가속기 진공 I
(가속기와 진공)

2025.03.14.

하태균
포항가속기연구소

- 진공이란?
  - 대기압보다 압력이 낮은 상태
- 압력이란?
  - 단위면적 당 작용하는 힘

- 압력 낮다

=

- 진공도 높다

- Low pressure

=

- High Vacuum

진공의 영역

ISO 3529-1:1981

Low (rough) vacuum:	10^5 to 10^2 Pa
Medium vacuum:	10^2 to 10^{-1} Pa
High vacuum (HV):	10^{-1} to 10^{-4} Pa
Very high vacuum (VHV):	10^{-4} to 10^{-7} Pa
Ultra high vacuum (UHV):	10^{-7} to 10^{-10} Pa
Extremely high vacuum (XHV):	below 10^{-10} Pa

❖ 1 atm = 760 Torr = 1.033 kgf/cm^2 = 14.7 psi = 1013 mbar = 1013 hPa

가속기와 진공 (진공의 필요성)

- 빔-입자 상호작용

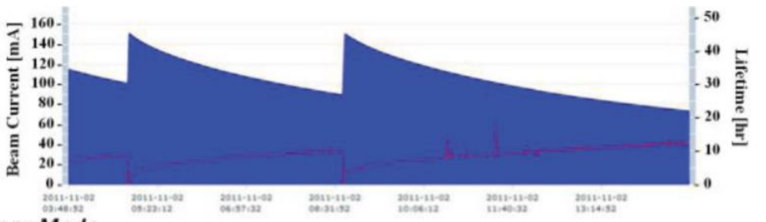
Beam–gas interactions		Type of affected beam particles
Inelastic	Bremsstrahlung	e^{+}, e^{-}
	Ionisation energy loss	All particles
	Electron capture	Low energy A^{+}, A^{Z+}
	Electron loss	A^{+}, A^{-}, A^{Z+}
	Nuclear reactions	All particles
Elastic	Single Coulomb scattering	All particles
	Multiple Coulomb scattering	$A^{Z+}, \overline{p}$
	Gas ionisation	
Space charge	Ion cloud space charge	Negatively charged beams
	Electron cloud space charge	Positively charged beams

가속기와 진공 (진공의 필요성)

- **빔손실 (빔수명)**

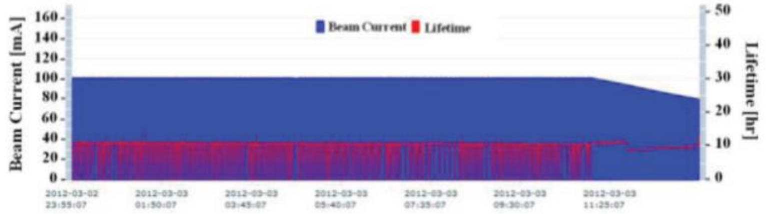
$$dI = -I\sigma n\, dx \qquad I = I_0 \exp\left(-\frac{t}{\tau}\right)$$

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{beam}}} + \frac{1}{\tau_{\text{gas}}}$$



Decay Mode

** Peak stored current : ~ 150 mA*

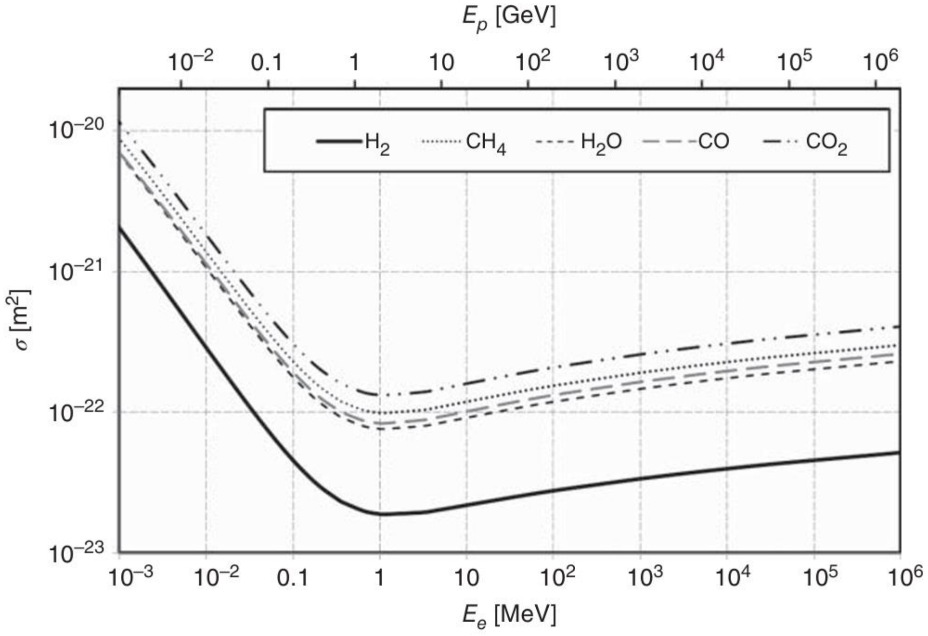


Top-Up Mode

- **잔류기체 이온화 (이온 불안정)**

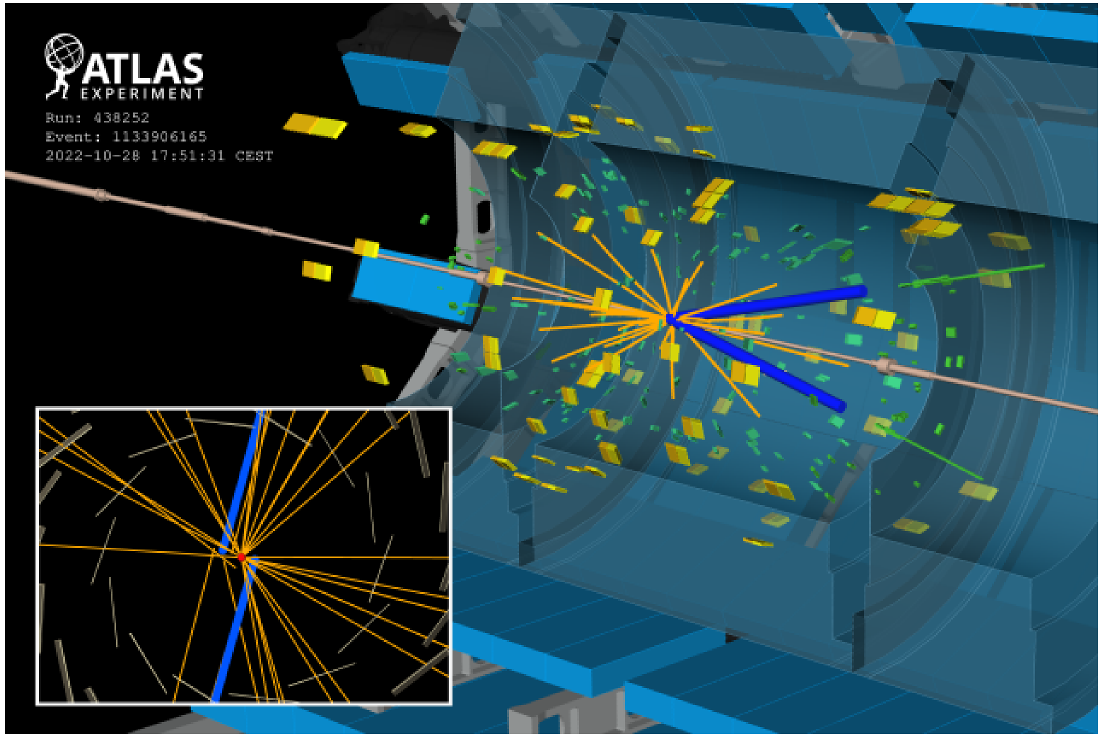
$$\sigma = 4\pi\left(\frac{\hbar}{mc}\right)^2 (M^2 x_1 + C x_2) = 1.874 \times 10^{-20}\ \text{cm}^2 (M^2 x_1 + C x_2)$$

$$x_1 = \frac{1}{\beta^2} \ln\left[\frac{\beta^2}{1-\beta^2}\right] - 1,\ x_2 = \beta^{-2},\ \beta = \frac{v}{c} = \sqrt{1 - \left(\frac{E_0}{E}\right)^2}$$

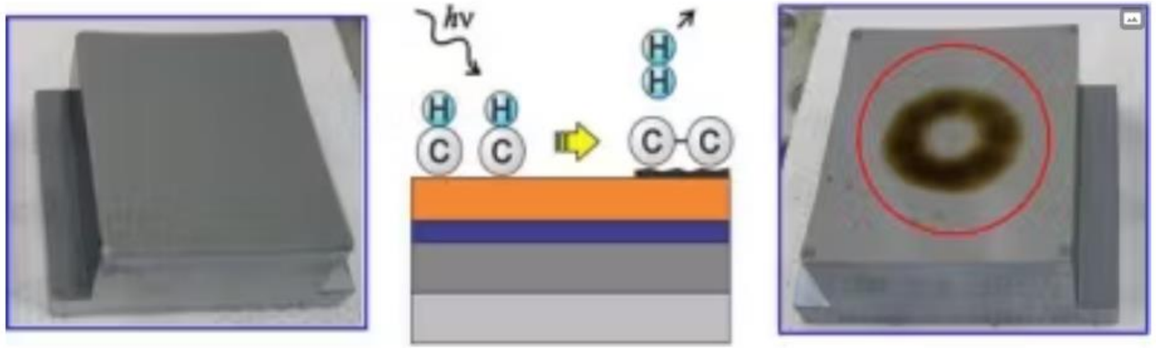


가속기와 진공 (진공의 필요성)

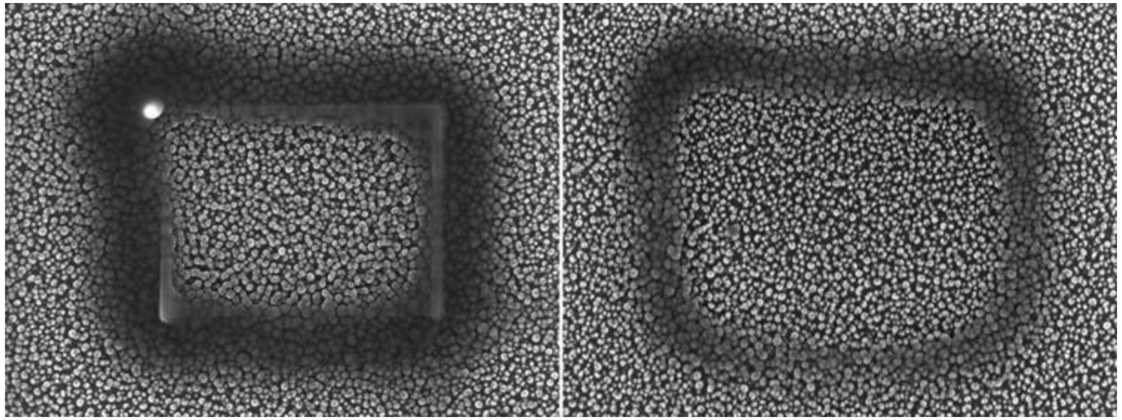
- **디텍터의 배경 잡음**



- **표면 오염 (거울장치 등)**



Contamination forms on a clean multilayer surface (left) when EUV photons react with gases (center), resulting in carbonaceous deposits (right).



방사광 가속기 진공 시스템

→방사광(Synchrotron radiation)에 의한 열발생과 기체방출 문제 해결

- Synchrotron radiation (SR) 이란?
  - 기본 개념과 중요한 공식

- SR의 영향?
  - 열 발생 (Heat load)
  - 기체 발생 (Gas load)

- An accelerated charged particle emits electro-magnetic radiation.
  - The radiation fields are given by

$$\vec{E} = -\frac{\partial}{\partial t}\vec{A} - \nabla\phi \quad \vec{B} = \nabla \times \vec{A}$$

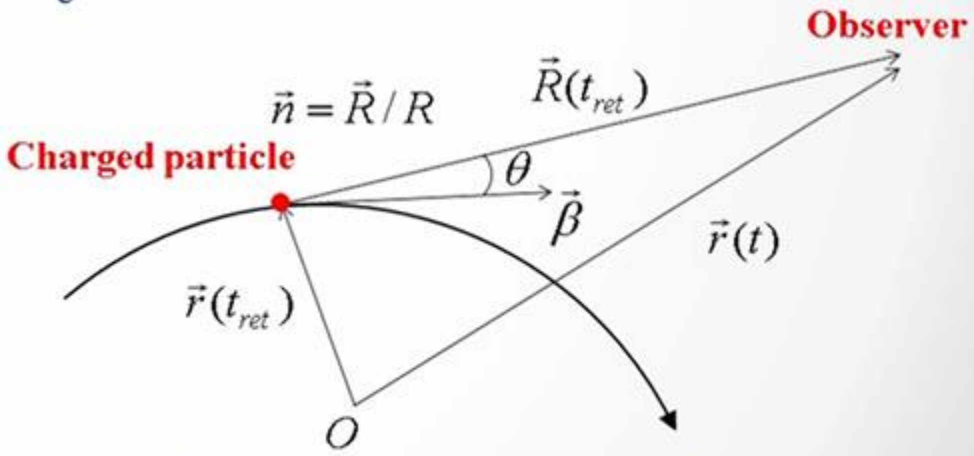
ϕ: Scalar potential
A: Vector potential

Here the retarded Lienard-Wiechert potentials are given by

$\beta = \frac{v}{c}$, v : velocity, c : speed of light

$$\vec{A}(t) = \frac{e}{4\pi\varepsilon_0 c}\left[\frac{\vec{\beta}}{R(1-\vec{n}\cdot\vec{\beta})}\right]_{ret}$$

$$\phi(t) = \frac{e}{4\pi\varepsilon_0}\left[\frac{1}{R(1-\vec{n}\cdot\vec{\beta})}\right]_{ret}$$



where $\vec{R}(t_{ret})$ is the distance vector form source to observer, and t_{ret} is the retarded time $ct_{ret} = ct - R(t_{ret})$

- Electric and magnetic fields are finally given by

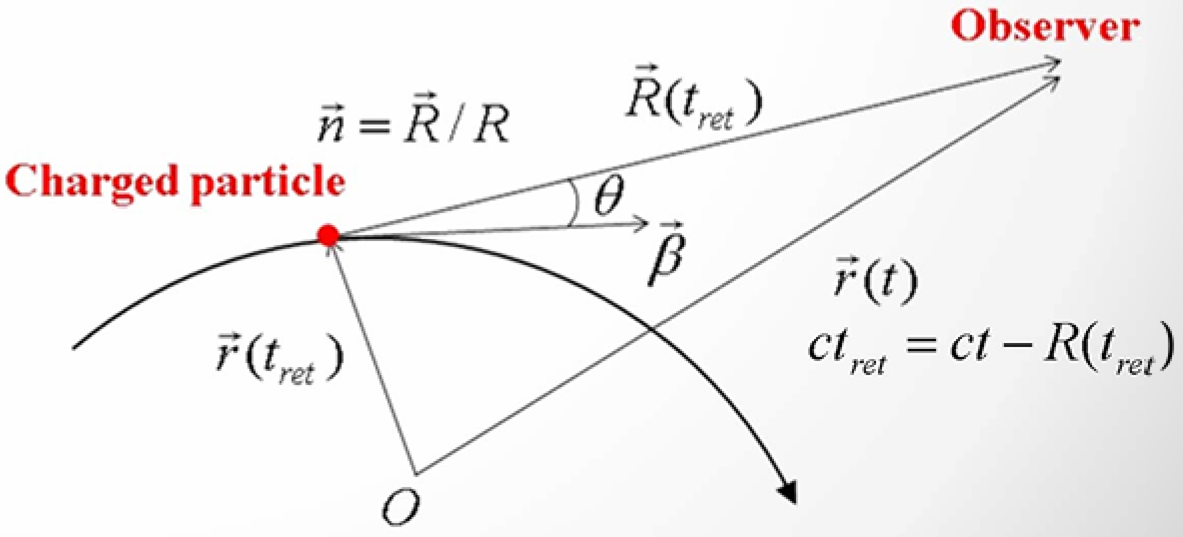
$$\vec{B} = \frac{1}{c}\left[\vec{n} \times \vec{E}\right]_{ret}$$

$$\vec{E} = \frac{e}{4\pi\varepsilon_0}\left[\frac{(1-\beta^2)(\vec{n}-\vec{\beta})}{R^2(1-\vec{n}\cdot\vec{\beta})^3}\right]_{ret} + \frac{e}{4\pi\varepsilon_0 c}\left[\frac{\vec{n}\times(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}}{R(1-\vec{n}\cdot\vec{\beta})^3}\right]_{ret}$$

Coulomb field $\propto 1/R^2$

Radiation field $\propto 1/R$

- At points far from emitting point, the radiation field ($\propto 1/R$) is more important.

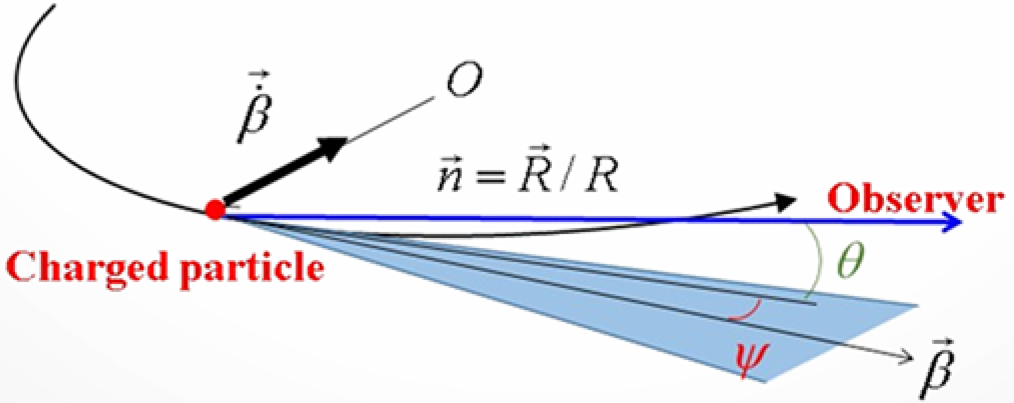


- Power of radiation per unit solid angle
  - Pointing vector = Radiation energy flow toward R per unit area.

$$\vec{S}_r(t) = \frac{1}{\mu_0}\vec{E}\times\vec{B} = \frac{1}{\mu_0 c}E^2\left(1-\vec{\beta}\cdot\vec{n}\right)\vec{n}\Big|_{ret} = \varepsilon_0 c E^2\left(1-\vec{\beta}\cdot\vec{n}\right)\vec{n}\Big|_{ret}$$

Then, the instantaneous differential radiation power per unit solid angle is

$$\frac{dP}{d\Omega} = \vec{n}\cdot\vec{S}R^2\Big|_{ret} = \varepsilon_0 c E^2\left(1-\vec{n}\cdot\vec{\beta}\right)R^2\Big|_{ret} = \frac{e^2}{16\pi^2\varepsilon_0 c}\frac{\left|\vec{n}\times\left\{\left(\vec{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right\}\right|^2}{\left(1-\vec{n}\cdot\vec{\beta}\right)^5}\Bigg|_{ret}$$



Beaming

- If β is parallel to $\dot{\beta}$

$$\frac{dP}{d\Omega} = \frac{e^2\dot{\beta}^2}{16\pi^2\varepsilon_0 c}\frac{\sin^2\theta}{(1-\beta\cos\theta)^5}$$

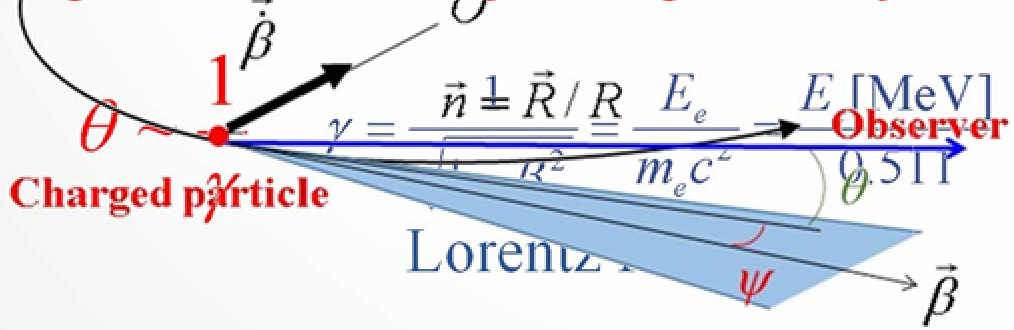
- If β is orthogonal to $\dot{\beta}$

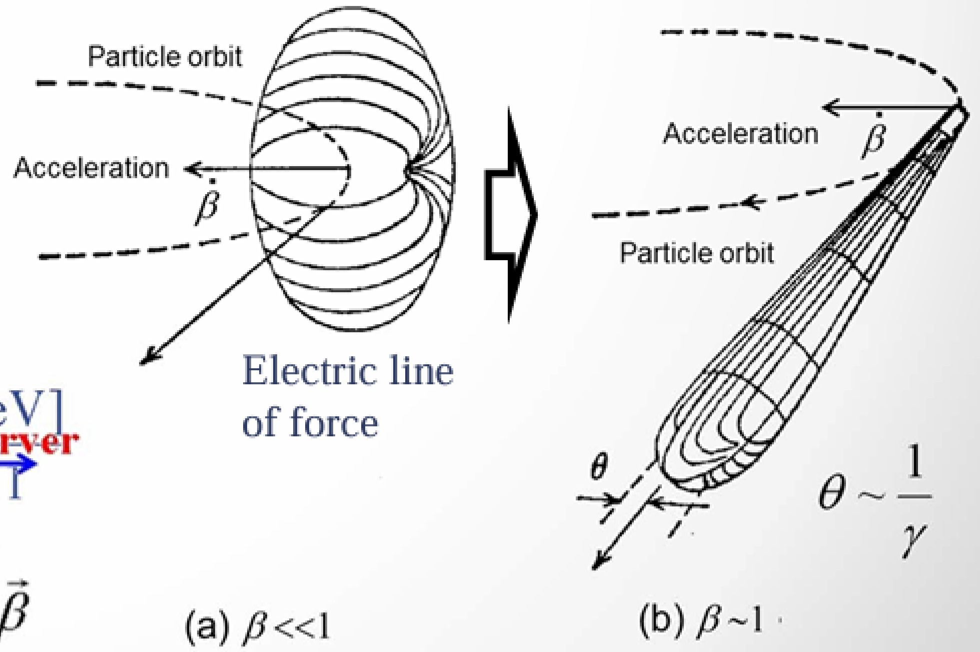
$$\frac{dP}{d\Omega} = \frac{e^2\dot{\beta}^2}{16\pi^2\varepsilon_0 c}\frac{(1-\beta\cos\theta)^2-(1-\beta^2)\sin^2\theta}{(1-\beta\cos\theta)^5}$$

When $\beta \sim 1$, $(1-\beta\cos\theta)^5 \to 0$ for $\theta \to 0$, then the power beams to the front of orbit.

$\Rightarrow$ Beaming

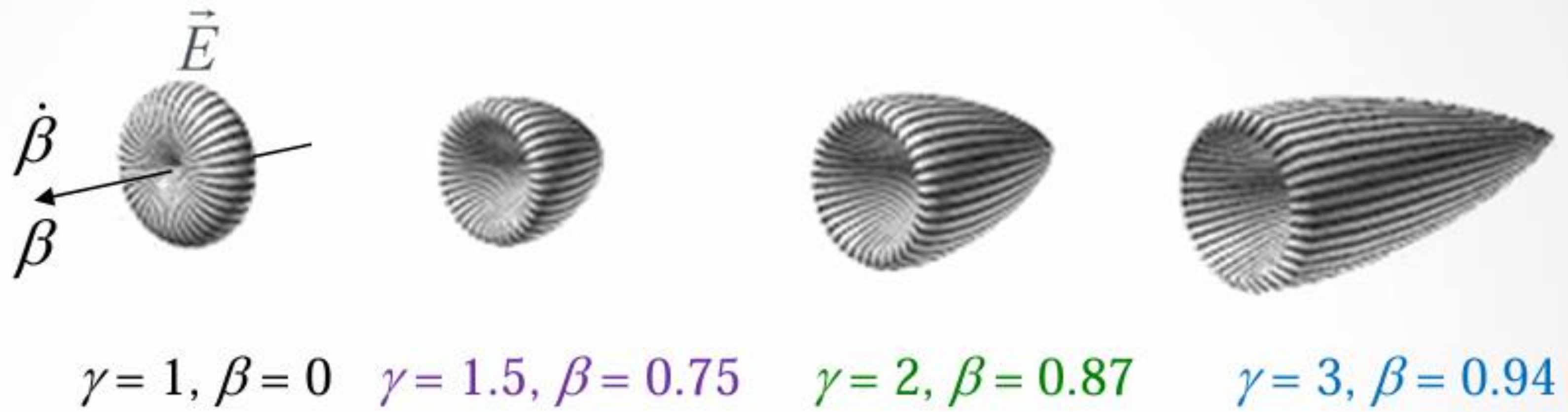
- Angle of beaming θ is given by



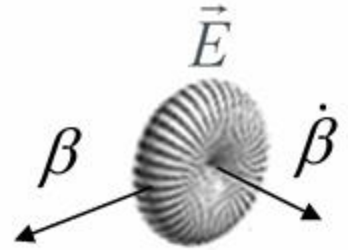


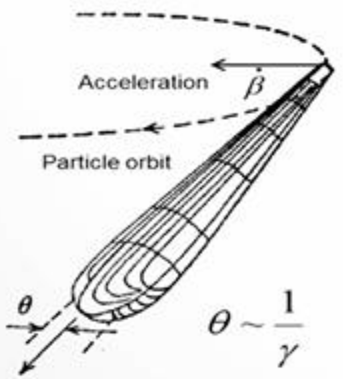
Beaming

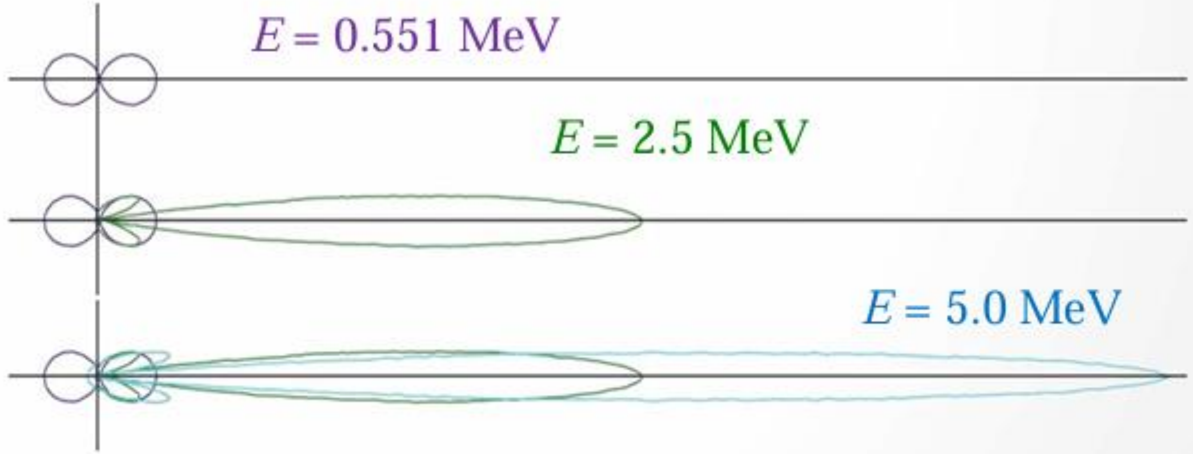
- $\beta \,//\, \dot{\beta}$



- $\beta \perp \dot{\beta}$







- Now, consider a charged particle in homogeneous field B.
  - The acceleration in B is given by

$$\dot{\vec{\beta}}_\perp = \frac{\beta^2 c}{\rho} \qquad m\dot{v} = \frac{mv^2}{\rho} \quad \text{Centripetal force}$$

where the bending radius of charged particle, ρ, at energy E_e is

$$\frac{1}{\rho\,[\mathrm{m}]} = \frac{eBc}{\beta E_e} = 0.2998 \frac{B\,[\mathrm{T}]}{\beta E_e\,[\mathrm{GeV}]} \qquad \rho = \frac{mv}{eB} = \frac{mc^2 v}{eBc^2} = \frac{E_e \beta}{eBc}$$

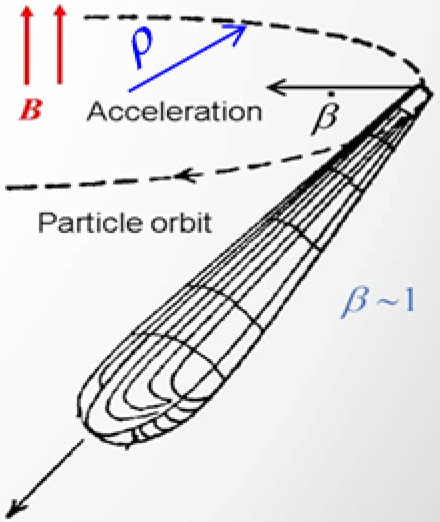
Larmor radius

Then the instantaneous radiation power becomes

$$P = \frac{2 c r_e m_e c^2}{3} \frac{\beta^4 \gamma^4}{\rho^2} = \frac{c C_\gamma}{2\pi} \frac{E_e^4}{\rho^2} \quad \text{(For electrons)}$$

$$C_\gamma \equiv \frac{4\pi}{3} \frac{r_e}{(m_e c^2)^3} = 8.85 \times 10^{-5} \frac{\mathrm{m}}{\mathrm{GeV}^3}$$

$$r_e = \frac{e}{4\pi\varepsilon_0 m_e c^2}$$



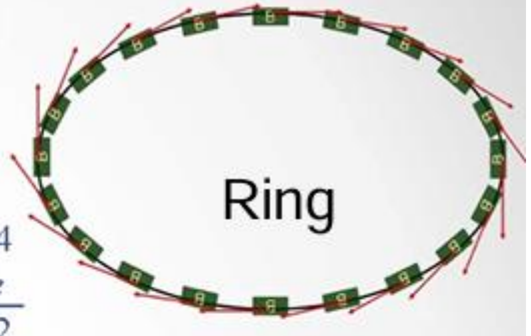
- Mass dependence of power
  - Radiation power depends on the mass of the radiating particle like $1/m^4$. For protons and electrons of the same total energy.

$$\frac{P_p}{P_e} = \left(\frac{m_e}{m_p}\right)^4 = 8.8 \times 10^{-14}$$

  - Synchrotron radiation is much more important for electron and positron ring.
  - Note that, for superconducting system, such as LHC, the SR is important even proton beams, since the heating might have a significant effect to the cryogenics system.
  - Hereafter, we consider the case of an electron or a positron deflected by a dipole magnet.

Total power

- The radiation along a ring per electron is



$$U_0 = \oint P dt = \frac{C_\gamma}{2\pi} E_e^4 \oint \left(\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2} \right) ds \qquad P = \frac{cC_\gamma}{2\pi} \frac{E_e^4}{\rho^2} \qquad cdt = ds$$

For an isomagnetic magnetic field (ρ = const.),

$$U_0 = C_\gamma \frac{E_e^4}{\rho} \qquad \oint ds = 2\pi\rho$$

For a circulating beam current I_e, the total radiation power P_{Ie} is

$$P_{Ie} = U_0 \times \frac{I_e}{e} = C_\gamma \frac{E_e^4}{\rho} \times \frac{I_e}{e}$$

$$P_{Ie}[W] = 8.85 \times 10^4 \frac{E\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]} I\,[\mathrm{A}] = 2.65 \times 10^4 E[\mathrm{GeV}]^3 B[\mathrm{T}] I_e[\mathrm{A}]$$

- Total power
  - The total radiation power

$$P_{Ie} = U_0 \times \frac{I_e}{e} = C_\gamma \frac{E_e^4}{\rho} \times \frac{I_e}{e}$$

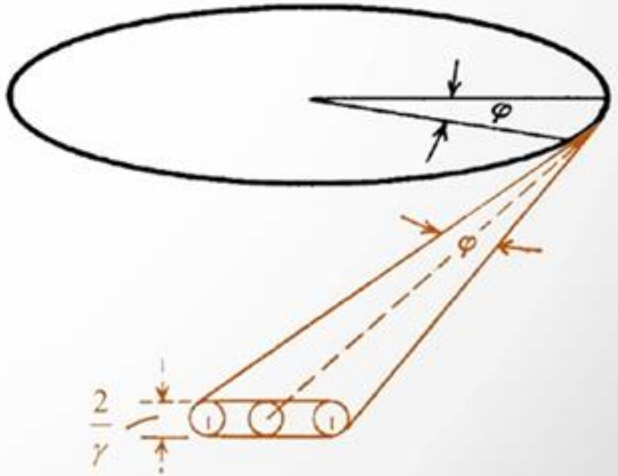
$$P_{Ie}[W] = 8.85\times10^4 \frac{E\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]} I\,[\mathrm{A}] = 2.65\times10^4 E[\mathrm{GeV}]^3 B[\mathrm{T}] I_e[\mathrm{A}]$$

  - The average power line density along the ring is obtained by

$$\langle P_{Ie,line} \rangle = P_{Ie} / C$$

  - The power in an angle of φ

$$P_{Ie}(\varphi) = P_{Ie} \frac{\varphi}{2\pi}$$



- Frequency spectrum of power
  - Frequency spectrum is obtained by Furrier transform of $E(t)$.

$$\tilde{E}(\omega)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}E(t)e^{i\omega t}dt$$

$$\frac{dP}{d\Omega}=\varepsilon_0 cE^2R^2\Big|_{ret}$$

$$\frac{dW}{d\Omega}=\int\frac{dP(t)}{d\Omega}dt=\frac{1}{\mu_0 c}\int_{-\infty}^{+\infty}(RE)^2\,dt=\frac{1}{\mu_0 c}\int_{-\infty}^{+\infty}\left|R\tilde{E}(\omega)\right|^2 d\omega$$

  - The frequency spectrum of power is given by

$$\frac{d^2W}{d\Omega d\omega}=\frac{1}{\mu_0 c}\left(R\tilde{E}(\omega)\right)^2=\frac{1}{2\pi\mu_0 c}\left|\int_{-\infty}^{+\infty}(RE)e^{i\omega t}dt\right|^2$$

$$=\frac{e^2}{16\pi^3\varepsilon_0 c}\left|\int_{-\infty}^{+\infty}\left[\frac{\left|\vec{n}\times\left\{\left(\vec{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right\}\right|^2}{\left(1-\vec{n}\cdot\vec{\beta}\right)^5}\right]_{ret}e^{i\omega\left(t'+\frac{R(t')}{c}\right)}dt'\right|^2$$

- The spatial and spectral energy distribution per unit frequency and solid angle is

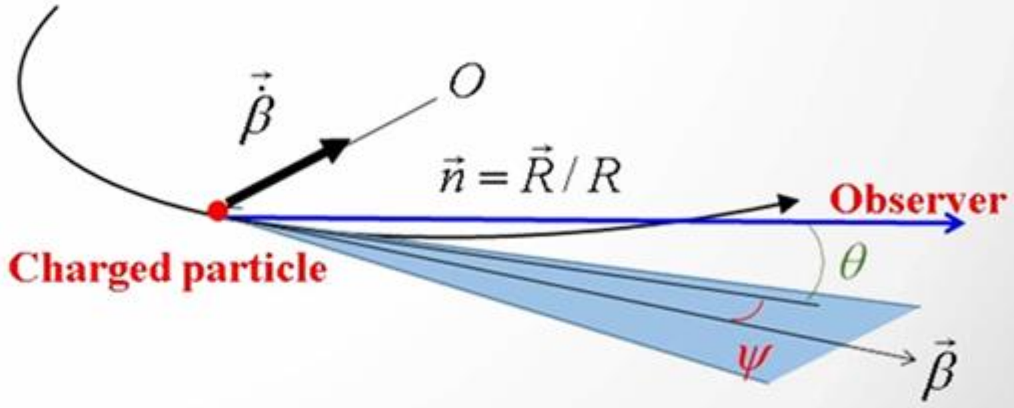
$$\frac{d^2W}{d\Omega d\omega} = \frac{e^2}{16\pi^3\varepsilon_0 c}\gamma^2\frac{\omega^2}{\omega_c^2}K_{2/3}^2(\xi)\,F(\xi,\theta)$$

$$\xi \equiv \frac{1}{2}\frac{\omega}{\omega_c}\left(1+\gamma^2\theta^2\right)^{3/2} \qquad F(\xi,\theta) \equiv \left(1+\gamma^2\theta^2\right)^2\left[1+\frac{\gamma^2\theta^2}{1+\gamma^2\theta^2}\frac{K_{1/3}^2(\xi)}{K_{2/3}^2(\xi)}\right]$$

where $K_i(\xi)$ is the modified Bessel function,

and $\omega_c \equiv \frac{3}{2}\frac{c\gamma^3}{\rho}$ is the critical frequency.

The frequency that halves the total energy



- The photon number (photon flux) with a beam current I_e per unit solid angle and frequency is given by

Plank's constant

$$\frac{d^2\dot{N}_{ph,Ie}}{d\Omega(d\omega/\omega)} = \frac{d^2P_{Ie}}{d\Omega d\omega}\frac{1}{\hbar} = \frac{d^2W}{d\Omega d\omega}\frac{I_e}{e}\frac{1}{\hbar} \qquad \dot{N}_{ph}\hbar\omega = P \quad \hbar = \frac{h}{2\pi}$$

- The spatial and spectral photon flux distribution per unit solid angle and band width (Brightness) is given

$$\frac{d^3\dot{N}_{ph,Ie}}{d\theta d\psi(d\omega/\omega)} = C_\omega E^2 I_e \frac{\omega^2}{\omega_c^2} K_{2/3}^2(\xi)F(\xi,\theta) \qquad \alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = 7.297\times10^{-3}$$

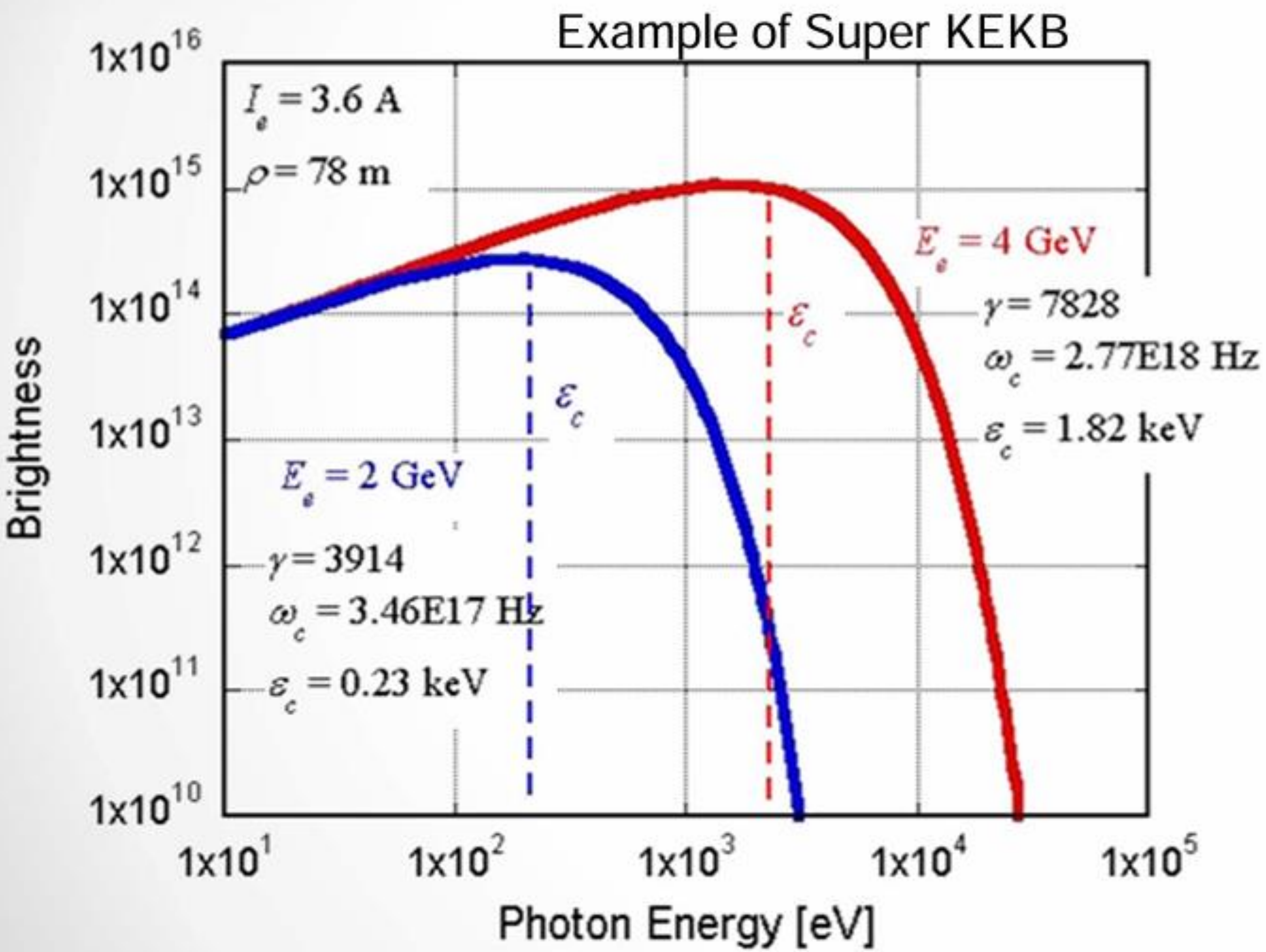
Fine-structure constant

$$C_\omega \equiv \frac{3\alpha}{4\pi^2 e(m_e c^2)^2} = 1.3255\times10^{22}\frac{\text{photons}}{\text{s rad}^2\ \text{GeV}^2\ \text{A}}$$

$$= 1.3255\times10^{13}\frac{\text{photons}}{\text{s mrad}^2\ \text{GeV}^2\ \text{A}\ 0.1\%\text{bandwidth}}$$

  - A key parameter of light (photon) sources.

Example of Brightness



Critical energy

$$\varepsilon_c = \frac{3}{2}\frac{\hbar c \gamma^3}{\rho} \equiv \hbar\omega_c$$

$$\varepsilon_c[\mathrm{eV}] = 2.218\times 10^3 \times \frac{E_e[\mathrm{GeV}]^3}{\rho[\mathrm{m}]}$$

$$= 0.665\times 10^3 \times E_e[\mathrm{GeV}]^2 B[\mathrm{T}]$$

Mean photon energy

$$\langle \varepsilon \rangle = \frac{8}{15\sqrt{3}}\varepsilon_c$$

Total photon flux

$$\dot{N}_{ph} = \frac{15\sqrt{3}}{8}\frac{P_{tot}}{\varepsilon_c}$$

- Important formula from practical view point as a summary
  - Total power along a ring:

$$P_{Ie}[W] = 8.85\times10^4 \frac{E_e\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]} I_e\,[\mathrm{A}] = 2.65\times10^4\, E[\mathrm{GeV}]^3\, B[\mathrm{T}] I_e[\mathrm{A}]$$

  - Total photon numbers along a ring:

$$\dot{N}_{ph,Ie} = 8.08\times10^{20}\, I_e[\mathrm{A}] E_e[\mathrm{GeV}] \quad [\mathrm{photons/s}]$$

  - Critical energy:

$$\varepsilon_c[\mathrm{eV}] = 2.218\times10^3 \times \frac{E_e\,[\mathrm{GeV}]^3}{\rho\,[\mathrm{m}]} = 0.665\times10^3 \times E_e\,[\mathrm{GeV}]^2\, B\,[\mathrm{T}]$$

  - Beaming angle:

$$\theta \sim \frac{1}{\gamma} = \sqrt{1-\beta^2}$$

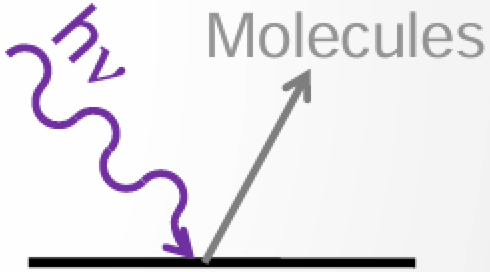
Effects of SR on vacuum system

- Thermal load
  - When the SR hit the surface, it deposits the power on it.

  ⇒ Heat up beam pipe, damage beam pipes by heating and thermal stress.

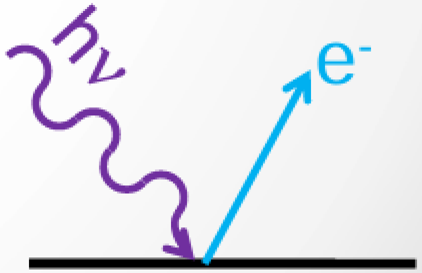
- Gas load
  - When the SR hit the surface, it desorbs the gas molecules on it.

  ⇒ Increase pressure, reduce beam lifetime, increase background noise.



- Emission of electrons
  - When the SR hit the surface, it emits electrons (photoelectrons) from it.

  ⇒ Enhance the forming of the electron cloud, leads to the electron cloud instabilities.



- Estimation of heat load
  - Total power along the ring

$$P_{Ie} = 88.4 \times 10^{3} E_e[\mathrm{GeV}]^4 \times I_e[\mathrm{A}] / \rho[\mathrm{m}] \quad [\mathrm{W}]$$

  - Average power line density (SR power per 1 m along the ring)

$$\left\langle P_{Ie,line} \right\rangle = 88.4 \times 10^{3} E_e[\mathrm{GeV}]^4 \times I_e[\mathrm{A}] / \rho[\mathrm{m}] / C[\mathrm{m}] \quad [\mathrm{W/m}]$$

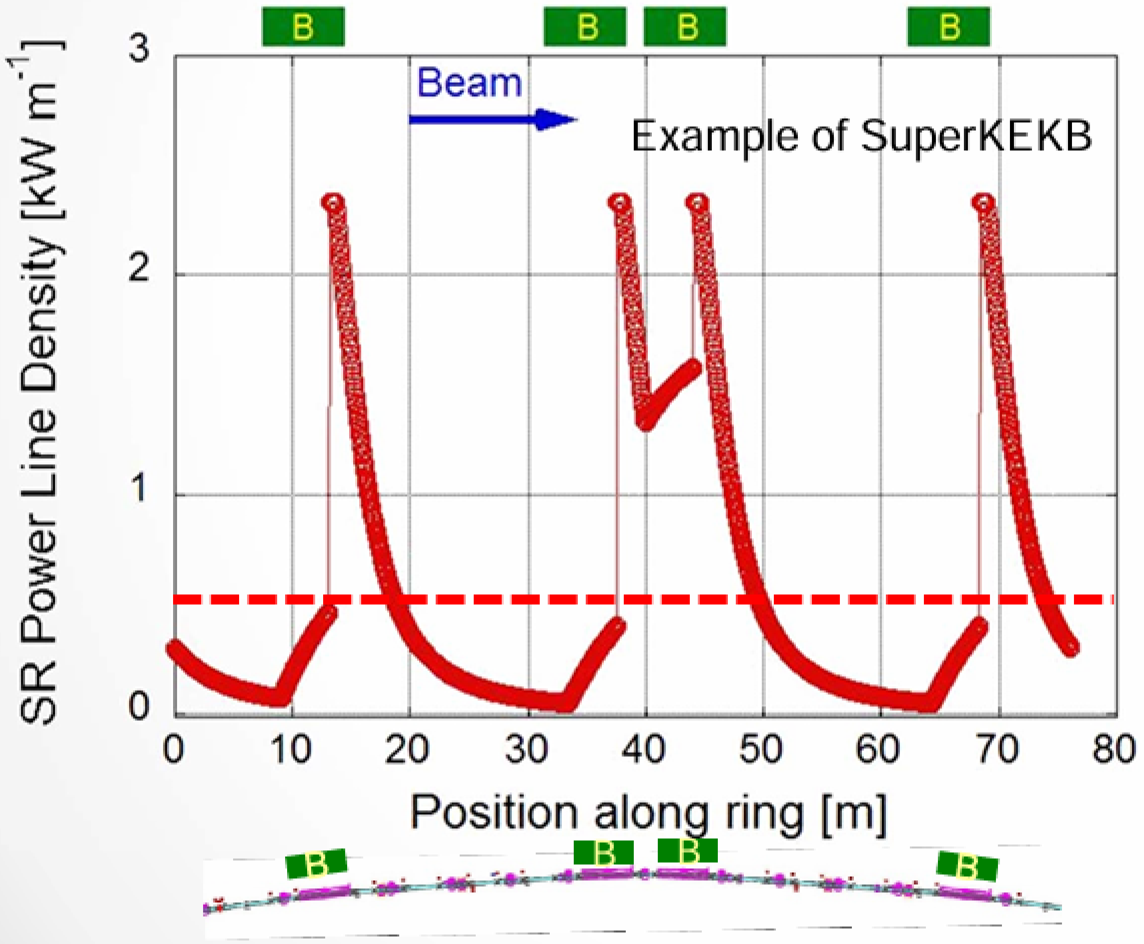
For example, if $E_e = 4$ GeV, $I_e = 3.6$ A, $\rho = 74$ m, $C = 2000$ m (arc)

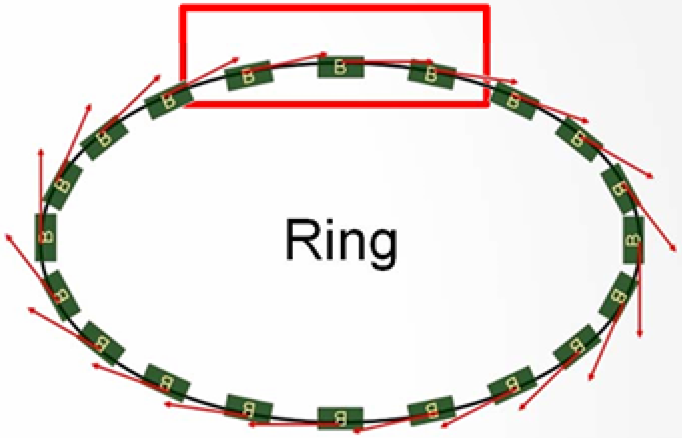
SuperKEKB positron ring

$$\left\langle P_{Ie,line} \right\rangle = 88.4 \times 10^{3} \times 4^4 \times 2.6 / 74 / 2000 = 550 \ \mathrm{W/m}$$

The power density is sufficiently high to melt metals if no cooling is prepared in vacuum.

- The heat load has actually a distribution along the ring.
  - The sources (emitting points) are in bending magnets.
- Then the maximum power density is more important than the average one.





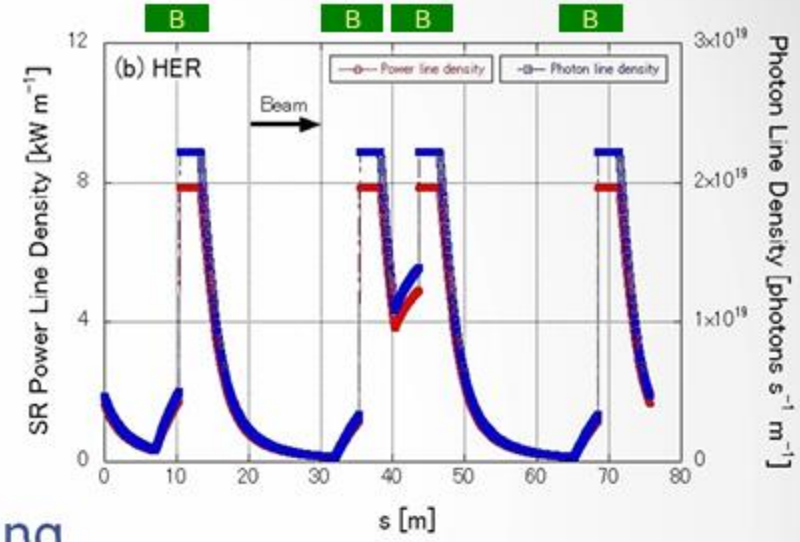
Average power line density
~0.6 kW m^{-1}

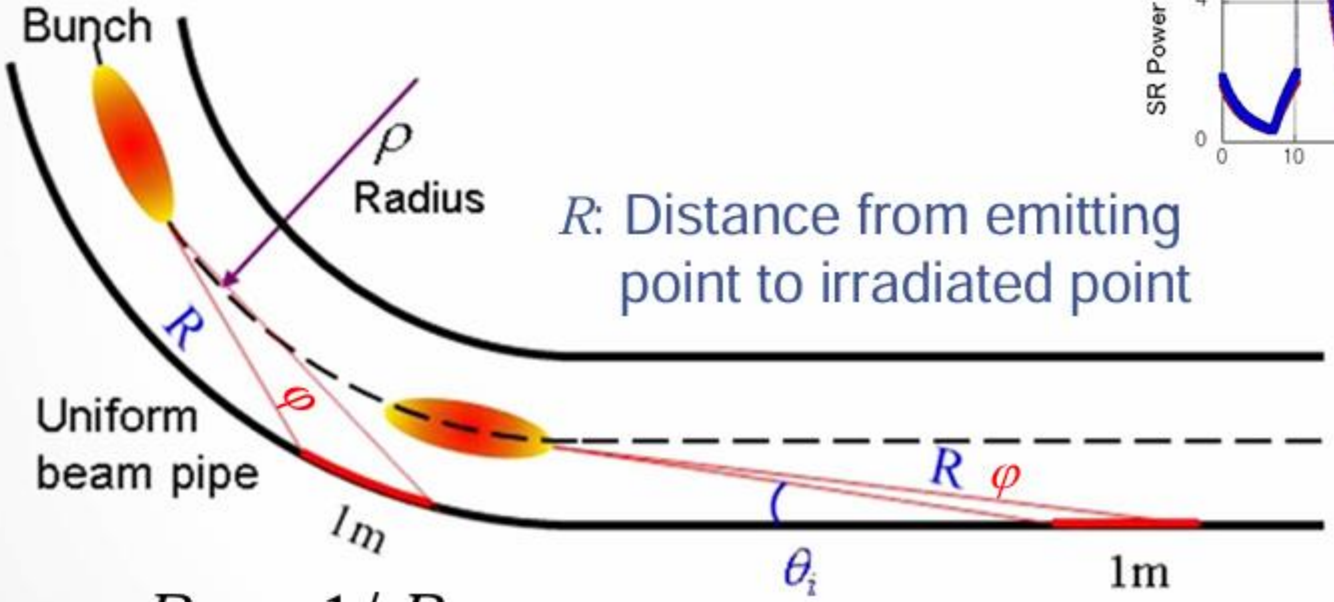
Peak power line density
~2.3 kW m^{-1}

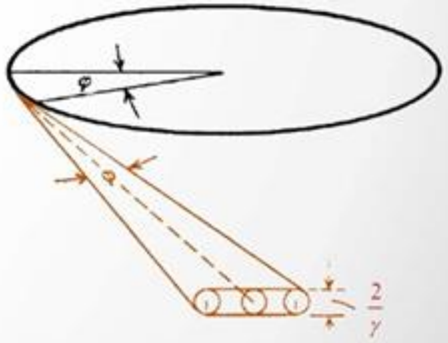
For a uniform beam pipe, the heat load has maximum in the bending magnets, and decrease gradually at down stream side.

Most of power are deposited at the directly irradiated points

- Dependence of the SR power line density on the distance from the emitting point to the hitting point, R, and the incident angle, θ_i, to the surface.
  - Power line density, P_{line} [W mm^{-1}], is important in evaluating temperature and thermal stress.







$$P_{line} \propto 1/R$$

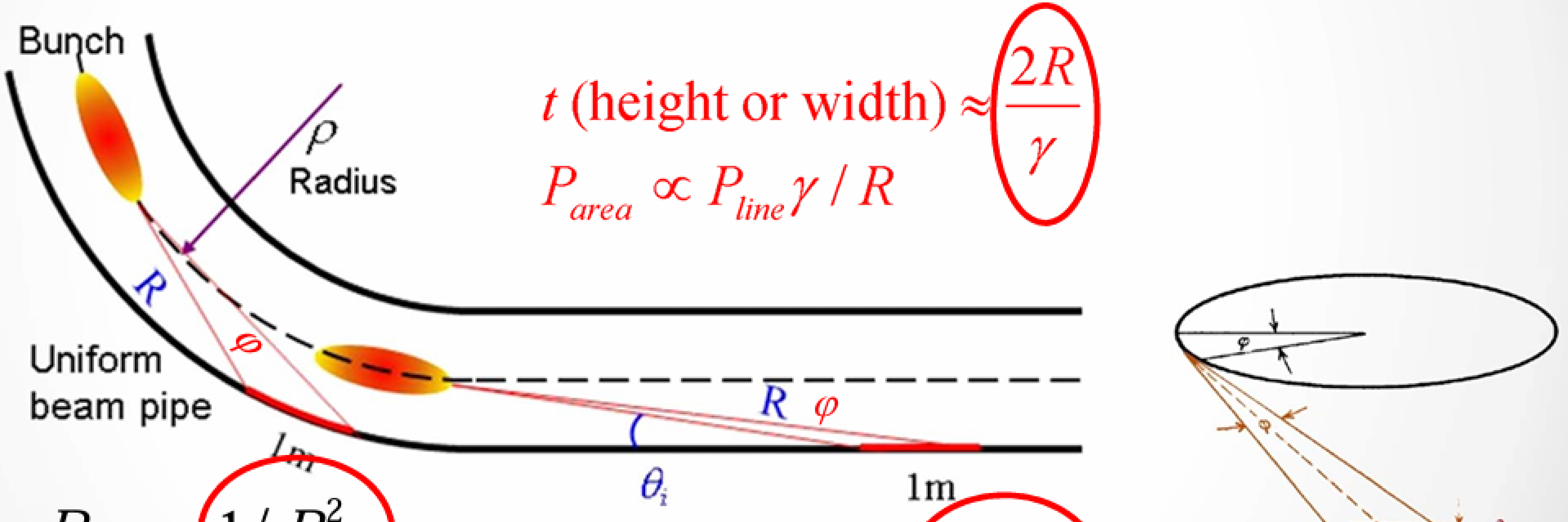
(inside of magnet)

$$P_{line} \propto 1/R \times \theta_i \propto 1/R^2$$

(outside of magnet)

Almost constant in a magnet for SR emitted in the same magnet (θ_i, R~const.)

- For the power area density, the vertical spread angle of $2/\gamma$ should be taken into account.
  - Power area density, P_{area} [W mm^{-2}], is key especially in evaluating thermal stress..



t (height or width) $\approx \dfrac{2R}{\gamma}$

$P_{area} \propto P_{line}\gamma / R$

$P_{area} \propto 1/R^2$ (inside of magnet)

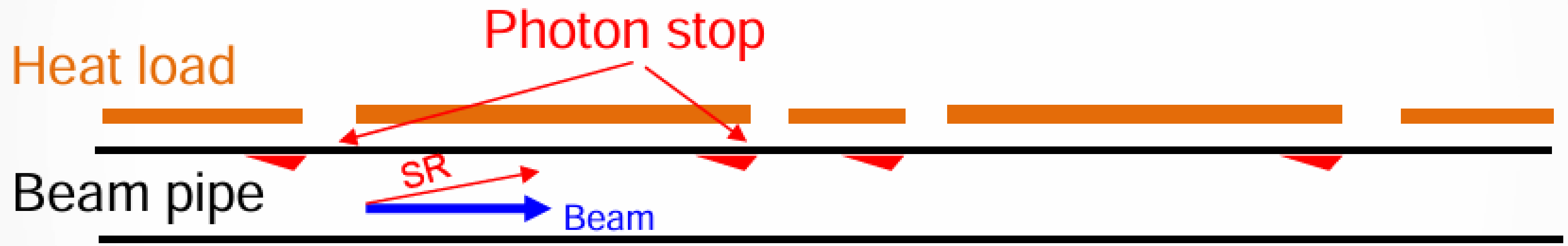
$P_{area} \propto 1/R^3$ (outside of magnet)

Almost constant in a magnet for SR emitted in the same magnet (θ_i, R~const.)

- Basic principle: Receive SR at specific places (photon stops) with cooling system at large R and small θ_i.
- There are two ways.

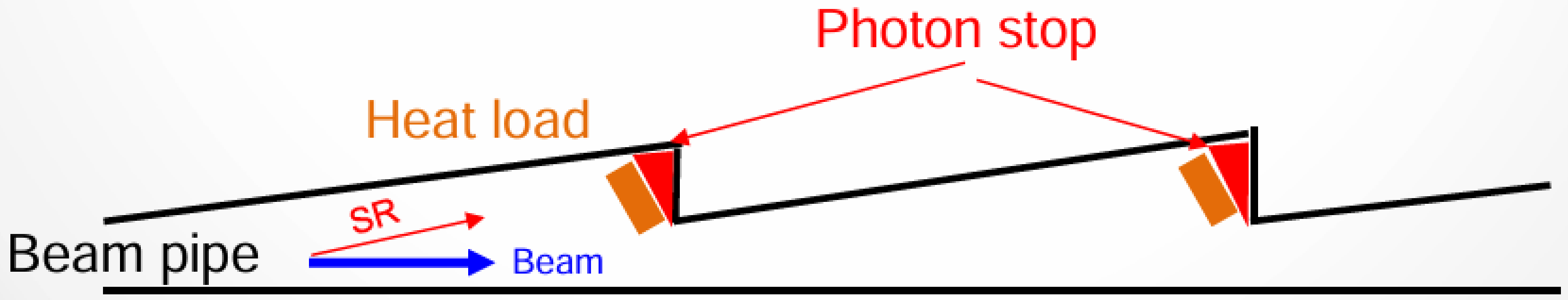
(1) Distributed photon stops (photon masks)

- Small photon stops enough to make short shadow



(2) Localized photon stops

- Large photon stops to make long shadow, and localize loads



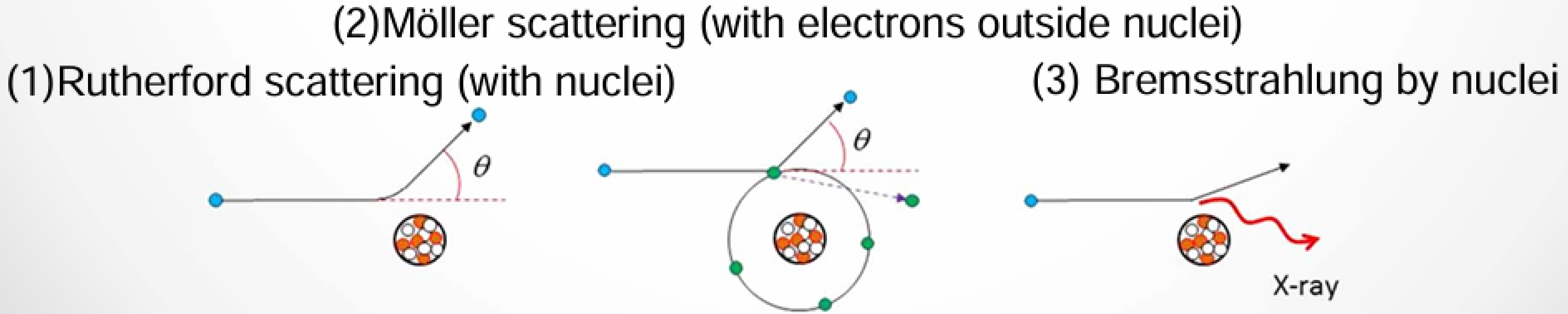
- Effect of the gas load
  - Energy loss due to the scattering with the residual gases
    ⇒ Particle loss ⇒ Shorten life time.
  - Lost particles also increase in the background noise of detectors and can be a cause of radiation.
  - Beam life time, τ, is defined as $I_e = I_{e0} e^{-\frac{t}{\tau}}$

$$\frac{1}{\tau} = \sum_i \left(\sigma_B(Z_i) + Z_i \sigma_M + \sigma_R(Z_i)\right) p_i$$

I_e : Beam current
I_{e0} : Initial beam current
τ : Life time

Here, σ_B, σ_M and σ_R are the cross sections of major three interaction processes with gas molecules.

  - The life time is in proportion to the pressure, p_i, i.e., gas load.



Effect of photoelectrons

- The SR hitting on the inner surface emits electrons

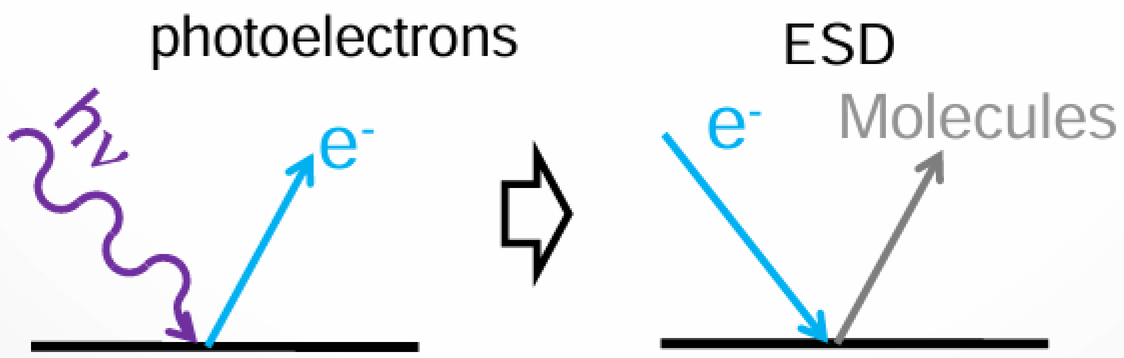
  = Photoelectrons (touched later again)

  The photon energy is sufficiently high to emit electrons (photoelectrons) from material surfaces, where the work functions are a few eV.

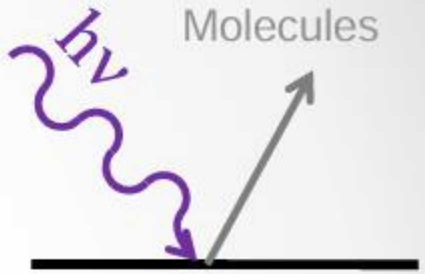
- The electrons hitting the surface desorb the molecules from the surface, since they have also sufficiently high energies.

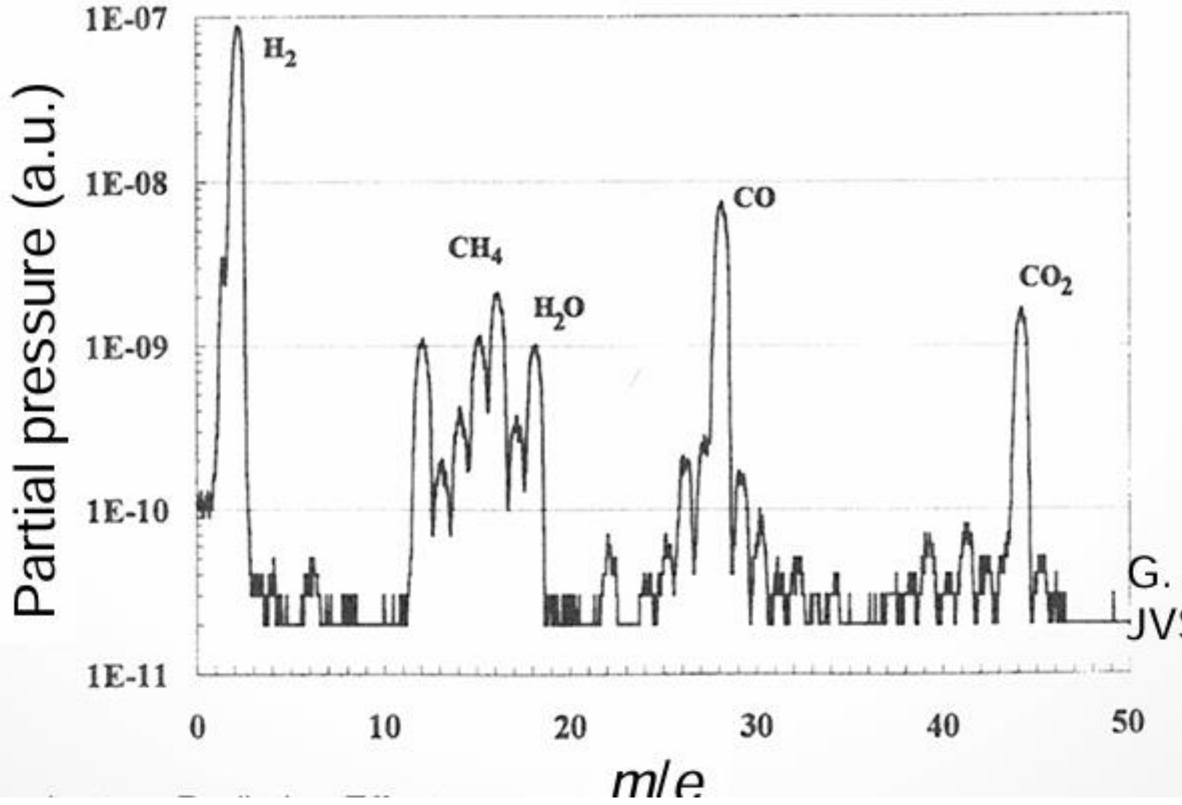
  = Electron stimulated gas desorption, ESD

- It is said that most of PSD come from ESD.



- Number of gas molecules emitted by one photon
  = Photon stimulated gas desorption rate
  (η [molecules photon^{-1}])
  - Major gases are Hydrogen (H_2)、Carbon mono-oxide (CO)、carbon double-oxide (CO_2), after usual baking.





G. Y. Hsiung et al.
JVST A12 (1994) 1631

- Energy dependence
  η increase with the incident photon energy (critical energy) since the deposit energy increases.

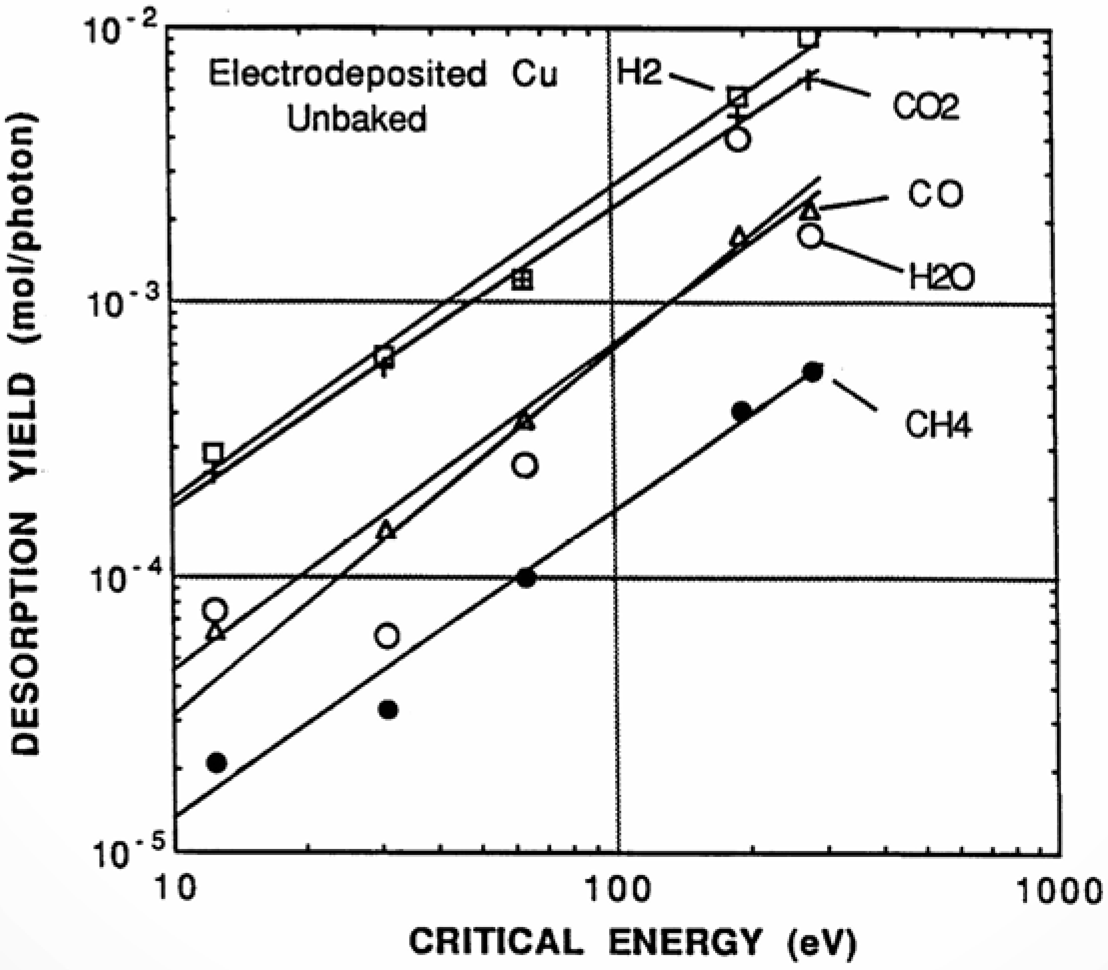
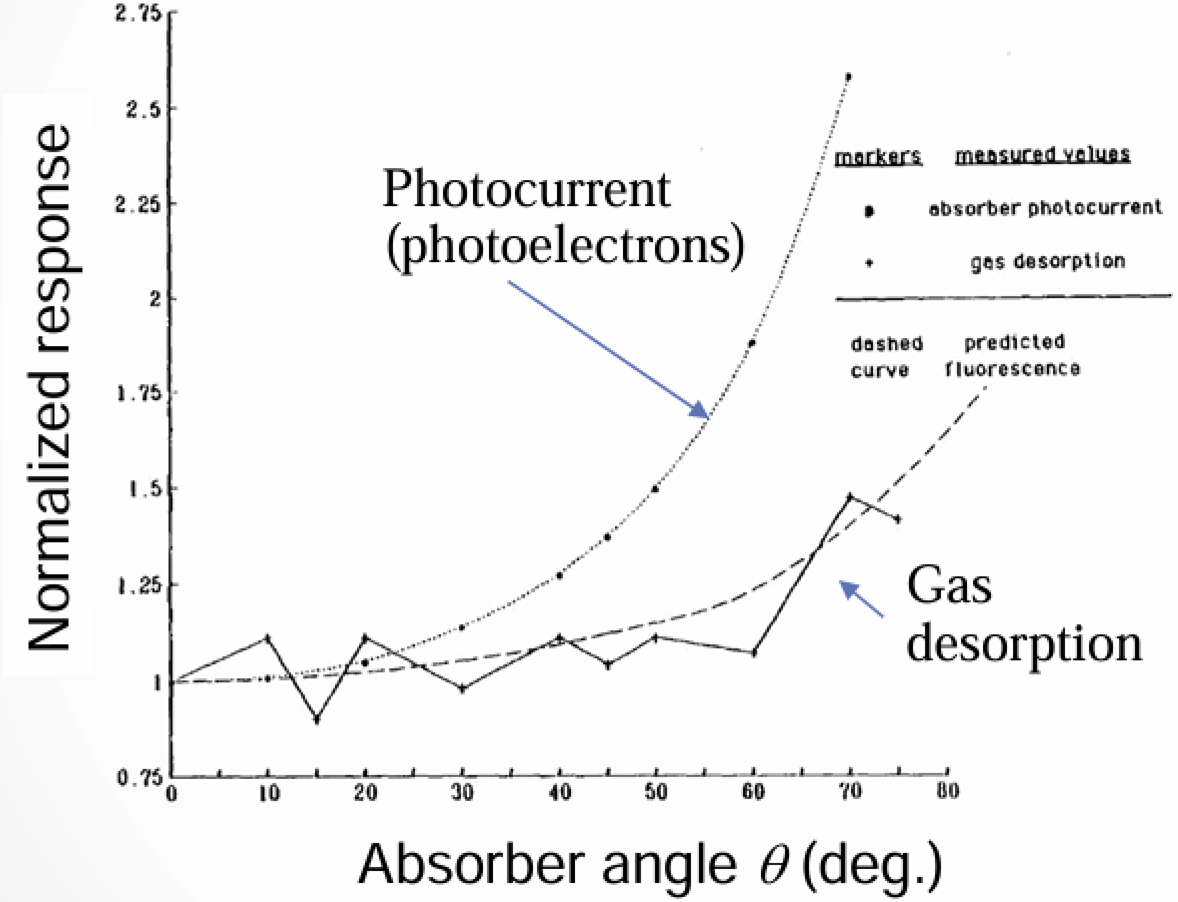


Fig. 10 Fits of the photon induced desorption yields as a function of the photon critical energy for electrodeposited Copper.

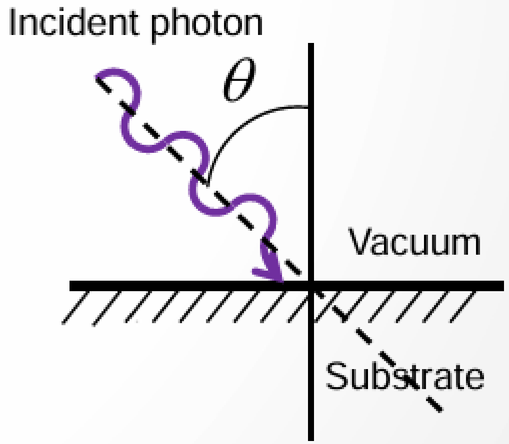
J. Gomez-Goni, et al., VT Note 93-1, CERN

- Angle dependence
  The shallower the incident angle is, the larger the η is.
  A rough surface can decrease η.



B. A. Trickett et al., JVST A10 (1992) 217

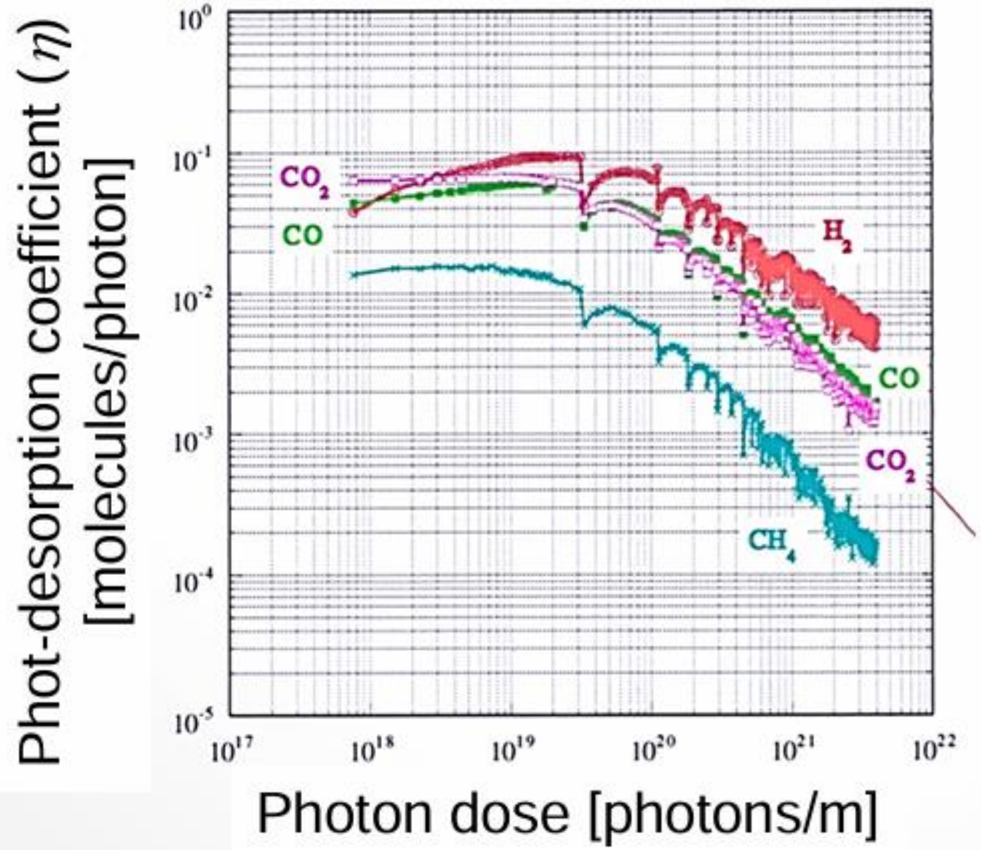
FIG. 4. The effect of absorber angle on gas desorption, shown along with the simultaneous recording of the photoelectron current. The dashed curve illustrates the predicted photon flux arising from fluorescence. All data normalized to the response at normal incidence.



- Note: If the surface is smooth and the incident angle is shallow, the reflection of SR should be taken into account.

Aging (Scrubbing)

- η decreases with integrated photon number (photon dose, D)
  = Beam aging or scrubbing
- Typical values of η at the beginning (before SR irradiation are $10^{-3} \sim 10^{-2}$ molecules/photon. η decreases down to $\sim 10^{-7}$ after sufficient aging.



- η decreases as

$$\eta \propto D^{-1\sim-0.6}$$

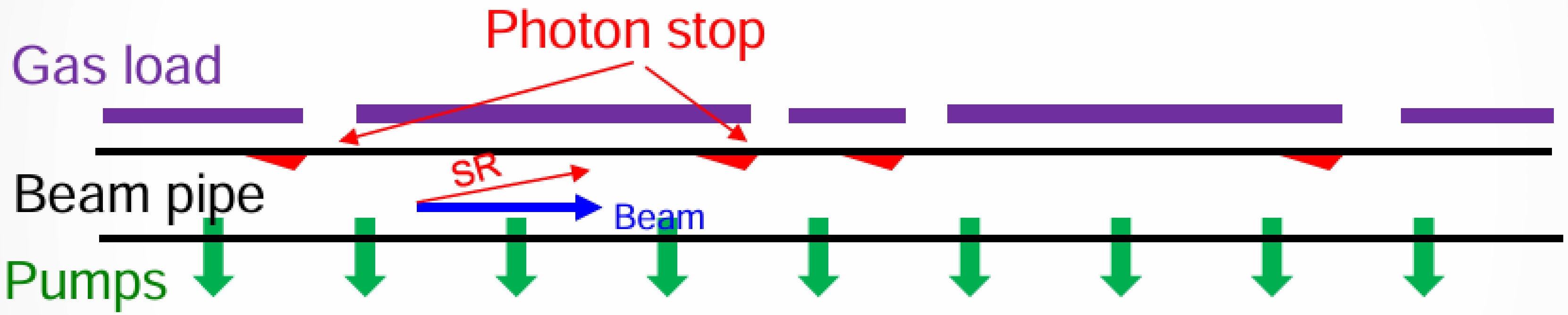
- In designing the vacuum system, the η of $1\times10^{-5} \sim 1\times10^{-6}$ molecules photon^{-1} are assumed expecting the aging effect.

Y. Suetsugu, KEK

- Basic principle: Prepare pumps at places where photons are irradiated.
- There are two ways to treat gas load:

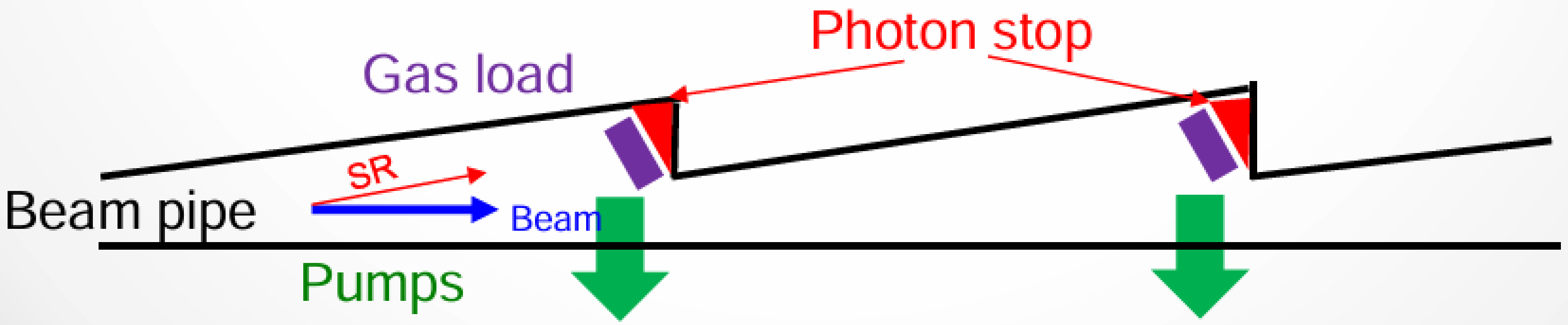
(1) Distributed pumping

- Works well with the distributed photon stops.

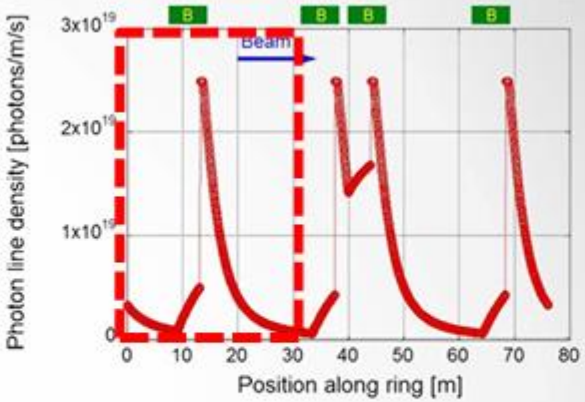


(2) Localized pumping

- Works well with the localized photon stops (reasonable way)



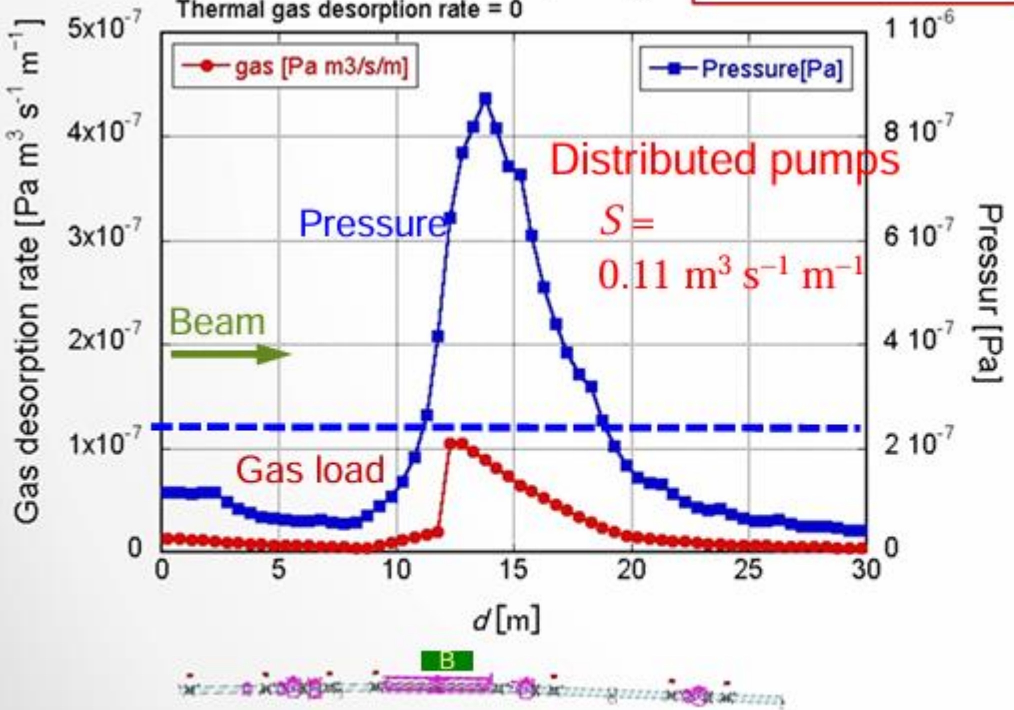
- Consider again the previous case.
  - If localized pumps are used as below, and the thermal gas desorption is ignored, a lower average pressure is obtained compared to the case of distributed pumping with smaller pumping speeds.

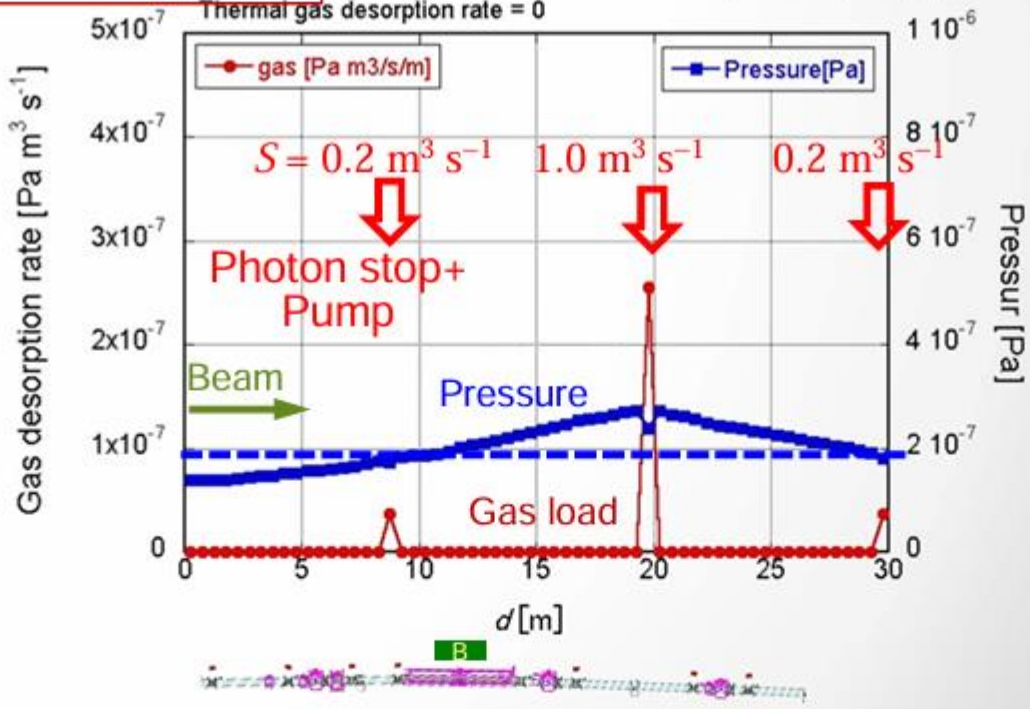


Distributed pumping

No thermal gas desorption

Localized pumping





Average pressure = 2.3×10^{-7} Pa

Average pressure = 2.0×10^{-7} Pa

요 약 (Effect of SR on the performance of accelerator)

- Heat load
  - Heat up beam pipe, damage beam pipes by heating and stress.
  - Install proper photon stops at proper locations.
  - Design to decrease power density.
  - Use materials for the photon stops with high thermal strength.
- Gas load
  - Increase pressure, reduce beam lifetime, increase background noise.
  - Install vacuum pumps at proper locations and prepare sufficient pumping speed, following the photon stops scheme.
  - Decrease contamination on the surface of beam pipes.

가속기 진공 I
(진공 기술의 기본 원리)

2025.03.14.

하태균
포항가속기연구소

진공시스템 사양 결정

기본사양

크기 V
기저진공도 P_0
유량 Q
작동압력 P
온도 T
분위기 (Air, H_2, Ar, - -)
펌프 위치

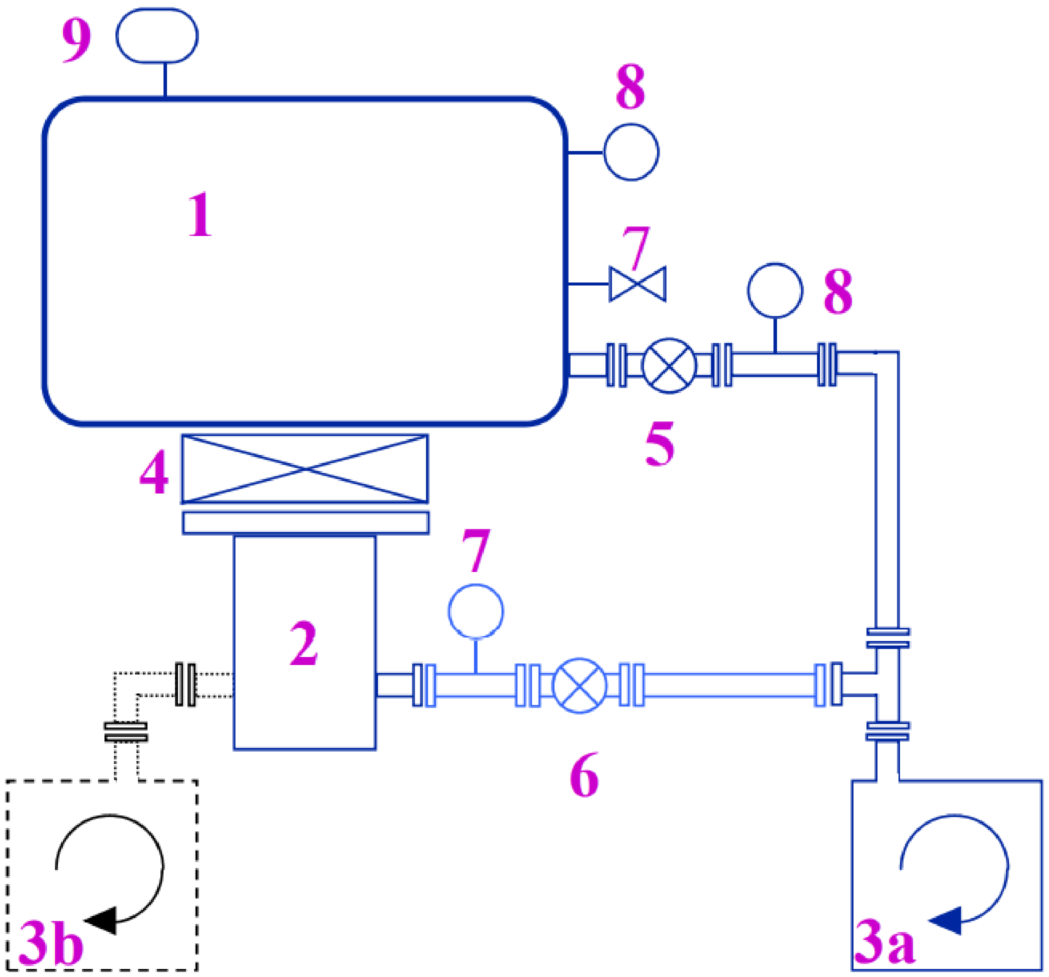
1차 결정사항

용기 재료 (SS, Al, - -)
가공, 표면처리
기체방출률 Q
도관
밸브
진공 게이지

2차 결정사항

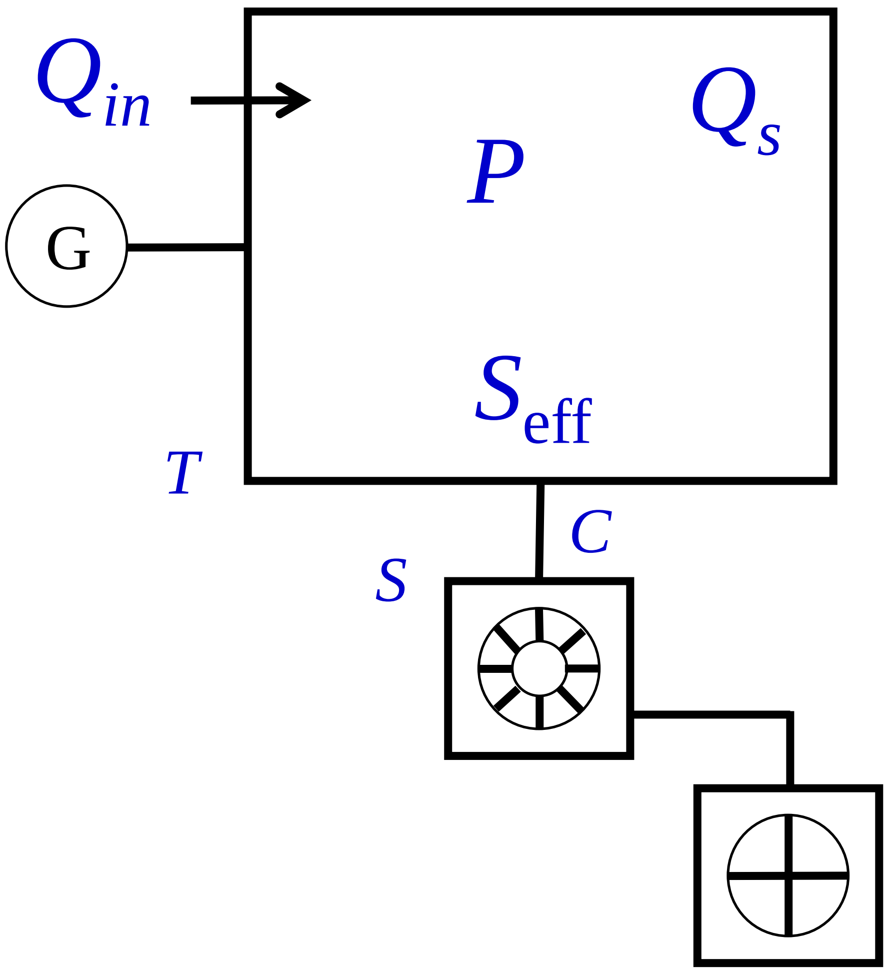
진공펌프 종류
배기속도 S
보조펌프 여부
보조펌프 용량

진공시스템의 구성 예



1	Chamber
2	High Vac. Pump
3a	Roughing Pump
3b	Foreline Pump
4	Hi-Vac. Valve
5	Roughing Valve
6	Foreline Valve
7	Vent Valve
8	Roughing Gauge
9	High Vac. Gauge

진공시스템의 배기



- $d(PV)/dt = Q - PS_{eff}$
- If Q=0: $dP/dt = -P(S_{eff}/V) = -P/\tau$

  → $P = P_0 e^{-t/\tau}$

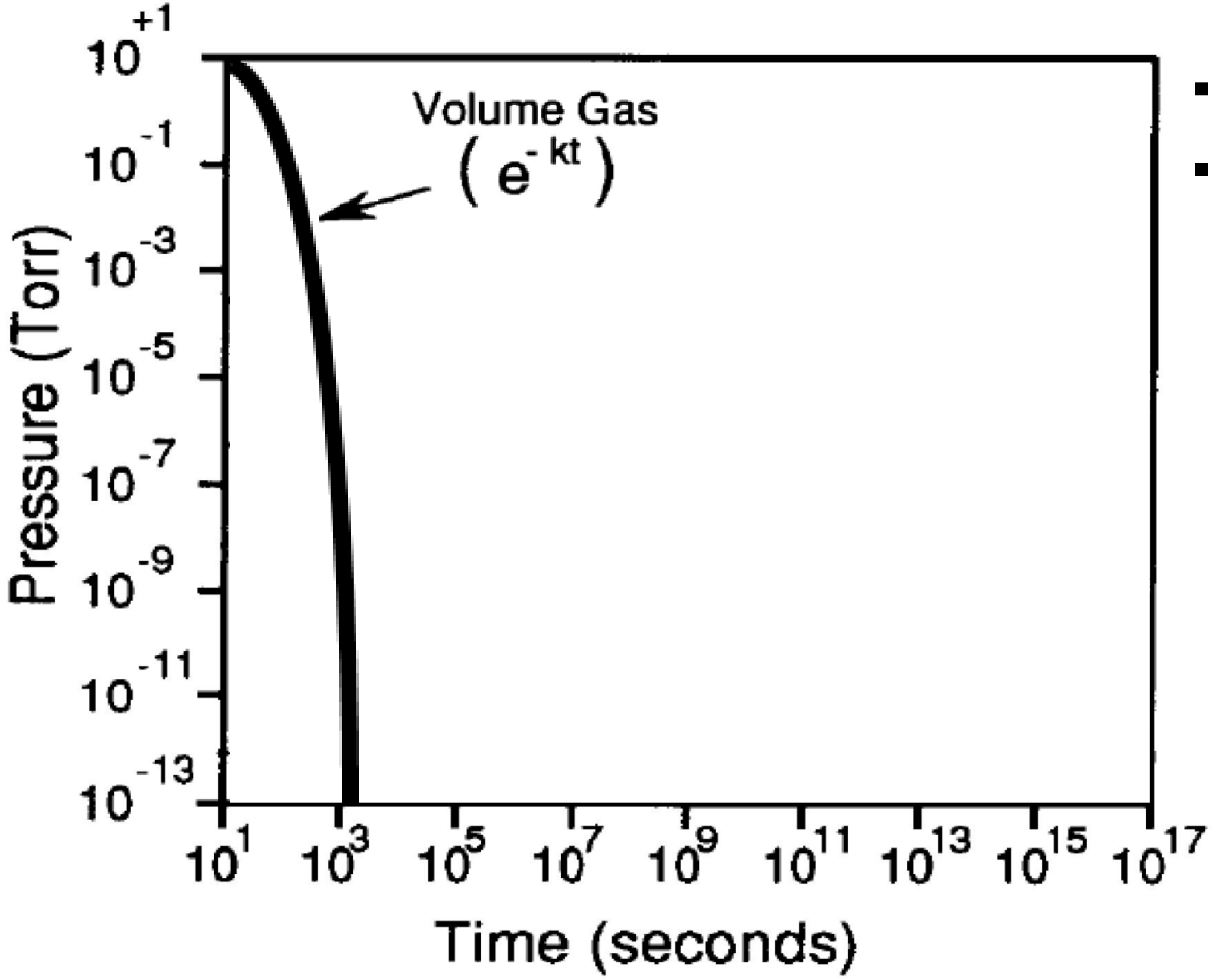
  $\tau(=V/S)$는 배기계의 시간상수로 공간에 있던 입 자들의 수가 약 2.7분의 1로 떨어지는 데 걸리는 시간이다.

- If Q>0: $dP/dt = Q/V - P/\tau$

  → $P = Q/S_{eff} + (P_0 - Q/S_{eff})e^{-t/\tau}$

  → $(P - Q/S_{eff})/(P_0 - Q/S_{eff}) = e^{-t/\tau}$

진공 배기 (공간 기체)

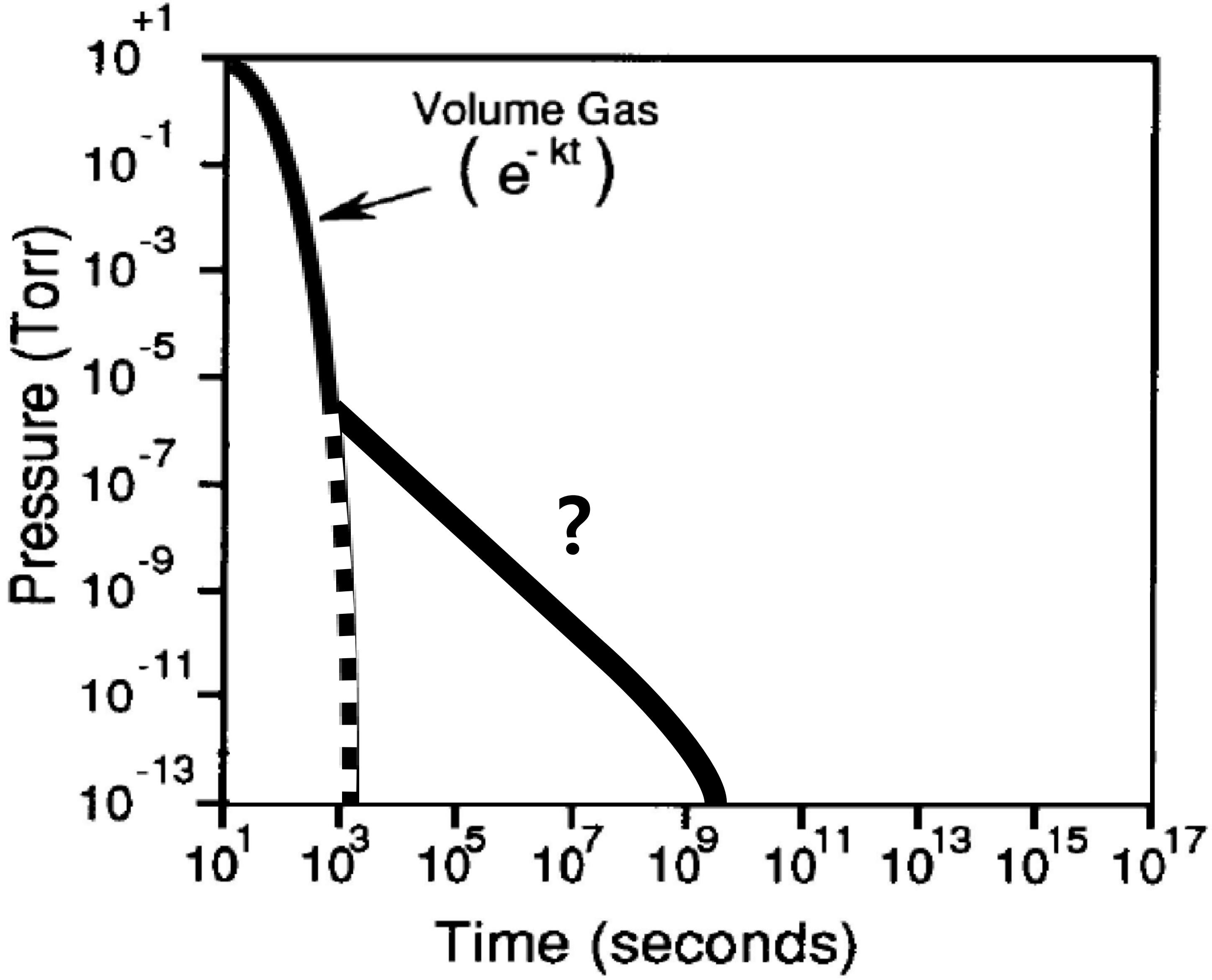


- $d(PV)/dt = Q - PS_{eff}$
- If $Q \ll 1$:

  $dP/dt = -P(S_{eff}/V) = -P/\tau$

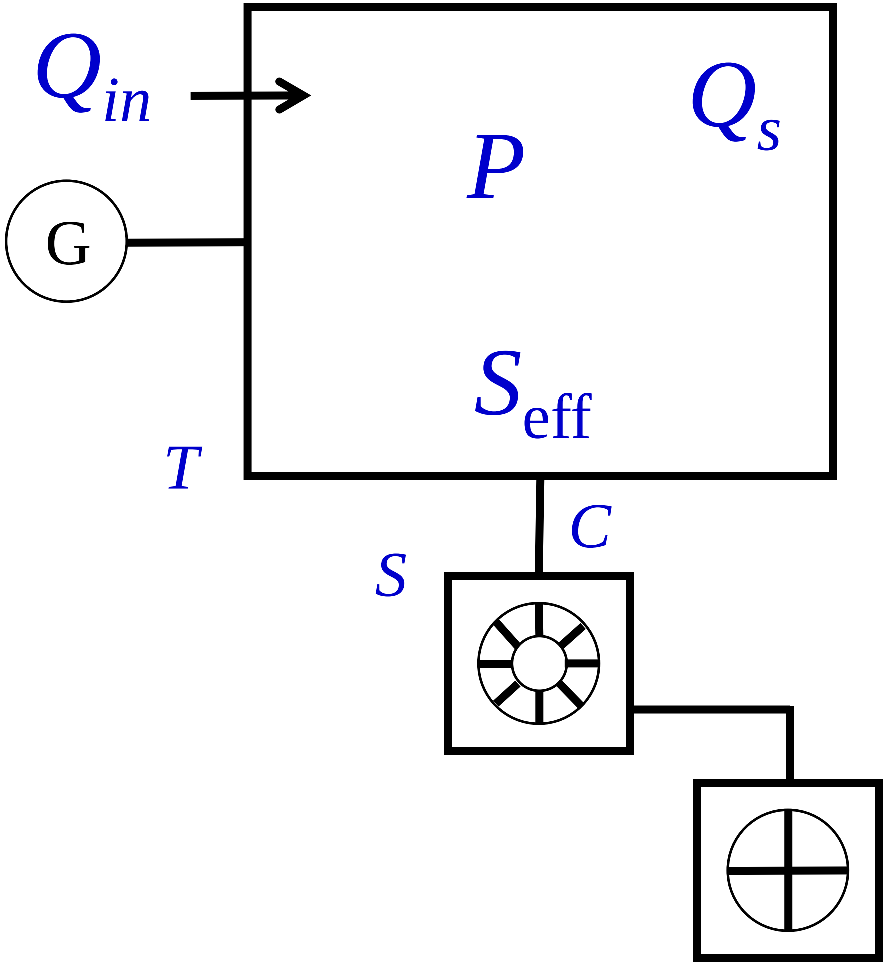
  $\rightarrow P = P_0 e^{-t/\tau}$

진공 배기 (공간 기체)



Volume Gas
(e⁻ᵏᵗ)
?
Pressure (Torr)
Time (seconds)
10+1
10-1
10-3
10-5
10-7
10-9
10-11
10-13
101
103
105
107
109
1011
1013
1015
1017

진공 배기 (표면탈착)



(quasi-steady state)

- ~~$d(PV)/dt$~~ $= 0 = Q_s - PS_{eff}$
- $P = Q_s/S_{eff}$

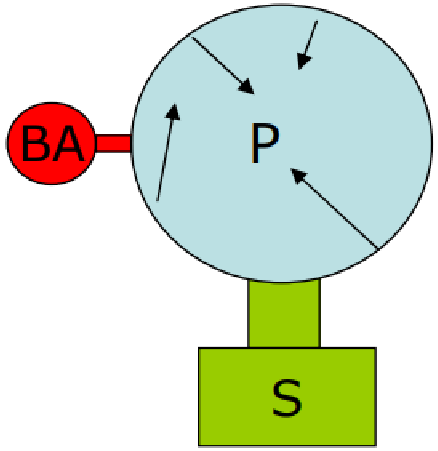
- For surface desorption

$$Q_s = Q_0 t^{-1} \rightarrow P \propto t^{-1}$$

표면 탈착 모델

[P. Chiggiato, IVC-16 (2004)]

Single desorption energy: pressure evolution without repumping



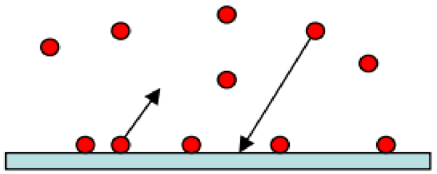
variation of the quantity of gas in the gas phase

quantity of gas leaving the surface

quantity of gas removed by the pump

$$\begin{cases} V\dfrac{dP}{dt} = -SP + \dfrac{N_s \Theta}{\tau_d} \\ \dfrac{d\Theta}{dt} = -\dfrac{\Theta}{\tau_d} \end{cases}$$

$$P(t) \cong \frac{N_s}{S \cdot \tau_d} e^{-\frac{t}{\tau_d}} \quad \text{for} \quad t > \tau_d$$

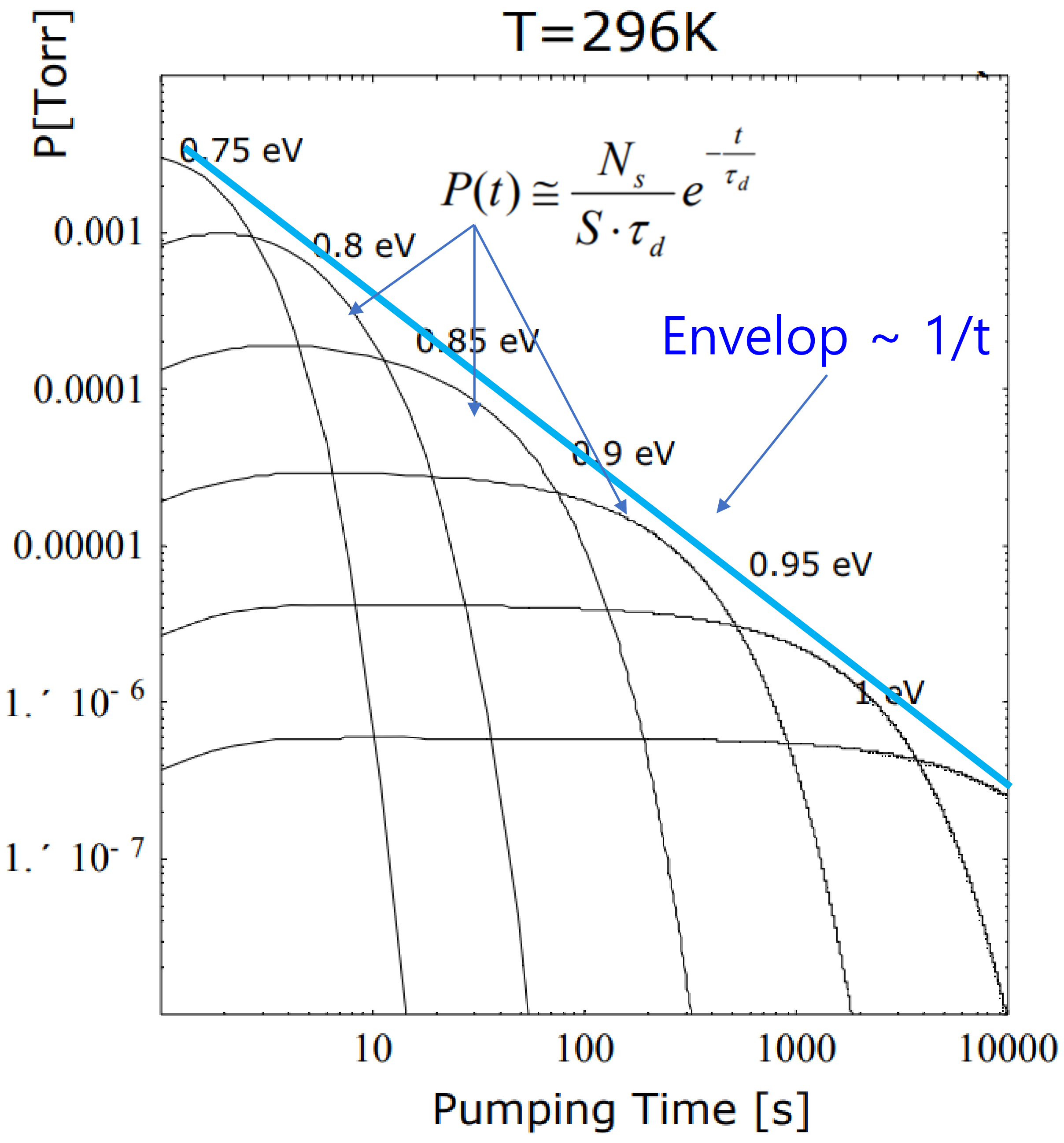


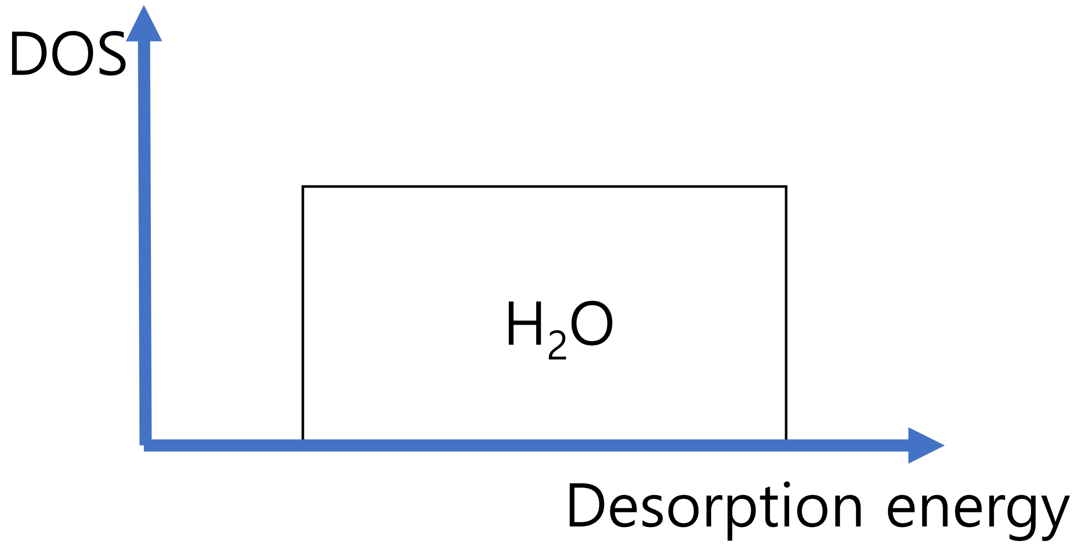
Θ= fraction of sites occupied
The total number of sites is assumed to be ≈10^{15} cm^{-2} → 3×10^{-5} Torr l $s^{-1} cm^{-2}$

The solution is plotted for:

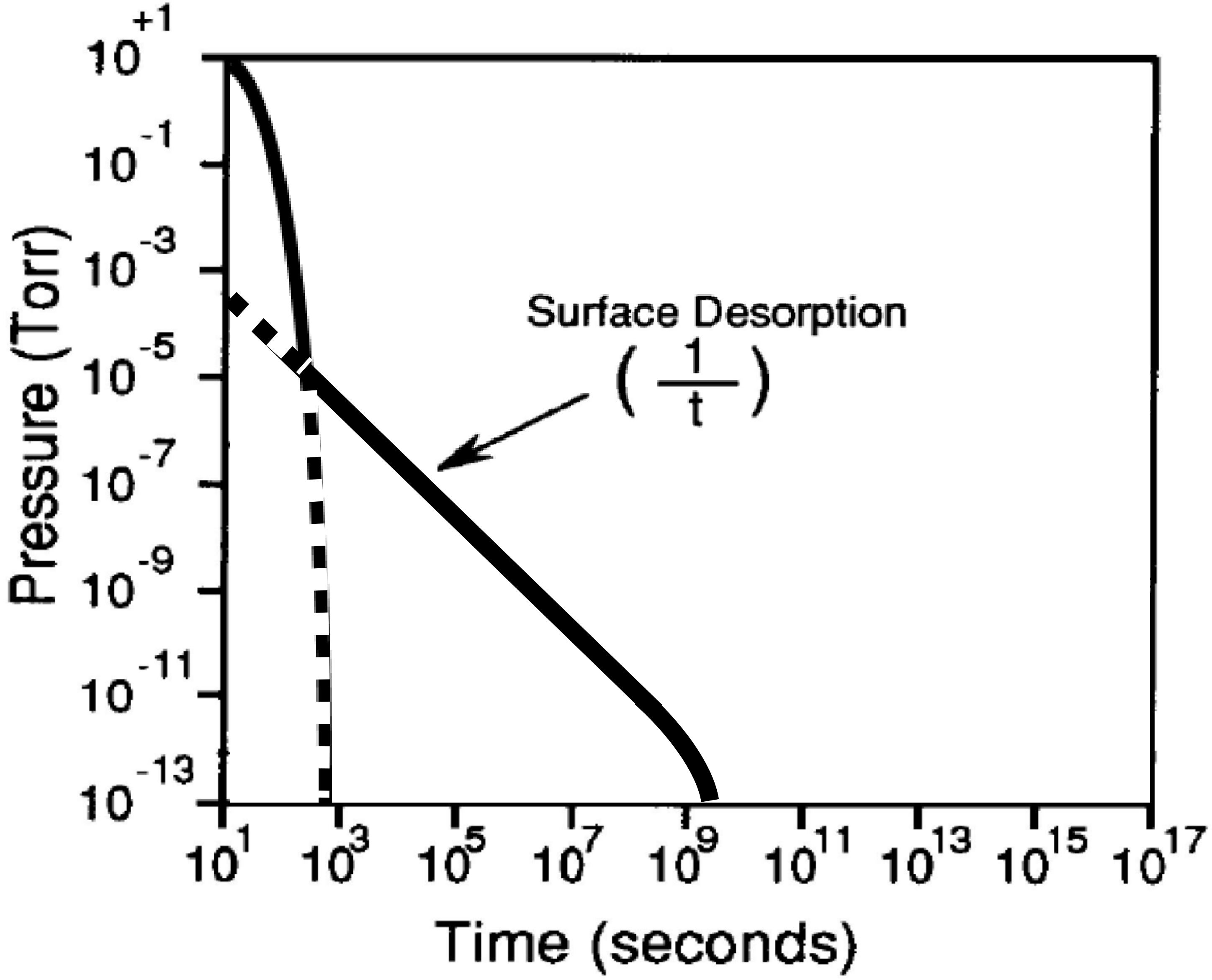
V=10 ℓ, S=10 ℓ /s, $N_s = 2245 \times 3 \times 10^{-5}$ Torr ℓ

and different energies


T=296K
P[Torr]
0.001
0.0001
0.00001
1.´ 10- 6
1.´ 10- 7
10
100
1000
10000
Pumping Time [s]
0.75 eV
0.8 eV
0.85 eV
0.9 eV
0.95 eV
1. eV
$P(t) \cong \frac{N_s}{S \cdot \tau_d} e^{-\frac{t}{\tau_d}}$
Envelop ~ 1/t

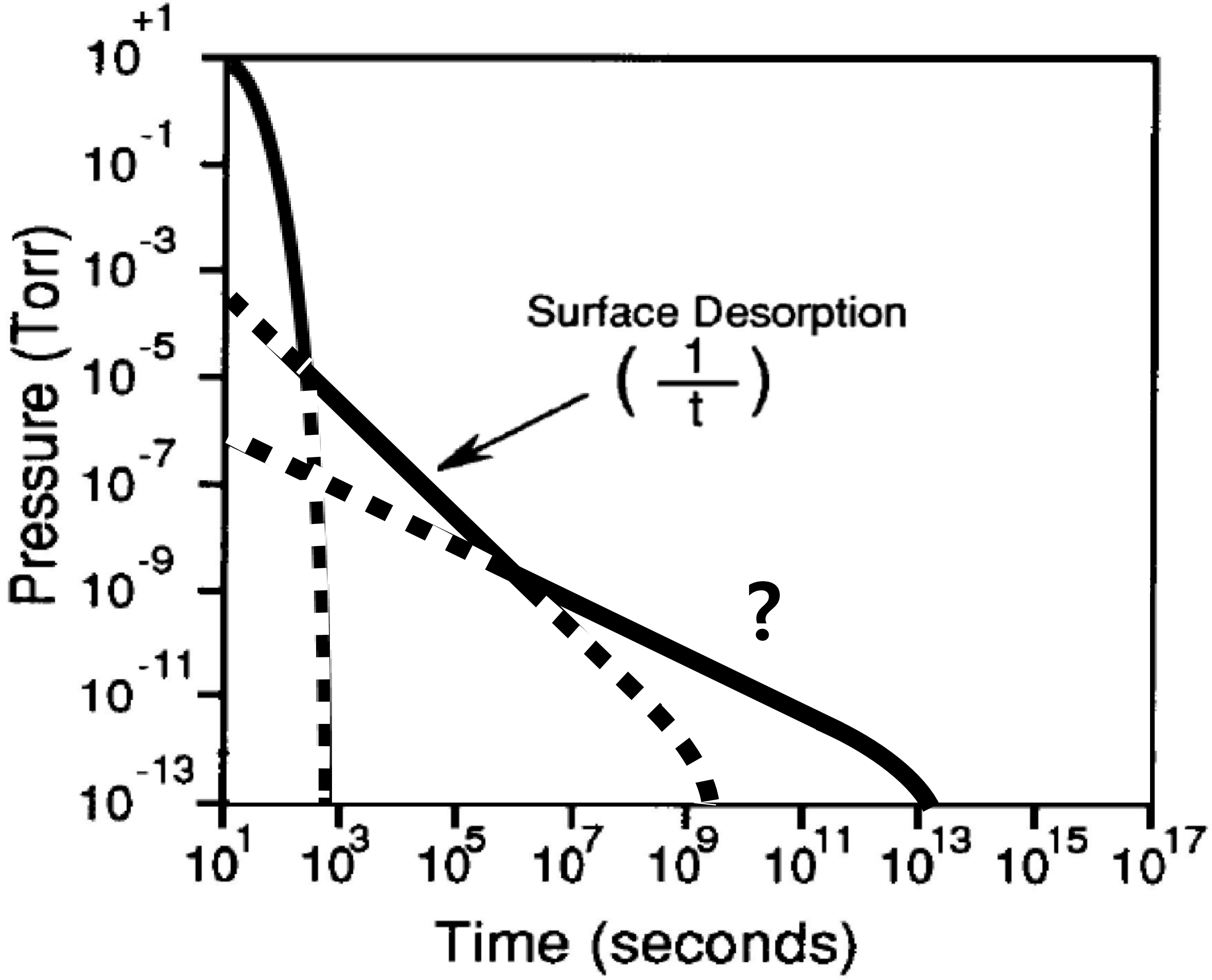

DOS
H_2O
Desorption energy

진공 배기 (표면탈착)



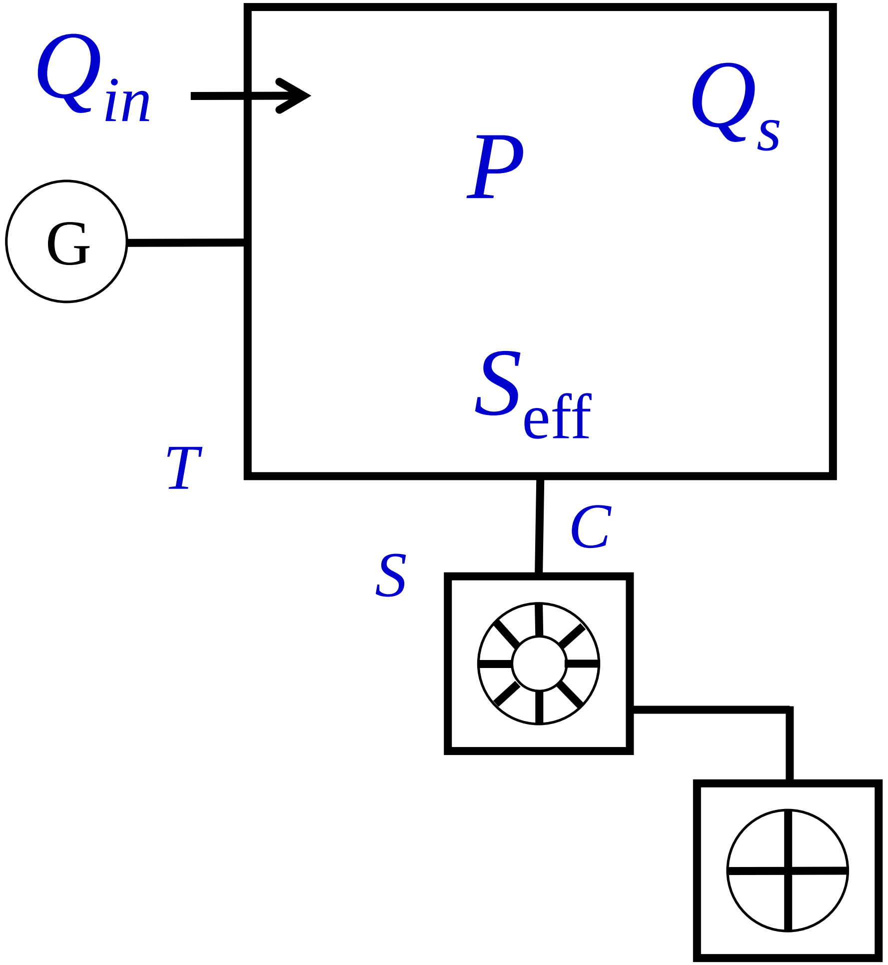
Pressure (Torr)
10^{+1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
Surface Desorption
$\left(\frac{1}{t}\right)$
10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17}
Time (seconds)

진공 배기 (표면탈착)



Surface Desorption
$(\frac{1}{t})$
?
Pressure (Torr)
Time (seconds)
10^{+1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}

진공 배기 (확산방출)



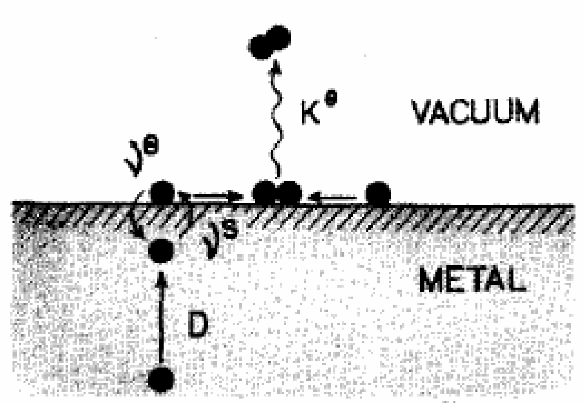
(quasi-steady state)

- $\text{d}(PV)/\text{d}t = 0 = Q_s - PS_{eff}$
- $P = Q_s/S_{eff}$
- For bulk diffusion

$$Q_s = Q_0 t^{-0.5} \rightarrow P \propto t^{-0.5}$$

수소 확산 방출 모델

[P. Chiggiato, IVC-16 (2004)]



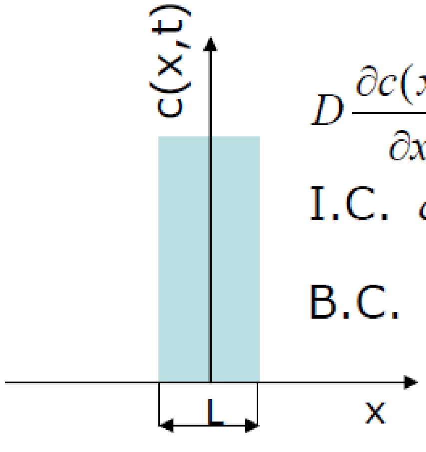
- Diffusion Limited Model (DLM)
  - Concentration gradient

$$q(t) \propto -\frac{\partial c}{\partial x}$$

- Recombination Limited Model (RLM)
  - Concentration on the surface

$$q(t) \propto {c_s}^2$$

- Solution of diffusion equation for slab (DLM)



$$D\frac{\partial c(x,t)}{\partial x^2} = \frac{\partial c(x,t)}{\partial t}$$

I.C. $c(x,0) = c_o$

B.C. $c(\pm\frac{L}{2},t) = c_w$

L>>(Dt)$^{0.5}$

$$q(t) = -D\frac{\partial c(x,t)}{\partial x}\bigg|_0 = \frac{D\cdot c_o}{\sqrt{\pi\cdot D\cdot t}} \propto t^{-0.5}$$

Dt>0.05 L^2

$$q \approx \frac{4\cdot(c_0 - c_w)\cdot D}{L}\exp\left[-\pi^2\cdot\frac{D(T_H)\cdot t_H}{L^2}\right]$$

- For arbitrary thermal cycle (thermal history)

$$q \approx \frac{4\cdot(c_0 - c_w)\cdot D}{L}\exp\left[-\pi^2\cdot\frac{\int_0^{t_H} D(T)\cdot dt}{L^2}\right]$$

Fourier number

$$F_o = \frac{\int_0^{t_H} D(T)\cdot dt}{L^2}$$

진공 배기 (확산방출)

Standard diffusion theory 2-step model :

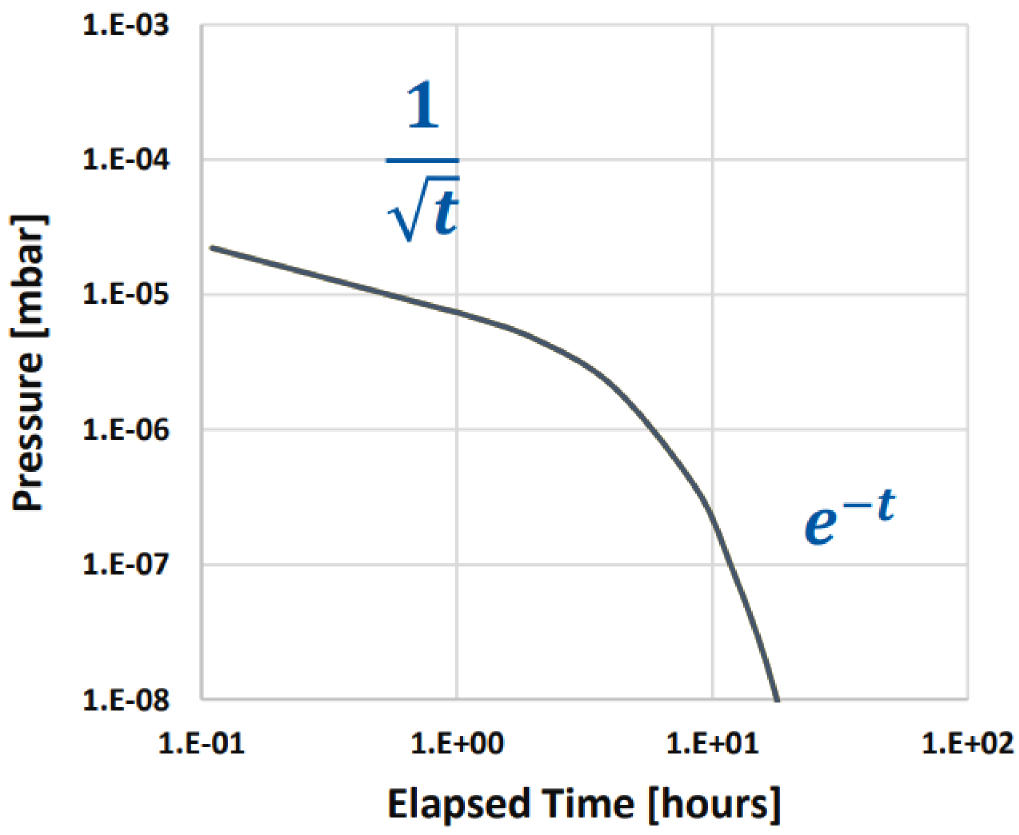
$$q_{face}(t) = \begin{cases} \frac{4D}{h} C_0 \sqrt{\frac{\pi\tau}{16t}} & for\ t \ll 0.5\tau \\ \frac{4D}{h} C_0 e^{-\frac{t}{\tau}} & for\ t \gg 0.5\tau \end{cases}$$

C_0 = initial diffusant concentration,

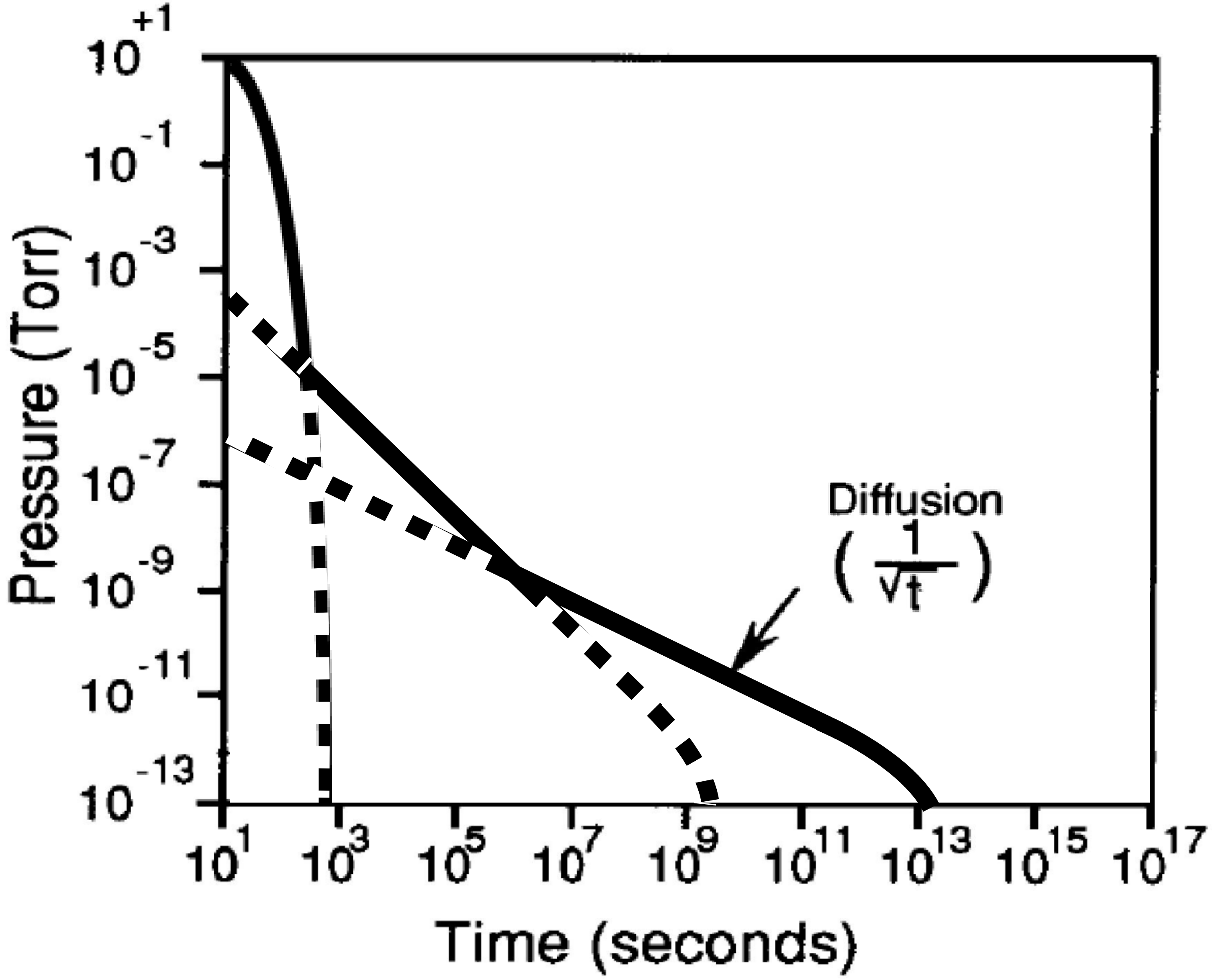
D= diffusion coefficient,

h= sample thickness

$$\tau = \frac{h^2}{\pi^2 D}$$

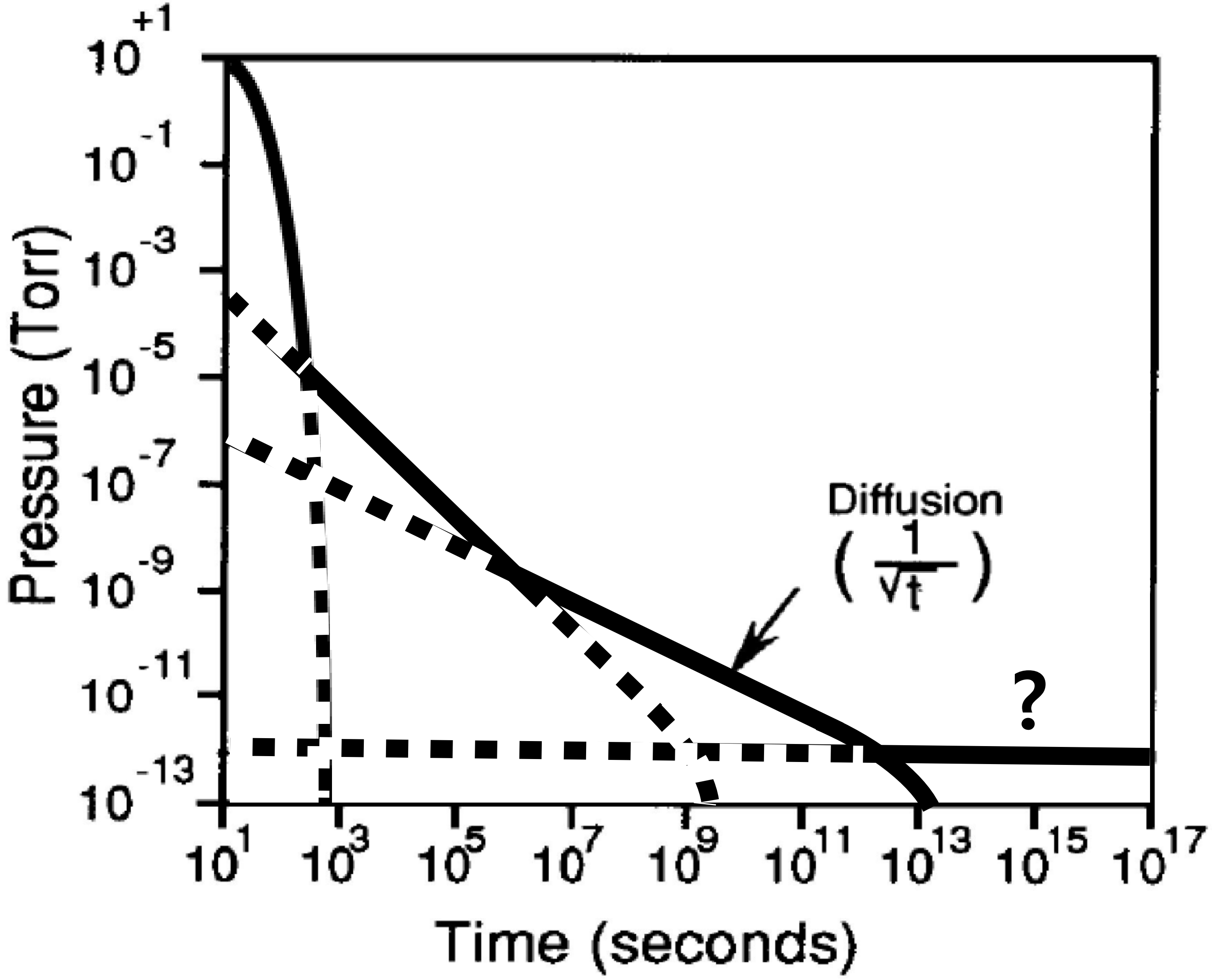


진공 배기 (확산방출)



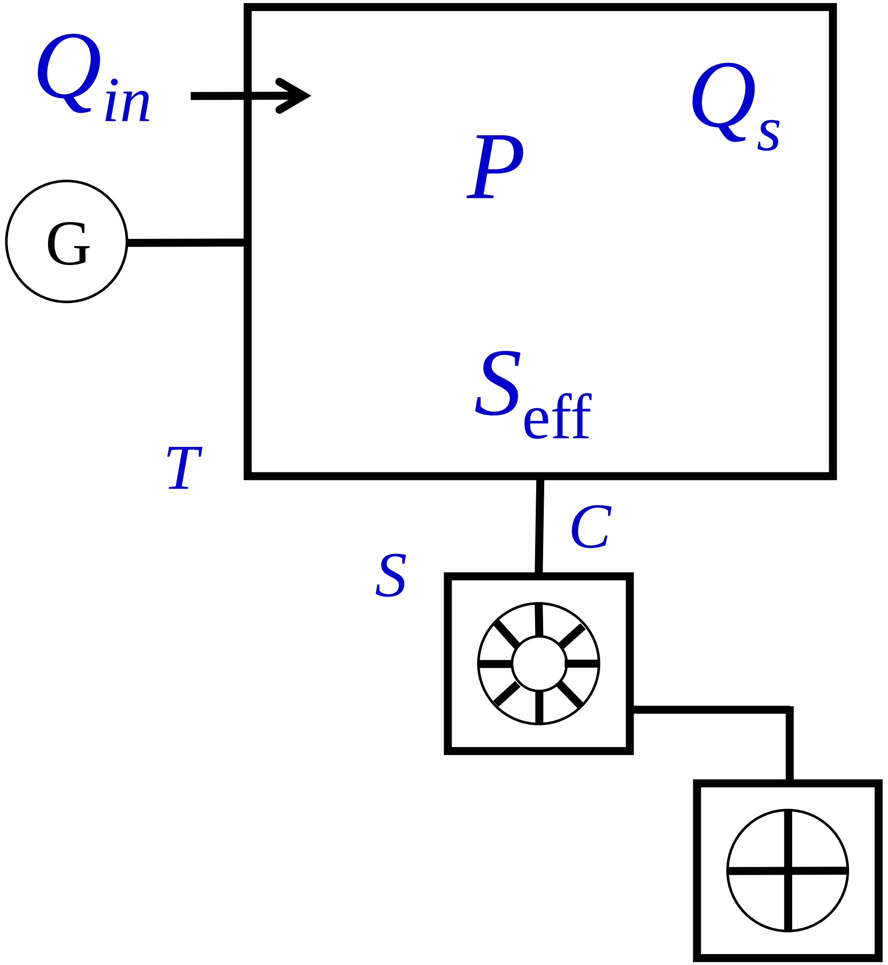
Pressure (Torr)
10^+1
10^-1
10^-3
10^-5
10^-7
10^-9
10^-11
10^-13
Time (seconds)
10^1
10^3
10^5
10^7
10^9
10^11
10^13
10^15
10^17
Diffusion
(1/√t)

진공 배기 (확산방출)



Pressure (Torr)
10^{+1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
Diffusion
$\left(\frac{1}{\sqrt{t}}\right)$
?
10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17}
Time (seconds)

진공 배기 (투과)



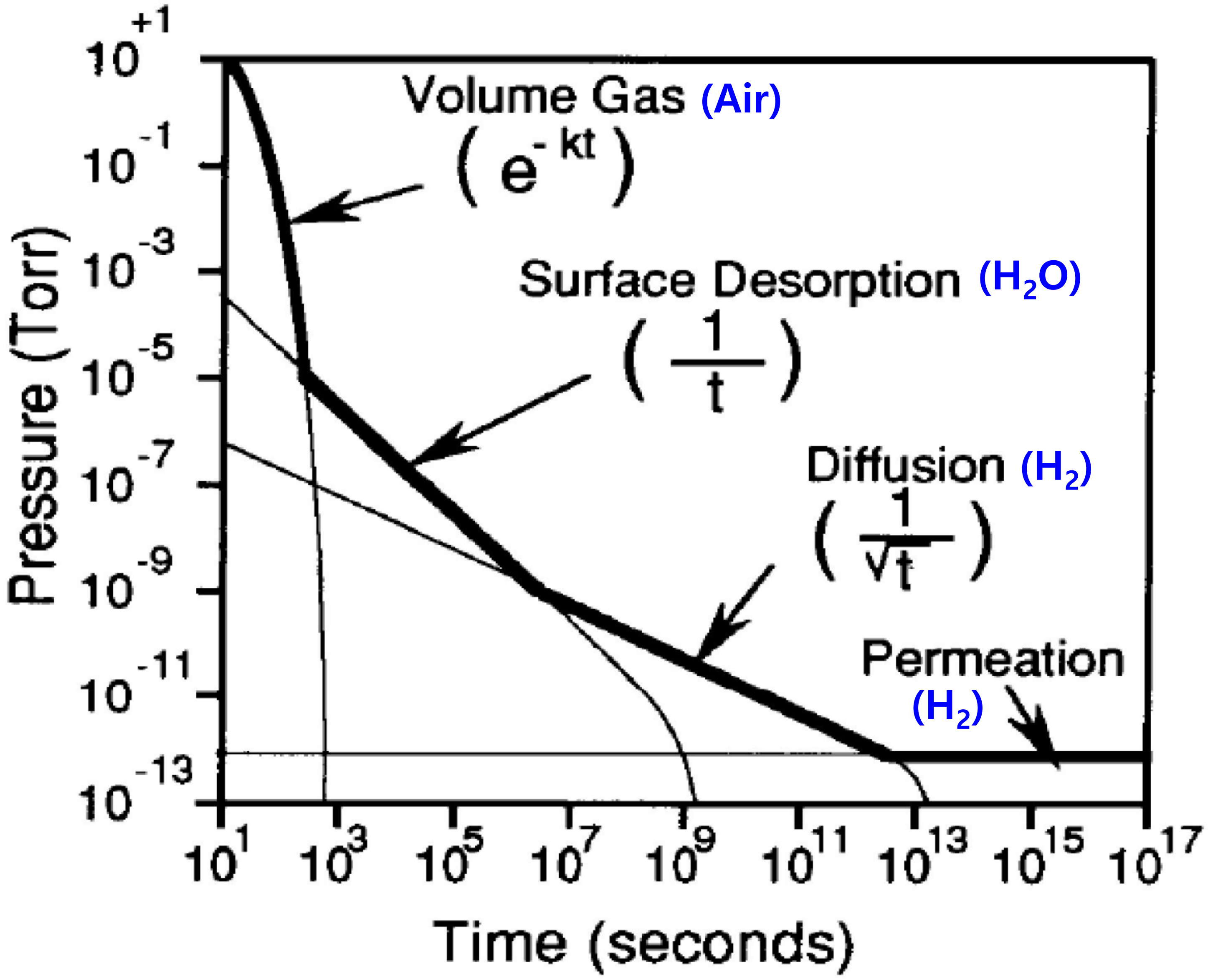
(quasi-steady state)

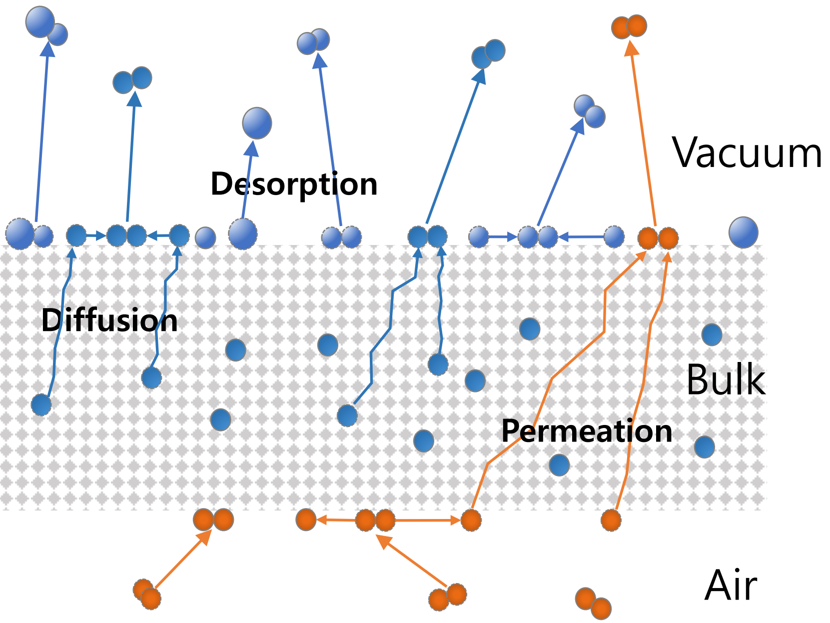
- ~~$d(PV)/dt$~~ $= 0 = Q_s - PS_{eff}$
- $P = Q_s/S_{eff}$

- For permeation

  $Q_s = const.$ → P = const.

요약 (진공 배기 과정)


Volume Gas (Air)
(e- kt)
Surface Desorption (H2O)
(1/t)
Diffusion (H2)
(1/√t)
Permeation
(H2)
Pressure (Torr)
10+1
10-1
10-3
10-5
10-7
10-9
10-11
10-13
101
103
105
107
109
1011
1013
1015
1017
Time (seconds)

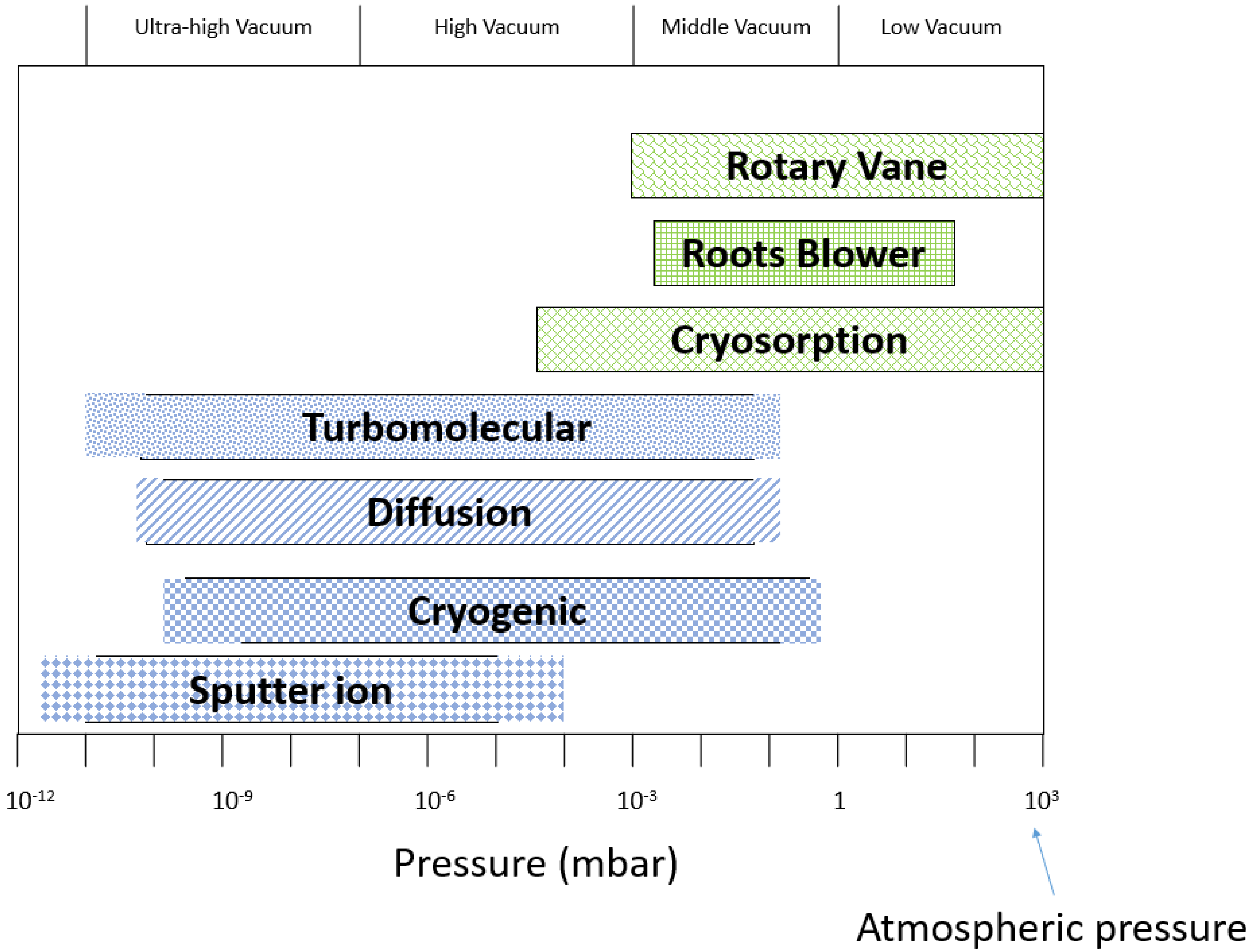

Desorption
Vacuum
Diffusion
Bulk
Permeation
Air

진공의 발생

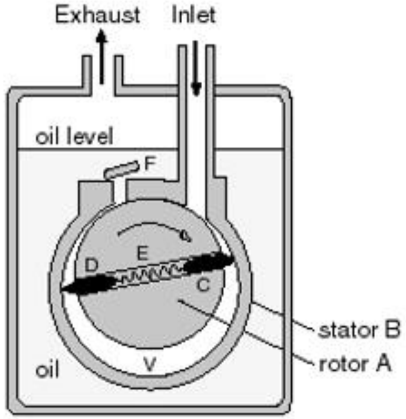
- **Throughput mechanisms:**
  - **Positive displacement**: Molecules are compressed into a smaller volume, raising the pressure
  - **Momentum transfer**: Molecules are given a preferred direction by very fast moving surfaces or oil molecules

- **Capture mechanisms:**
  - **Chemical combination**: Molecules react with active metal surfaces and are converted to a solid
  - **Condensation**: Molecules land on a very cold surface and freeze into a solid
  - **Adsorption**: Molecules land on a surface and remain there
  - **Absorption**: Molecules land on a surface and dissolve into the bulk material
  - **Ionization & burial**: Molecules are ionized and accelerated into a surface with enough energy to burrow in

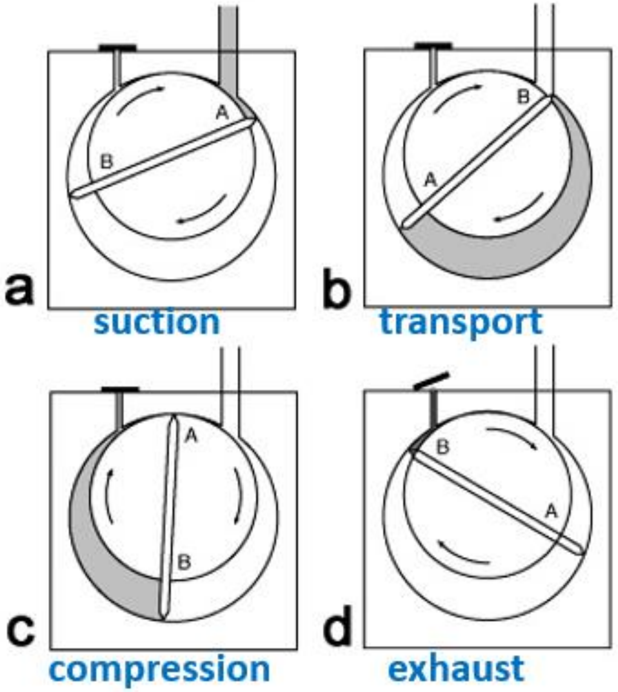
진공도와 진공 펌프


Ultra-high Vacuum
High Vacuum
Middle Vacuum
Low Vacuum
Rotary Vane
Roots Blower
Cryosorption
Turbomolecular
Diffusion
Cryogenic
Sputter ion
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
Pressure (mbar)
Atmospheric pressure

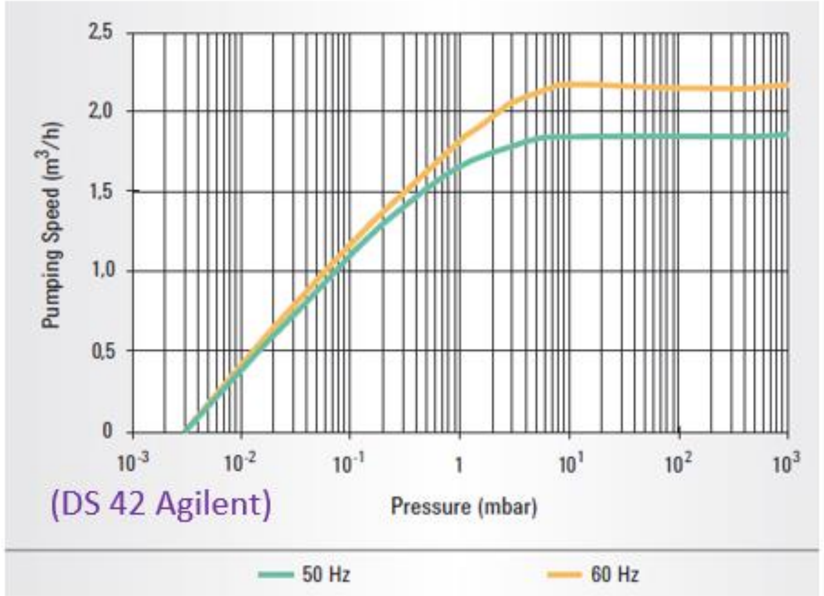
회전베인펌프 (Rotary Vane Pump)



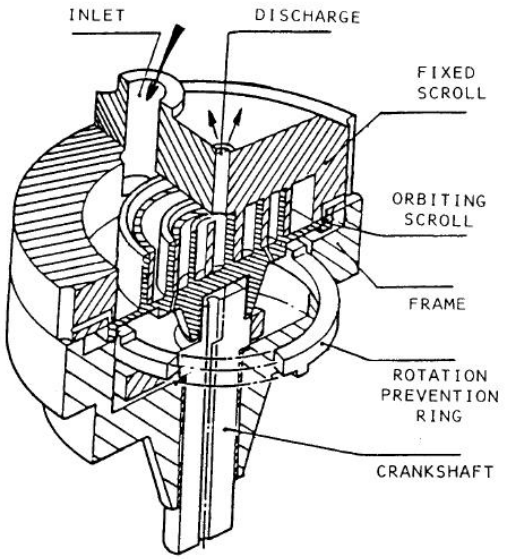
Positive displacement

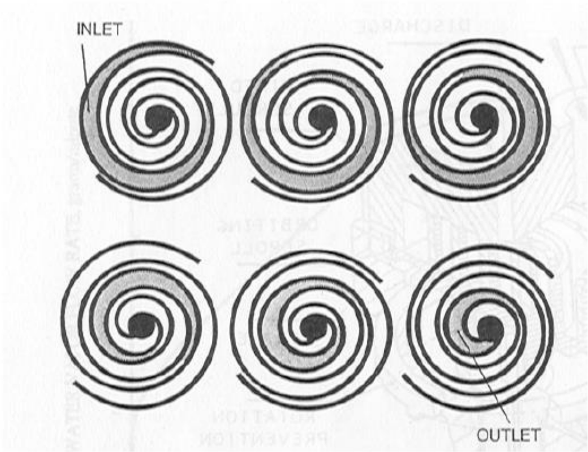


Typical pumping speed curve



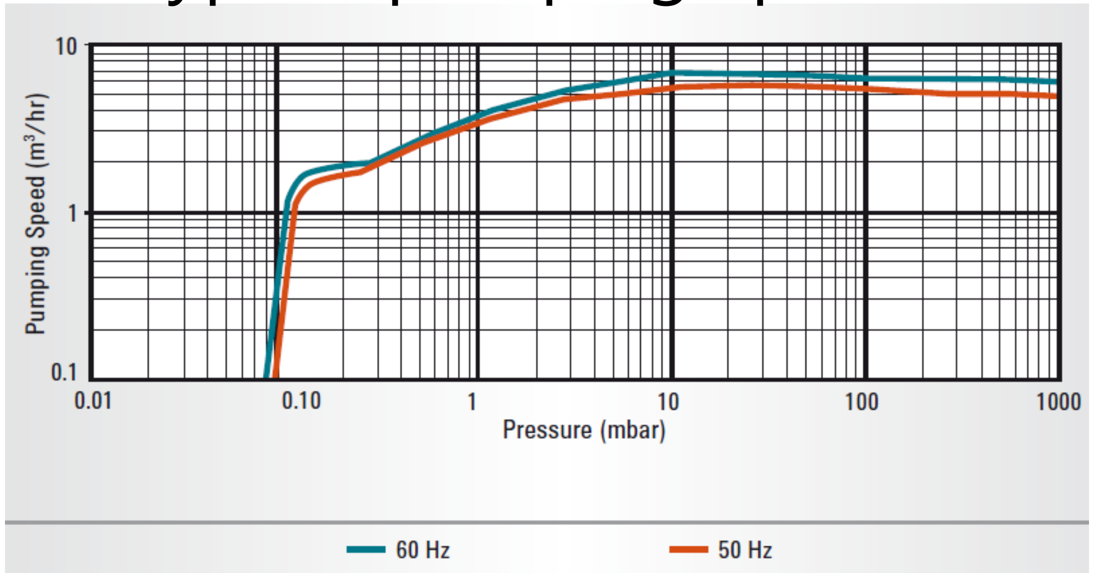
스크롤 펌프 (Scroll Pump)



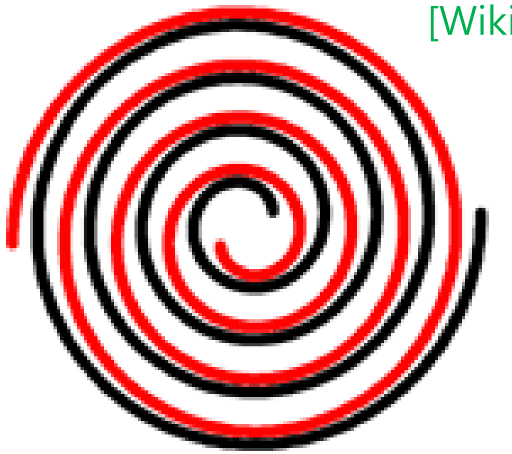


Positive displacement

Typical pumping speed curve

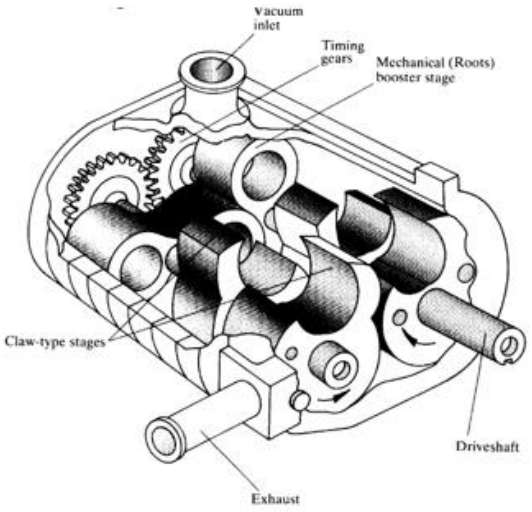


[Wikipedia]

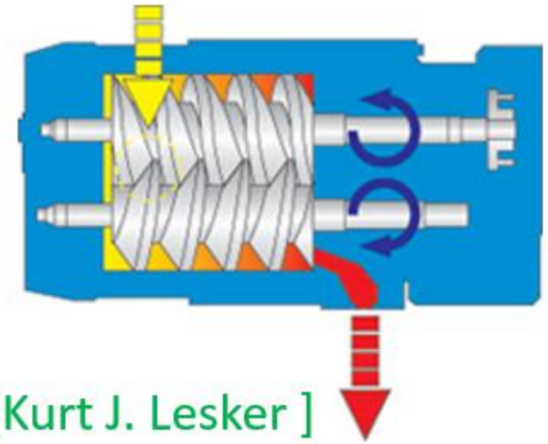


다양한 저진공 펌프 (Dry pump)

Claw Pump

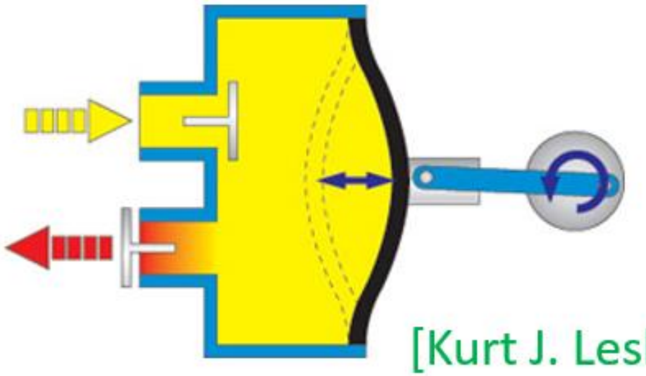


Screw Pump



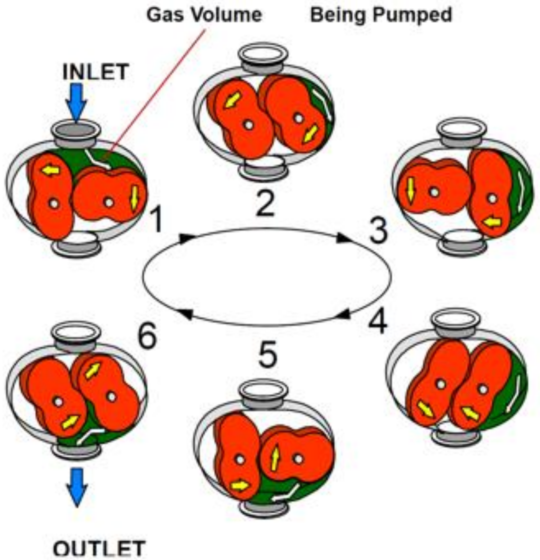
[Kurt J. Lesker]

Diaphram Pump

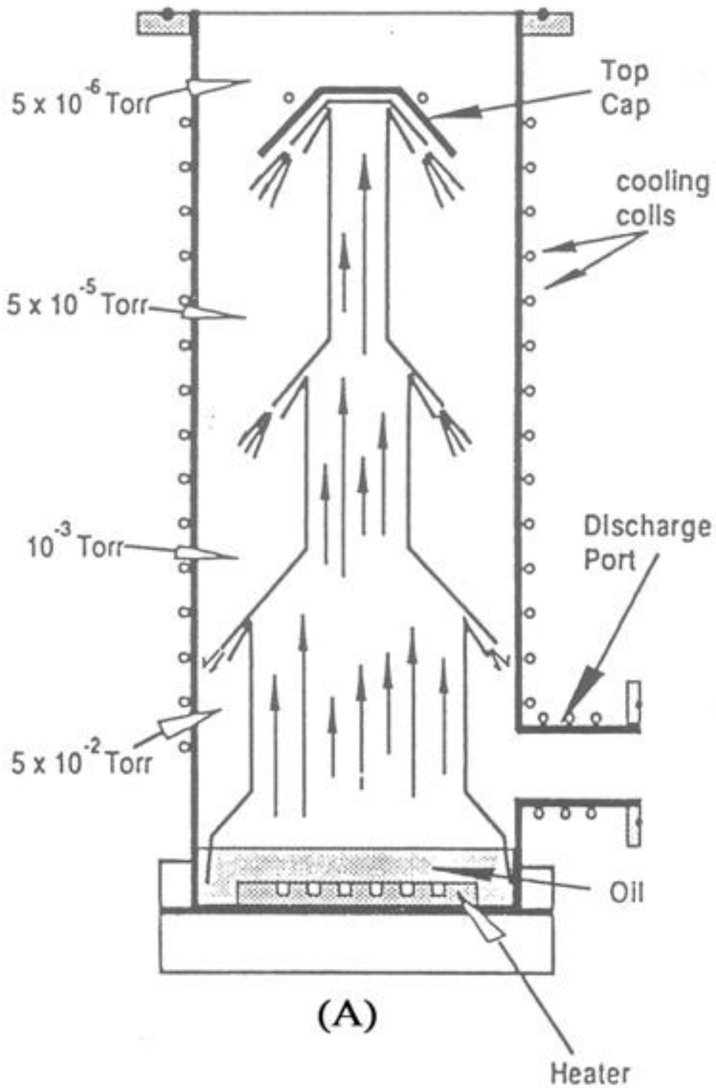


[Kurt J. Lesker]

Roots Pump

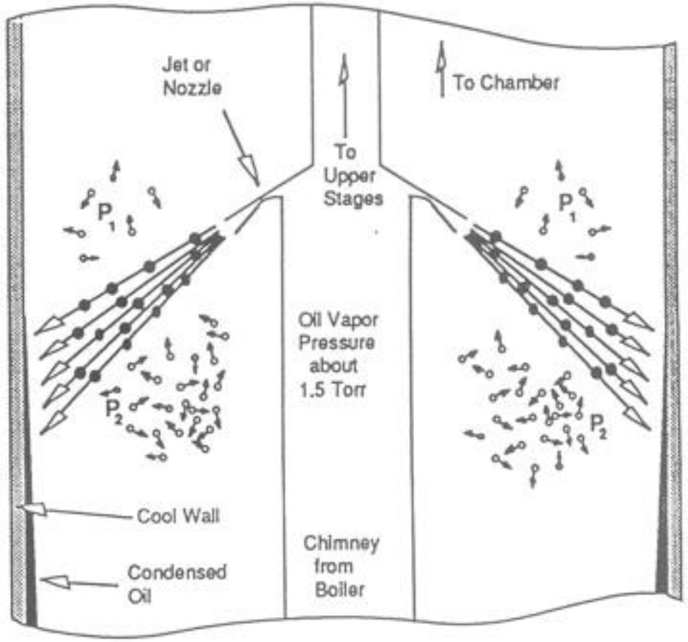


확산펌프 (Diffusion pump)



(A)

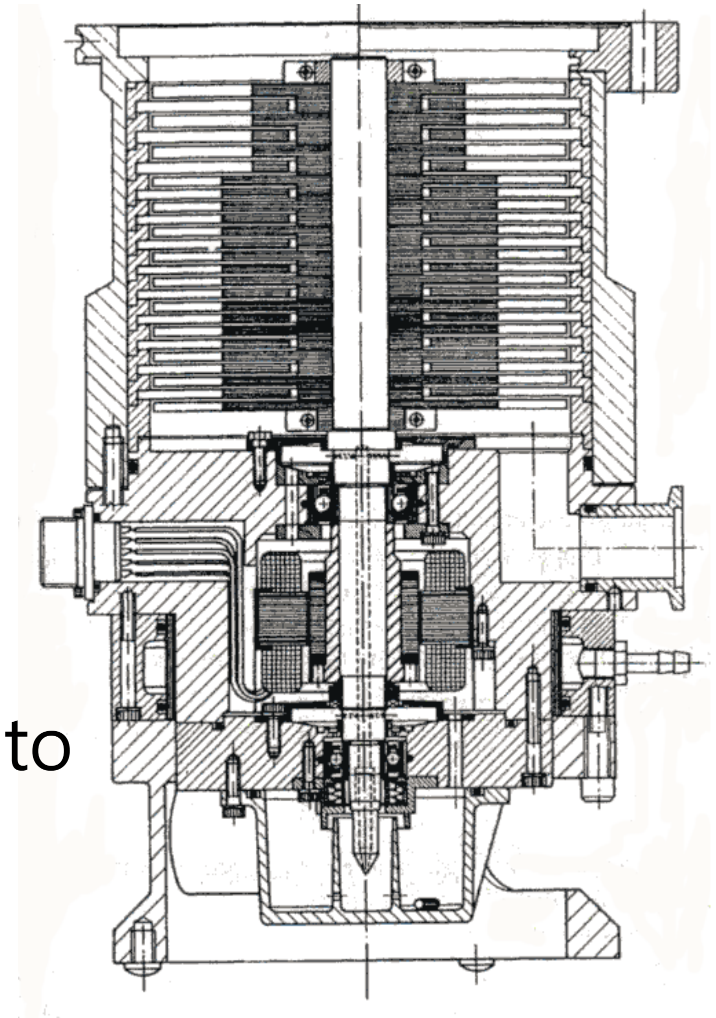
Momentum transfer



터보분자펌프 (Turbo Molecular Pump: TMP)

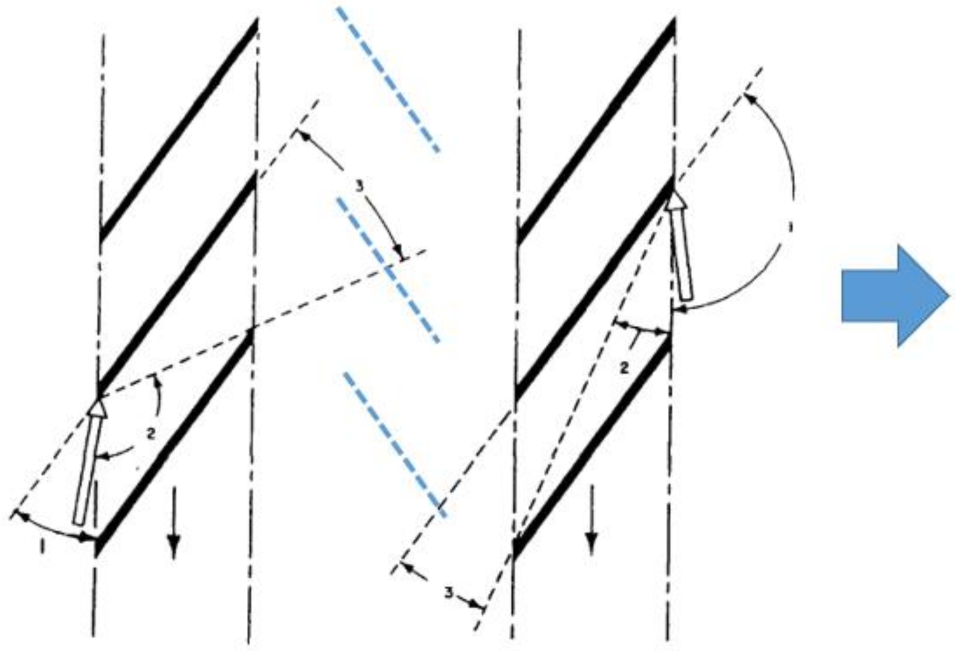
Momentum transfer

- Operate in the molecular flow regime
- Operating range 10^{-2} to 10^{-10} Torr
- Pumping speed 10 to 10,000 l/s
- Infinite pumping capacity
- Blade rotation speed ranges from 14,000 to 90,000 rpm (mechanically vulnerable)

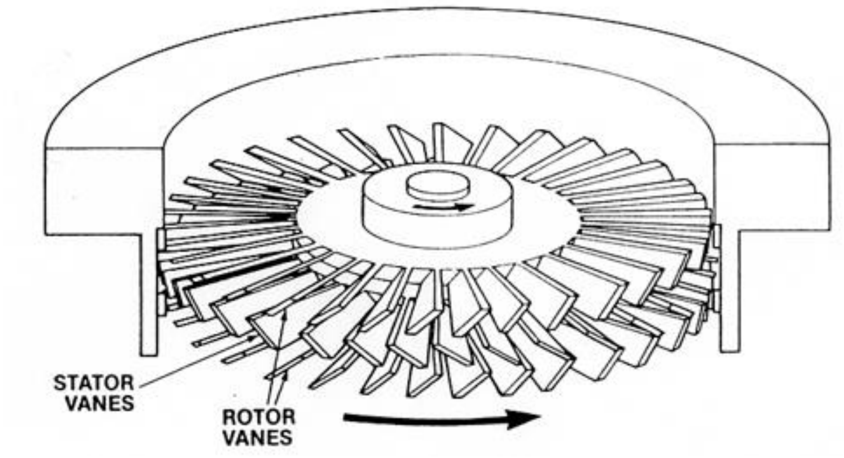


터보분자펌프 (Turbo Molecular Pump: TMP)

Vacuum side

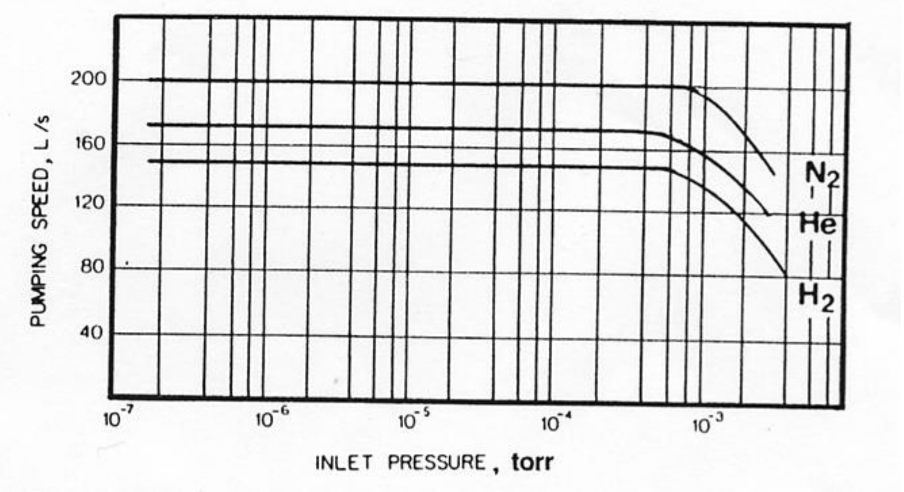


Air side

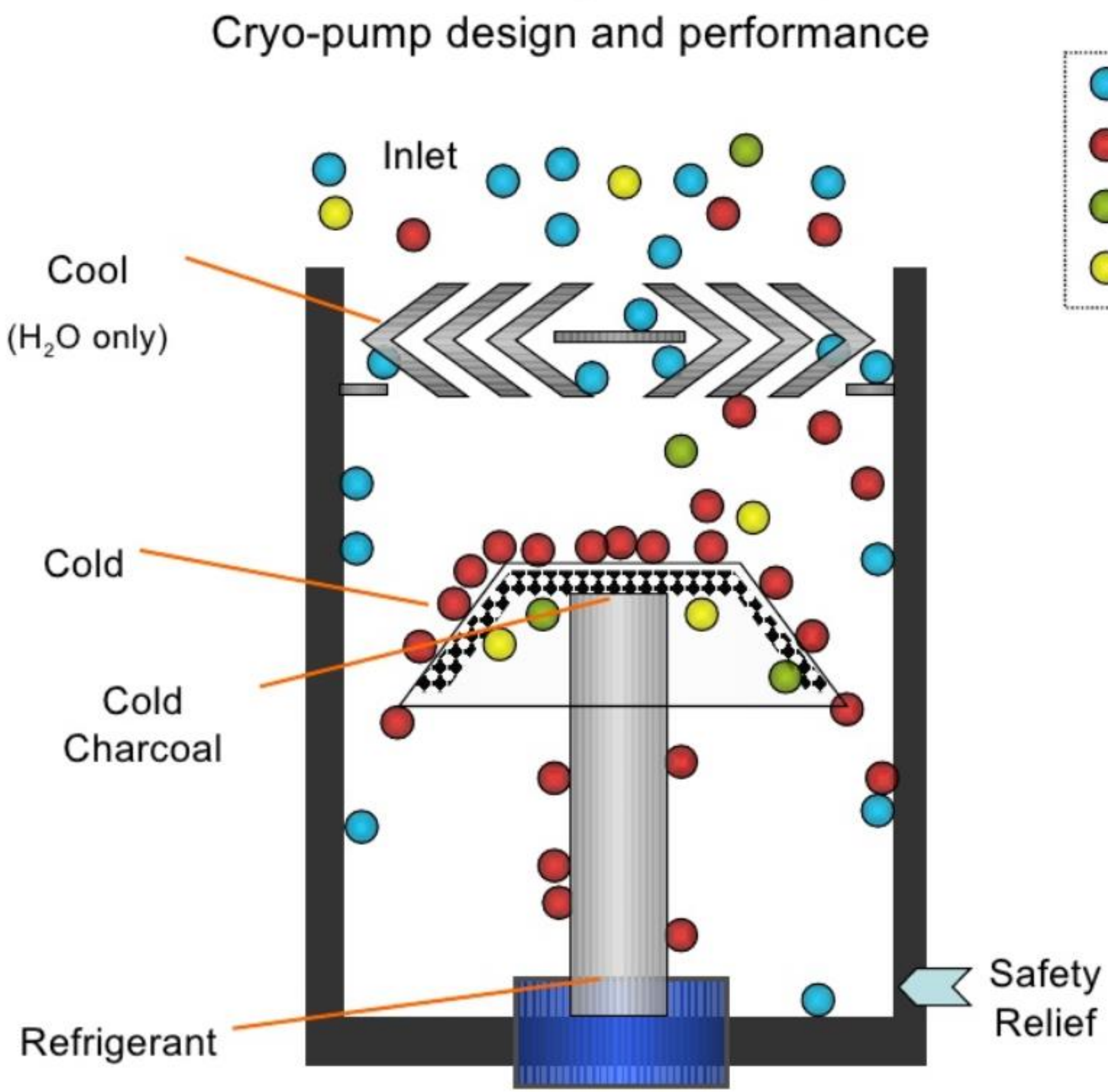


"Stators redistribute directions of molecules at each stage"

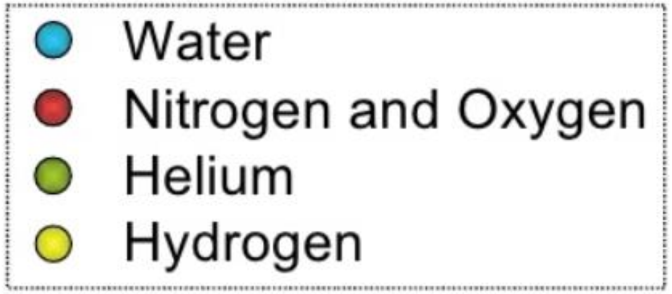
$$v_a = \int_0^\infty v f(v)\,dv = \sqrt{\frac{8kT}{\pi m}} = 146\sqrt{\frac{T}{M}}$$



크라이오펌프 (Cryo-pump)



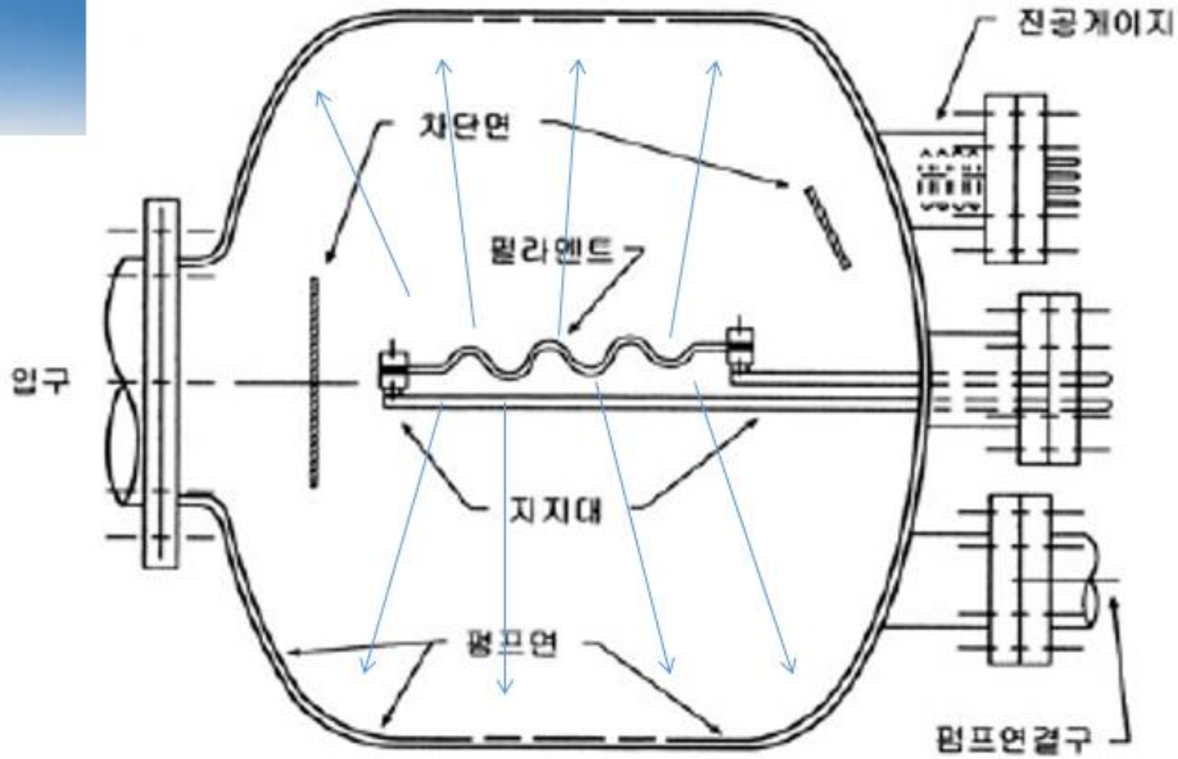
Physical combination



티타늄 승화펌프 (TSP)

Ti filament

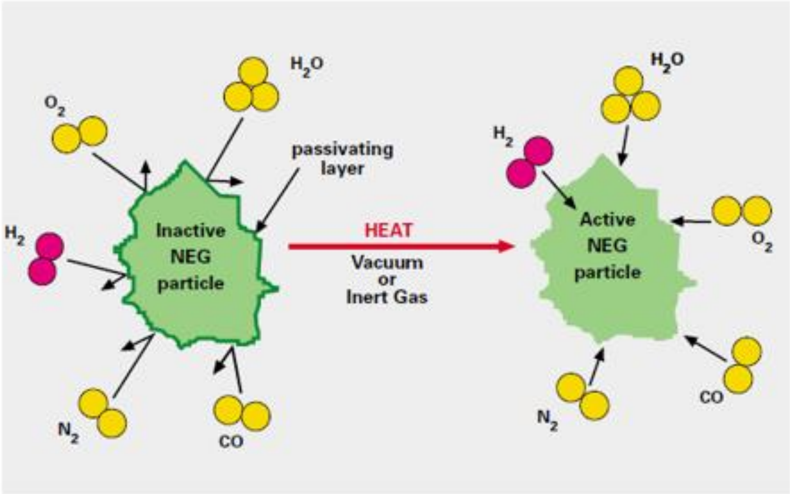
Chemical combination

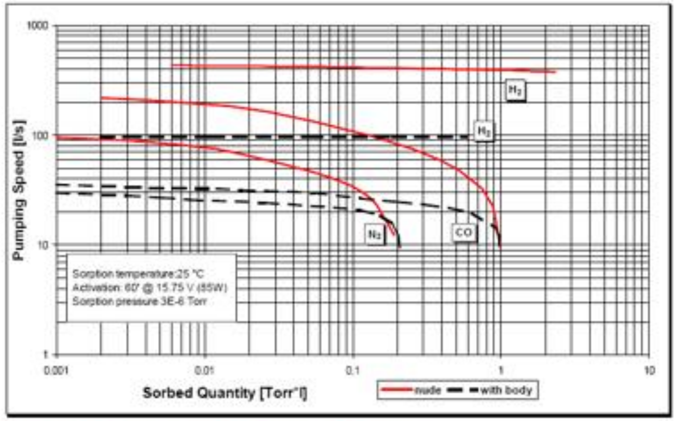


- ✓ Ti evaporation → Deposited fresh Ti layer → Gas-Ti chemical combination
- ✓ No pumping ability for inactive gas (Ar, He, CH_4)

NEG 펌프 (Non Evaporable Getter)

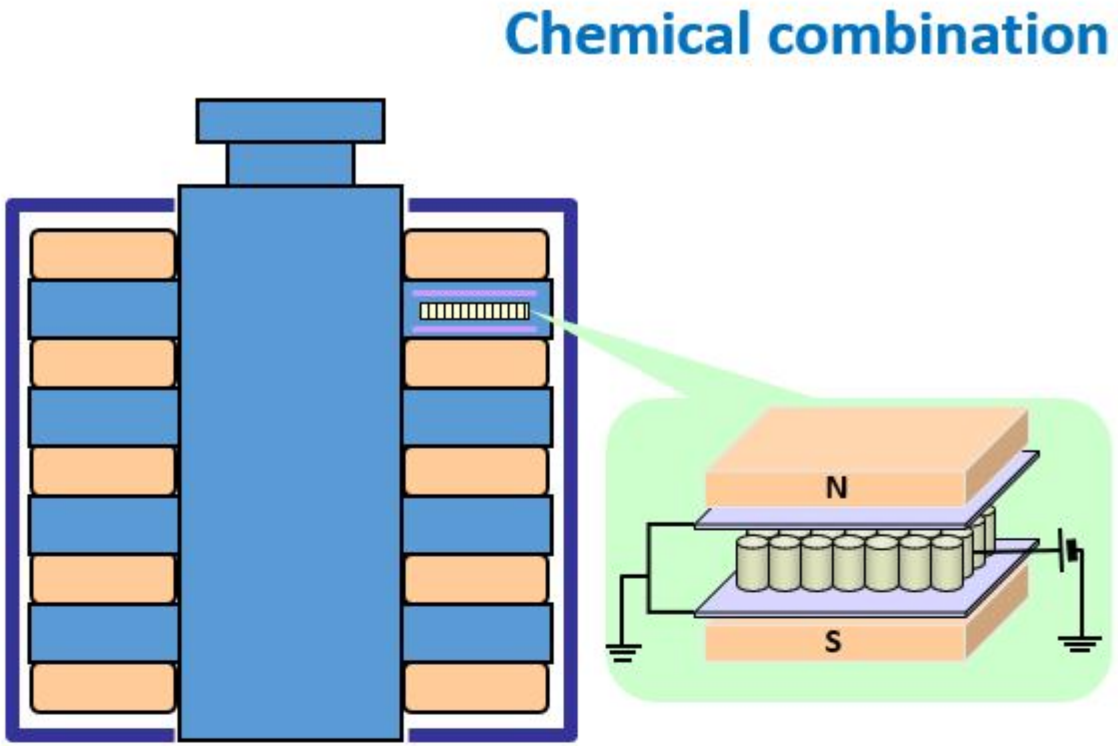
Chemical combination





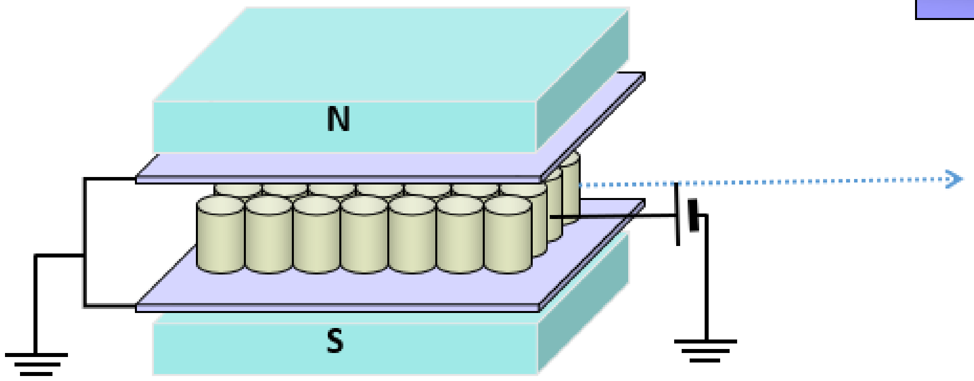
- ✓ Activation of surface (by heating) → chemical combination
- ✓ No pumping ability for inert gas (Ar, He, CH4)

스퍼터 이온펌프 (Sputter Ion Pump: SIP)

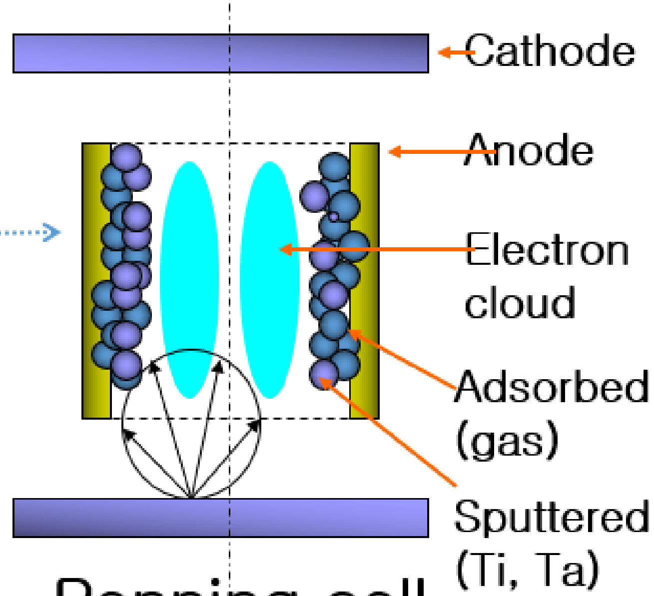


- ✓ Electron cloud → ionization → high energy impact on Ti plate → Ti Sputtering → Deposited fresh Ti layer → chemical combination
- ✓ Pumping ability for CH_4
- ✓ Low pumping speed for noble gas (Ar, He)

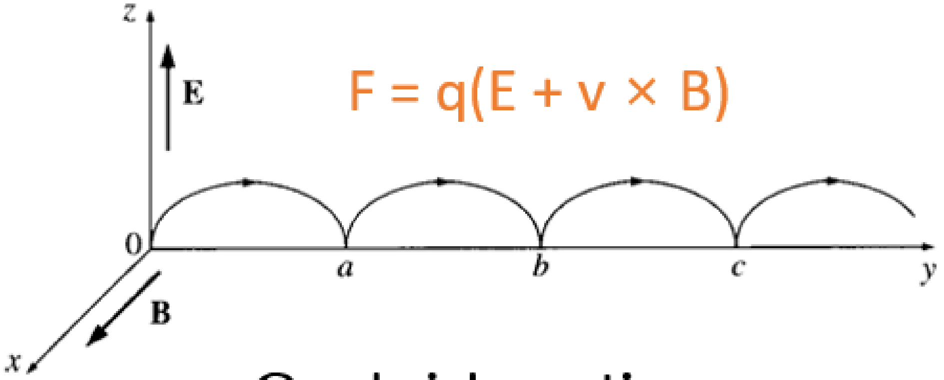
스퍼터 이온펌프의 배기 원리



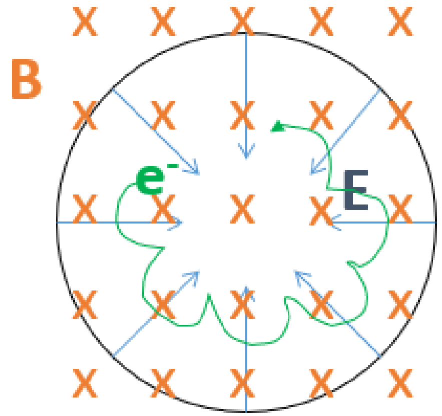
SIP cell module



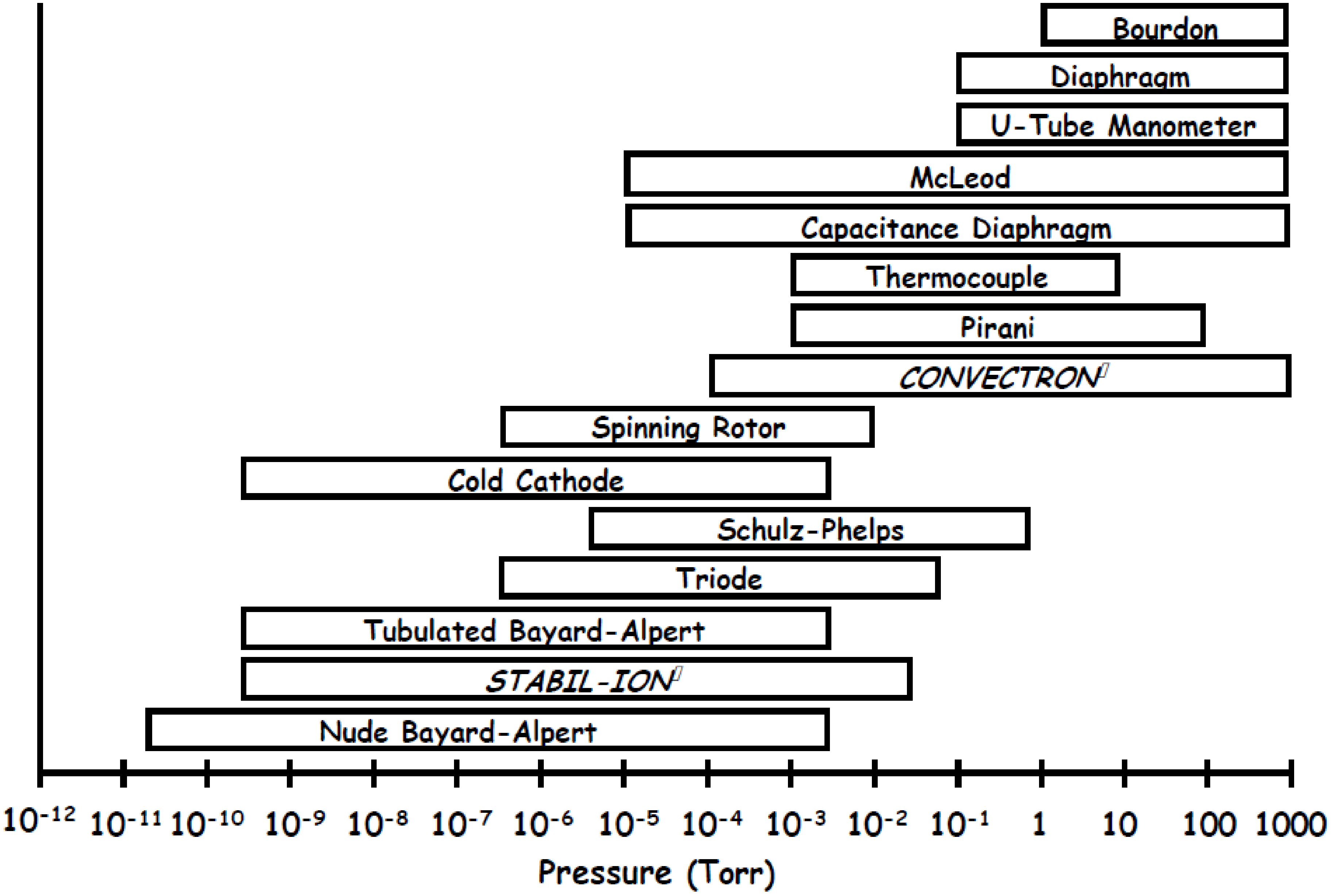
Penning cell



Cycloid motion
in cross field



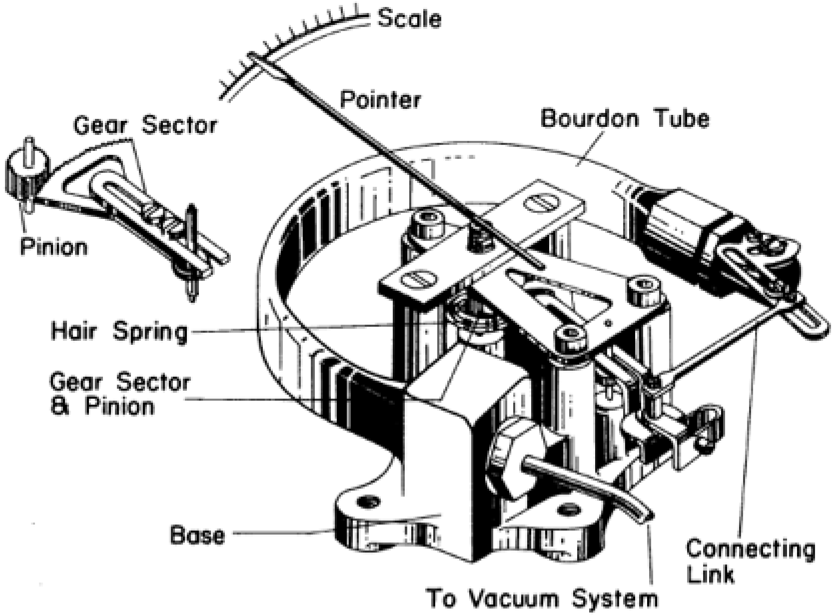
진공의 측정



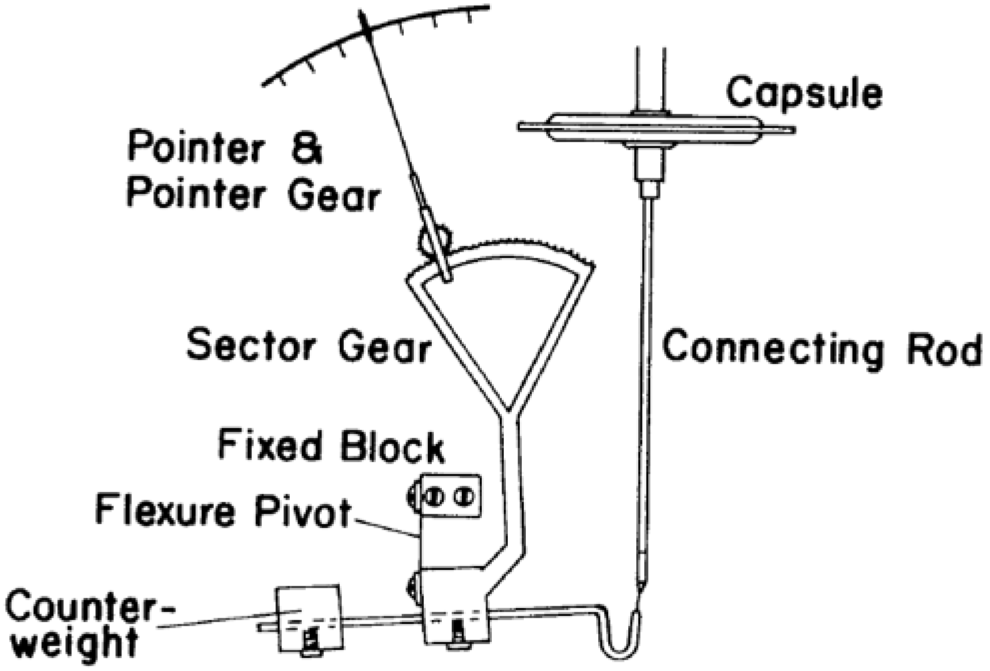
Bourdon
Diaphragm
U-Tube Manometer
McLeod
Capacitance Diaphragm
Thermocouple
Pirani
CONVECTRON
Spinning Rotor
Cold Cathode
Schulz-Phelps
Triode
Tubulated Bayard-Alpert
STABIL-ION
Nude Bayard-Alpert
10-12 10-11 10-10 10-9 10-8 10-7 10-6 10-5 10-4 10-3 10-2 10-1 1 10 100 1000
Pressure (Torr)

직접 압력 측정식 게이지

Direct force on surface



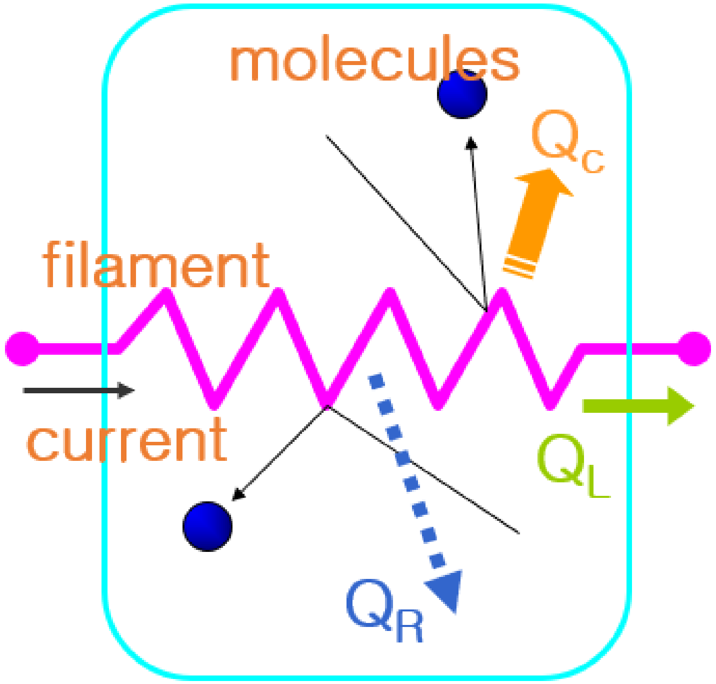
Burdon gauge



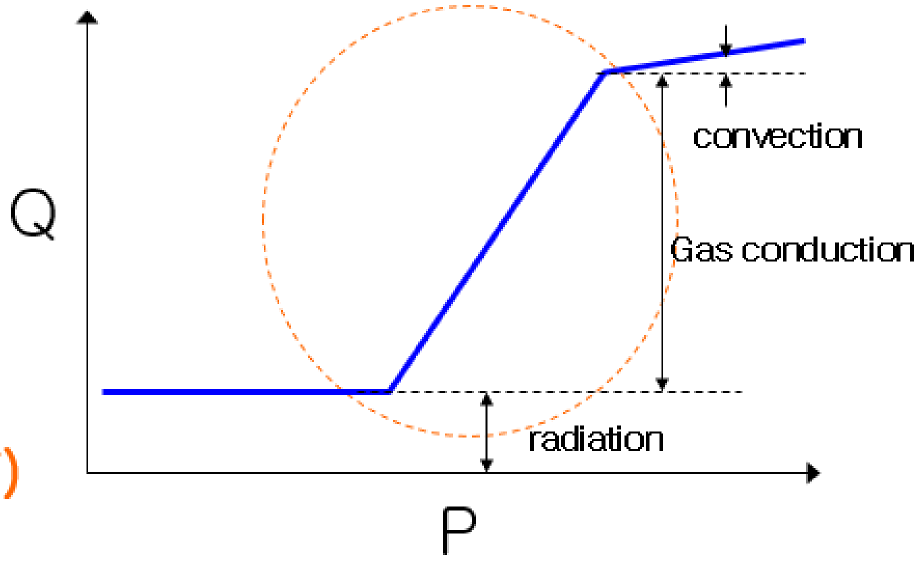
Diaphram gauge

열전도형 게이지

Indirect (neutral gas)

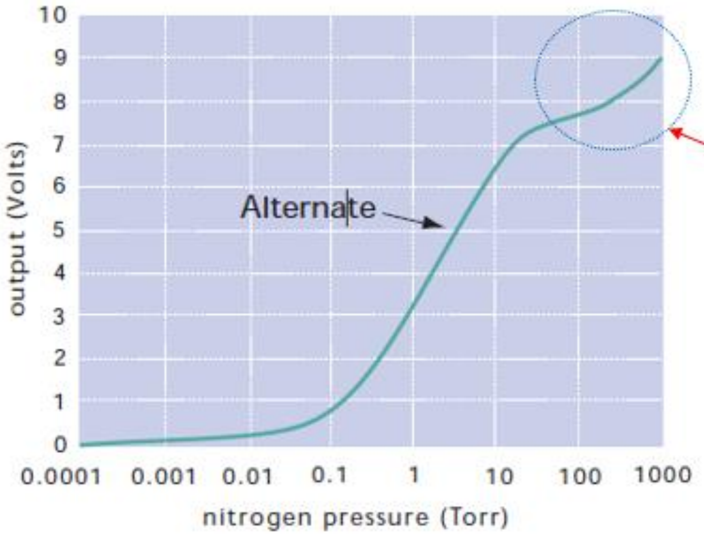


$$Q_S = Q_R + Q_L + Q_C$$

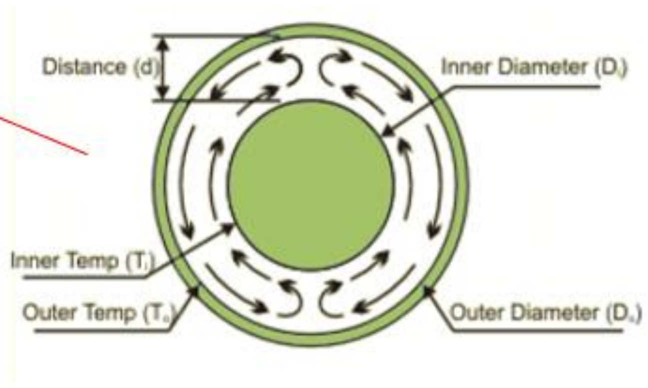


Q_R : radiation ($\propto T^4$)
Q_L : wire conduction ($\propto \Delta T$)
Q_C : gas conduction ($\propto P\Delta T$)

컨벡션 형 게이지 (Convection gauge)



Indirect (neutral gas)



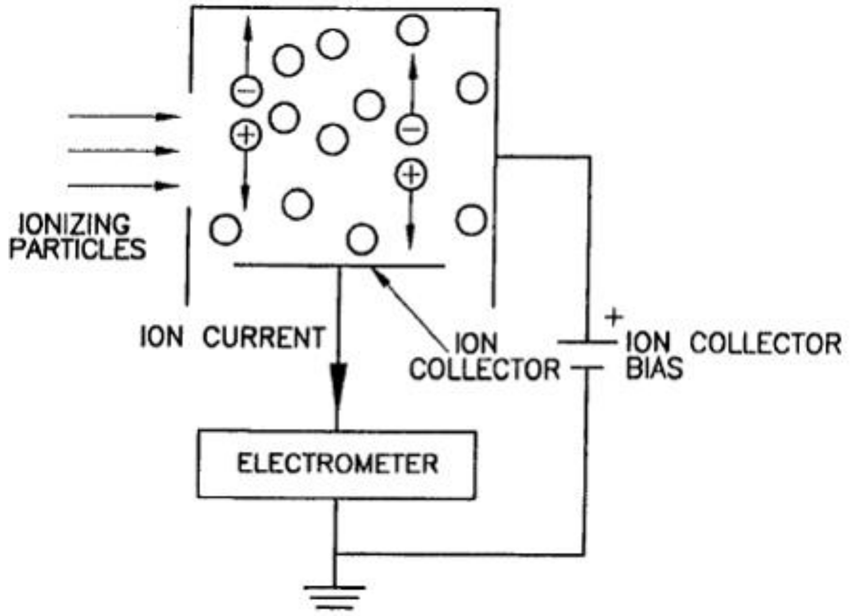
(O)

(X)

열음극 형 이온 게이지 (Hot filament ion gauge)

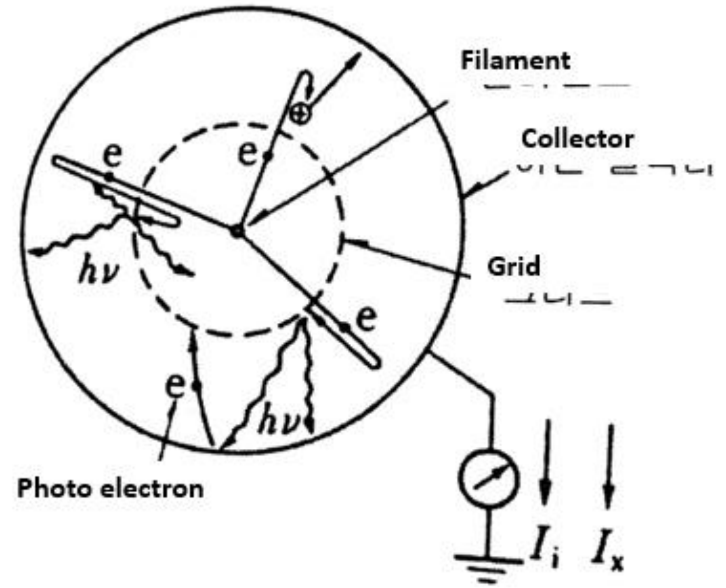
Indirect (ionized gas)

Triode ionization gauge



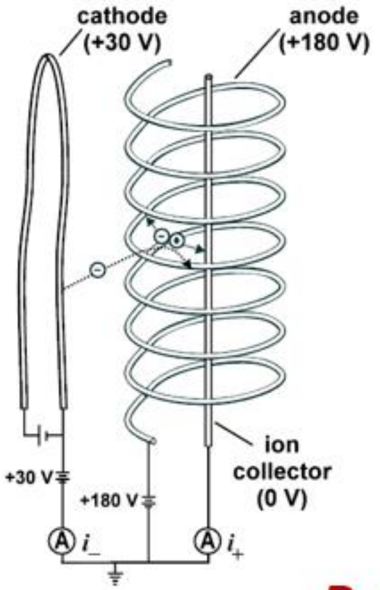
$$I_i = S\, I_e\, P$$

principle

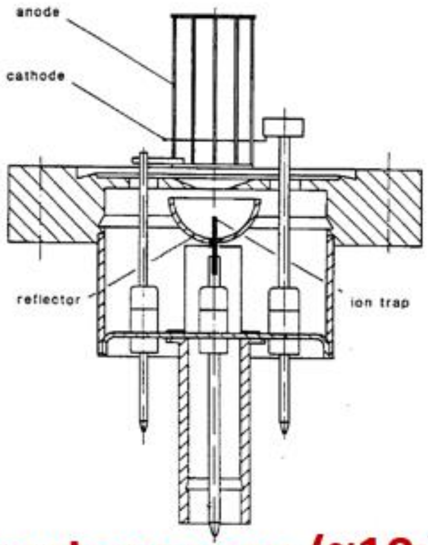


X-ray limit

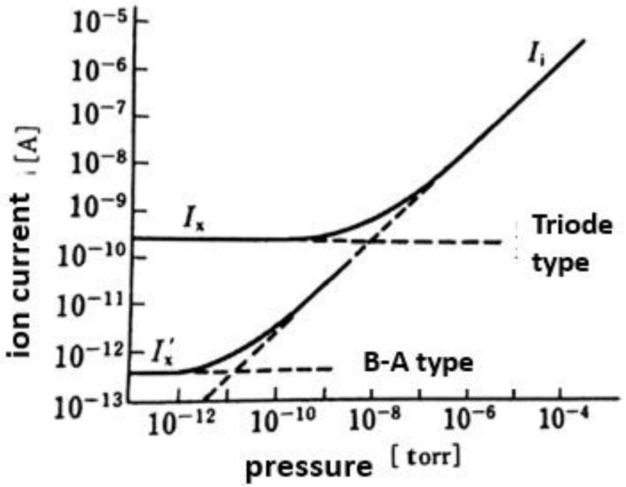
Lower limit of the ion gauge



B-A gauge (<10^{-10} mbar)

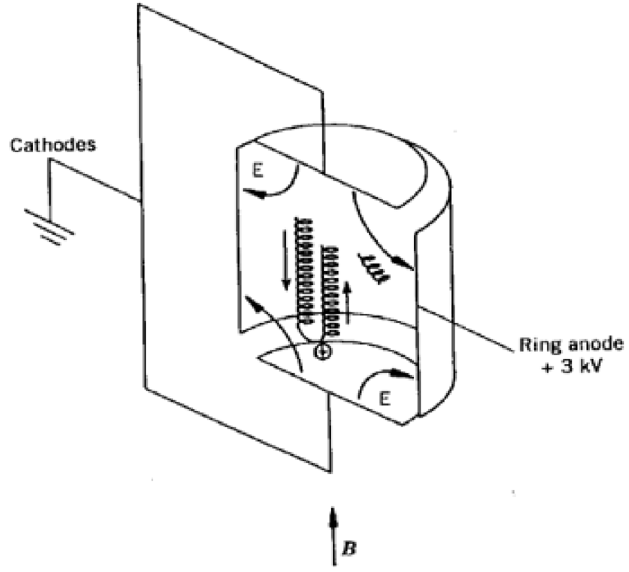


Extractor gauge (~10^{-12} mbar)



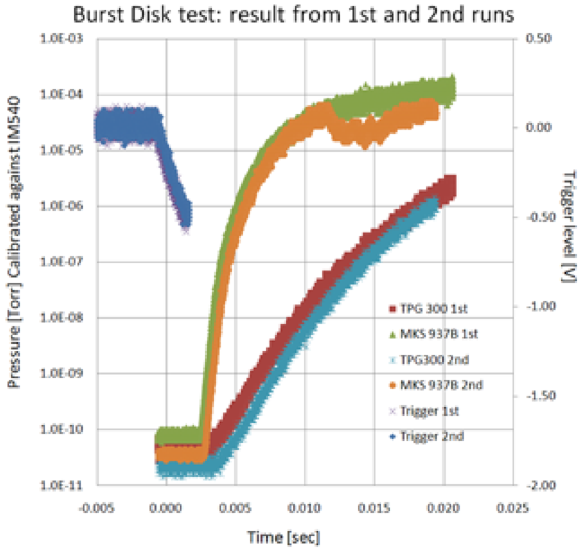
3B gauge (<10^{-14} mbar)

냉음극 형 이온 게이지 (Cold cathode ion gauge)



Penning discharge

Fast response time

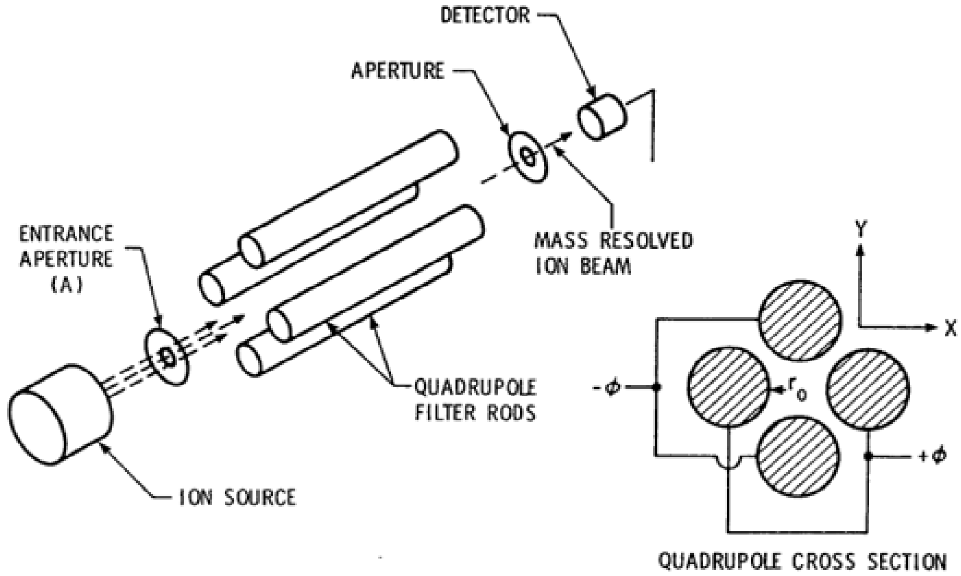


Time interval upto 1 x 10^{-7} Torr:
- MKS 937B 1st run = 4.8 ms
- MKS 937B 2sd run = 5.2 ms
- TPG 300 1st run = 13.8 ms
- TPG 300 2st run = 15.0 ms

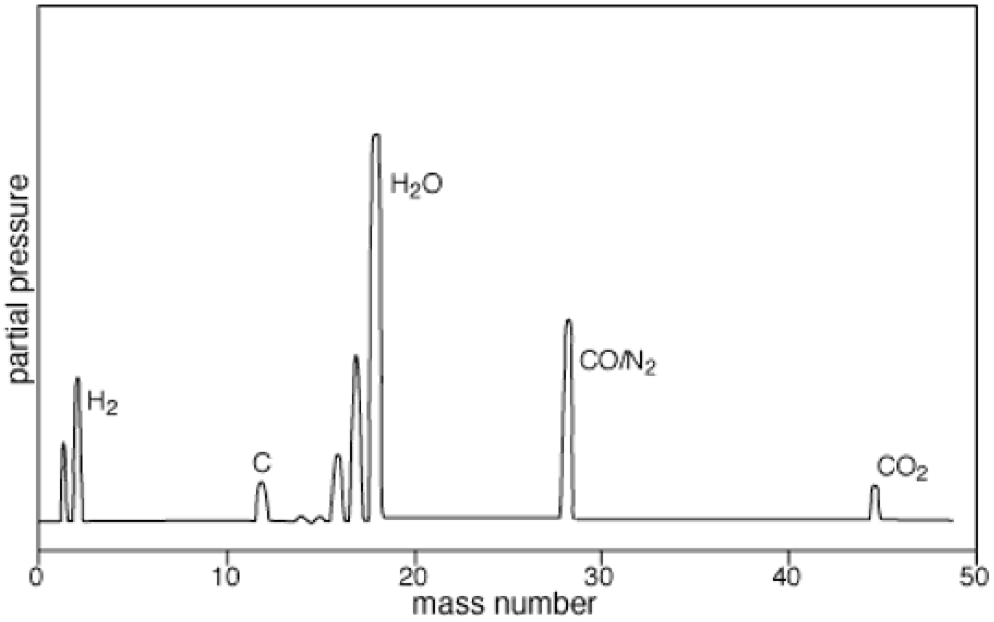
Time travel for the gas reach the gauge using the most probable velocity equation:
Temp = 24 C
M = 28 g/ mol (N_2)
Distance = 100 cm
Time = 2 ms

Time response of the controllers at analog port:
MKS 937B = 3-4 ms
TPG300 = 12-13 ms

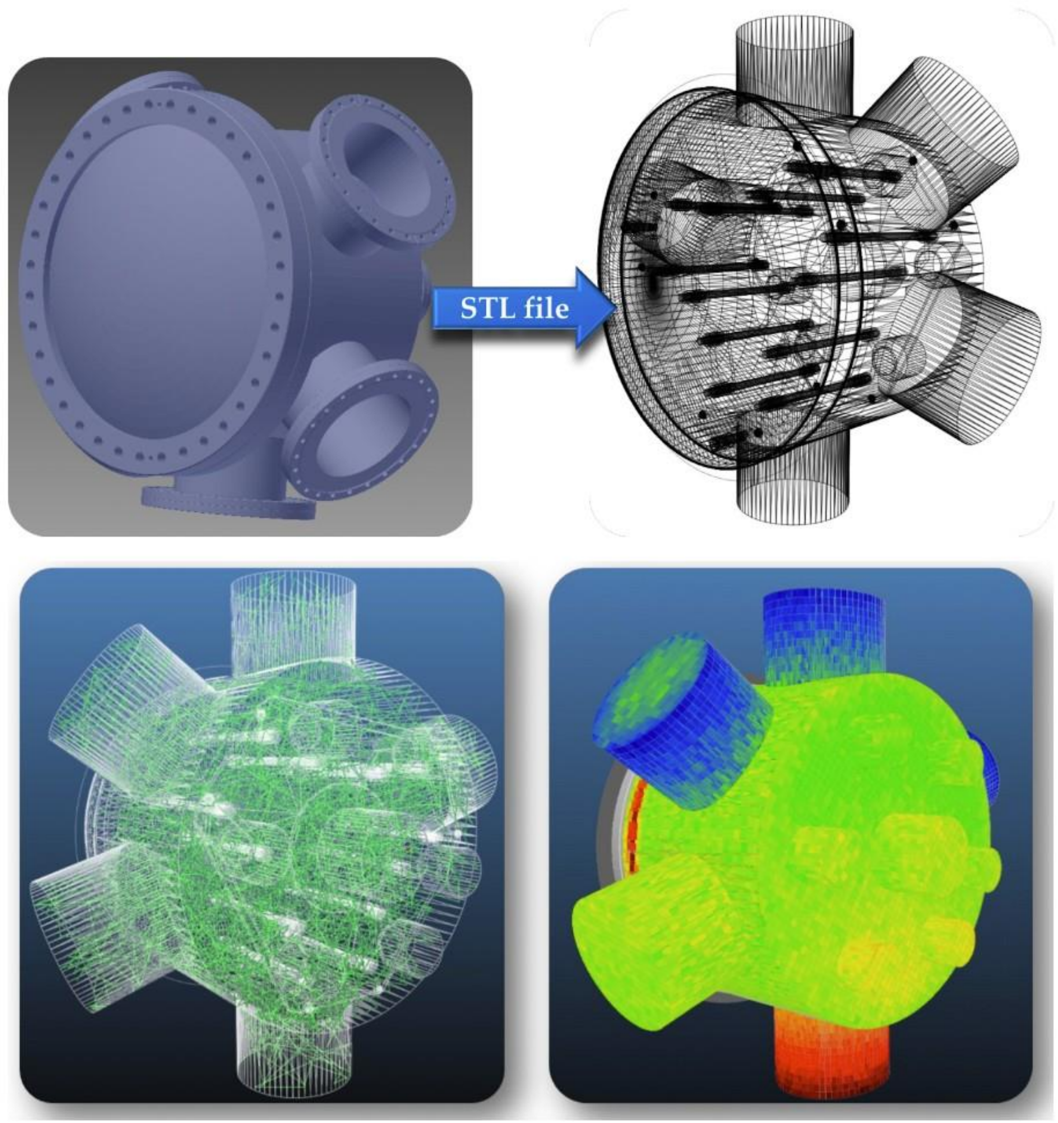
사극 질량 분석기 (QMS, RGA)

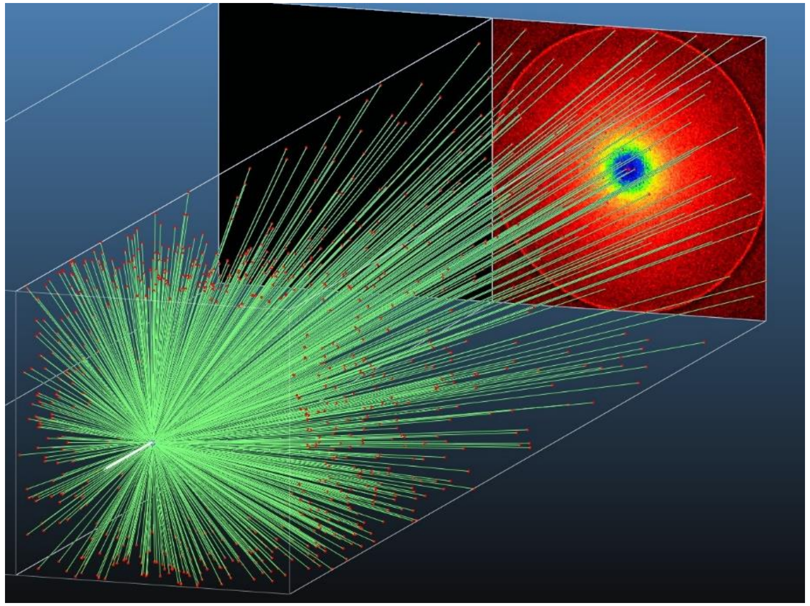


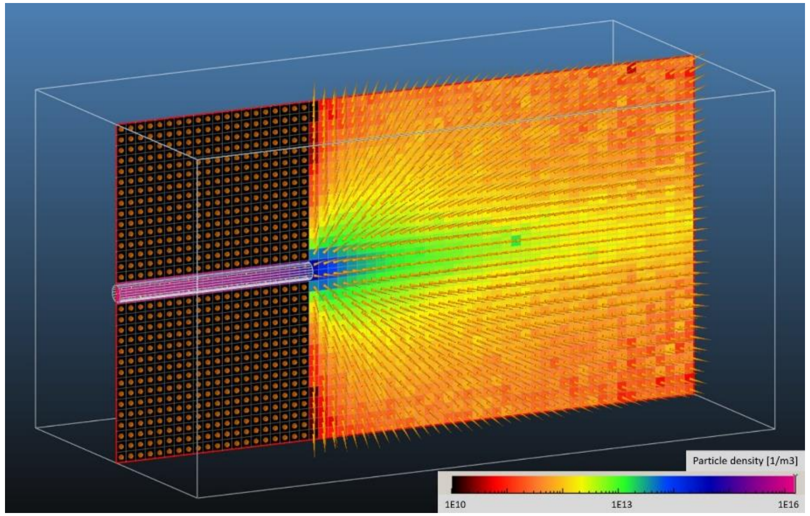
Quadrupole mass filter.

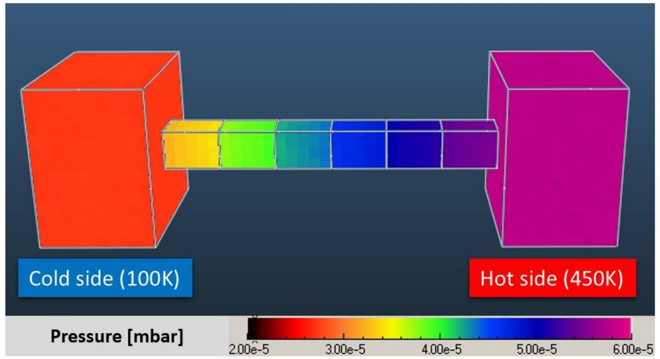


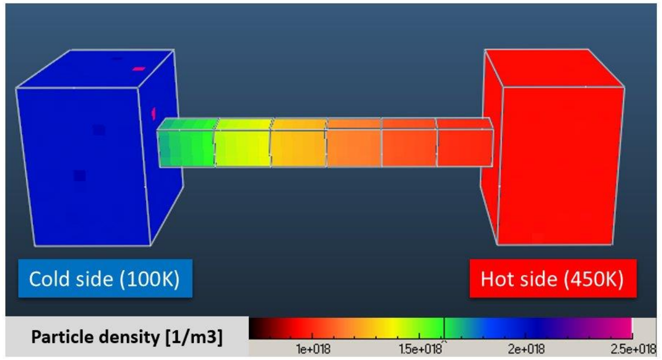
컴퓨터 시뮬레이션을 활용한 진공 시스템의 설계 “https://molflow.docs.cern.ch/gallery/”











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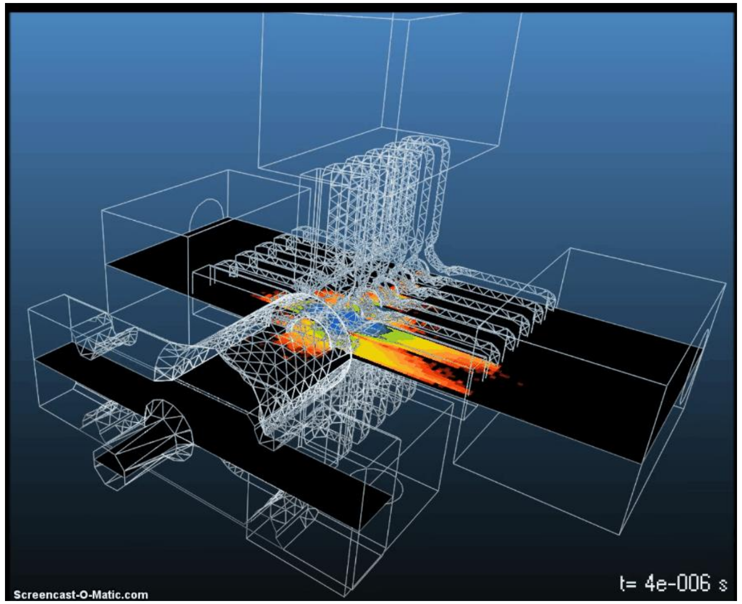

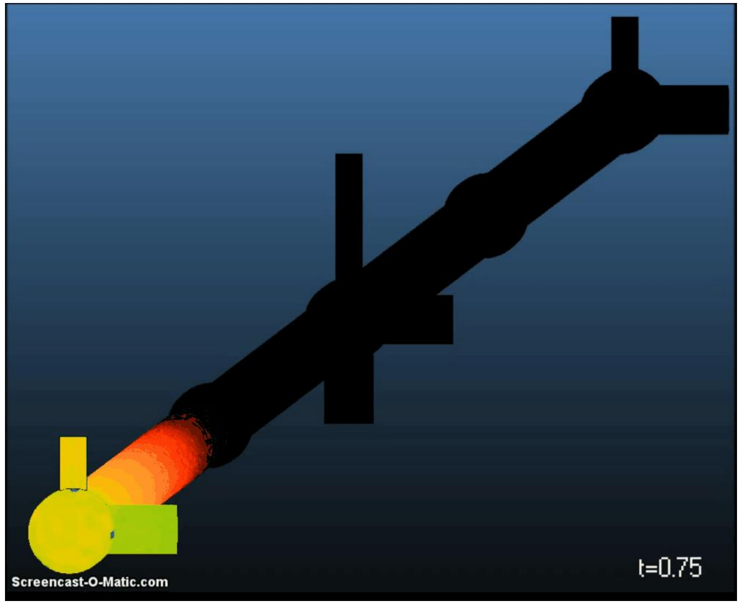

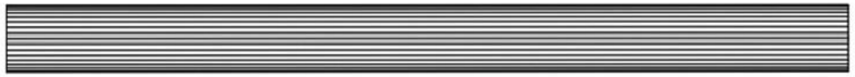

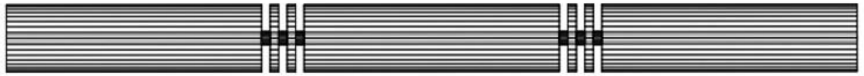

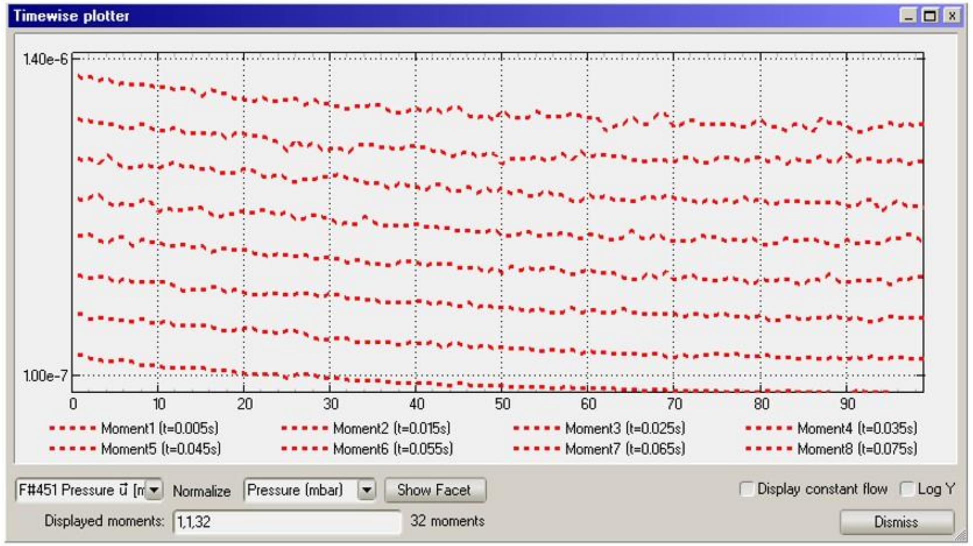

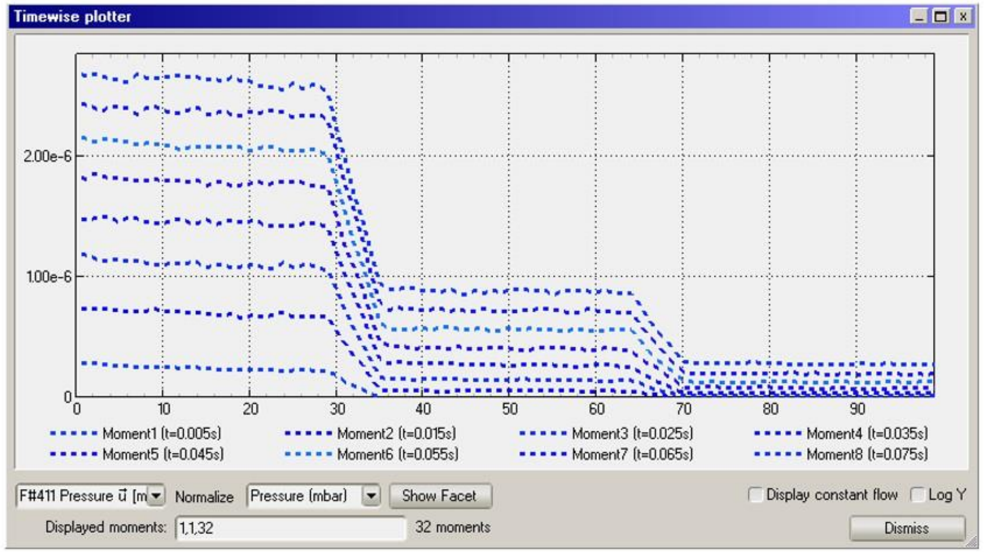

참고 문헌

- “Vacuum in Particle Accelerators : Modelling, Design and Operation of Beam Vacuum Systems” (John Wiley & Sons, Malyshev, Oleg B)
- “Accelerator School–SR and vacuum system” (Join Accelerator School 14, Yusuke Suetsugu)
- “진공과학입문” (청문각, 정석민 외)
- “진공공학” (한국경제신문 한경BP, 인상열 외)
- “진공기술실무” (홍릉과학출판사, 주장헌)
- “진공기술핸드북” (청문각, 홍승수 외 역)
- “진공기술강좌” (한국진공학회, 인상열)
- “진공기술강좌” (한국진공학회, 박종도)
- “진공튜토리얼” (한국진공학회, 하태균)