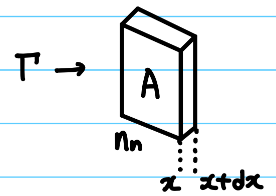
20강

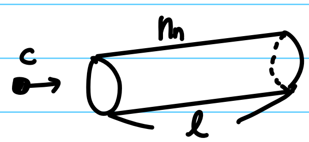
{ ① gas (Fick's law 유도)
② weakly ionized $\vec{B}=0$
③ 〃 $\vec{B}\neq 0$
④ fully ionized $\vec{B}\neq 0$ }



$$\Gamma(x+dx)=\Gamma(x)-n_n A\,dx\,\frac{\sigma}{A}\Gamma(x)$$

$$\Gamma(x)=\Gamma_0 e^{-\frac{x}{\lambda}},\quad \lambda=\frac{1}{n_n\sigma}\ :\ \text{mean free path}$$

*전자의 속도가 빠를 때

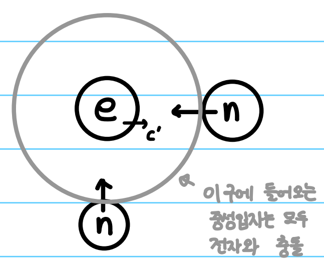


(during t)

$$\frac{l}{\text{충돌 수}}=\frac{l}{\text{입자 개수}},\quad \frac{ct}{n_n\pi d^2 ct}=\frac{1}{n_n\pi d^2}=\frac{1}{n_n\sigma}$$

d : 전자의 반경 + 중성입자의 반경

*전자의 속도가 느릴 때 (중성입자가 더 빠르게 움직이는 상황)



$$\frac{l}{\text{충돌 수}}=\frac{l}{\text{입자 개수}},\quad \frac{c't}{\frac{1}{4}n\bar{c}\,4\pi d^2 t}=\frac{c'}{n(\pi d^2)\bar{c}}=\frac{c'}{n\sigma\bar{c}}\sim\frac{1}{\sqrt{2}}\frac{1}{n\sigma}$$

(구 내부의)

molecule partial current $J=\frac{1}{4}n\bar{c}A$

maxwellian $\bar{c}\simeq\sqrt{2}c'$

· mean collision time : τ

$$\tau=\frac{\lambda}{c'}=\frac{1}{\sqrt{2}n\sigma c'}=\frac{kT}{\sqrt{2}nkT\sigma c'}=\frac{kT}{\sqrt{2}P\sigma c'}$$

(1 atm, 20°C → τ = 100 ps)

② weakly ionized $\vec{B}=0$

Diffusion and mobility in weakly ionized gases $\vec{B}=0$

neutral과의 충돌이 main

- $nm\left(\cancel{\frac{d\vec{u}}{dt}+(\vec{u}\cdot\nabla)\vec{u}}\right)=\pm ne\vec{E}-\nabla P-mn\nu\vec{u}$

편의상 무시

$mn\nu\vec{u}=\pm ne\vec{E}-\nabla P$

$p=nkT$, isothermal

전자도 충돌에 의해 종단속도가 나타날수 있다. ($\vec{u}=\mu\vec{E}$)

$$\vec{u}=\pm\frac{e}{m\nu}\vec{E}-\frac{kT}{m\nu}\frac{\nabla n}{n}=\pm\mu\vec{E}-D\frac{\nabla n}{n}\qquad\left(\mu=\frac{e}{m\nu},\ D=\frac{kT}{m\nu}\right)$$

μ: mobility, D: diffusion coefficient

- $\vec{\Gamma}=n\vec{u}=\pm\mu n\vec{E}-D\nabla n$

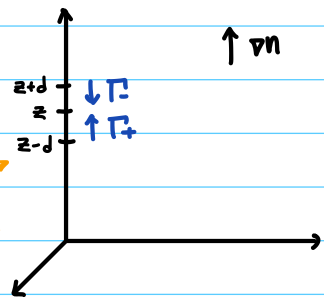
$\underline{-D\nabla n}$: Fick's law

(i) $\vec{E}=0$, $\vec{\Gamma}=-D\nabla n$
(ii) $\nabla n=0$, $\vec{\Gamma}=\pm\mu n\vec{E}$
(iii) $\nu=0$, Boltzmann relation

- Einstein's relation $\frac{D}{\mu}=\frac{m\nu}{e}\cdot\frac{kT}{m\nu}=\frac{kT}{e}$

① gas

· Adolf Gaston Eugene Fick's law



d가 λ(mean free path)가 되면,
$D=\frac{1}{2}\bar{c}d \sim D=\frac{kT}{m\nu}$ 같음

$$\Gamma_{net} = \Gamma_+ - \Gamma_-$$

$$= \frac{J_+ - J_-}{A}$$

} molecule partial current
$J = \frac{1}{4} n \bar{c} A$

n의 parameter가 z−d 인것!

$$= \frac{\frac{1}{4}n(z-d)\bar{c}\cancel{A} - \frac{1}{4}n(z+d)\bar{c}\cancel{A}}{\cancel{A}}$$

$$= \frac{1}{4}\bar{c}\left\{\left[n(\cancel{z}) - d\frac{dn}{dz}\right] - \left[n(\cancel{z}) + d\frac{dn}{dz}\right]\right\}$$

$$= -\frac{1}{2}\bar{c}d\frac{dn}{dz} = -\frac{1}{2}\bar{c}d\nabla n = -D\nabla n$$

$D \sim \bar{c}d \sim \frac{\lambda}{\tau}\lambda = \frac{\lambda^2}{\tau}$ ← $D = \frac{1}{2}\bar{c}d$ $\left(\begin{matrix} c \sim v_{TH} \\ d \sim \lambda \end{matrix}\right)$

$\sim \frac{(\Delta x)^2}{\Delta t}$

핵융합 플라스마에서는
이것을 잘 모름.

$$D = \frac{kT}{m\nu} = \frac{\frac{1}{2}m v_{TH}^2}{m v_{TH}/\lambda} = \frac{v_{TH}\lambda}{2} \sim \lambda^2\nu$$

$v_{TH} = \frac{\lambda}{\tau} = \lambda\nu$

· Ambipolar diffusion

$$\vec{\Gamma_e} = \vec{\Gamma_i} = \vec{\Gamma}, \quad n = n_i = n_e$$

$$\vec{\Gamma_i} = \mu_i n\vec{E} - D_i\nabla n$$
$$\vec{\Gamma_e} = -\mu_e n\vec{E} - D_e\nabla n$$

$$\Rightarrow \mu_i n\vec{E} - D_i\nabla n = -\mu_e n\vec{E} - D_e\nabla n$$

$$(\mu_i n + \mu_e n)\vec{E} = (D_i - D_e)\nabla n \quad \therefore \vec{E} = \frac{D_i - D_e}{\mu_i + \mu_e}\frac{\nabla n}{n}$$

$$\vec{\Gamma_i} = \mu_i\cancel{n}\frac{D_i - D_e}{\mu_i + \mu_e}\frac{\nabla n}{\cancel{n}} - D_i\nabla n$$

$$= \left(\frac{\mu_i D_i - \mu_i D_e}{\mu_i + \mu_e} - D_i\right)\nabla n = \frac{\cancel{\mu_i D_i} - \mu_i D_e - \cancel{\mu_i D_i} - \mu_e D_i}{\mu_i + \mu_e}\nabla n$$

$$= -\frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e}\nabla n = -D_a\nabla n \quad \left(D_a = \frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e}\right)$$

$$D_a = \frac{\mu_i D_e + \mu_e D_i}{\mu_i + \mu_e} \simeq D_i + \frac{\mu_i}{\mu_e}D_e \quad \left(\mu = \frac{e}{m\nu}, \ \mu_i \ll \mu_e \text{ 가정}\right)$$

$$= D_i + \frac{\frac{D_i \cancel{e}}{\cancel{k}T_i}}{\frac{D_e \cancel{e}}{\cancel{k}T_e}}\cancel{D_e} = D_i + \frac{T_e}{T_i}D_i \simeq 2D_i \ (\text{if } T_e = T_i) \longrightarrow \vec{\Gamma_i} = -2D_i\nabla n$$

e^- 가 먼저 빠져나가고,
이게 만드는 전기장이 이온을 끌어당겨서,
이온도 더 잘 빠져나간다.

21강

$$\frac{\partial n}{\partial t} + \nabla\cdot(n\vec{u}) = S_{ource} - S_{ink}$$

$\vec{\Gamma} = n\vec{u} = -D_a \nabla n$

$$\frac{\partial n}{\partial t} + \nabla\cdot(-D_a \nabla n) = 0$$

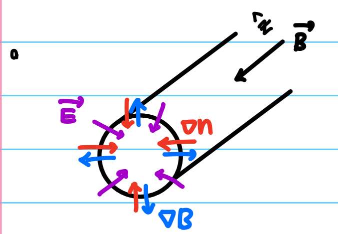
D_a : constant

$$\boxed{\frac{\partial n}{\partial t} - D_a \nabla^2 n = 0}$$

← 초기조건과 경계조건을 알면, 미분방정식을 풀수 있다.

③ weakly ionized $\vec{B}=0$

Diffusion and mobility in weakly ionized gases $\vec{B} \neq 0$

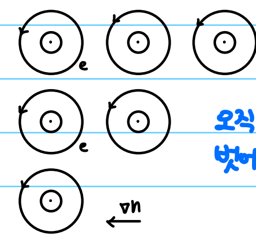


$\frac{\partial n}{\partial z} \rightarrow \Gamma_z = -D\frac{\partial n}{\partial z}$

$\frac{\partial n}{\partial r} \rightarrow$

$B \times \nabla P$

자기장이 있으면, drift 하므로 벽을 벗어날수 없음.



오직 collision으로만 벗어날수 있음.

$\vec{u_r}$에 관심이 있다!

* uniform magnetic field 가정 , 중성입자의 속도는 0으로 가정

$$0 = \pm ne(\vec{E} + \vec{u}\times\vec{B}) - kT\nabla n - mn\nu\vec{u}$$

$$mn\nu\vec{u} = \pm ne\vec{E} \pm ne\vec{u}\times\vec{B} - kT\nabla n$$

$$\begin{vmatrix} i & j & k \\ u_x & u_y & u_z \\ 0 & 0 & B \end{vmatrix}$$

$$\vec{u} = \pm\frac{e}{m\nu}\vec{E} \pm \frac{e}{m\nu}\vec{u}\times\vec{B} - \frac{kT}{m\nu}\frac{\nabla n}{n} = \pm\mu\vec{E} \pm \frac{e}{m\nu}\vec{u}\times\vec{B} - D\frac{\nabla n}{n}$$

$$u_x = \pm\mu E_x \pm \frac{e}{m\nu}u_y B - \frac{D}{n}\frac{dn}{dx} \quad , \quad u_y = \pm\mu E_y \mp \frac{e}{m\nu}u_x B - \frac{D}{n}\frac{dn}{dy}$$

$$= \pm\mu E_x \pm \frac{eB}{m\nu}\left(\pm\mu E_y \mp \frac{e}{m\nu}u_x B - \frac{D}{n}\frac{dn}{dy}\right) - \frac{D}{n}\frac{dn}{dx}$$

$$= \pm\mu E_x + \frac{\omega_c}{\nu}\mu E_y - \frac{\omega_c^2}{\nu^2}u_x \mp \frac{\omega_c}{\nu}\frac{D}{n}\frac{dn}{dy} - \frac{D}{n}\frac{dn}{dx}$$

$$\left(1+\frac{\omega_c^2}{\nu^2}\right)u_x = \pm\mu E_x - D\frac{1}{n}\frac{dn}{dx} + \underbrace{\frac{\omega_c}{\nu}\frac{e}{m\nu}\frac{B}{B}E_y}_{=\frac{\omega_c^2 E_y}{\nu^2 B}} \mp \underbrace{\frac{\omega_c}{\nu}\frac{kT}{m\nu}\frac{Be}{Be}\frac{1}{n}\frac{dn}{dy}}_{=\frac{\omega_c^2}{\nu^2}\frac{kT}{neB}\frac{dn}{dy}}$$

$$= \pm\mu E_x - D\frac{1}{n}\frac{dn}{dx} + \frac{\omega_c^2}{\nu^2}\left(\frac{E_y}{B} \mp \frac{kT}{neB}\frac{dn}{dy}\right)$$

$$u_x = \pm\frac{\mu}{1+\omega_c^2/\nu^2}E_x - \frac{D}{1+\omega_c^2/\nu^2}\frac{1}{n}\frac{dn}{dx} + \frac{\omega_c^2/\nu^2}{1+\omega_c^2/\nu^2}\left(\frac{E_y}{B} \mp \frac{kT}{neB}\frac{dn}{dy}\right)$$

$\left(\frac{B\times\nabla P}{nqB^2} = \vec{u_D}\right)$

$$= \underbrace{\pm\mu_\perp E_x}_{\text{mobility}} \underbrace{- D_\perp\frac{1}{n}\frac{dn}{dx}}_{\text{diffusivity}} \pm \underbrace{\frac{\omega_c^2/\nu^2}{1+\omega_c^2/\nu^2}\left(\vec{u_E} + \vec{u_D}\right)}_{E\times B,\ \text{diamagnetic drift}}$$

22강

복습

Diffusion in plasmas.

$$0 = \pm ne(\vec{E}+\vec{u}\times\vec{B}) - kT\nabla n - mn\nu\vec{u}$$

Collision는 중성입자들에 의한 것

(i) weakly ionized , $B=0$

$$\vec{u} = \pm\mu\vec{E} - D\frac{\nabla n}{n} \quad , \quad \mu = \frac{e}{m\nu} \quad D = \frac{kT}{m\nu} \quad , \vec{\Gamma} = n\vec{u}$$

(ii) weakly ionized , $B \neq 0$

$$\vec{u_\perp} = \pm\boxed{\frac{\mu}{1+\omega_c^2/\nu^2}}\vec{E} - \boxed{\frac{D}{1+\omega_c^2/\nu^2}}\frac{\nabla n}{n} + \frac{(\vec{u_E}+\vec{u_D})\omega_c^2/\nu^2}{1+\omega_c^2/\nu^2}$$

collision을 무시하고 얻은 $\vec{u_E}$와 $\vec{u_D}$ 였는데, 이제 collision을 고려하면 둘다 $\frac{\omega_c^2/\nu^2}{1+\omega_c^2/\nu^2}$ 만큼 줄어들어 나타난다.

$$\mu_\perp = \frac{1}{1+\omega_c^2/\nu^2}\mu \qquad D_\perp = \frac{1}{1+\omega_c^2/\nu^2}D$$

→ 자기장이 있으면 mobility와 diffusivity 줄어듦

경우 ① $\omega_c^2/\nu^2 \ll 1$ [collision 매우 많은 경우 / 자기장이 매우 작은 경우

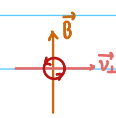
$\mu_\perp \sim \mu$, $D_\perp \sim D$

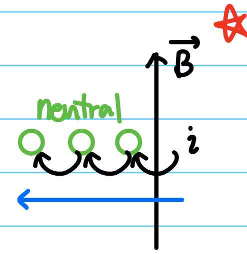
↳ $D_\perp = \frac{kT}{m\nu} \propto \frac{1}{\nu}$ 자기장이 없는 경우 collision이 적을수록 잘 퍼져나간다.

↳ $D_\perp = \frac{kT}{m\nu} \propto \frac{1}{m}$ 질량이 클수록 덜 퍼져나감

경우 ② $\omega_c^2/\nu^2 \gg 1$ - 자기장이 매우 큰 경우

$\mu_\perp \sim \frac{\mu}{\omega_c^2/\nu^2}$, $D_\perp \sim \frac{D}{\omega_c^2/\nu^2}$ Diffusion해서 나가야 하는데, 자기장이 붙잡는 상황





↳ $D_\perp \sim \frac{kT/m\nu}{\omega_c^2/\nu^2} = \frac{kT\nu}{\omega_c^2 m} \propto \nu$ neutral과의 collision이 있으므로 자기력선을 빠져나갈 수 있다.

↳ $r_L = \frac{m\nu}{|q|B}$; $D_\perp \propto m$ 한 번 충돌해서 빠져나가는데 질량이 크면, r_L도 커서 더 많이 이동할 수 있다.

<gas>

$$D = \frac{(\Delta x)^2}{\Delta t} = \frac{\lambda^2}{\tau} = \nu\lambda^2$$

$(\Delta x = \lambda , \Delta t = \tau)$

λ : mean free path

τ : collision time

Δx : characteristic length

Δt : characteristic time

<경우①>

$$D = \frac{kT}{m\nu} \sim \frac{m v_{th}^2}{m\nu} \sim \frac{v_{th}^2}{\nu} = \frac{(\nu\lambda)^2}{\nu} \sim \nu\lambda^2$$

<경우②>

$$D_\perp = \frac{kT\nu}{\omega_c^2 m} \sim \frac{\cancel{m v_{th}^2}\nu}{\left(\frac{\cancel{v_{th}}}{r_L}\right)^2 \cancel{m}} = \nu r_L^2$$

$(\Delta x = r_L , \Delta t = \tau)$

r_L : larmor radius

τ : collision time

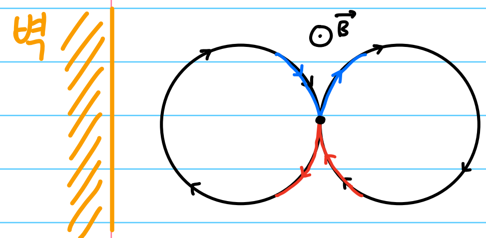
↳ 한번 충돌할 때 하면 r_L 단위로 빠져나감.

(자기장을 걸면, physics가 달라짐)

· Fully ionized , $\vec{B} \neq 0$

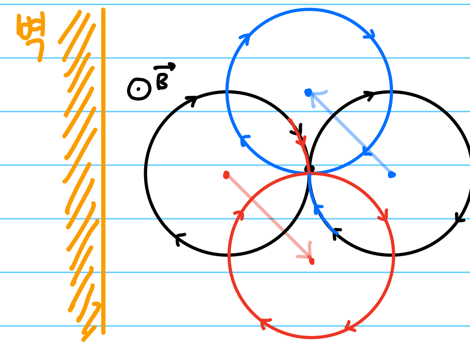
⟨ like-particle collision ⟩ → diffusion에 영향을 주지 않음.

180˚ collision



→ 서로 자리만 바꿈
(COM은 전혀 변하지 않음)

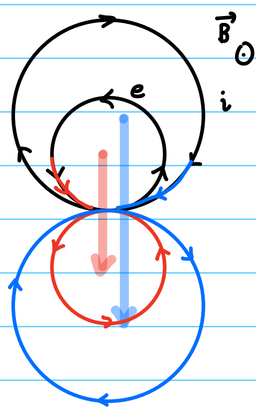
90˚ collision



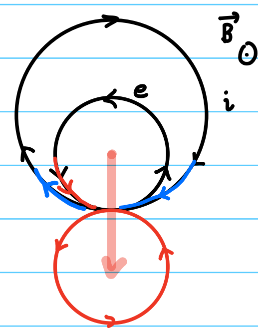
→ 위치 변화는 있지만
(COM은 전혀 변하지 않음)

⟨unlike-particle collision⟩

180˚ collision ($M \approx m$)



180˚ collision ($M \gg m$)



$\nu \propto T_e^{-\frac{3}{2}}$ (쌩하고 지나침)

$r_L = \frac{mv_\perp}{qB}$

$B\uparrow$: $D\downarrow$

$T\downarrow \rightarrow \nu_{ei}\uparrow$: $D\uparrow$

$n\uparrow$: $D\uparrow$

(D의 관계 예상 사고실험)

Recall

*Single fluid equation (Magneto Hydro Dynamics : MHD (자기유체역학)

(i) $\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0 , \quad \frac{\partial \sigma}{\partial t} + \nabla\cdot\vec{J} = 0$

(ii) $\boxed{\rho\frac{d\vec{v}}{dt} = \sigma\vec{E} + \vec{J}\times\vec{B} - \nabla P}$

(iii) $\boxed{\vec{E} + \vec{v}\times\vec{B} = \eta\vec{J} + \frac{\vec{J}\times\vec{B} - \nabla P_e}{ne}}$

(iv) $\frac{d}{dt}\left(\frac{\rho^{\gamma}}{P}\right) = 0$

(v) $\varepsilon_0 \nabla\cdot\vec{E} = \sigma , \quad \nabla\cdot\vec{B} = 0$

$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} , \quad \nabla\times\vec{B} = \mu_0\vec{J} + \mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t}$

think of steady state plasma.

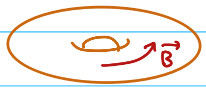
$$\rho \cancel{\frac{d\vec{v}}{dt}} = \underbrace{\cancel{\sigma \vec{E}}}_{\text{무시}} + \vec{J}\times\vec{B} - \nabla P$$

$$\vec{E} + \vec{v}\times\vec{B} = \eta\vec{J} + \underbrace{\cancel{\frac{\vec{J}\times\vec{B} - \nabla P_e}{ne}}}_{\text{무시}}$$

→

$$\vec{J}\times\vec{B} = \nabla P \quad \cdots (A)$$

$$\vec{E} + \vec{v}\times\vec{B} = \eta\vec{j} \quad \cdots (B)$$



우리의 관심사는 벽으로 가는 플라즈마 이므로 $v_\perp$에 관심이 있음.

$\vec{B}\times(\vec{B}\times\vec{u}) = \vec{B}(\vec{B}\cdot\vec{u}) - \vec{u}B^2$

$$\vec{E}\times\vec{B} + (\vec{v}\times\vec{B})\times\vec{B} = \eta\vec{j}\times\vec{B}$$

$$\vec{E}\times\vec{B} - B^2 v_\perp = \eta_\perp \nabla P = \eta_\perp kT\nabla n$$

$$\boxed{\vec{v}_\perp = \frac{\vec{E}\times\vec{B}}{B^2} - \frac{\eta_\perp kT\nabla n}{B^2}}$$

$$\vec{\Gamma} = n\vec{v}_\perp = -\frac{n\eta_\perp kT\nabla n}{B^2} = -D_\perp\nabla n$$

$$\boxed{D_\perp = \frac{n\eta_\perp kT}{B^2}} \quad \left(\eta_\perp = \frac{m\nu_{ei}}{ne^2} : \text{resistivity}\right)$$

자연스럽게 ambipolar diffusion 형태로 나타남. ?

$\vec{E}$에 의한 mobility도 나타나지 않음.

- $B\uparrow$: $D\downarrow$
- $\nu_{ei}\uparrow$: $D\uparrow$
- $n\uparrow$: $D\uparrow$
- $T_e\uparrow$: $D\downarrow$

$\eta_\perp \propto v_\perp/n$, $v_\perp \propto n$

∴ $\eta_\perp$는 n의 함수가 아님. ?

$\eta_\perp \propto \nu_{ei} \propto T_e^{-3/2}$

↳ $D_\perp \propto T_e^{-1/2}$

비교

· weakly ionized, $\vec{B}\neq 0$

$$D_\perp = \frac{kT}{m\nu}\frac{\nu^2}{\omega_c^2} = \frac{kT\nu}{m\omega_c^2} \propto T$$

$\propto 1/B^2$

(ν : neutral과의 collision)

· fully ionized

$$D_\perp = \frac{n\eta_\perp kT}{B^2} \quad \left(\eta_\perp = \frac{m\nu_{ei}}{ne^2}\right) \propto T_e^{-1/2}$$

$\propto 1/B^2$

· David Bohm의 실험 → $\boxed{D_\perp = \frac{1}{16}\frac{kT}{eB}}$

이론 계산과 다르다.

23강

* Diffusion in plasmas

(i) gas : $\vec{\Gamma} = -D\nabla n$, $D = \frac{(\Delta x)^2}{\Delta t} \sim \lambda^2 \nu$

비슷

(ii) weakly ionized gas, $\vec{B} = 0$: $\vec{\Gamma} = \pm n\mu\vec{E} - D\nabla n$, $D = \frac{kT}{m\nu}$

(iii) weakly ionized gas, $\vec{B} \neq 0$: $\vec{\Gamma} = \pm n\mu_\perp\vec{E} - D_\perp\nabla n + \frac{n\omega_c^2/\nu^2}{1+\omega_c^2/\nu^2}(\vec{u_E} + \vec{u_D})$, $D_\perp = \frac{kT/m\nu}{1+\omega_c^2/\nu^2}$

(iv) fully ionized plasma, $\vec{B} \neq 0$: $\vec{\Gamma} = \frac{\vec{E}\times\vec{B}}{B^2} - D_\perp\nabla n$, $D_\perp = \frac{n\eta\Sigma kT}{B^2}$ $\sim \frac{kT/m\nu}{\omega_c^2/\nu^2}$

① ν $kT = \frac{1}{2}mv^2 = \text{const}$ 가정 , $v \sim \frac{\lambda}{\tau} = \nu\lambda$

(i) $D \sim \lambda^2\nu \sim \frac{v^2}{\nu^2}\nu \sim \frac{v^2}{\nu} \propto \frac{1}{\nu}$

(ii) $D = \frac{kT}{m\nu} \propto \frac{1}{\nu}$

(iii) $D_\perp = \frac{kT/m\nu}{\omega_c^2/\nu^2} \propto \nu$

(iv) $D_\perp = \frac{n\eta\Sigma kT}{B^2} = \frac{nkT}{B^2}\frac{m\nu_{ei}}{ne^2} \propto \nu_{ei}$

자기장이 있으면 ν에 비례
없으면 ν에 반비례.

② n $\nu = n\sigma v$

(i) $D \sim \frac{v^2}{\nu^2}\nu = \frac{v^2}{\nu} = \frac{v^2}{n\sigma v} = \frac{v}{n\sigma} \propto \frac{1}{n}$

(ii) $D = \frac{kT}{m\nu} \sim \frac{1}{\nu} = \frac{1}{n\sigma v} \propto \frac{1}{n}$

(iii) $D_\perp = \frac{kT/m\nu}{\omega_c^2/\nu^2} \sim \nu \propto n$

(iv) $D_\perp = \frac{n\eta\Sigma kT}{B^2} \sim n\eta = \cancel{n}\frac{m\nu_{ei}}{\cancel{n}e^2} \propto \nu_{ei} = \frac{ne^4}{16\pi\varepsilon_0^2 m^2 v^3} \propto \frac{n}{v^3} \propto nT^{-3/2} \propto n$

자기장이 있으면 n에 반비례
없으면 n에 비례
(입자가 많아야 잘 충돌해서 빠져나감)

③ T

(i) $D \sim \left(\frac{v}{\nu}\right)^2\nu = \frac{v^2}{\nu} = \frac{v^2}{n\sigma v} \sim v \propto T^{1/2}$

(ii) $D = \frac{kT}{m\nu} = \frac{kT}{mn\sigma v} \sim \frac{T}{v} \propto T^{1/2}$

(iii) $D_\perp = \frac{kT/m\nu}{\omega_c^2/\nu^2} \sim \frac{kT/\nu}{1/\nu^2} = kT\nu \sim Tv \propto T^{3/2}$

딱 두가지 경우로 구분할 수 없다!

(iv) $D_\perp = \frac{n\eta\Sigma kT}{B^2} \sim \eta T = \frac{m\nu_{ei}}{ne^2}T \sim T^{-3/2}\cdot T \propto T^{-1/2}$

플라즈마끼리 충돌↑, D↑
$\left(\because \nu_{ei} \propto \frac{n}{v^3} \propto nT^{-3/2}\right)$
온도↑ → 충돌↓ ∴ T↑ → D↓

④ m $kT = \frac{1}{2}mv^2 = const$ 가정

(i) $D \sim \left(\frac{v}{\nu}\right)^2 \nu = \frac{v^2}{\nu} = \frac{v^2}{n\sigma v} \sim v \propto \frac{1}{\sqrt{m}}$

(ii) $D = \frac{kT}{m\nu} = \frac{kT}{mn\sigma v} \sim \frac{mv^2}{mv} \sim v \propto \frac{1}{\sqrt{m}}$

자기장이 있으면 $\sqrt{m}$에 비례
없으면 $\sqrt{m}$에 반비례.

(iii) $D_\perp = \frac{kT/m\nu}{\omega_c^2/\nu^2} = \frac{\cancel{m}v^{\cancel{2}}/\cancel{m}n\sigma \cancel{v}}{B^2e^2/m^2n^2\sigma^2v^2} = \frac{m^2n^2\sigma^2v^3}{Be^2n\sigma} \sim m^2v^3 \sim m^2\left(\frac{1}{\sqrt{m}}\right)^3 \propto \sqrt{m}$

(iv) $D_\perp = \frac{n\eta\Sigma kT}{B^2} \sim nkT \sim m\nu_{ei}mv^2 \sim m\left(\frac{1}{m^2v^3}\right)mv^2 \sim \frac{1}{v} \propto \sqrt{m}$

$\eta = \frac{m\nu_{ei}}{ne^2}$

⑤ $\vec{B}$

(iii) $D_\perp = \frac{kT/m\nu}{\omega_c^2/\nu^2} \sim \frac{1}{\omega_c^2} \propto \frac{1}{B^2}$

(iv) $D_\perp = \frac{n\eta\Sigma kT}{B^2} \propto \frac{1}{B^2}$

classical transport
neoclassical transport
anomalous transport

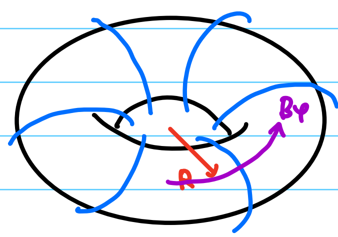
· 핵융합 플라즈마 (iv)의 경우

(예측) $D_\perp \propto \frac{1}{B^2}, T^{-1/2}$ ↔ David Bohm의 실험 : $D_B = \frac{kT}{16eB}$

$D_i \sim 40D_e$, $D \sim 10^{-4}\,m^2/s$ ↔ $D_i \sim D_e$, $D \sim 1\,m^2/s$

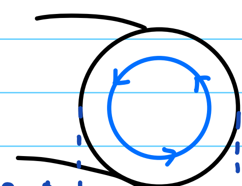
여태껏 유도한 것과 실제가 차이가 너무 크게 나타남.

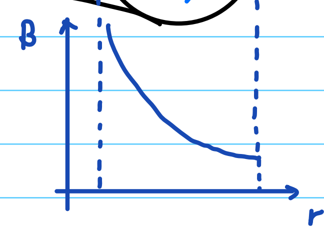
< banana orbit >



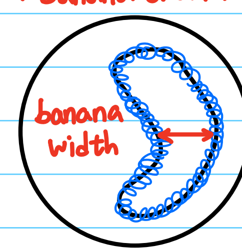
$B_\phi = \frac{\mu_0 IN}{2\pi R}$

단면 →





→



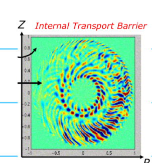
∇B, curvature drift 뿐만 아니라, parallel 방향의 mirror 효과도 생긴다.

$D = \frac{(\Delta x)^2}{\Delta t}$ 에서 Δx가 이제 r_L이 아니라, banana width가 된다. 이를 고려해보니

$D_i \sim (3\sim5)\,m^2/s$ (어느정도 비슷)

$D_e \sim 10^{-2}\,m^2/s$ (아직 한참부족)

Turbulence에서 그 문제를 찾는 중
(난류를 만들면 잘 퍼져나감.)



eddy의 길이

$D = \frac{(1cm)^2}{1ms}$ ~ 이론과 비슷