Introduction to plasma Physics

* Content:

1. Historical background
2. plasma defination.
3. plasma parameters.
4. plasma criteria.
5. plasma classification.
6. plasma applications.

د/ إبراهيم العماش

Any field

⇒ عارف	طالب	عالم	
terminology	concept	principle.	law
↓	↓	↓	↓
knows	understant	follow	apply

* Plasma history:

- when the blood is cleared of its various corpuscles there remains a transparent liquid which was named plasma (In Greek: jelly or moldable substance)

1927: Langmuir used it to describe the ionized gas.
→ radio transmission: Ionospheric plasma
→ current rectification: Gasous electron tube.

blood plasma carries white and red corpuscles such as positive / negative charges.

1940: Alfvèn and MHD for Solar flares and wind.

MHD → magnetic reconnection. / → dynamo theory.

1952: Controlled thermonuclear (hydrogen bomb).

1958: Van Allen radiation belts (space plasma).

1970: laser plasma physics → plasma processing

Plasma defination: (Qualiletevely).

①

Plasma: It is an ionized medium which is

① Quasineutrall ② exhibits a collective behaviour

- plasma is a state of a any matter (it any)

That has
① Ionized
② quasineutrally.
③ Behave collectively.

State: could be:
- plasma gas of
- " liquid of
- " solid of

* Ionization; net charge $\neq 0$

neutral gas

+ + + +
- - - -

$Q=0$: (net charge $\Delta Q = 0$)

Ionized gas

+ + + + +
- - - - -

$Q_+ > Q_-$

$Q_- > Q_+$

$Q \neq 0$ (net charge $\Delta Q \neq 0$).

- It is a process by which an atom or molecule acquires a negative or positive charge by gaining or lossing energy.

H $E_{Ion} = 13.6$ eV/atom

$E_0 = 12.5$ eV/atom

* Quasineutrallity: (locally)

neutrall gas

$\Delta Q = 0$

Ionized gas

$\Delta Q \neq 0$

charge imbalance globally

Plasma gas

$\Delta Q \simeq 0$

charge imbalance locally

- For a ionized gas to be plasma

$E \simeq 0 \Rightarrow Q_+ \simeq Q_-$

$\Delta Q \neq 0$

→ Saha eq:

$$\frac{n_i}{n_n} \sim 2.4 \times 10^{21} \frac{T^{3/2}}{n_i} e^{-U_i/k_B T}$$

; U_i: ionization energy

→ for ordinary air: $\frac{n_i}{n_n} \simeq 10^{-122}$

③

④

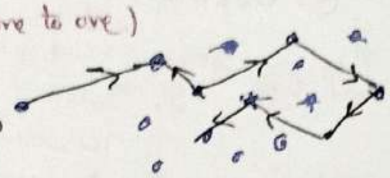
* Collective behaviour :

(i) Individual behaviour:

neutral gas

- Short-range interaction.
- Contact force.
- mutual collision. (one to one)
- Straight line trajectory
- one time interaction

"Hard sphere collision"
Short-range interaction



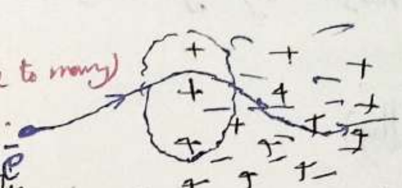
- The particle interact only with one at a time.
- The " doesn't feel the other.
- The ~~orbit~~ trajectory of the particle is a straight line.
- The motion is controlled by short-range force such as collisions force
  Contact force.

(ii) Collective behaviour:

Plasma

"Coulomb collision"
"Long-range interaction"

- Long-range interaction
- Field force
- Coulomb collision (one to many)
- curvylinear trajectory.
- Simultanously interaction



inter-particle interaction
- short → collision → one to one
- long → electromagnetic → one to many

- The particle interact simultanously with many other charged particles (not just binary mutual collision).
- The net force on the charge due to many other charges in certain range.
- The trajectory of the particle is curvy.
- The motion is controlled by long-range force or field force
  such EM force.

Neutral State
- net charge = 0
- Individual behavior
- Short range interaction: hard sphere ~~coulomb force~~
- contact force
- mutual collision or binary collision
- straight line trajectory

Plasma
- net charge ≃ 0.
- collective behavior. Coulomb collision
- Long-range interaction: Lorentz force.
- Field force
- Coulomb collision
- curvy trajectory.

Plasma frequency:

Plasma parameter ⇒ time scale, length

(natural frequency, inertial)

Assume a plasma consists of electrons with charge $(-e)$ and mass m_e and same number of ions (e) and mass m_i: $n_i \simeq n_e \simeq n_o$

$T_i \simeq T_e \simeq T$.

- The linearized eqs:

$$n_e = n_o + n_e(r,t) \quad (1)$$

$$\frac{\partial n_e(r,t)}{\partial t} + n_o \nabla \cdot u_e(r,t) = 0 \quad (2)$$

$$\frac{\partial u_e}{\partial t} = -\frac{e}{m_e} E(r,t) \quad (3)$$

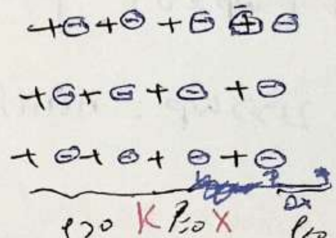
$$\rho = -e[n_o + n_e] + e n_o = -e n_e(r,t) \quad (4)$$

- Restoring force: $E \propto n_o$
- Inertia: m

$$\nabla \cdot E = \frac{\rho}{\varepsilon_o} = -\frac{e}{\varepsilon_o} n_e(r,t) \quad (5)$$

$\xleftarrow{e^2 n_o k_o}$ $F \equiv K_p \nabla \cdot E$

$K \propto \frac{e n_o^2}{\varepsilon_o}$



$$\nabla \cdot (3) \Rightarrow \frac{\partial}{\partial t} \nabla \cdot u = -\frac{e}{m_e} \nabla \cdot E$$

$$(2) \Rightarrow \nabla \cdot u_e = \frac{1}{n_o} \frac{\partial n}{\partial t}$$

$$\frac{1}{n_o} \frac{\partial}{\partial t} \frac{\partial}{\partial t} n = -\frac{e}{m_e} \nabla \cdot E \rightarrow m_e \frac{\partial^2 n}{\partial t^2} = -e n_o \nabla \cdot E \rightarrow F = -KX$$

$\nabla \cdot E$

$$\text{from } (5) \Rightarrow \frac{\partial^2 n_e}{\partial t^2} = -\frac{n_o e}{m_e} \cdot -\frac{e}{\varepsilon_o} n_e(r,t)$$

- restoring force: $-\frac{e^2 n_o}{\varepsilon_o} n_e \equiv -KX$ K X
- Inertia: m_e

$$\frac{\partial^2 n_e}{\partial t^2} = -\left(\frac{n_o e^2}{\varepsilon_o m_e}\right) n_e(r,t)$$

$\nu_c \sim \frac{n_e e^2}{\sigma m}$ — collision frequency; σ — electrical conductivity

$$\frac{\partial^2 n_e}{\partial t^2} + \omega_p^2 n_e(r,t) = 0$$

$$\text{where } \omega_p^2 = \frac{n_o e^2}{\varepsilon_o m_e} \Rightarrow \omega_p = \sqrt{\frac{e^2 n_o}{\varepsilon_o m}}$$

restoring force; create fluctuation of perturbation

$$\omega_p = \sqrt{\frac{K}{m}}$$

$$\boxed{K \equiv \frac{e n_o^2}{\varepsilon_o}}$$ medium const

$$\omega_p = \left(\frac{e^2 n_o}{\varepsilon_o m}\right)^{1/2} \simeq C\sqrt{n_o} \ \frac{rad}{sec}; \ n_o(cm^{-3})$$

$\omega_p \simeq 56\sqrt{n_e(m^{-3})}$ rad/sec

$f_p \simeq 9\sqrt{n_e(m^{-3})}$ Hz

$10^{19} m^{-3}$

for n_e: $\omega_p \sim 1.8 \times 10^{11}$ rad/sec, $f_p \sim 28$ GHz

$C = 5.64 \times 10^4$

$$(5) \quad \boxed{n_e(r,t) = n_e(r) e^{-i\omega_p t}}$$

$$n_e(r,t) = n_e(r) \cos(\omega_p t)$$

$$\tau_p = \frac{1}{\omega_p}:$$ plasma time response to external perturbation

~ 5.6 ps

microwave.

$-\omega_p \propto n_0$ | $\tau_p \propto \frac{1}{n_0} \rightarrow$ more particles less time to response to E.

$\propto e^2$ | $\propto \frac{1}{e^2} \rightarrow$ " charge " " " " to E.

$\propto \frac{1}{\varepsilon_0}$ | $\propto \varepsilon_0 \rightarrow$ high premittivity more time " " E.

$\propto \frac{1}{m}$ | $\propto m \rightarrow$ heavy mass " " " " ".

Debye

* **Collision frequency (ν):**

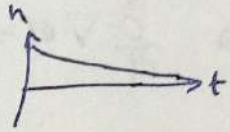
$$\frac{d^2 n}{dt^2} + \nu \frac{dn}{dt} + \omega_p^2 n = 0 \; ; \; \nu = \frac{b}{n_0 m} = \frac{b}{\rho_m} \qquad \nu = \frac{b}{m}$$

(collision factor)

(i) light damping ($\simeq$ collisionless) $\omega_p \gg \nu \Rightarrow n(r,t) = n(r)\, e^{-\nu t} \cos(\omega_p t)$

(ii) critical ($\omega_p = \nu$) $e^{-\nu t}$

(iii) heavy: $\nu \gg \omega_p$: $n(r,t) = n(r)\, e^{-\frac{\nu}{2} t}$



$\rightarrow$ So, we in plasma intersted in light damping ($\nu \ll \omega_p$).

* **Thermal pressure:**

collision $\rightarrow$ with neutral; $\rightarrow$ with charges, Coulomb collision

$\hookrightarrow$ deflection of charges with 90°. when it pass near the charges.

$$\frac{\partial^2 n_e}{\partial t^2} + \nu \frac{\partial n_e}{\partial t} - V_{the}^2 \nabla^2 n_e + \omega_p^2 n_e = 0$$

$$V_{the} = \frac{K T_e}{m_e}$$

(i) $\nu \rightarrow 0$, $\omega_p \rightarrow 0$

$$\frac{\partial^2 n_e}{\partial t^2} + V_{the}^2 \nabla^2 n_e = 0$$

* for ionosphere $n_e \simeq 10^{12}\, m^{-3}$

$\omega_{pe} \sim 56\sqrt{n_e} \simeq 6 \times 10^7 \frac{rad}{sec}$

$f_{pe} \sim 10\, MHz = \frac{\omega_{pe}}{2\pi}$

(ii) $\nu \rightarrow 0$, ~~V_{the}~~ $\rightarrow 0$

$$\frac{\partial^2 n_e}{\partial t^2} + \omega_p^2 n_e = 0$$

(iii) $V_{the} \rightarrow 0$

$$\frac{\partial^2 n_e}{\partial t^2} + \nu \frac{\partial n_e}{\partial t} + \omega_p^2 n_e = 0$$

$$V = \mu E - \frac{D}{n}\frac{\partial n}{\partial x}$$

$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{\text{Area}}{\text{time}}$$

$$\mu = \frac{q}{m\nu}$$

(iv) $\frac{1}{\nu}\frac{\partial^2 n_e}{\partial t^2} + \frac{\partial n_e}{\partial t} - \frac{V_{the}^2}{\nu} \nabla^2 n_e + \frac{\omega_{pe}^2}{\nu} n_e = 0$

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

6

$$\frac{1}{\nu}\frac{\partial^2 n_e}{\partial t^2} + \frac{\partial n_e}{\partial t} - D_e \nabla^2 n_e + \frac{\omega_{pe}^2}{\nu} n_e = 0 \; ; \; D = \frac{K T_e}{m_e \nu_e} = \frac{(\text{mean free path})^2}{\text{collision time}}$$

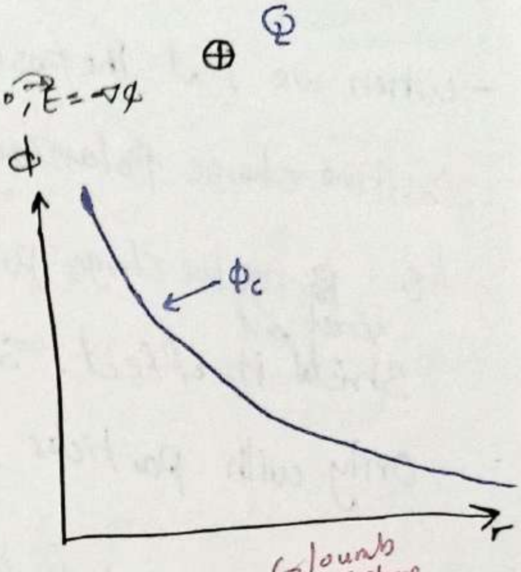
$\hookrightarrow$ Diffusion coefficient.

Debye Length

i) Test charge in Vacuum:

- The electrostatic potential due to Q (Coloumb potential)

$$\nabla \cdot E = \frac{Q}{\varepsilon_0} \quad \Bigg| \quad \begin{aligned} &\nabla \cdot E = \frac{\rho}{\varepsilon_0} \\ &\nabla \cdot B = 0 \\ &\nabla \times E = -\frac{\partial B}{\partial t} \overset{\approx 0}{} \Rightarrow \nabla \times (\nabla \phi) = 0 \; ; \; E = -\nabla \phi \\ &\nabla \times B \overset{\approx 0}{=} \mu_0 \left[J + \varepsilon_0 \frac{\partial E}{\partial t} \right] \end{aligned}$$

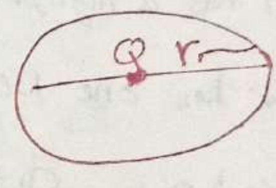


$$\because \quad E = -\nabla \phi$$

$$\nabla^2 \phi = -\frac{Q}{\varepsilon_0} \Rightarrow \frac{d^2 \phi_c(r)}{dr^2} = -\frac{Q}{\varepsilon_0}$$

$$\phi_c(r) = \frac{1}{\varepsilon_0} \underbrace{\frac{1}{4\pi r}}_{\text{circumference of sphere}} Q$$

$$\phi_c \sim \frac{1}{r}$$



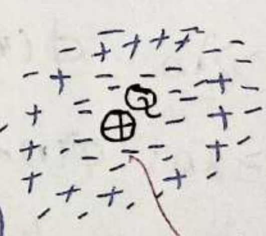
$$\lim_{r \to \infty} \phi_c(r) \to 0$$

radius of effect (influence)

(ii) Test charge in plasma:

$$\nabla^2 \phi = -\frac{Q}{\varepsilon_0} + \frac{\rho}{\varepsilon_0} \quad ; \quad \rho = e n_0 e^{\frac{e\phi}{k_B T}}$$

$$\simeq e n_0 \left(1 + \frac{e\phi}{k_B T} + \cdots \right)$$



$$\rho \simeq \frac{e^2 n_0}{\varepsilon_0 k_B T_e} \phi$$

spatial simple harmonic motion → oscillation in space.

$$\nabla^2 \phi_D - \left(\frac{e^2 n_0}{\varepsilon_0 k_B T_e} \right) \phi_D(r) = -\frac{Q}{\varepsilon_0}$$

ω spatial frequency.

$$\nabla^2 \phi_D - K_D^2 \, \phi(r)_D = -\frac{Q}{\varepsilon_0} \quad ; \quad K_D^2 = \frac{e^2 n_0}{\varepsilon_0 k_B T_e}$$

Restoring force ($e^2 n_0$)

create displacement ($k_B T_e$)

$$\lambda_D^2 = \frac{\varepsilon_0 k_B T_e}{e^2 n_0}$$

$$\phi_D(r) = \phi_c \, e^{-K_D r}$$

$$\boxed{\phi_D(r) = \phi_c \, e^{-\frac{r}{\lambda_D}}}$$

$$\phi_D \sim \frac{1}{r} e^{-r}$$

at $r \to \lambda_D$ $\quad \phi_D = e^{-1} \approx 0.37 \, \phi_c$

at $r \approx 10 \lambda_D$ $\quad \phi_D \approx 0.01 \, \phi_c \to 0$

- At $r \gg \lambda_D$

$\phi \longrightarrow 0$

* Physical mechanism:

- when we Put the positive test charge in the plasma, the Positive charge ~~polarizes~~ (attracts) the negative charge, i.e. negative charges polarize toward the positive charge and shield its effect. So, a charged plasma interacts effectively only with particles situated at distance less than one Debye length (λ_D) and it has a negligible influence on particles lying at distances greater than one Debye length.

screen out

$\phi(r) \propto \frac{1}{r} e^{-r}$

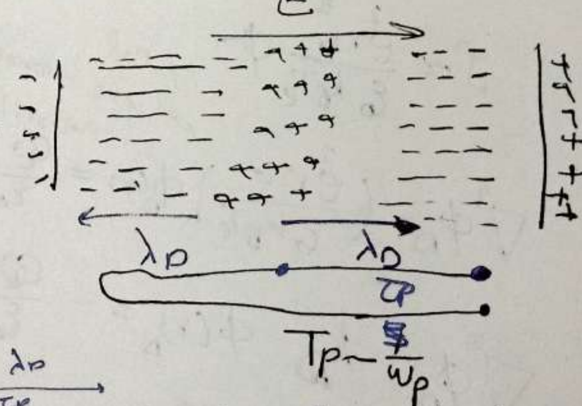
(i) $r \ll \lambda_D$: $\phi(r) \longrightarrow \phi_0(r)$: charge in vacuum.

(ii) $r \gg \lambda_D$: $\phi(r) \longrightarrow 0$: charge in plasma.

(iii) $r \simeq \lambda_D$: $\phi(r) \sim \frac{\phi_e}{e} \sim 0$

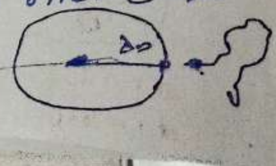
* Applying an Electric field:

- when we apply an electric field, the plasma will displace a distance with speed v_{th} λ_D ~~...~~. then it will oscillate with frequency ω_p.



$\xrightarrow[v_{th},\ \tau_p]{\lambda_D}$

① - λ_D: is the maximum distance over which the electrons can move with respect to the ions, against the electrostatic force with its thermal energy
② the distance at that electrons move it at τ_p with velocity v_{th}. (maximum displacement of oscillation)
③ the distance beyond it, the ions has no influence on other charges

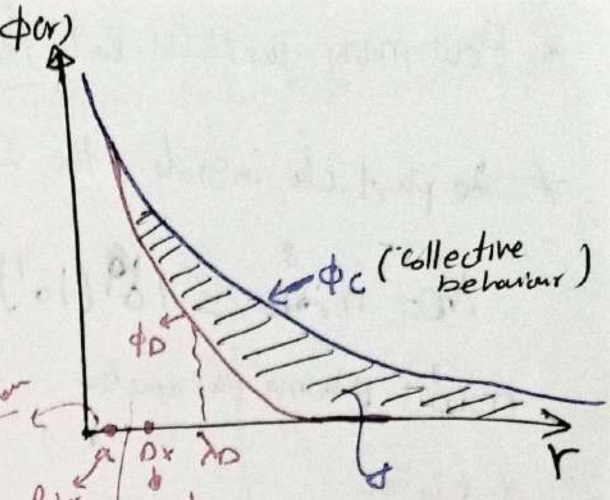


$$\lambda_D = \sqrt{\frac{e_0^2 n_0}{\varepsilon_0 K_B T}}$$

$$\lambda_D = \sqrt{\frac{\varepsilon_0 K_B T}{e^2 n_0}} \simeq 6.9 \sqrt{\frac{T_e(K)}{n_0(cm^{-3})}} \; cm$$

7×10^3

$$\simeq 7340 \; m \sqrt{\frac{T_e(ev)}{n_e(m^{-3})}} \quad \propto \sqrt{T_e} \quad \propto \frac{1}{\sqrt{n_e}}$$



* Typical laboratory plasma:

$T_e \sim 1.\, Kev = 10^3 ev$

$n_e \sim 10^{19} m^{-3}$; $n = 10^{13}_{cm}$ in vacuum.

$- \lambda_D \simeq 10^{-4} m \simeq 10^{-2} cm$ ($\simeq 0.1 mm$), $\omega_{pe} \sim 1.8 \times 10^{11} \frac{rad}{sec}$ (2×10^{11}), $f_{pe} \sim 28 GHz$ (microwave).

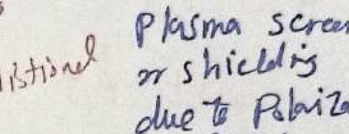
$- \Delta x \simeq n^{-\frac{1}{3}} \simeq 0.5 \times 10^{-6} m \simeq 0.5 \, \mu m$ $\quad U_{the} \sim 3 \times 10^7 m/sec$.

$- a_0$ (Bohr radius) $\simeq 10^{-10} m$

$10^{-8} < 10^{-5} < 10^{-2} < 1$
$a_0 < \Delta x < \lambda < L$

* Physical interpretation:

- $U_{the} = \omega_p \lambda_D$: thermal velocity:



- Debye length:

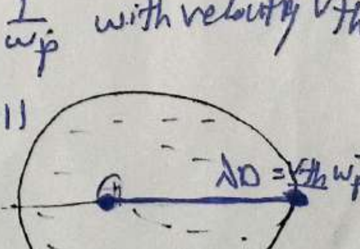
The length at which the Potential $\varphi = 0$

① The length at which the potential affect by φ.
i.e: if there is a charge at $r > \lambda_D$, it will not affect by φ.

② The length of shielding a test charge.

③ " " the test charge interacts collectively with other charges.

④ The distance that the charge moves at $t \simeq \frac{1}{\omega_p}$ with velocity V_{th}.
as ~~$\sqrt{T}$~~ increases, v_{th} increases, so the charge will mover further distance λ_D until it stop.



⑤ the distance over which, the plasma is not neutral.

⑨

* How many particles that <u>feels</u> the collective behaviour (Coulomb potential

the particle inside the Debye sphere.

$$N_D = n\lambda_D^3 \simeq 10^{19}(10^{-4})^3 \simeq 10^{7} \frac{\#}{m^3}.$$

$n\lambda_D^3$: plasma parameter.

* <u>Note</u>;

$$\frac{\partial^2 n_e}{\partial t^2} + \omega_p^2 n = 0 \; ; \; \omega_p^2 = \frac{e^2 n_0}{\varepsilon_0 m_e} \; ; n_e \sim e^{-i\omega t} \; ; + \equiv -i$$

$$\frac{\partial^2 \phi}{\partial x^2} - k_D^2 \phi = 0 ; \quad k_D^2 = \frac{e^2 n_0}{\varepsilon_0 k_B T_e} \; ; \phi \sim e^{-k_D x} ; - \equiv -1 ;$$

→ <u>temporal frequency</u>:

$$\omega_p^2 = \frac{\text{Restoring force to neutral}}{\text{Perturbation (Inertia)}} = \frac{e^2 n_0/\varepsilon_0}{m} \; ; \omega_p \sim \frac{1}{\tau_p} \; ; \tau_p : \text{Response time}$$

* <u>spatial frequency</u>:

$$k_D^2 = \frac{\text{Restoring force to}}{\text{Inertia}} = \frac{e^2 n_0/\varepsilon_0}{k_B T_e} \; ; \; k_D \sim \frac{1}{\lambda_D} ; \lambda_D : \text{Response length}$$

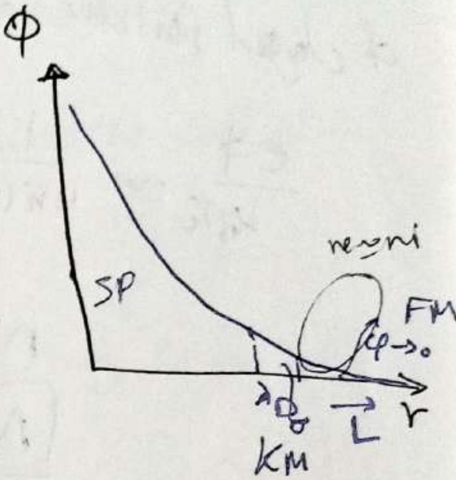
*Restoring force: to restore the neutrality or electrical equilibrium
* Inertia: try to keep the non-equilibrium situation.

→ charge imbalances may exist only over a short distance (Debye length) or for a short period of time (inverse of plasma frequency).

Plasma criteria : (Quantitvelly)

- The Conditions for any ionized medium to be considered a Plasma

(i) Quasinentrallity :



- From Gauss's law:

$$\frac{L}{\lambda_D} \nabla \cdot E = \nabla^2 \phi = n_e - n_i$$

$$\frac{\lambda_D^2}{L^2} \phi = n_e - n_i$$

for $\lambda_D \ll L$: LHS $= 0$

$\therefore n_e - n_i \simeq 0 \longrightarrow \boxed{n_e \simeq n_i}$

So, the condition for quasinentrality

$$\boxed{L \gg \lambda_D}$$

plasma size: L.
high temperature and low dense plasma

- Typical laboratory plasma :

$$L \simeq 10\,cm \simeq 0.1\,m \approx 10^3 \lambda_D .$$

* Conditions :

(1) collective behavior :
$\Gamma \ll$; $N_D \gg 1$; necessary condition

(2) quasinentrality : sufficient "

(3) $\tau_p \gg \tau_c$: Sufficient
$\omega_p \gg \nu_c$

② Collective behaviour:

- ~~That~~ the mean interparticle distance, collective interaction of charged particles dominate over binary interaction.

one to one interaction < one to many interaction

$\Gamma = \frac{e\phi}{K T_e} \ll 1 \rightarrow N_D \gg 1$

$$\frac{e\phi}{k_B T_e} \cong \frac{1}{4\pi (n_e \lambda_D^3)^{\frac{2}{3}}} \ll 1$$

one-to-one interaction

$\Gamma = \frac{e\varphi}{K_B T_e} \ll 1$ (weakly coupled).

↳ field interaction.

$$n\lambda_D^3 \gg 1$$

$$\boxed{N_D \gg 1}$$

- It means you need so many particles inside the debye sphere in order plasma to interact collectively.

- Typical laboratory plasma:

~~$n \sim 10^{19}$~~ ; $N_D \sim 10^6 \# \gg 1$

- there is a million particle inside the Debye sphere.

$\because L \simeq 10^3 \lambda_D \Rightarrow (N_D)^{3^2} \simeq 10^{18} m^{-3}$.

- there is $10^{19} \frac{\#}{m^3}$ in L.

→ Another meaning (Coupling parameter) Γ:

$\Gamma = \frac{E_c}{E_{th}} \ll 1$.

↳ plasma parameter

$$\Gamma \quad \frac{\text{thermal fluctuation}}{\text{collecting thermal energy density}} = \frac{\frac{\epsilon_0}{2} |E|^2}{n_e T_e} \sim \frac{1}{n_e \lambda_D^3} \ll 1$$

$\boxed{n_e \lambda_D \gg 1}$ - So the thermal fluctuations level is so small compared to the thermal energy density

Weakly collistion (weakly Coupled):

- The long-range interaction force is dominate over the Short-rang interaction force or binary collistion force.
- the plasma oscillate many times before, the collistion happen.
- the time response of the plasma to the long-rang force is smaller than the time response to the collistion :

$\Lambda = \frac{4}{3}\pi \lambda_D^3 n$

$\nu \sim \frac{\ln \Lambda}{\Lambda} \omega_p$;

$\nu_c \sim \frac{\omega_p}{(n \lambda_D)^3}$

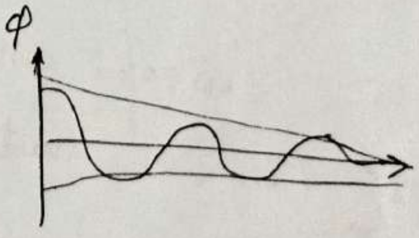
diffuse low dense plasma, high temperature ← (i) $\omega_p \gg \nu_c$: weakly coupled plasma: $\Lambda \gg 1$ collistion do not interfere with plasma oscillation

dense low temperature ← (ii) $\nu_c \gg \omega_p$: strongly coupled plasma: $\Lambda \ll 1$ collistions effectively prevent plasma oscillation

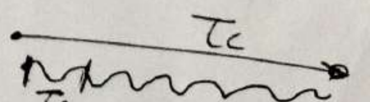
$\because (n \lambda_D)^3 \gg 1$

(i) $\therefore \boxed{\nu_c \ll \omega_p}$ (light-damping)

(ii) $\boxed{\tau_c \gg \tau_p}$



(iii) $\cancel{d \gg}\ \lambda_{mfp} \gg L$: collistionless plasma.



$$\lambda_{mfp} = \frac{V_{th}}{\nu_c} = V_{th} \tau_c .$$

ν_c : is the inverse of the typical time needed for enough collistion to occur that the particle trajectory is deviated through 90° or 90° scattering rate.

★ Plasma in a tokamak:

$n_e \simeq 10^{14}\ cm^{-3}$, $T_e = 1\ keV$, $L = 20\ cm$.

So, the plasma parameters

$V_{the} \simeq \sqrt{\frac{2T_e}{m_e c^2}}\, c \simeq 2\times10^{9}\ cm/sec$

$\omega_{pe} \simeq 5.6\times10^{11}\ sec^{-1}$

$\lambda_{de} \simeq 0.003\ cm$

$L = 20\ cm$

$N_D = n_e \lambda_{De}^3 \simeq 3\times10^{6}$

a_0 (Bohr radius) $\simeq 10^{-8}$ cm

$\Delta x \sim n^{-\frac{1}{3}} \simeq 10^{-5}$ cm ... Interparticle distance.

⇒ plasma conditions

① ← No quantum effect

$a_0 \ll \Delta x \ll \lambda_D \ll L$

cm $10^{-8} \ll 10^{-5}\ cm \ll 3\times10^{-3}\ cm \ll \overset{10^{1}}{20\ cm}$

② $N_D \gg 1$

① $\lambda_D < \Delta x$: collisional.

② $\lambda_D < a_0$: Quantum.

Plasma ~~classifications~~ Category (Scale):

① Laboratory plasma: (~~earth-scale~~ earth lengths scale).

② Space plasma: (Solar-system length scale).

③ Astrophysics plasma: (stars Galaxy - length scale).

④ Cosmology plasma: (universe - length scale).

* Plasma ~~Category~~ Classification by n_e & T_e:

$\cancel{d}\, d \ll \lambda_D \ll L$, $n^{-\frac{1}{3}}$

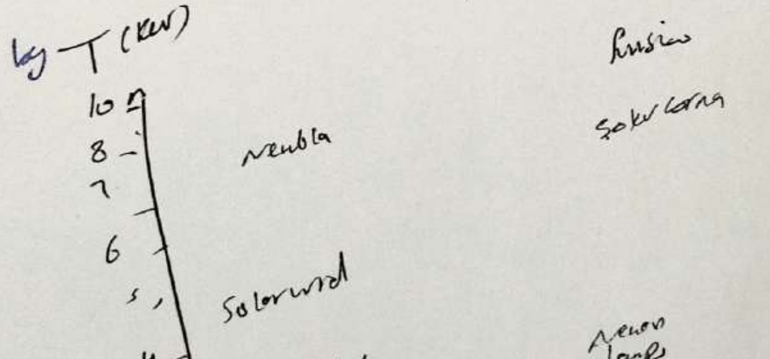
① classical plasma. $L \gg \lambda_{dB}$ OR $T_{th} \gg T_F$.

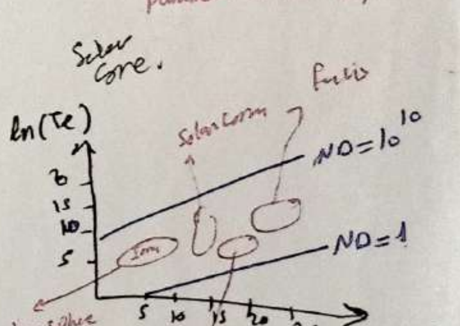
$\lambda_D < d$; ~~in gold~~: $n^{-\frac{1}{3}}$

② Quantum plasma: $L \sim \lambda_{dB}$ OR $T_F \gg T_{th}$, $E_T < 2.75\, E_F$

$\lambda_D < a_0$

" parameter space of plasma "





" Parameter space of Plasma "

③ relativistic plasma:

$KT > m_e c^2$

④ Collisional plasma:

$d \gg \lambda_D$ ~~$\lambda_D \ll d$~~, $\lambda_D^3 n < 1$

interparticle dis

* plasma applications:

* **Fusion:**

Lawson criterion

cc: cm^3

$n\tau > 1.7\times10^{14}$ sec/cc

low density | long confinement time

MCF: $n = 10^{14}$/cc $\quad \tau = 1$ sec

high density | short confinement time

ICF: $n = 10^{25}$/cc $\quad \tau = 10^{-11}$ sec