Practice Course in Plasma

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Thursday 9:10-12:00

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

Lecture 6

2021/4/8 updated

Reference

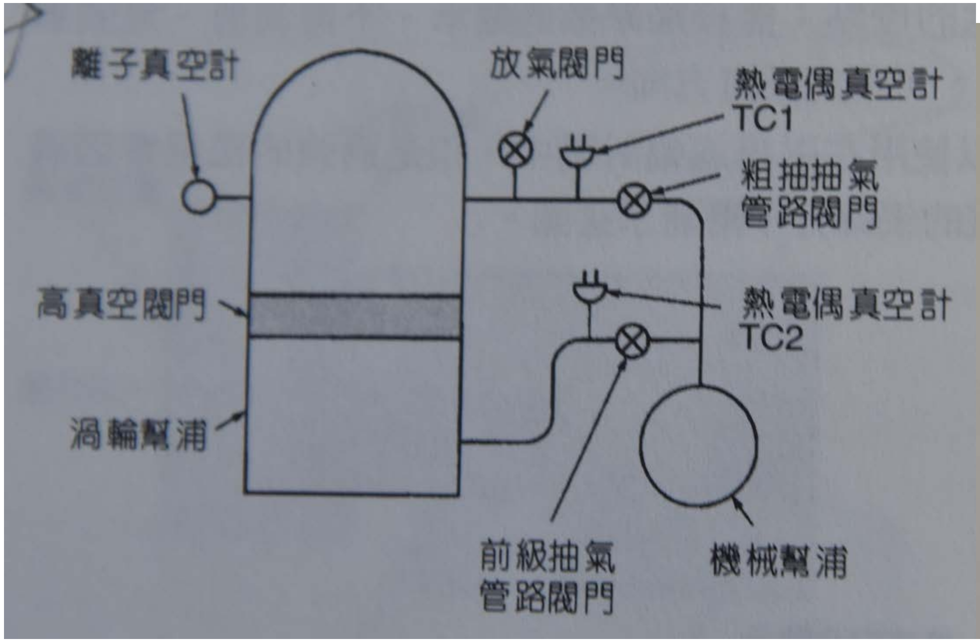
- 真空技術與應用, 國家實驗研究院儀器科技研究中心出版

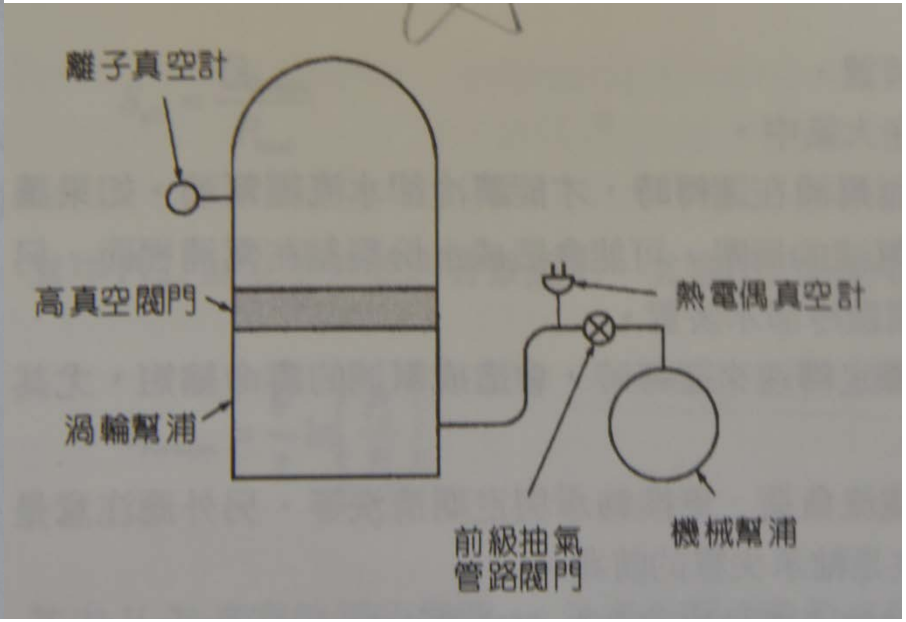
Vacuum Levels

Levels	Pressure	Mean Free Path (λ) vs System size (d)	Flow type
Rough Vacuum (粗略真空)	10^{-1}~760 Torr	$\lambda << d$	Viscos flow
Medium Vacuum (中度真空)	10^{-5}~10^{-1} Torr	$\lambda \sim d$	Transition flow
High Vacuum (高真空)	10^{-9}~10^{-5} Torr	$\lambda >> d$	Molecular flow
Ultra High Vacuum (超高真空)	< 10^{-9} Torr	$\lambda >> d$	Molecular flow

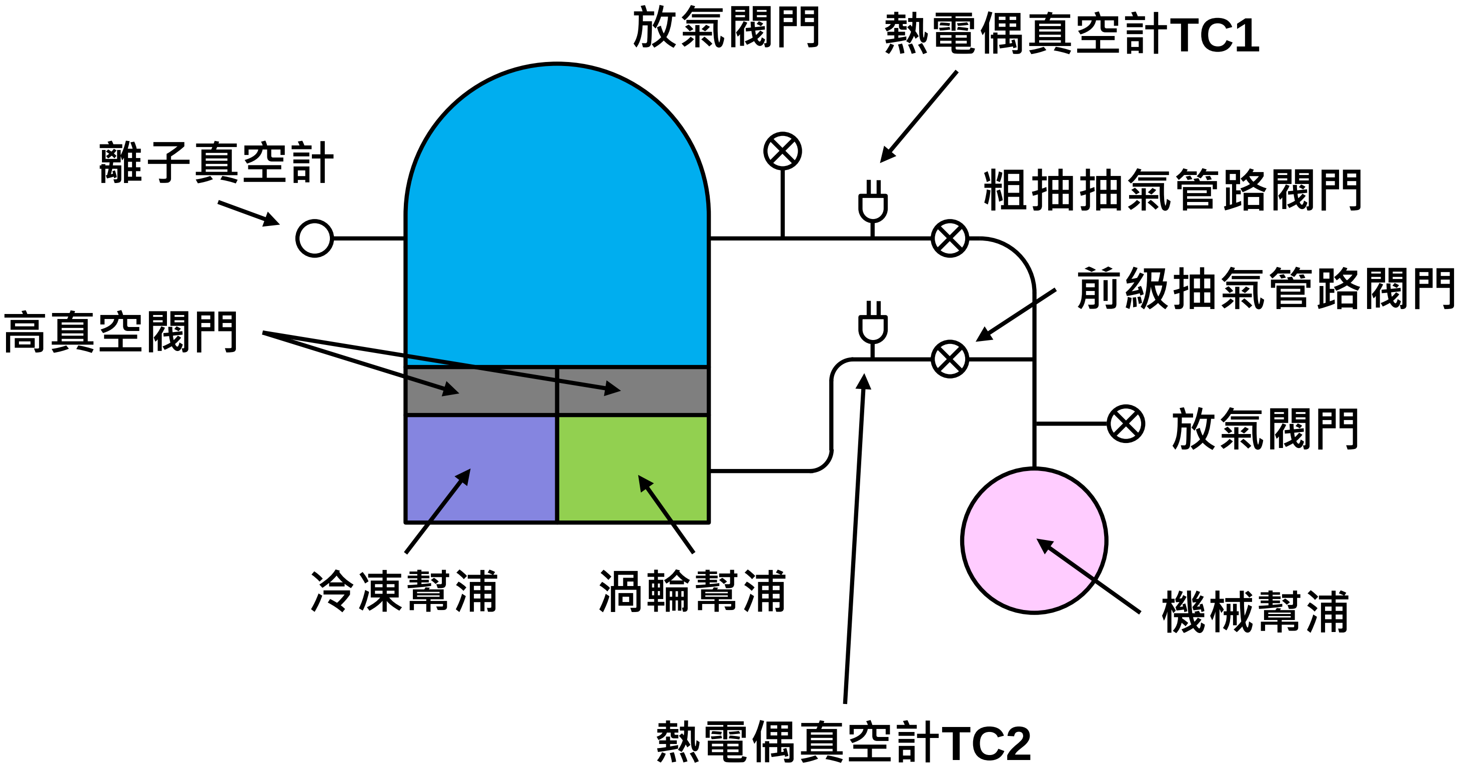
渦輪真空幫浦系統

- 有預抽管
- 無預抽管

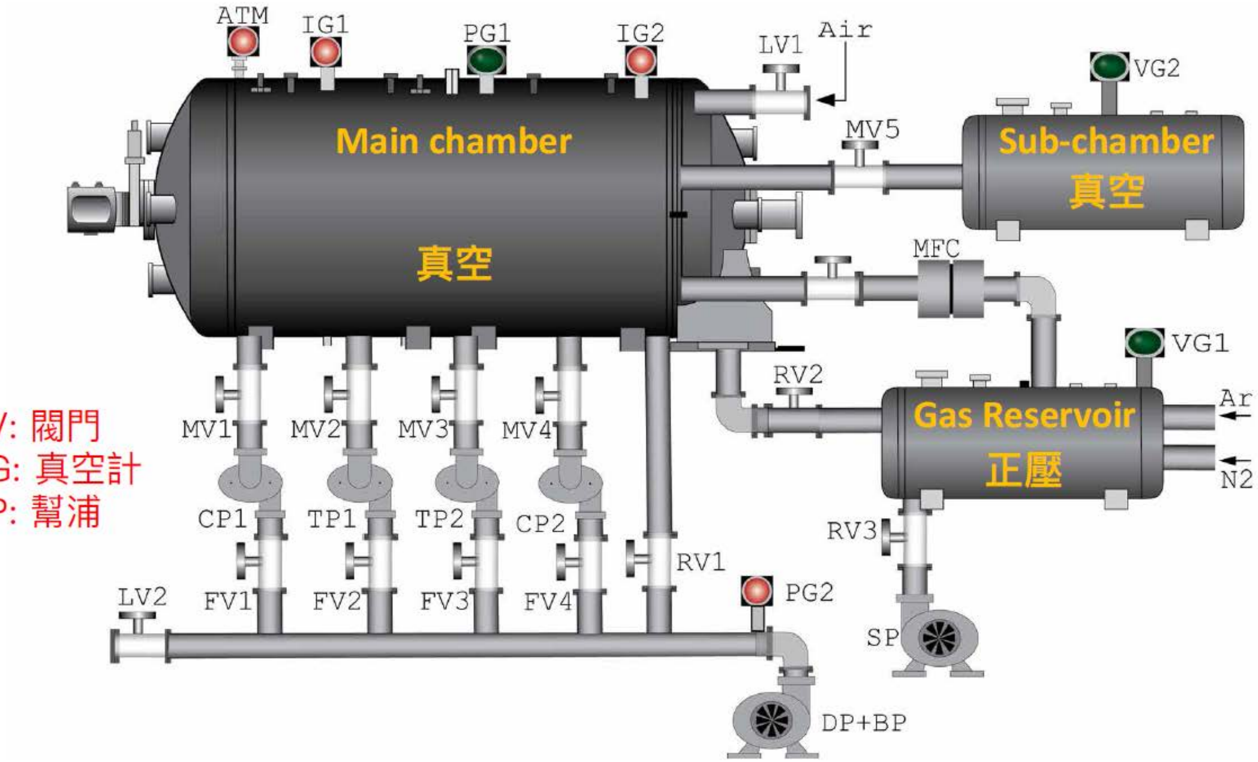




冷凍幫浦系統


放氣閥門
熱電偶真空計TC1
離子真空計
粗抽抽氣管路閥門
前級抽氣管路閥門
高真空閥門
放氣閥門
冷凍幫浦
渦輪幫浦
機械幫浦
熱電偶真空計TC2

SPOC



__V: 閥門
__G: 真空計
__P: 幫浦

(5) (　　　) 30% 抽真空開關的順序：

(a) 開FV2; (b) 關RV1; (c) 開TP1; (d) 開DP+BP; (e) 開RV1; (f) 開MV2.

(6) (　　　) 30% 破真空開關的順序：

(a) 關FV2; (b) 關DP+BP; (c) 聽到``搭”一聲; (d) 開LV1; (e) 關LV2;
(f) 關MV2; (g) 開艙; (h) 關RV1; (i) 關TP1; (j) 開LV2.

Space Plasma Operation Chamber (SPOC)

- **Training of using SPOC is scheduled for next lecture (3/25)**

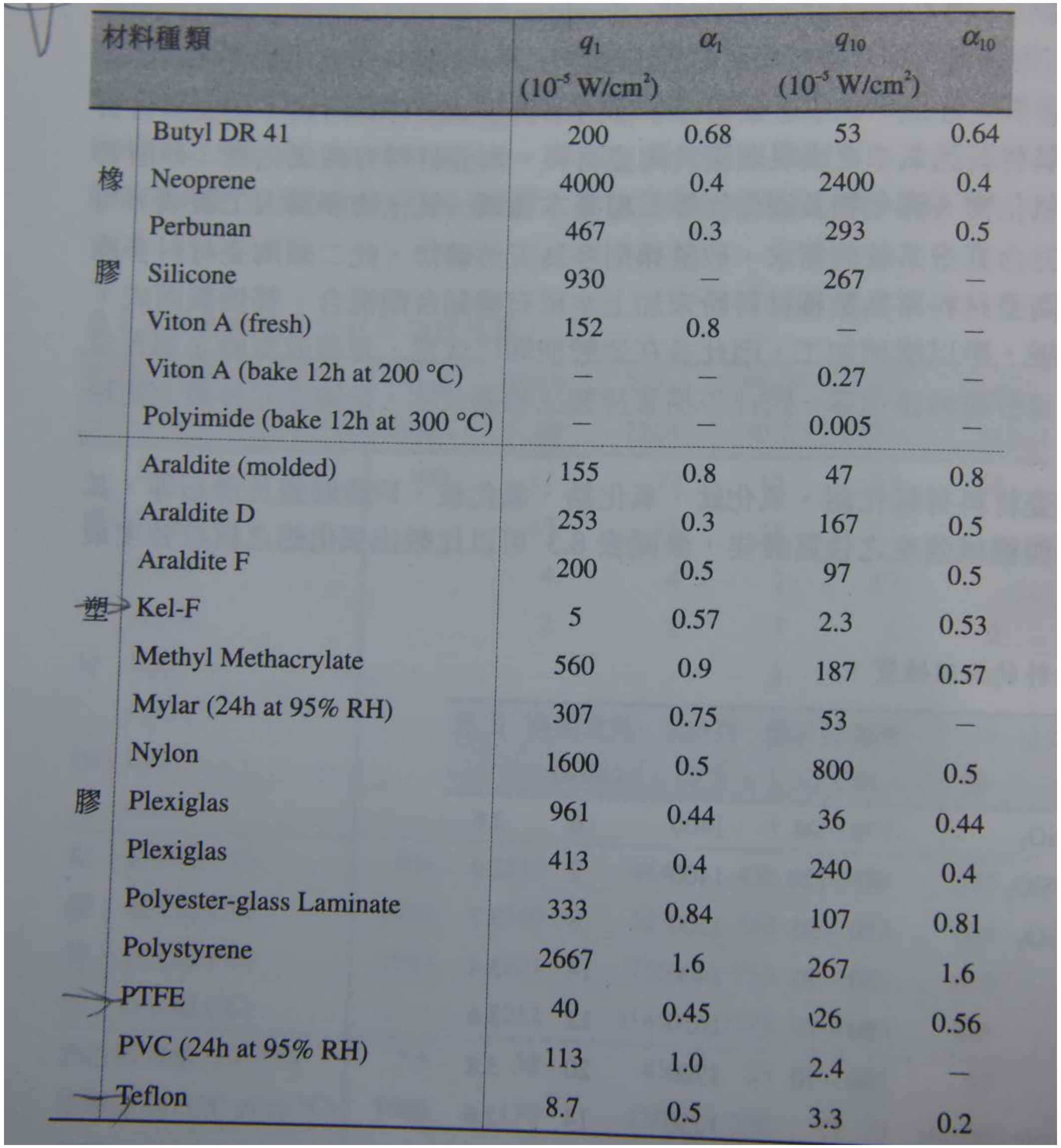
各種真空系統相關功能之比較

	離子幫浦系統	擴散幫浦系統	渦輪分子幫浦系統	冷凍幫浦系統
抽氣速率	低	高	中	中
終極壓力	< 10^{-9} Torr	10^{-6} ~ 10^{-9} Torr	10^{-9} Torr	10^{-9} Torr
使用難易	簡單	普通	簡單	普通
使用壽命	有限時間	長久	長久	再生後使用
系統潔淨度	好	差	好	好
系統震動	最小	小	差	小
維護難易	容易	容易	難	難
裝置成本	高	低	高	高
運轉成本	低	高	中	中

真空系統結構元件要求

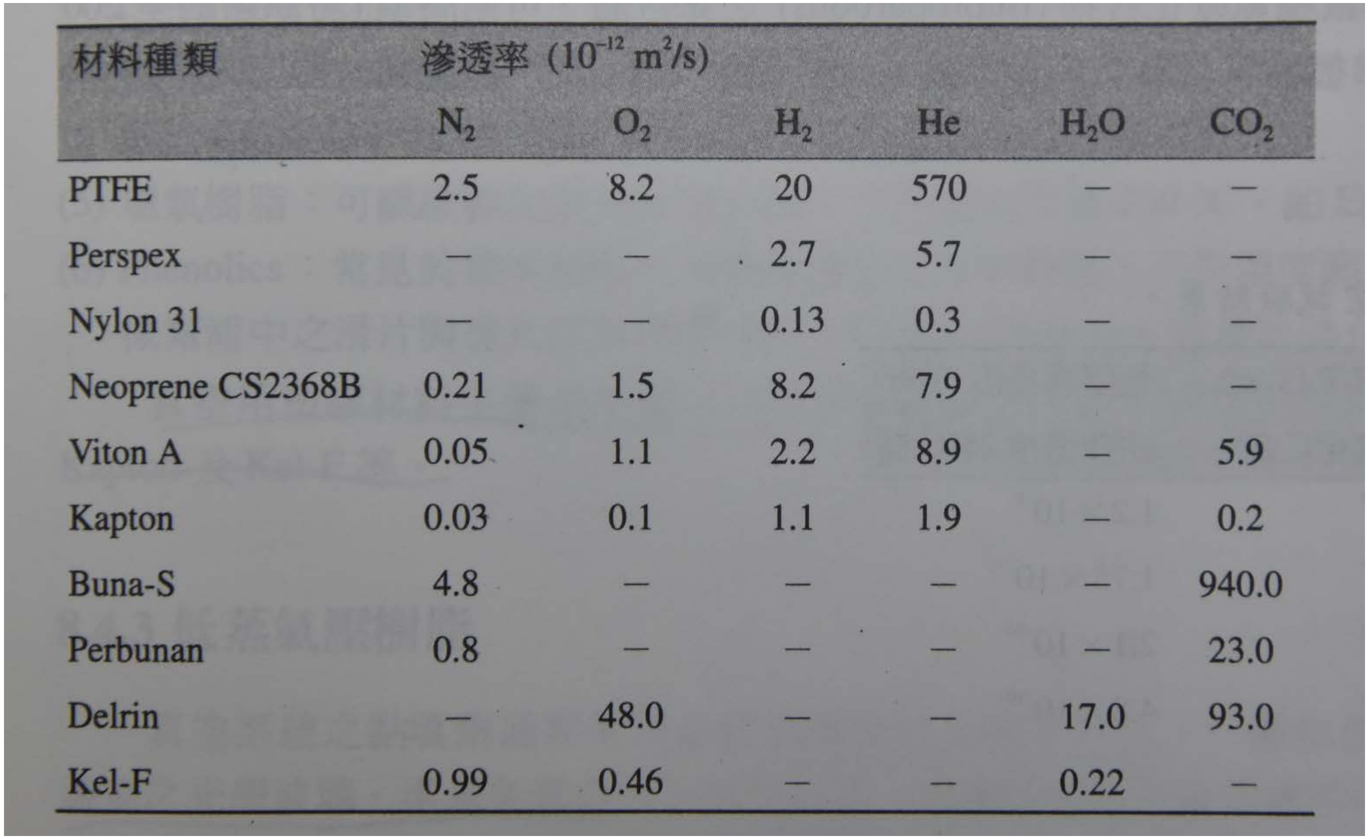
- 機械強度能承受壓差所產生的外力。
- 氣密佳，不應是多乙結構，不能有裂縫、小孔等成為洩漏通道的缺陷。
- 低逸氣率與低滲透率。
- 在工作溫度及烘烤溫度下的蒸氣要低。
- 化學隱定性佳，不易氧化、耐腐蝕。
- 在一定溫度範圍內保持其真空性能及機械強度。
- 加工容易、銲接性佳。
- Ex：不銹鋼、無氧高導銅、碳鋼、鋁
- Not good：鋅、鉛、鎘、銓、鋰、鉀、硒、硫、…
- 氫氣滲透率：鋁<鉬<銅<鉑<鐵<鎳<鈀

常見橡膠與塑膠真空材料逸氣率



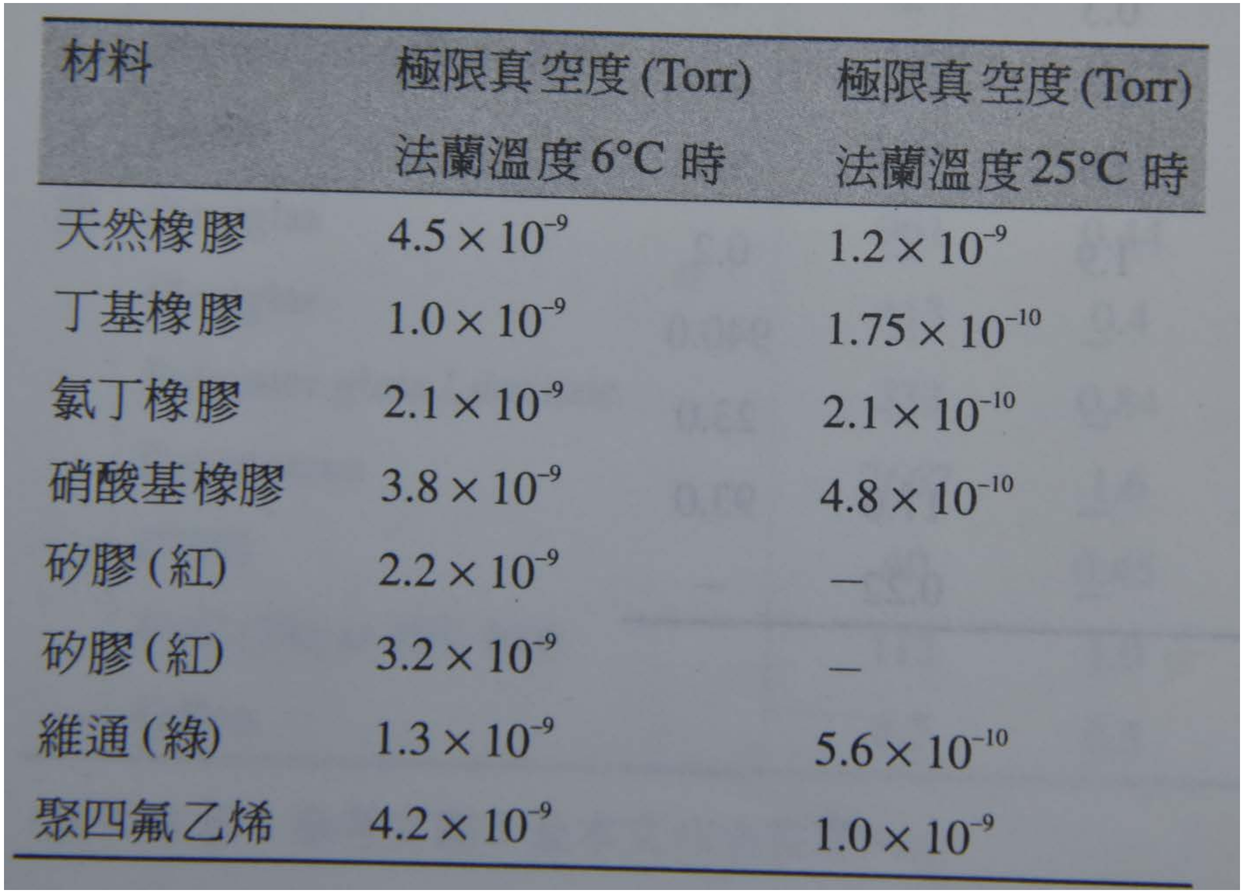
材料種類		q_1 (10^{-5} W/cm^2)	α_1	q_{10} (10^{-5} W/cm^2)	α_{10}
橡膠	Butyl DR 41	200	0.68	53	0.64
	Neoprene	4000	0.4	2400	0.4
	Perbunan	467	0.3	293	0.5
	Silicone	930	—	267	—
	Viton A (fresh)	152	0.8	—	—
	Viton A (bake 12h at 200 °C)	—	—	0.27	—
	Polyimide (bake 12h at 300 °C)	—	—	0.005	—
塑膠	Araldite (molded)	155	0.8	47	0.8
	Araldite D	253	0.3	167	0.5
	Araldite F	200	0.5	97	0.5
	Kel-F	5	0.57	2.3	0.53
	Methyl Methacrylate	560	0.9	187	0.57
	Mylar (24h at 95% RH)	307	0.75	53	—
	Nylon	1600	0.5	800	0.5
	Plexiglas	961	0.44	36	0.44
	Plexiglas	413	0.4	240	0.4
	Polyester-glass Laminate	333	0.84	107	0.81
	Polystyrene	2667	1.6	267	1.6
	PTFE	40	0.45	126	0.56
	PVC (24h at 95% RH)	113	1.0	2.4	—
	Teflon	8.7	0.5	3.3	0.2

常見高分子真空材料之氣體滲透率



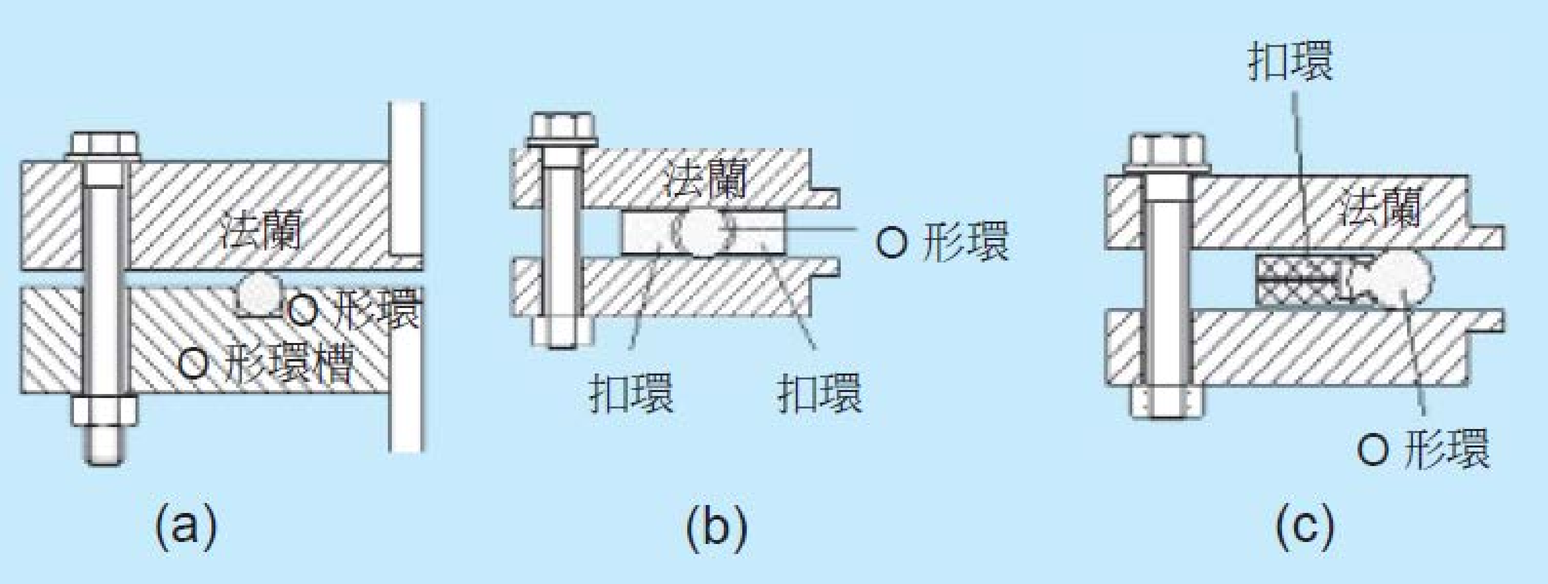
材料種類	滲透率 (10^{-12} m^2/s)					
	N_2	O_2	H_2	He	H_2O	CO_2
PTFE	2.5	8.2	20	570	—	—
Perspex	—	—	2.7	5.7	—	—
Nylon 31	—	—	0.13	0.3	—	—
Neoprene CS2368B	0.21	1.5	8.2	7.9	—	—
Viton A	0.05	1.1	2.2	8.9	—	5.9
Kapton	0.03	0.1	1.1	1.9	—	0.2
Buna-S	4.8	—	—	—	—	940.0
Perbunan	0.8	—	—	—	—	23.0
Delrin	—	48.0	—	—	17.0	93.0
Kel-F	0.99	0.46	—	—	0.22	—

橡膠材料極限真空試驗結果

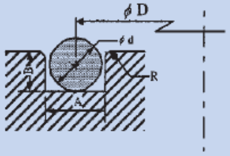
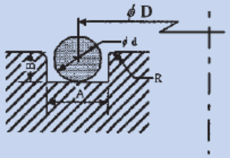
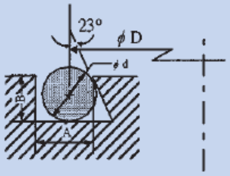
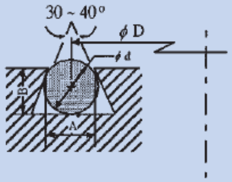
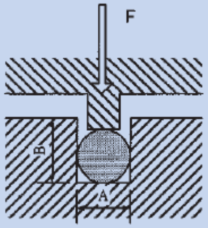


材料	極限真空度 (Torr)	極限真空度 (Torr)
	法蘭溫度6°C 時	法蘭溫度25°C 時
天然橡膠	4.5×10^{-9}	1.2×10^{-9}
丁基橡膠	1.0×10^{-9}	1.75×10^{-10}
氯丁橡膠	2.1×10^{-9}	2.1×10^{-10}
硝酸基橡膠	3.8×10^{-9}	4.8×10^{-10}
矽膠(紅)	2.2×10^{-9}	—
矽膠(紅)	3.2×10^{-9}	—
維通(綠)	1.3×10^{-9}	5.6×10^{-10}
聚四氟乙烯	4.2×10^{-9}	1.0×10^{-9}

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

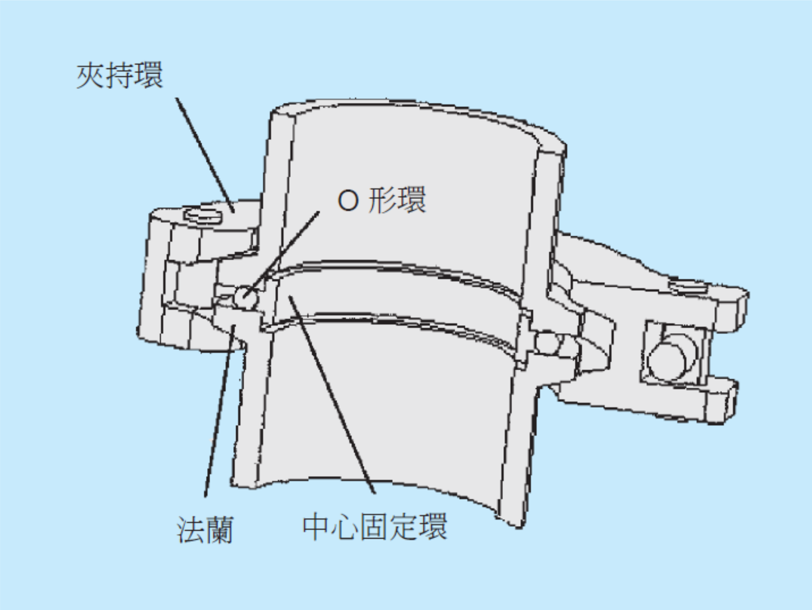


圖 3. KF 法蘭封合結構示意圖。

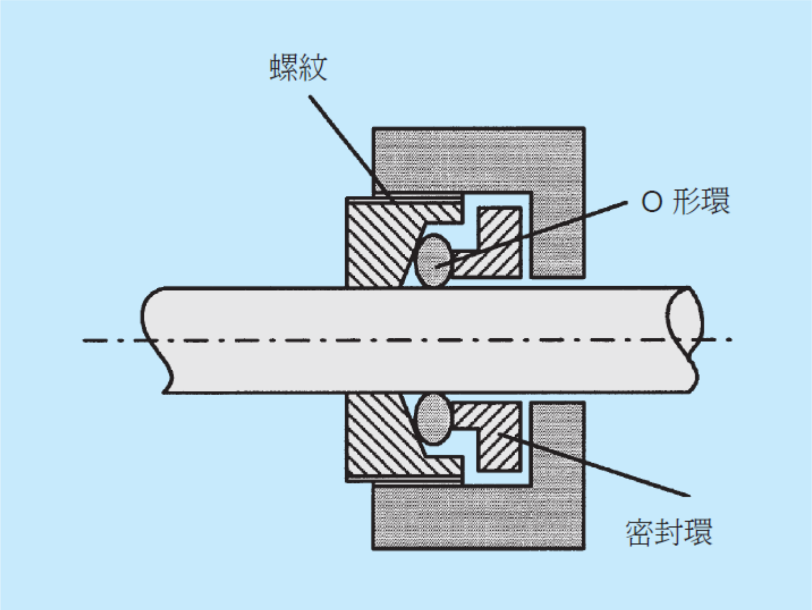
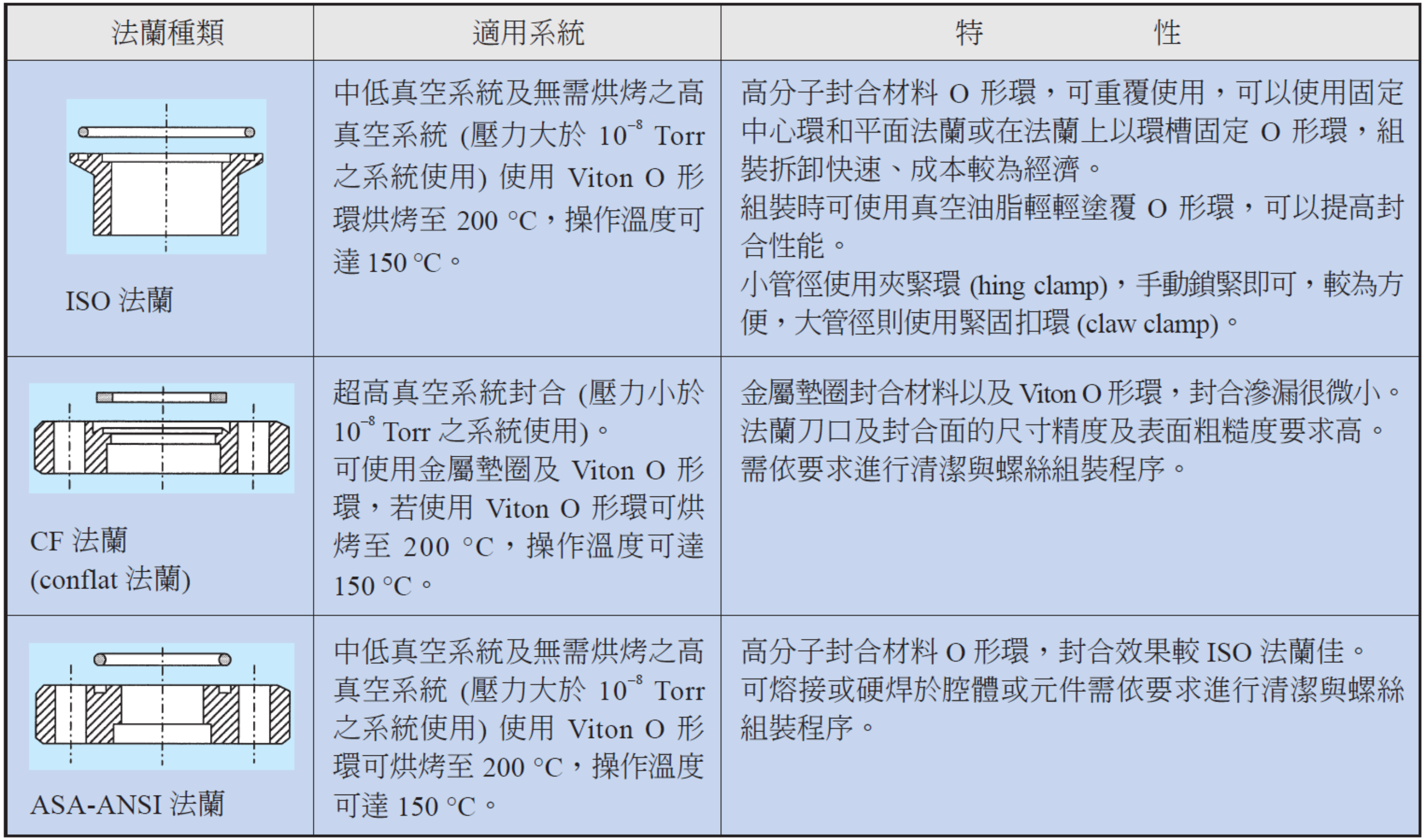


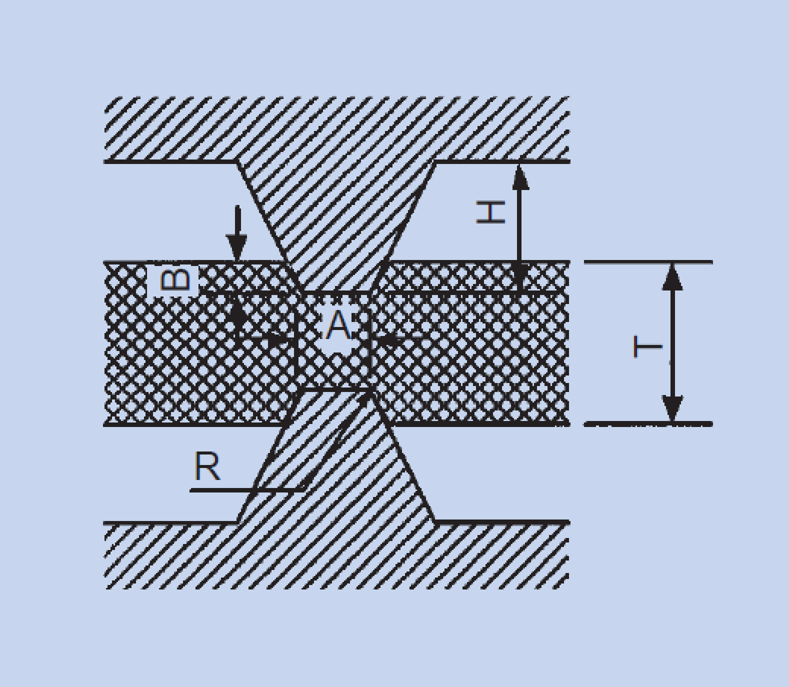
圖 4. 管路之錐形壓縮封合。

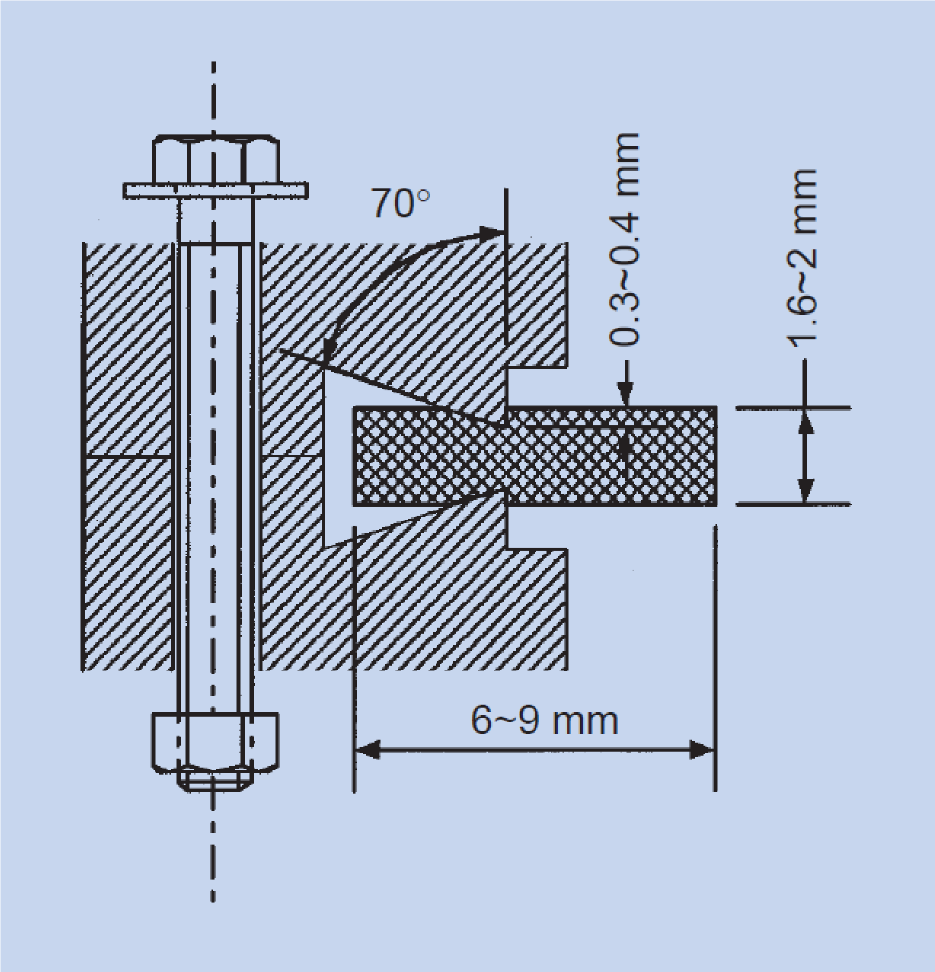
Comparison of different types of flange



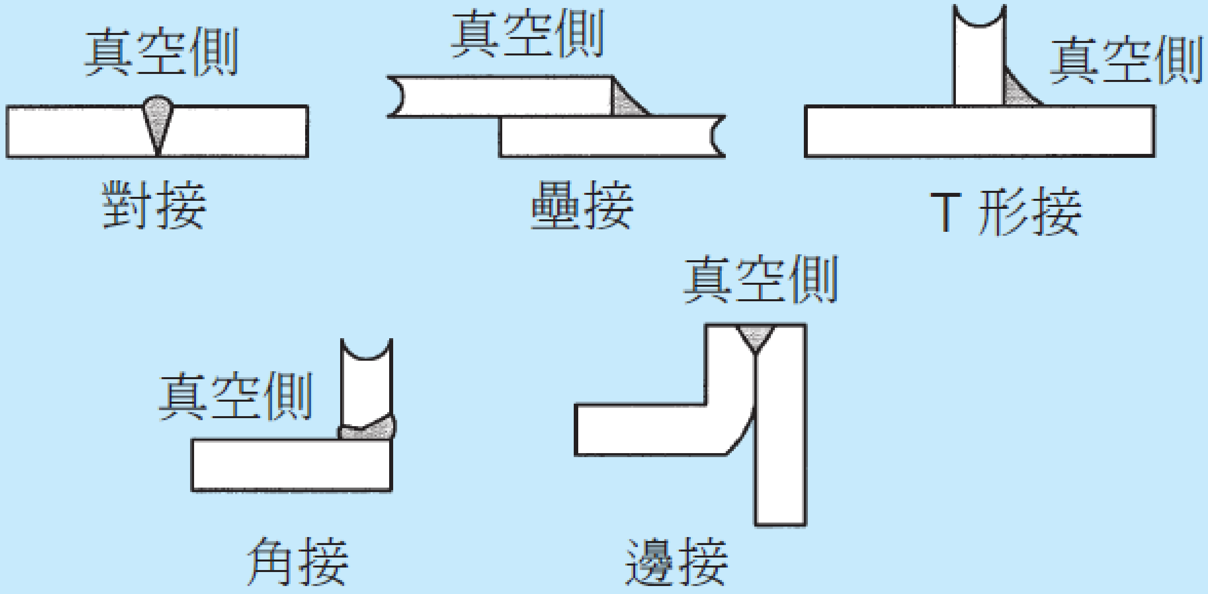
法蘭種類	適用系統	特性
ISO 法蘭	中低真空系統及無需烘烤之高真空系統 (壓力大於 10^{-8} Torr 之系統使用) 使用 Viton O 形環烘烤至 200 °C，操作溫度可達 150 °C。	高分子封合材料 O 形環，可重覆使用，可以使用固定中心環和平面法蘭或在法蘭上以環槽固定 O 形環，組裝拆卸快速、成本較為經濟。 組裝時可使用真空油脂輕輕塗覆 O 形環，可以提高封合性能。 小管徑使用夾緊環 (hing clamp)，手動鎖緊即可，較為方便，大管徑則使用緊固扣環 (claw clamp)。
CF 法蘭 (conflat 法蘭)	超高真空系統封合 (壓力小於 10^{-8} Torr 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。

金屬墊圈刀刃及斜楔法蘭封合

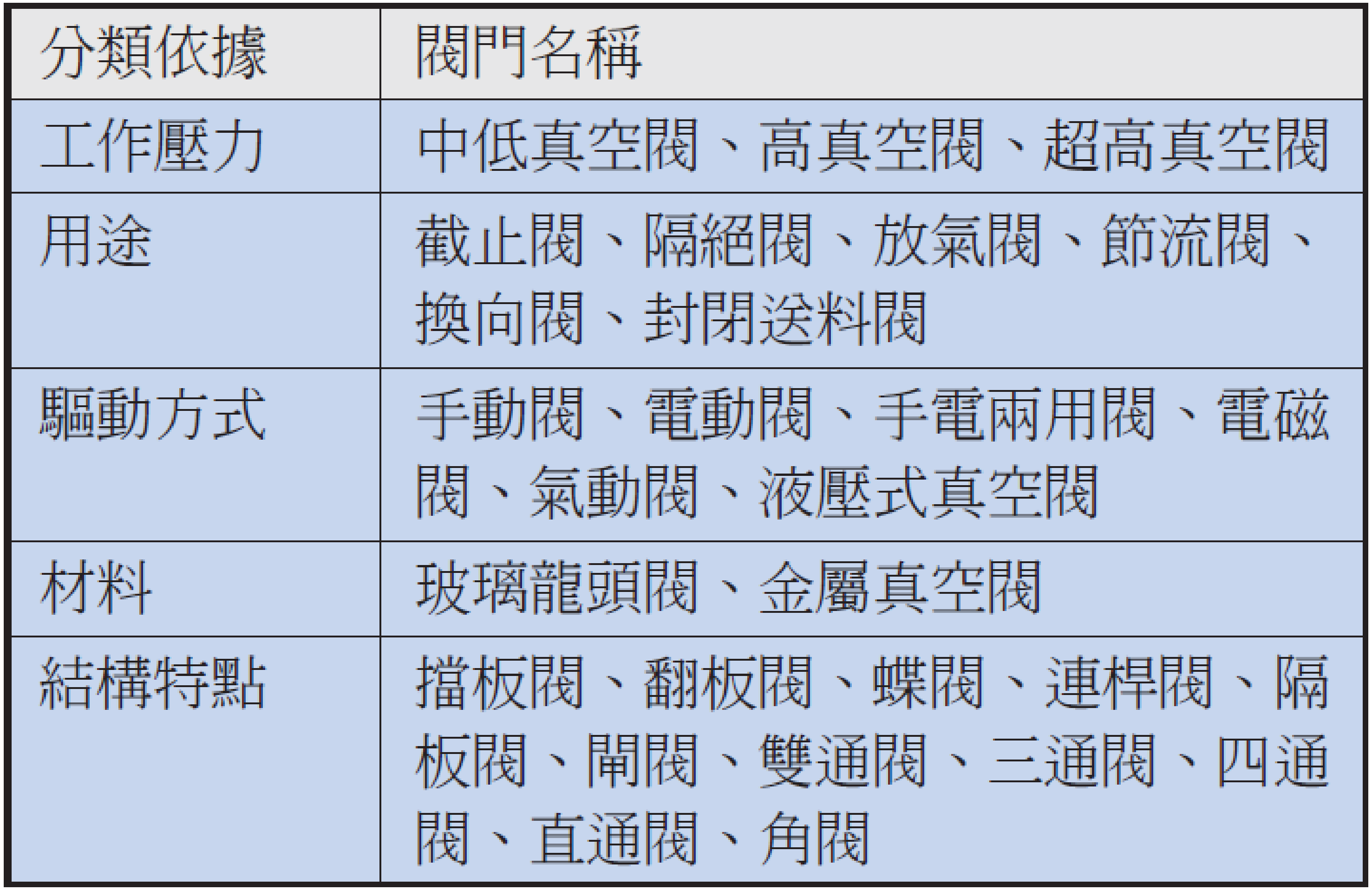




永久封合

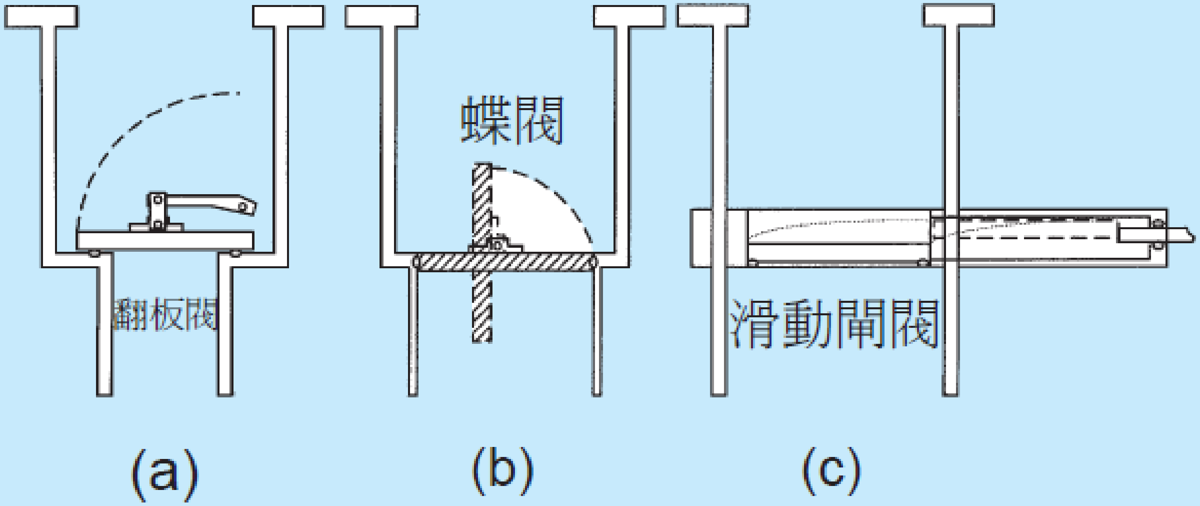


真空閥門分類

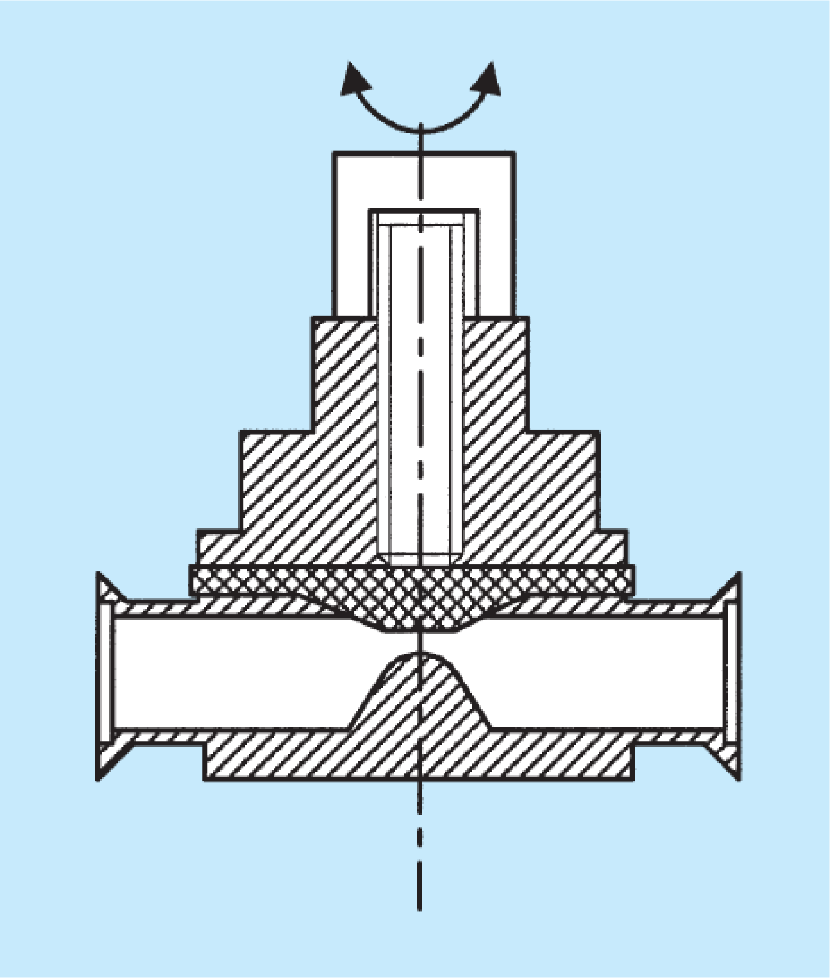


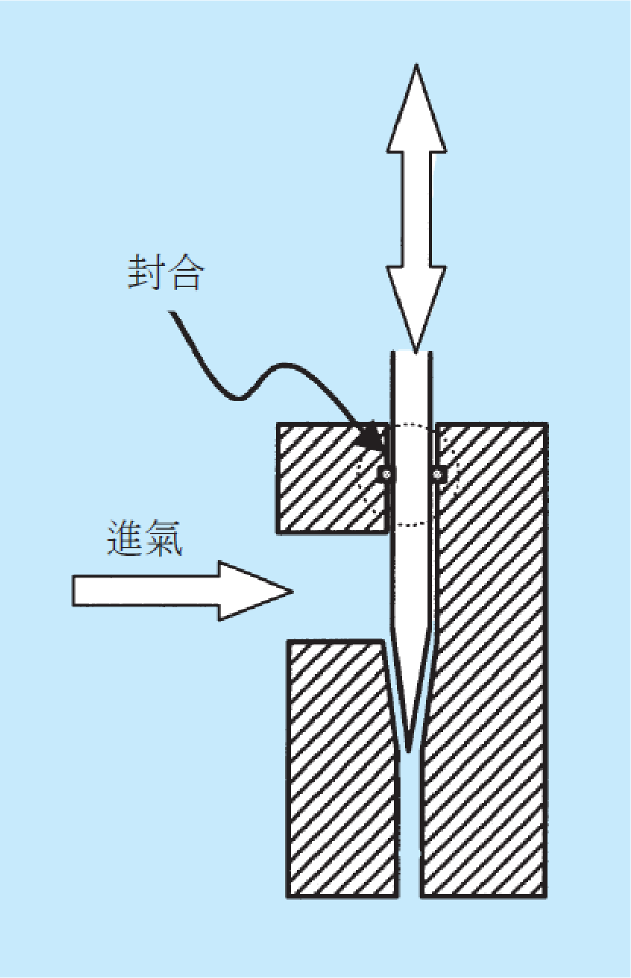
分類依據	閥門名稱
工作壓力	中低真空閥、高真空閥、超高真空閥
用途	截止閥、隔絕閥、放氣閥、節流閥、換向閥、封閉送料閥
驅動方式	手動閥、電動閥、手電兩用閥、電磁閥、氣動閥、液壓式真空閥
材料	玻璃龍頭閥、金屬真空閥
結構特點	擋板閥、翻板閥、蝶閥、連桿閥、隔板閥、閘閥、雙通閥、三通閥、四通閥、直通閥、角閥

閘閥結構

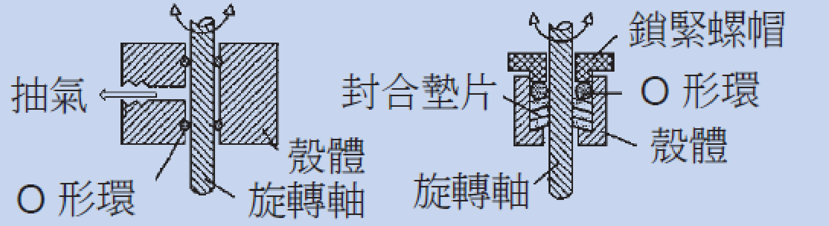


可調流量閥門 - 薄膜真空閥、針閥

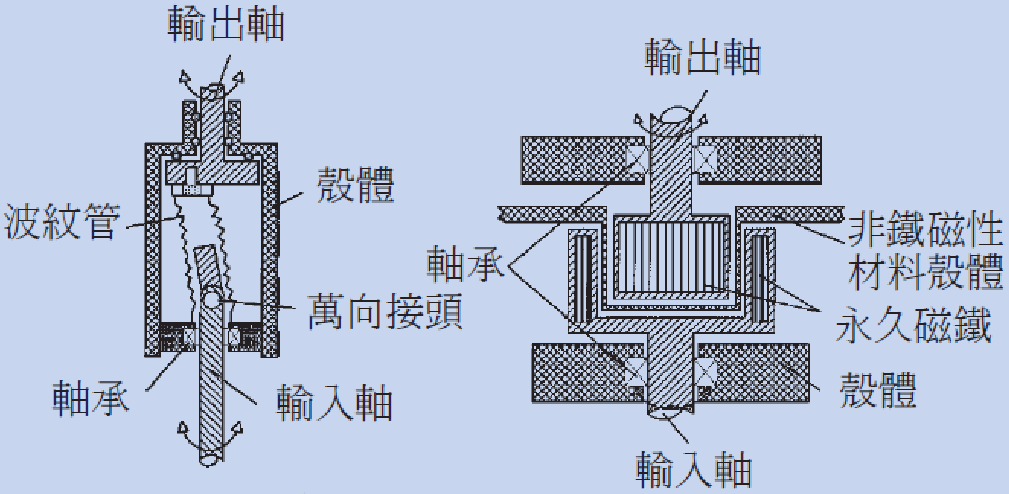




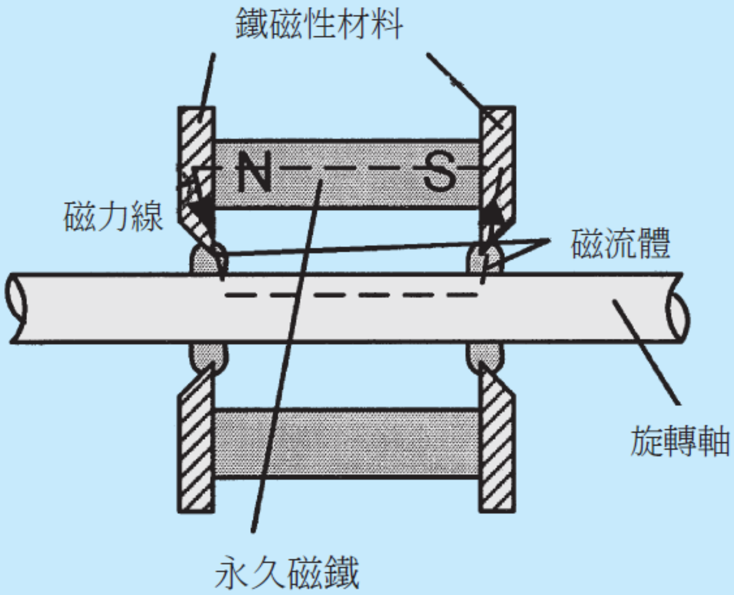
機械運動引入(feedthrough)



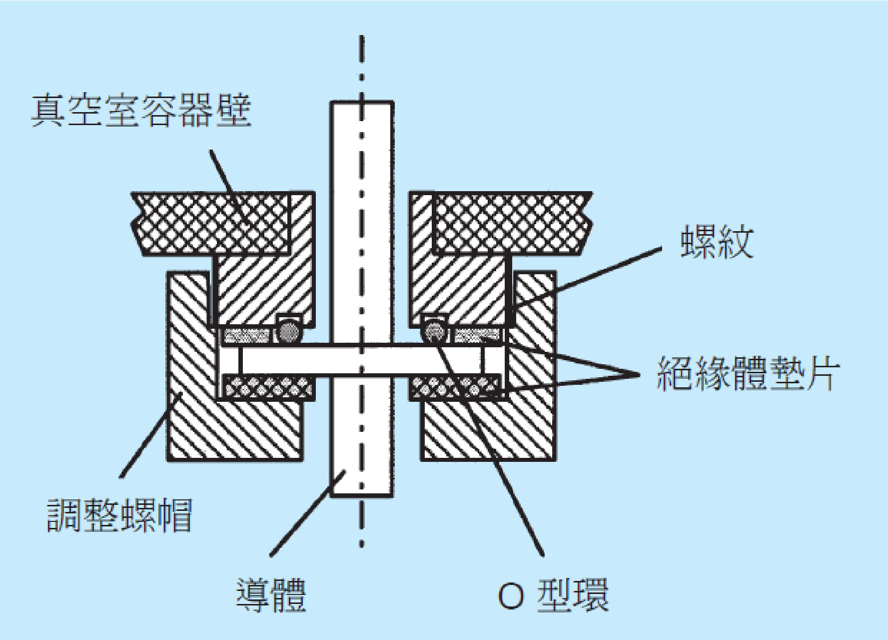
(a) O-型環型合　　(b) 墊圈封合

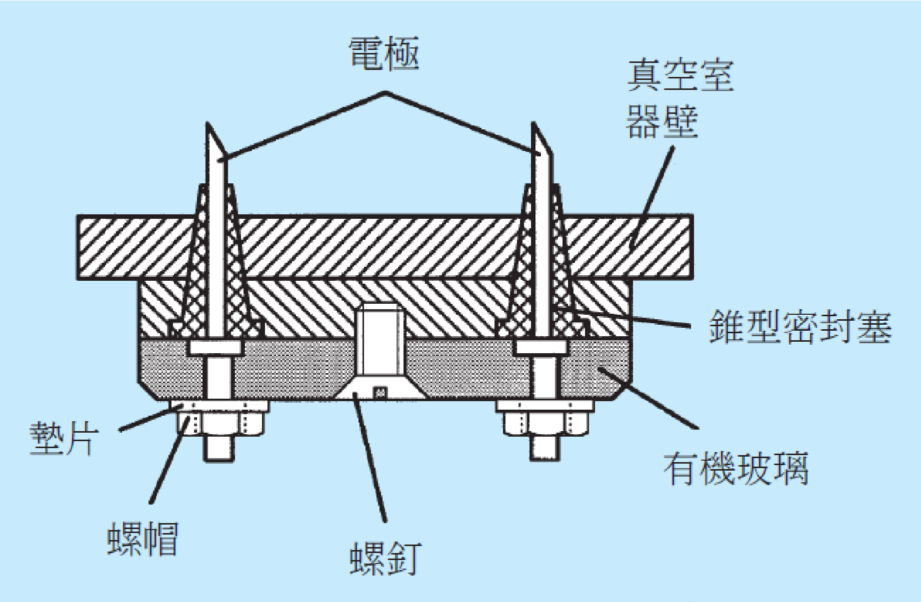


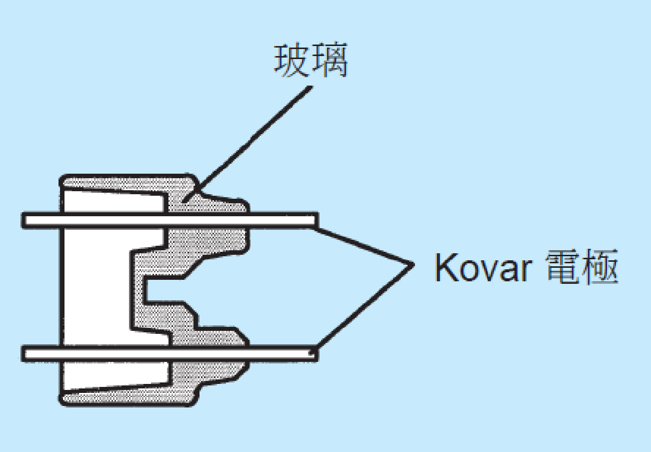
(c) 波紋管封合　　(d) 磁力耦合傳導

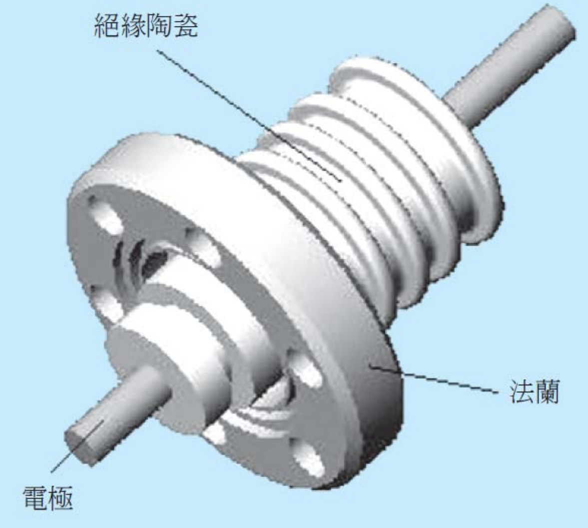


電引入

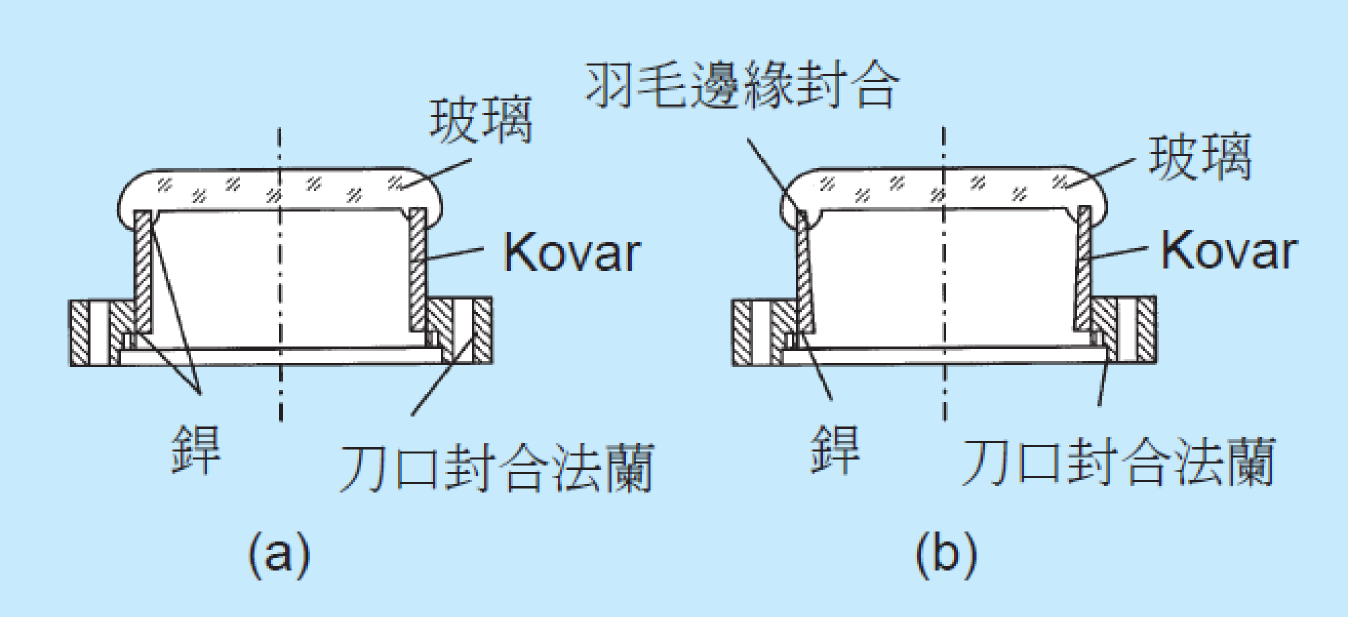

真空室容器壁
螺紋
絕緣體墊片
調整螺帽
導體
O 型環


電極
真空室
器壁
錐型密封塞
墊片
有機玻璃
螺帽
螺釘

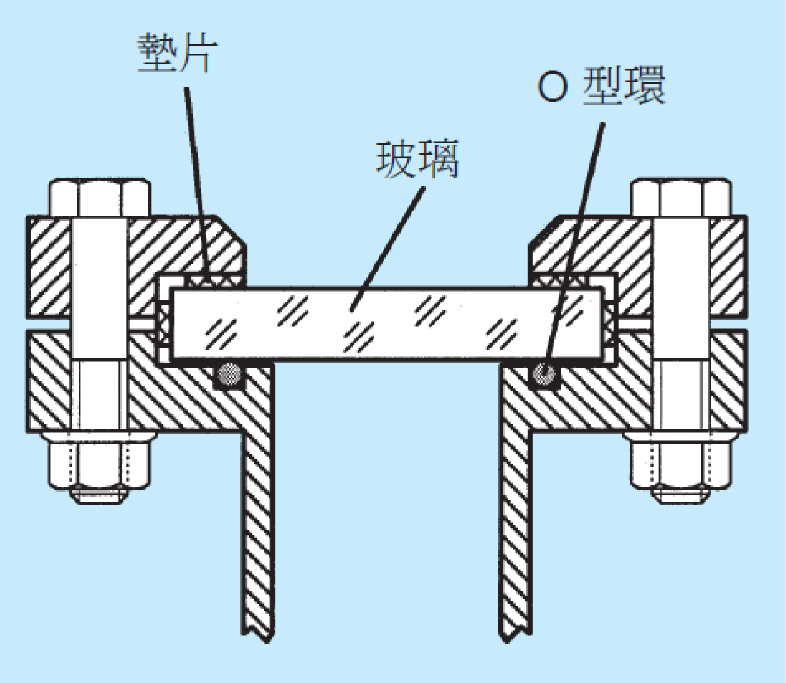

玻璃
Kovar 電極

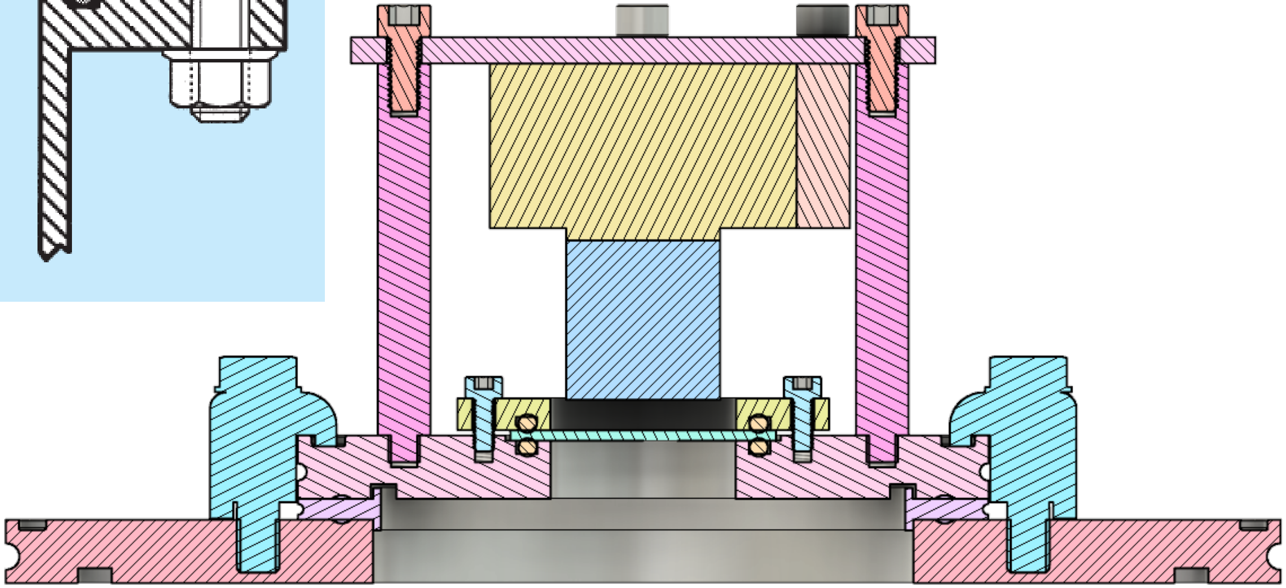

絕緣陶瓷
法蘭
電極

封合式視窗

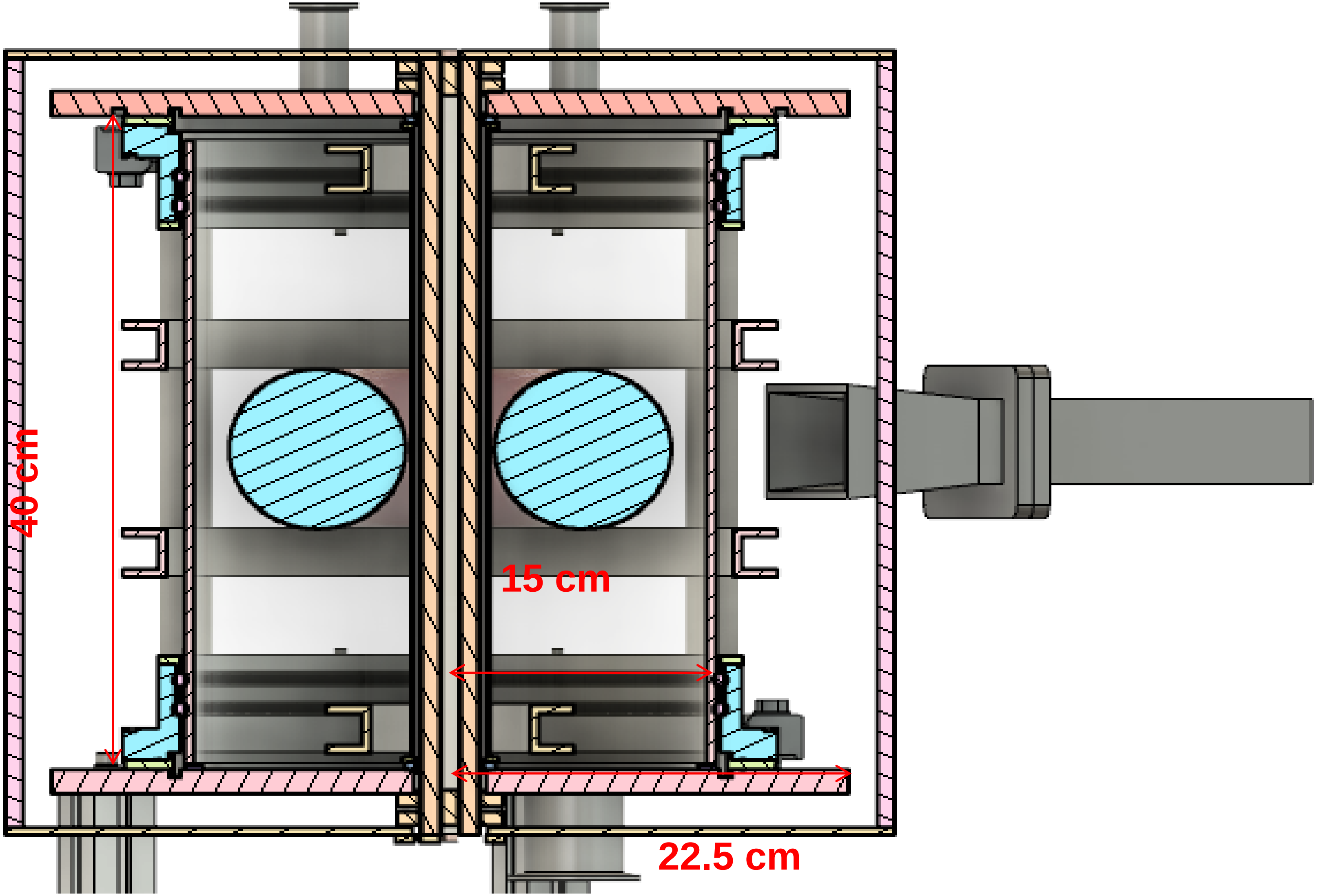


可拆式視窗

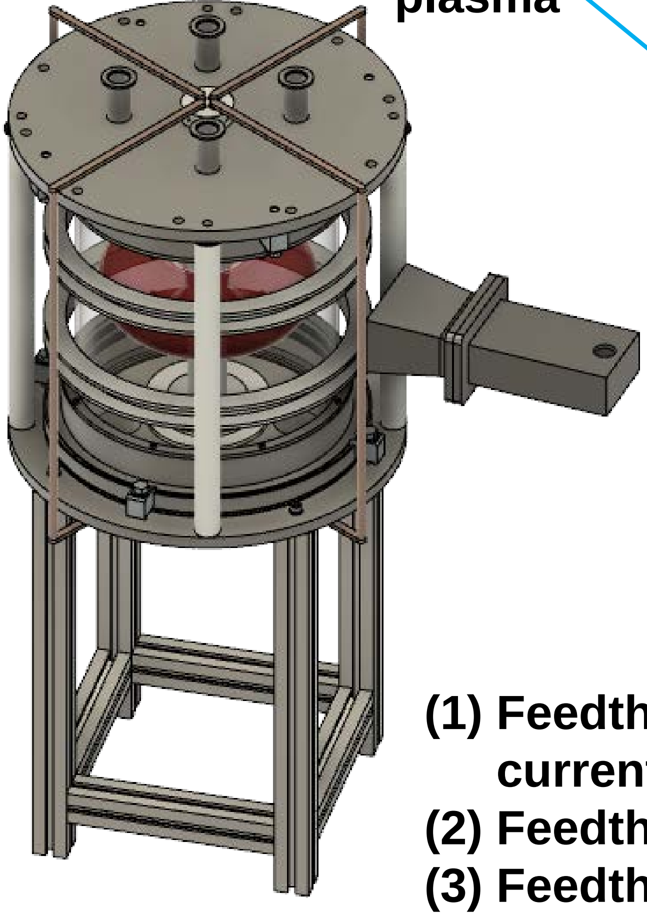


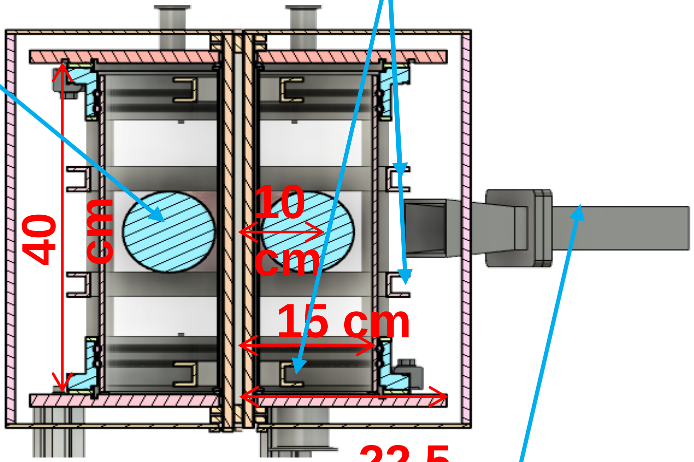


Flange of the vacuum chamber for the spherical tokamak



We need to work with a vacuum system





Tokamak plasma

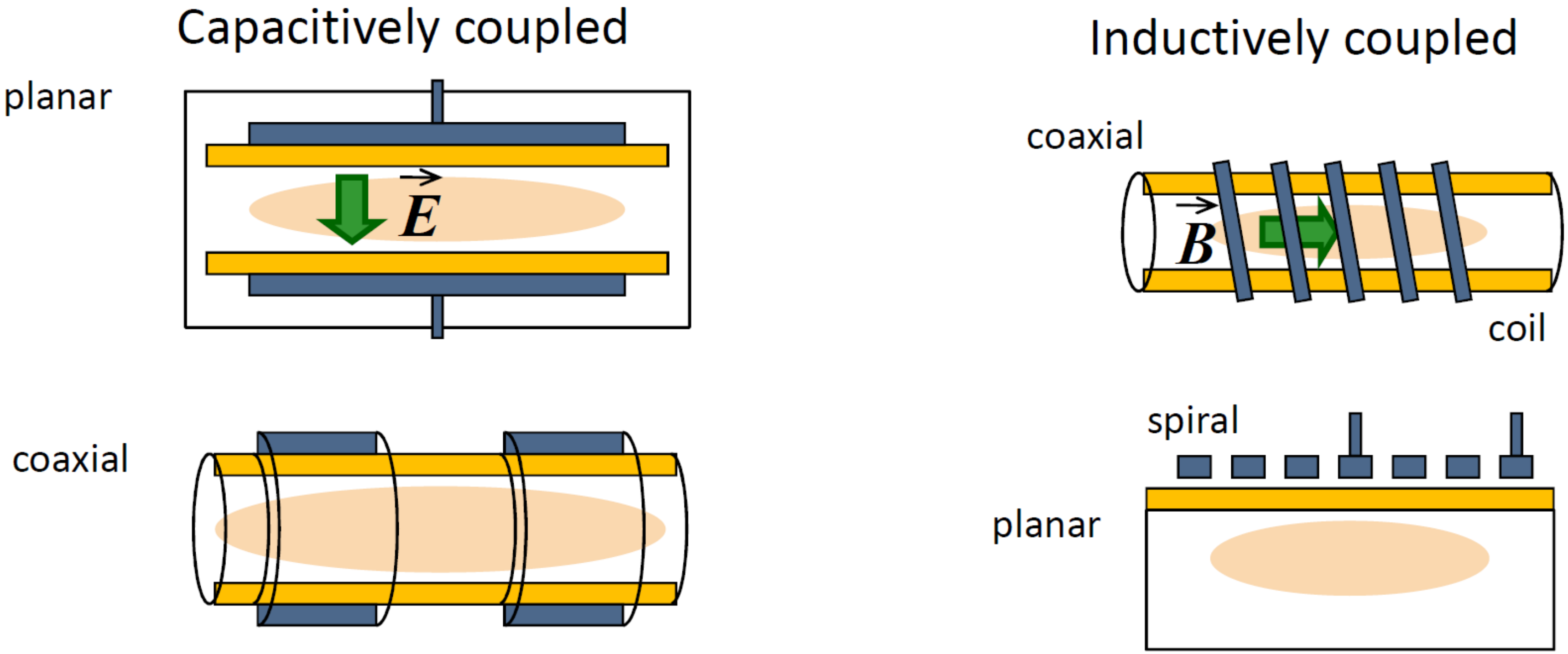
Vertical-field coils

1 kW, 2.45 GHz Magnetron

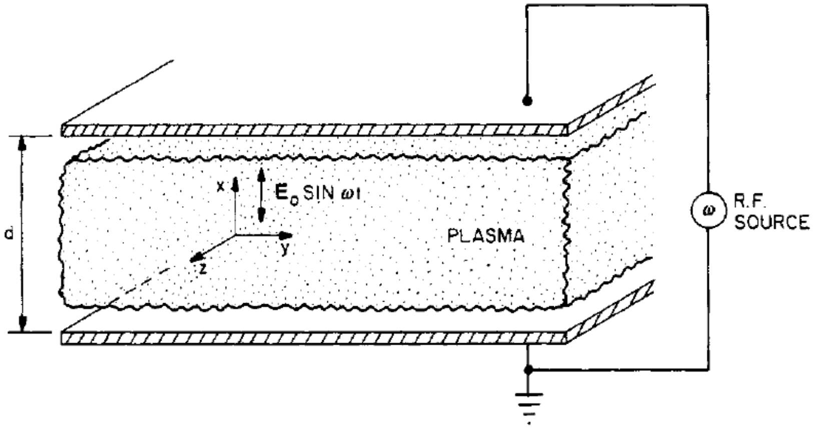
(1) Feedthrough for conducting current to drive the vertical coil.
(2) Feedthrough for Rogowski coil.
(3) Feedthrough for triple probe.

Plasma will first be generated using capacitive coupling

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



Capacitive RF coupling plasma without magnetic fields



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

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

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

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

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

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

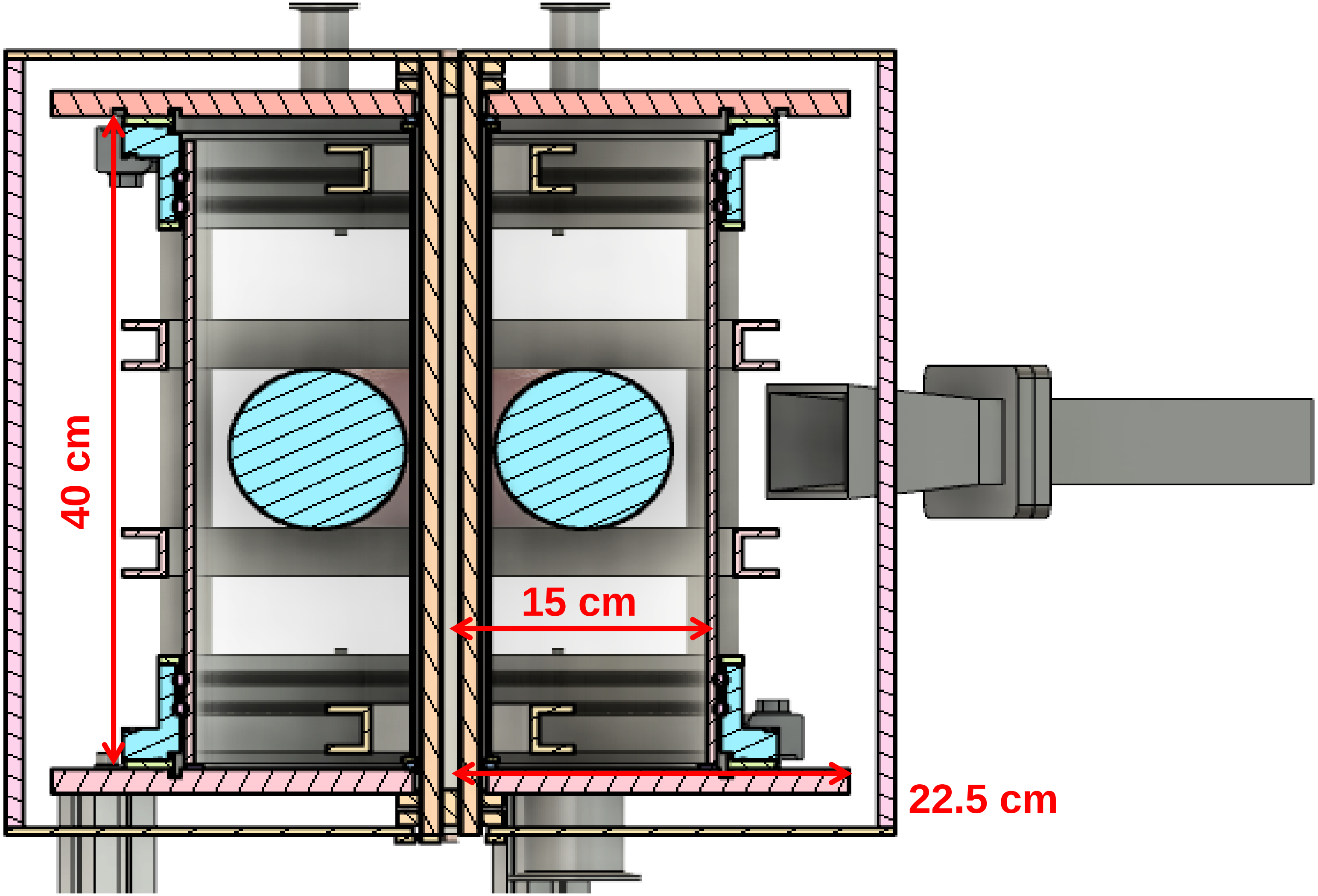
$$C_2 = -\frac{\nu_c eE_0}{\omega\mathrm{m}}\,\frac{1}{\omega^2 + \nu_c{}^2}$$

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

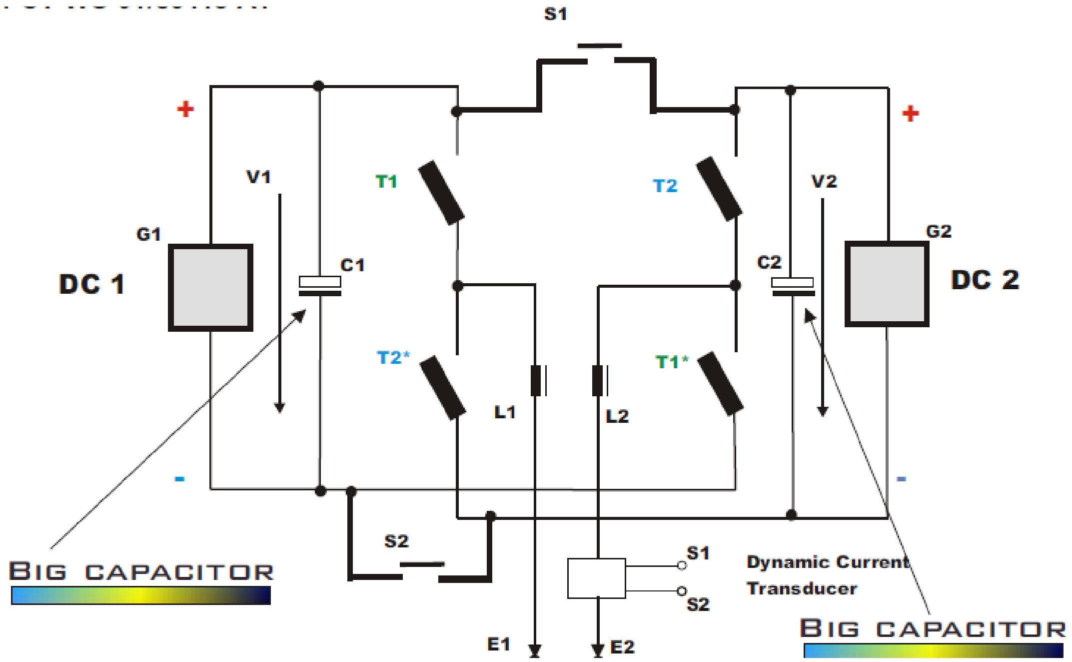
$$P = \frac{dW}{dt} = \mathrm{eE_0}\sin(\omega\mathrm{t})v_x$$

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

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

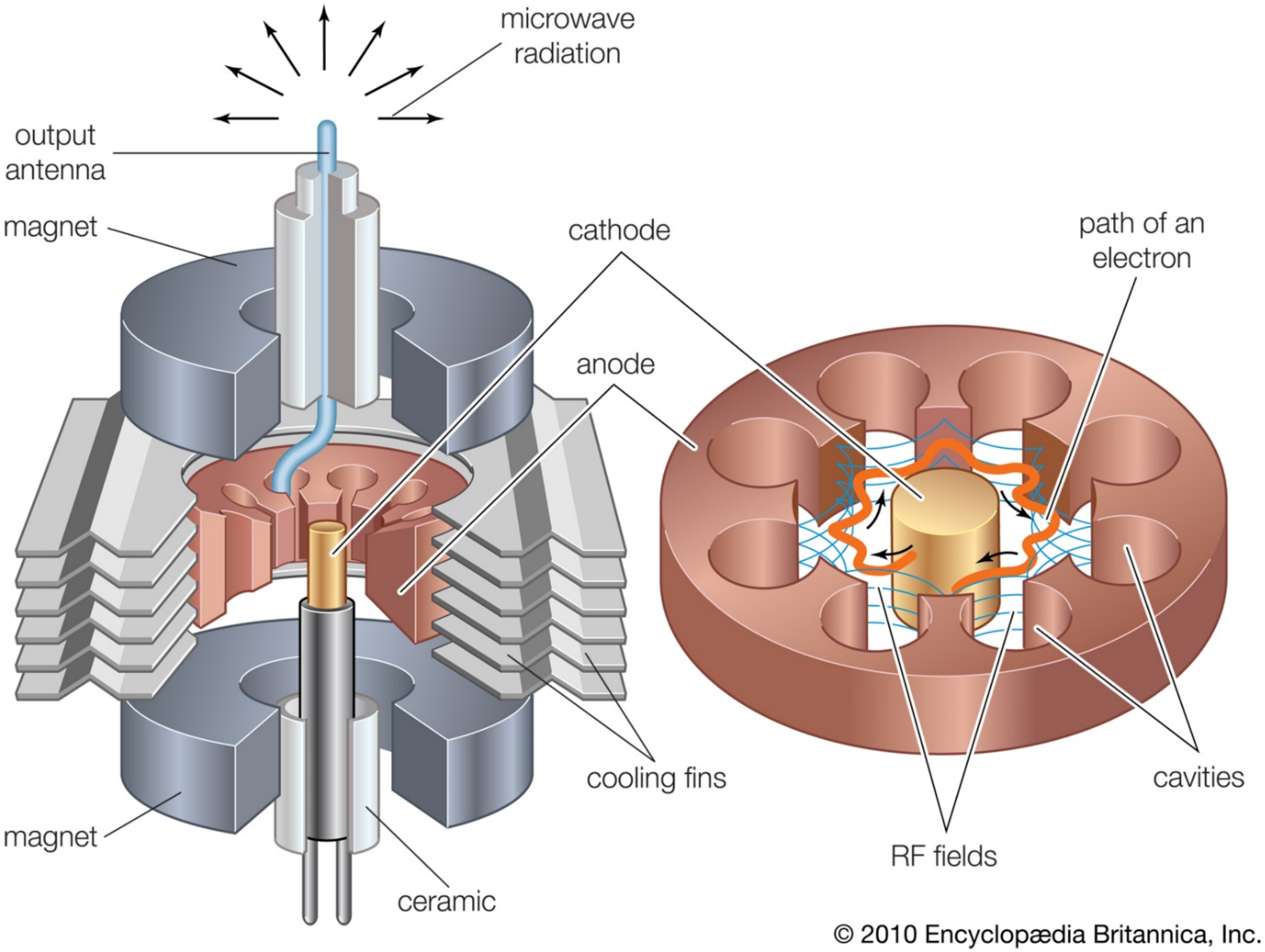
Transformer

HV- RF output

Microwave heating

- **Microwave generation:**
  - **Magnetron**
  - **Driver of magnetron**
  - **Microwave coupling**
  - **Microwave isolation**
  - **ECR heating – 1w, 2w, 3w**
  - **Required toroidal magnetic field -> coil design, current requirement**
  - **Required poloidal magnetic field, using safety factor**
  - **Required vertical field estimated from the density**

Internal of a magnetron



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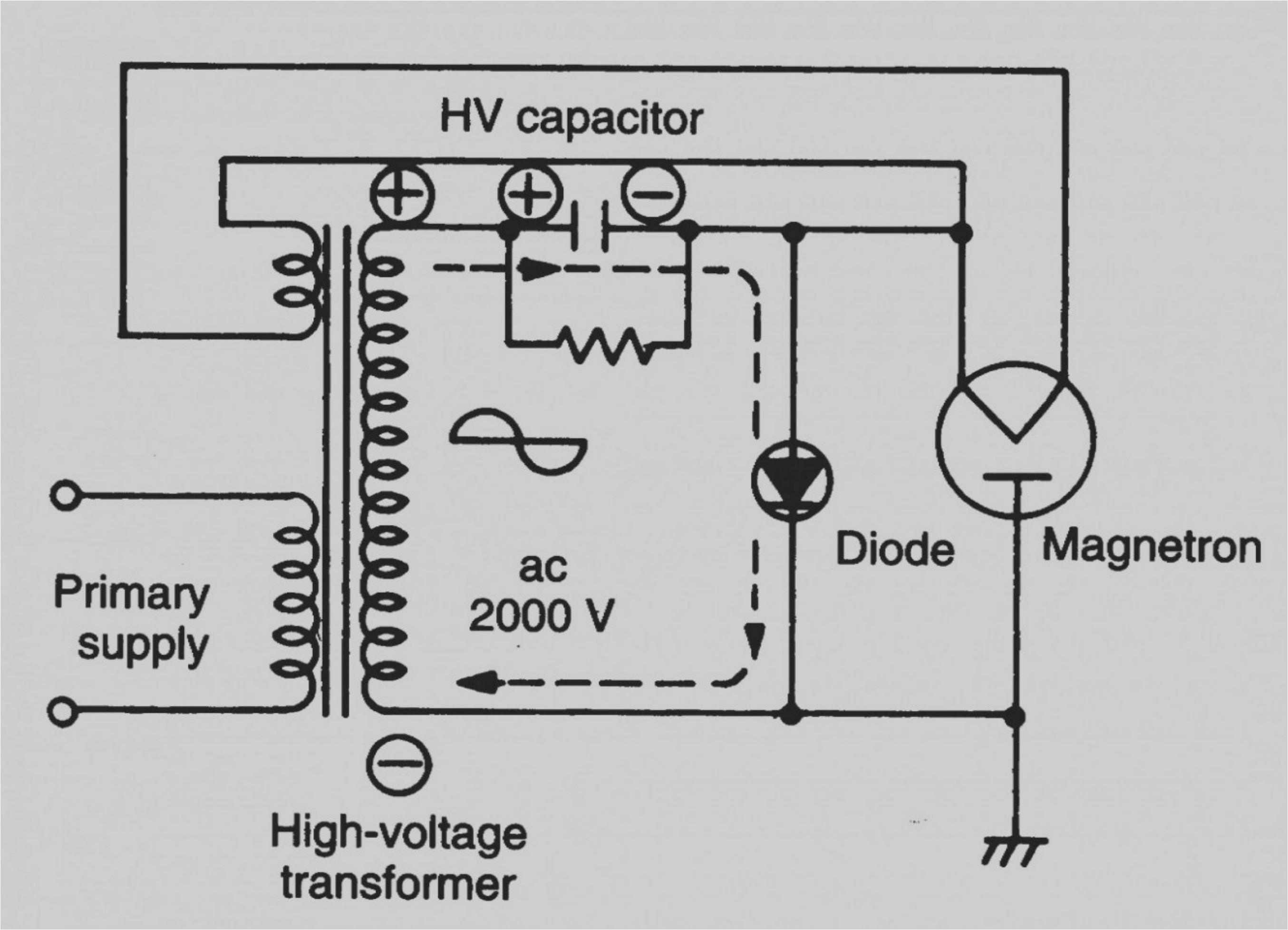
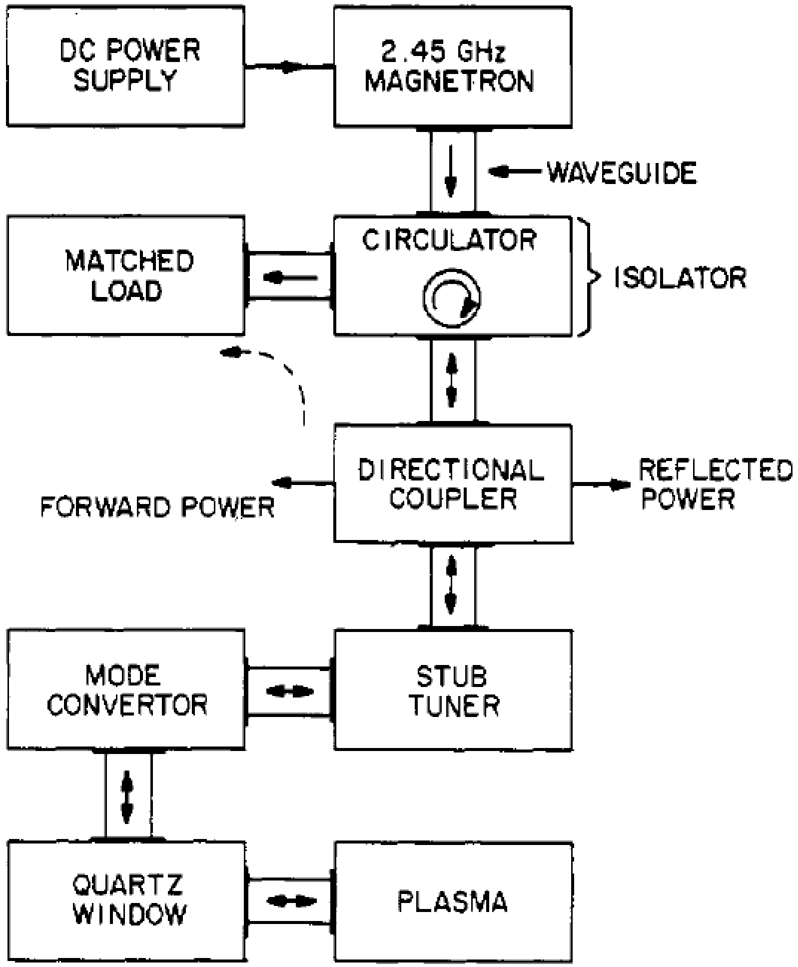
https://kids.britannica.com/students/article/electron-tube/106024/media?assemblyId=137

Magnetron schematic diagram



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

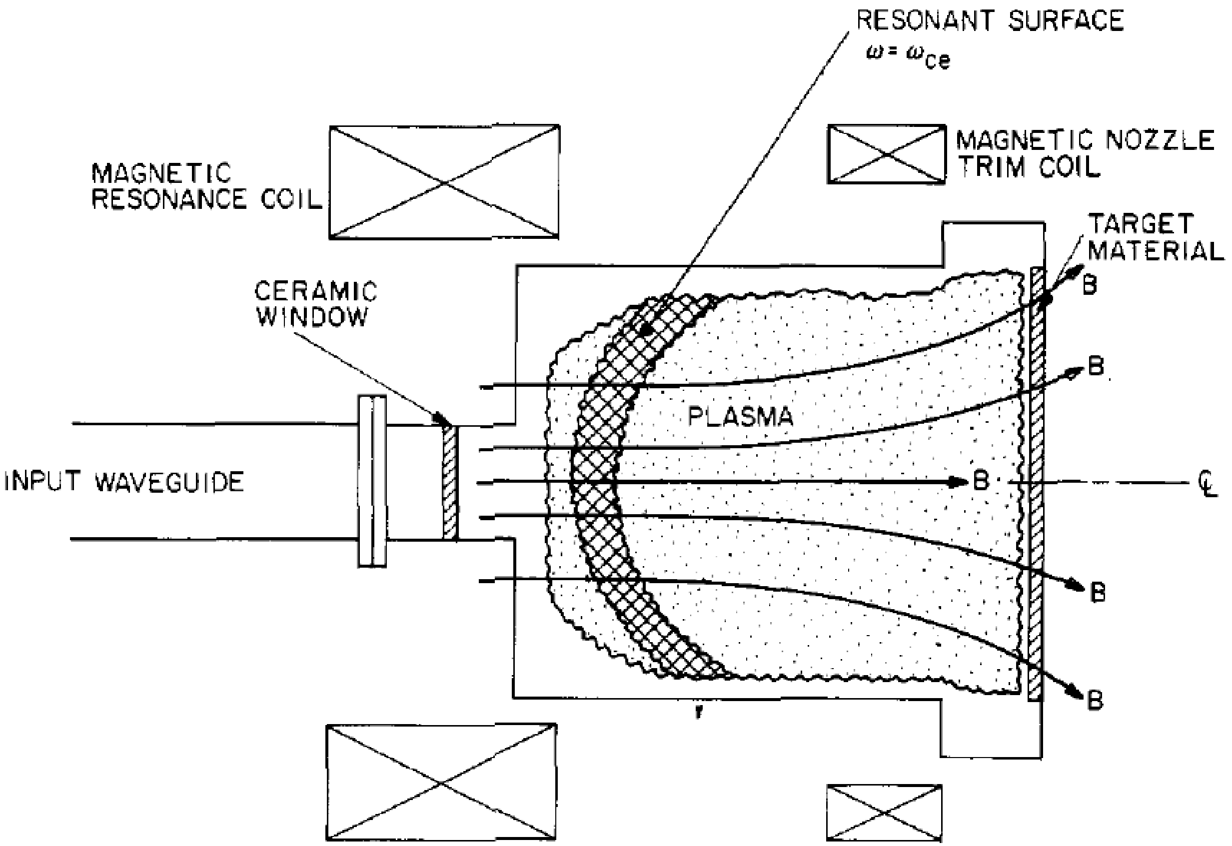
Electron cyclotron resonance (ECR) microwave systems



microwave systems

Strong absorption occurs when the frequency matches the electron cyclotron frequency

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



Electron cyclotron frequency depends on magnetic field only

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

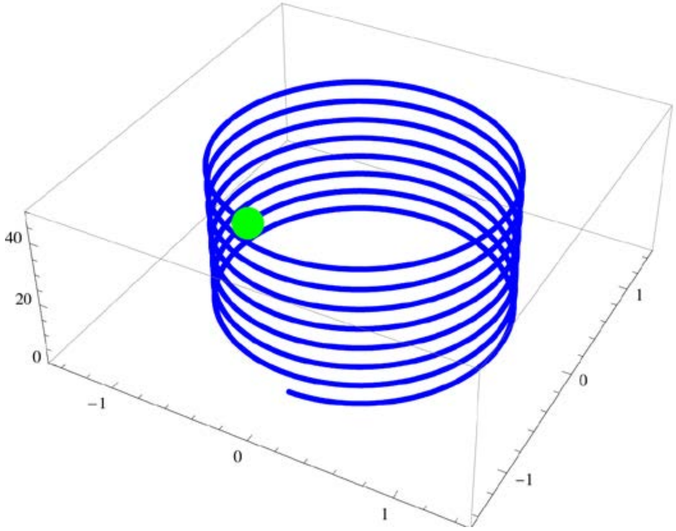
- Assuming $\vec{B} = B\hat{z}$ and the electron oscillates in x-y plane

$$m_e \dot{v}_x = -\frac{e}{c} B v_y \qquad m_e \dot{v}_z = 0$$

$$m_e \dot{v}_y = \frac{e}{c} B v_x$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y = -\left(\frac{eB}{m_e c}\right)^2 v_x$$

$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x = -\left(\frac{eB}{m_e c}\right)^2 v_y$$



- Therefore

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

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

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

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

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

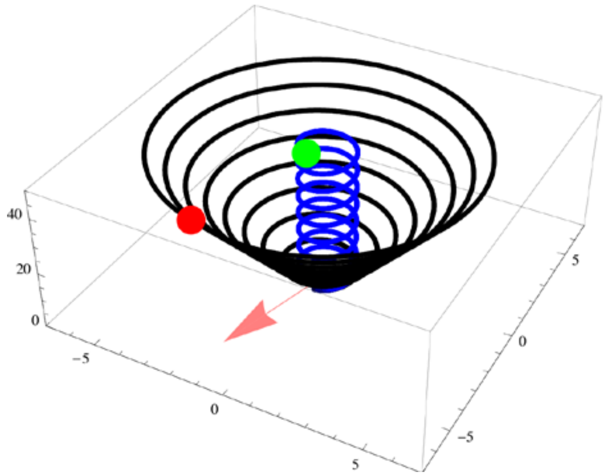
$$m_e\dot{v}_y = \frac{e}{c}Bv_x + E_0\sin(\omega t)$$

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

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

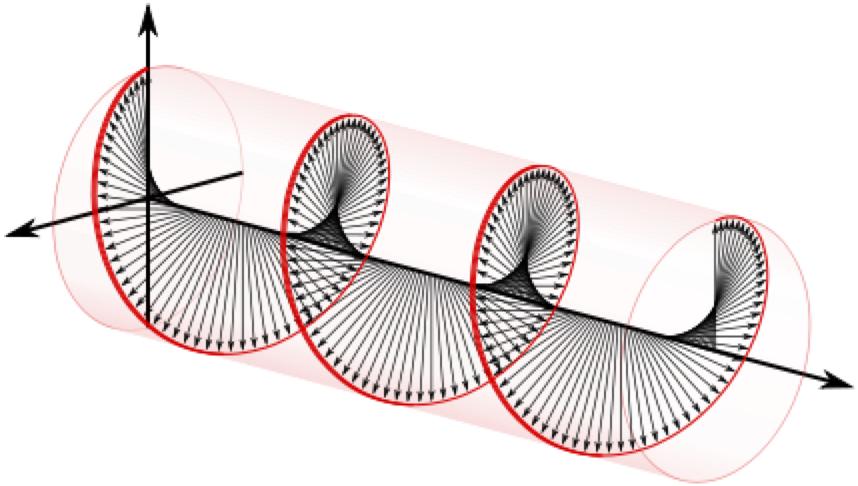
$$\ddot{v}_y = -\omega_{ce}{}^2 v_y + \frac{E_0}{m_e}(\omega_{ce} + \omega)\sin(\omega t)$$

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

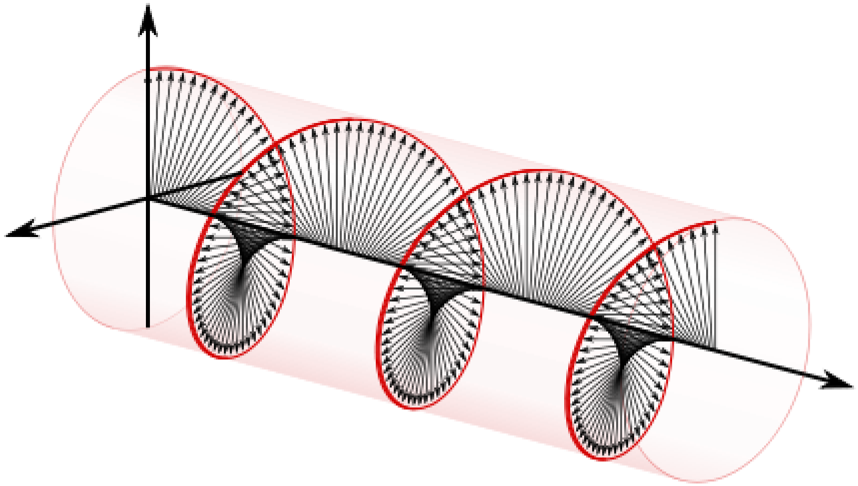


Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**



- **Left-handed polarization**



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

Only right-handed polarization can resonance with electron’s gyromotion

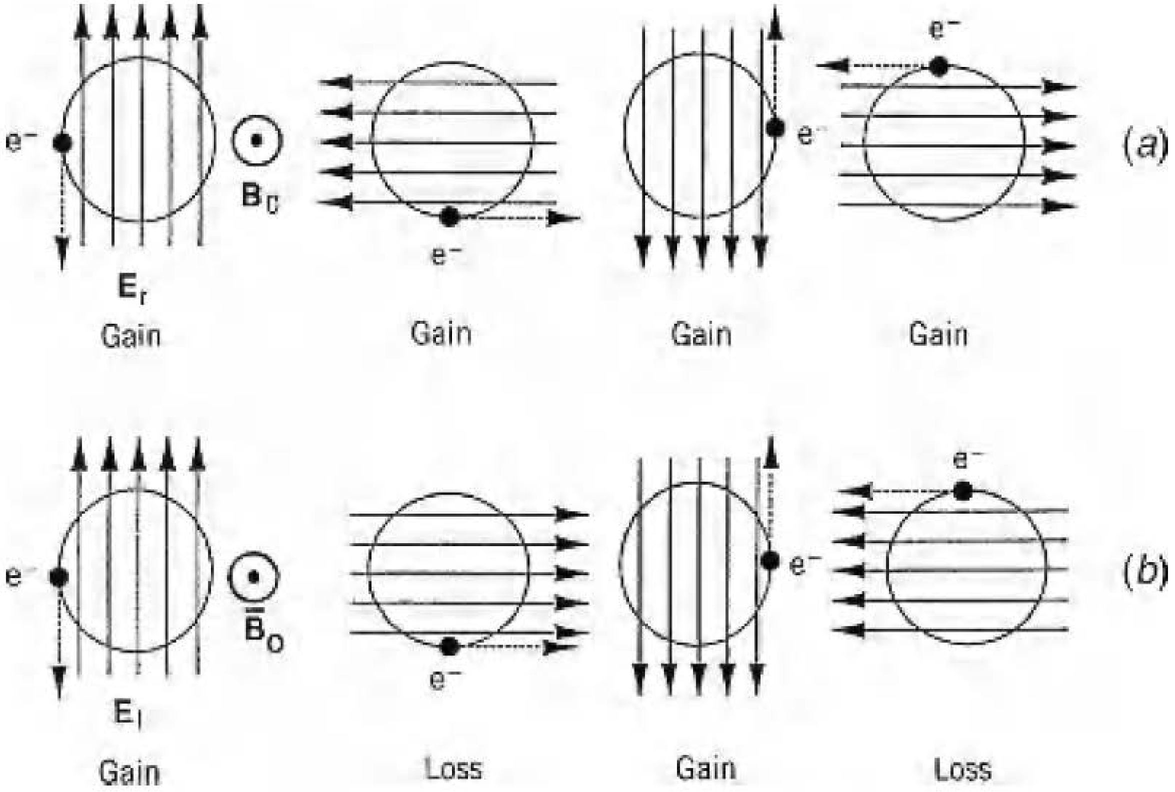


FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

A magnetic field of 0.0876 T is needed for ECH

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

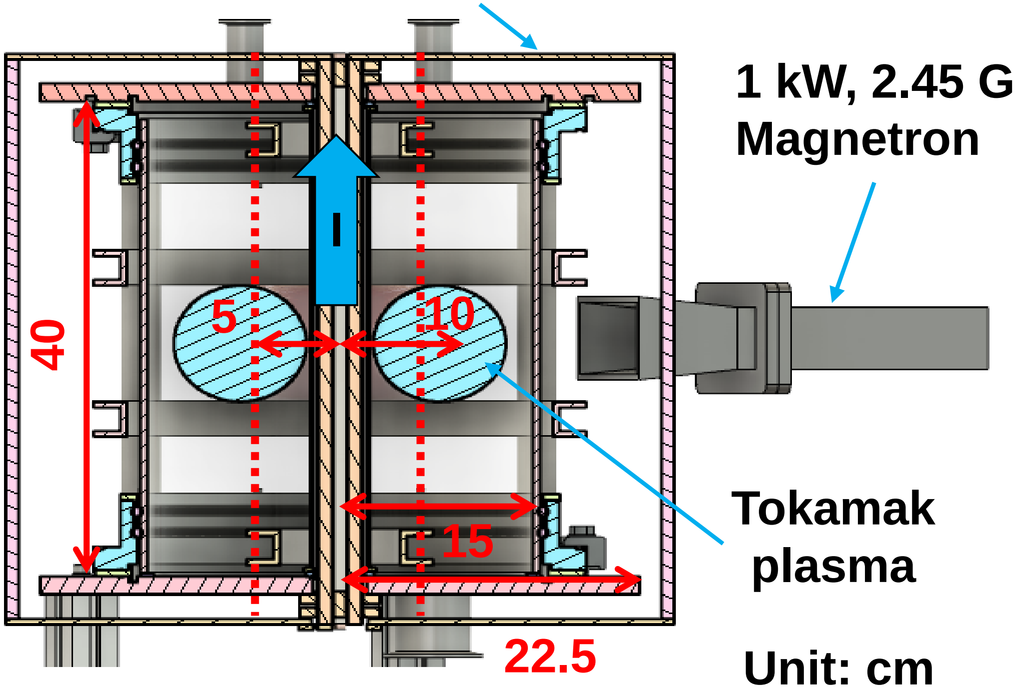
$$B = \frac{2\pi \times 2.45 \times 10^9 m_e c}{e} = 876\ \mathrm{G} = 0.0876\ \mathrm{T}$$

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

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

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

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



Unit: cm

- A pulsed-power system will be used to generate the current.

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

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

- **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.**

- **Ar will be used.**

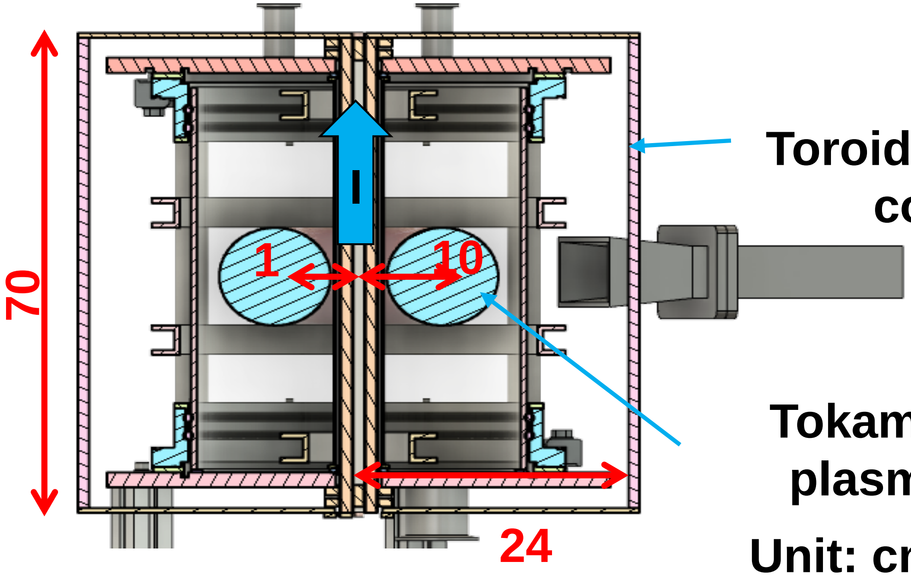
The magnetic field energy of the toroidal field is ~100 J

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

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

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

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



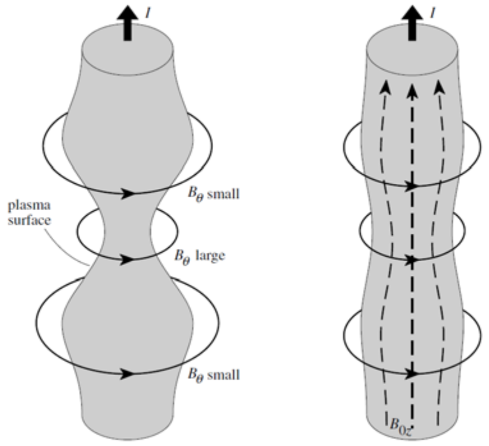
Toroidal field coil

Tokamak plasma

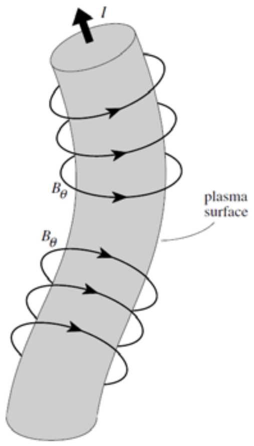
Unit: cm

Instabilities occur in a cylindrical plasma column

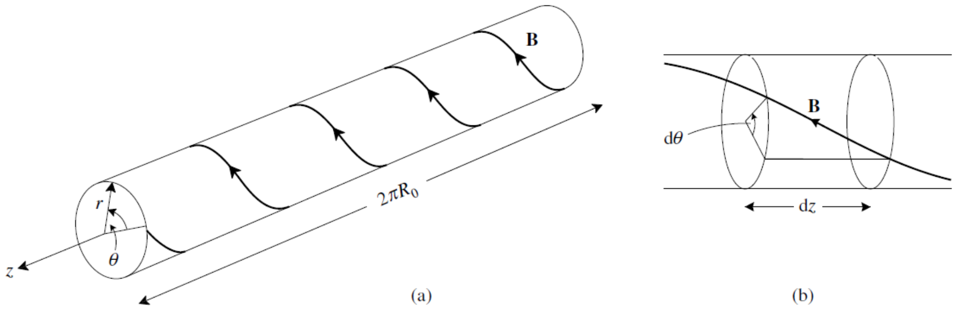
- **Sausage instability:**



- **Kink instability:**



- **Safety factor *q*:**

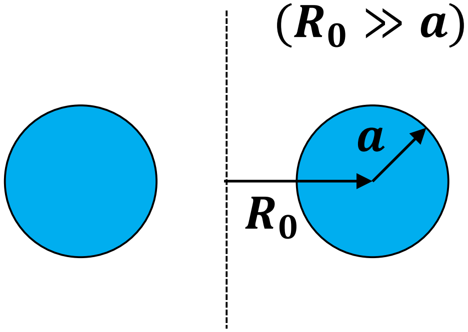


(a) (b)

Fig. 4.6. Screw pinch geometry.

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

$$(R_0 \gg a)$$



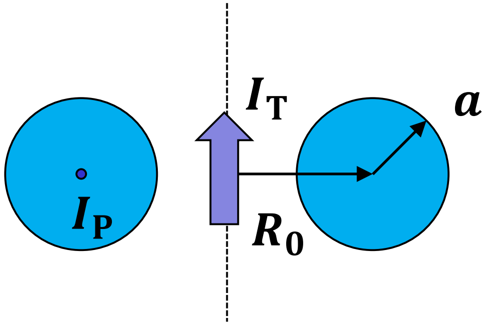
A plasma current of ~ 2 kA is needed

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

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

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

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

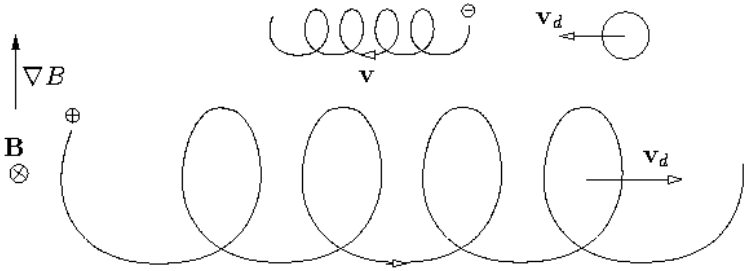


$R_0 \sim 10$ cm

a ~ 5 cm

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

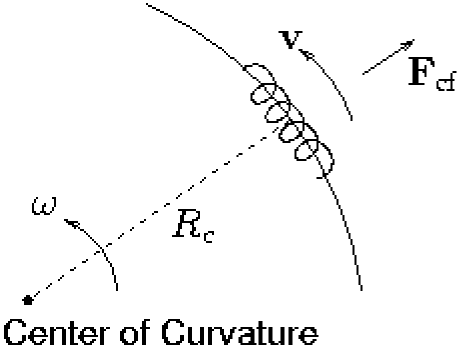
- **Grad-B drift**

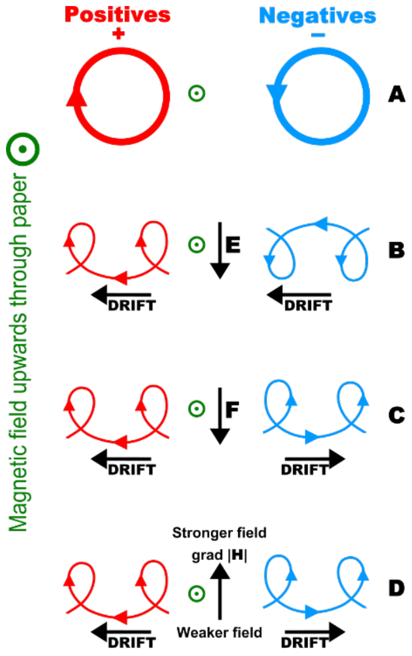


$$V_{\nabla B} = \pm\frac{1}{2}v_\perp r_L \frac{\vec{B}\times\nabla B}{B^2}$$

- **Curvature drift**

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





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

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

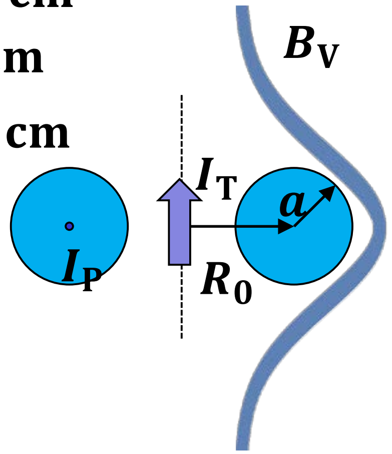
https://en.wikipedia.org/wiki/Guiding_center
http://silas.psfc.mit.edu/introplasma/chap2.html

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

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

$$R_0\sim 10\text{ cm}$$
$$\text{a}\sim 5\text{ cm}$$
$$R_C\sim 5\text{ cm}$$



Assuming the ionization fraction is 1%:

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

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

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

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

$$B_V\sim\frac{1}{V_{\text{drift}}}\frac{3T}{q}\frac{1}{R_C}\sim\frac{1}{5\times10^4}3\times1\times\frac{1}{0.05}\sim 0.0012\text{ T}=12\text{ G}\qquad(B_{\text{earth}}\sim0.5\text{ G})$$

- For T$_e$ = 1 eV, B$_V$ = 12 G

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

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, $n_e \sim 10^{19}$ m^{-3}.