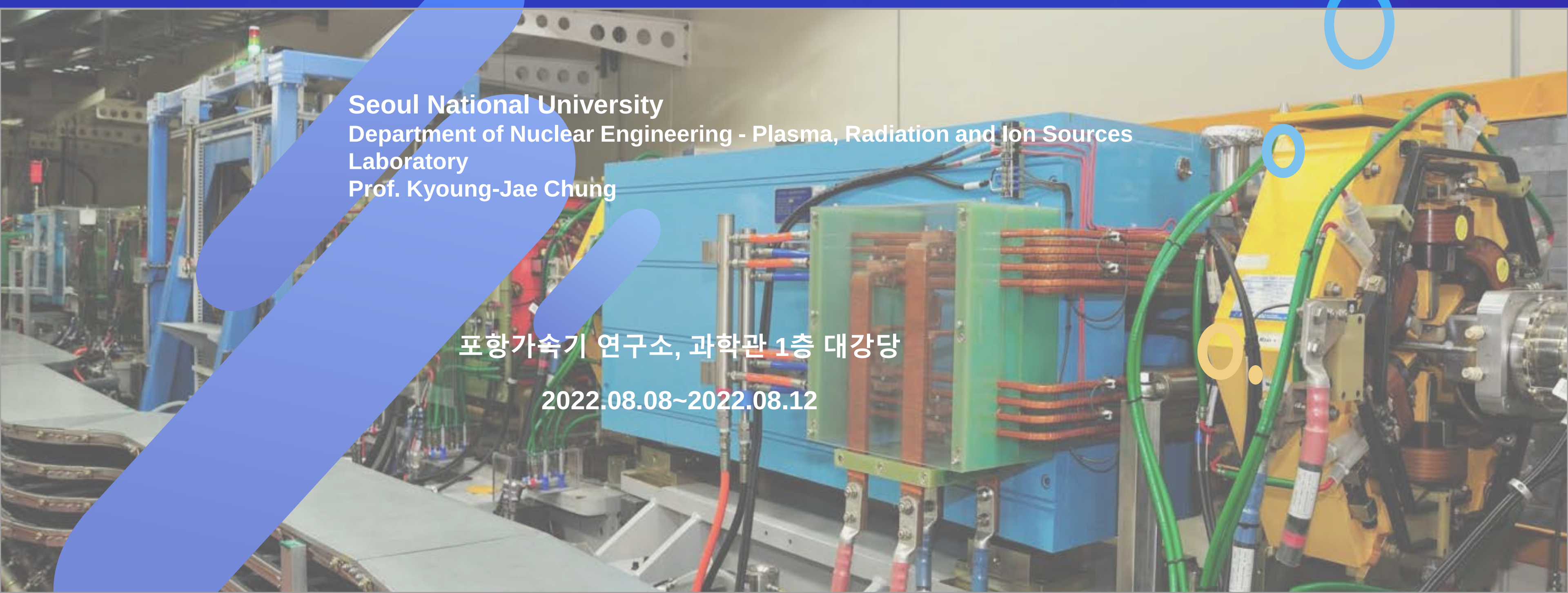
2022 ATE accelerator school

Introduction to High-voltage Pulsed Power



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Introduction

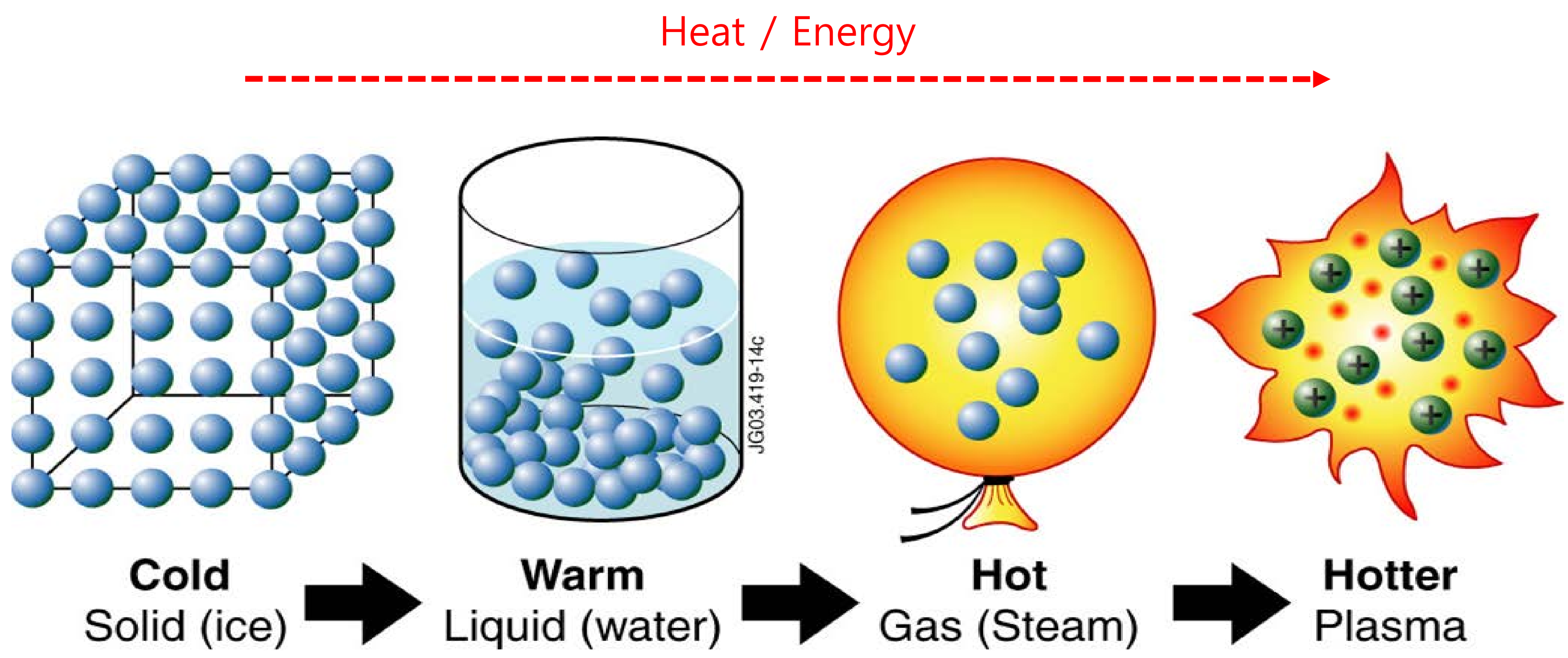
- Pulsed power technology is an area of interest to physicists and engineers in fields requiring high voltages and large currents.

- Modern pulsed power runs the gamut from its historical roots in flash radiography, X-ray generation, and the simulation of weapons effects, such as nuclear electromagnetic pulse (EMP), to packaged pulsed power for directed energy weapons and biological and medical applications. New applications and techniques continue to emerge.

- References

  - J. Lehr and P. Ron, Foundations of Pulsed Power Technology, IEEE Press (2017).
  - H. Bluhm, Pulsed Power Systems: Principles and Applications, Springer (2006).
  - G. A. Mesyats, Pulsed Power, Springer (2005).
  - P. W. Smith, Transient Electronics: Pulsed Circuit Technology, John Wiley and Sons (2002).
  - S. T. Pai and Qi Zhang, Introduction to High Power Pulse Technology, World Scientific (1995).

Plasma: energy compression in space

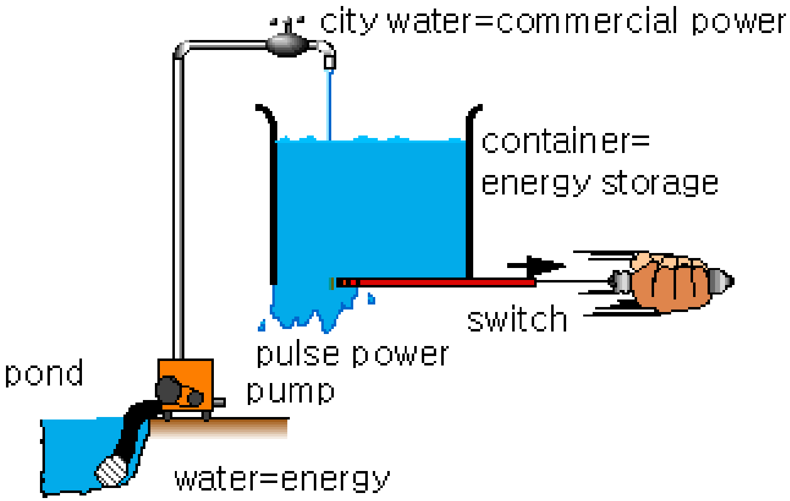


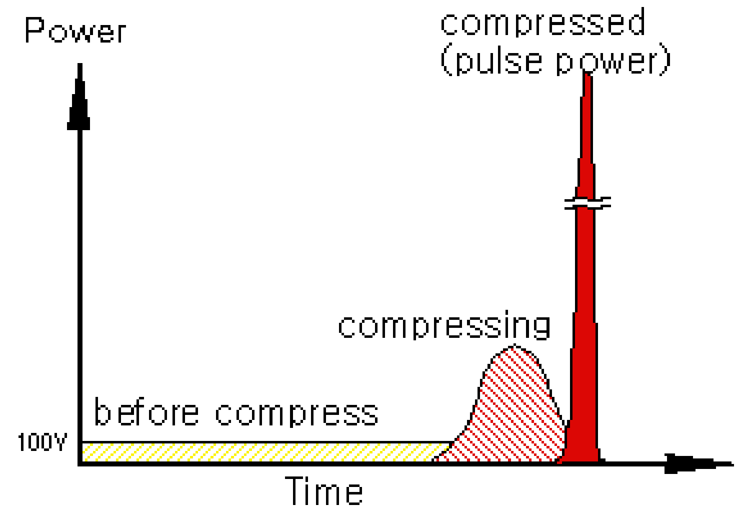
- Generation of spatial region where energy state is higher than surroundings (tokamak, processing chamber, plasma jet)

  → Generation of energetic particles, chemically active species

- Energy confinement (compression) in space

Pulsed power: energy compression in time





- **Pulsed Power Technology: the storage of electrical energy over a relatively long time scale and its release in a short duration to create very high power level**

- Example: E = 1 kW x 1 sec = 1 kJ
  P = 1 kJ / 1 us = **1 GW**

Features of pulsed power

- Pulsed power is a scheme where stored energy is discharged as electrical energy into a load in a single short pulse or as short pulses with a controllable repetition rate.

High Power (大電力)

- Short rise time
- Short pulse width
- Focusing of high power in a narrow space

↓

- Generation of high voltage and current
- New application of electromagnetic energy

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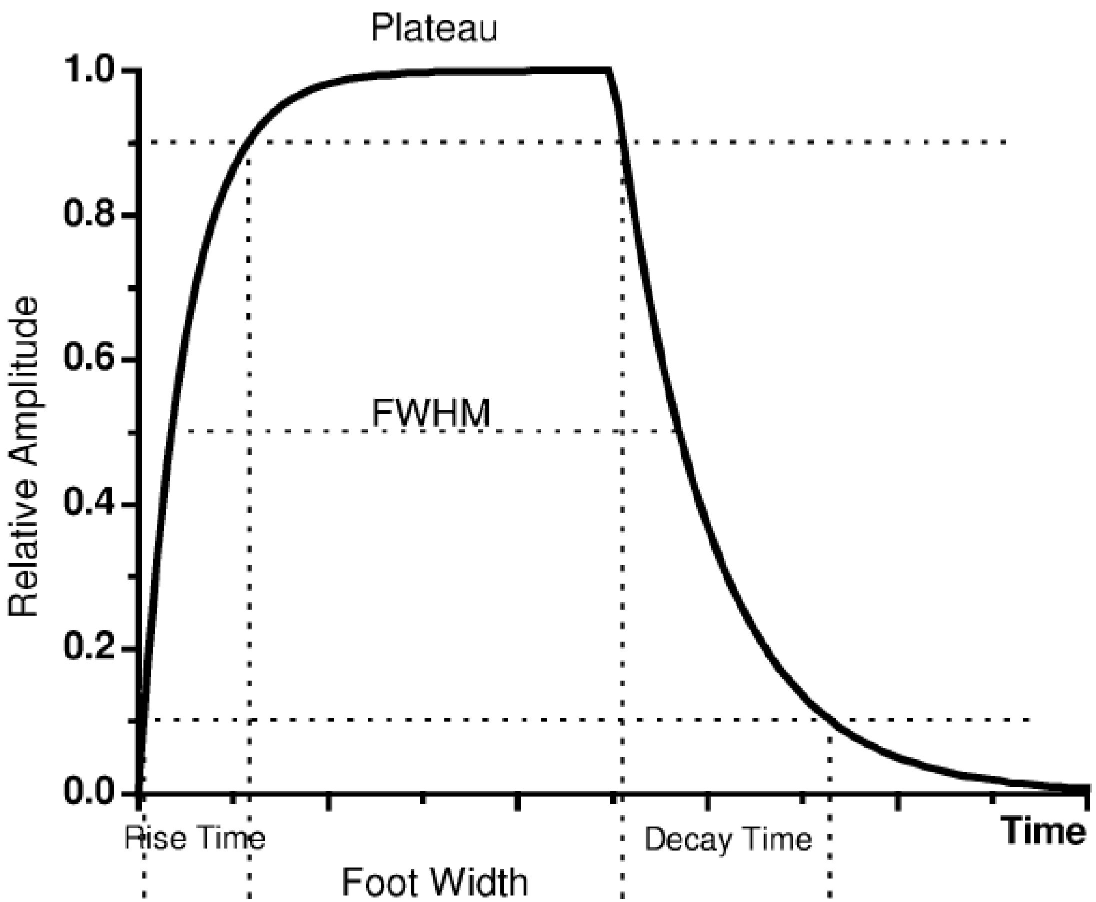
Features of pulsed power

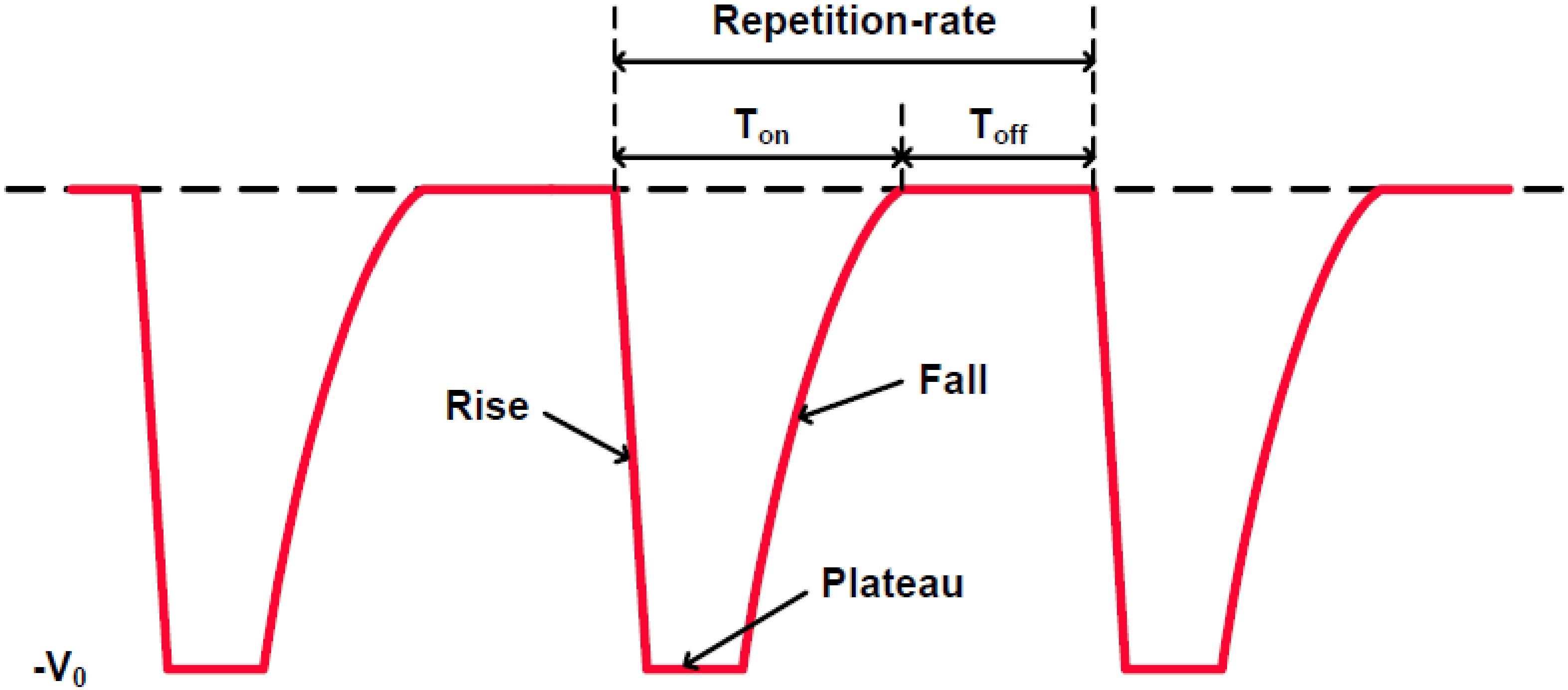
- Pulsed power is a special power conditioning technique that transforms the characteristics of the prime energy source to the electrical requirements of the load.
- Energy from a primary source is accumulated over a relatively long time scale and compressed into pulses of high instantaneous power.
- Several stages may be needed to fully exploit the time dependence of breakdown of insulating materials to deliver energy with the required time dependence and amplitude for the application.
- The resulting peak power delivered to the load has a large ratio of instantaneous-to-average power.

Energy per pulse	$1–10^7$ J
Peak power	$10^6–10^{14}$ W
Peak voltage	$10^3–10^7$ V
Peak current	$10^3–10^8$ A
Pulse width	$10^{-10}–10^{-5}$ s

Pulse shape parameters

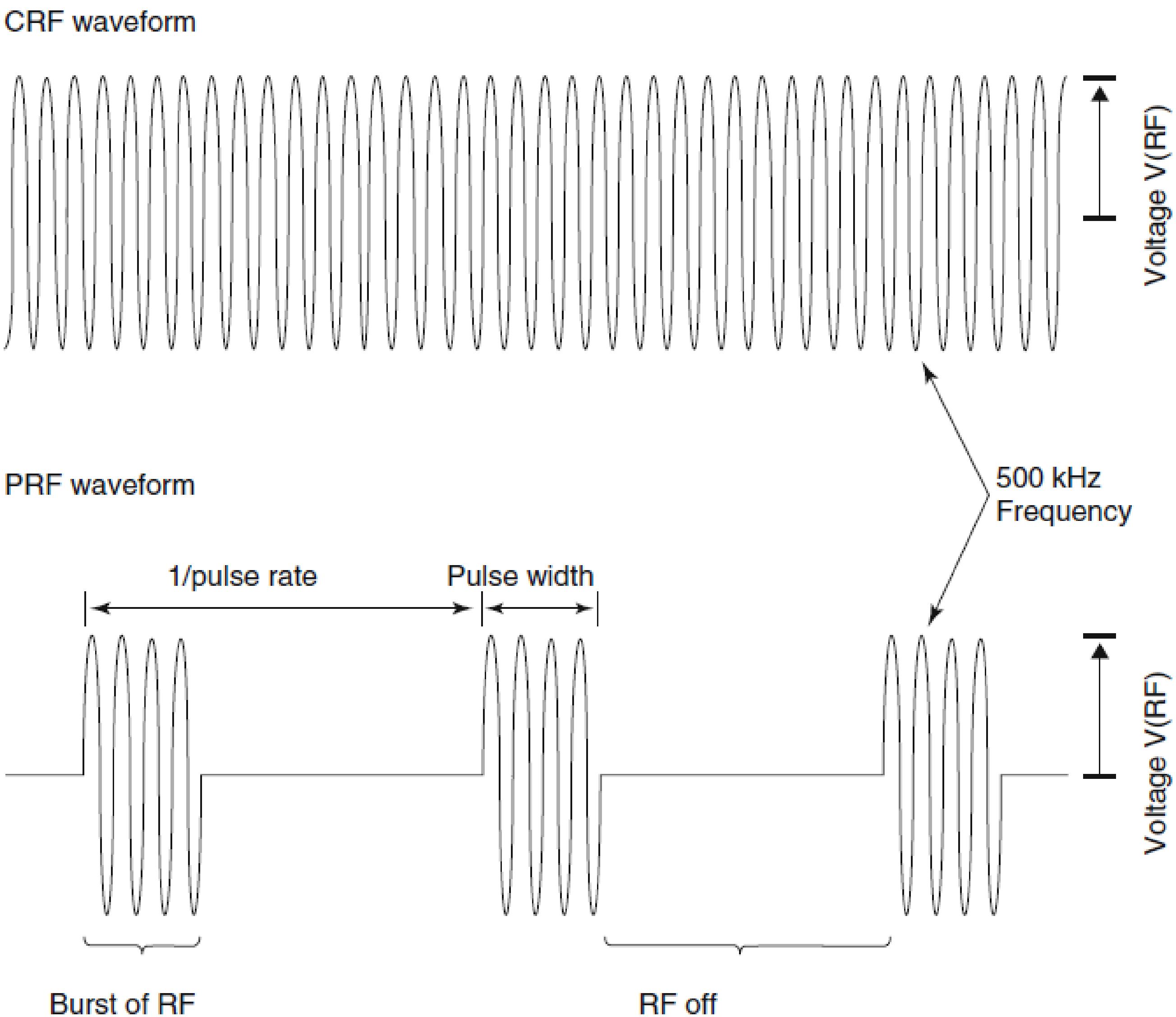


Typical waveform of repetitive pulses

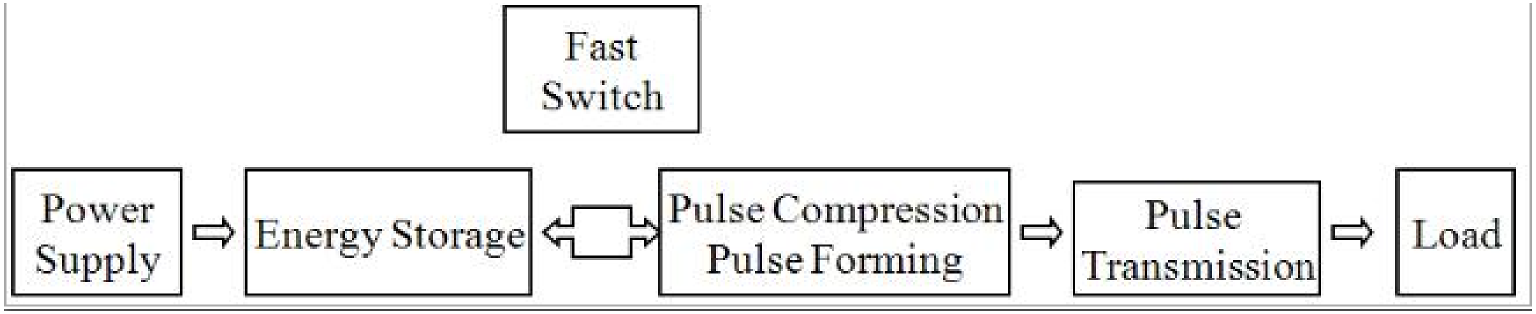


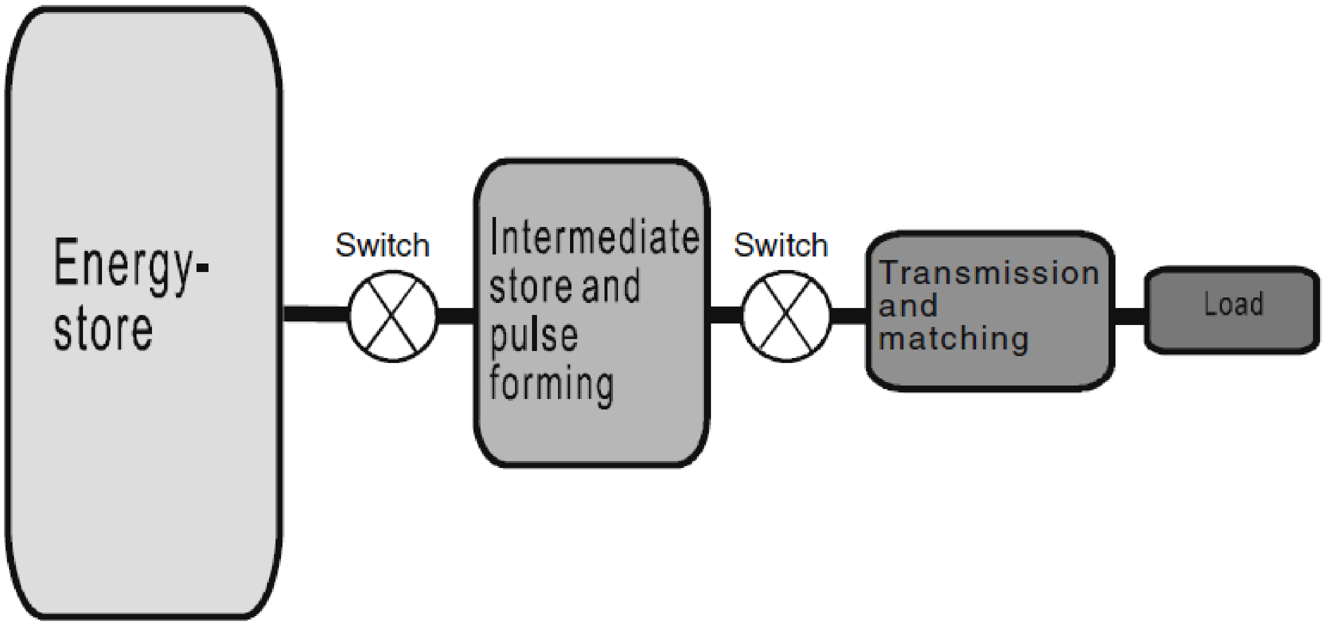
$$D(duty) = \frac{T_{on}}{T_{on} + T_{off}}$$

RF pulse


CRF waveform
Voltage V(RF)
500 kHz
Frequency
PRF waveform
1/pulse rate
Pulse width
Voltage V(RF)
Burst of RF
RF off

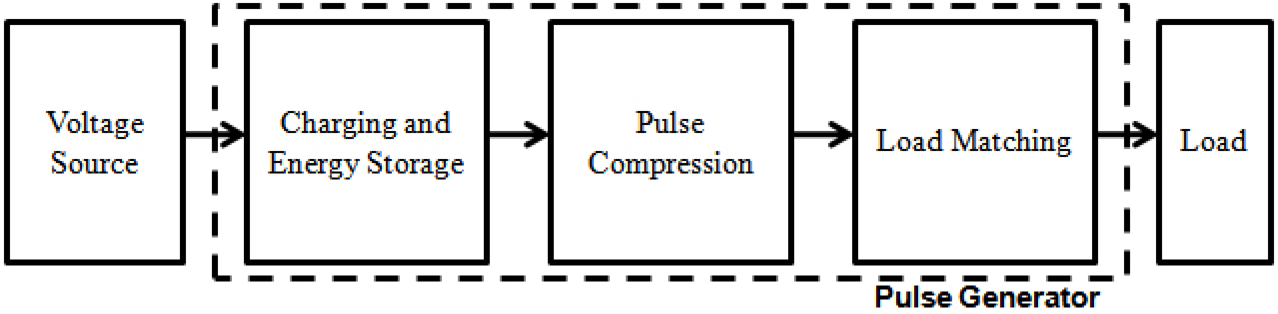
Generation of high power pulses





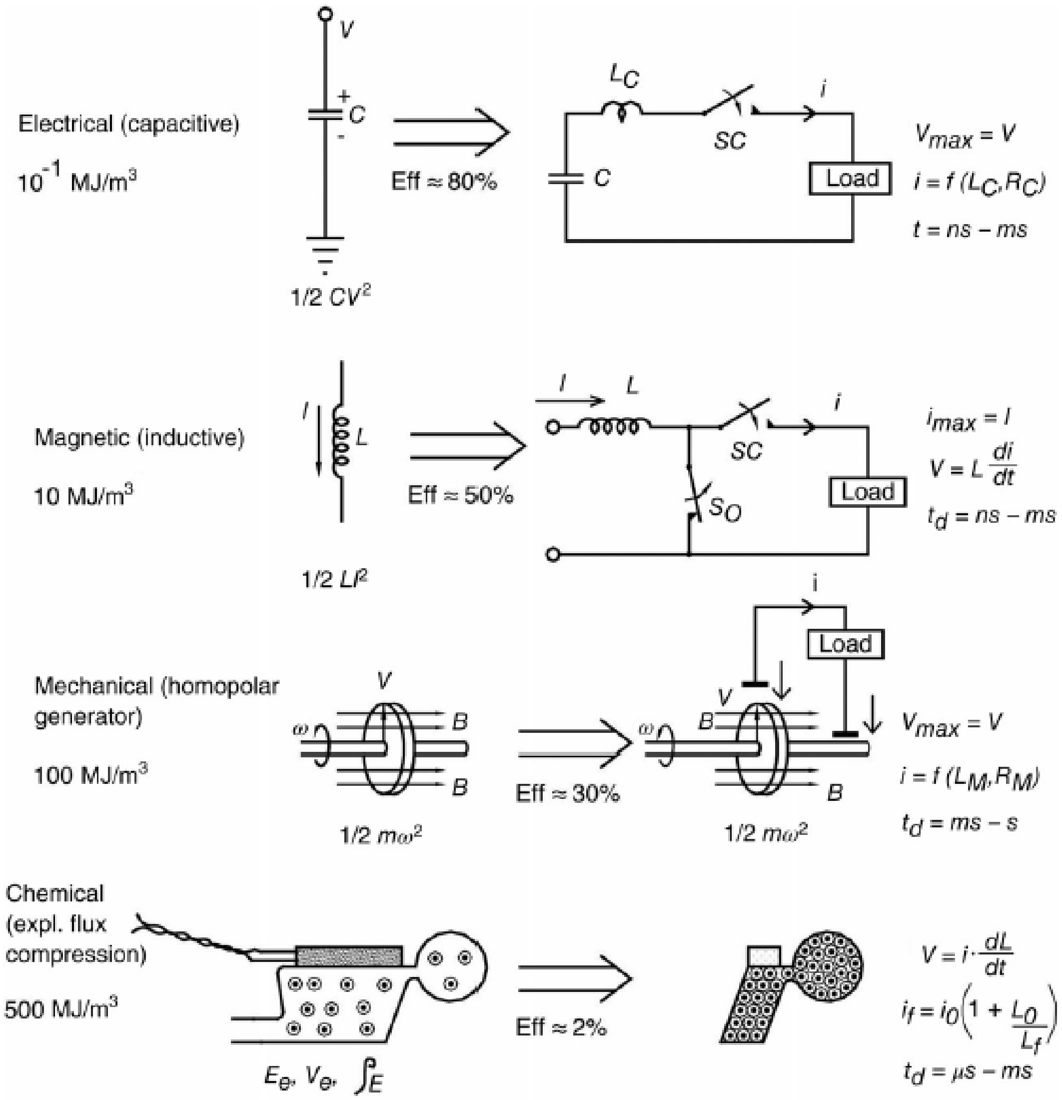
Pulsed power system

- Energy storage and fast switching play a key role in pulsed power technology.

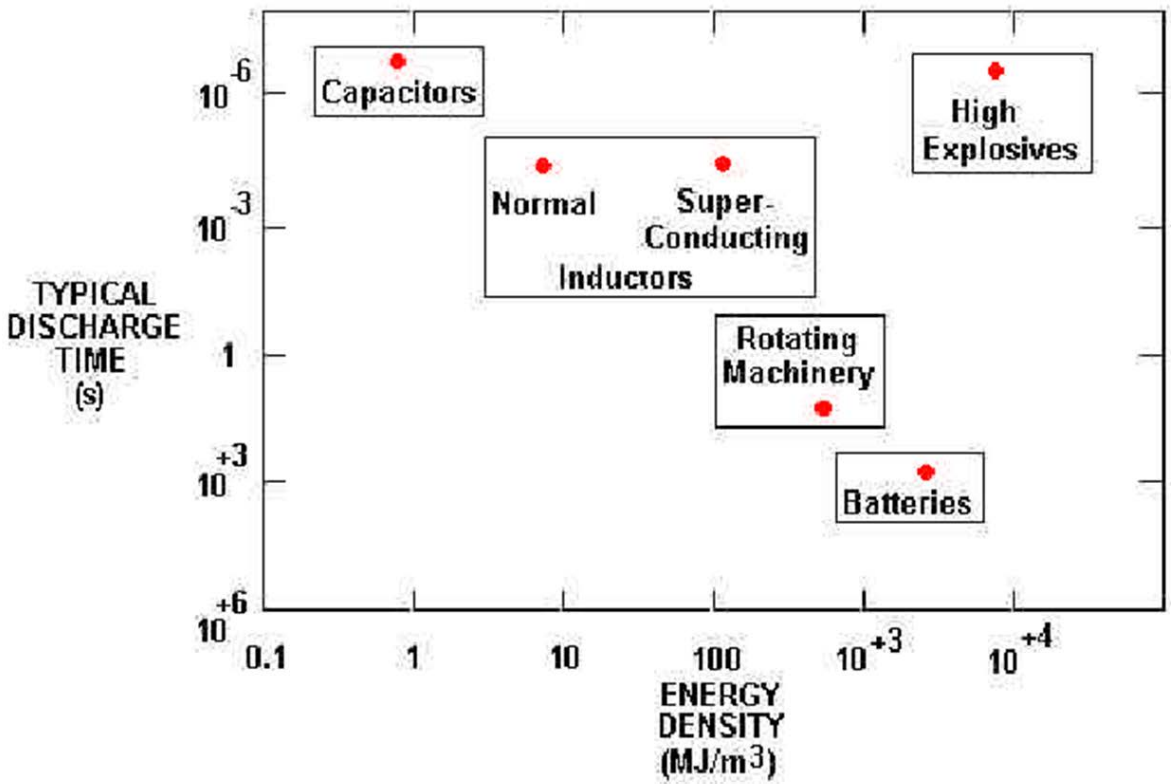


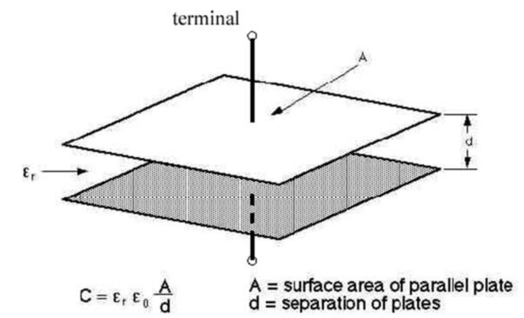
- Requirements of energy storage device for pulsed power application
  - ➢ High energy density
  - ➢ High breakdown strength
  - ➢ High discharge current capability
  - ➢ Long storage time (low rate of energy leakage)
  - ➢ High charging and discharging efficiency
  - ➢ Large power multiplication (ratio of power during charging to power during discharging)
  - ➢ Repetition rate capability and long lifetime
  - ➢ Low specific cost

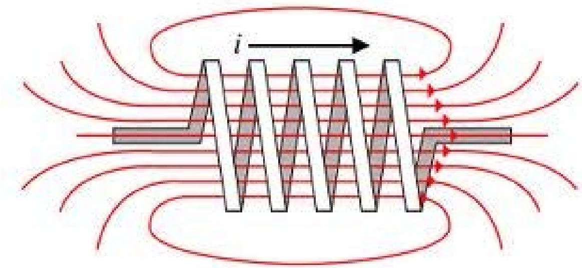
Various energy storage devices



Typical characteristics of energy storage devices







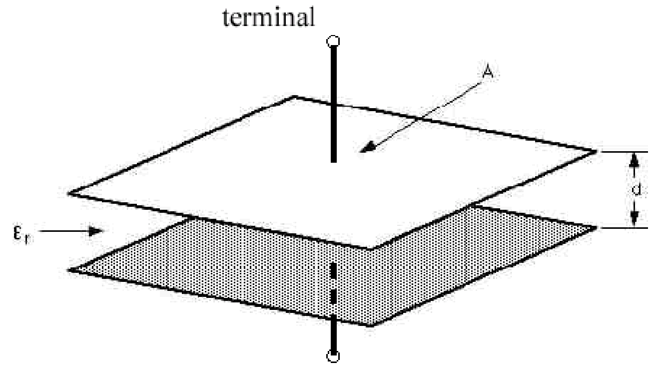
Consider

$$\varepsilon_r \approx 10$$
$$E \approx 10^8 \text{ V/m}$$
$$B \approx 10 \text{ T}$$
$$\mu = \mu_o$$

Then

$$\frac{1}{2}\varepsilon E^2 = 4.4 \times 10^5 \text{ J/m}^3$$
$$\frac{1}{2}\frac{B^2}{\mu_o} \approx 4 \times 10^7 \text{ J/m}^3$$

Energy storage capacitor



$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

A = surface area of parallel plate
d = separation of plates

- High-voltage capacitor

High energy cap (0.3 kJ/kg)

Self healing cap
for laser market

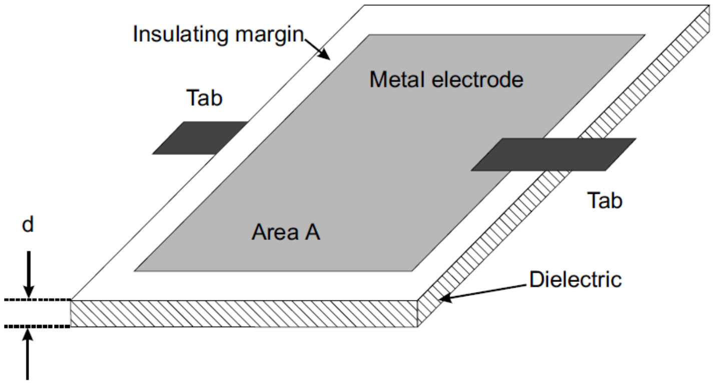
- Supercapacitor (ultracapacitor)

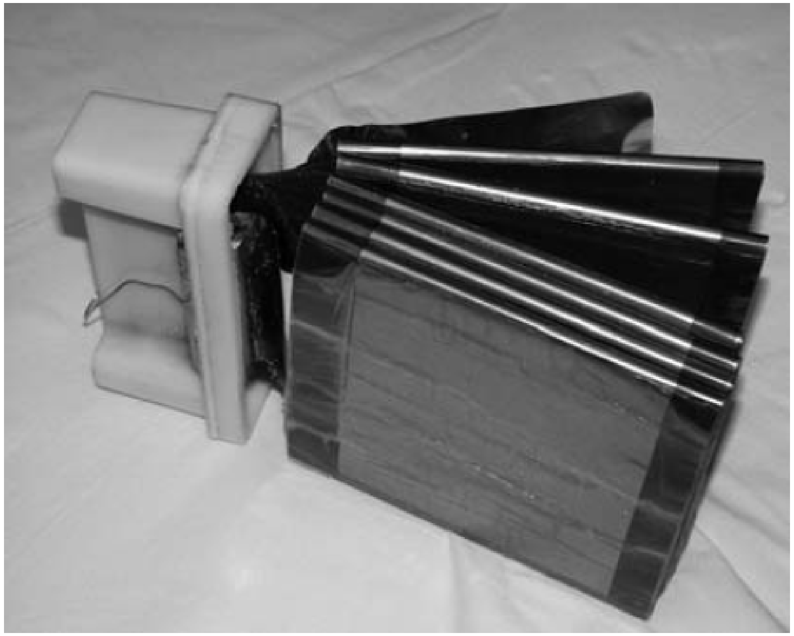
Super caps:

2.3 V, 100 F,
125 A peak current
Size: 35 x 60 x 20 mm
Weight: 35 g
ESR: 15 mOhm
Energy/weight: 7.5 kJ/kg

(Peak electrical output comparable to a Li-Ion battery with ten times the weight.)

Inside a high-voltage capacitor





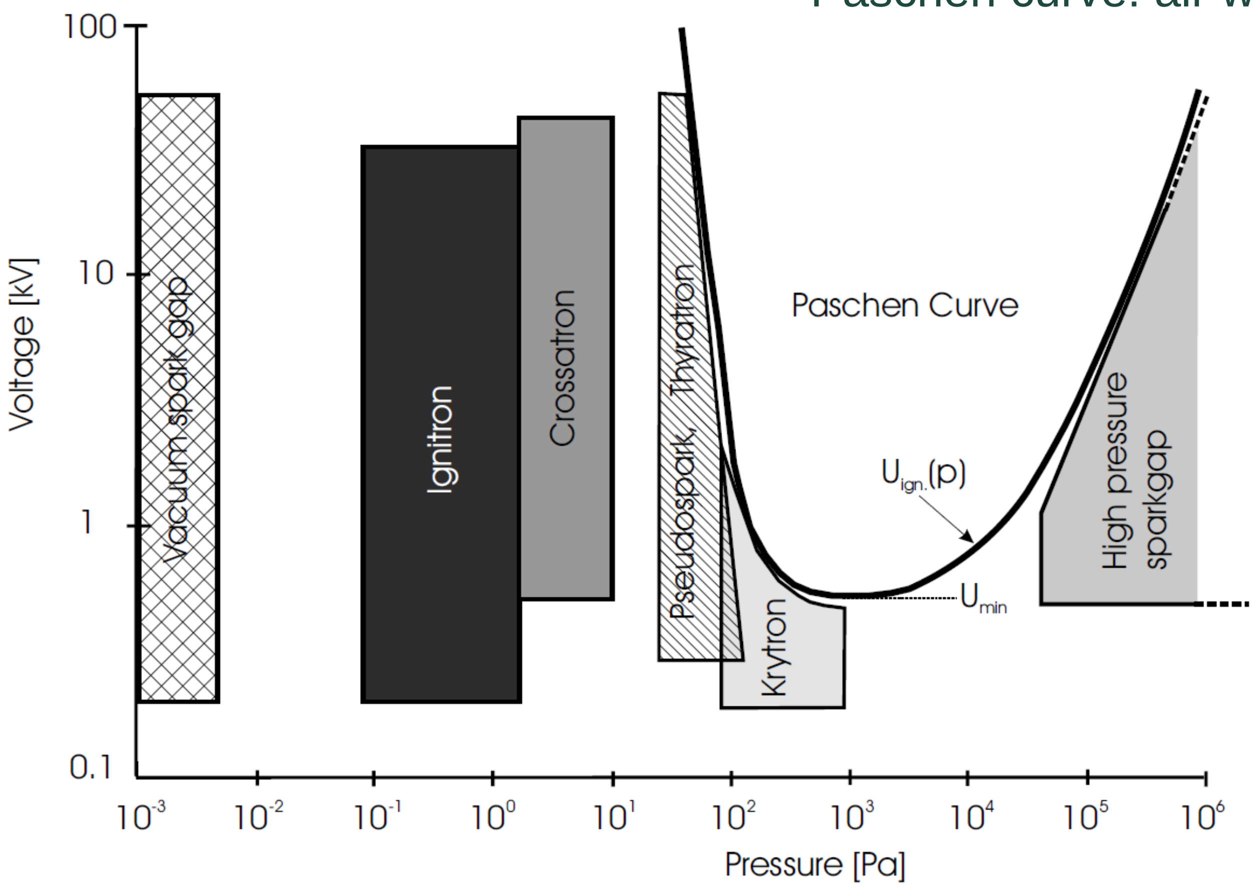
- Dielectric materials

Material	ε	E_{DB} (kV/cm)	tg(δ)
Impregnated paper	3–4	200–800	0.01–0.03
Epoxy	3.5	320	0.014
Mylar	3	400	0.001
Polypropylene	2.55	256	0.0005
Teflon	2.1	216	0.0002
Kapton	3.4	2800 (25 μm)	0.01
Plexiglas	3.3	200	0.009
Transformer oil	3.4	400	0.0002
Aluminiumoxide	8.8	126	0.01
Bariumtitanate	1143	30	0.01
Glass (borosilicate)	4.84	157	0.0036

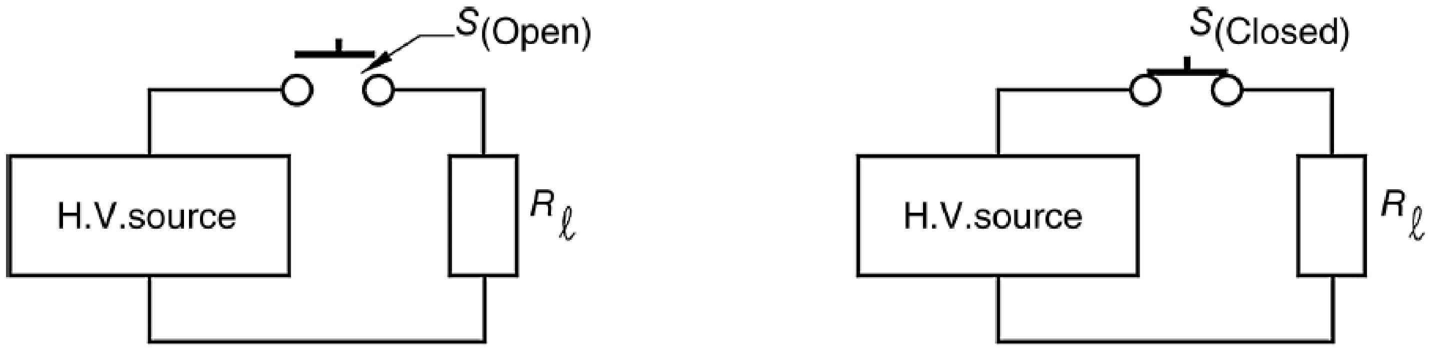
Gas switches are commonly used

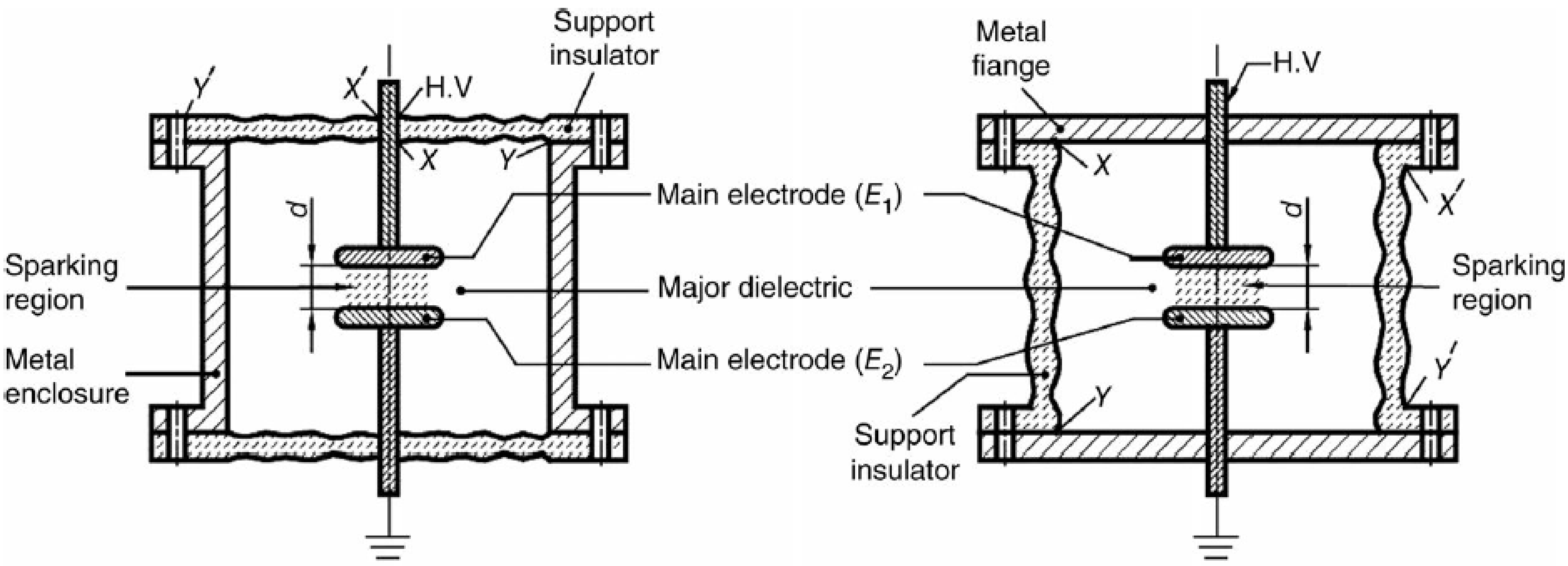
- Range of gas pressures and operating voltages

Paschen curve: air with 3 mm gap



Typical configuration



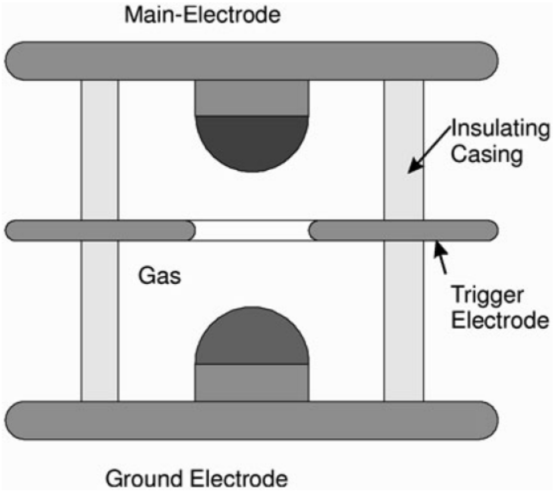


Spark gap switches

- Characteristics of spark gap switches

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

Three-electrode field distortion spark gap



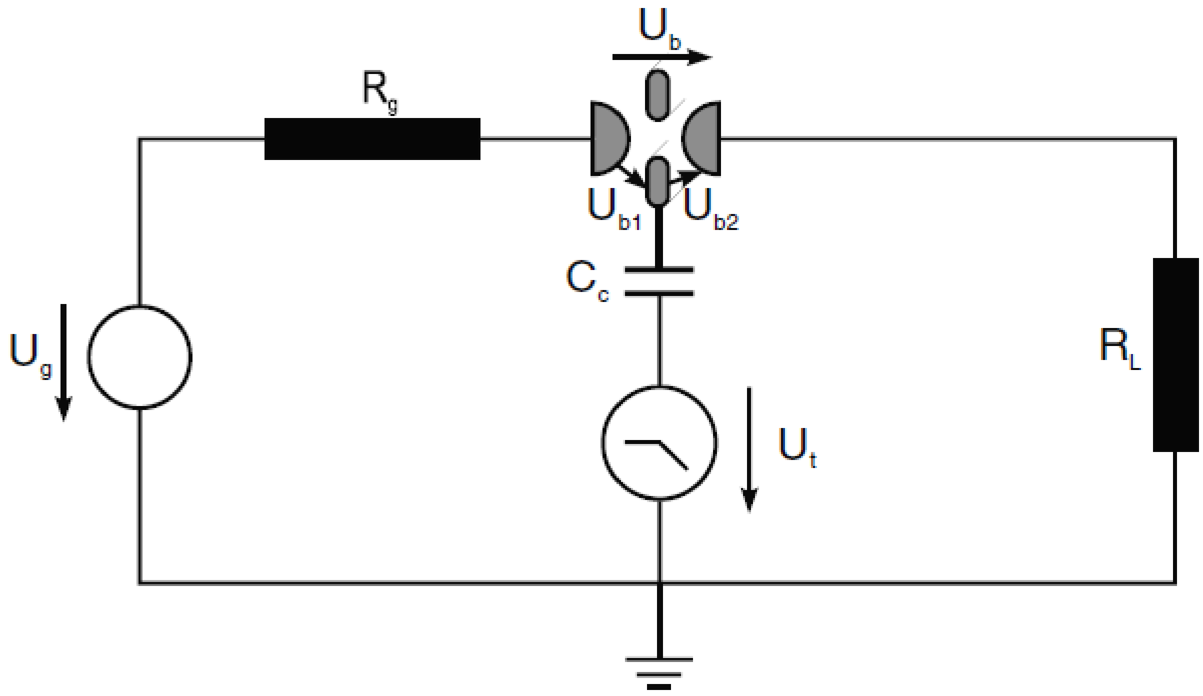
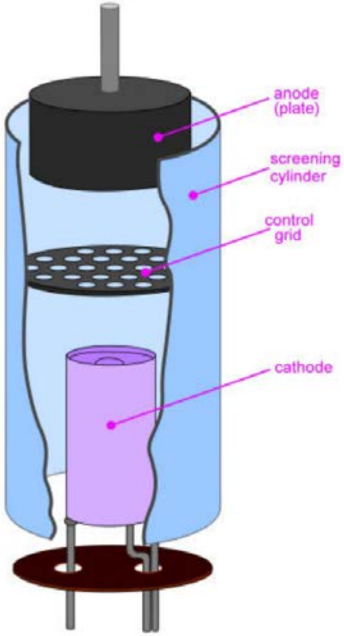


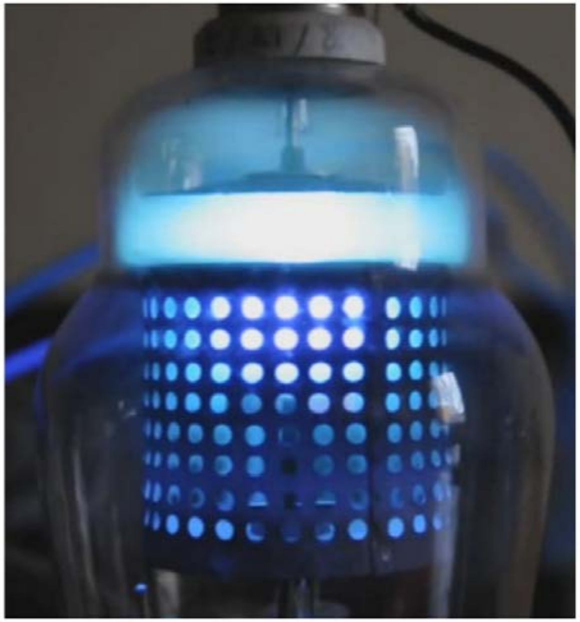
Fig. 4.4. Wiring diagram of a three-electrode spark gap (U_g = generator voltage, U_t = trigger voltage, U_b = breakdown voltage, U_b1, U_b2 = breakdown voltages of the partial gaps, R_g = generator impedance, R_L = load impedance, C_c = coupling capacitor)

Thyratron

- A thyratron is a type of gas filled tube used as a high energy electrical switch and controlled rectifier. Triode, tetrode and pentode variations of the thyratron have been manufactured in the past, though most are of the triode design.
- A thyratron is basically a "controlled gas rectifier". Irving Langmuir and G. S. Meikle of GE are usually cited as the first investigators to study controlled rectification in gas tubes, about 1914.



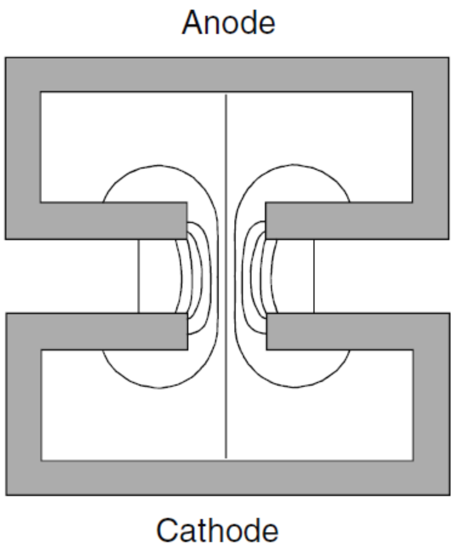
Cut-away view of the electrode arrangement of a thyratron
(there may be a screen-grid above and below the control-grid)

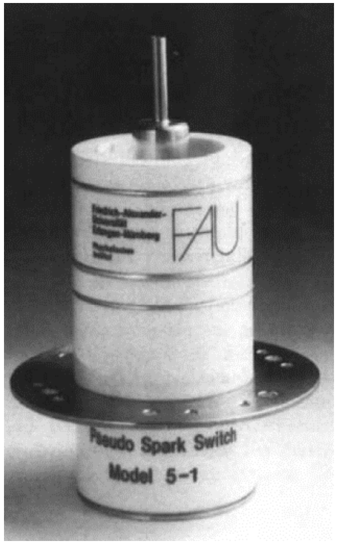


1962 RCA 714/7021 gas-mercury thyratron in action
(1250 V max anode foward & reverse voltage, 1 A average current, 3 A peak current, convection-cooled, 15 cm (6.125") tall, 5 cm (2") diameter)

Pseudospark switch

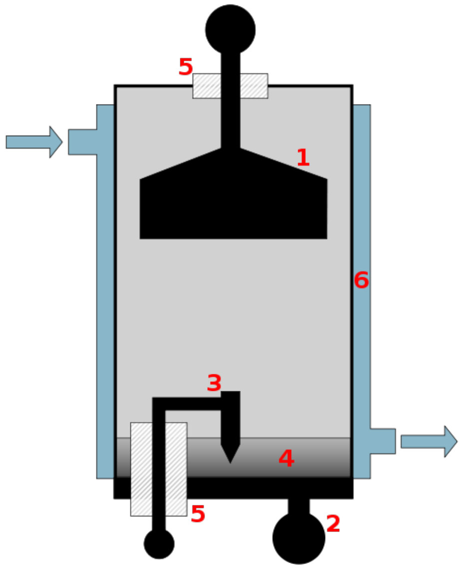
- The pseudospark switch, also known as a cold-cathode thyratron due to the similarities with regular thyratrons, is a gas-filled tube capable of high speed switching.
- Advantages of pseudospark switches include the ability to carry reverse currents (up to 100%), low pulse, high lifetime, and a high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





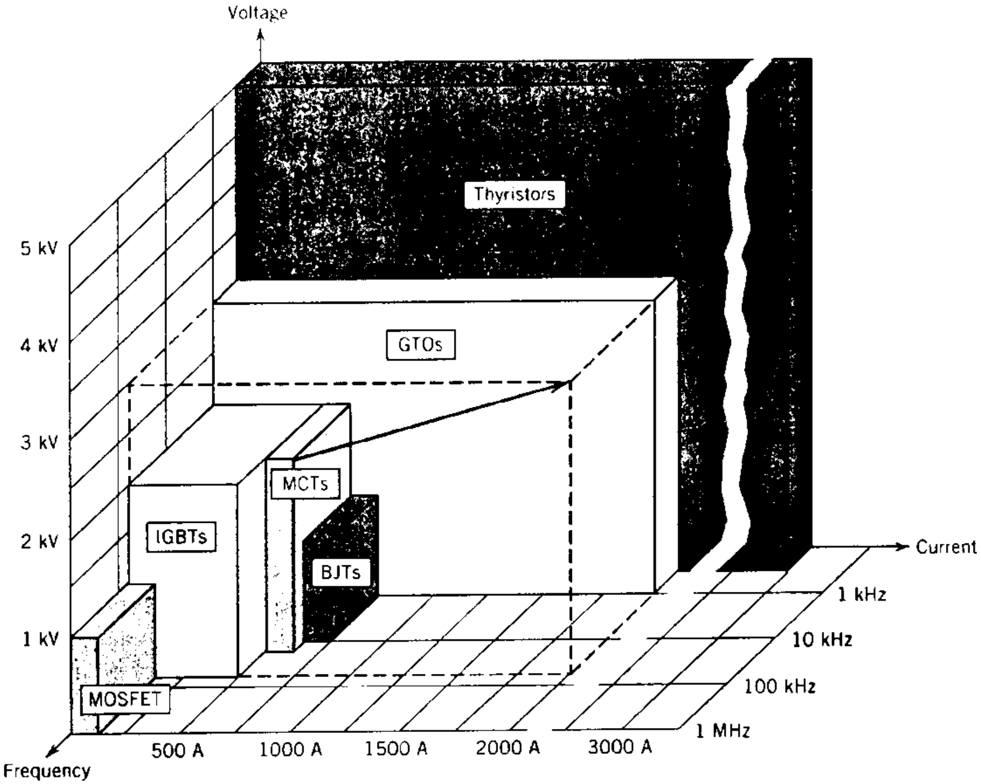
Ignitron switch

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



Solid-state switches

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

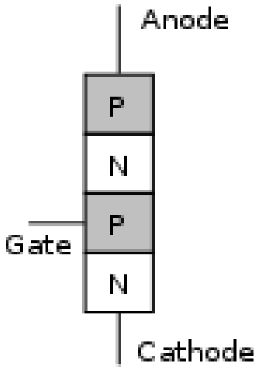


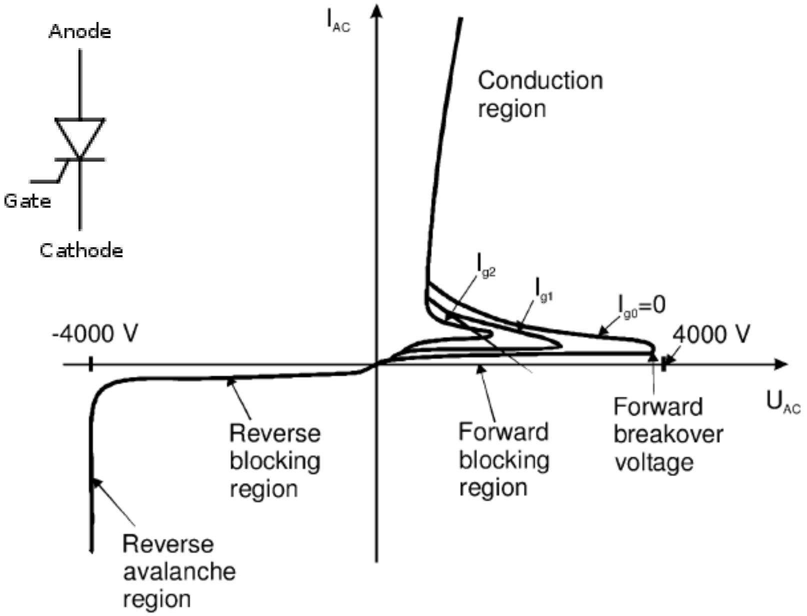
- Power Diode
- BJT (Bipolar Junction Transistor)
- MOSFET (Metal Oxide Semiconductor Field Effect Transistor)
- Thyristor
- GTO (Gate Turn-off Thyristor)
- IGBT (Insulated Gate Bipolar Transistor)

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

Thyristor (SCR, silicon-controlled rectifier)

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





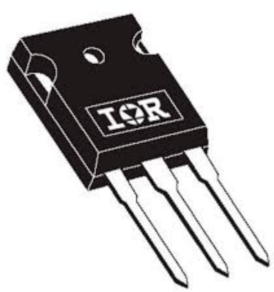
Thyristor for pulsed power (high di/dt)

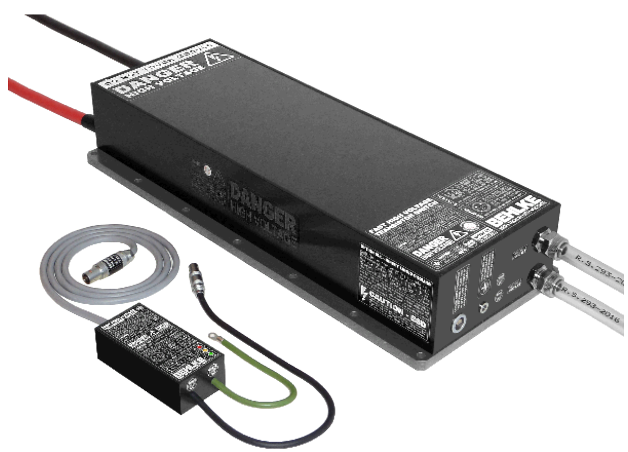
- Laser triggered thyristor
- Gate turn-off (GTO) thyristor

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

IGBT and MOSFET

- The insulated-gate bipolar transistor (IGBT) combines the advantages of bipolar transistors (low resistance in the switch-on state) with those of field effect transistors (loss-free gate control).
- The metal–oxide–semiconductor field-effect transistor (MOSFET) is a type of field-effect transistor (FET), most commonly fabricated by the controlled oxidation of silicon. It has an insulated gate, whose voltage determines the conductivity of the device.

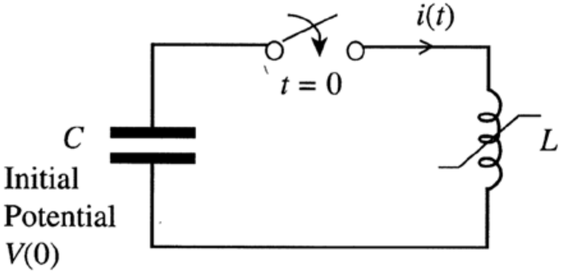




https://www.behlke.com/

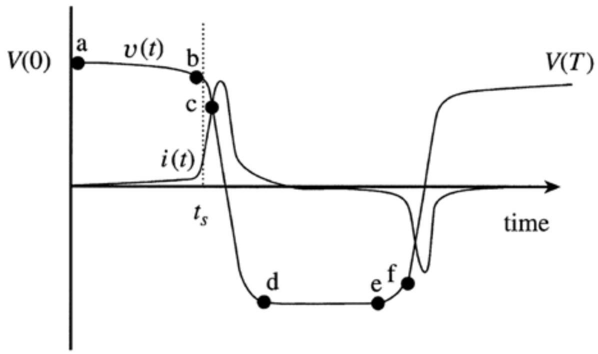
Magnetic switch

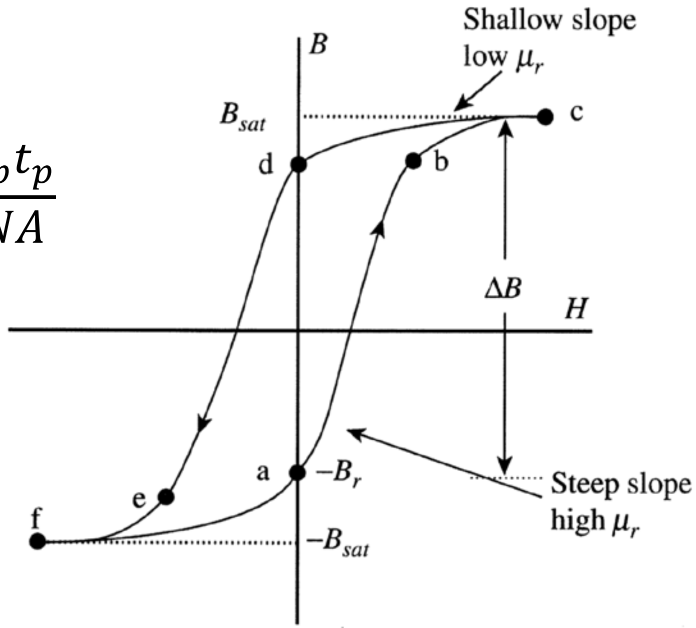
- Melville (1951) exploits the use of the nonlinearity of inductors to achieve fast switching in pulse generators.
- The basic concept is to drive sufficient current through a winding on a magnetic core such that the applied field H produces a flux density B in the core in excess of the core's saturation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



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

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





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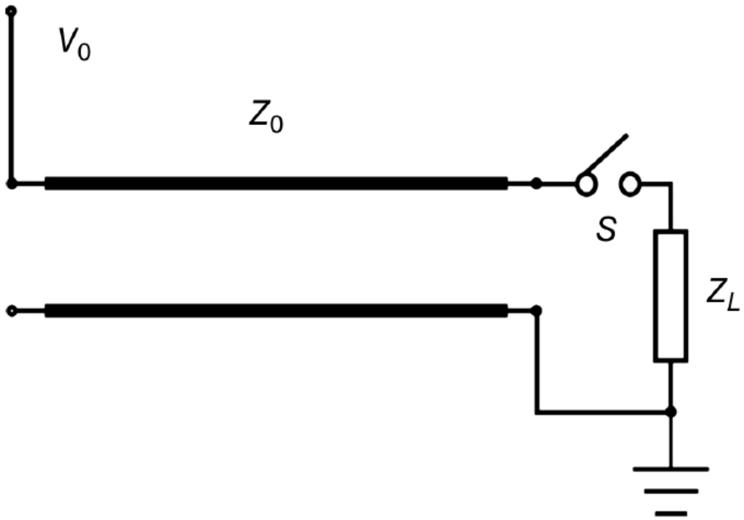
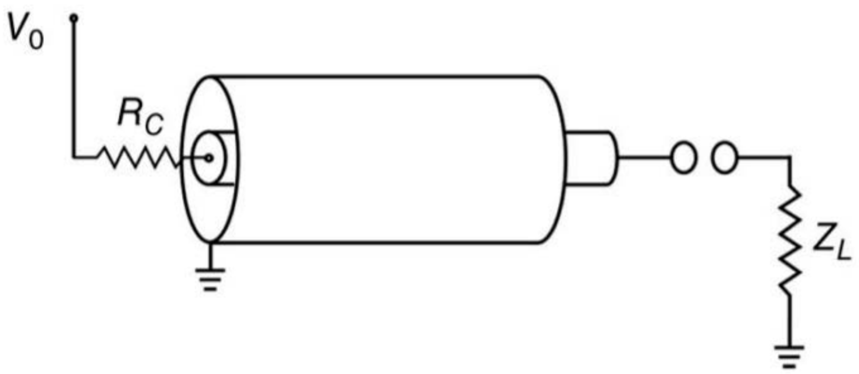
Summary of closing switches

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

Pulse forming line (PFL)

- There are numerous applications in both physics and electrical engineering for short ($\sim 10\ ns < t_p < 100\ \mu s$) electrical pulses. These applications often require that the pulses have a "good" square shape.
- Although there are many ways for generating such pulses, the pulse-forming line (PFL) is one of the simplest techniques and can be used even at extremely high pulsed power levels.
- A transmission line of any geometry of length l and characteristic impedance Z_0 makes a pulse forming line (PFL), which when combined with a closing switch S makes the simple transmission line pulser.



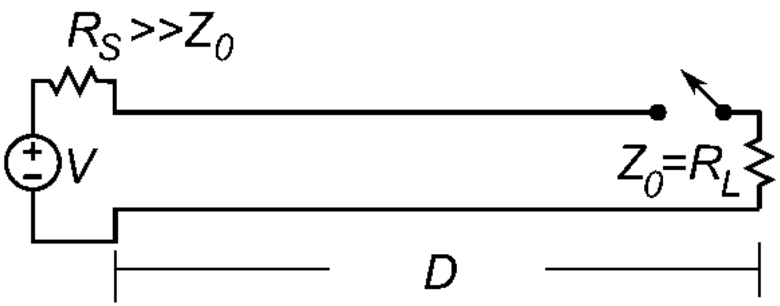


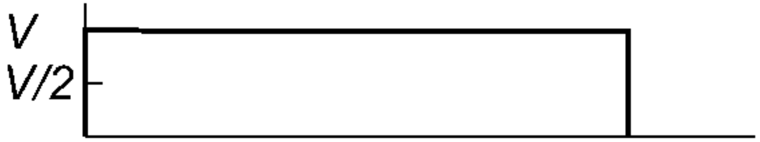
Simple PFL

- When the switch closes, the incident wave V_I, with a peak voltage of $(1/2)V_0$, travels toward the load, while the reverse-going wave V_R, also with a peak voltage of $(1/2)V_0$, travels in the opposite direction.
- The incident wave V_I, then, supplies a voltage of $(1/2)V_0$ for a time determined by the electrical length of the transmission line T_T to the load. The reverse-going wave V_R travels along the transmission line for a duration T_T and then reflects from the high impedance of the voltage source, and becomes a forward-going wave traveling toward the load with peak voltage $(1/2)V_0$ and duration T_T.
- The two waves add at the load to produce a pulse of amplitude $(1/2)V_0$ and pulse duration $T_p = 2T_T$.
- Matching condition: $R_L = Z_0$
- Pulse characteristics

$$V = \frac{V_0}{2}$$

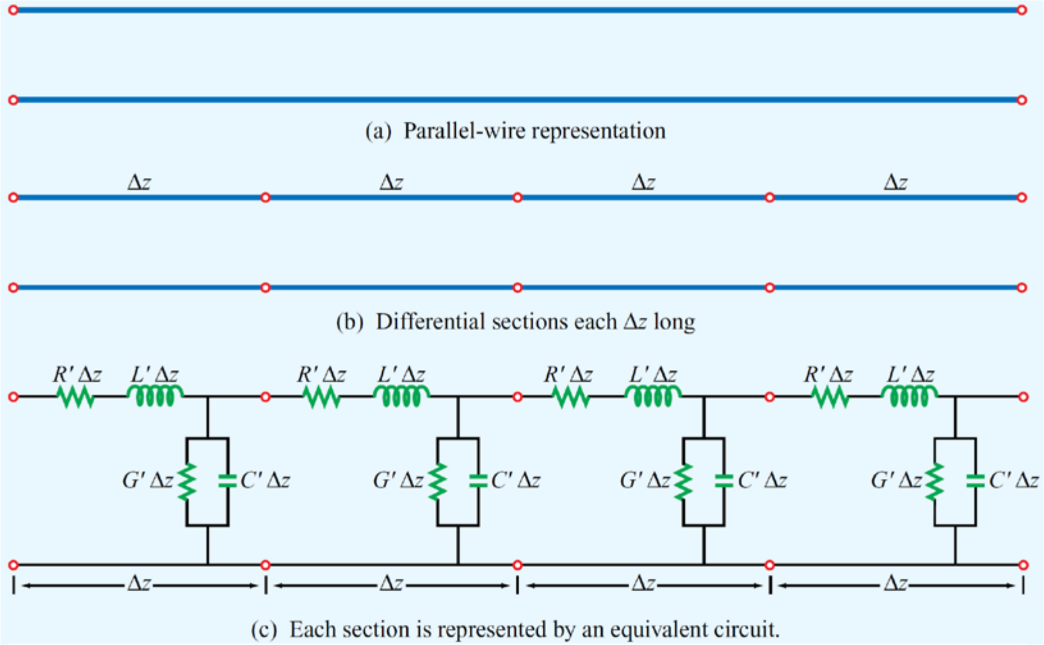
$$T_p = 2T_T = \frac{2l}{v_p} \approx \frac{2l}{c}\sqrt{\epsilon_r}$$



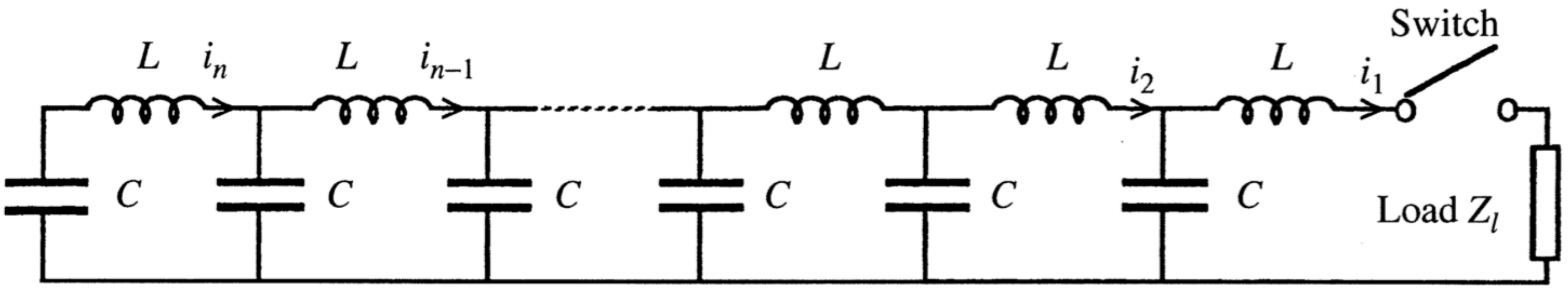


Pulse forming network (PFN)

- A main disadvantage of the PFL is the speed of propagation of EM waves along transmission lines.
- The material used in transmission lines is some type of polymer plastic such as polypropylene, and the dielectric constant tends to be quite low ($\epsilon_r = 2\sim 3$). Thus, it is impractical for making a long pulse over $1\ \mu s$.
- An alternative approach is to build a simulated line using a ladder network of inductors and capacitors.



Basic LC PFN

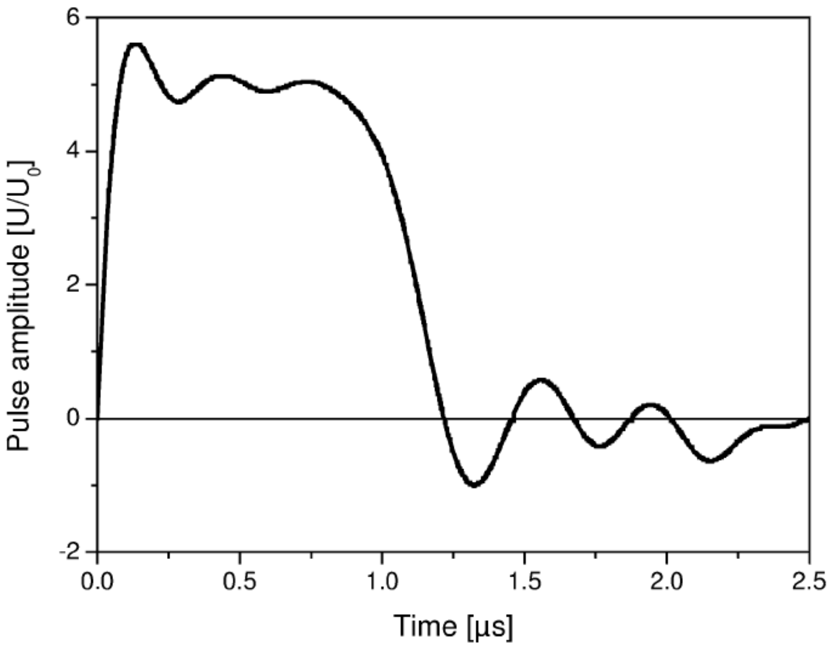


- Approximately, for $n > 10$

$$Z_N = \sqrt{\frac{L_N}{C_N}} = \sqrt{\frac{L}{C}}$$

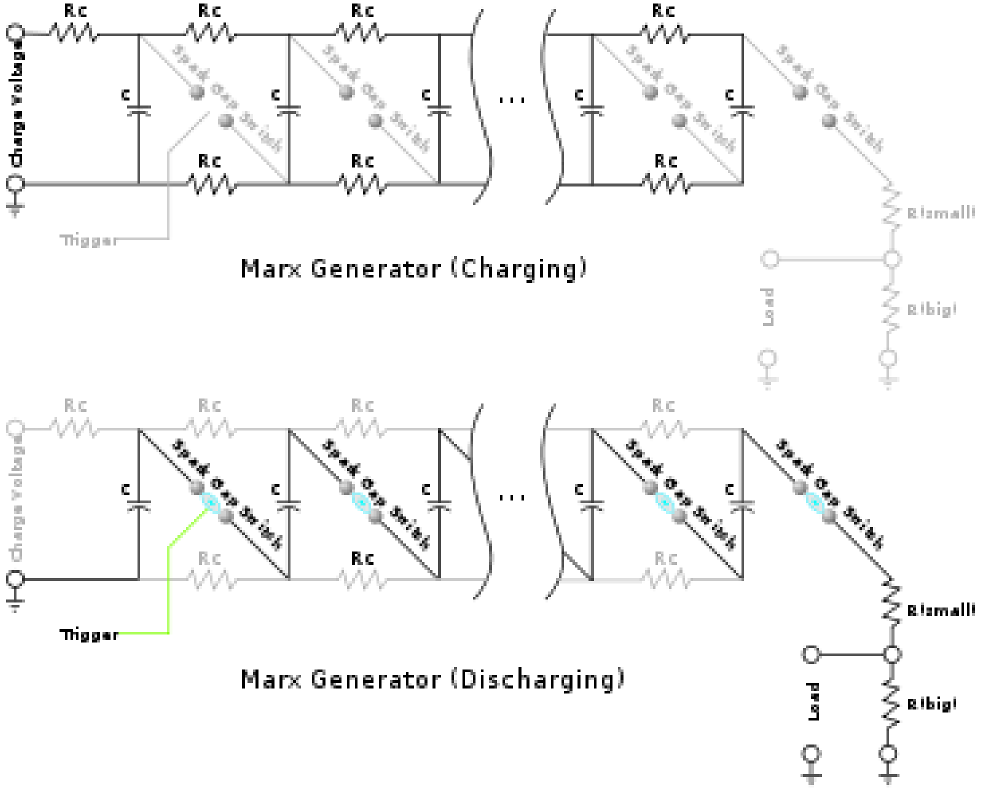
$$t_p = 2\delta = 2\sqrt{L_N C_N} = 2n\sqrt{LC}$$

Waveform of 5-element LC PFN



Marx generator (1925)

- A Marx generator is a voltage-multiplying circuit that charges a number of capacitors in parallel and discharges them in series.
- The process of transforming from a parallel circuit to a series one is known as "erecting the Marx."



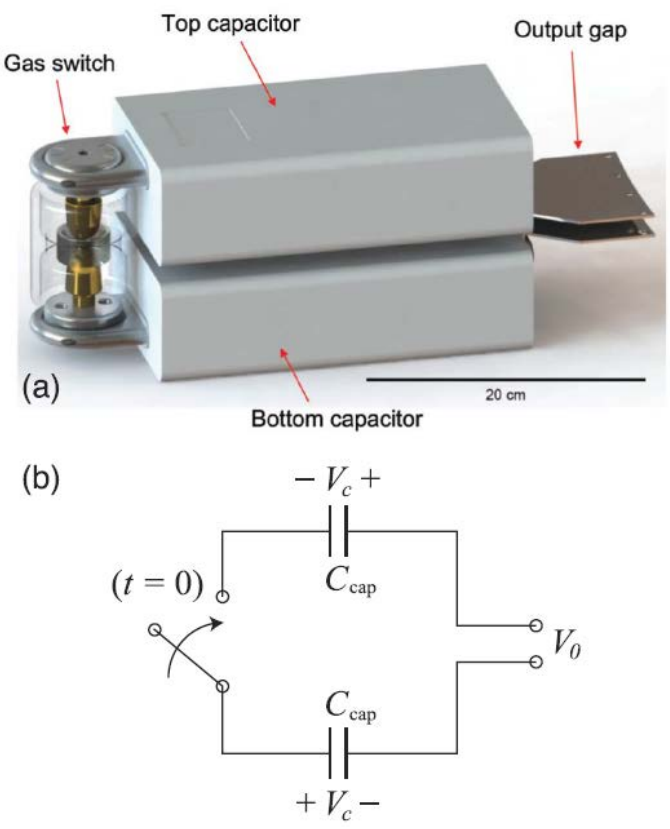
$$V_M = NV_0$$

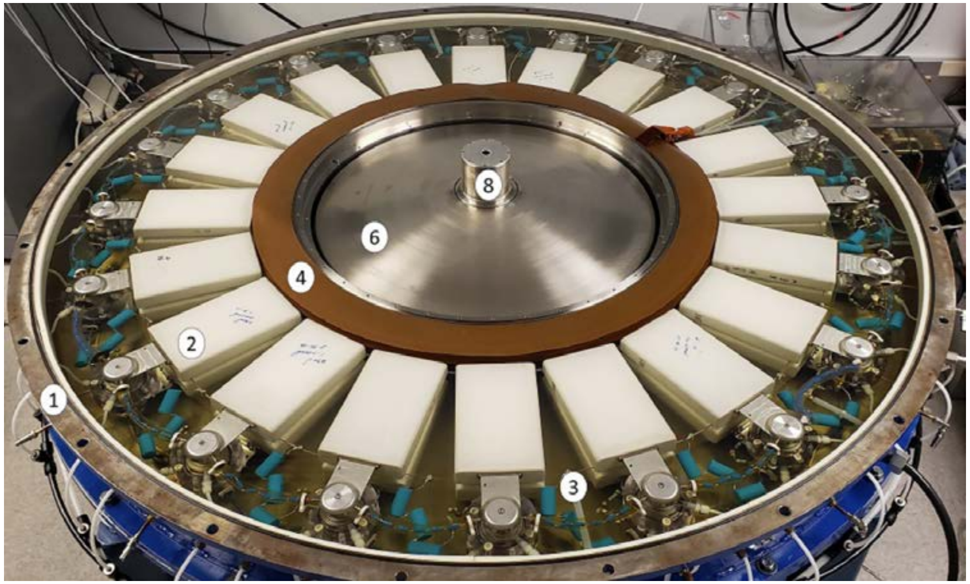
$$C_M = C_0/N$$

- What is a role of resistors?
  - Current limiting
  - Ground path
  - Isolation during discharge
  - Could be replaced with inductors

Linear Transformer Driver (1997)

- The linear transformer driver (LTD) was introduced in 1997 as a fast, high current circuit architecture inspired by linear pulse transformers. LTDs use low-inductance, capacitive energy storage circuits (known as bricks) arranged in parallel to produce a high-peak current directly from the primary energy store.





Applications of pulsed power

- High Energy Density Plasma
  - Nuclear fusion plasma, X-ray generation, Pinch plasma
- High Power Pulse Laser
  - Solid state laser (Nd:YAG), Gas laser (Excimer, CO_2, Nitrogen)
- Particle Beam Generation & Application
  - Electron (Ion) acceleration, Material processing, Surface treatment
- Electromagnetic Acceleration
  - Rail gun (EM gun), Electrothermal chemical gun (ETC gun), Electromagnetic Forming
- Electromagnetic Wave Generation
  - High power microwave (HPM), Electromagnetic pulse (EMP)

Applications of pulsed power

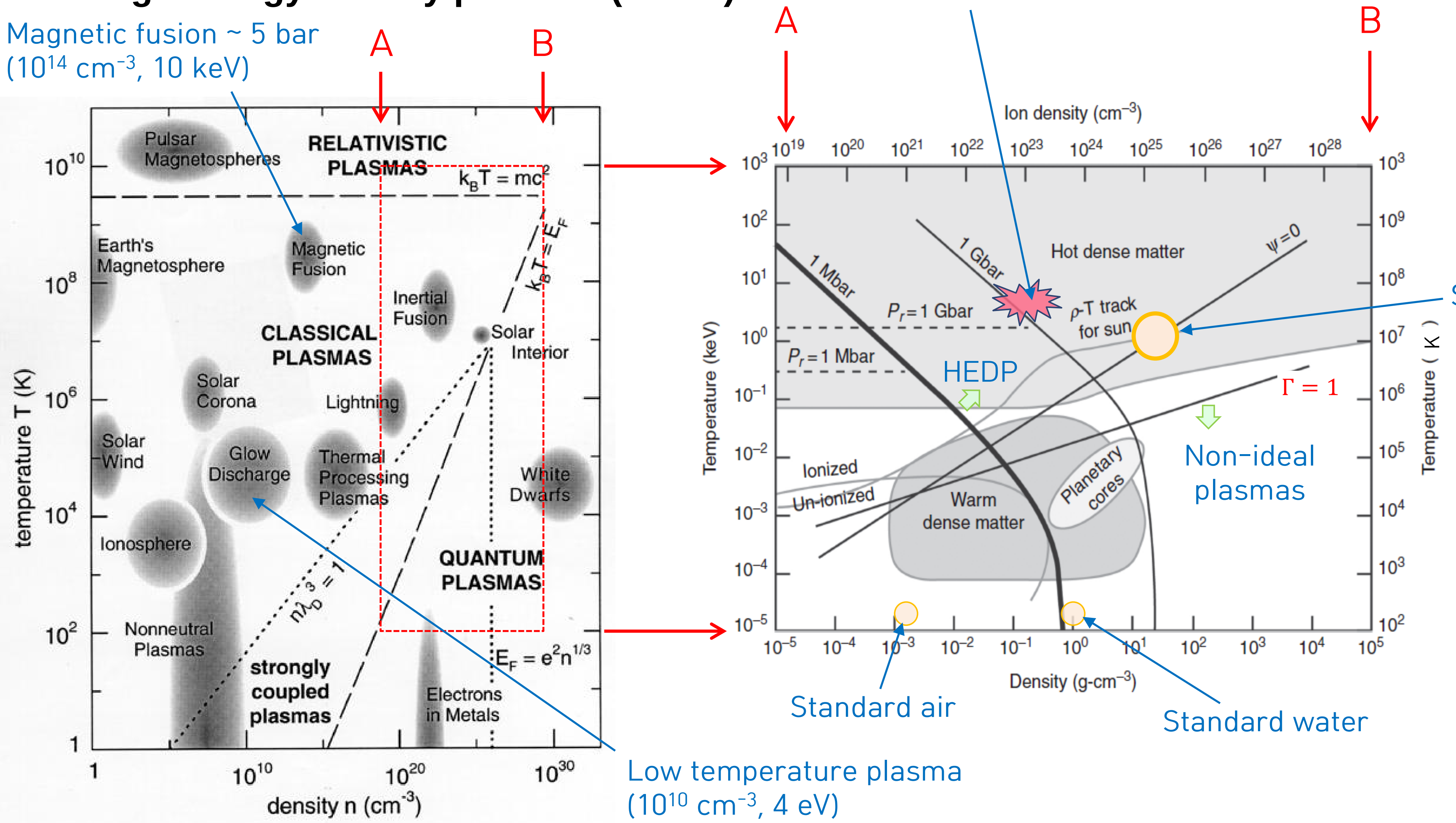
- Industrial applications
  - Metal shaping (complex geometries)
  - Nano-sized particle fabrication
  - Rock blasting (at construction site)
  - Exhaust gas treatment
  - Thermal power plant (electric dust collector)
  - Waste water treatment (organic matter decomposition)
  - Ballast water treatment

Examples of pulsed power

- **Lightning vs Pikachu**

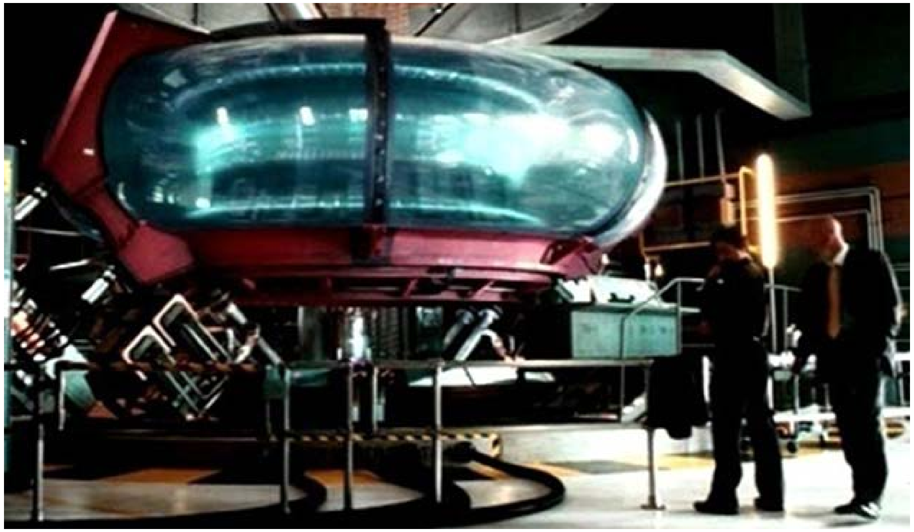
Examples of pulsed power

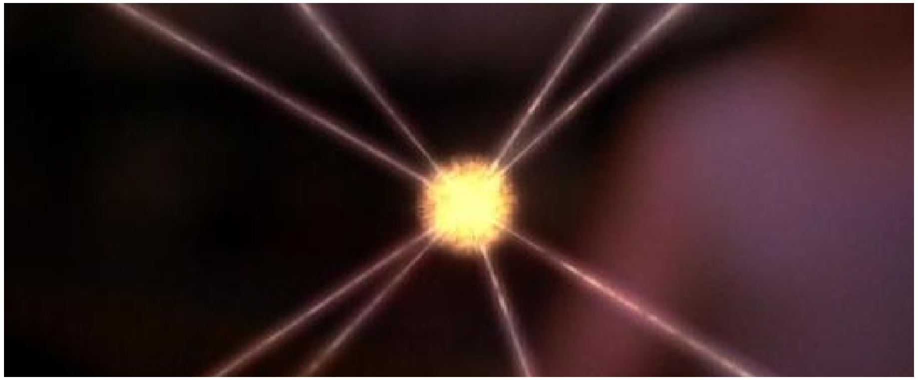
- **High energy density plasmas (HEDP)**



Examples of pulsed power

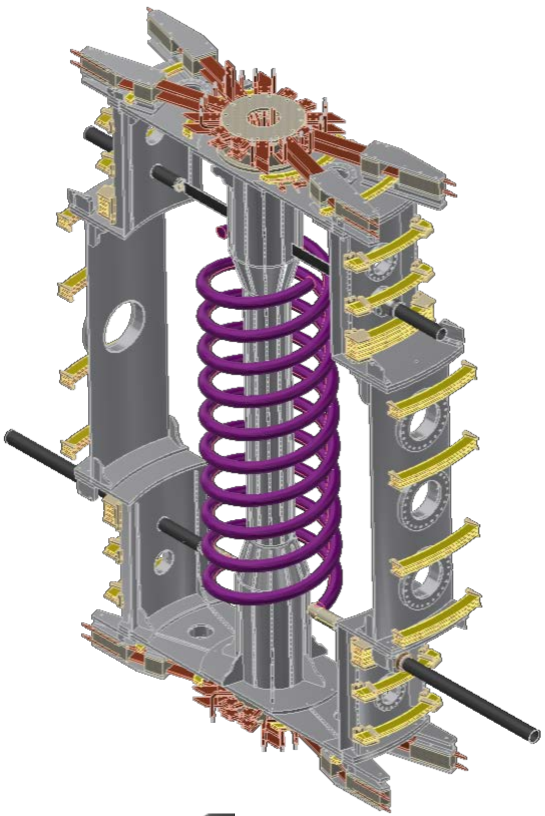
- **Fusion (MCF vs. ICF)**



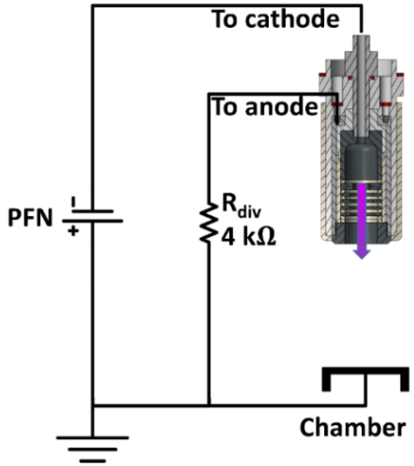


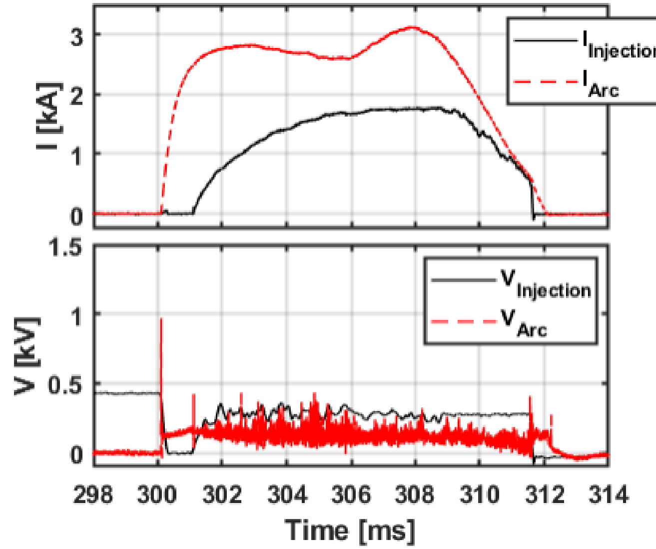
Examples of pulsed power

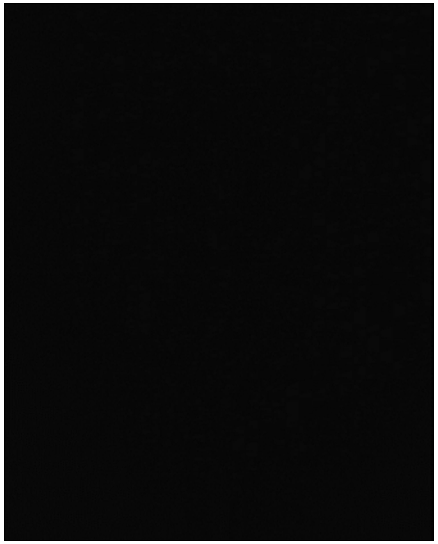
- **Helicity injection system for VEST**

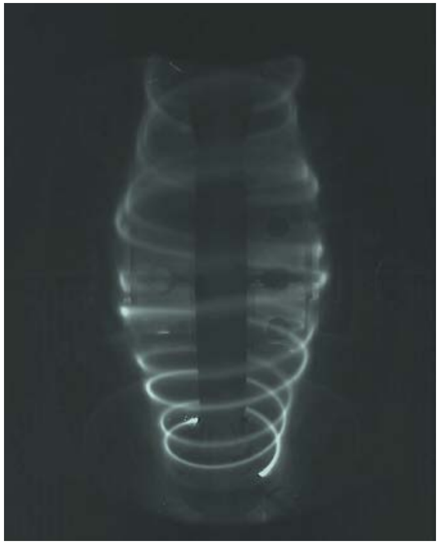


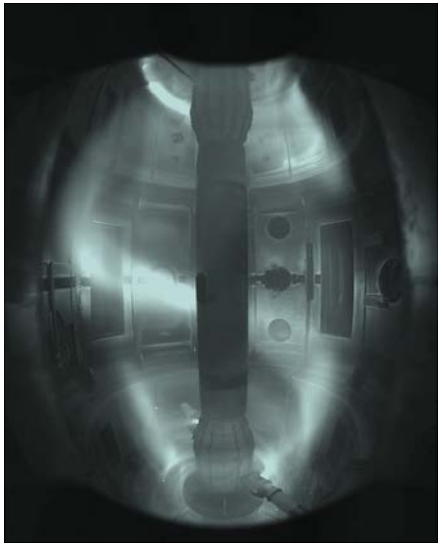
Washer gun





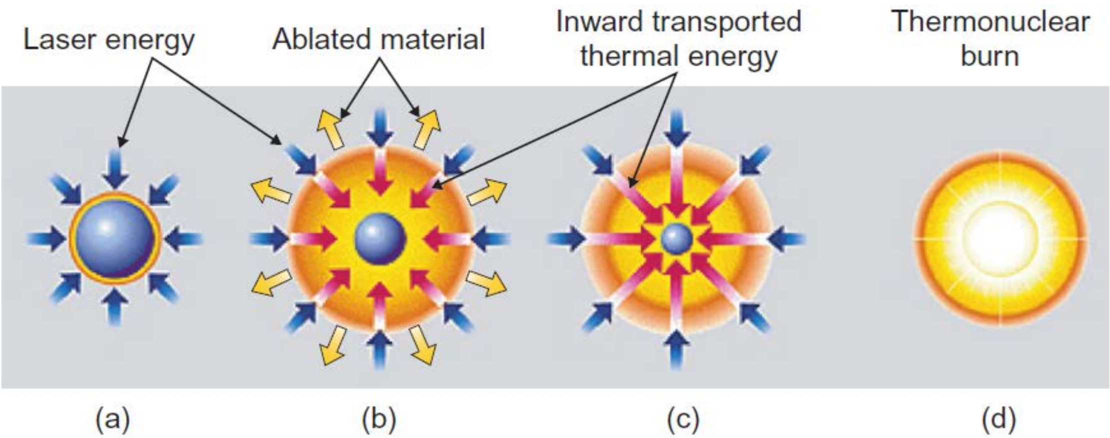


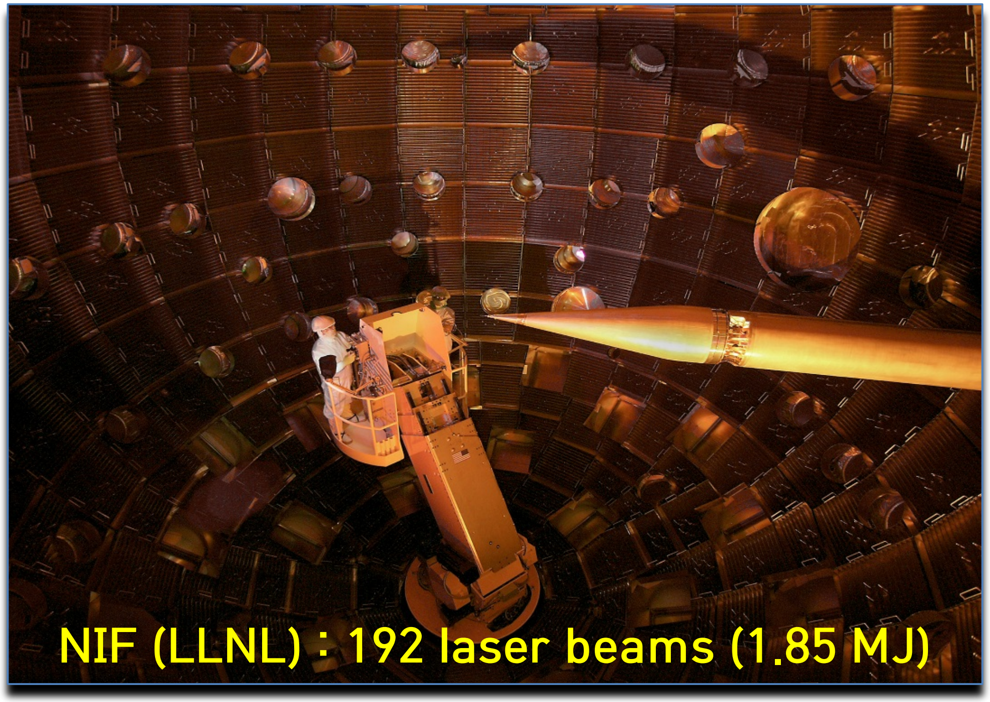




Examples of pulsed power

- **Laser fusion**



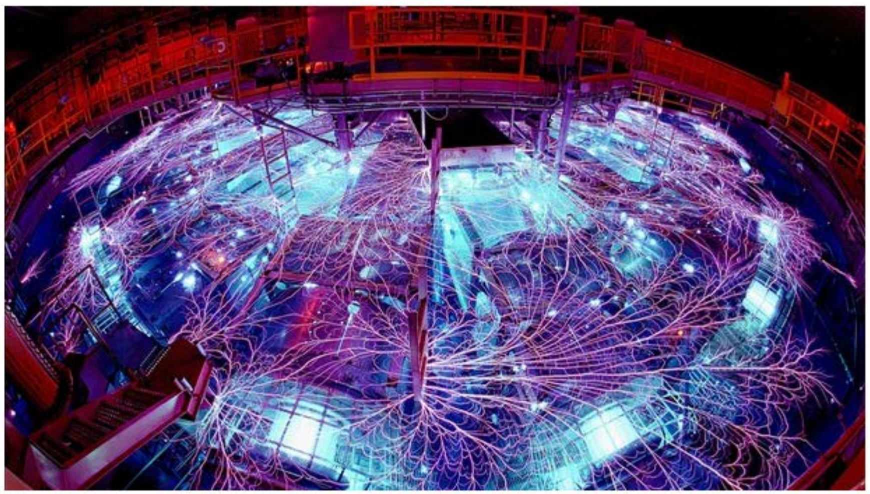


Examples of pulsed power

- **Z pinch**

Monster x-ray machine blasts apart black hole theory

Michael Franco | August 31st, 2017



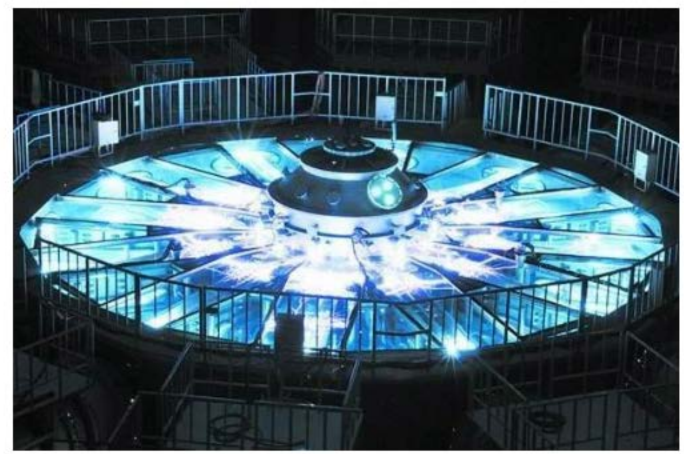
The Z machine at Sandia National Laboratories creates tremendous bursts of energy using less power than it would take to light 100 homes for a few minutes (Credit: Randy Montoya/Sandia Labs, CC2.0)

Z-machine (SNL) : 직경 33m (26 MA)

中國科學院 CHINESE ACADEMY OF SCIENCES Contact Sitema

China Makes Breakthrough in 'Man-made Sun' Research

Mar 17, 2016

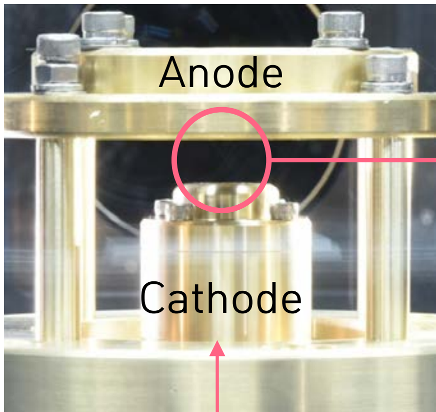


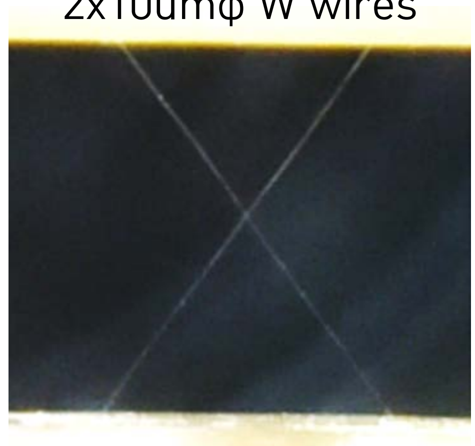
PTS experimental device discharges instantly. [File Photo]

PTS (CAEP) : 직경 33m (10 MA)

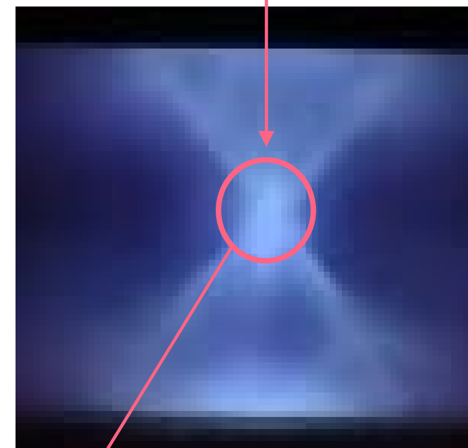
Examples of pulsed power

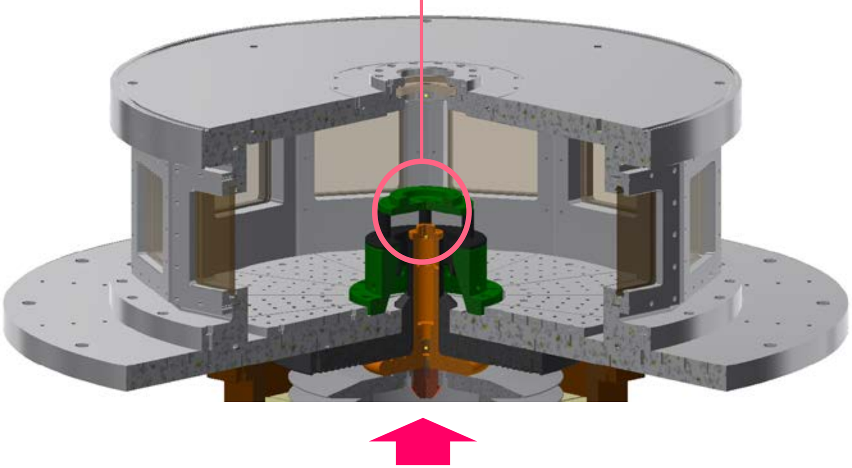
- **SNU X-pinch device**



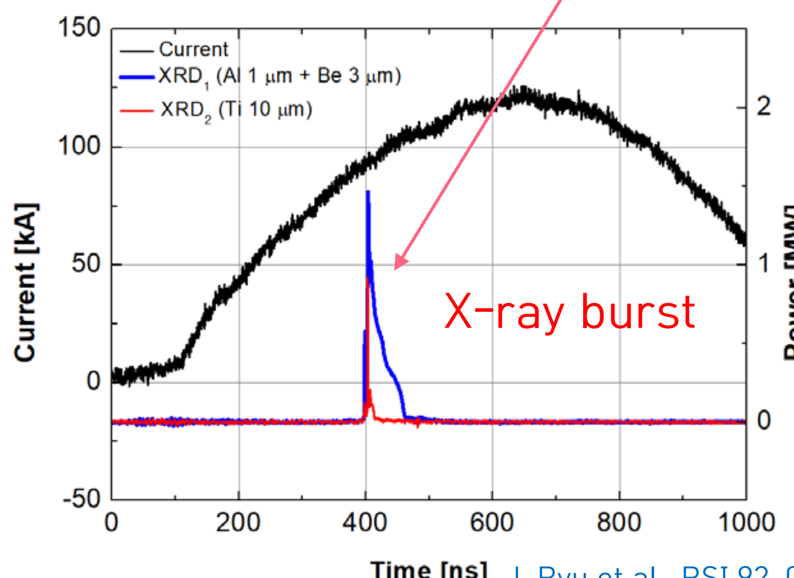


Hot spot





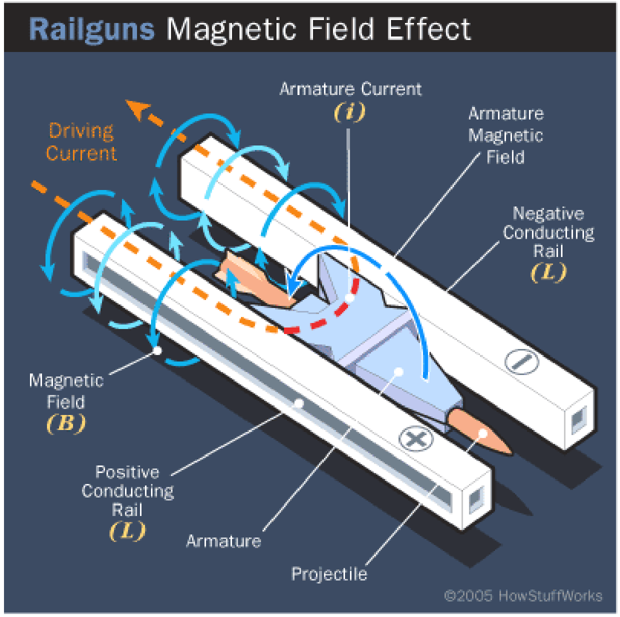
High current from pulsed power system



J. Ryu et al., RSI 92, 053533 (2021)

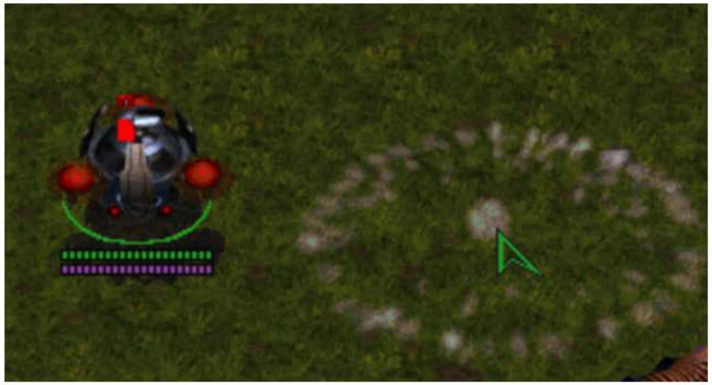
Examples of pulsed power

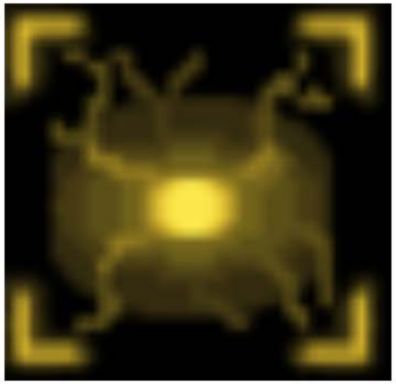
- **Railgun**

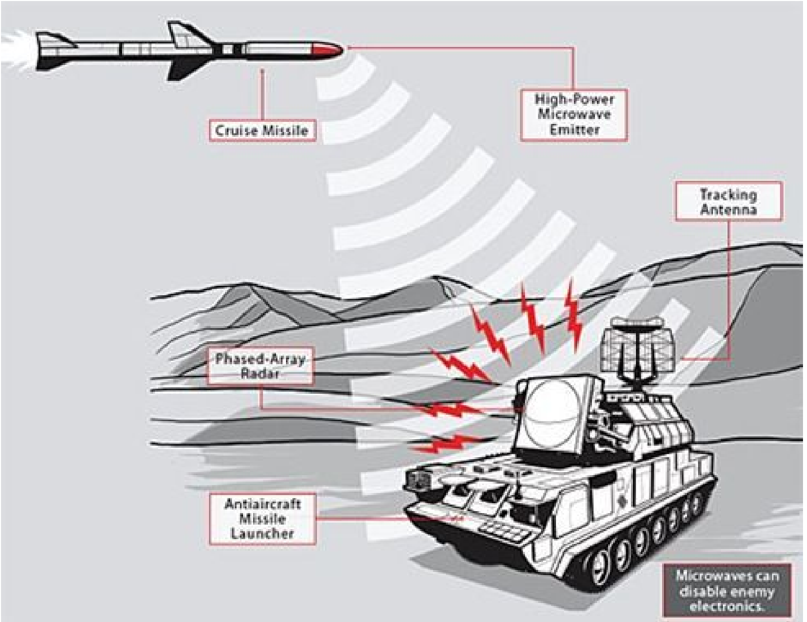


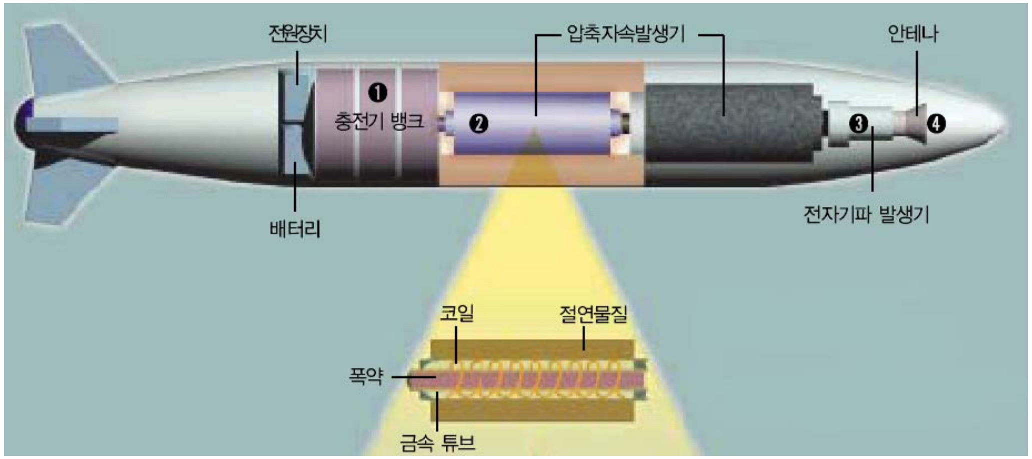
Examples of pulsed power

- **High Power Microwave or EMP**



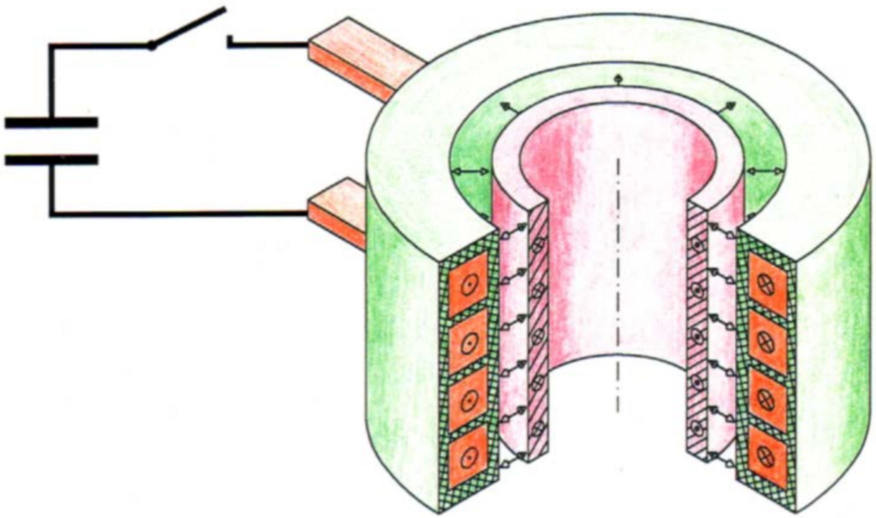






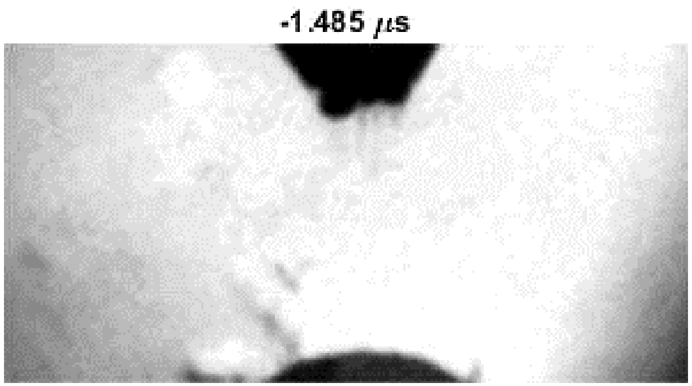
Examples of pulsed power

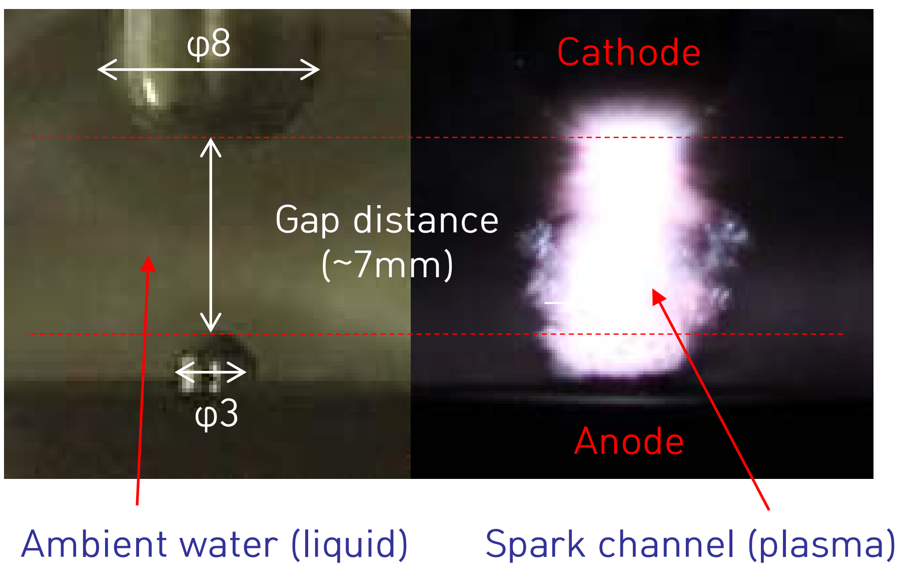
- **EM forming**

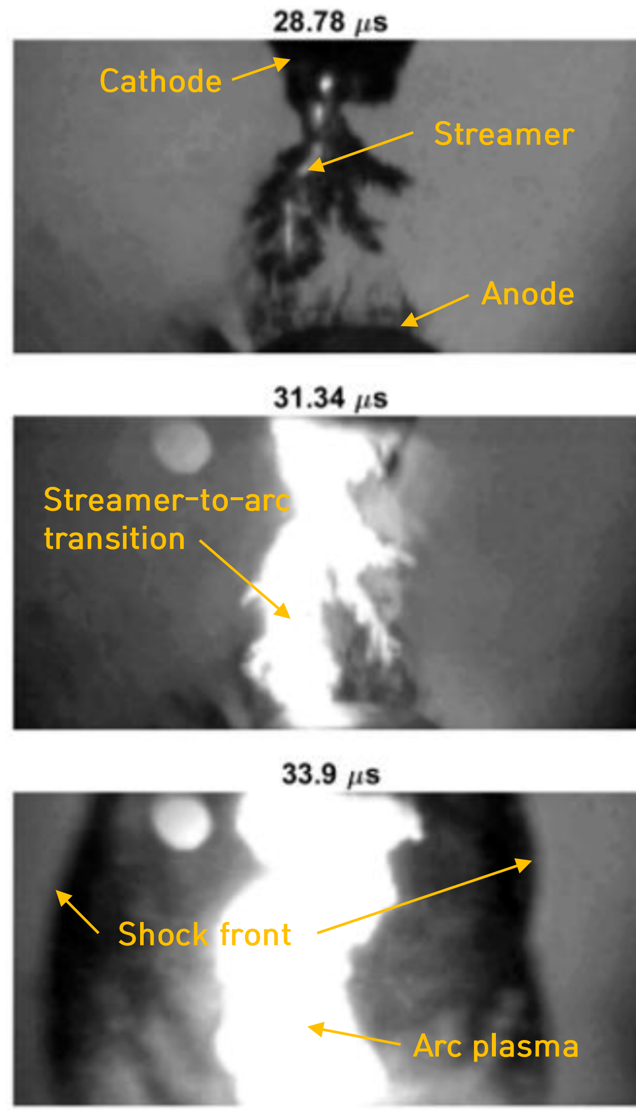


Examples of pulsed power

- **Underwater shock wave generation**

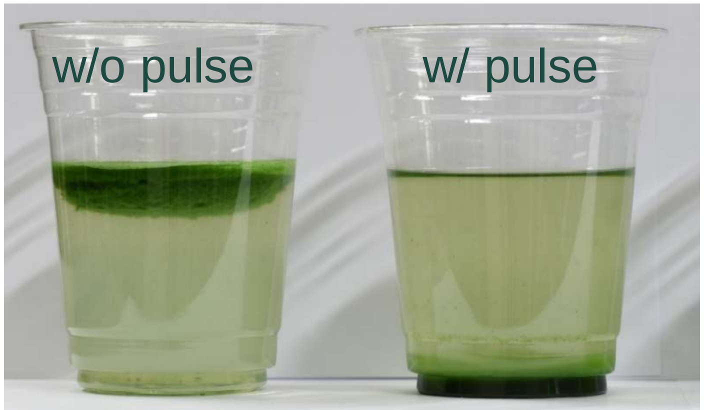


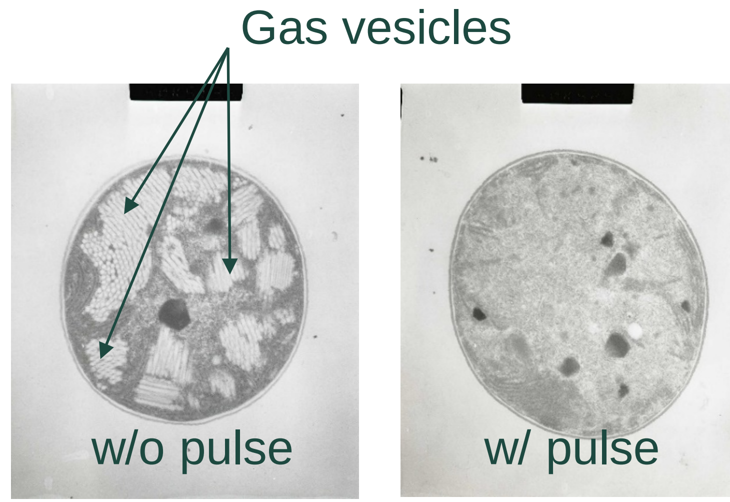




Examples of pulsed power

- **Water-bloom removal**

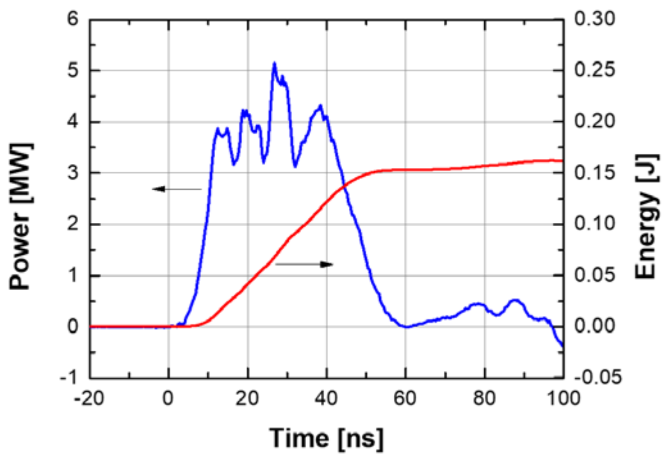


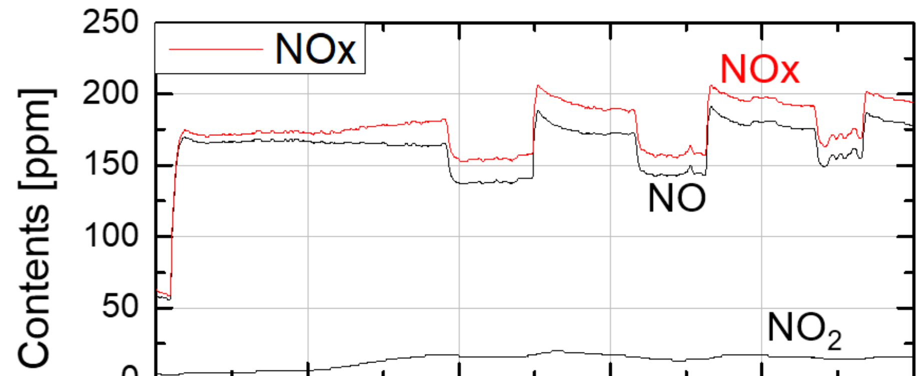


→ Shock wave destroys gas vesicles to sink the water-bloom down to the bottom

- **NOx removal**

40 kV, 4 MW, 0.15 J/pulse, 100 Hz
→ 20% reduction of NOx with 15 W

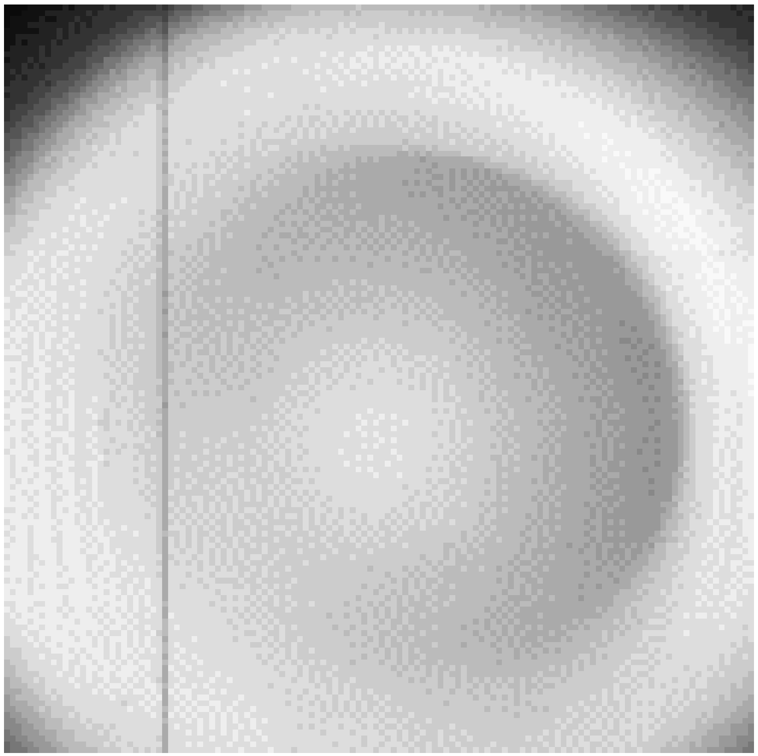


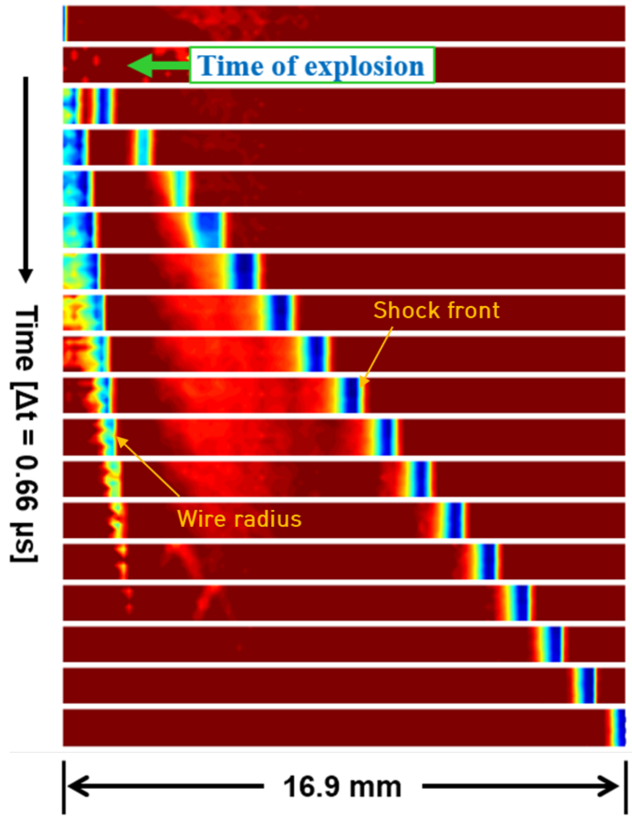


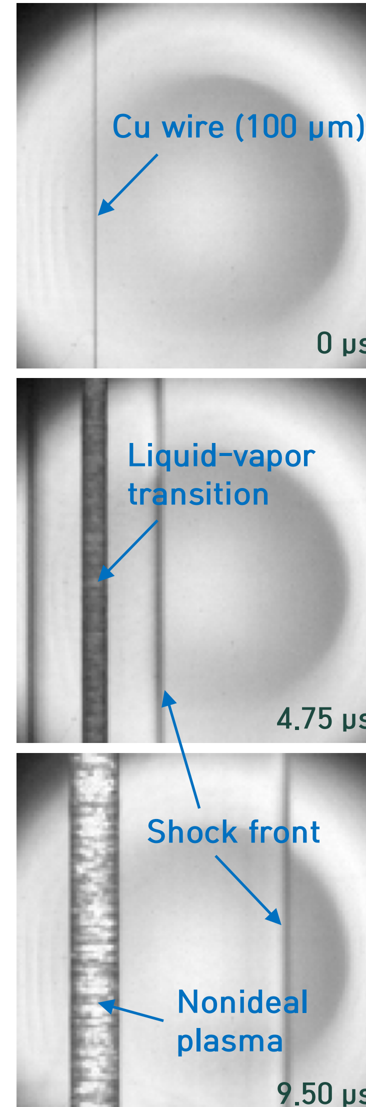
Examples of pulsed power

- **Non-ideal plasma research**

Cu wire : ϕ 100 μm @ V_c = 10 kV







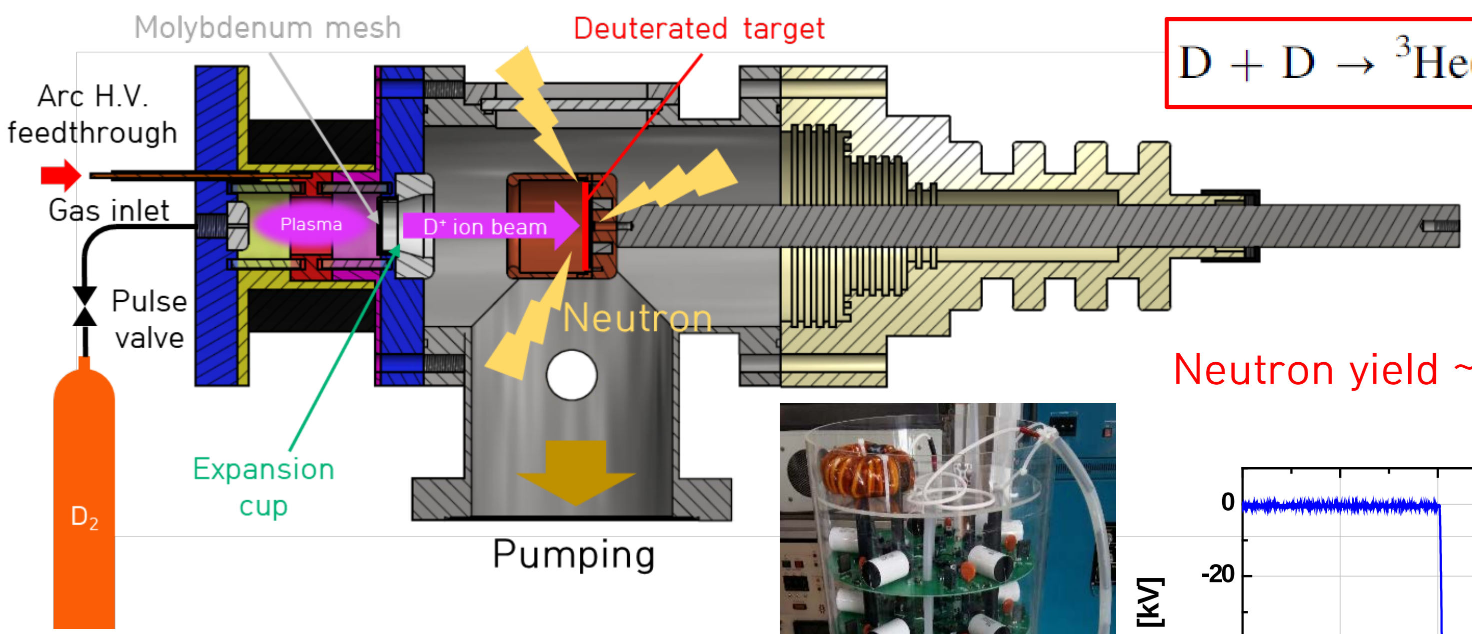
Recording = 21,052 fps
Frame interval = 4.75 μs
Exposure = 0.31 μs

K. J. Chung et al., J. Appl. Phys. 120, 203301 (2016)

Examples of pulsed power

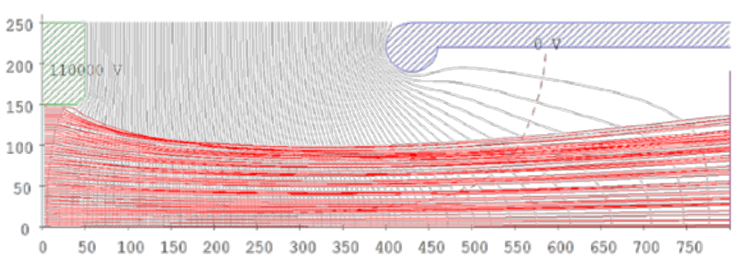
- **Pulsed ion beam → pulsed D-D beam-target fusion neutron source**

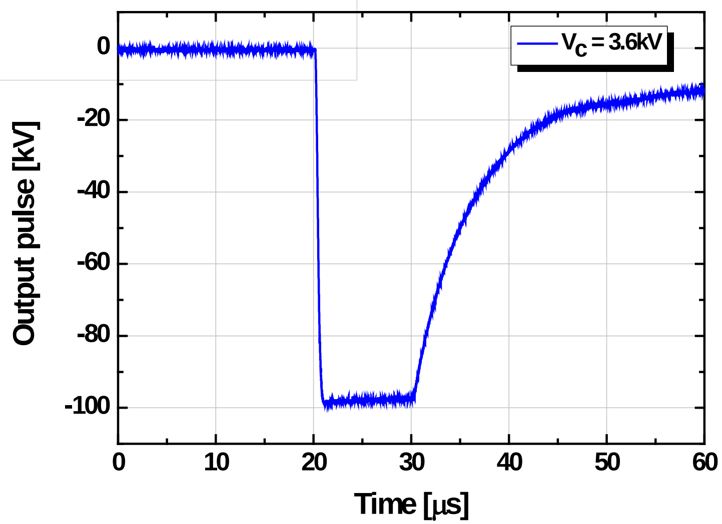
$$D + D \rightarrow {}^{3}He(0.82) + n(2.45)$$



Neutron yield ~10^4 neutrons / 10 us

D+ beam extraction/acceleration





← Solid-state Marx generator

Thank you for your attention!

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SNU Plasma, Radiation & Ion Sources Laboratory