Practice Course in Plasma

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Institute of Space and Plasma Sciences, National Cheng Kung University

2021 spring semester

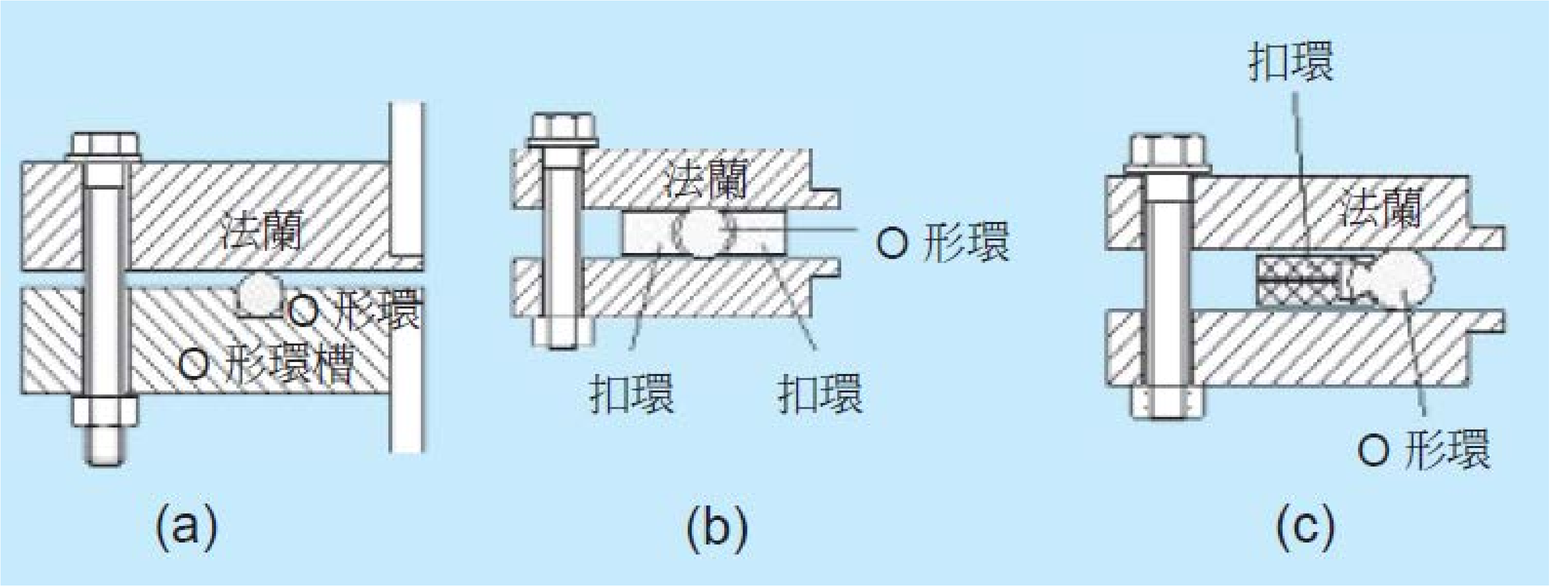
Thursday 9:10-12:00

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

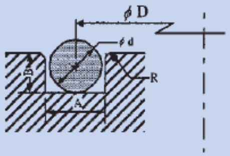
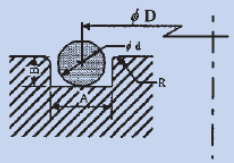
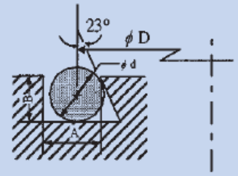
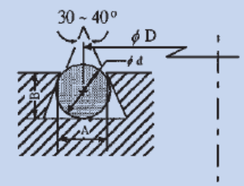
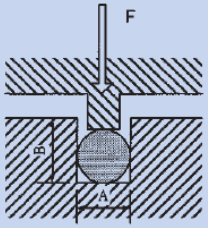
Lecture 7

2021/4/15 updated

可拆卸真空封合 – O-ring



O-ring groove design

特徵尺寸					
A	1.15d	1.4d	1.4d	0.9d－0.95d	d
B	0.72d	0.7d	0.7d	0.75d－0.8d	1.15d－1.3d
R	0.15d－0.22d 圓角磨光 $R_a < 1.6\ \mu m$	0.15d－0.22d 圓角磨光 $R_a < 1.6\ \mu m$	0.15d－0.22d 圓角磨光 $R_a < 1.6\ \mu m$	0.15d－0.22d 圓角磨光 $R_a < 1.6\ \mu m$	0.15d－0.22d 圓角磨光 $R_a < 1.6\ \mu m$

More clamp

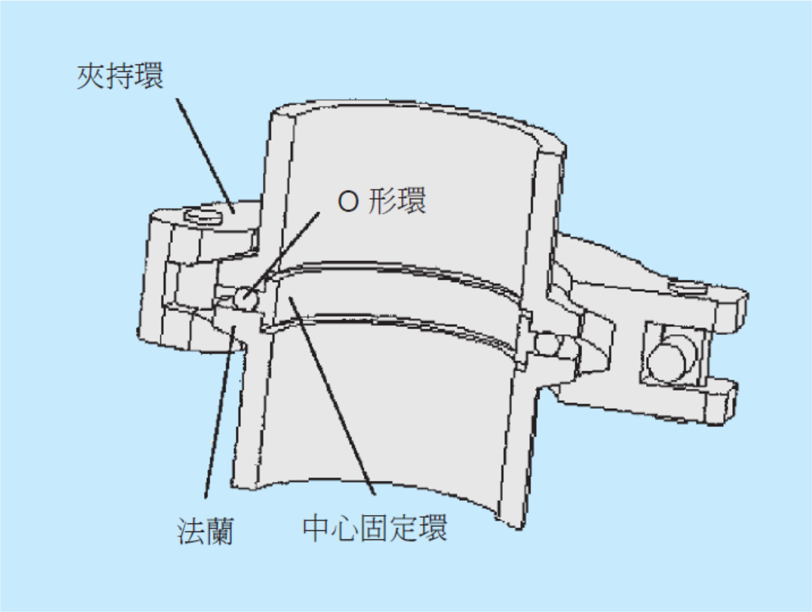


圖 3. KF 法蘭封合結構示意圖。

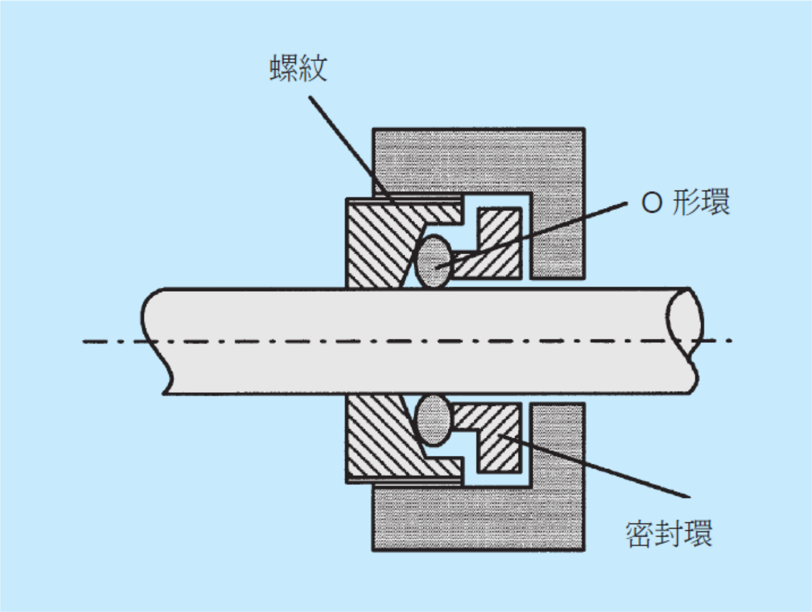
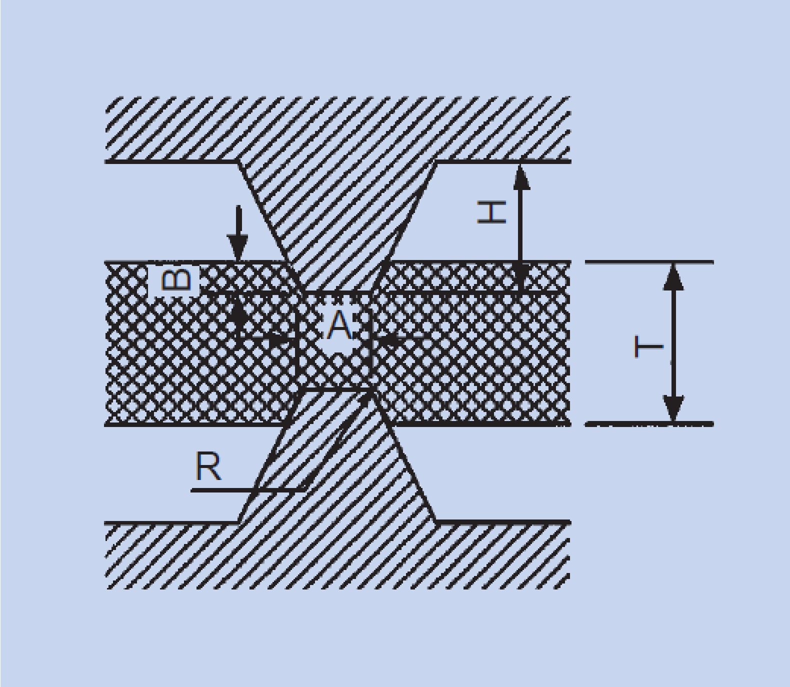
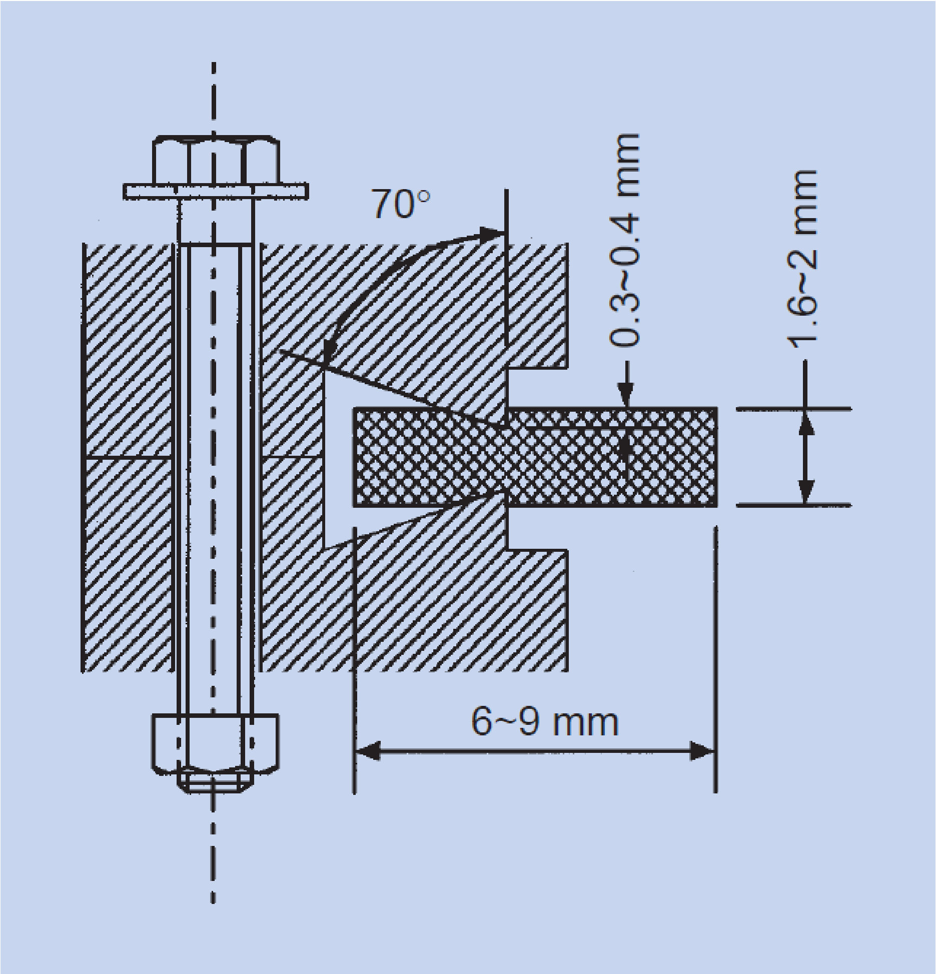


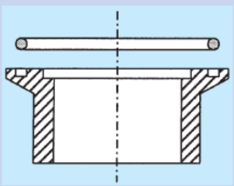
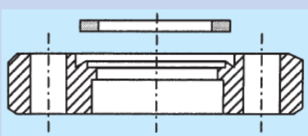
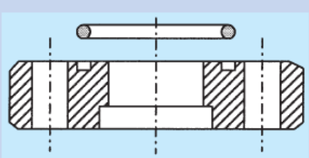
圖 4. 管路之錐形壓縮封合。

金屬墊圈刀刃及斜楔法蘭封合

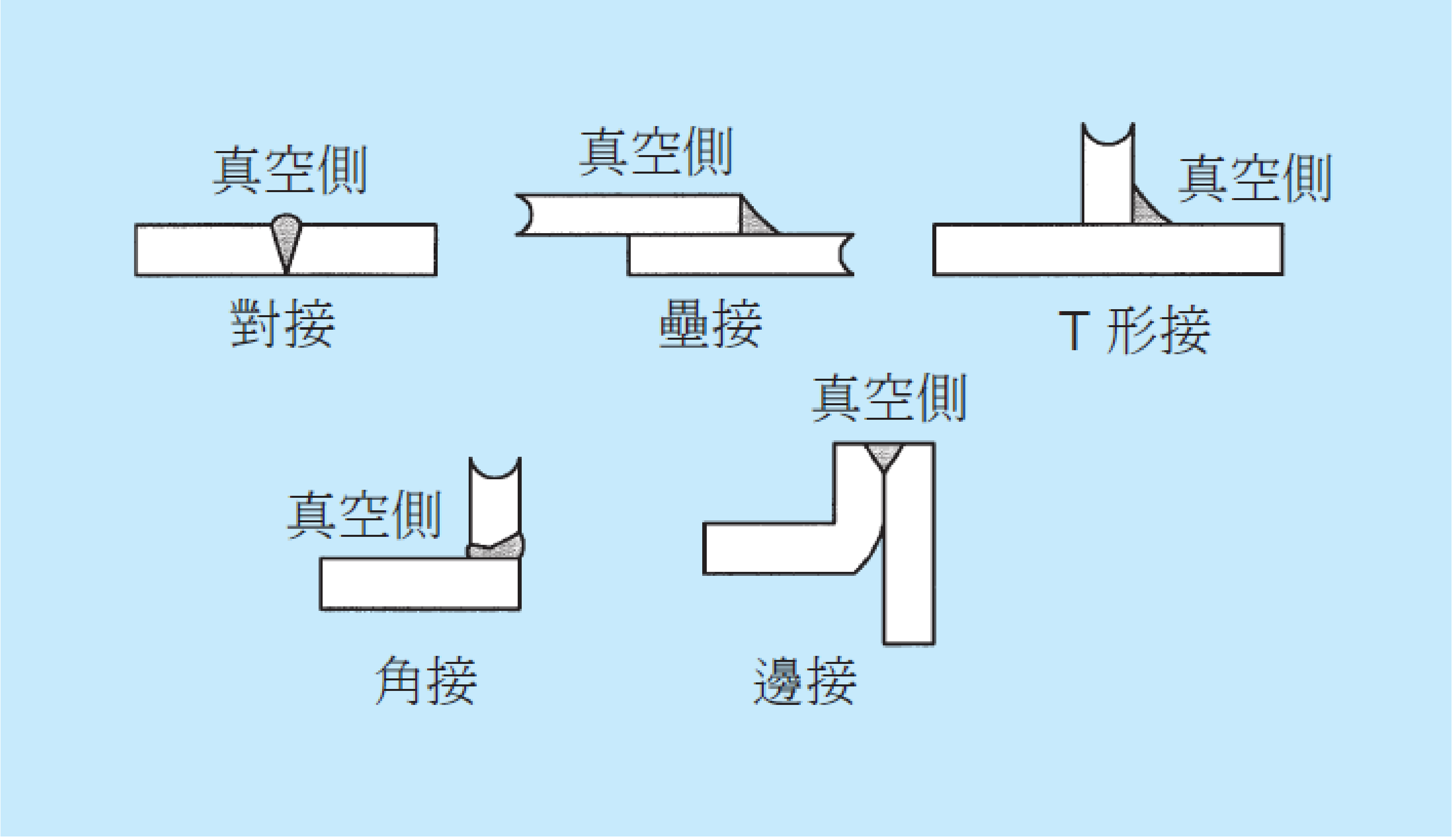




Comparison of different types of flange

法蘭種類	適用系統	特　　性
 ISO 法蘭	中低真空系統及無需烘烤之高真空系統 (壓力大於 10^{-8} Torr 之系統使用) 使用 Viton O 形環烘烤至 200 °C，操作溫度可達 150 °C。	高分子封合材料 O 形環，可重覆使用，可以使用固定中心環和平面法蘭或在法蘭上以環槽固定 O 形環，組裝拆卸快速、成本較為經濟。 組裝時可使用真空油脂輕輕塗覆 O 形環，可以提高封合性能。 小管徑使用夾緊環 (hing clamp)，手動鎖緊即可，較為方便，大管徑則使用緊固扣環 (claw clamp)。
 CF 法蘭 (conflat 法蘭)	超高真空系統封合 (壓力小於 10^{-8} Torr 之系統使用)。 可使用金屬墊圈及 Viton O 形環，若使用 Viton O 形環可烘烤至 200 °C，操作溫度可達 150 °C。	金屬墊圈封合材料以及 Viton O 形環，封合滲漏很微小。 法蘭刀口及封合面的尺寸精度及表面粗糙度要求高。 需依要求進行清潔與螺絲組裝程序。
 ASA-ANSI 法蘭	中低真空系統及無需烘烤之高真空系統 (壓力大於 10^{-8} Torr 之系統使用) 使用 Viton O 形環可烘烤至 200 °C，操作溫度可達 150 °C。	高分子封合材料 O 形環，封合效果較 ISO 法蘭佳。 可熔接或硬焊於腔體或元件需依要求進行清潔與螺絲組裝程序。

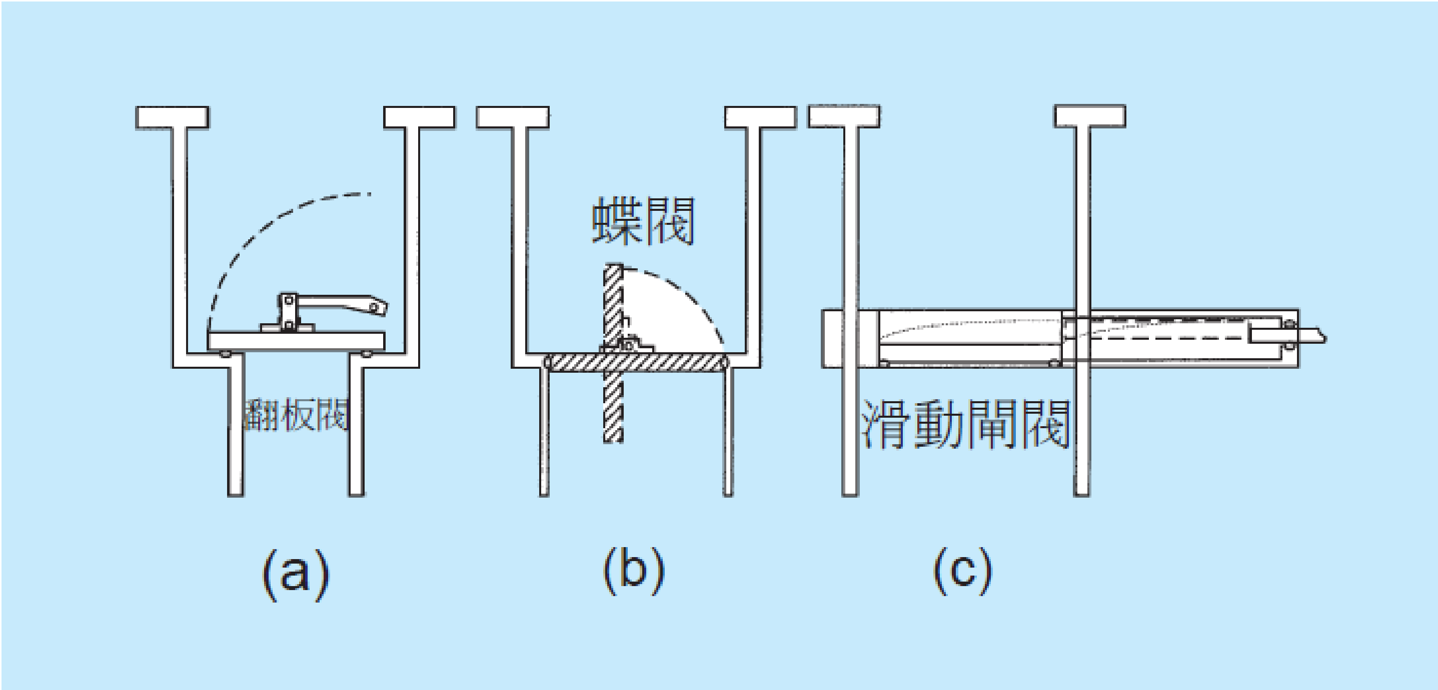
永久封合



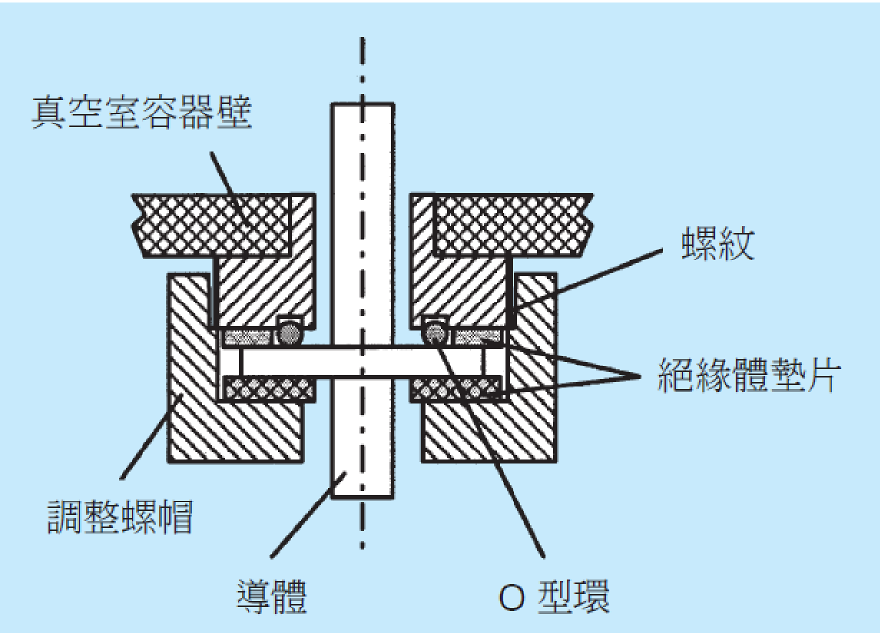
真空閥門分類

分類依據	閥門名稱
工作壓力	中低真空閥、高真空閥、超高真空閥
用途	截止閥、隔絕閥、放氣閥、節流閥、換向閥、封閉送料閥
驅動方式	手動閥、電動閥、手電兩用閥、電磁閥、氣動閥、液壓式真空閥
材料	玻璃龍頭閥、金屬真空閥
結構特點	擋板閥、翻板閥、蝶閥、連桿閥、隔板閥、閘閥、雙通閥、三通閥、四通閥、直通閥、角閥

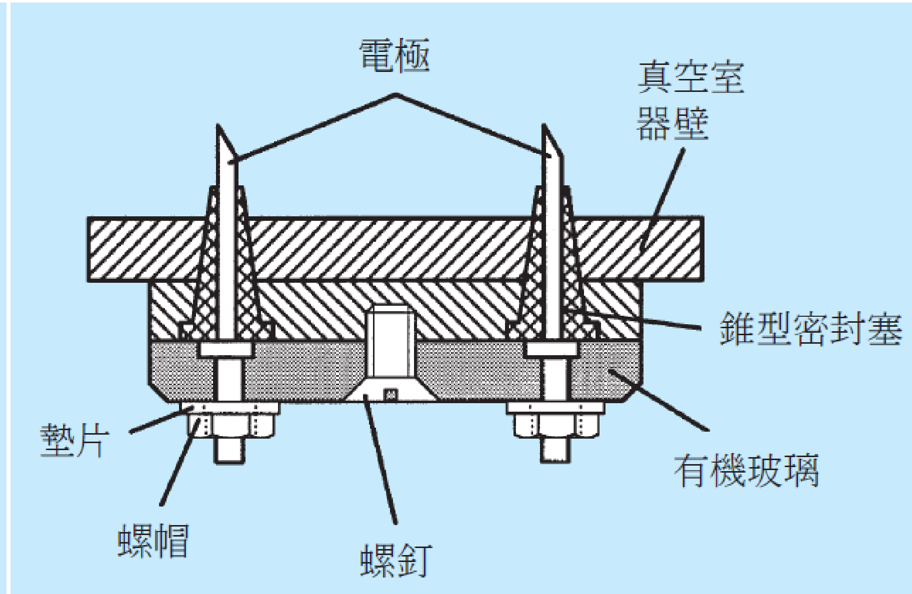
閘閥結構



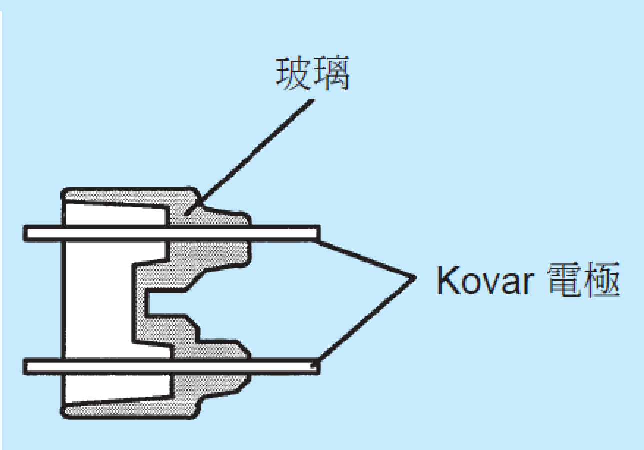
電引入



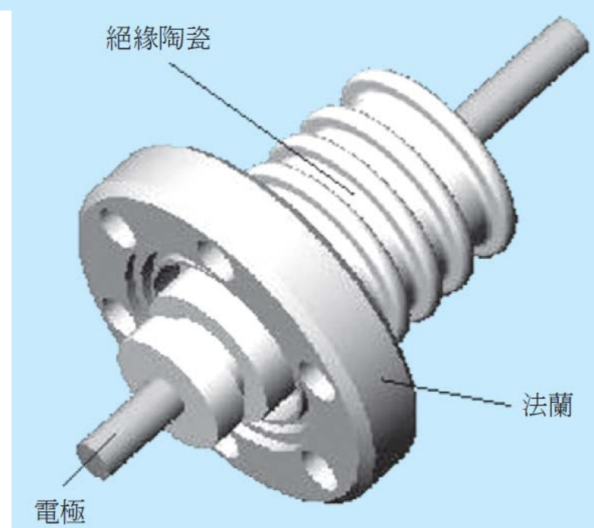
真空室容器壁
螺紋
絕緣體墊片
調整螺帽
導體
O 型環



電極
真空室
器壁
錐型密封塞
墊片
有機玻璃
螺帽
螺釘

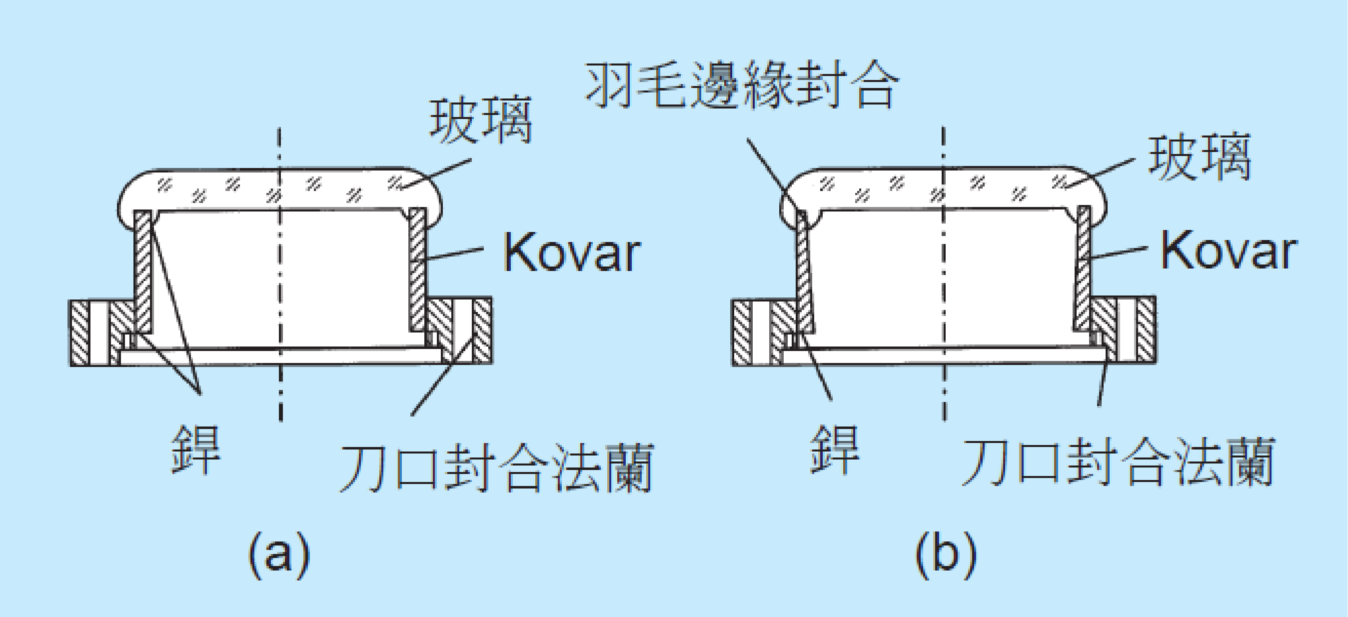


玻璃
Kovar 電極

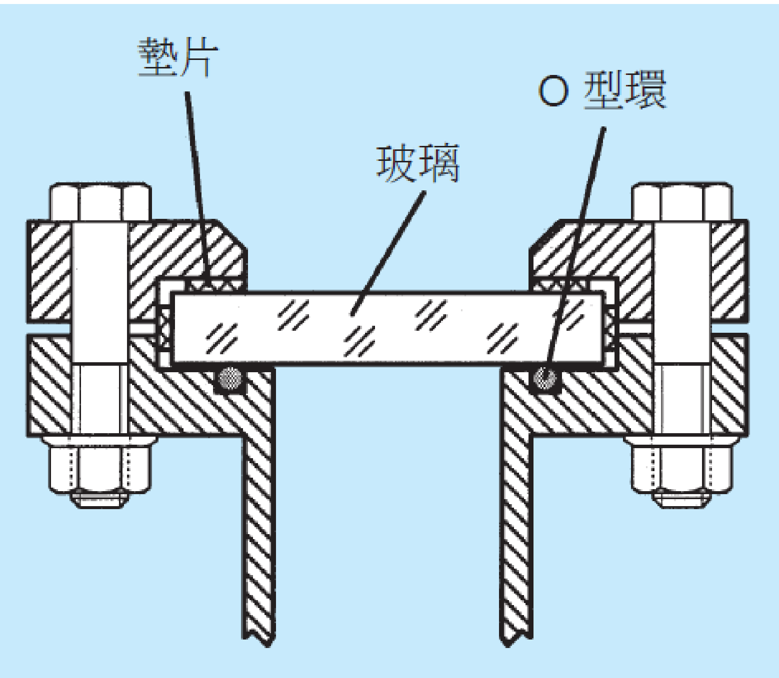


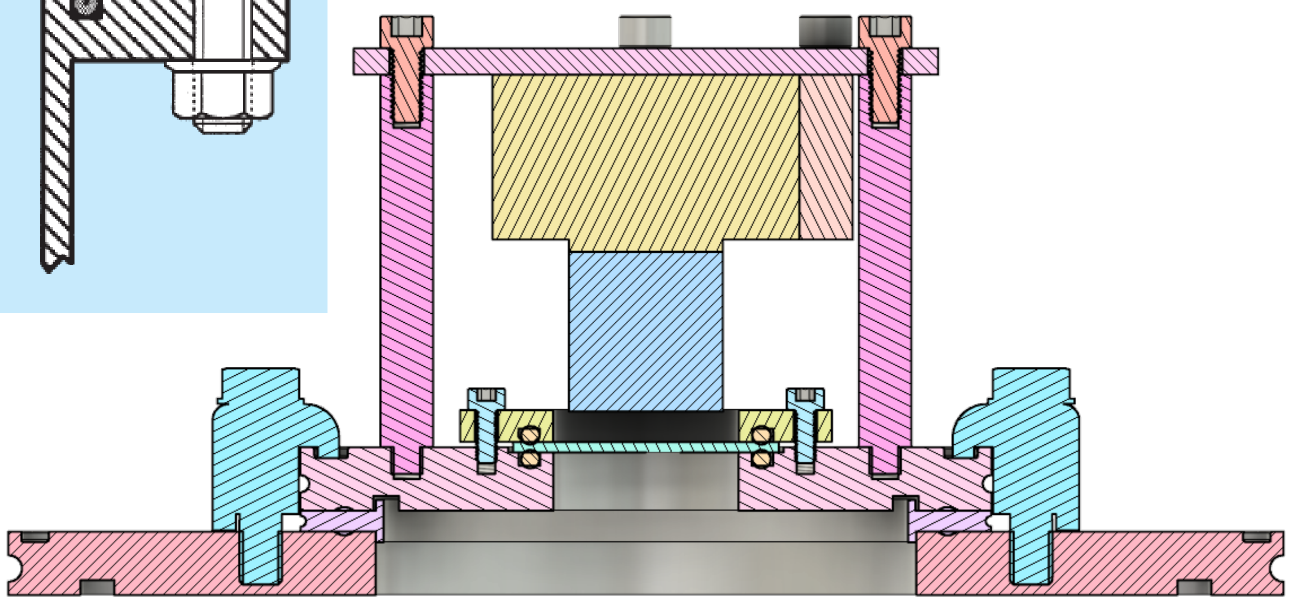
絕緣陶瓷
法蘭
電極

封合式視窗

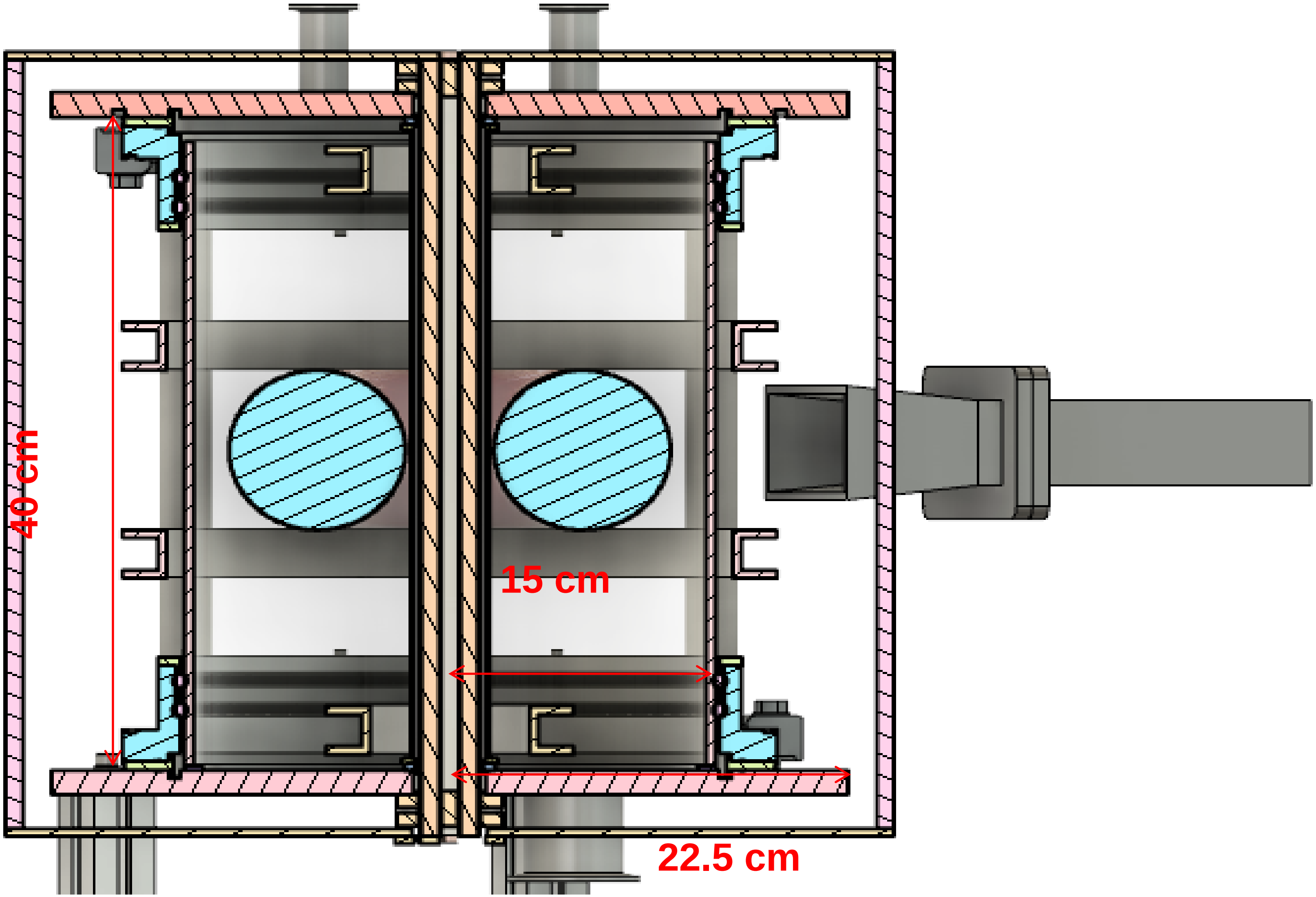


可拆式視窗

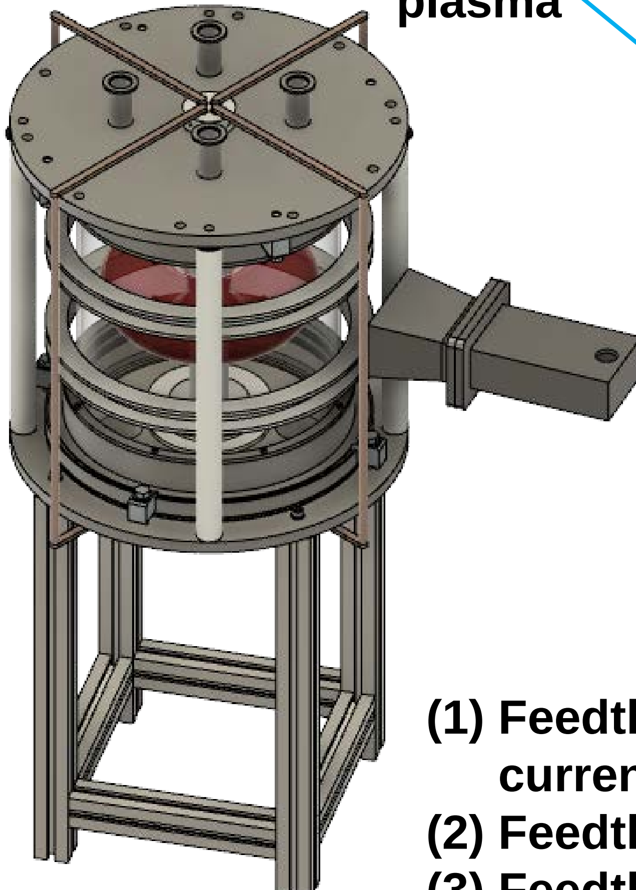


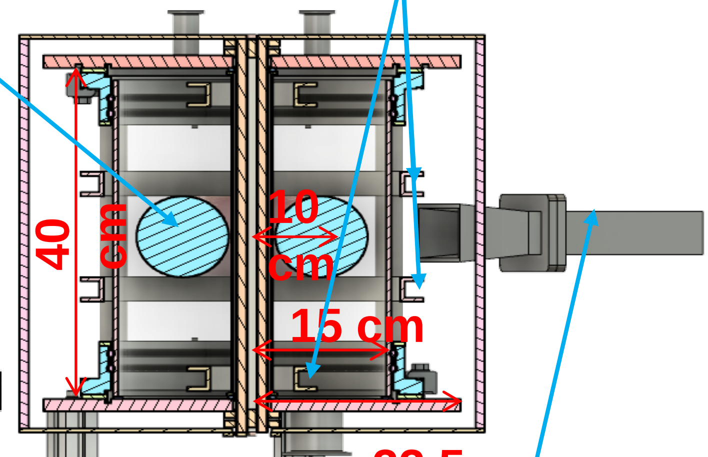


Flange of the vacuum chamber for the spherical tokamak



We need to work with a vacuum system

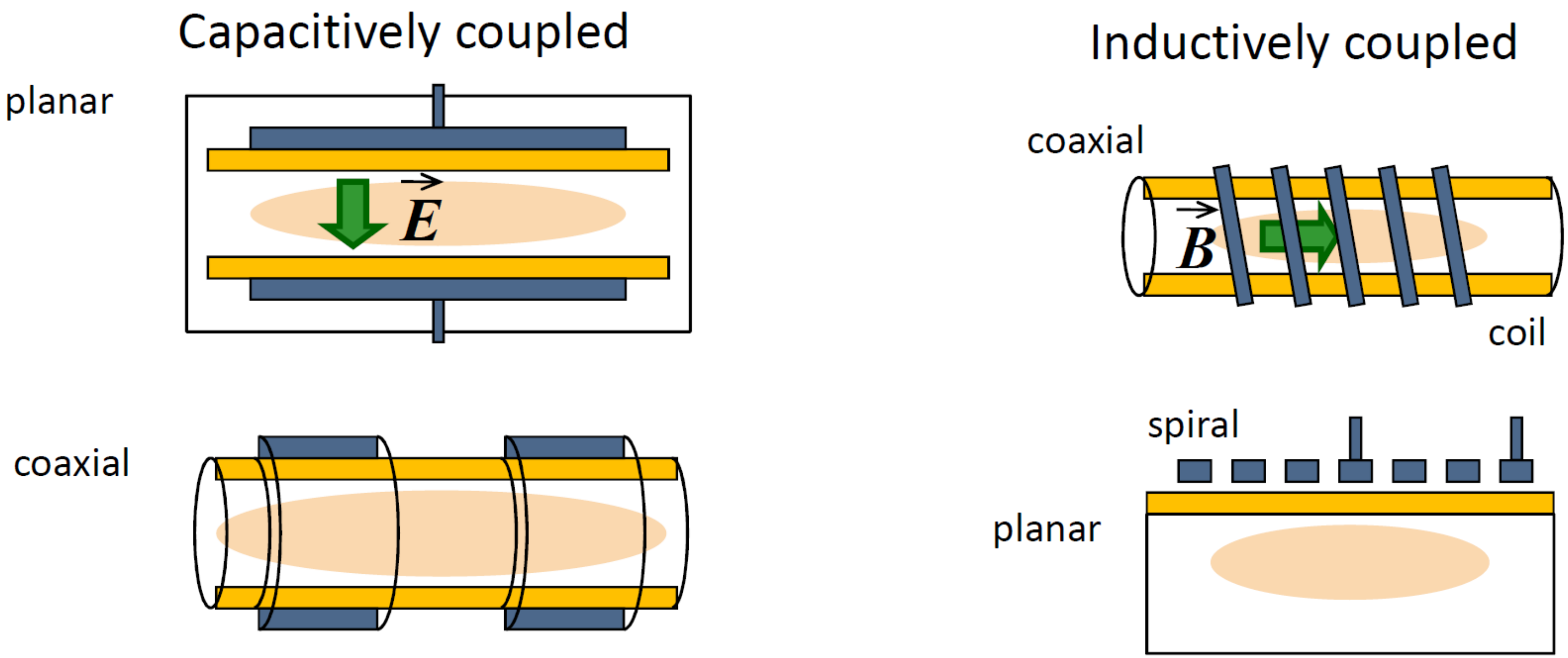




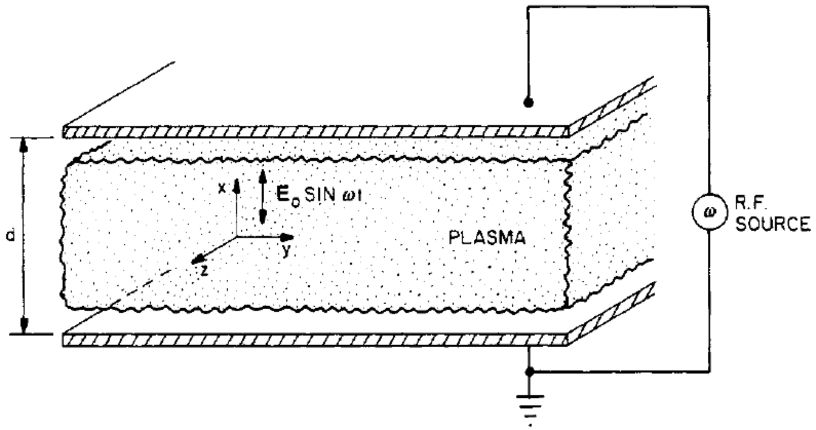
(1) Feedthrough for conducting current to drive the vertical coil.
(2) Feedthrough for Rogowski coil.
(3) Feedthrough for triple probe.

Plasma will first be generated using capacitive coupling

- **RF can interact with plasma inductively or capacitively.**



Capacitive RF coupling plasma without magnetic fields



$$\vec{F} = m\,\vec{a} = -\nu_c m\,\vec{v} - e\,\vec{E}$$

$$m\frac{\mathrm{dv}_y}{\mathrm{dt}} + m\nu_c v_y = 0$$

$$v_y(t) = v_{y0}\exp(-\nu_c t)$$

$$m\frac{d^2x}{\mathrm{dt}^2} + m\nu_c\frac{dx}{\mathrm{dt}} = eE_0\sin(\omega t)$$

$$x = C_1\sin(\omega t) + C_2\cos(\omega t)$$

$$C_1 = -\frac{eE_0}{m}\frac{1}{\omega^2 + {\nu_c}^2}$$

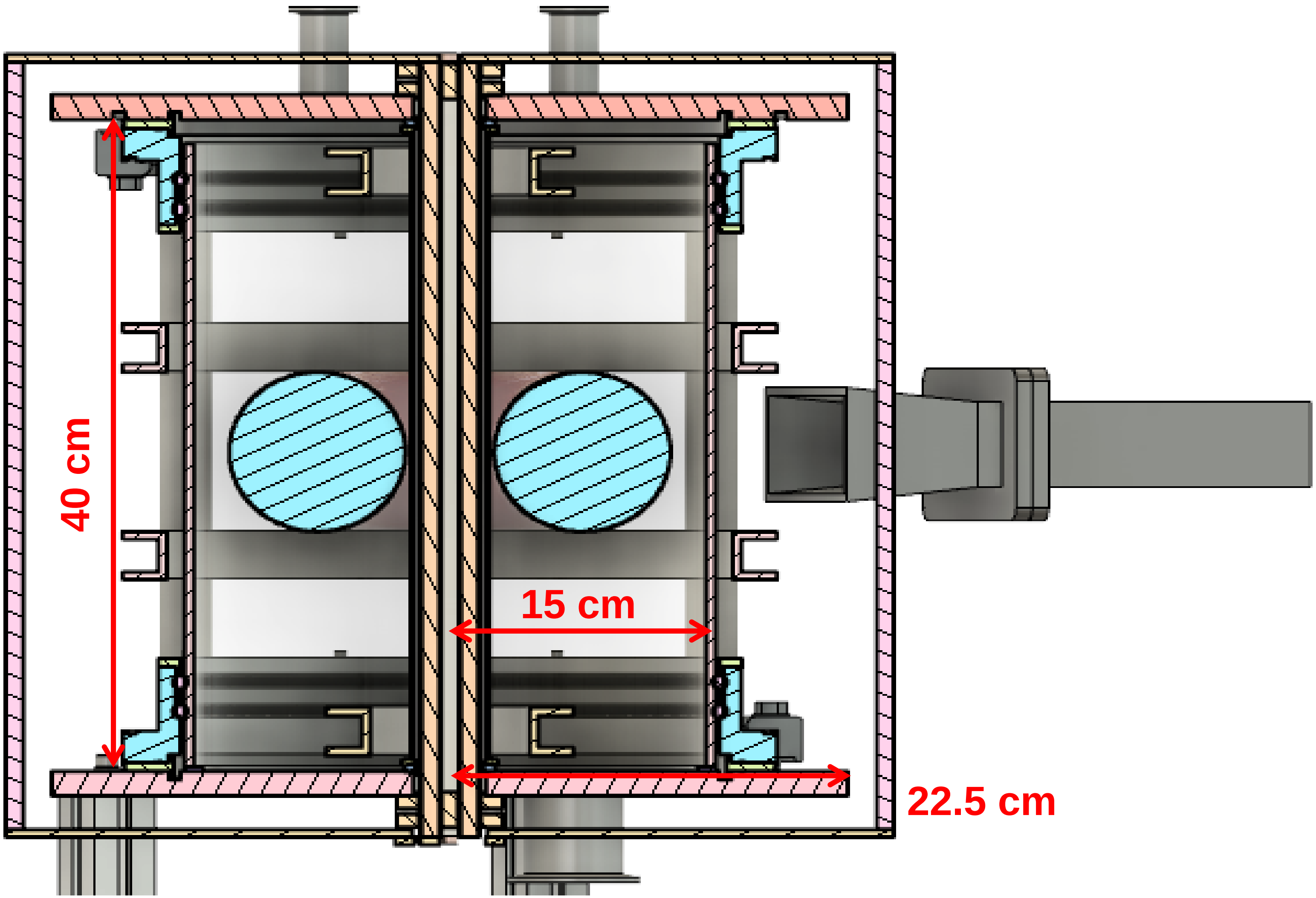
$$C_2 = -\frac{\nu_c eE_0}{\omega m}\frac{1}{\omega^2 + {\nu_c}^2}$$

$$v_x(t) = -\frac{eE_0\omega}{m(\omega^2+{\nu_c}^2)}\left[\cos(\omega t) - \frac{\nu_c}{\omega}\sin(\omega t)\right]$$

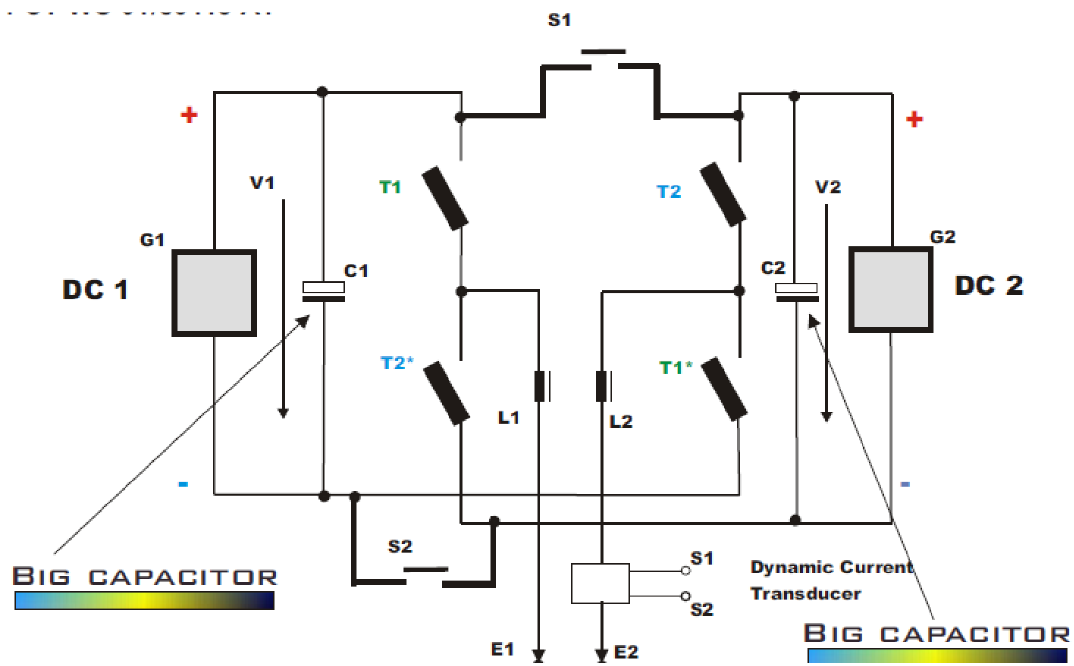
$$P = \frac{dW}{dt} = \mathrm{eE_0}\sin(\omega t)v_x$$

$$\bar{P}_{\mathrm{tot}} = n_e\bar{P} = \frac{1}{4}\epsilon_0{E_0}^2\frac{2n_e e^2}{m\epsilon_0}\frac{\nu_c}{\omega^2 + {\nu_c}^2}$$

High voltage electrode inserted from the feedthrough at the bottom of the chamber will be used for CCP

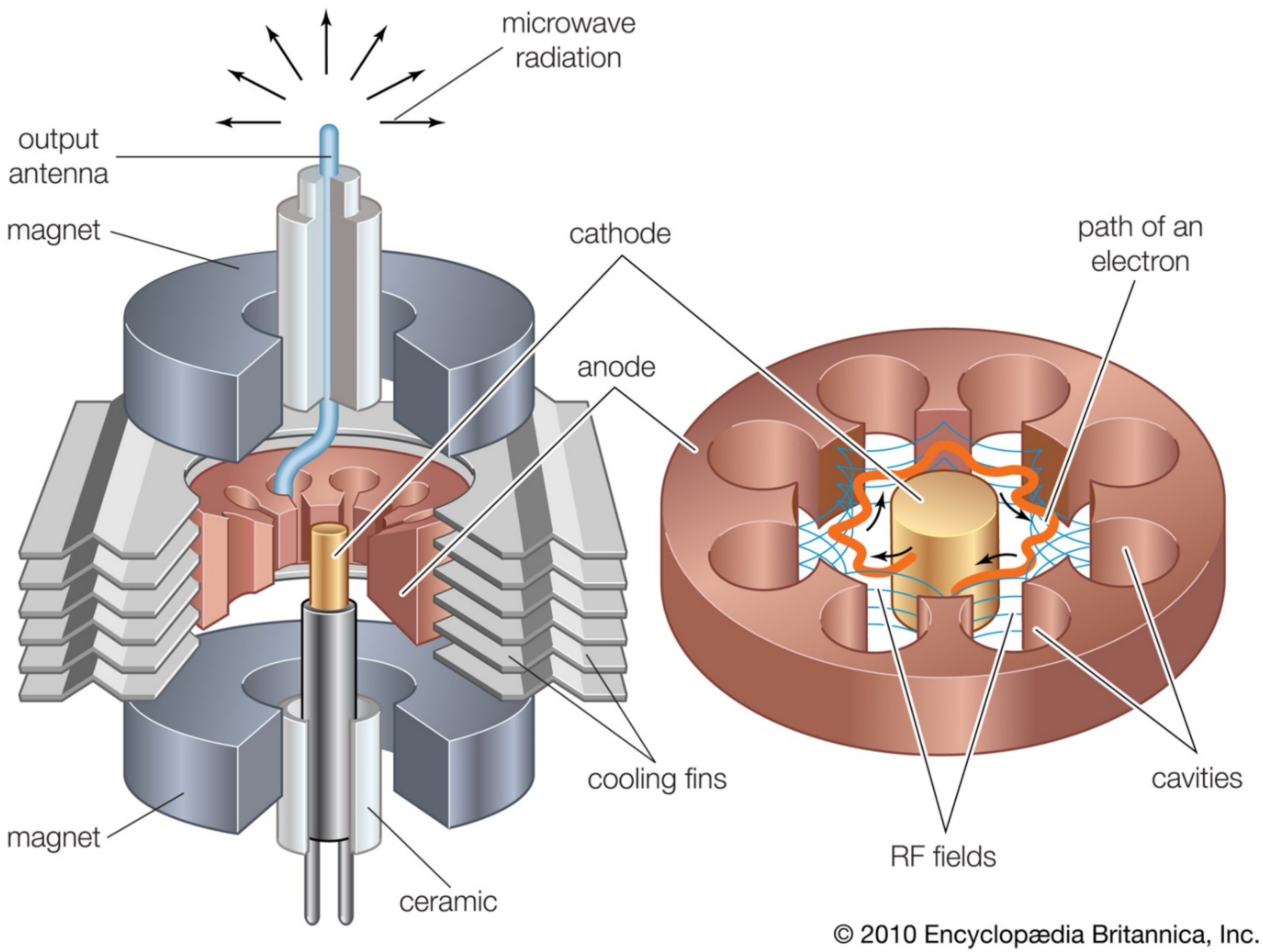


A pulse generator will be used to convert a DC voltage to an AC voltage



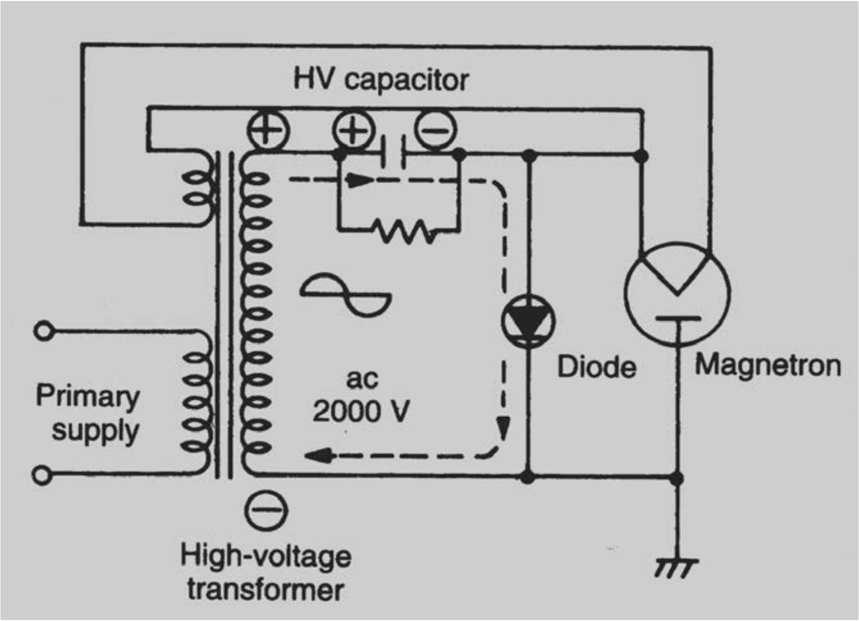
DC power supply → **Pulse generator** → **Transformer** → **HV- RF output**

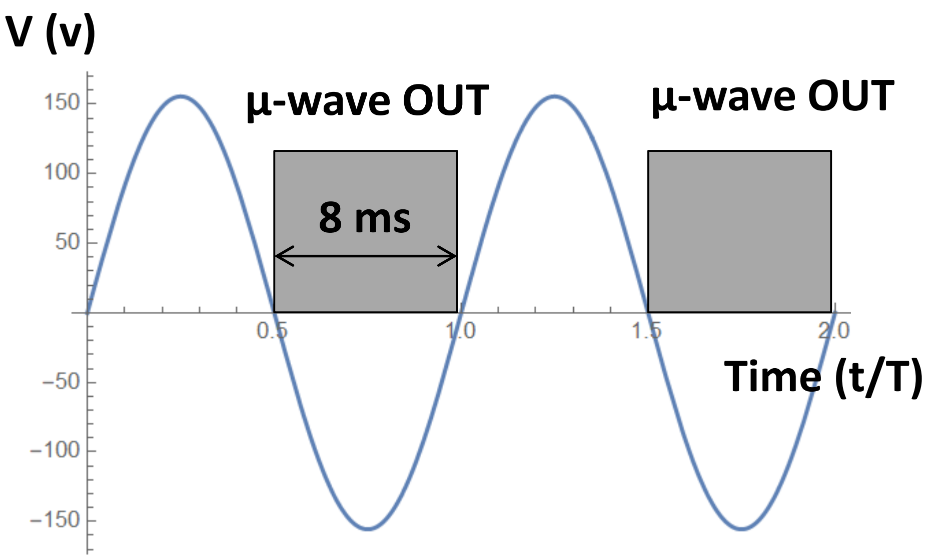
Internal of a magnetron



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

Microwave is generated in pulses





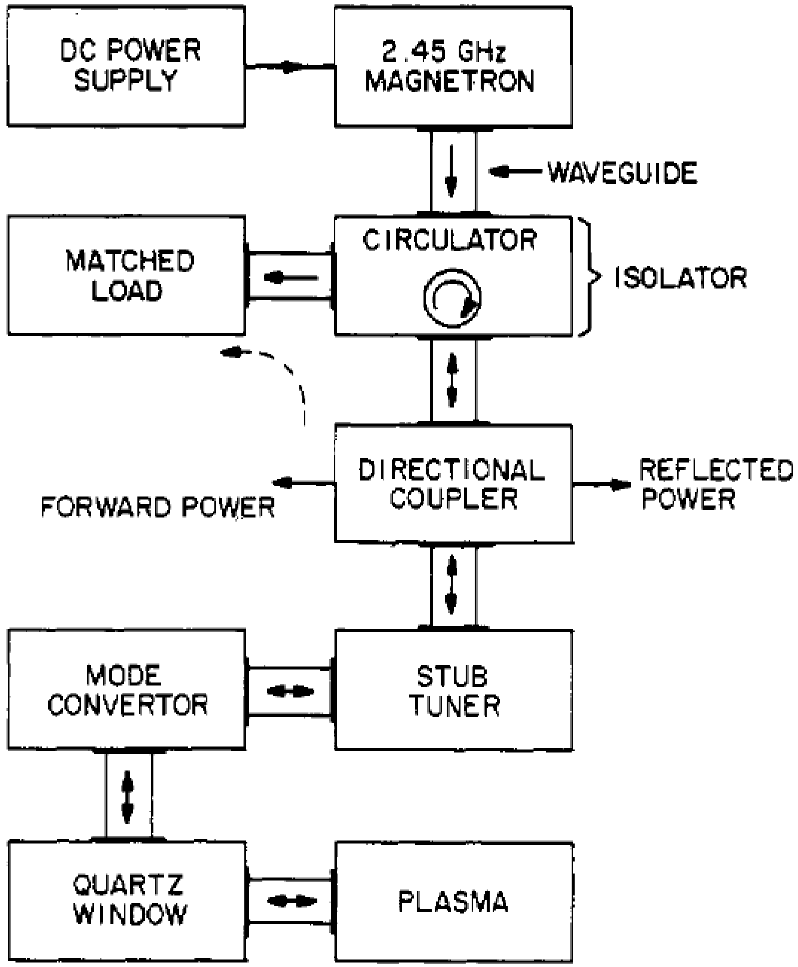
$$T = \frac{1}{60} = 16.7\text{ms}$$

- **The width of the microwave pulses is ~ 8 ms.**

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

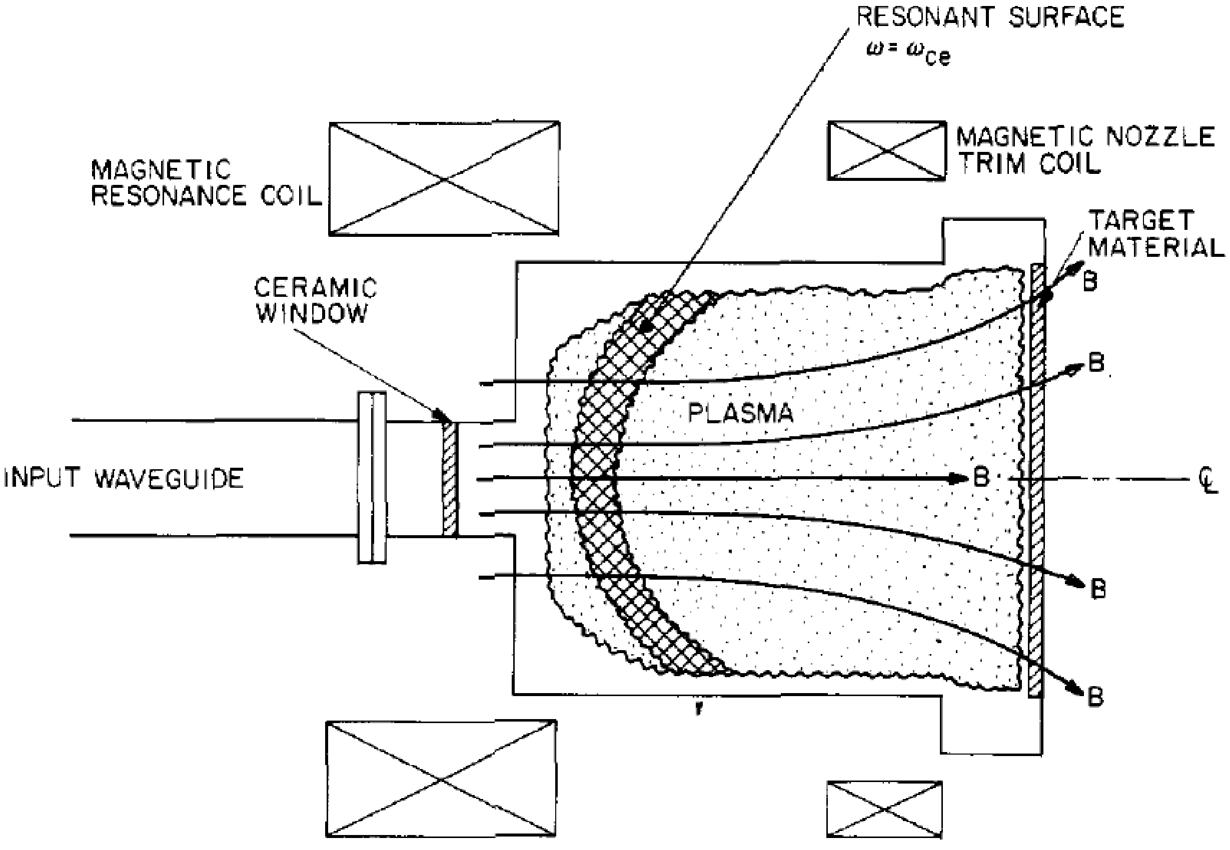
Electron cyclotron resonance (ECR) microwave systems

microwave systems



Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance heating (ECH, ECR heating)**



Electrons keep getting accelerated when a electric field rotates in electron's gyrofrequency

$$m_e \frac{d\vec{v}}{dt} = -\frac{e}{c}\vec{v}\times\vec{B} - e\vec{E}$$

$$\vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)]$$

$$m_e\dot{v}_x = -\frac{e}{c}Bv_y + E_0\cos(\omega t)$$

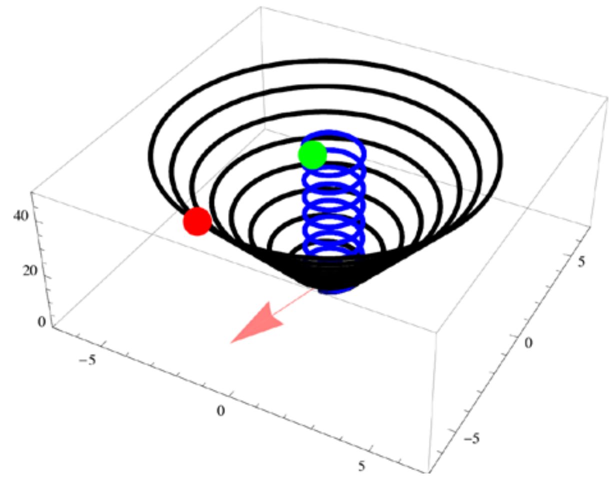
$$m_e\dot{v}_y = \frac{e}{c}Bv_x + E_0\sin(\omega t)$$

$$m_e\dot{v}_z = 0$$

$$\ddot{v}_x = -{\omega_{ce}}^2 v_x - \frac{E_0}{m_e}(\omega_{ce}+\omega)\cos(\omega t)$$

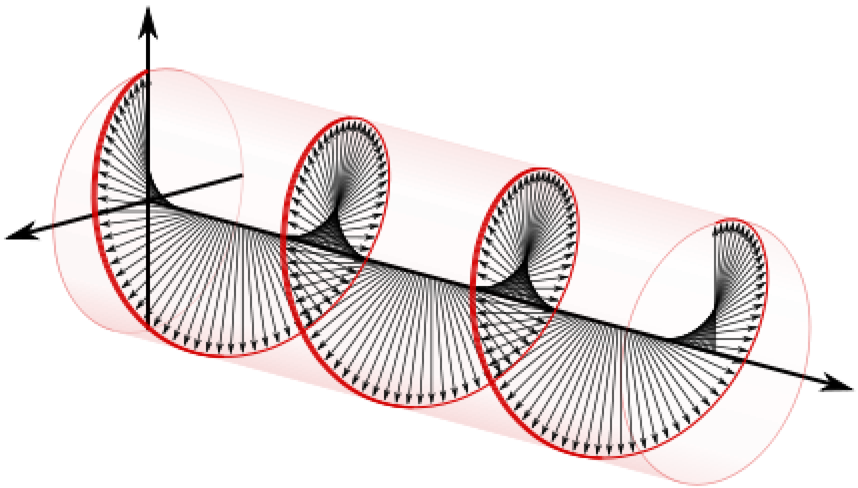
$$\ddot{v}_y = -{\omega_{ce}}^2 v_y + \frac{E_0}{m_e}(\omega_{ce}+\omega)\sin(\omega t)$$

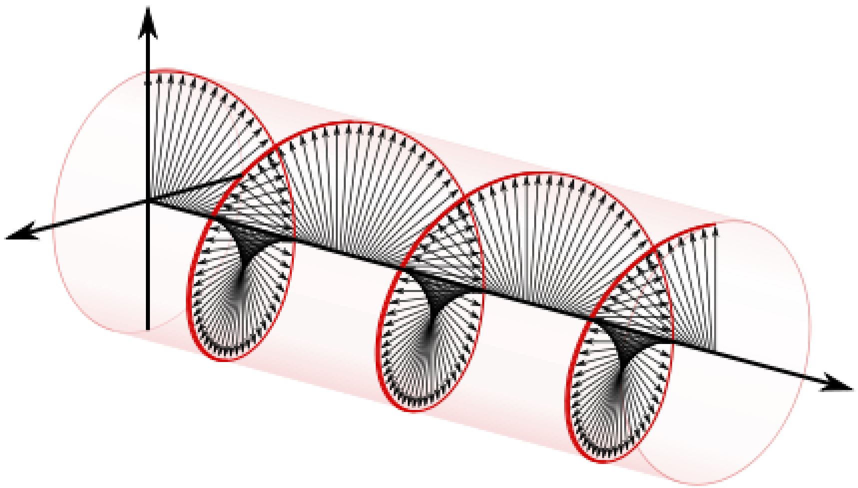
$$\omega_{ce} = \frac{eB}{m_e c}$$



Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**
- **Left-handed polarization**





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

A magnetic field of 0.0876 T is needed for ECH

$$\omega_{ce} = \frac{eB}{m_e c} \equiv \omega = 2\pi \times 2.45\ \mathrm{GHz}$$

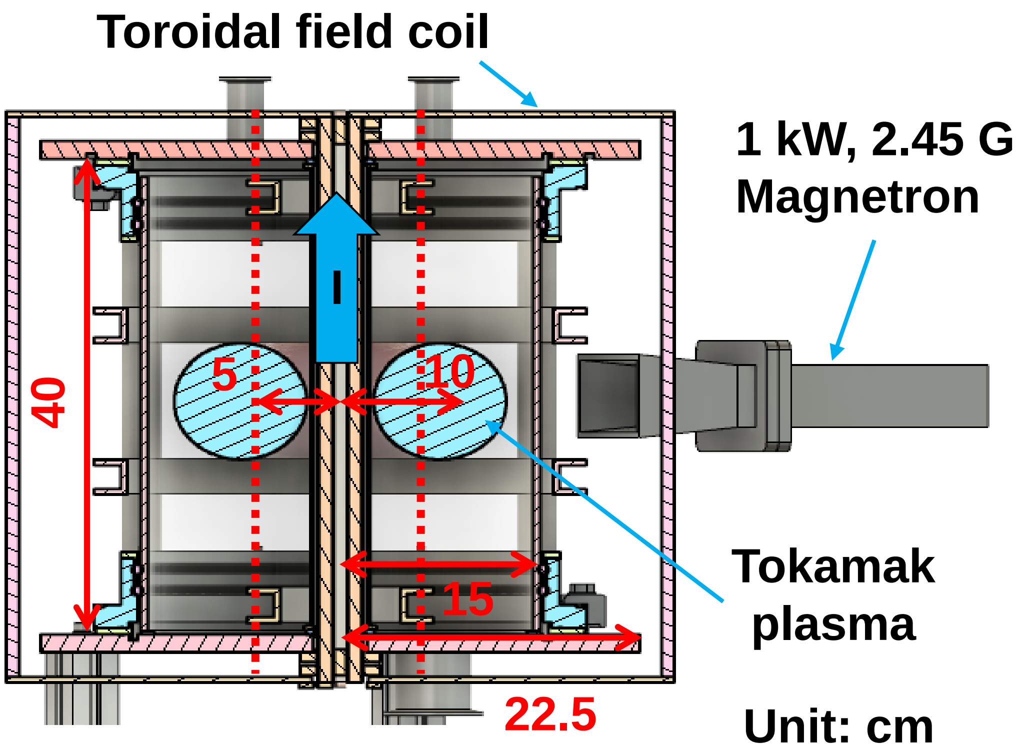
$$B = \frac{2\pi \times 2.45 \times 10^9 m_e c}{e} = 876\ \mathrm{G} = 0.0876\ \mathrm{T}$$

$$B = \frac{\mu_0 I}{2\pi r}$$

$$I = \frac{2\pi r B}{\mu_0} = \frac{2\pi r B}{4\pi \times 10^{-7}}$$

$$= 5 B_{(\mathrm{T})} r_{(\mathrm{m})} (\mathrm{MA})$$

$$= 22\ \mathrm{kA}\ @\ 5\ \mathrm{cm}$$



- A pulsed-power system will be used to generate the current with a pulse width of 1 ms.

The 0.1-T magnetic field is sufficient to confine 10-eV Ar ion

$$v = r\omega \qquad \frac{1}{2}mv^2 = kT \qquad \omega = \frac{eB}{m} \qquad r = \frac{\sqrt{2mkT}}{eB}$$

- **Larmor radius in mm @ B=0.1 T:**

T (eV)	H (1g/mole)	D (2g/mole)	T (3g/mole)	He (4g/mole)	Ar (40g/mole)
1	1.4	2.0	2.5	2.9	9.1
10	4.6	6.5	7.9	9.1	28.9
100	14.4	20.4	25.0	28.9	91.3
1000	45.6	64.5	79.1	91.3	288.7

- **The Larmor radius of 1-keV electron @ B=0.1 T is 1.1 mm. Electrons are confined in our system.**

- **Ar will be used.**

The magnetic field energy of the toroidal field is ~100 J

$$B = \frac{\mu_0 I}{2\pi r}$$

$$E = \int \frac{B^2}{2\mu_0}\, dv = \int_{r_{min}}^{r_{max}} \frac{B^2}{2\mu_0} 2\pi r L\, dr = \frac{2\pi L}{2\mu_0} \frac{{\mu_0}^2 I^2}{(2\pi)^2} \int_{r_{min}}^{r_{max}} \frac{1}{r^2} r\, dr = \frac{\mu_0 L I^2}{4\pi} \int_{r_{min}}^{r_{max}} \frac{1}{r}\, dr$$

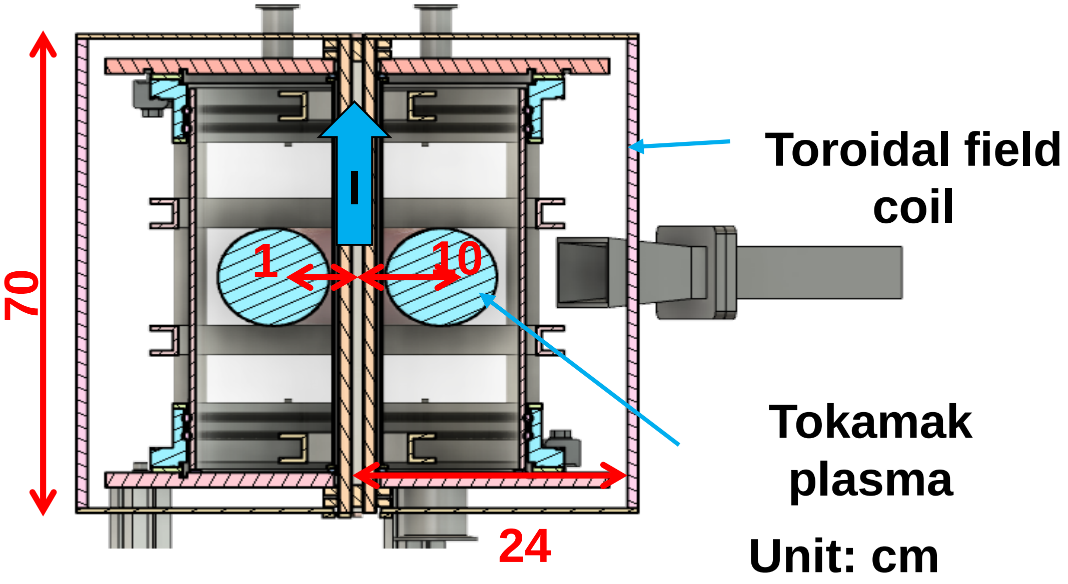
$$= \frac{\mu_0 L I^2}{4\pi} \ln\left(\frac{r_{max}}{r_{min}}\right) = 10^{-7} \times 0.7 \times \left(20 \times 10^3\right)^2 \ln\left(\frac{24}{1}\right)$$

$$= 89\ \mathrm{J}$$

$$E = \frac{1}{2} L I^2 \qquad L = \frac{2E}{I^2}$$

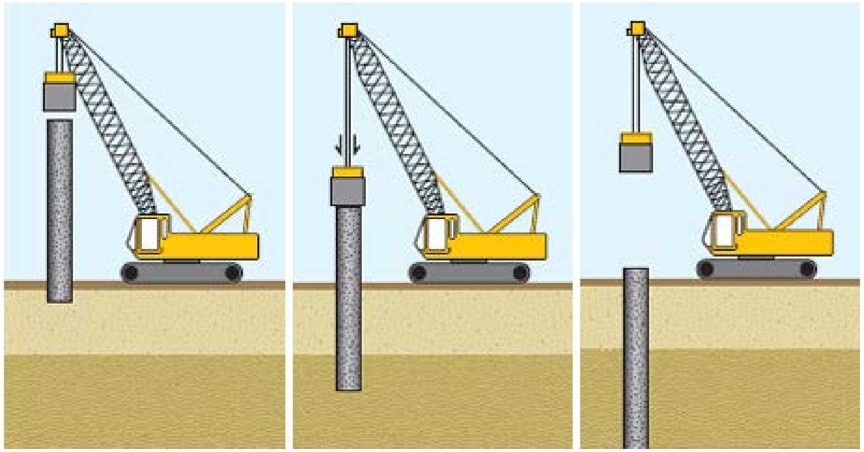
#/ of Turns	*I* (kA)	*L* (μH)
1	20	0.45
4	5	7.1
8	2.5	28.5

- Measured *L*=15 μH



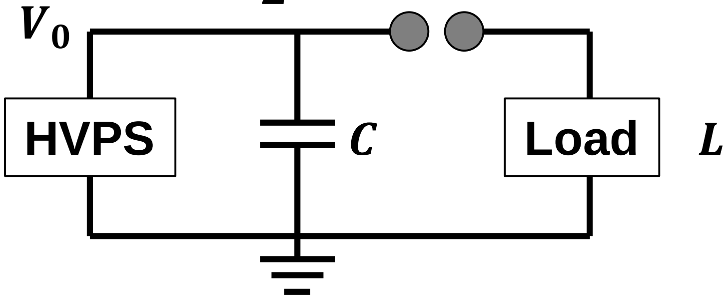
A pulsed-power system is capable of providing a high-power output

- **Driven piles**



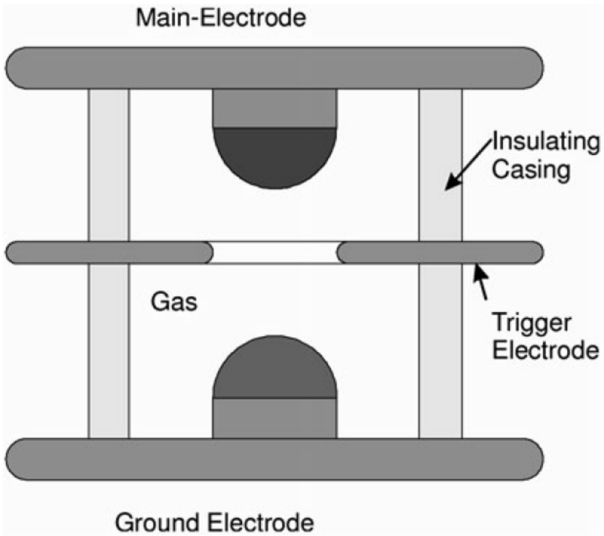
- **Capacitive-storage pulsed-power system**

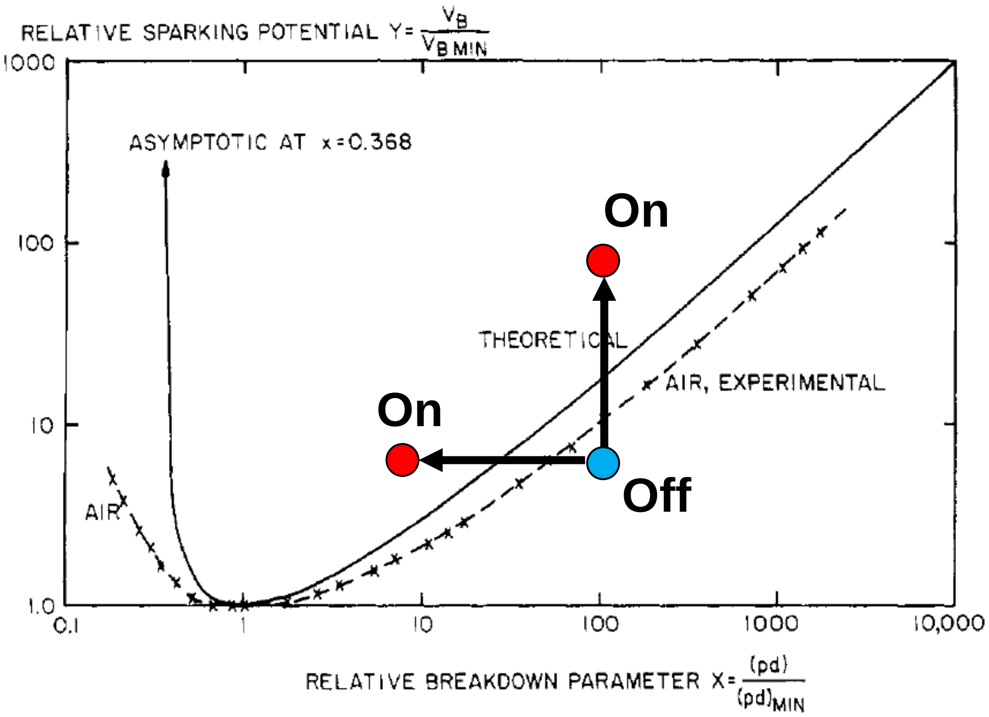
$$E = \frac{1}{2} C V_0^2$$



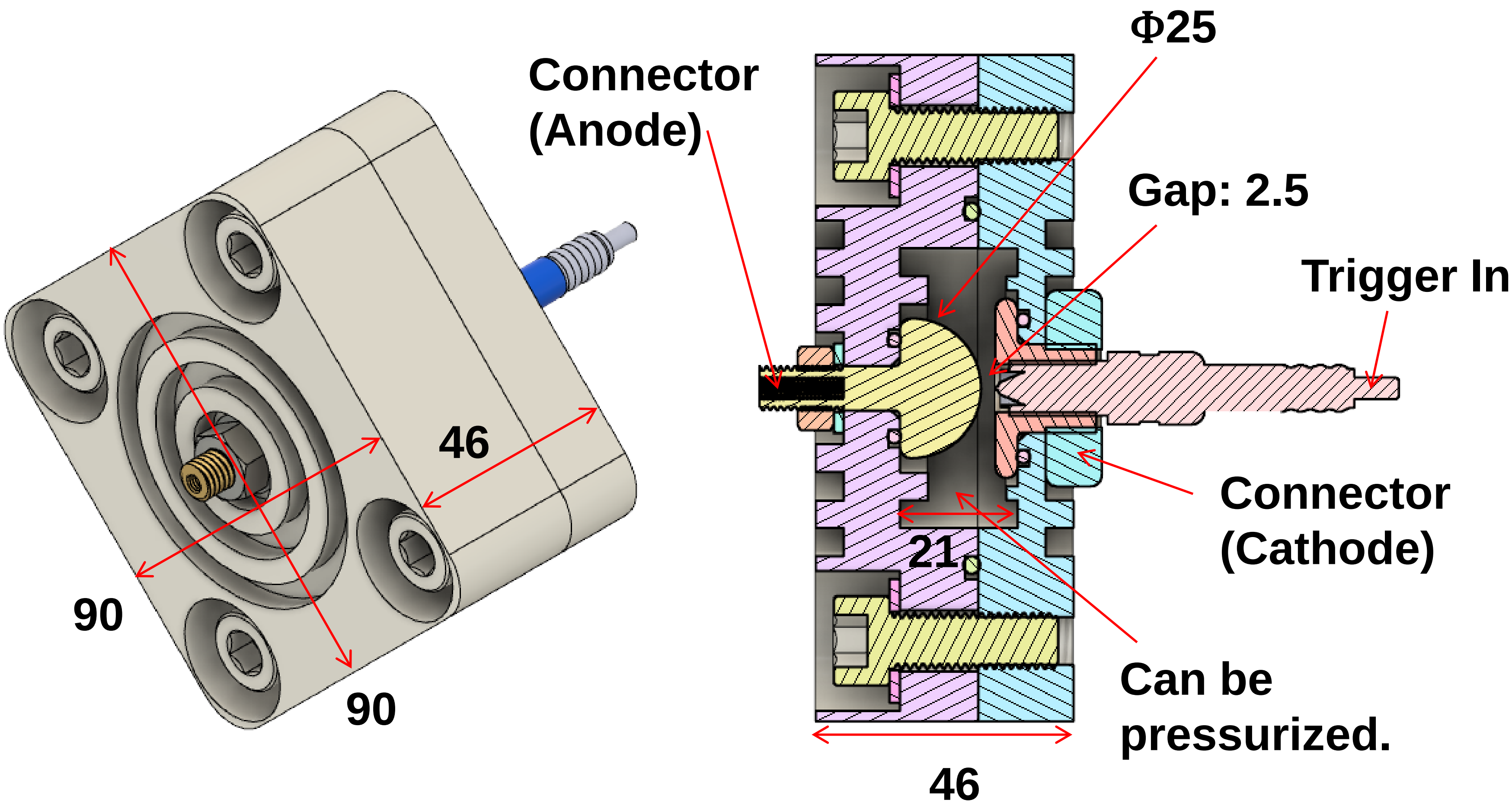
http://www.saudifoundations.com/driven.html

A spark gap switch is closed when electron breakdown occurs



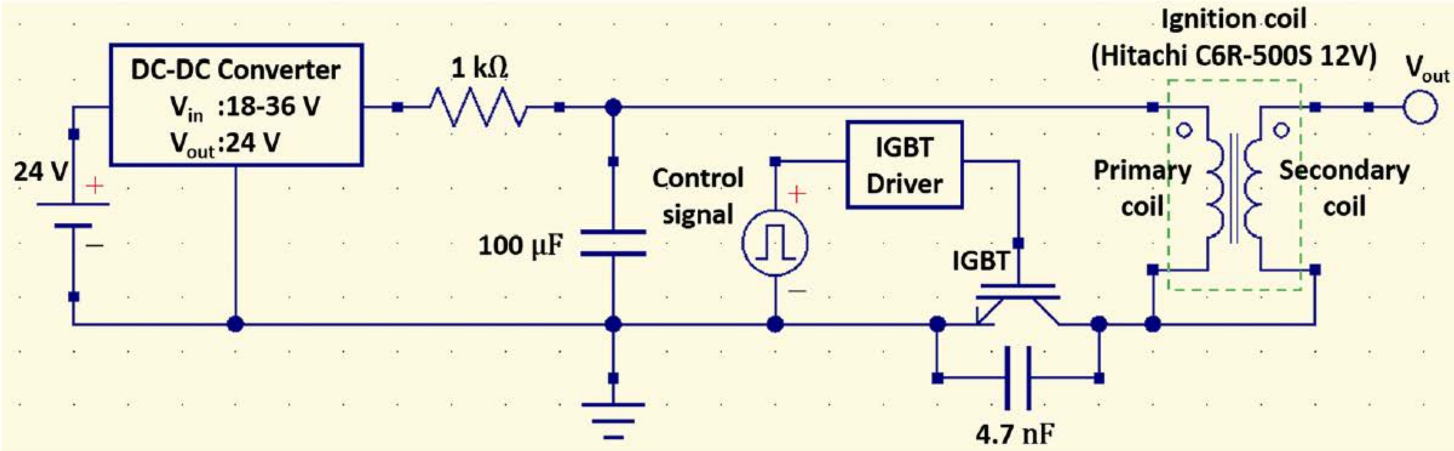


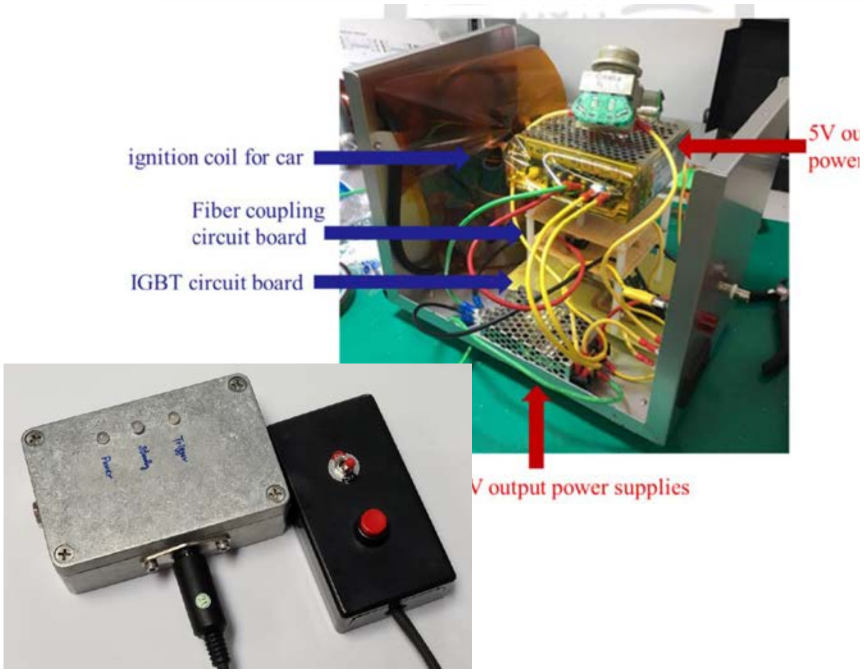
Trigatron will be used as the controlled-spark gap switch

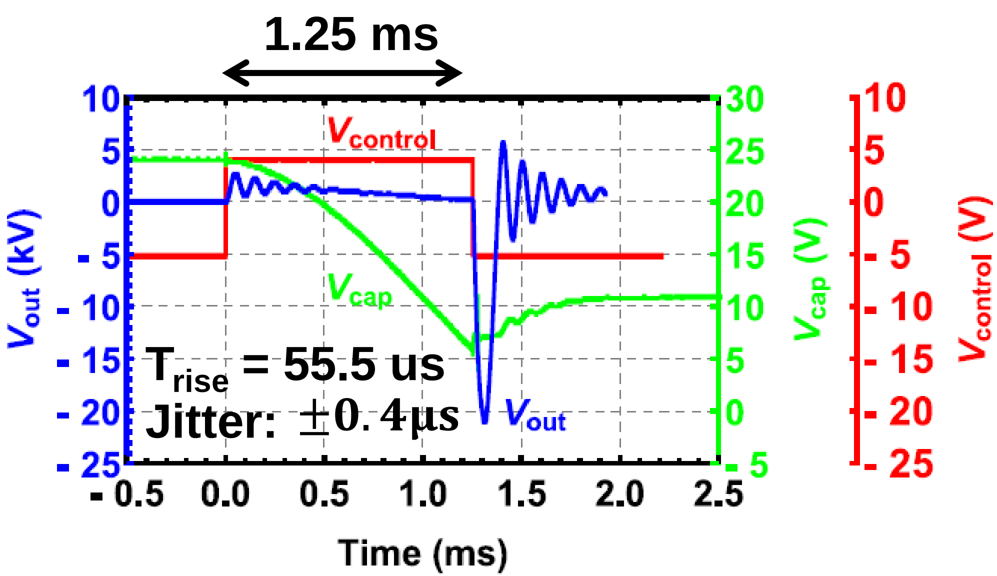


Unit: mm

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

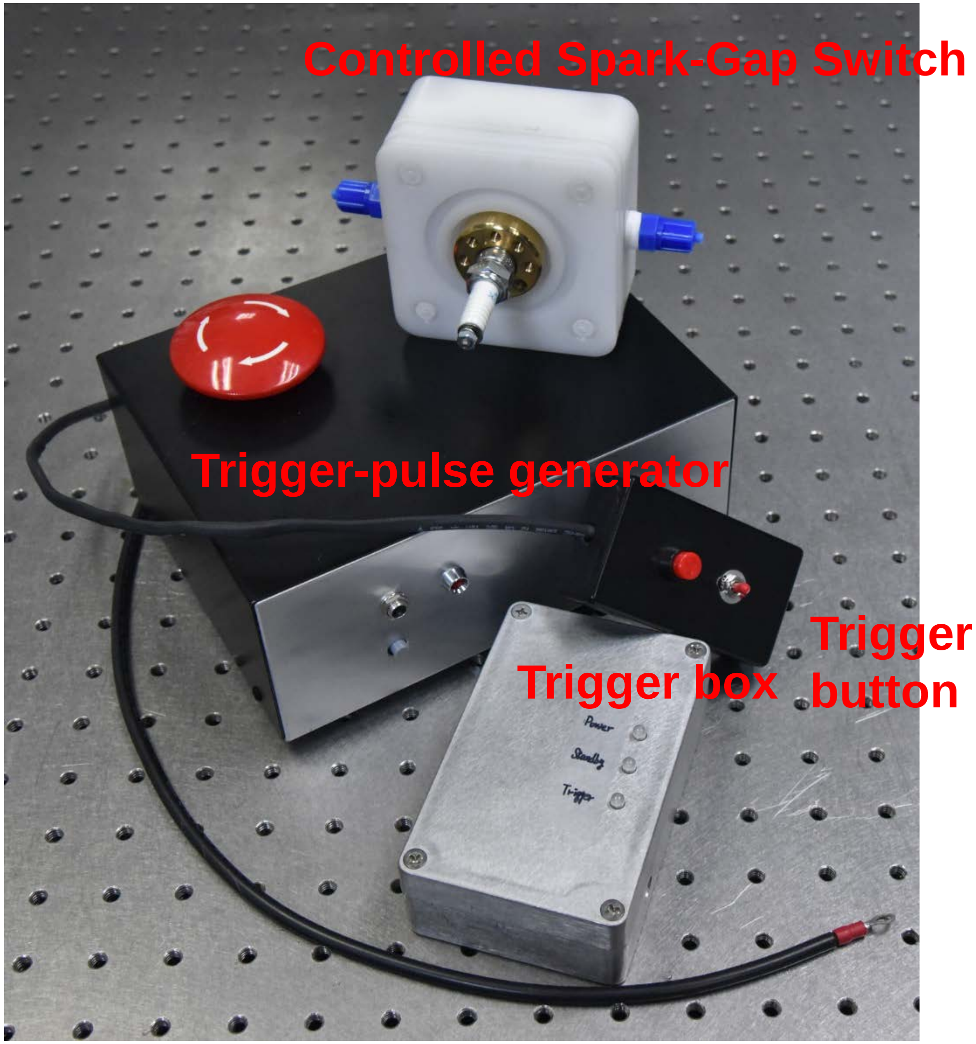






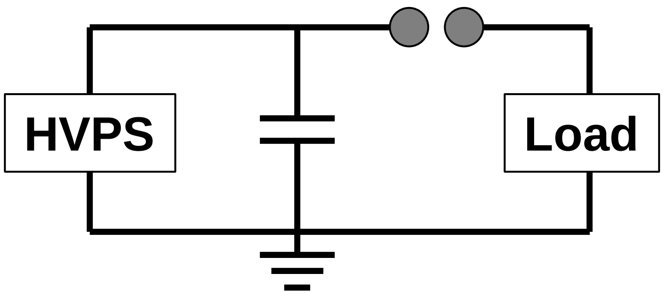
P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)

The controlled spark-gap switch

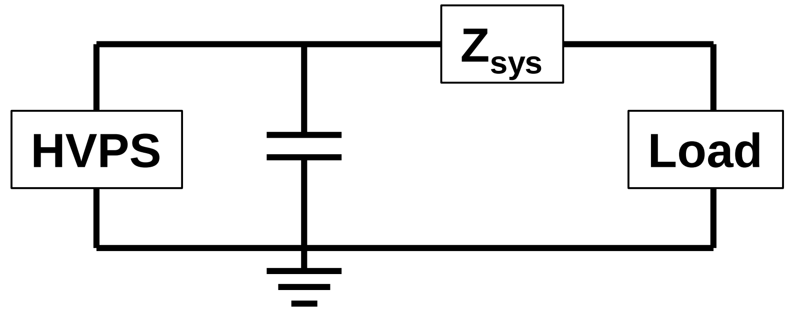


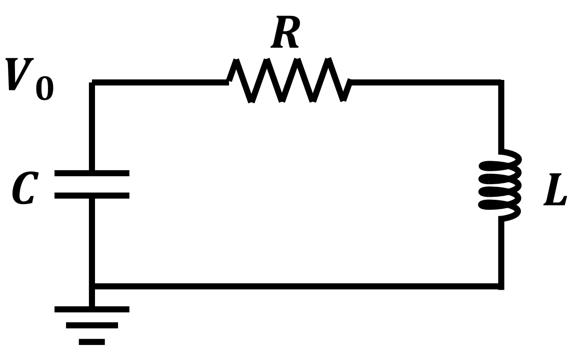
A simple pulsed-power system is a RLC circuit

- **Before discharge**

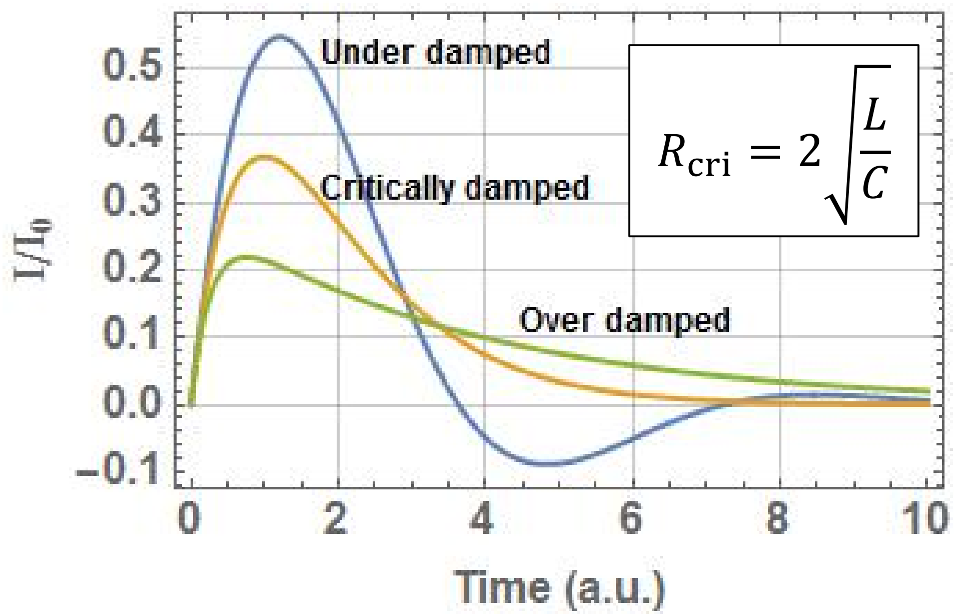


- **After discharge**

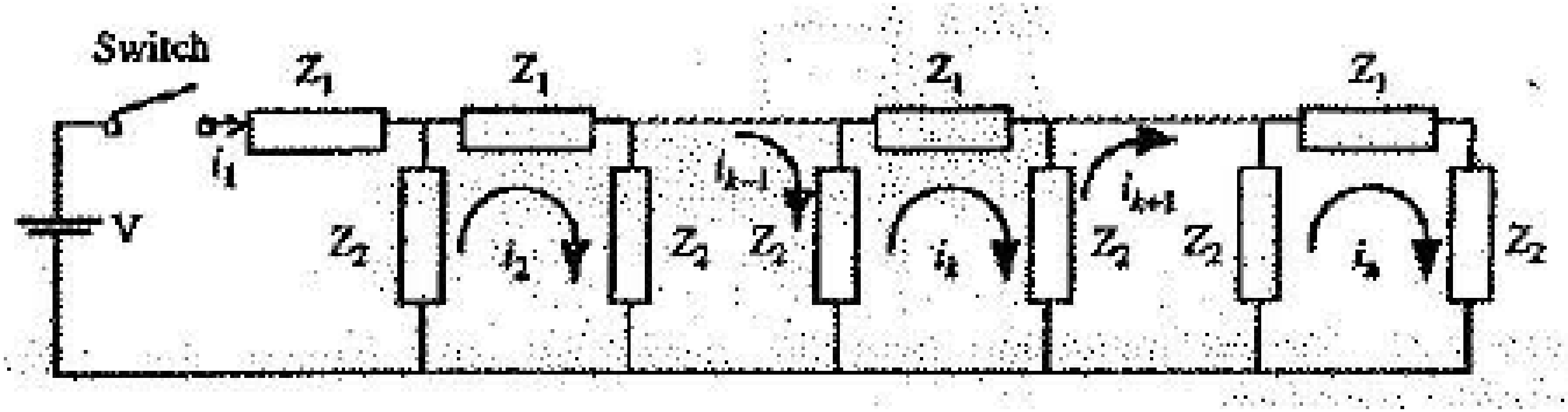




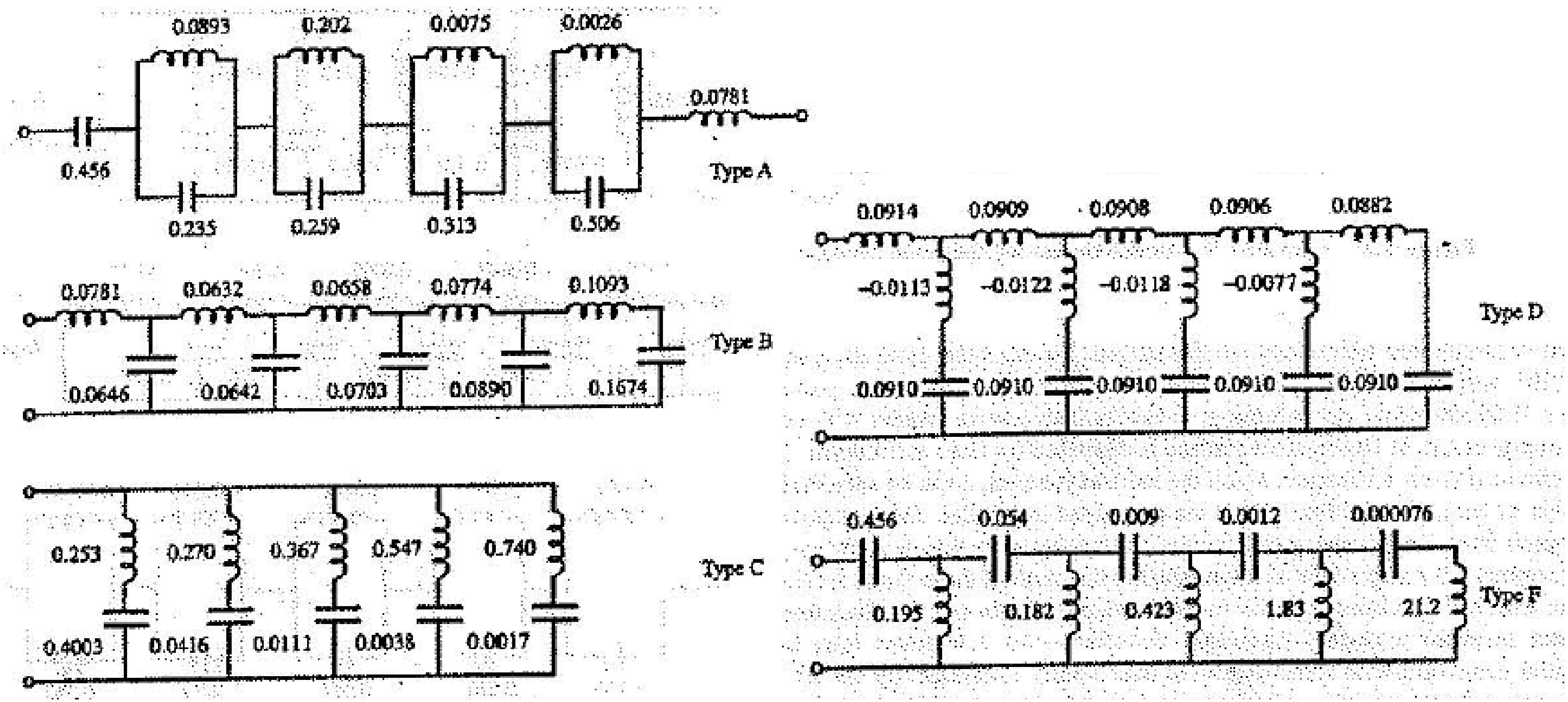
- **How can we generate a square current pulse?**



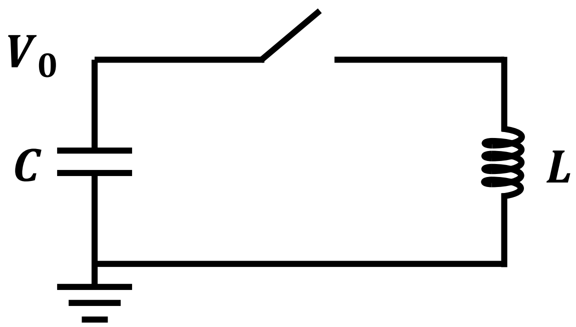
Pulse-forming network (PFN)



Different type of PFN



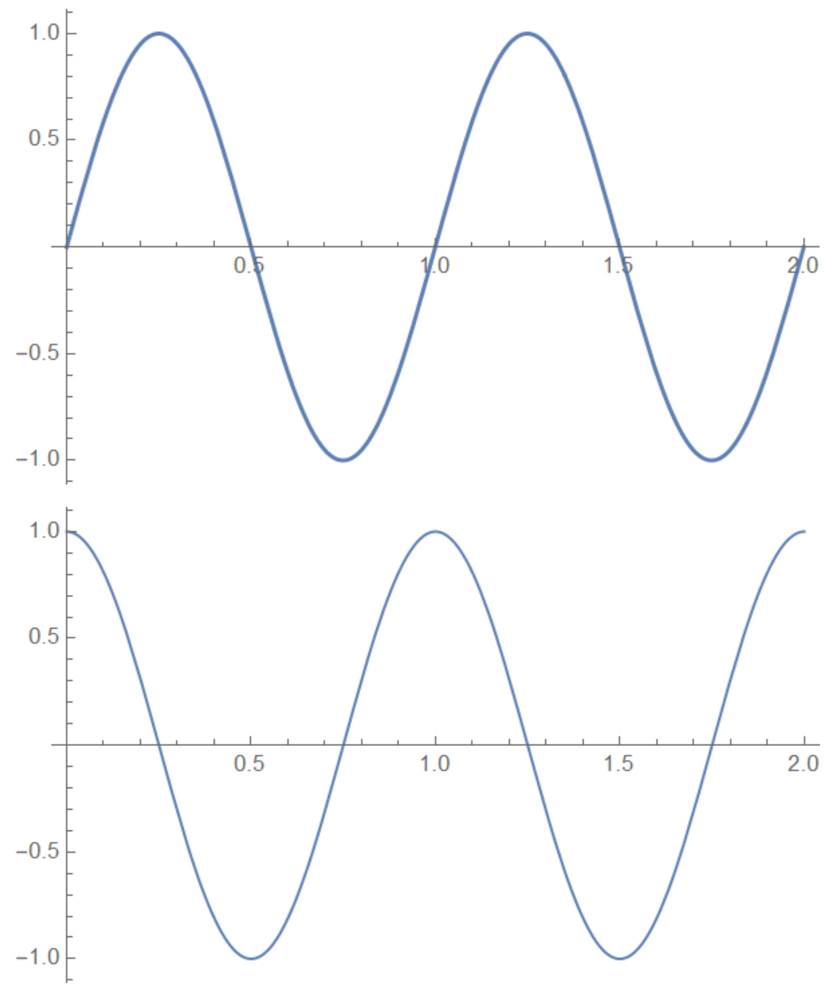
The current output of a LC circuit is a basis of Fourier series



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

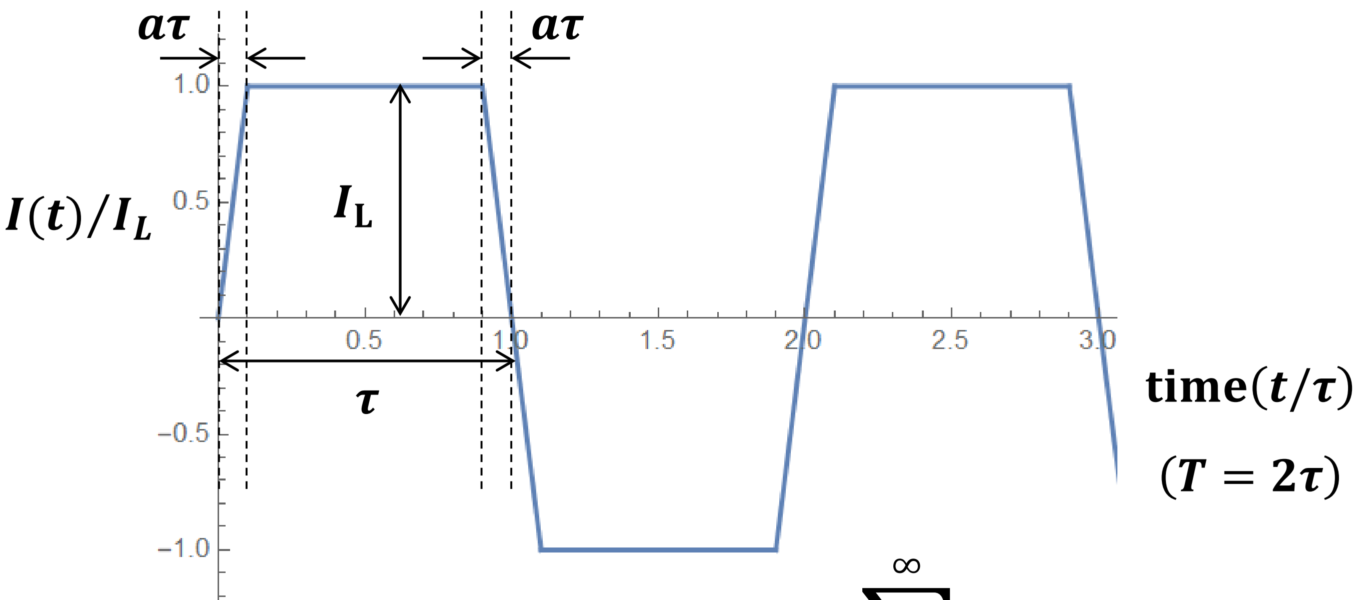
$$V(t) = V_0\cos\left(\frac{t}{\sqrt{LC}}\right)$$

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



time(t/T)

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



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

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

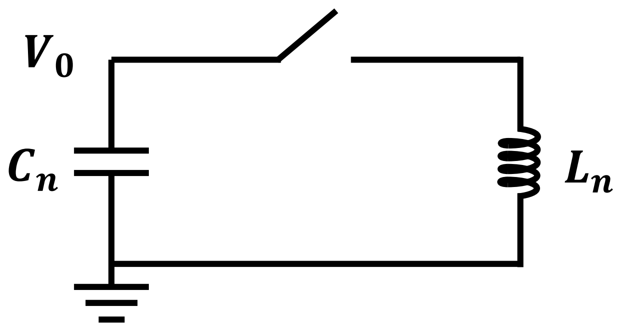
$$\frac{i(t)}{I_L} = \frac{\tau - t}{a\tau} \qquad , \tau - a\tau \le t \le \tau$$

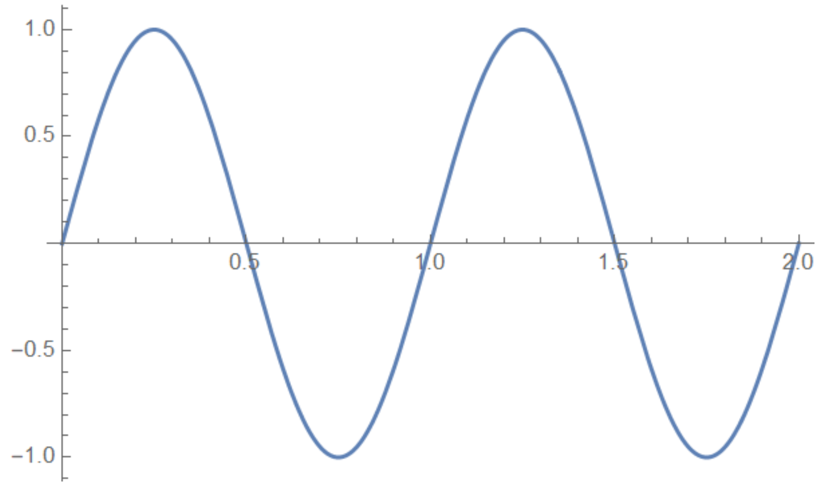
$$i(t) = I_L \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi t}{\tau}\right)$$

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

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

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





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

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

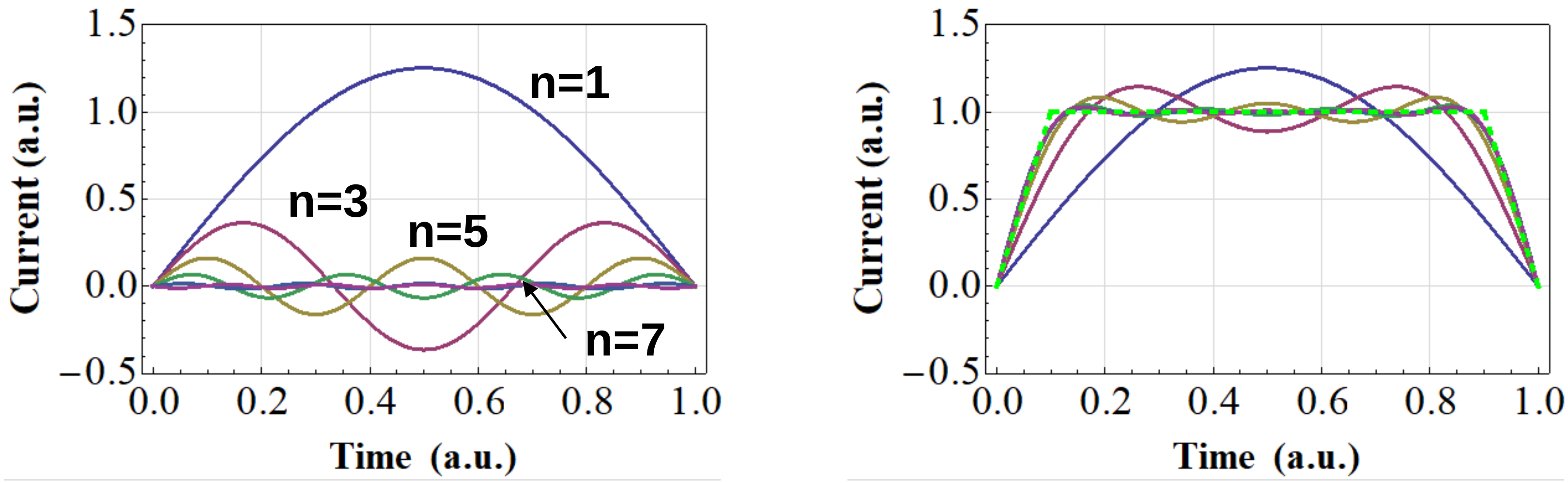
$$i(t) = I_L\sum_{n=1}^{\infty} b_n\sin\left(\frac{n\pi t}{\tau}\right)$$

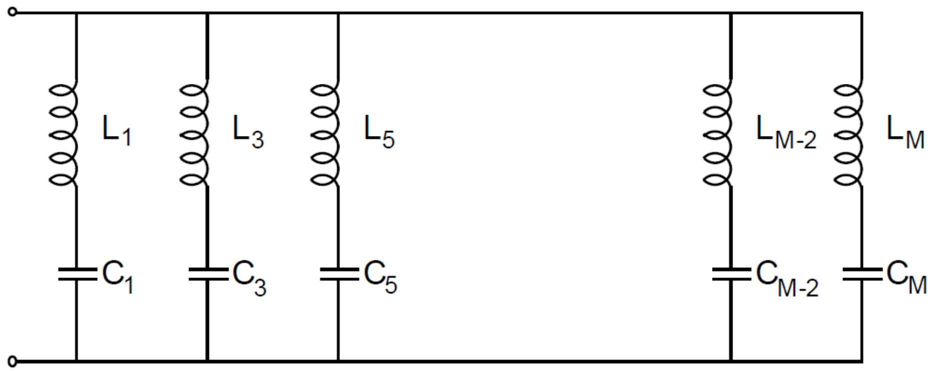
$$C_n = \frac{\tau b_n}{n\pi Z_n} = \frac{I_L}{V}\frac{\tau b_n}{n\pi}$$

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

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

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



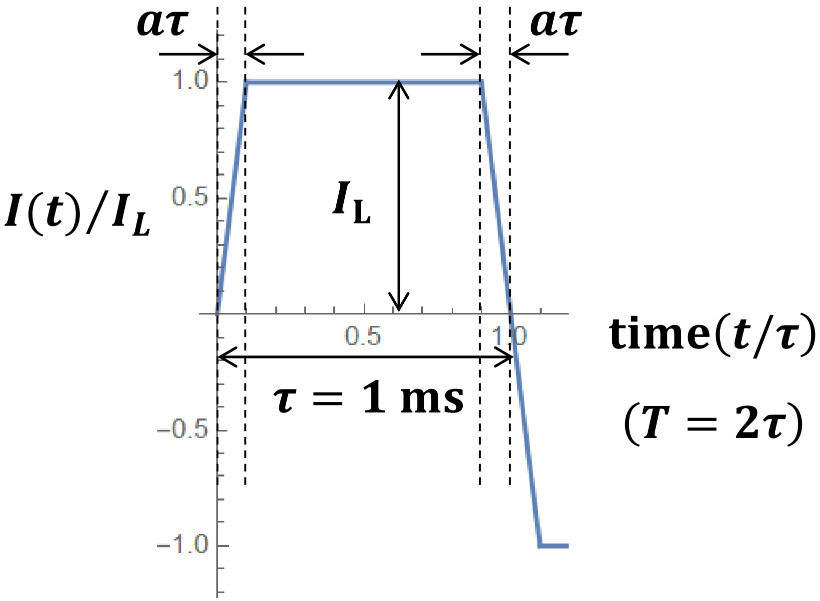


$$I(t) = I_L \Sigma b_n \mathrm{Sin}\left(\frac{n\pi t}{\tau}\right)$$

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

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

Fourier components of τ=1 ms, a=0.1



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

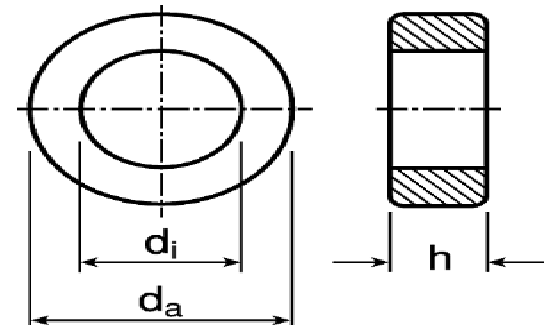
$$b_n = \frac{4}{n\pi}\,\frac{\sin(n\pi a)}{n\pi a}, \text{where } n = 1, 3, 5\ldots$$

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 ferrite ring will be used to make the inductors



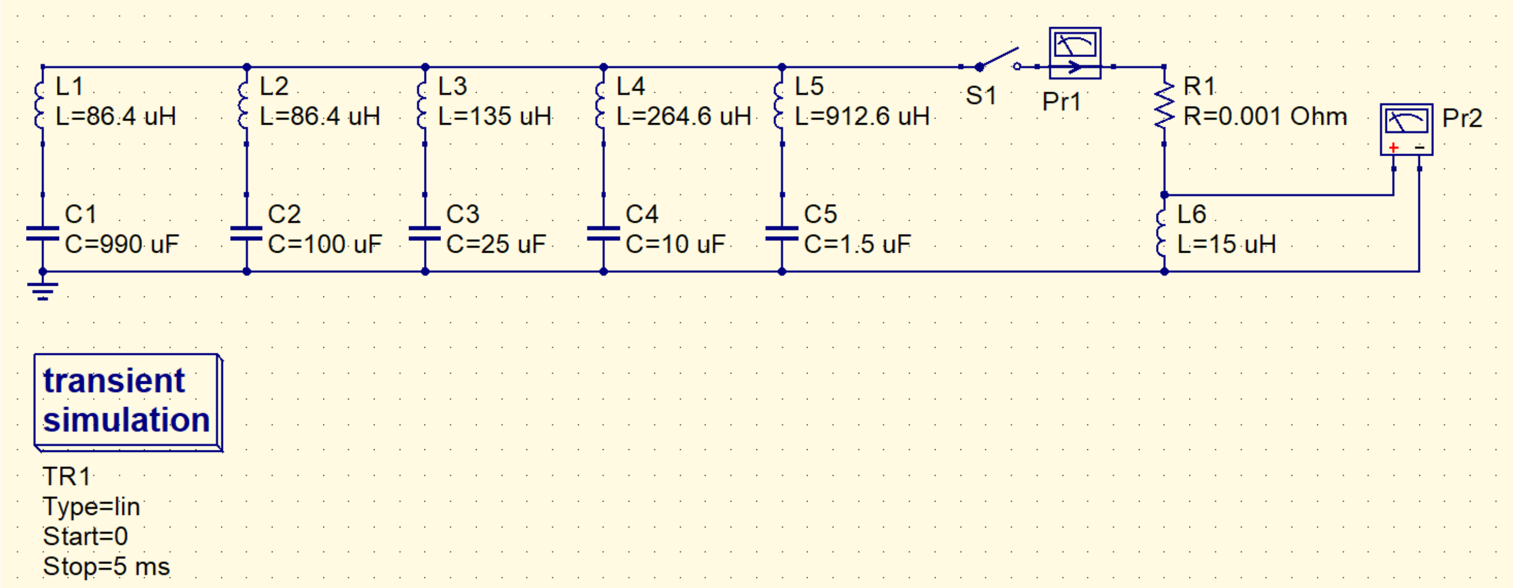
$$d_a = 25.3 \pm 0.5\text{mm}$$
$$d_i = 14.8 \pm 0.5\text{mm}$$
$$h = 10. \pm 0.2\text{mm}$$

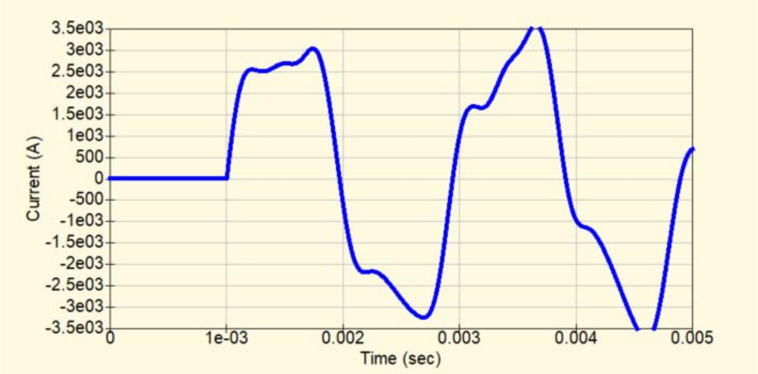
$\mu_r \approx 5000$ $L = A_L N^2$ $A_L = 5400 \pm 25\%\ \text{nH}$

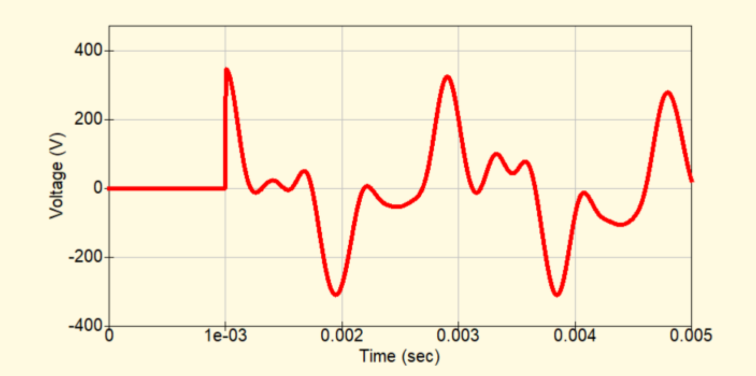
N	1	2	3	4	5	6	7	8	9	10	11	12	13
L(μH)	5.4	21.6	48.6	86.4	135	194	265	346	437	540	653	778	913

L(uH)	101.7	116.5	157.1	271.8	915.0

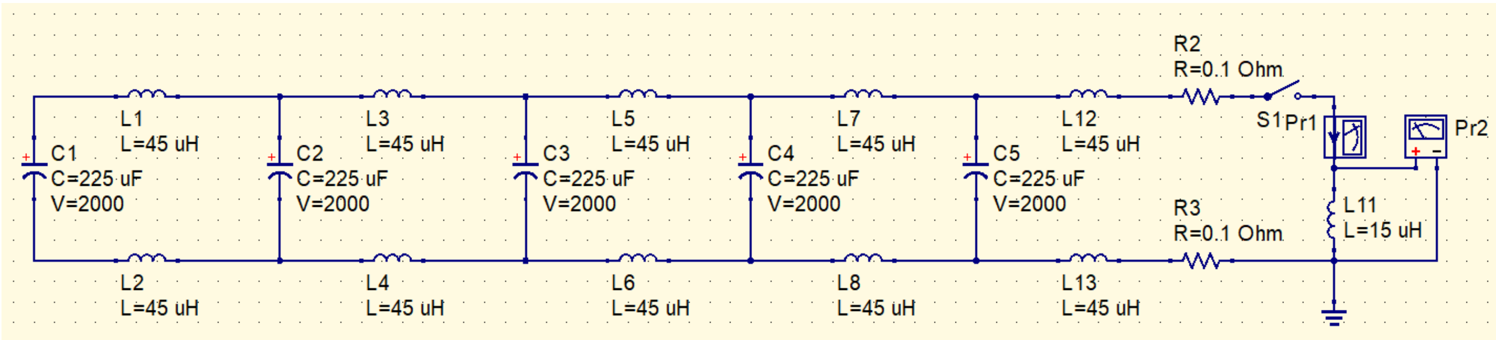
A square pulse with a flat top of 2.5 kA can be generated







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



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

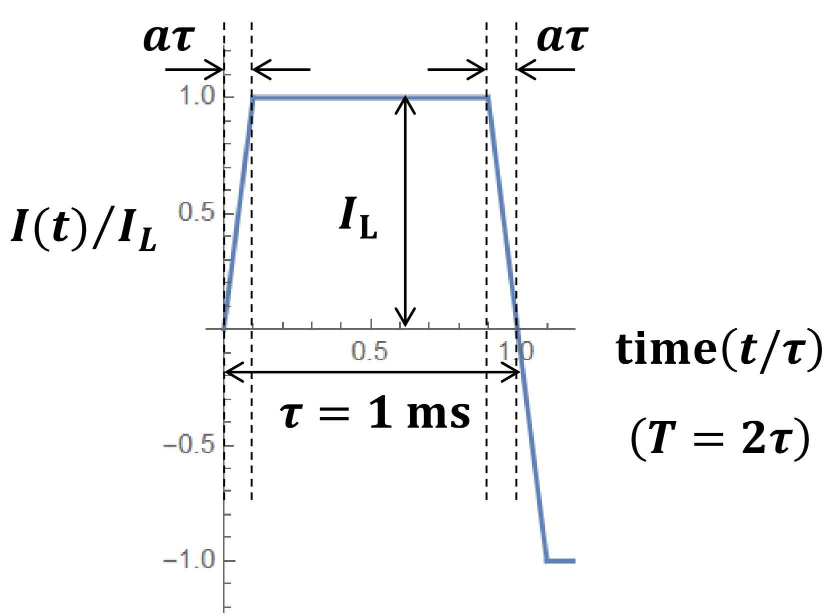
$$L_n = 2nL + L_L \approx 2nL$$

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

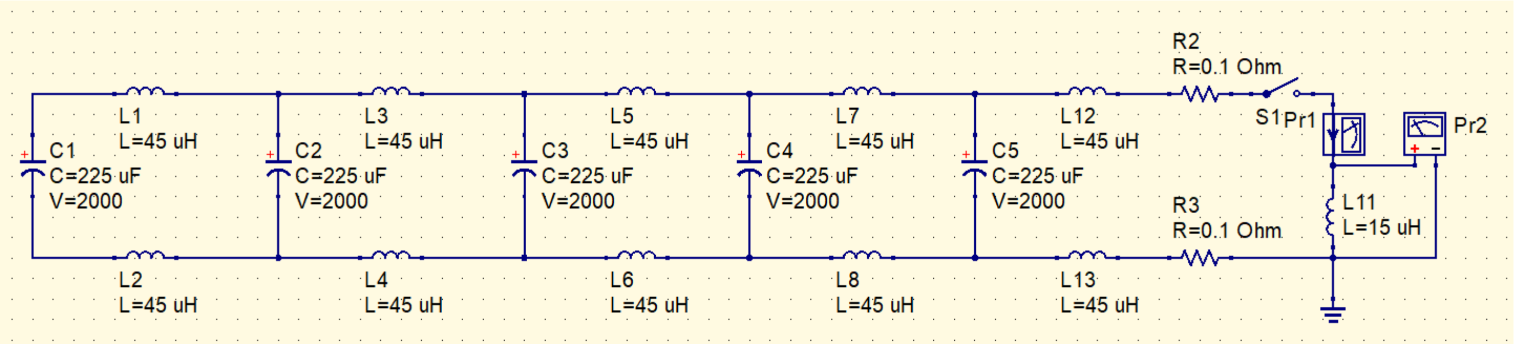
- **For 5 stages:**

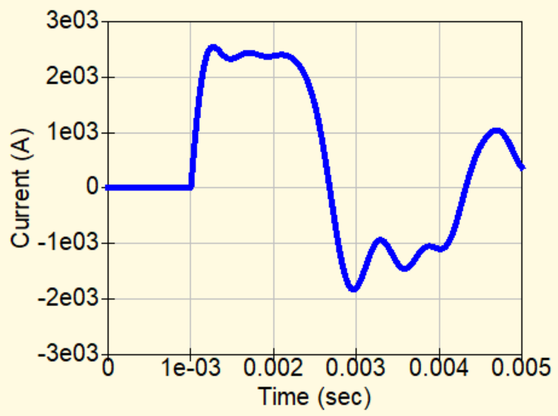
$$\omega_5 = \frac{2\pi}{T} = \frac{\pi}{\tau} = \frac{\pi}{1\text{ms}}$$

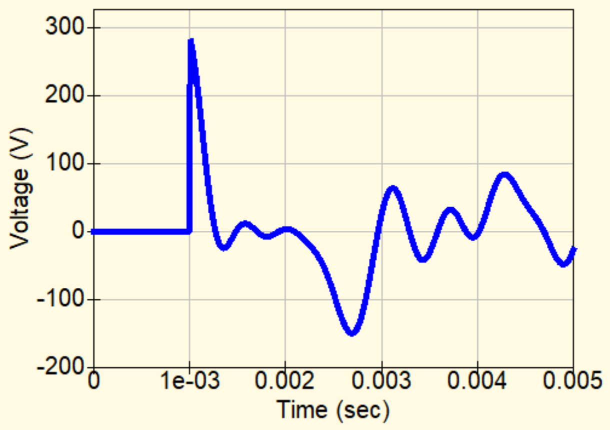
$$L = 45\mu\text{H}$$



The energy coupling efficiency is lower using the simple PFN



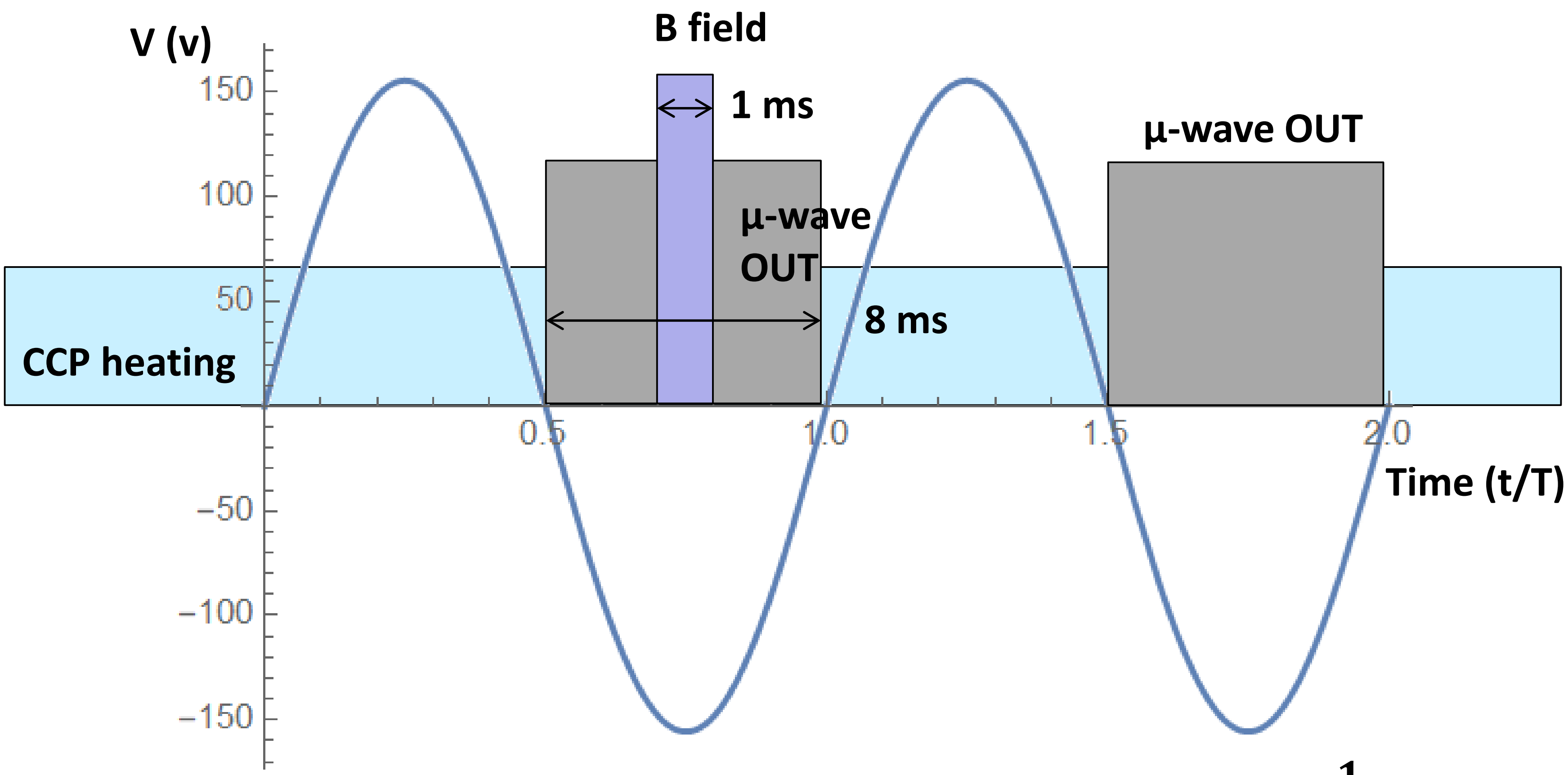




$$E = \frac{1}{2}CV^2 = 2.25\text{kJ}$$

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

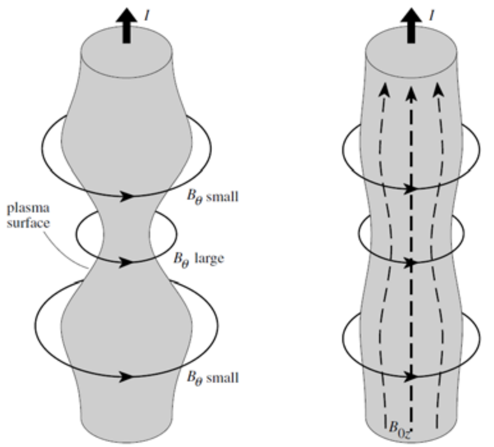
Time sequence



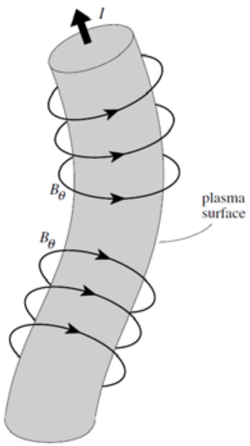
$$T = \frac{1}{60} = 16.7\text{ms}$$

Instabilities occur in a cylindrical plasma column

- **Sausage instability:**



- **Kink instability:**



- **Safety factor *q*:**

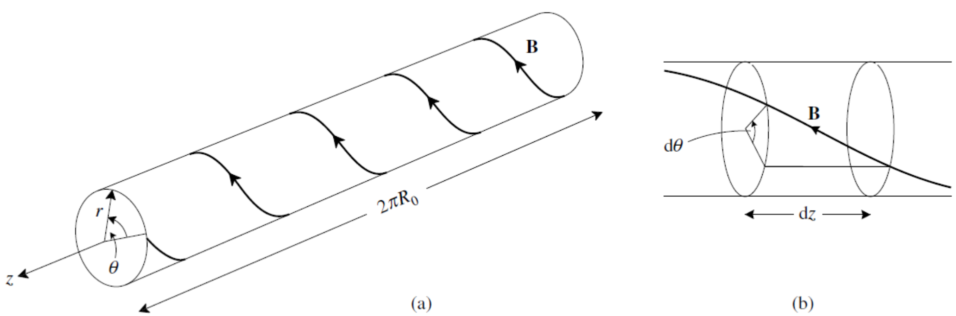
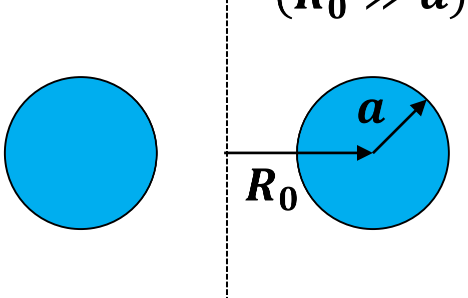


Fig. 4.6. Screw pinch geometry.

$$q(r) = \frac{rB_r(r)}{R_0 B_\theta(r)} \approx \frac{rB_t}{R_0 B_p}$$

$(R_0 \gg a)$



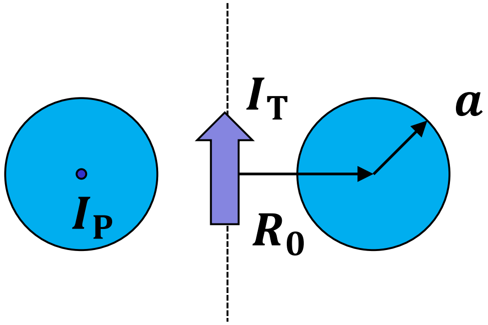
A plasma current of ~ 2 kA is needed

$$q(r) \approx \frac{rB_t}{R_0 B_p} \approx \frac{\mathrm{a}\,B_t}{R_0 B_p}$$

$$B_T = \frac{\mu_0 I_T}{2\pi R_0} \qquad B_P = \frac{\mu_0 I_p}{2\pi a}$$

$$I_p \sim \frac{1}{q}\left(\frac{a}{R_0}\right)^2 I_T = \frac{1}{3}\left(\frac{5}{10}\right)^2 20\mathrm{kA} \sim 2\mathrm{kA}$$

$$B_p \sim 40\ \mathrm{G}$$

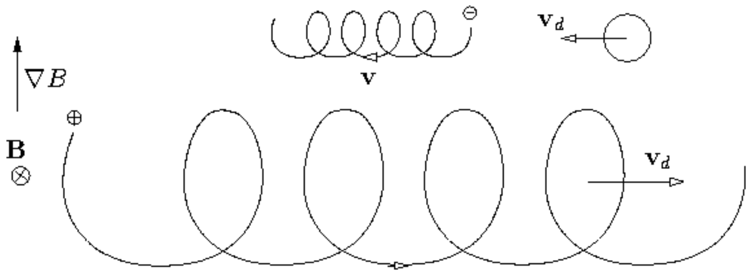


$R_0 \sim 10$ cm

a ~ 5 cm

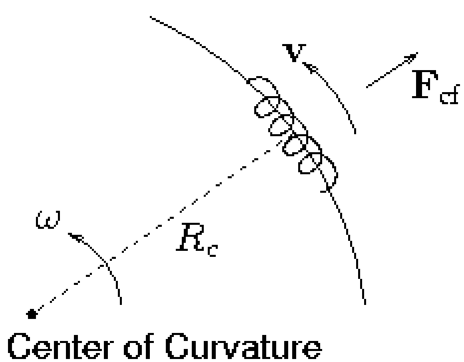
Plasma current will be generated by the Grad-B drift and the Curvature drift current

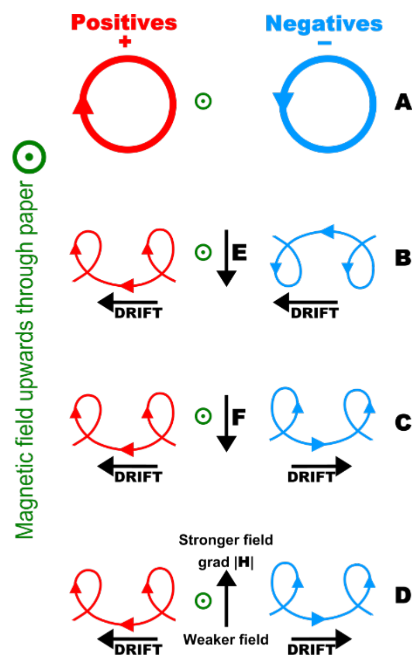
- **Grad-B drift**



$$V_{\nabla B} = \pm \frac{1}{2} v_\perp r_L \frac{\vec{B} \times \nabla B}{B^2}$$

- **Curvature drift**





$$V_R = \frac{m v_{||}^2}{q} \frac{\vec{R_c} \times \vec{B}}{R_c^2 B^2}$$

$$V_R + V_{\nabla B} = \frac{m}{q}\left(v_{||}^2 + \frac{1}{2} v_\perp^2\right) \frac{\vec{R_c} \times \vec{B}}{R_c^2 B^2}$$

$$\approx \frac{1}{q}(2T_{||} + T_\perp) \frac{\vec{R_c} \times \vec{B}}{R_c^2 B^2}$$

https://en.wikipedia.org/wiki/Guiding_center
http://silas.psfc.mit.edu/introplasma/chap2.html

A vertical field B_V of 12 G with a curvature of 5 cm is needed to generate the required plasma current

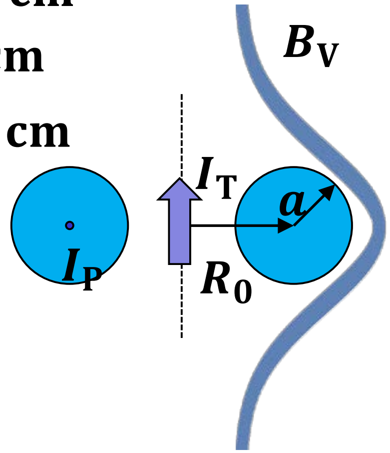
- For P = 10^{-1} Torr = 13 Pa = 13 N/m^2

$$n = \frac{P}{T} = \frac{13}{4.1\times10^{-21}} = 3.1\times10^{21}\ m^{-3}$$

$R_0 \sim 10$ cm

a ~ 5 cm

$R_C \sim 5$ cm



Assuming the ionization fraction is 1%:

$$n_e = n_i = 3.1\times10^{19}\ m^{-3}$$

$$j = qn_e v \qquad I \sim \pi a^2 j = \pi a^2 q n_e v$$

$$v = \frac{I}{\pi a^2 q n_e} = \frac{2\times10^3}{\pi 0.05^2\times1.6\times10^{-19}\times3.1\times10^{19}} \sim 5\times10^4\ \mathrm{cm/s}$$

$$v_{\mathrm{drift}} = V_R + V_{\nabla B} \approx \frac{1}{q}\left(2T_{||}+T_{\perp}\right)\frac{\vec{R_c}\times\vec{B_V}}{{R_c}^2{B_V}^2} \sim \frac{3T}{q}\frac{1}{R_C B_V}$$

$$B_V \sim \frac{1}{V_{\mathrm{drift}}}\frac{3T}{q}\frac{1}{R_C} \sim \frac{1}{5\times10^4}3\times1\times\frac{1}{0.05} \sim 0.0012\ \mathrm{T} = 12\ \mathrm{G} \quad (B_{\mathrm{earth}} \sim 0.5\ \mathrm{G})$$

- For T_e = 1 eV, B_V = 12 G

$$r_c = \frac{\sqrt{2\mathrm{mT}}}{\mathrm{e}B_V} = \frac{\sqrt{2\times9.11\times10^{-31}\times1.6\times10^{-19}}}{1.6\times10^{-19}\times0.0012} = 2.8\ \mathrm{mm}$$

The prospective system design

(1) Vertical field coil (VF coil): B_V=12 G w/ curvature of 5 cm.
(2) Pulse forming network for driving VF coil: ? kA.
(3) Rogowski coil for measuring plasma current: I_P = 2 kA.
(4) Triple probe for measuring Plasma characteristics: Te~1 eV, n_e ~ 10^{19} m^{-3}.