PULSED POWER SYSTEM
脈衝功率系統

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2023 Fall Semester

Tuesday 9:10-12:00

Lecture 7

http://capst.ncku.edu.tw/PGS/index.php/teaching/

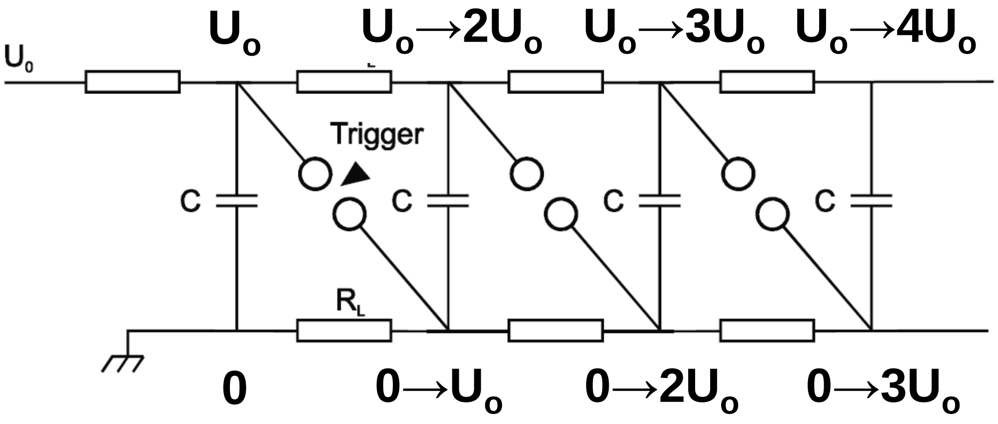
Online courses:

https://nckucc.webex.com/nckucc/j.php?MTID=md577c3633c5970f80cbc9e821927e016

2023/10/24 updated

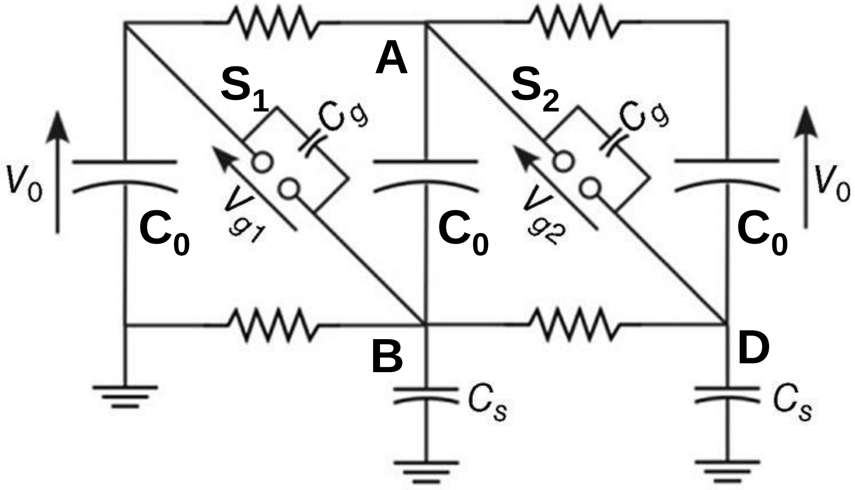
Requirements of triggering the Marx generator

- **Triggering the Marx generator means starting the erosion process by external-command control at a preselected instant in time.**
  - **Small jitter.**
  - **Low prefire probability.**
  - **Large operating range.**
- **First stage – triggable three-electrode spark-gap switch.**
- **Later stage – self-breaking spark-gap switch.**

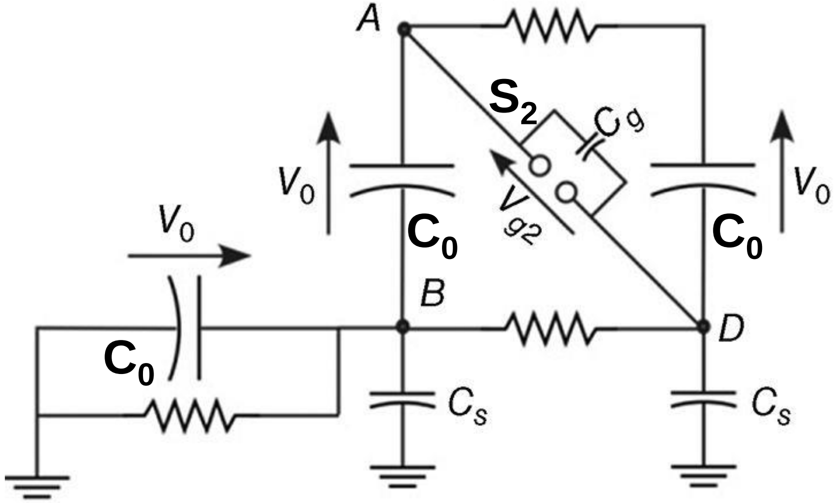


Stray capacitors needed to be considered

- **Charging cycle:**



- **After the first stage has fired:**



C_S: between the stage capacitors and ground.
C_g: between the switch electrodes.

- **Assumption: (1) each capacitor is charged to V_0; (2) S_1 is triggered first.**

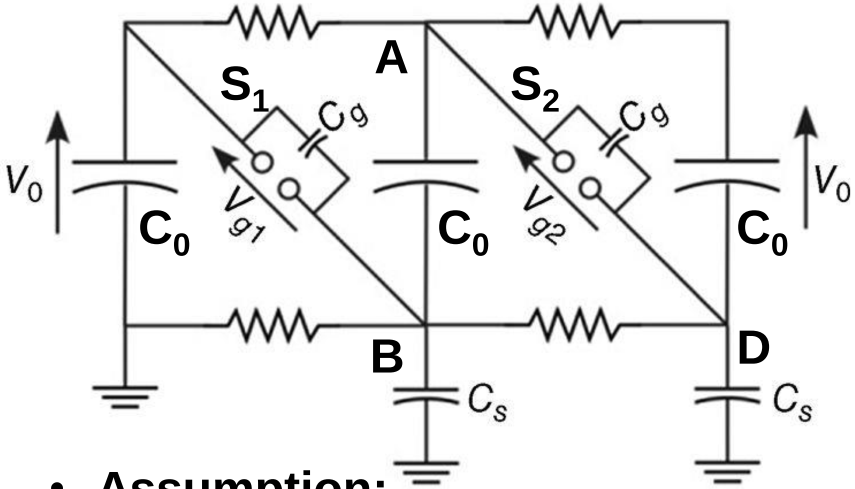
=> C_S @ B try to hold B to ground.

=> C_0 >> C_S, so C_S is charged to V_0 rapidly.

=> A → 2V0 => S_2 will fire only if it is over voltaged sufficiently long.

Stray capacitors needed to be considered

- **Charging cycle:**



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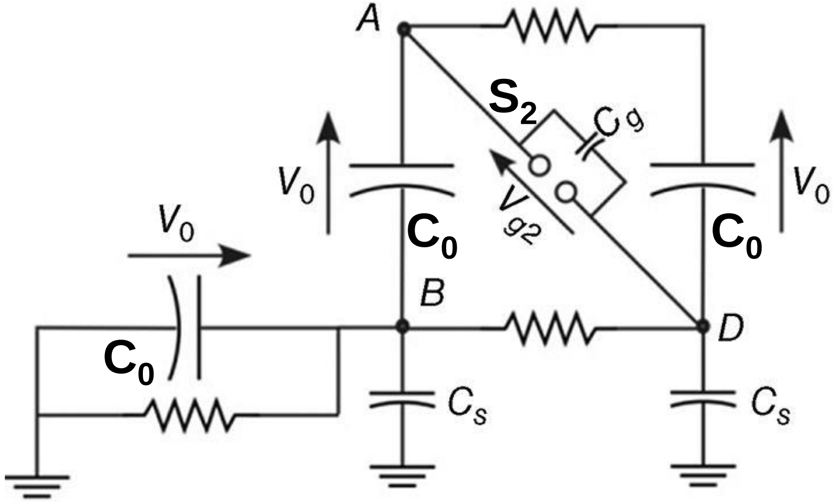


- **Assumption:**

=> A → 2V0 => S$_2$ will fire only if it is overvoltaged sufficiently long.

=> C$_g$ @ S$_2$ and C$_S$ @ D form a capacitive voltage divider.

$$V_A = 2V_0 \qquad V_D = 2V_0\frac{C_g}{C_S + C_g} \qquad V_{S2} = V_A - V_D = 2V_0\frac{C_S}{C_S + C_g} = \frac{2V_0}{1 + C_g/C_S}$$

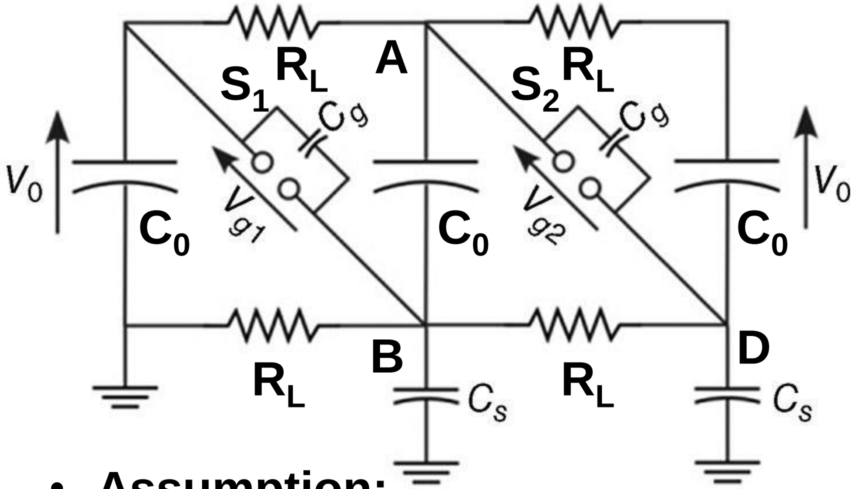
=> C$_g$/C$_S$ needs to be sufficiently small.

=> placing a ground conducting plate closed to the case of the storage capacitor.

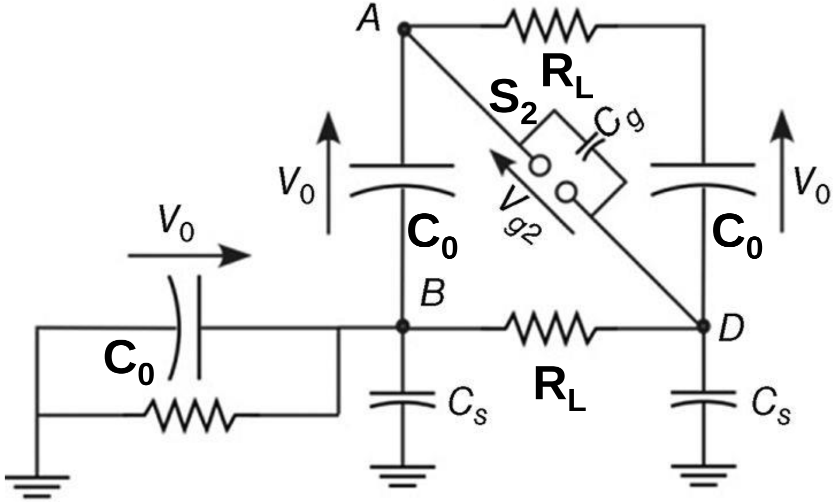
$$C = \epsilon\frac{A}{d}$$

Stray capacitors needed to be considered

- Charging cycle:



- After the first stage has fired:



- Assumption:

=> $V_B = V_0$ $\quad V_D = 2V_0 \dfrac{c_g}{C_S + C_g} \approx 0 \rightarrow V_D = V_0$, CS @ D is charged by V_B through R_L with a time constant of $\tau = \frac{1}{2} R_L C_S$

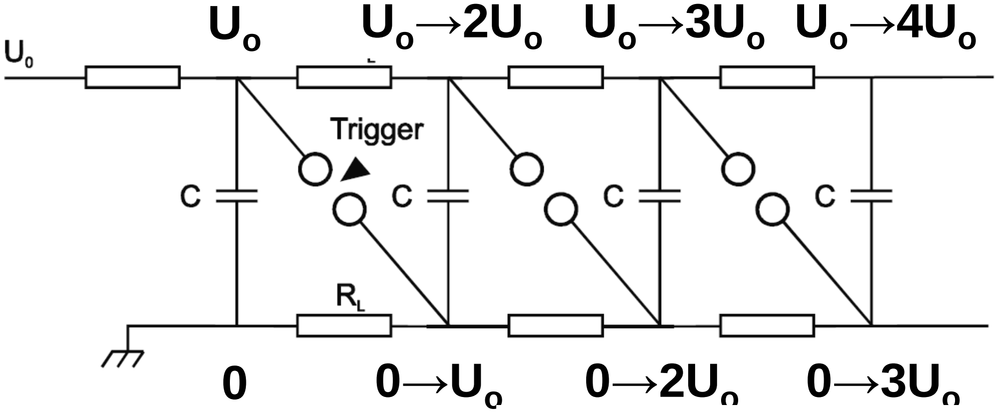
=> overvoltage across switch S2 drops to V0.

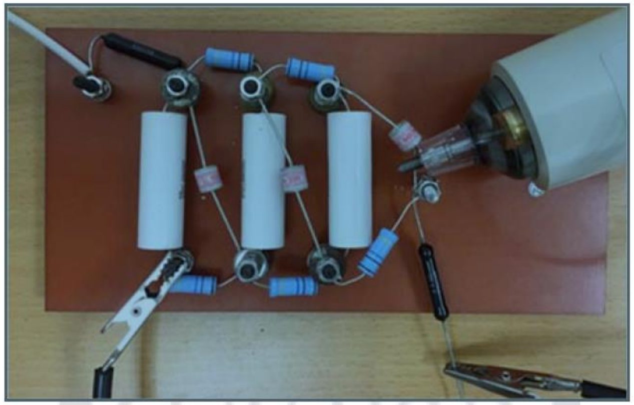
=> breakdown at an overvoltage across each switch with a delay time less than τ is needed.

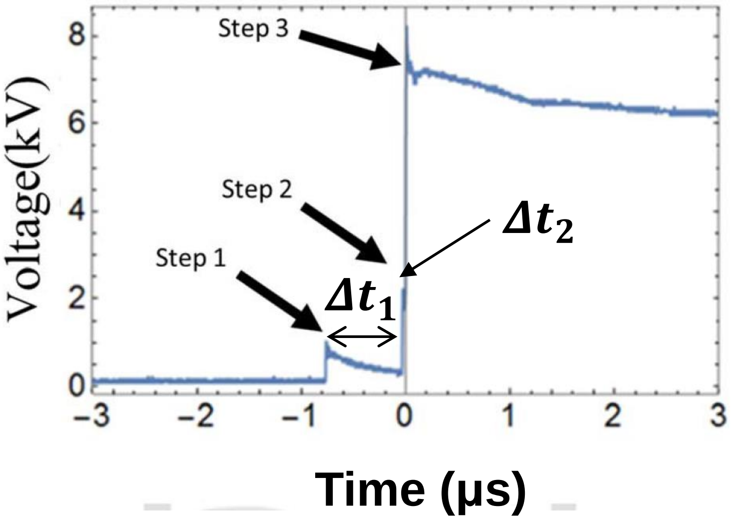
The delay between breakdown in each spark gap becomes shorter and shorter

- ∵ overvoltage becomes increasingly large,

  ∴ easier and easier to breakdown the other spark gaps.



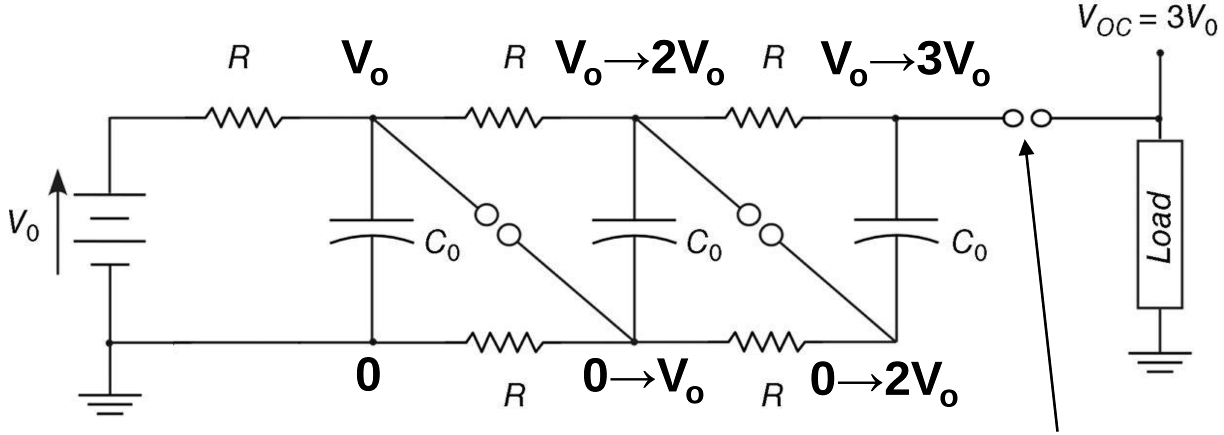




M.-F. Huang, Master Thesis, ISAPS 2017

Positive vs Negative output and peaking switch

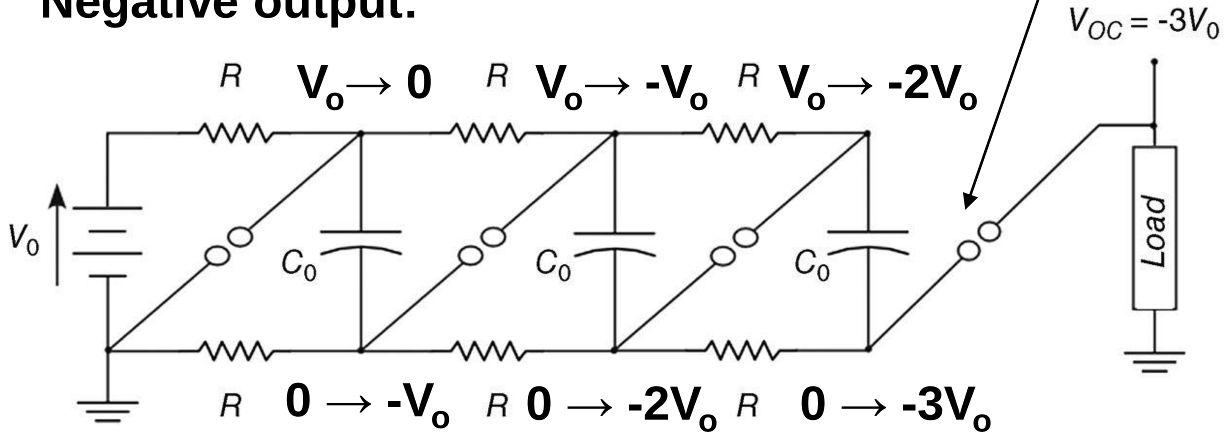
- **Positive output:**



(a)

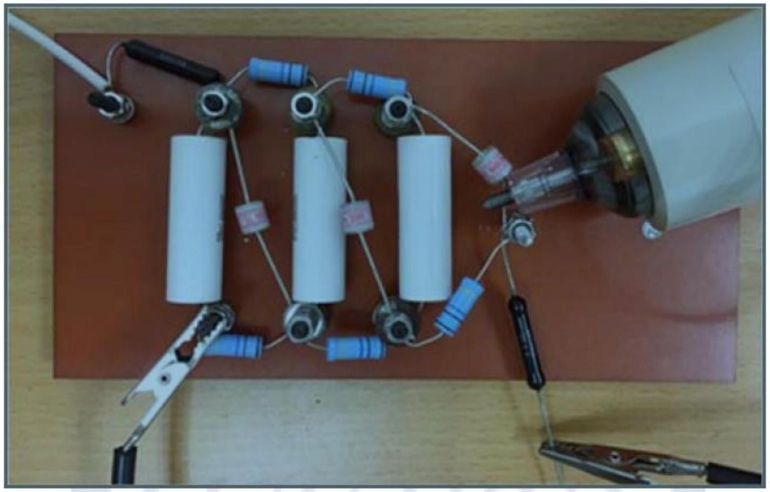
Peaking switch

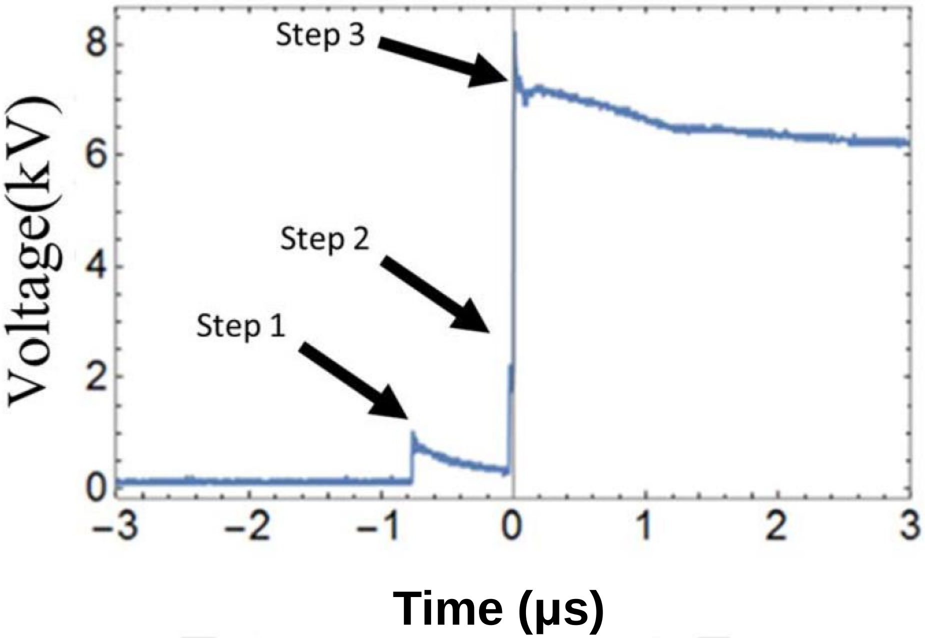
- **Negative output:**



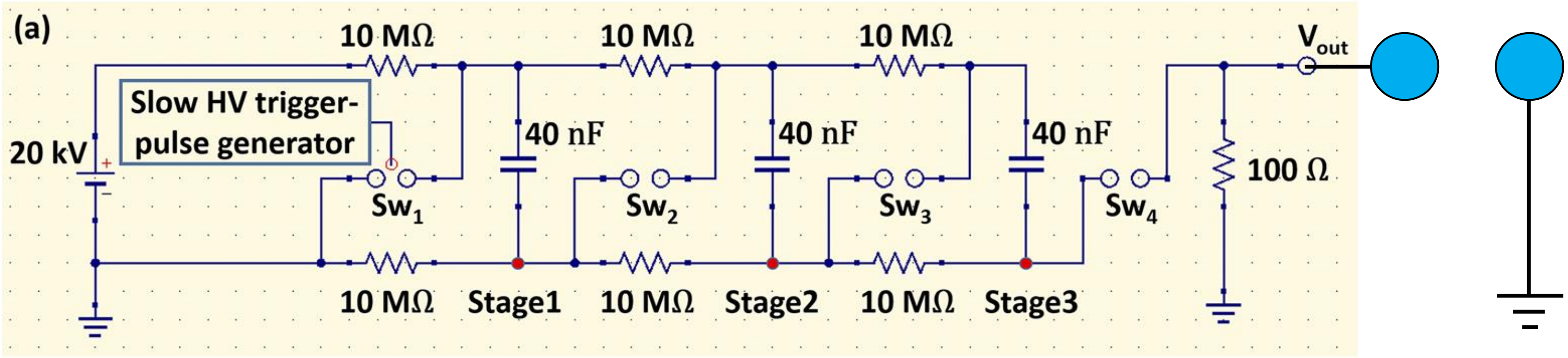
(b)

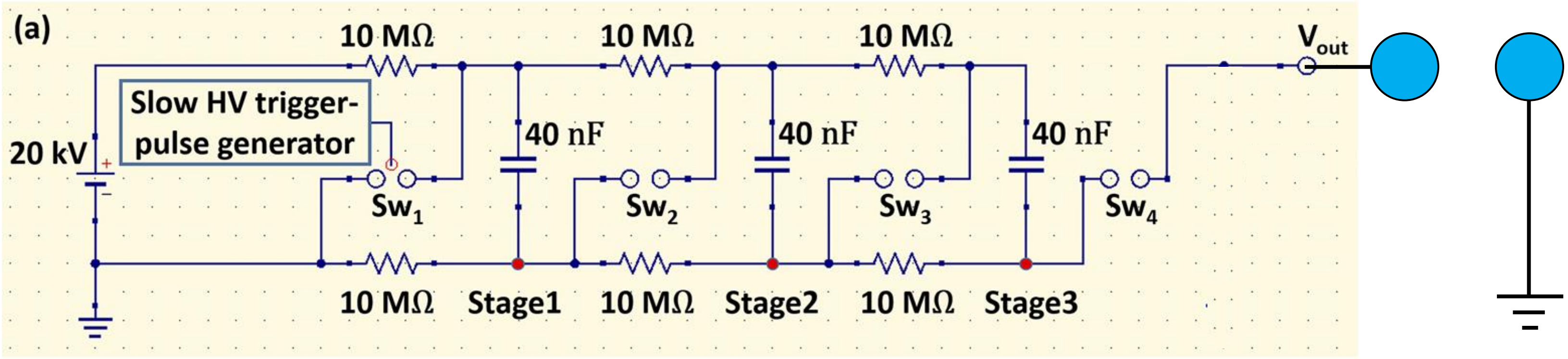
Step output of a Marx generator



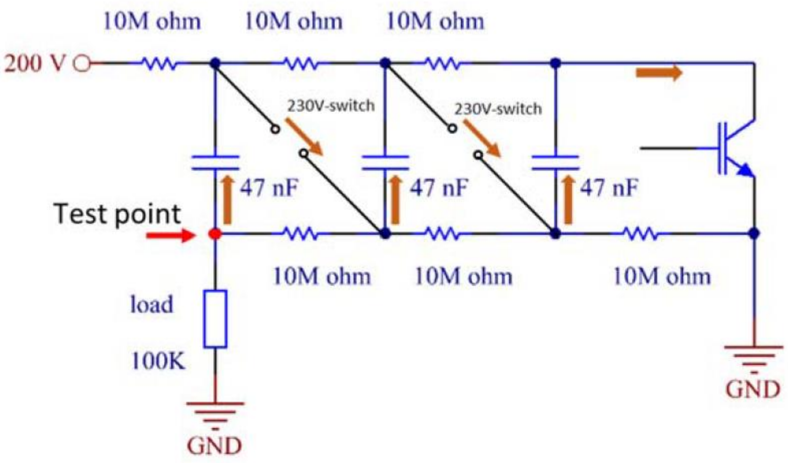


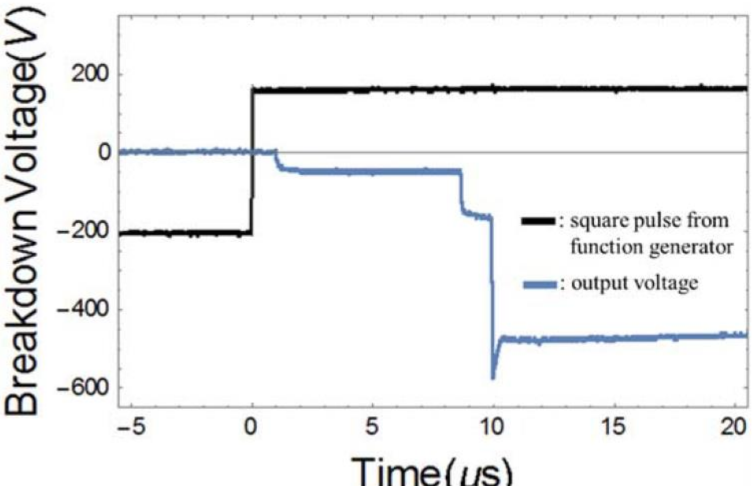
A grounding resistor is needed if a load is a “gap”

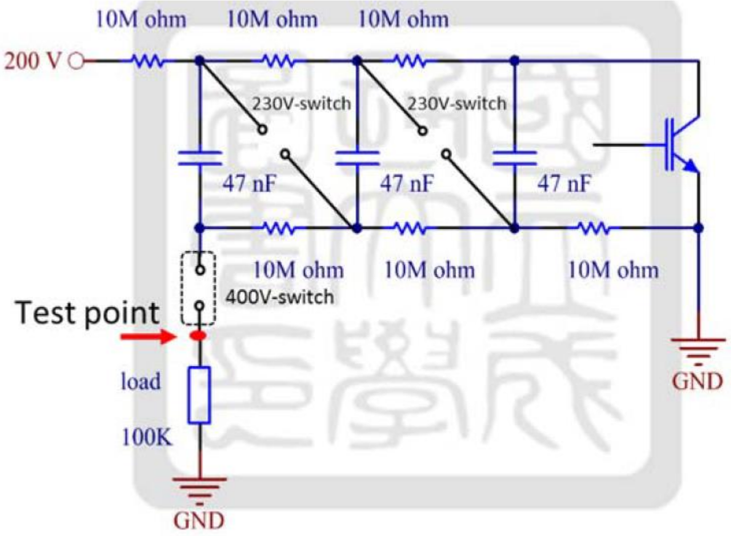


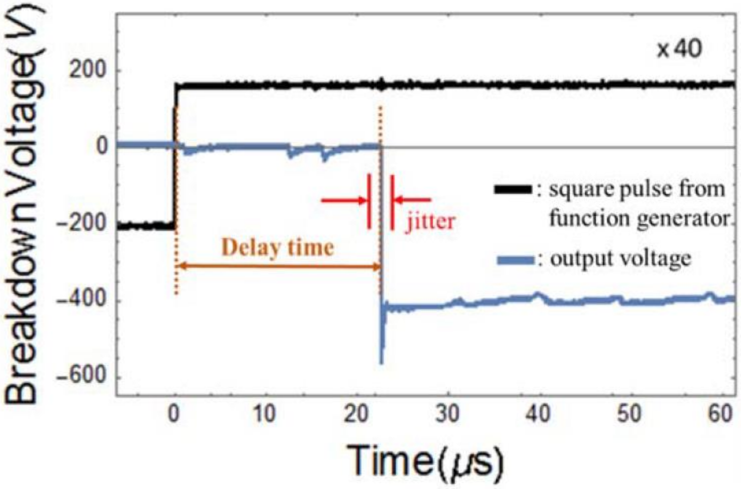


Step output is removed with using a peaking switch

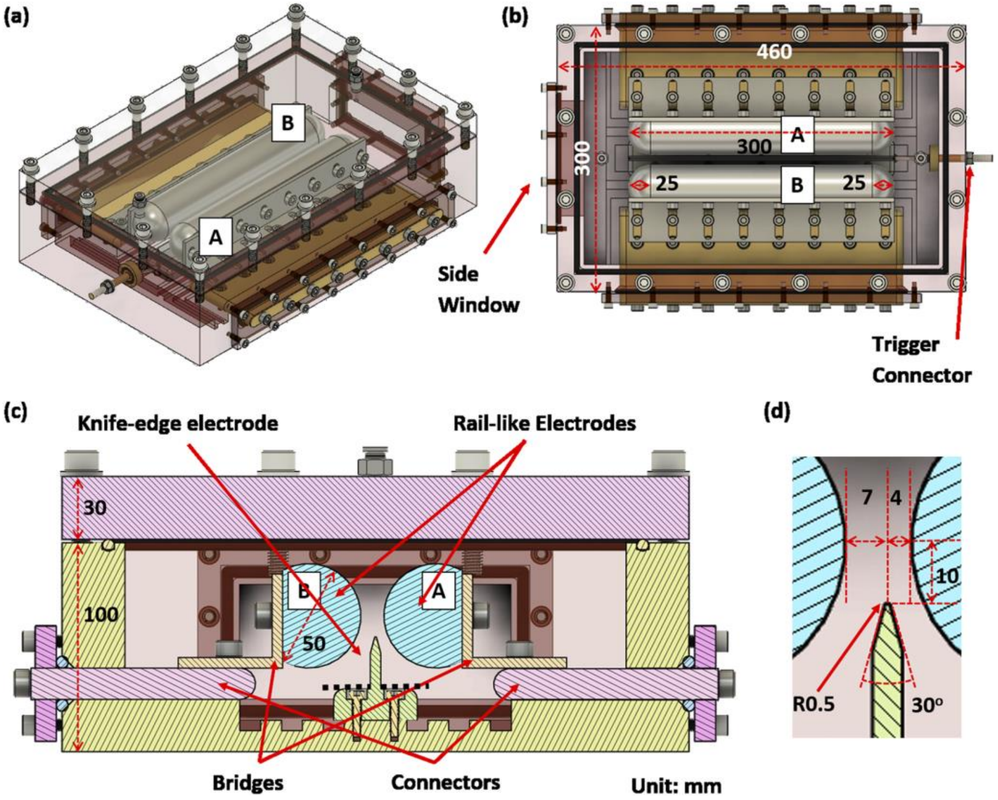


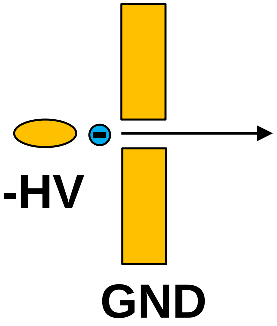


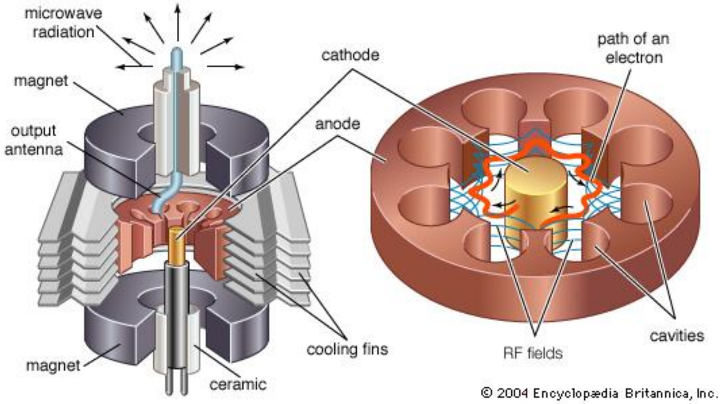




Examples of gaps as loads







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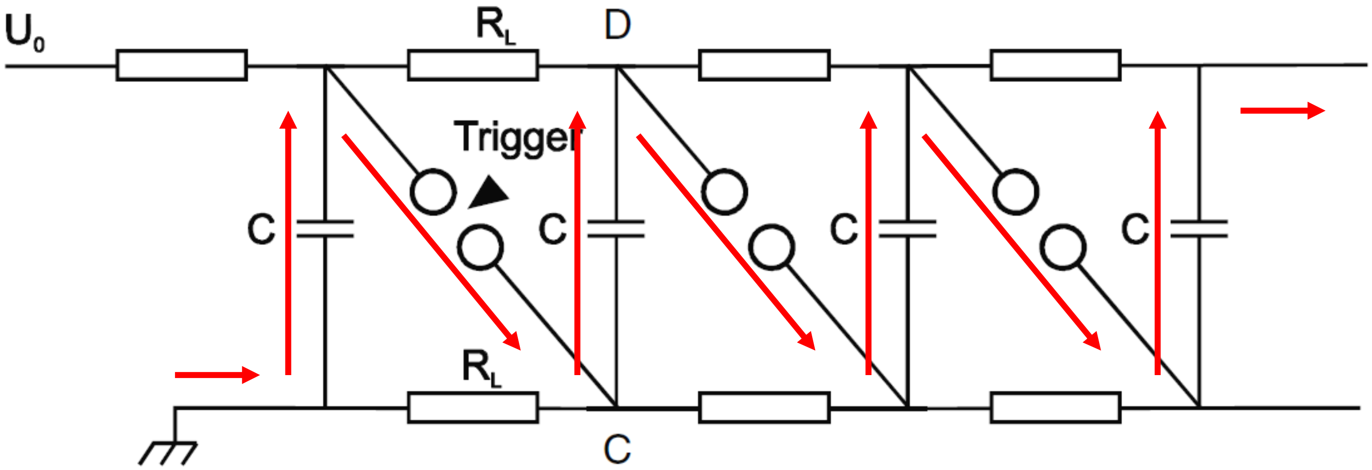
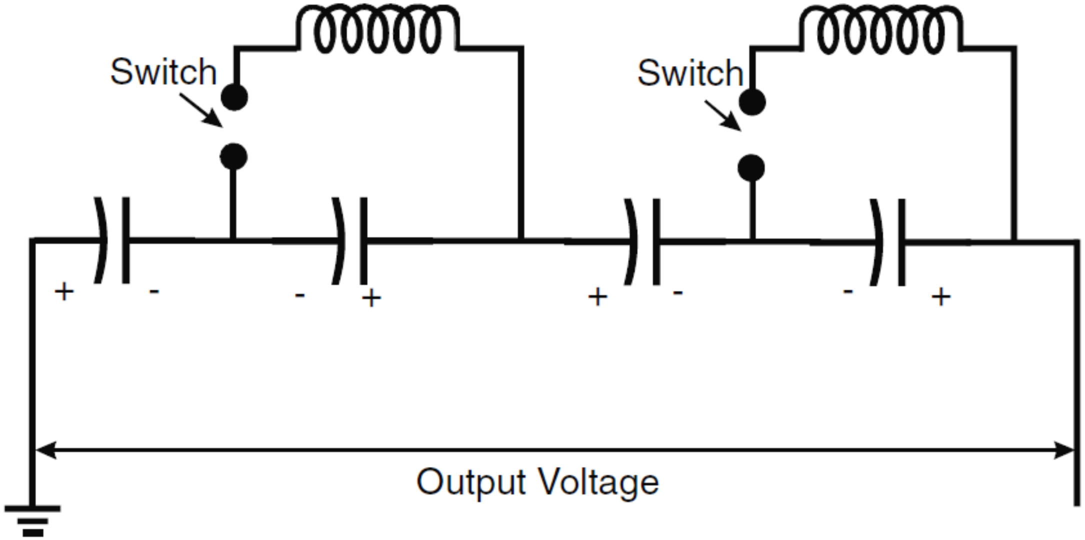
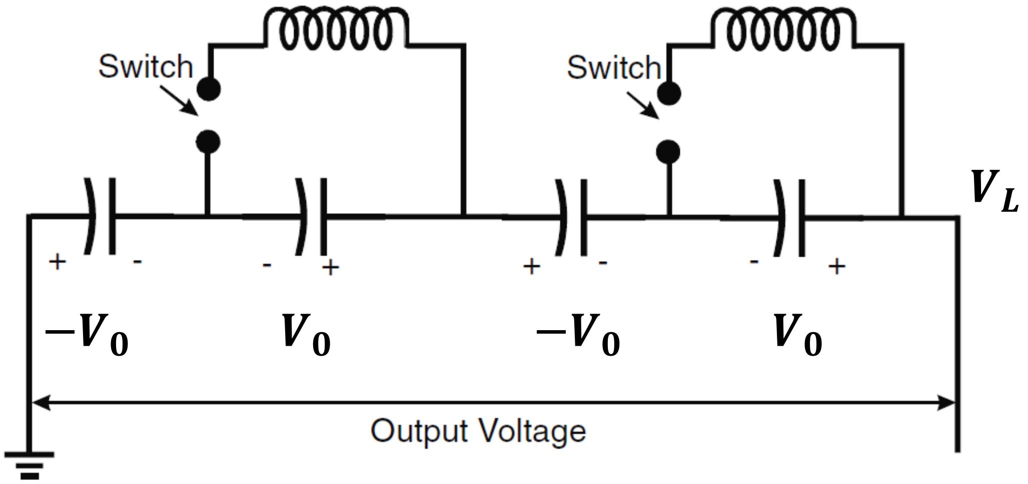
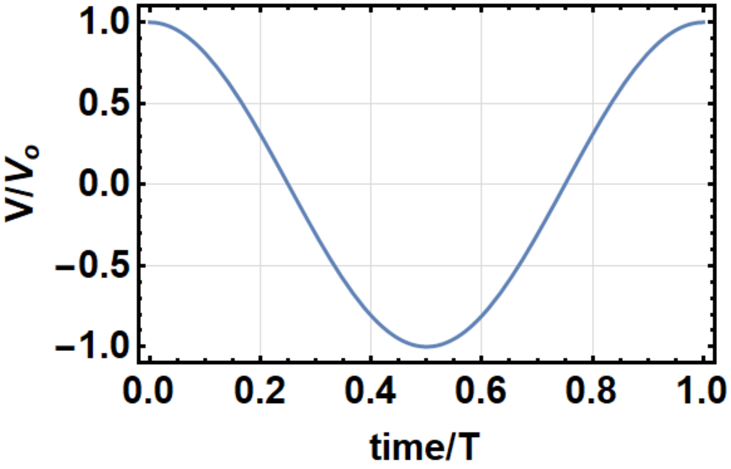
Switch can be taken away from the discharge path to reduce system inductance using “LC Marx Generator”





Switch can be taken away from the discharge path to reduce system inductance using “LC Marx Generator”



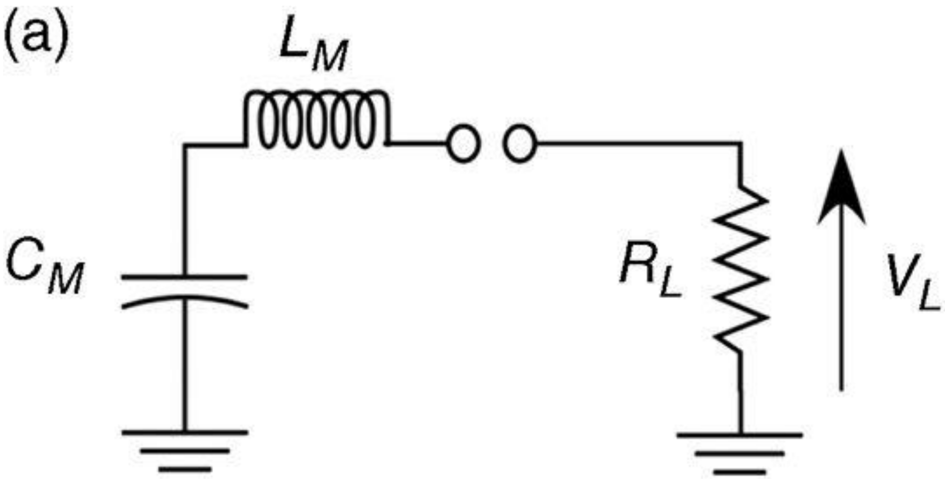


- $V_L = 0$ @ time = 0 .
- When switches are closed, LC oscillations happen.
- @ time=T/2, $V_L = -nV_0$. $V(t) = \frac{1}{2}\mathrm{nV_0}\left[1 - e^{-t/2\tau}\cos(\omega t)\right]$ $\omega = \frac{1}{\sqrt{LC}}$ $\tau = \frac{L}{R}$

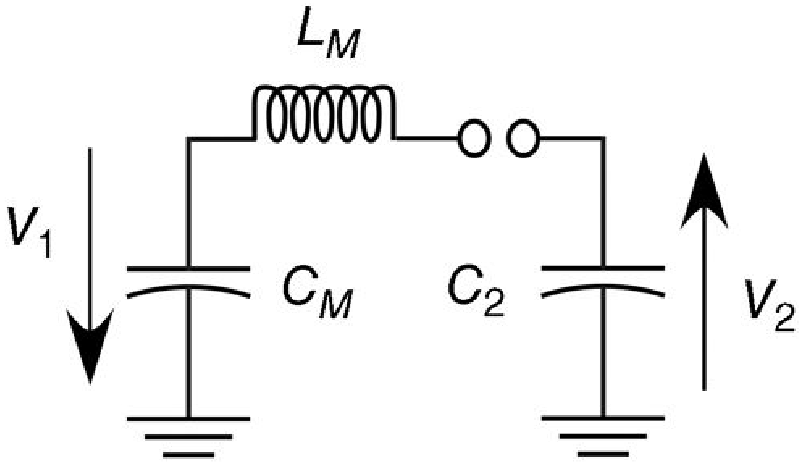
  R: sum of resistance from switches, capacitors, and wires.
- Advantage: since switches locate outside the erected Marx circuit, inductance of the system is low!
- Disadvantage: all switches must be fired with very low jitter!

Load effects on the Marx discharge

- **A resistor**



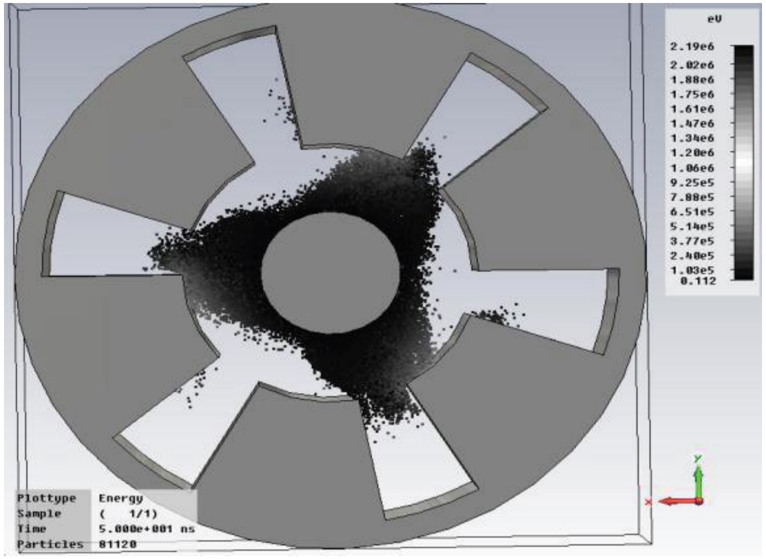
- **A capacitor**



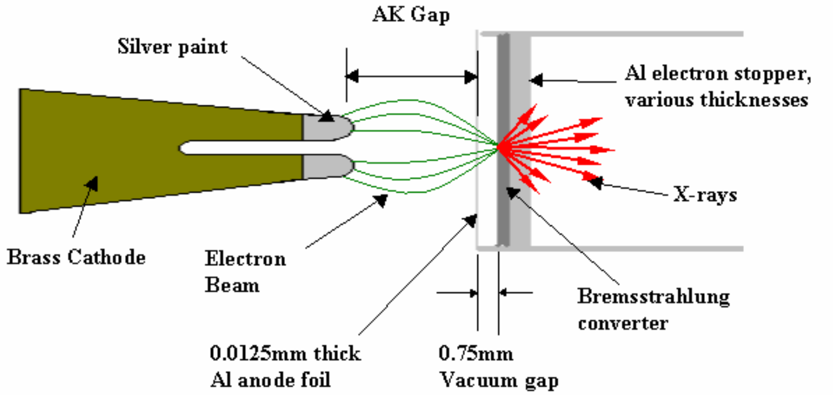
Resistive load

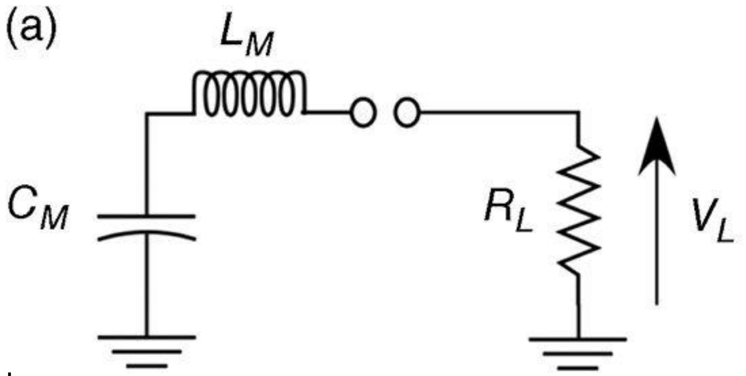
- **The current and voltage are in phase and proportional, such as for relativistic e-beam generator or relativistic magnetron.**

  - **Relativistic magnetron**



  - **Relativistic e-beam**

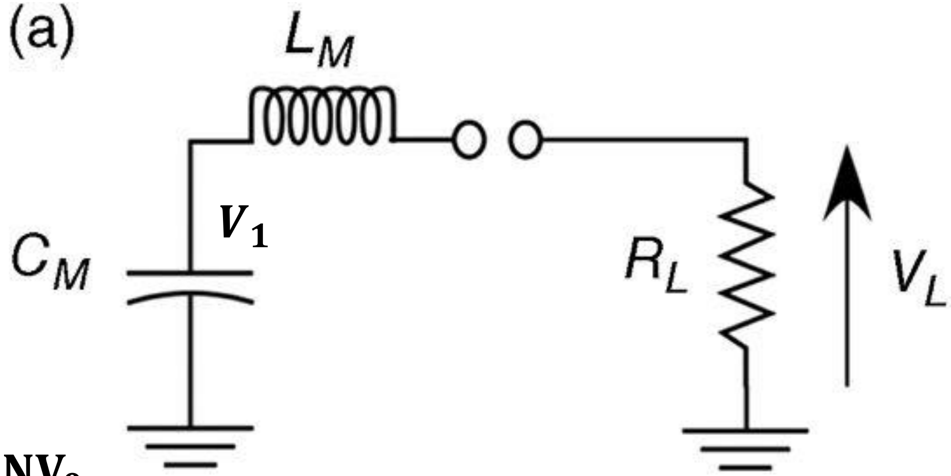




R. Chandra, etc., Proceedings of LINAC2014, Geneva, Switzerland
K. J. Thomas, etc., Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

Resistive load

- **The current and voltage are in phase and proportional, such as for relativistic e-beam generator or relativistic magnetron.**
- **If L_M=0:** $V_L(t) = V_M e^{-t/(R_L C_M)}$
- **In general cases, L_M≠0.**



$$V_1 - L_M \frac{\mathrm{dI}}{\mathrm{dt}} - R_L I = 0$$

$$V_1 = V_M - \frac{1}{C_M} \int I \, \mathrm{d}t$$

$$V_M = \mathrm{NV_0}$$

$$\frac{dV_1}{\mathrm{dt}} = \frac{I}{C_M}$$

$$\frac{I}{C_M} - L_M \frac{d^2 I}{\mathrm{dt}^2} - R_L \frac{\mathrm{dI}}{\mathrm{dt}} = 0$$

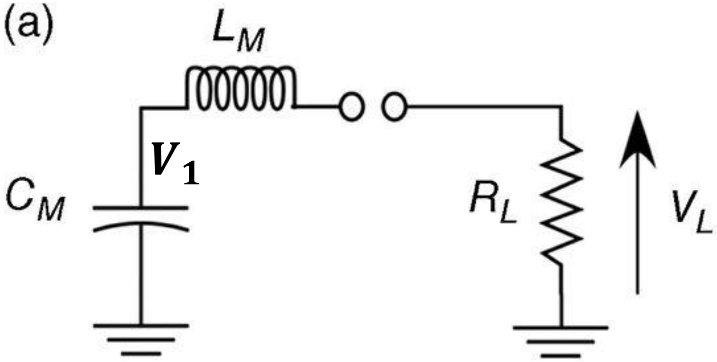
$$\frac{d^2 I}{\mathrm{dt}^2} + \frac{R_L}{L_M} \frac{\mathrm{dI}}{\mathrm{dt}} + \frac{1}{L_M C_M} I = 0$$

$$D^2 + \frac{R_L}{L_M} D + \frac{1}{L_M C_M} = 0$$

$$D = -\frac{R_L}{2L_M} \pm \sqrt{\left(\frac{R_L}{2L_M}\right)^2 - \frac{1}{L_M C_M}}$$

Resistive load

$$\mathbf{For}\ \frac{1}{L_M C_M} > \left(\frac{R_L}{2L_M}\right)^2, \qquad \omega \equiv \sqrt{\frac{1}{L_M C_M} - \left(\frac{R_L}{2L_M}\right)^2}$$



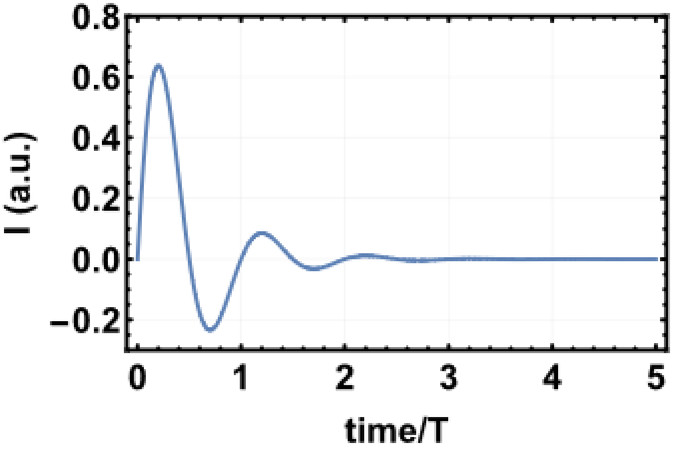
$$I(t) = e^{-\frac{R_L}{2L_M}t}[\alpha \sin(\mathrm{\omega t}) + \beta \cos(\mathrm{\omega t})]$$

$$I(0) = 0 => I(0) = \beta = 0$$

$$I(t) = \mathrm{\alpha e}^{-\frac{R_L}{2L_M}t} \sin(\mathrm{\omega t})$$

$$\frac{dI}{\mathrm{dt}} = \alpha\left[-\frac{R_L}{2L_M}\mathrm{\alpha e}^{-\frac{R_L}{2L_M}t}\sin(\mathrm{\omega t}) + \mathrm{\omega e}^{-\frac{R_L}{2L_M}t}\cos(\mathrm{\omega t})\right]$$

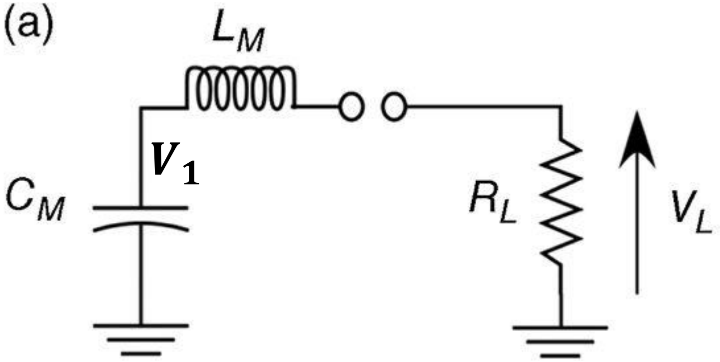
$$L_M \left.\frac{dI}{dt}\right|_{t=0} = V_M \qquad L_M \mathrm{\alpha\omega} = V_M, \qquad \alpha = \frac{V_M}{L_M \omega}$$



$$I = \frac{V_M}{L_M \omega} e^{-\frac{R_L}{2L_M}t} \sin(\mathrm{\omega t})$$

Resistive load

For $\frac{1}{L_M C_M} < \left(\frac{R_L}{2L_M}\right)^2$, $\quad \gamma \equiv \sqrt{\left(\frac{R_L}{2L_M}\right)^2 - \frac{1}{L_M C_M}}$



$$I(t) = e^{-\frac{R_L}{2L_M}t}[\alpha e^{\gamma t} + \beta e^{-\gamma t}]$$

$$I(0) = 0 => \alpha + \beta = 0 => \beta = -\alpha$$

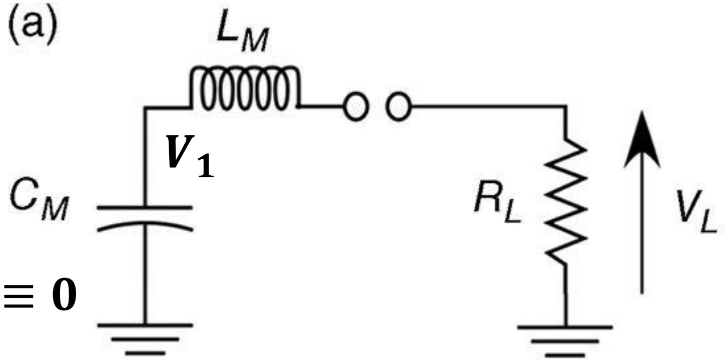
$$I(t) = \alpha e^{-\frac{R_L}{2L_M}t}[e^{\gamma t} - e^{-\gamma t}] = \alpha e^{\left(\gamma - \frac{R_L}{2L_M}\right)t} - \alpha e^{-\left(\gamma + \frac{R_L}{2L_M}\right)t}$$

$$\frac{dI}{dt} = \alpha\left[\left(\gamma - \frac{R_L}{2L_M}\right)e^{\left(\gamma - \frac{R_L}{2L_M}\right)t} + \left(\gamma + \frac{R_L}{2L_M}\right)e^{-\left(\gamma + \frac{R_L}{2L_M}\right)t}\right]$$

$$L_M \left.\frac{dI}{dt}\right|_{t=0} = L_M \alpha\left[\left(\gamma - \frac{R_L}{2L_M}\right) + \left(\gamma + \frac{R_L}{2L_M}\right)\right] = V_M \qquad 2L_M \alpha\gamma = V_M, \qquad \alpha = \frac{V_M}{2L_M\gamma}$$

$$I = \frac{V_M}{2L_M\gamma} e^{-\frac{R_L}{2L_M}t}[e^{\gamma t} - e^{-\gamma t}] \approx \frac{V_M}{2L_M\gamma} e^{-\frac{R_L}{2L_M}t} e^{\gamma t}$$

Resistive load



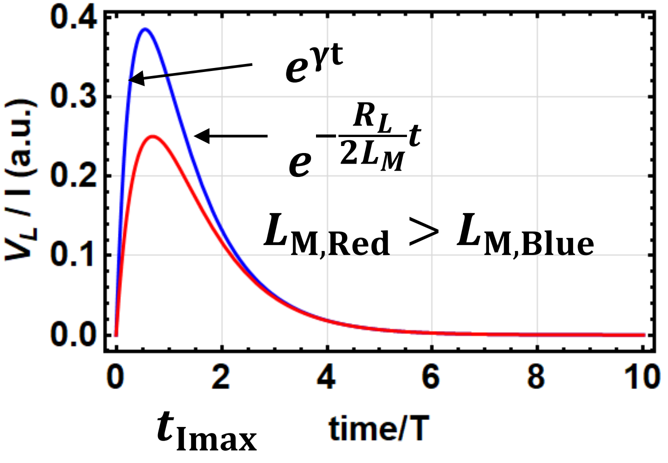
$$I=\frac{V_M}{2L_M\gamma}e^{-\frac{R_L}{2L_M}t}\left[e^{\gamma t}-e^{-\gamma t}\right]\approx\frac{V_M}{2L_M\gamma}e^{-\frac{R_L}{2L_M}t}e^{\gamma t}$$

$$\frac{dI}{dt}=\alpha\left[\left(\gamma-\frac{R_L}{2L_M}\right)e^{\left(\gamma-\frac{R_L}{2L_M}\right)t}+\left(\gamma+\frac{R_L}{2L_M}\right)e^{-\left(\gamma+\frac{R_L}{2L_M}\right)t}\right]\equiv 0$$

$$\left(\gamma-\frac{R_L}{2L_M}\right)e^{\gamma t}+\left(\gamma+\frac{R_L}{2L_M}\right)e^{-\gamma t}=0 \qquad \gamma\equiv\sqrt{\left(\frac{R_L}{2L_M}\right)^2-\frac{1}{L_MC_M}}$$

$$\left(\gamma-\frac{R_L}{2L_M}\right)e^{2\gamma t}+\left(\gamma+\frac{R_L}{2L_M}\right)=0$$

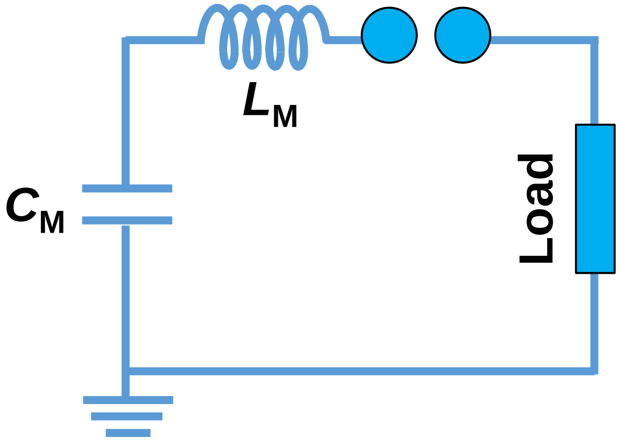
$$e^{2\gamma t}=\frac{\frac{R_L}{2L_M}+\gamma}{\frac{R_L}{2L_M}-\gamma} \qquad t_{\text{Imax}}=\frac{1}{2\gamma}\ln\left(\frac{\frac{R_L}{2L_M}+\gamma}{\frac{R_L}{2L_M}-\gamma}\right)$$

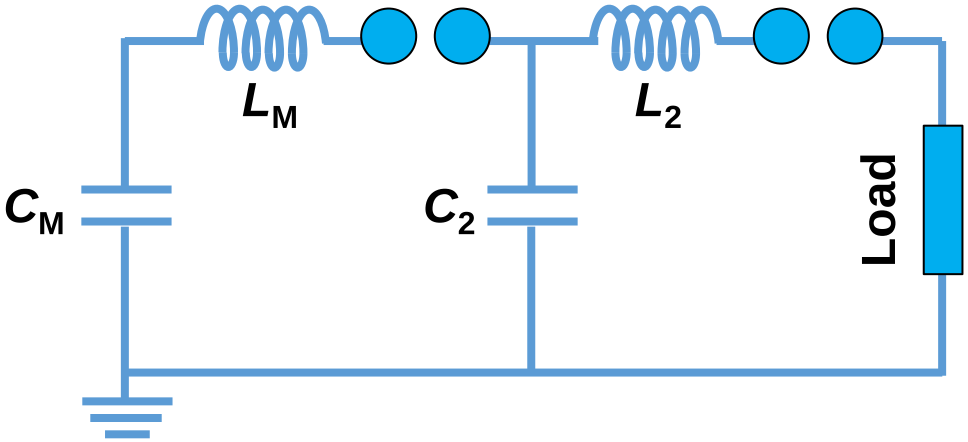


$L_M\uparrow$ ➡ $\gamma\downarrow$ $e^{\gamma t}\downarrow$ $-\frac{R_L}{2L_M}\uparrow$ $e^{-\frac{R_L}{2L_M}t}\uparrow$

Capacitor load

- **Pulse compression scheme: a charged capacitor can transfer almost all of its energy to an uncharged capacitor if connected through an inductor.**
- **Output voltage can be doubled in a peaking circuit.**



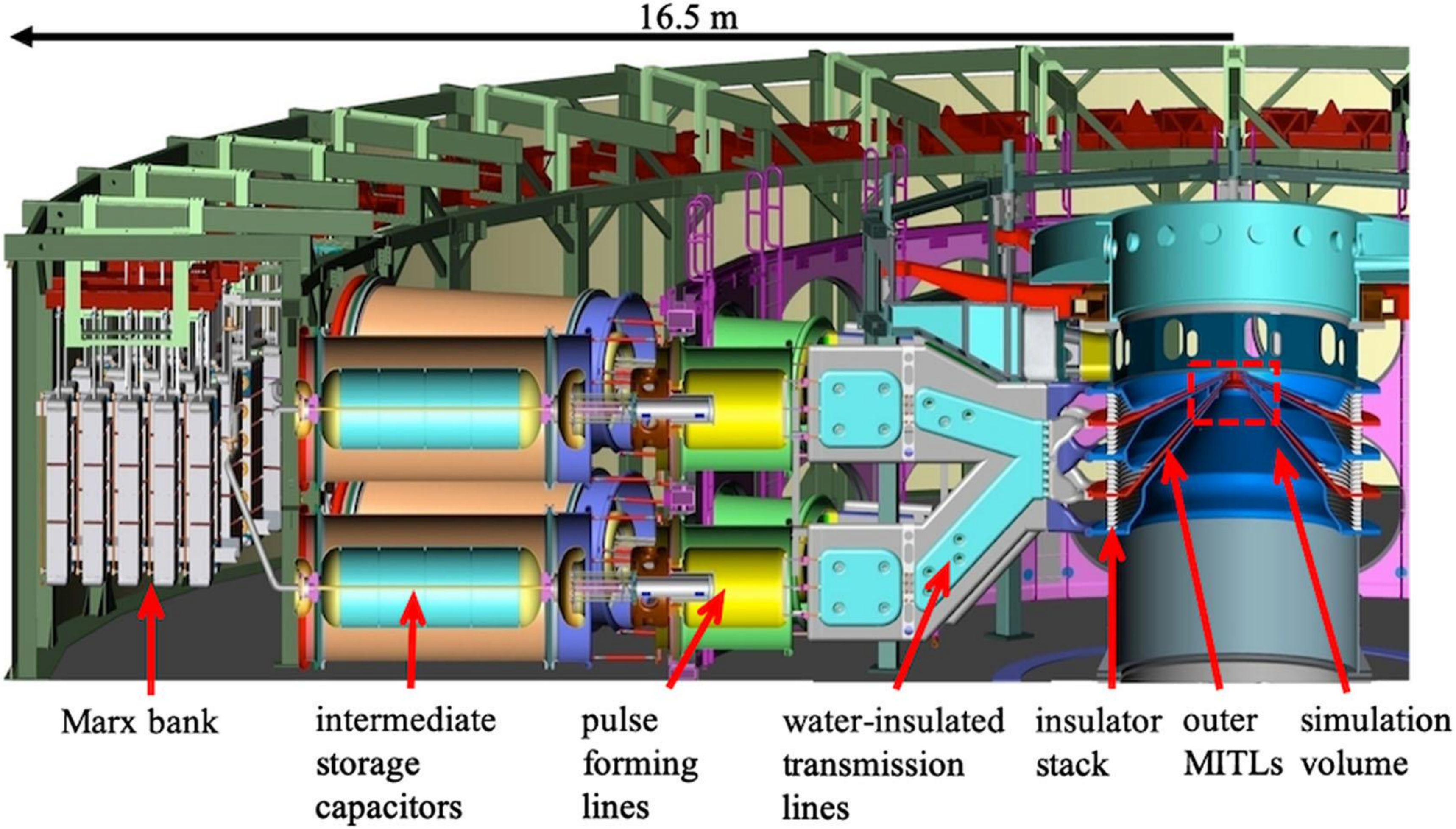


$$I_0 = \frac{V_0}{\sqrt{L_M/C_M}} \qquad \omega_0 = \frac{1}{\sqrt{L_M C_M}}$$

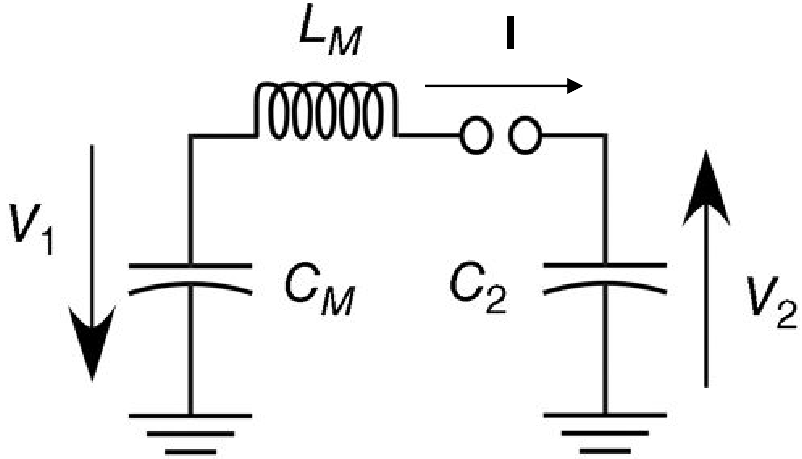
$$I_2 = \frac{V_0}{\sqrt{L_2/C_2}} \qquad \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

$L_M > L_2$ **=>** $I_M < I_2$ $\omega_M < \omega_2$ $T_M > T_2$

Intermediate storage capacitors can be used to compress the pulse



Capacitor load



$$V_1 - L_M \frac{\mathrm{dI}}{\mathrm{dt}} = V_2$$

$$V_1 = V_M - \frac{1}{C_M}\int I\, \mathrm{d}t \qquad V_M = \mathrm{NV_0}$$

$$V_2 = \frac{1}{C_2}\int I\, \mathrm{d}t$$

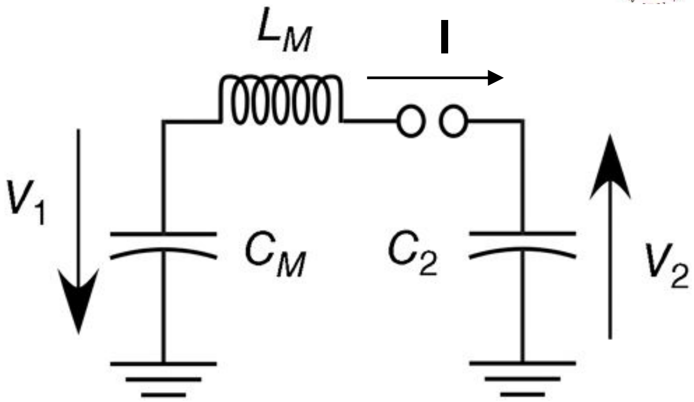
$$V_M - \frac{1}{C_M}\int I\, \mathrm{d}t - L_M \frac{\mathrm{dI}}{\mathrm{dt}} = \frac{1}{C_2}\int I\, \mathrm{d}t$$

$$-\frac{1}{C_M} I - L_M \frac{d^2 I}{\mathrm{dt}^2} = \frac{1}{C_2} I \qquad L_M \frac{d^2 I}{\mathrm{dt}^2} + \left(\frac{1}{C_M} + \frac{1}{C_2}\right) I = 0$$

$$\frac{d^2 I}{\mathrm{dt}^2} + \frac{1}{L_M C_{\mathrm{eff}}} I = 0 \qquad \frac{1}{C_{\mathrm{eff}}} = \frac{1}{C_M} + \frac{1}{C_2} \qquad \omega = \sqrt{\frac{1}{L_M C_{\mathrm{eff}}}}$$

$$I = \alpha \sin(\omega \mathrm{t}) + \beta \cos(\omega \mathrm{t})$$

Capacitor load



$$I = \alpha\sin(\omega t) + \beta\cos(\omega t)$$

$$I(t=0) = 0 => \beta = 0$$

$$I = \alpha\sin(\omega t)$$

$$\frac{dI}{dt} = \alpha\omega\cos(\omega t)$$

$$L_M \left.\frac{dI}{dt}\right|_{t=0} = L_M\alpha\omega = V_M \qquad \alpha = \frac{V_M}{L_M\omega}$$

$$I(t) = \frac{V_M}{L\omega}\sin(\omega t)$$

$$V_1 = V_M - \frac{1}{C_M}\int_0^t \frac{V_M}{L\omega}\sin(\omega t)\,dt = V_M - \frac{V_M C_2}{C_M + C_2}[1-\cos(\omega t)]$$

$$V_2 = \frac{1}{C_2}\int_0^t \frac{V_M}{L\omega}\sin(\omega t)\,dt = \frac{V_M C_M}{C_M + C_2}[1-\cos(\omega t)] \qquad \left.\frac{V_2}{V_M}\right|_{\max} = \frac{2C_M}{C_M + C_2}$$

$$\text{for } C_2 \sim C_M, \frac{V_2}{V_M} \sim 1 \qquad \text{for } C_2 << C_M, \frac{V_2}{V_M} \sim 2$$

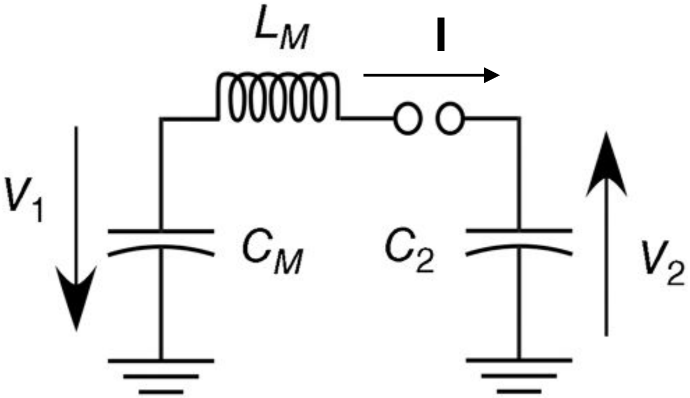
Peaking circuit, $C_2 << C_M$

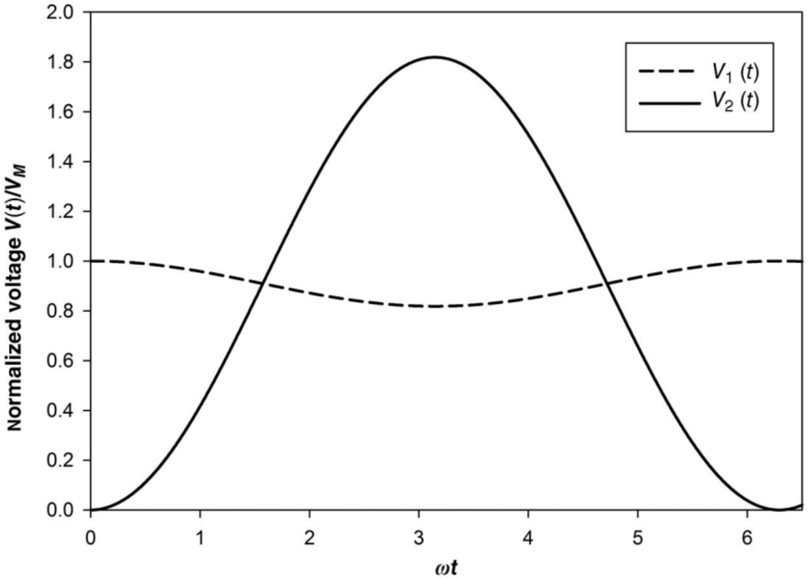
$$V_1 = V_M - \frac{V_M C_2}{C_M + C_2}[1 - \cos(\omega t)] \approx V_M - \frac{V_M C_2}{C_M}[1 - \cos(\omega t)]$$

$$V_2 = \frac{V_M C_M}{C_M + C_2}[1 - \cos(\omega t)] \approx V_M[1 - \cos(\omega t)]$$

$$\text{For } t = \frac{\pi}{\omega}, \cos(\omega t) = \cos(\pi) = -1$$

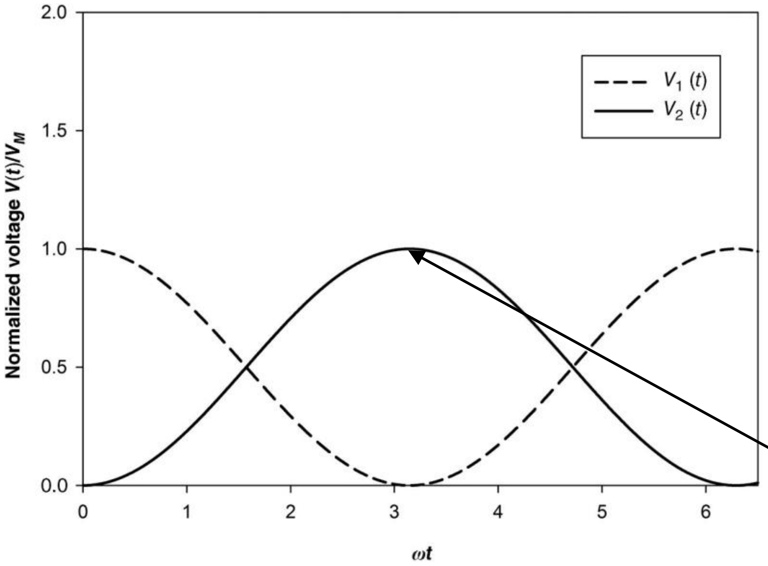
$$V_1 \approx V_M \qquad V_2 \approx 2V_M$$

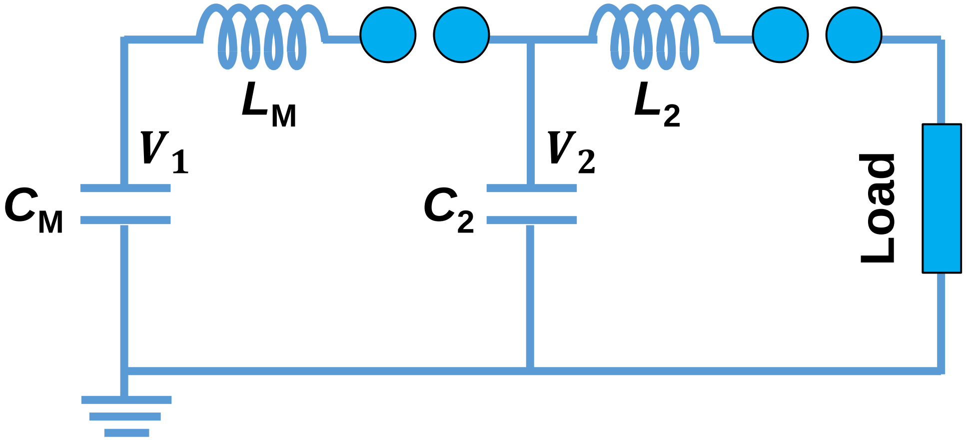




- **The energy transfer is inefficient.**
- **C_M/C_2~10 is normally used.**

Pulse compression scheme: $C_2 \sim C_M$





Energy is fully transferred to the 2nd cap, i.e., intermediate storage capacitor.

$$V_1 = V_M - \frac{V_M C_2}{C_M + C_2}[1 - \cos(\omega t)] \approx V_M - \frac{V_M}{2}[1 - \cos(\omega t)]$$

$$V_2 = \frac{V_M C_M}{C_M + C_2}[1 - \cos(\omega t)] \approx \frac{V_M}{2}[1 - \cos(\omega t)]$$

$$\text{For } t = \frac{\pi}{\omega}, \qquad V_1 \approx 0, \qquad V_2 \approx V_M$$

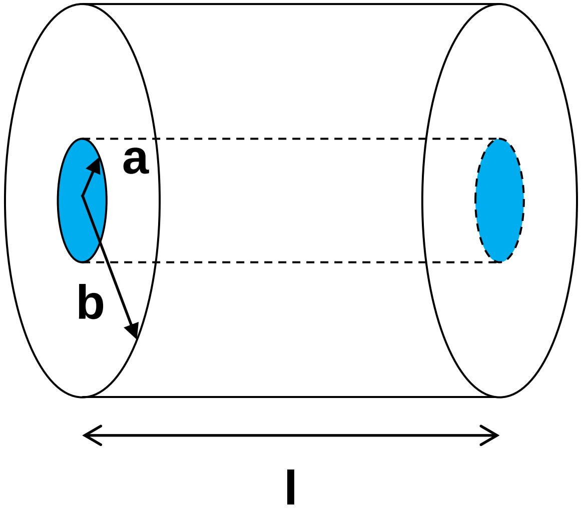
Water is commonly used as the dielectric material for the intermediate capacitor

$$C = \frac{2\pi\epsilon_r\epsilon_0}{\ln(b/a)} l \qquad \text{For } \frac{b}{a} = \frac{1}{0.9} \approx 1.1$$

- **The gap between two cylinders need to be able to handle the high voltage.**

$$\text{Air: } \epsilon_r = 1 => \frac{C}{l} = 0.5 \times 10^{-9}\, F/m$$

$$\text{Water: } \epsilon_r = 80 => \frac{C}{l} = 4 \times 10^{-8}\, F/m$$



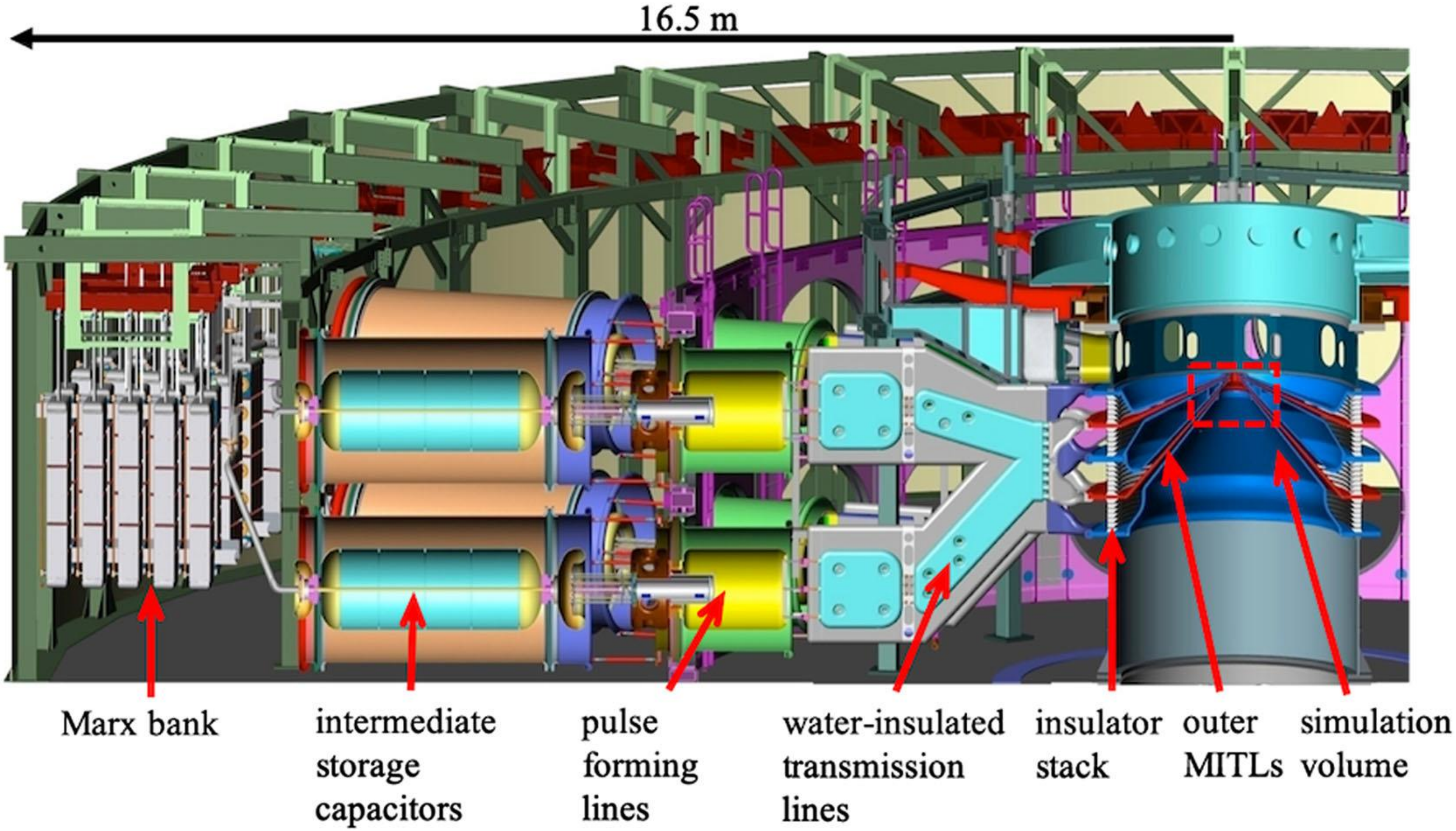
Ex: KALIF, bipolar Marx generator, charged up to ±100 kV. $V_{M,out}$=5 MV.

$$C_M = \frac{0.5\mu\text{F}}{25} = 25\text{nF}$$

$$\text{Using air: } \quad \text{l} = \frac{25 \times 10^{-9}}{0.5 \times 10^{-9}} = 50\text{ m}$$

$$\text{Using water: } \quad \text{l} = \frac{25 \times 10^{-9}}{4 \times 10^{-8}} = 0.625\text{ m}$$

Intermediate storage capacitors can be used to compress the pulse



Outlines

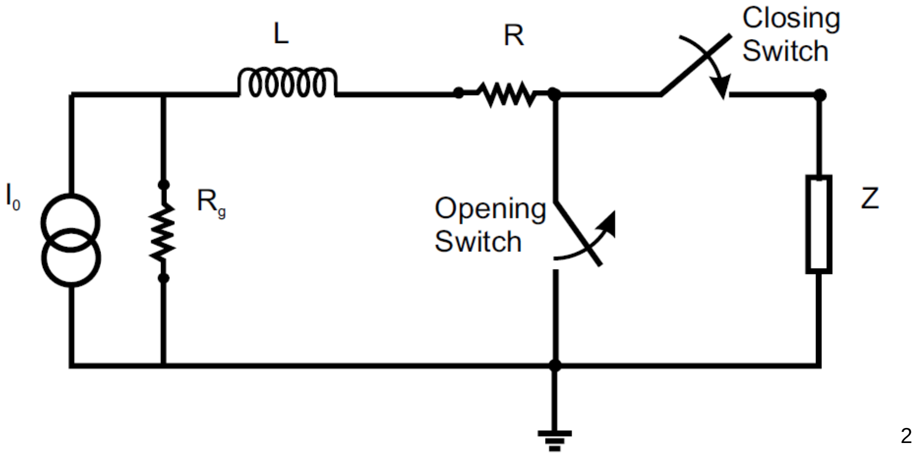
- Introduction to pulsed-power system
- Review of circuit analysis
- Static and dynamic breakdown strength of dielectric materials
  - Gas – Townsend discharge (avalanche breakdown), Paschen’s curve
  - Liquid
  - Solid
- **Energy storage**
  - Pulse discharge capacitors
  - Marx generators
  - **Inductive energy storage**

Inductive energy storage

- **Capacitive energy storage – current amplifier.**
- **Inductive energy storage – voltage amplifier.**
- **Notice that energy density of the inductive energy storage is 2 order higher than that of the capacitive energy storage.**
- **If I_o is large, charging of the inductor must be fast. It is because the energy loss in the resistance of the inductor windy and the opening switch.**
- **Current source has high internal impedance (R_g >> R) and a large power ($t_{charge}\downarrow$).**

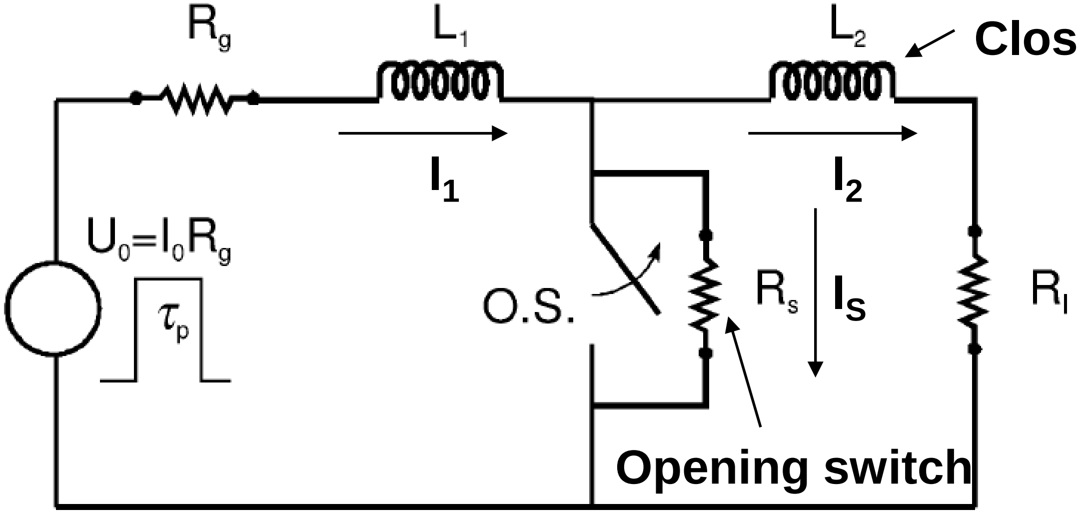
$$I_{\max} = I_o \frac{R_g}{R_g + R}$$

$$I(t) = I_o \frac{R_g}{R_g + R}\left(1 - e^{-\frac{R+R_g}{L}t}\right)$$



Output of the inductive storage

- **Assumption: at t=0, inductance is fully charged. Resistance of the inductive storage is neglected.**



Closing switch

Opening switch

$$R_gI_1 + L_1\frac{\mathrm{dI_1}}{\mathrm{dt}} + R_S(I_1 - I_2) = 0$$

$$R_lI_2 + L_2\frac{\mathrm{dI_2}}{\mathrm{dt}} + R_S(I_2 - I_1) = 0$$

$$\tau_{\pm} = \left(\frac{R_l + R_S}{2L_S} + \frac{R_g + R_S}{2L_1}\right) \times \left[1 \pm \sqrt{1 - \frac{4L_1L_2\left[(R_l + R_S)(R_g + R_S) - {R_S}^2\right]}{\left[L_1(R_l + R_S) + L_2(R_g + R_S)\right]^2}}\right]$$

Output of the inductive storage

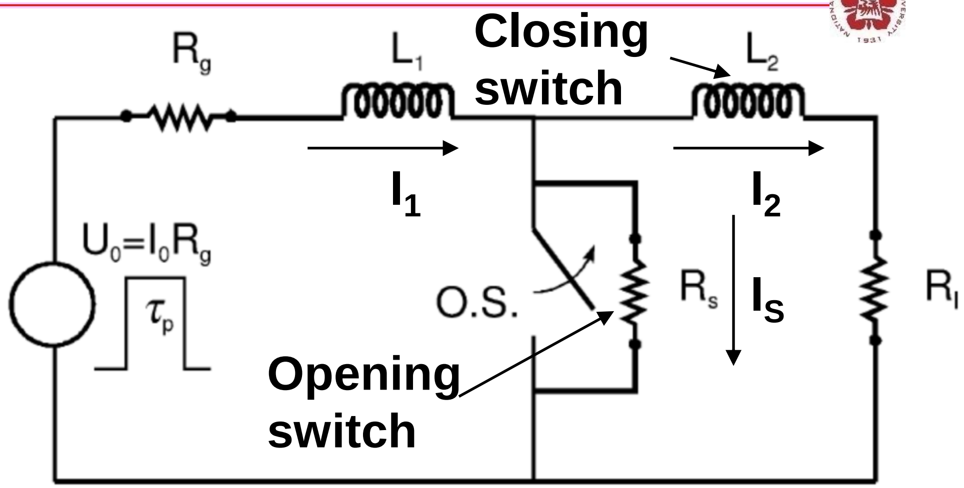
$$\boldsymbol{\tau_+ = \frac{L_2}{R_S}}$$

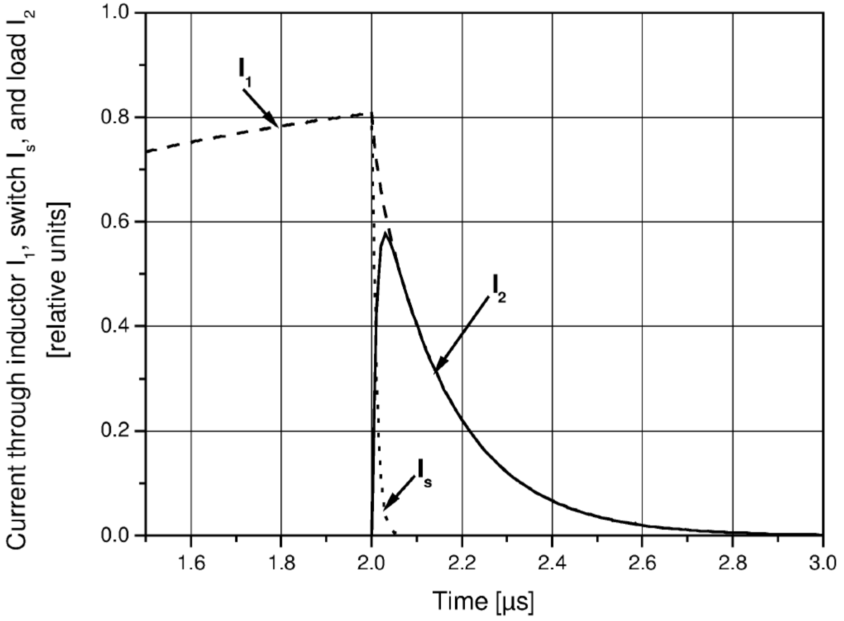
$$\boldsymbol{\tau_- = \frac{L_1}{R_g + R_l}} \qquad \boldsymbol{\tau_+ << \tau_-}$$

$$\boldsymbol{I_1(t) \approx \frac{L_1 I_o}{L_1 + L_2}\left(e^{-t/\tau_-} + \frac{L_2}{L_1} e^{-t/\tau_+}\right)}$$

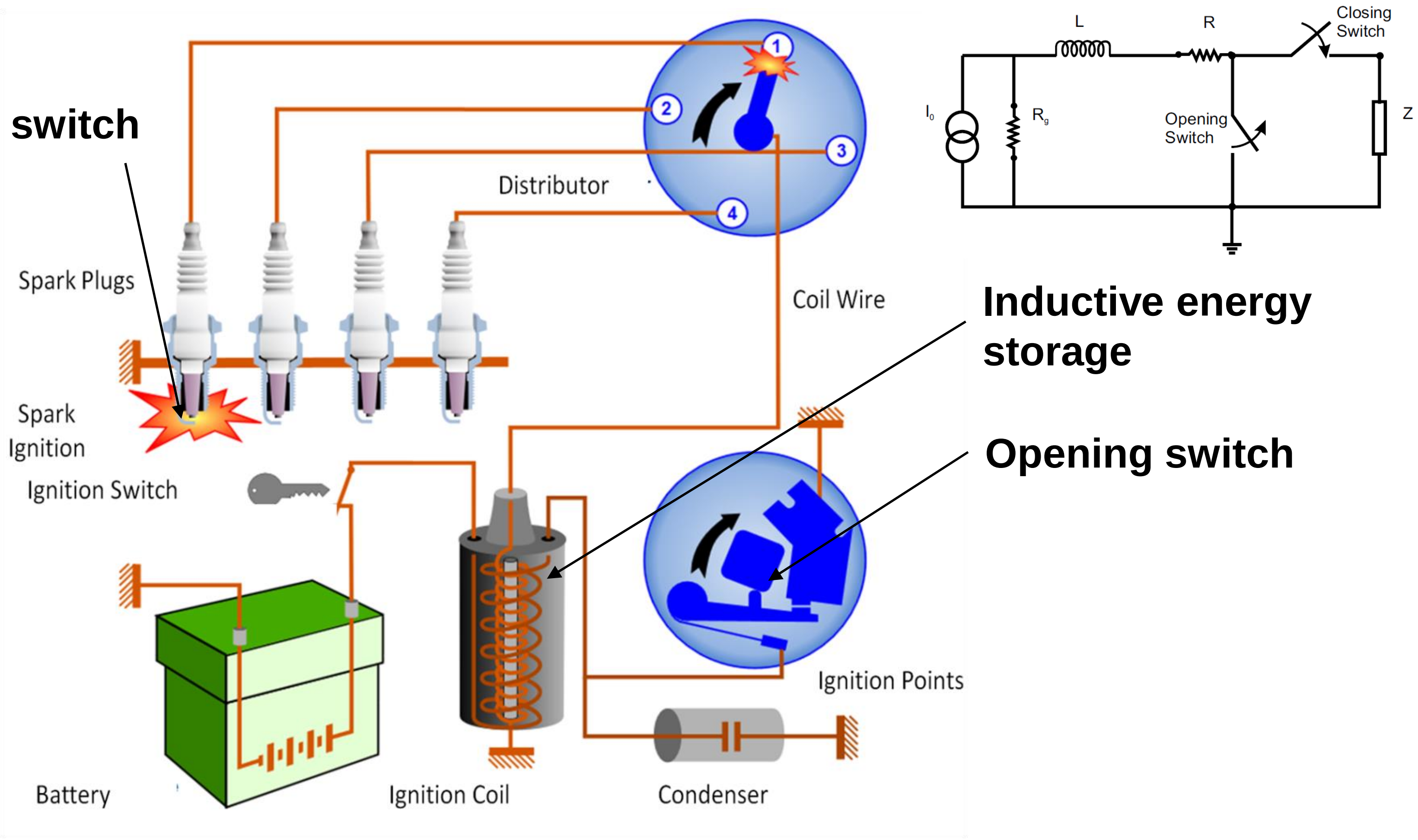
$$\boldsymbol{I_2(t) \approx \frac{L_1 I_o}{L_1 + L_2}\left(e^{-t/\tau_-} - e^{-t/\tau_+}\right)}$$

$$\boldsymbol{I_S(t) = I_1 - I_2 \approx I_o e^{-t/\tau_+}}$$





Spark plugs in cars are triggered by the inductive energy storage



Closing switch /load

Inductive energy storage

Opening switch

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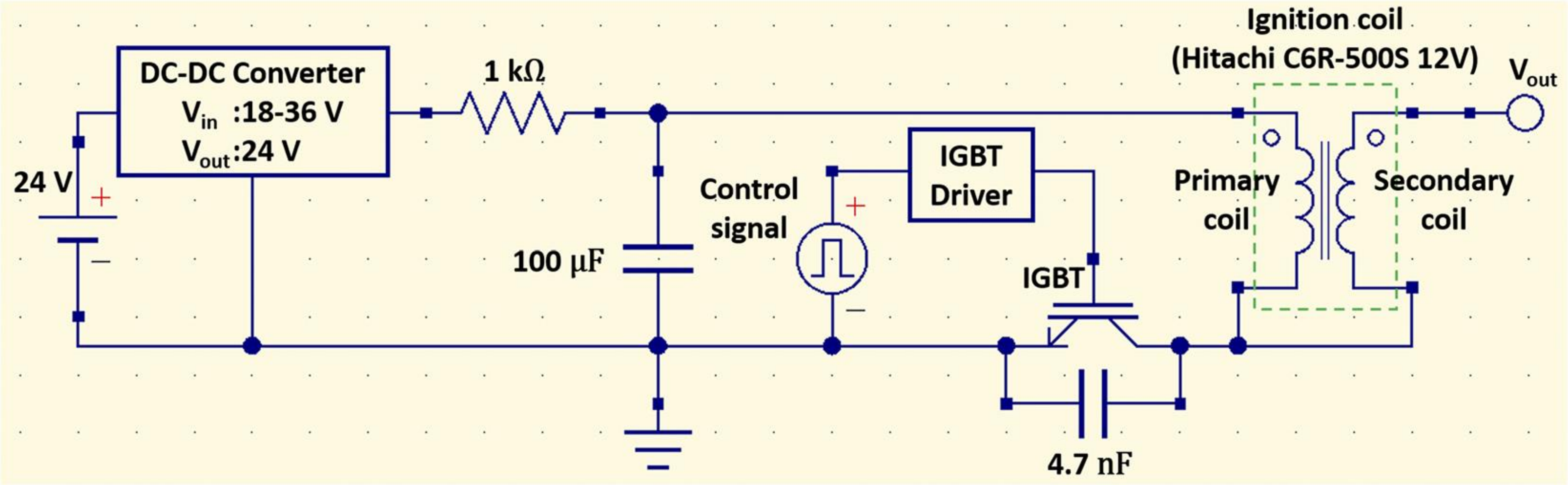
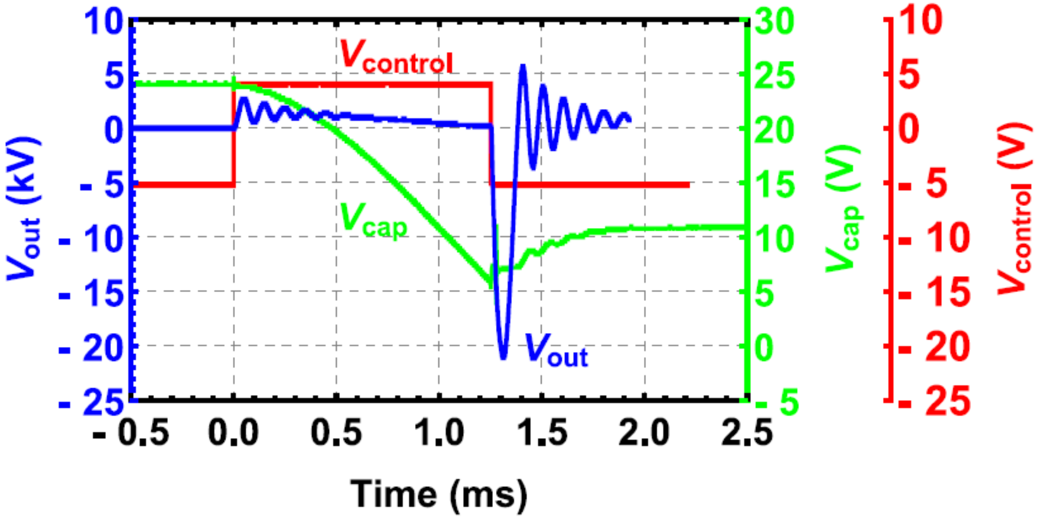
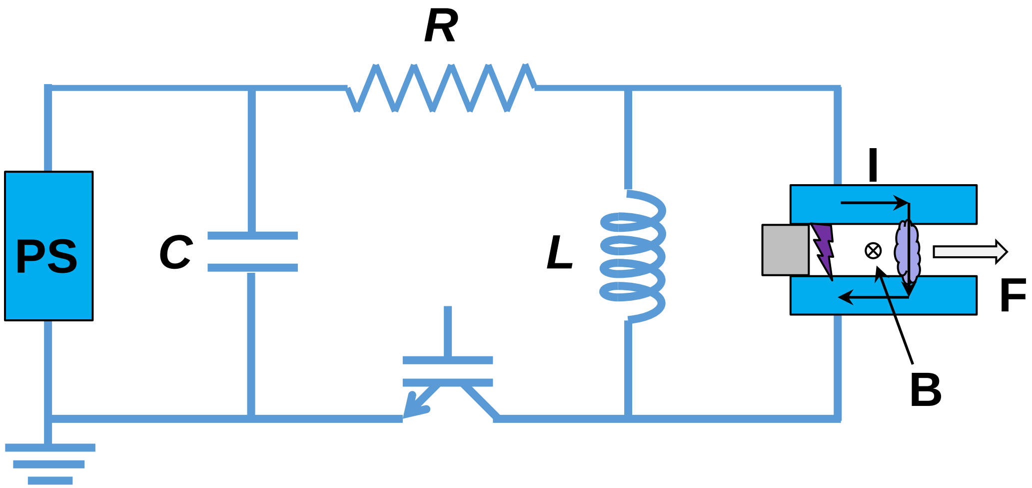
Triggering pulse for PGS machine





Pulsed-plasma thruster



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  - Solid
- **Energy storage**
  - Pulse discharge capacitors
  - Marx generators
  - Inductive energy storage
  - **Rotors and Homopolar generators**

Rotors and Homopolar generators

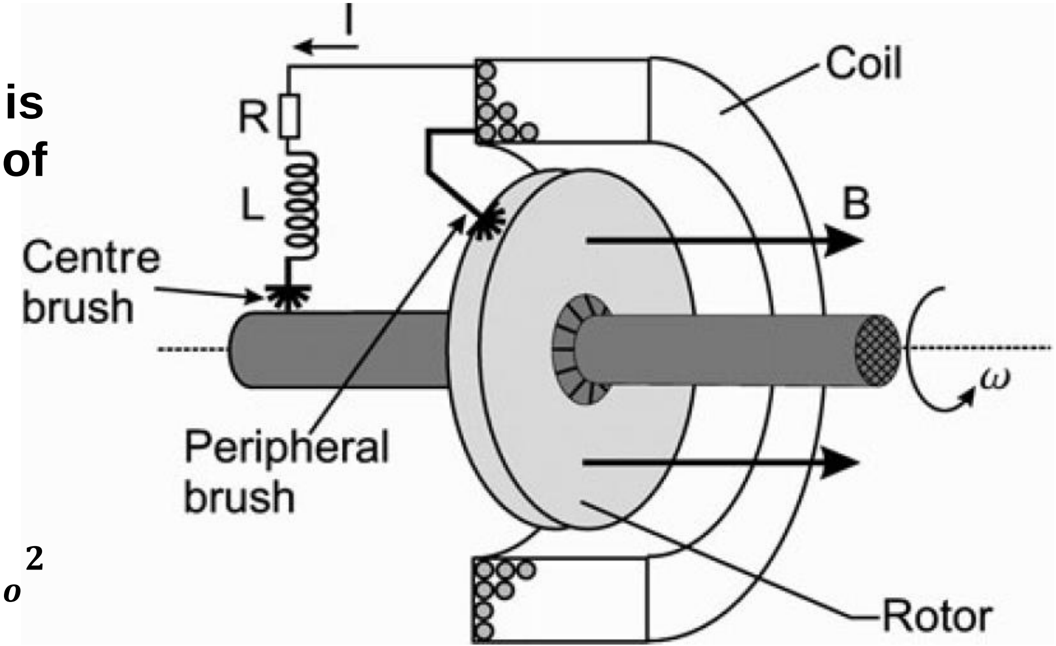
- Pulsed current source is needed such that charge time << L/R

  => using flywheel. $\boldsymbol{W_{\mathbf{kin}} = \frac{1}{2}\theta\omega^2}$
- Energy density ~ 300 MJ/m^3, total energy > 100 MJ.
- Can transfer its energy only in a time > 10 ms in most cases.
- Homopolar generator:
- In a self-exciting generator, B is created by the output current of the rotor.

$$V = \alpha I \omega$$

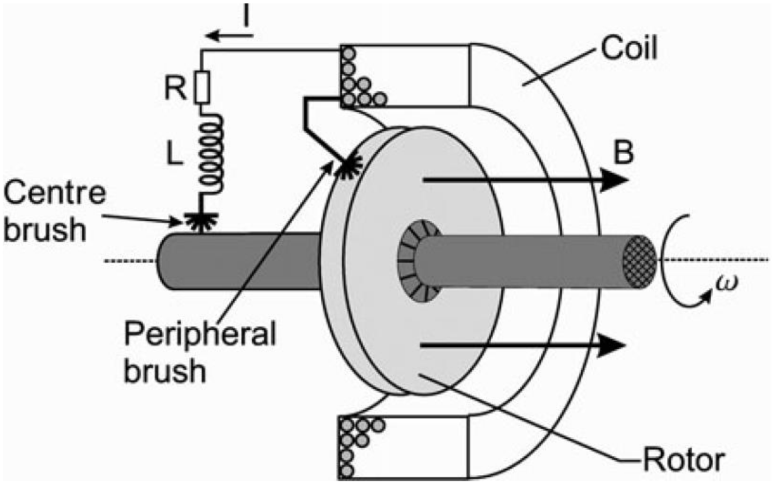
$$L\frac{dI}{dt} + IR = \alpha I \omega$$

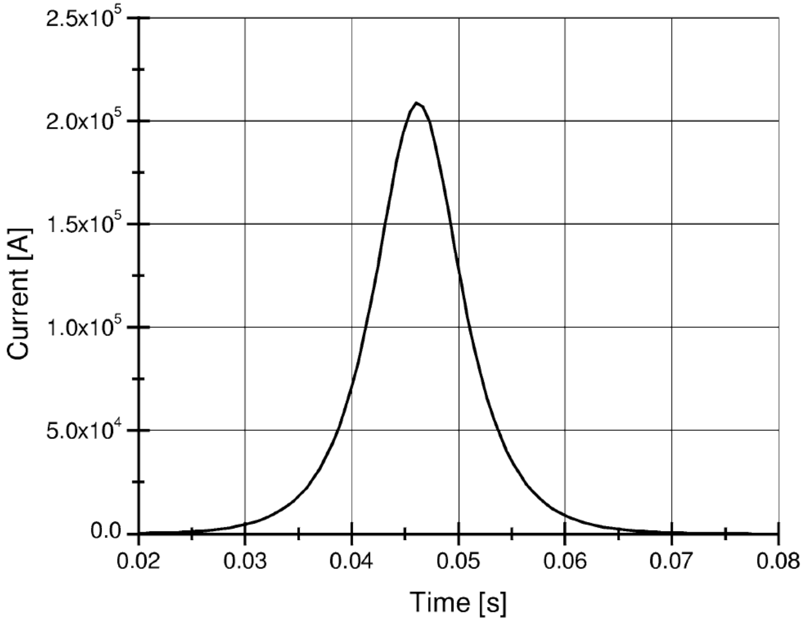
$$\frac{1}{2}\theta\omega^2 + \frac{1}{2}LI^2 + \int_0^t I^2 R\, dt = \frac{1}{2}\theta{\omega_o}^2$$

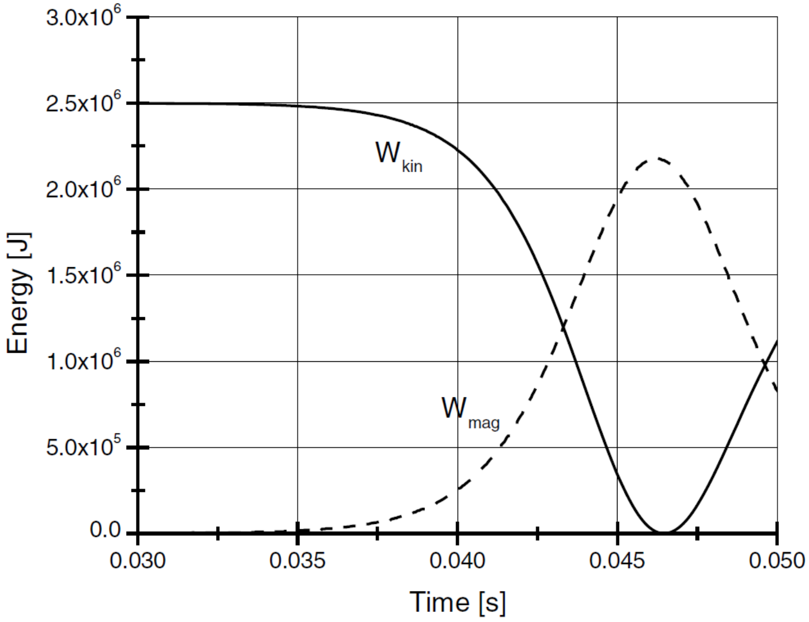


(flywheel)

Homopolar generators







Outlines

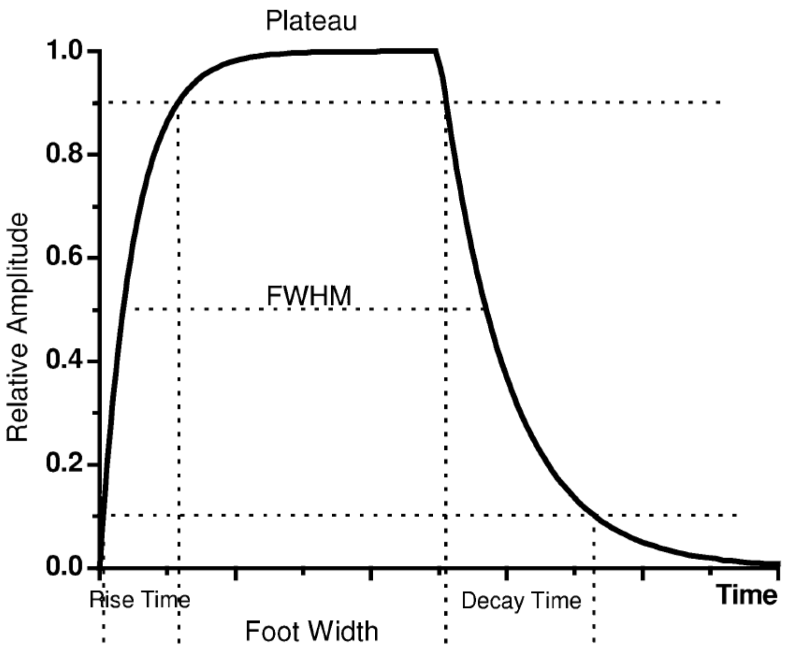
- **Switches**
  - **Closing switches: the switching process is associated with voltage breakdown across an initially insulant element.**
  - **Opening switches: the switching process is associated with a sudden growth of its impedance.**
- **Pulse-forming lines**
  - **Blumlein line**
  - **Pulse-forming network**
  - **Pulse compressor**
- **Pulse transmission and transformation**

Outlines

- **Switches**
  - **Closing switches**
  - Opening switches
- Pulse-forming lines
  - Blumlein line
  - Pulse-forming network
  - Pulse compressor
- Pulse transmission and transformation
  - Self-magnetic insulation
  - Pulse transformer
  - Voltage multiplier
  - H-bridge pulse generator
  - Fast high-voltage pulse generator

Switches

- High-power switching systems are the connecting elements between the storage device and the load.
- Characteristics of the generator output pulse that is strongly dependent on the properties of the switches:
  - Rise time.
  - Shape.
  - Amplitude.



Closing switches

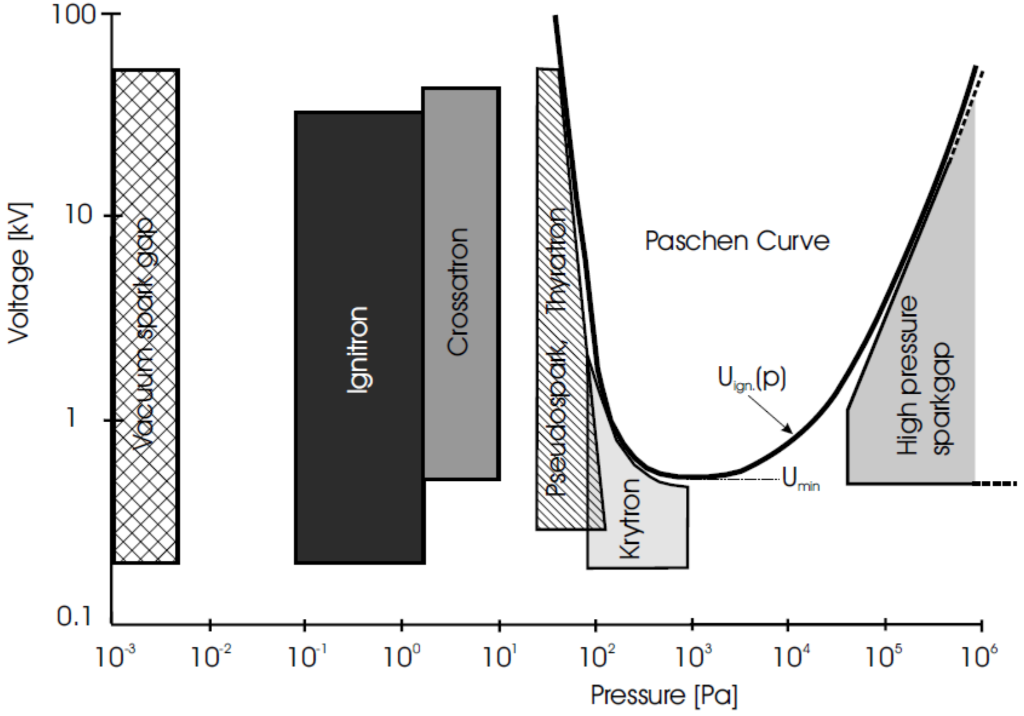
- **The switching process is associated with voltage breakdown across an initially insulant element.**
    - **Automatically.**
    - **Externally supplied trigger pulse.**

Gas switches (Spark-gap switches)

- **Advantage of a gas switch:**
  - **Commonly applied in high-power pulse generators.**
  - **Easy to use.**
  - **Capable of handling large currents.**
  - **Capable of handling large charges.**
  - **Can be triggered precisely.**
- **Many applications require a precisely controlled initiation of the voltage breakdown.**
- **The trigger method has a big influence on the ignition delay and its variance (jitter).**

Different closing switches operate in different pressure

84 4 Switches



All switching systems operates in 4 phases

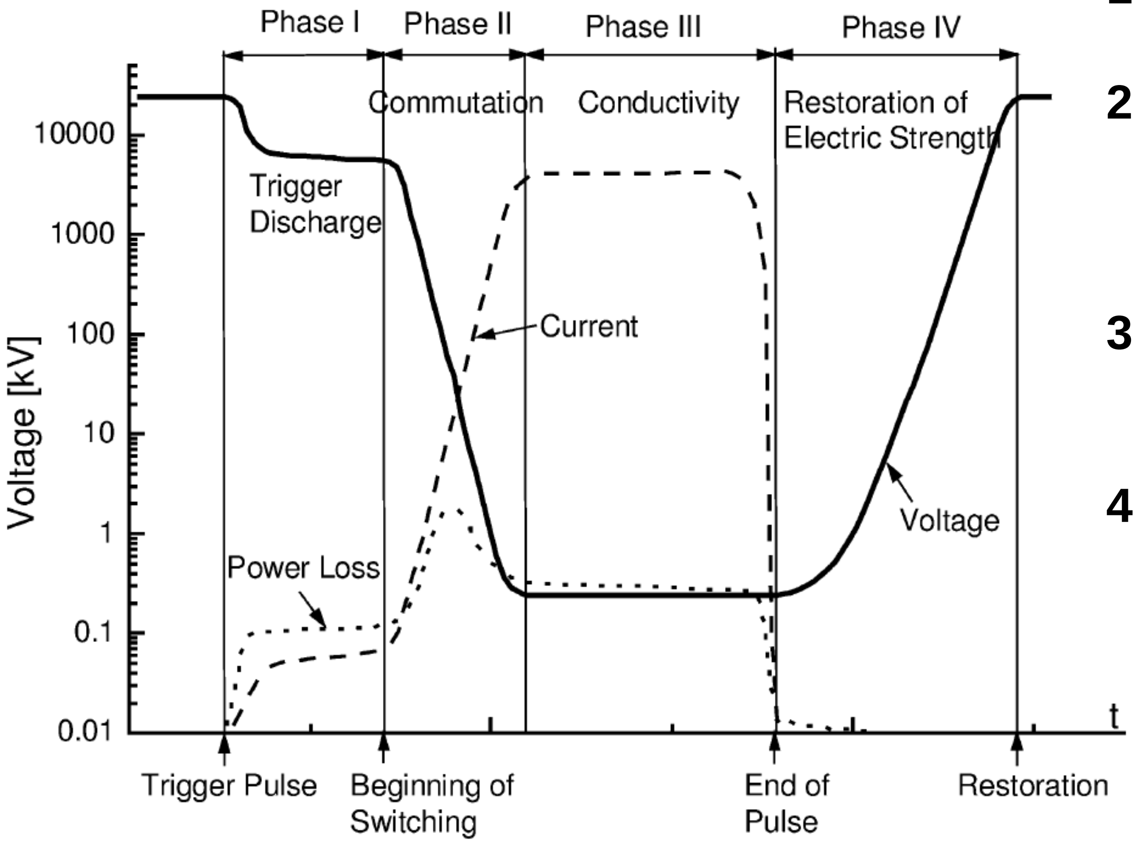


Fig. 4.2. Evolution of voltage, current, and power loss in a gas-filled switching system

1. **Trigger phase: build-up of a trigger discharge.**
2. **Transition/commutation phase: transition from high to low switch impedance.**
3. **Stationary/conductivity phase: constant conductivity.**
4. **Recovery/restoration phase: restoration of the previous electric strength.**

Cooling is needed to remove the energy loss for the breakdown.

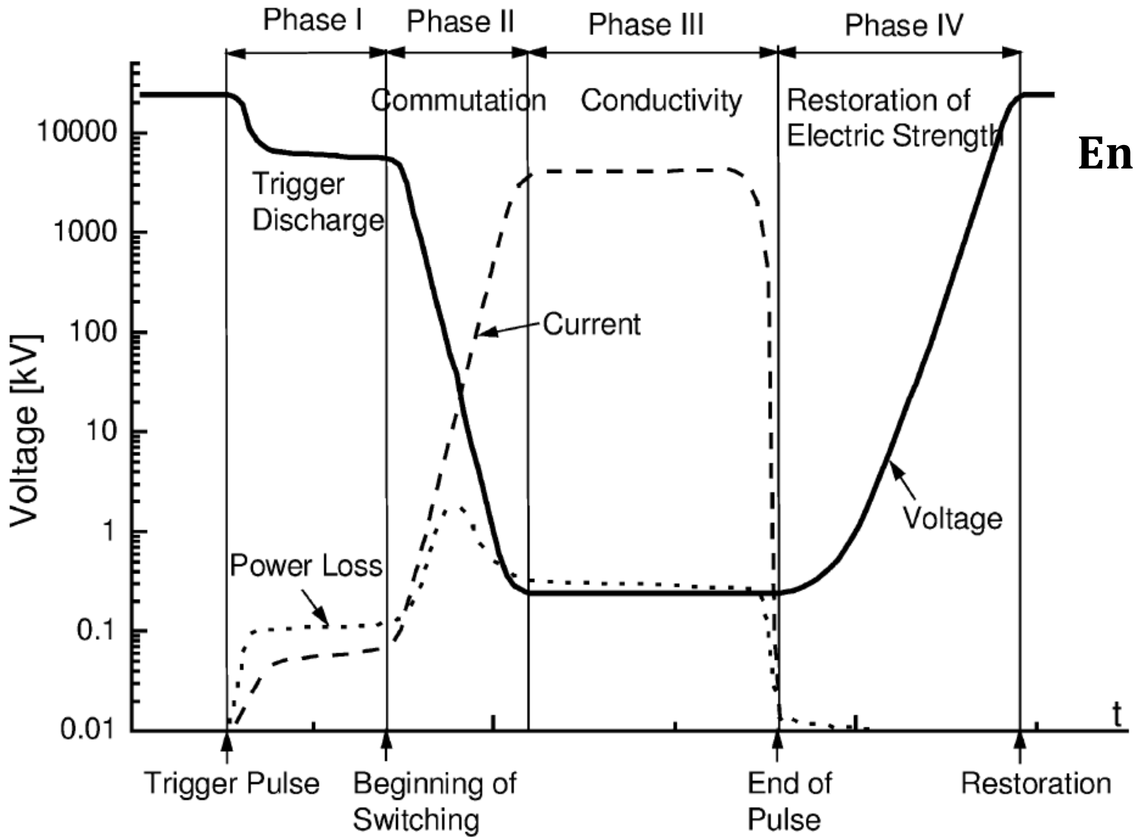


Fig. 4.2. Evolution of voltage, current, and power loss in a gas-filled switching system

$$\mathbf{Eng} = \int_0^{\tau_S} U(t)I(t)\,\mathrm{d}t$$

$$\approx \int_0^{\tau_S} U_M\left(1 - \frac{t}{\tau_S}\right) I_M \frac{t}{\tau_S}\,\mathrm{d}t$$

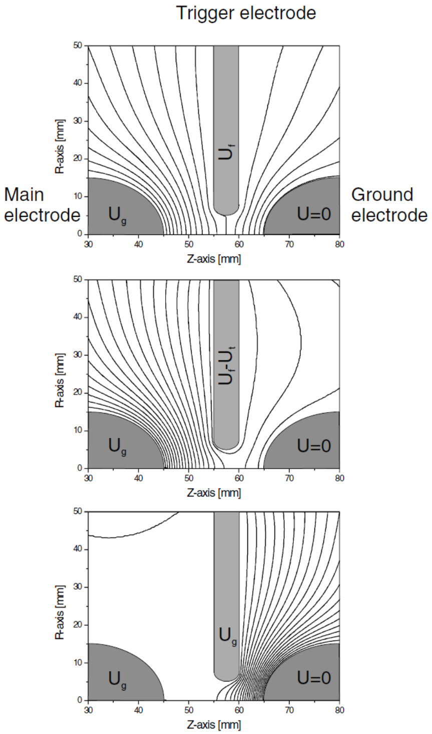
$$= U_M I_M \int_0^{\tau_S} \left(1 - \frac{t}{\tau_S}\right) \frac{t}{\tau_S}\,\mathrm{d}t$$

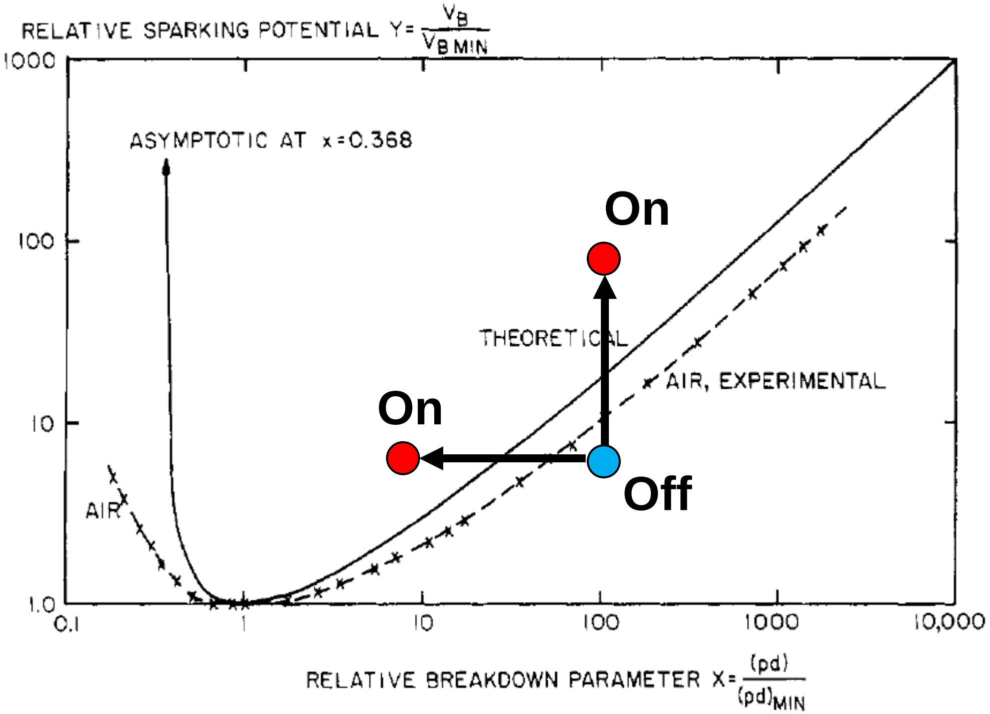
$$= \frac{U_M I_M \tau_S}{6} \approx 0.2 U_M I_M \tau_r$$

- **τ_S: switching time**
- **τ_r: pulse rise time ($\tau_r \approx 0.8\ \tau_r$)**
- **U_M/I_M: maximum voltage/current**

Gas-filled spark gaps

- **Breakdown due to:**
  - **Breakdown voltage has been exceeded.**
  - **Breakdown strength has been reduced by certain events (UV radiation, plasma diffusion, etc.)**

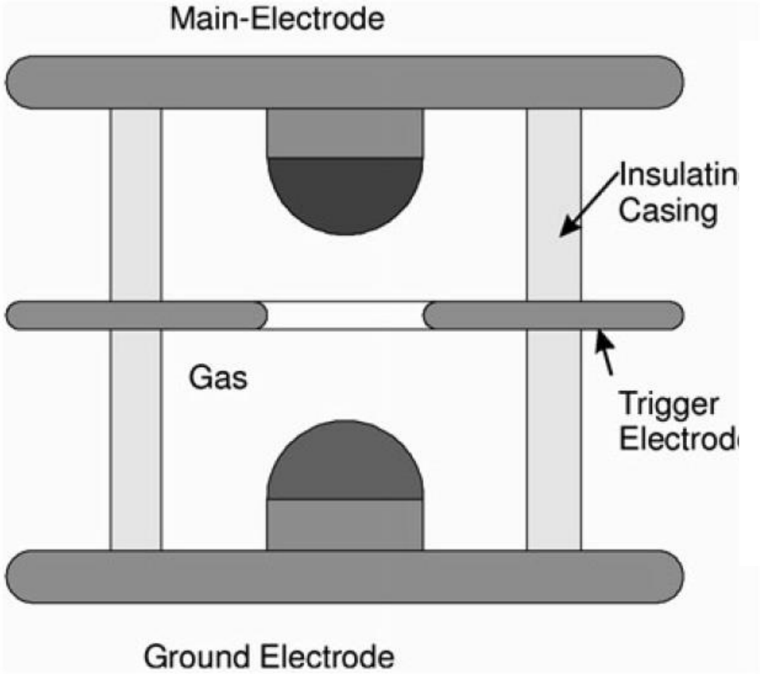


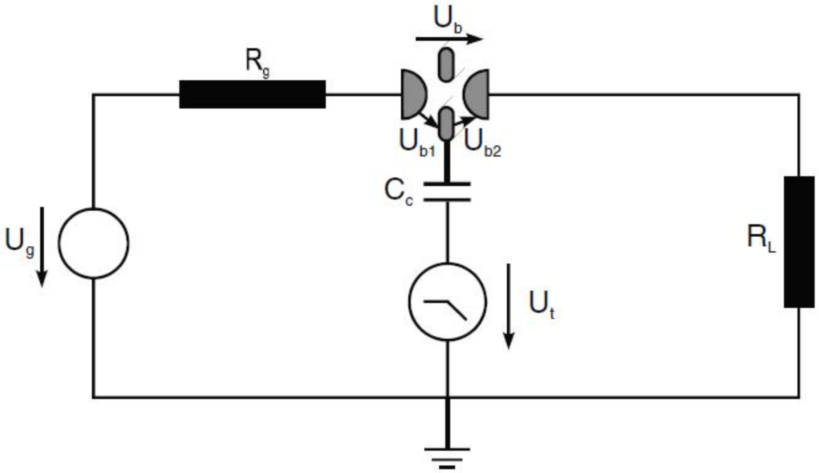


Gas-filled spark gaps

- **Important parameters:**
  - **Self-breakdown / hold-off voltage U_b.**
  - **Variance of U_b: determines the probability of breakdown.**
  - **Operation range: range of voltage**
    - **Held off with sufficiently low pre-breakdown possibility.**
    - **Reliably triggered.**
  - **Jitter.**
  - **Switching time t_s: decay of the impedance (resistance and inductance).**
  - **Pre-breakdown inductance and capacitance.**
  - **Repetition rate capability.**
  - **Lifetime and cost.**
- **Triggering can be achieved by (1) a High-voltage pulse; (2) a laser pulse.**

Spark-gap switch



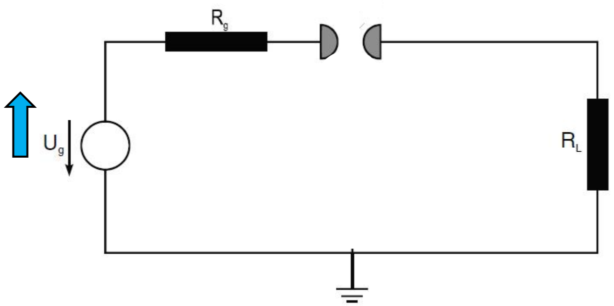


- U_g: generator voltage.
- U_t: triggering voltage.
- R_g: generator impedance.
- R_L: load impedance.
- U_b: breakdown voltage.
- U_{b1}/U_{b1} : breakdown voltage of the partial gaps.
- C_c: coupling capacitor.

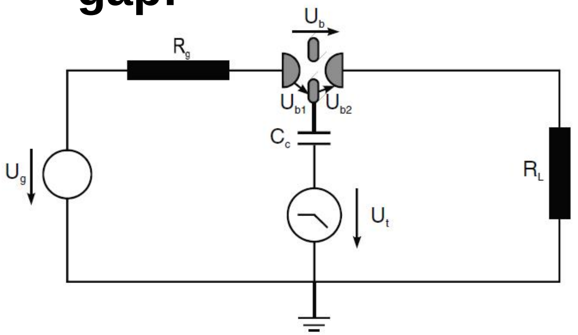
Spark-gap switch

- **Longitudinal overvoltage triggering – if the voltage amplitude of the trigger pulse added to the applied operating voltage is sufficient to breakdown a partial gap.**
- **Ignition of the 2nd partial gap occurs if its breakdown voltage is less than the operating voltage.**
- **Cc is used to decouple the trigger source from the generator.**
- **Cc >> Cb1 =>** $\boldsymbol{U_t(t=0) = U_g \frac{C_{\mathrm{b1}}}{C_c + C_{\mathrm{b1}}} \approx 0}$

  - **Longitudinal overvoltage triggering:**



  - **Ignition of the 2nd partial gap:**



Spark-gap switch

$U_g + |U_t| > U_{\mathrm{b1}}$ (longitudinal overvoltage triggering)

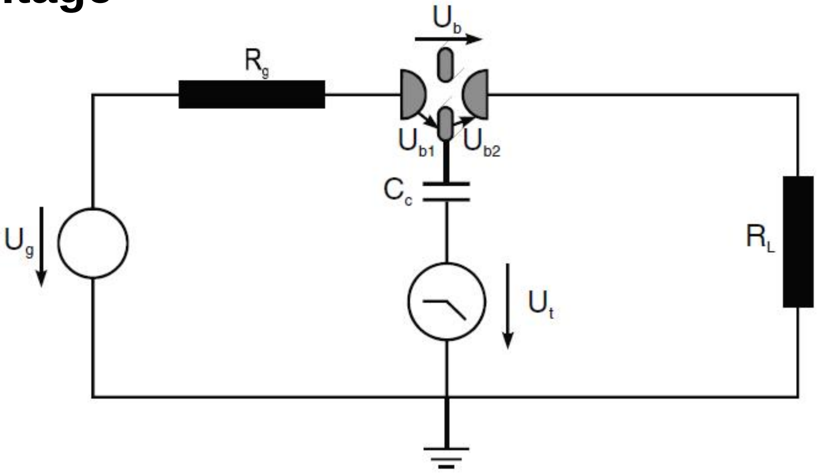
$|U_t| < U_{\mathrm{b2}}$ (U$_t$ doesn't cause breakdown @ gap2)

$U_g > U_{\mathrm{b2}}$

$U_g \geq U_{\mathrm{b2}} => U_{g,\mathrm{min}} = U_{\mathrm{b2}}$

$|U_{t,max}| \leq U_{\mathrm{b2}} => |U_{t,max}| = u_{\mathrm{b2}}$

$$U_{g,\mathrm{min}} + |U_{t,max}| = 2U_{\mathrm{b2}} > U_{\mathrm{b1}} => U_{\mathrm{b2}} = \frac{1}{2}U_{\mathrm{b1}}$$

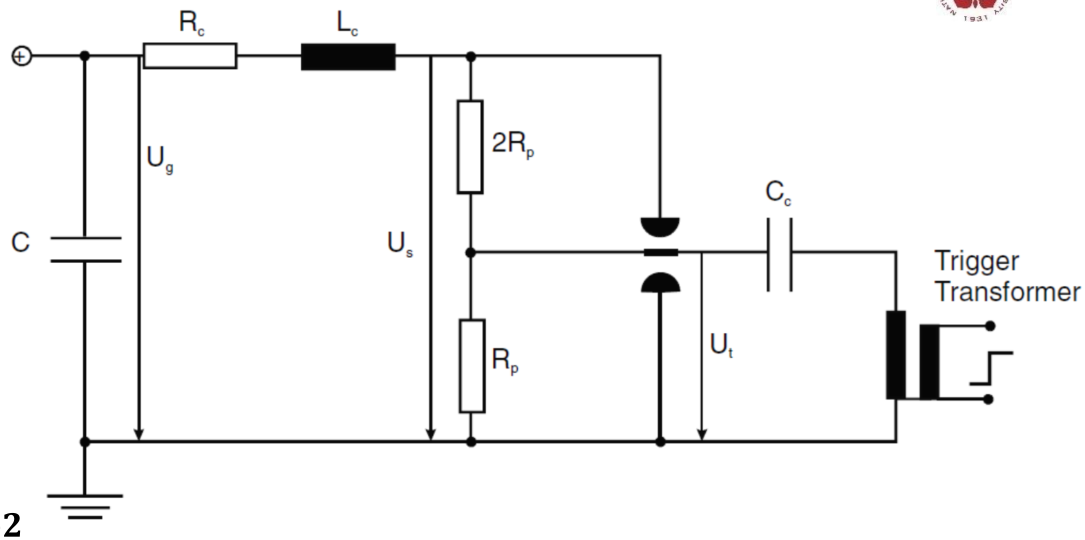


- For a symmetric spark gap configuration, the trigger electrode should be positioned at 2/3 of the gap spacing from the main electrode.

$$U_g < U_{\mathrm{b1}} = 2U_{\mathrm{b2}}$$

$$U_{\mathrm{b2}} < U_g < U_{\mathrm{b2}} \qquad \text{or} \quad \frac{1}{3}U_b < U_g < \frac{2}{3}U_b$$

Three-electrode trigger set-up



$$\frac{2}{3}U_g < U_{\mathrm{b1}}$$

$$U_g > U_{\mathrm{b2}}$$

$$U_g + |U_t| > U_{\mathrm{b1}}$$

$$|U_t| < U_{\mathrm{b2}}$$

$$U_g \geq U_{\mathrm{b2}} => U_{g,\min} = U_{\mathrm{b2}}$$

$$\left|U_{t,max}\right| \leq U_{\mathrm{b2}} => \left|U_{t,max}\right| = u_{\mathrm{b2}}$$

$$U_{g,\min} + \left|U_{t,max}\right| = 2U_{\mathrm{b2}} > U_{\mathrm{b1}} => U_{\mathrm{b2}} = \frac{1}{2}U_{\mathrm{b1}}$$

$$\frac{2}{3}U_g < U_{\mathrm{b1}} = 2U_{\mathrm{b2}} => \frac{1}{3}U_g < U_{\mathrm{b2}} \text{ or } U_g < 3U_{\mathrm{b2}}$$

$$U_{\mathrm{b2}} < U_g < 3U_{\mathrm{b2}} \qquad U_b = U_{\mathrm{b1}} + U_{\mathrm{b2}} = 2U_{\mathrm{b2}} + U_{\mathrm{b2}} = 3U_{\mathrm{b2}}$$

$$\text{or } \frac{1}{3}U_b < U_g < U_b$$

Potential distribution of a spark-gap

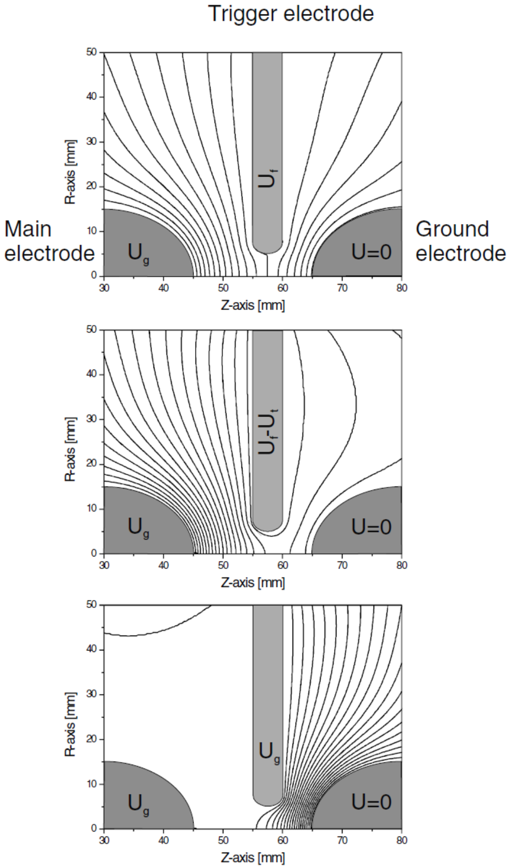
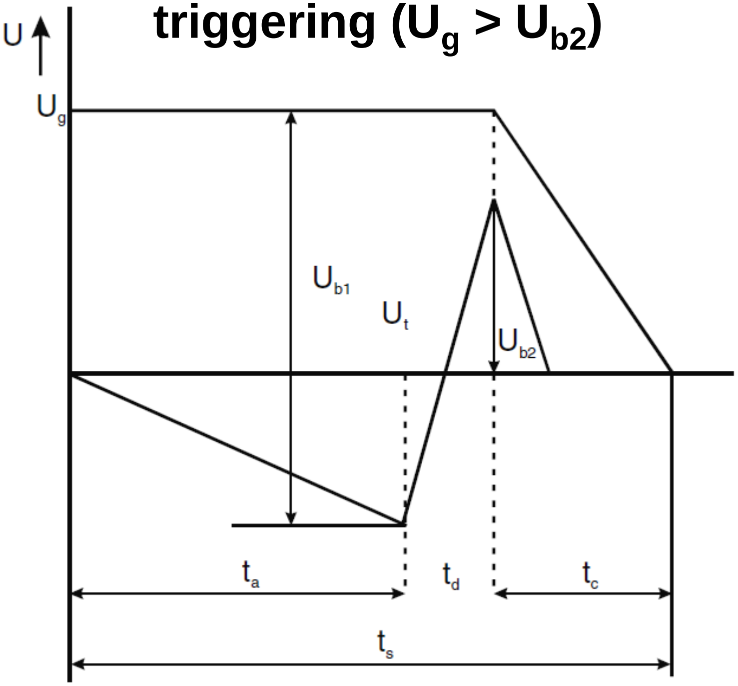


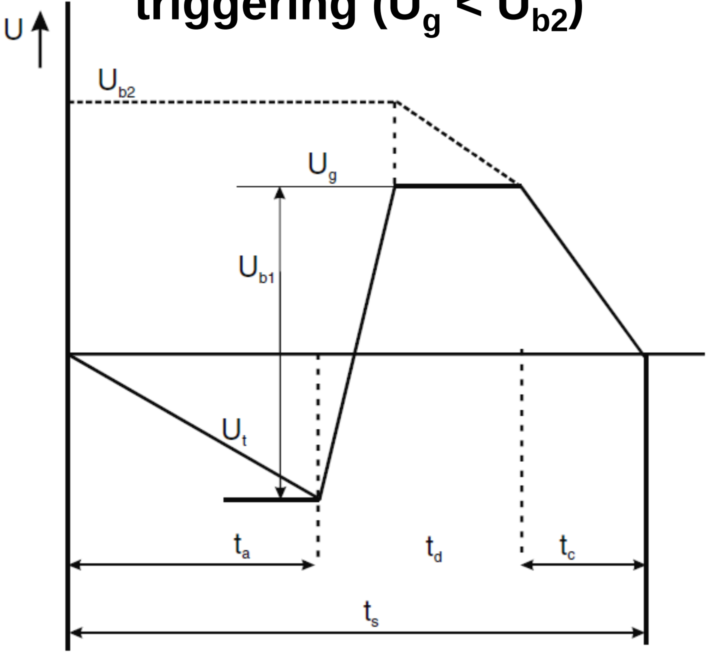
Fig. 4.6. Potential distribution in a three-electrode spark gap switch, before ignition (*top*), after application of a trigger signal (*centre*), and after breakdown of the first gap (*bottom*)

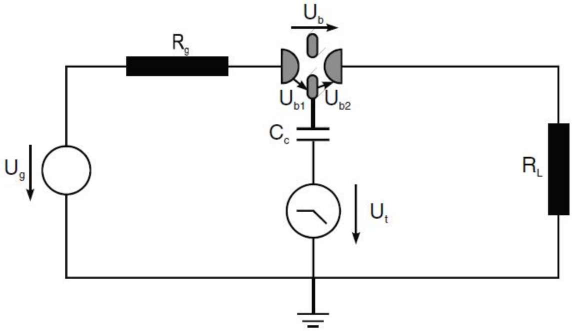
Longitudinal triggering

- **Longitudinal-overvoltage triggering ($U_g > U_{b2}$)**



- **Longitudinal-plasma triggering ($U_g < U_{b2}$)**

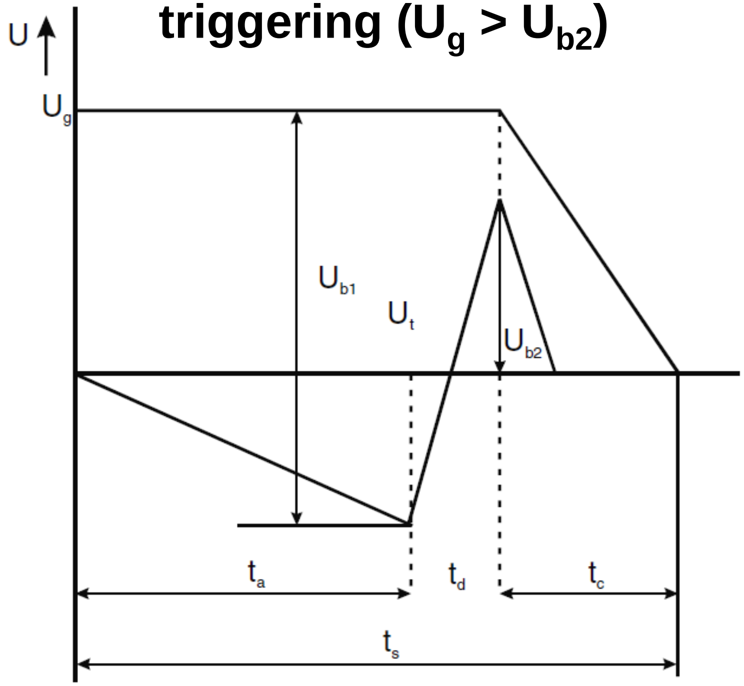




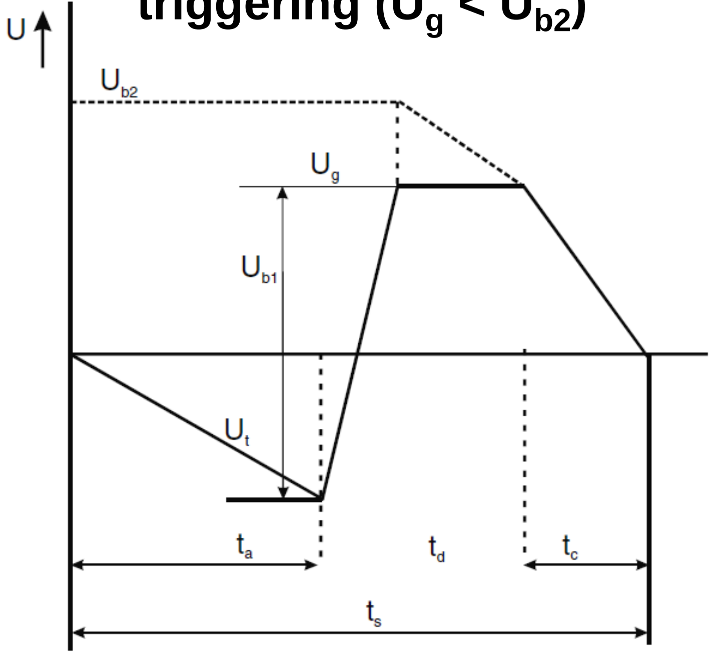
- **t_a: trigger actuating time.**
- **t_d: switching delay.**
- **t_c: commutation time.**
- **t_s: switching time.**

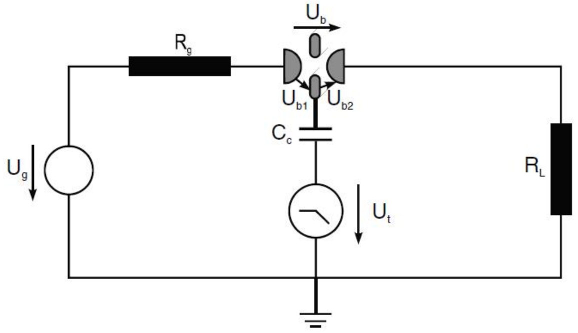
Longitudinal triggering

- **Longitudinal-overvoltage triggering ($U_g > U_{b2}$)**



- **Longitudinal-plasma triggering ($U_g < U_{b2}$)**

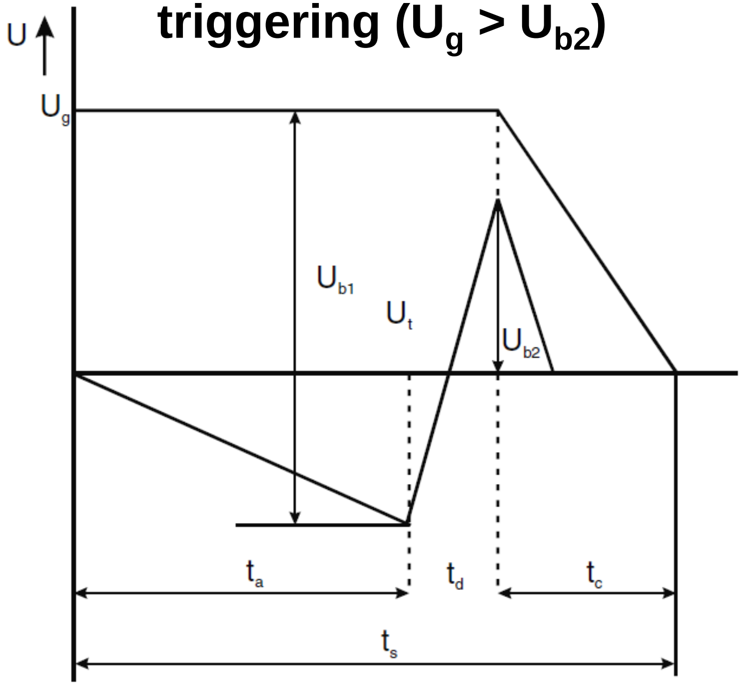




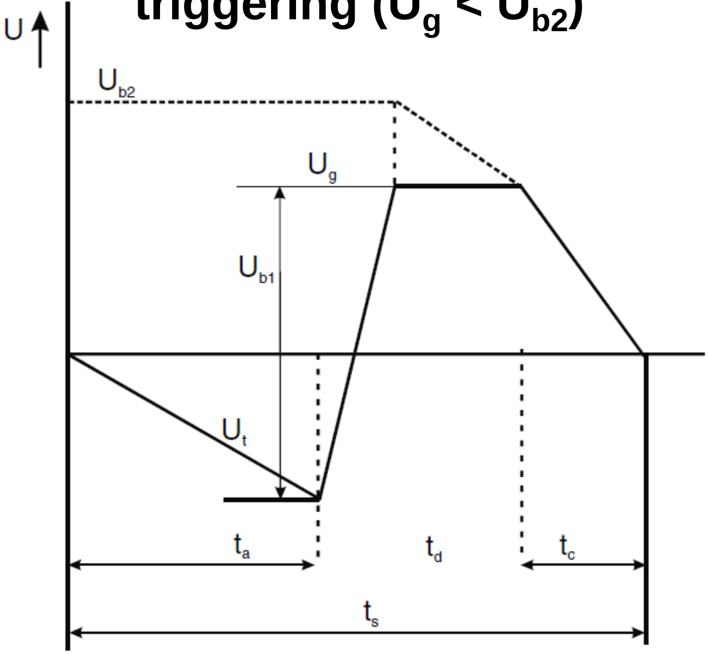
- **2^{nd} gap can fire only if its breakdown strength is continuous reduced by UV radiation from the spark channel plasma of the 1^{st} gap. => much larger switch delay time.**

Longitudinal triggering

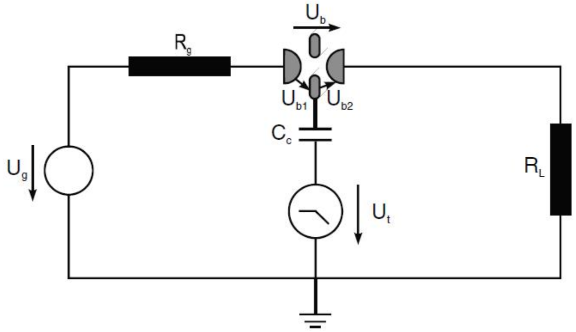
- **Longitudinal-overvoltage triggering ($U_g > U_{b2}$)**



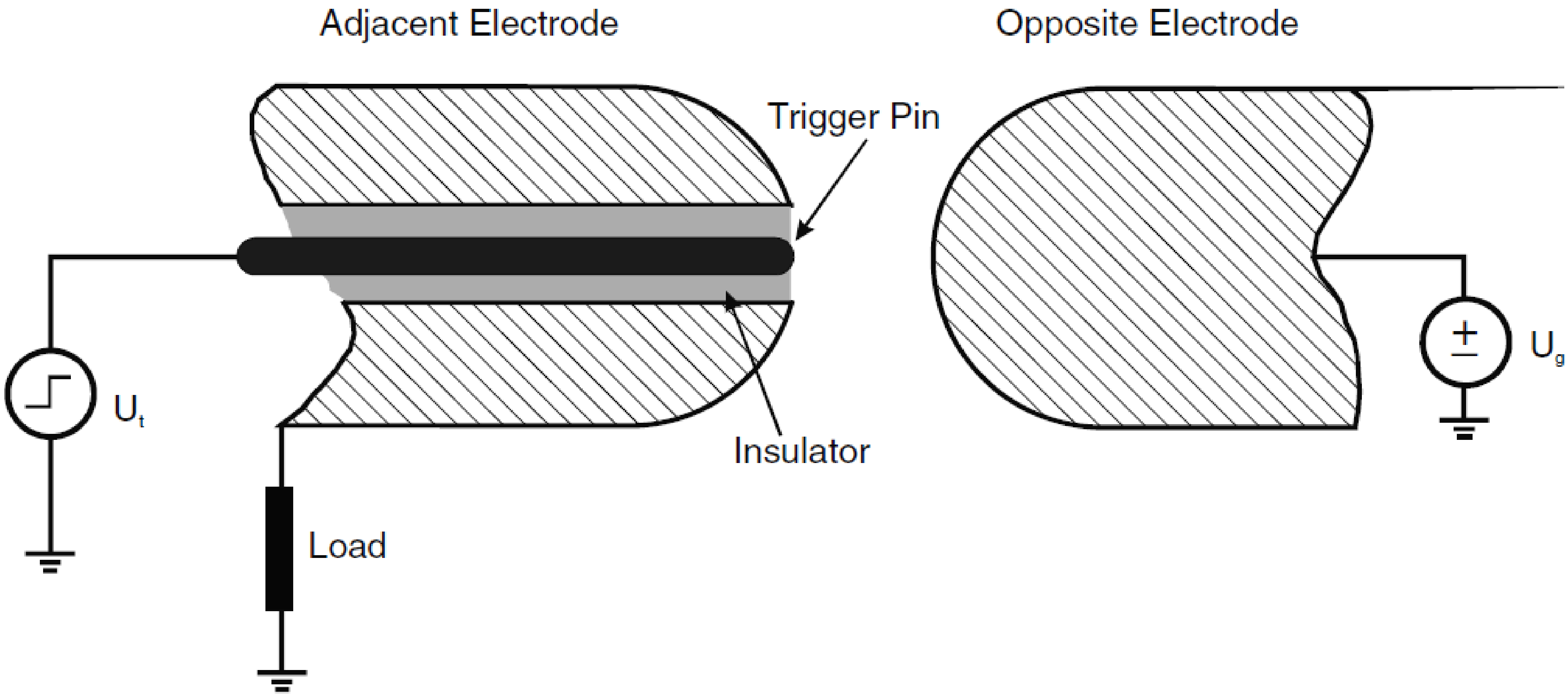
- **Longitudinal-plasma triggering ($U_g < U_{b2}$)**



- **Longitudinal trigger can occur only for opposite polarities of the operating and triggering voltages.**



Trigatron spark gap



- **Best trigger performance: trigger and operation voltage are opposite, i.e.,**

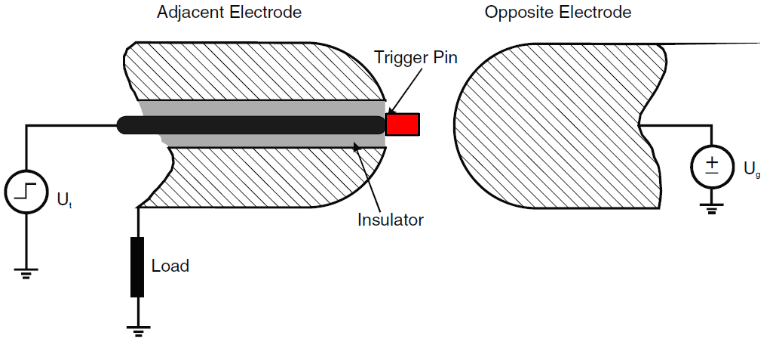
$$\boldsymbol{U_t \times U_g < 0}$$

$$\boldsymbol{U_g \sim (80 \sim 99\%) U_b}$$

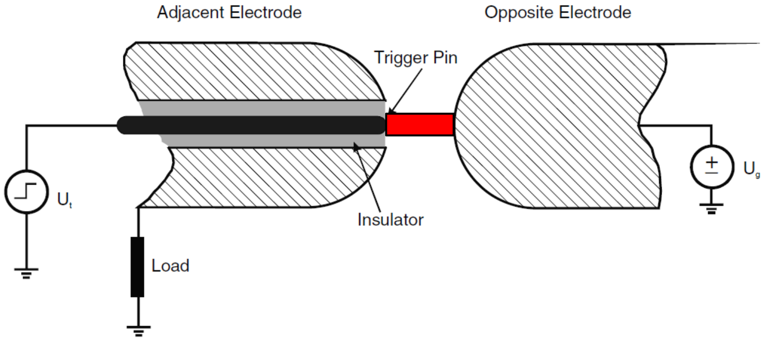
- **U_g~50% U_b is possible, but with large delay and jitter.**

Trigatron spark gap – $U_t \times U_g < 0$

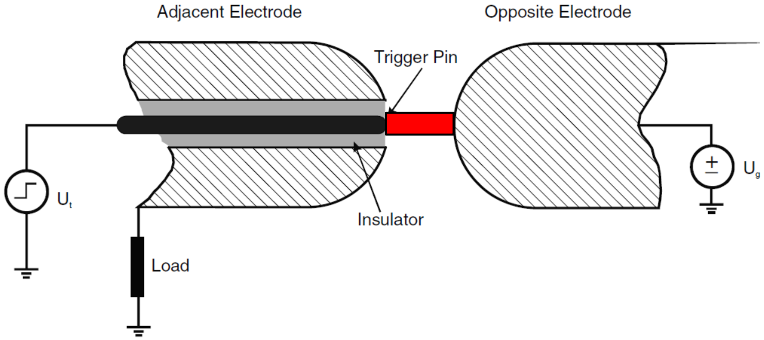
- **Step 1: Streamers begin to grow.**



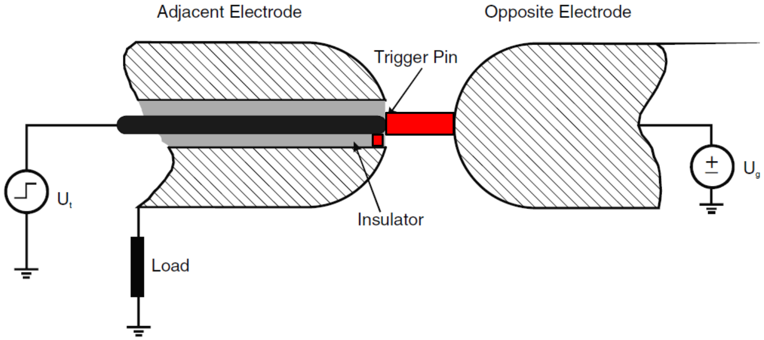
- **Step 2: ionization density in the channel to grow after streamer touch the electrode**



- **Step 3: conducting channel is formed.**

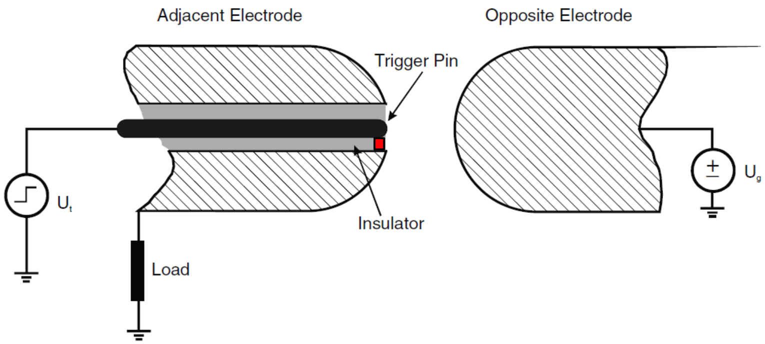


- **Step 4: two thermalized arcing connecting two electrode and pin.**

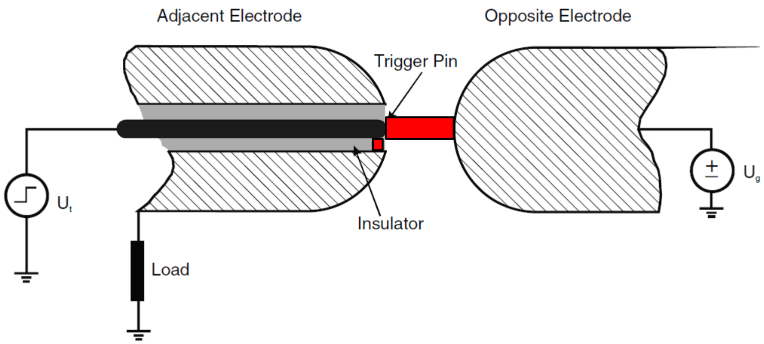


Trigatron spark gap – $U_t \times U_g > 0$

- **Step 1: breakdown between the trigger pin and the grounded electrode.**

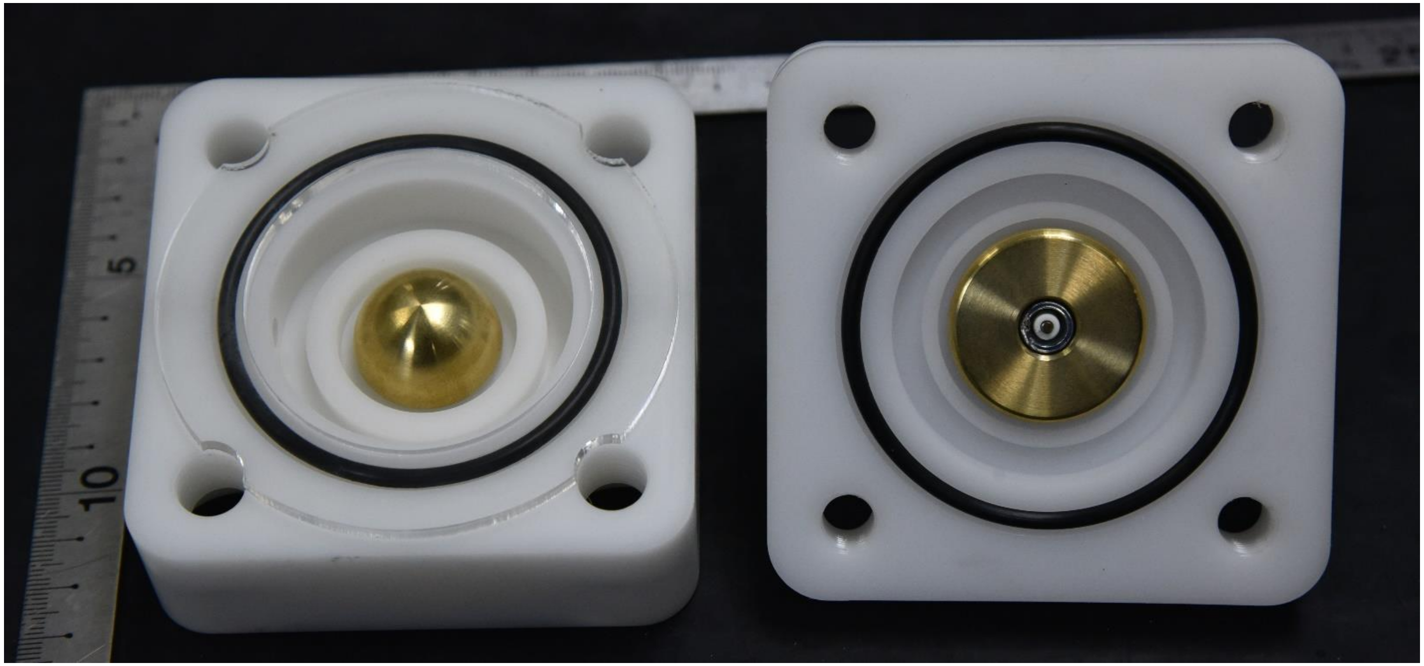


- **Step 2: breakdown between two main electrodes occurs due to the UV radiation emitted from the 1st arc.**

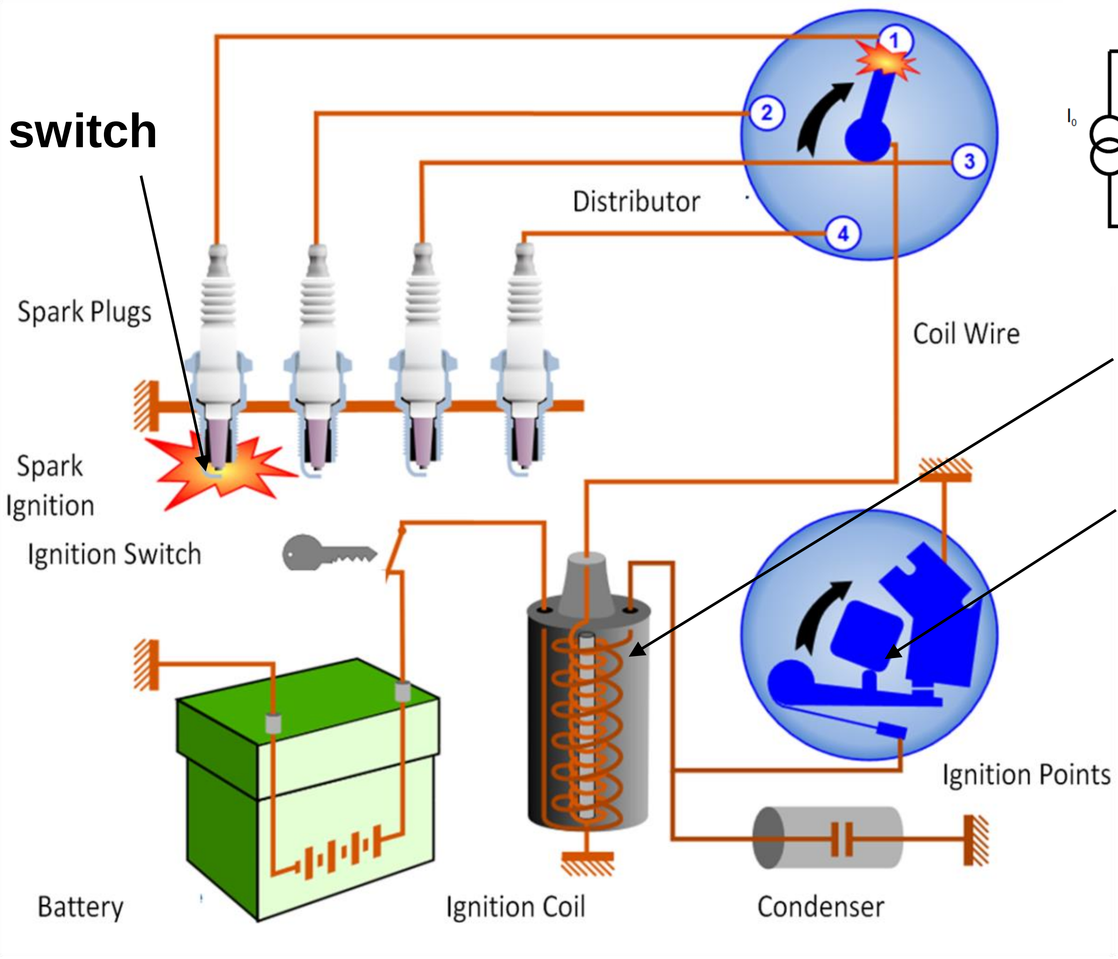


- **Breakdown is possible but with large delay and jitter.**

Spark plug is a Trigatron



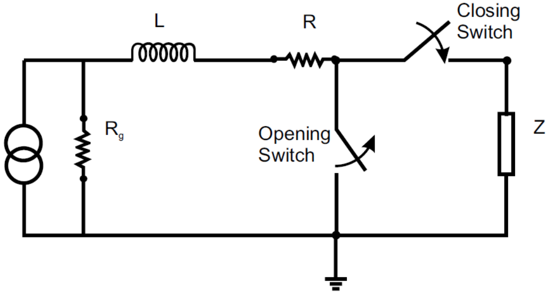
Spark plugs in cars are triggered by the inductive energy storage



Closing switch /load

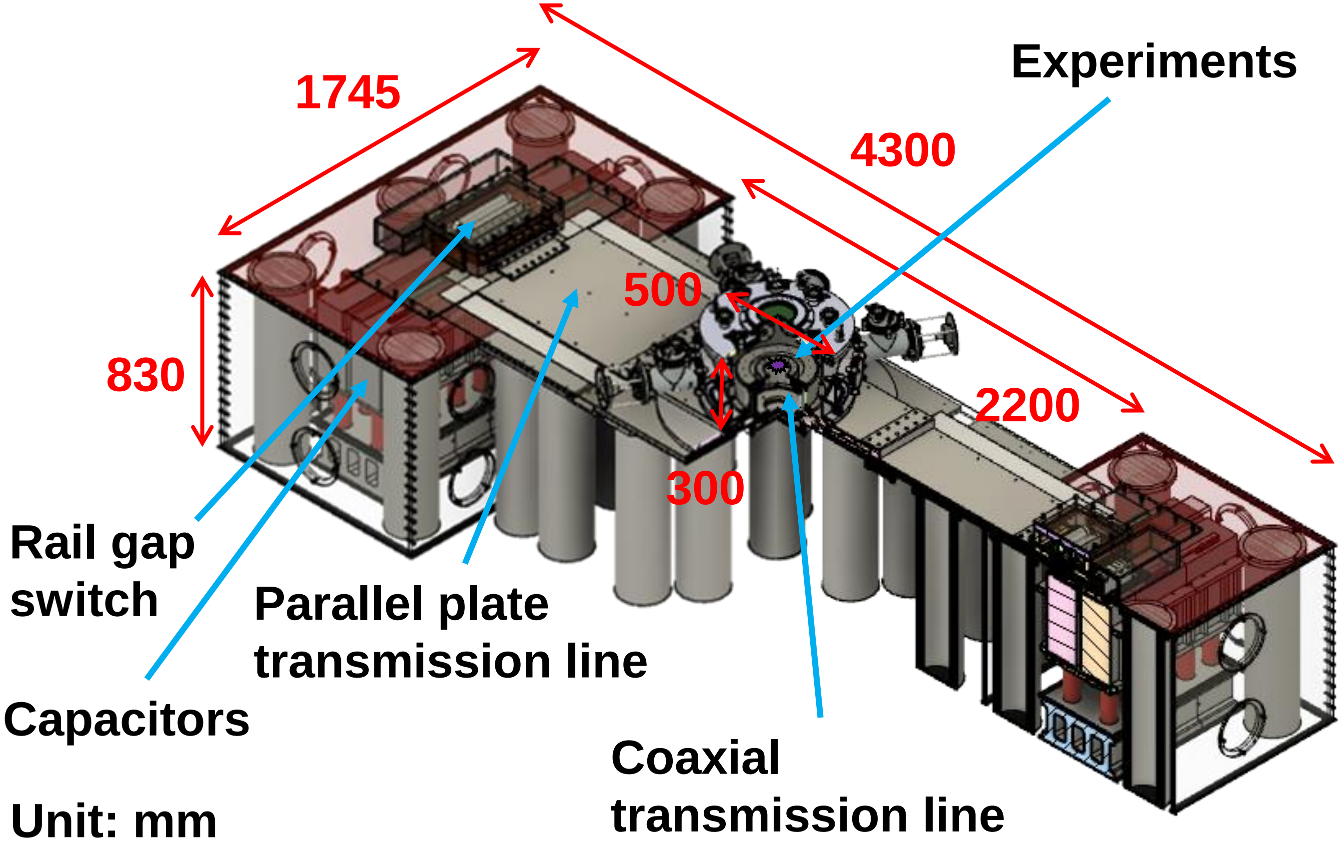
Inductive energy storage

Opening switch



https://images.saymedia-content.com/.image/t_share/MTc0Mjk3MzYyODg0MjA4NTA4/diy-auto-service-ignition-systems-operation-diagnosis-and-repair.png

The pulsed-power system in Pulsed-Plasma Laboratory



Experiments

Rail gap switch

Parallel plate transmission line

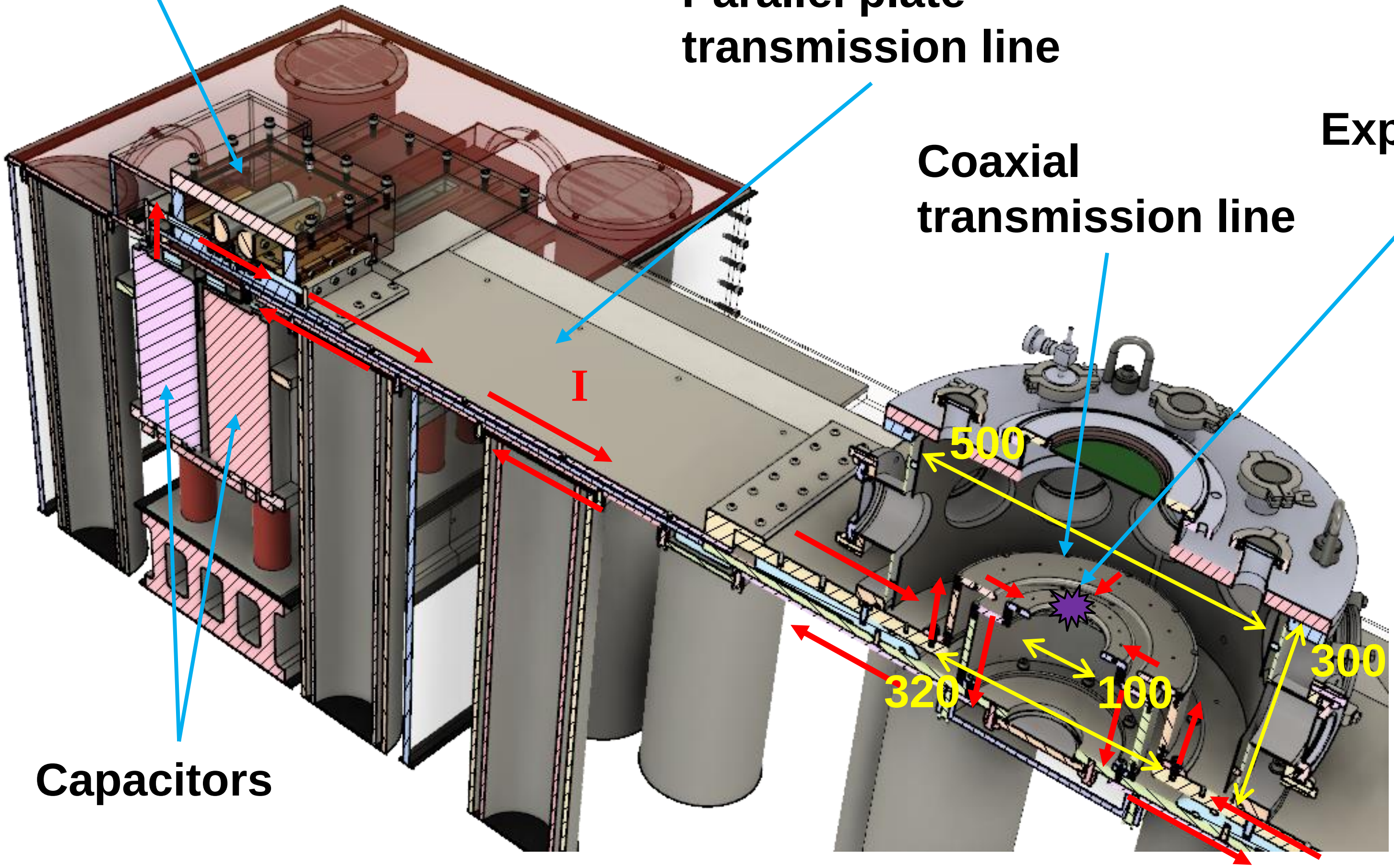
Capacitors

Coaxial transmission line

Unit: mm

- **A 1 kJ pulsed-power system at ISAPS, NCKU started being operated since September, 2019.**

Experiments will be taken placed at the center of the vacuum chamber



Rail gap switch

Parallel plate transmission line

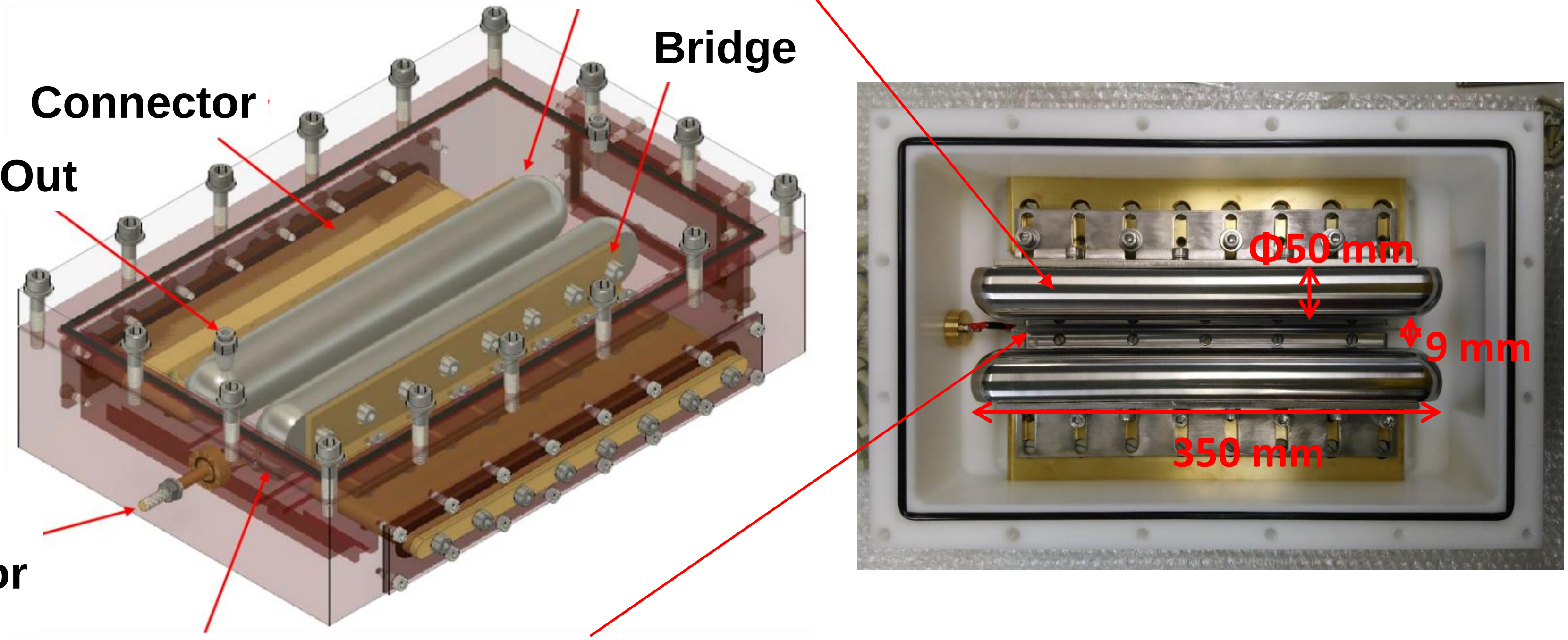
Coaxial transmission line

Experiments

Capacitors

Unit: mm

Low inductance rail-gap switches are used



Electrode

Bridge

Connector

Gas Out

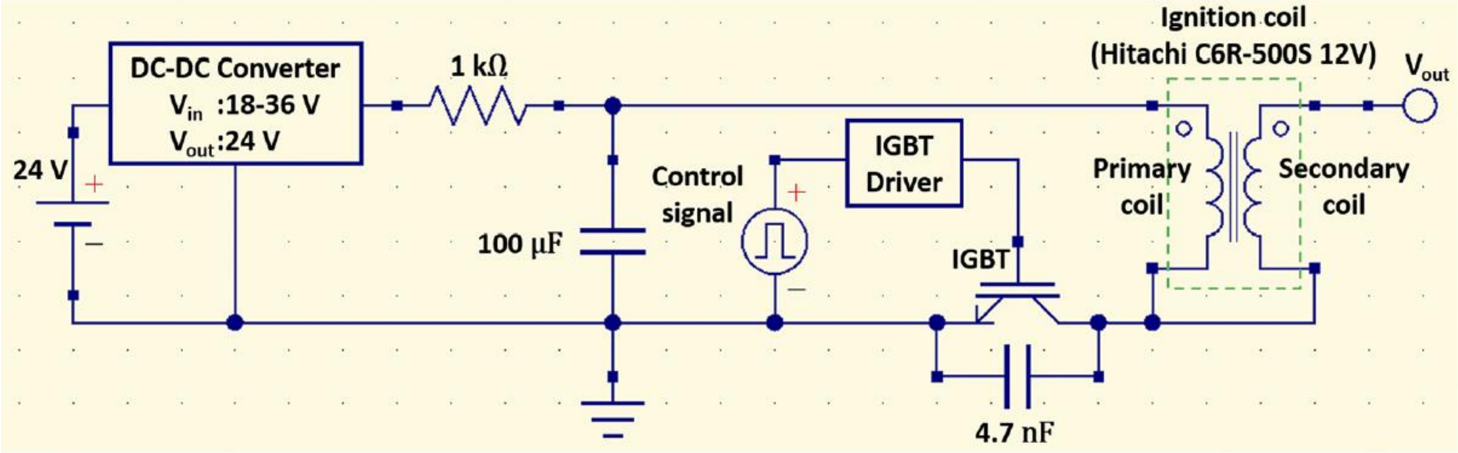
Trigger Connector

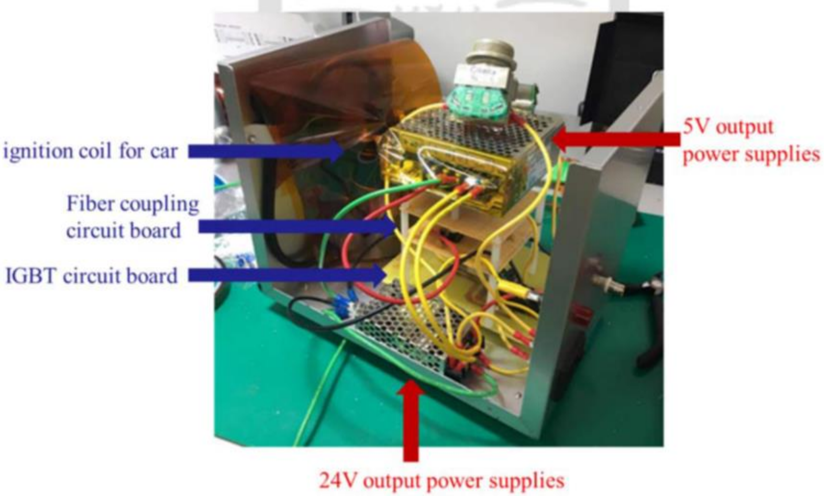
Knife edge trigger electrode

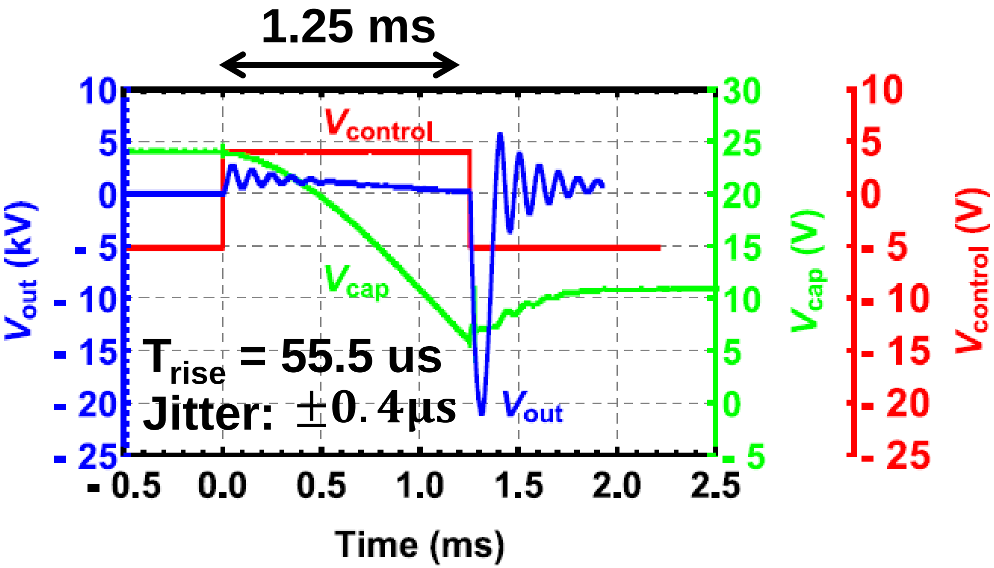
- The switch is pressurized with nitrogen gas (1~3 atm).
- Multi-channel discharges between two rail-like electrodes will be triggered by a fast trigger pulse generator (rising speed > 5kV/ns).

P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)
R.Verma etc., Rev. Sci. Instrum. 85, 095117 (2014)

A slow trigger pulse generator was built using a ignition coil for cars

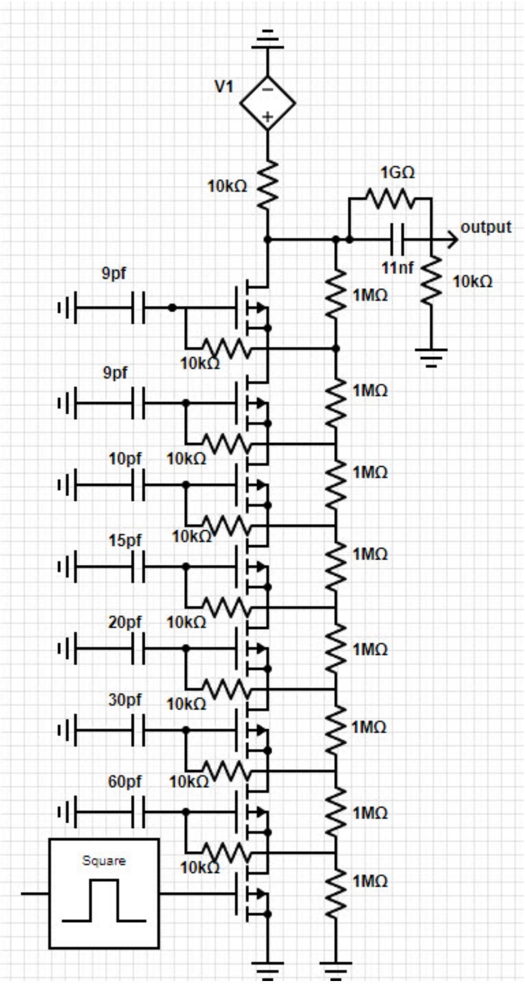


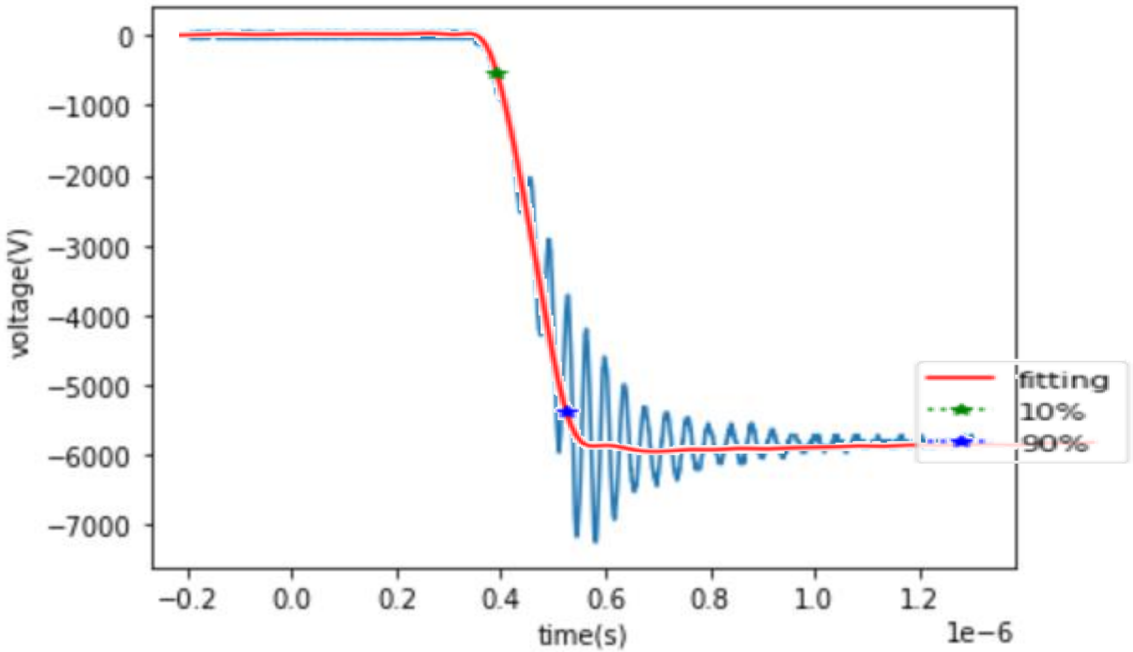




P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)

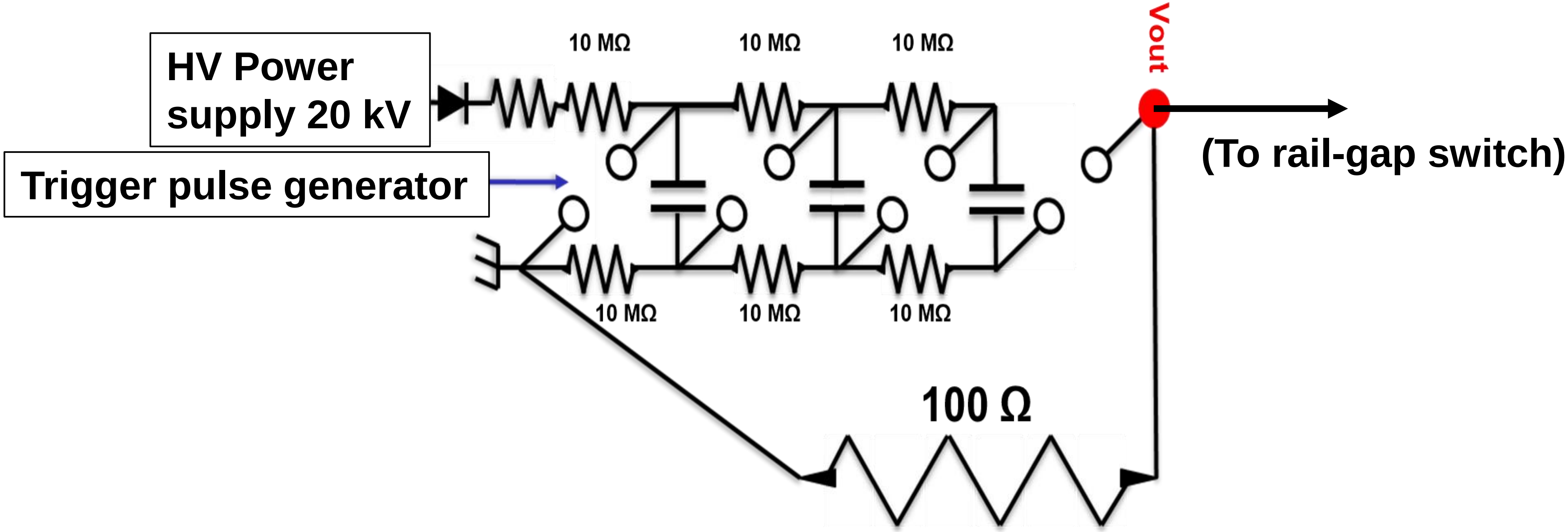
Many MOSFET connected in series can be used to provide a fast high-voltage triggering pulse





T_{rise}=140 ± 1 ns

A three-stage Marx generator is used to provide a fast high voltage trigger pulse

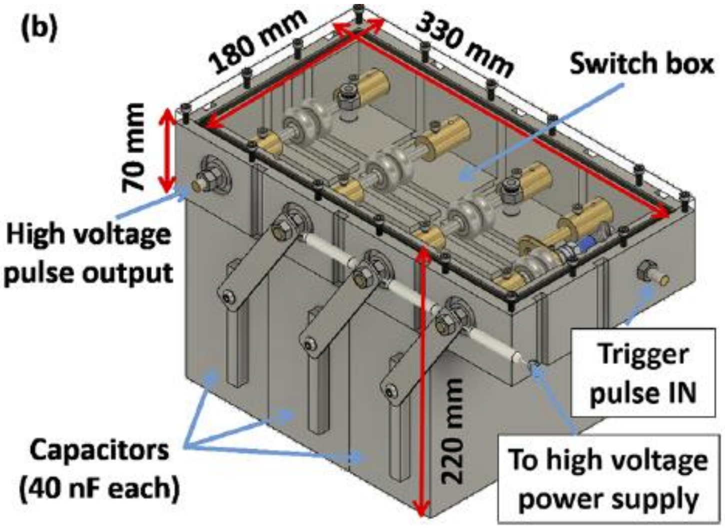


- **In a Marx generator, capacitors are connected in parallel when they are being charged.**
- **Capacitors in the Marx generator are connected in series during discharge.**

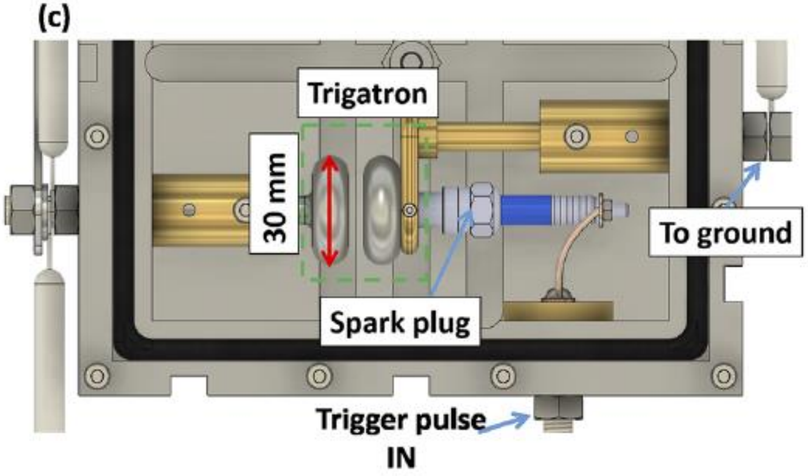
$$\boldsymbol{V_{\text{out, ideal}} = -N \times V_0 = -3 \times 20\ \text{kV} = -60\ \text{kV}}$$

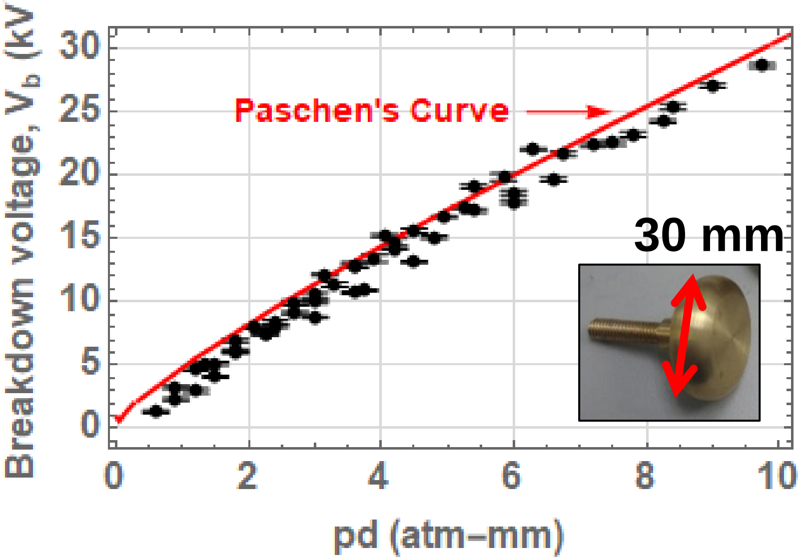
The falling speed of high voltage pulse from the Marx meets the requirement for triggering rail-gap switches

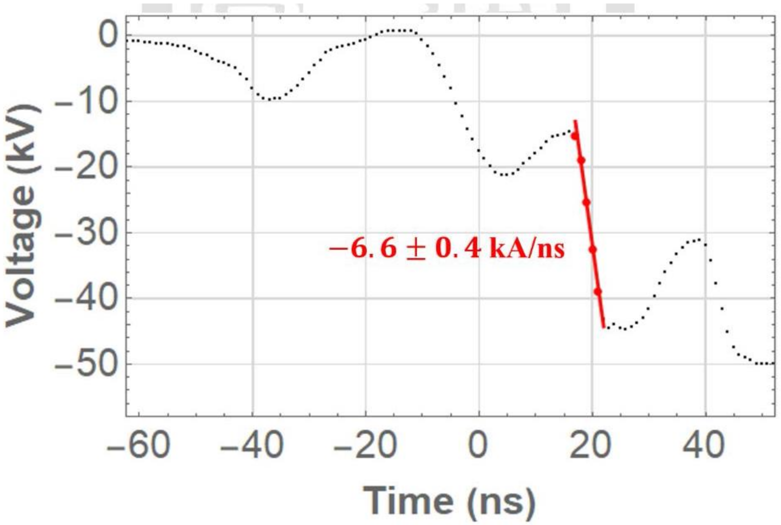
(b)



(c)







P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)

Multistep trigger system is used

TTL

Fiber Transmitter

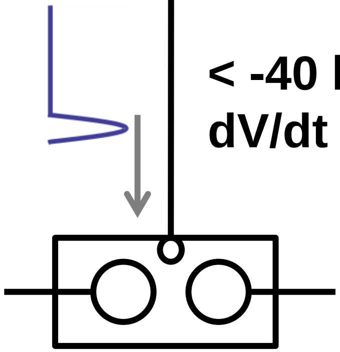
Optical fiber

Slow Trigger generator

-20 kV
t_{rise}=55 us

Marx Generator

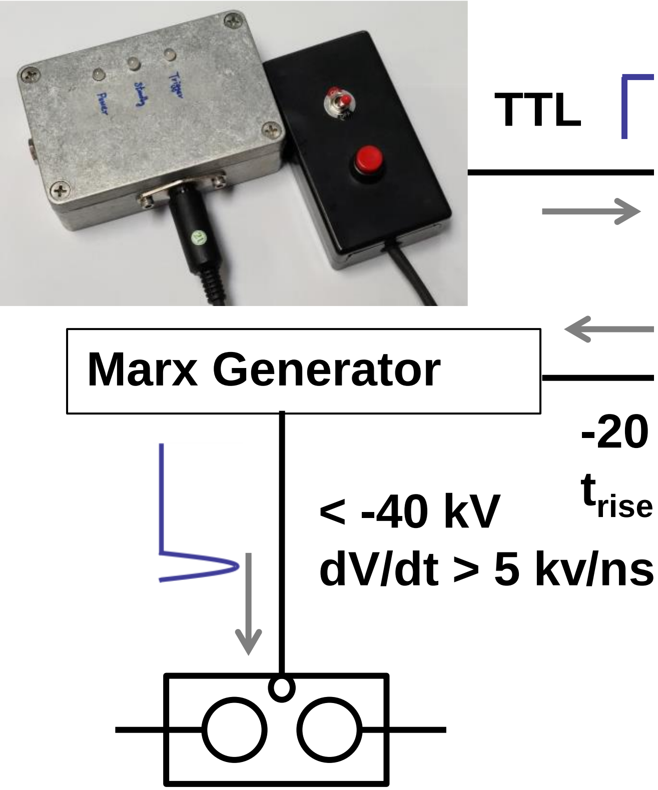
< -40 kV
dV/dt > 5 kv/ns



Spark-gap switch

- **At least 3 channels were generated in each shot.**

Multistep trigger system is used



TTL

Marx Generator

-20

t_{rise}

< -40 kV

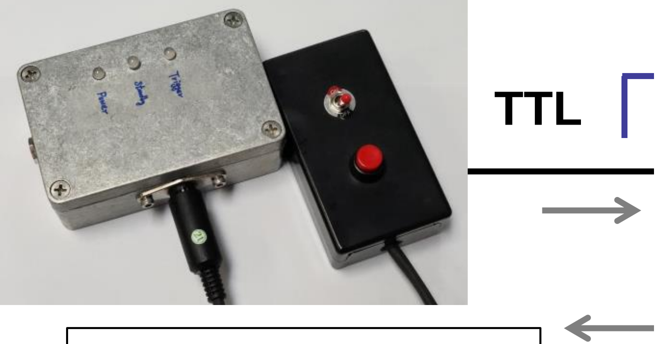
dV/dt > 5 kv/ns

Spark-gap switch

- **At least 3 channels were**

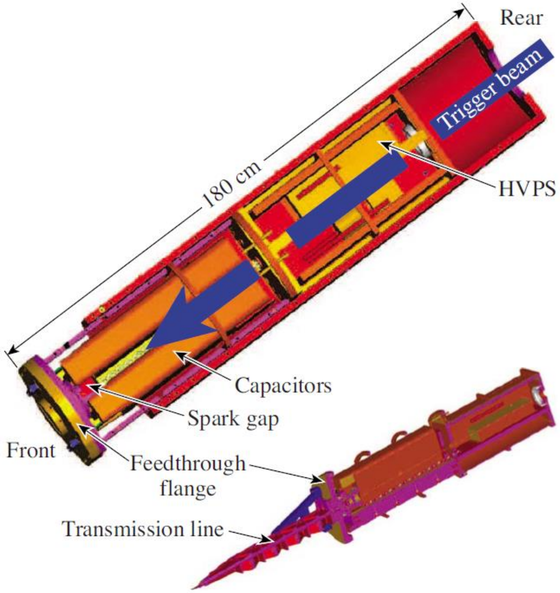
https://goods.ruten.com.tw/item/show?21941221827043

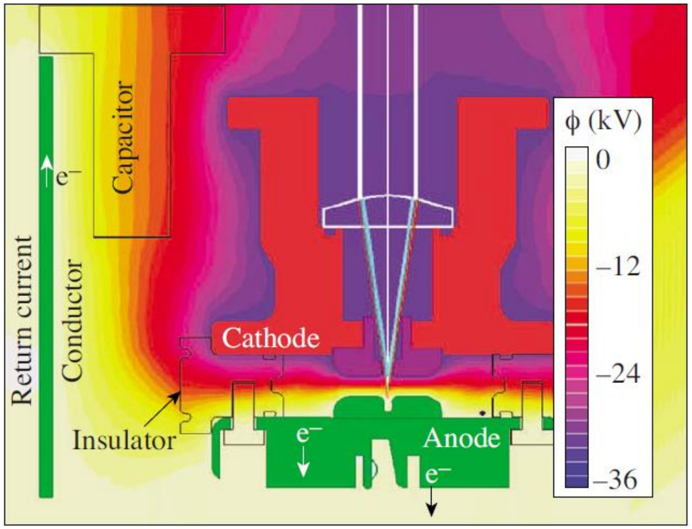
Multistep trigger system is used



https://goods.ruten.com.tw/item/show?21941221827043

Magneto-inertial fusion electrical discharge system

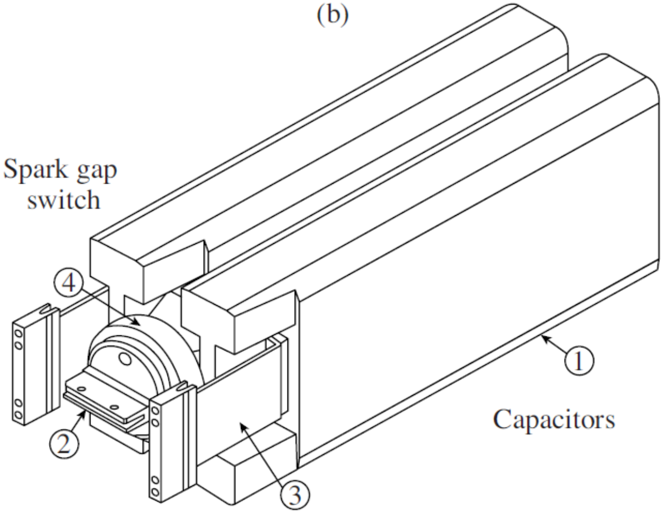


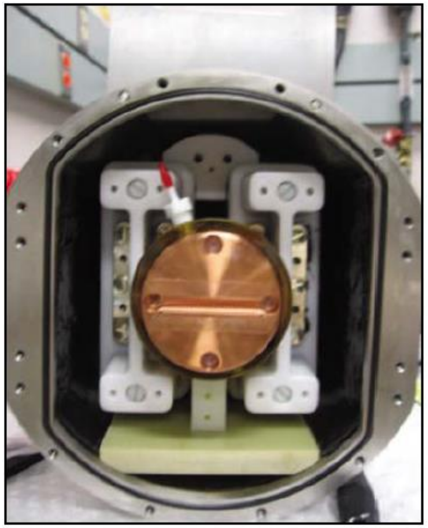


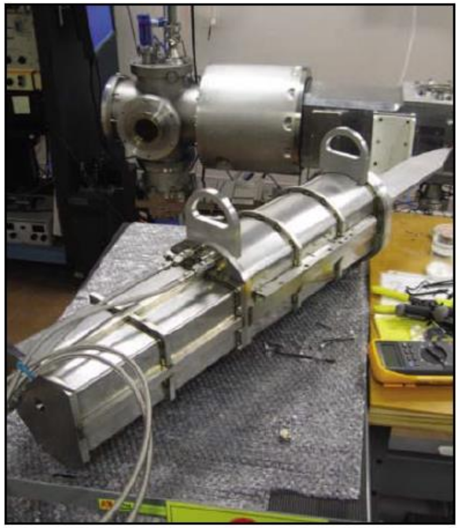
6-7 ns pulse
60 mJ @ 266 nm
300 mJ @ 532 nm
150 mJ @ 1064 nm

Delay: < 1 ns
Jitter: < 1 ns

(b)



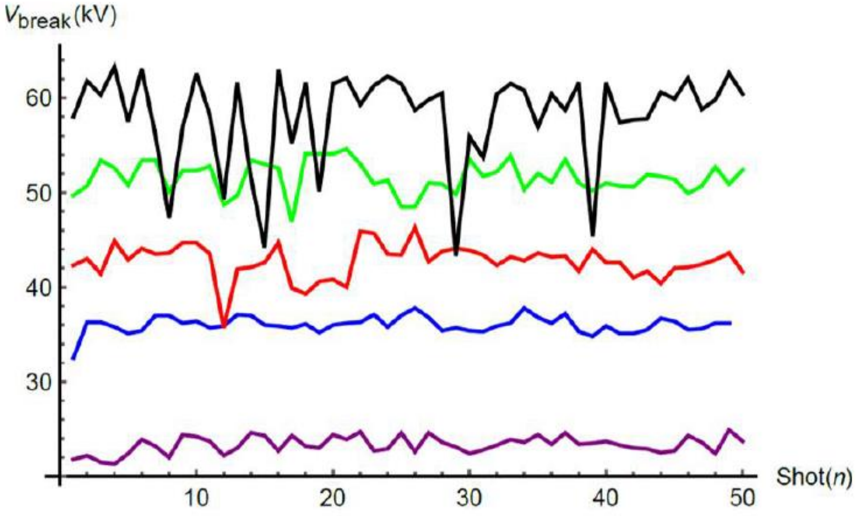


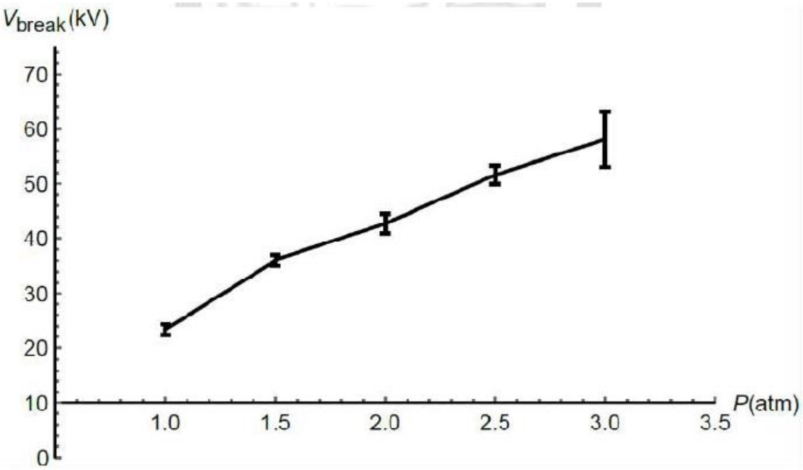


O. V. Gotchev, etc., Rev. Sci. Instrum. **80**, 043504 (2009)

Breakdown uncertainty increases with a larger holding voltage

	Trigatron With Spacer	Trigatron No Spacer	SparkGap With 2 Spacer	SparkGap With 1 Spacer	SparkGap No Spacer
Gap	6 mm	9 mm	6 mm	9 mm	12 mm
Avg	17.49	24.55	19.21	28.86	35.83
Std	0.60	0.32	0.39	1.50	1.43
Max	18.70	25.10	19.80	32.40	38.60
Min	16.80	23.80	18.40	26.10	33.00

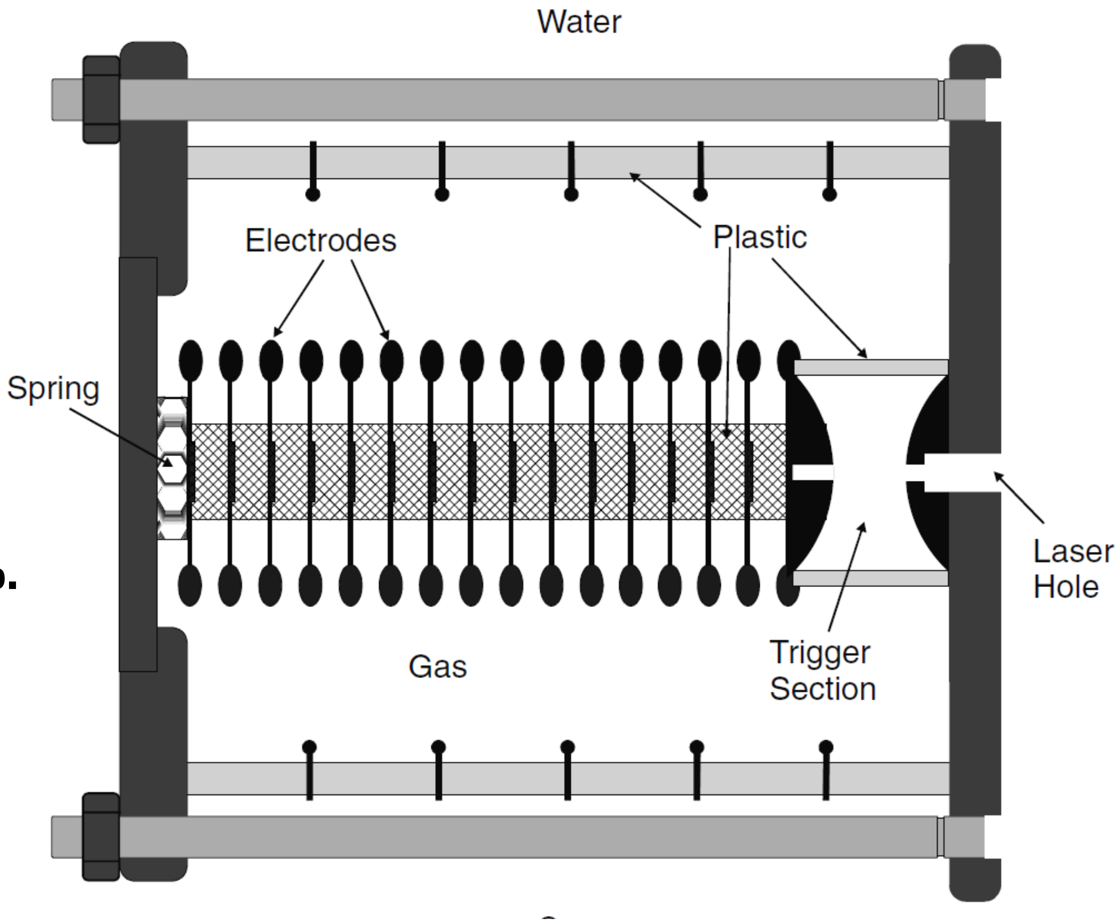




Sheng-Hua Yan, Master Thesis 2018

Multistage spark-gap switch with laser triggering

- Simply scaling a three-electrode spark gap to multimegavolt operating voltages would lead to large gaps, making the jitter and inductance unacceptably high.
- Operating voltage of up to 6 MV and a switch current of 0.5 MA.
- It consists of 15 equal spark gaps and a trigger section.
- The operating voltage is around 90% of the self-breakdown value with a prefire probability of 0.1 %.
- The gap capacitances are small, 20 % of the operating voltage occurs across the trigger section.



Multistage spark-gap switch with laser triggering

- The switch is 68 cm long and 61 m in diameter.
- The 1st gap is 5.7 cm and a UV laser pulse (KrF) with a 25 mJ pulse energy is necessary.
- ~1 ns after the laser pulse, a breakdown occurs in thetrigger gap and the voltage increases across the remaining gaps rapidly. An ignition wave propagates to the other gaps and ignites them sequentially.
- Total inductance: 400 nH; Trigger delay: 20 ns; jitter <0.4 ns.

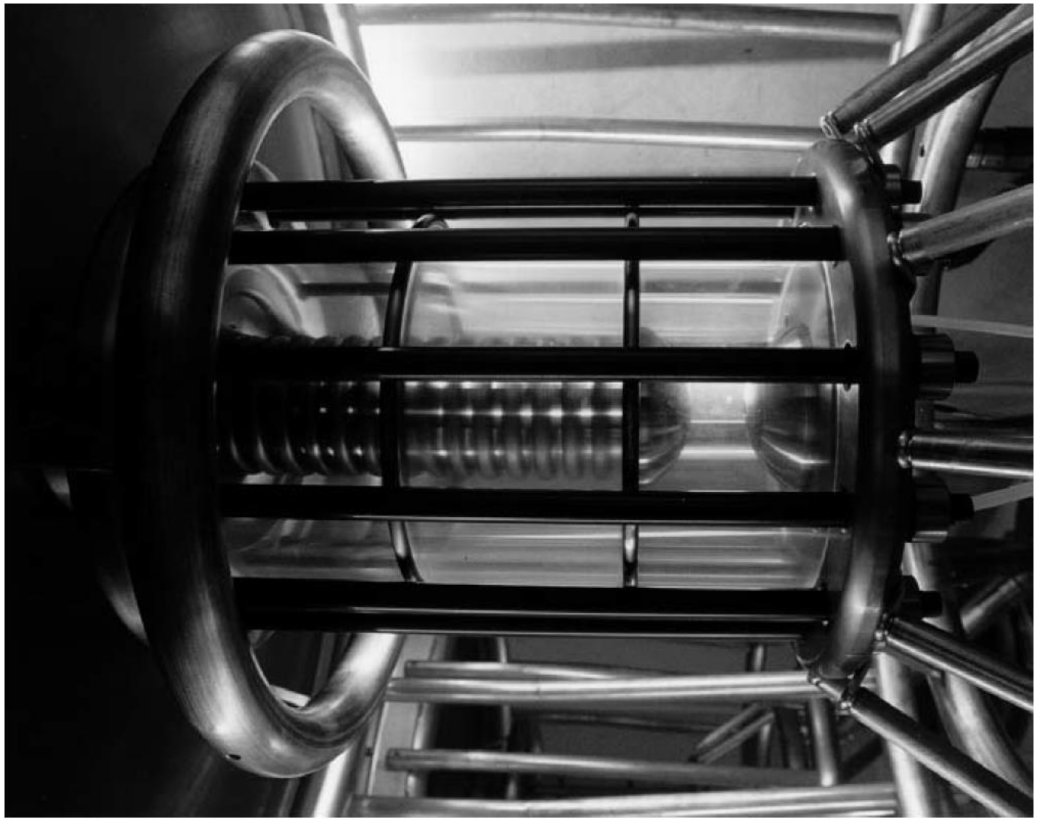
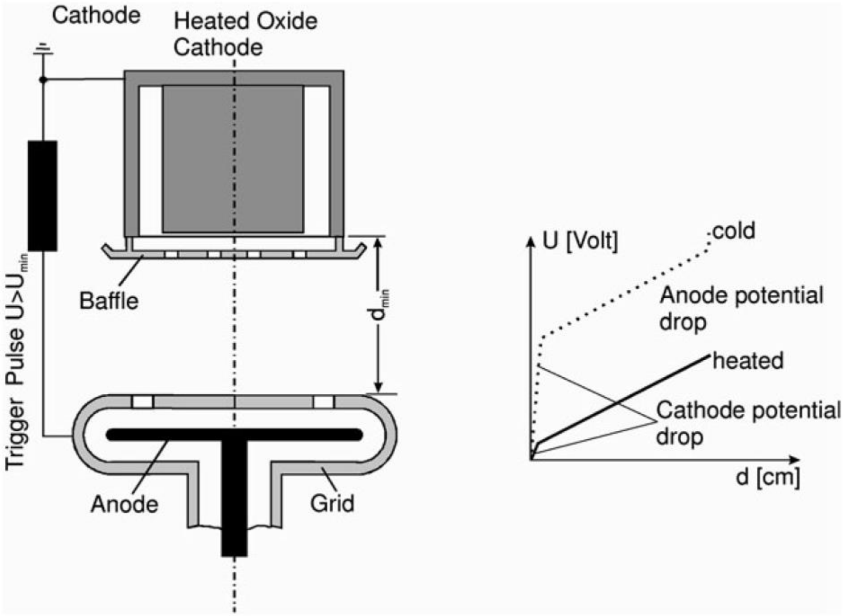
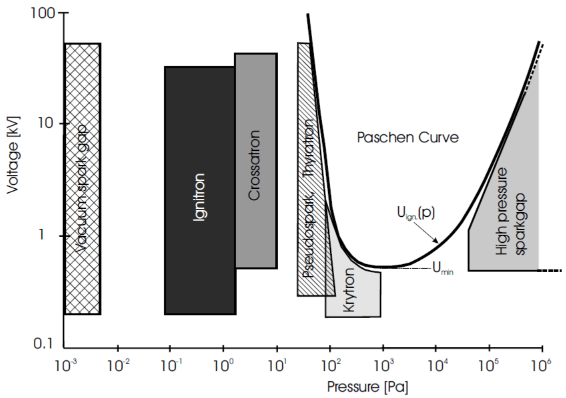


Fig. 4.13. A 4 MV version of a multigap spark switch

Thyratrons

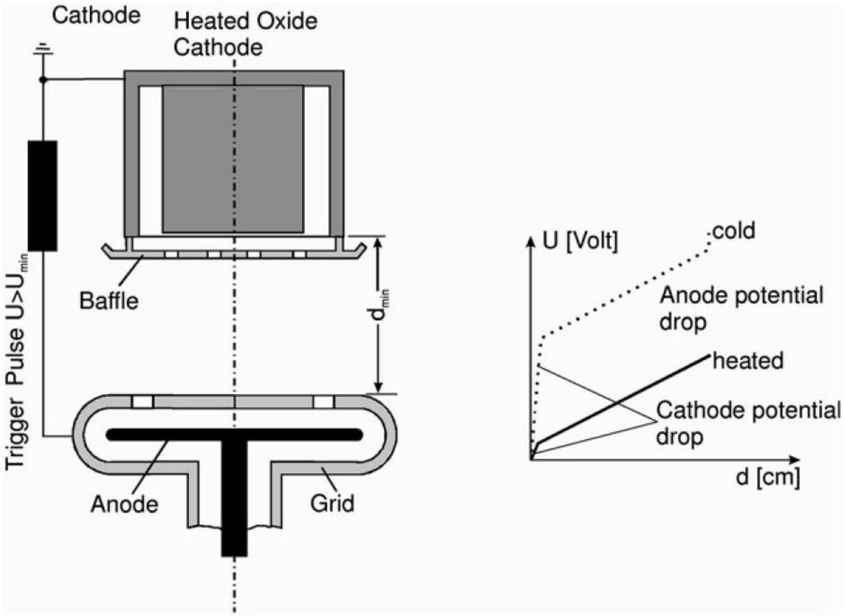
- Thyratrons are gas-filled switching devices with a gas pressure (30-80 Pa/3x10^{-4} – 8x10^{-4} atm) much lower than a spark-gap switches.
- A triode configuration is used.
- The thyratron is characterized by the presence of a plasma, which allows the passage of large currents without significant electrode erosion.
- The hold-off voltage is limited by field emission, > 10^5 V/cm.
- The anode-grid distance is 2-3 mm, ~40 kV hold-off voltage.

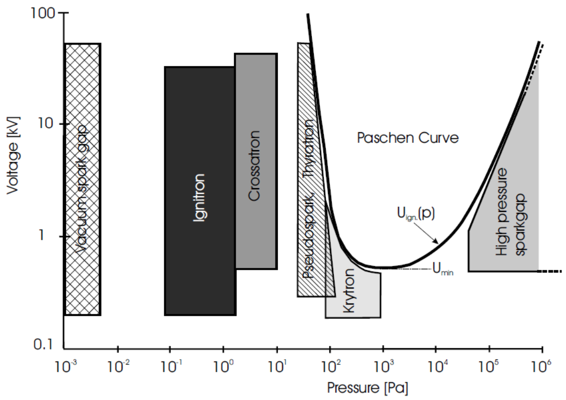




Thyratrons

- The cathode-grid distance corresponds to the Paschen minimum U_{min}.
- If $U > U_{min}$, a glow discharge is initiated between the cathode and the grid. => electrons from the glow discharge plasma can migrate rapidly through the openings in the grid to the main discharge region between the grid and the anode. => thyratron closes.





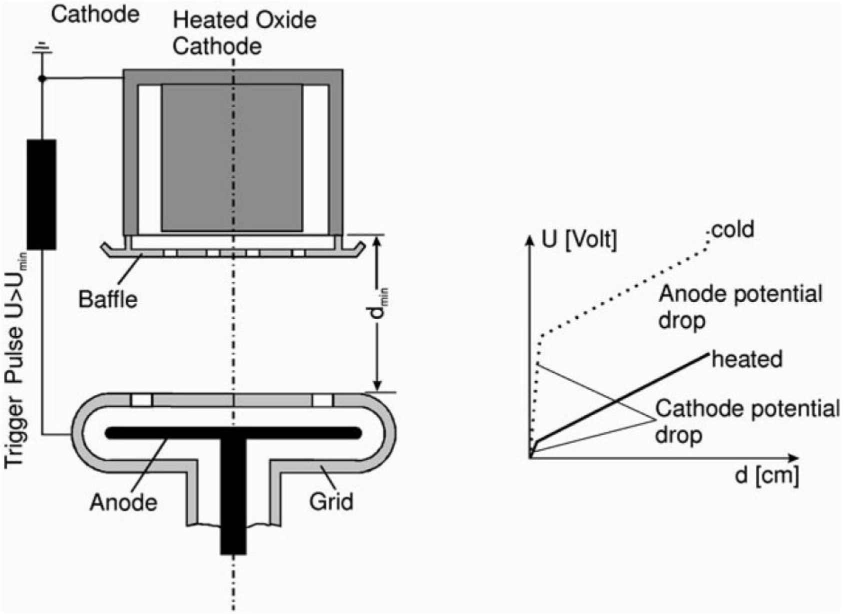
Thyratrons

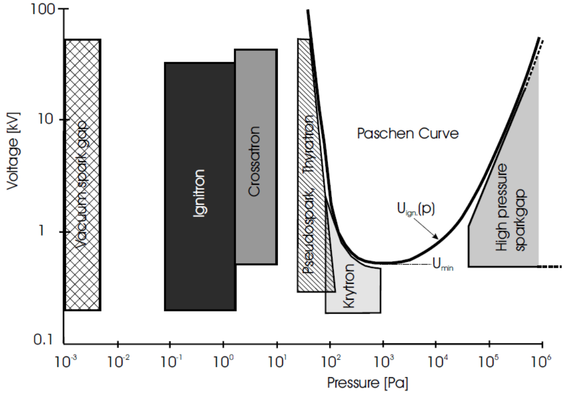
- **Operating voltage: several times 10 kV. After ignition: ~100 V => an appreciable power loss occurs and need to be dealt with by cooling.**

- **Delay: ~200 ns; jitter: ~ns.**

- **Operating times: 10^5 hours; Repetition rates: few kHz; Operating power: MW.**

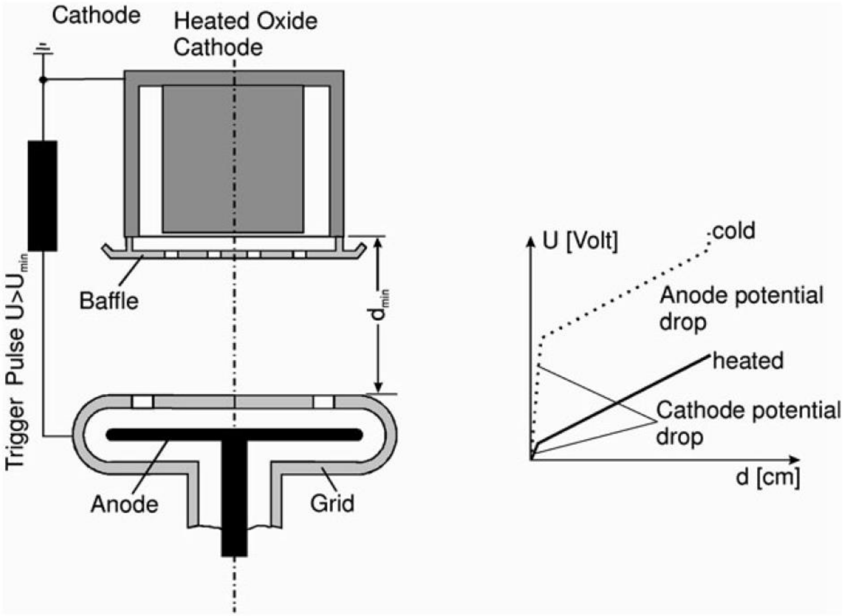
- **To regain the initial hold-off voltage: anode voltage must become slightly negative for 25-75 us for plasma to decay.**

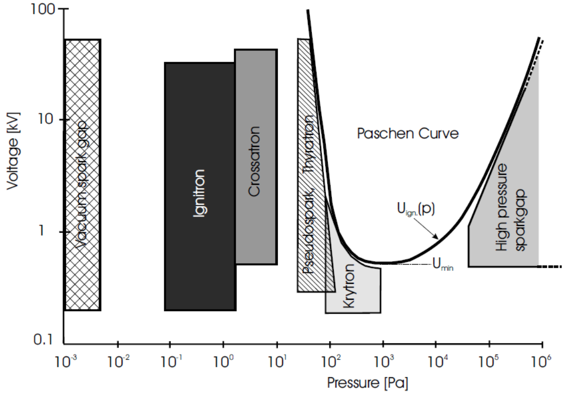




Thyratrons

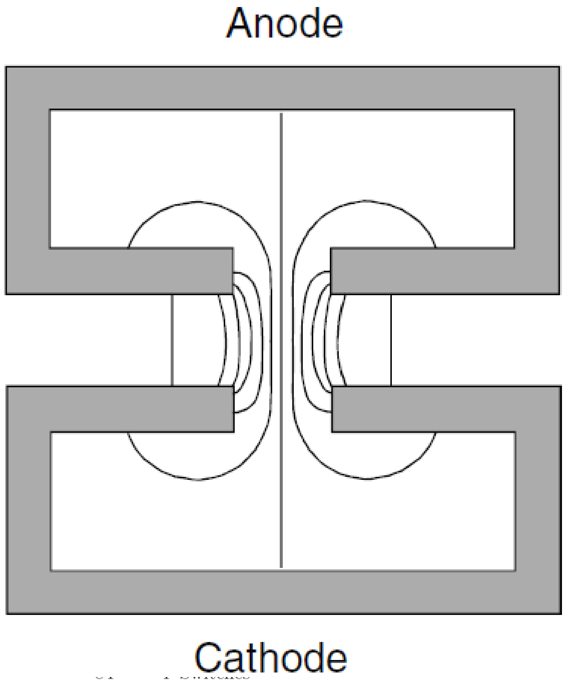
- **A thermionic cathode is used in a thyratron.**
- **Advantage: absence of a marked cathode potential drop using hot cathode.**
- **If cold cathode is used, potential drop is needed to accelerate the ions for secondary-electron production => lead to erosion of the cathode and thus the lifetime.**
- **A baffle is used as a screening element to avoide electron directly reaching the anode and causing the damage. It is shifted relatively to the grid to prevent a direct line of sight between cathode and anode.**

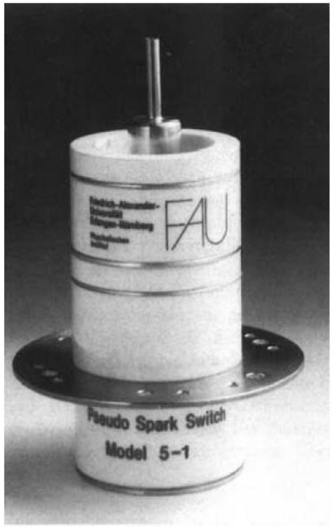


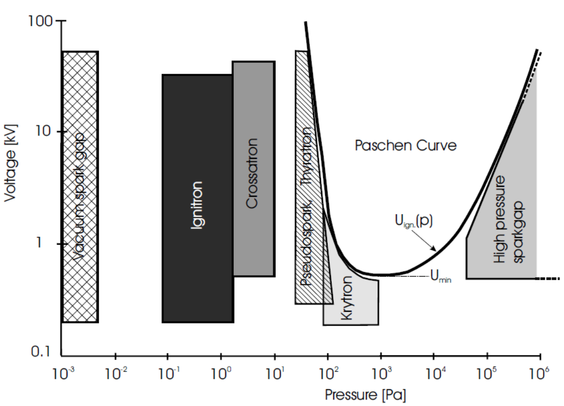


The pseudospark switch

- **The pseudospark switch operates in a low-pressure regime, where the mean free path of electrons and ions become comparable to the electrode spacing. Most electrons reach the anode without any ionizing collisions in the gas.**
- **Hollow cathode: increases the possible discharge path lengths.**
- **The diameter of the aperture determines the field penetration into the hollow cathode.**

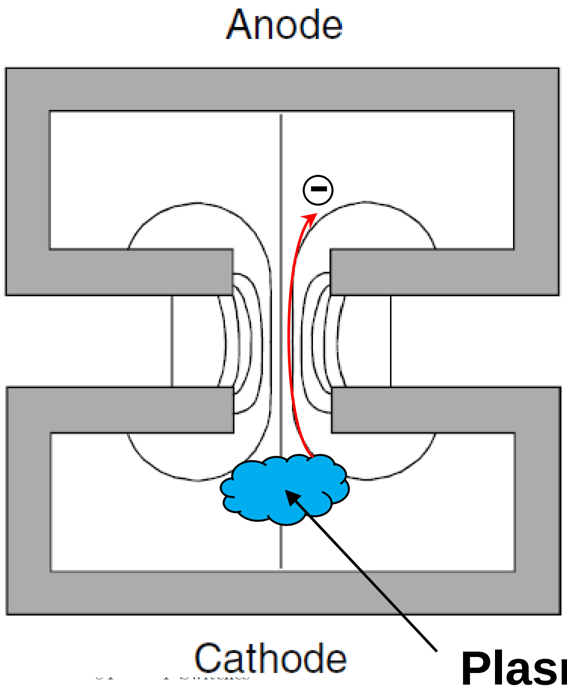




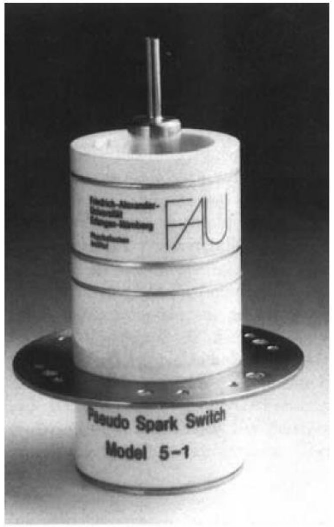


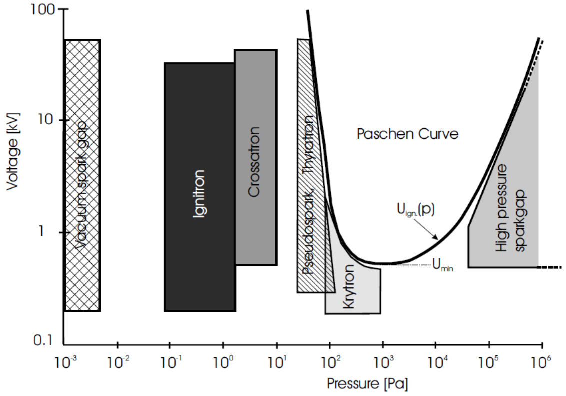
The pseudospark switch

- A small number of initial electrons, triggered discharge in the hollow cathode can initiate the pseudospark discharge.
- The switching mechanism is based on the build-up of a highly ionized plasma.
- plasma build-up occurs first inside the hollow cathode where E/P is low.



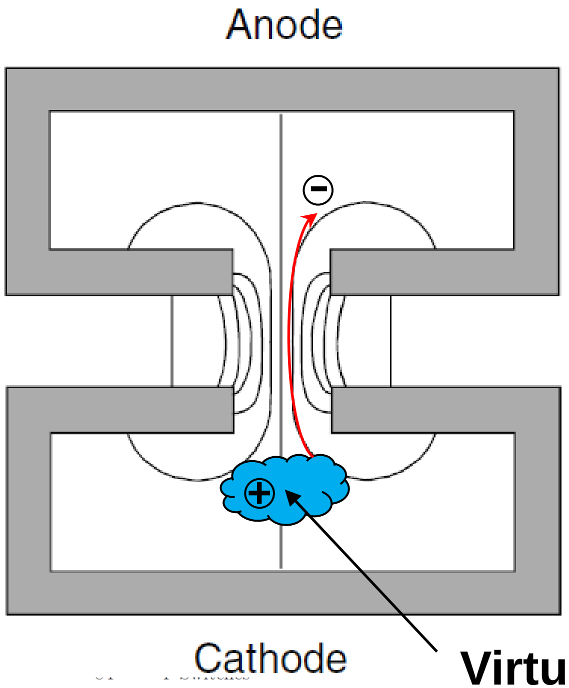
Plasma formed first.



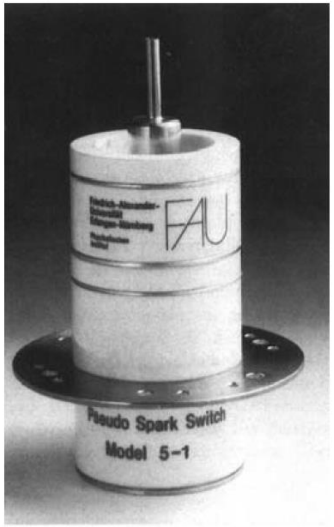


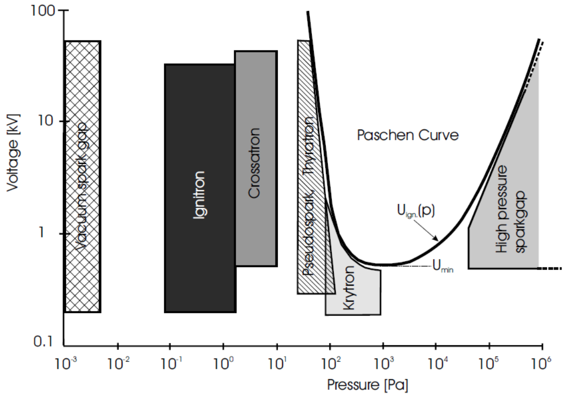
The pseudospark switch

- Ions drift back into the hollow cathode => forming a positive space charge (virtual anode).
- Static electric field inside the hollow cathode is distorted.
- Electron production rate > loss rate in the hollow cathode and subsequently in the anode-cathode gap.
- A low-resistivity plasma is estabilished, and breakdown of the gap occurs.
- Jitter: 10 ns; Delay: 0.5 us.
- Advantage: high dI/dt, reverse current, long lifetime, low jitter.

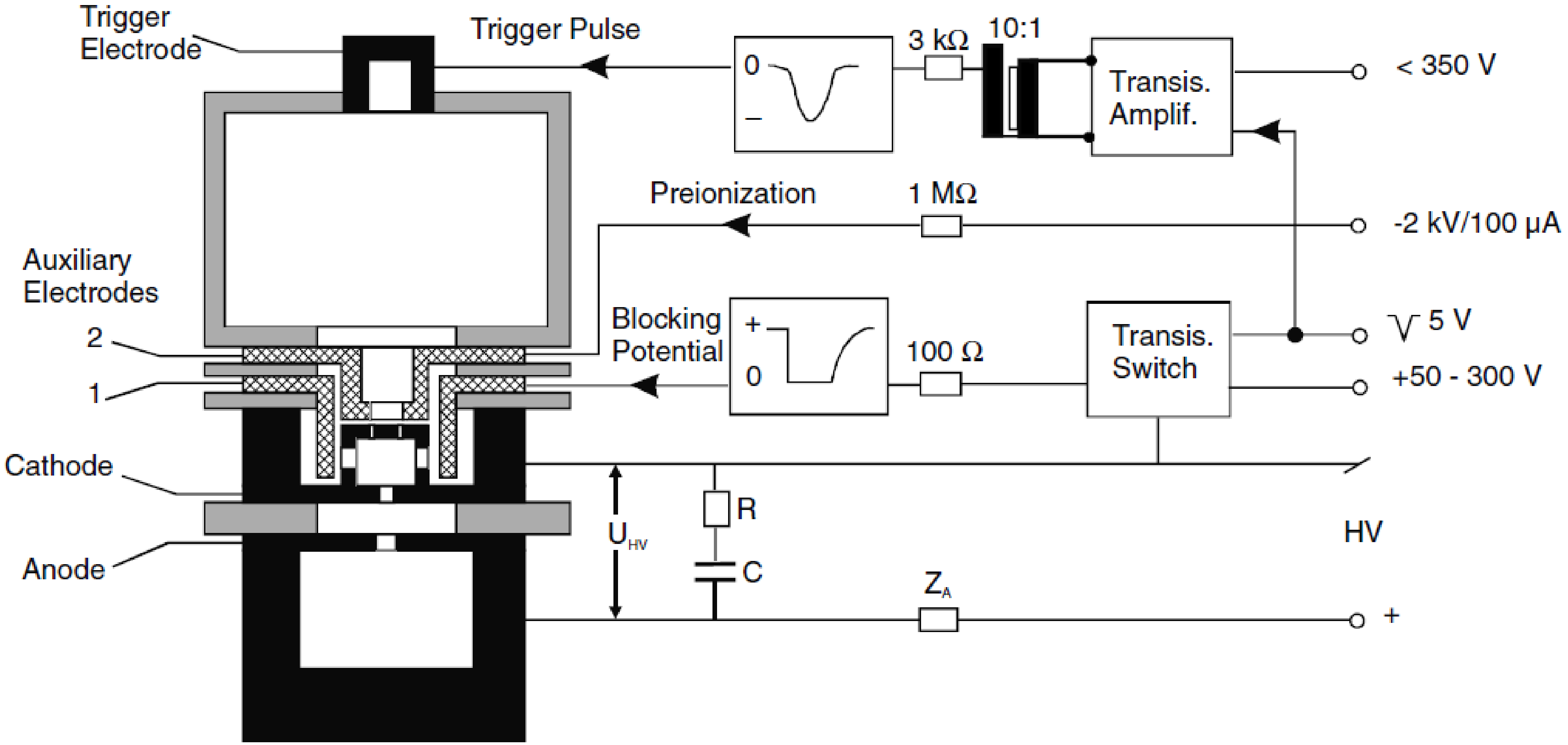


Virtual anode





The pseudospark switch with triggering system

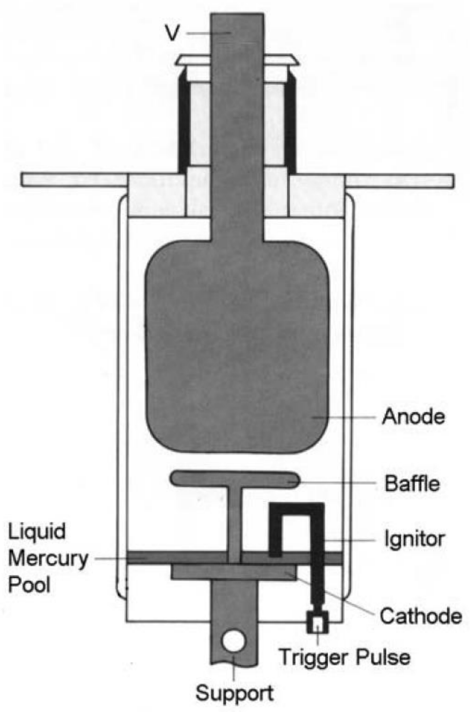


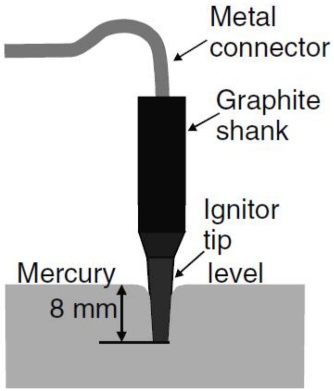
Ignitrons

- Ignitron is a very high-current, high-voltage switch with
  - a liquid mercury pool cathode
  - an ignitor pin dipping into the liquid-metal reservoir.
- Internal mercury pressure: ~5 Pa
- Can switch a pulse charge of up to 2000 Colum.
- Air/water cooled may be needed.
- Internal splash and deionization baffles may be contained in some devices.
- Anode:
  - Anode is massive to prevent an impulsive temperature rise during conduction.
  - Anode is cooled through

    (1) anode stem;

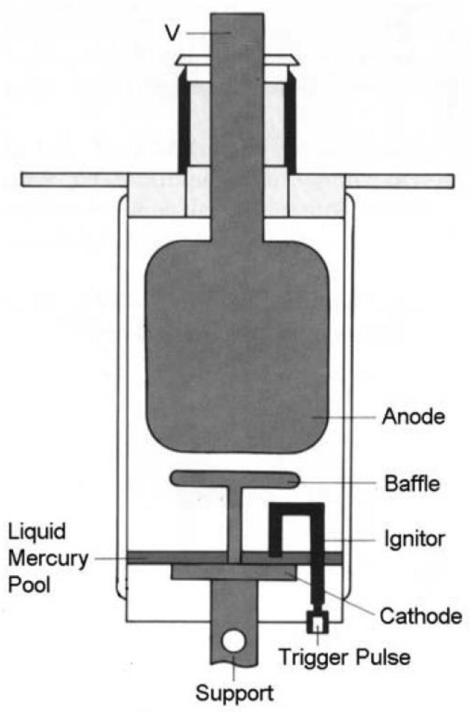
    (2) radiation to the cooled walls.

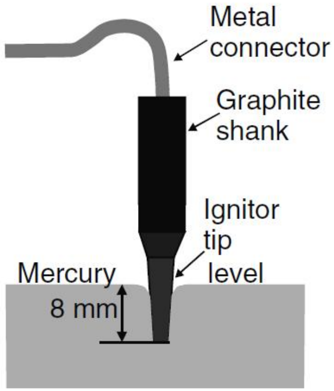




Ignitrons

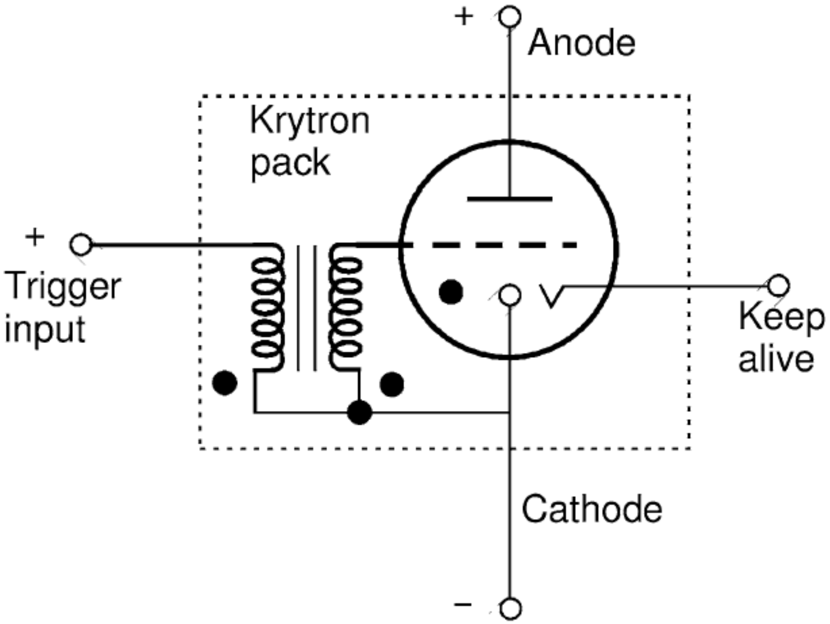
- **Rise time ~ 300-500 ns.**
- **After current drops below a critical value => no more additional vapor is produced => with additional time to allow recombination and recondensation of mercury.**
- **The mercury vapor must be forced to recondense back into the pool.**
- **Repetition rate ~1 Hz**
- **Progressively eliminated due to the mercury-containing waste.**





Krytrons

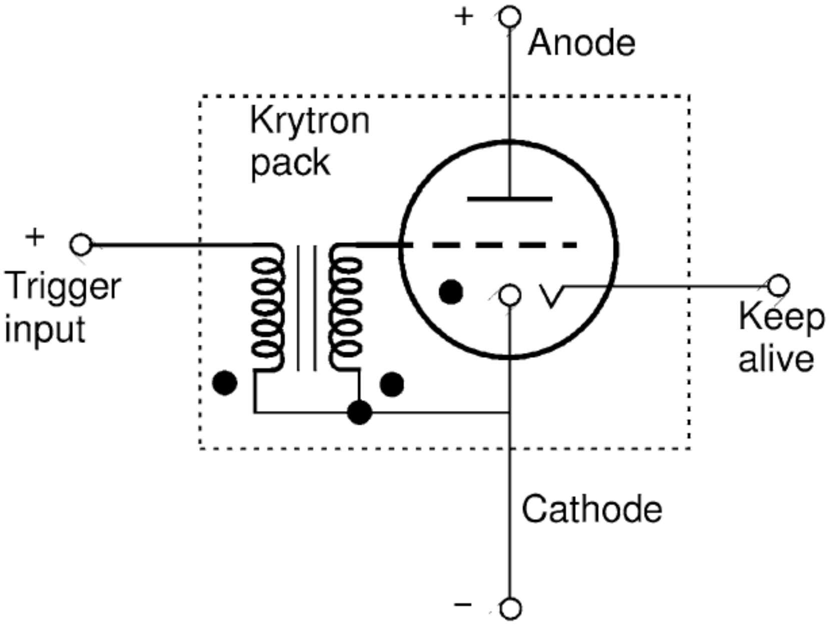
- Low-pressure gas discharge device with a tetrode configuration, sealed in a glass tube with a cold cathode.
- 1.3 kPa (9.75 torr) of helium gas.
- A special design of the anode-grid area + applied gas pressure
  => large hold-off voltage.
- An already existing plasma is created by a glow discharge between the special keep-alive electrode and the cathode.
  => short trigger delay: ~30 ns.
- Rise time: ~1 ns, Vmax: 8kV,
  Imax: 3 kA.
- Pulse length~10 us,
  repetition rate ~1 kHz
- A positive pulse at the control grid initiate the switch.



Krytrons

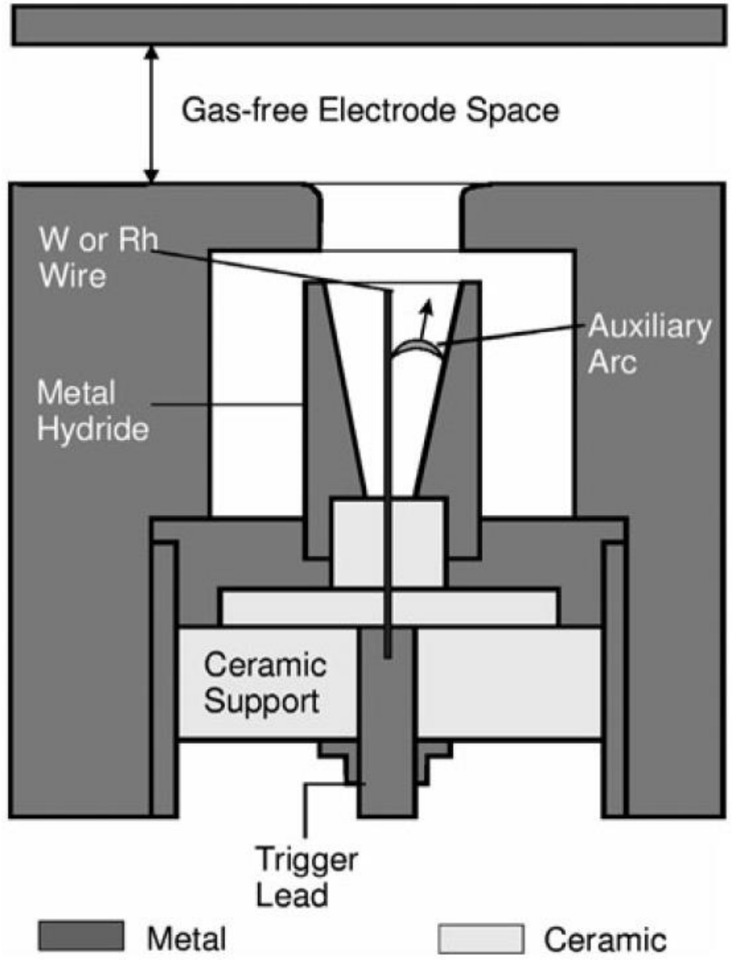
- **A ^{63}Ni β-emitter may be enclosed to create a weak permanent pre-ionization.**

- **It is widely used in fast trigger generators and Pockels cell driver and also ideal for use in the detonating circuitry of bombs.**



Triggered Vacuum Gap (TVG)

- A three-electrode system with P=0.001 Pa (7.5 x 10^{-6} Torr).
- Closed by injection of a plasma cloud.
- Hold-off voltage depends on the properties of the electrode surfaces.
- I up to 10 kA, V up to 100 kV. Repetition rates of several kHz are possible if cooled.
- The gas-plasma mixture is created with the help of an auxiliary arc, burning between two electrodes inserted into one of the main electrodes.
- Jitter ~ 30 ns; switching time ~100 ns.



Semiconductor closing switches

- The limiting switching characteristics of semiconductor devices are:
  - Relatively low mobility
  - Low density of charge carries
  - Comparatively low operating temperature

=> Large volume of the conducting region is required to conduct large currents.

Thyristors

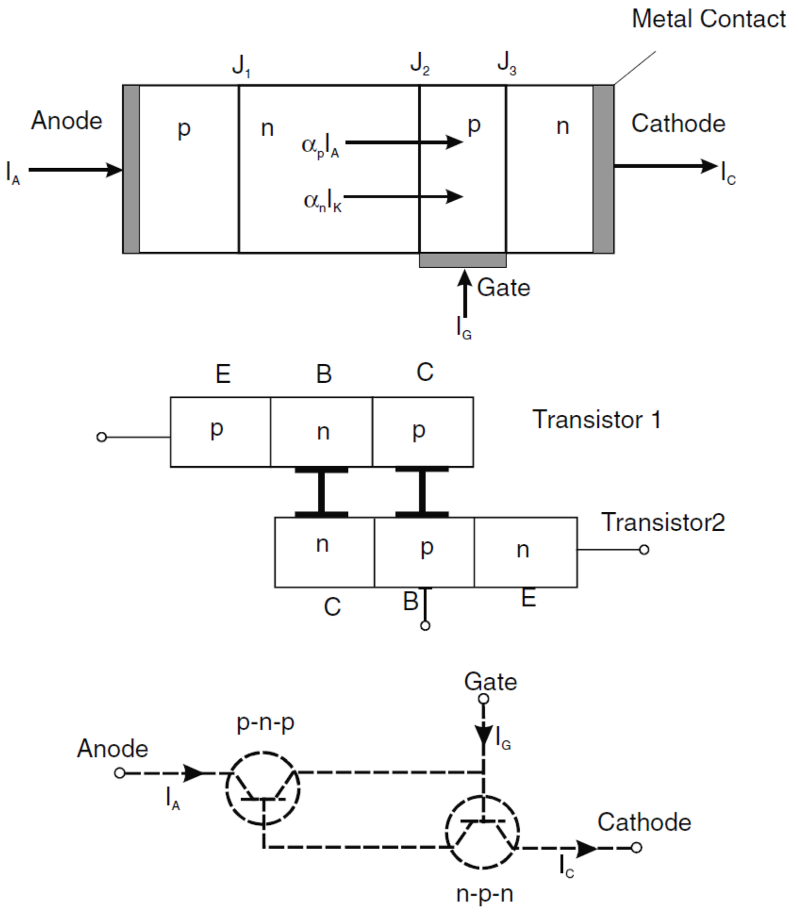
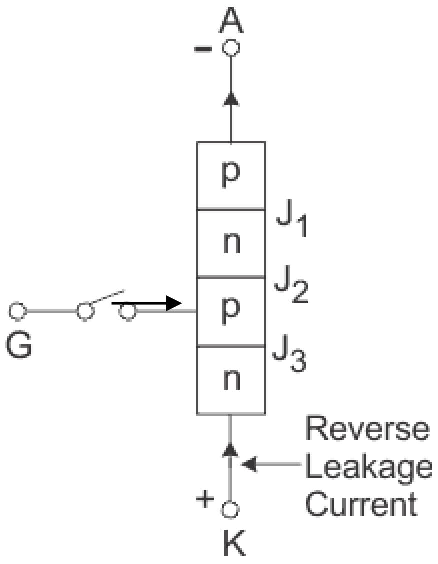


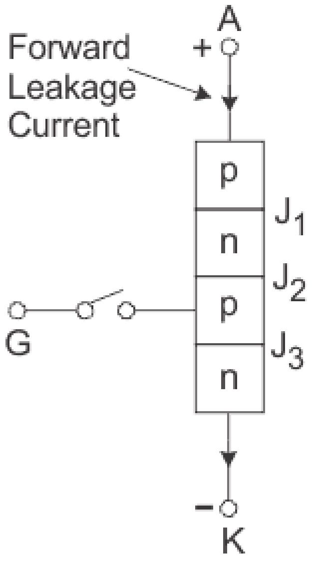
Fig. 4.22. Structure of thyristor, and two-transistor equivalent circuit

Thyristors

- **Three modes of operation:**
  - **Reverse blocking state**
  - **Forward blocking state**
  - **Conduction or on state**



Reverse Blocking Mode



Forward Biased Condition

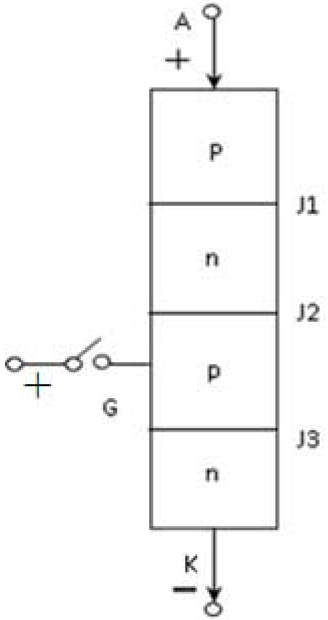


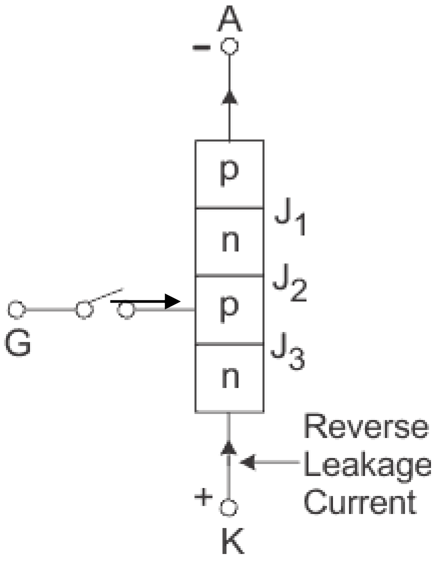
Fig 2: Forward Conduction

Most of the voltage is held by J_1.

Most of the voltage is held by J_2.

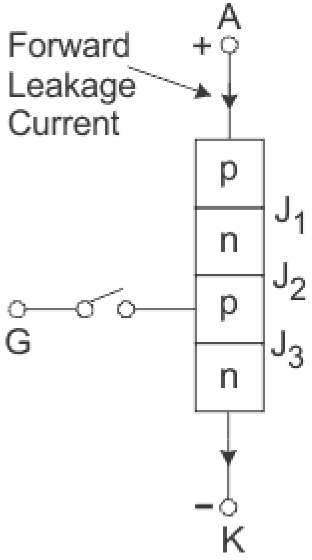
Thyristors

- Three modes of operation:
  - Reverse blocking state
  - Forward blocking state
  - Conduction or on state



Reverse Blocking Mode

Most of the voltage is held by J_1.



Forward Biased Condition

Most of the voltage is held by J_2.

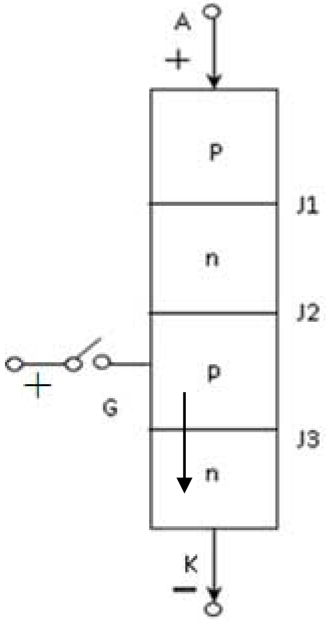


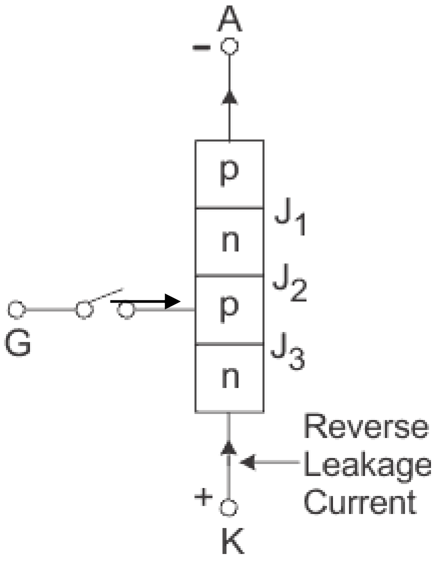
Fig 2: Forward Conduction

e^- will fill up the holes

w/ more e^- => p type becomes N type

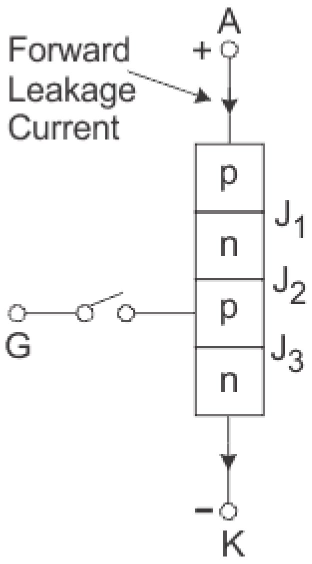
Thyristors

- Three modes of operation:
  - Reverse blocking state
  - Forward blocking state
  - Conduction or on state



Reverse Blocking Mode

Most of the voltage is held by J_1.



Forward Biased Condition

Most of the voltage is held by J_2.

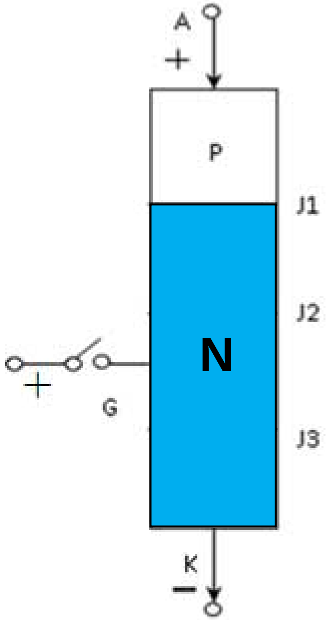


Fig 2: Forward Conduction

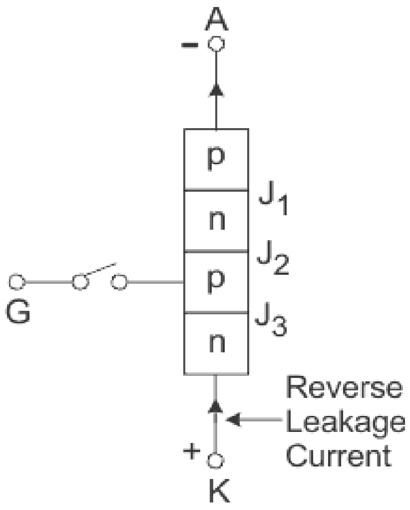
e^- will fill up the holes

⇩

w/ more e^-
=> p type becomes N type

Thyristors

- Without any external action, the thyristor cannot come back from the conducting to the blocking state.
- Two methods are generally applied:
  - Commutation of the current by polarity inversion.
  - Commutation of the current, supported by gate-assisted turn-off.



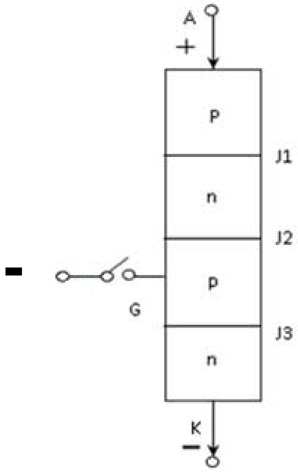
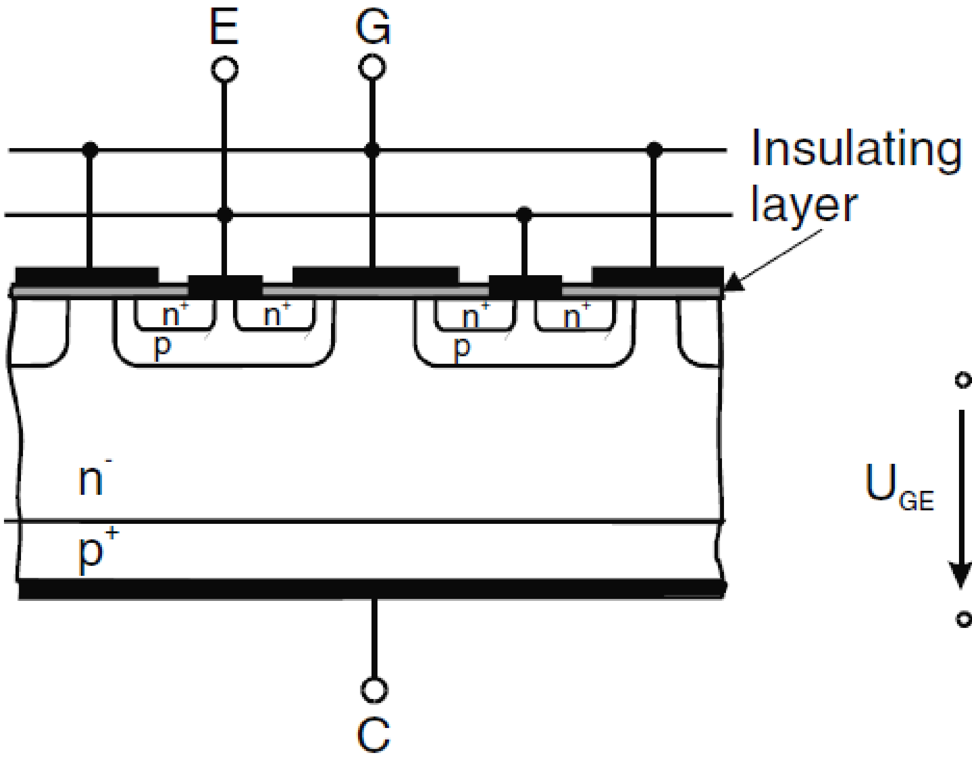
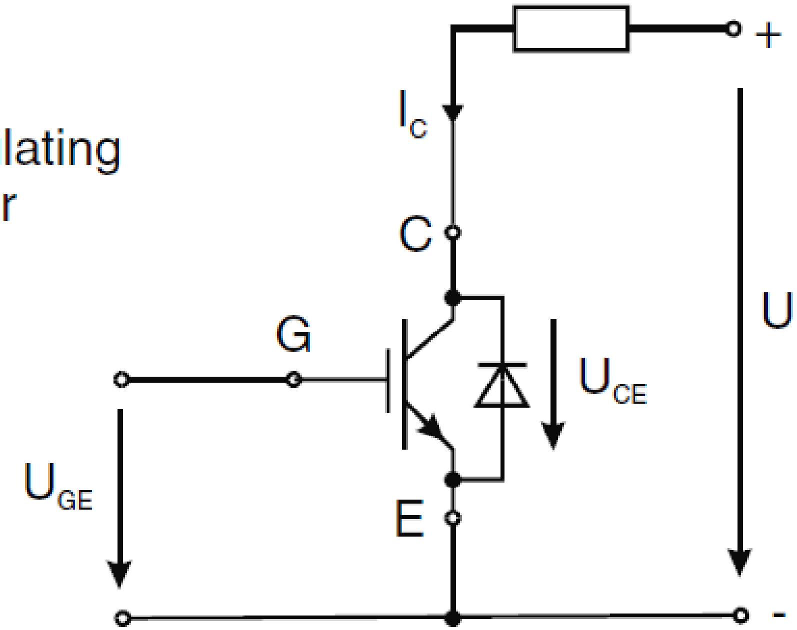


Fig 2: Forward Conduction

IGBT

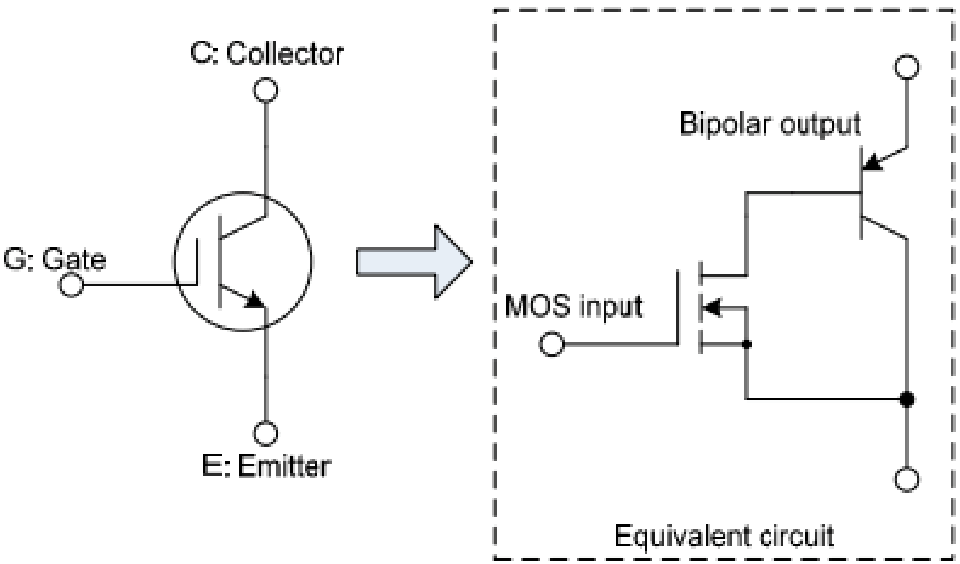




IGBT

- **Advantage:**
  - **Bipolar transistors (BJT) – low resistance in the switched-on state**
  - **Field effect transistors (FET) – loss-free gate control**
- **Switch-on times:**

  ~ several times 10 ns.
- **It has a limited reverse-blocking capability => an external diode is sometimes used in parallel.**
- **High-power IGBT: blocking voltages V~4 kV, on state I ~3kA**



Optically activated semiconductor switches

$$\nabla j_n = e(R_n - G_n) + e\frac{\partial n}{\partial t}$$

$$\nabla j_p = -e(R_p - G_p) - e\frac{\partial p}{\partial t}$$

$$\mathrm{eG_{av}} = \alpha_n|j_n| + \alpha_p|j_p|$$

Rn: recombination rate.
Gn: generation rate.

- **Electron and hole generation is caused either by optical excitation or by avalanche ionization at sufficiently high electric fields.**

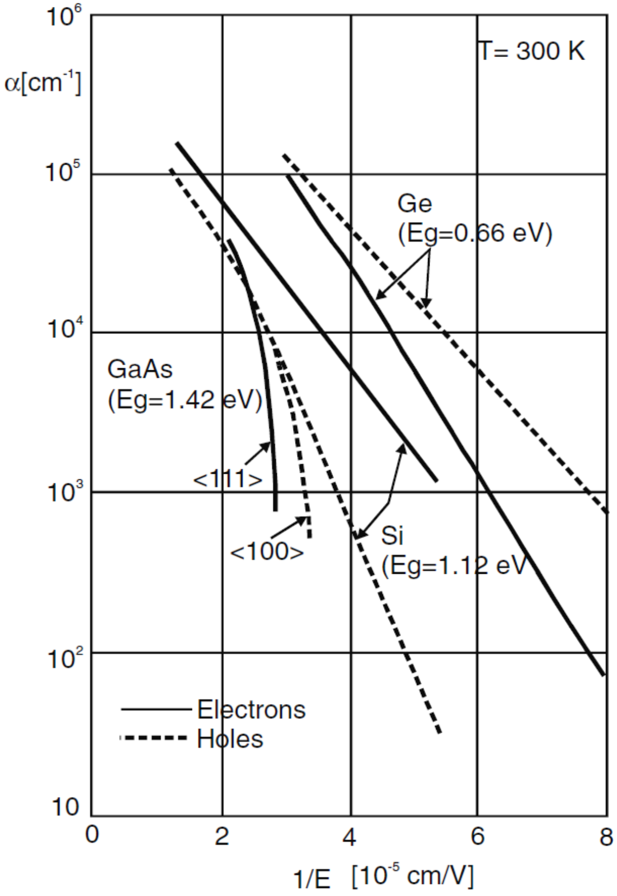


Fig. 4.31. Ionisation rate coefficients α_n and α_p

Optically activated semiconductor switches

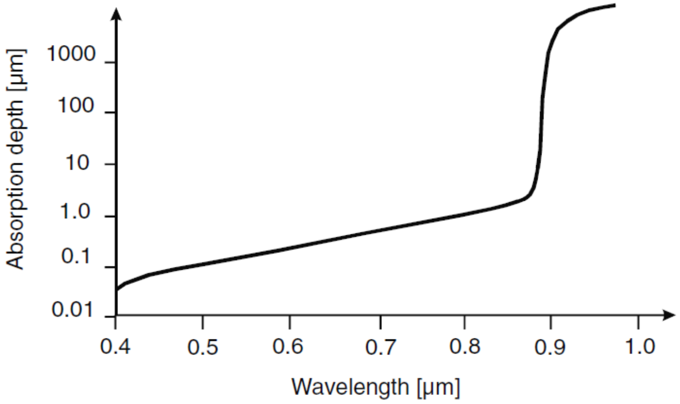
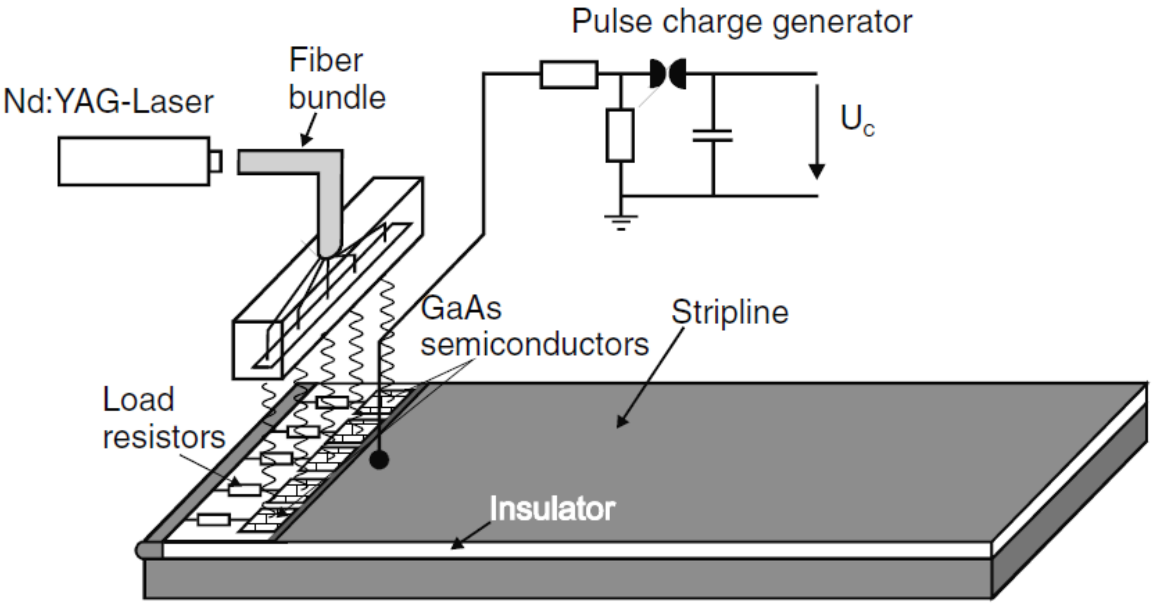
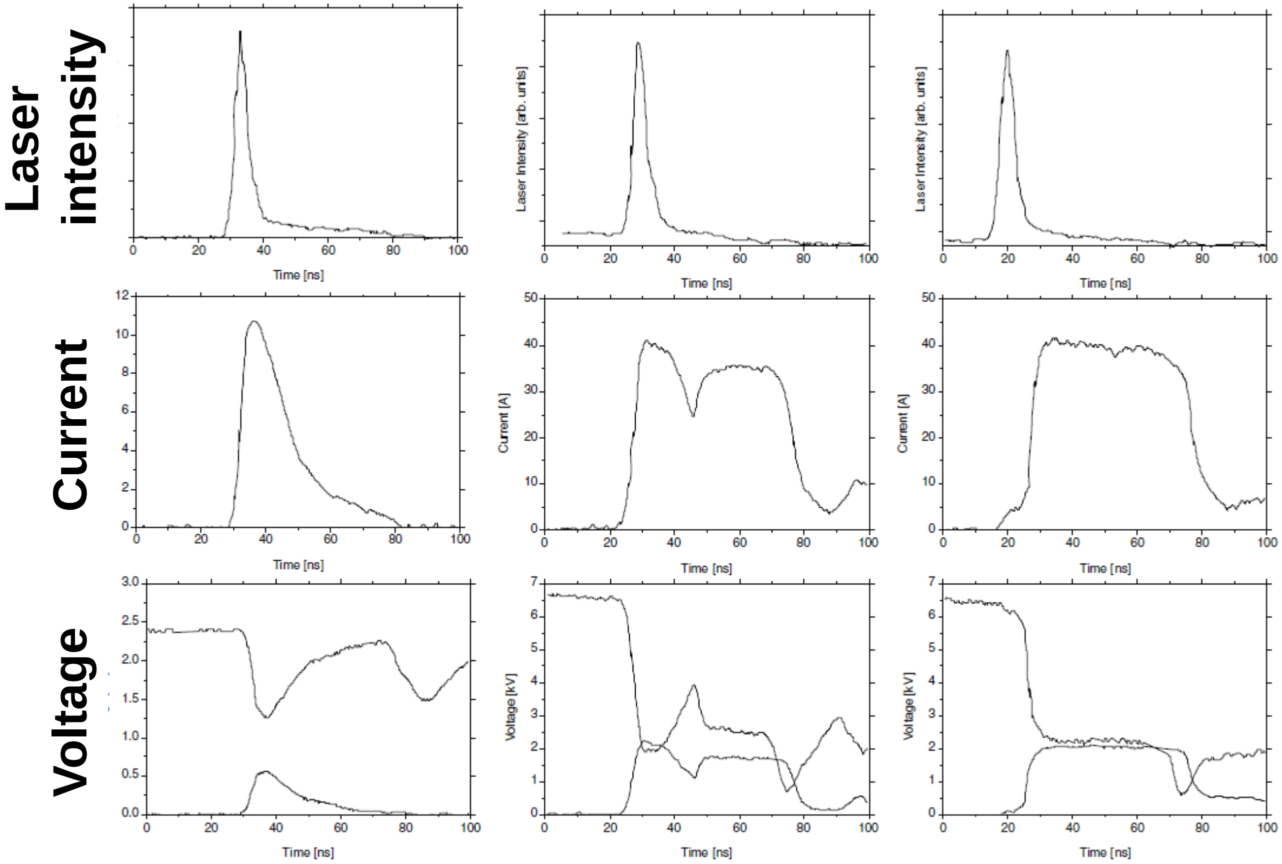


Fig. 4.32. Optical absorption depth in GaAs as a function of wavelength

- **The wavelength should be larger than 0.9 um. Therefore a Nd:YAG laser, wavelength = 1.06 um, is an appropriate light source.**

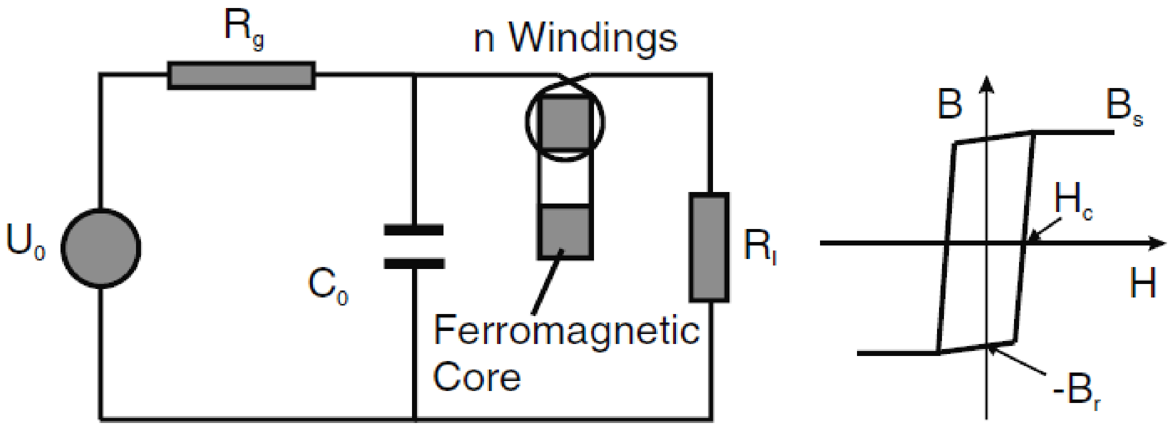


Optically activated semiconductor switches



- **Linear photoconducting regime: the available number of charge carriers is determined only by the laser intensity.**
- **Nonlinear regime: the number of charge carriers is increased by collisional ionization and as in a gas switch increases exponentially.**

Magnetic switches



- Relatively small losses and without wear.
- While the capacitor is being charged: the coil has a ferromagnetic core with high inductance at the beginning: V=LdI/dt => like an open switch.
- When saturation of the core is reached by the leakage current flowing through the coil => L drops abruptly by a factor of μ => switch is closed.
- μ=B/H ->0 when saturated.
- The hysteresis loop should approximate a rectangular form, with an abrupt change of the permeability over several orders of magnitude when the saturation point is reached.

Summary

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