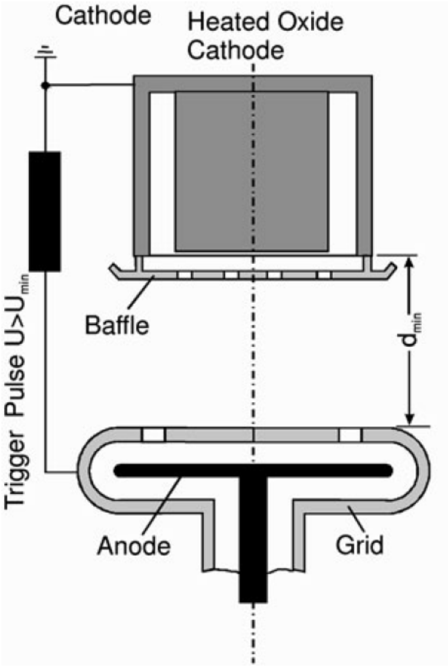


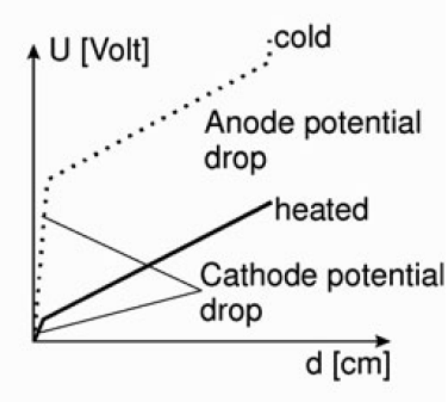
Thyratron

- A thyratron is a type of gas filled tube used as a high energy electrical switch and controlled rectifier. Triode, tetrode and pentode variations of the thyratron have been manufactured in the past, though most are of the triode design.
- A thyratron, especially hydrogen thyratron, emerged from efforts during World War II to develop effective military radar system.
- A thyratron is basically a "controlled gas rectifier". Irving Langmuir and G. S. Meikle of GE are usually cited as the first investigators to study controlled rectification in gas tubes, about 1914.

Thyratron: operating principle

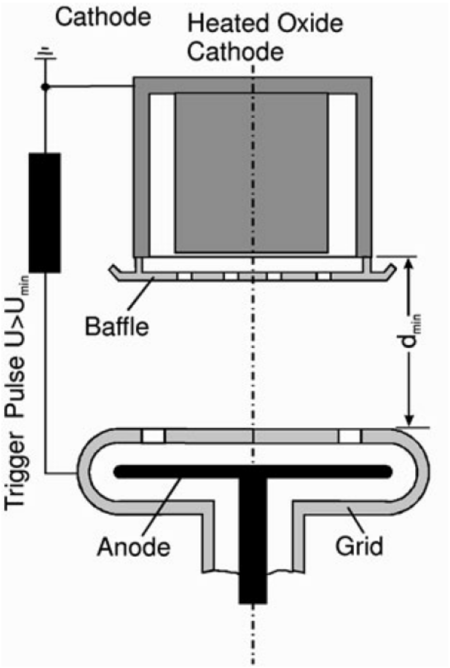
- It operates on the left-hand side of the Paschen minimum.
- The hold-off voltage is limited by field emission, which sets in at fields larger than 10^5 V/cm. Generally, the anode-grid distance is of the order of 2~3 mm, which limits the hold-off voltage to values of around 40 kV.
- The distance between the control grid and the cathode corresponds to the Paschen minimum U_{min} for hydrogen.
- If a trigger pulse of amplitude $U > U_{min}$ is applied to the grid, a glow discharge is initiated between the cathode and the grid.

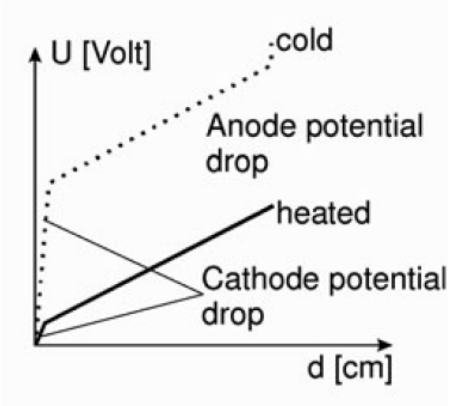




Thyratron: operating principle

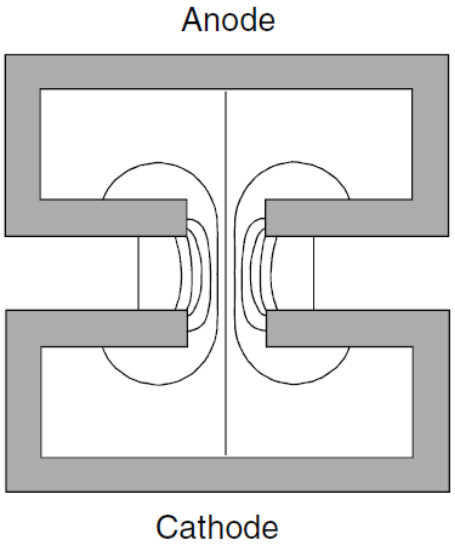
- An essential feature of the thyratron is that it uses a thermal electron source. An important advantage of the hot cathode is the absence of a marked cathode potential drop.
- The function of the baffle, which is maintained at the cathode potential, is to prevent a large number of energetic electrons emitted from the cathode reaching the anode spontaneously which may lead to spurious triggering of the switch.
- The tube is filled with hydrogen gas at the pressure range of about 0.3 to 0.5 Torr and a titanium hydride reservoir is usually employed to maintain the required hydrogen pressure.

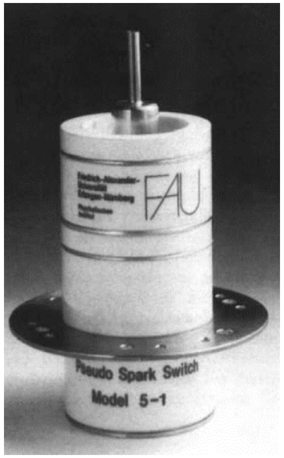




Pseudospark switch

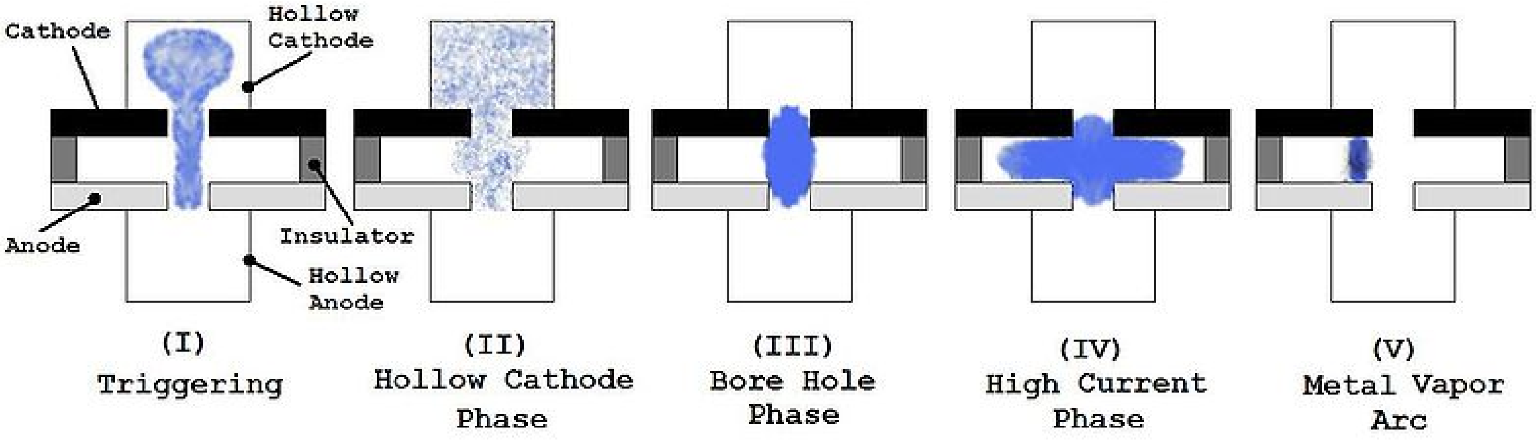
- The pseudospark switch, also known as a cold-cathode thyratron due to the similarities with regular thyratrons, is a gas-filled tube capable of high speed switching.
- Advantages of pseudospark switches include the ability to carry reverse currents (up to 100%), low pulse, high lifetime, and a high current rise of about 10^{12} A/sec.
- Since the cathode is not heated prior to switching, the standby power is approximately one order of magnitude lower than in thyratrons.
- However, pseudospark switches have undesired plasma phenomena at low peak currents. Issues such as current quenching, chopping, and impedance fluctuations occur at currents less than 2-3 kA while at very high peak currents (20-30 kA) a transition to a metal vapor arc occurs which leads to erosion of the electrodes.





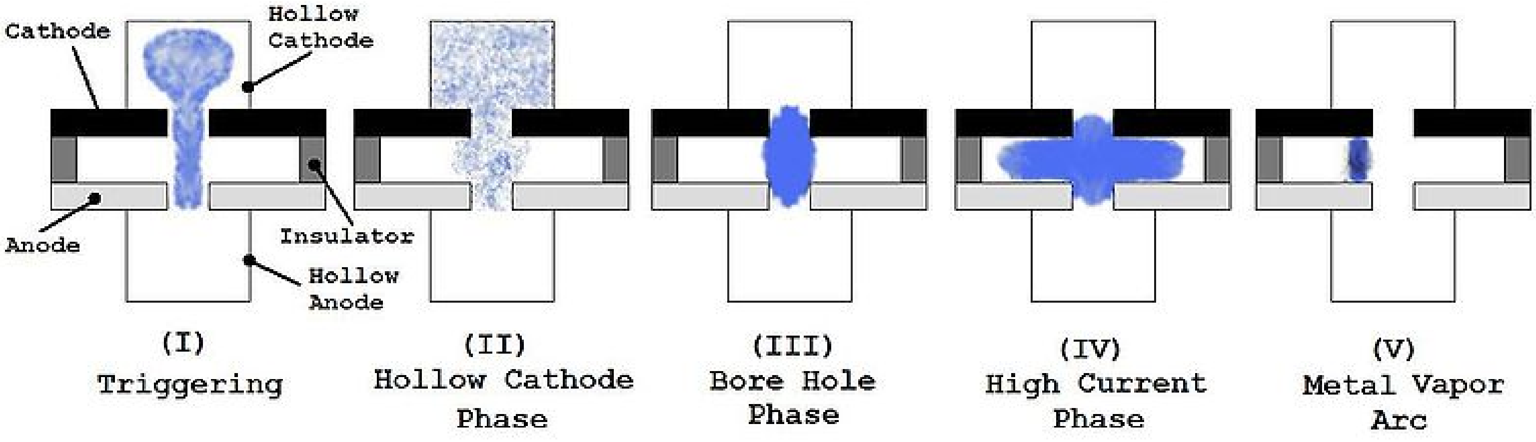
Pseudospark switch: discharge mechanism

- Plasma build-up occurs first inside the hollow cathode, owing to the relatively low E/p values in this region.
- Electrons from the hollow cathode lead to ionization, mainly on the symmetry axis of the arrangement.
- Ions left behind in this region drift back into the hollow cathode, forming a positive space charge (virtual anode) and, finally distorting the static electric field inside the hollow cathode.



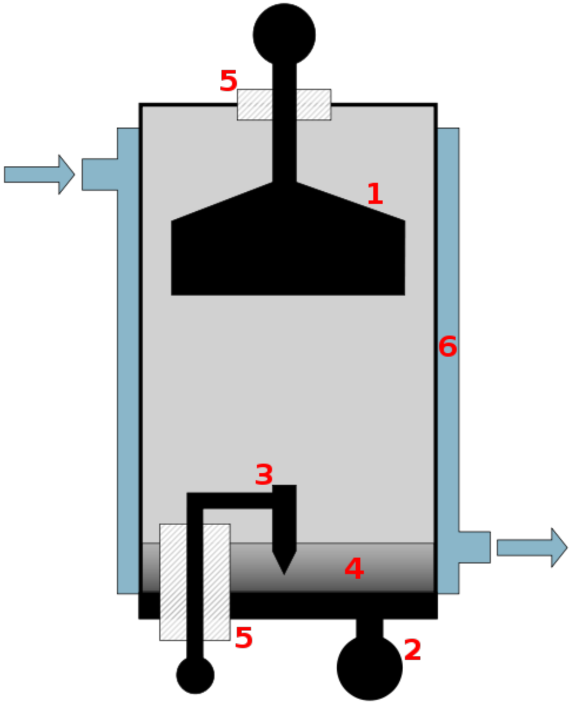
Pseudospark switch: discharge mechanism

- Stage (I) is the triggering or low current phase. The discharges in both stage (II), the hollow cathode phase, and stage (III), the borehole phase, are capable of carrying currents of several hundred amps.
- The transition from the borehole phase to the high current phase (IV) is very fast, characterized by a sudden jump in switch impedance.
- The last phase (V) only occurs for currents of several 10 kA and is unwelcome as it results in high erosion rates.



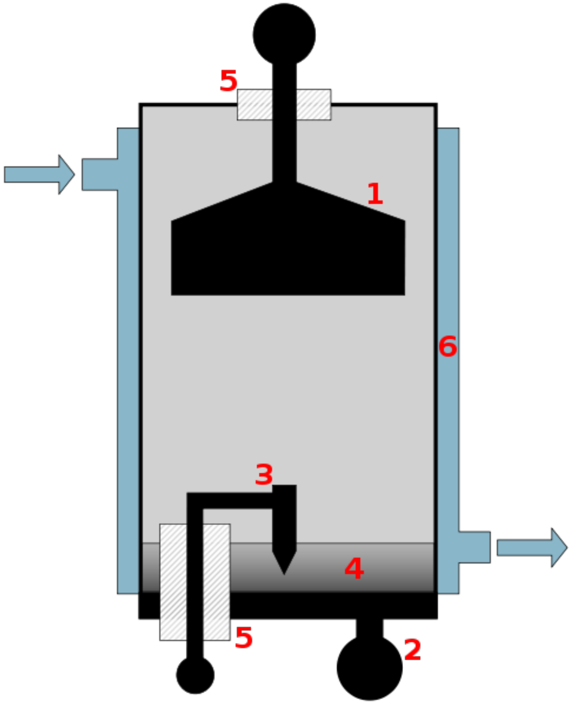
Ignitron switch

- An ignitron is a type of controlled rectifier dating from the 1930s. Invented by Joseph Slepian while employed by Westinghouse.
- An ignitron is a very high-current, high-voltage switch with a liquid mercury pool cathode (4) and an ignitor pin (3) dipping into the liquid-metal reservoir.
- It is usually a large steel container (6) with a pool of mercury in the bottom that acts as a cathode during operation.
- A large graphite or refractory metal cylinder, held above the pool by an insulated electrical connection (5), serves as the anode (1).



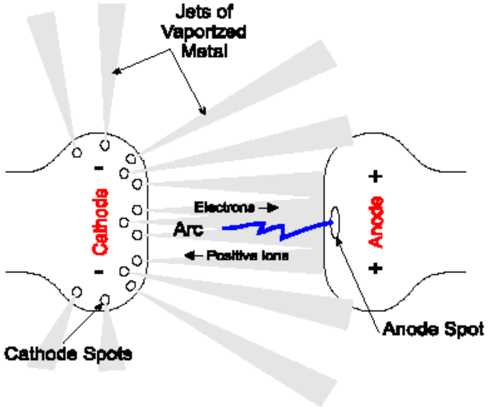
Ignitron switch

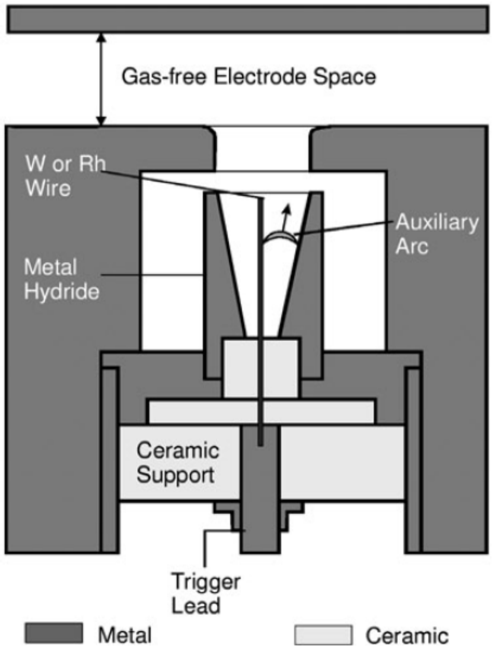
- An igniting electrode (called the "ignitor"), made of a refractory semiconductor material such as silicon carbide, is briefly pulsed with a high current to create a puff of electrically conductive mercury plasma.
- The plasma rapidly bridges the space between the mercury pool and the anode, permitting heavy conduction between the main electrodes.
- At the surface of the mercury, heating by the resulting arc liberates large numbers of electrons which help to maintain the mercury arc.



TVS (triggered vacuum switch)

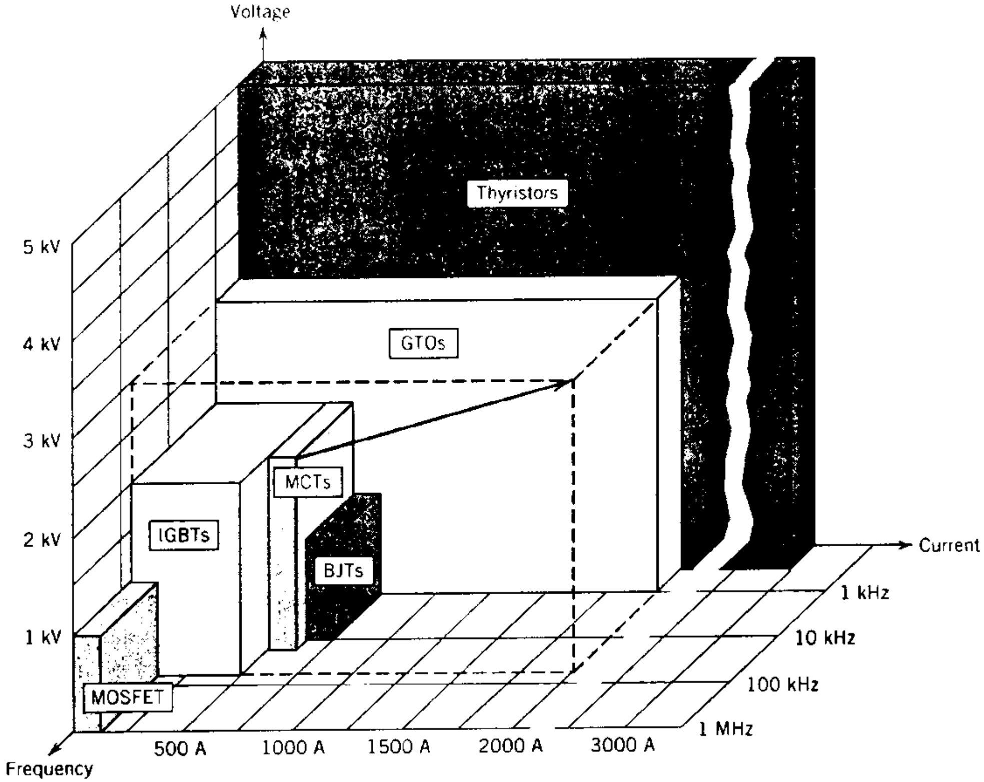
- The TVS is a three-electrode system pumped down to 0.001 Pa.
- It is closed by injection of a plasma cloud.
- The hold-off voltage depends only on the properties of the electrode surfaces.
- Currents of up to 10 kA can be switched at voltages of up to 100 kV.
- The jitter of the TVS is the order of 30 ns, and the switching time is around 100 ns.
- Small dimension, no need of heating.
- Lifetime is limited due to erosion





Solid-state switches

- With progresses in power electronics, the solid-state devices (thyristors, IGBTs, MOSFETs) are rapidly replacing the conventional gas switches in pulsed power engineering.

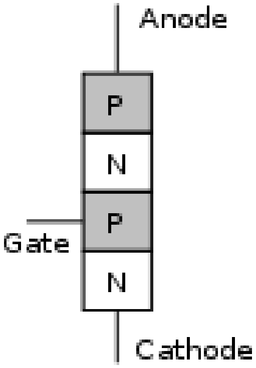


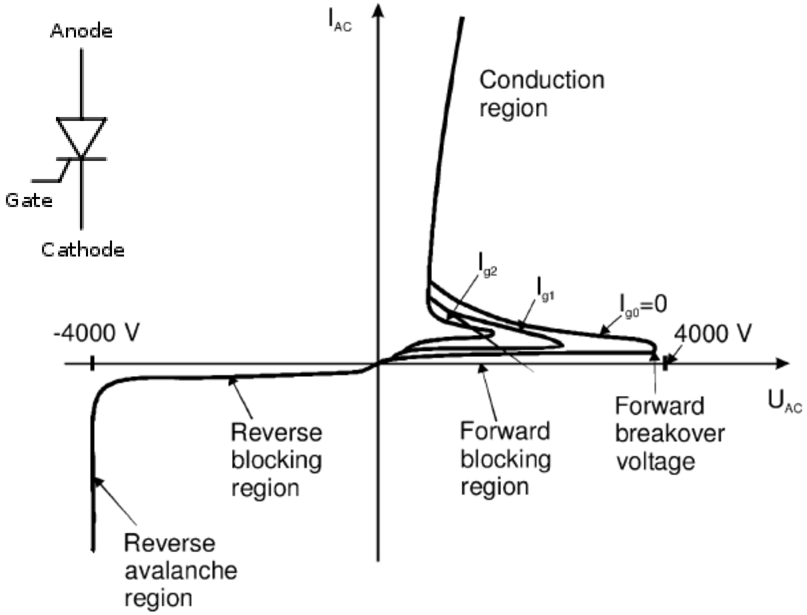
- Power Diode
- BJT (Bipolar Junction Transistor)
- MOSFET (Metal Oxide Semiconductor Field Effect Transistor)
- Thyristor
- GTO (Gate Turn-off Thyristor)
- IGBT (Insulated Gate Bipolar Transistor)

N. Mohan, et al.," Power Electronics" (1995)

Thyristor (SCR, silicon-controlled rectifier)

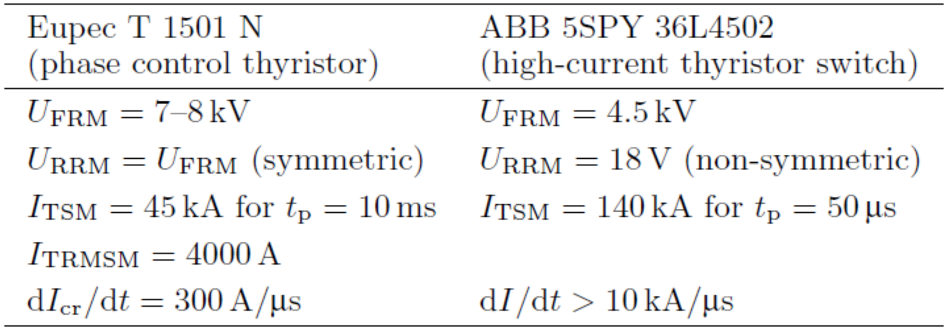
- The thyristor is a four-layer, three terminal semiconducting device, with each layer consisting of alternately N-type or P-type material, for example P-N-P-N.
- The main terminals, labeled anode and cathode, are across the full four layers, and the control terminal, called the gate, is attached to p-type material near to the cathode.
- The operation of a thyristor can be understood in terms of a pair of tightly coupled bipolar junction transistors, arranged to cause the self-latching action.





Thyristor for pulsed power (high di/dt)

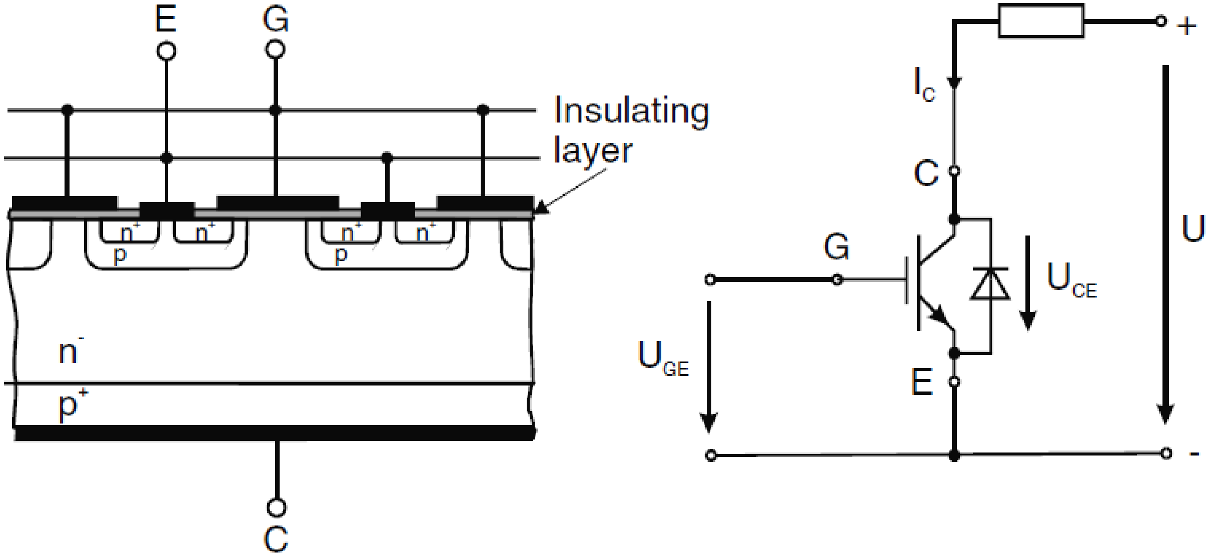
- Laser triggered thyristor
- Gate turn-off (GTO) thyristor



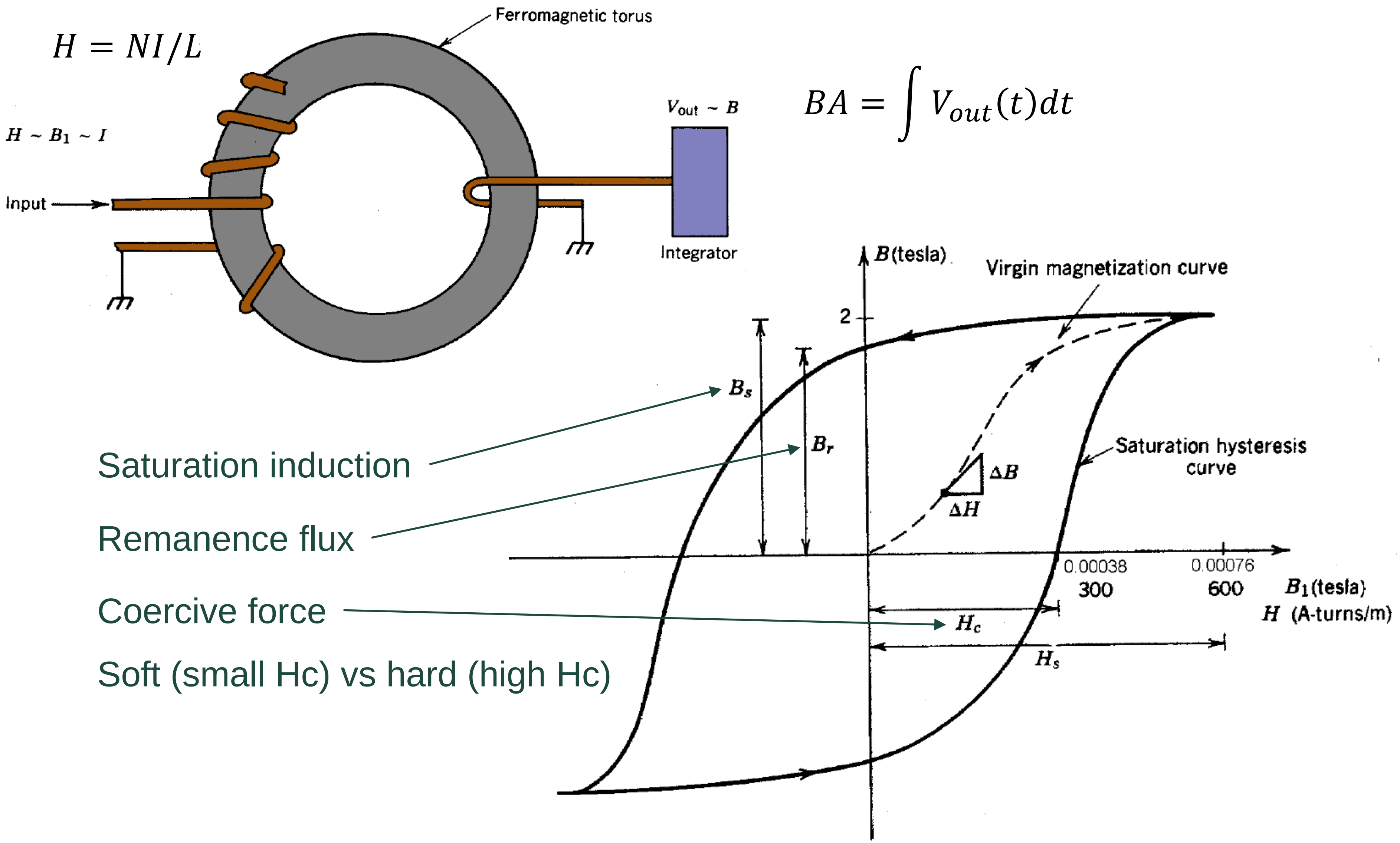
Eupec T 1501 N (phase control thyristor)	ABB 5SPY 36L4502 (high-current thyristor switch)
$U_{\mathrm{FRM}} = 7$–$8\,\mathrm{kV}$	$U_{\mathrm{FRM}} = 4.5\,\mathrm{kV}$
$U_{\mathrm{RRM}} = U_{\mathrm{FRM}}$ (symmetric)	$U_{\mathrm{RRM}} = 18\,\mathrm{V}$ (non-symmetric)
$I_{\mathrm{TSM}} = 45\,\mathrm{kA}$ for $t_{\mathrm{p}} = 10\,\mathrm{ms}$	$I_{\mathrm{TSM}} = 140\,\mathrm{kA}$ for $t_{\mathrm{p}} = 50\,\mu\mathrm{s}$
$I_{\mathrm{TRMSM}} = 4000\,\mathrm{A}$	
$\mathrm{d}I_{\mathrm{cr}}/\mathrm{d}t = 300\,\mathrm{A}/\mu\mathrm{s}$	$\mathrm{d}I/\mathrm{d}t > 10\,\mathrm{kA}/\mu\mathrm{s}$

IGBT

- The insulated-gate bipolar transistor (IGBT) combines the advantages of bipolar transistors (low resistance in the switch-on state) with those of field effect transistors (loss-free gate control).
- They can easily be arranged in parallel configurations and can easily be switched off.



Static hysteresis curve for ferromagnetic materials



$$H = NI/L$$

$$BA = \int V_{out}(t)dt$$

Saturation induction

Remanence flux

Coercive force

Soft (small Hc) vs hard (high Hc)

Advantage of including ferromagnetic material

- The ampere turn product is related to the magnetic field in the circuit through:

$$\int \left(\frac{B}{\mu}\right) \cdot dl = NI$$

- The constant circuit flux is given by

$$\Psi = B_g A_g = B_c A_c$$

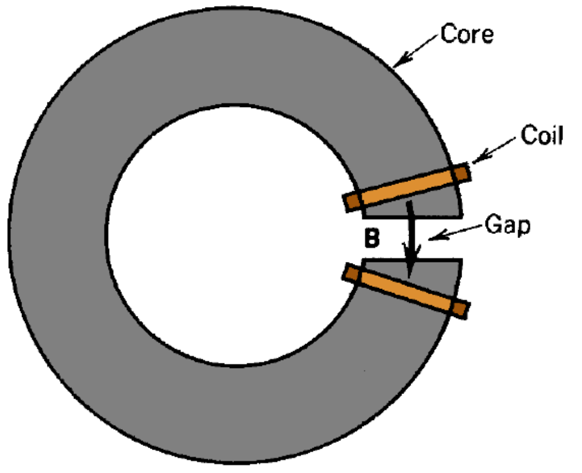
- For the air core circuit:

$$B_g\left(\frac{g}{\mu_0}\right) + B_c\left(\frac{l}{\mu_0}\right) = \Psi\left(\frac{g}{A_g\mu_0} + \frac{l}{A_c\mu_0}\right) = NI$$

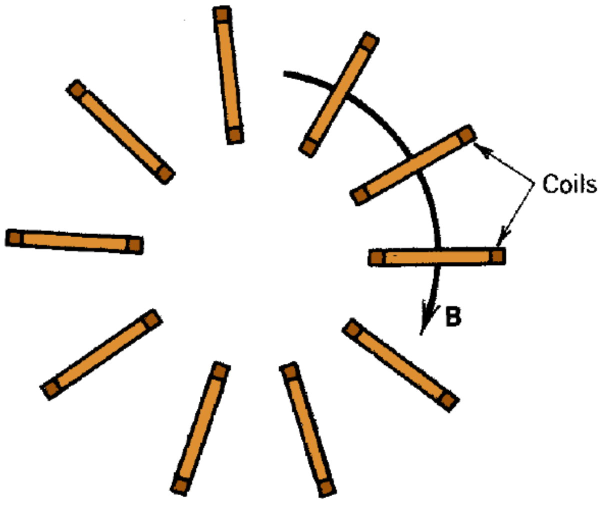
- For the ferromagnetic core circuit:

$$B_g\left(\frac{g}{\mu_0}\right) + B_c\left(\frac{l}{\mu}\right) = \Psi\left(\frac{g}{A_g\mu_0} + \frac{l}{A_c\mu}\right) = NI$$

Reluctance of the air gap Reluctance of iron core



(a)



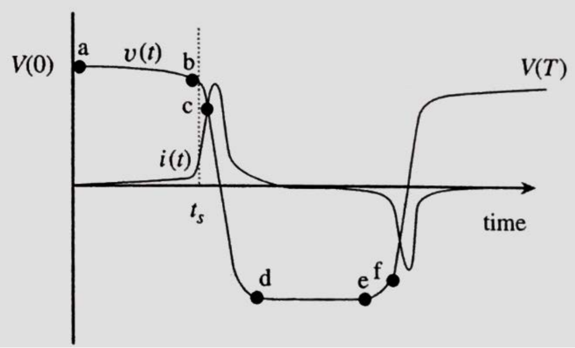
(b)

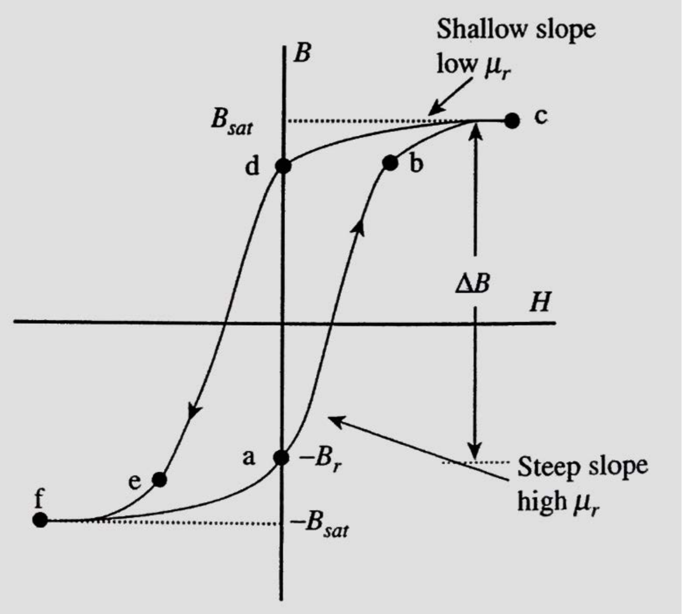
Magnetic switch

- Melville (1951) exploits the use of the nonlinearity of inductors to achieve fast switching in pulse generators.
- The basic concept is to drive sufficient current through a winding on a magnetic core such that the applied field H produces a flux density B in the core in excess of the core's saturation flux.
- In doing so, the inductance of the winding changes from a relatively high value to a very low value and the inductor behaves as a magnetic switch.

$$V(t) = N\frac{d\phi}{dt}$$

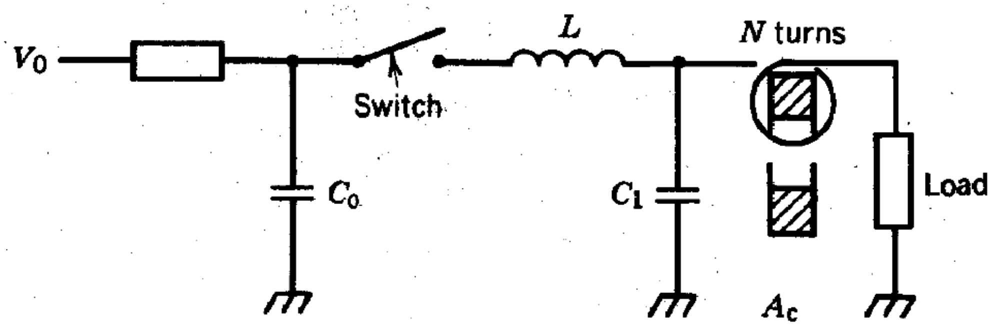
$$\Delta B = \frac{1}{NA}\int_0^{t_p} V_p(t)dt \approx \frac{V_p t_p}{NA}$$

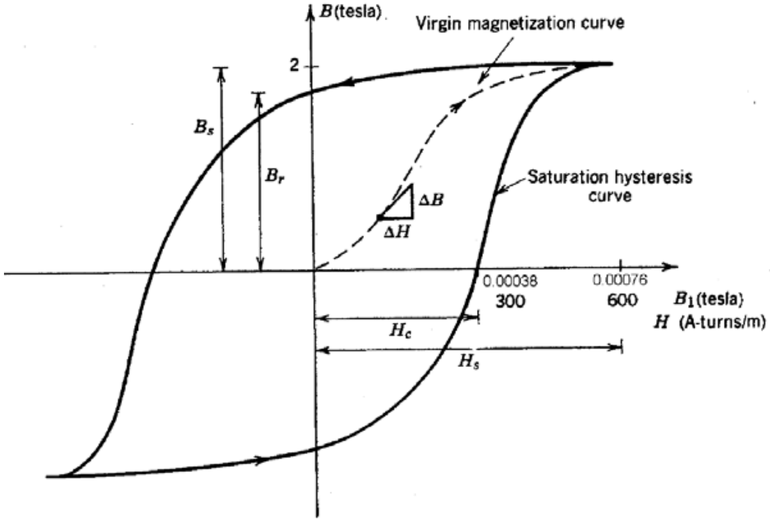




Magnetic switching with peaking capacitor

- A two-stage power compression circuit





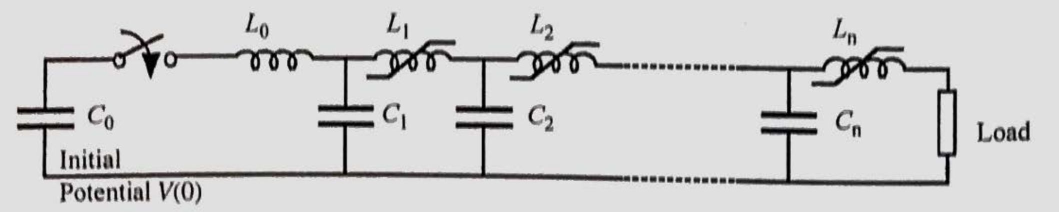
- At early times, the right-hand portion of the circuit is approximately an open circuit because of the high inductance of the winding around the high μ core. Energy flows from C_0 to C_1.
- The core reaches saturation when

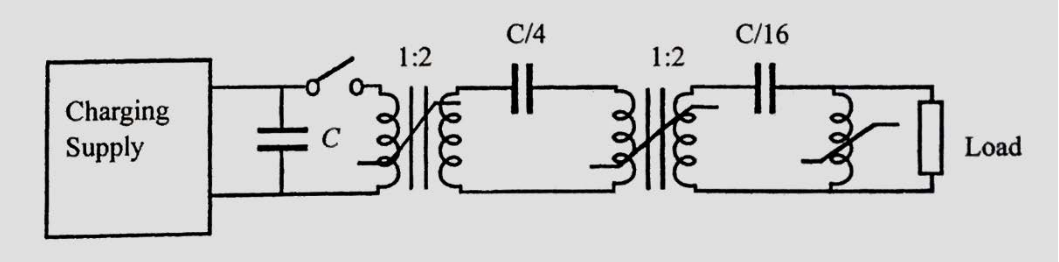
$$\int V_1(t)dt = NA_c(B_s + B_r) \qquad \Longleftarrow \qquad V_1(t) = NA_c\frac{dB}{dt}$$

- After saturation, the inductance L_2 decreases by a large factor, approaching the vacuum inductance of the winding. The transition from high to low inductance is a bootstrapping process that occurs rapidly.

Magnetic pulse compression

- On switch closure the capacitor C_0, initially charged to a potential V(0), is discharged through the inductor L_0 into capacitor C_1.
- As the potential on C_1 rises a point is reached at which the first magnetic switch L_1 will saturate. C_1 then discharges rapidly into capacitor C_2.
- This process continues until C_n discharges into the load.

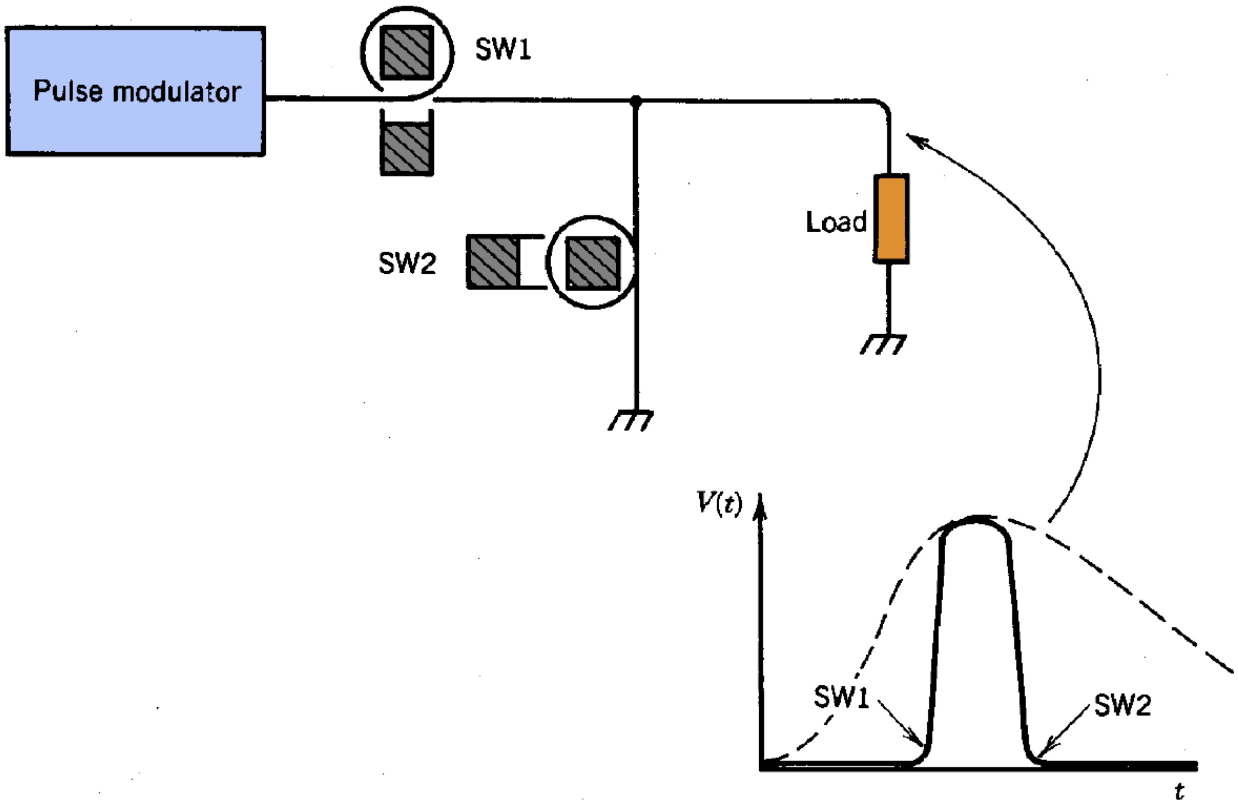




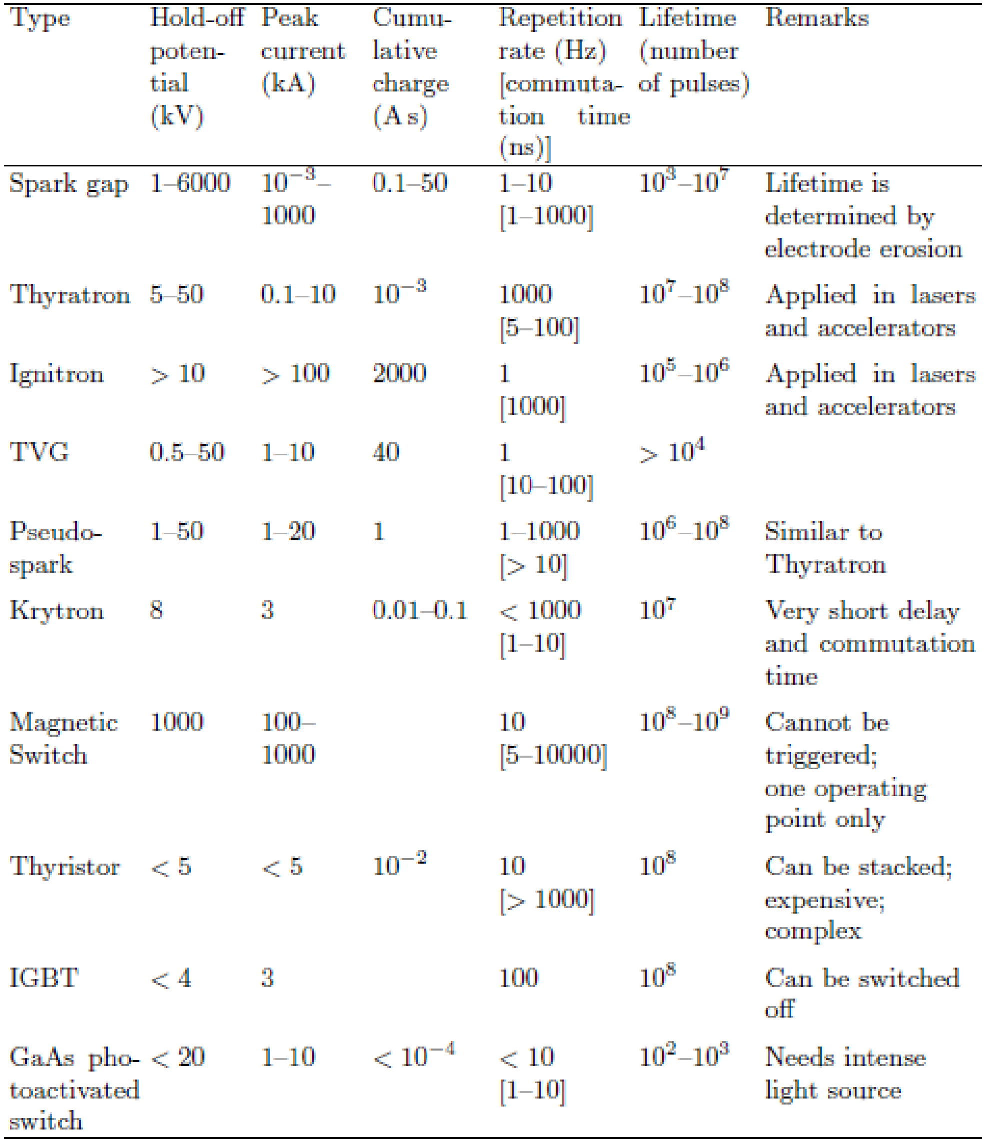
Using saturable transformer

Pulse shaping with saturable core magnetic switches

- Saturable core inductors can also be used for pulse length shortening and rise time sharpening if efficiency is not a prime concern.
- The following circuit can produce a short, fast-rising voltage pulse from a slow pulse generator.



Summary of closing switches



Type	Hold-off potential (kV)	Peak current (kA)	Cumulative charge (A s)	Repetition rate (Hz) [commutation time (ns)]	Lifetime (number of pulses)	Remarks
Spark gap	1–6000	10^{-3}–1000	0.1–50	1–10 [1–1000]	10^{3}–10^{7}	Lifetime is determined by electrode erosion
Thyratron	5–50	0.1–10	10^{-3}	1000 [5–100]	10^{7}–10^{8}	Applied in lasers and accelerators
Ignitron	> 10	> 100	2000	1 [1000]	10^{5}–10^{6}	Applied in lasers and accelerators
TVG	0.5–50	1–10	40	1 [10–100]	$> 10^{4}$	
Pseudo-spark	1–50	1–20	1	1–1000 [> 10]	10^{6}–10^{8}	Similar to Thyratron
Krytron	8	3	0.01–0.1	< 1000 [1–10]	10^{7}	Very short delay and commutation time
Magnetic Switch	1000	100–1000		10 [5–10000]	10^{8}–10^{9}	Cannot be triggered; one operating point only
Thyristor	< 5	< 5	10^{-2}	10 [> 1000]	10^{8}	Can be stacked; expensive; complex
IGBT	< 4	3		100	10^{8}	Can be switched off
GaAs photoactivated switch	< 20	1–10	$< 10^{-4}$	< 10 [1–10]	10^{2}–10^{3}	Needs intense light source