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 9

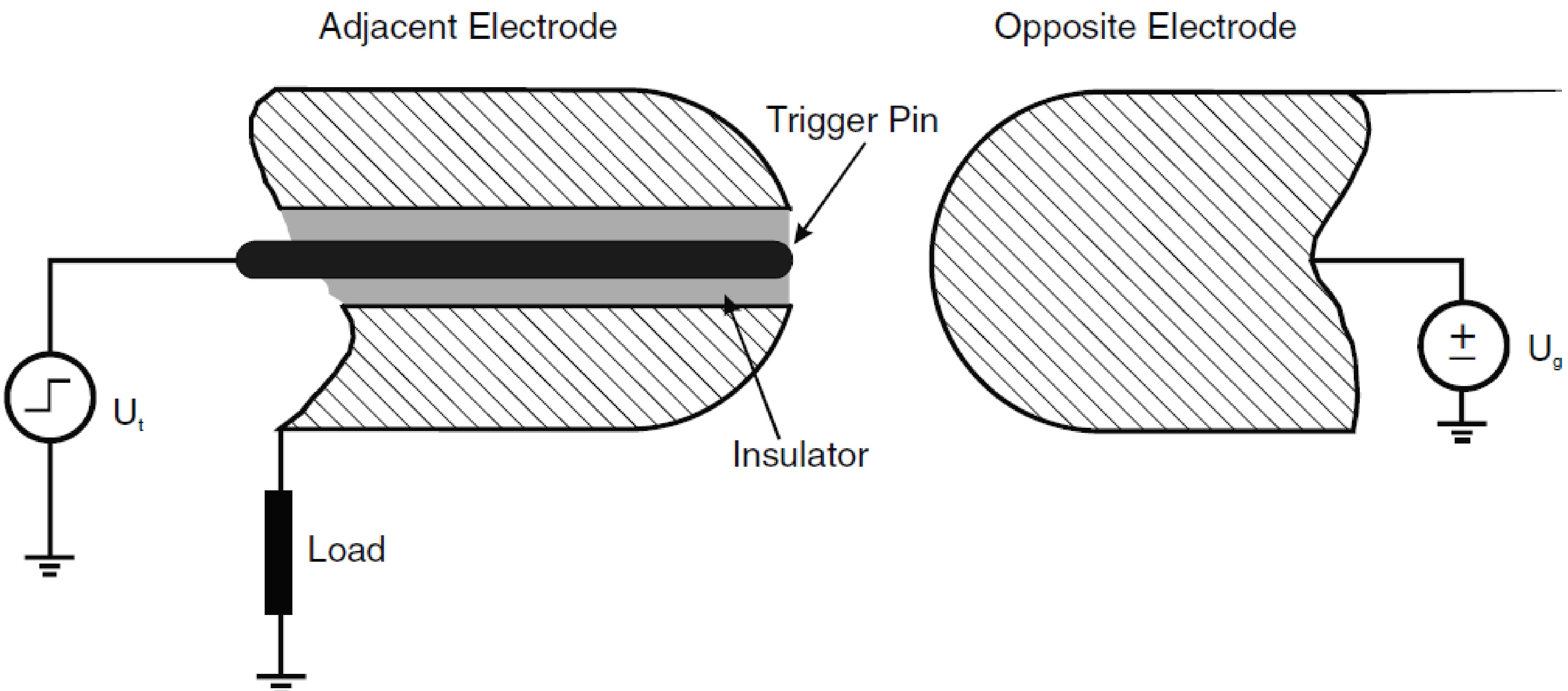
http://capst.ncku.edu.tw/PGS/index.php/teaching/

Online courses:

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

2023/11/14 updated

Trigatron spark gap



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

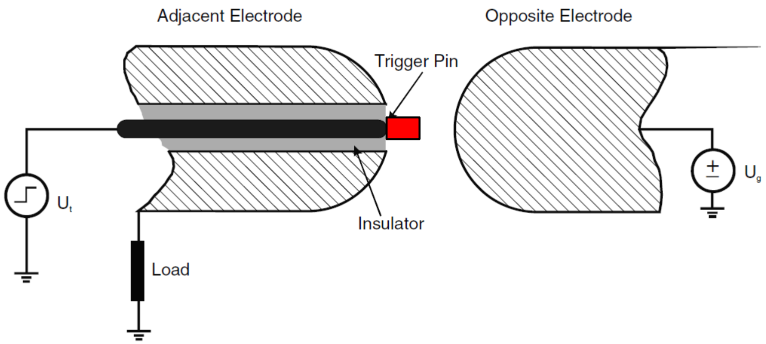
$$\boldsymbol{U_t \times U_g < 0}$$

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

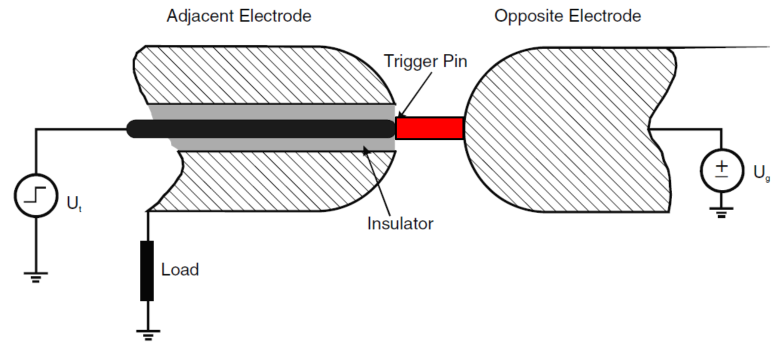
- **U_g~50% U_b is possible, but with large delay and jitter.**

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

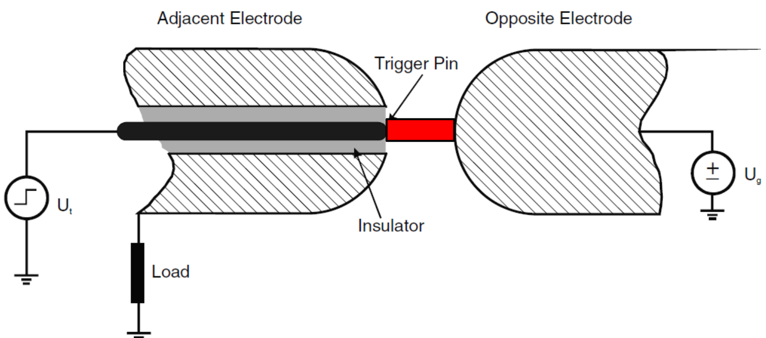
- **Step 1: Streamers begin to grow.**



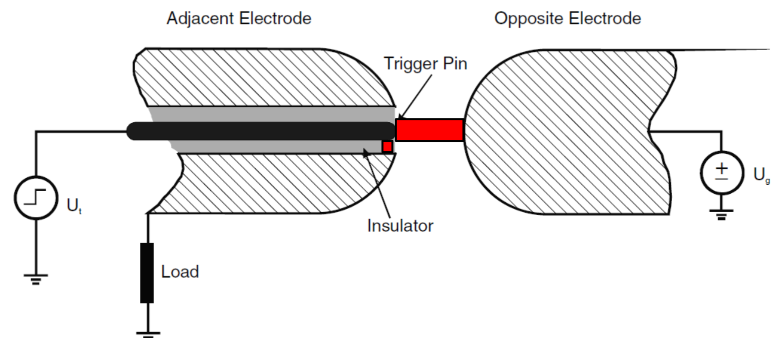
- **Step 2: ionization density in the channel to grow after streamer touch the electrode**



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

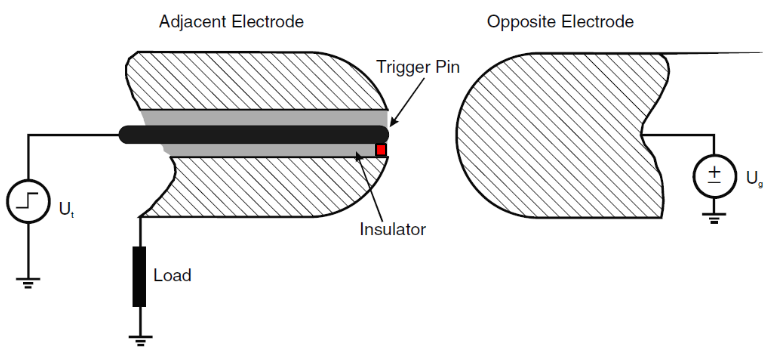


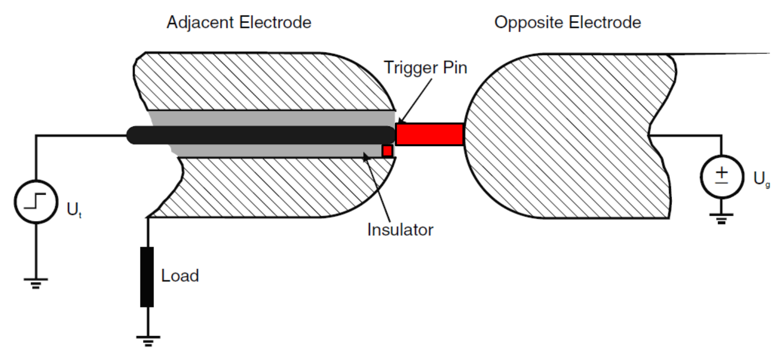
- **Step 4: two thermalized arcing connecting two electrode and pin.**



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.**

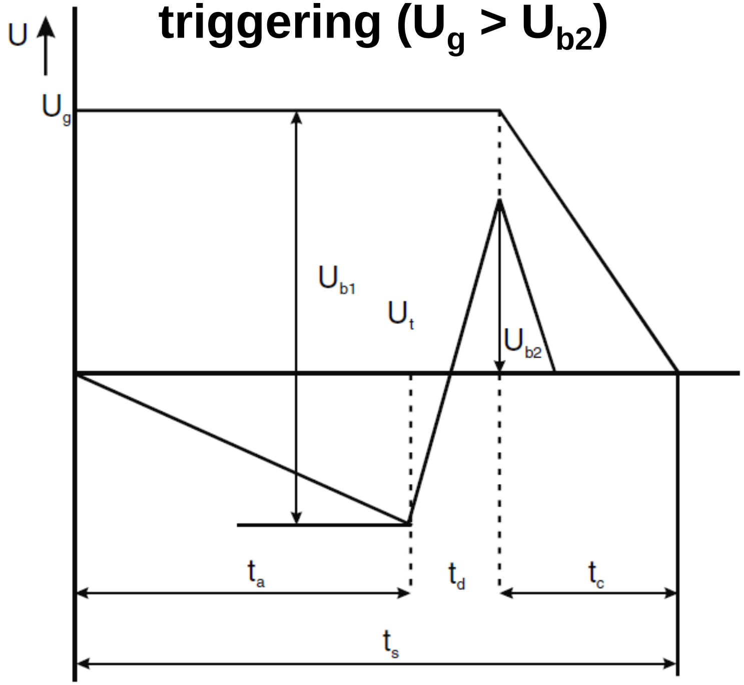




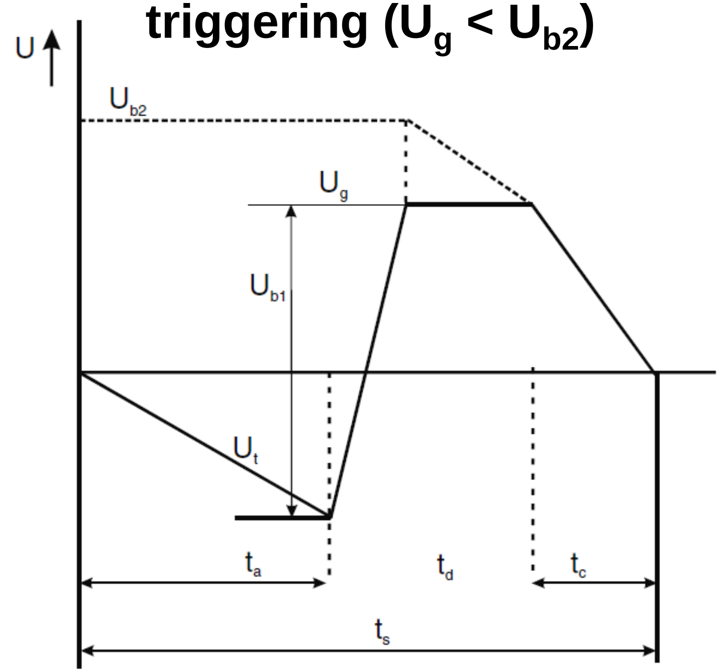
- **Breakdown is possible but with large delay and jitter.**

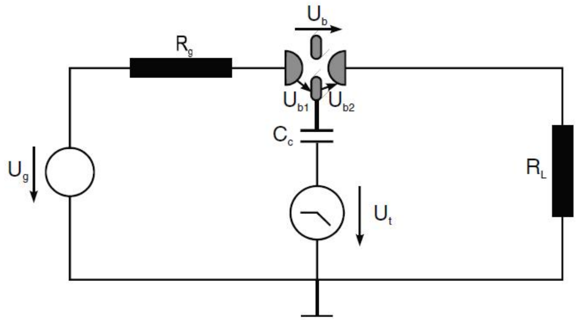
Longitudinal triggering

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



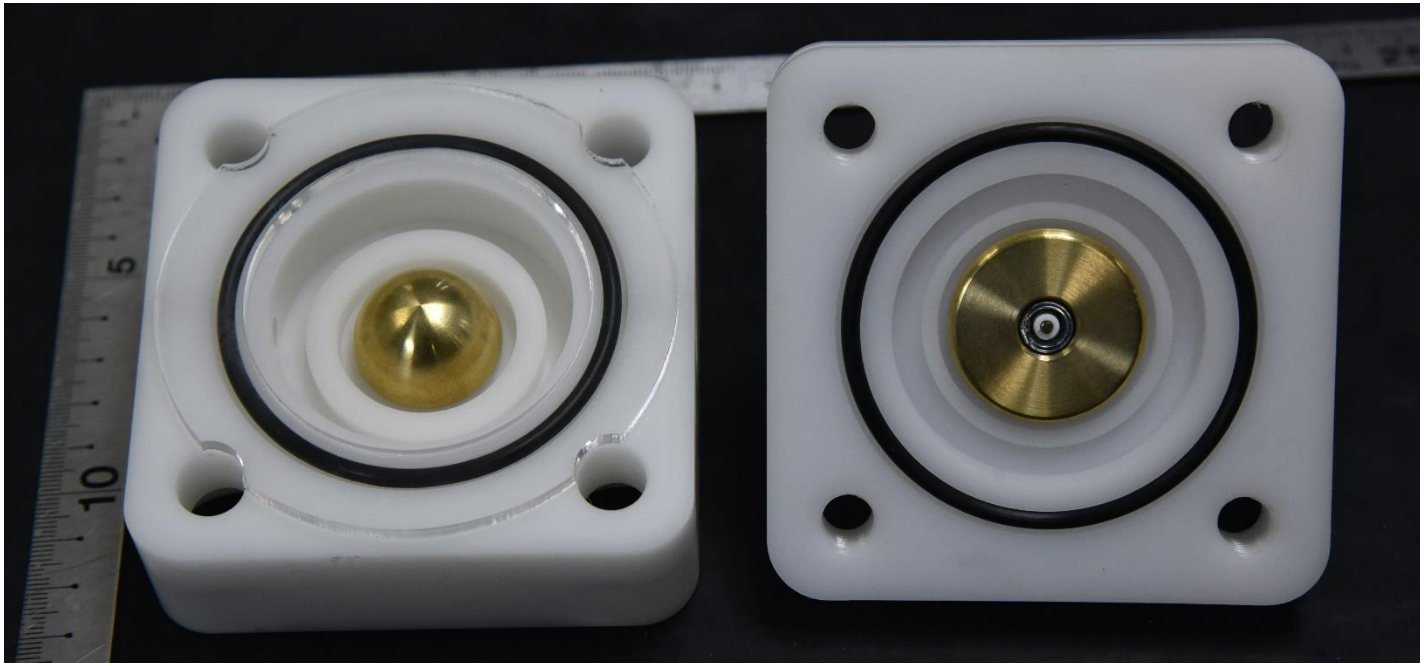
- **Longitudinal-plasma triggering ($U_g < U_{b2}$)**





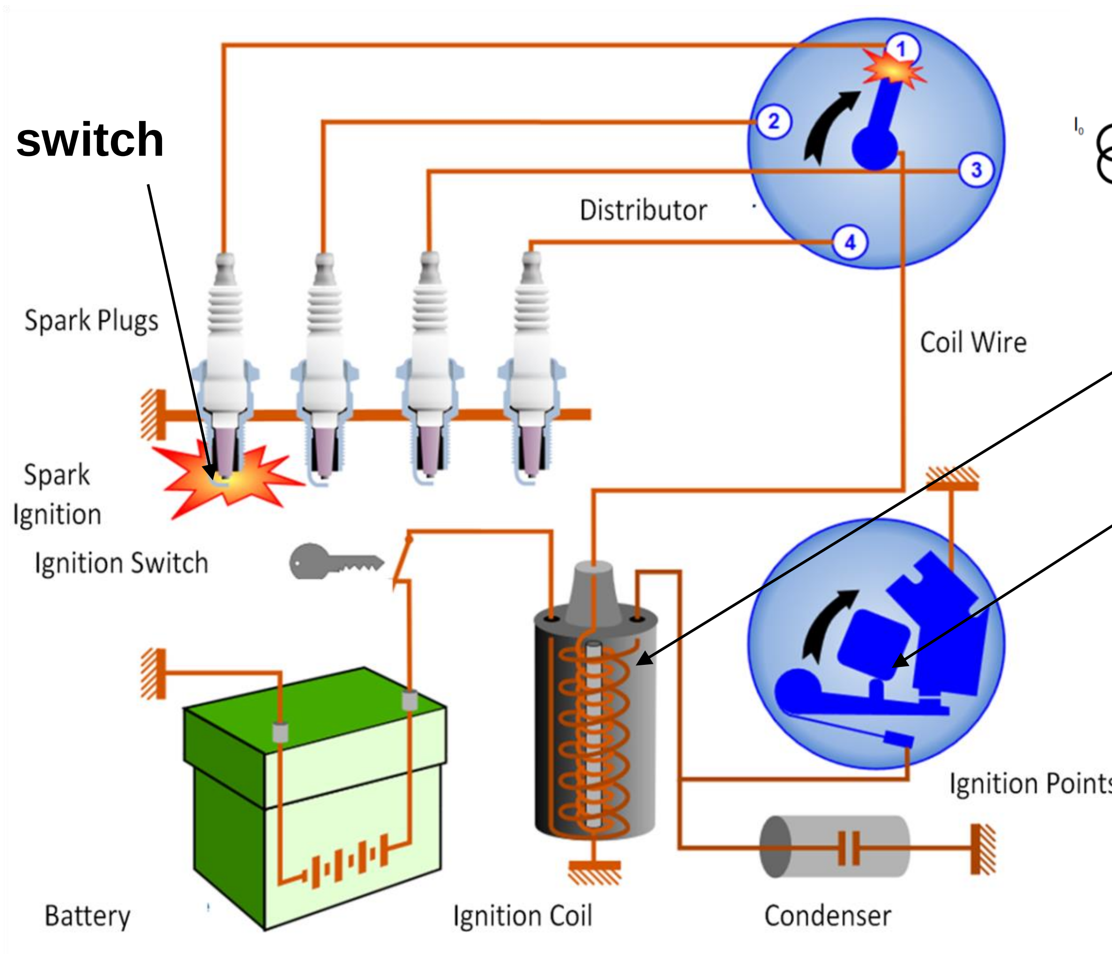
- **t_a: trigger actuating time.**
- **t_d: switching delay.**
- **t_c: commutation time.**
- **t_s: switching time.**

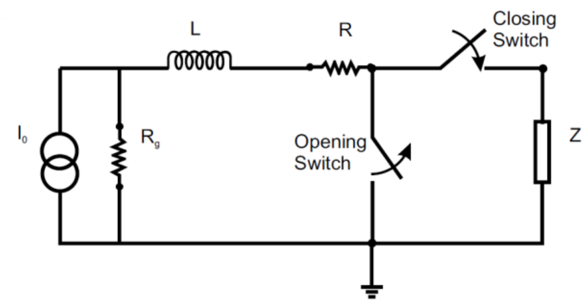
Spark plug is a Trigatron



Spark plugs in cars are triggered by the inductive energy storage

Closing switch /load



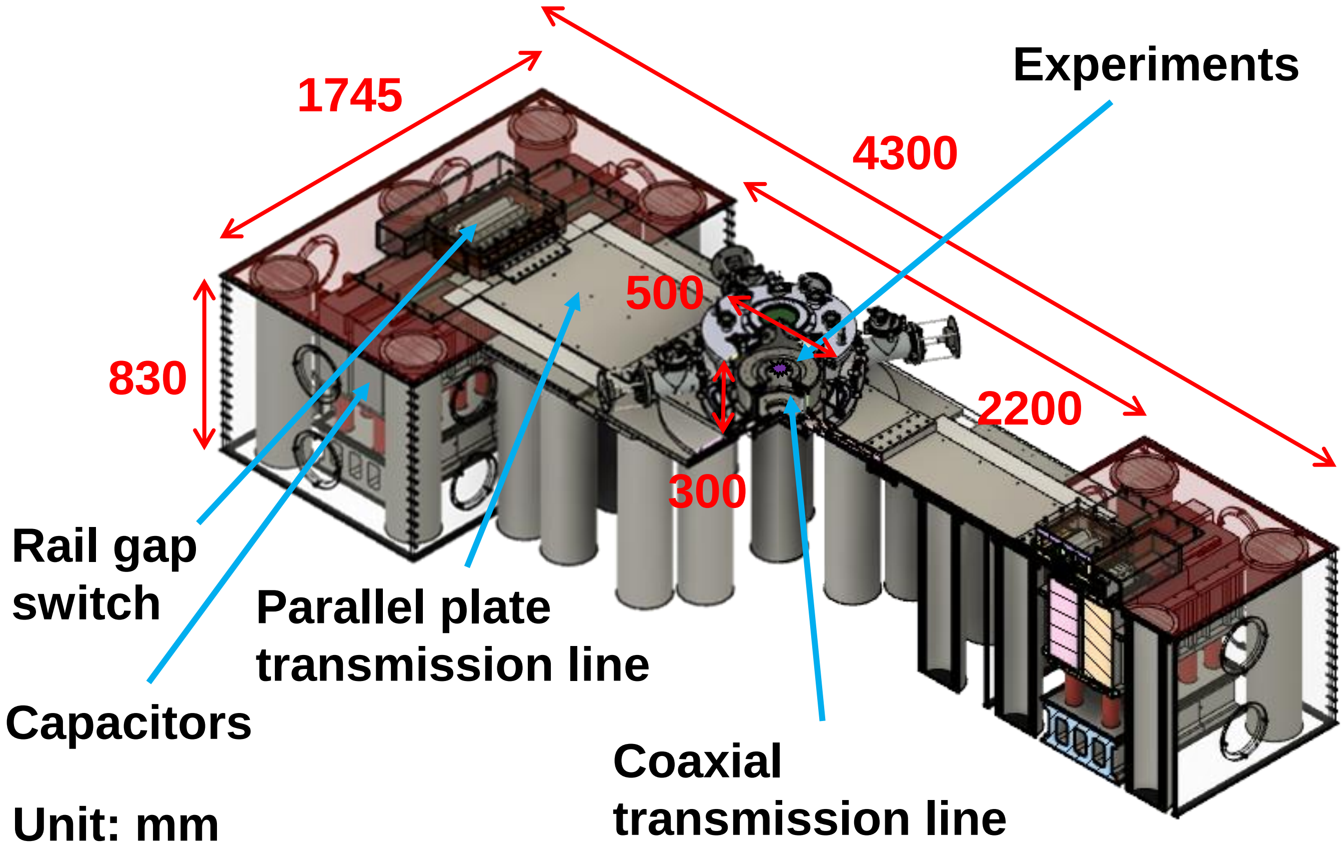


Inductive energy storage

Opening switch

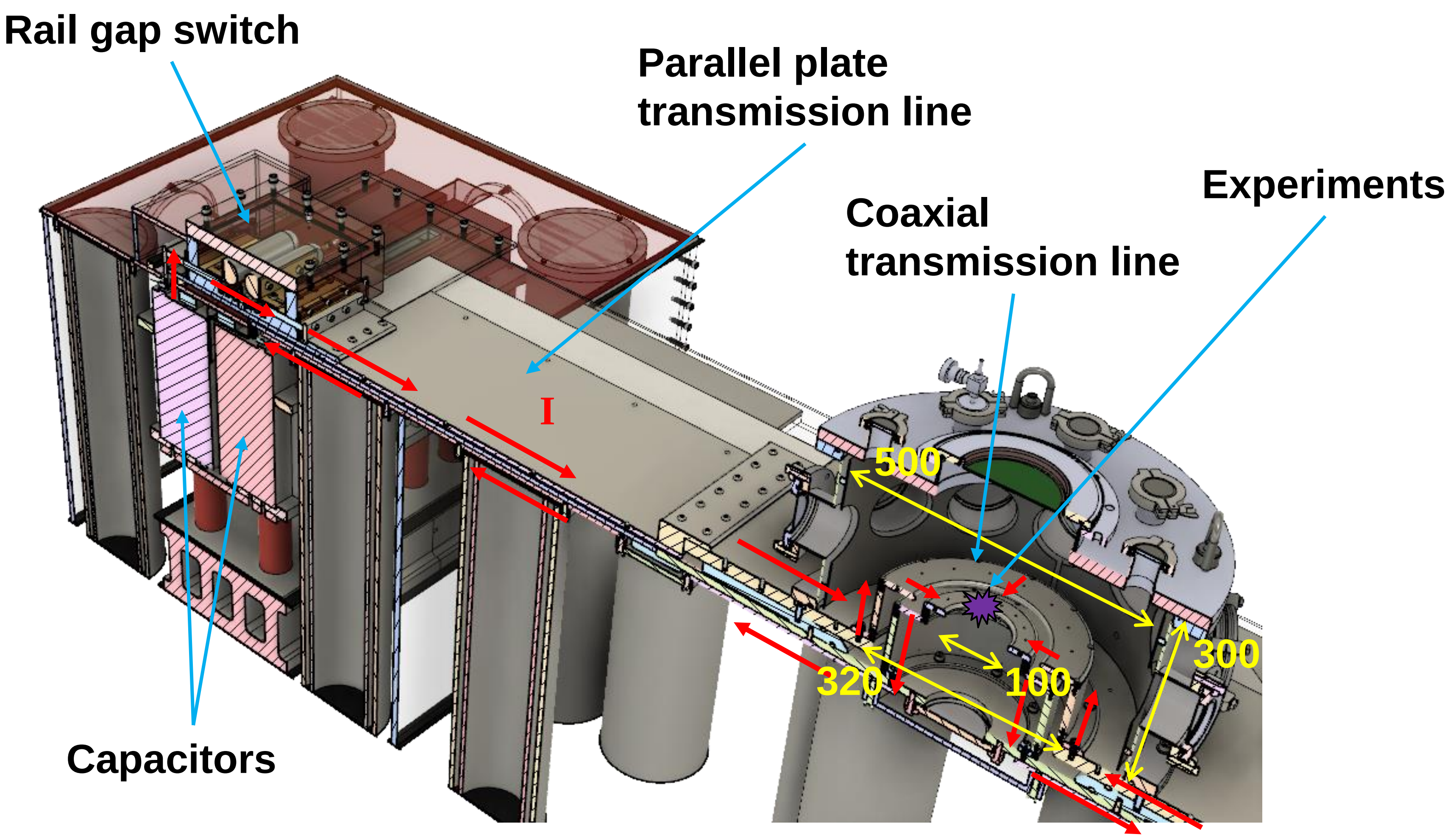
https://images.saymedia-content.com/.image/t_share/MTc0Mjk3MzYyODg0MjA4NTA4/diy-auto-service-ignition-systems-operation-diagnosis-and-repair.png

The pulsed-power system in Pulsed-Plasma Laboratory



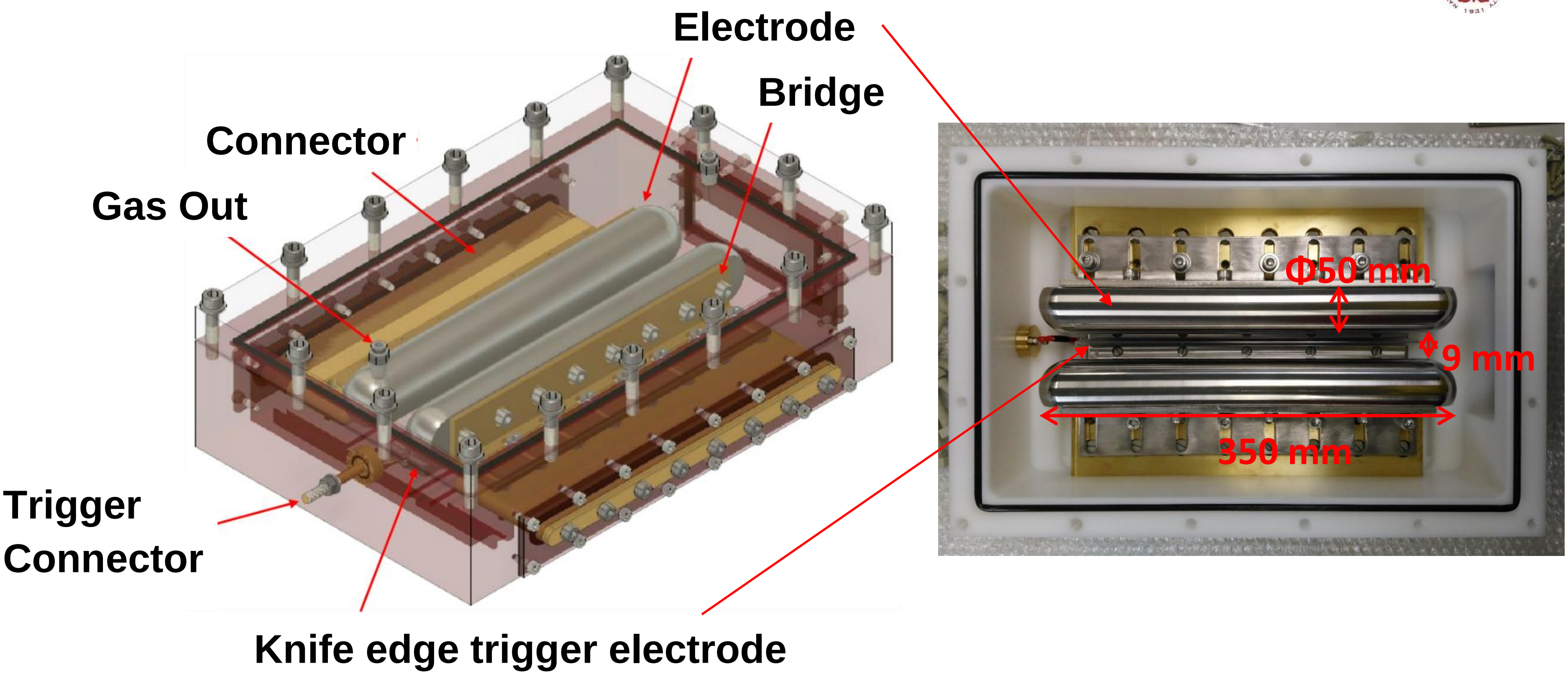
- **A 1 kJ pulsed-power system at ISAPS, NCKU started being operated since September, 2019.**

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



Unit: mm

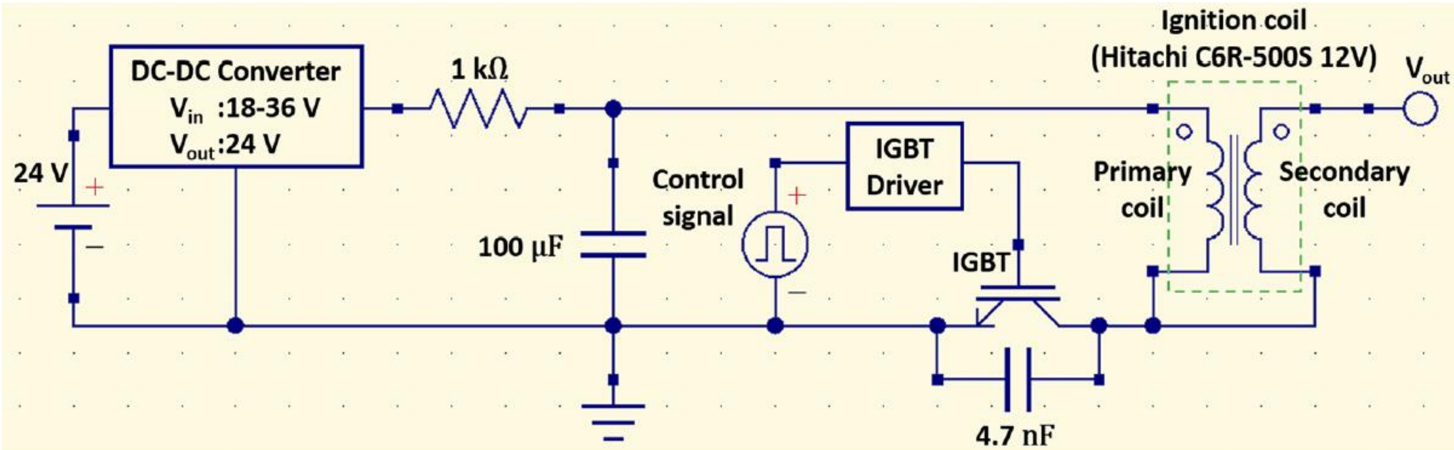
Low inductance rail-gap switches are used

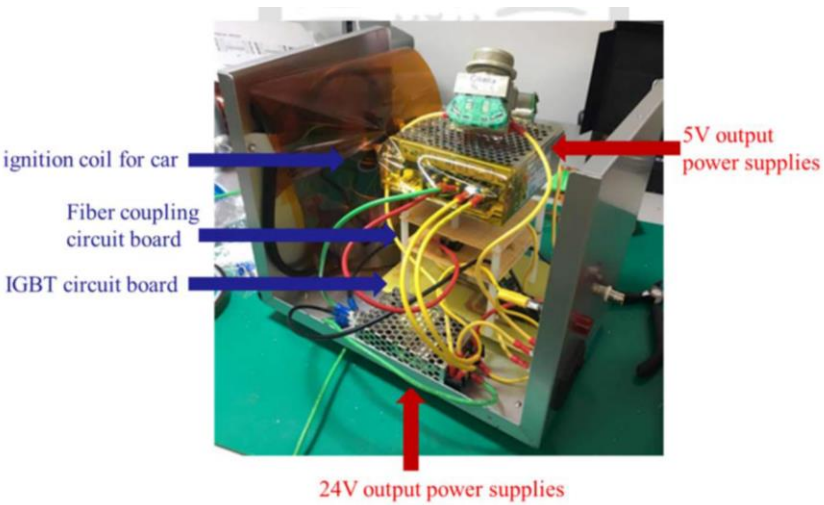


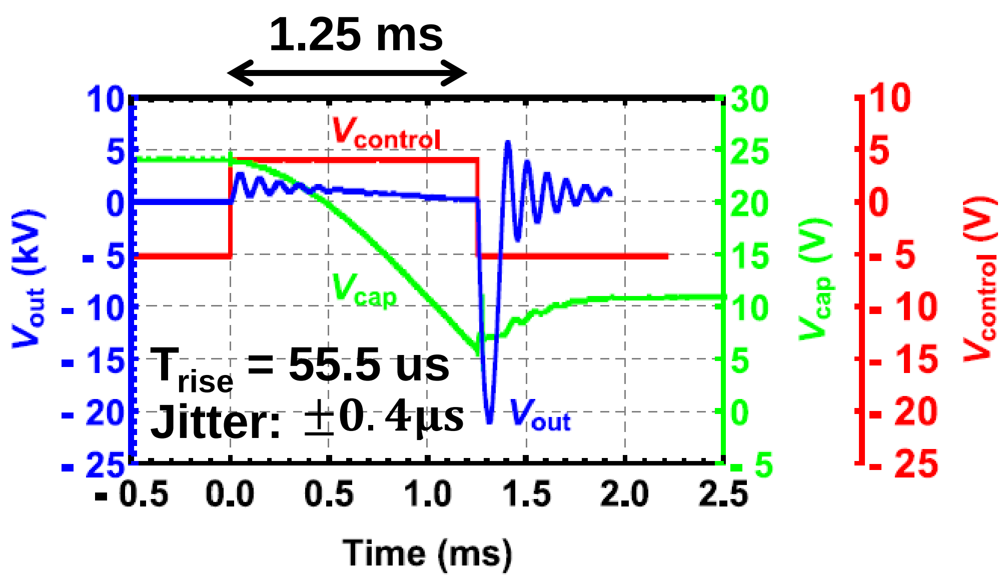
- **The switch is pressurized with nitrogen gas (1~3 atm).**
- **Multi-channel discharges between two rail-like electrodes will be triggered by a fast trigger pulse generator (rising speed > 5kV/ns).**

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

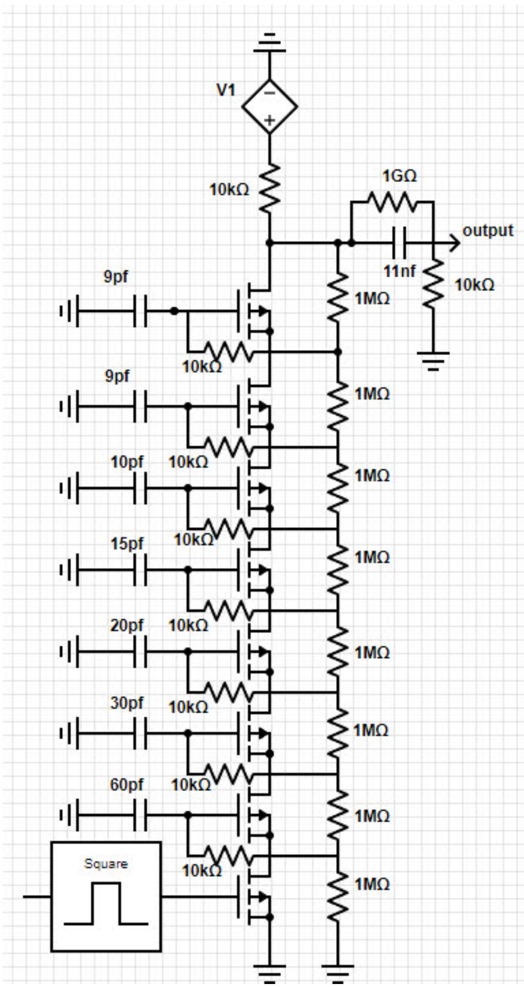


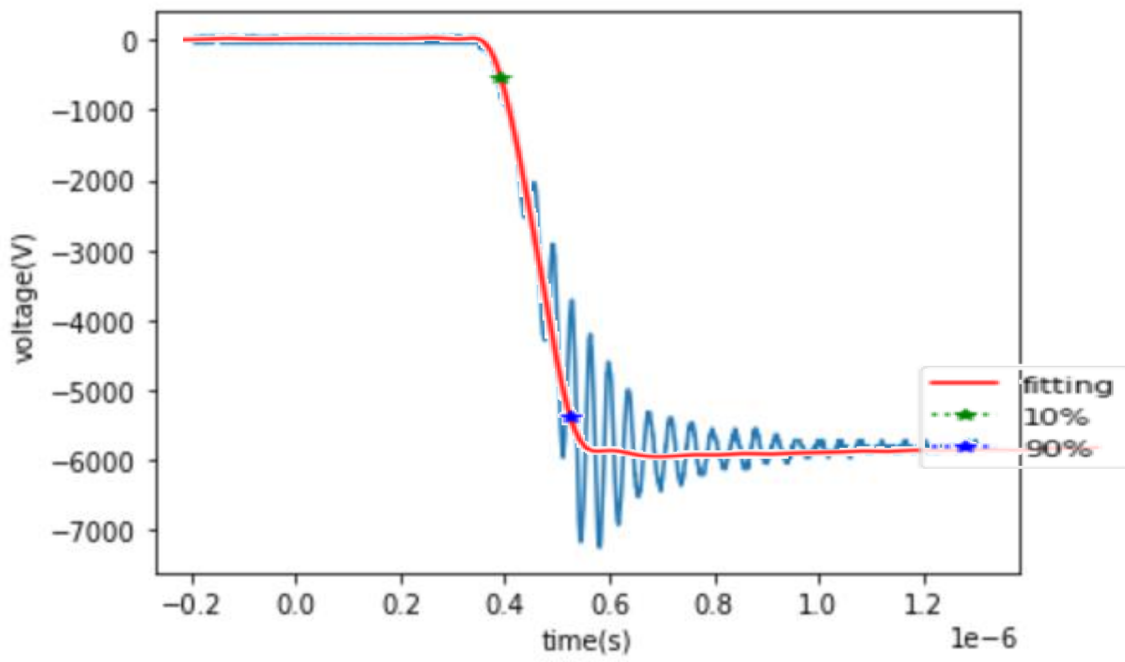




P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)

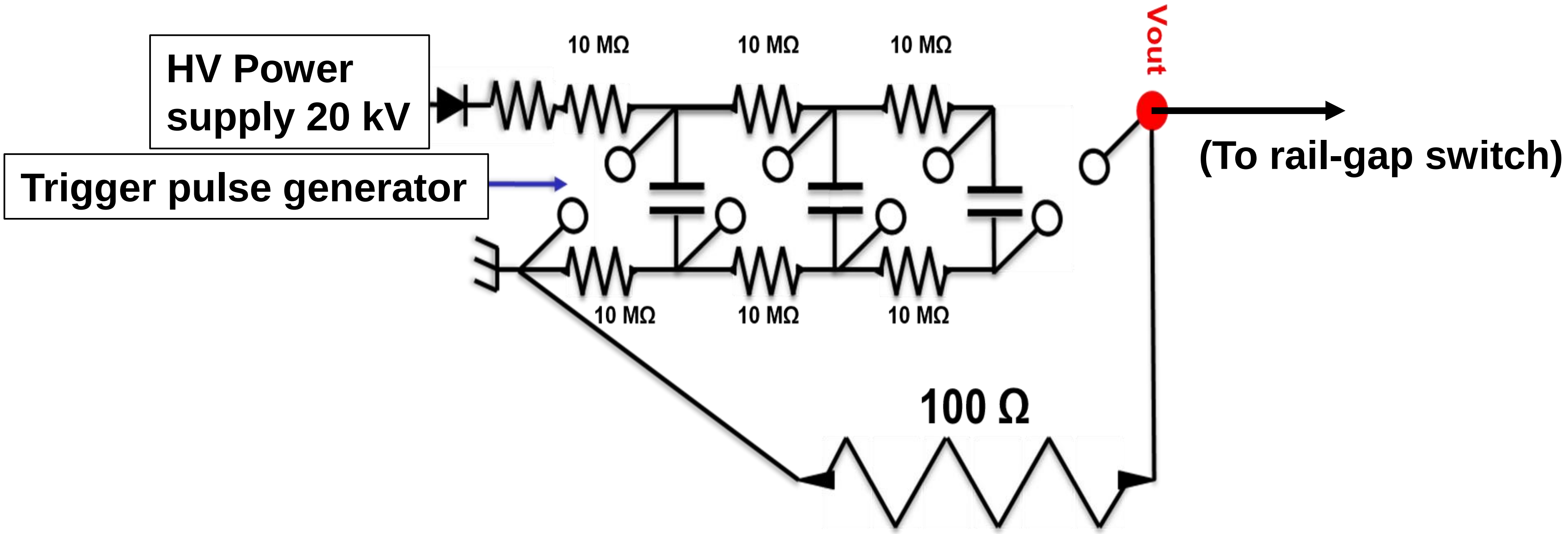
Many MOSFET connected in series can be used to provide a fast high-voltage triggering pulse





T_{rise}=140 ± 1 ns

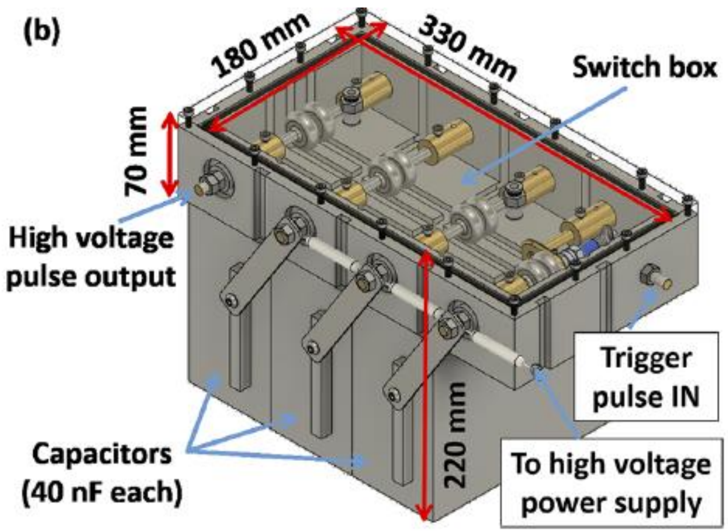
A three-stage Marx generator is used to provide a fast high voltage trigger pulse

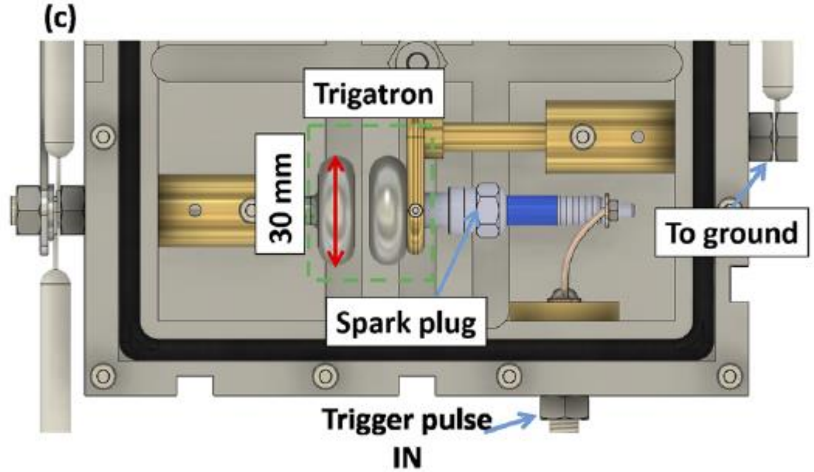


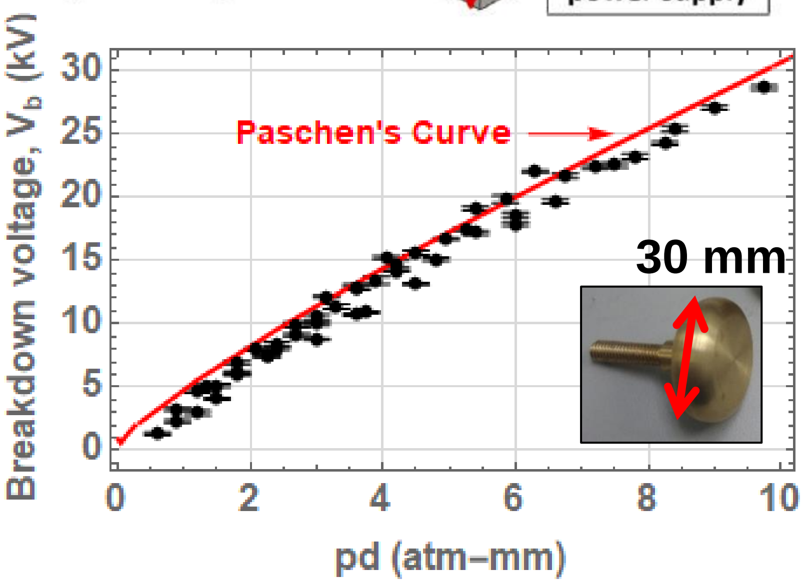
- In a Marx generator, capacitors are connected in parallel when they are being charged.
- Capacitors in the Marx generator are connected in series during discharge.

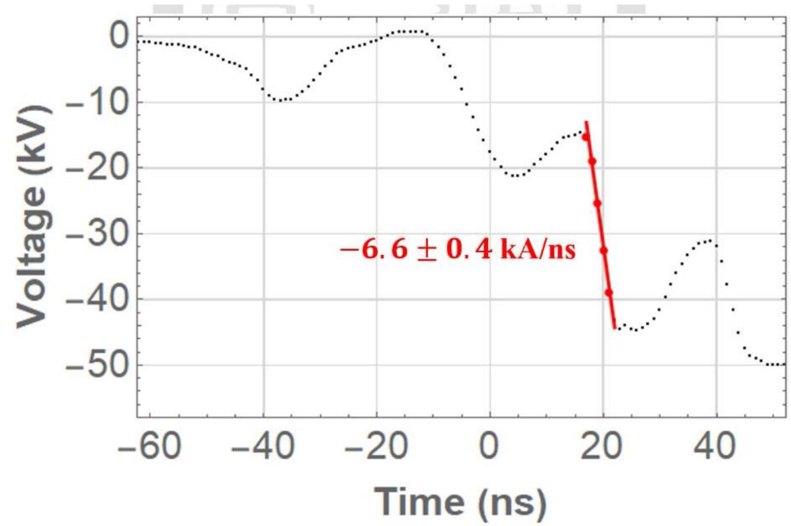
$$V_{\text{out, ideal}} = -N \times V_0 = -3 \times 20\ \text{kV} = -60\ \text{kV}$$

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



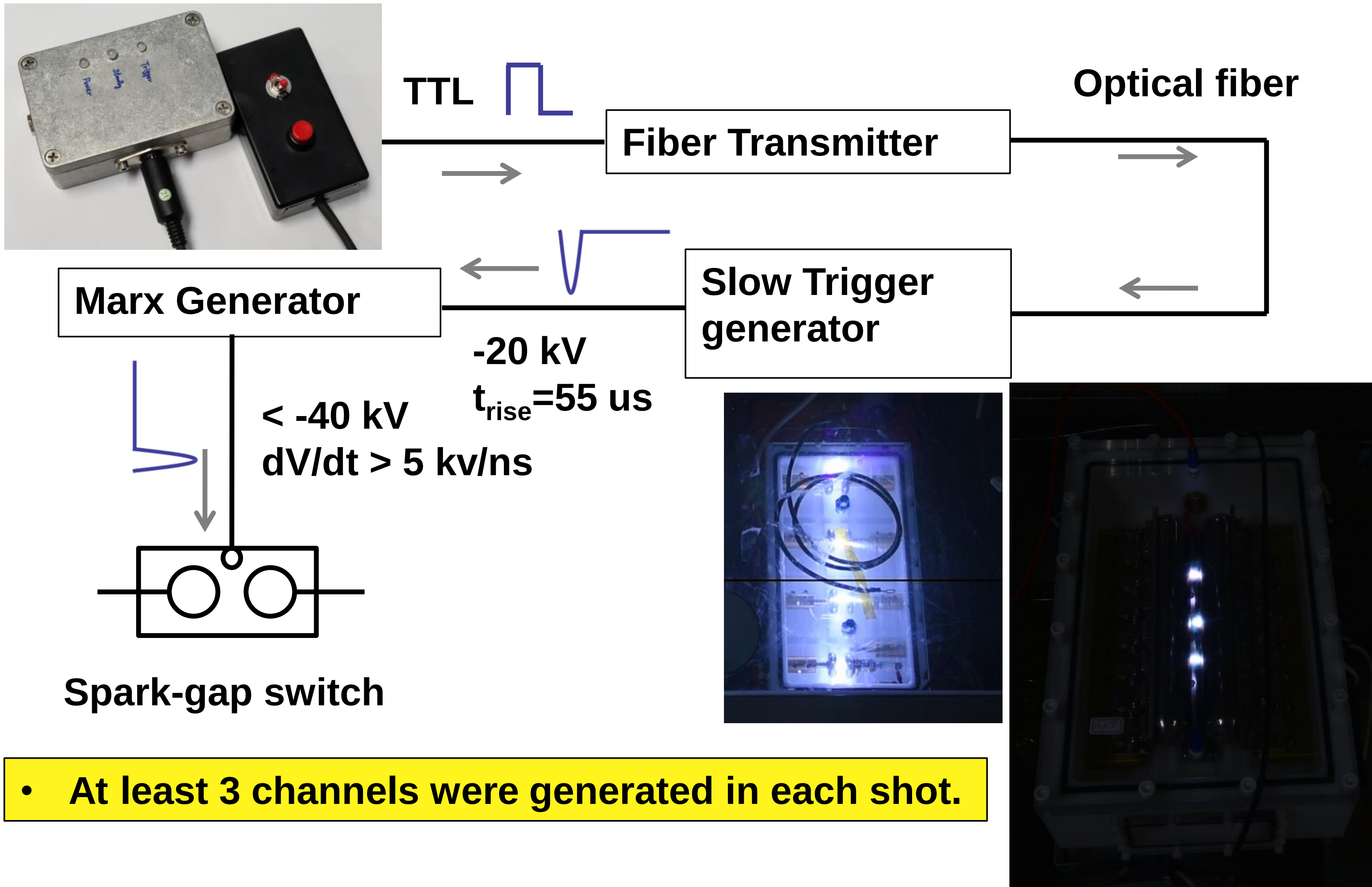






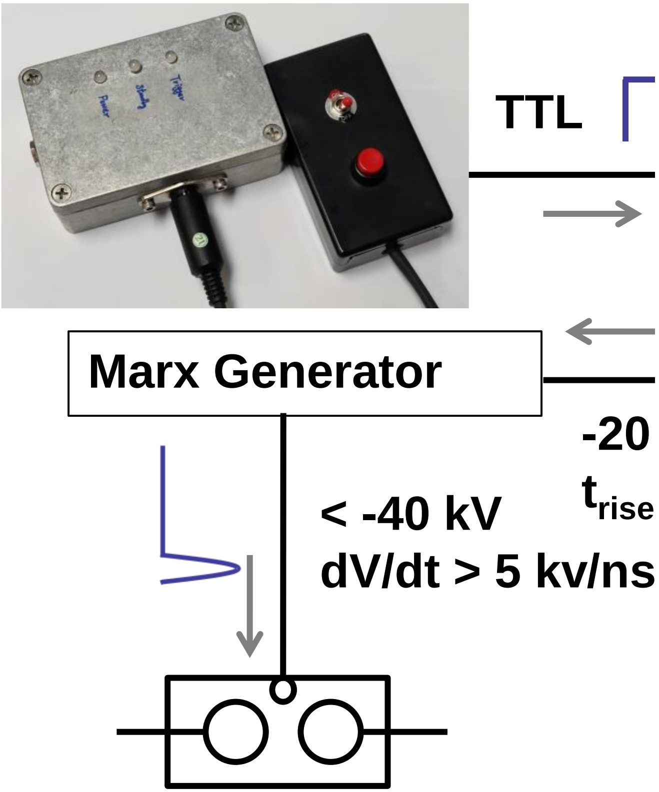
P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)

Multistep trigger system is used



- At least 3 channels were generated in each shot.

Multistep trigger system is used



Spark-gap switch

- **At least 3 channels were**

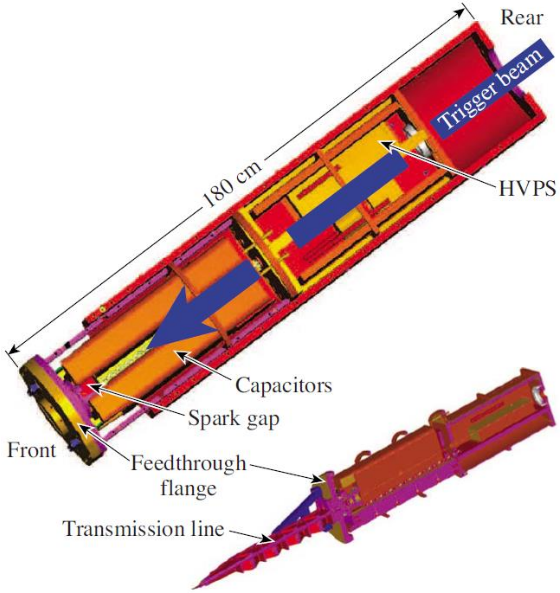
https://goods.ruten.com.tw/item/show?21941221827043

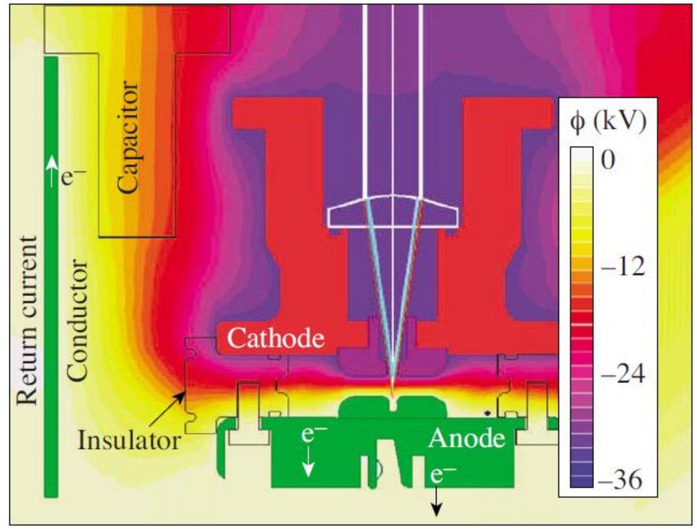
Multistep trigger system is used

TTL

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

Magneto-inertial fusion electrical discharge system

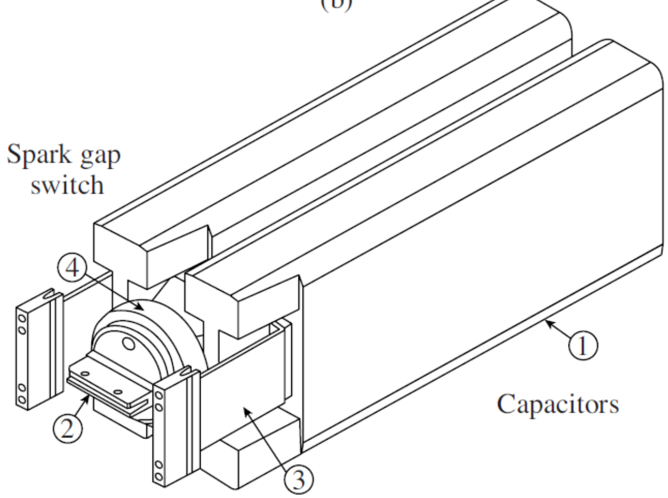


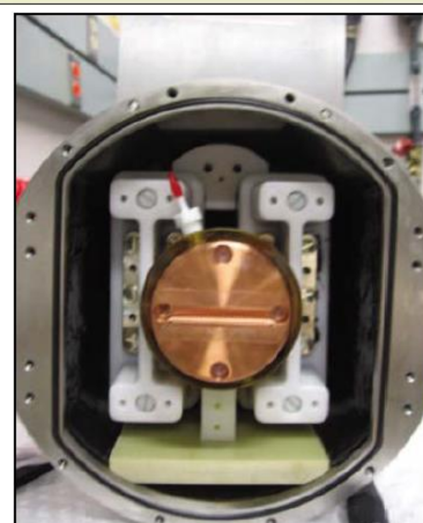


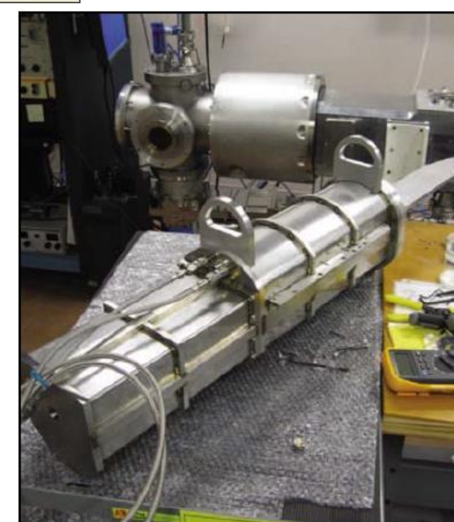
6-7 ns pulse
60 mJ @ 266 nm
300 mJ @ 532 nm
150 mJ @ 1064 nm

Delay: < 1 ns
Jitter: < 1 ns

(b)



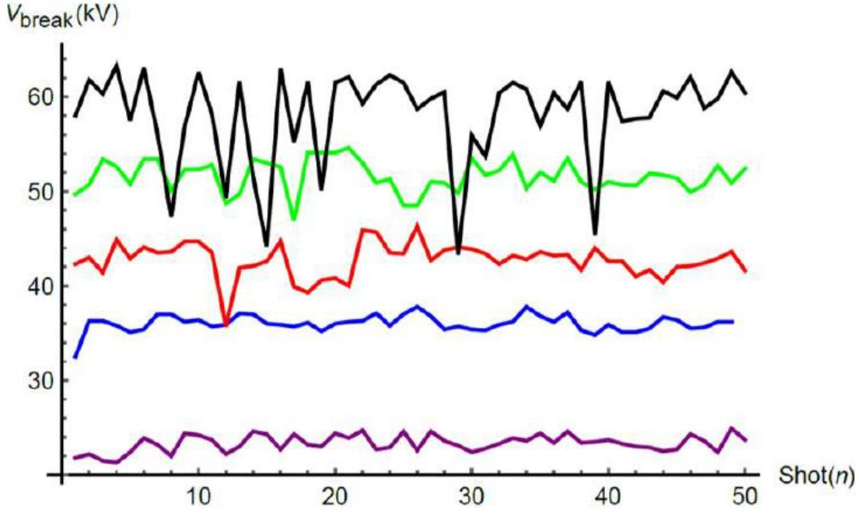


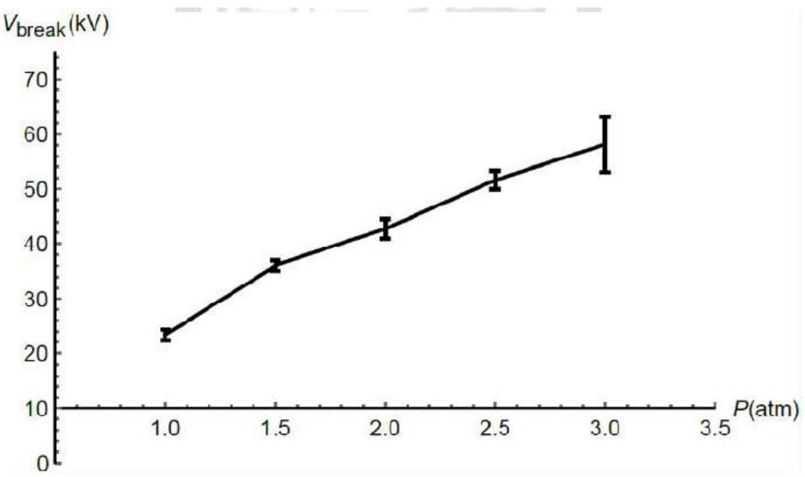


O. V. Gotchev, etc., Rev. Sci. Instrum. **80**, 043504 (2009)

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

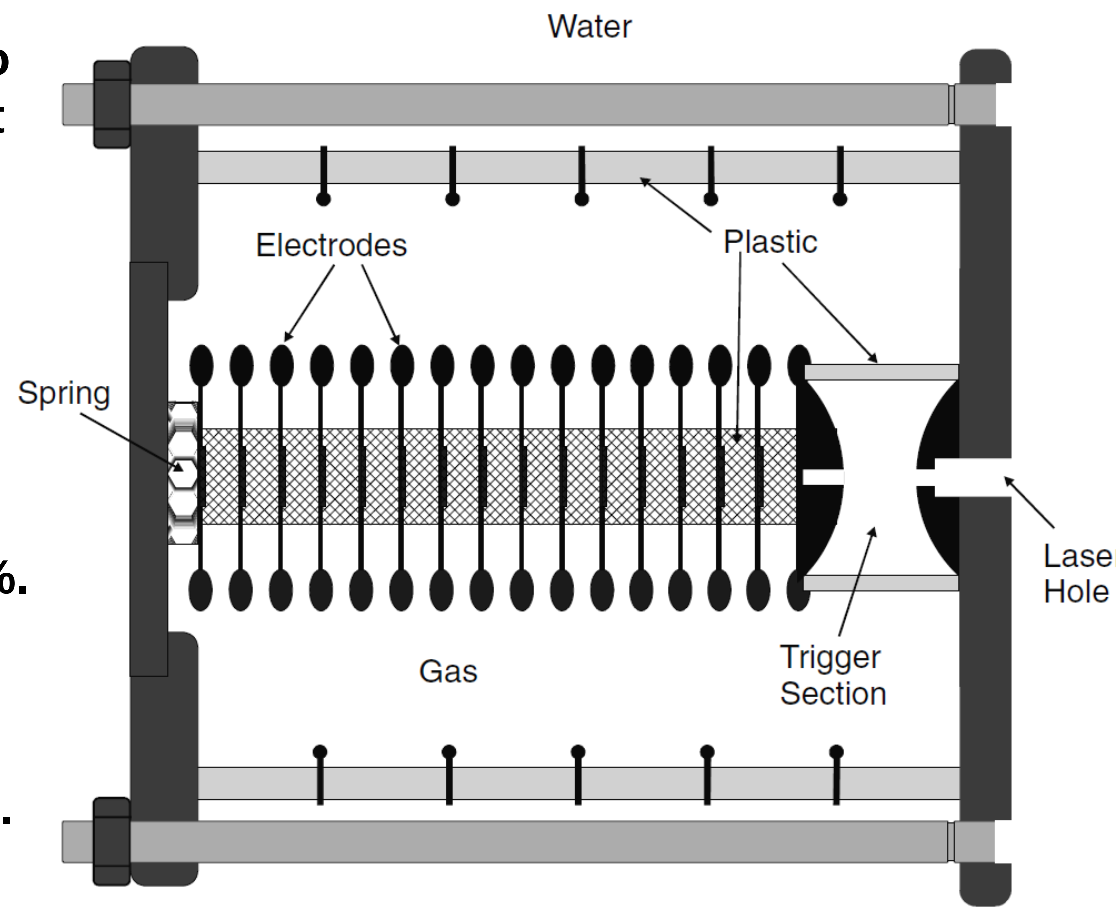




Sheng-Hua Yan, Master Thesis 2018

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.**

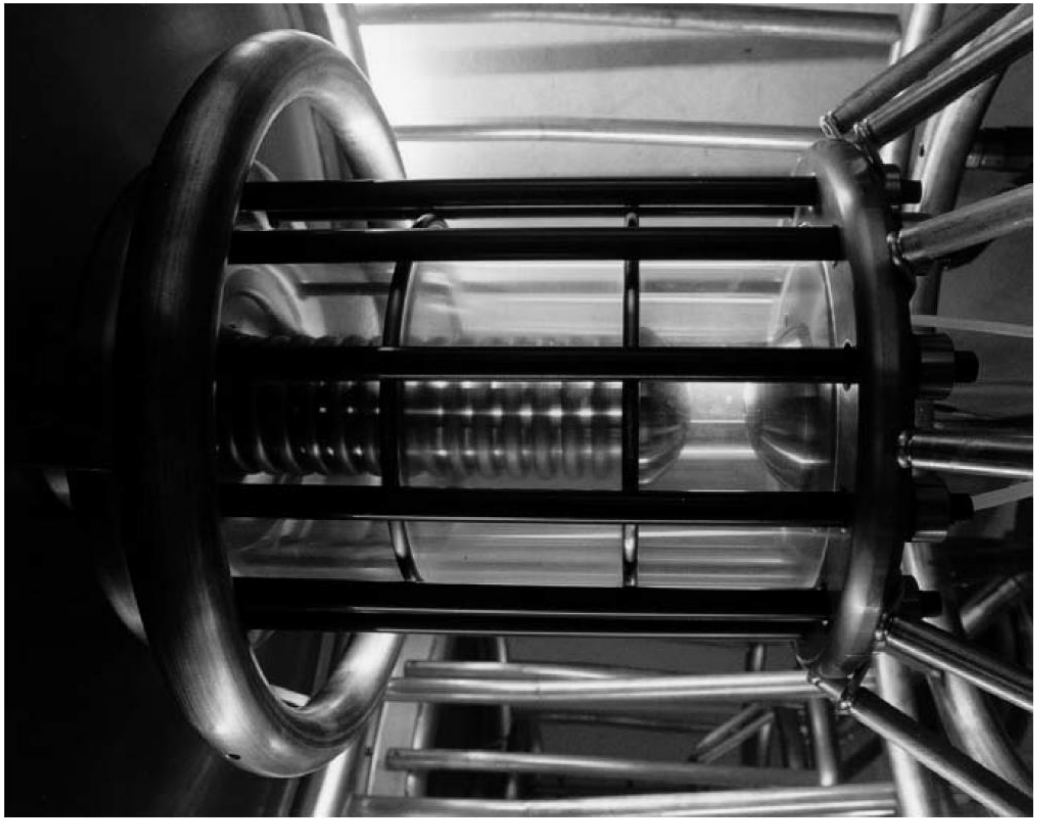
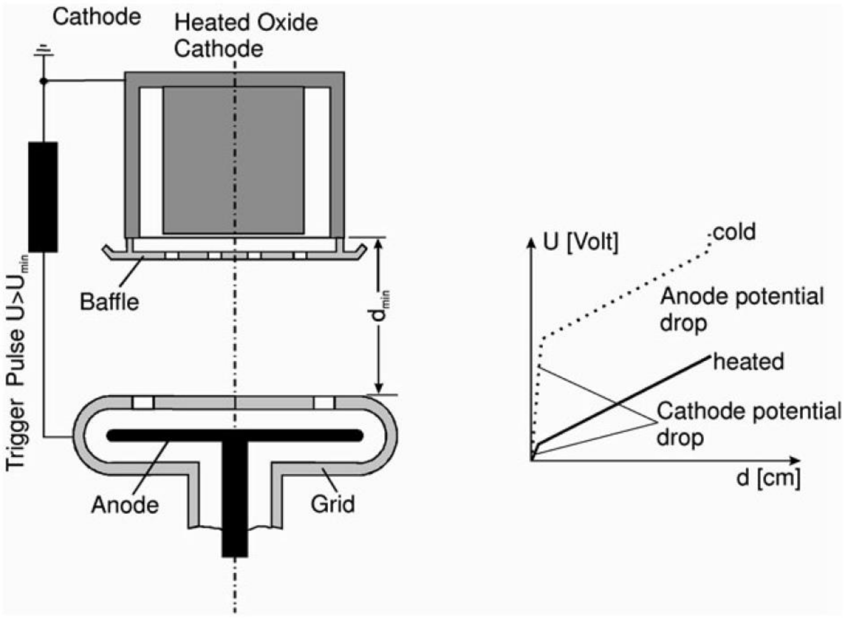
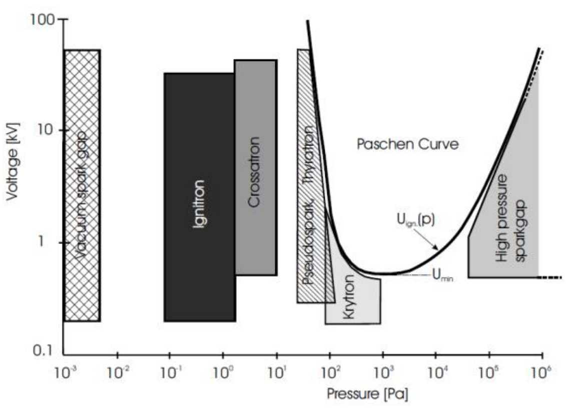


Fig. 4.13. A 4 MV version of a multigap spark switch

Thyratrons

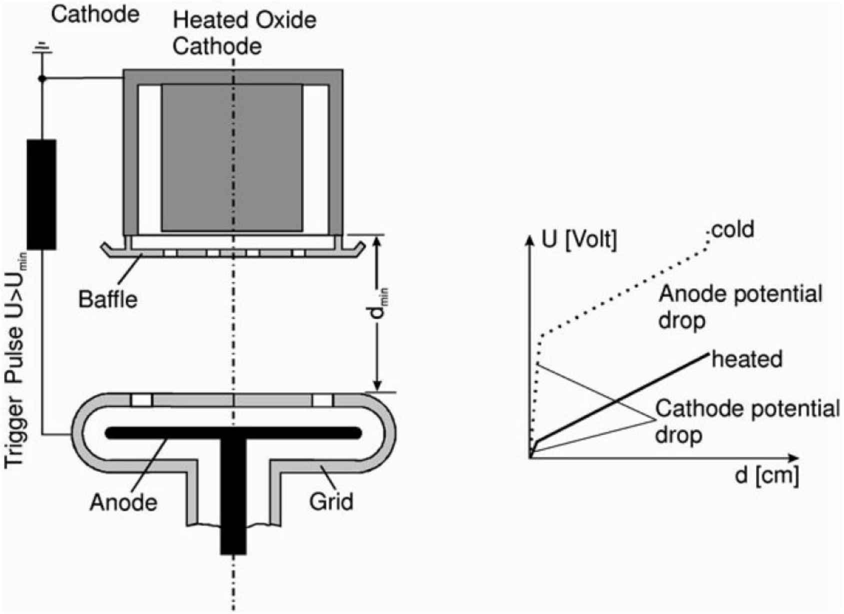
- **Thyratrons are gas-filled switching devices with a gas pressure (30-80 Pa/3x10^{-4} – 8x10^{-4} atm) much lower than a spark-gap switches.**
- **A triode configuration is used.**
- **The thyratron is characterized by the presence of a plasma, which allows the passage of large currents without significant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

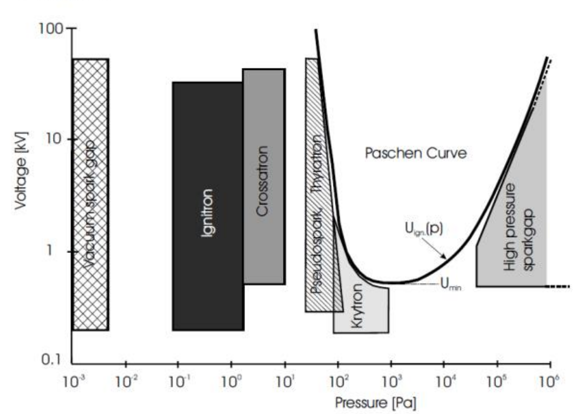




Thyratrons

- **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.**





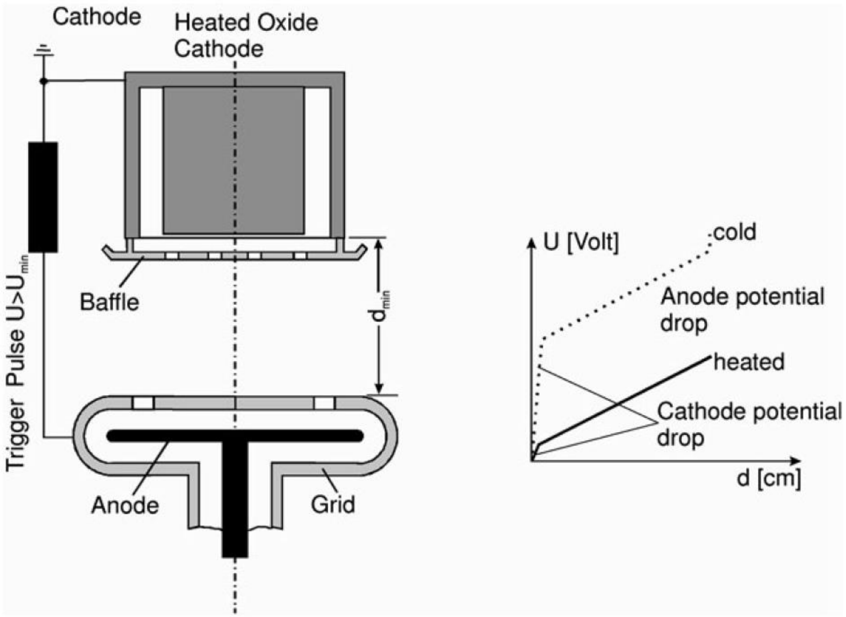
Thyratrons

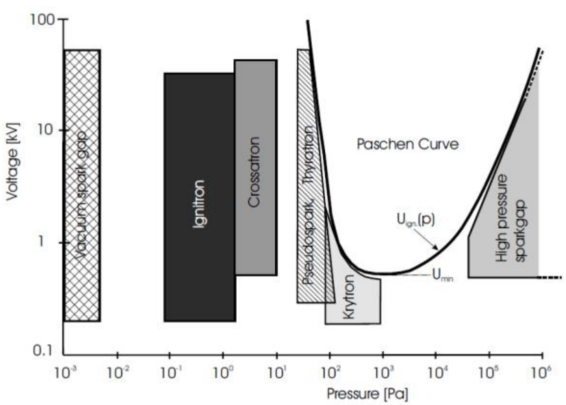
- **Operating voltage: several times 10 kV. After ignition: ~100 V => an appreciable power loss occurs and need to be dealt with by cooling.**

- **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.**





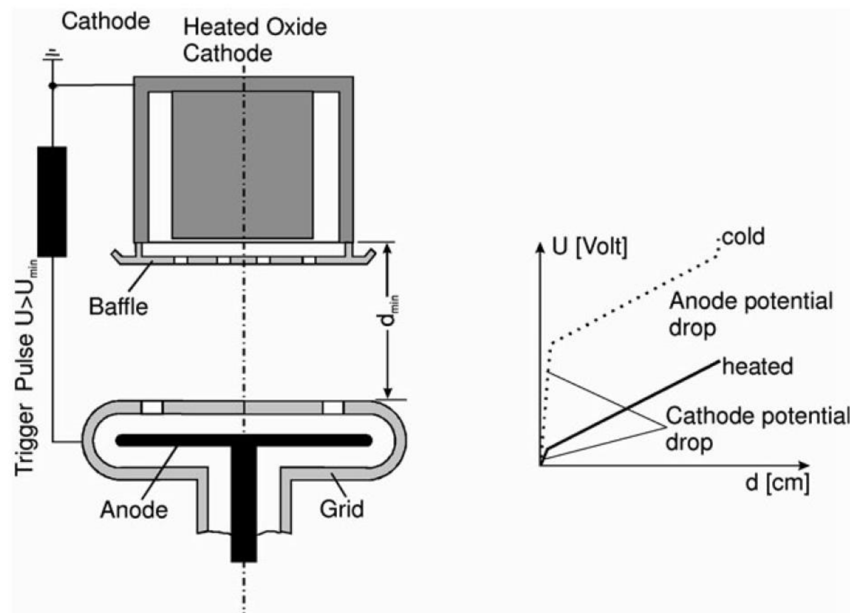
Thyratrons

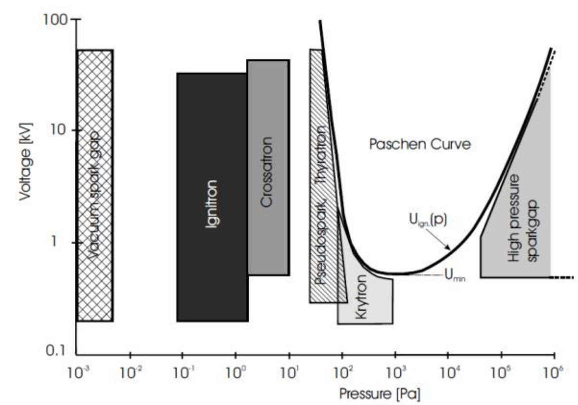
- **A thermionic cathode is used in a thyratron.**

- **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.**

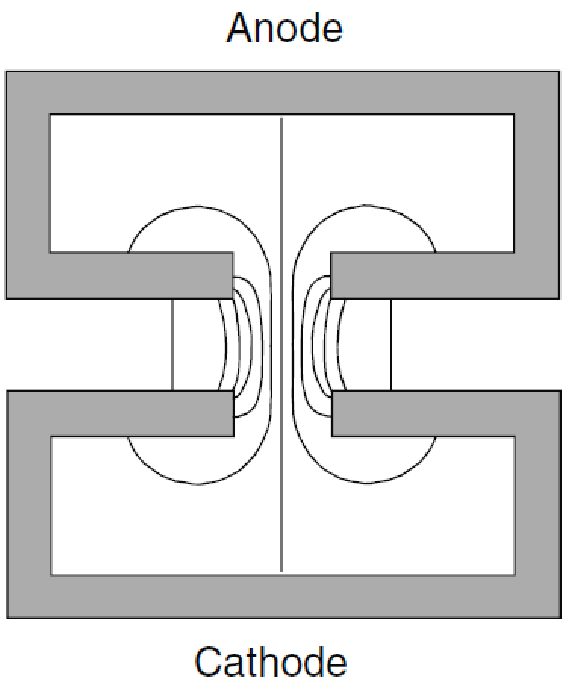
- **A baffle is used as a screening element to avoide electron directly reaching the anode and causing the damage. It is shifted relatively to the grid to prevent a direct line of sight between cathode and anode.**

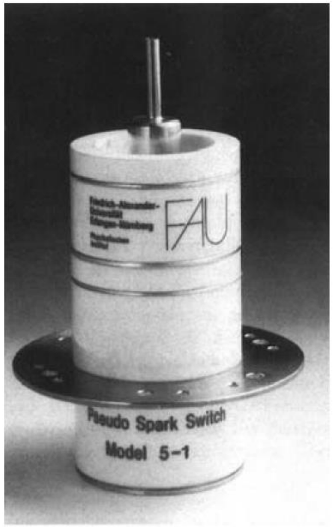


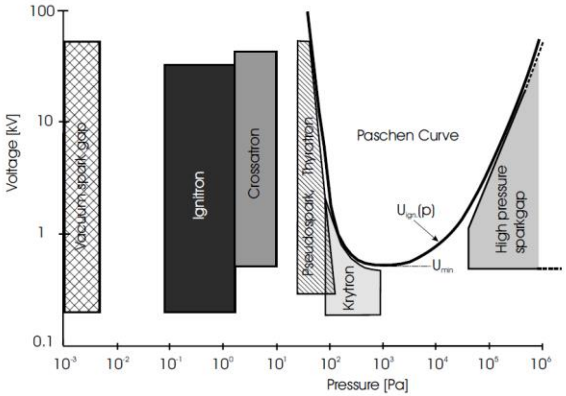


The pseudospark switch

- **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.**

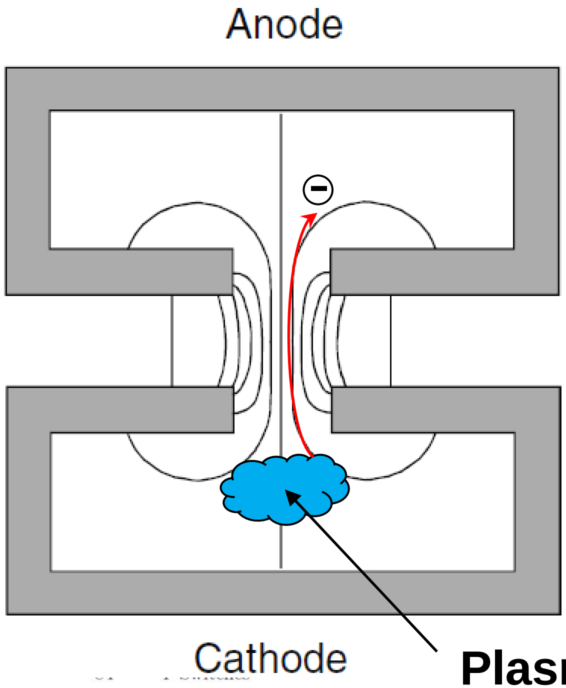


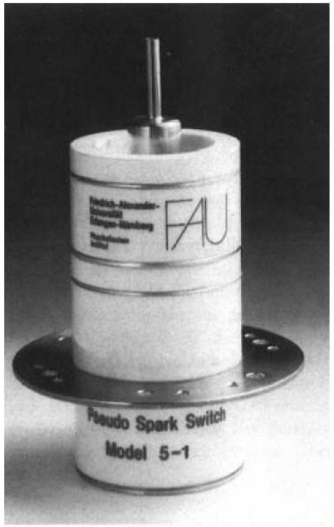


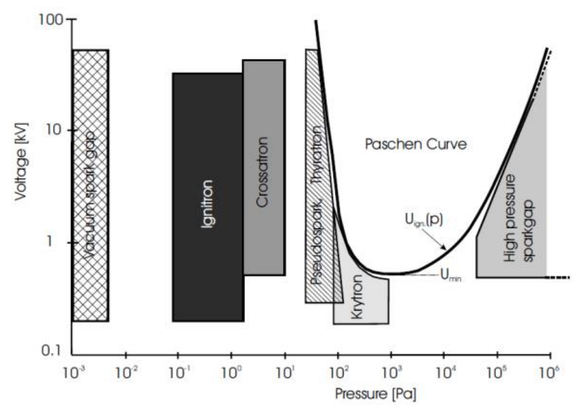


The pseudospark switch

- **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.**

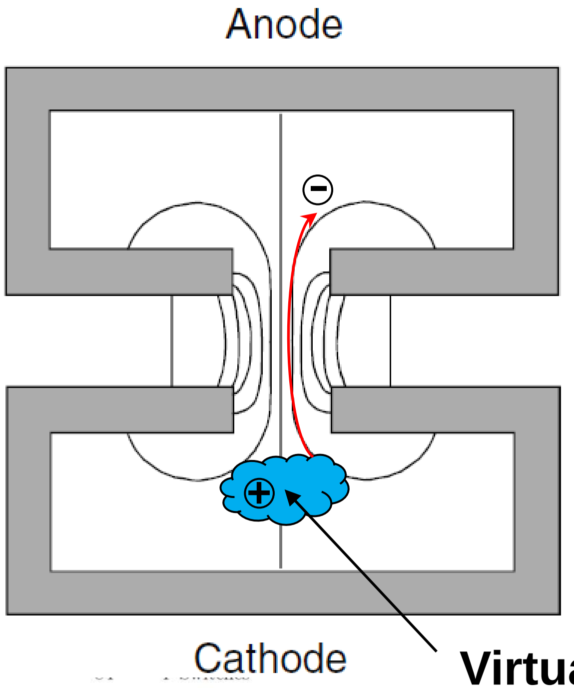


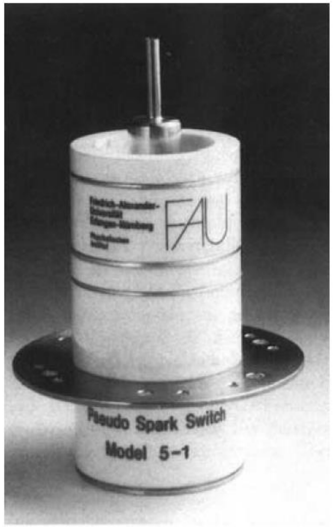


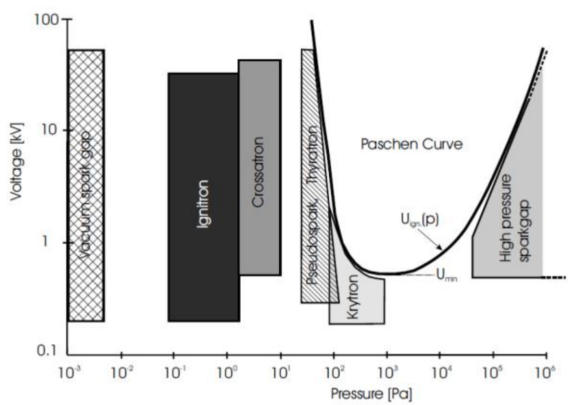


The pseudospark switch

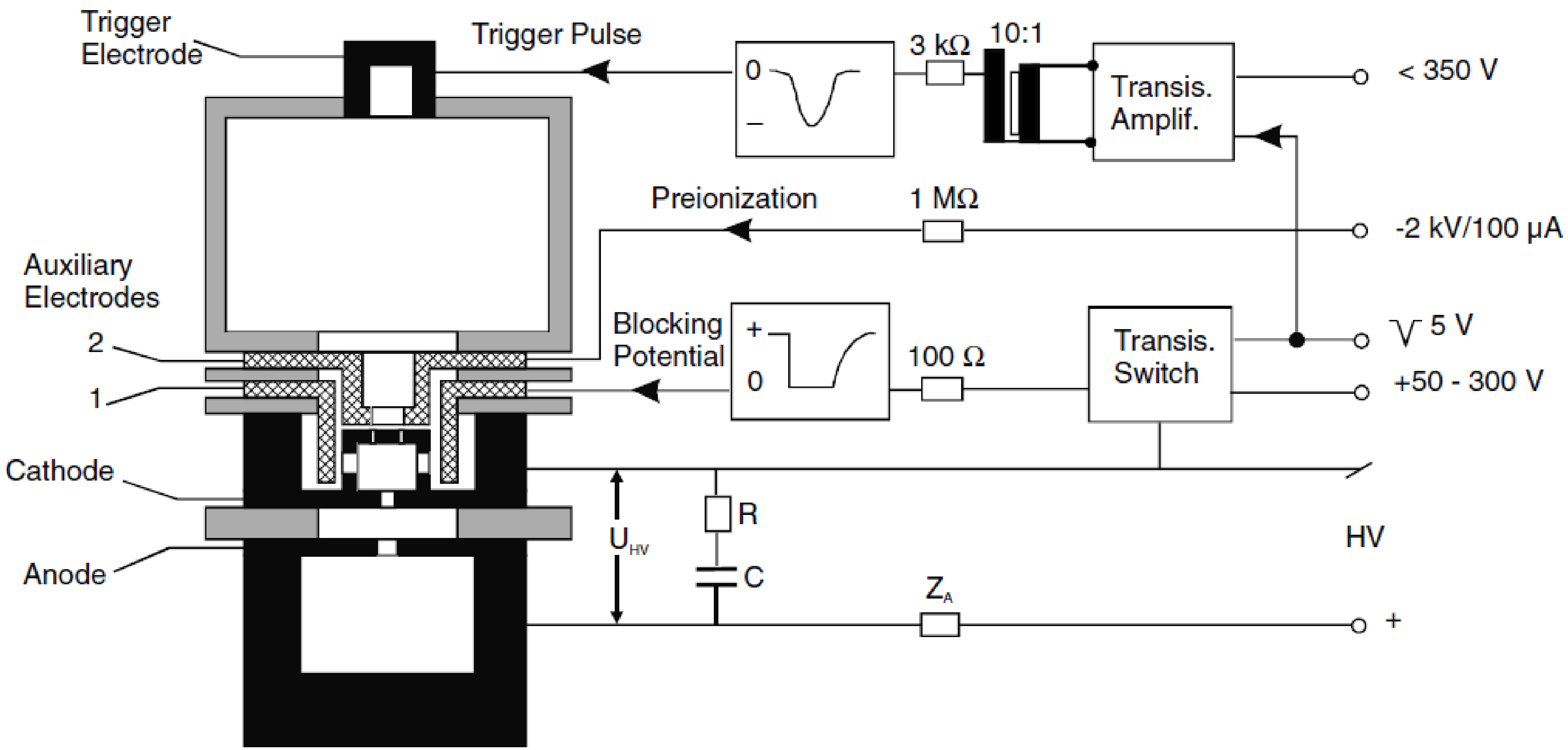
- **Ions drift back into the hollow cathode => forming a positive space charge (virtual anode).**
- **Static electric field inside the hollow cathode is distorted.**
- **Electron production rate > loss rate in the hollow cathode and subsequently in the anode-cathode gap.**
- **A low-resistivity plasma 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.**





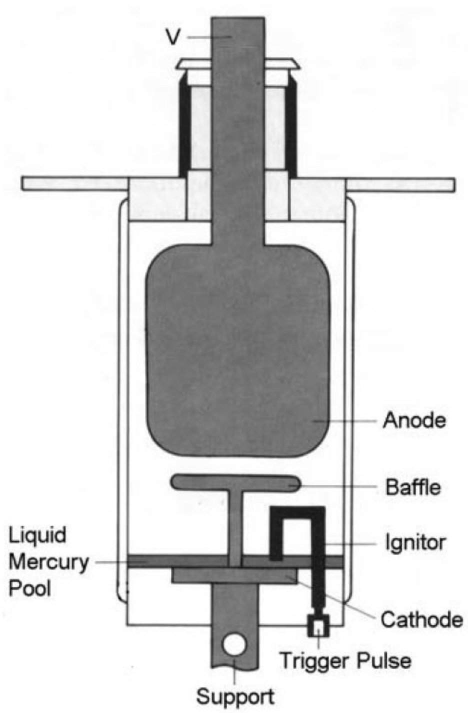


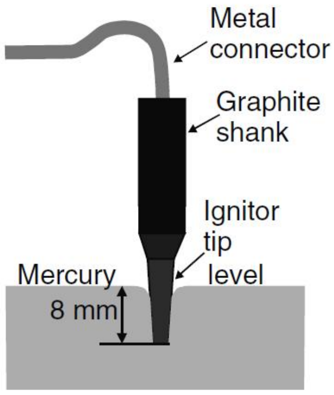
The pseudospark switch with triggering system



Ignitrons

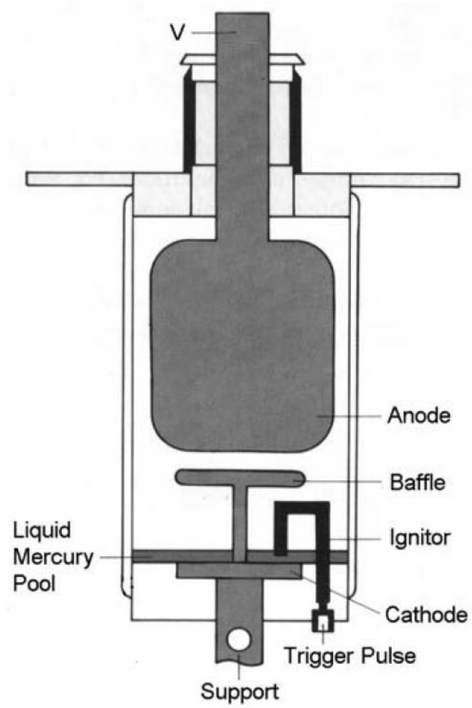
- Ignitron is a very high-current, high-voltage switch with
  - a liquid mercury pool cathode
  - an ignitor pin dipping into the liquid-metal reservoir.
- Internal mercury pressure: ~5 Pa
- Can switch a pulse charge of up to 2000 Colum.
- Air/water cooled may be needed.
- Internal splash and deionization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

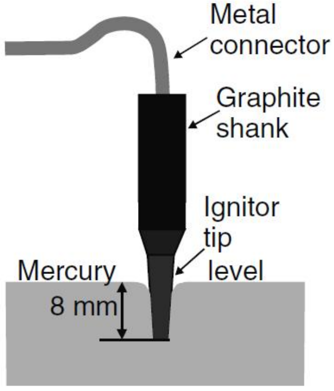




Ignitrons

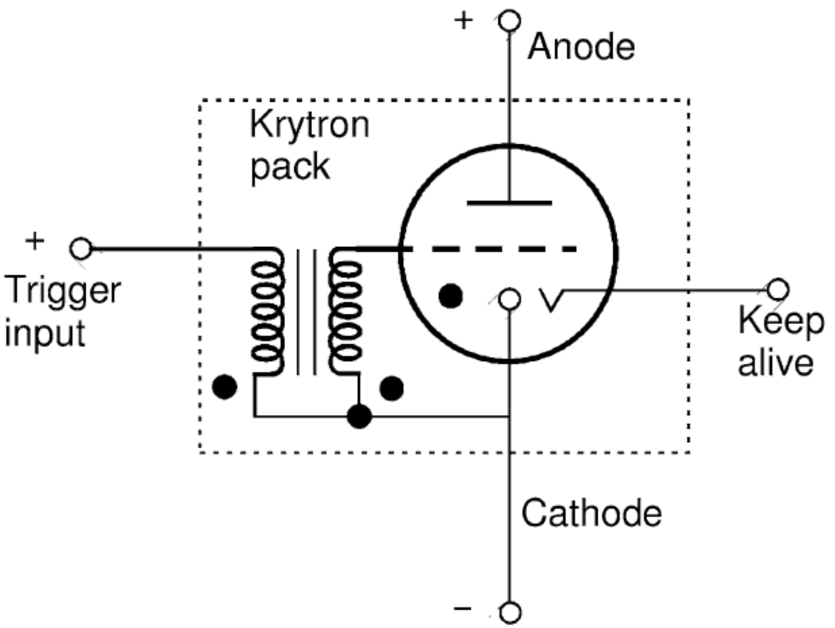
- **Rise time ~ 300-500 ns.**
- **After current drops below a critical value => no more additional vapor is produced => with additional time to allow recombination and recondensation of mercury.**
- **The mercury vapor must be forced to recondense back into the pool.**
- **Repetition rate ~1 Hz**
- **Progressively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





Krytrons

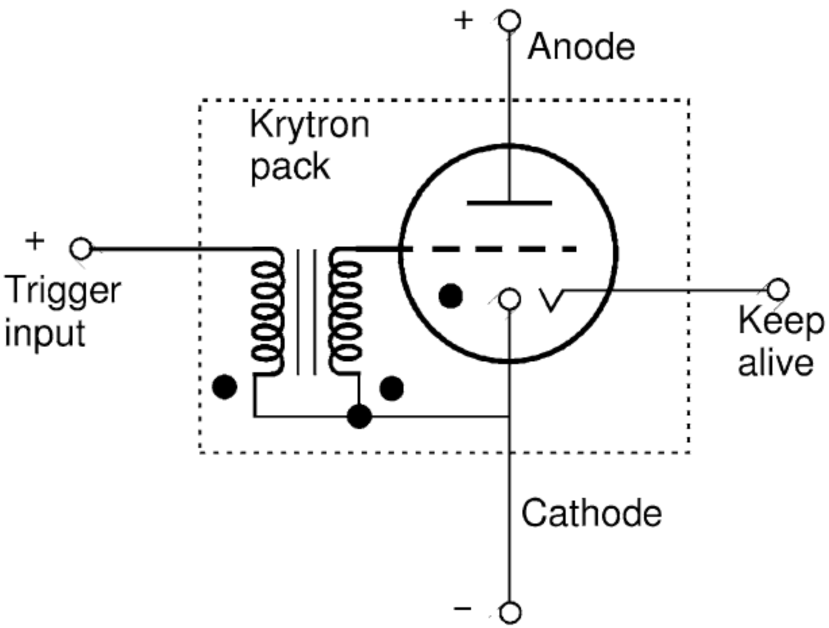
- **Low-pressure gas discharge device with a tetrode configuration, sealed in a glass tube with a cold cathode.**
- **1.3 kPa (9.75 torr) of helium gas.**
- **A special design of the anode-grid area + applied gas pressure**
  => large hold-off voltage.
- **An already existing plasma is created by a glow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

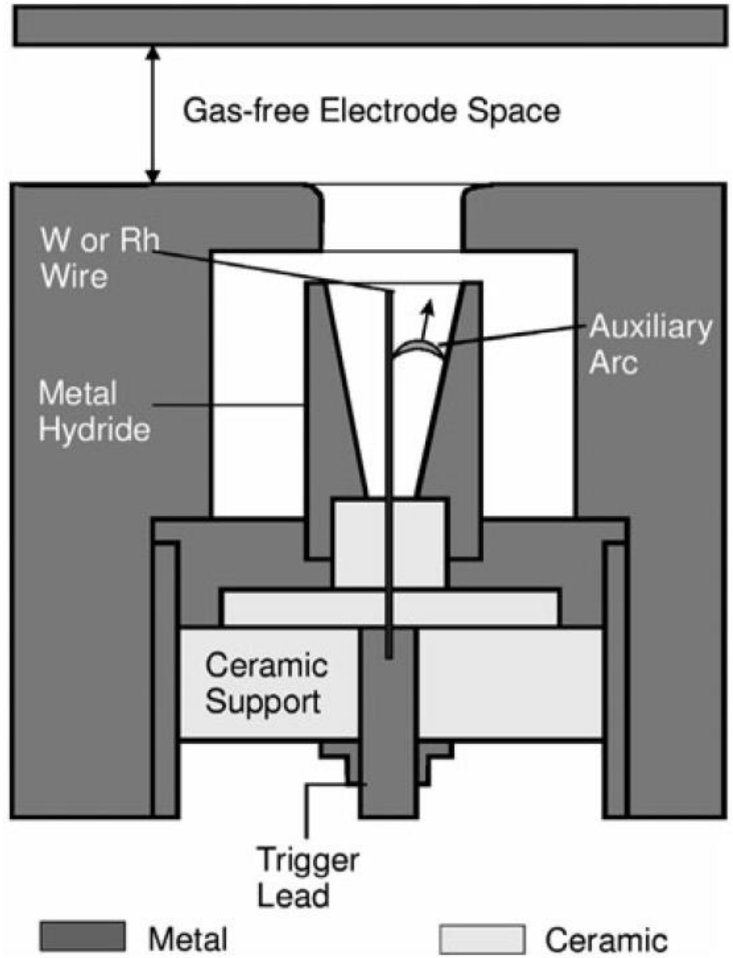
- A ^{63}Ni β-emitter may be enclosed to create a weak permanent pre-ionization.

- 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

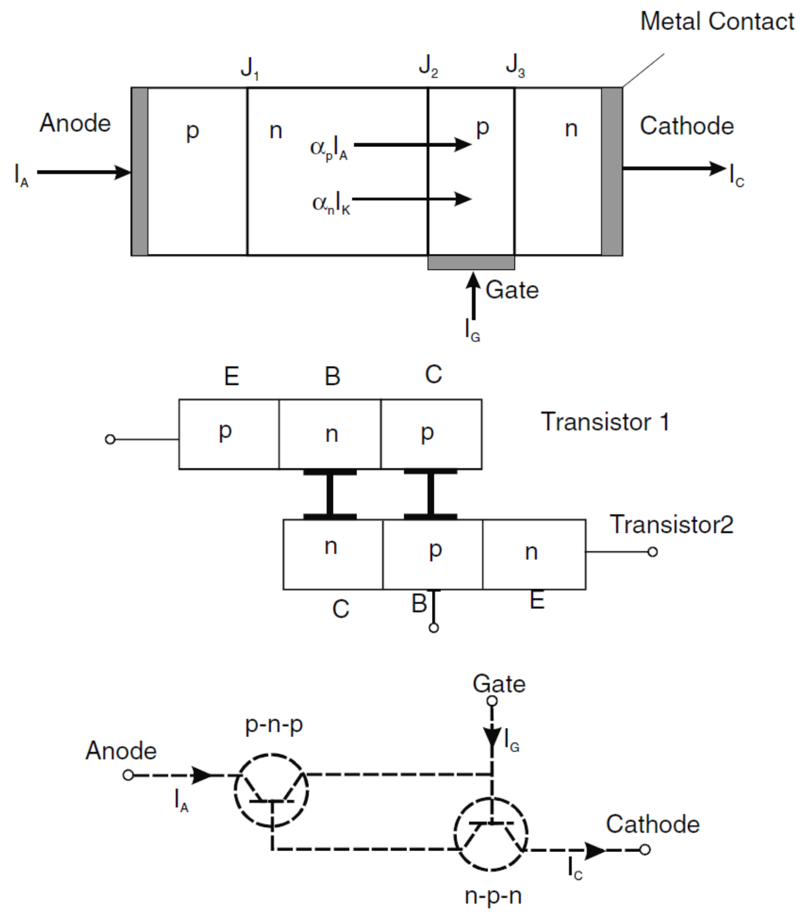
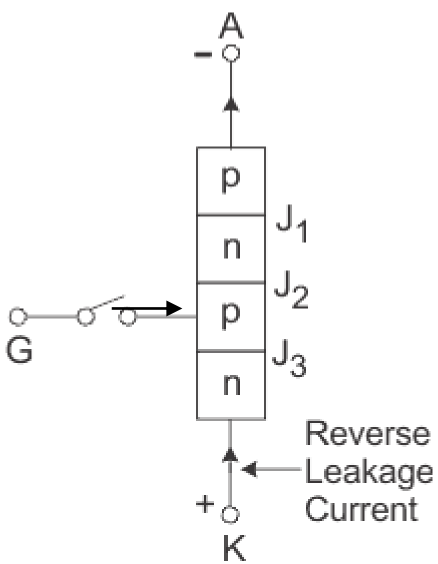


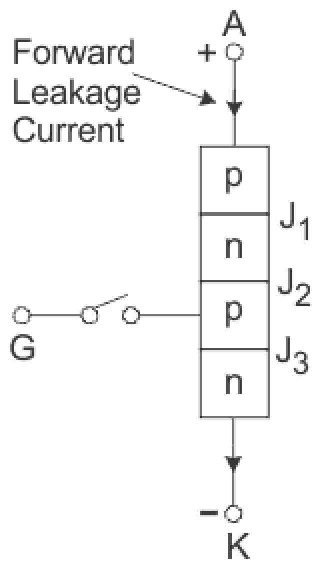
Fig. 4.22. Structure of thyristor, and two-transistor equivalent circuit

Thyristors

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



Reverse Blocking Mode



Forward Biased Condition

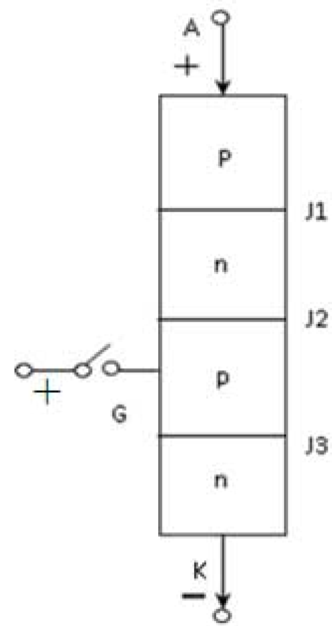


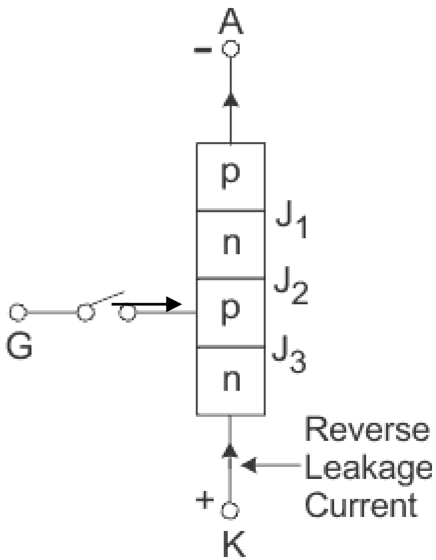
Fig 2: Forward Conduction

Most of the voltage is held by J_1.

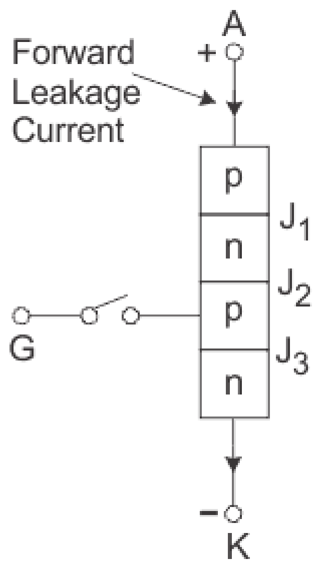
Most of the voltage is held by J_2.

Thyristors

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



Reverse Blocking Mode



Forward Biased Condition

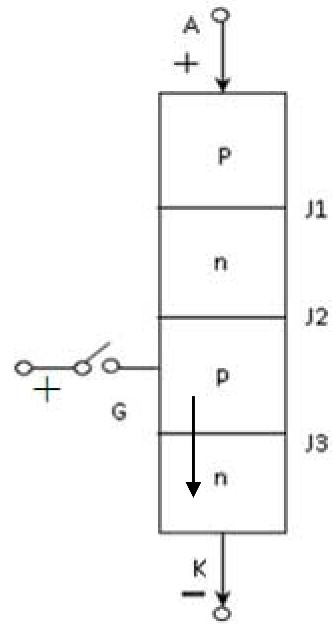


Fig 2: Forward Conduction

e^- will fill up the holes

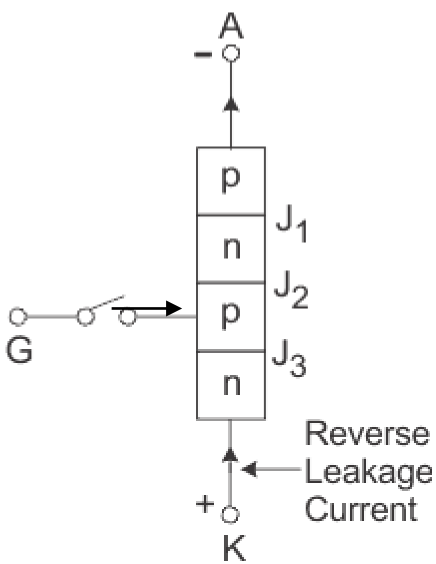
w/ more e^- => p type becomes N type

Most of the voltage is held by J_1.

Most of the voltage is held by J_2.

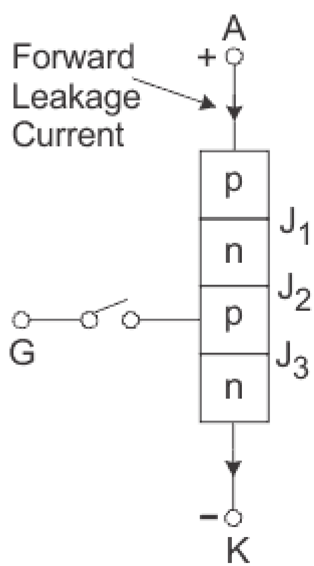
Thyristors

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



Reverse Blocking Mode

Most of the voltage is held by J_1.



Forward Biased Condition

Most of the voltage is held by J_2.

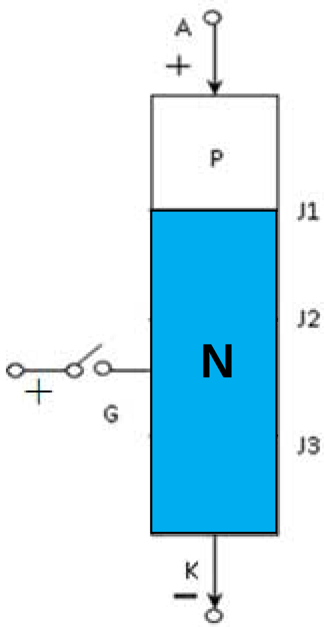


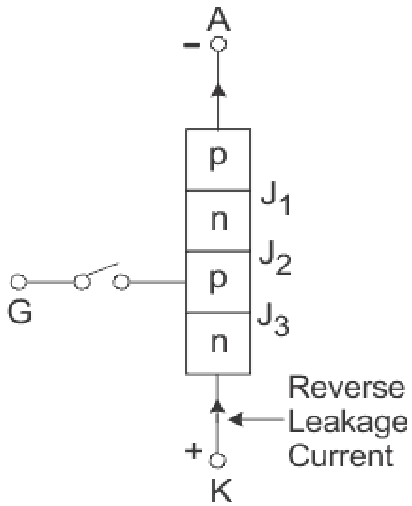
Fig 2: Forward Conduction

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.**



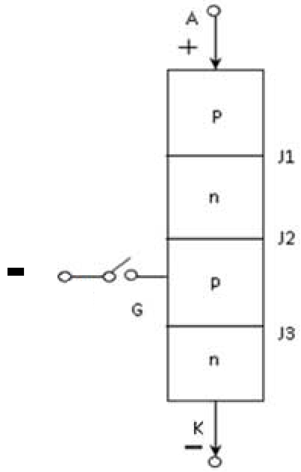
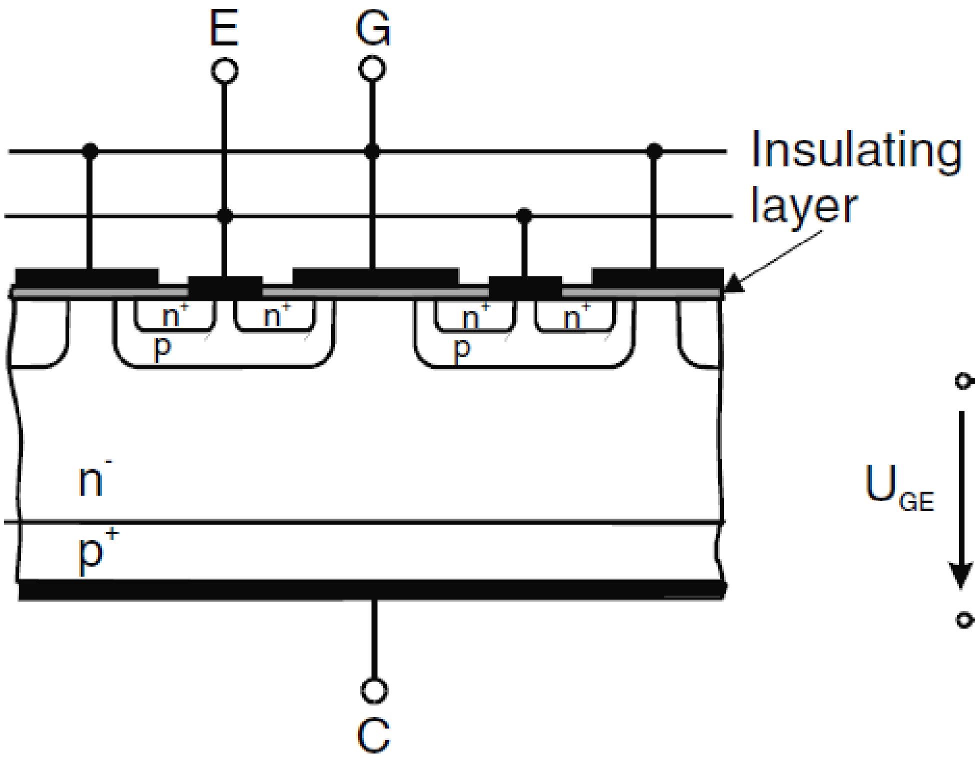
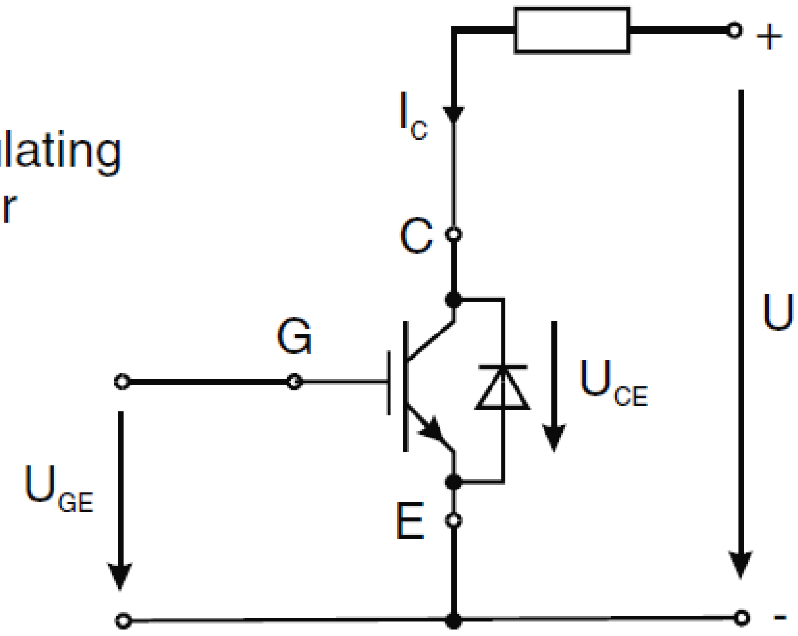


Fig 2: Forward Conduction

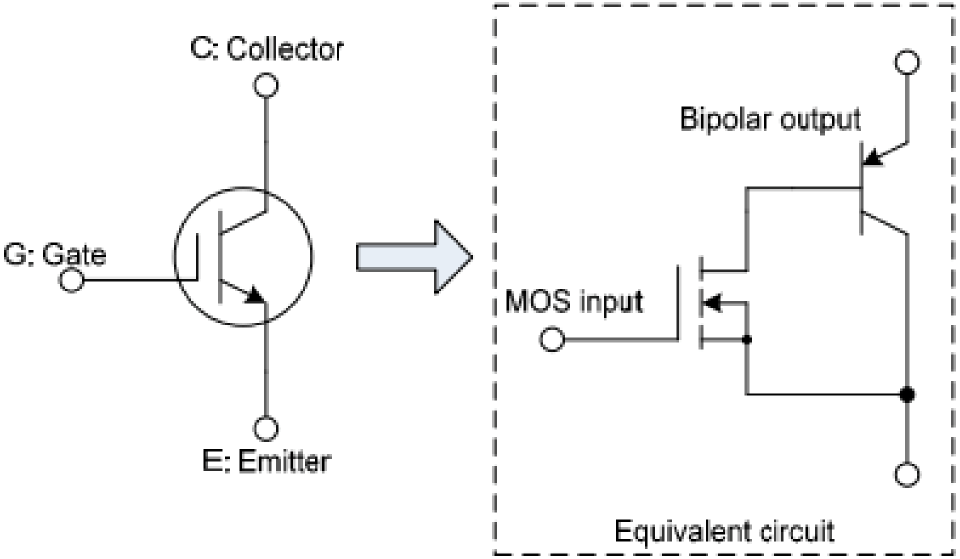
IGBT





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.**

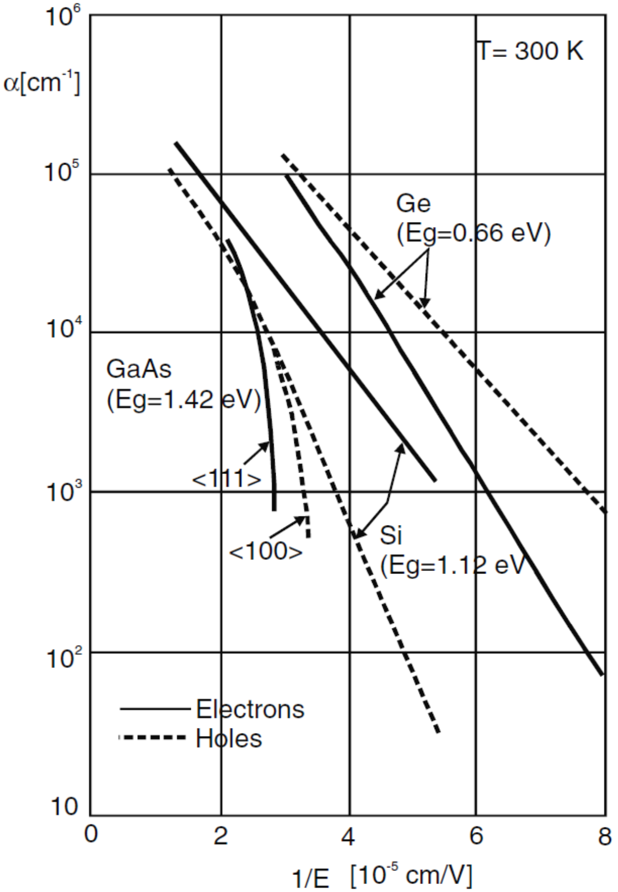


Fig. 4.31. Ionisation rate coefficients α_n and α_p

Optically activated semiconductor switches

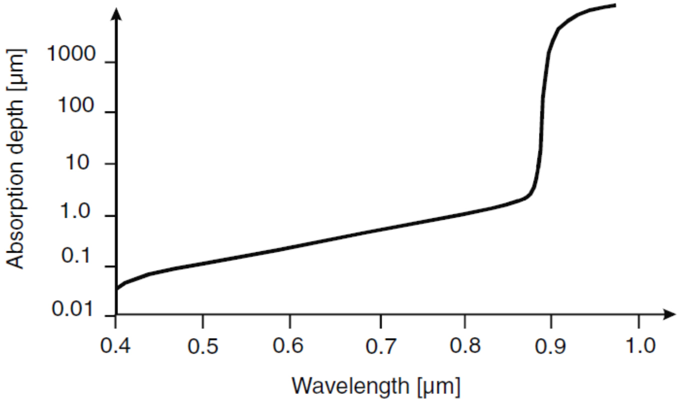
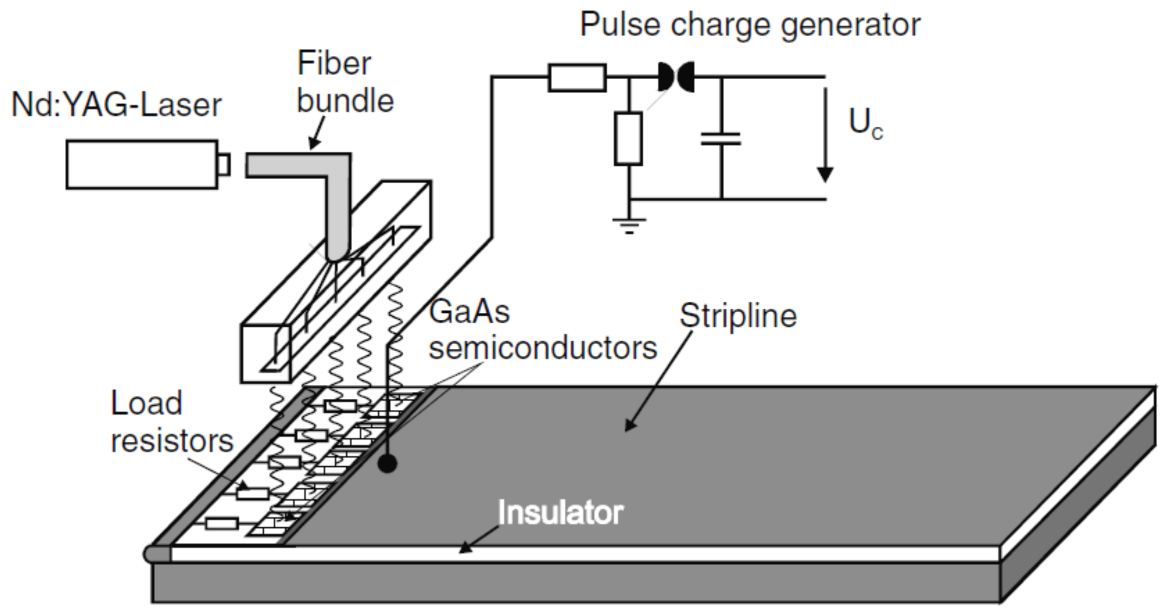
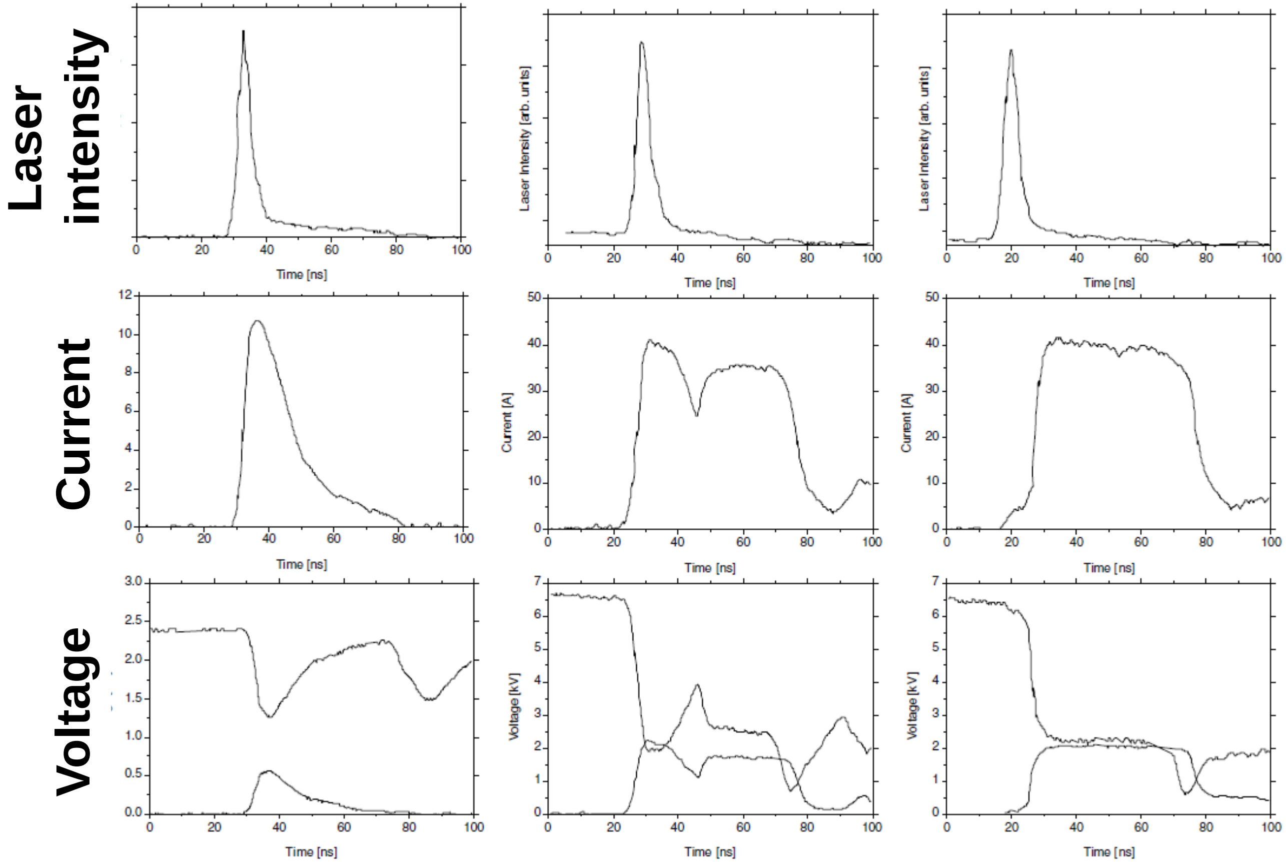


Fig. 4.32. Optical absorption depth in GaAs as a function of wavelength

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

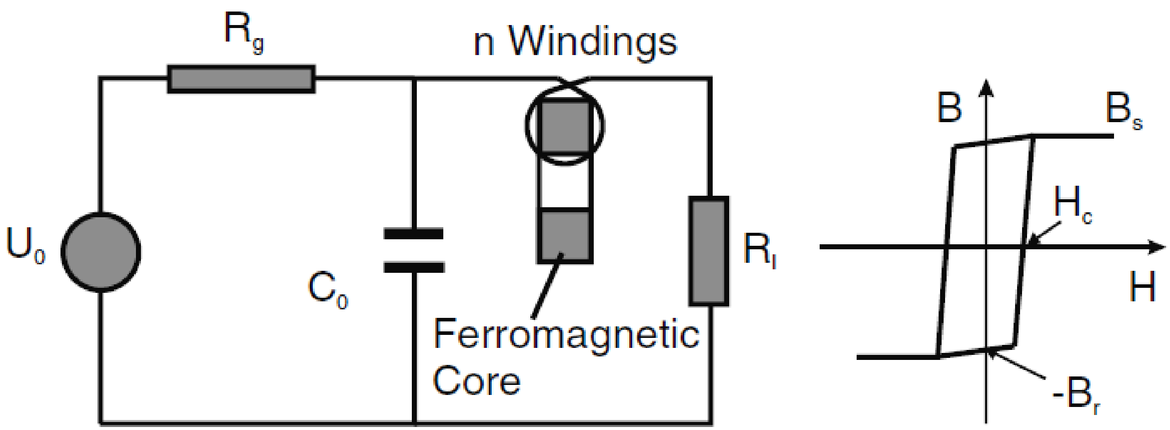


Optically activated semiconductor switches



- **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

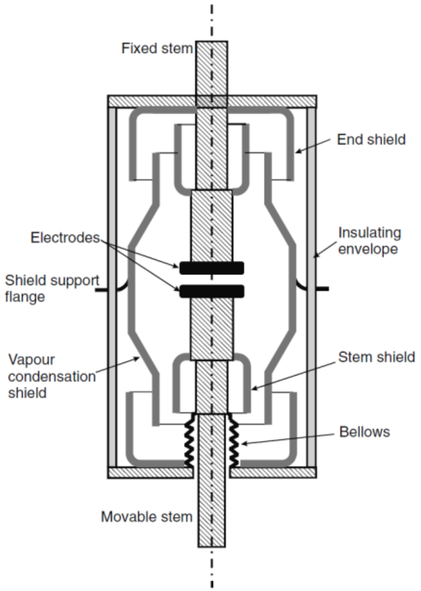
Type	Hold-off potential (kV)	Peak current (kA)	Cumulative charge (A s)	Repetition rate (Hz) [commutation time (ns)]	Lifetime (number of pulses)	Remarks
Spark gap	1–6000	10^{-3}–1000	0.1–50	1–10 [1–1000]	10^3–10^7	Lifetime is determined by electrode erosion
Thyratron	5–50	0.1–10	10^{-3}	1000 [5–100]	10^7–10^8	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

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

Opening switches

- An opening switch is characterised by "a sudden growth of its impedance" by
  - External actuator
  - Internal process – depend on the amount of the charge conducted through the switch
- The mechanism can be
  - Resistive nature: common fuse
  - Inductive nature: flux compression, L(t) >> L(0)
  - Capactive nature, C(t) << C(0)

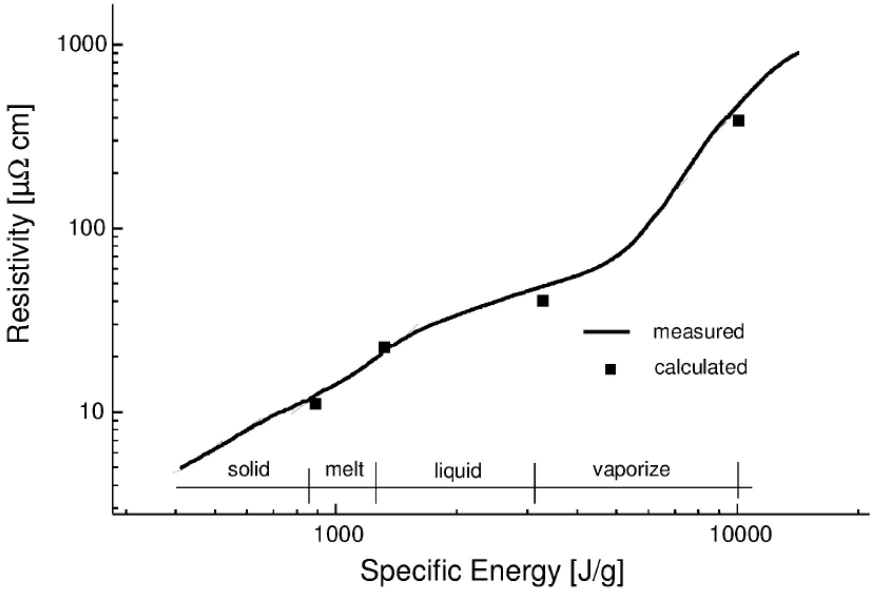


Opening switches

- **Requirement:**
  - **Long current conduction time.**
  - **Large current and small losses during conduction.**
  - **Fast impedance rise during opening.**
  - **High impedance after opening & large voltage hold-off during current interruption.**
  - **Short recovery time, i.e., high repetition rate capability.**
  - **Long lifetime, i.e., small wear.**

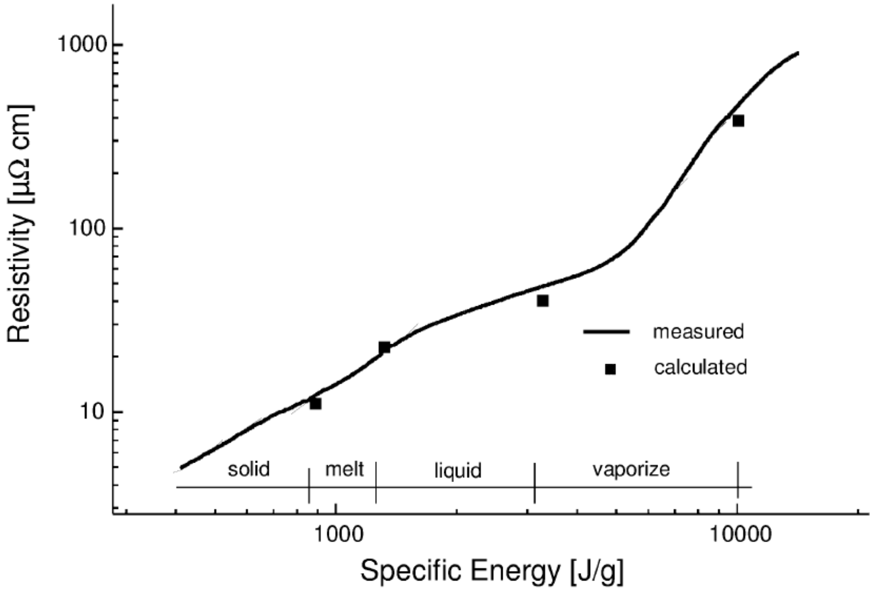
Fuses

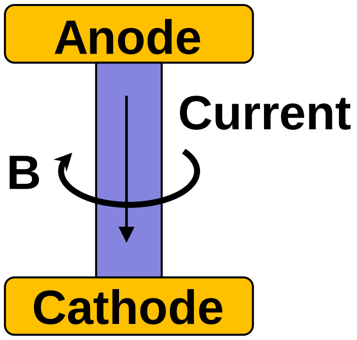
- **Melting fuse – the most widely known opening switch.**
- **A thin wire / a foil embedded in a gaseous, liquid or granular medium.**
- **Based on Melting, Boiling, or Vaporization of a conductor,**
- **Fast opening is possible: <50 ns**
- **Conduction time can be determined by the type of material and its geometry.**



Fuses

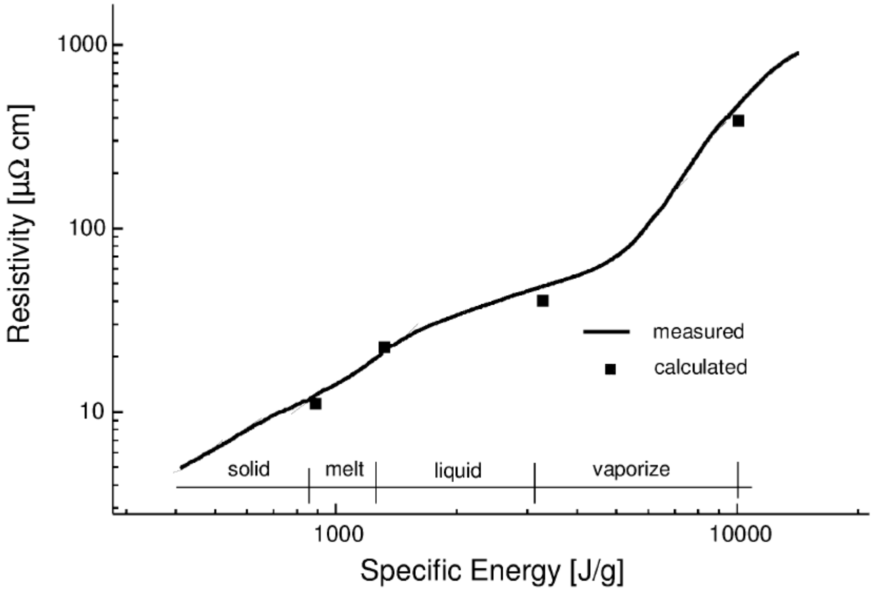
- The resistivity of most metals rises continuously with T both in the solid and in the liquid phase.
- The high magnetic pressure associated with the current flowing through the fuse can maintain a high density and therefore metallic conductivity beyond the critical temperature.
- Only after the onset of expansion does the metallic conductivity disappear.

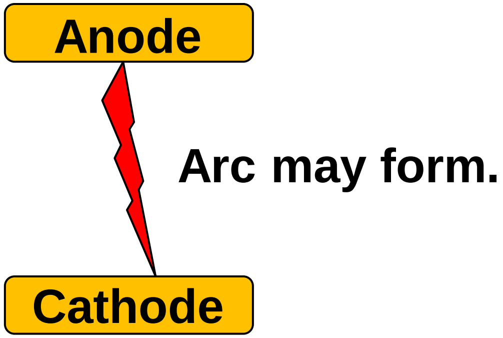




Fuses

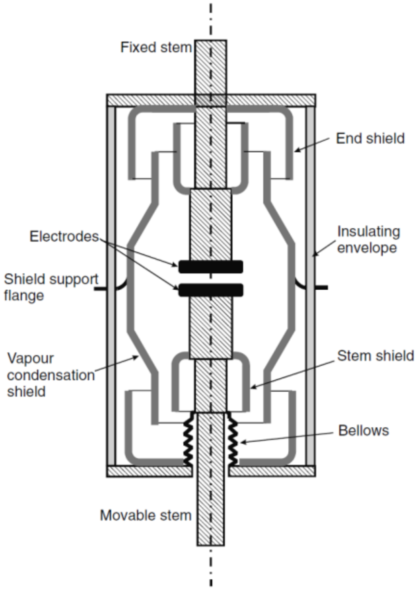
- **If the density of the metal vapor becomes sufficiently small -> electron avalanche processes can lead to the initiation of arcs in the vapor.**
- **The purpose of the surrounding medium is therefore to quench or prevent arc formation.**
- **Advantage – simplicity, adapt their parameters to the experimental conditions by choosing the appropriate cross-section, length, and #/ of elements.**



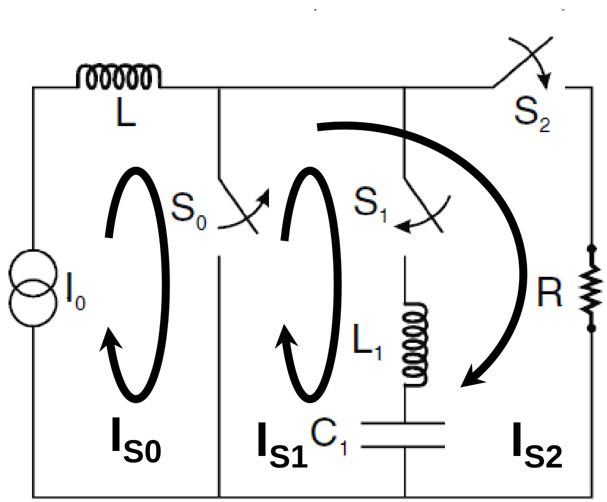


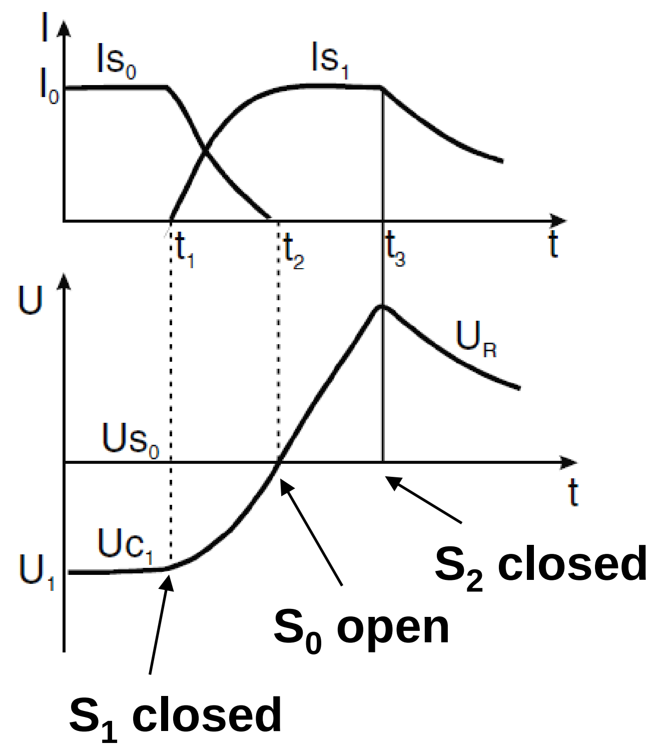
Mechanical Interrupters

- **Vacuum interrupter switch: 2 planar/disc electrodes (1 fixed the other movable) in a vacuum envelope (0.1 Pa (7.5 x 10^{-4} Torr) or less).**
- **Closed position – low resistance (10-50 uΩ) from a tight metal-to-metal contact**
- **Open position – separated by an actuator (致動器).**
- **During the process of switch breaking – an arc is likely to be drawn and sustained by metal vapor evaporated from the electrodes.**
- **In unipolar system, a current counter-pulse is needed to reduce the power input to the arc to allow the residual arc plasma to recombine.**
- **After I=0, dU/dt=24 kV/us is possible.**
- **Repetitive frequency – few tens of hertz.**
- **Opening speed – tens of us.**



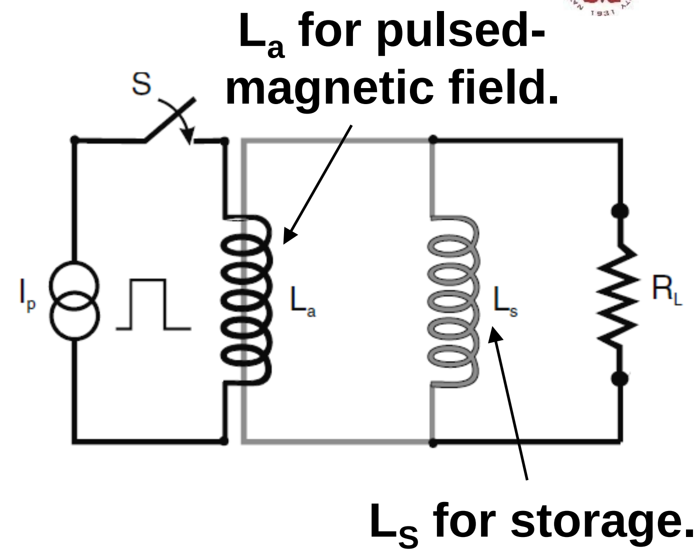
Counter-pulse arrangement





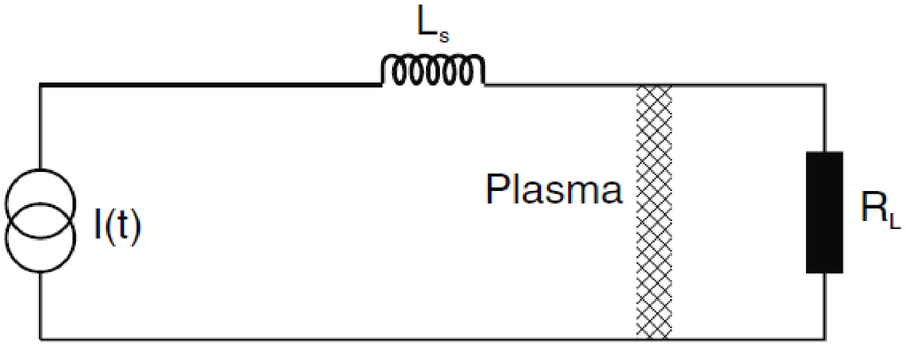
Superconducting opening switches

- **Superconducting state -> normal conduction**
- **Three ways to trigger:**
  - **The current itself**
  - **An external pulsed magnetic field**
  - **pulse heating**
- **The repetition rate depends on the speed of recovery to the superconducting state.**
- **Problem: consists of the additional cooling necessary to remove the heat flowing into the cryogenic coolant during opening.**

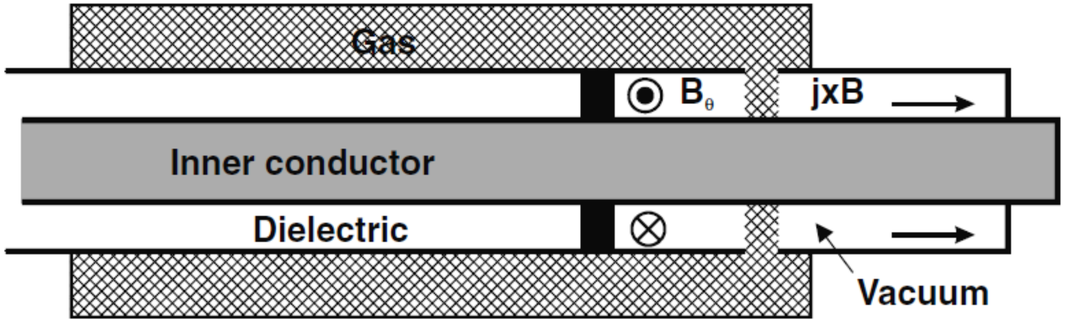


Plasma opening switches

- Suitable for high currents and short switching times.
- Plasma bridge of low density (10^{13}-10^{15} cm^{-3}).
- 10^{15}-10^{16} cm^{-3} for several hundred kA or MA.
- 10^{13} cm^{-3} is needed to conduct currents for less than 100 ns and opening in less than 10 ns.

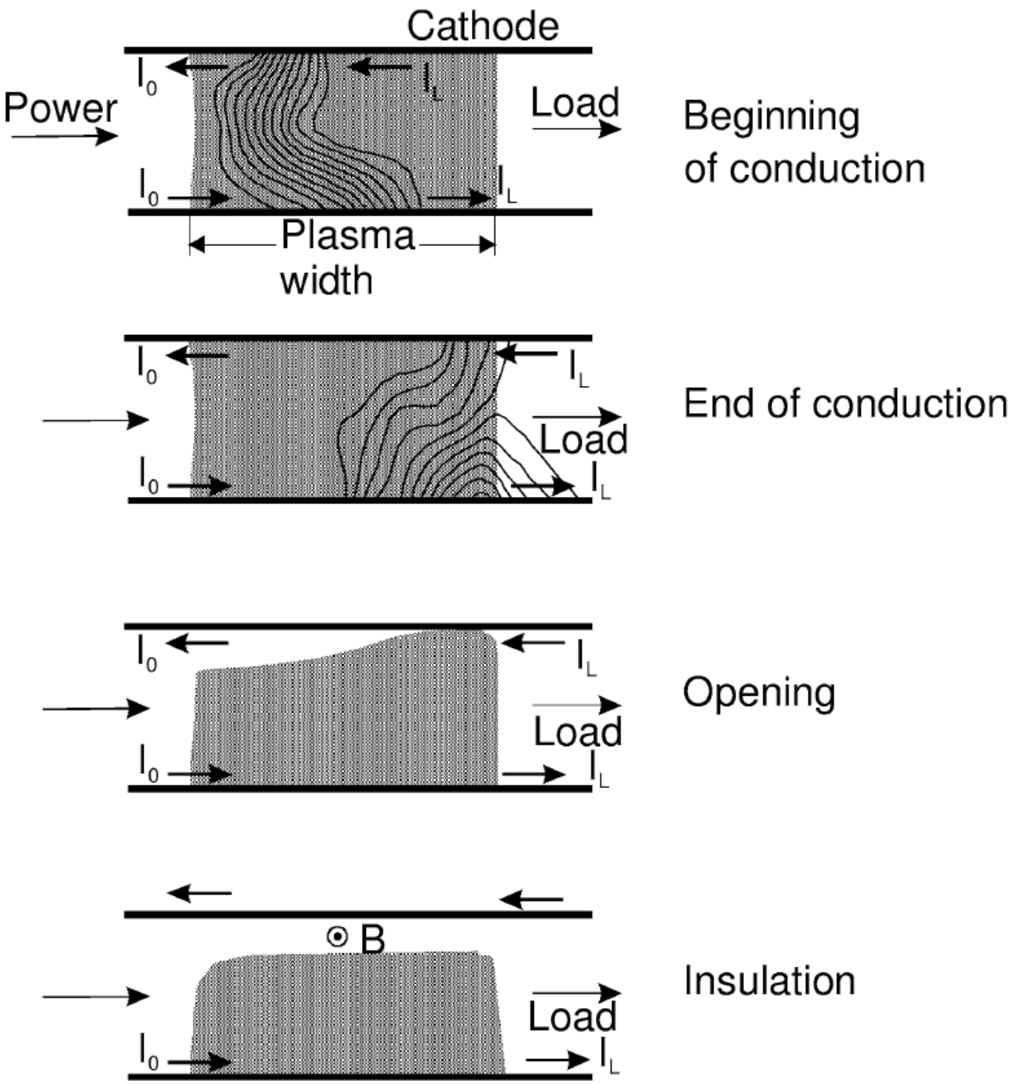


Coaxial system with an injected pulsed gas column



- **The gas is made into a plasma by an auxiliary electric pulse before the coaxial inductor is charged.**
- **Conduction phase – the current, the magnetic field penetrates into the plasma**
- **Opening – occurs if the plasma becomes pushed out determined by self-magnetic insulation**

Self-magnetic insulation process



Plasma Flow Switches

- **Higher plasma densities (10^{15} cm^{-3}).**
- **Conduction times – μs.**