PULSED POWER SYSTEM
脈衝功率系統

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2023 Fall Semester

Tuesday 9:10-12:00

Lecture 11

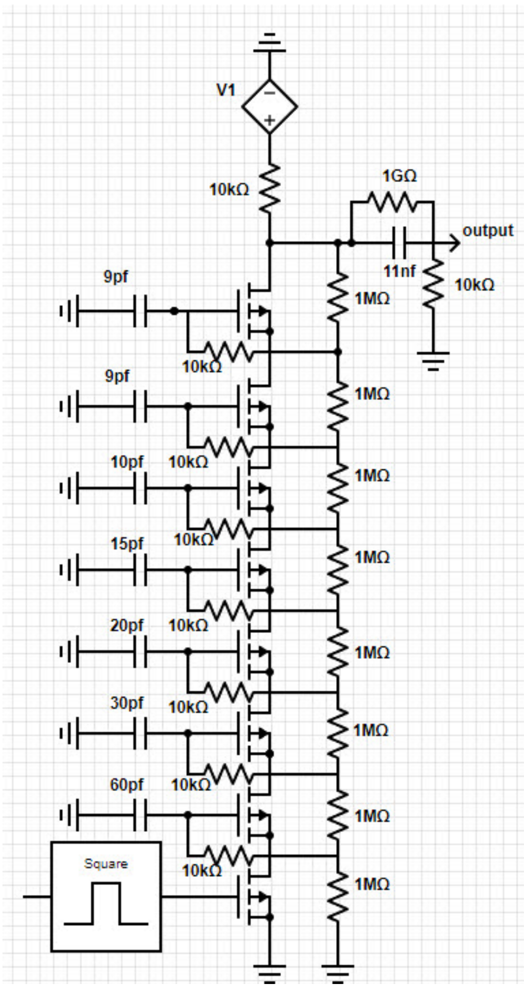
http://capst.ncku.edu.tw/PGS/index.php/teaching/

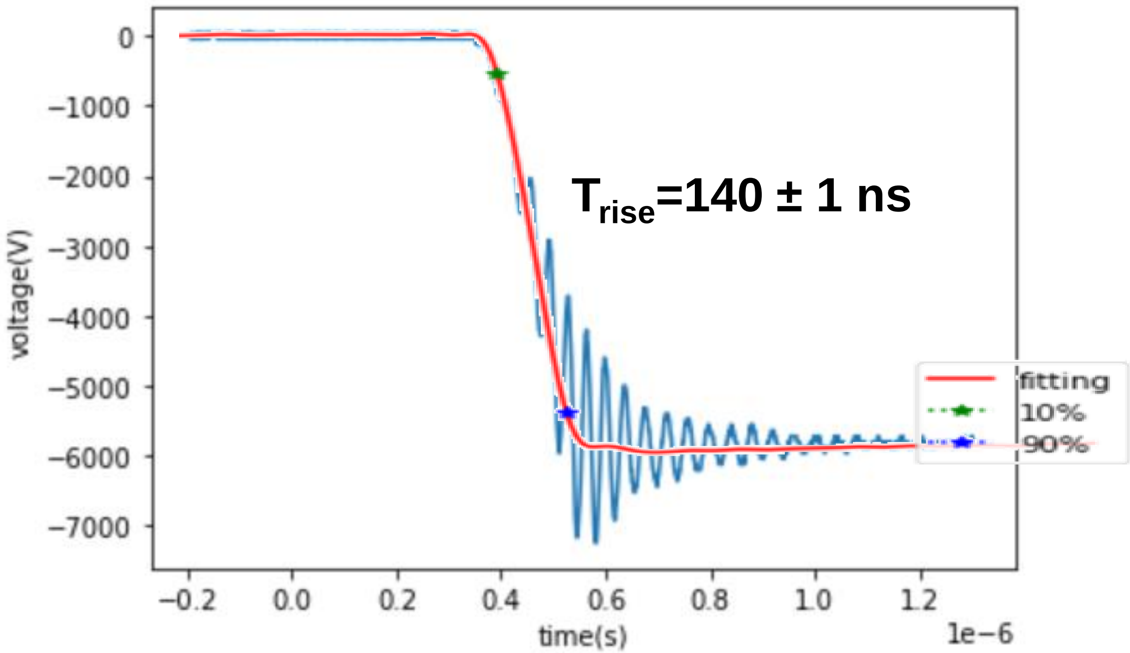
Online courses:

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

2023/11/28 updated

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





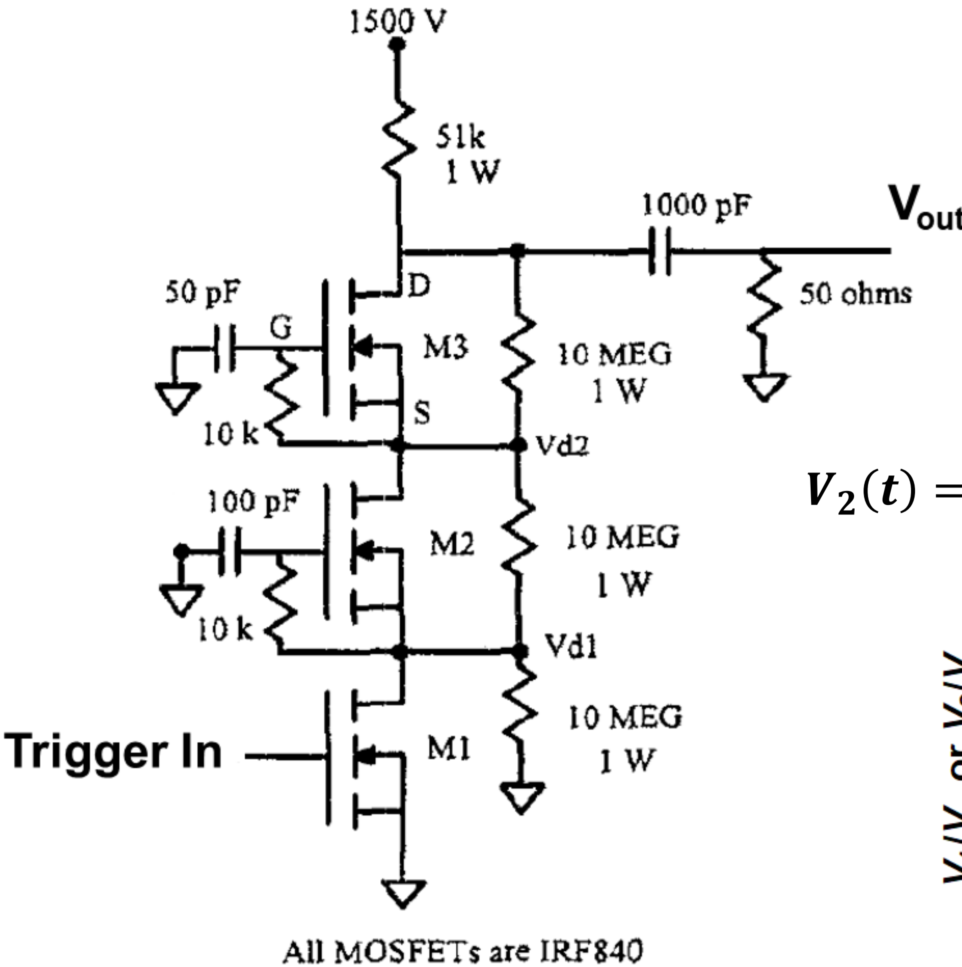
T_{rise}=140 ± 1 ns

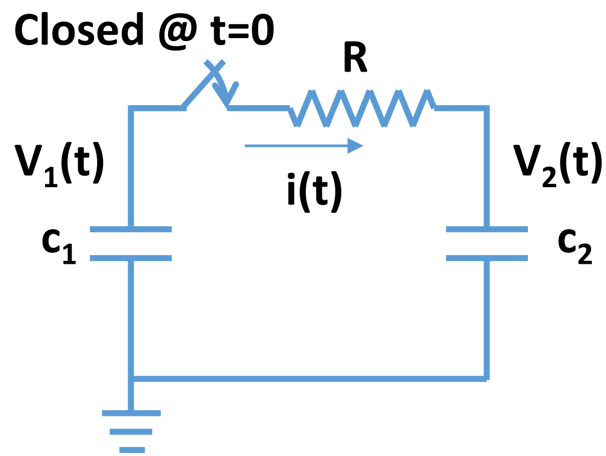
Old one:

T_{rise} = 55.5 us

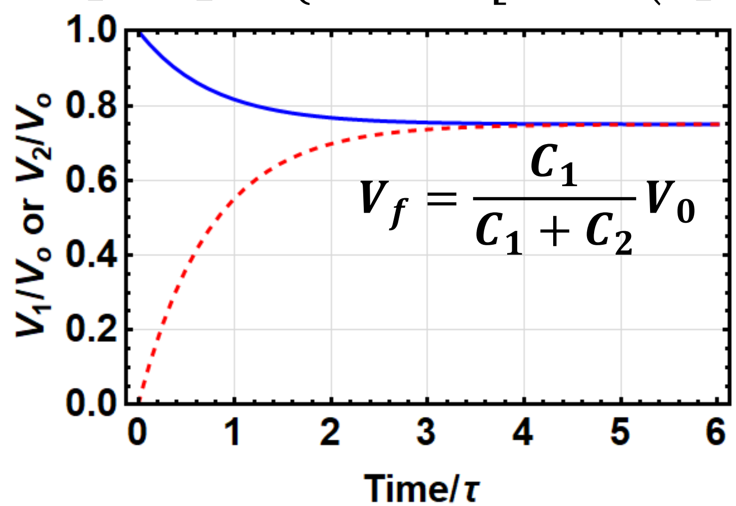
Jitter: $\pm 0.4\mu s$

Pulse generator by stacking power MOSFETs





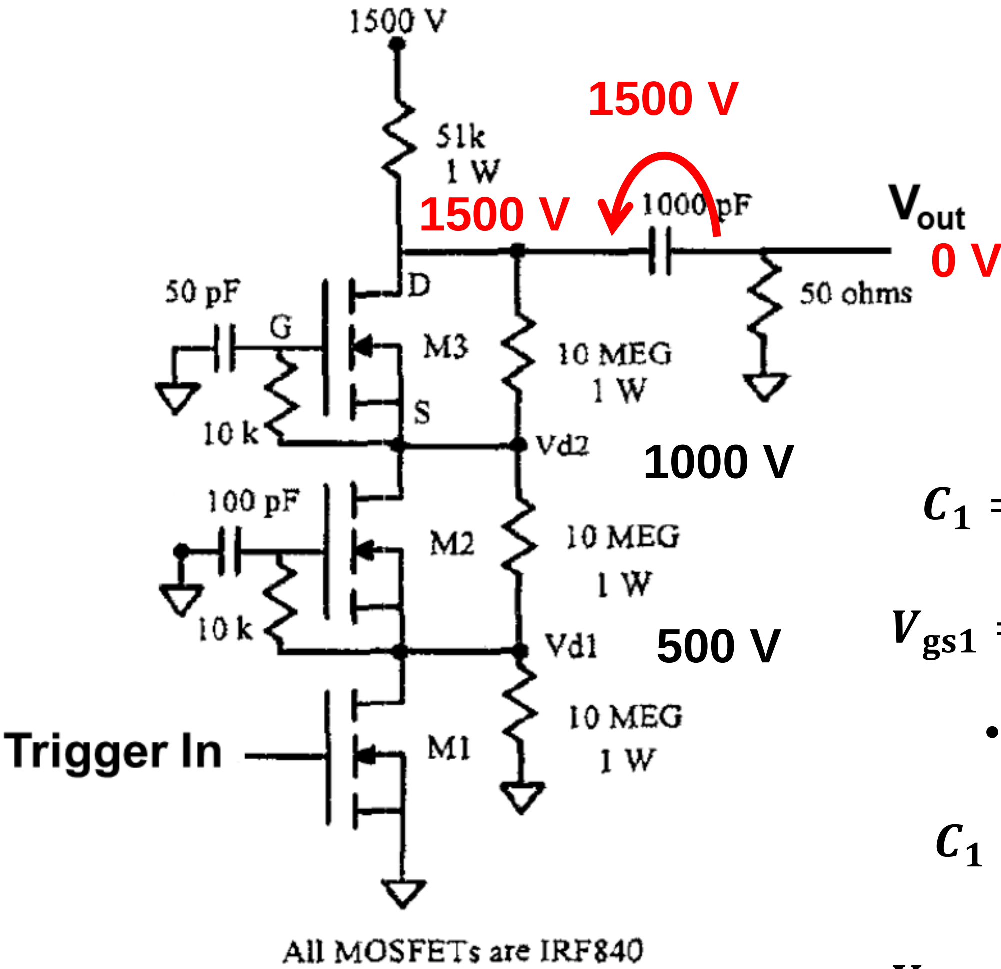
$$V_2(t) = \frac{C_1}{C_1 + C_2} V_0 \left\{ 1 - exp\left[1 - \frac{t}{R}\left(\frac{1}{C_1} + \frac{1}{C_2} \right) \right] \right\}$$



C_{gs}=2500 pF

R. J. Baker and B. P. Johnson, Rev. Sci. Instrum. 63, 5799 (1992)

Pulse generator by stacking power MOSFETs



C_{gs}=2500 pF

$$V_f = \frac{C_1}{C_1 + C_2} V_0 = \frac{C_i}{C_i + C_{gs}} V_0$$

$$C_i = \frac{V_f}{V_0 - V_f} C_{gs}$$

- **i=1:**

$$C_1 = \frac{20}{500 - 20} \times 2500 = 104 \approx 100\text{pF}$$

$$V_{gs1} = \frac{100}{2500 + 100} \times 500 = 19.2V$$

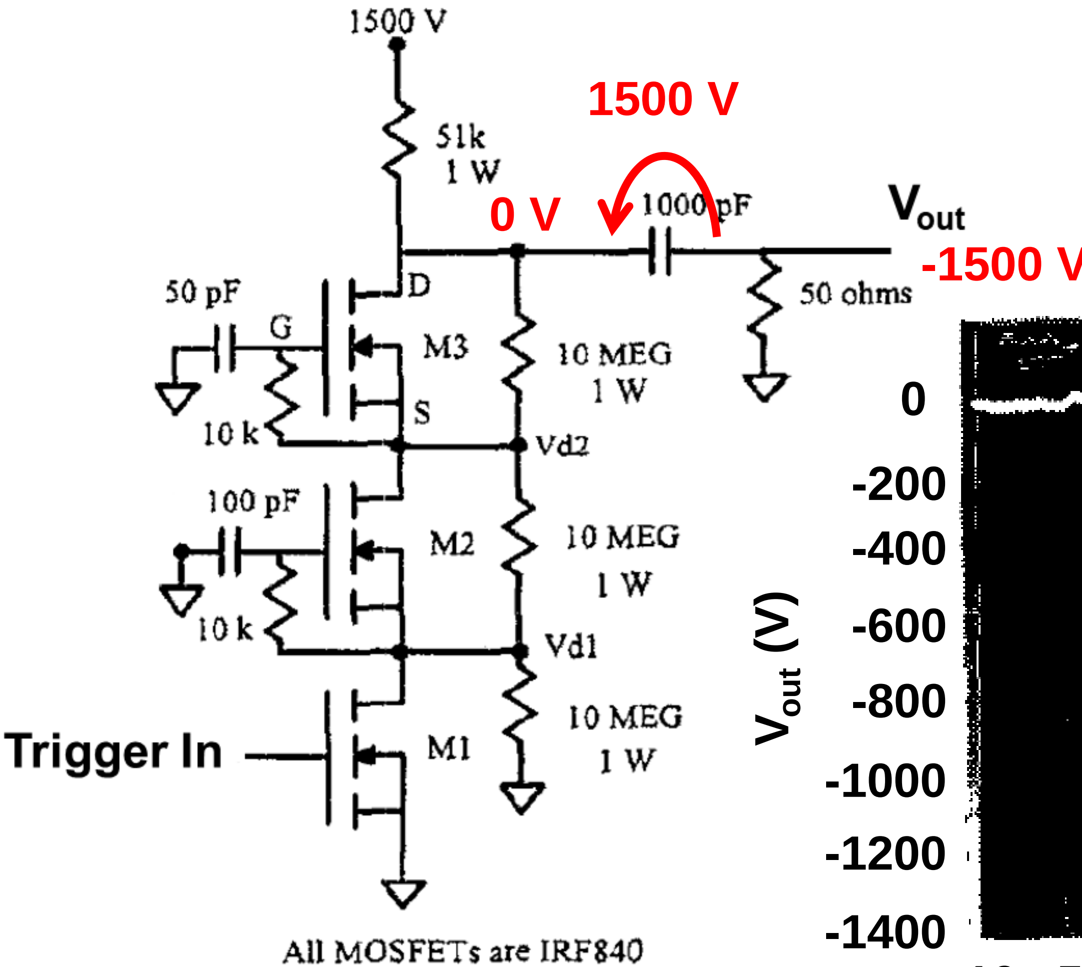
- **i=2:**

$$C_1 = \frac{20}{1000 - 20} \times 2500 = 51 \approx 50\text{pF}$$

$$V_{gs2} = \frac{50}{2500 + 50} \times 1000 = 19.6V$$

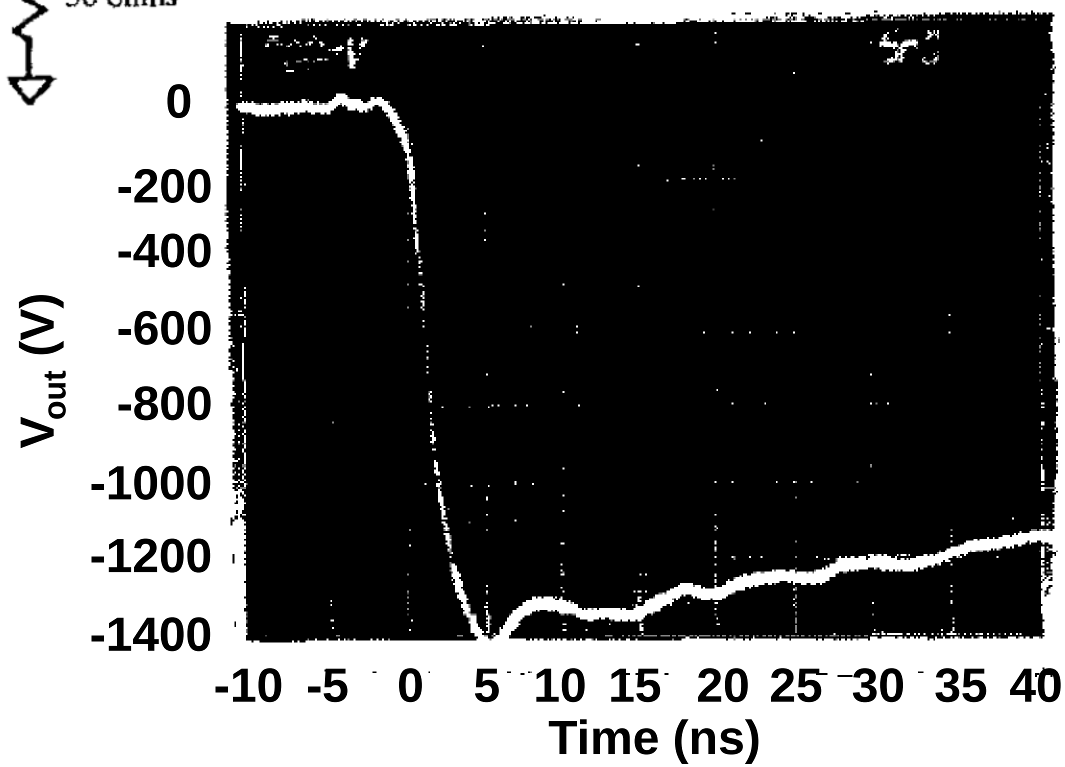
R. J. Baker and B. P. Johnson, Rev. Sci. Instrum. 63, 5799 (1992)

Pulse generator by stacking power MOSFETs



All MOSFETs are IRF840

C_{gs}=2500 pF



R. J. Baker and B. P. Johnson, Rev. Sci. Instrum. 63, 5799 (1992)

Outlines

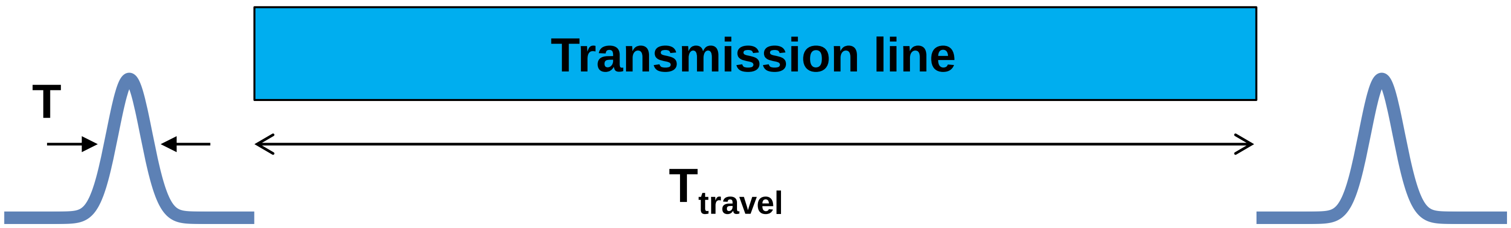
- Switches
  - Closing switches: the switching process is associated with voltage breakdown across an initially insulant element.
  - Opening switches: the switching process is associated with a sudden growth of its impedance.
- **Pulse-forming lines**
  - **Blumlein line**
  - Pulse-forming network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

Pulse-forming lines

- A constant-voltage plateau is needed for many pulsed-power applications.
- Various arrangements of LC elements are necessary. It is called "Pulse-Forming Networks (PFN)".

Transmission lines

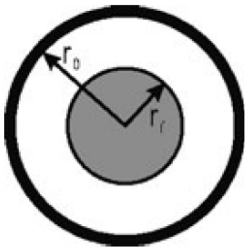
- **Transmission lines are the continuous borderline case of a network consisting of discrete LC elements.**
- **Depending on the time T during which energy is extracted from or supplied to the element, a transmission line can be described as lumped circuit element or an extended object.**
  - **$T > T_{travel}$, the time it takes for an EM wave to move from one terminal of the element to the next → lumped circuit element.**
  - **$T < T_{travel}$, the time it takes for an EM wave to move from one terminal of the element to the next → Transmission line.**



Different kinds of transmission line and the inductance and the capacitance per unit

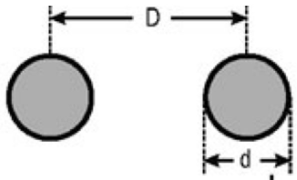
1. Coaxial transmission line:

$$C' = 2\pi\varepsilon / \ln(r_o/r_i)$$
$$L' = (\mu/2\pi)\ln(r_o/r_i)$$
$$Z_0 = \left((\mu/\varepsilon)^{1/2}/2\pi\right)\ln(r_o/r_i)$$
$$= 60(\mu_r/\varepsilon_r)^{1/2}\ln(r_o/r_i)$$



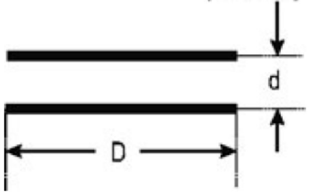
2. Double-wire line:

$$C' = \pi\varepsilon / \operatorname{arcosh}(D/d)$$
$$L' = (\mu/\pi)\operatorname{arcosh}(D/d)$$
$$Z_0 = \left((\mu/\varepsilon)^{1/2}/\pi\right)\operatorname{arcosh}(D/d)$$



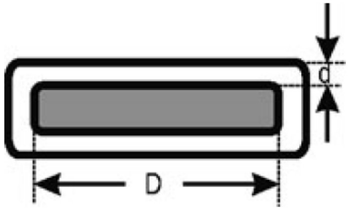
3. Parallel-plate line:

$$C' = \varepsilon D/d$$
$$L' = \mu d/D$$
$$Z_0 = (\mu/\varepsilon)^{1/2}(d/D)$$

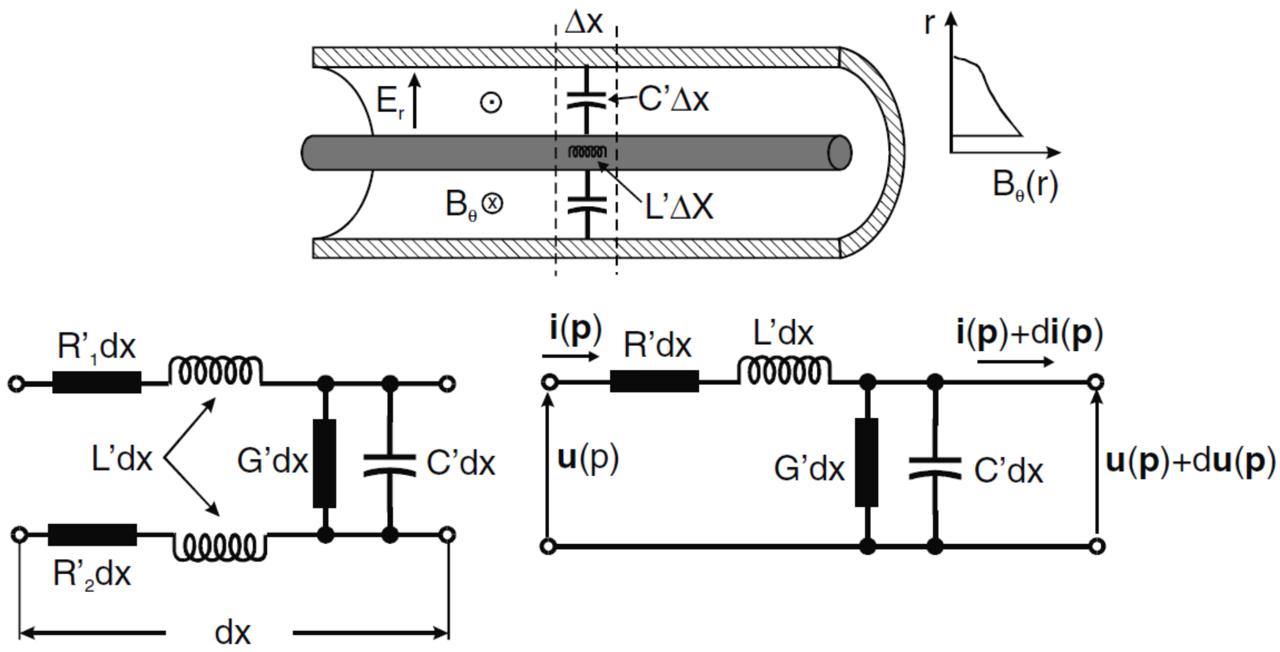


4. Stripline:

$$C' = 2\varepsilon D/d$$
$$L' = \mu d/2D$$
$$Z_0 = (\mu/\varepsilon)^{1/2}(d/2D)$$

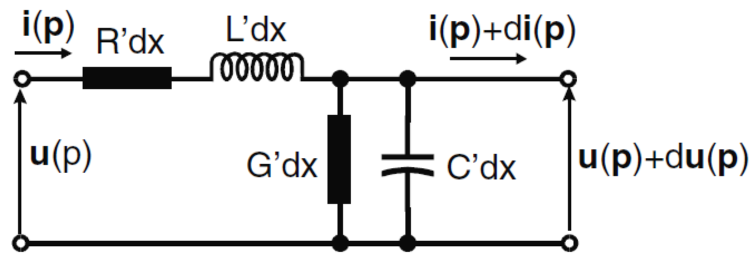


An infinitesimal section of a homogeneous coaxial transmission line



- **Resistances per unit length: $R'_1 + R'_2 \rightarrow R' \rightarrow R$.**
- **Conductance per unit length: $G' \rightarrow G$.**
- **All quantities are frequency-dependent because of the skin effect and because the dielectric constant depends on the frequency.**
- **Assume that they are independent of the position x, the voltage V and current I.**

An infinitesimal section of a homogeneous coaxial transmission line



$$U - I\mathrm{R}\mathrm{d}x - \mathrm{L}\mathrm{d}x\frac{\mathrm{d}I}{\mathrm{d}t} - U' = 0$$

$$I - U'\mathrm{G}\mathrm{d}x - \mathrm{C}\mathrm{d}x\dot{U}' - I' = 0 \qquad U' = U + \frac{\partial U}{\partial x}\mathrm{d}x \qquad \dot{U}' = \dot{U} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial U}{\partial x}\right)\mathrm{d}x$$

$$I - \left(U + \frac{\partial U}{\partial x}\mathrm{d}x\right)\mathrm{G}\mathrm{d}x - \mathrm{C}\mathrm{d}x\left[\dot{U} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial U}{\partial x}\right)\mathrm{d}x\right] - I' = 0$$

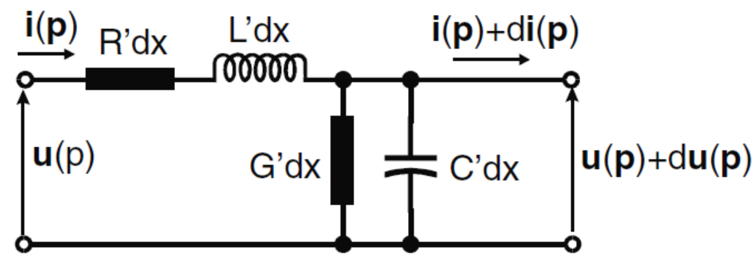
$$I - U\mathrm{G}\mathrm{d}x - \frac{\partial U}{\partial x}\mathrm{G}\mathrm{d}x^2 - \dot{U}\mathrm{C}\mathrm{d}x - \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial U}{\partial x}\right)\mathrm{C}\mathrm{d}x^2 - I' = 0$$

$$I - U\mathrm{G}\mathrm{dx} - \mathrm{C}\mathrm{d}x\dot{U} - I' = 0$$

$$\begin{cases} \dfrac{U' - U}{\mathrm{dx}} \equiv \dfrac{\partial U}{\partial x} = -\mathrm{R}I - L\dot{I} \\[2ex] \dfrac{I' - I}{\mathrm{dx}} \equiv \dfrac{\partial I}{\partial x} = -\mathrm{G}U - C\dot{U} \end{cases}$$

An infinitesimal section of a homogeneous coaxial transmission line

$$\begin{cases} \dfrac{U' - U}{\mathrm{dx}} \equiv \dfrac{\partial U}{\partial x} = -\mathrm{R}I - L\dot{I} \\ \dfrac{I' - I}{\mathrm{dx}} \equiv \dfrac{\partial I}{\partial x} = -\mathrm{G}U - C\dot{U} \end{cases}$$



- **Laplace transform:** $x = \tilde{x}e^{\mathrm{pt}}$, $\dfrac{d}{\mathrm{dt}} \to p$

$$\frac{\mathrm{d}\tilde{U}}{\mathrm{d}x} = -R\tilde{I} - \mathrm{pL}\tilde{I} = -(R + \mathrm{pL})\tilde{I} \qquad \frac{\mathrm{d}^2\tilde{U}}{\mathrm{d}x^2} = -(R + \mathrm{pL})\frac{\mathrm{d}\tilde{I}}{\mathrm{d}x} = (R + \mathrm{pL})(G + \mathrm{pC})\tilde{U}$$

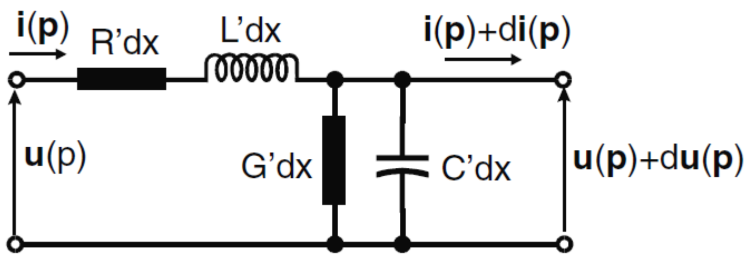
$$\frac{\mathrm{d}\tilde{I}}{\mathrm{d}x} = -G\tilde{U} - \mathrm{pC}\tilde{U} = -(G + \mathrm{pC})\tilde{U} \qquad \frac{\mathrm{d}^2\tilde{I}}{\mathrm{d}x^2} = -(G + \mathrm{pC})\frac{\mathrm{d}\tilde{U}}{\mathrm{d}x} = (G + \mathrm{pC})(R + \mathrm{pL})\tilde{I}$$

- **Lossless line where R=0, G=0:**

$$\frac{\mathrm{d}\tilde{U}}{\mathrm{d}x} = -p\mathrm{L}\tilde{I} \qquad \frac{\mathrm{d}^2\tilde{U}}{\mathrm{d}x^2} = p^2\mathrm{LC}\tilde{U}$$

$$\frac{\mathrm{d}\tilde{I}}{\mathrm{d}x} = -p\mathrm{C}\tilde{U} \qquad \frac{\mathrm{d}^2\tilde{I}}{\mathrm{d}x^2} = p^2\mathrm{LC}\tilde{I}$$

An infinitesimal section of a homogeneous coaxial transmission line



- **Lossless line where R=0, G=0:**

$$\frac{\mathrm{d}^2\tilde{U}}{\mathrm{d}x^2} = p^2\mathrm{LC}\tilde{U}$$

$$\frac{\mathrm{d}^2\tilde{I}}{\mathrm{d}x^2} = p^2\mathrm{LC}\tilde{I}$$

$$U(x,p) = U_x(p) = \begin{cases} \tilde{U}_+ e^{-p\sqrt{\mathrm{LC}}x} \\ \tilde{U}_- e^{p\sqrt{\mathrm{LC}}x} \end{cases}$$

- **Inverse Laplace transform:** $L\{U_x(t-\tau)\} = \tilde{U}e^{-\mathrm{pt}}$

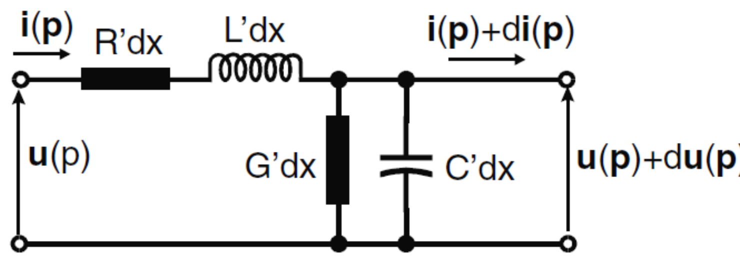
$$U(x,t) = U_x(t) = \begin{cases} U_+\left(t - x\sqrt{\mathrm{LC}}\right) \\ U_-\left(t + x\sqrt{\mathrm{LC}}\right) \end{cases}$$

or Linear combination:

$$U_x(t) = U_+\left(t - x\sqrt{\mathrm{LC}}\right) + U_-\left(t + x\sqrt{\mathrm{LC}}\right)$$

An infinitesimal section of a homogeneous coaxial transmission line

$$U(x,t) = U_x(t) = \begin{cases} U_+\left(t - x\sqrt{\mathrm{LC}}\right) \\ U_-\left(t + x\sqrt{\mathrm{LC}}\right) \end{cases}$$



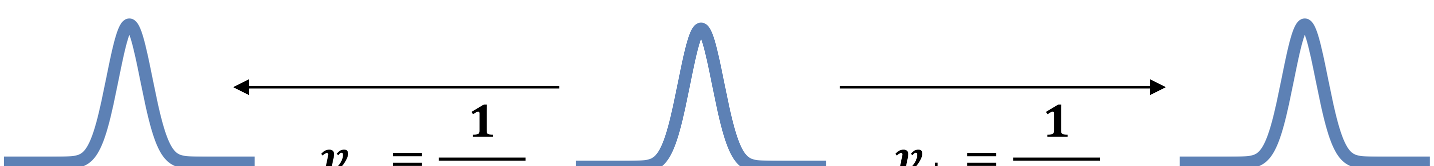
or Linear combination: $$U_x(t) = U_+\left(t - x\sqrt{\mathrm{LC}}\right) + U_-\left(t + x\sqrt{\mathrm{LC}}\right)$$

$$\frac{\mathrm{d}\tilde{U}}{\mathrm{d}x} = -p\mathrm{L}\tilde{I} \qquad \mp p\sqrt{\mathrm{LC}}\tilde{U}_\pm = -\mathrm{pL}\tilde{I}_\pm$$

$$\frac{\tilde{U}_+}{\tilde{I}_+} = -\frac{\tilde{U}_-}{\tilde{I}_-} = \sqrt{\frac{L}{C}} \equiv Z_0$$

$$Z_0 = \frac{U_+\left(t - x\sqrt{\mathrm{LC}}\right)}{I_+\left(t - x\sqrt{\mathrm{LC}}\right)} = -\frac{U_-\left(t + x\sqrt{\mathrm{LC}}\right)}{I_-\left(t + x\sqrt{\mathrm{LC}}\right)}$$

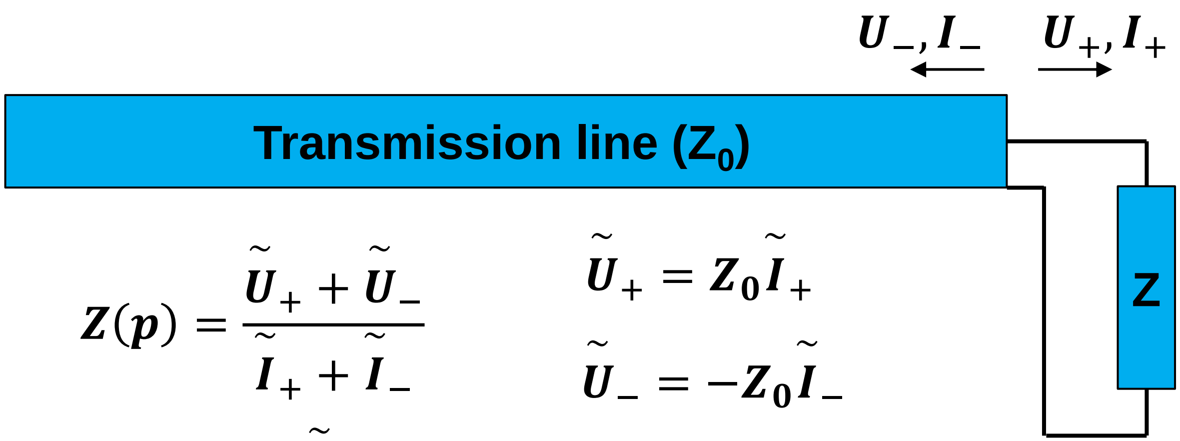
Transmission line



$$v_- = \frac{1}{\sqrt{\mathrm{LC}}} \qquad v_+ = \frac{1}{\sqrt{\mathrm{LC}}}$$

Termination of arbitrary freq-dependent impedance Z(p)

- **Lossless transmission line terminates with an arbitrary freq-dependent impedance Z(p) in Laplace space.**



Ohm's law: $$Z(p) = \frac{\tilde{U}_+ + \tilde{U}_-}{\tilde{I}_+ + \tilde{I}_-}$$

$$\tilde{U}_+ = Z_0 \tilde{I}_+$$

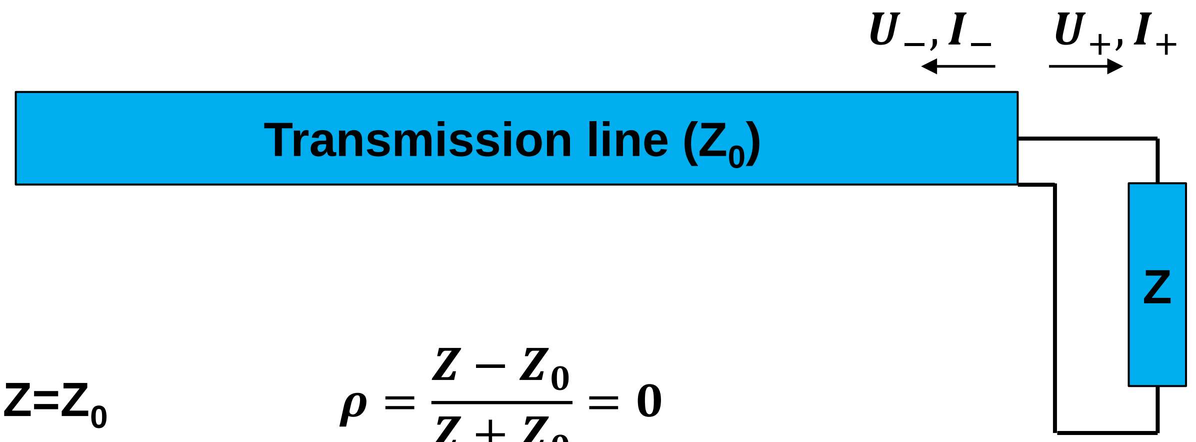
$$\tilde{U}_- = -Z_0 \tilde{I}_-$$

$$Z = \frac{\tilde{U}_+ + \tilde{U}_-}{\frac{\tilde{U}_+}{Z_0} - \frac{\tilde{U}_-}{Z_0}} = Z_0 \frac{1 + \frac{\tilde{U}_-}{\tilde{U}_+}}{1 - \frac{\tilde{U}_-}{\tilde{U}_+}} = Z_0 \frac{1+\rho}{1-\rho}$$

$$Z - Z\rho = Z_0 + Z_0 \rho$$

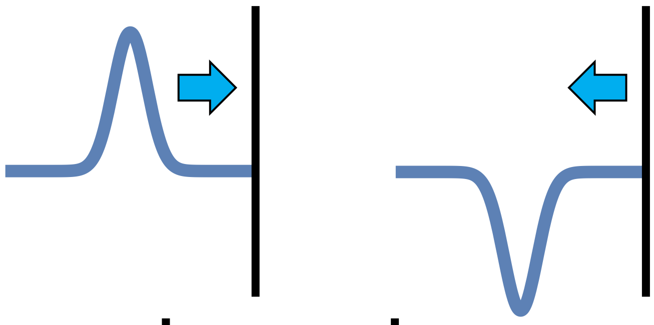
Reflection: $$\rho \equiv \frac{\tilde{U}_-}{\tilde{U}_+} = \frac{Z - Z_0}{Z + Z_0}$$

Termination of arbitrary freq-dependent impedance Z(p)



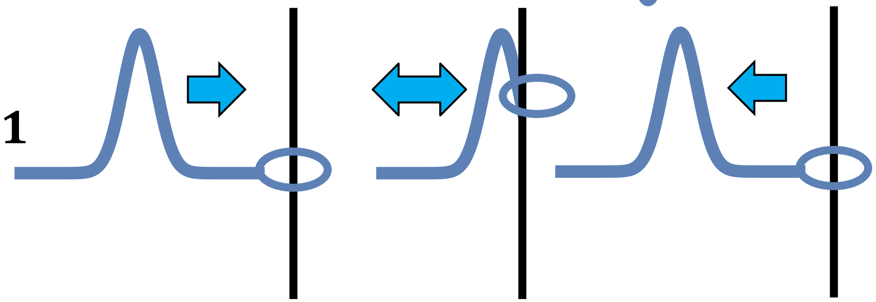
- **Match load: $Z=Z_0$**
  - **No reflection.**

$$\rho = \frac{Z - Z_0}{Z + Z_0} = 0$$



- **Short-circuit case: $Z=0$**
  - **Completely reflective with inverted voltage amplitude.**

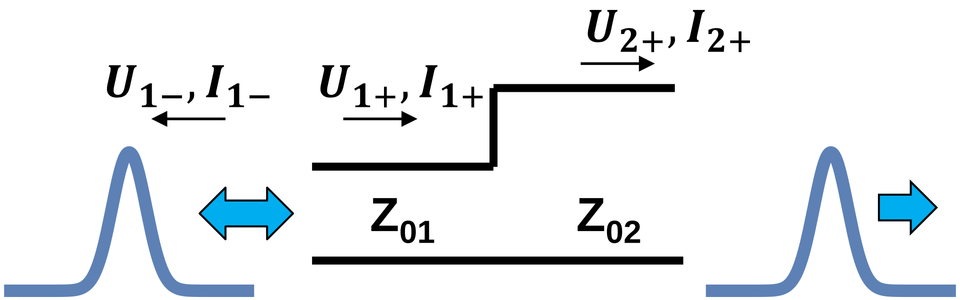
$$\rho = \frac{Z - Z_0}{Z + Z_0} = -1$$



- **Open-circuit case: $Z=\infty$**
  - **Completely reflective with the same polarity.**

$$\rho = \frac{Z - Z_0}{Z + Z_0} = 1$$

Pulse is reflected when there is an impedance mismatch



Reflection: $$\rho = \frac{U_{1-}}{U_{1+}} = \frac{Z_{02} - Z_{01}}{Z_{02} + Z_{01}}$$ $$\rho \equiv \frac{\tilde{U}_-}{\tilde{U}_+} = \frac{Z - Z_0}{Z + Z_0}$$

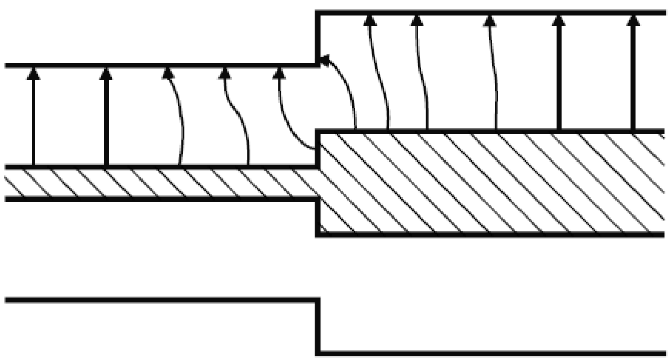
$$U_{1+} + U_{1-} = U_{2+}$$

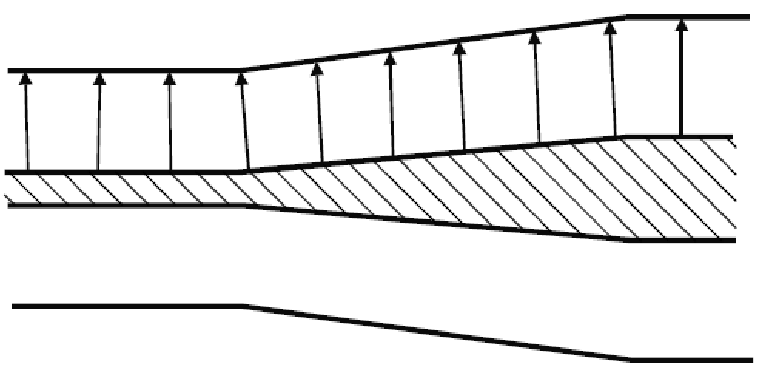
Transmission: $$T \equiv \frac{U_{2+}}{U_{1+}} = 1 + \frac{U_{1-}}{U_{1+}} = 1 + \rho$$

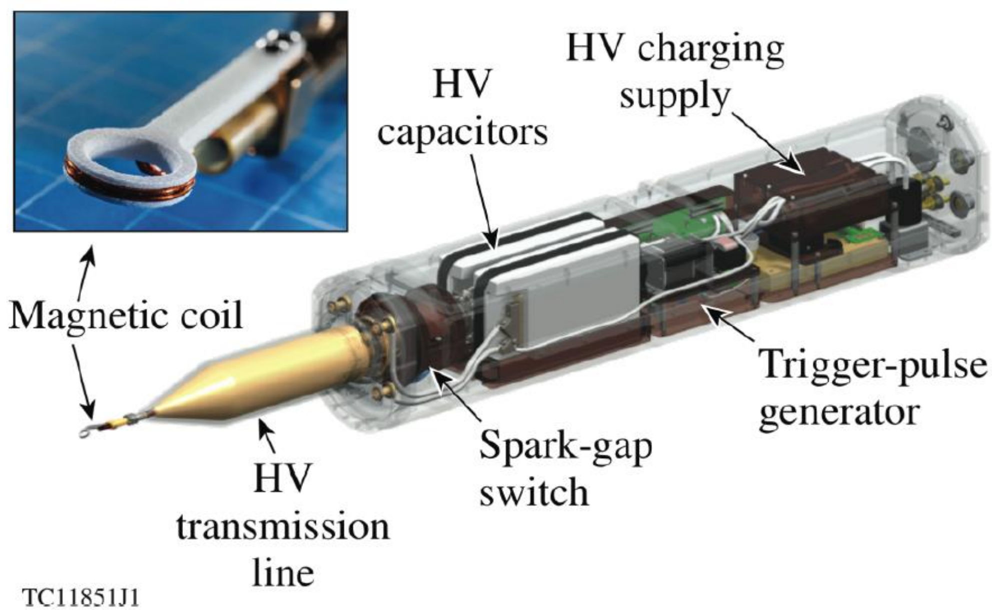
- **For impedance match, i.e., $Z_{01}=Z_{02}$:** $\rho = 0$ $T = 1$
  - **Reflection-free junction: $Z_{01}=Z_{02}$ is necessary but not sufficient.**
- **If the geometry of a line changes arbitrary, it becomes impossible to satisfy Maxell's equation just by superposing the fundamental waves.**

Smooth transition is required

- **Only by a smooth transition can we achieve the condition that the fields are not disturbed too much so that the reflections can be avoid for high frequency.**

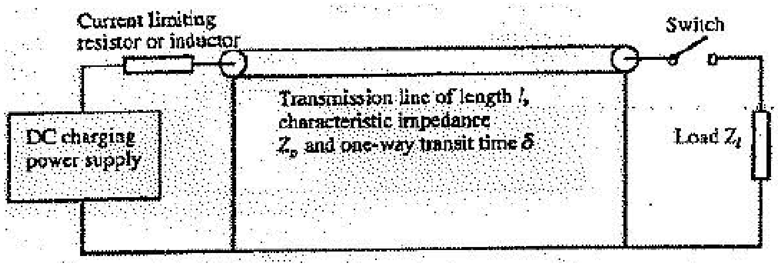






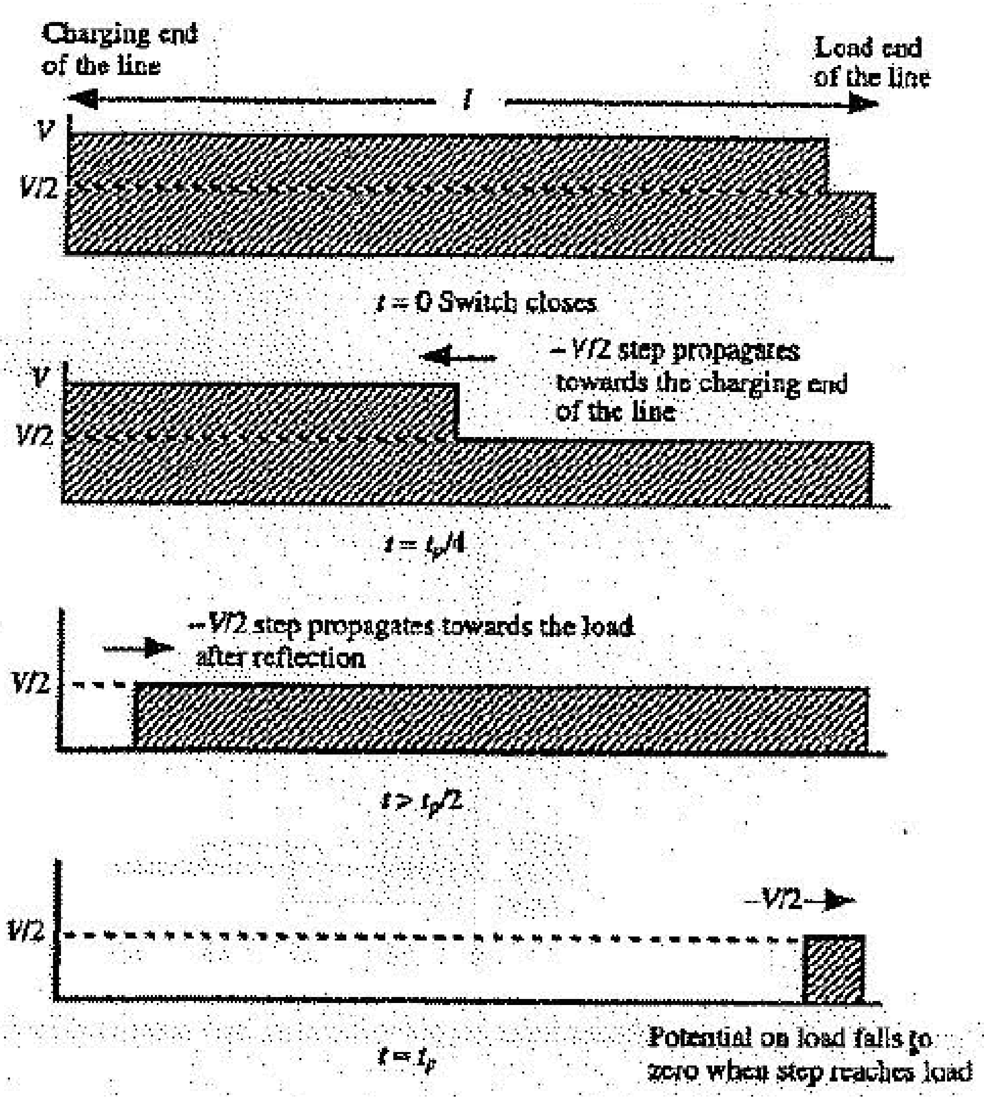
G. Fiksel, etc., Rev. Sci. Instrum. 86, 016105 (2015)

Only half of charged voltage is provided in a basic pulse forming line (PFL)

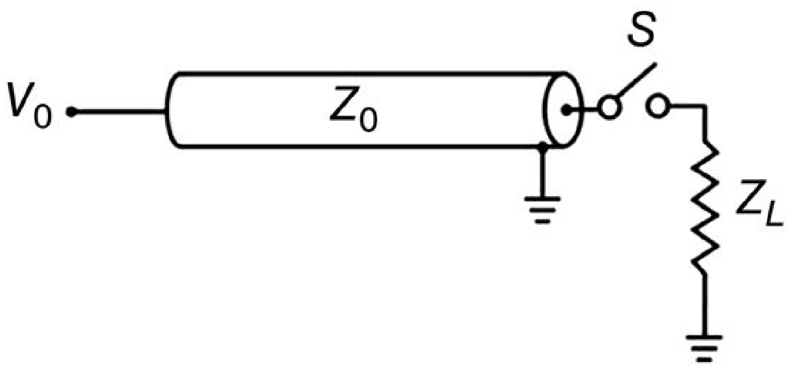


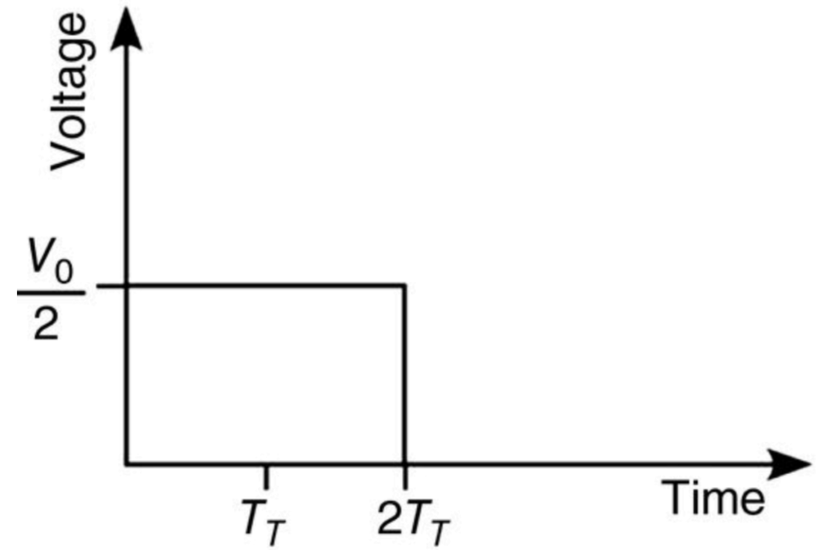
$$t_p = \frac{2l}{v_p} = 2\delta$$

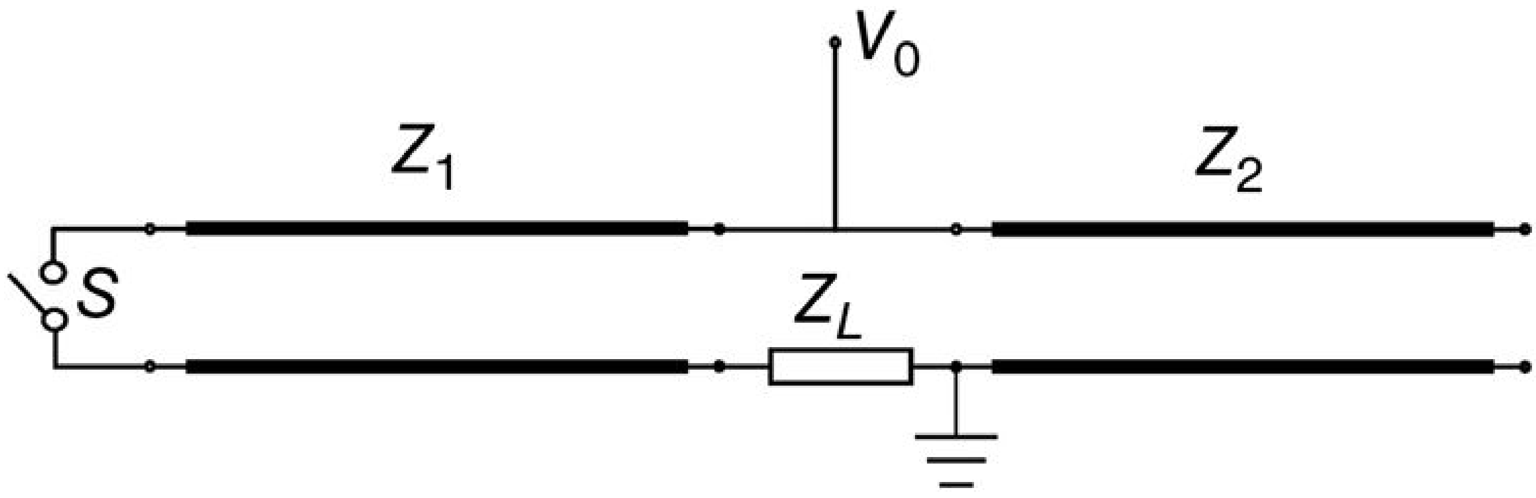
$$V_L = V\frac{Z_L}{Z_0 + Z_L}$$



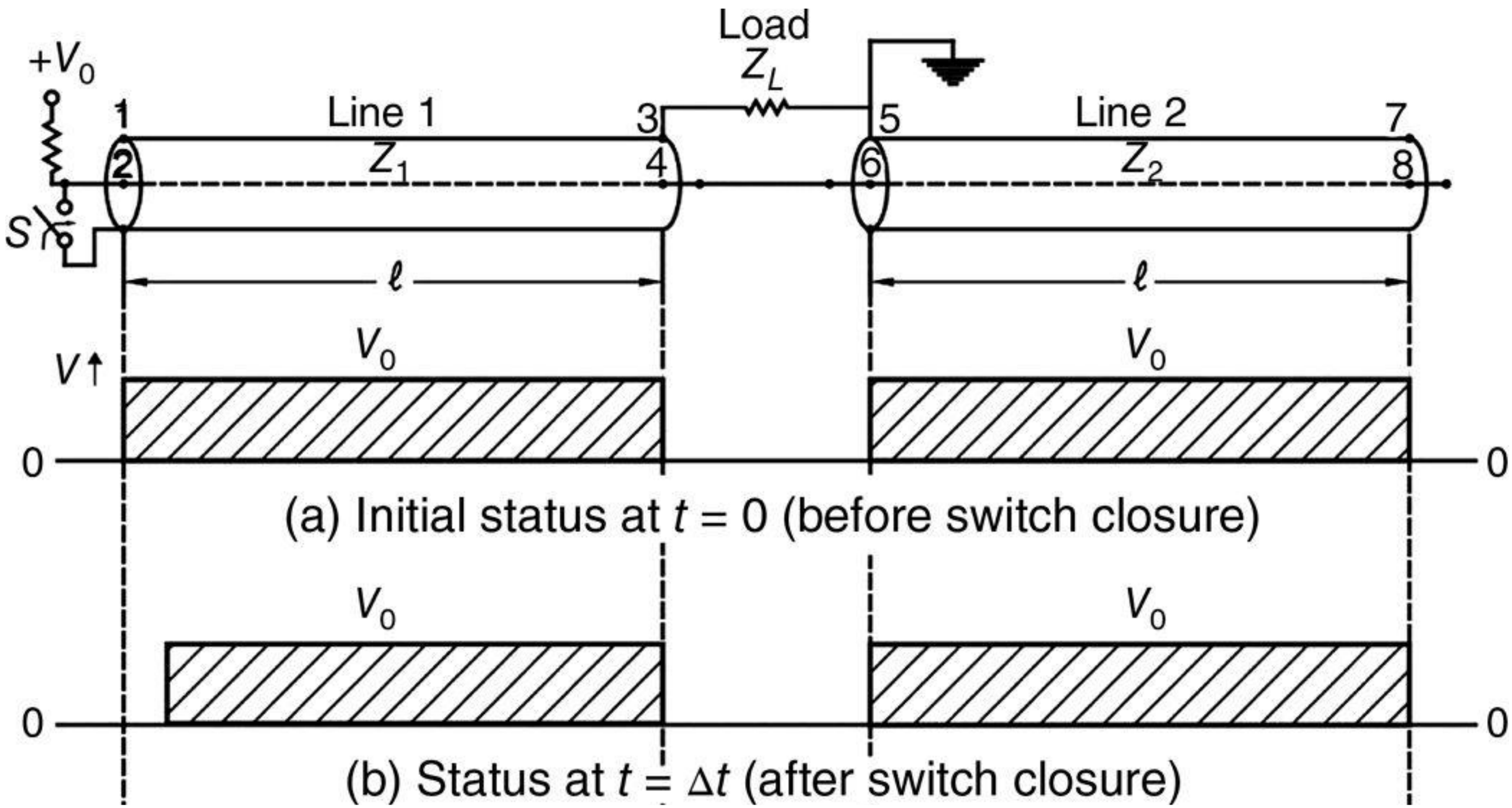
Blumlein pulse forming line (PFL)





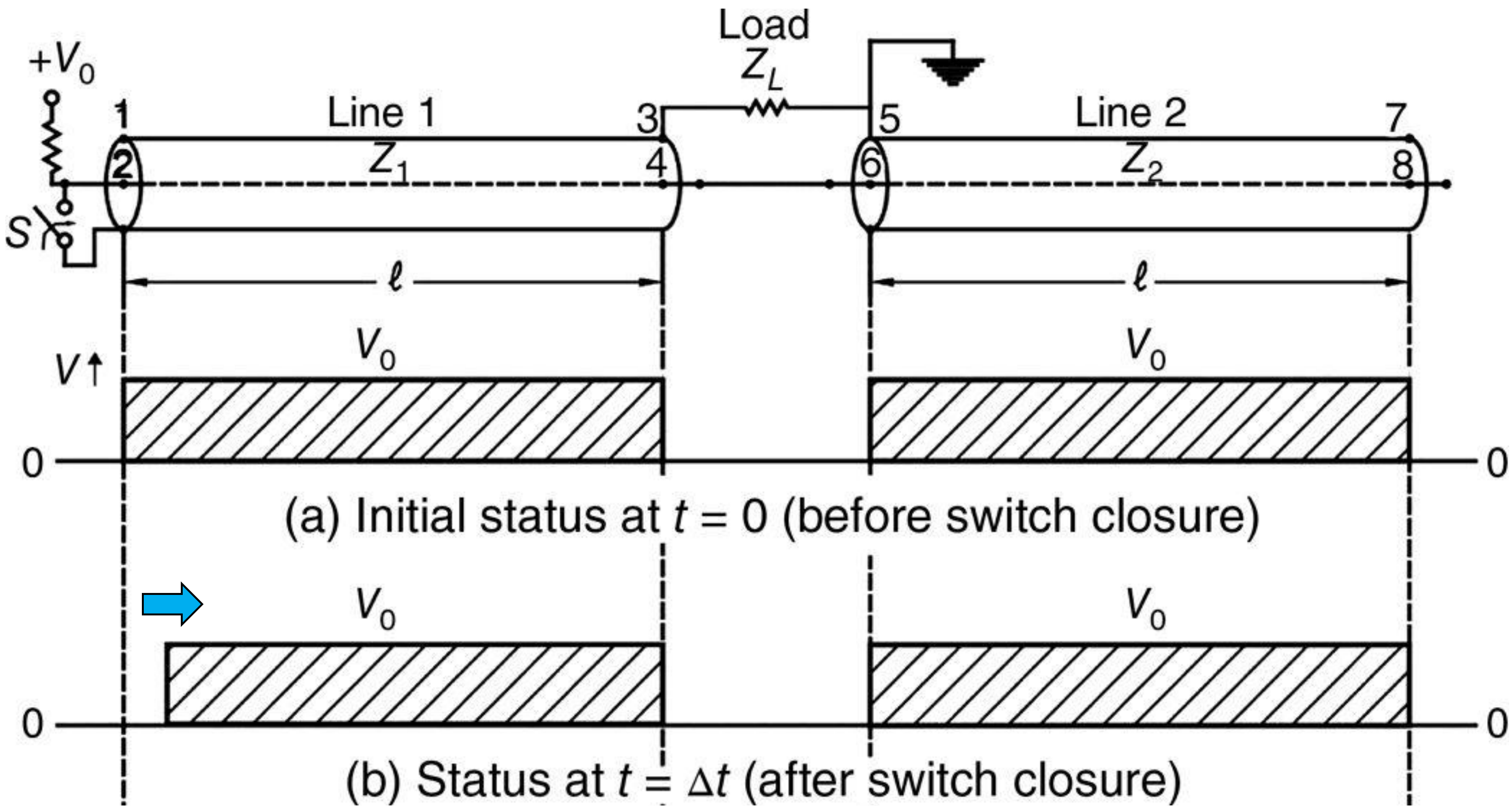


Sequence of Blumlein line



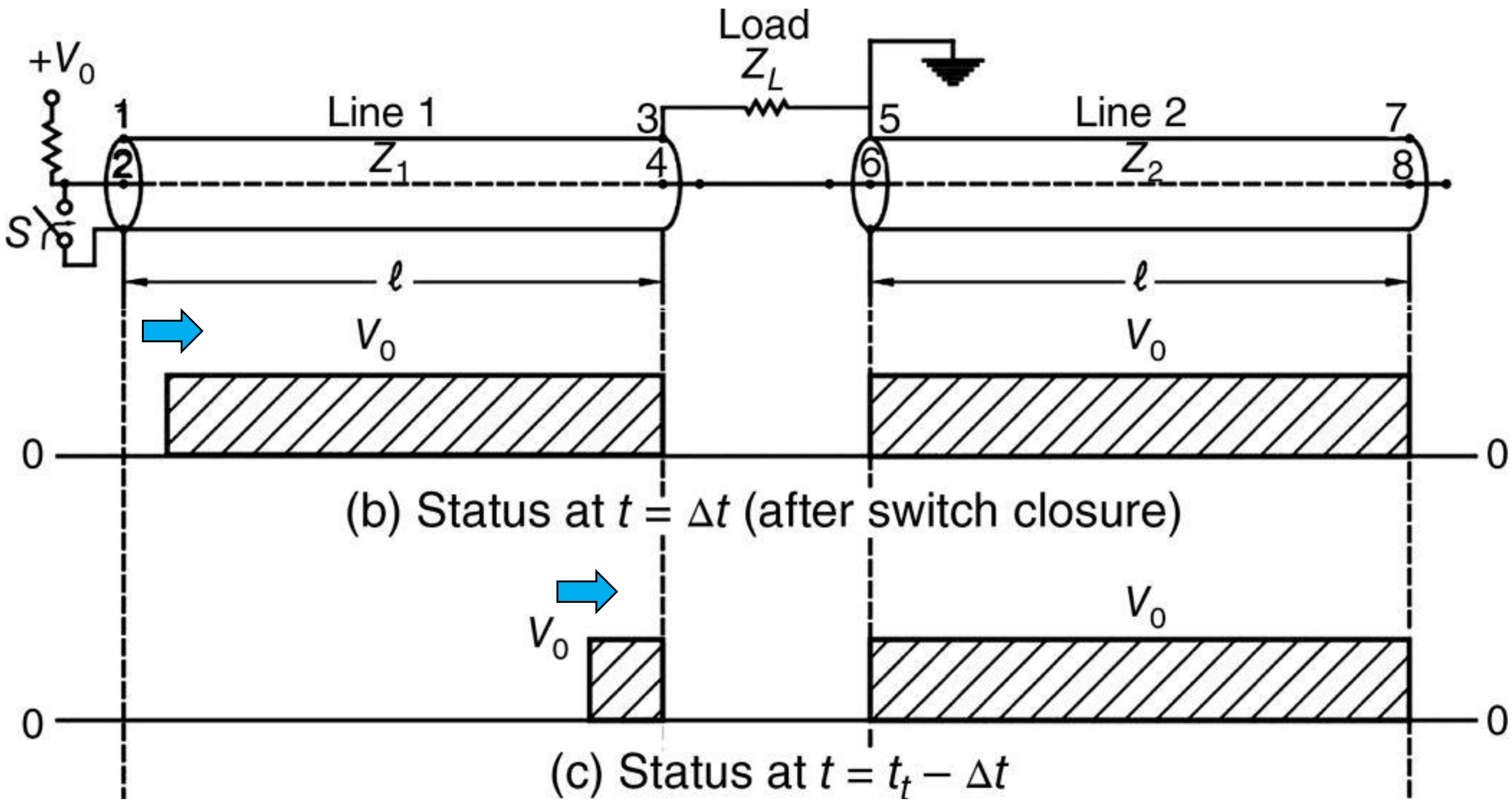
(a)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	V_0	V_0	0	V_0	V_0	0	V_0	V_0	0	0	V_0	V_0

Sequence of Blumlein line



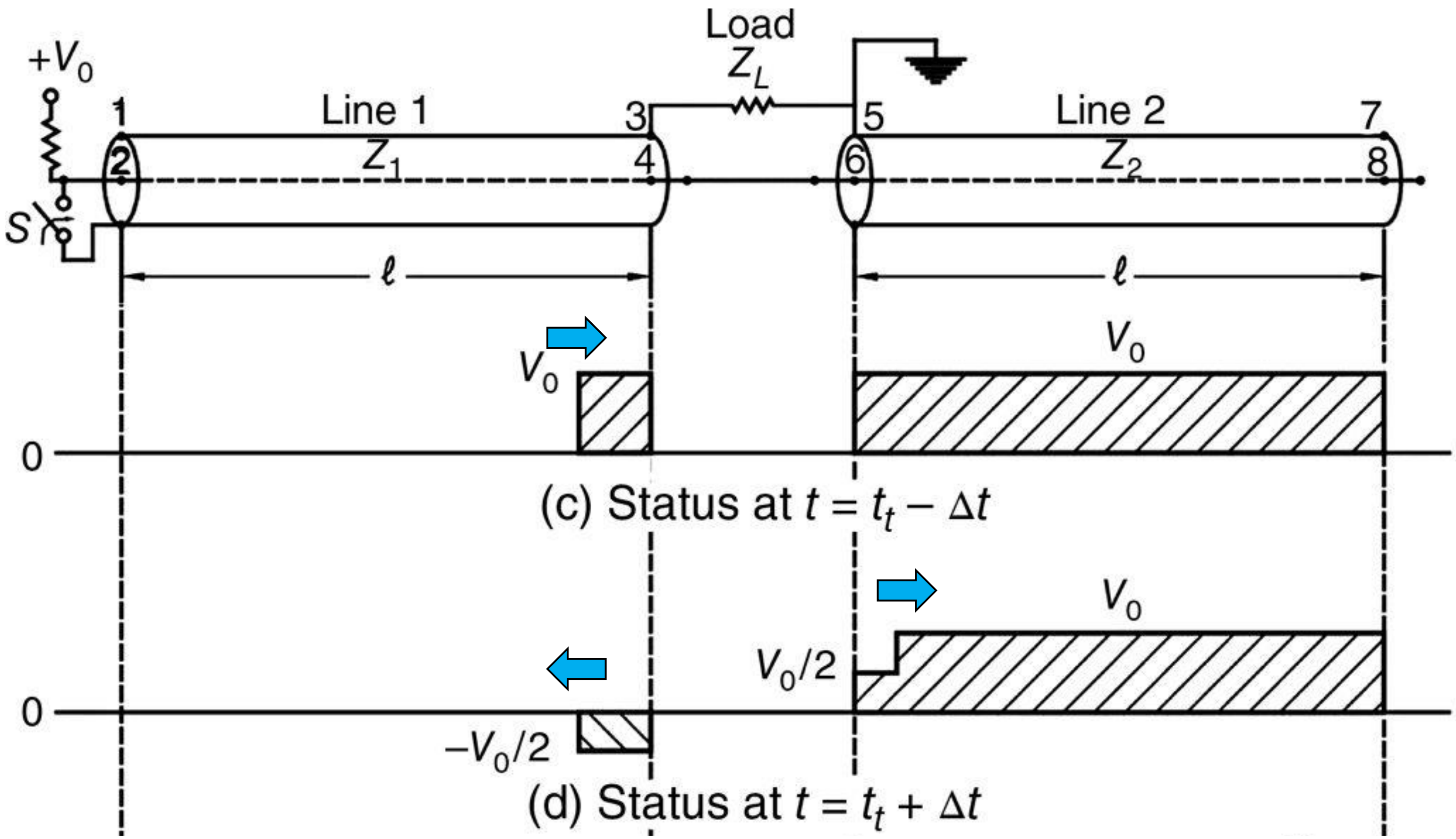
(b)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	0	0	0	V_0	V_0	0	V_0	V_0	0	0	V_0	V_0

Sequence of Blumlein line



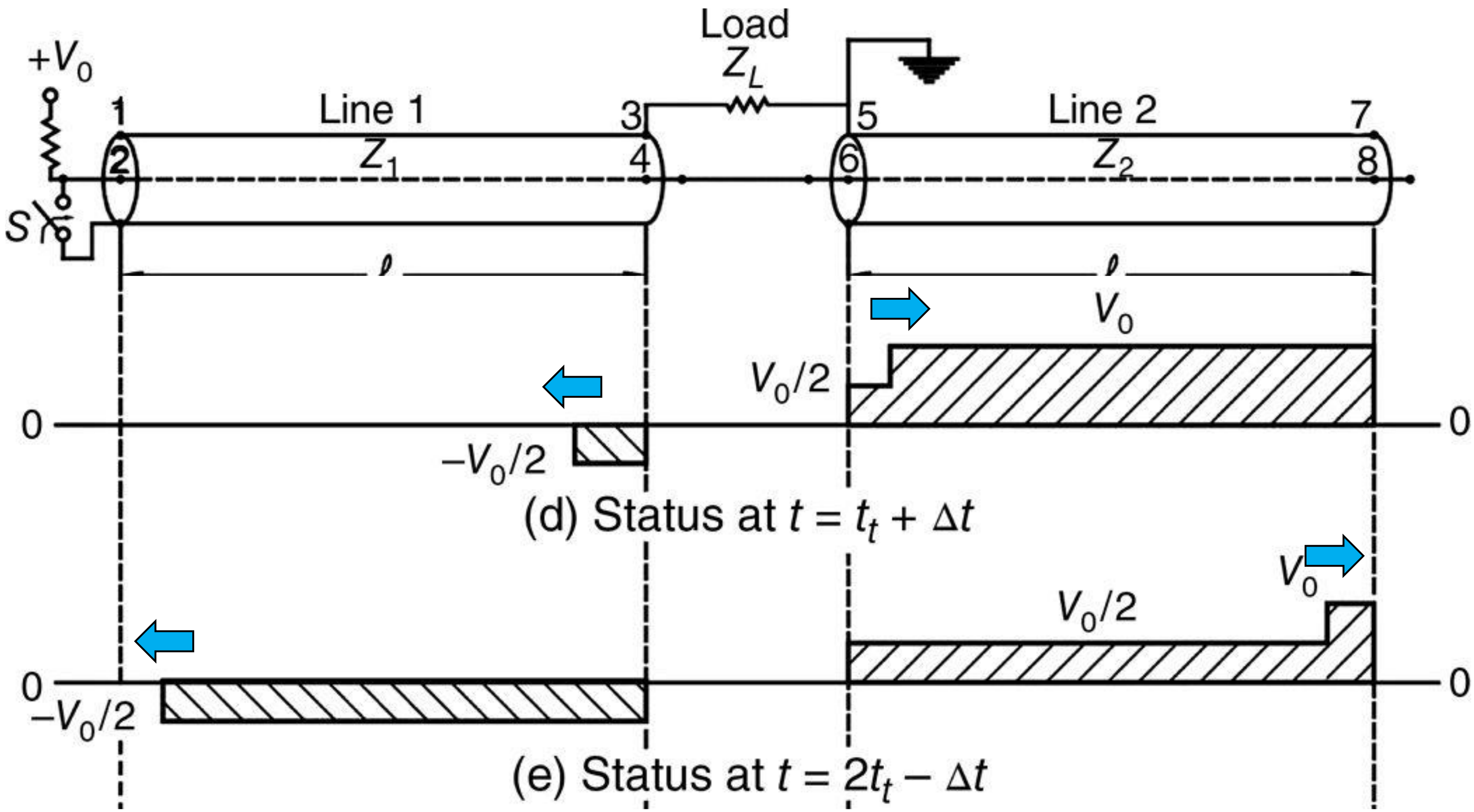
(c)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	0	0	0	V_0	V_0	0	V_0	V_0	0	0	V_0	V_0

Sequence of Blumlein line



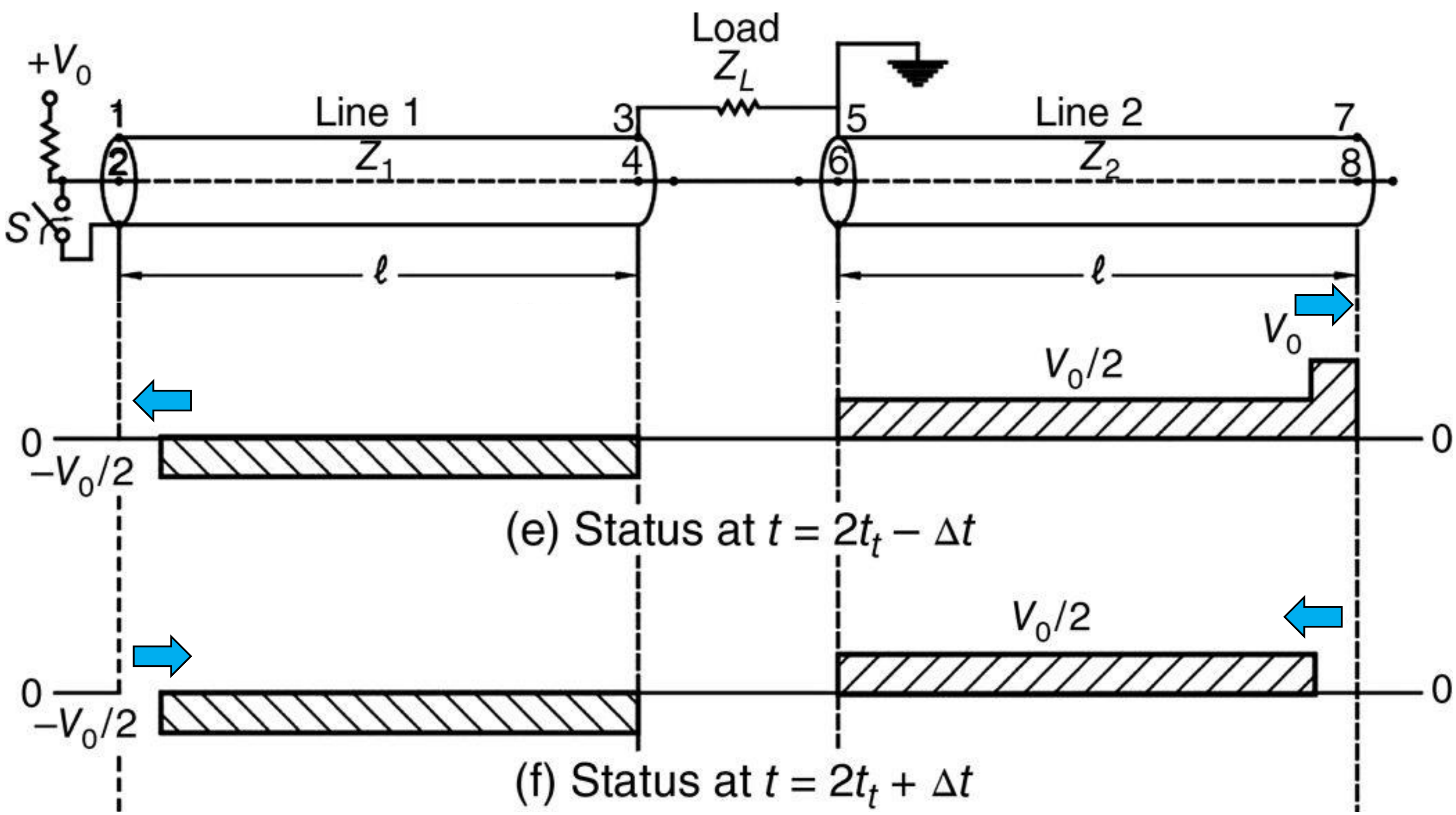
(d)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	0	0	V_0	$V_0/2$	$-V_0/2$	0	$V_0/2$	$V_0/2$	V_0	0	V_0	V_0

Sequence of Blumlein line



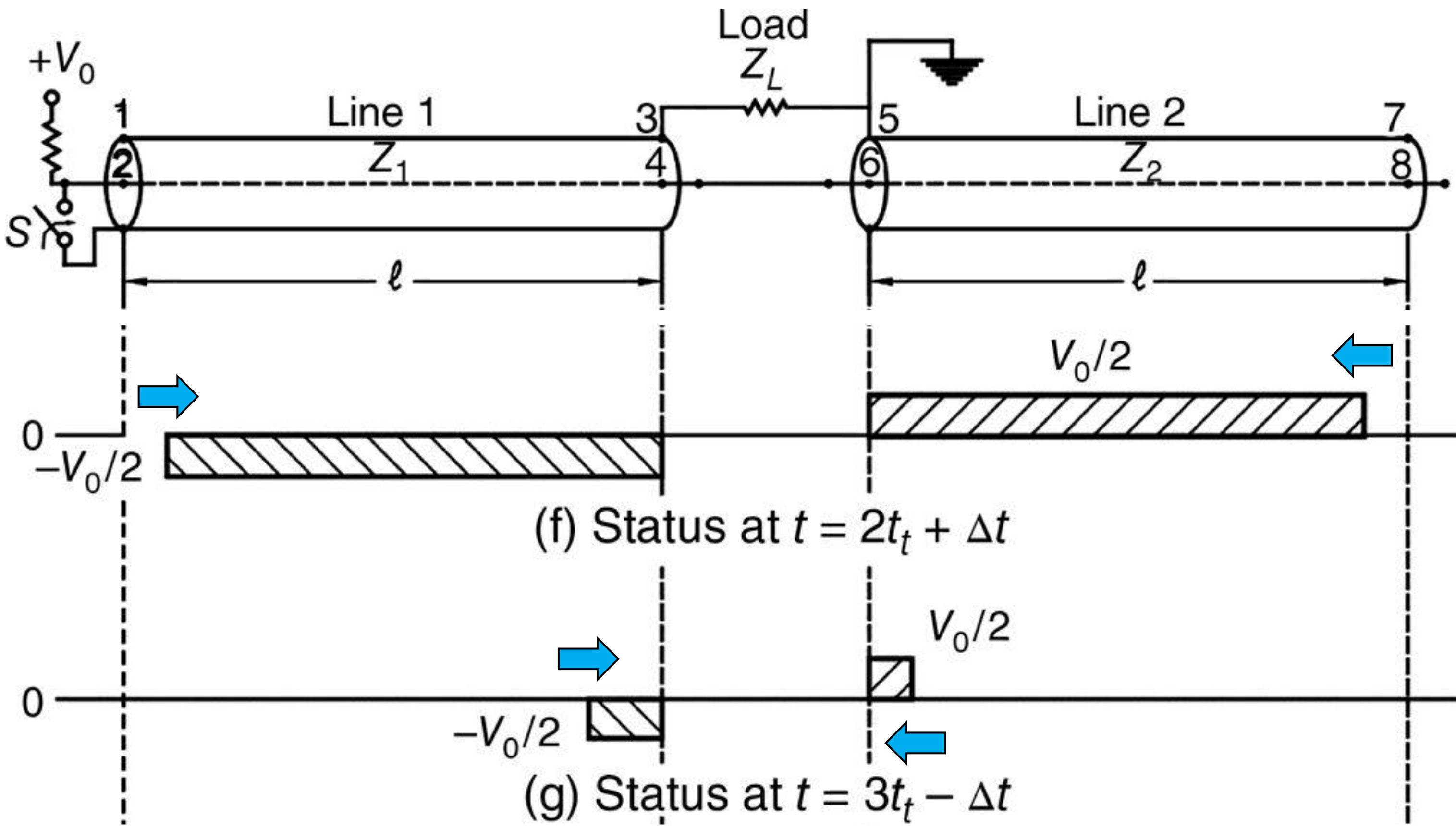
(e)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	0	0	V_0	$V_0/2$	$-V_0/2$	0	$V_0/2$	$V_0/2$	V_0	0	V_0	V_0

Sequence of Blumlein line



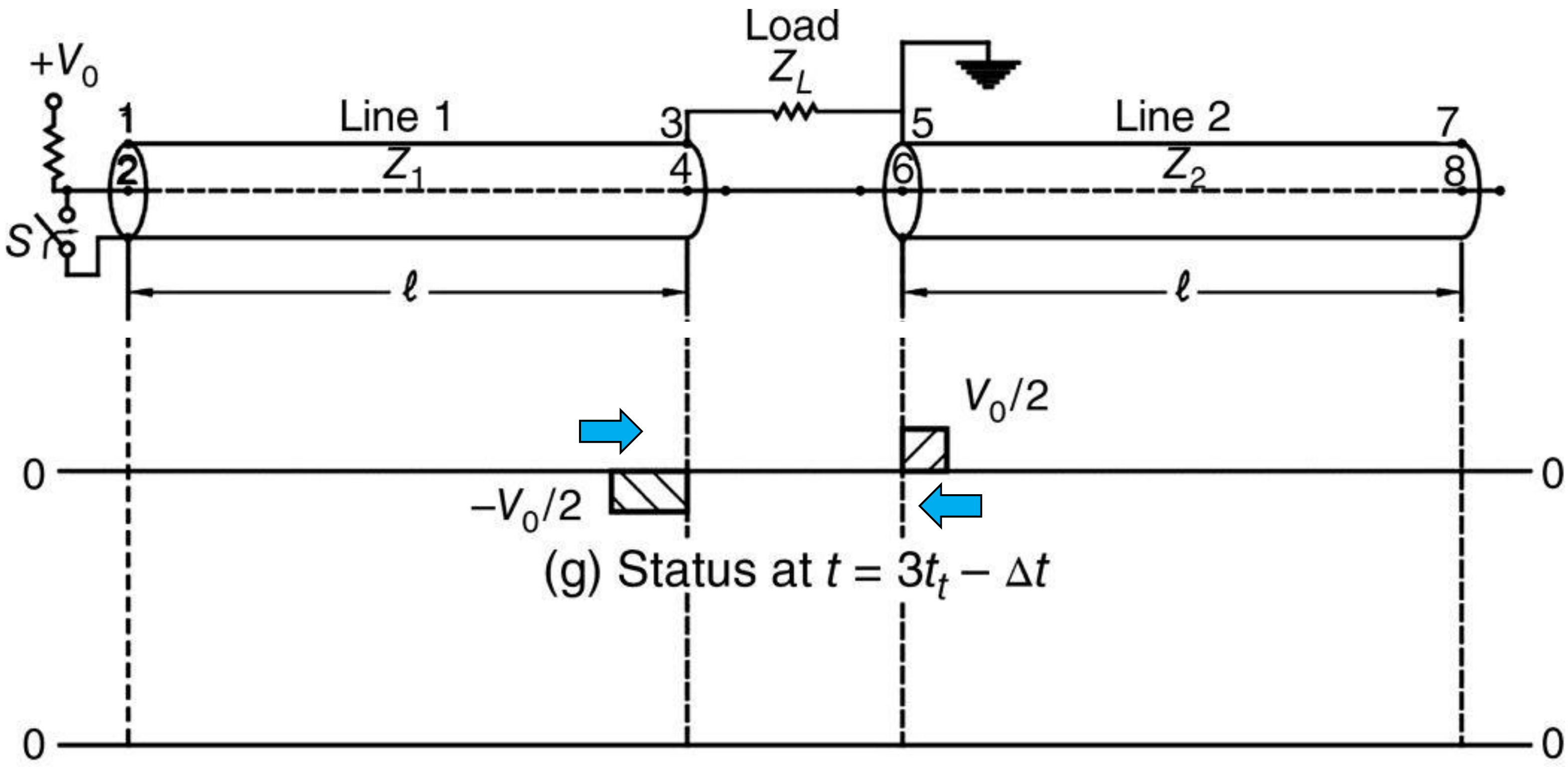
(f)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	0	0	V_0	$V_0/2$	$-V_0/2$	0	$V_0/2$	$V_0/2$	V_0	0	0	0

Sequence of Blumlein line



(g)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	0	0	V_0	$V_0/2$	$-V_0/2$	0	$V_0/2$	$V_0/2$	V_0	0	0	0

Sequence of Blumlein line

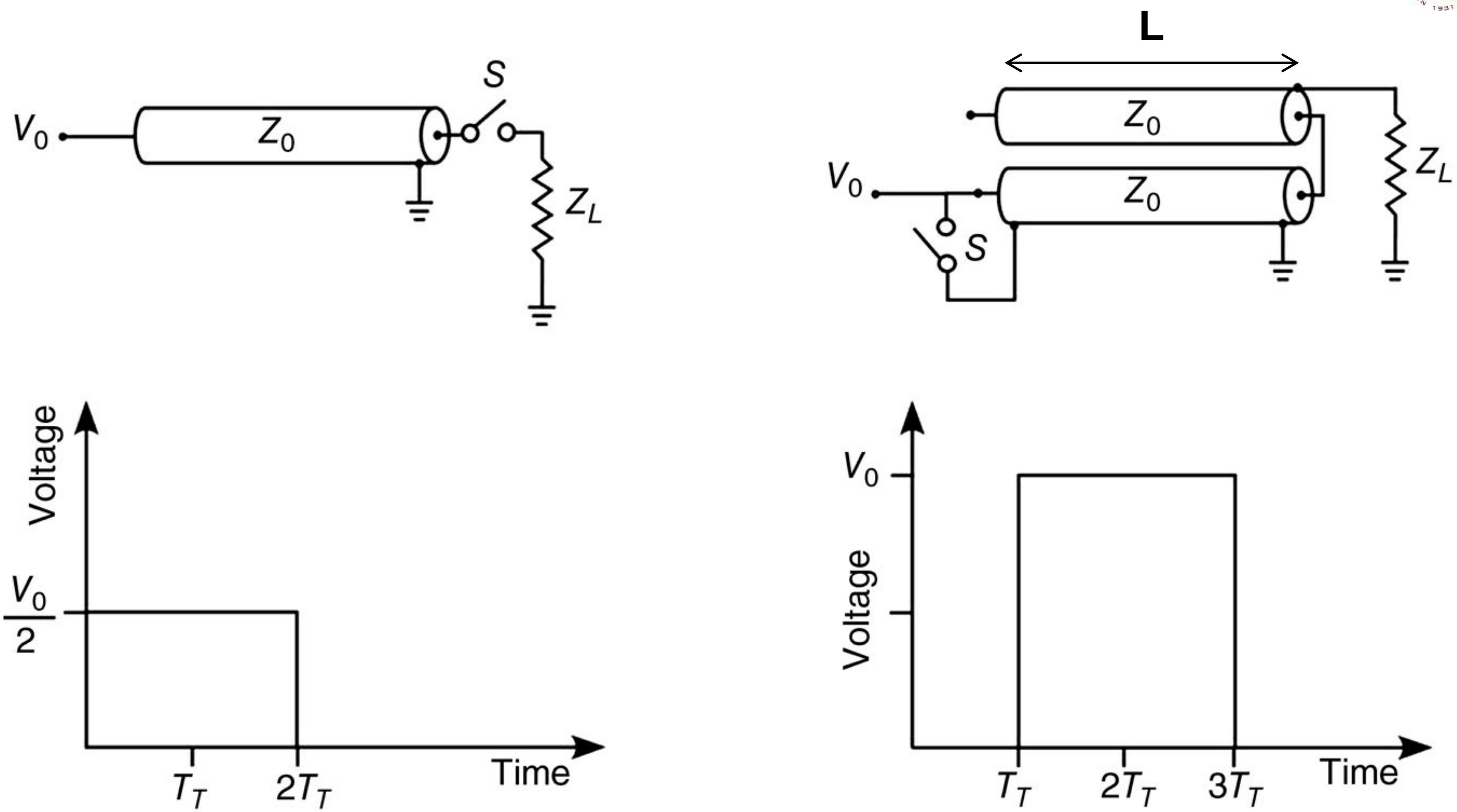


(g) Status at $t = 3t_t - \Delta t$

(h) Status at $t = 3t_t$

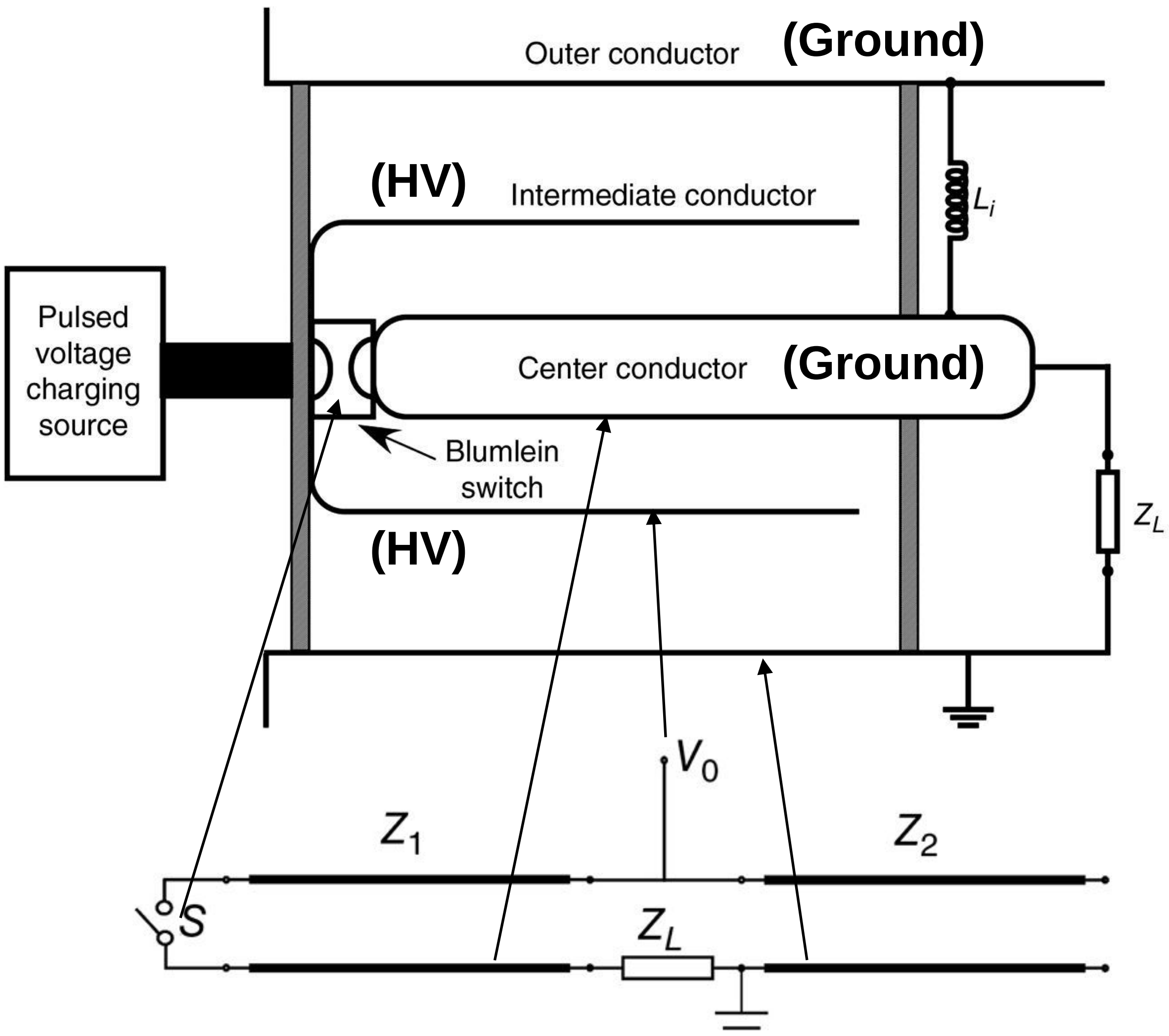
(h)	V_1	V_2	ΔV_{21}	V_3	V_4	ΔV_{43}	V_5	V_6	ΔV_{65}	V_L	V_7	V_8	ΔV_{87}
	0	0	0	0	0	0	0	0	0	0	0	0	0

A Blumlein line can be built by using two coaxial transmission line



- **Example: RG58 coaxial cable, 50 Ω, V_{signal}~$2\text{x}10^{10}$ cm/s => L=10 cm, Δt=1 ns.**

Coaxial Blumlein line

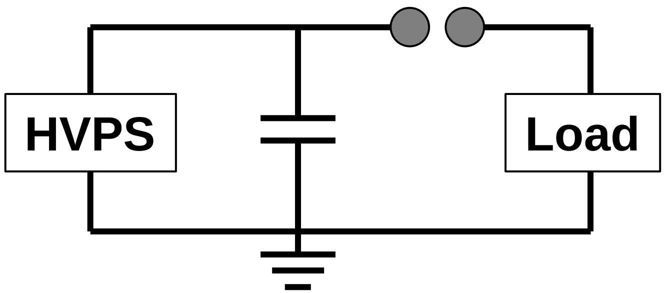


Outlines

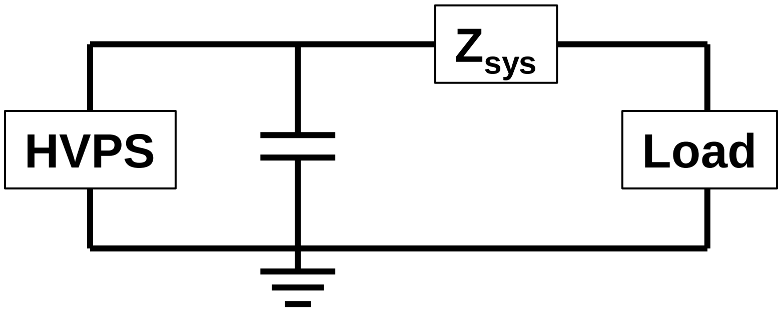
- Switches
  - Closing switches: the switching process is associated with voltage breakdown across an initially insulant element.
  - Opening switches: the switching process is associated with a sudden growth of its impedance.
- **Pulse-forming lines**
  - Blumlein line
  - **Pulse-forming network**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

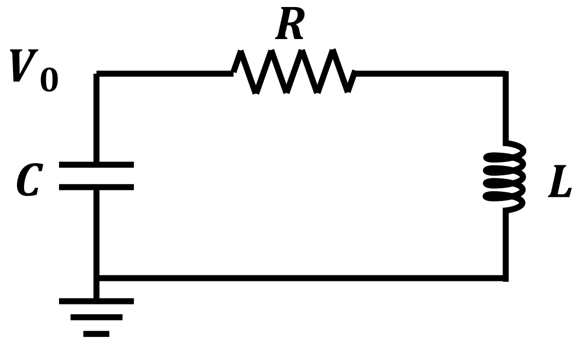
A simple pulsed-power system is a RLC circuit

- **Before discharge**

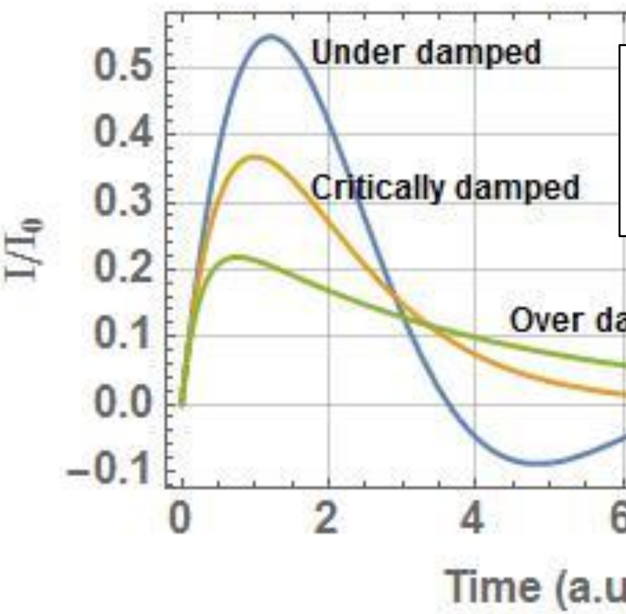


- **After discharge**



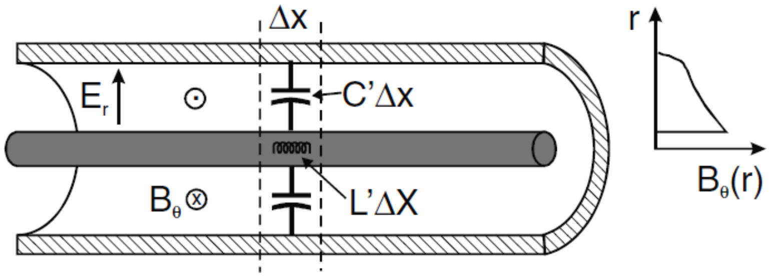


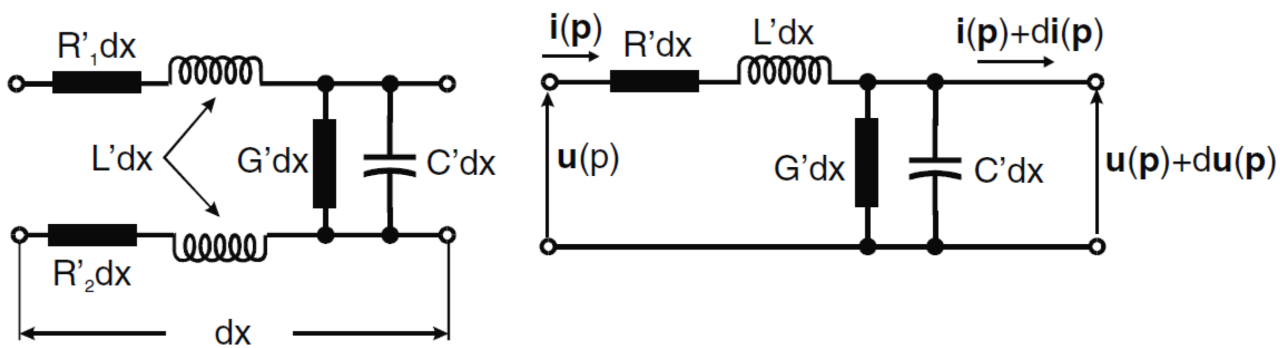
- **How can we generate a square current pulse?**

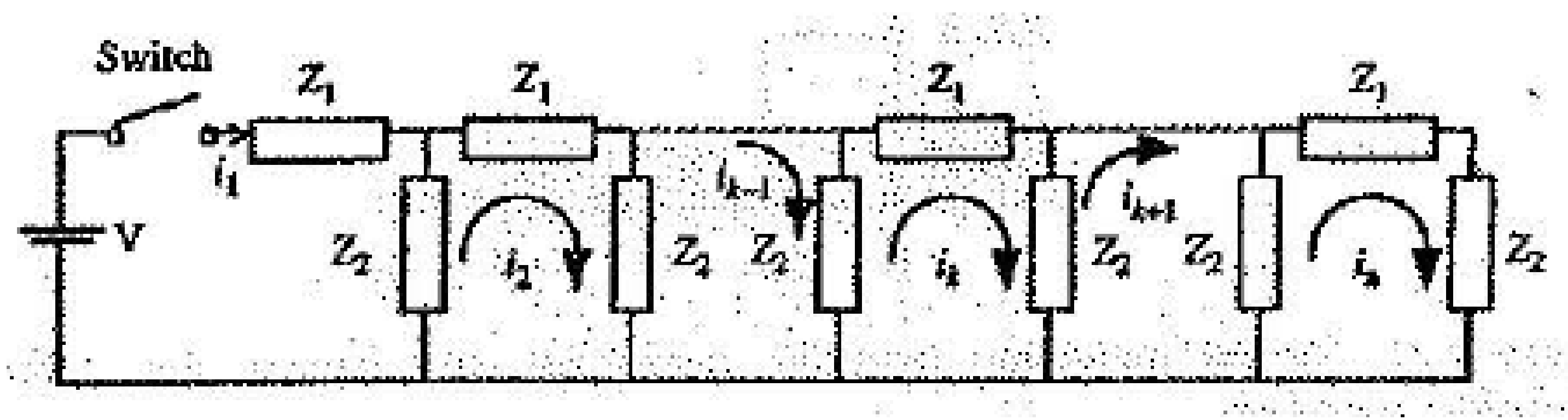


$$R_{\text{cri}} = 2\sqrt{\frac{L}{C}}$$

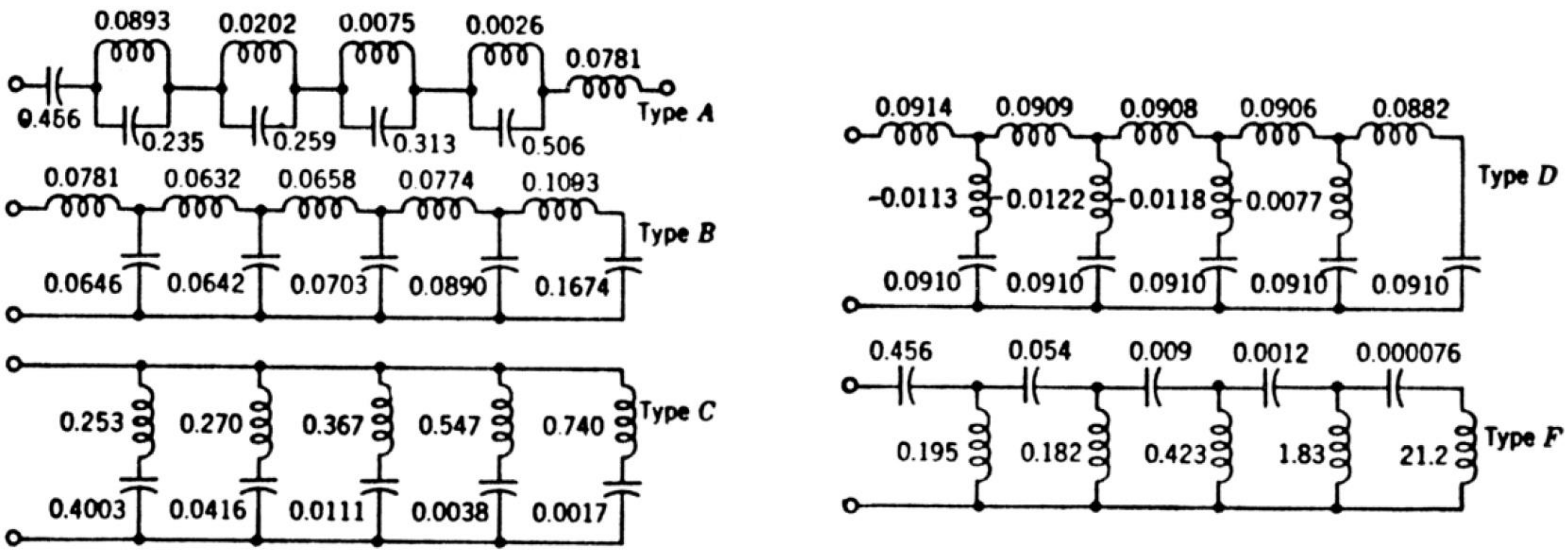
Pulse-forming network (PFN)







Equivalent Guillemin Networks



Pule-forming LC chain

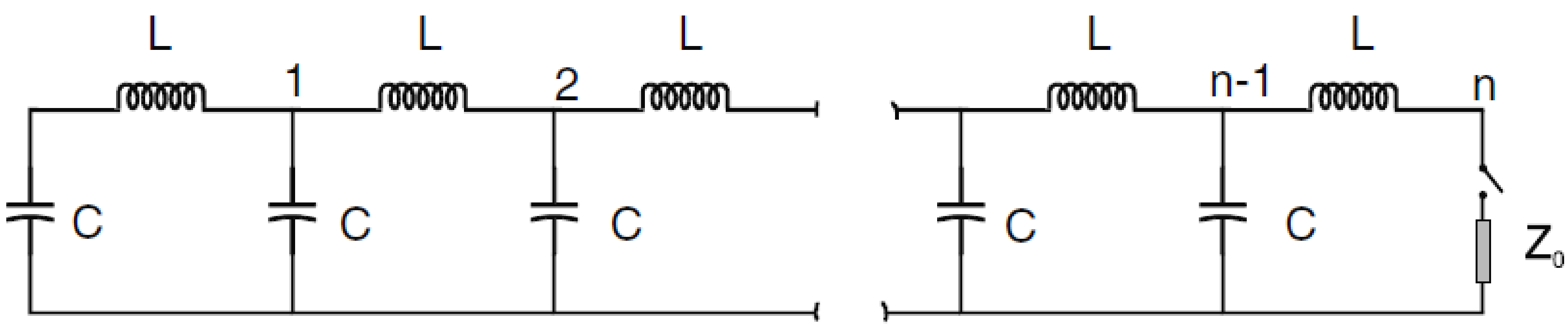
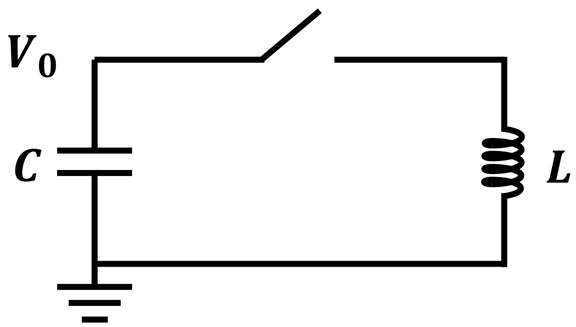


Fig. 5.11. Pulse-forming LC chain

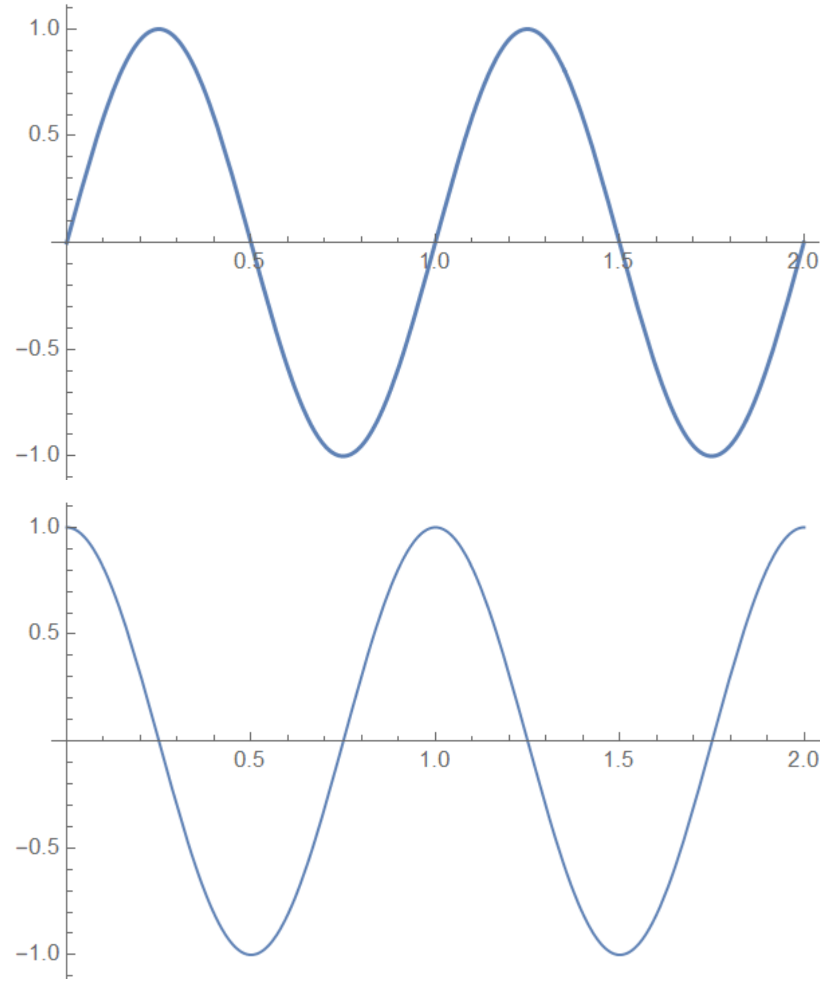
The current output of a LC circuit is a basis of Fourier series



$$I(t) = V_0\sqrt{\frac{C}{L}}\sin\left(\frac{t}{\sqrt{LC}}\right)$$

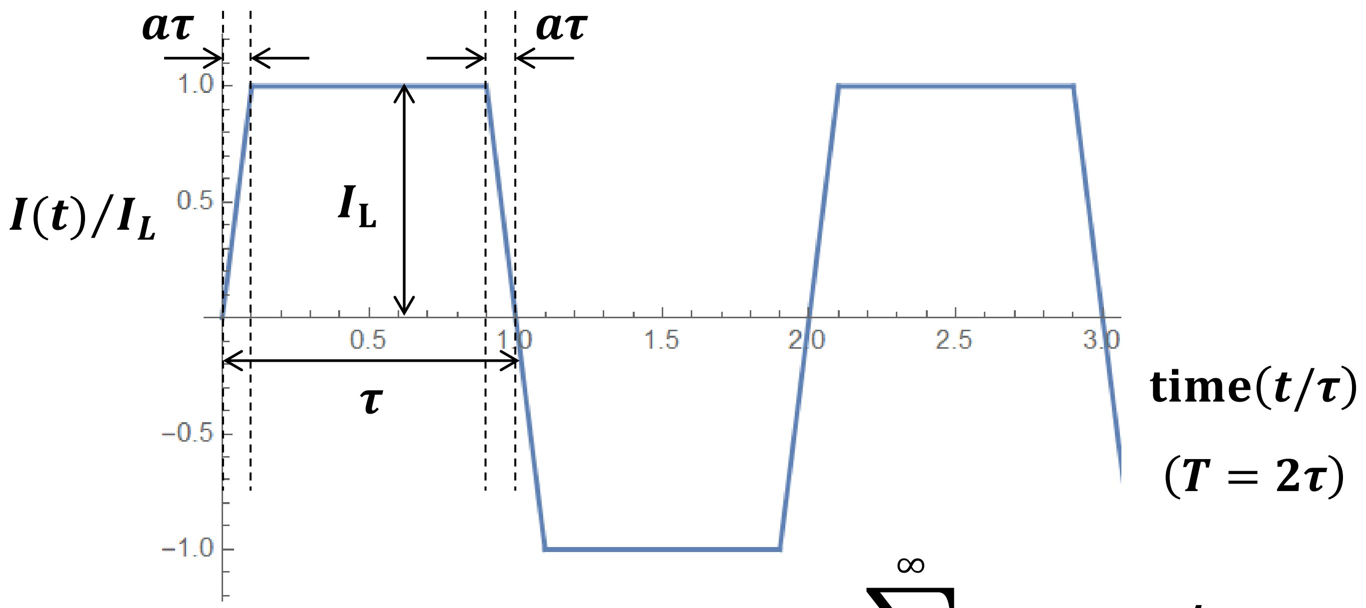
$$V(t) = V_0\cos\left(\frac{t}{\sqrt{LC}}\right)$$

$$Z = \sqrt{\frac{L}{C}} \qquad \omega = \frac{1}{\sqrt{LC}}$$



$\mathrm{time}(t/T)$

A trapezoidal wave can be expressed by Fourier series (Guillemin's method)



$$i(t) = I_L \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi t}{\tau}\right)$$

$$\frac{i(t)}{I_L} = \frac{t}{a\tau} \quad , 0 \le t \le a\tau$$

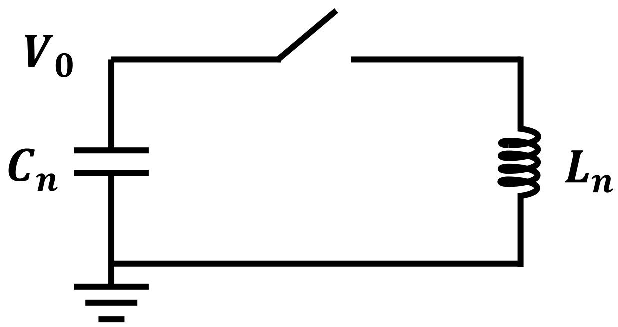
$$\frac{i(t)}{I_L} = 1 \quad , a\tau \le t \le \tau - a\tau$$

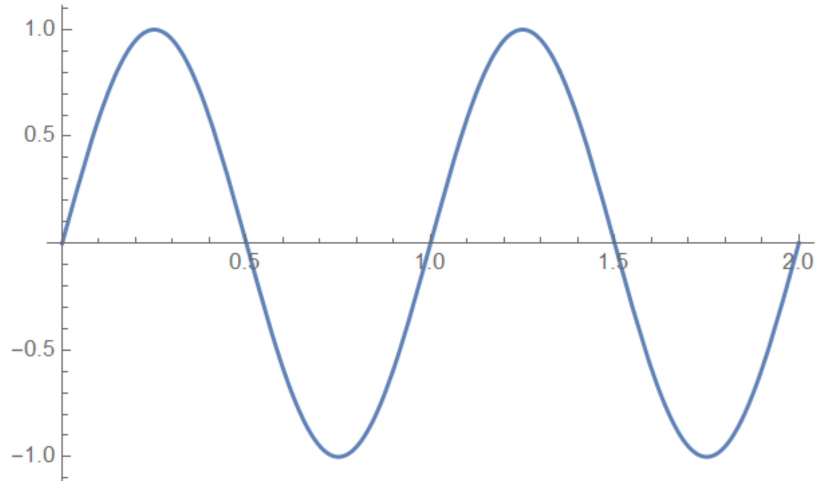
$$\frac{i(t)}{I_L} = \frac{\tau - t}{a\tau} \quad , \tau - a\tau \le t \le \tau$$

where $b_n = \frac{2}{\tau}\int_0^{\tau} \frac{i(t)}{I_L} \sin\left(\frac{n\pi t}{\tau}\right) \mathrm{d}t$

$$b_n = \frac{4}{n\pi}\frac{\sin(n\pi a)}{n\pi a}, \text{where } n = 1, 3, 5 \ldots$$

The required inductance and capacitance are obtained by comparing LC output with the Fourier series





$$I_n(t) = V_0\sqrt{\frac{C_n}{L_n}}\sin\left(\frac{t}{\sqrt{L_nC_n}}\right)$$

$$i(t) = I_L\sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi t}{\tau}\right)$$

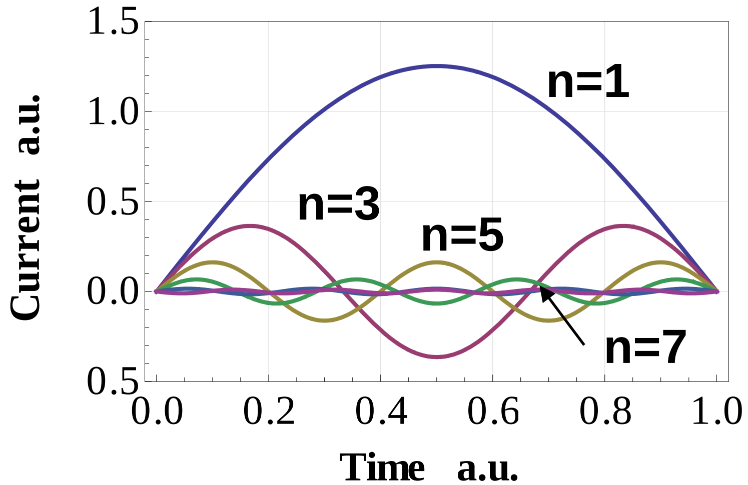
$$b_n = \frac{4}{n\pi}\,\frac{\sin(n\pi a)}{n\pi a}, \text{where } n = 1, 3, 5\ldots$$

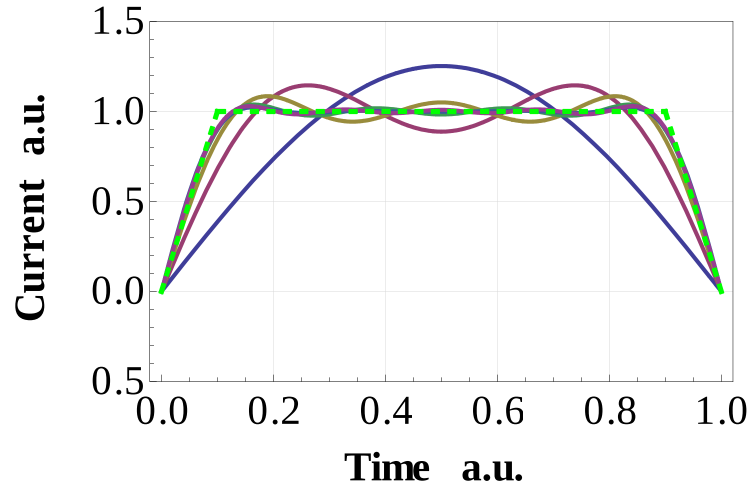
$$L_n = \frac{Z_n\tau}{n\pi b_n} = \frac{V}{I_L}\,\frac{\tau}{n\pi b_n}$$

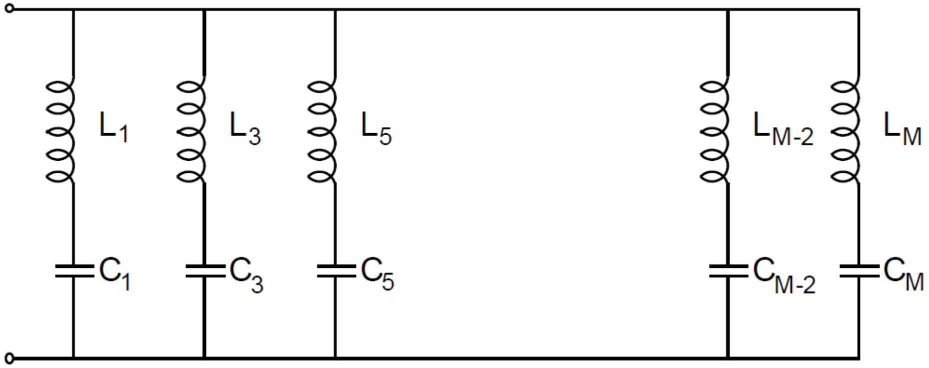
$$C_n = \frac{\tau b_n}{n\pi Z_n} = \frac{I_L}{V}\,\frac{\tau b_n}{n\pi}$$

$$Z_n = \frac{V}{I_L}$$

A trapezoidal current output can be generated using Guillemin's pulse-forming networks





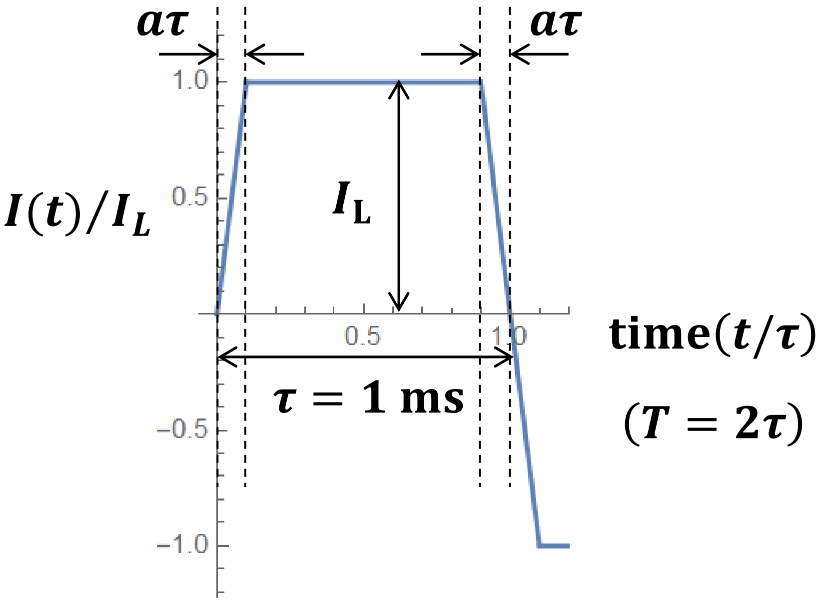


$$I(t) = I_L \Sigma b_n \mathrm{Sin}\left(\frac{n\pi t}{\tau}\right)$$

$$b_n = \frac{4}{n\pi}\,\frac{\mathrm{Sin}(n\pi a)}{n\pi a}$$

$$L_n = \frac{Z\tau}{n\pi b_n} \quad C_n = \frac{\tau b_n}{n\pi Z} \quad Z = \frac{V}{I_L}$$

Fourier components of τ=1 ms, a=0.1



$$i(t) = I_L \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi t}{\tau}\right)$$

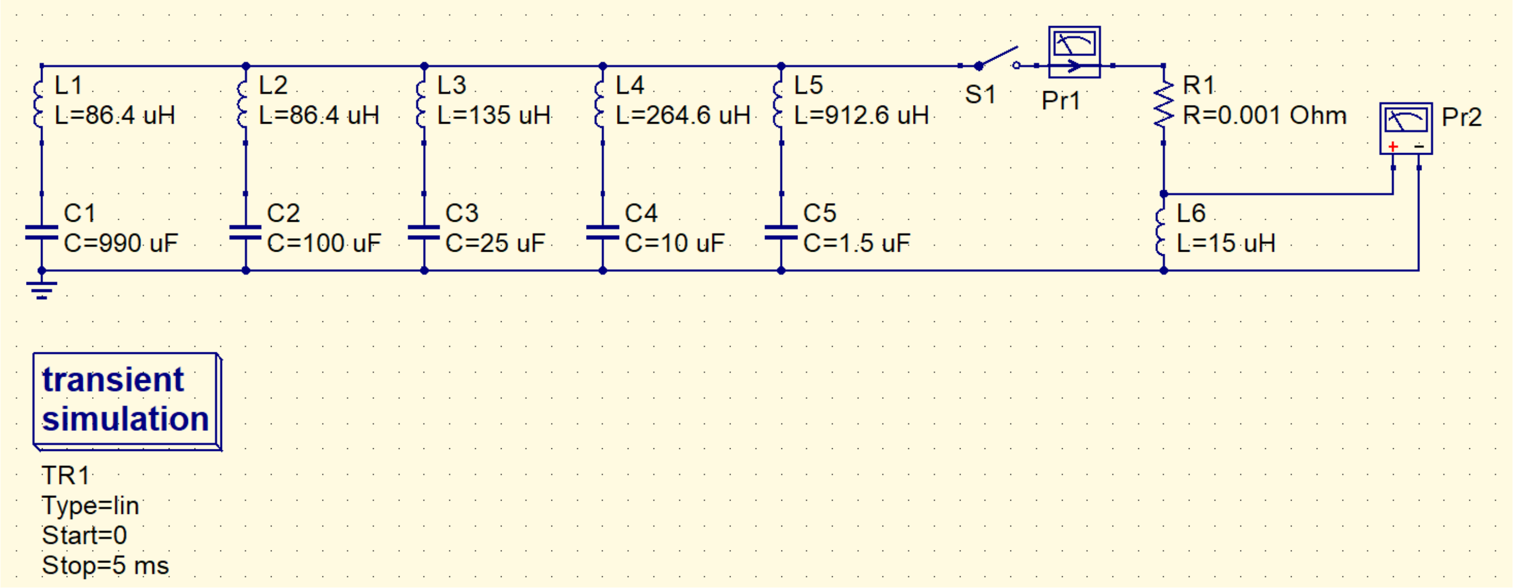
$$b_n = \frac{4}{n\pi}\frac{\sin(n\pi a)}{n\pi a}, \text{where } n = 1, 3, 5\ldots$$

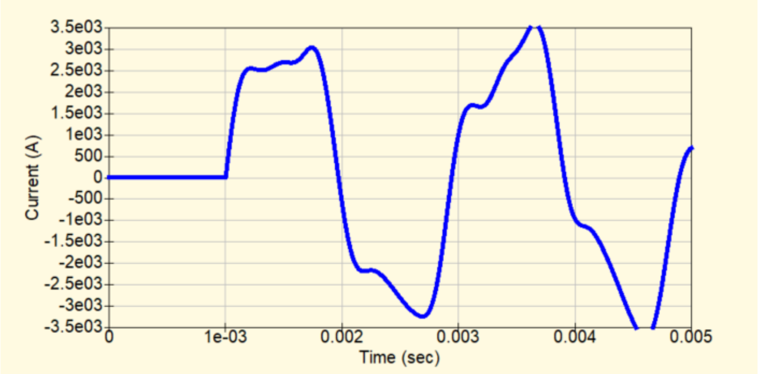
n	#I
b1	1.2524
b3	0.3643
b5	0.1621
b7	0.069
b9	0.0155

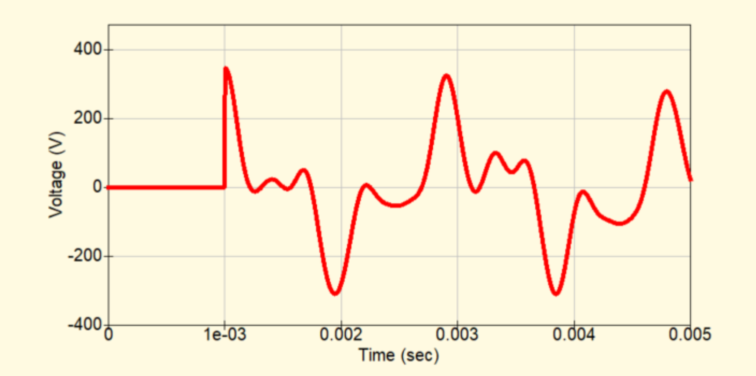
Coils with 8 turns and a PFN charged to 1 kV will be used

I (kA)	V (kV)		1	2	3	4	5	E (kJ)	% to 100 J
20	2	L(uH)	25.4	26.1	39.3	68.0	228.7	9.0	1.1 %
		C(uF)	3986.5	386.5	103.2	30.4	5.5		
20	1	L(uH)	12.7	14.6	19.6	34.0	114.4	4.5	2.2 %
		C(uF)	7973.0	773.1	206.4	60.9	10.9		
2.5	2	L(uH)	203.3	233.0	314.2	543.7	1830.0	1.1	8.9 %
		C(uF)	498.3	48.3	12.9	3.8	0.7		
2.5	1	L(uH)	101.7	116.5	157.1	271.8	915.0	0.6	17.7 %
		C(uF)	996.6	96.6	25.8	7.6	1.4		

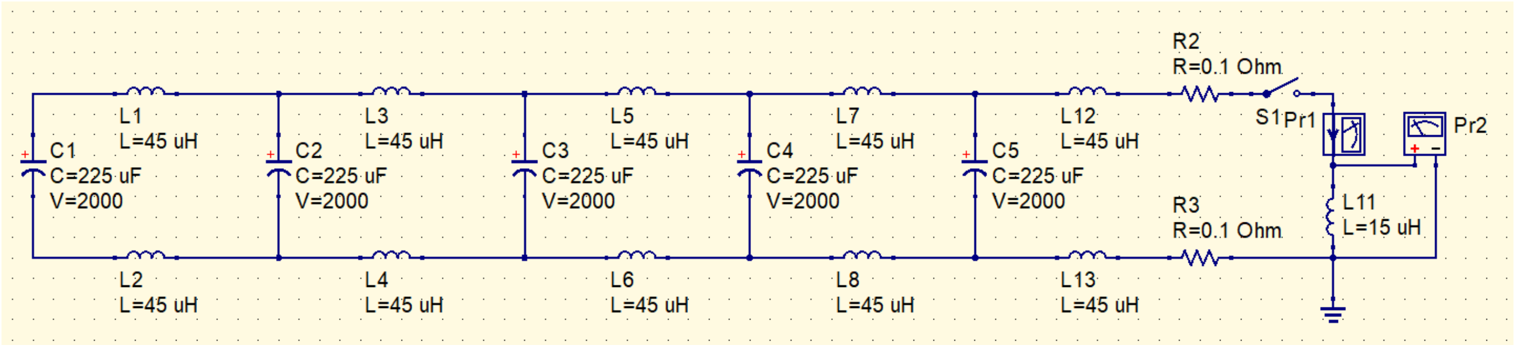
A square pulse with a flat top of 2.5 kA can be generated







A simple PFN with constant C and L in all stages can also be used



$$C \equiv \bar{C} = \frac{1}{N}\sum_{n=1}^{N} C_n = 225\mu\text{F}$$

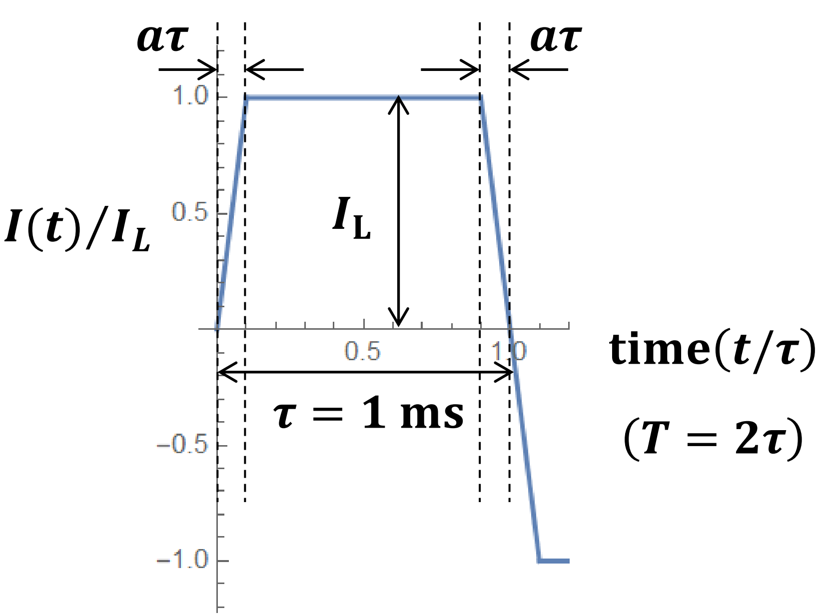
$$L_n = 2nL + L_L \approx 2nL$$

$$\omega_n = \frac{1}{\sqrt{L_n C}} \approx \frac{1}{\sqrt{2nLC}}$$

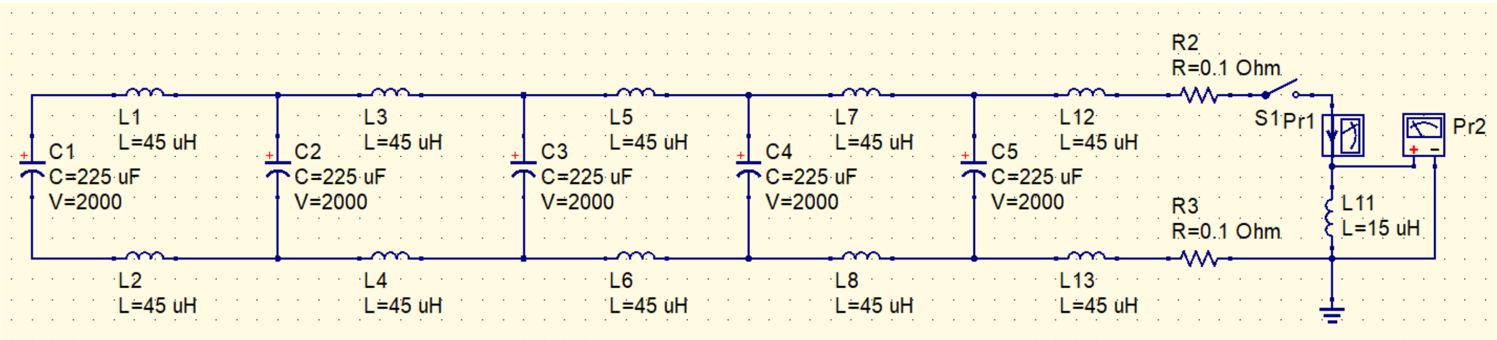
- **For 5 stages:**

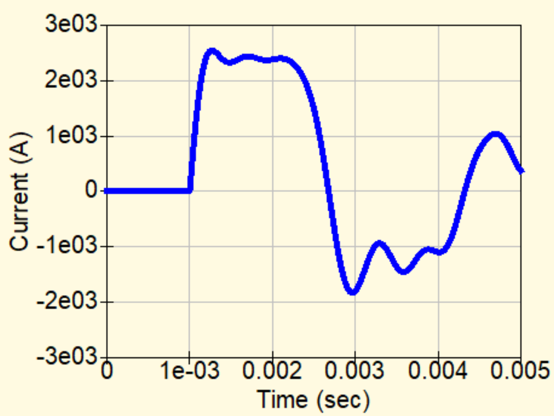
$$\omega_5 = \frac{2\pi}{T} = \frac{\pi}{\tau} = \frac{\pi}{1\text{ms}}$$

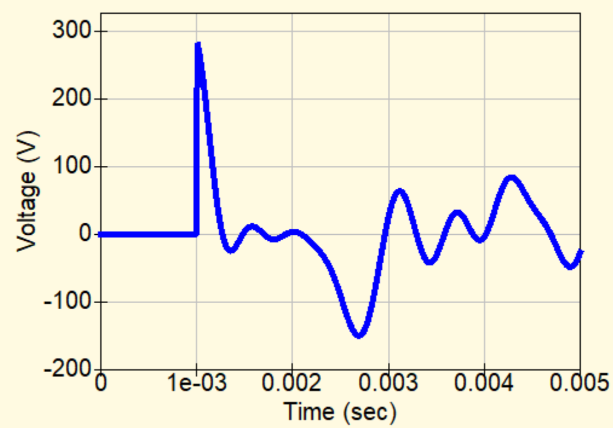
$$L = 45\mu\text{H}$$



The energy coupling efficiency is lower using the simple PFN



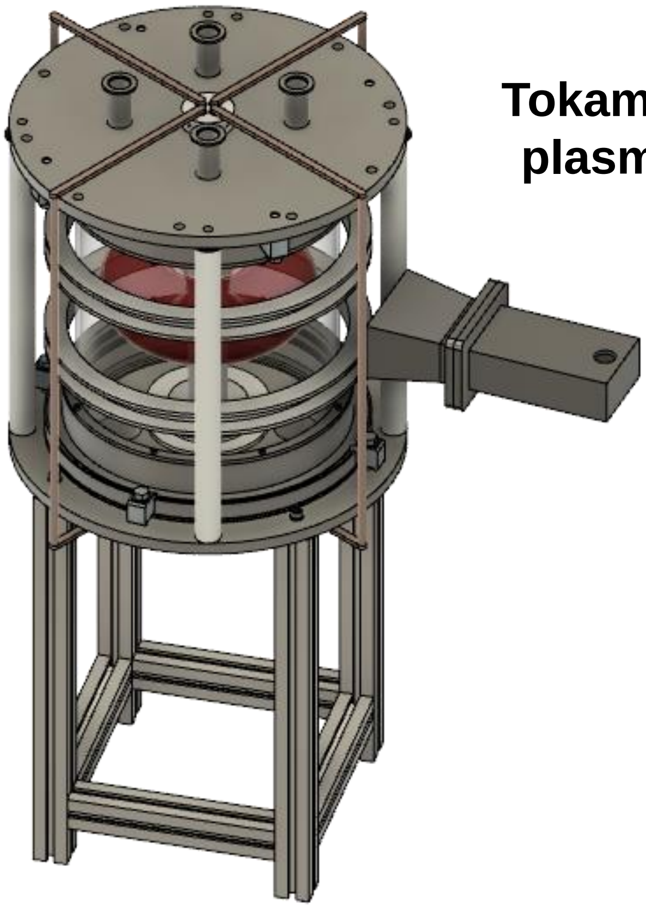


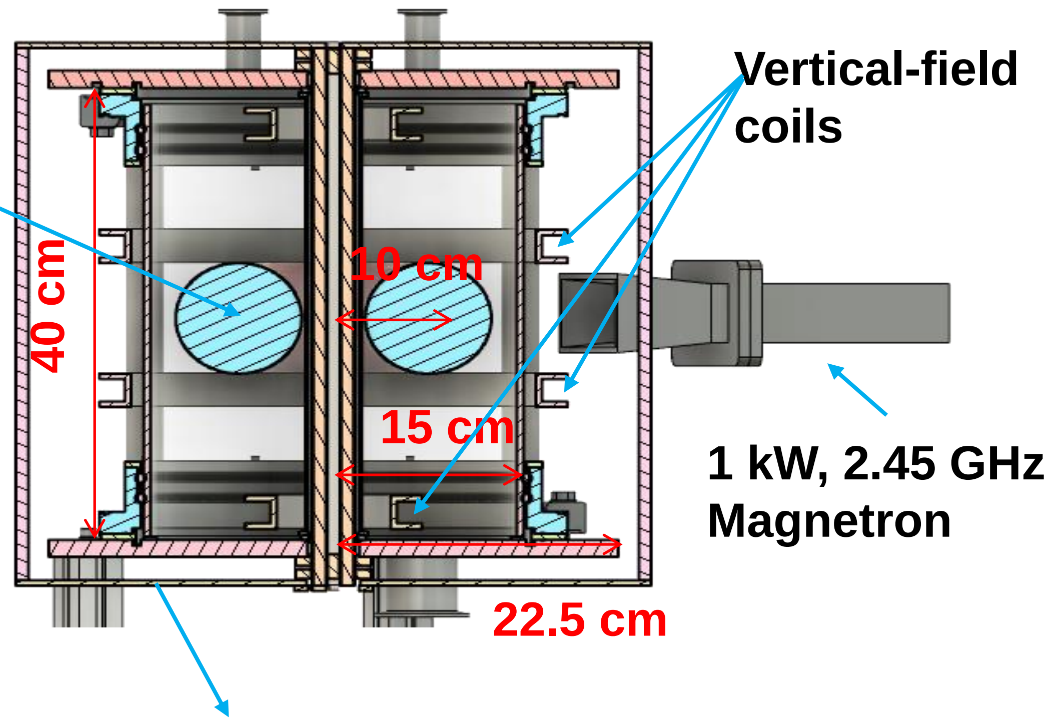


$$E = \frac{1}{2}CV^2 = 2.25\text{kJ}$$

- **Only 4.4 % of the energy is transferred to magnetic energy.**

Mini-spherical tokamak

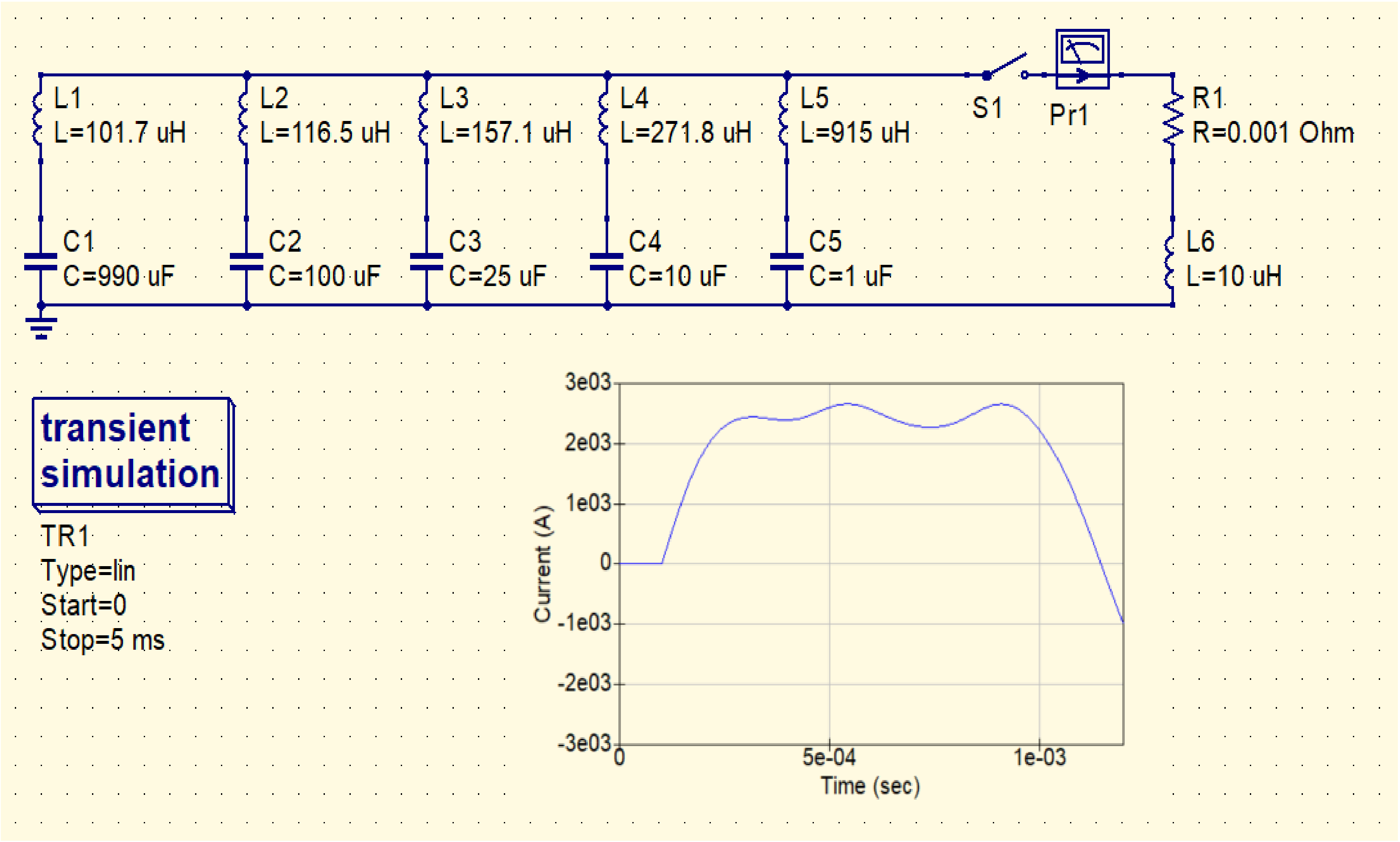




4 toroidal-field coil connected in series. 1 ms, 2.5 kA pulsed-current.

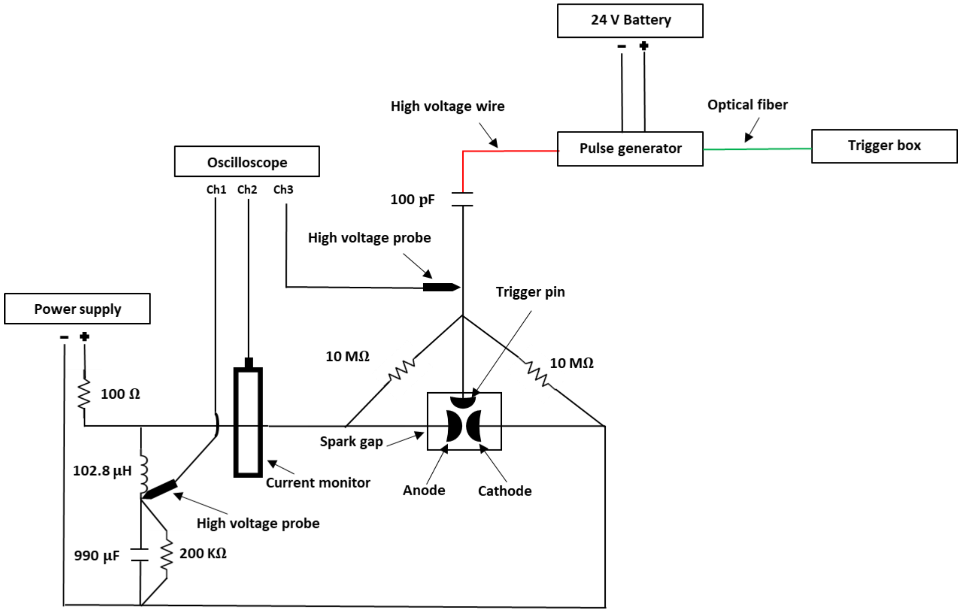
B=876 G @ 4.6 cm will be used for ECR heating.

A square pulse of 2.5-kA current output with duration of 1 ms can be provided

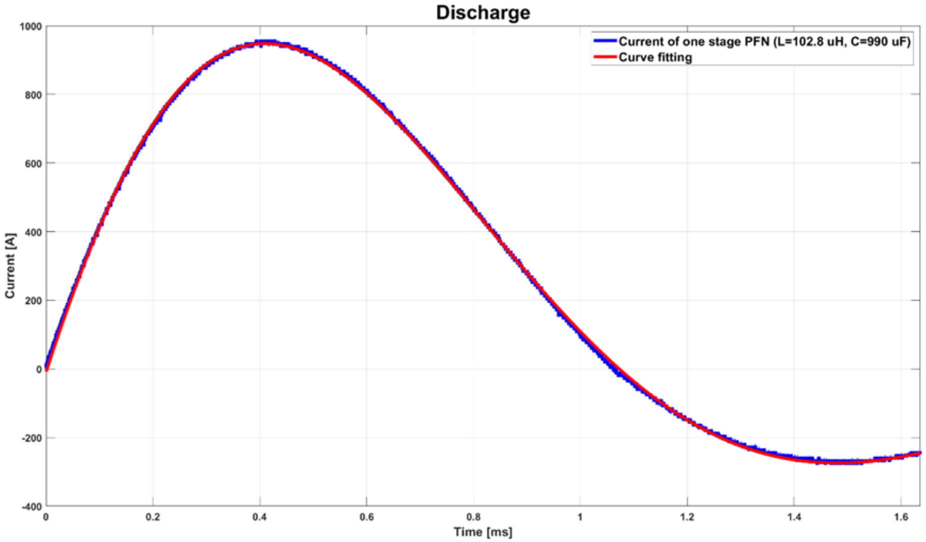


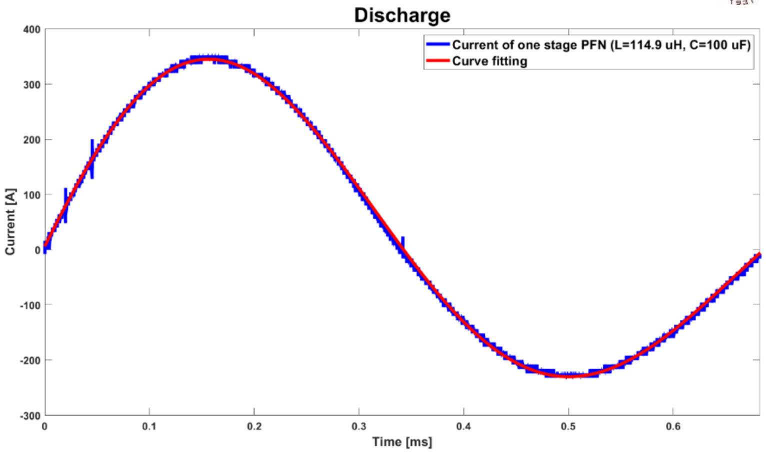
The actual components were determined by what we could get

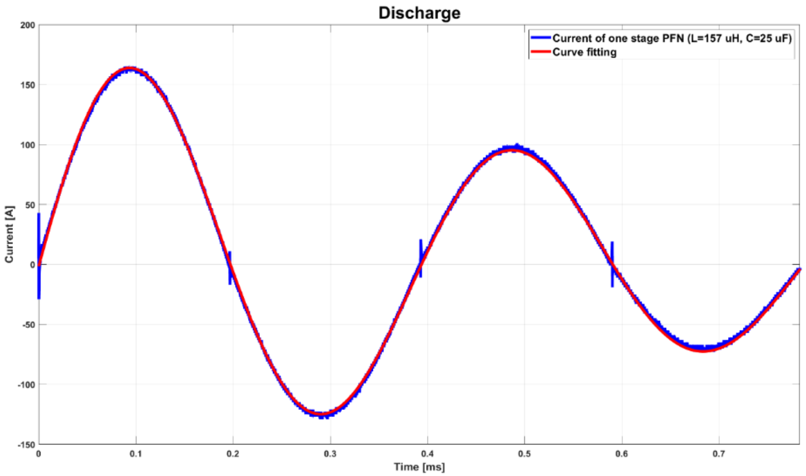
	I (kA)	V (kV)		1	2	3	4	5
• Design:	2.5	1	L(uH)	101.7	116.5	157.1	271.8	915.0
			C(uF)	996.6	96.6	25.8	7.6	1.4
• Built:	2.5	1	L(uH)	102.8	114.9	157	270	-
			C(uF)	990	100	25	10	-

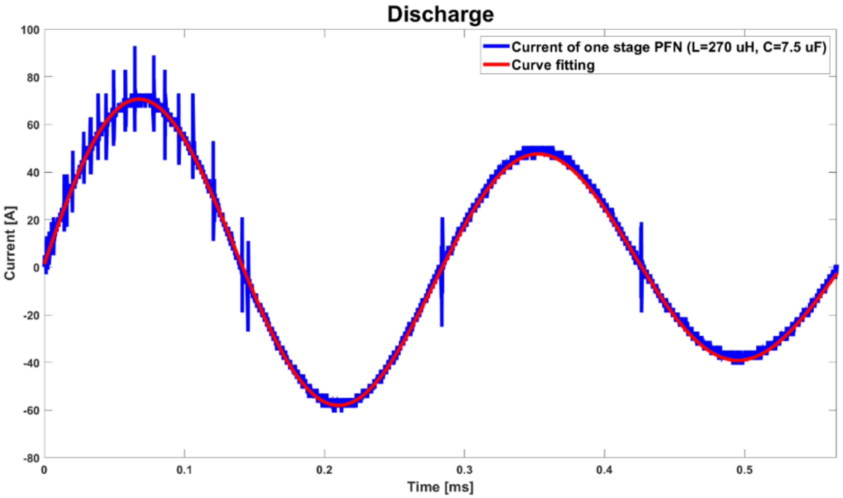


Discharge current measurements

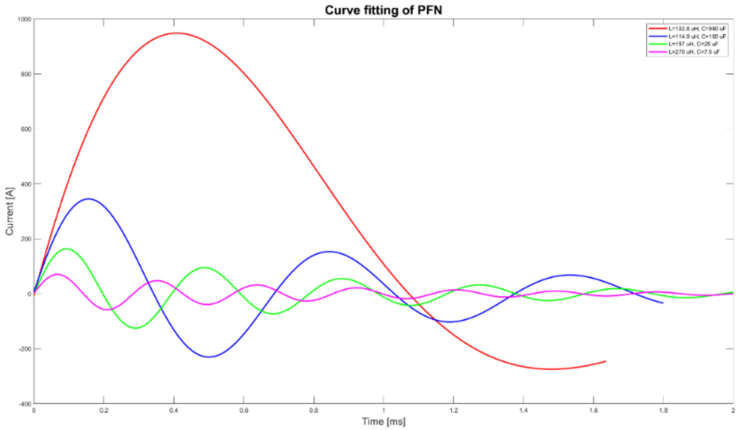




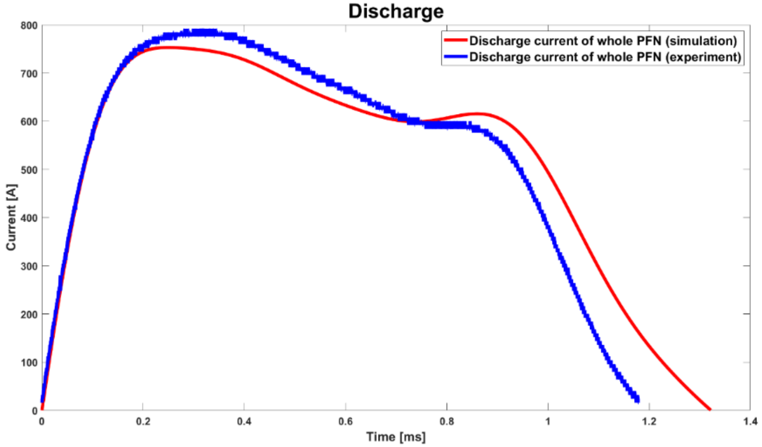


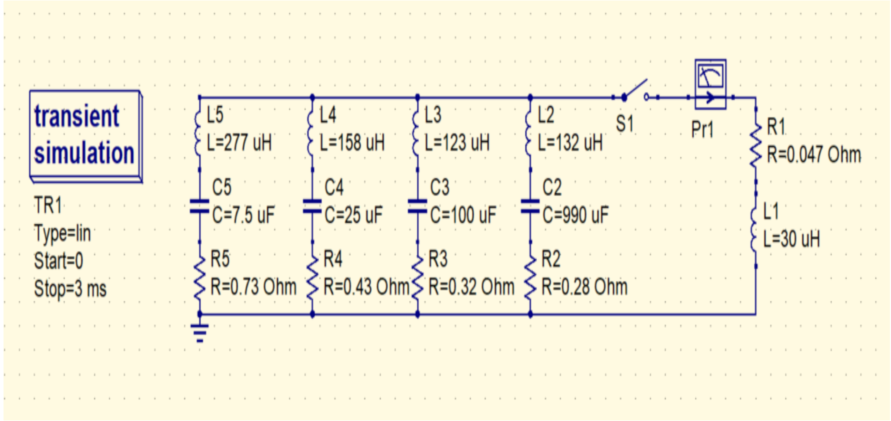


Resistant played an important role



Stage	C (theory)	L (theory)	L (measure)	R (measure)
1	990 (uF)	102.8 (uH)	132±4 (uH)	0.28±0.01 (Ω)
2	100 (uF)	114.9 (uH)	123±0.4 (uH)	0.32±0.02 (Ω)
3	25 (uF)	157 (uH)	158±1 (uH)	0.43±0.01 (Ω)
4	7.5 (uF)	270 (uH)	277±7 (uH)	0.73±0.03 (Ω)



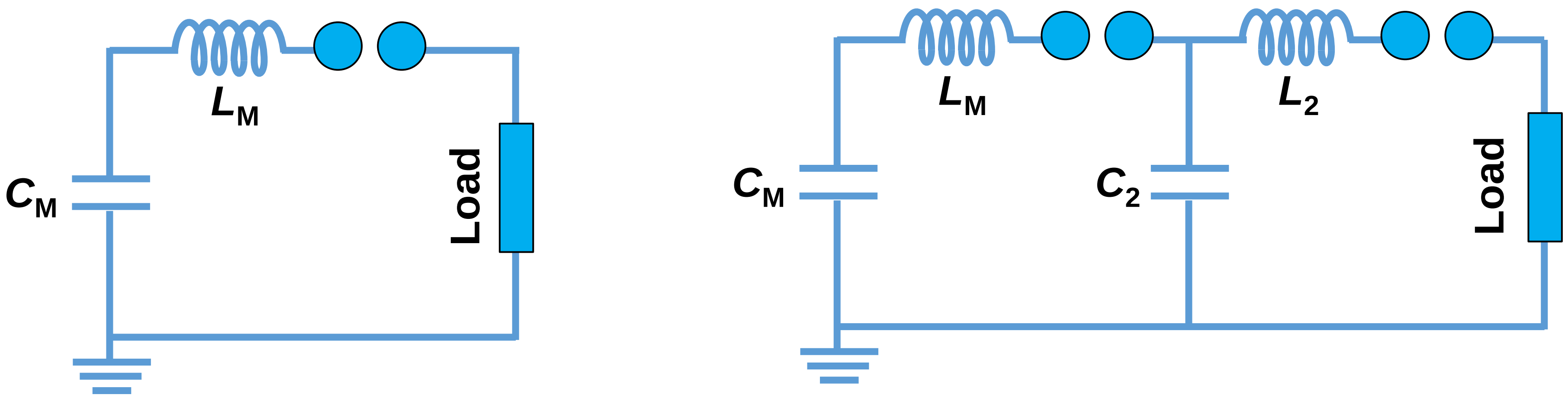


Outlines

- 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

Capacitor load

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



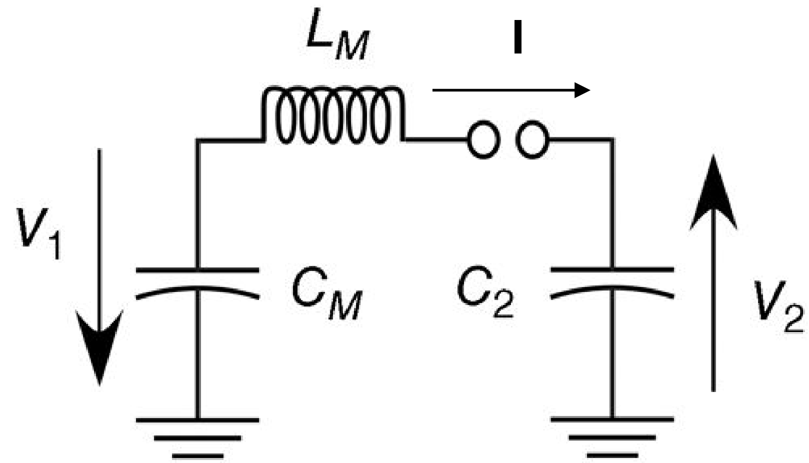
$$I_0 = \frac{V_0}{\sqrt{L_M/C_M}} \qquad \omega_0 = \frac{1}{\sqrt{L_M C_M}}$$

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

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

Capacitor load

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



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

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

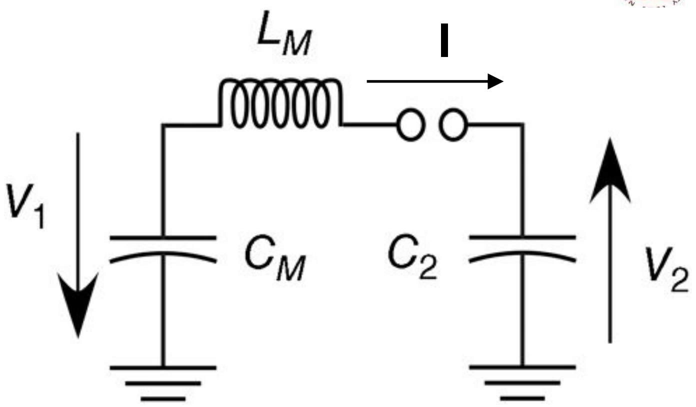
$$V_M - \frac{1}{C_M} \int I \,\mathrm{d}t - L_M \frac{\mathrm{dI}}{\mathrm{dt}} = \frac{1}{C_2} \int I \,\mathrm{d}t$$

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

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

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

Capacitor load



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

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

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

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

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

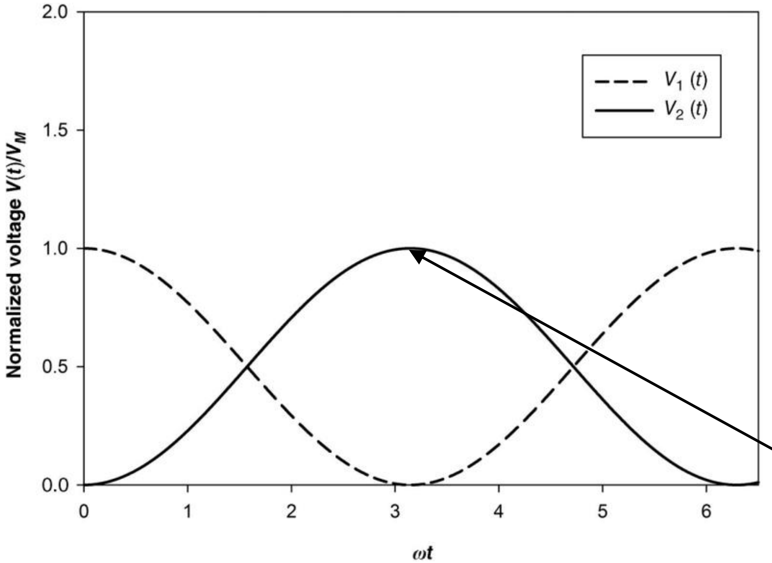
$$I(t) = \frac{V_M}{L\omega} \sin(\omega t)$$

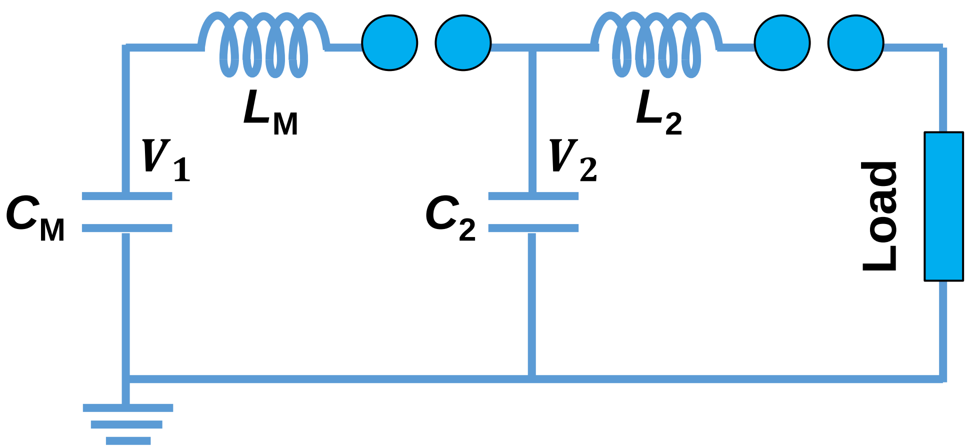
$$V_1 = V_M - \frac{1}{C_M}\int_0^t \frac{V_M}{L\omega} \sin(\omega t)\, dt = V_M - \frac{V_M C_2}{C_M + C_2}[1 - \cos(\omega t)]$$

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

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

Pulse compression scheme: $C_2 \sim C_M$





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

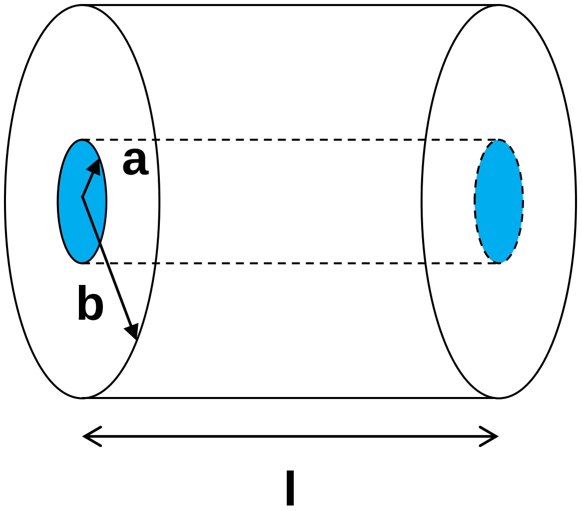
$$V_1 = V_M - \frac{V_M C_2}{C_M + C_2}[1 - \cos(\omega t)] \approx V_M - \frac{V_M}{2}[1 - \cos(\omega t)]$$

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

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

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

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



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

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

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

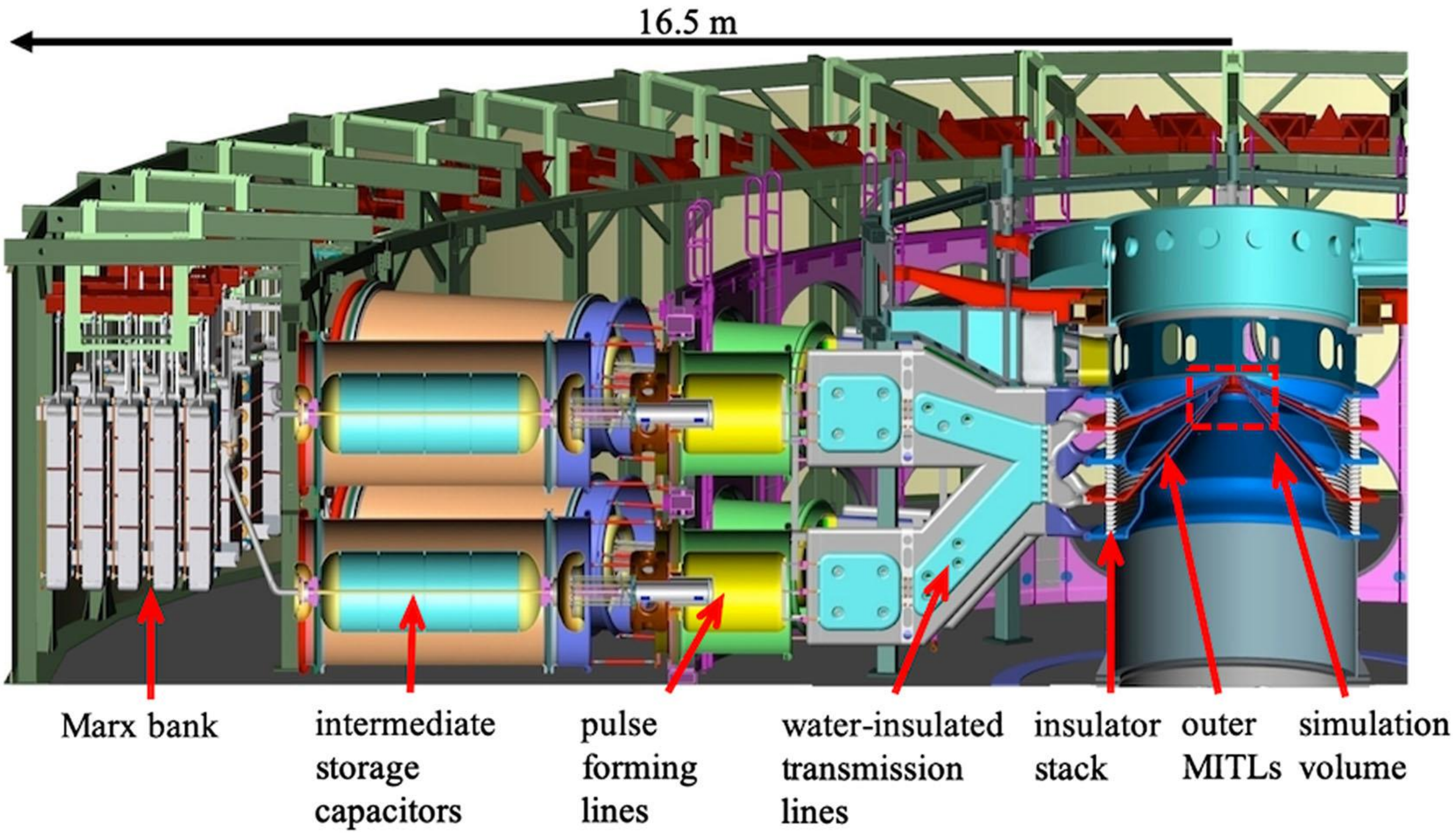
Ex: KALIF, bipolar Marx generator, charged up to ±100 kV. $V_{M,out}$=5 MV.

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

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

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

Intermediate storage capacitors can be used to compress the pulse

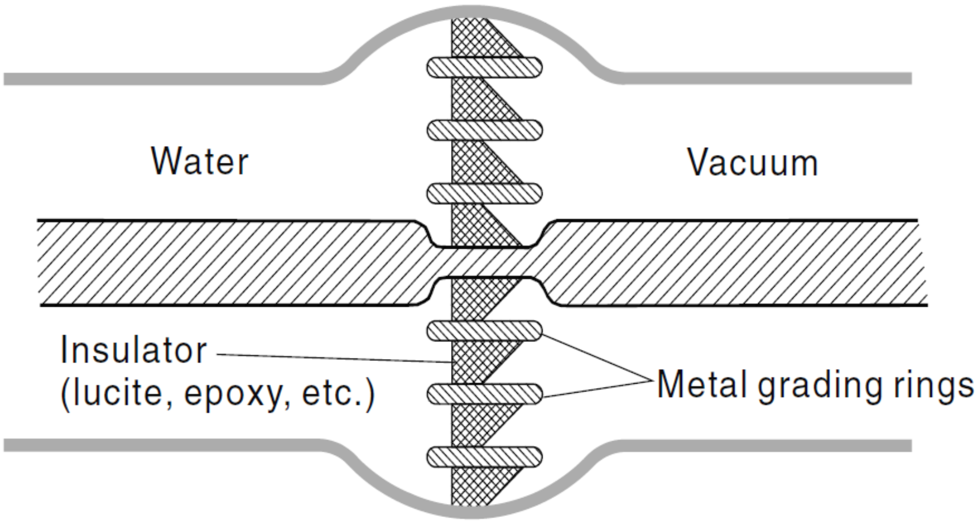


Outlines

- 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**

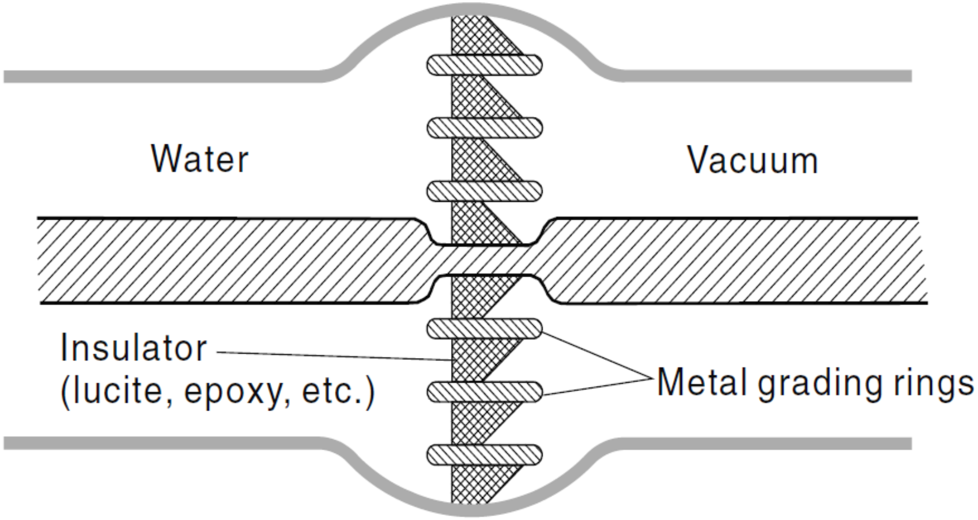
Insulating interface separating the vacuum section and the liquid dielectric is needed

- Some tasks in science and technology required brightness of intense pulsed radiation > 100 TW/cm^2-Sr. With E > 1 MJ, electric power > 100 TW, electric power flux density > 100TW/m^2 are needed.
- Vacuum environment is required.
- High-voltage pulse must enter a vacuum vessel hosting the source through an insulating interface separating the liquid dielectric from the vacuum section.



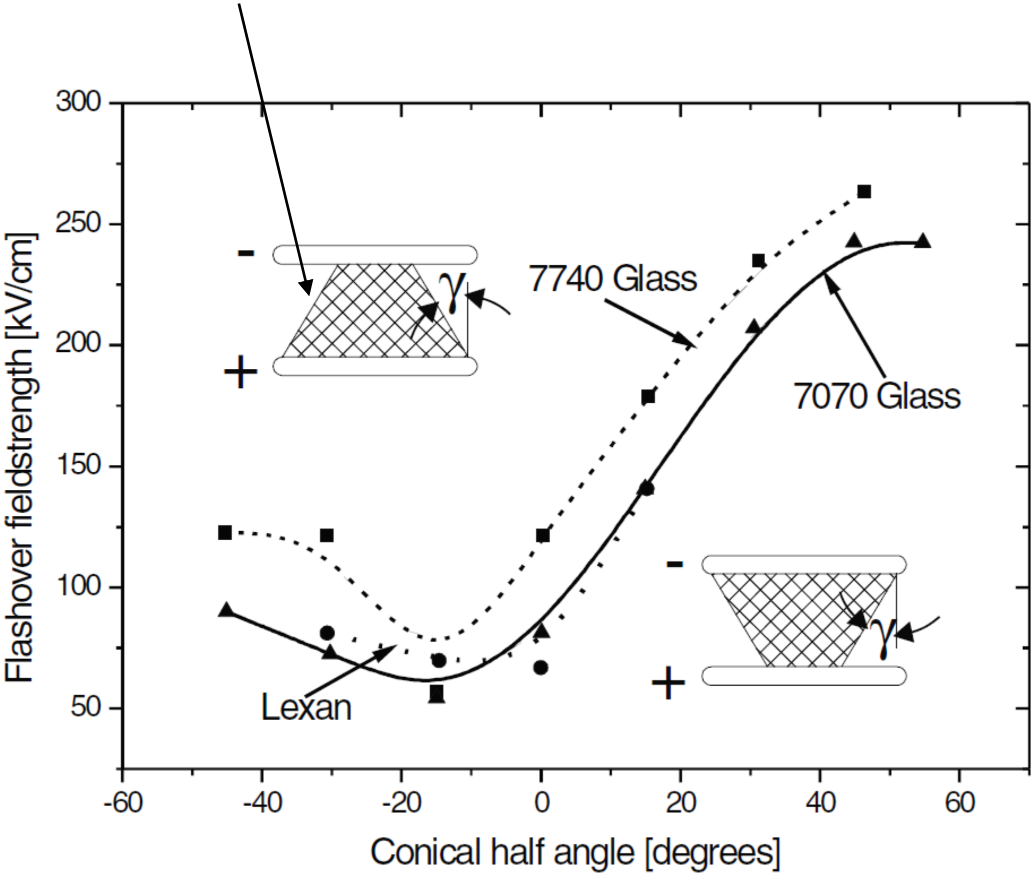
The interface consists of insulating rings separated by metallic grading rings

- The metal grading rings are used to distribute the potential homogeneously over the interface on the vacuum surface.
- The metallic and dielectric rings are sealed to hold the high vacuum either by O-rings or by Metal-to-dielectric bond.
- Sparking on the surface on the vacuum side is more important.
- Electrons may be produced by field emission on metallic surfaces.



The side surface of the dielectric material is tilted to prevent flash over

- Out gassing: gas from the "absorbs" released by electron bombardment.
- Electron avalanches may occur with the tangential electric field from the space charge on insulator.

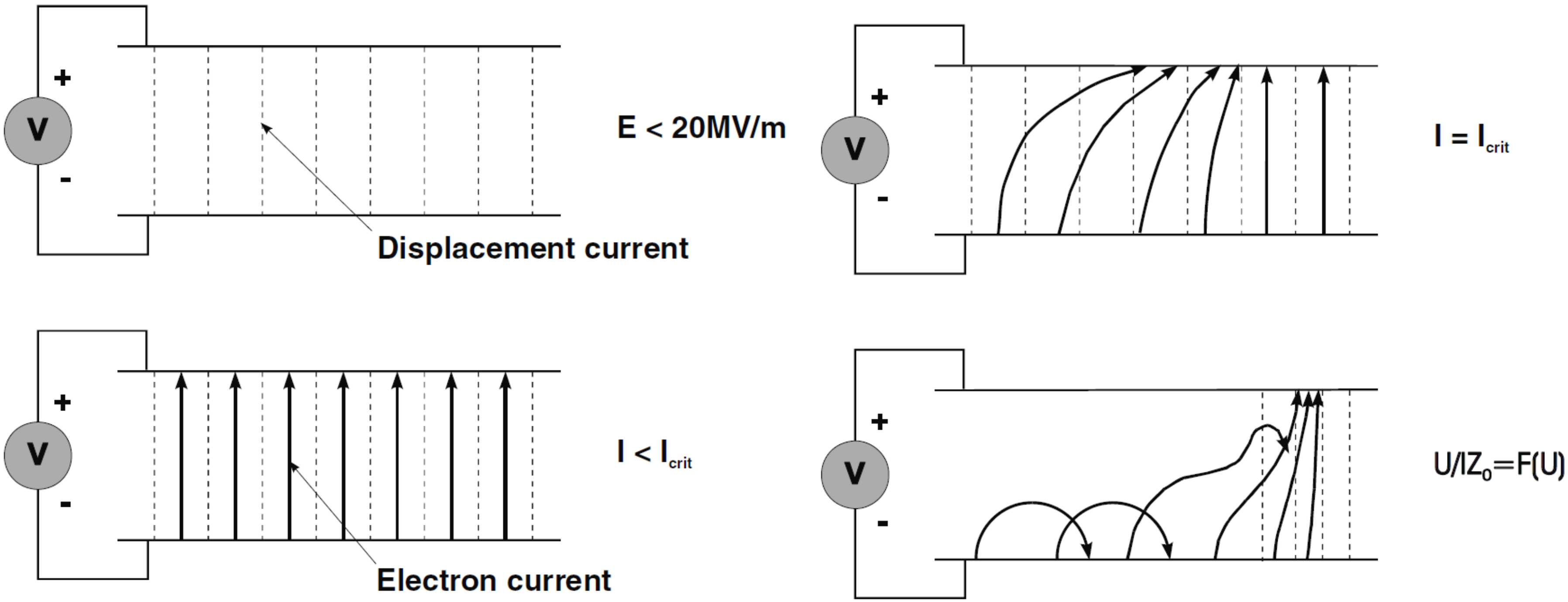


- **Dielectric-vacuum interface is the weakest element of a high-voltage pulse line under E-field stress.**

$$E_{\mathrm{DB}} = \frac{7 \times 10^5}{t^{1/6} A^{1/10}} (V/m)$$

- **t: time when E > 87% E_{max}.**
- **For t=10 ns, E_{max}=20MV/m, Max power density that can be delivered is 1 TW/m^2.**

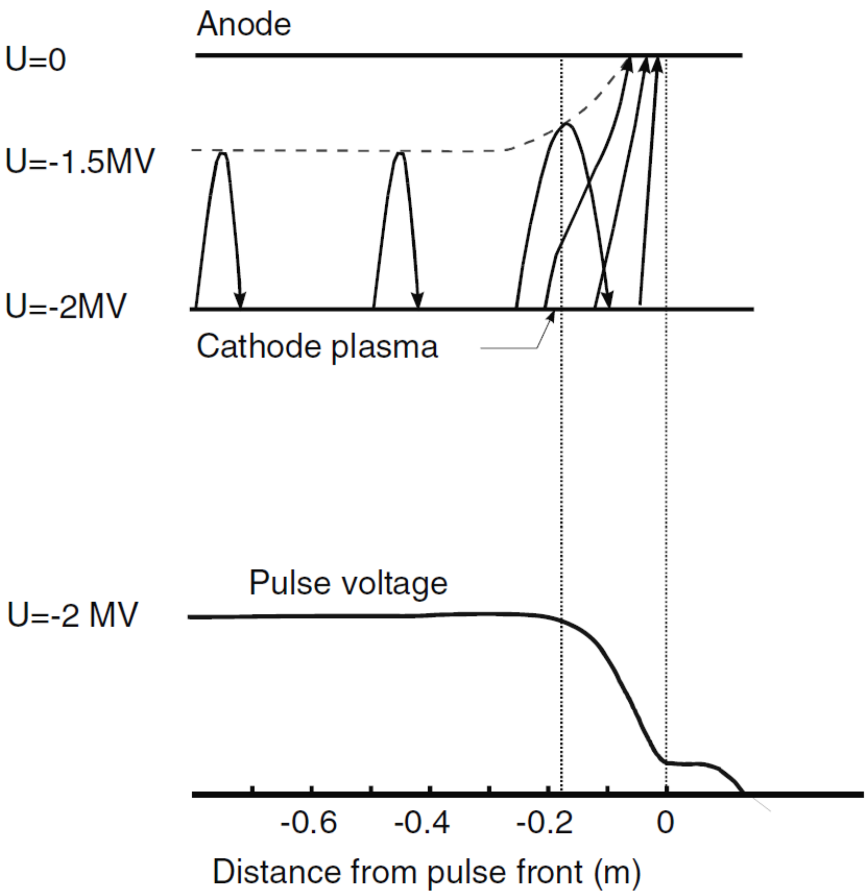
Self-magnetic insulation



- For E > 20 MV/m, homogeneous plasma layer is generated within a few nanosecond.
- For $I > I_{crit}$, electron orbits can no longer reach the anode => more and more sections are insulated. => An electron sheath forms on the negative conductor.

Electromagnetic shock wave is formed

- **The propagation velocity of the loss front is less than the speed of light, c.**
- **As long as the voltage ramp remains below the breakdown threshold, the wave propagates at the speed of light.**



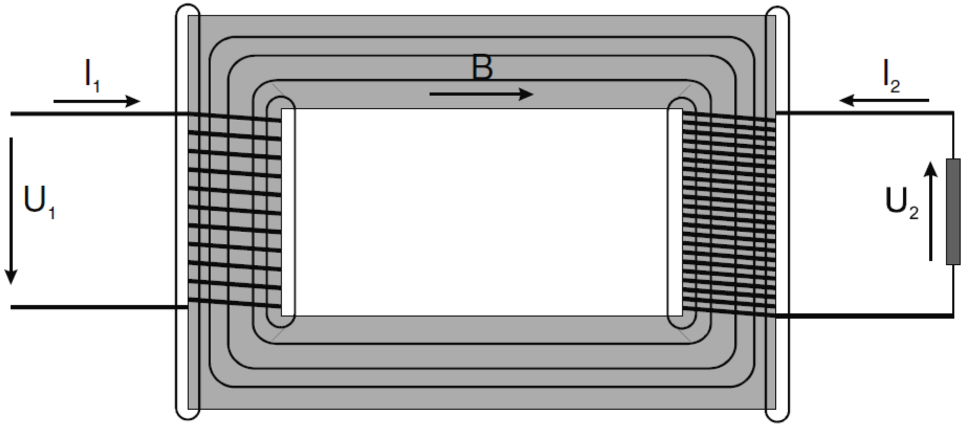
Pulse transformers

- High-voltage transformers: used for transformation of current, voltage, impedance, polarity inversion, insulation and coupling between circuits at different potentials.
- Based on magnetic coupling between two conducting circuits.
- Perfect or ideal transformer: no ohmic losses, no eddy currents, without hysteresis and stray field => magnetic flux goes completely through both the primary and second coil.
- Faraday's law:

$$U_1 = N_1 \frac{d\phi}{dt}$$

$$U_2 = -N_2 \frac{d\phi}{dt}$$

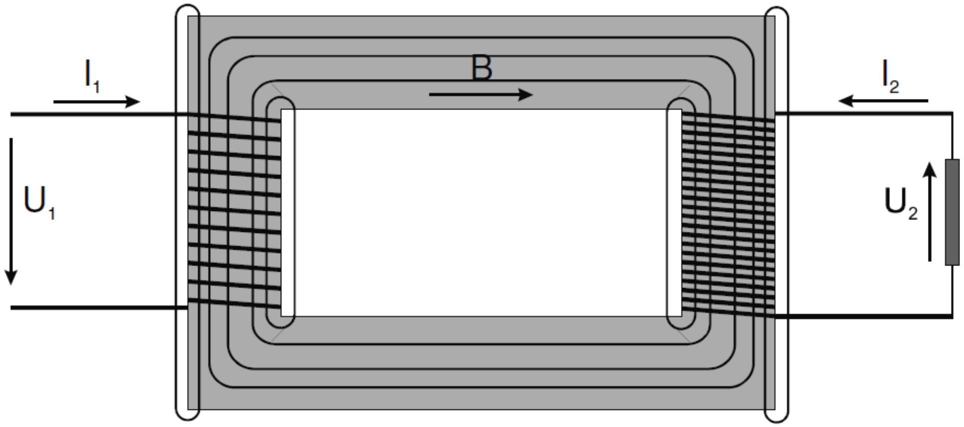
$$\frac{U_2}{U_1} = -\frac{N_2}{N_1}$$



The transformer rise the voltage but reduce the current

$$U_1 = N_1 \frac{\mathrm{d}\phi}{\mathrm{dt}} \qquad \frac{U_2}{U_1} = -\frac{N_2}{N_1}$$

$$U_2 = -N_2 \frac{\mathrm{d}\phi}{\mathrm{dt}}$$



- **For open circuit, i.e. secondary coil is open => ϕ is caused by i_1 only:**

$$i_{10} = \frac{U_1}{\mathrm{i}\omega \mathrm{L}_1}$$

- **If a load of complex impedance Z is connected to the secondary coil:**

$$i_2 = \frac{U_2}{Z} \qquad N_2 i_2 = N_1 i_1'$$

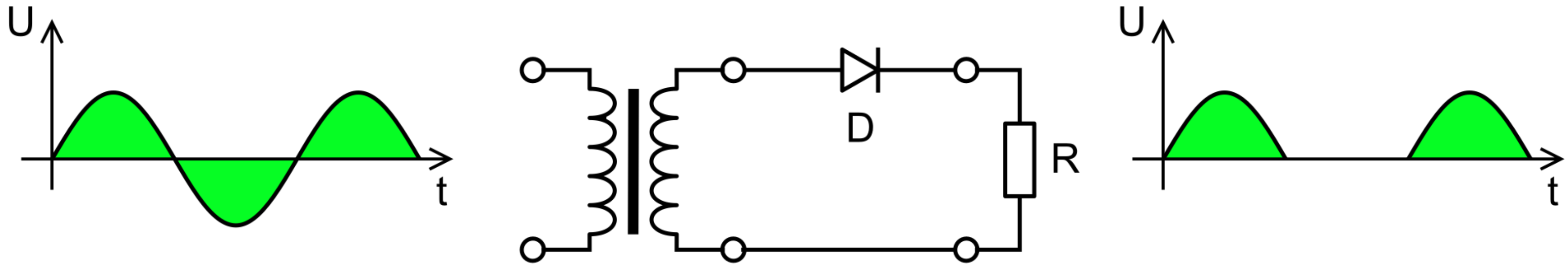
Additional flux from the secondary coil is compensated from primary coil.

$$i_1' = i_{10} + i_1' = i_{10} - \frac{N_2}{N_1} i_2 \qquad \mathrm{Power} = (i_1' - i_{10})U_1 = -\frac{N_2}{N_1} i_2 U_1 = i_2 U_2$$

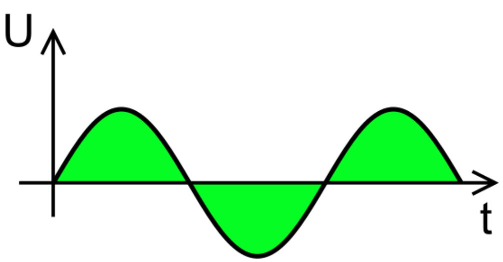
- **If** $i_{10} << \frac{N_2 i_2}{N_1} \quad => \quad i_1 = -\frac{N_2}{N_1} i_2$

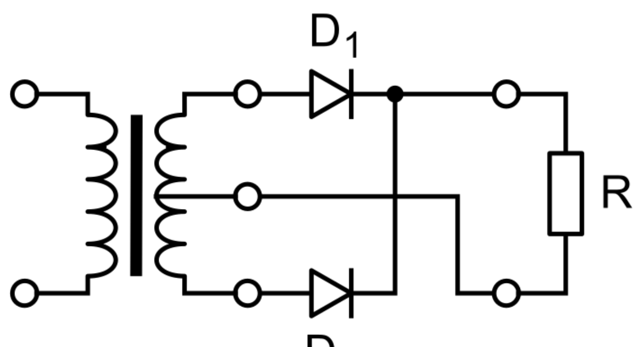
Rectifier

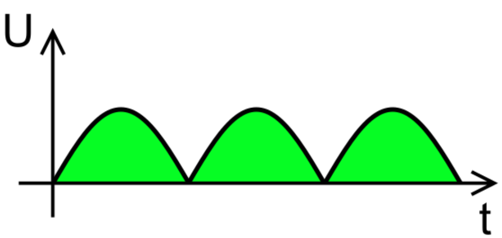
- **Half-wave rectifier:**



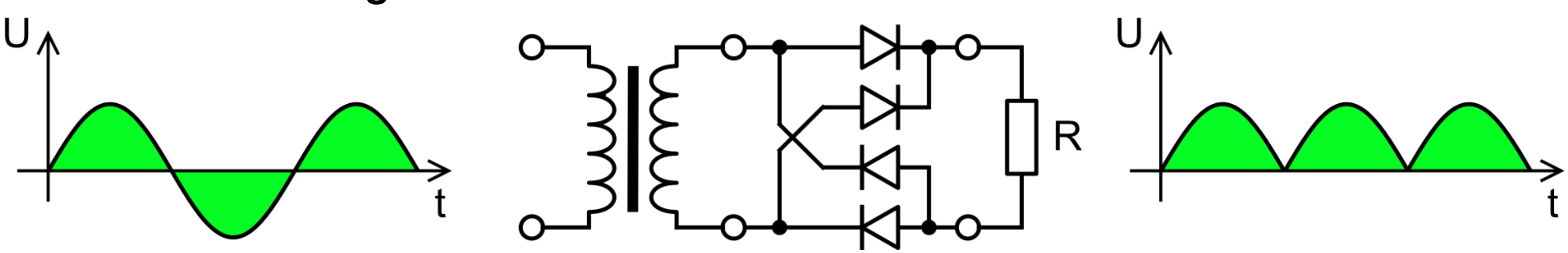
- **Center-tapped full-wave rectifier:**





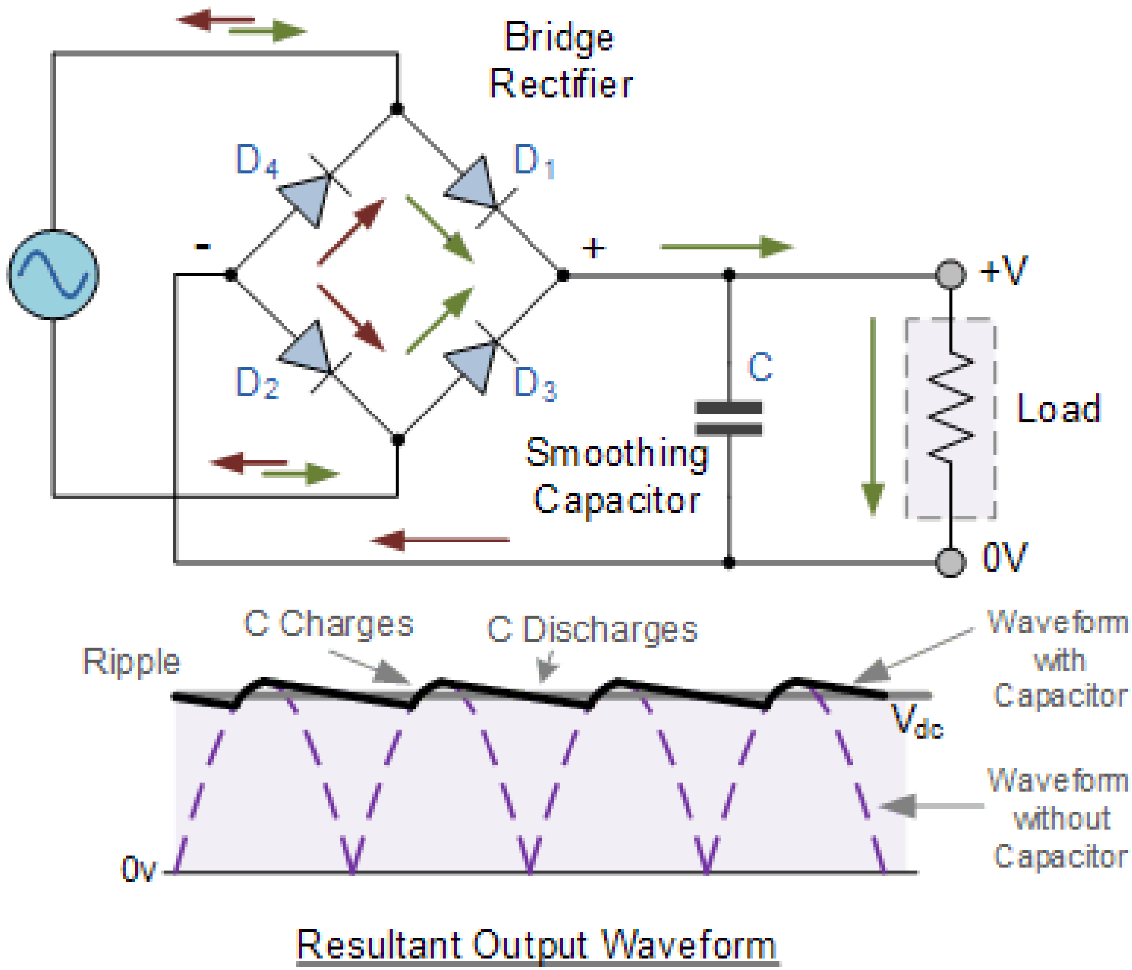


- **Full-wave bridge rectifier:**



https://zh.wikipedia.org/wiki/%E6%95%B4%E6%B5%81%E5%99%A8

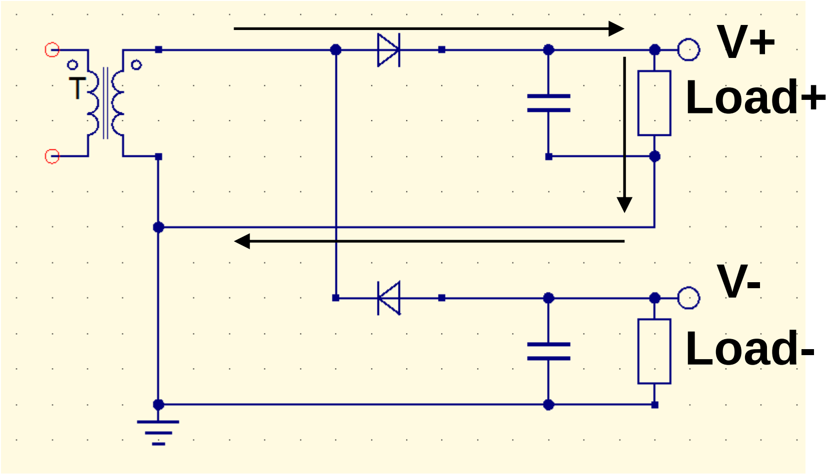
Full-wave rectifier with smoothing capacitor



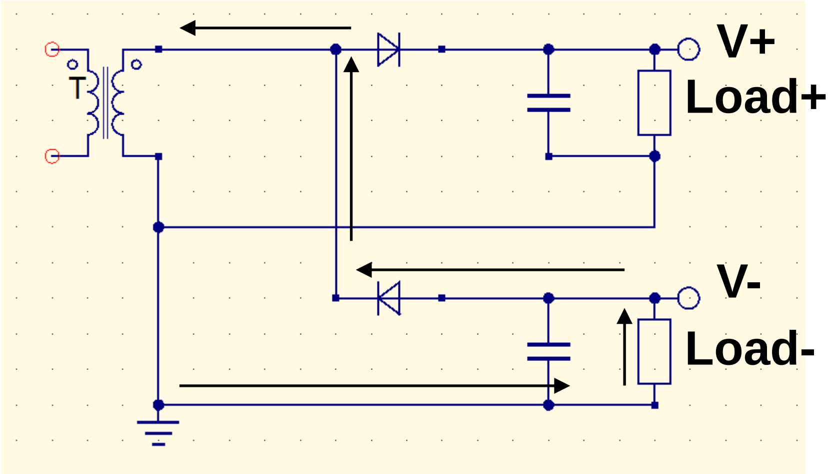
https://electronics.stackexchange.com/questions/363454/smoothing-a-full-wave-rectifier-voltage

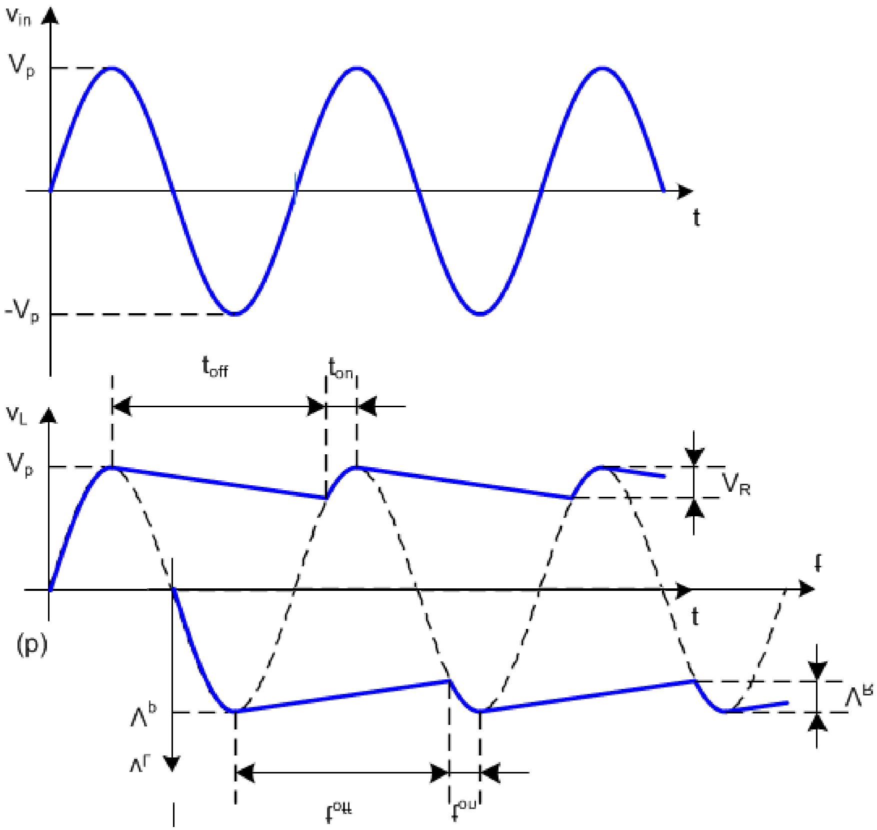
Dual output

- **Positive cycle:**

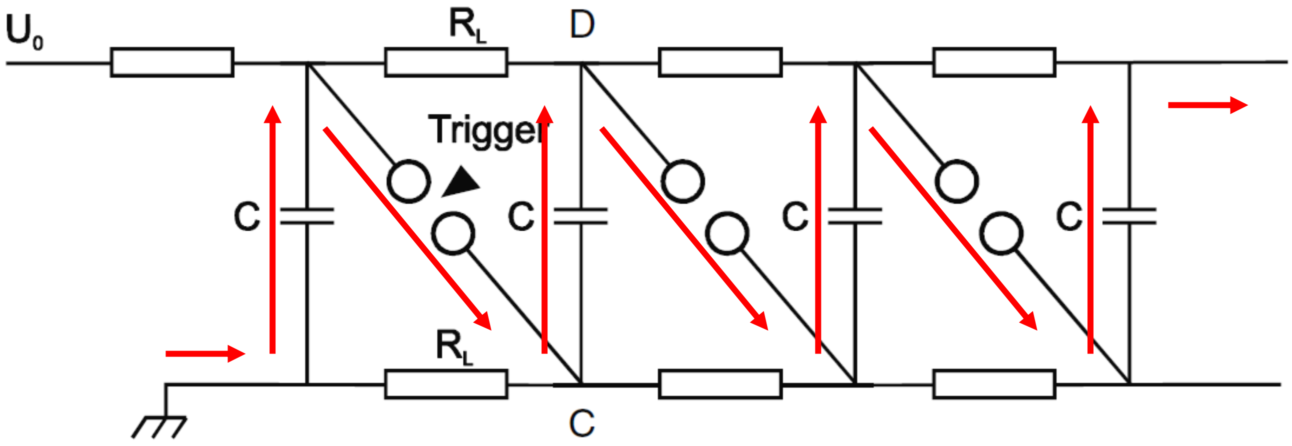


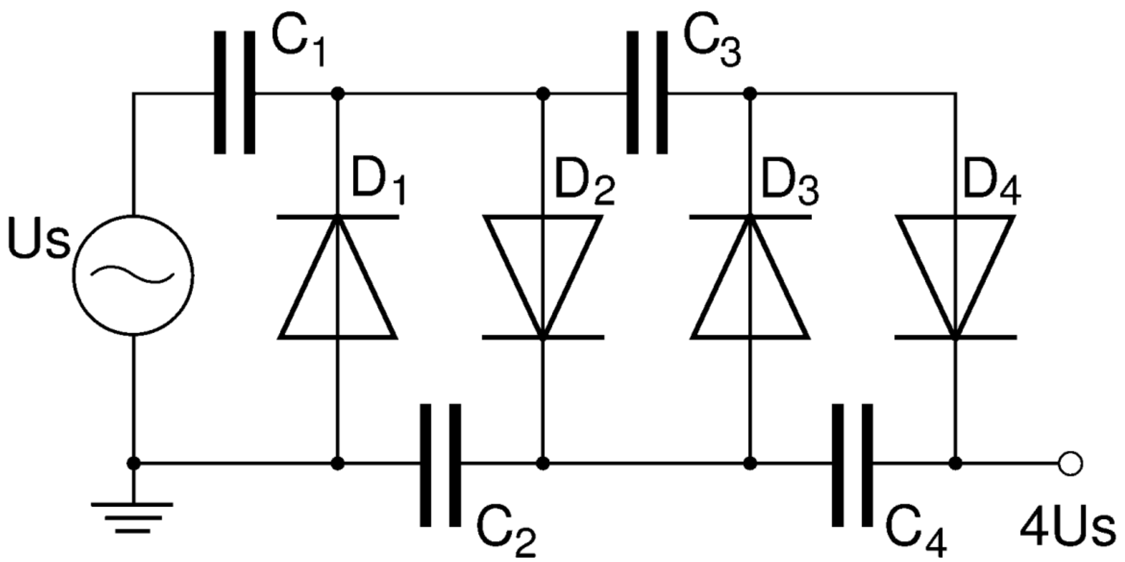
- **Negative cycle:**





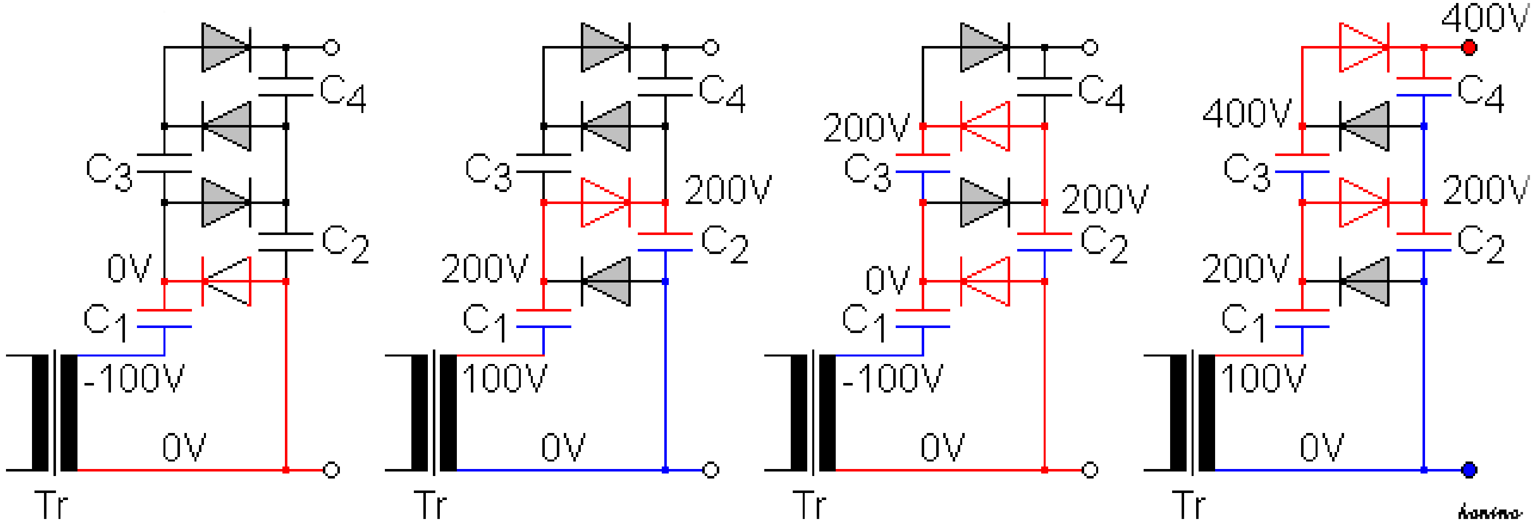
Voltage multiplier (Cockcroft–Walton (CW) generator)

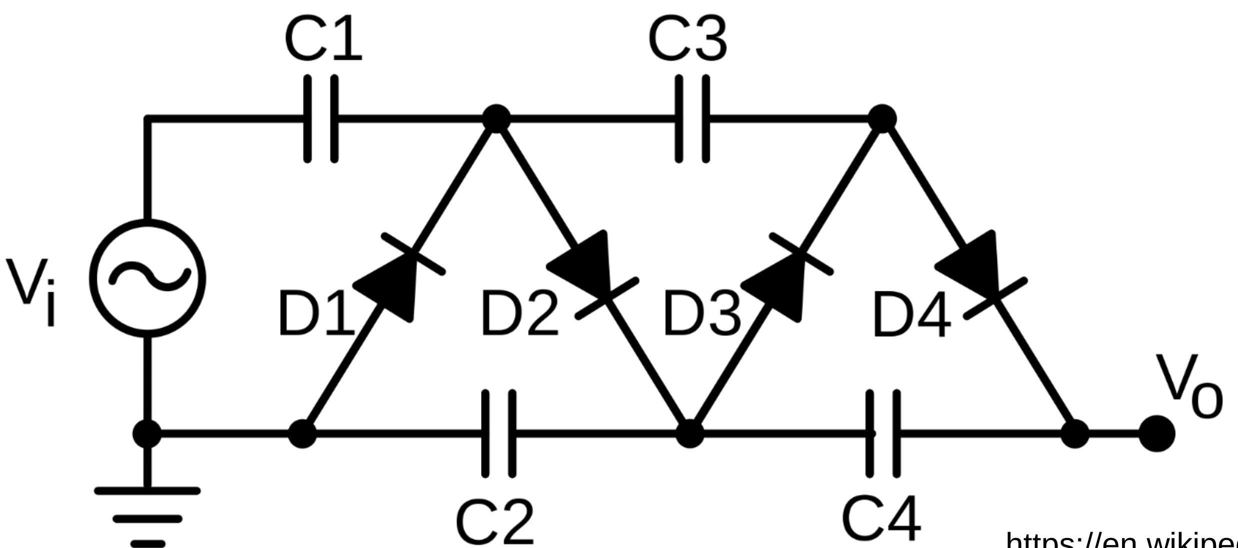




https://en.wikipedia.org/wiki/Voltage_multiplier

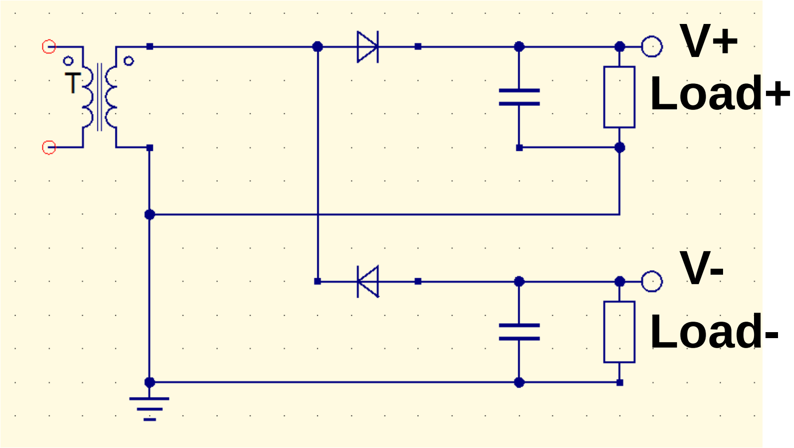
Voltage multiplier (Cockcroft–Walton (CW) generator)

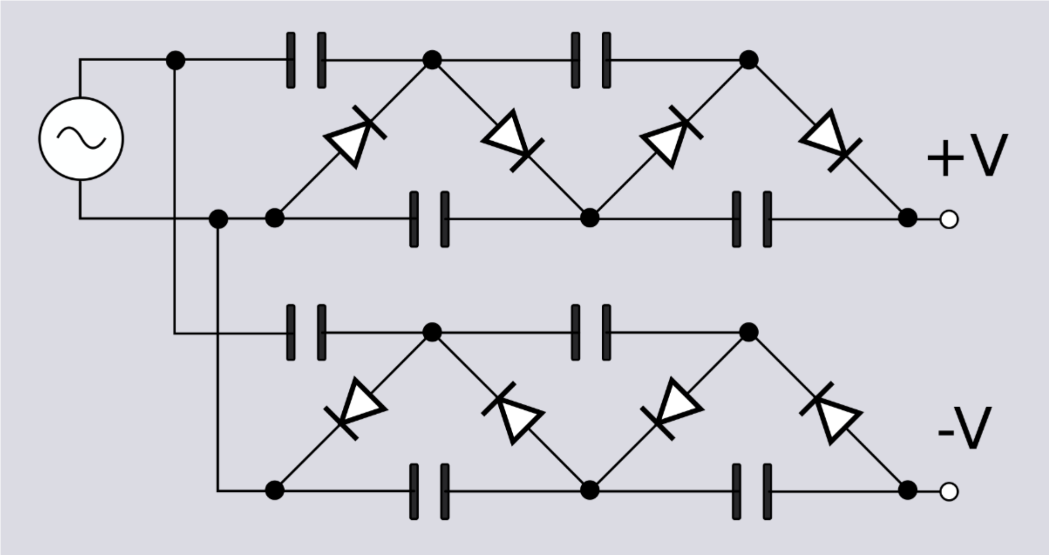




https://en.wikipedia.org/wiki/Voltage_multiplier

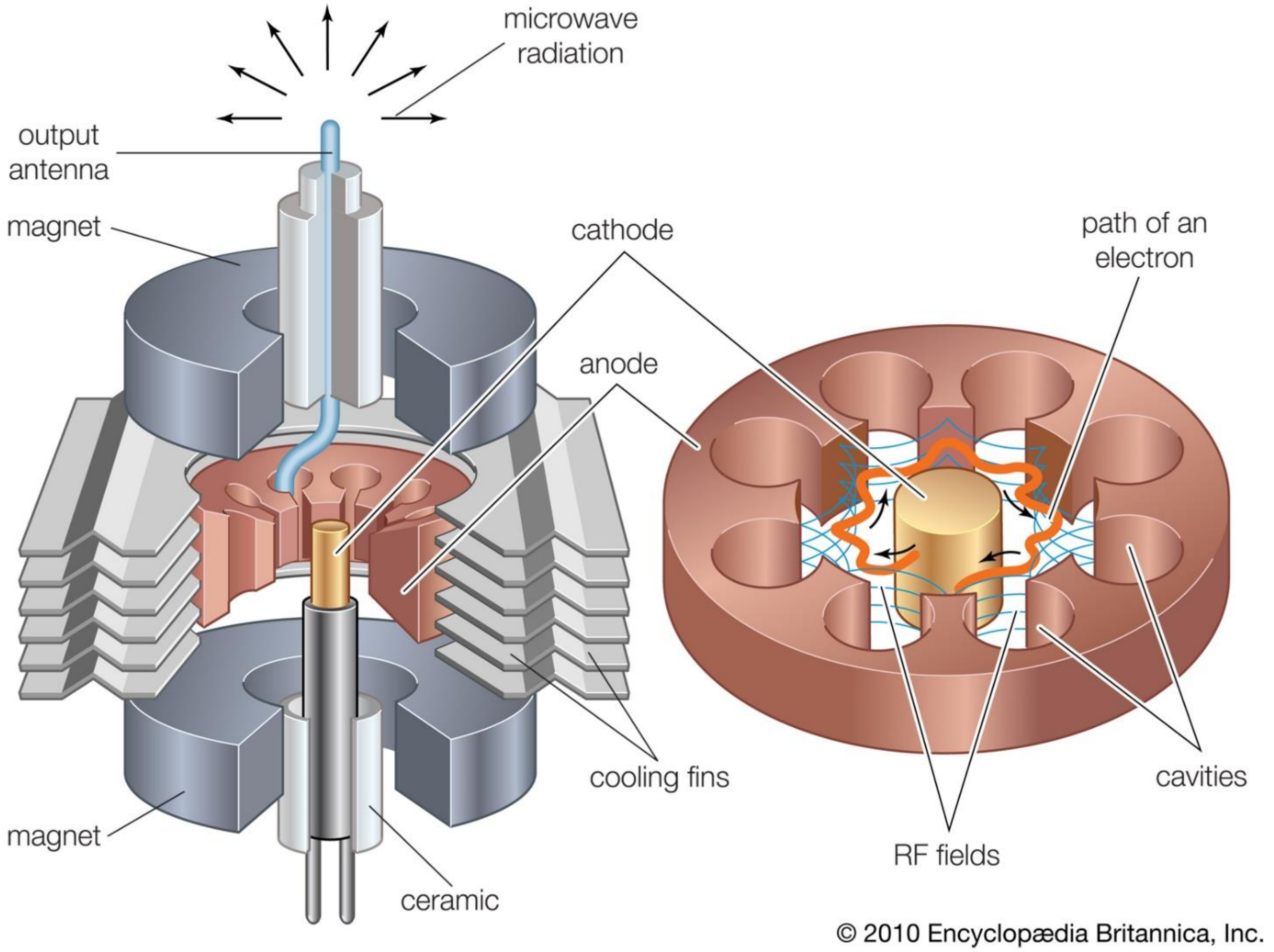
Dual-output





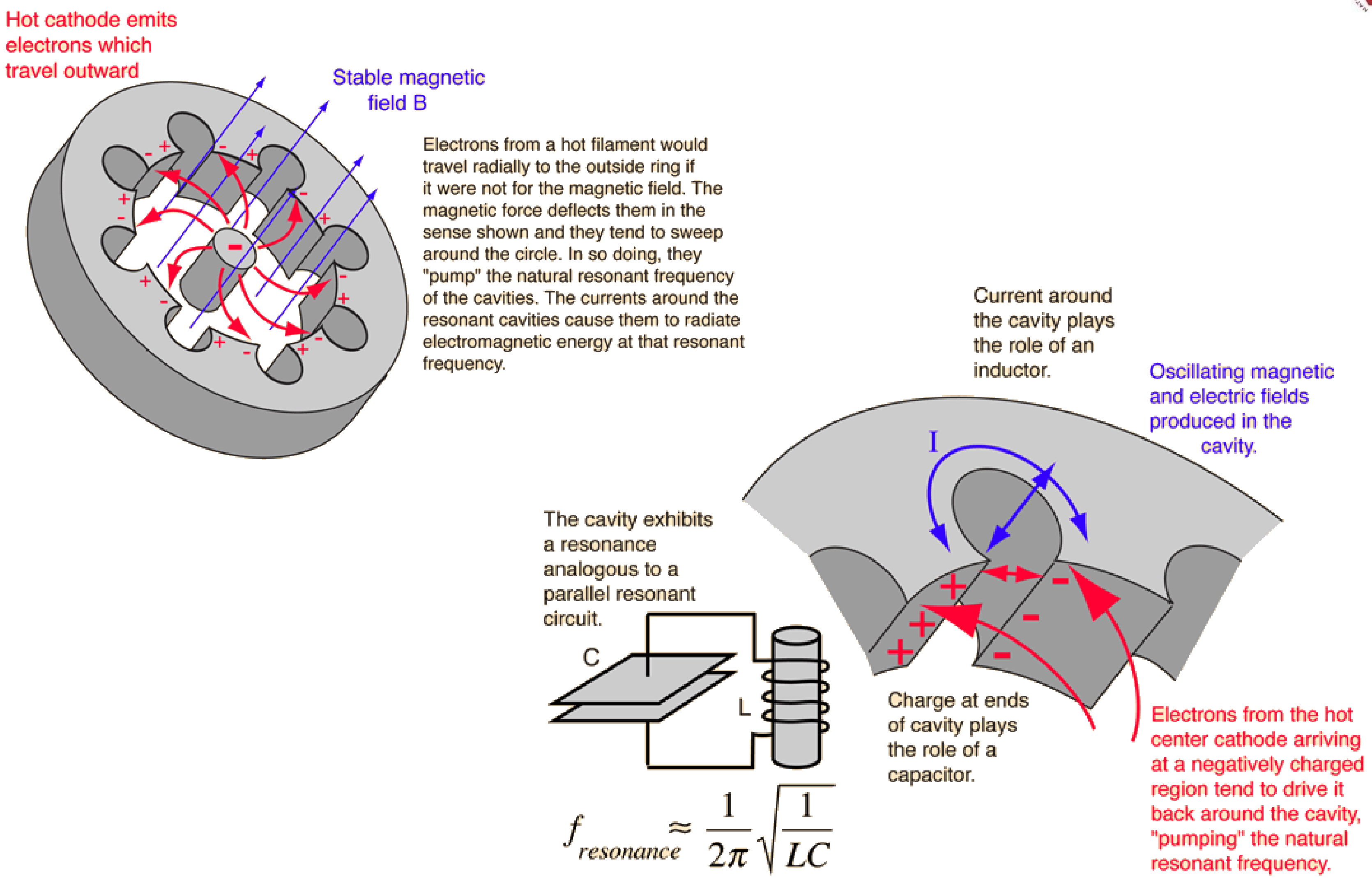
https://en.wikipedia.org/wiki/Voltage_multiplier

Internal of a magnetron



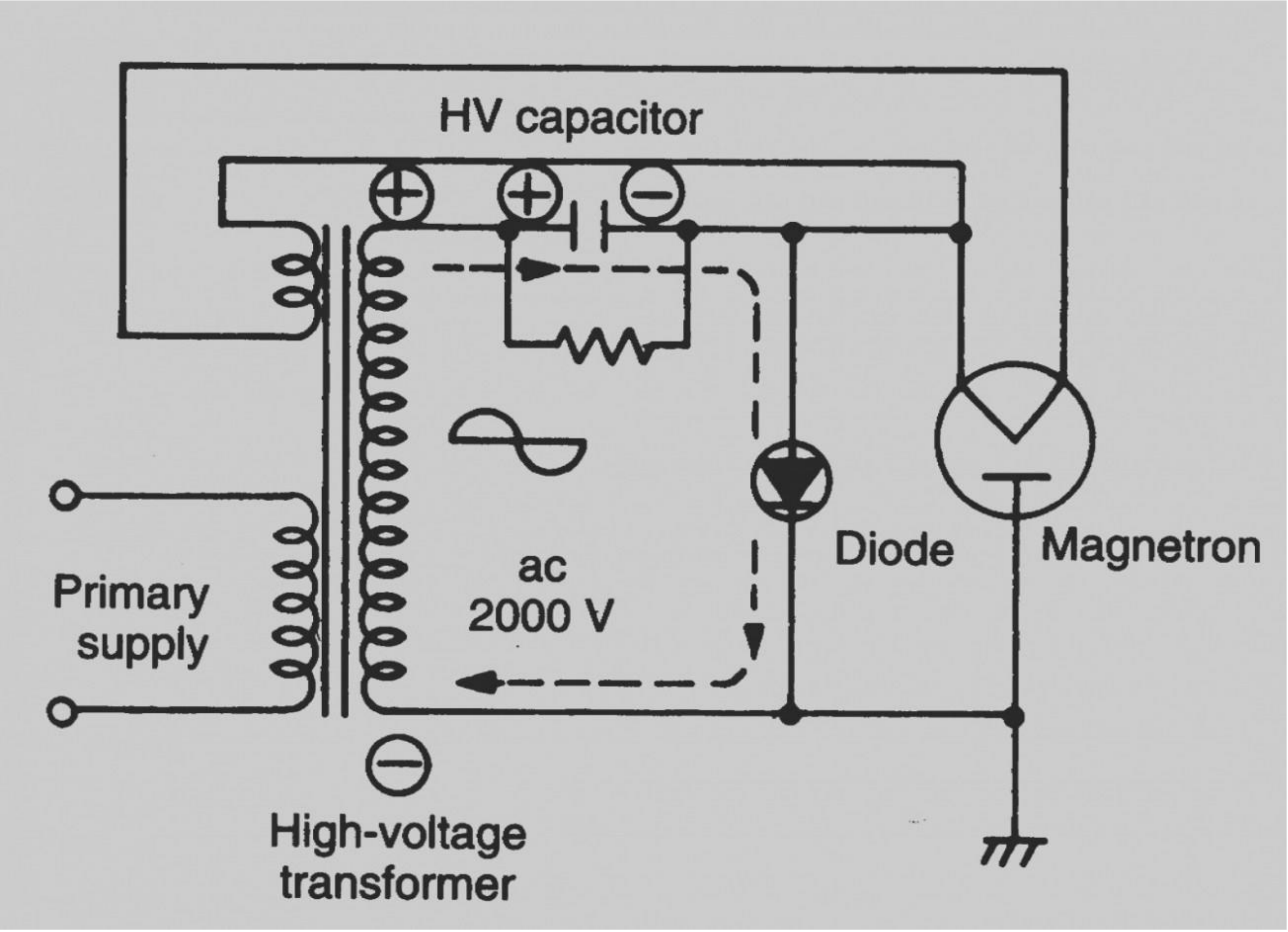
https://kids.britannica.com/students/article/electron-tube/106024/media?assemblyId=137

Magnetron is a forced oscillation driven by electrons between the gap



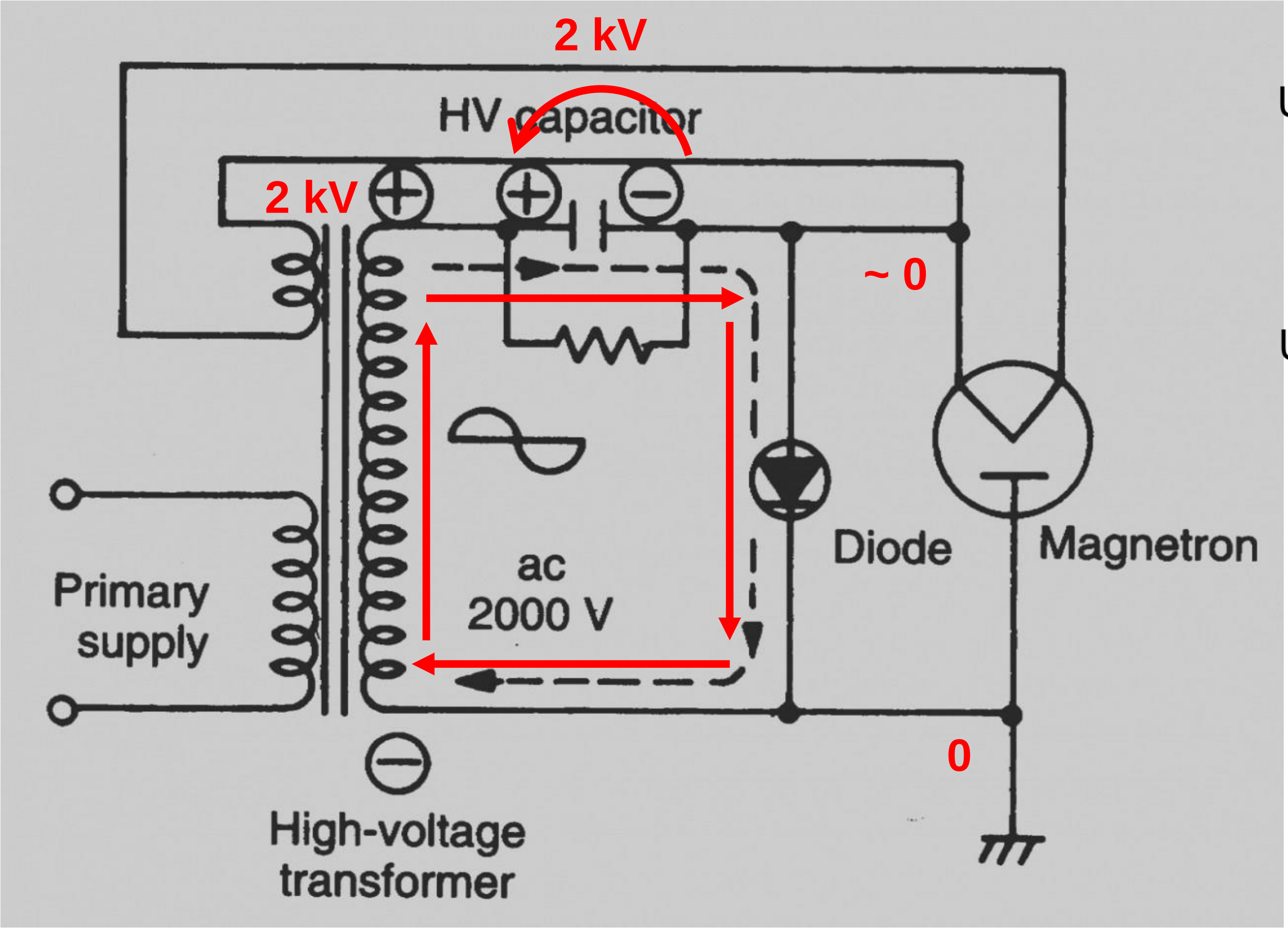
http://hyperphysics.phy-astr.gsu.edu/hbase/Waves/magnetron.html

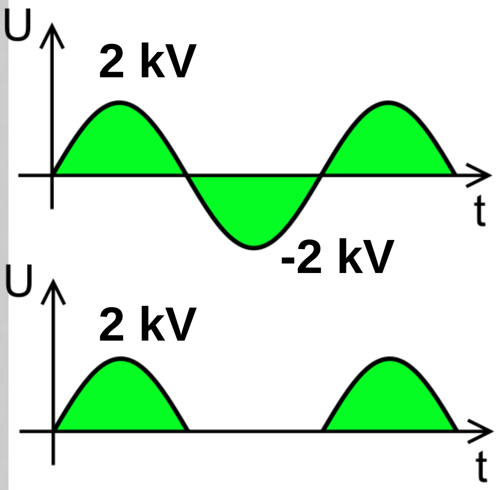
Magnetron schematic diagram



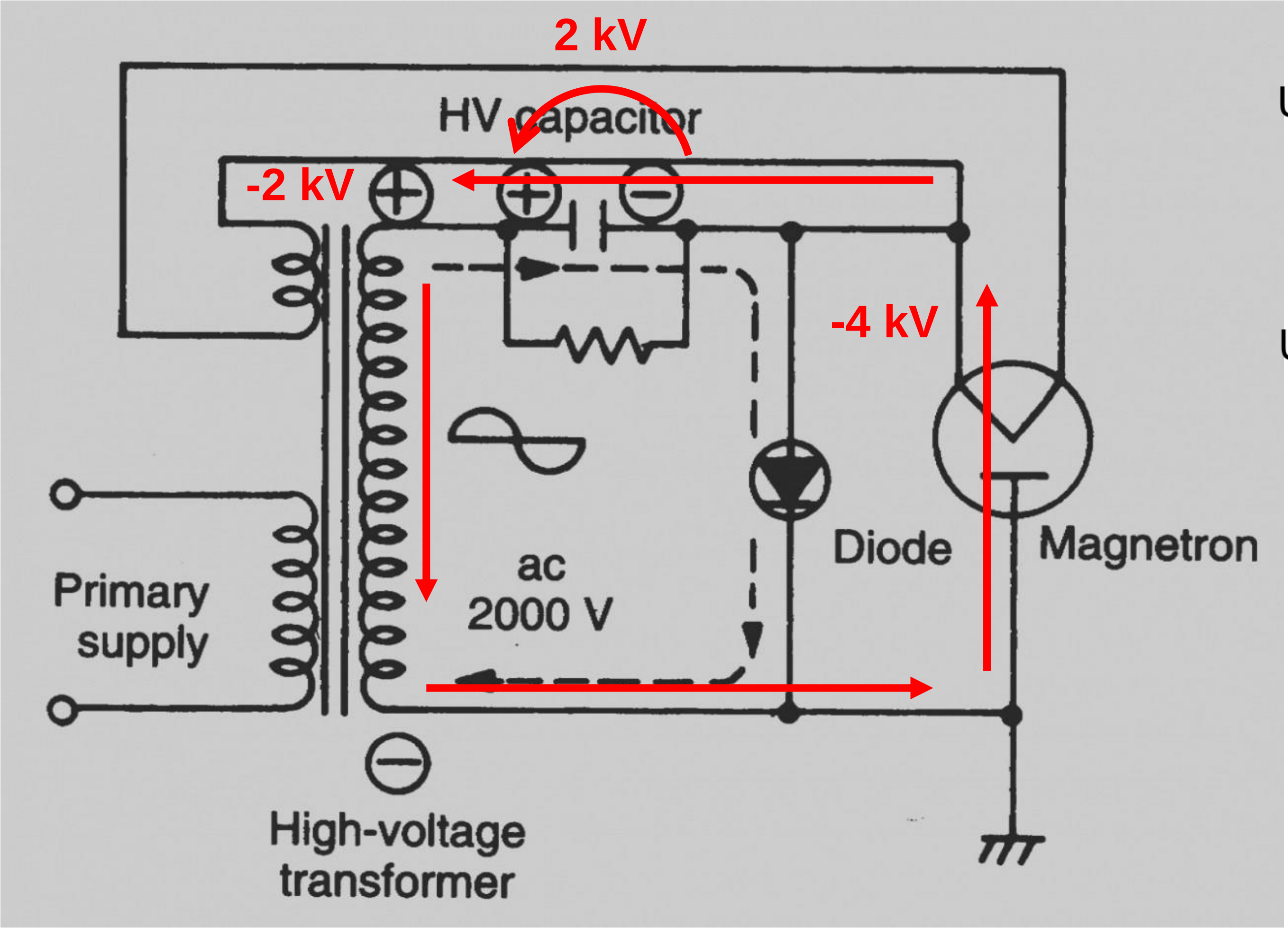
http://www.sciencemadness.org/talk/viewthread.php?tid=154071

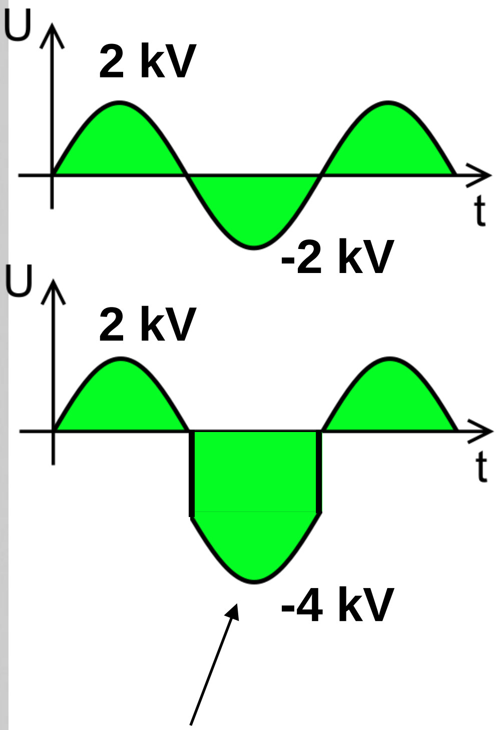
Magnetron schematic diagram





Magnetron schematic diagram

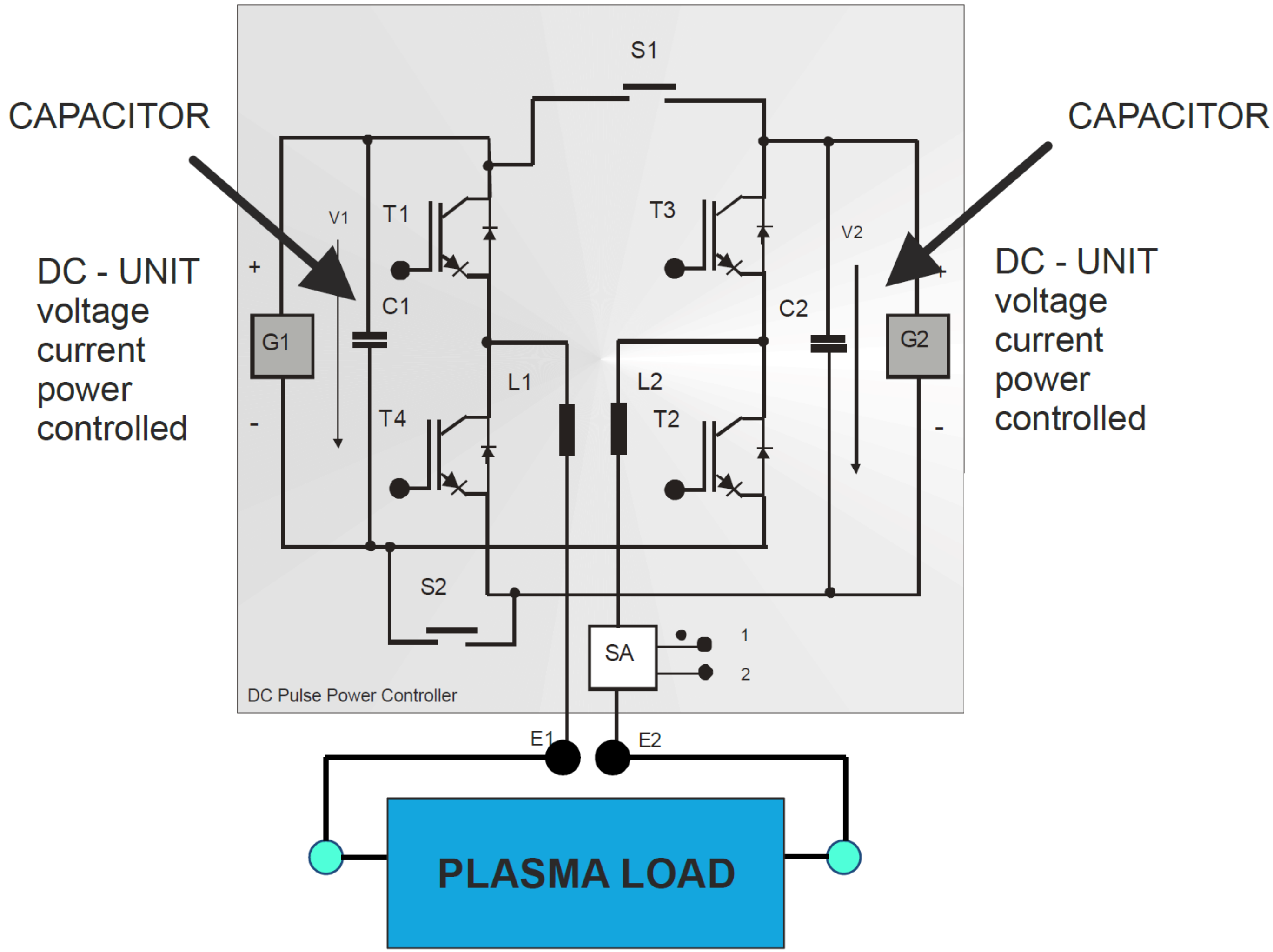




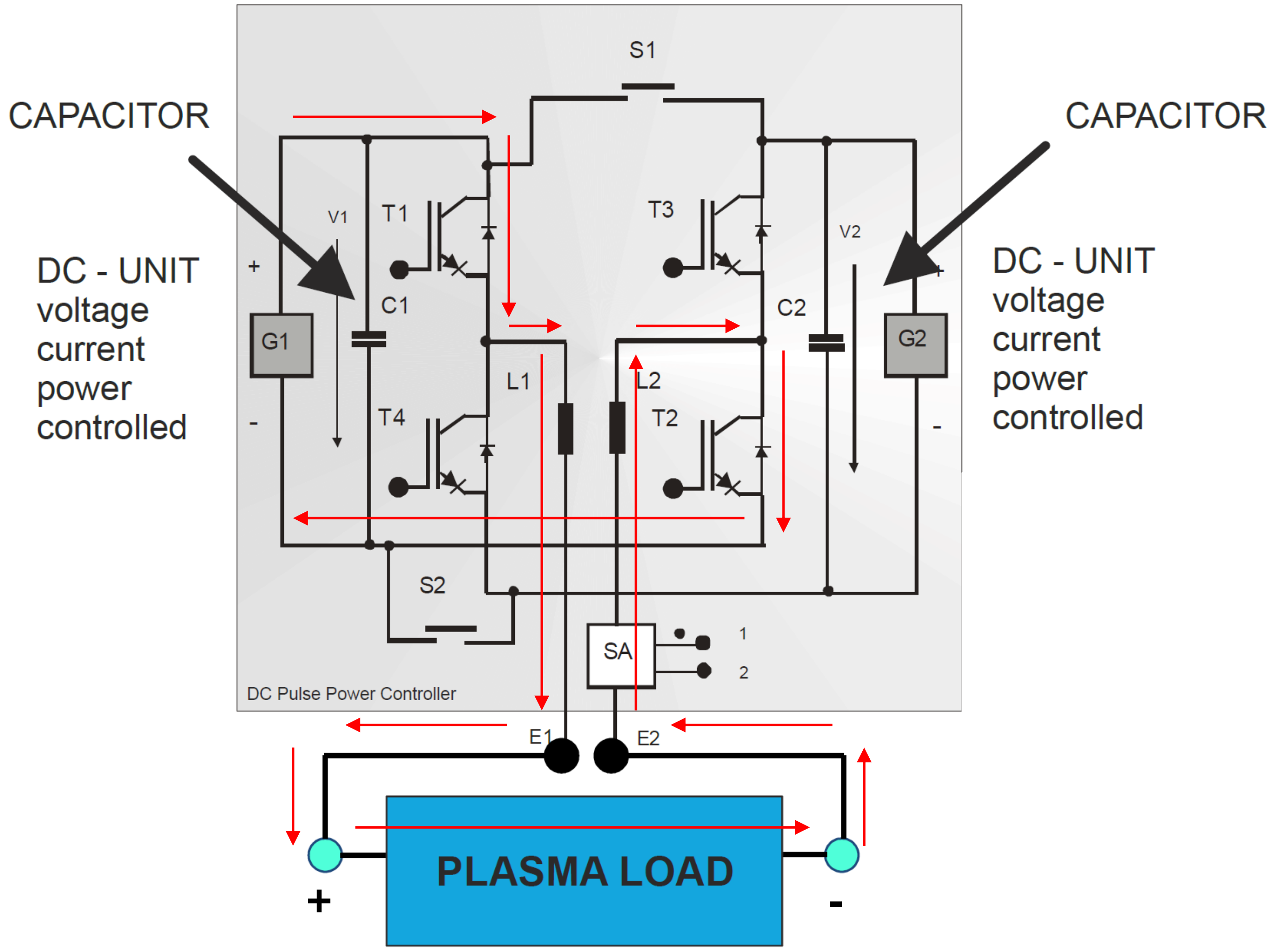
Microwave is generated.

http://www.sciencemadness.org/talk/viewthread.php?tid=154071

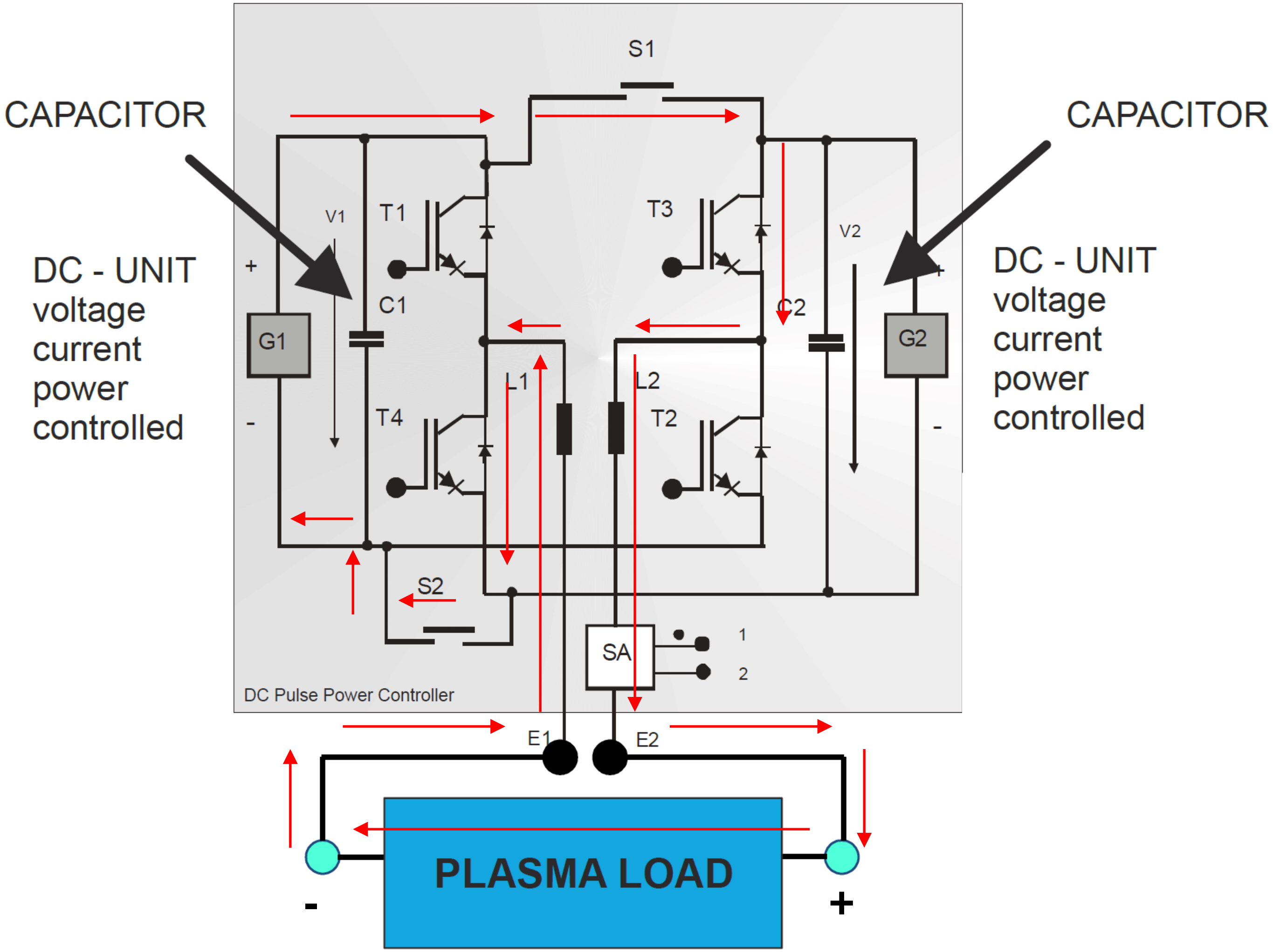
Pulse generator using H-bridge inverter



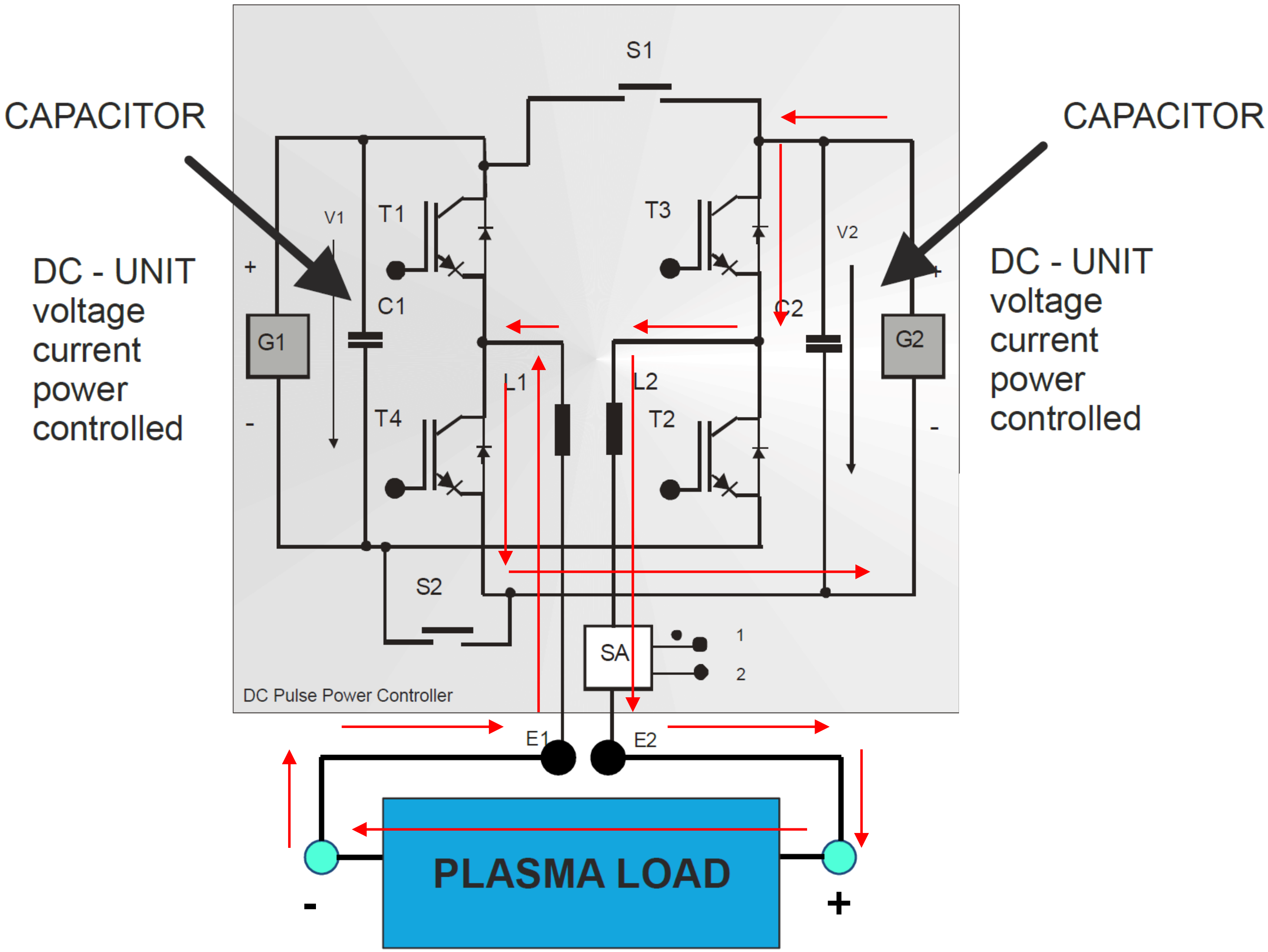
Pulse generator using H-bridge inverter



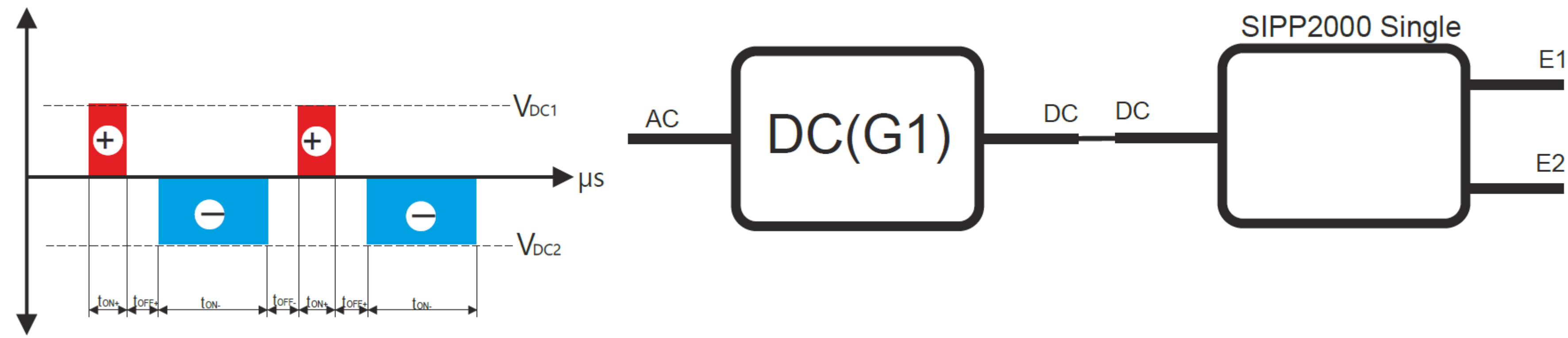
Pulse generator using H-bridge inverter



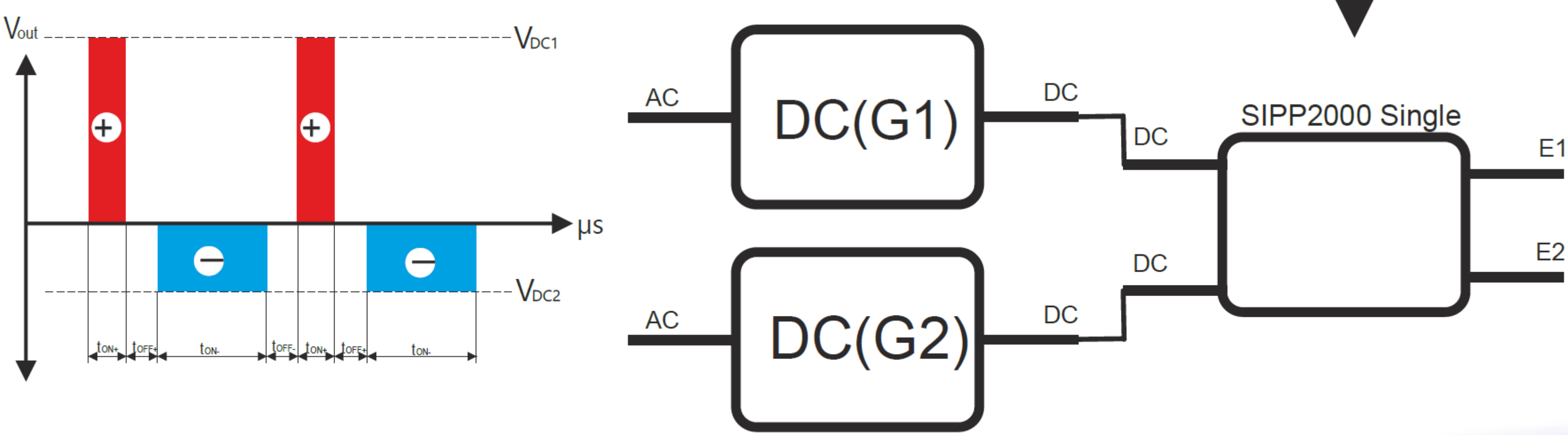
Pulse generator using DC power supply



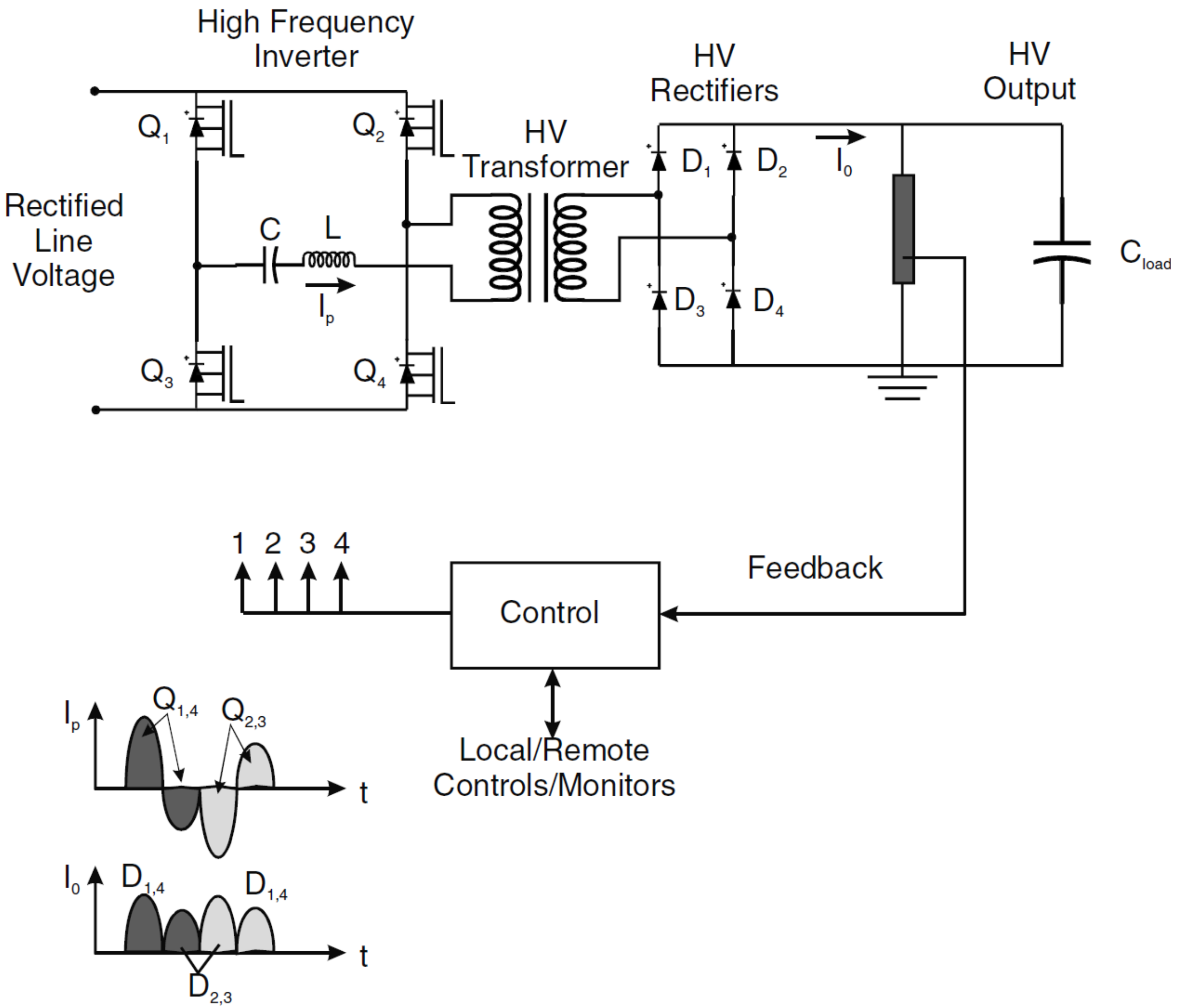
Pulse generator



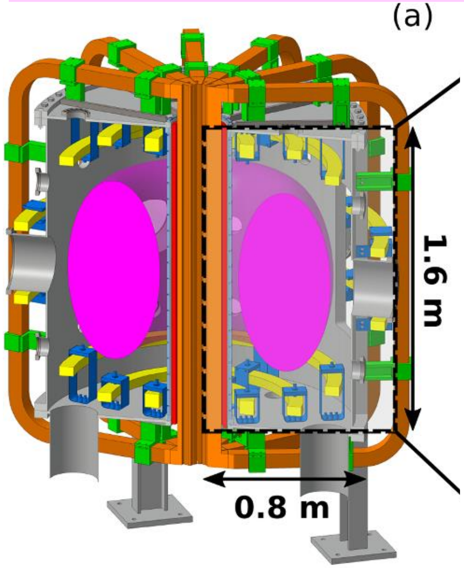
ASYMMETRIC : S1/S2 open- G1/G2

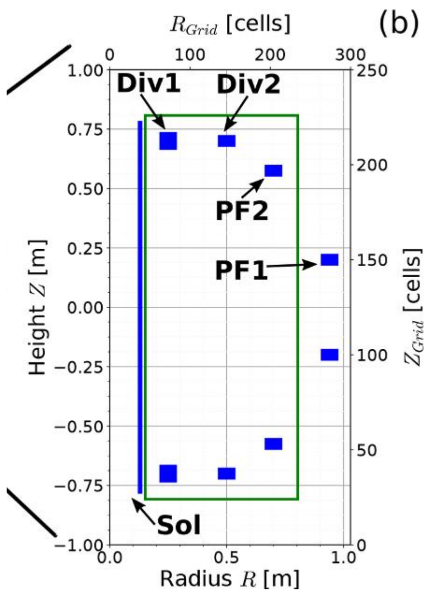


High-frequency switch mode power supply

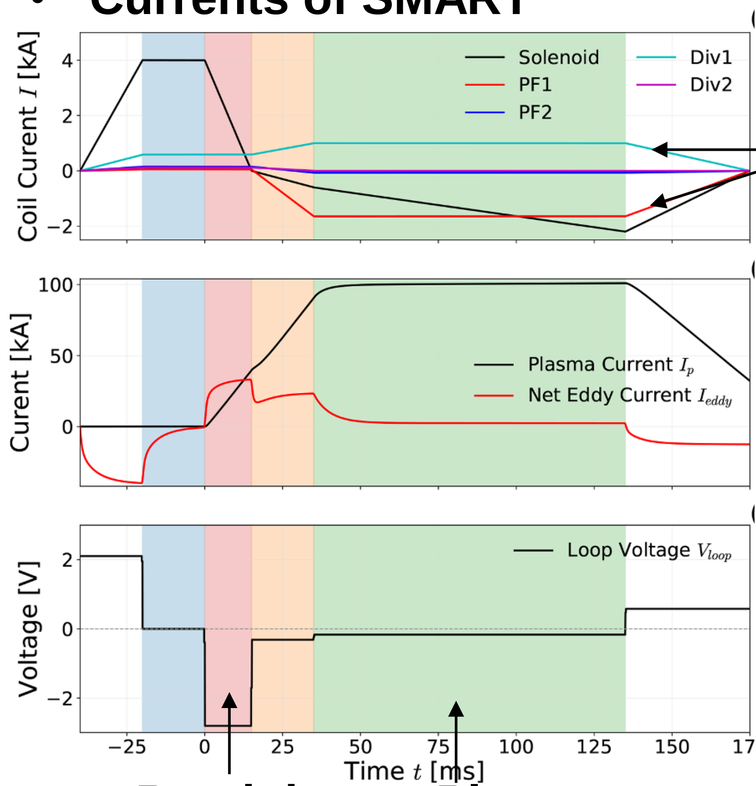


Currents with specific profiles needed to be provided to drive coils in Tokamaks to confine the plasma





- **Currents of SMART**



Breakdown **Plasma current is driven.**

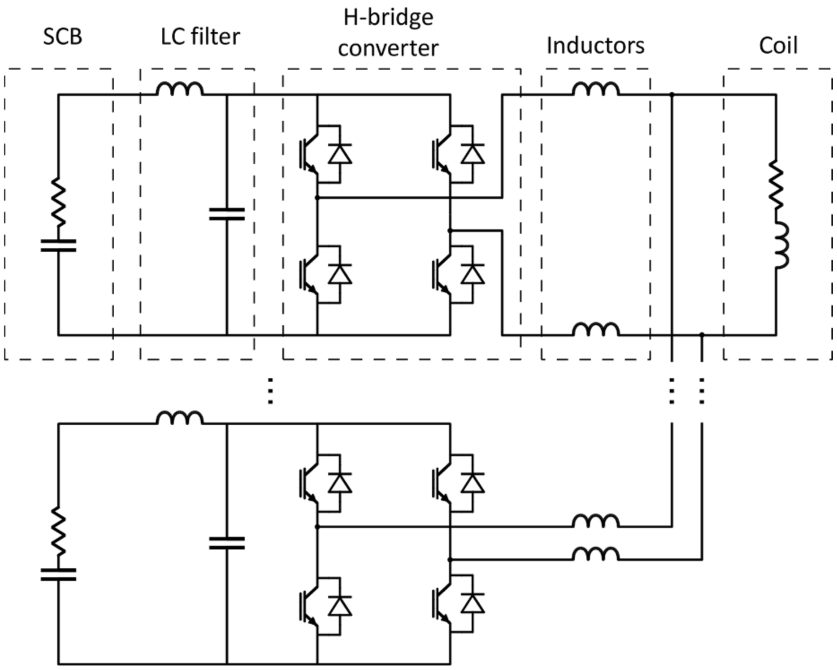
Equilibrium state can be achieved with poloidal field coils.

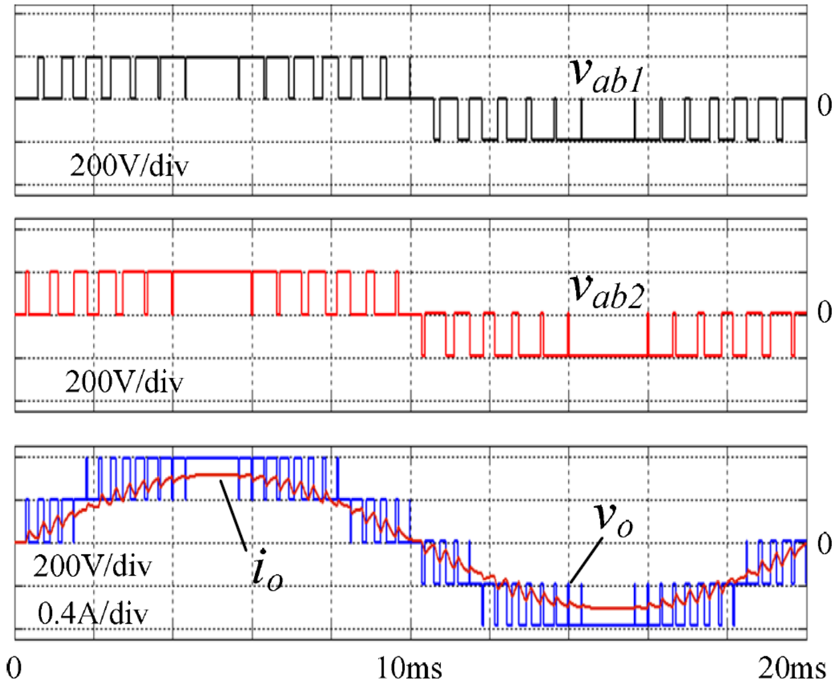
- **The current of the CS will be determined by the required breakdown voltage and plasma current.**

S. J. Doyle, etc., Fusion Eng. Des. **171**, 112706 (2021)

An H-bridge combining pulse width modulation technique will be used to provide the controllable currents

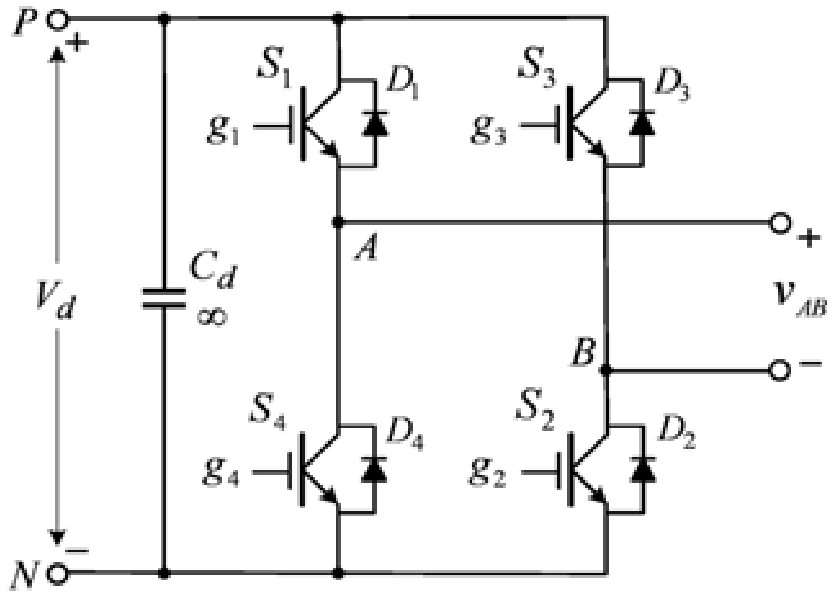
- **H-bridge configuration provides the capability of reversing the current direction:**
- **Pulse width modulation provides the capability of controllable currents**





M. Agredano-Torres, etc., Fusion Eng. Des. **168**, 112683 (2021)
C. Boonmee and Y. Kumsuwan, 2012 15th International Power Electronics and Motion Control Conference, Novi Sad, Serbia, 2012, pp. LS8c.3-1

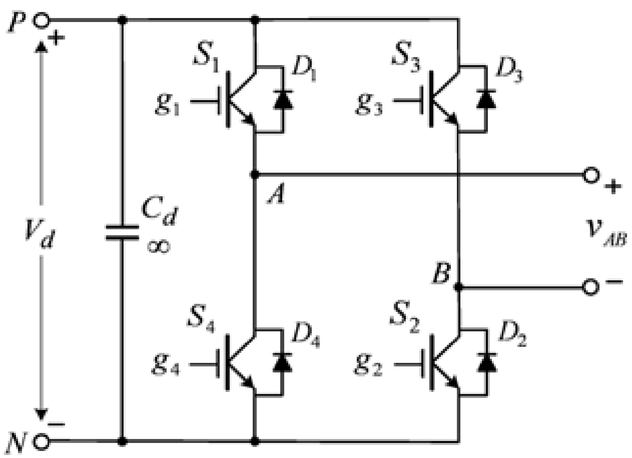
The output voltage is controlled by the status of switches S1~S4

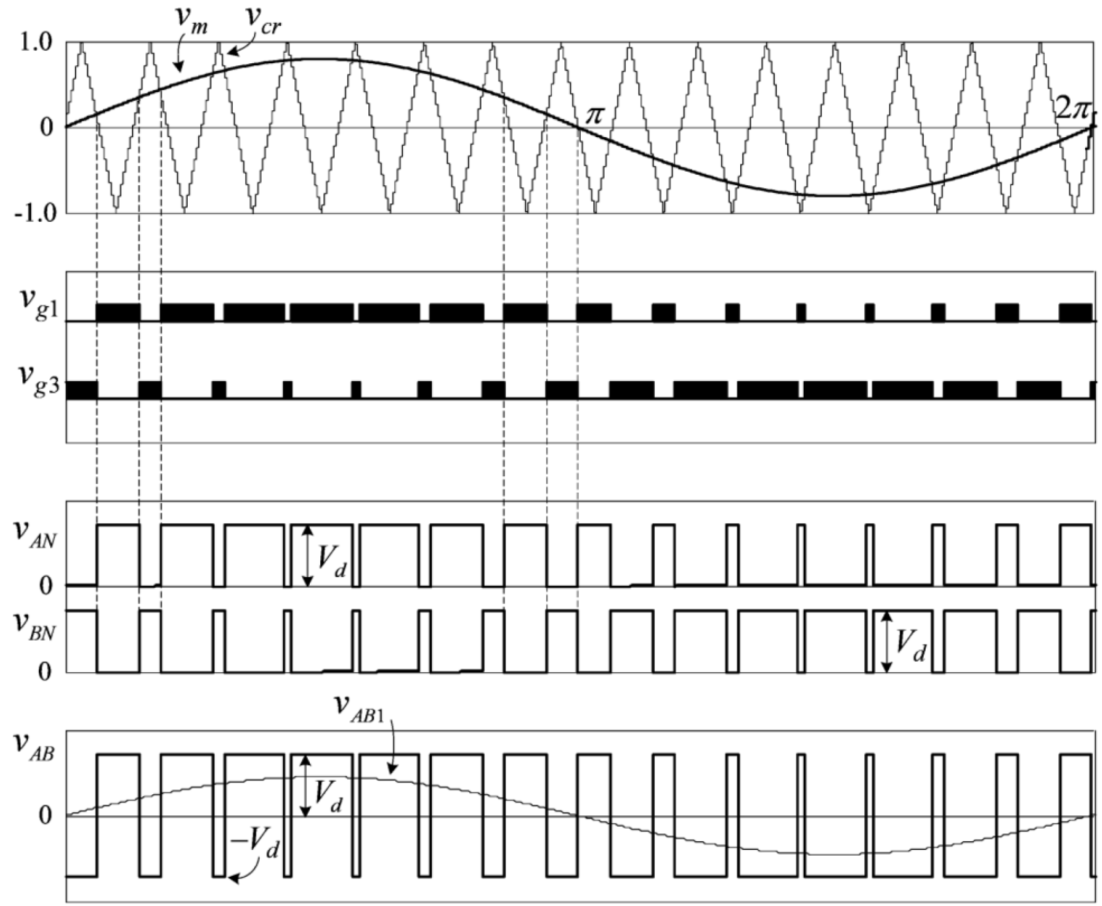


- S_1/S_2 ON; S_3/S_4 Off: $V_{AB} = V_d$.
- S_1/S_2 Off; S_3/S_4 ON: $V_{AB} = -V_d$.
- S_1/S_2 ON; S_3/S_4 ON: $V_{AB} = 0$.

A. Namboodiri & H. S. Wani, I. J. Innovative Research in Sci. & Tech. 1, 2349 (2014)

Bipolar Modulation Scheme

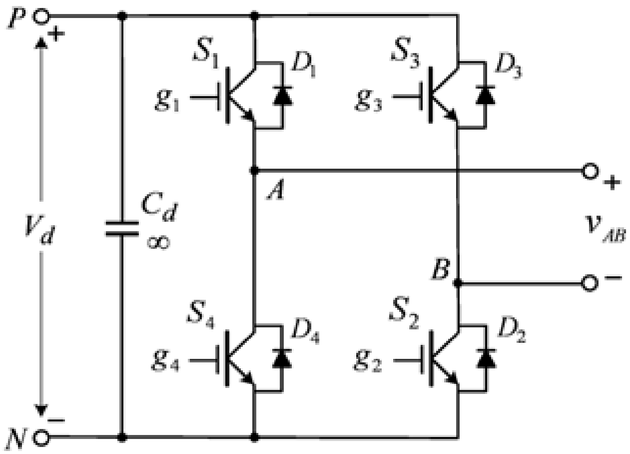


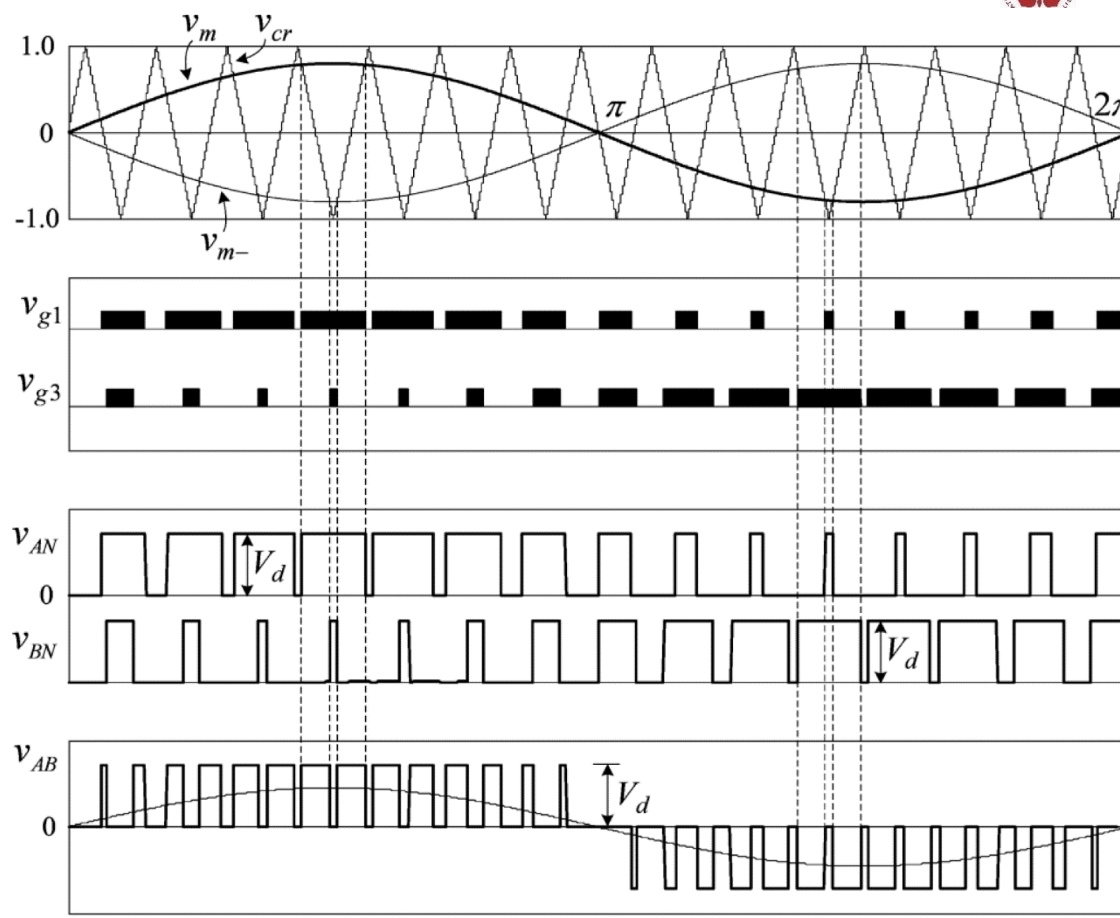


- S_1/S_2 ON; S_3/S_4 Off: $V_{AB} = V_d$.
- S_1/S_2 Off; S_3/S_4 ON: $V_{AB} = -V_d$.
- S_1/S_2 ON; S_3/S_4 ON: $V_{AB} = 0$.

A. Namboodiri & H. S. Wani, I. J. Innovative Research in Sci. & Tech. 1, 2349 (2014)

Unipolar Modulation Scheme

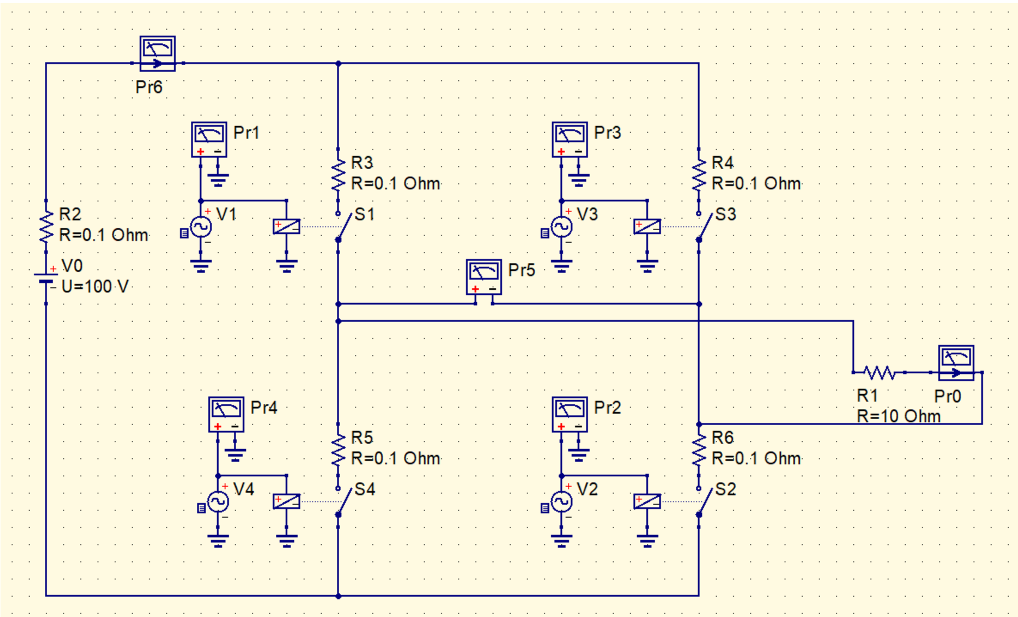


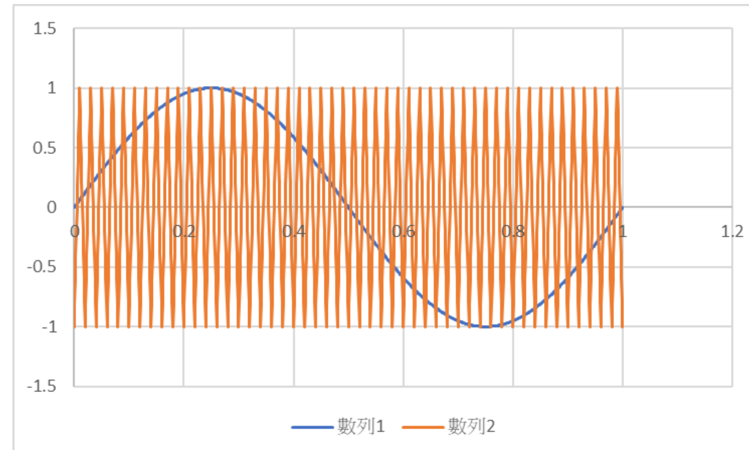


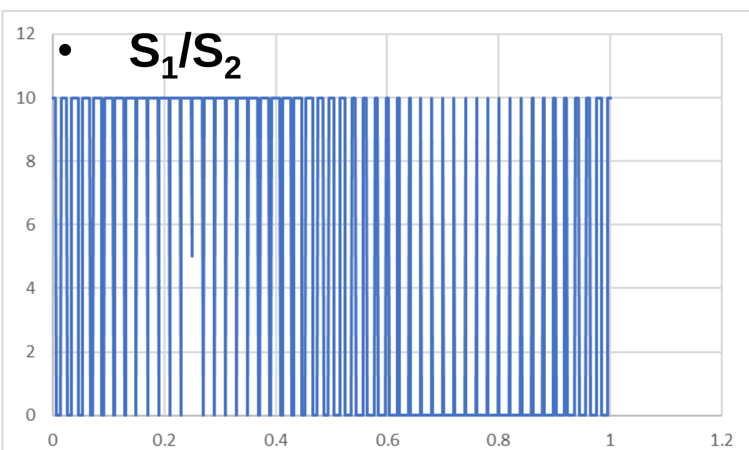
- S_1/S_2 ON; S_3/S_4 Off: $V_{AB} = V_d$.
- S_1/S_2 Off; S_3/S_4 ON: $V_{AB} = -V_d$.
- S_1/S_2 ON; S_3/S_4 ON: $V_{AB} = 0$.

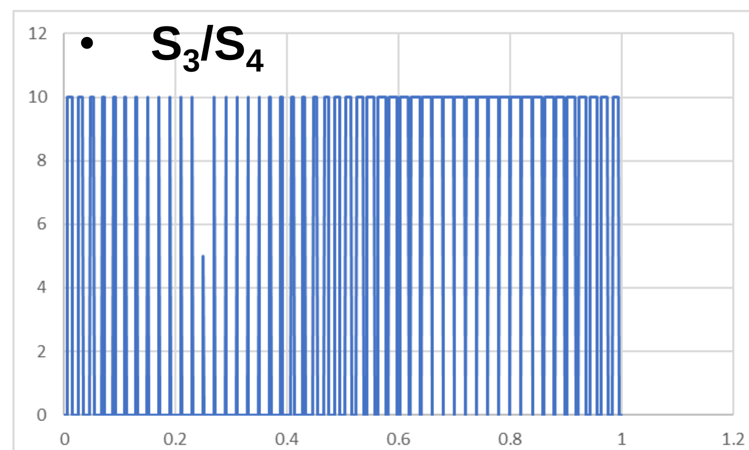
A. Namboodiri & H. S. Wani, I. J. Innovative Research in Sci. & Tech. 1, 2349 (2014)

Simulation using bipolar modulation scheme

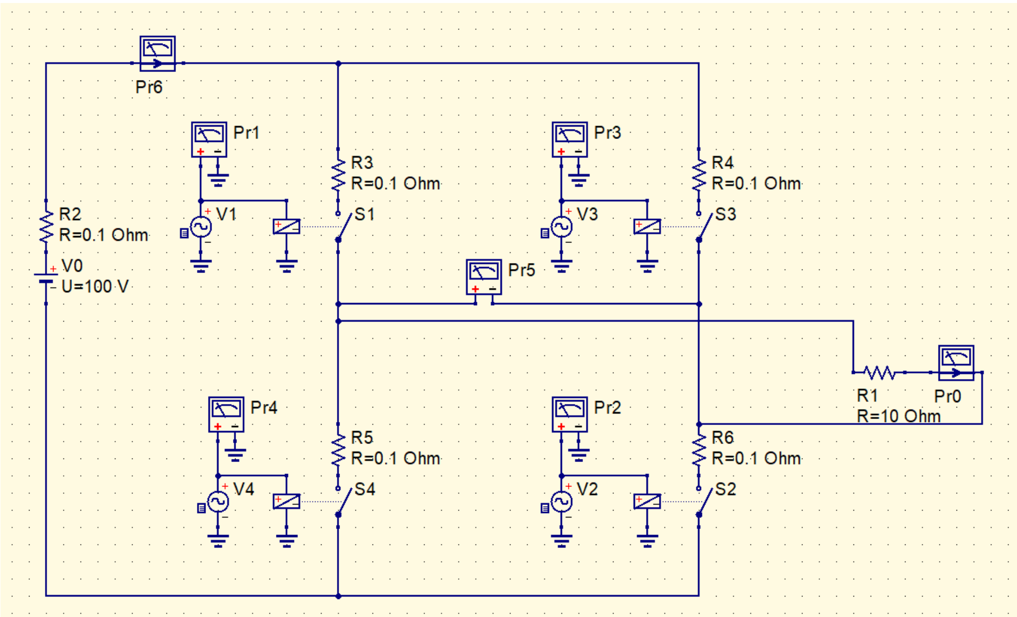




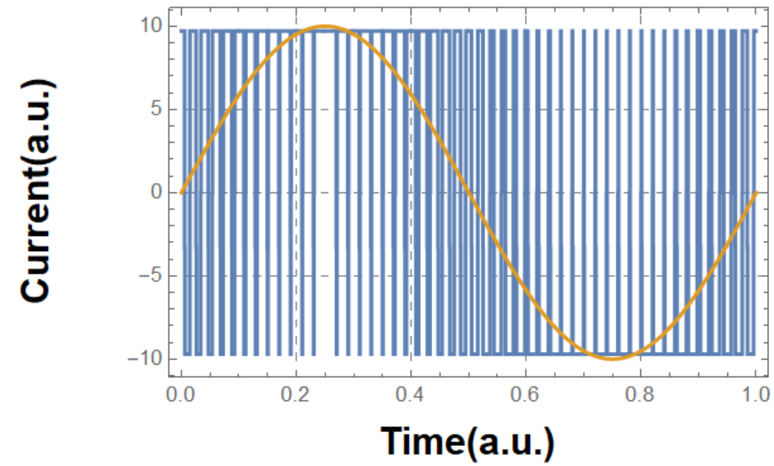




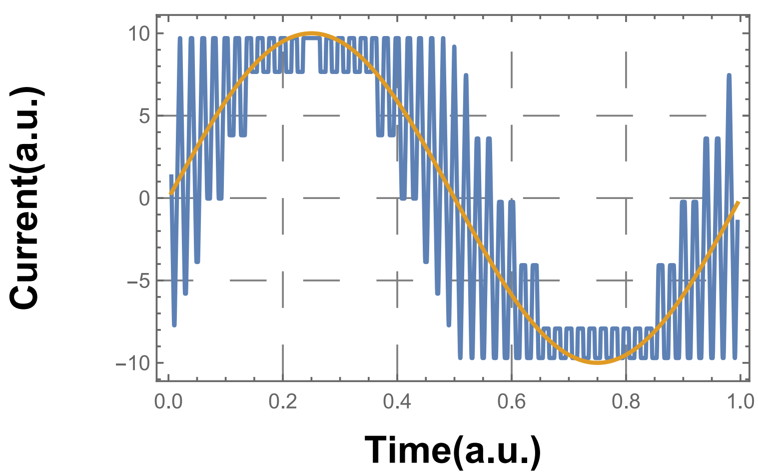
Simulation using bipolar modulation scheme



- **Raw data**



- **Moving average = 100**



- **Moving average = 1000**