Introduction to plasma Physics

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علوم - المنصورة

*** Content:**

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

Any field

⇒ عارف — terminology & knows

طالب — Concept & understand

عالم — principle & follow

law & 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: Langumir used it to describe the ionized gas.
→ radio transmission: Ionosphere
→ current rectification: Gaseous electron tube.

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

1940: Alfrèn 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

...sma defination: (Qualiletenely).

① Plasma: It is an ionized medium which is
① Quasineutrall ③ exhibits a collective behaviour

- plasma is it any a state of a varying matter that has ① Ionized ② Quasineutrally. ③ Behave collectively.

state: could be: - plasma gas of - liquid of - solid of

* IoniZation: net charge ≠ 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 moleale acquires a negative or positive charge by gaining ~~or~~ losing 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:

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

; U_i: ionization energy

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

③

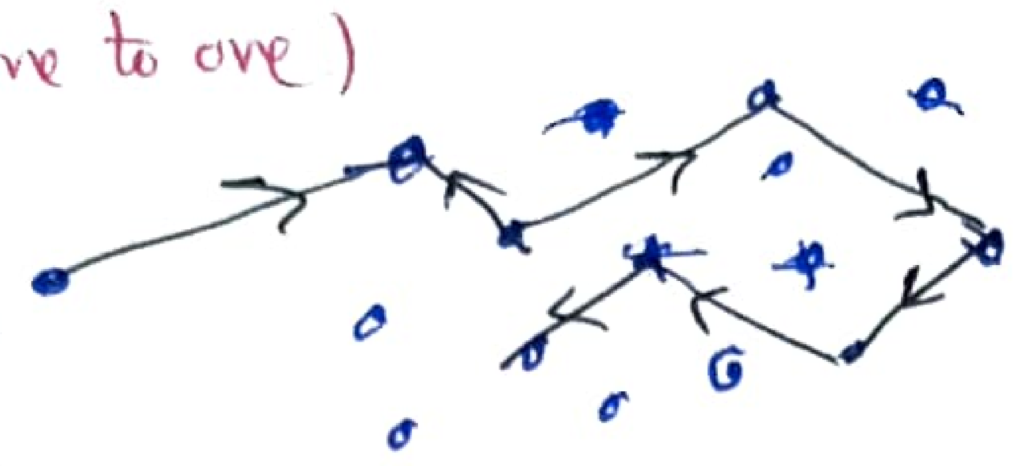
* Collective behaviour :

(i) Individual behaviour:

neutral gas

"Hard sphere collision"
Short-range interaction.

- Short-range interaction.
- contact force.
- ~~mutual~~ collision. (one to one)
- straight line trajectory
- one time interaction



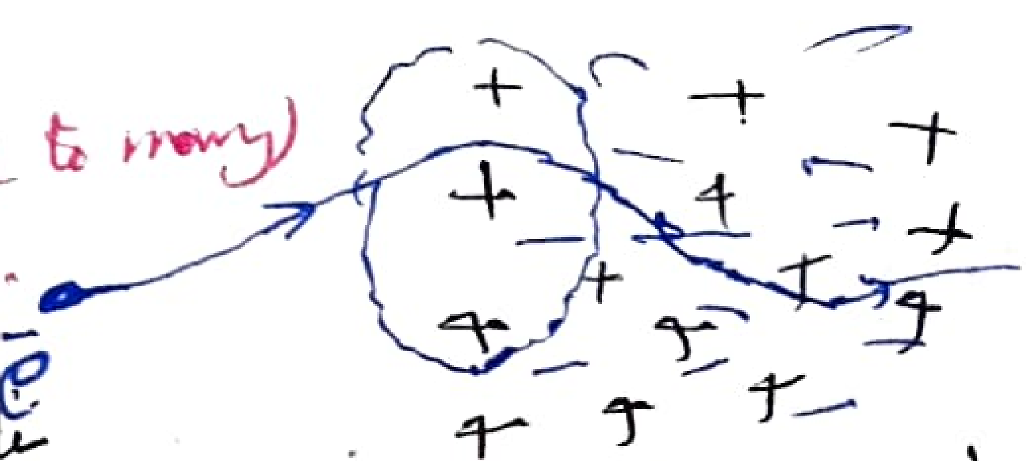
- The particle interact only with one at a time.
- The " doesn't feel the other.
- the ~~orbit~~ trajectory of the particle is a straight line.
- The motion is controlled by short-range force such as collisions force. Contact force.

(ii) ~~C~~Collective behaviour:

plasma

"Coloumb collision"
"Long-range interaction"

- long-range interaction
- field force
- Coloumb collision (one to many)
- curvylinear trajectory.
- Simultaneously interaction



inter-particle interaction
short. collision (one to one)
long electromagnetic

- The particle interact simultaneously with many other binary charged particles (not just mutual collision). one to many
- 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: ~~contact force~~ hard sphere
- contact force
- mutual collision or binary collision
- straight line trajectory

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

Plasma frequency: (natural frequency) (Inertial)

Plasma parameters → time scale, → length

- The linearized eqs:

$n_e = n_0 + n_e(r,t)$ ①

$\frac{\partial n_e(r,t)}{\partial t} + n_0 \nabla \cdot u_e(r,t) = 0$ ②

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

Assume a plasma consists of electrons with charge $(-e)$ and mass m_e and same number of ions (e) and mass m_i: $n_i \simeq n_e \simeq n_0$

$T_i \simeq T_e \simeq T$.

$\xrightarrow{E}$

$\rho = -e[n_0 + n_e] + e n_0 = -e n_e(r,t)$ ④

- Restoring force: $E \propto n_0$
- Inertia: m

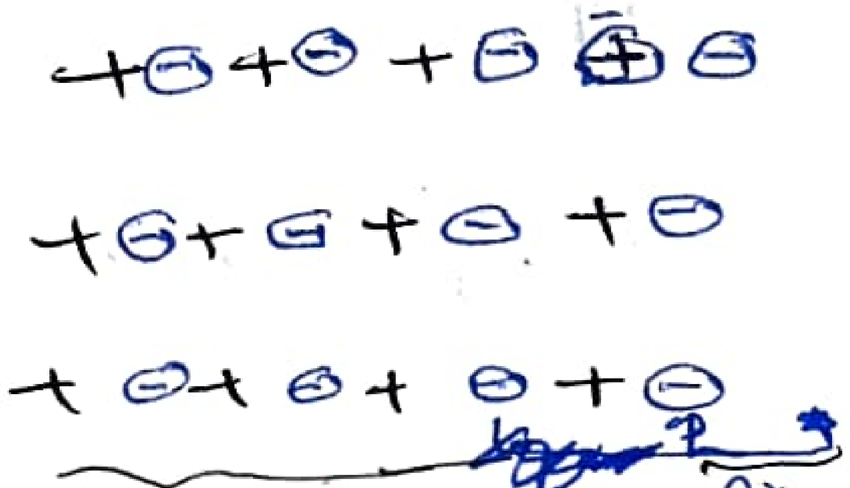
$\nabla \cdot E = \frac{\rho}{\varepsilon_0} = -\frac{e}{\varepsilon_0} n_e(r,t)$ ⑤

$\xleftarrow{e^2 n_0/\varepsilon_0}$ $F = K_\rho \nabla \cdot E$

$K \propto \frac{e n_0^2}{\varepsilon_0}$

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

② $\Rightarrow \nabla \cdot u_e = \frac{1}{n_0} \frac{\partial n}{\partial t}$



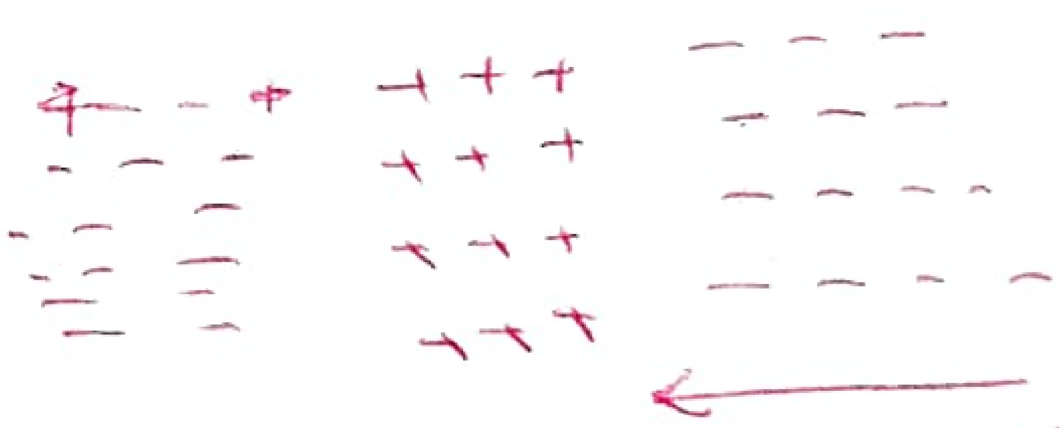
$\rho > 0$ $K \rho_0 X$ ρ_0

$\frac{1}{n_0} \frac{\partial}{\partial t} \frac{\partial}{\partial t} n = -\frac{e}{m_e} \nabla \cdot E \rightarrow m \frac{\partial^2 n}{\partial t^2} = -e n_0 \nabla \cdot E$

$F = -K X$ $\quad e n_0 \quad \nabla \cdot E$

from ⑤ $\Rightarrow \frac{\partial^2 n_e}{\partial t^2} = -\frac{n_0 e}{m_e} \cdot -\frac{e}{\varepsilon_0} n_e(r,t)$

- restoring force: $-\frac{e^2 n_0}{\varepsilon_0} n_e \equiv -KX$ $\quad K \quad X$
- Inertia: m_e $\quad \frac{\partial^2 n_e}{\partial t^2} = -\left(\frac{n_0 e^2}{\varepsilon_0 m_e}\right) n_e(r,t)$



$- e n_0 \nabla \cdot E$

→ collision frequency

$\sigma \sim \frac{n e e^2}{\sigma m}$ → electrical conductivity

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

where $\omega_p^2 = \frac{n_0 e^2}{\varepsilon_0 m_e} \Rightarrow \omega_p = \sqrt{\frac{e^2 e n_0}{\varepsilon_0 m}}$

restoring force — create fluctuation of perturbation

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

$\boxed{K \equiv \frac{e n_0^2}{\varepsilon_0}}$ medium const

$\omega_p = \left(\frac{e^2 n_0}{\varepsilon_0 m}\right)^{1/2} \simeq C\sqrt{n_0}$ $\frac{rad}{sec}$; $n_0\,(cm^{-3})$ $\omega_p \sim 56\sqrt{n_e (cm^{-3})}\ \frac{rad}{sec}$

$f_{pe} \sim 9\sqrt{n_e (m^{-3})}$ Hz

$C = 5.64 \times 10^4$

for $n_e \sim 10^{19}\ m^{-3}$: $\omega_p \sim 1.8 \times 10^{11}$ rad/sec, $f_p \sim 28$ GHz

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

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

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

$\sim 5.6\ ps$ microwave

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

$\propto e^2$ | $\propto \frac{1}{e^2}$ → " chase " " " " to E.

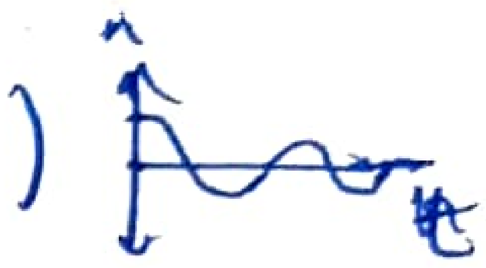
$\propto \frac{1}{\varepsilon_o}$ | $\propto \varepsilon_o$ → high Premittivity more time " " E.

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

* Collestion frequency (ν):

$$\frac{d^2 n}{dt^2} + \nu \frac{dn}{dt} + \omega_p^2 n = 0 \quad ; \quad \nu = \frac{b}{n_o m} = \frac{\overset{\text{collistion factor}}{b}}{\rho_m} \qquad \nu = \frac{b}{m}$$

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



(ii) critical ($\omega_p = \nu$)

$e^{-\nu t}$

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

→ So, we in plasma intersted in light dampis ($\nu \ll \omega_p$).

* Thermal pressure:

Collistion → with neutral
→ with charges, Coloumb collistion
↳ 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) $\nu \to 0, \omega_p \to 0$

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

* 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) $\nu \to 0$, $\cancel{V_{the}} \to 0$

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

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

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

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

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

$$\mu = \frac{q}{m\nu} \; ; \quad \frac{(\Delta x)^2}{\Delta t}$$

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

6 $\quad \frac{1}{\nu}\frac{\partial^2 n_e}{\partial t^2} + \frac{\partial n_e}{\partial t} - D_e \nabla^2 n_e + \frac{\omega_{pe}^2}{\nu} n_e = 0 \quad ; \quad D = \frac{K T_e}{m_e \nu_e} \doteq \frac{(\text{mean free path})^2}{\text{collision time}}$

↳ Diffusion coefficient.

Debye Length

(i) Test charge in Vacuum:

- The electrostatic potential due to Q (Coloumb potential)

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \Rightarrow \nabla \times (\nabla \varphi) = 0,\ E = -\nabla \phi$$

$$\nabla \times B = \mu_0 (J + \varepsilon_0 \frac{\partial E}{\partial t})$$

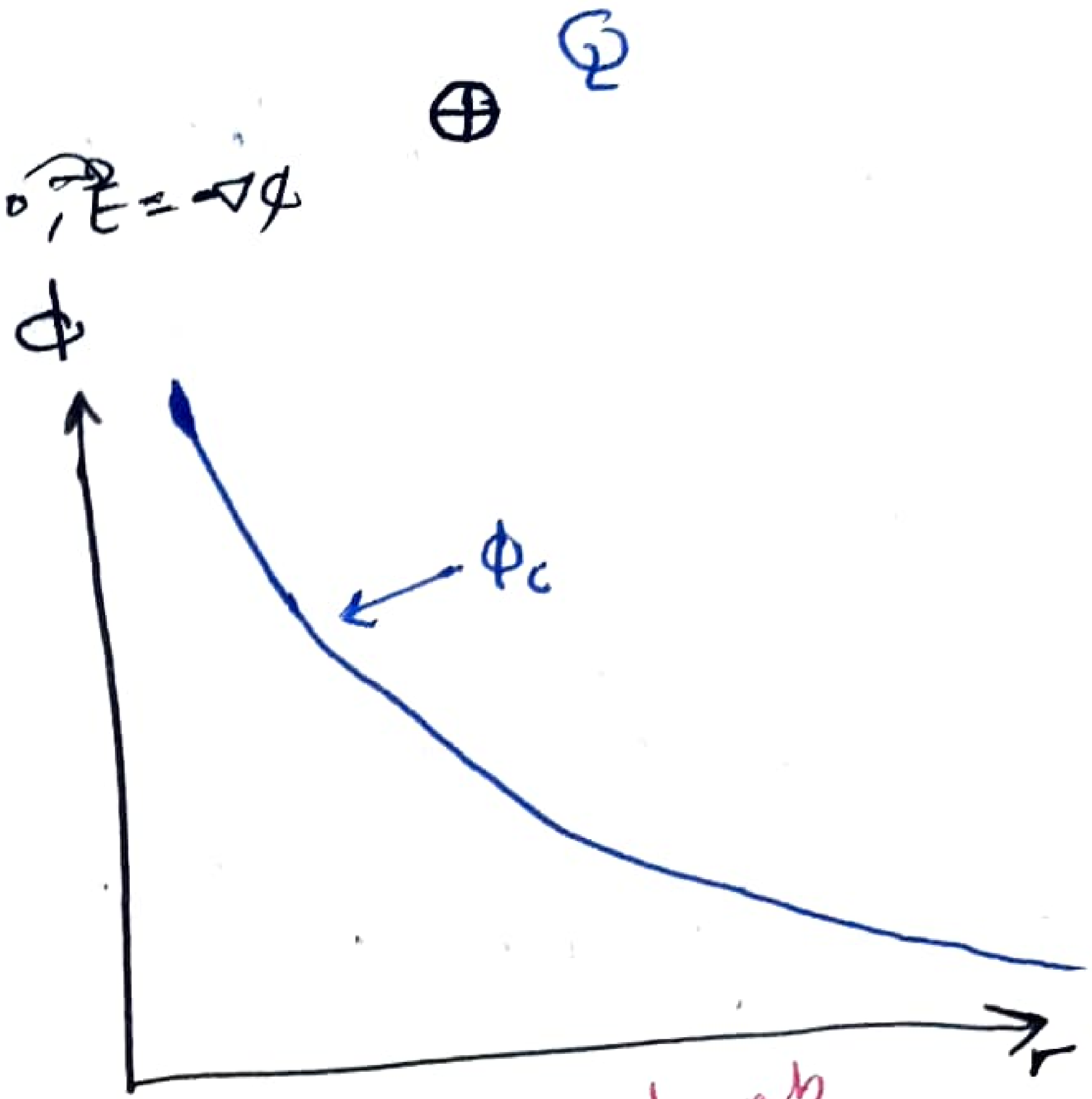
$$\nabla \cdot E = \frac{Q}{\varepsilon_0}$$

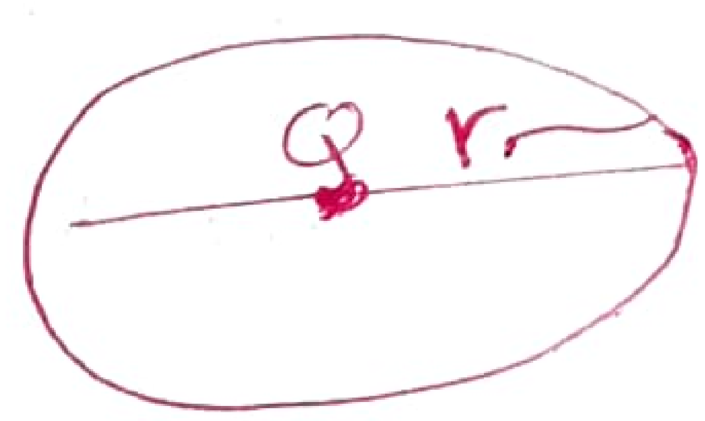
$$\therefore \quad E = -\nabla \phi$$

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

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

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



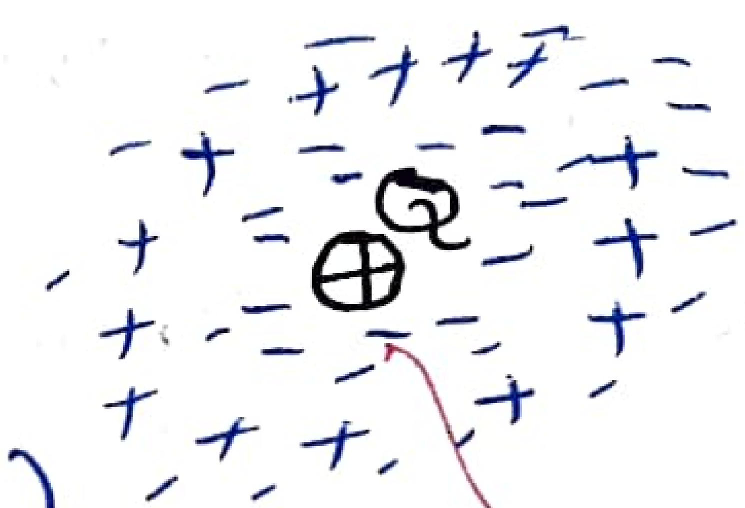


$$\lim_{r \to \infty} \phi_c(r) \to 0$$

radius of effect (influence)

(ii) Test charge in plasma:

$$\nabla^2 \phi = -\frac{Q}{\varepsilon_0} + \frac{\rho}{\varepsilon_0} \quad ; \quad \rho = e n_0 e^{\frac{e\phi}{k_B T}} \simeq e n_0 \left(1 + \frac{e\phi}{k_B T} + \dots\right)$$



Polarization effect for negative charges

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

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.

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

Restoring force

create displacement

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

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

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

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

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

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

at $r \sim 10\lambda_D$ $\quad \phi_D = 0.01\ \phi_c \to 0$

- At $r \gg \lambda_D$

$\phi \rightarrow 0$

* 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 (screen out) 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. $\phi(r) \propto \frac{1}{r} e^{-r}$

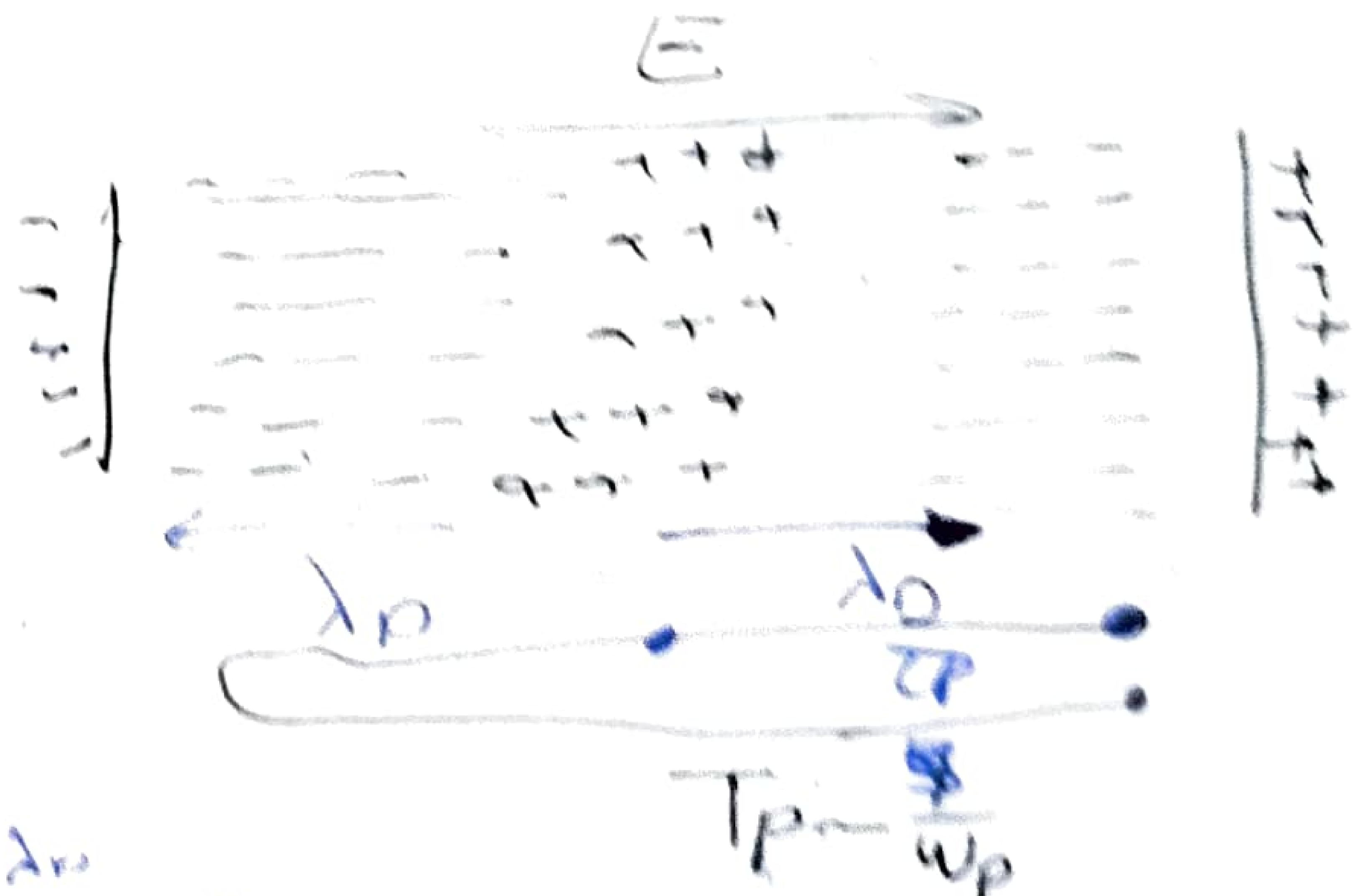
(i) $r \ll \lambda_D$: $\phi(r) \longrightarrow \phi(r)$: charge in vacuum.

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

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

* Applyin an Electric field:

- when we apply an electric field, the plama will displace a distance (with speed v_{th}) λ_D ~~τ_p~~. then it will oscillate with frequeny w_p.

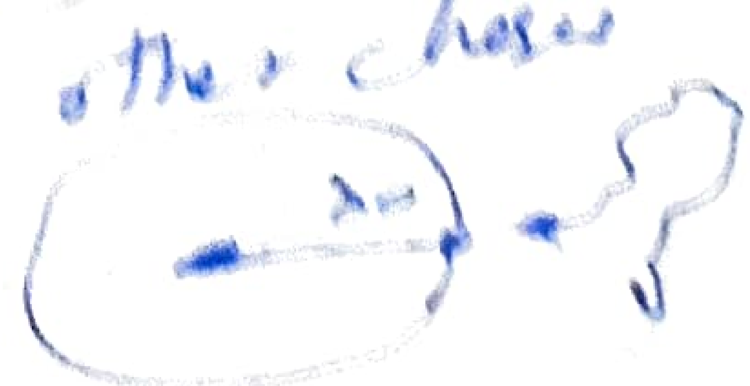


λ_D
v_{th}, τ_p

(1) - λ_D: is the maximum distance over which the electrons can move with its thermal energy with respect to the ions, agains the electrostatic force. (kT = ½ m v²)

(2) the distance that electrons move it at τ_p with velocity v_{th} (maximum displacement of oscillation)

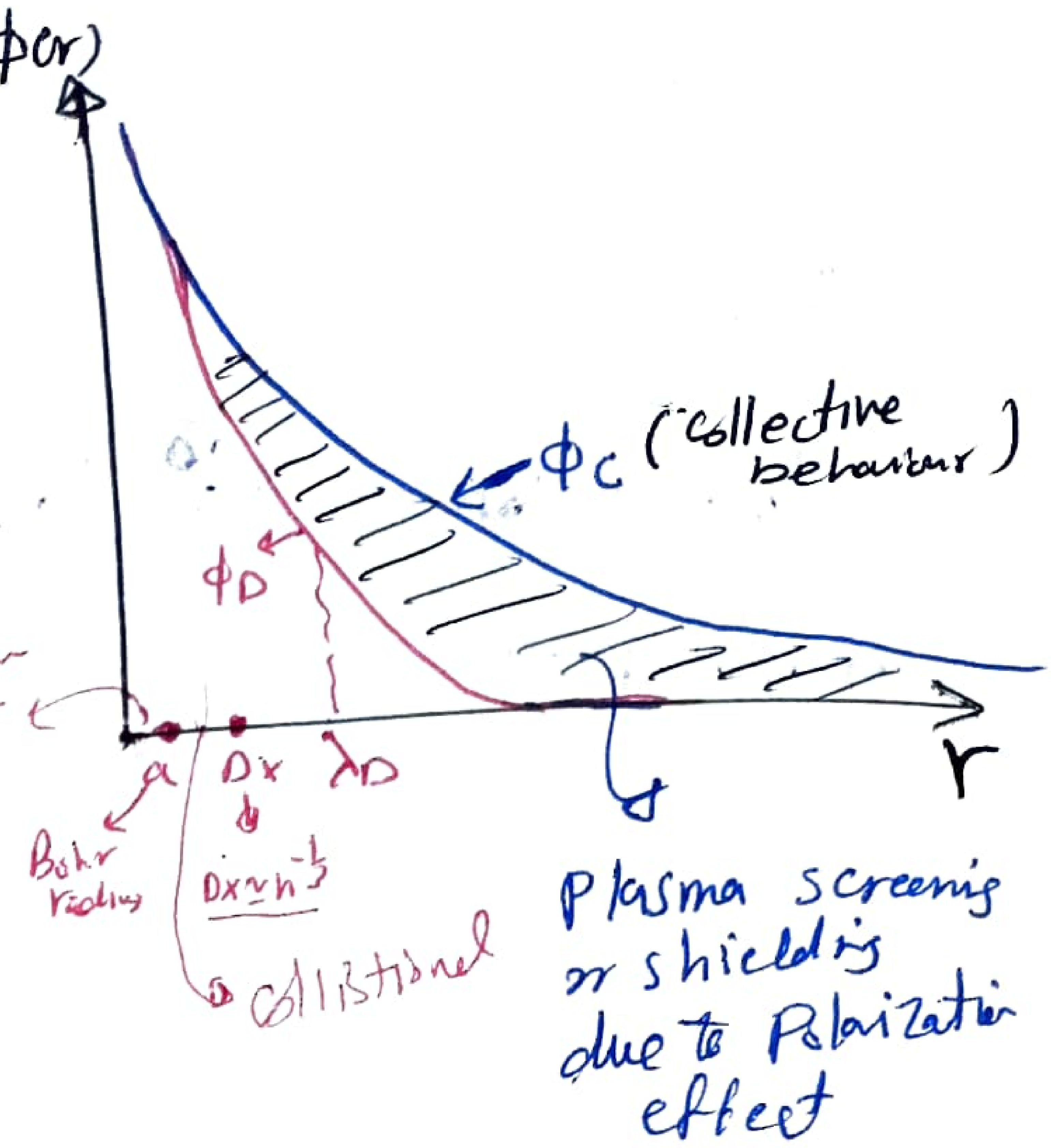
(3) the distance beyond it, the ions have no influence on other charges



$$D = \sqrt{\frac{e_0^2 n_0}{\varepsilon_0 k_B T}}$$

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{e^2 n_0}} \simeq \overset{7}{6.9} \sqrt{\frac{T_e(K)}{n_0(cm^{-3})}} \ cm$$

$$\overset{7\times10^3}{\simeq 7340\, m} \sqrt{\frac{T_e(eV)}{n_e(m^{-3})}} \quad \propto \sqrt{T_e}, \quad \propto \frac{1}{\sqrt{n_e}}$$



* Typical laboratory plasma:

$T_e \sim 1$ keV $= 10^3$ eV

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

- $\lambda_D \simeq 10^{-4} m \simeq 10^{-2} cm$ ($\simeq 0.1mm$), $\omega_{pe} \sim 1.8\times10^{11} \frac{rad}{sec}$ (2×10^{11}), $f_{pe} \sim 28$ GHz (microwave).

$v_{the} \sim 3\times10^7$ m/sec.

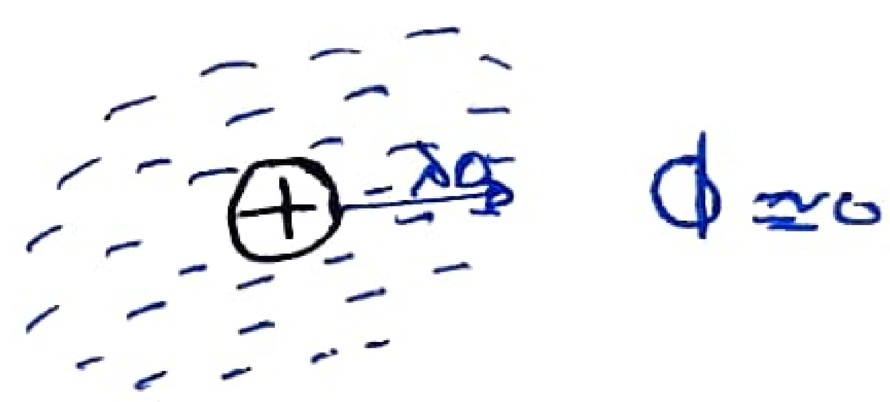
- $\Delta x \simeq n^{-\frac{1}{3}} \simeq 0.5\times10^{-6} m \simeq 0.5\, \mu m$

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

$$\begin{array}{ccccccc} 10^{-8} & < & 10^{-5} & < & 10^{-2} & < & 1 \\ a_0 & < & \Delta x & < & \lambda & < & L \end{array}$$

* physical interpretation:

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



- Debye length:

The length at which the potential φ = 0

① The length at which the potential φ = 0 ... if there is a charge at $r > \lambda_D$, it will not affect by φ.

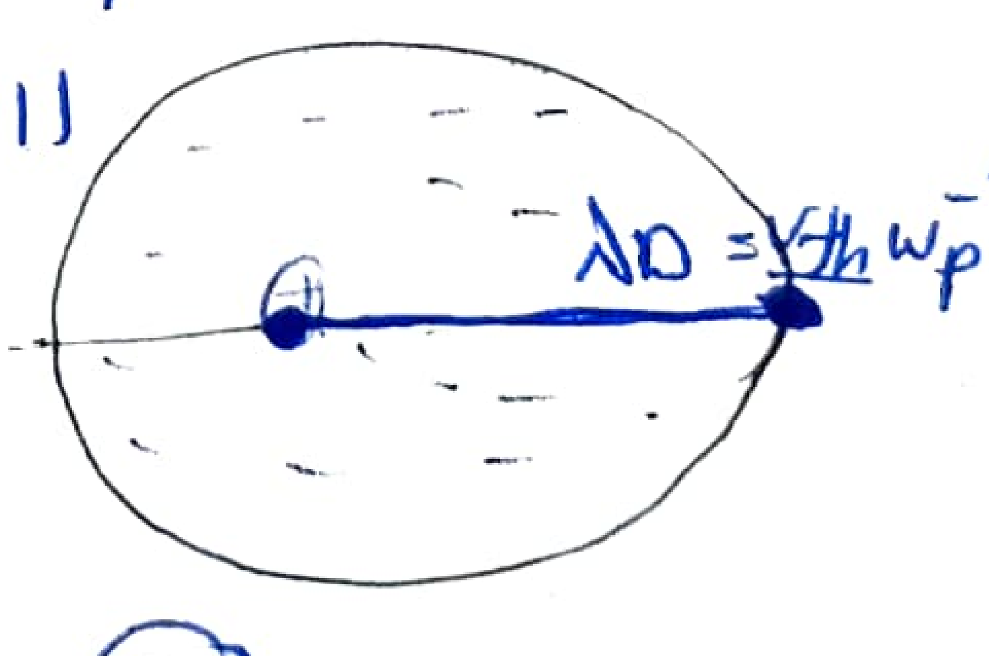
i.e.: if there is a charge at $r > \lambda_D$, it will not affect by φ.

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 ~~T~~ T increases, v_{th} increases, so the charge will moves further distance λ_D until it stop.



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

* How many particles that feels the collective behavior (Coloumb Poten

≠ 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.

* Note;

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

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

→ temporal frequency:

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

* spatial frequency:

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

* 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 : (Quantitively)

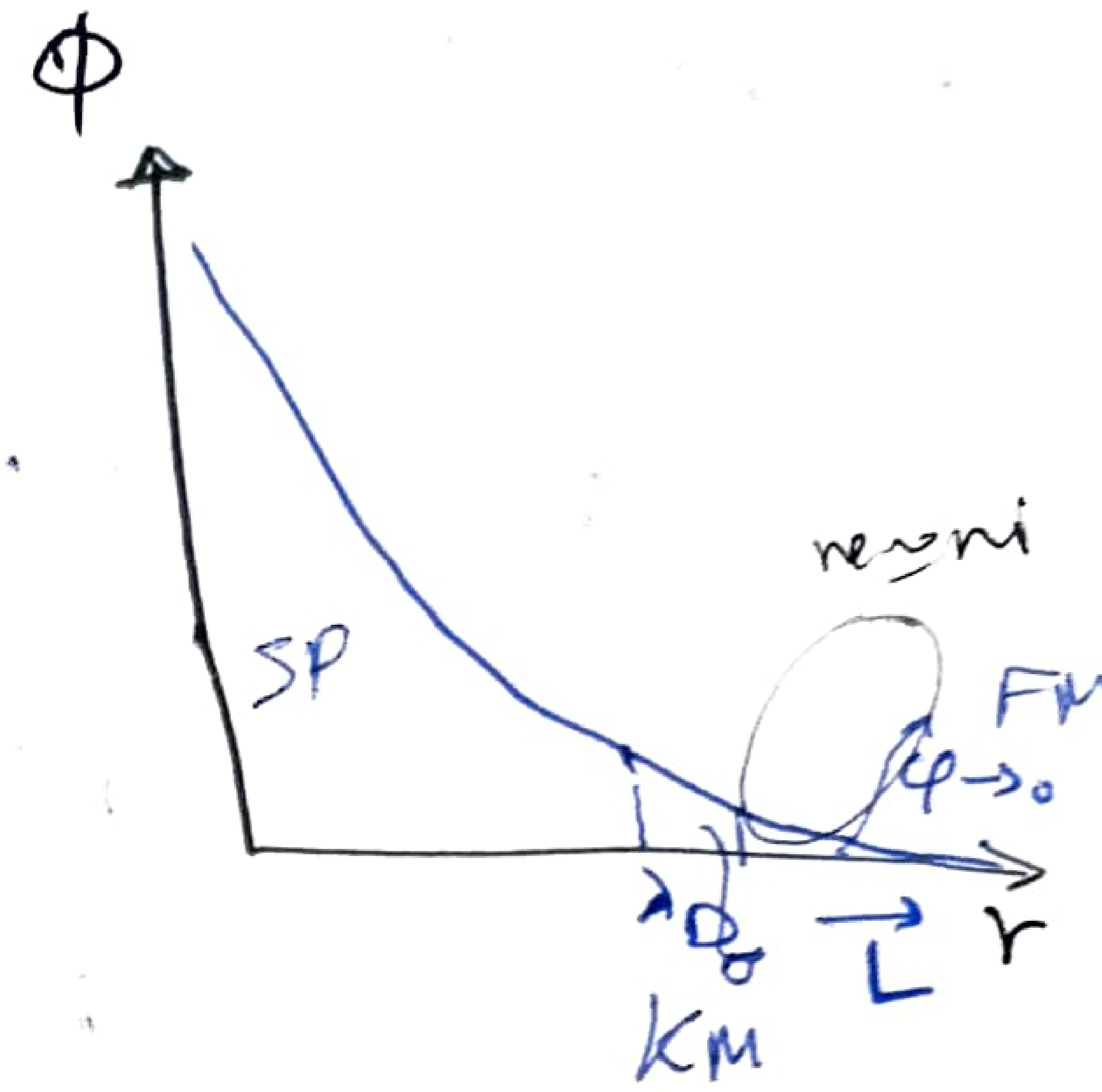
- The conditions for any ionized medium to be considered a plasma

(i) Quasineutrallity:

- From Gauss's law:

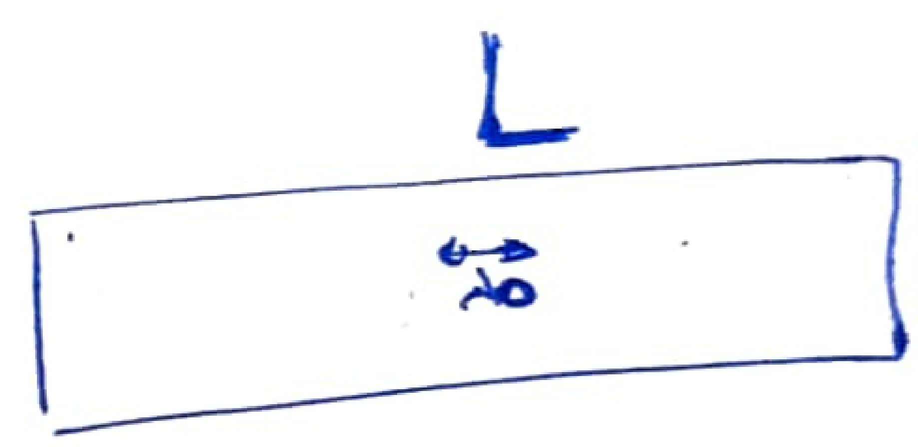
$\frac{L}{\lambda_D} \nabla \cdot E = \nabla^2 \phi = n_e - n_i$

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



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

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



So, the condition for quasineutrality

$\boxed{L \gg \lambda_D}$ plasma size: L. high temperature and low dense plasma

- Typical laboratory plasma:

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

* Conditions:

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

(2) quasineutrality: sufficient "

(3) ~~$\tau_p \ll \tau_c$~~ : sufficient
$\omega_p \gg \nu_c$:

② Collective behaviour:

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

one to one interaction < one to many interaction

$\Gamma = \frac{e\varphi}{KTe} \ll 1 \rightarrow N_D \gg 1$

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

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

↳ field interaction.

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

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

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

- Typical laboratory plasma:

~~$n \sim 10^{19}\ m^{-3}$~~ ; $N_D \sim 10^6 \# \gg 1$

- there is a million particle inside the Debye sphere.

$\therefore L \simeq 10^3 \lambda_D \Rightarrow (N_D \# \text{ to } 10^{18}\ m^{-3}$.

- 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 interacti 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:

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

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

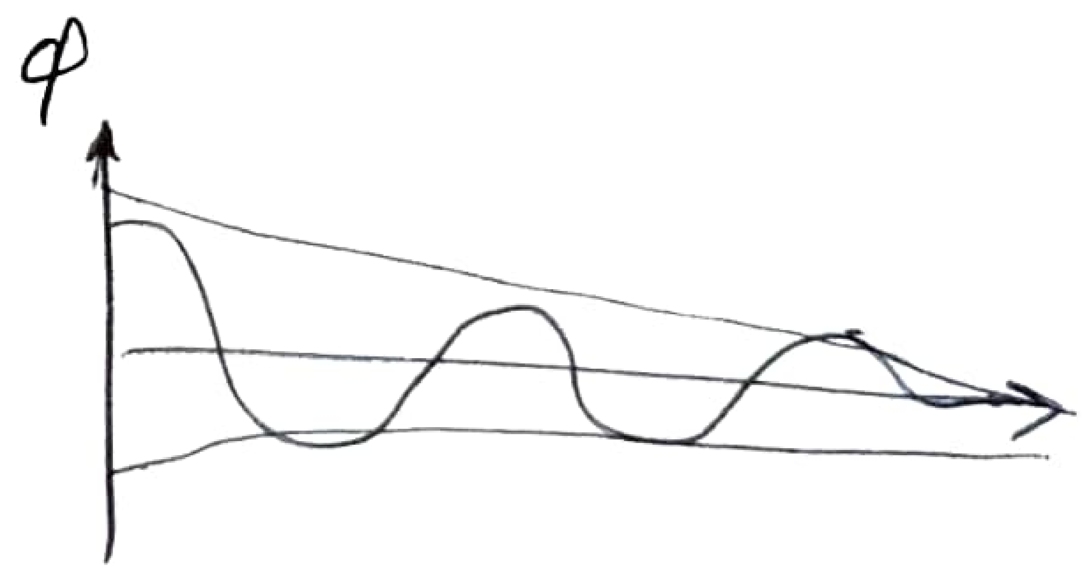
$$\nu_c \sim \frac{\omega_p}{(n \lambda_D)^3}$$

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

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

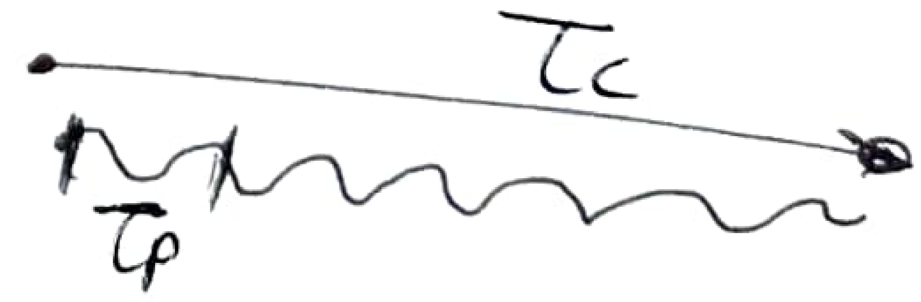
$\therefore (n \lambda_D)^3 \gg 1$

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



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

(iii) $\lambda_{mfp} \gg L$: 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

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

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

$\Rightarrow$ plasma conditions

① $a_0 \ll \Delta x \ll \lambda_D \ll L$ ← No quantum effect

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

② $N_D \gg 1$

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

② $\lambda_D < a_0$: Quantum.

lasma ~~classifications~~ Category (scale):

① Laboratory plasma: (earth-~~scale~~ length 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:

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

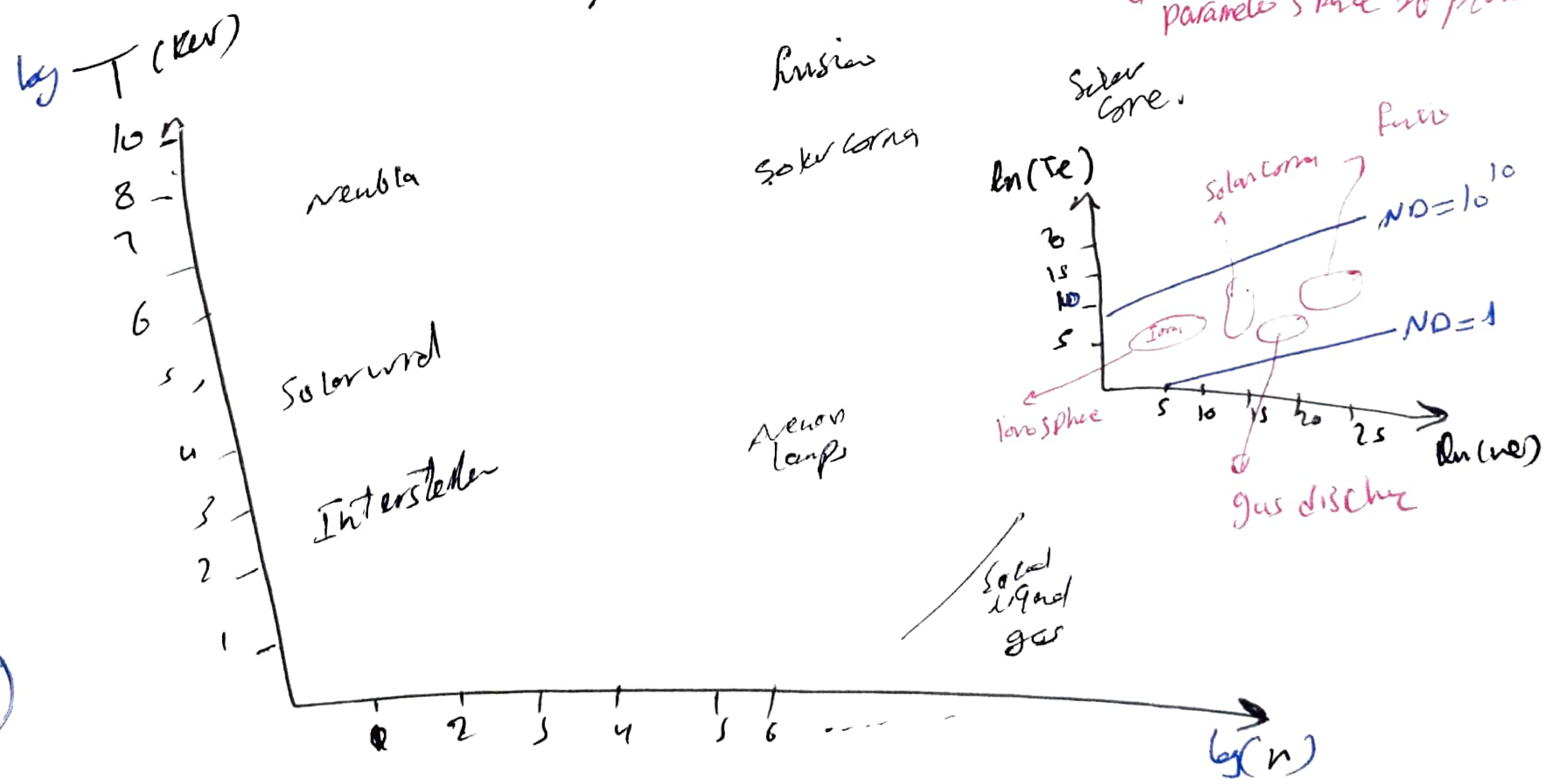
① classical plasma. $L \gg \lambda_{dB}$ OR $T_{th} \gg T_F$.

$\lambda_D < d$; ~~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"



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"Parameter Space of Plasma"

③ Relativistic plasma:

$KT > m_e c^2$

④ Collisional plasma:

$\cancel{d} > \lambda_D$ ~~λ_D~~, $\lambda_D^3 n < 1$

↳ interparticle dist.

* 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 $\tau = 1$ sec

high density   short confinement time

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