PULSED POWER SYSTEM
脈衝功率系統

Po-Yu Chang

Institute of Space and Plasma Sciences, National Cheng Kung University

2023 Fall Semester

Tuesday 9:10-12:00

Lecture 8

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

Online courses:

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

2023/11/5 updated

Reference

- **Foundations of pulsed power technology, by Jane Lehr & Pralhad Ron**
- **Pulsed power systems, by H. Bluhm**
- **Pulsed power, by Gennady A. Mesyats**
- **J. C. Martin on pulsed power, edited by T. H. Martin, A. H. Guenther, and M. Kristiansen**
- **Pulse power formulary, by Richard J. Adler**

- **Circuit analysis, by Cunningham and Stuller**

Outlines

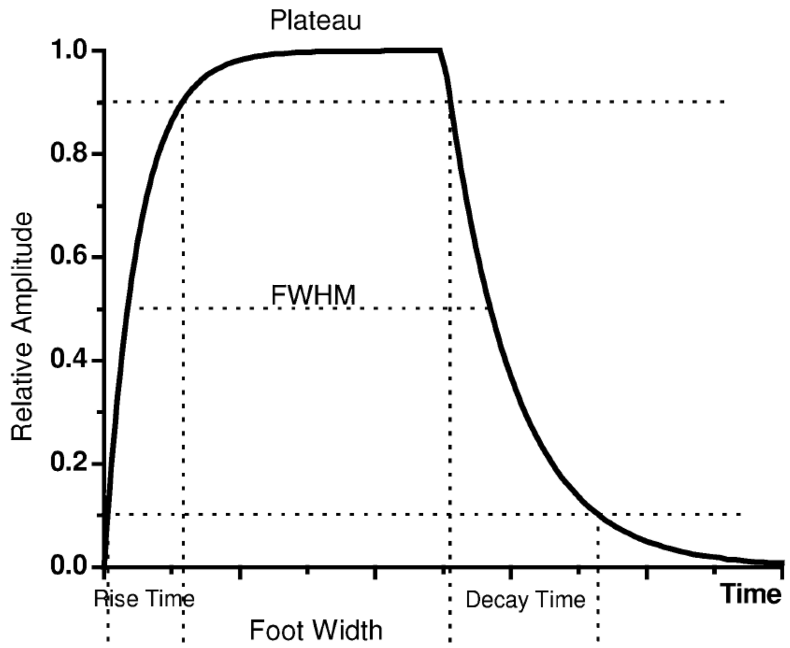
- **Switches**
  - **Closing switches: the switching process is associated with voltage breakdown across an initially insulant element.**
  - **Opening switches: the switching process is associated with a sudden growth of its impedance.**
- **Pulse-forming lines**
  - **Blumlein line**
  - **Pulse-forming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

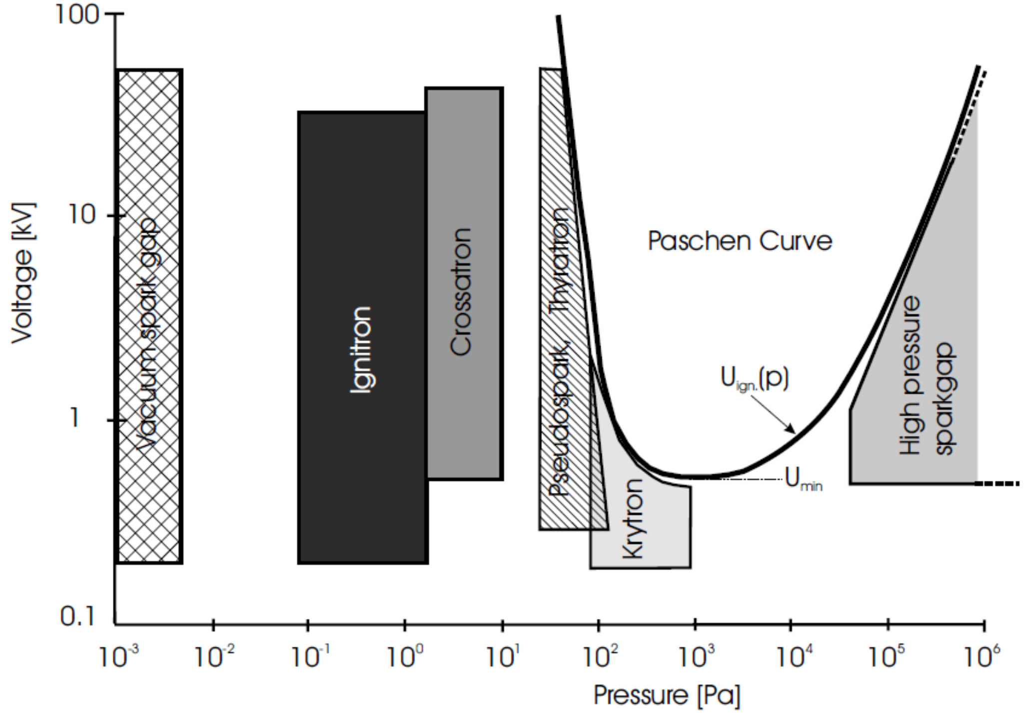
- **The switching process is associated with voltage breakdown across an initially insulant element.**
  - **Automatically.**
  - **Externally supplied trigger pulse.**

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

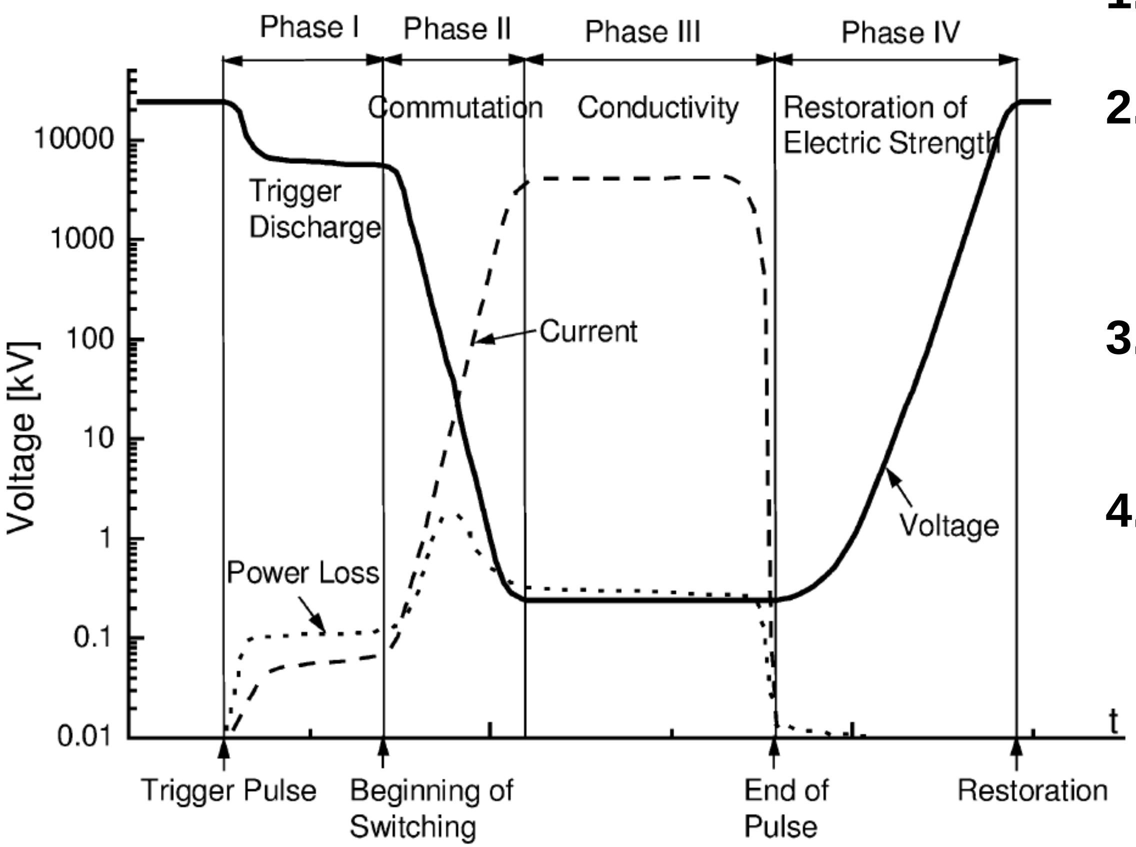


Fig. 4.2. Evolution of voltage, current, and power loss in a gas-filled switching system

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.

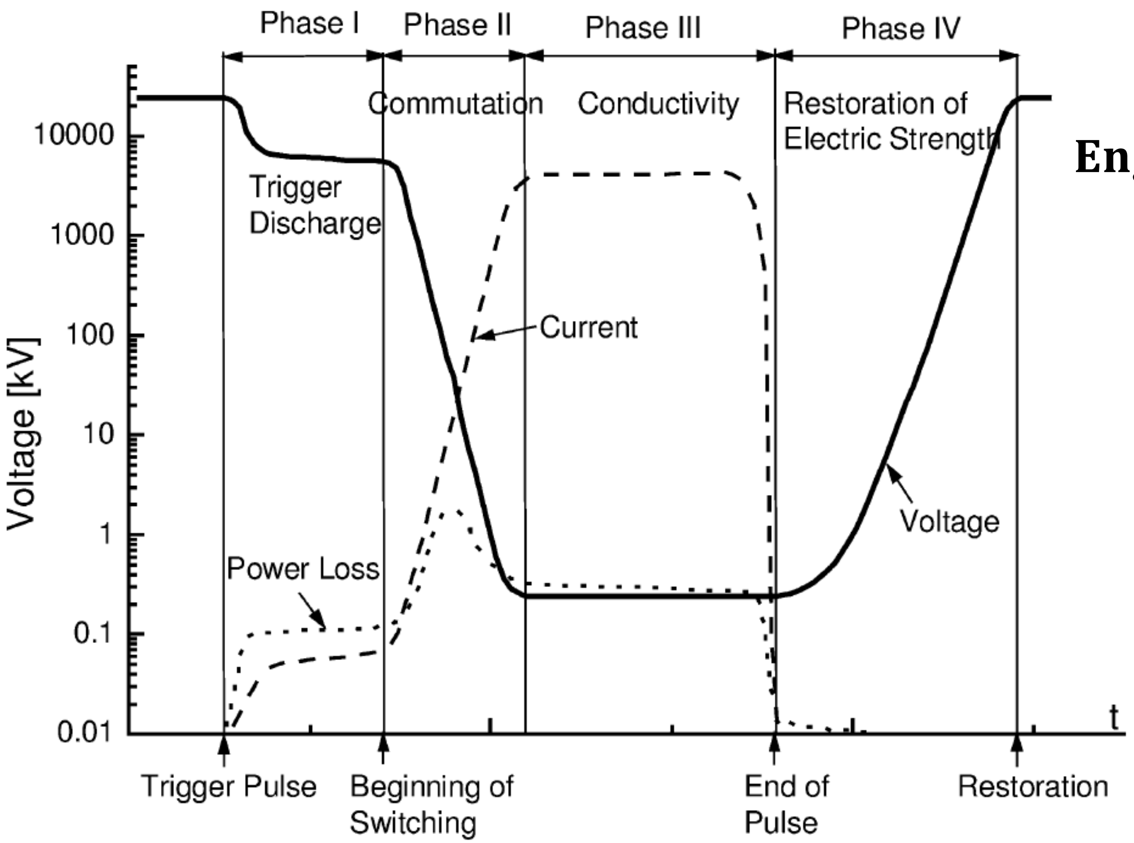


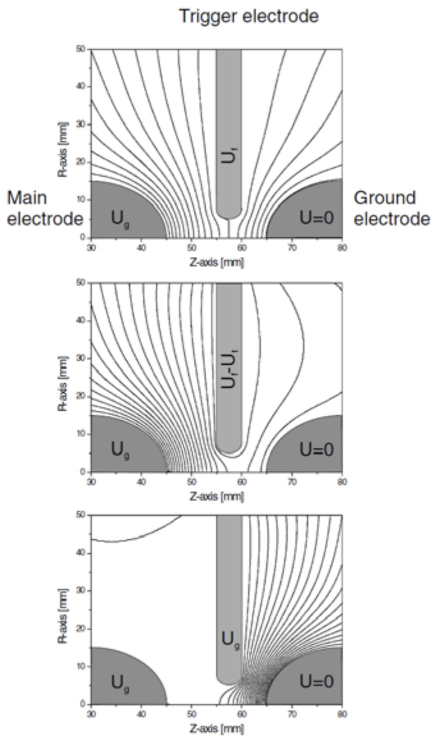
Fig. 4.2. Evolution of voltage, current, and power loss in a gas-filled switching system

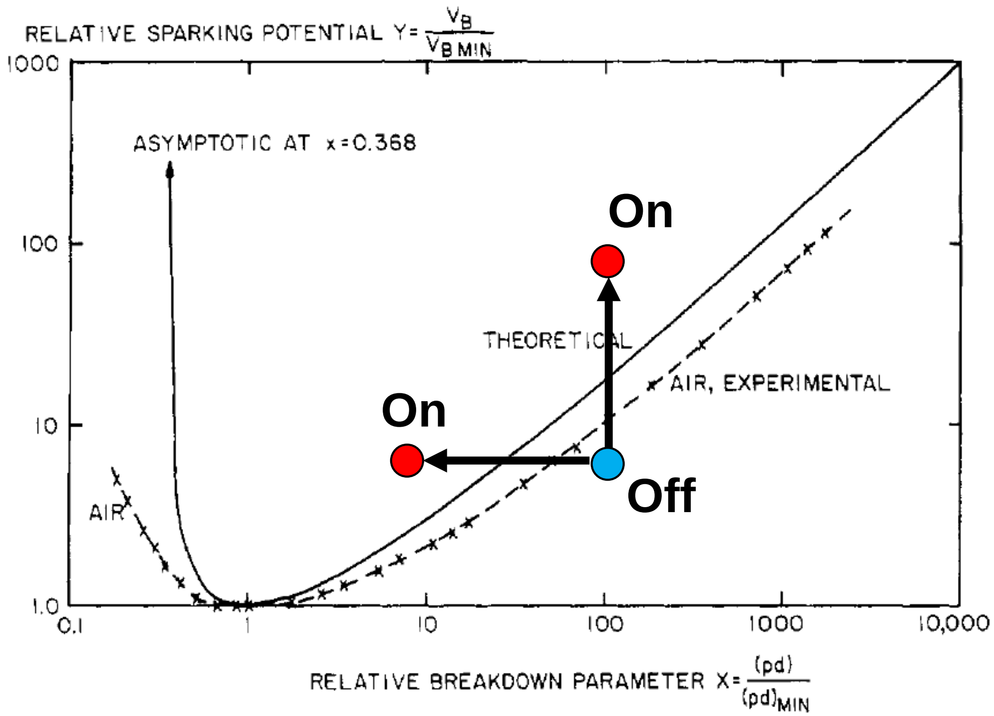
$$\mathrm{Eng} = \int_0^{\tau_S} U(t) I(t)\,\mathrm{d}t$$
$$\approx \int_0^{\tau_S} U_M \left(1 - \frac{t}{\tau_S}\right) I_M \frac{t}{\tau_S}\,\mathrm{d}t$$
$$= U_M I_M \int_0^{\tau_S} \left(1 - \frac{t}{\tau_S}\right) \frac{t}{\tau_S}\,\mathrm{d}t$$
$$= \frac{U_M I_M \tau_S}{6} \approx 0.2 U_M I_M \tau_r$$

- 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.)**

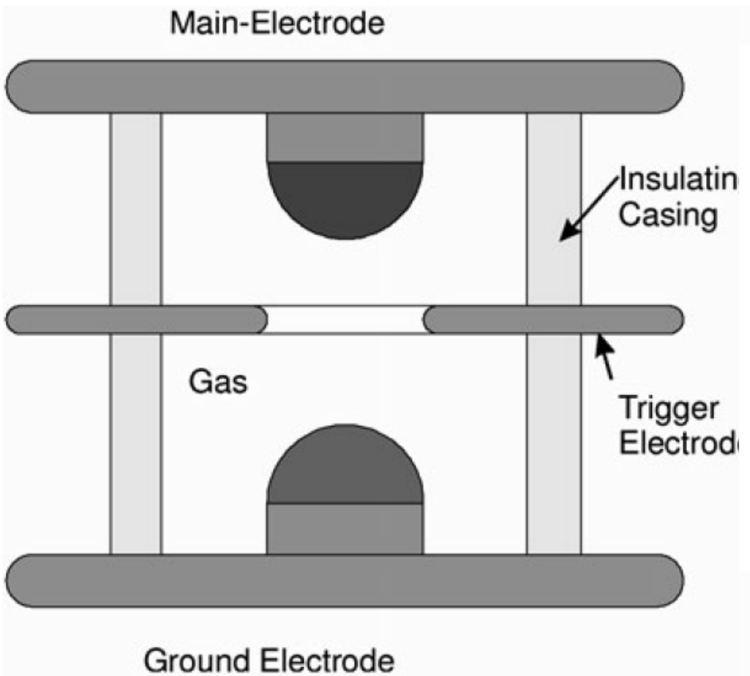


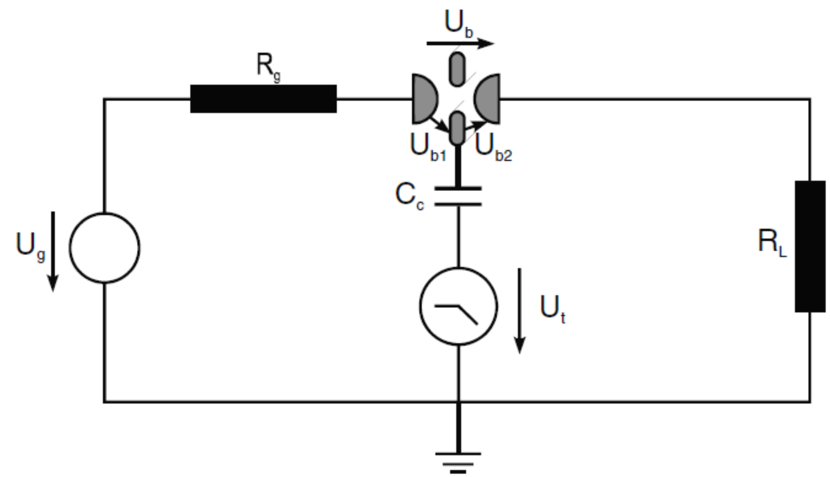


Gas-filled spark gaps

- 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



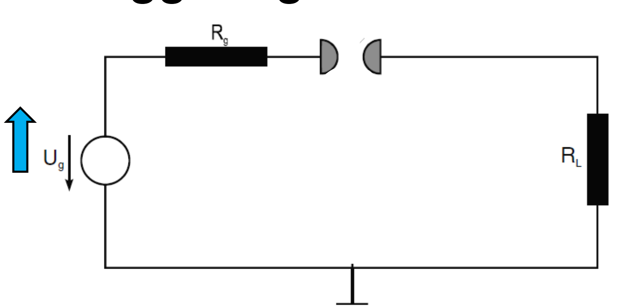


- **U_g: generator voltage.**
- **U_t: triggering voltage.**
- **R_g: generator impedance.**
- **R_L: load impedance.**
- **U_b: breakdown voltage.**
- **U_{b1}/U_{b1} : breakdown voltage of the partial gaps.**
- **C_c: coupling capacitor.**

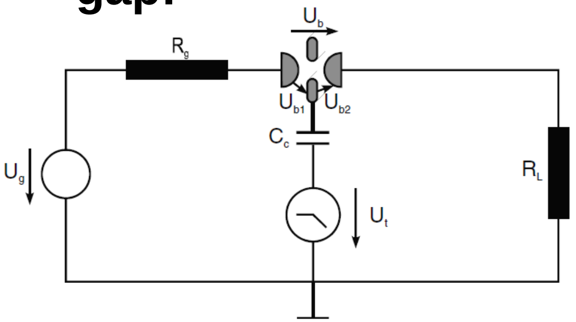
Spark-gap switch

- 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 => $$U_t(t=0) = U_g \frac{C_{\mathrm{b1}}}{C_c + C_{\mathrm{b1}}} \approx 0$$

  - Longitudinal overvoltage triggering:



  - Ignition of the 2nd partial gap:



Spark-gap switch

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

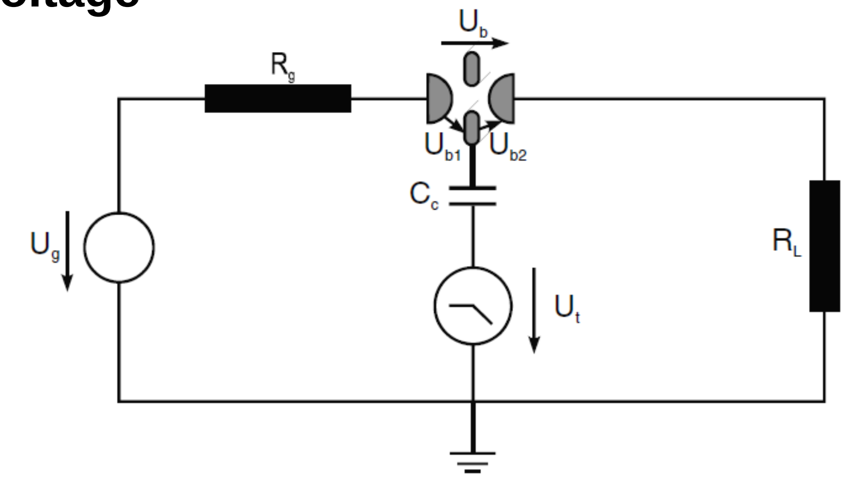
$|U_t| < U_{b2}$ (U_t doesn't cause breakdown @ gap2)

$U_g > U_{b2}$

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

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

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

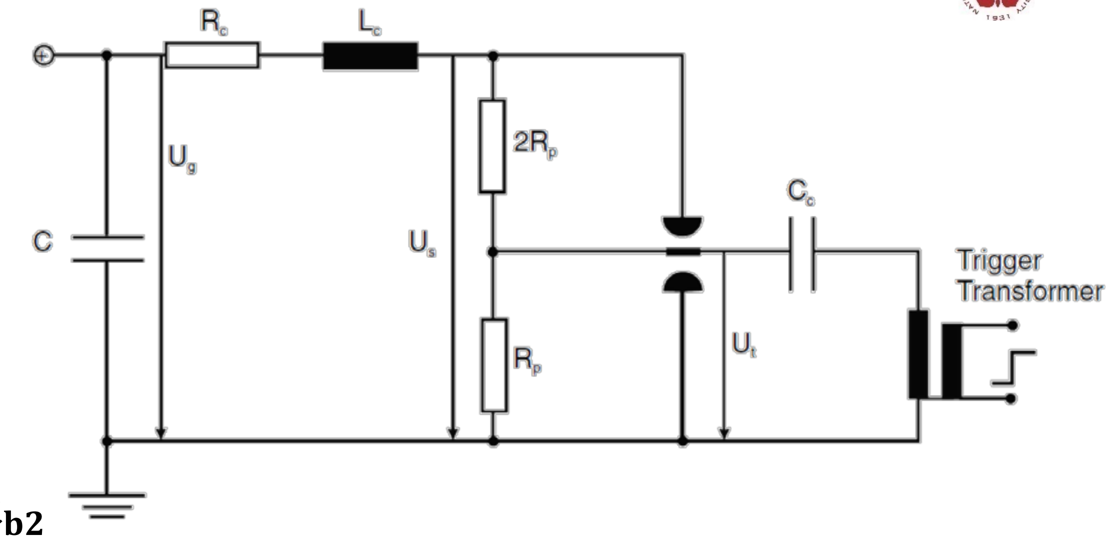


- For a symmetric spark gap configuration, the trigger electrode should be positioned at 2/3 of the gap spacing from the main electrode.

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

$U_{b2} < U_g < U_{b2}$ or $\frac{1}{3} U_b < U_g < \frac{2}{3} U_b$

Three-electrode trigger set-up



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

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

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

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

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

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

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

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

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

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

Potential distribution of a spark-gap

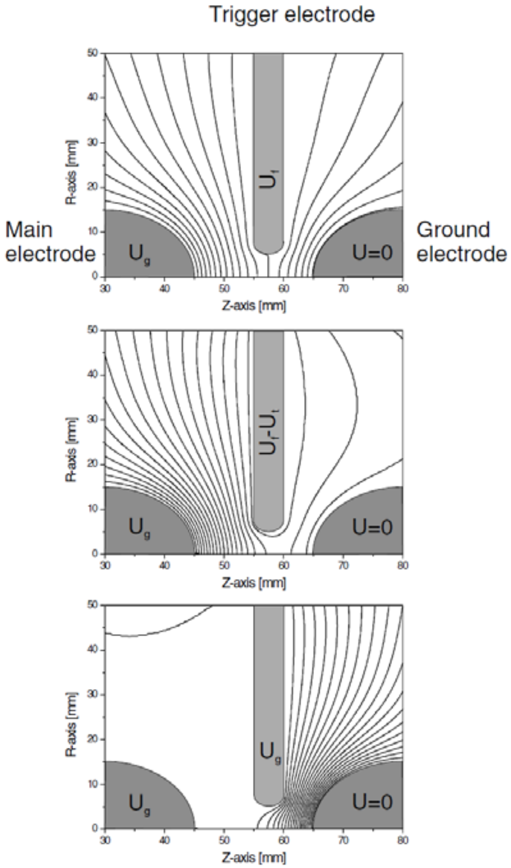
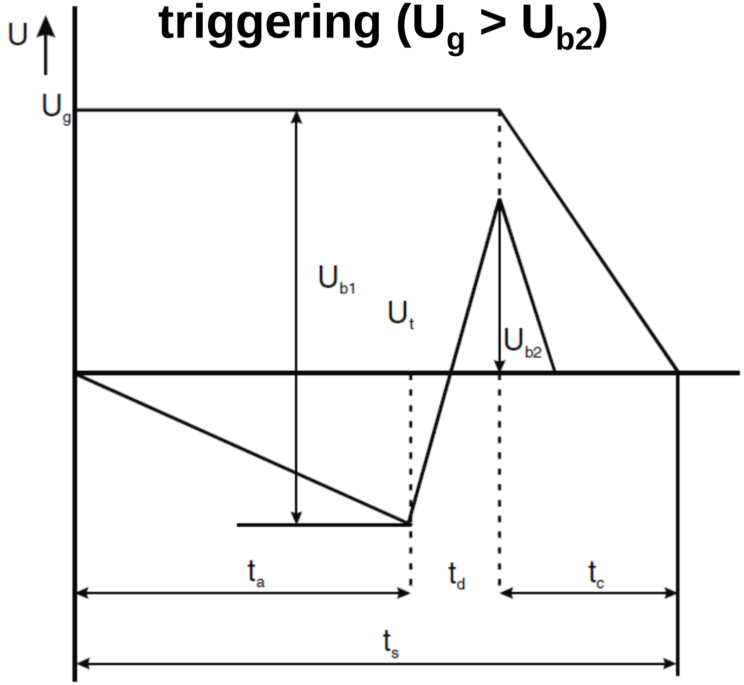


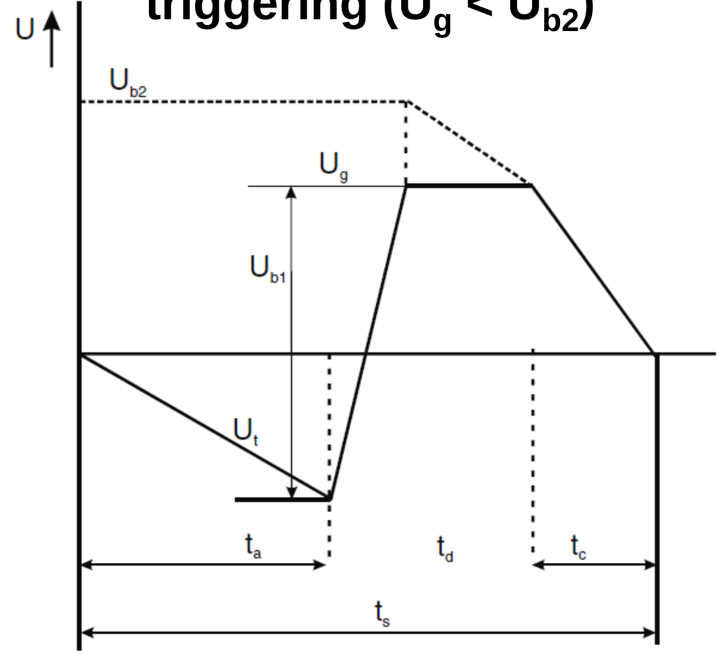
Fig. 4.6. Potential distribution in a three-electrode spark gap switch, before ignition (*top*), after application of a trigger signal (*centre*), and after breakdown of the first gap (*bottom*)

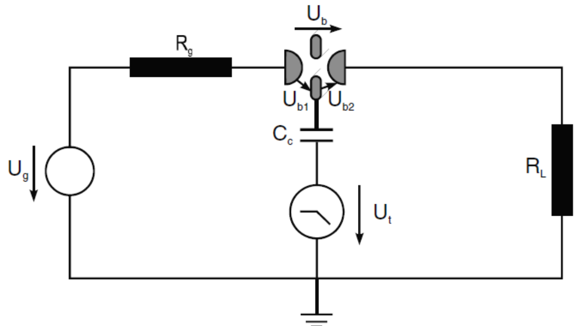
Longitudinal triggering

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



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

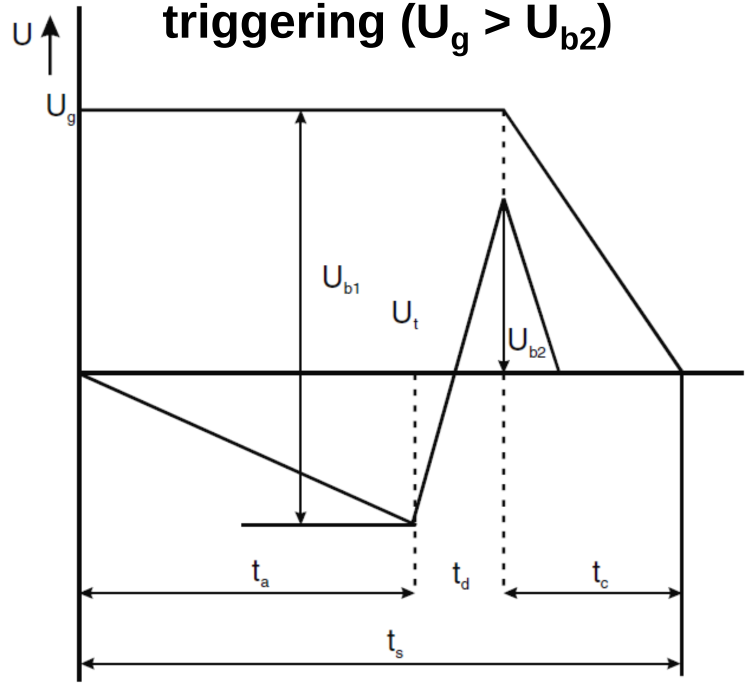




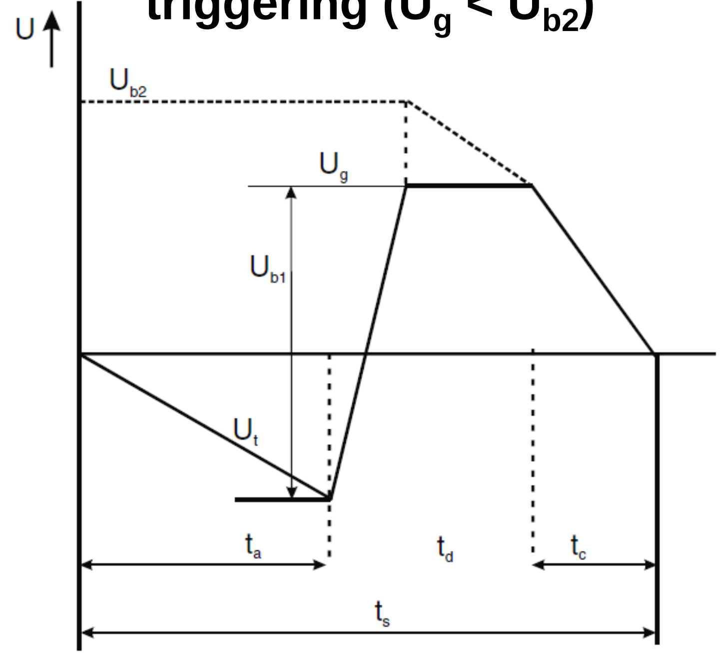
- **t_a: trigger actuating time.**
- **t_d: switching delay.**
- **t_c: commutation time.**
- **t_s: switching time.**

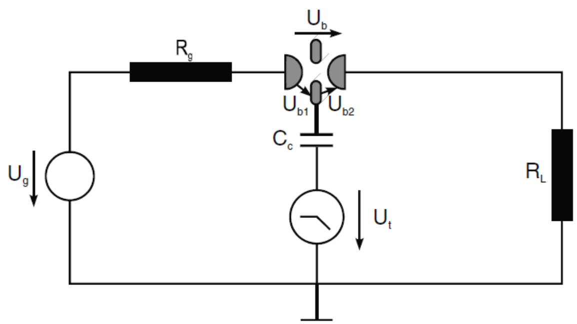
Longitudinal triggering

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



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

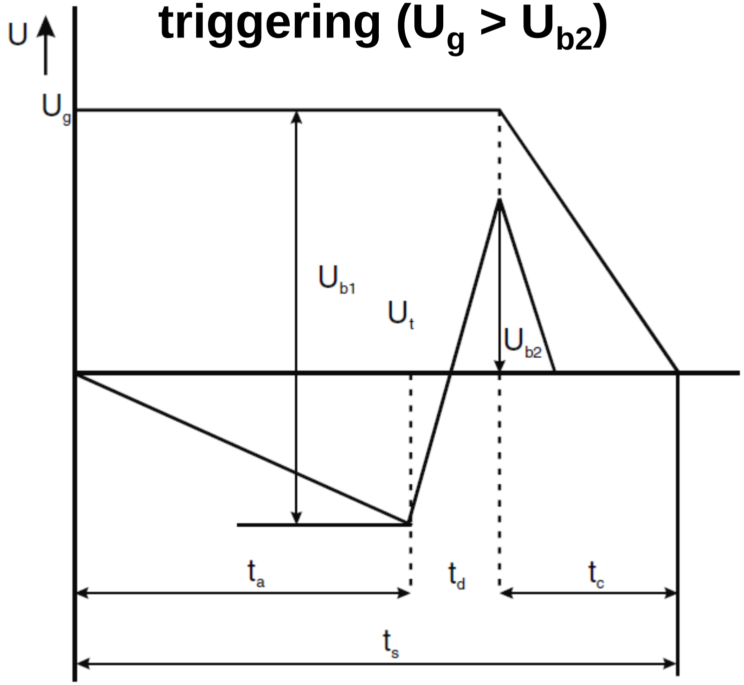




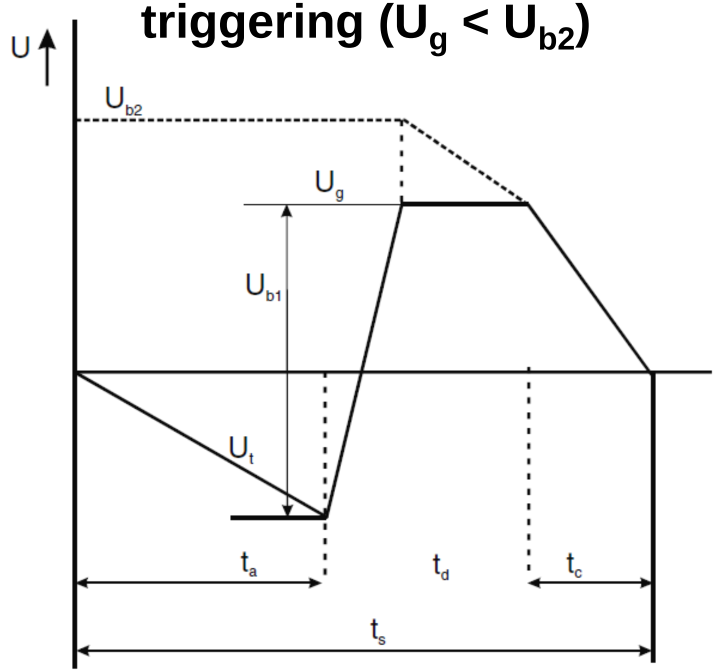
- **2^{nd} gap can fire only if its breakdown strength is continuous reduced by UV radiation from the spark channel plasma of the 1^{st} gap. => much larger switch delay time.**

Longitudinal triggering

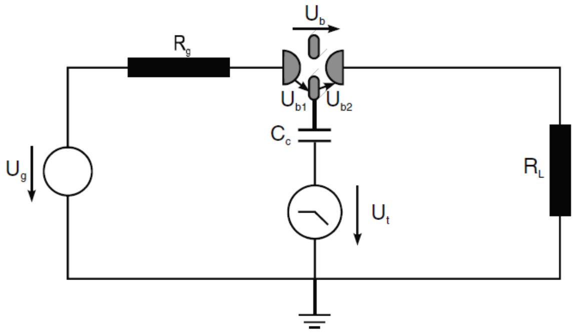
- **Longitudinal-overvoltage triggering ($U_g > U_{b2}$)**



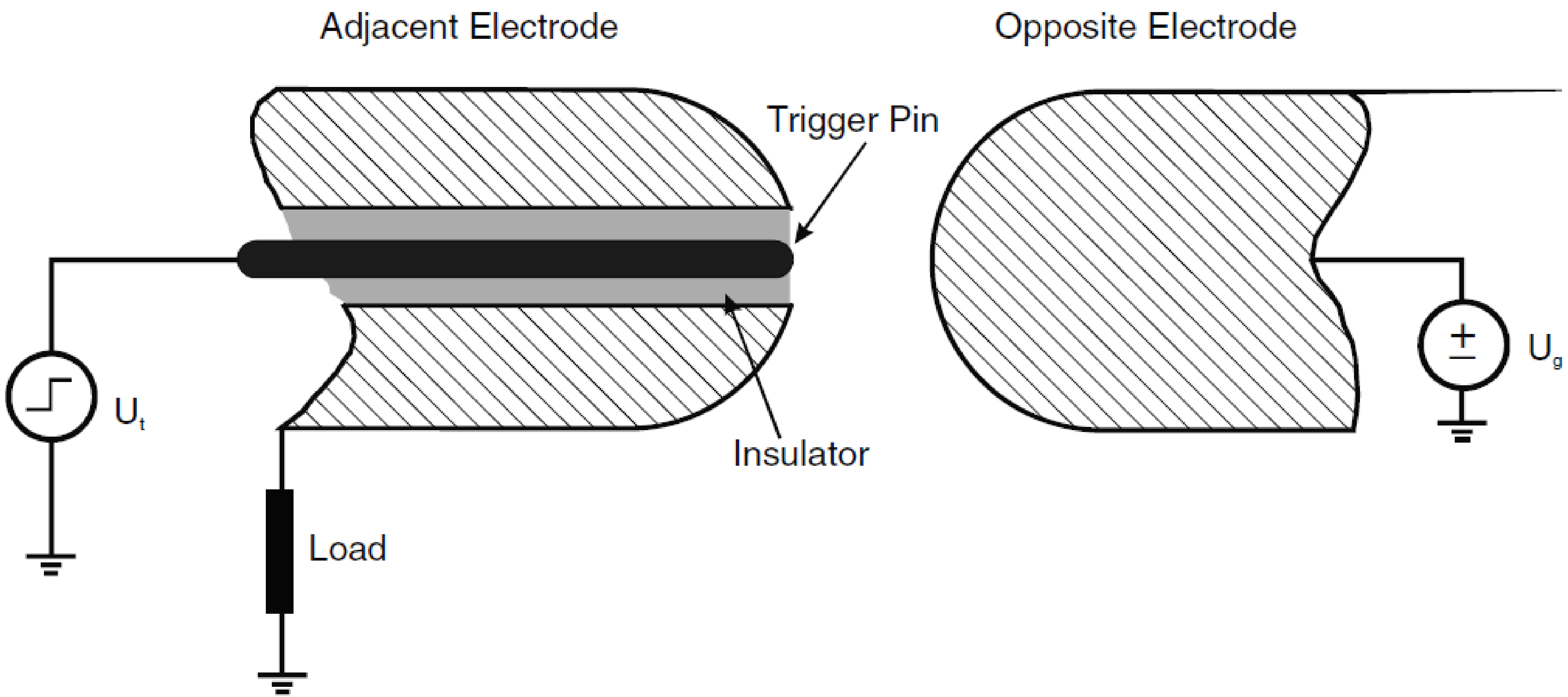
- **Longitudinal-plasma triggering ($U_g < U_{b2}$)**



- **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.,**

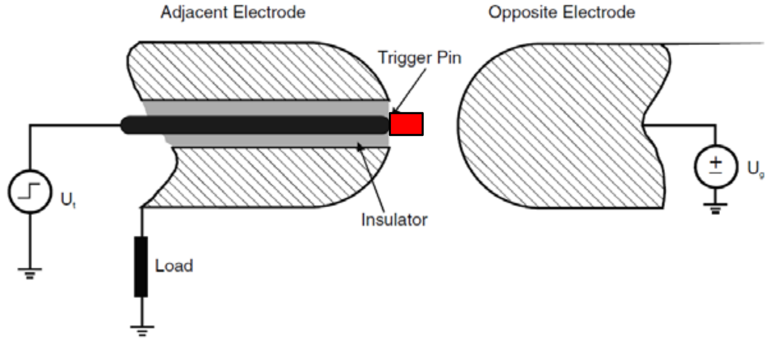
$$\boldsymbol{U_t \times U_g < 0}$$

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

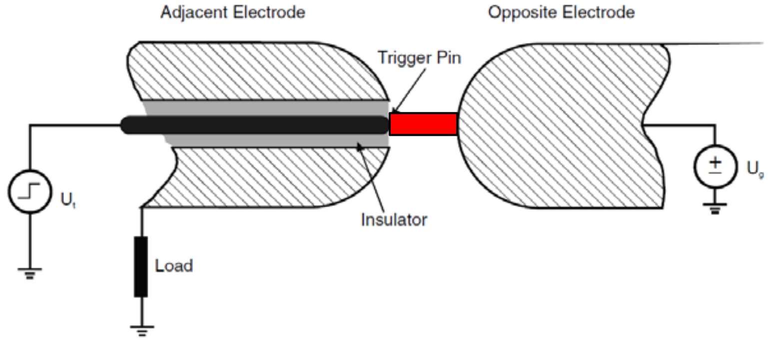
- **U_g~50% U_b is possible, but with large delay and jitter.**

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

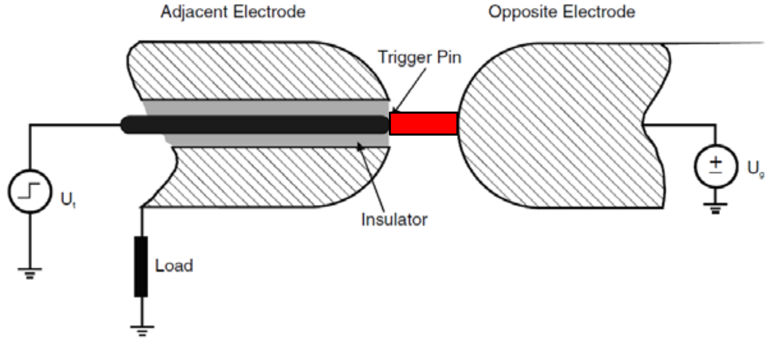
- **Step 1: Streamers begin to grow.**



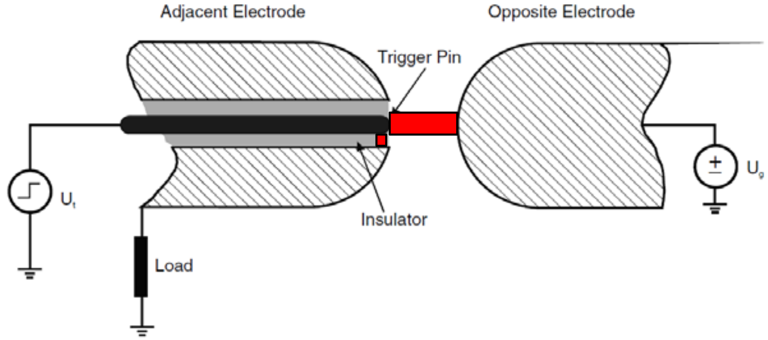
- **Step 2: ionization density in the channel to grow after streamer touch the electrode**



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

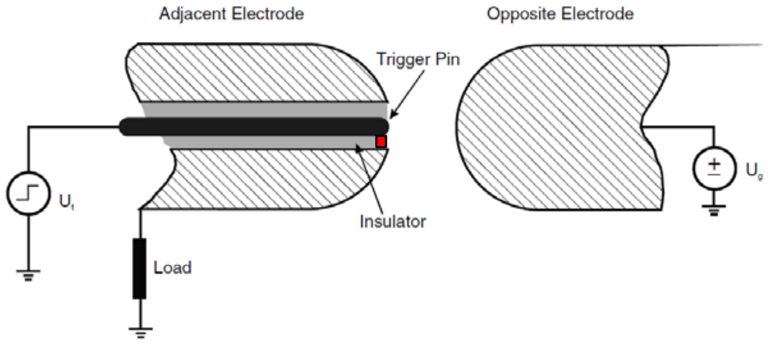


- **Step 4: two thermalized arcing connecting two electrode and pin.**

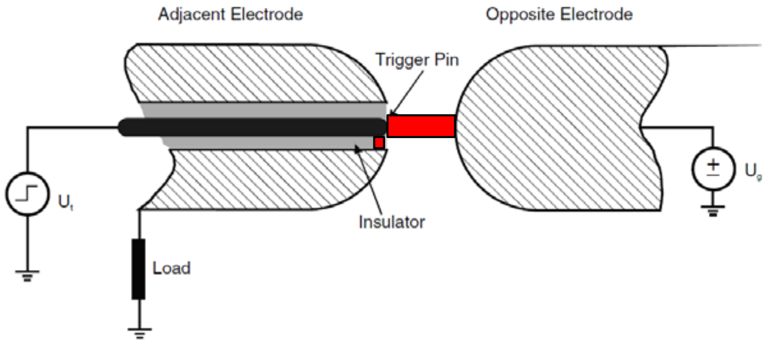


Trigatron spark gap – $U_t \times U_g > 0$

- **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.**

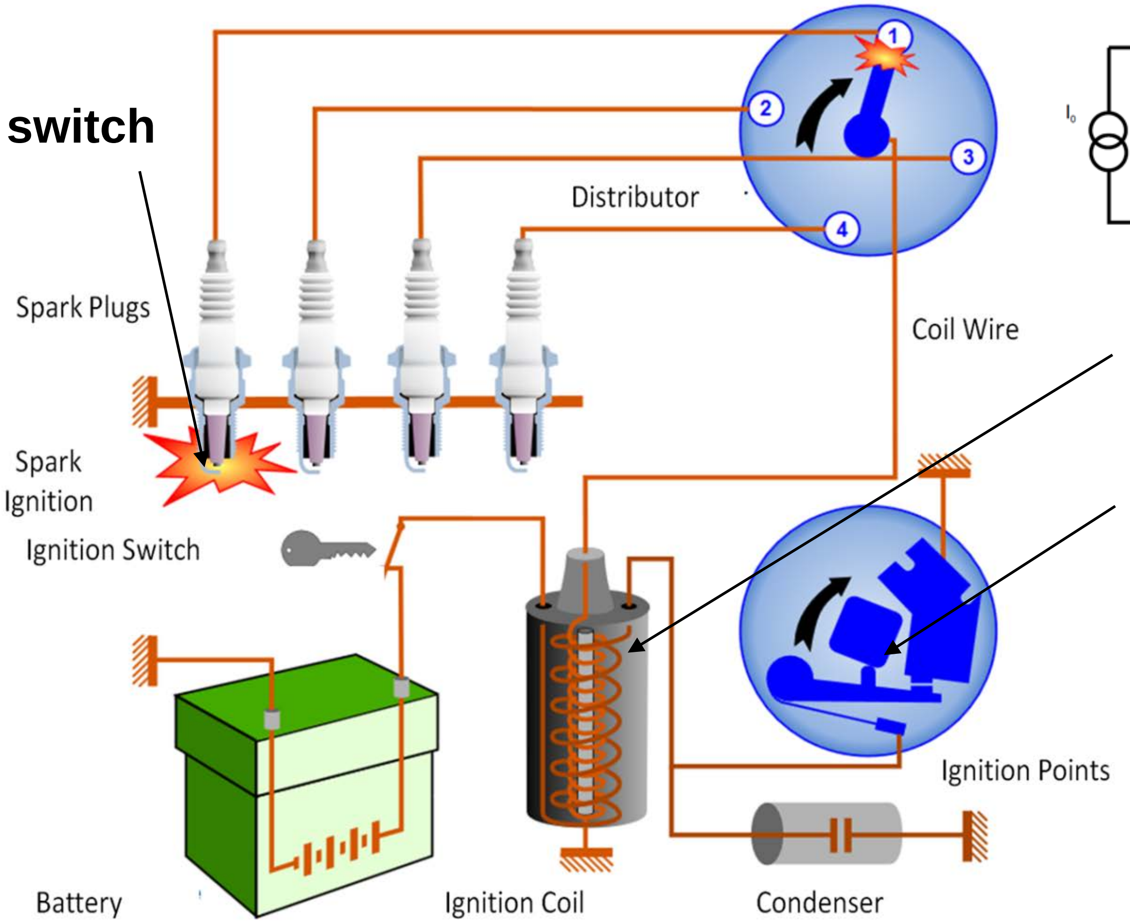


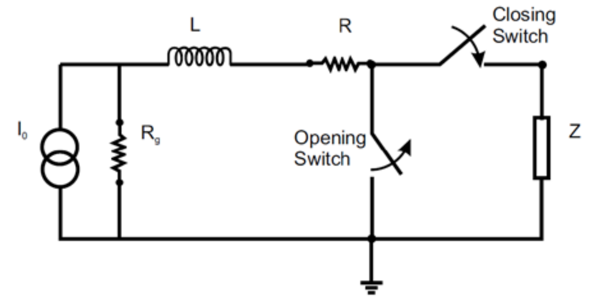
- **Breakdown is possible but with large delay and jitter.**

Spark plug is a Trigatron

Spark plugs in cars are triggered by the inductive energy storage

Closing switch /load



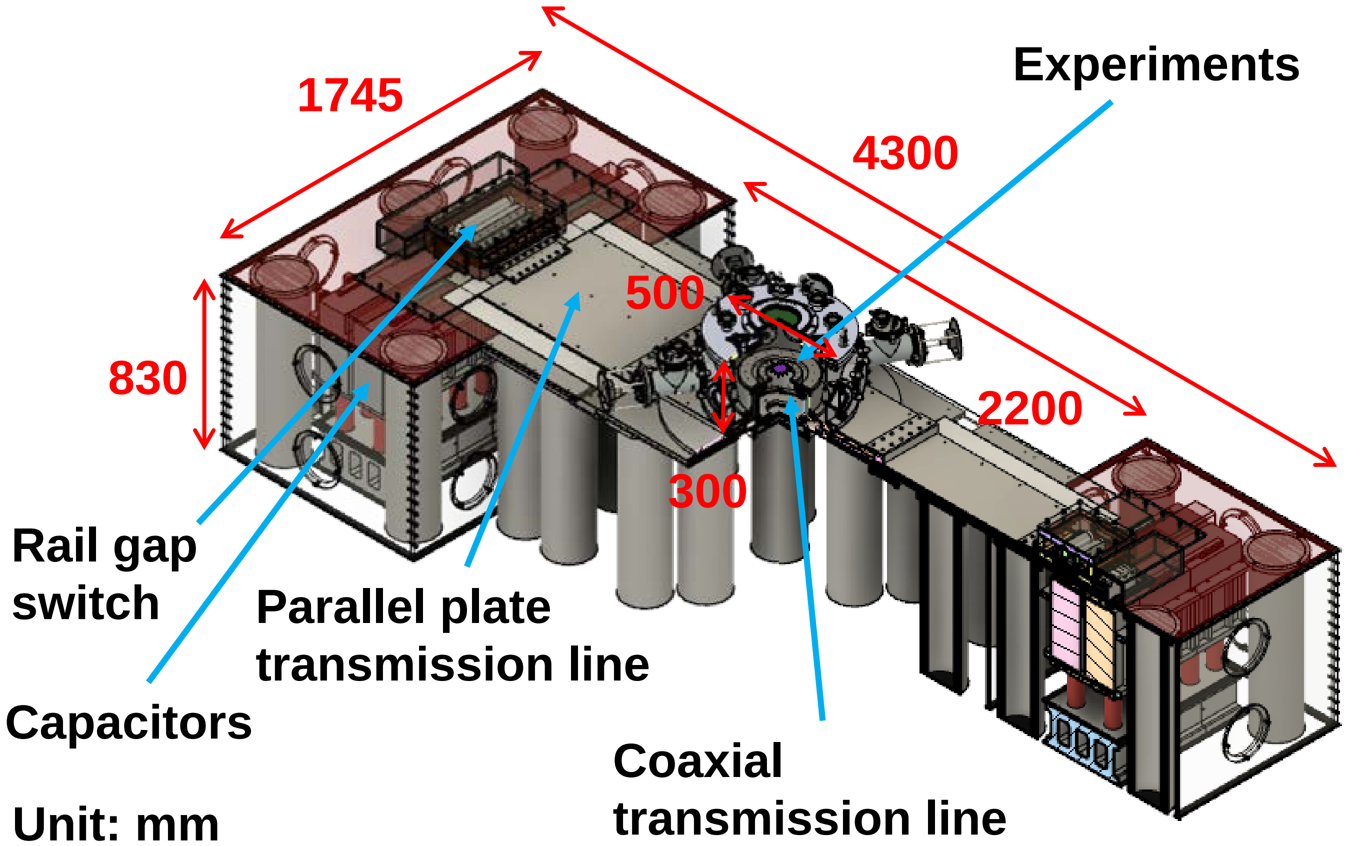


Inductive energy storage

Opening switch

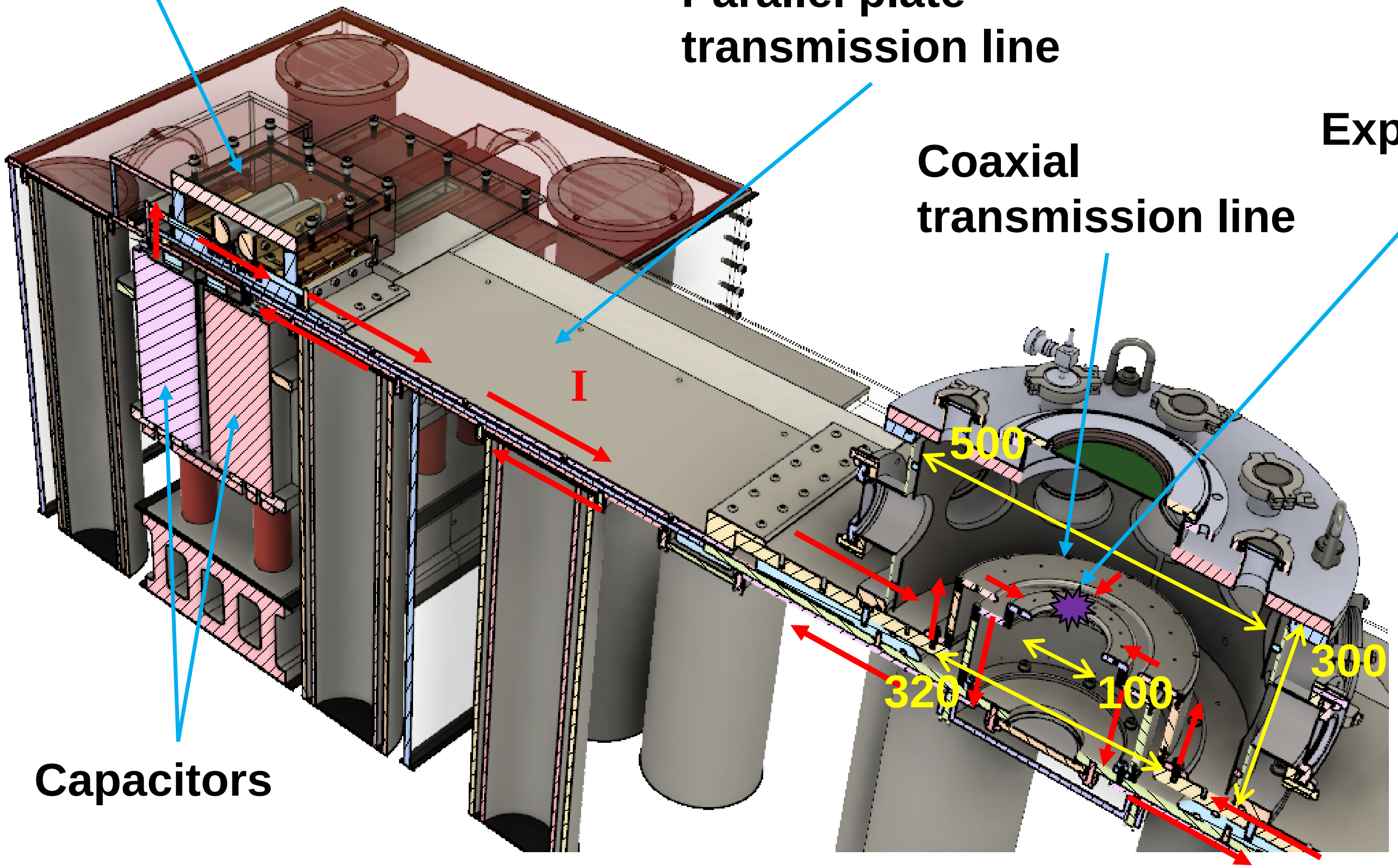
https://images.saymedia-content.com/.image/t_share/MTc0Mjk3MzYyODg0MjA4NTA4/diy-auto-service-ignition-systems-operation-diagnosis-and-repair.png

The pulsed-power system in Pulsed-Plasma Laboratory



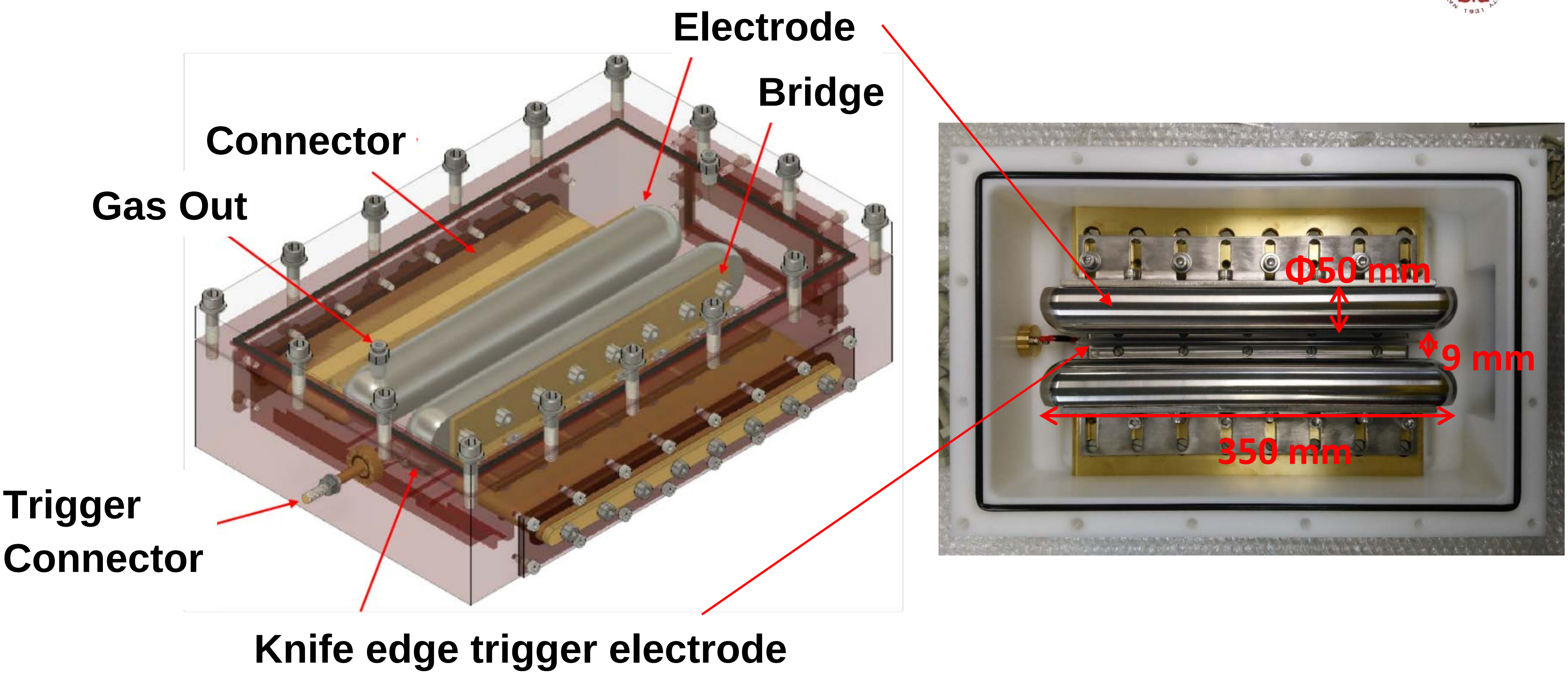
- **A 1 kJ pulsed-power system at ISAPS, NCKU started being operated since September, 2019.**

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



Unit: mm

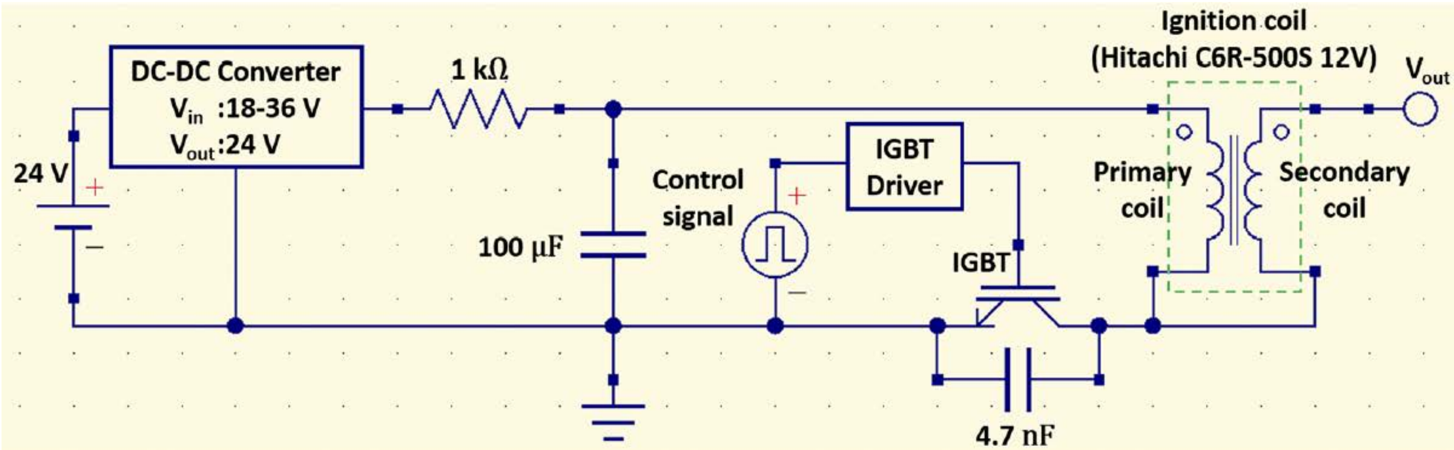
Low inductance rail-gap switches are used

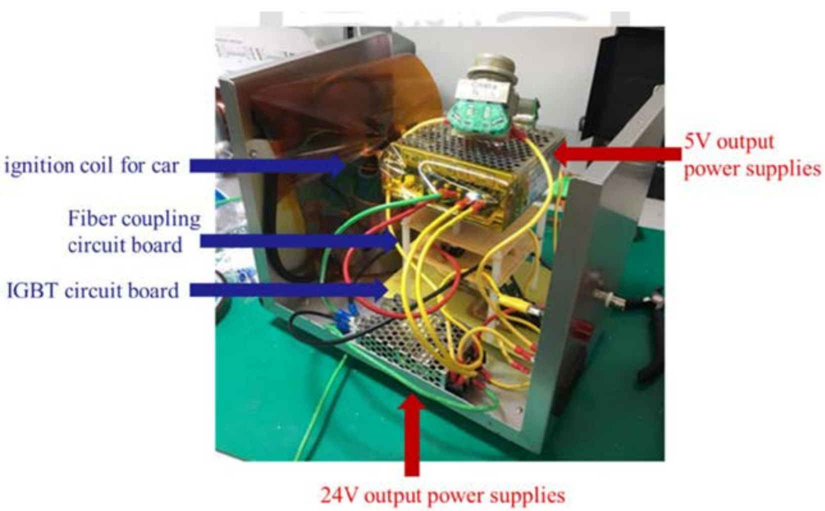


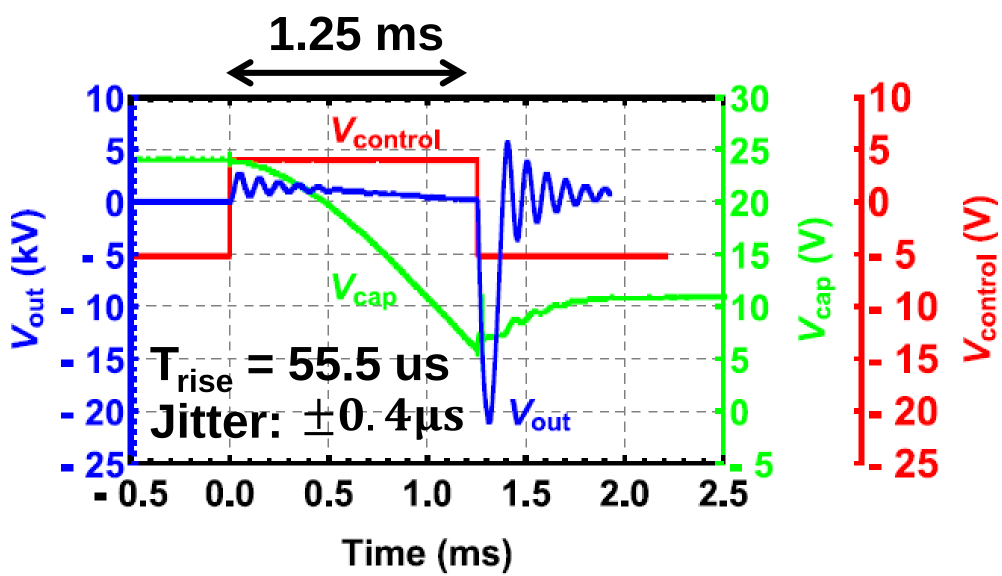
- The switch is pressurized with nitrogen gas (1~3 atm).
- Multi-channel discharges between two rail-like electrodes will be triggered by a fast trigger pulse generator (rising speed > 5kV/ns).

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

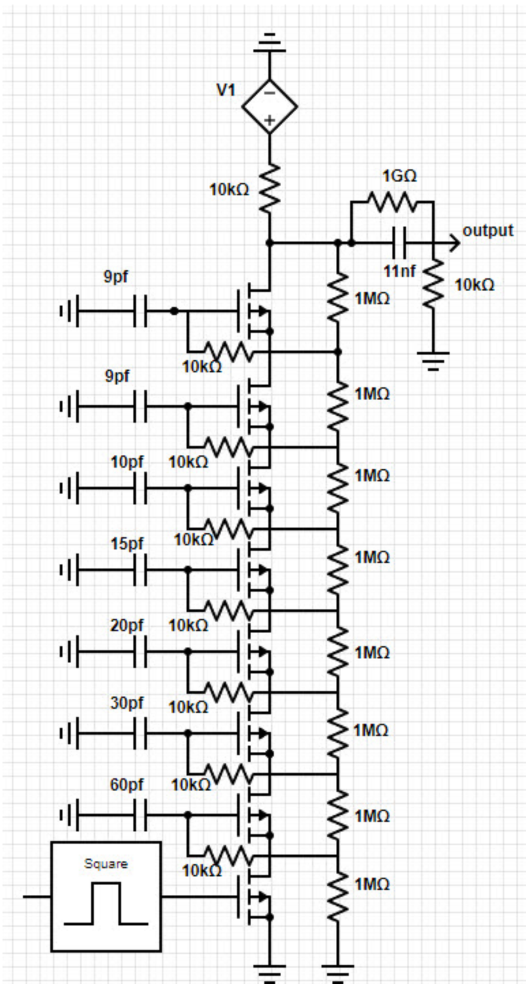


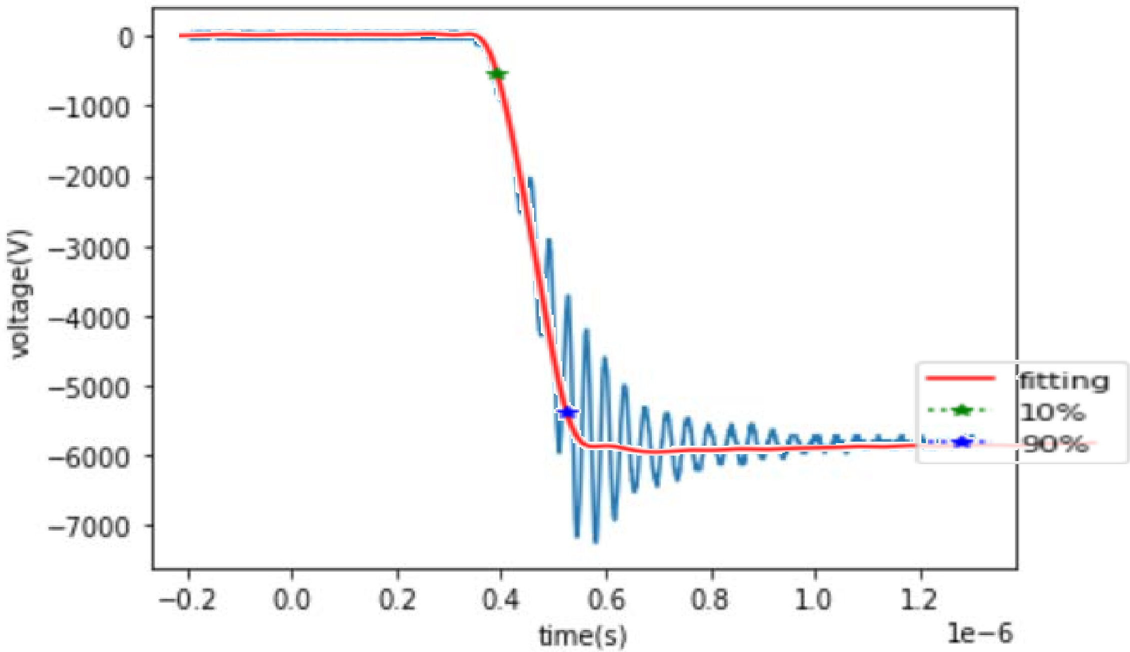




P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)

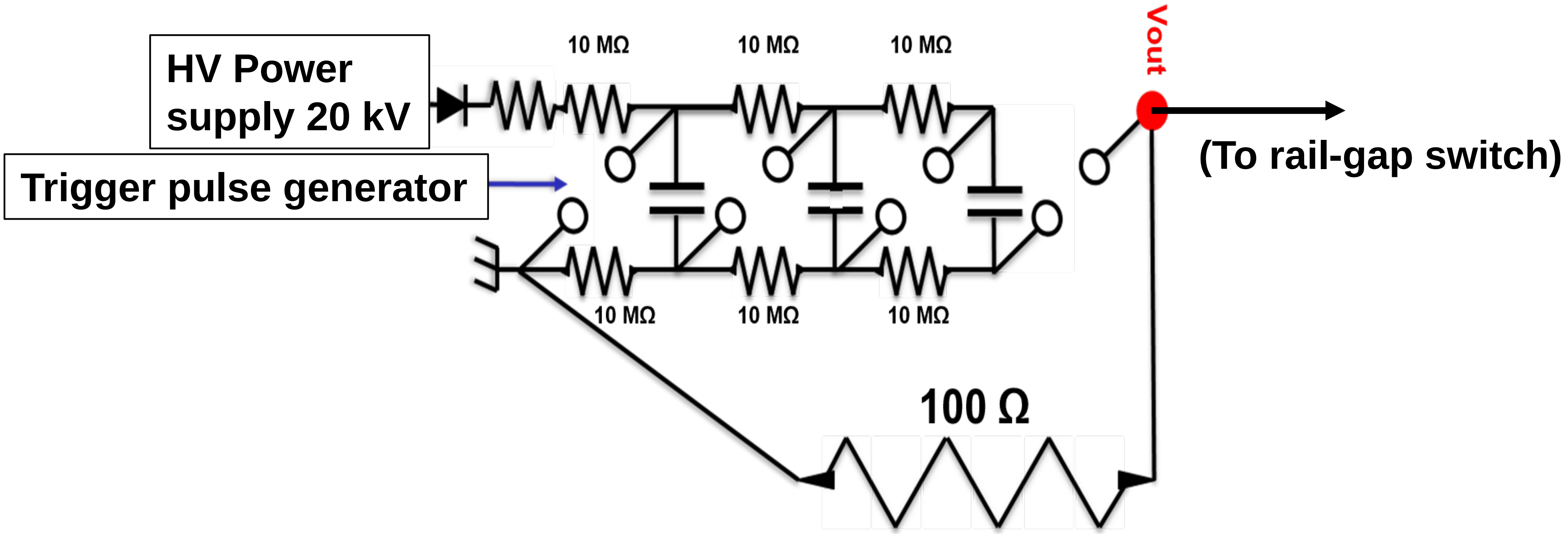
Many MOSFET connected in series can be used to provide a fast high-voltage triggering pulse





T_{rise}=140 ± 1 ns

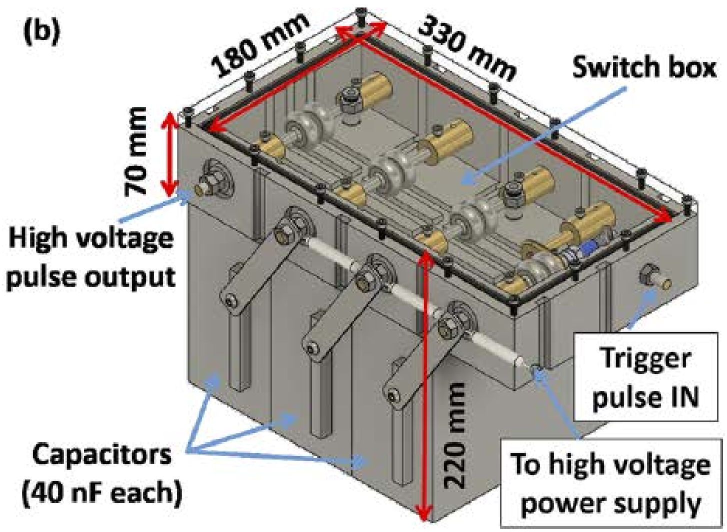
A three-stage Marx generator is used to provide a fast high voltage trigger pulse

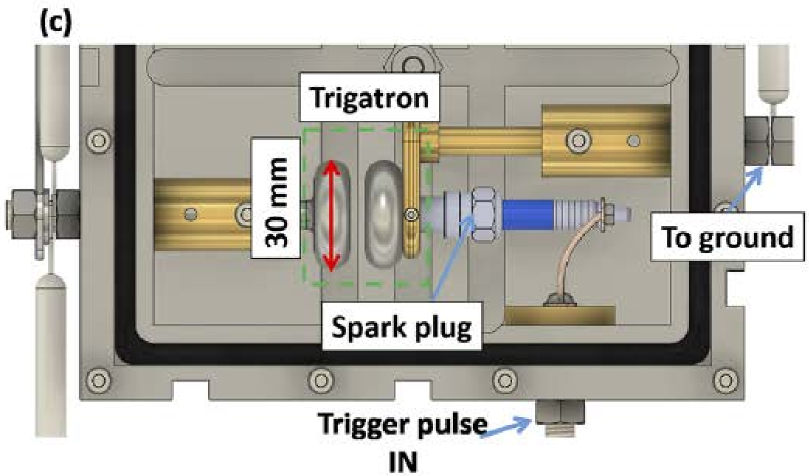


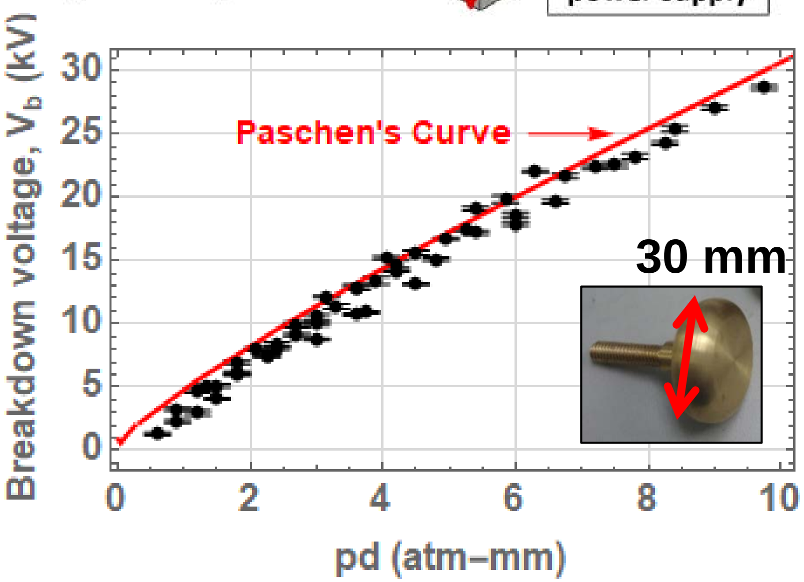
- In a Marx generator, capacitors are connected in parallel when they are being charged.
- Capacitors in the Marx generator are connected in series during discharge.

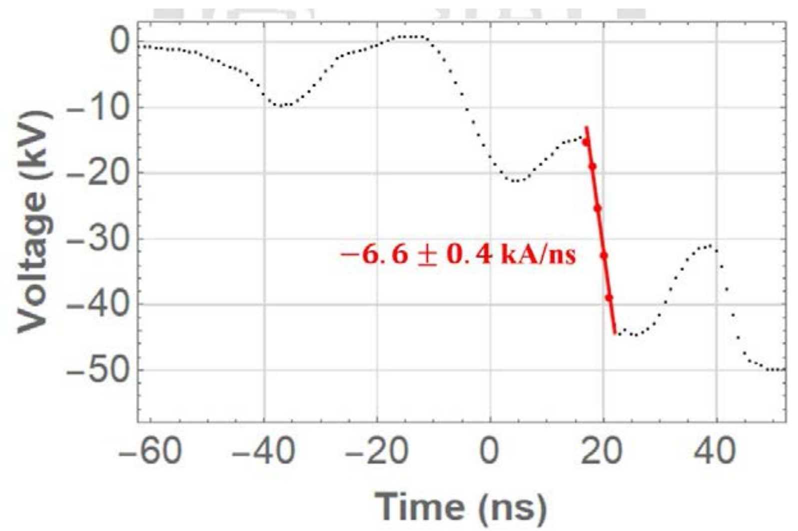
$$V_{\text{out, ideal}} = -N \times V_0 = -3 \times 20\text{ kV} = -60\text{ kV}$$

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



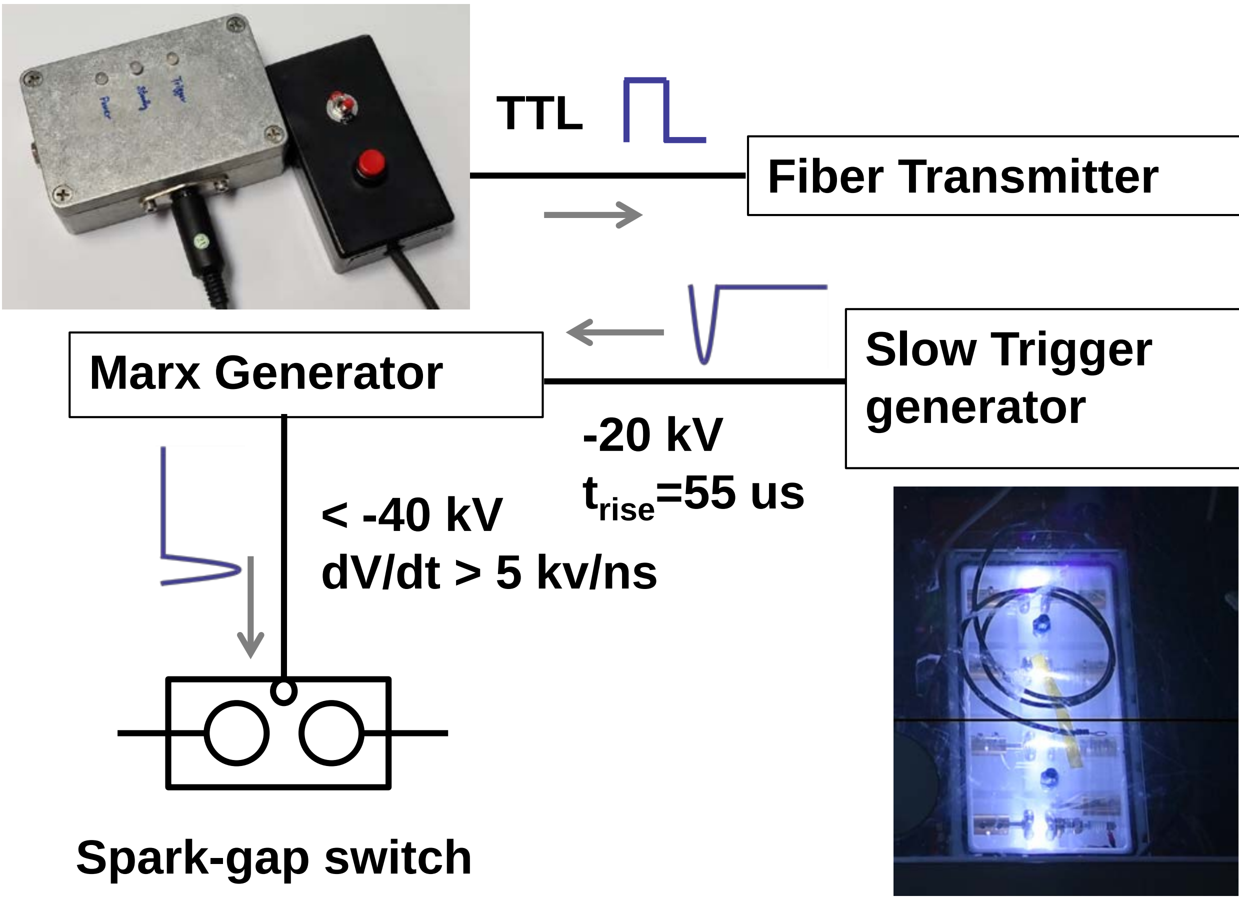


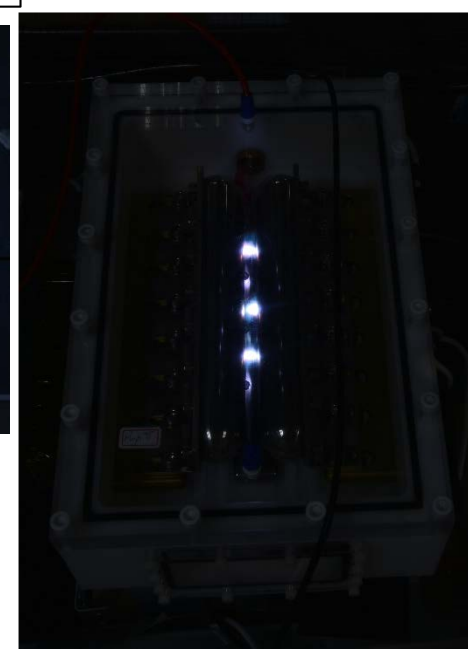




P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)

Multistep trigger system is used





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

Multistep trigger system is used

TTL

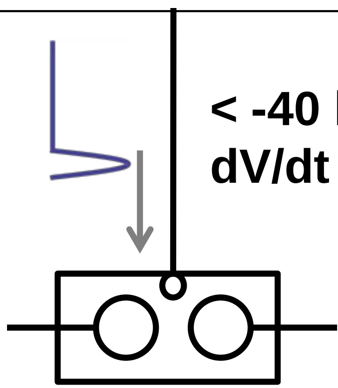
Marx Generator

-20

t_{rise}

< -40 kV

dV/dt > 5 kv/ns



Spark-gap switch

- At least 3 channels were

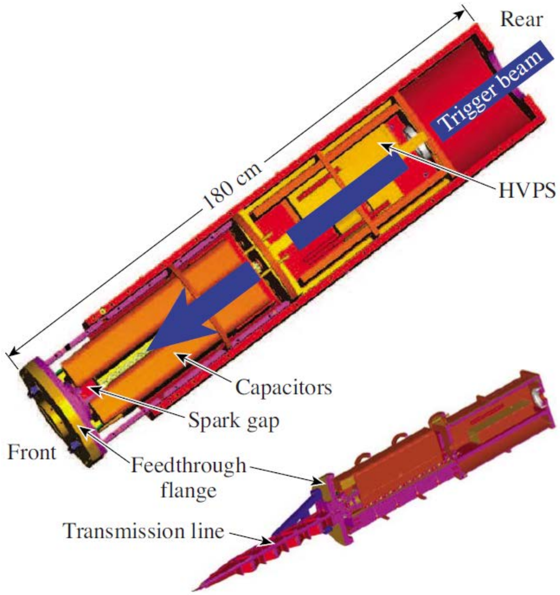
https://goods.ruten.com.tw/item/show?21941221827043

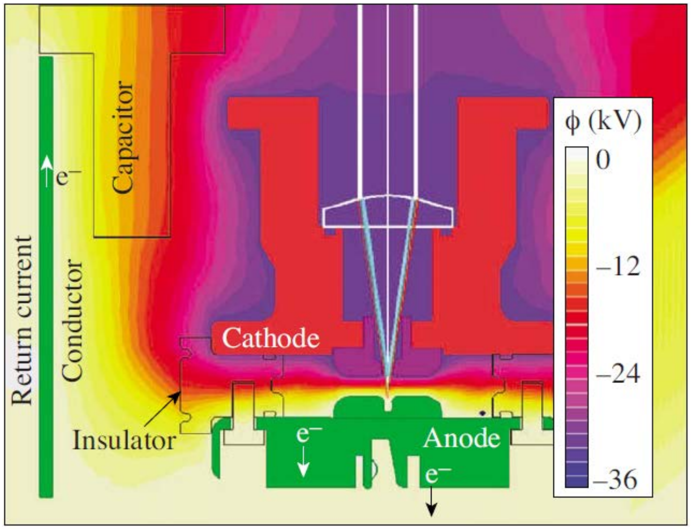
Multistep trigger system is used

TTL

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

Magneto-inertial fusion electrical discharge system

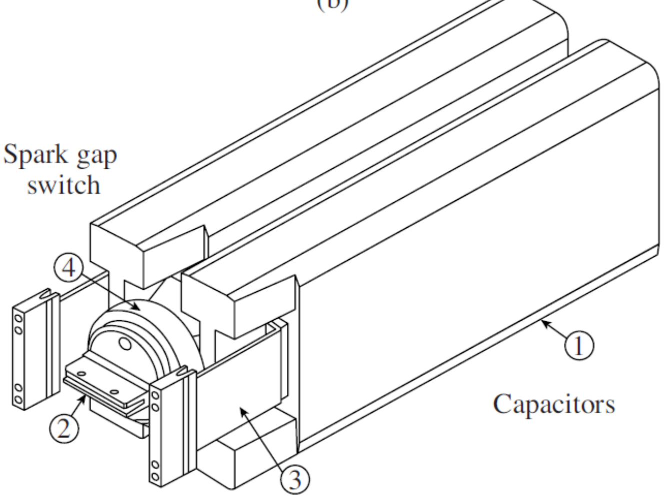


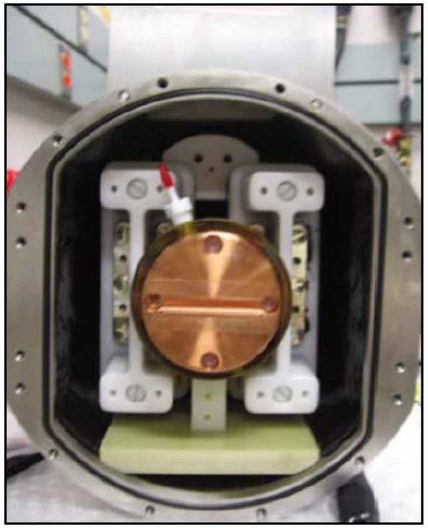


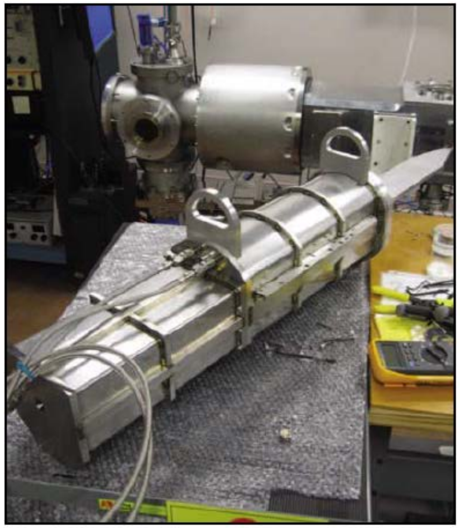
6-7 ns pulse
60 mJ @ 266 nm
300 mJ @ 532 nm
150 mJ @ 1064 nm

Delay: < 1 ns
Jitter: < 1 ns

(b)



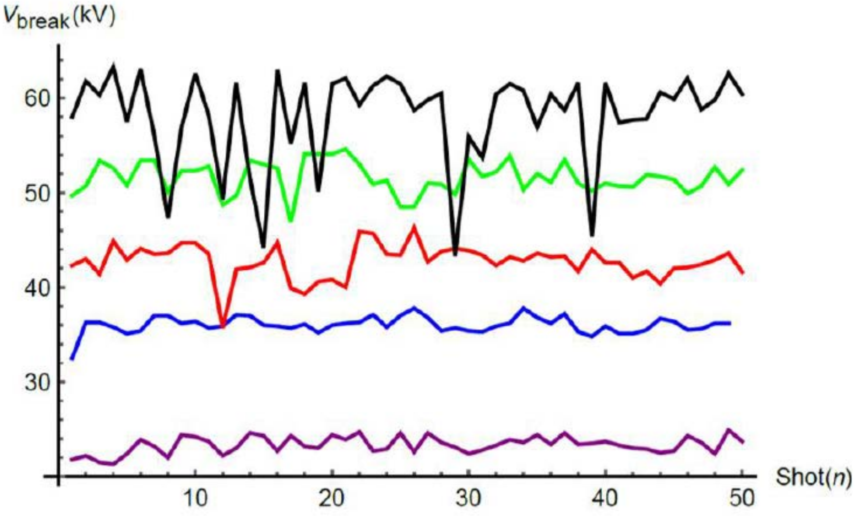


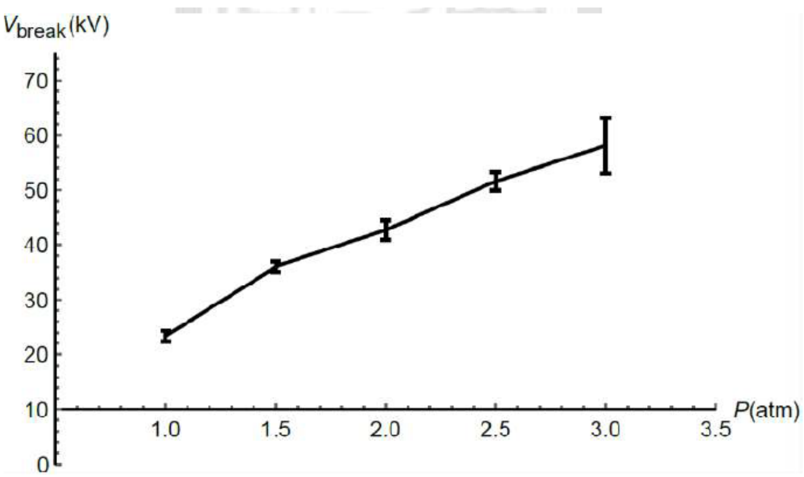


O. V. Gotchev, etc., Rev. Sci. Instrum. **80**, 043504 (2009)

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

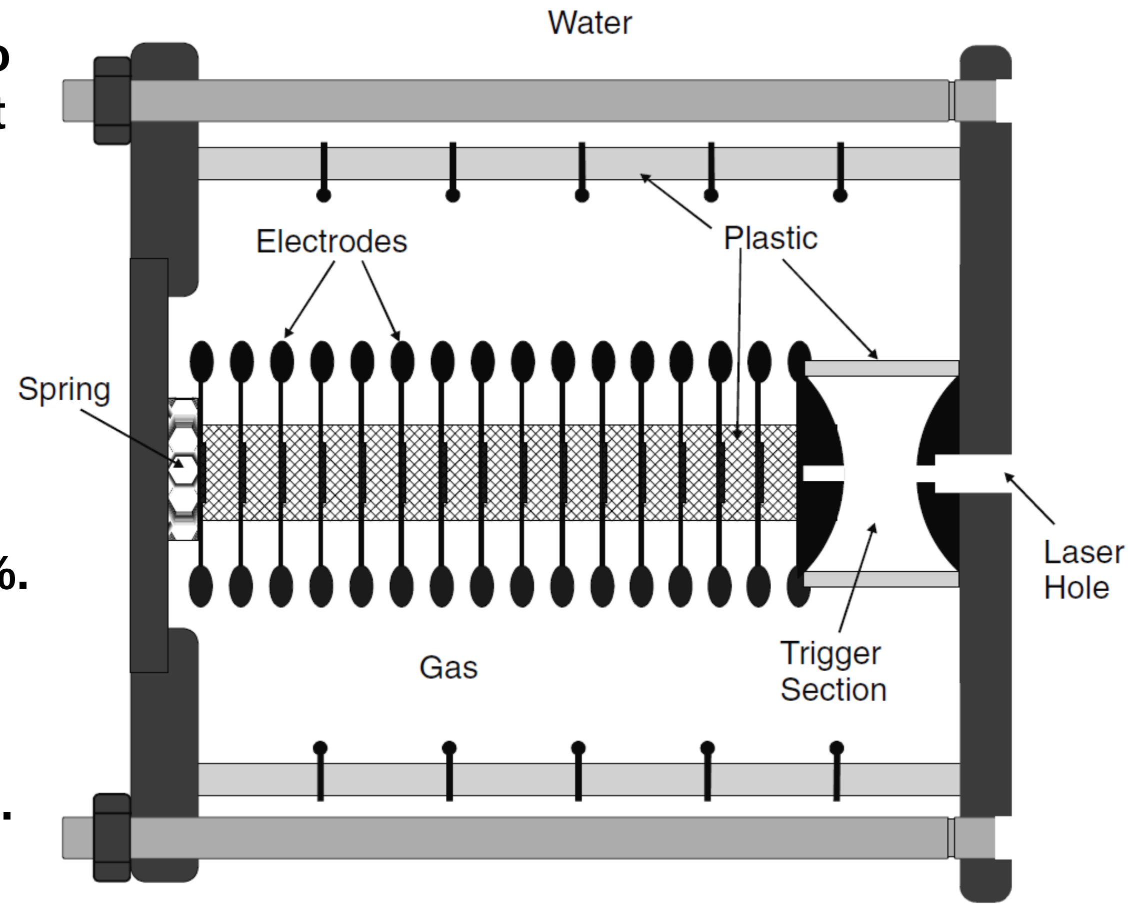




Sheng-Hua Yan, Master Thesis 2018

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.

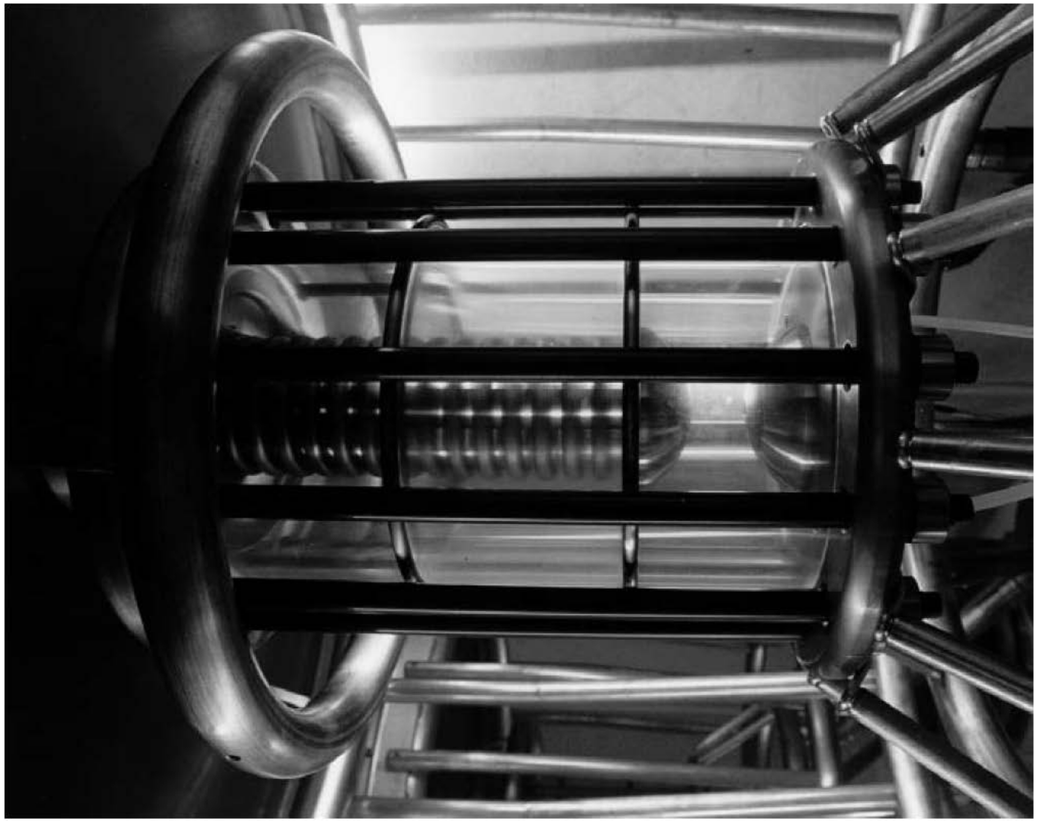
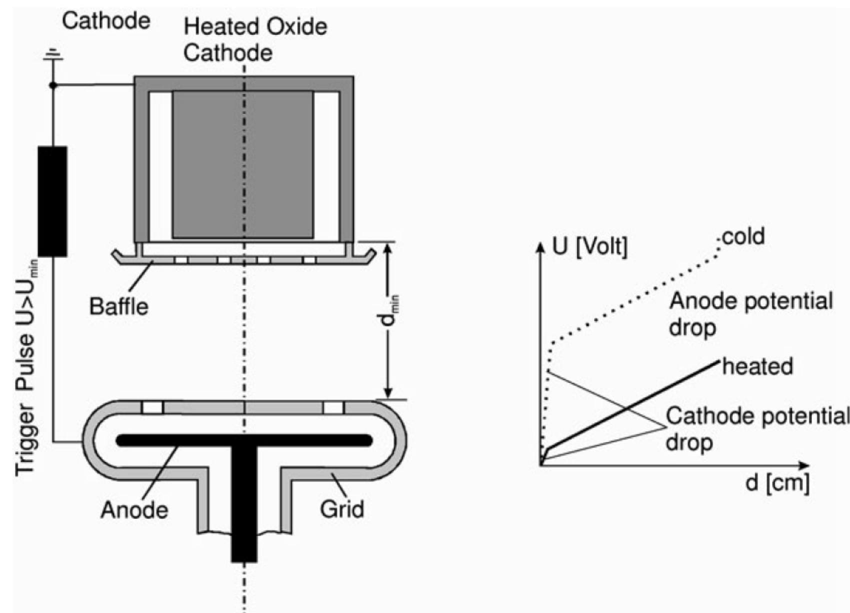
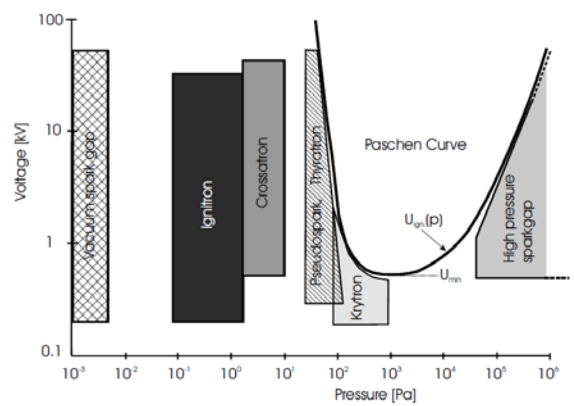


Fig. 4.13. A 4 MV version of a multigap spark switch

Thyratrons

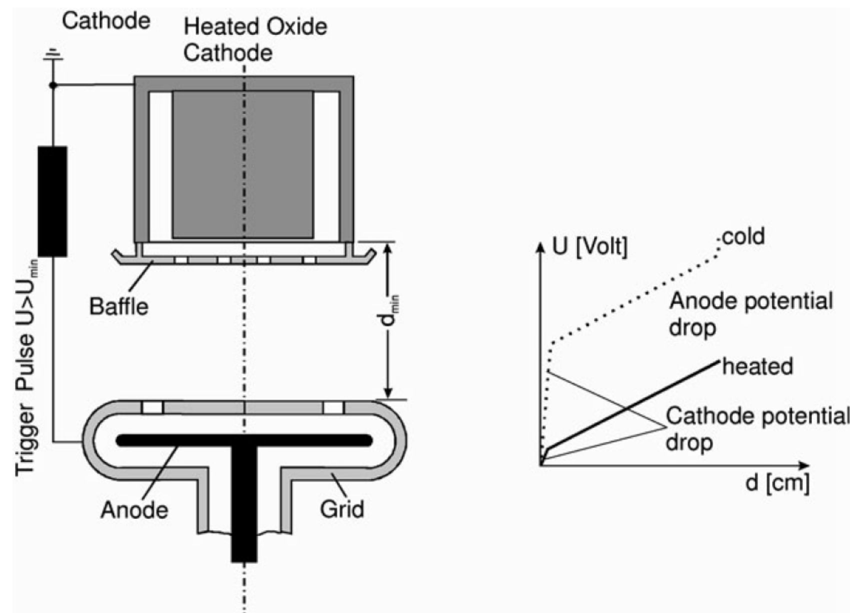
- **Thyratrons are gas-filled switching devices with a gas pressure (30-80 Pa/3x10^{-4} – 8x10^{-4} atm) much lower than a spark-gap switches.**
- **A triode configuration is used.**
- **The thyratron is characterized by the presence of a plasma, which allows the passage of large currents without significant 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.**

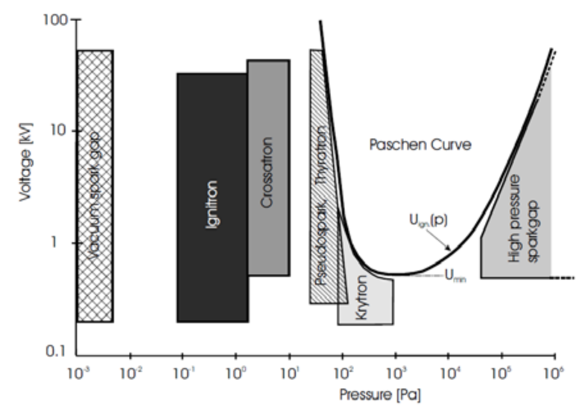




Thyratrons

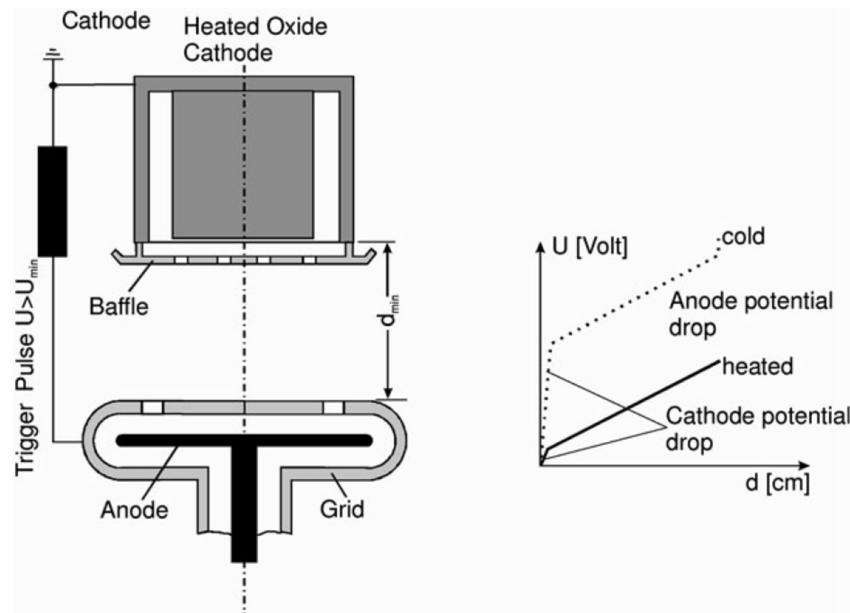
- **The cathode-grid distance corresponds to the Paschen minimum U_{min}.**
- **If $U > U_{min}$, a glow discharge is initiated between the cathode and the grid. => electrons from the glow discharge plasma can migrate rapidly through the openings in the grid to the main discharge region between the grid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

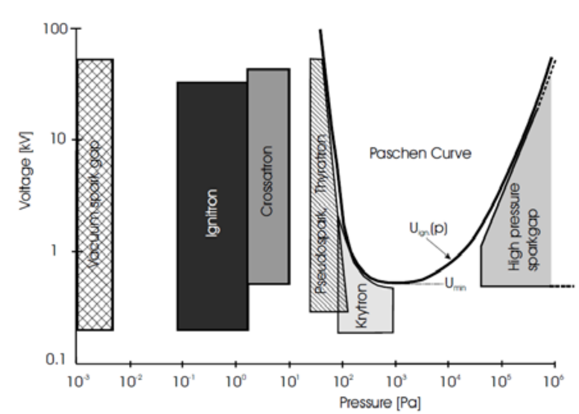




Thyratrons

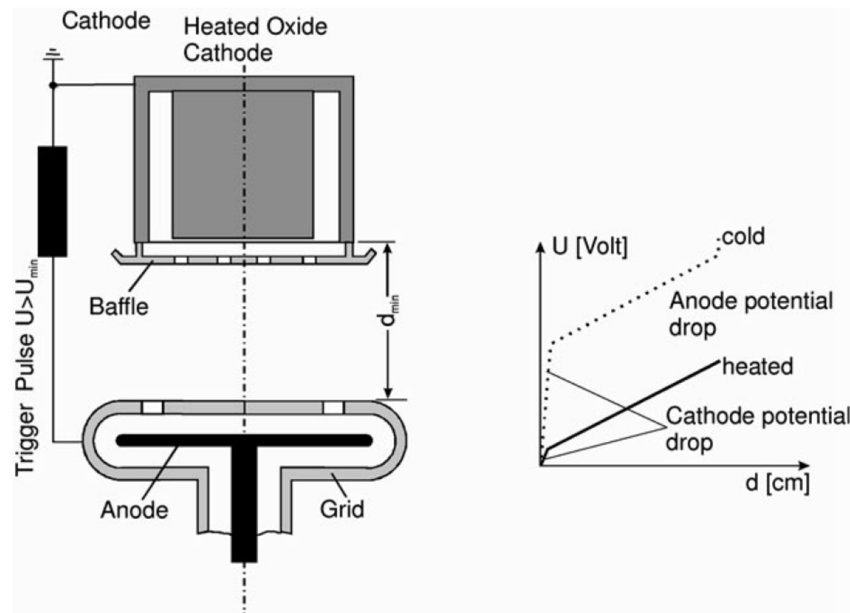
- **Operating voltage: several times 10 kV. After ignition: ~100 V => an appreciable power loss occurs and need to be dealt with by cooling.**
- **Delay: ~200 ns; jitter: ~ns.**
- **Operating times: 10^5 hours; Repetition rates: few kHz; Operating power: MW.**
- **To regain the initial hold-off voltage: anode voltage must become slightly negative for 25-75 us for plasma to decay.**

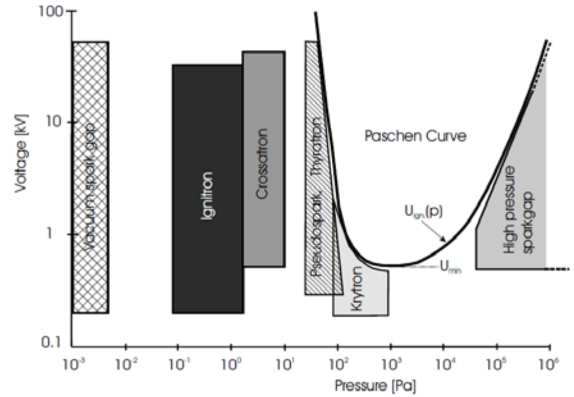




Thyratrons

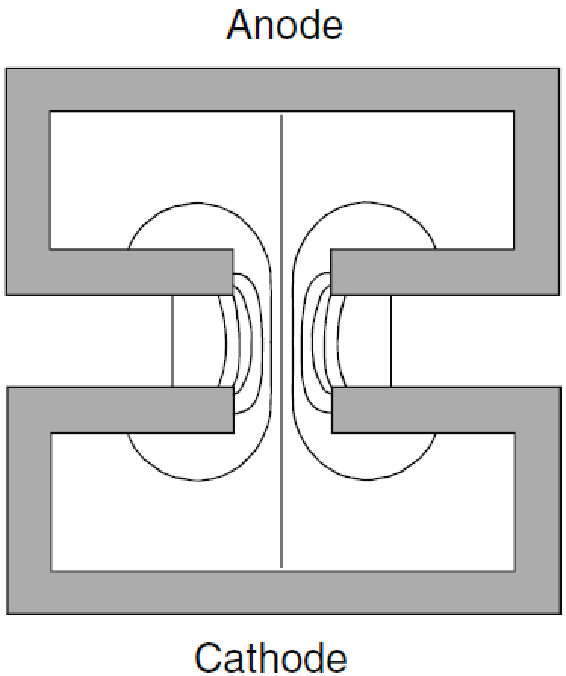
- **A thermionic cathode is used in a thyratron.**
- **Advantage: absence of a marked cathode potential drop using hot cathode.**
- **If cold cathode is used, potential drop is needed to accelerate the ions for secondary-electron production => lead to erosion of the cathode and thus the lifetime.**
- **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.**

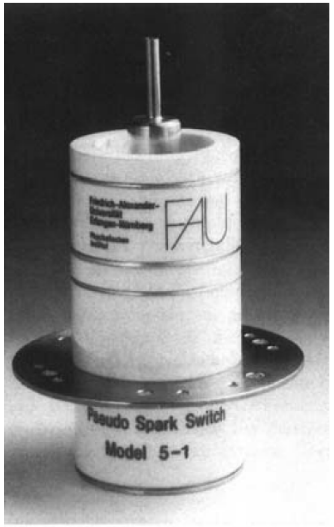


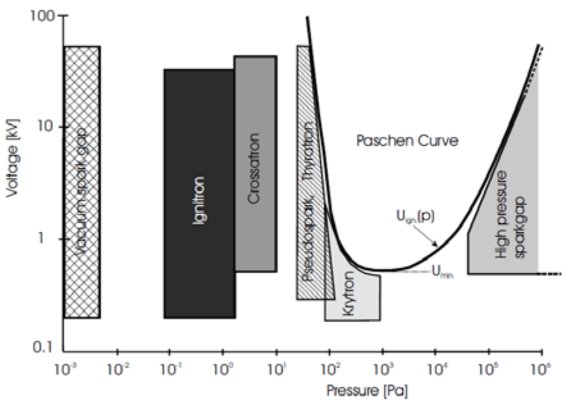


The pseudospark switch

- **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.**

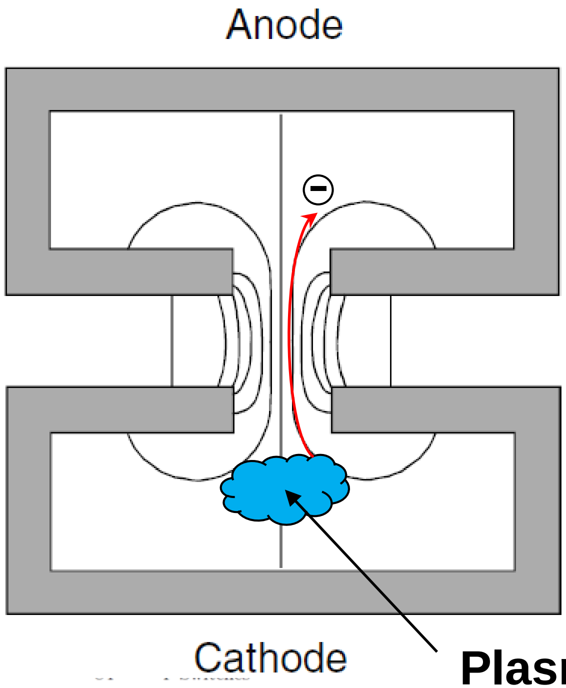




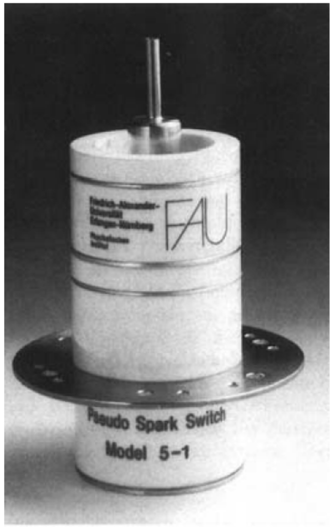


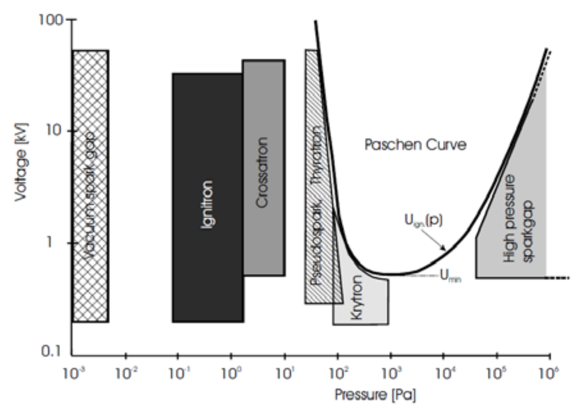
The pseudospark switch

- **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.**



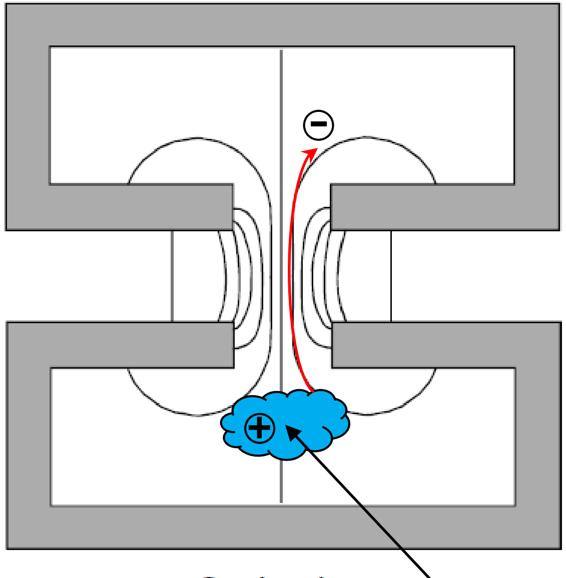
Plasma formed first.

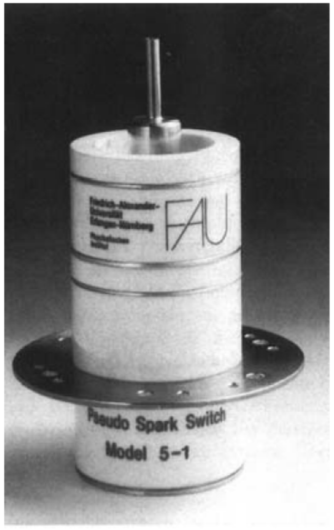


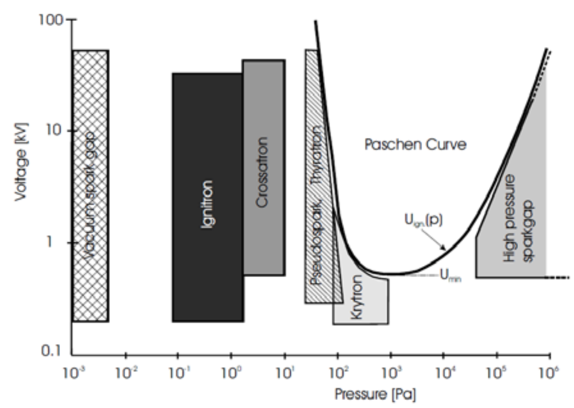


The pseudospark switch

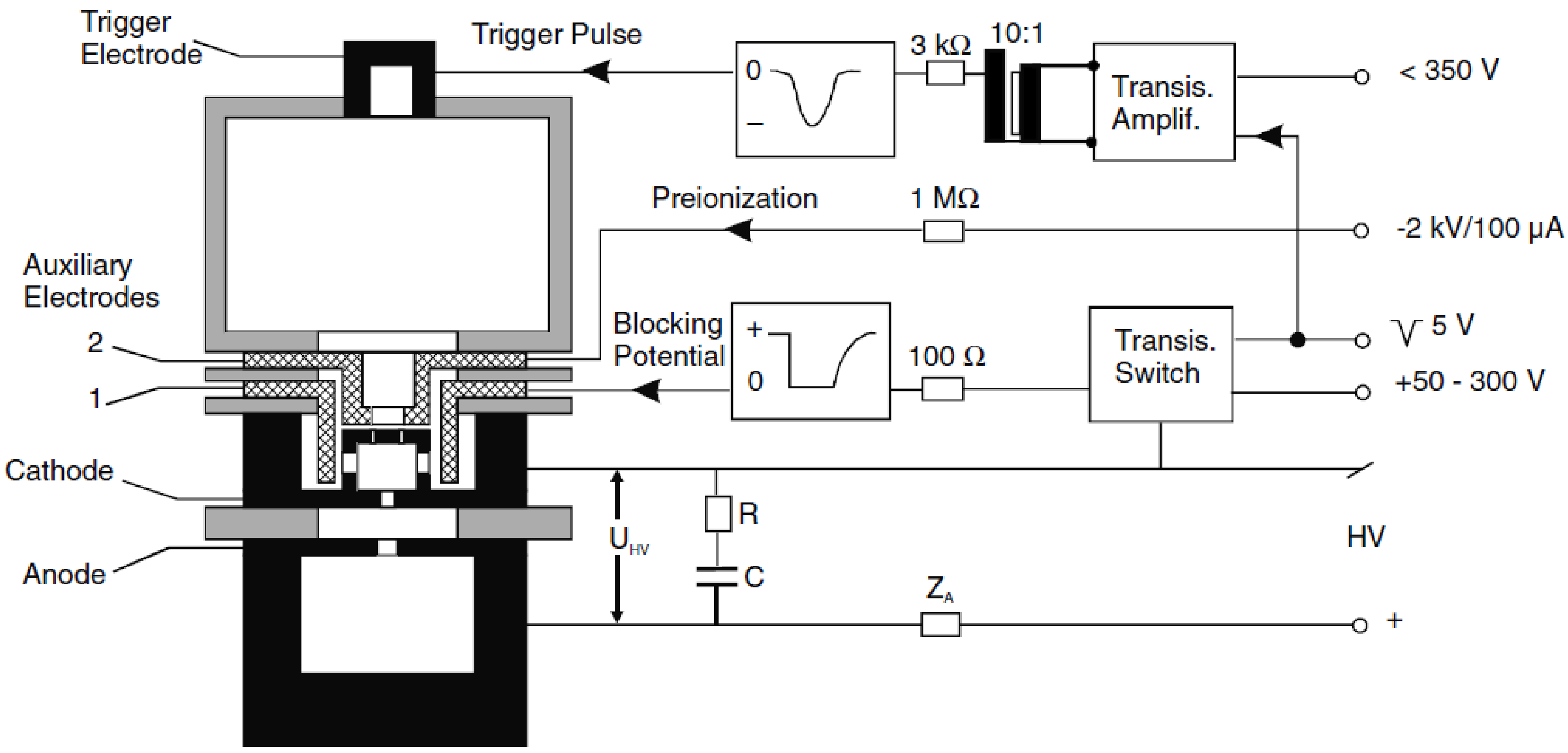
- Ions drift back into the hollow cathode => forming a positive space charge (virtual anode).
- Static electric field inside the hollow cathode is distorted.
- Electron production rate > loss rate in the hollow cathode and subsequently in the anode-cathode gap.
- A low-resistivity plasma is estabilished,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





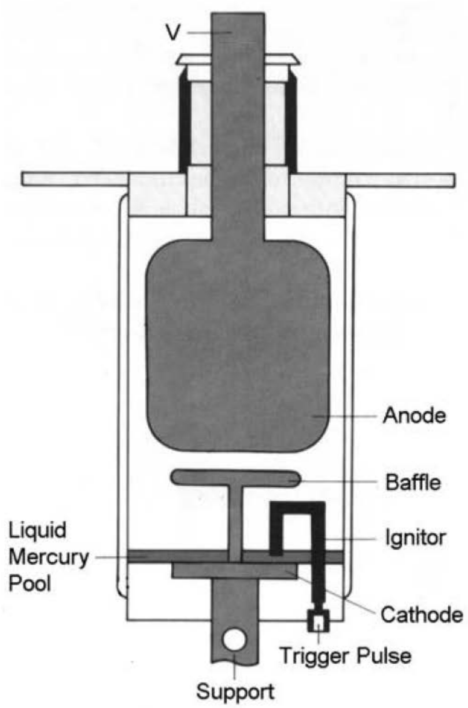


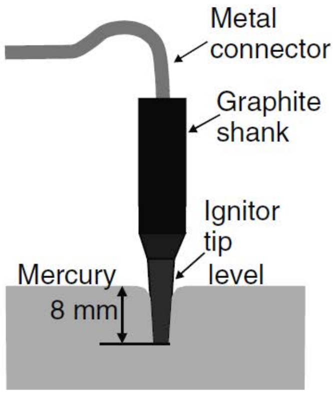
The pseudospark switch with triggering system



Ignitrons

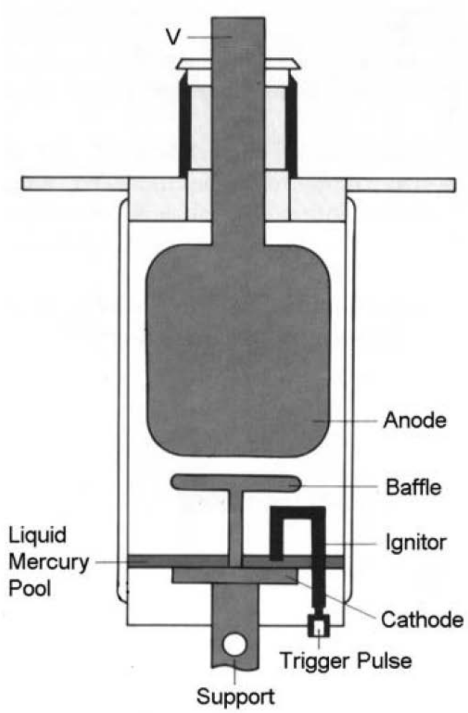
- Ignitron is a very high-current, high-voltage switch with
  - a liquid mercury pool cathode
  - an ignitor pin dipping into the liquid-metal reservoir.
- Internal mercury pressure: ~5 Pa
- Can switch a pulse charge of up to 2000 Colum.
- Air/water cooled may be needed.
- Internal splash and deionization 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.

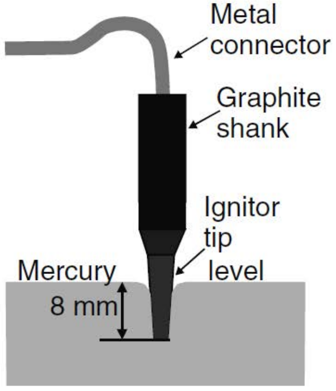




Ignitrons

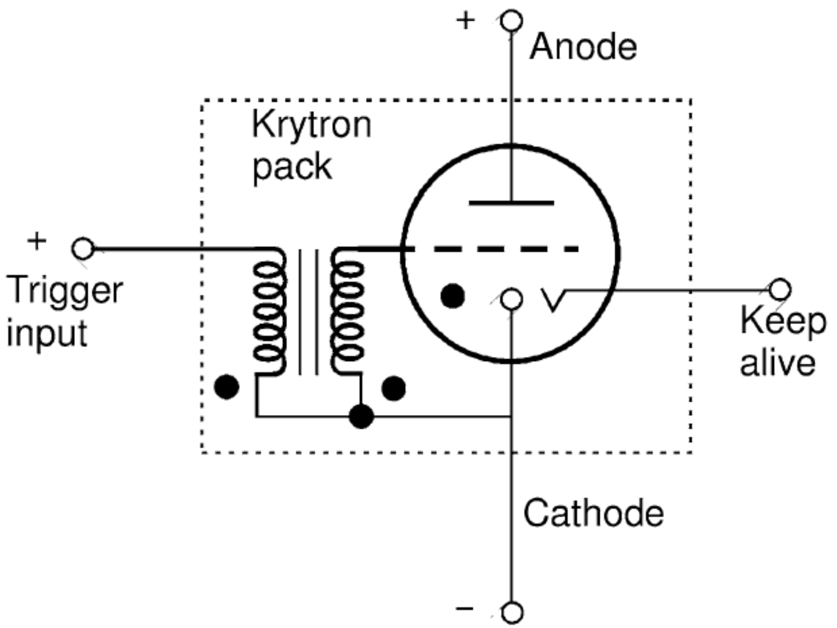
- **Rise time ~ 300-500 ns.**
- **After current drops below a critical value => no more additional vapor is produced => with additional time to allow recombination and recondensation of mercury.**
- **The mercury vapor must be forced to recondense back into the pool.**
- **Repetition rate ~1 Hz**
- **Progressively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





Krytrons

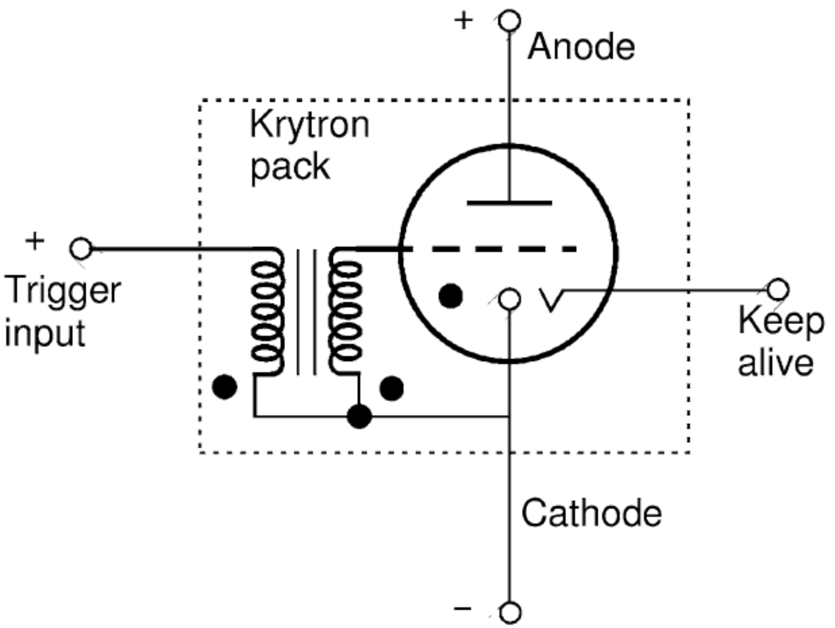
- **Low-pressure gas discharge device with a tetrode configuration, sealed in a glass tube with a cold cathode.**
- **1.3 kPa (9.75 torr) of helium gas.**
- **A special design of the anode-grid area + applied gas pressure**
  => large hold-off voltage.
- **An already existing plasma is created by a glow 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

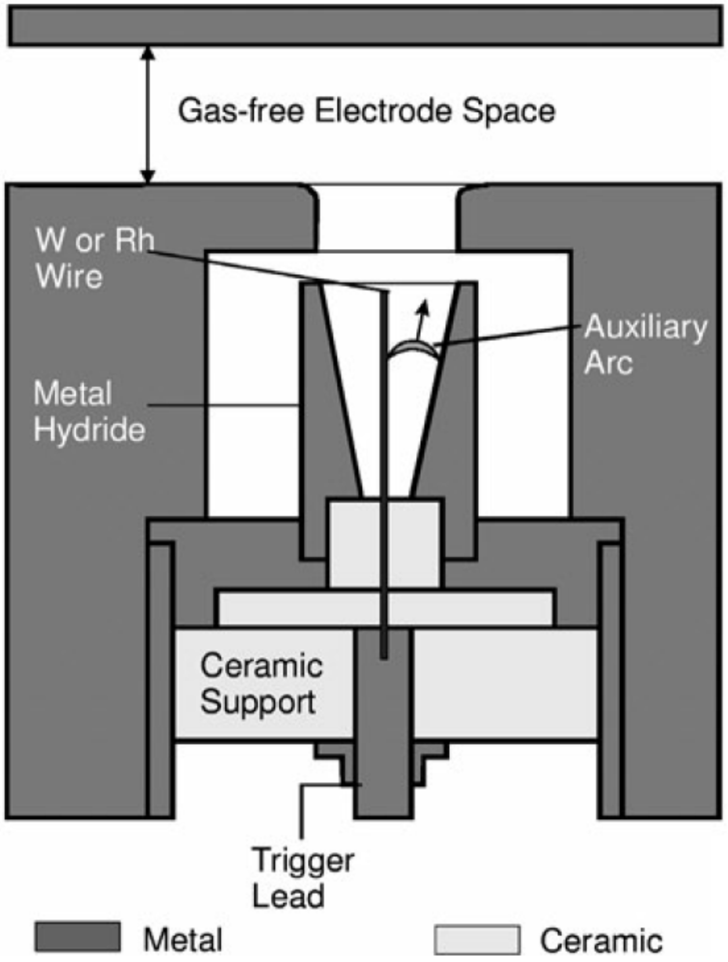
- **A ^{63}Ni β-emitter may be enclosed to create a weak permanent pre-ionization.**

- **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

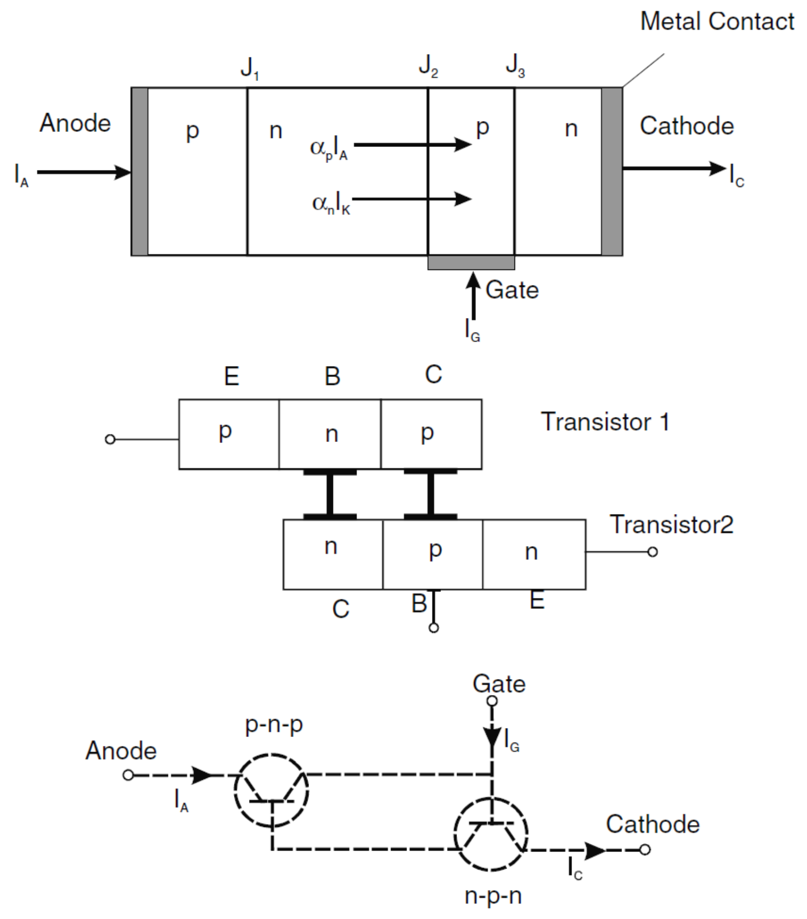
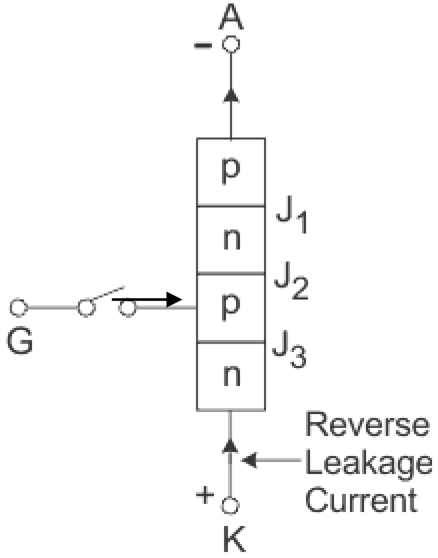


Fig. 4.22. Structure of thyristor, and two-transistor equivalent circuit

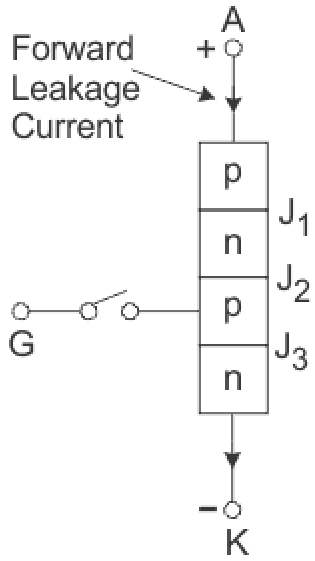
Thyristors

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



Reverse Blocking Mode

Most of the voltage is held by J_1.



Forward Biased Condition

Most of the voltage is held by J_2.

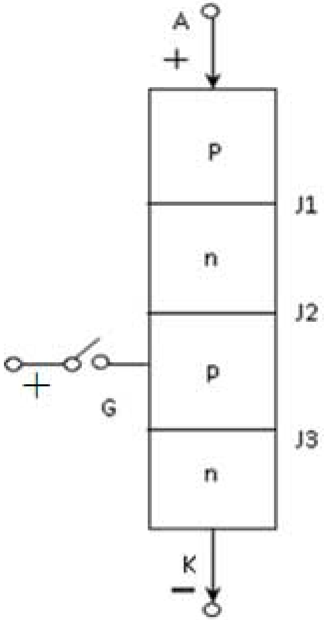
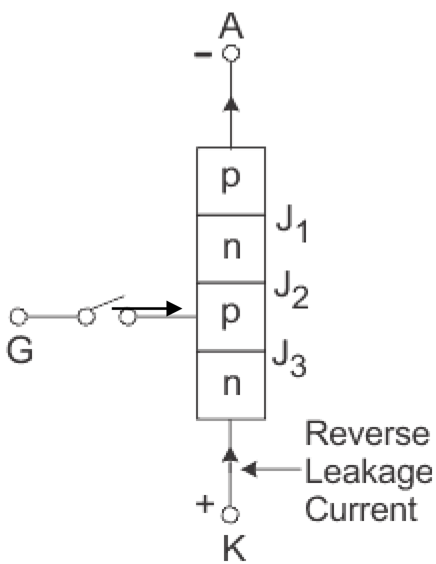


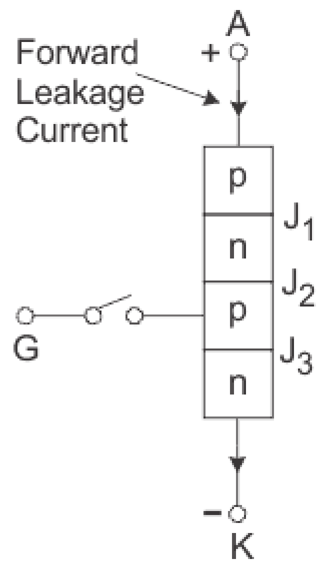
Fig 2: Forward Conduction

Thyristors

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



Reverse Blocking Mode



Forward Biased Condition

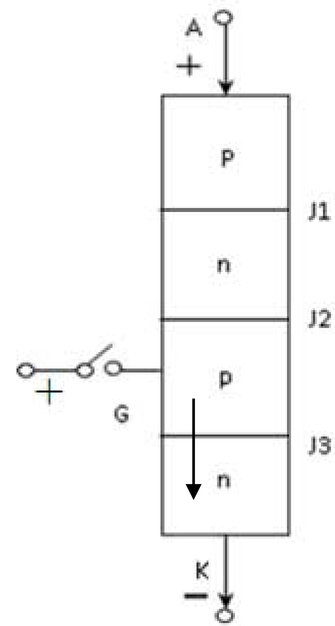


Fig 2: Forward Conduction

e^- will fill up the holes

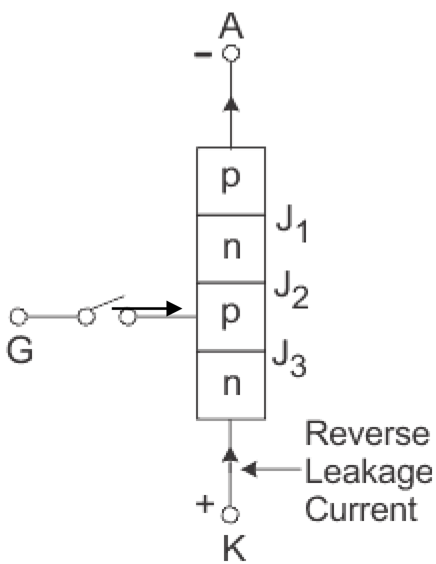
w/ more e^- => p type becomes N type

Most of the voltage is held by J_1.

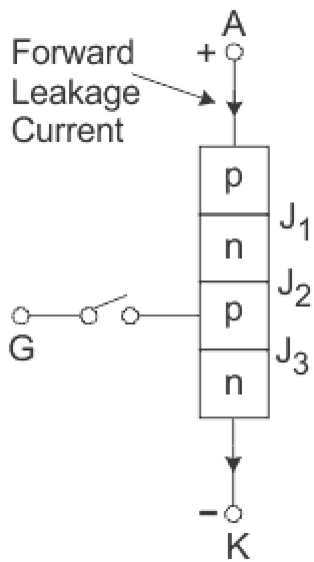
Most of the voltage is held by J_2.

Thyristors

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



Reverse Blocking Mode



Forward Biased Condition

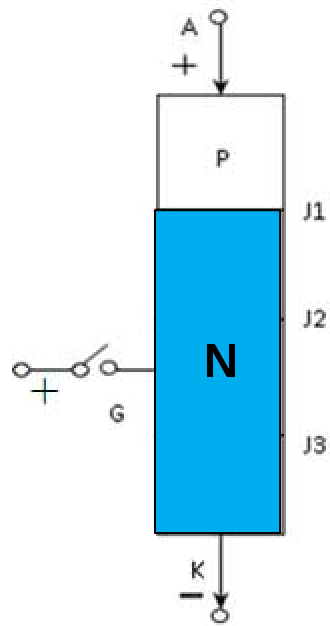


Fig 2: Forward Conduction

e^- will fill up the holes

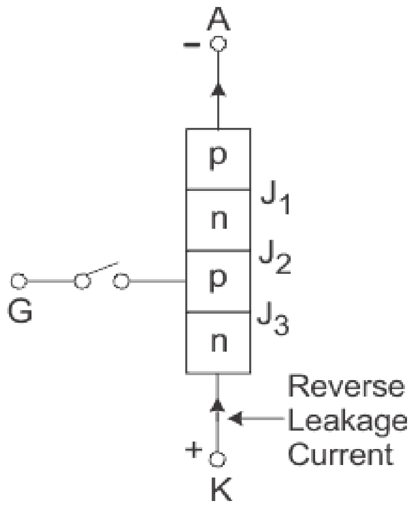
w/ more e^- => p type becomes N type

Most of the voltage is held by J_1.

Most of the voltage is held by J_2.

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.**



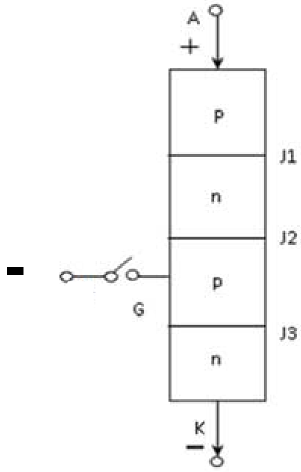
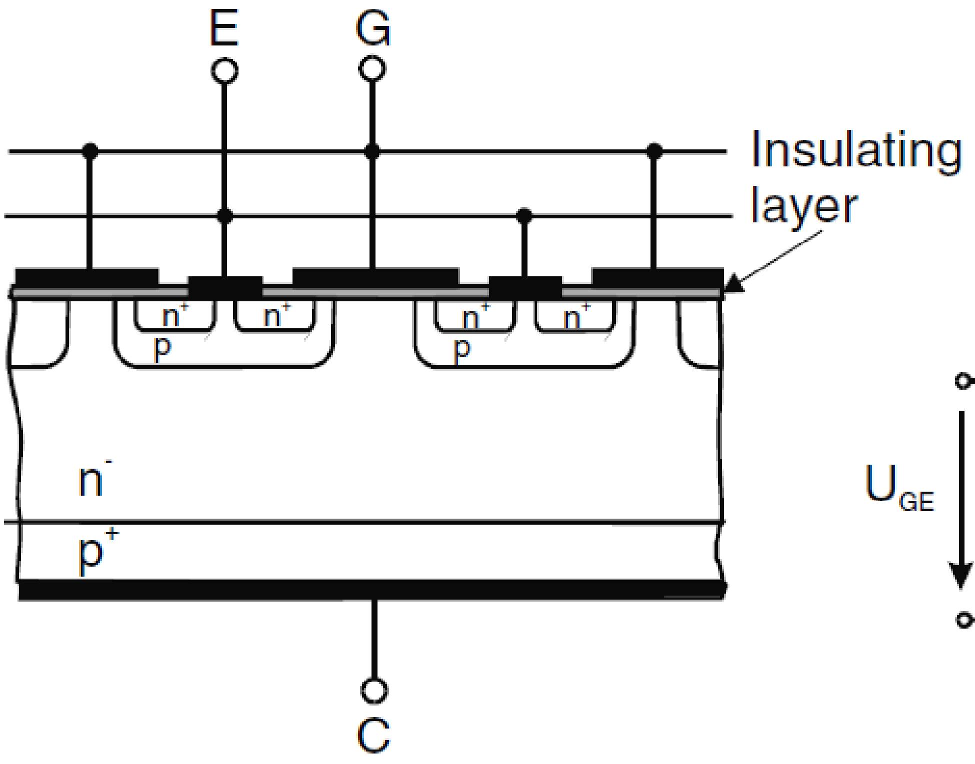
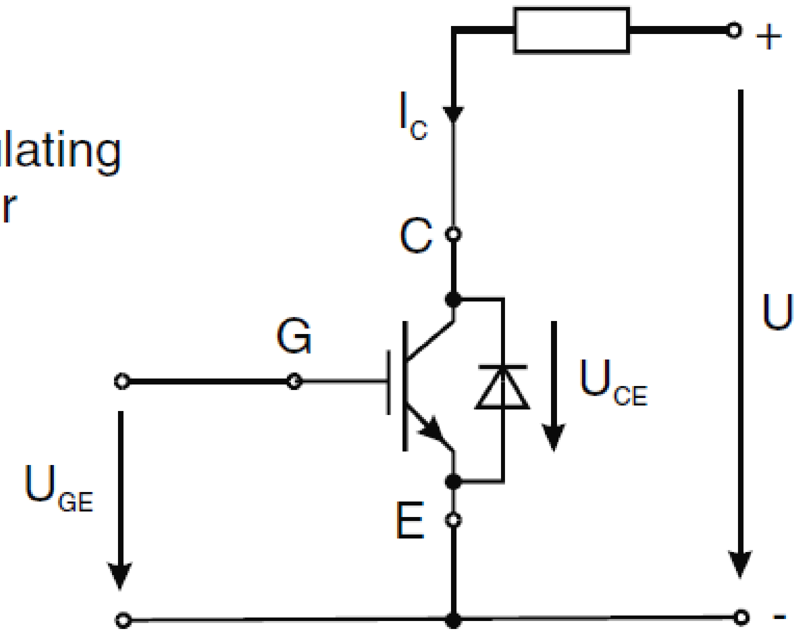


Fig 2: Forward Conduction

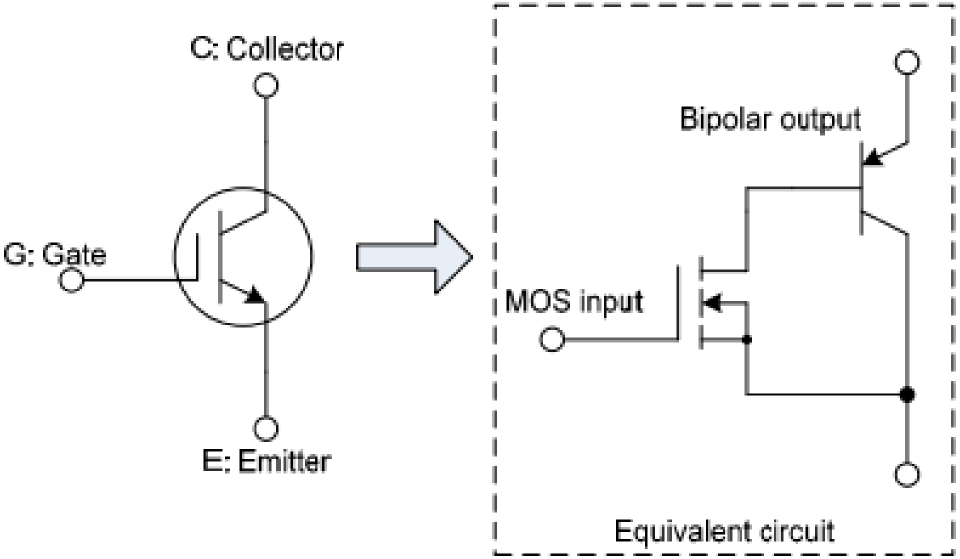
IGBT





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.**

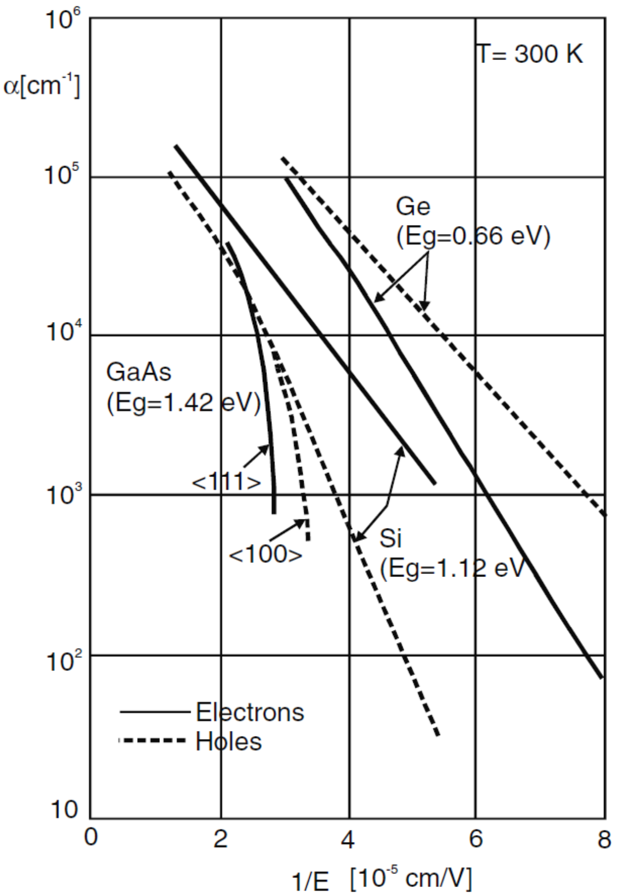


Fig. 4.31. Ionisation rate coefficients α_n and α_p

Optically activated semiconductor switches

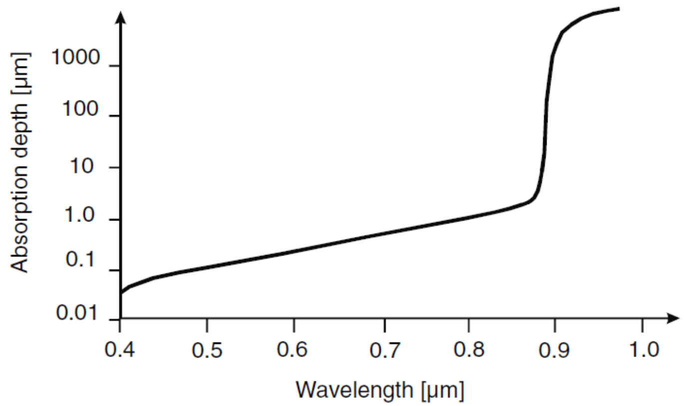
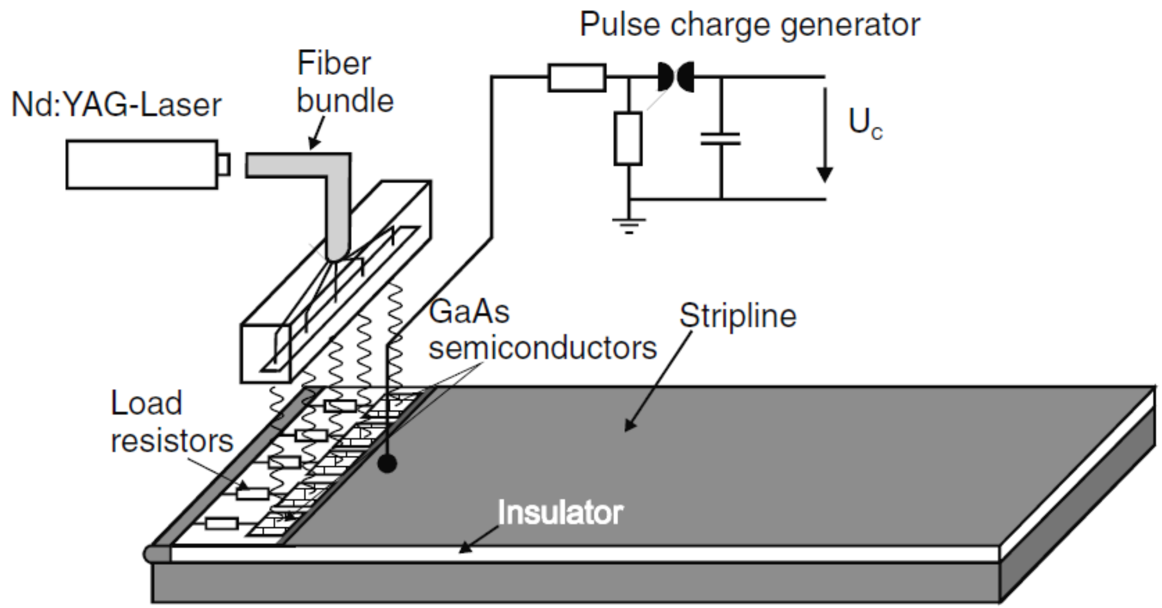
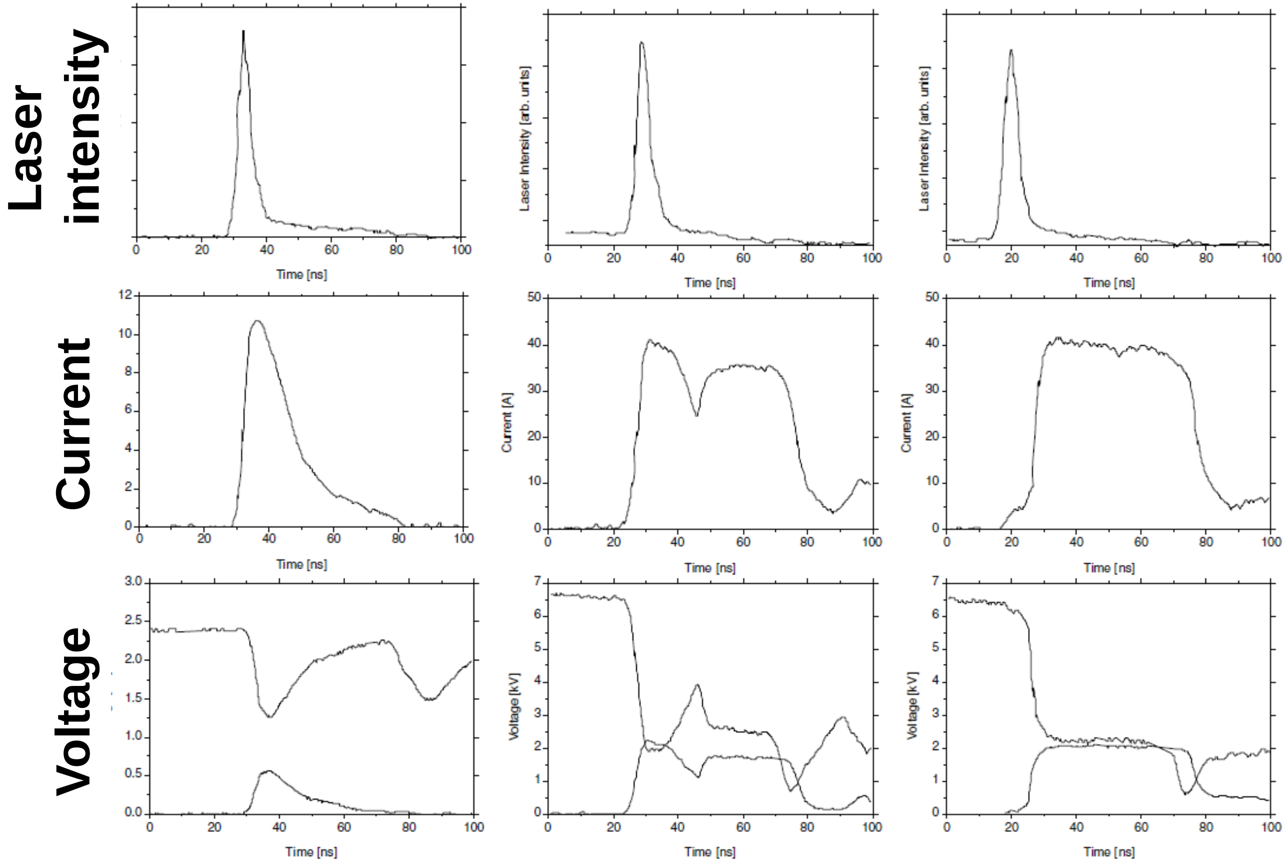


Fig. 4.32. Optical absorption depth in GaAs as a function of wavelength

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

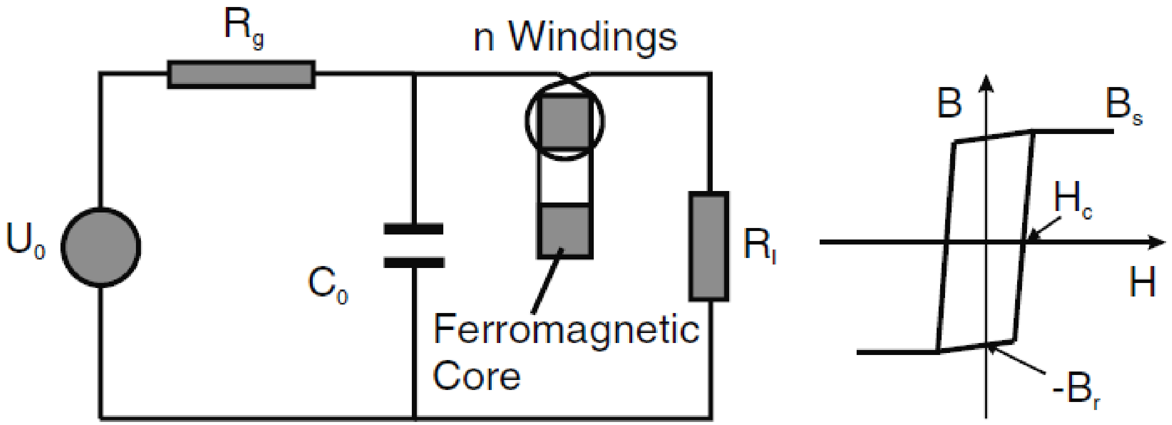


Optically activated semiconductor switches



- **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