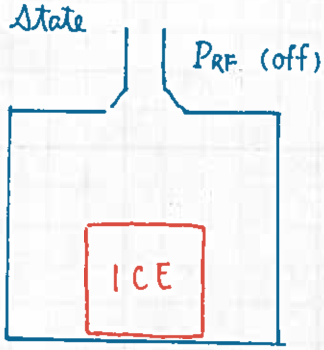
222 A. 9/30.

Plasma Physics.

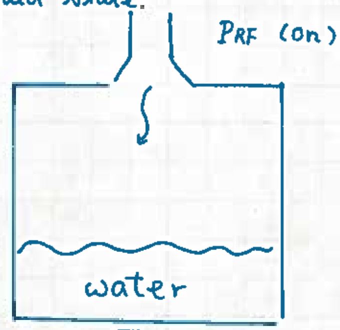
1. What is a plasma ?
 - 4th state of matter.

(i) Solid State



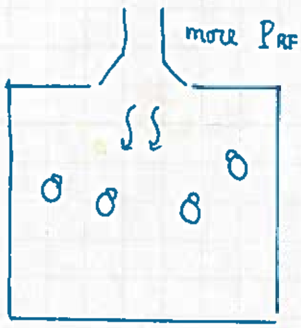
T_1

(ii) Liquid State.



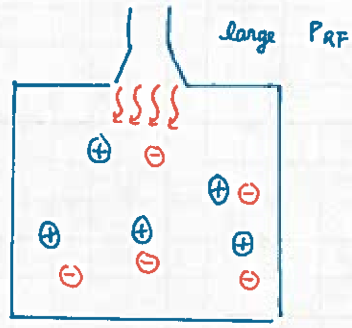
$<$ T_2

(iii) Gas



$<$ T_3

(iv)



$<$ T_4

* Temperature alone does not define a plasma. ($1\,eV \simeq 11.6 \cdot 10^3\ {}^\circ K$)

- white dwarf $\longrightarrow$ not a plasma
  $T \sim 10\,eV$
  $n \sim 10^{30}\ cm^{-3}$
- ionisphere $\longrightarrow$ a plasma.
  $T \sim 0.1\,eV$
  $n \sim 10^5\ cm^{-3}$

2. What parameter determines plasma behavior.
 - Temperature
 - Density.

• DEGREE OF CORRELATION $\approx \dfrac{\text{Interaction Energy}}{\langle KE \rangle}$

$$\boxed{\text{DEF} : \Gamma = \frac{\phi}{kT}}$$

• Estimation of plasma parameter.

$$\boxed{\langle \phi \rangle \approx \frac{e^2}{\langle r \rangle} \approx e^2 n^{+1/3}}$$ $\langle r \rangle \approx n^{-1/3}$

$$\therefore \Gamma \equiv \frac{\langle \phi \rangle}{\langle KE \rangle} = (\ ) \frac{e^2 n^{1/3}}{T}$$

numerical constant.

$\therefore \exists$ 2 plasma regimes
- low density.
- high temperature.

$$\boxed{\begin{array}{l} \Gamma << 1 \longrightarrow \text{plasma.} \\ \Gamma >> 1 \longrightarrow \text{degenerate QM Fluid} \end{array}}$$

* $\Gamma \approx 1 \longrightarrow$ strongly coupled plasma.

** in 2-D, crystalization occurs @ $\Gamma \approx 170$ (Exp. and simulation)

$$\Gamma = \frac{e^2 n^{1/3}}{T} = \frac{4\pi \ e^2 \boxed{(n^{2/3} \ n^{1/3}) = n}}{4\pi \ n^{2/3} \ T \cdot \frac{m}{m}}$$

Recall.

$$\omega_p^2 = \frac{4\pi n e^2}{m} = \text{"electron" plasma frequency.}$$

electron mass

$$\boxed{\omega_p \approx 5.6 \cdot 10^4 \cdot \sqrt{n} \ \frac{\text{rad}}{\text{sec.}}}$$ (n in cm^{-3})

$$\bar{v}_T^2 = \frac{T}{m}.$$

$$\Gamma = \frac{1}{4\pi} \boxed{\frac{\omega_{pe}^2}{\bar{v}_e^2}} \cdot \frac{1}{n^{2/3}}$$

* $\frac{\bar{v}_e}{\omega_p} \approx$ distance traveled in one plasma cycle $= \lambda_D$.

$$\lambda_D \equiv \frac{\bar{v}_e}{\omega_p} = \text{DEBYE LENGTH.}$$

$$\boxed{\lambda_D = 7.4 \cdot 10^2 \sqrt{T} \ n^{-1/2} \ cm}$$

$$\therefore \Gamma = \left(\frac{1}{4\pi}\right) \frac{1}{\lambda_D^2 \ n^{2/3}}$$

recall

$$N = \left(\frac{4\pi}{3}\right) \lambda_D^3 \ n. \longrightarrow \text{\# of particles in a debye sphere.}$$

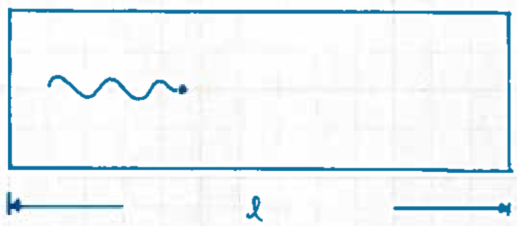
$$\Gamma = (\#) \frac{1}{N^{2/3}} \longrightarrow$$

∴ plasma is determined by # of particles in a Debye sphere.

plasma requires $\boxed{N >> 1}$

- in an experiment, $N \approx 10^6$.

3. How large a container do you need to see plasma behavior.



* $T_{TRANSIT} = \dfrac{\ell}{\tilde{v}_e}$ = transit.

* Typical time in a plasma is $\simeq \dfrac{2\pi}{\omega_p}$

$$\boxed{\ell >> \lambda_D = \frac{\tilde{v}_e}{\omega_p}}$$

Dual Constrains.

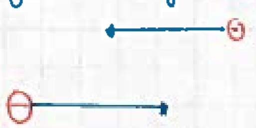
(i) $N >> 1$

(ii) $\ell >> \lambda_D$ ⟶ in practice: $\ell \approx 10\,\lambda_D$ is good enough.

Recall: any external influence is wiped out by DEBYE SHIELDING.

Subtleties of plasma physics ⟶ Why don't we use classical Thermodynamics for plasmas?

(i)



Plasma.

(ii) in an ideal gas

However, far away interactions $\left(\frac{e^2}{r}\right)$ decays slowly in a plasma.

⟹ plasma is interaction w/ collective oscillation; i.e., "waves"

⟹ a plasma is really a "classical duality"

- particle behavior exists.
- wave behavior exists.

i.e., particle interacts w/ wave, and it is the wave itself.

1. historical perspective.

Date (~)	Event	Name	
1879	Exp. on gas discharges	Crooks	
1906	Plasma Osc. → in jellium model of atom.	Lord Rayleigh.	
1926.	Named "Plasma" invented + basic properties explained	Langmuir Tonks.	→ Papers available.
1936.	MHD waves. → couples matter w/ EM waves	Alfvén	
1938.	Collision model → strange for an strongly interacting system.	Vlasov.	
1945.	Collisionless damping (!!!) / Linear response of plasmas	Landau.	
1944-50.	Isotope separation + H bomb studies. (i.e., large release of energy)	Classified (Bohm)	
1957.	Fusion research de-classified. - MHD Theory - Fokker-planck description.	USSR, UK, USA.	

Modern Age of Plasma Physics

1960	Q-machine.	Rynn + D'angelo.	
1962.	Exp. observation of Landau. damping.	Malmberg. Wharton.	→ Theory done @ 1945.
1965 - 70	Linear waves, mirror machines, stellarators		
1970 - 80	NL-waves. (ponderomotive force, para. instability). Tokamac.		
1980 - 90	Tokamac confinement. Application to space science. Non-neutral plasmas. Non-uniform properties		
Today.	Transport... → Scott's work. Non-equilibrium.		

2. System of units. $\longrightarrow$ Gaussian.

$$\nabla \times \underline{E} = -\frac{1}{c}\frac{\partial}{\partial t}\vec{B}$$

$$\nabla \times \underline{B} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial}{\partial t}\vec{E}$$

$$\nabla \cdot \underline{E} = 4\pi\rho.$$

* $c =$ '3' $\cdot 10^{10}$ cm/sec.

$$[E] = \frac{\text{stat-volt}}{\text{cm}}$$

Exp. unit.

$$[E] = \frac{\text{volt}}{\text{meter}} = \frac{1}{3}\cdot 10^{-4}\ \frac{\text{stat volt}}{\text{cm}}$$

$[I]$: stat-amps. * 1 amp $= 3 \cdot 10^9$ stat-amp.

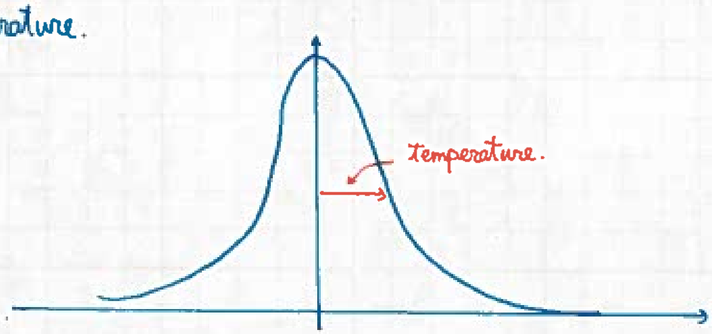
$[B]$: in Gaussian in lab.

$[e]$: in stat-coulomb * 1 coulomb $= 3 \cdot 10^9$ stat-coulomb.

- temperature in eV $\boxed{1\,eV \approx 11.6 \cdot 10^3\ {}^\circ K}$

3. Macro-scopic parameters.

- temperature.



- density. $= n$
- L_T = temperature scale length.
- L_n = density scale length.

$$L_T^{-1} = \frac{\partial}{dx}\ln(T)$$

$\longrightarrow$ where is L_T, L_n, measured in a plasma.

$$L_n^{-1} = \frac{\partial}{dx}\ln(n)$$

Equilibrium Problem

$$\frac{M}{m} > 1836.$$

- fastest. → electron - electron equilibration : τ_{ee}.
- ion - ion equilibration. $\tau_{ii} = \sqrt{\frac{M}{m}}\,\tau_{ee}$.
- slowest → electron - ion equilibration : $\tau_{ei} = \frac{M}{m}\,\tau_{ee}$

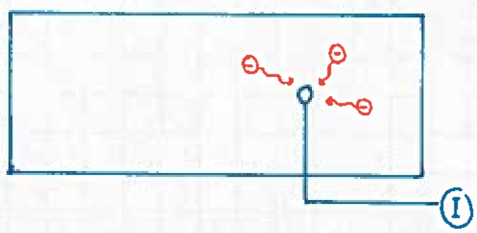
$\boxed{\therefore \text{ in general, } T_e \neq T_i \text{ (except in well-confined plasmas)}}$

How to measure macroscopic parameters

I. for low density, low temperature plasma → Langmuir Probe.

$n < 10^{12}\ \text{cm}^{-3}$

$T < 20\ \text{eV}$

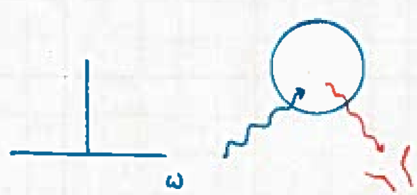


- measure current for a given voltage.
- can extract n_e, T_e.

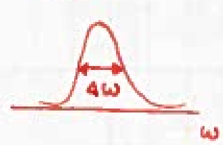
II High density, high temperature.

1. T_e (i) To get T_e : in magnetized plasma → get $T_\perp$ from cyclotron emission.

 (ii) Non-magnetized plasma → Use Thompson scattering.

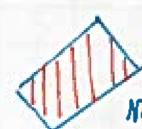


Doppler - broadening → can infer T_e.

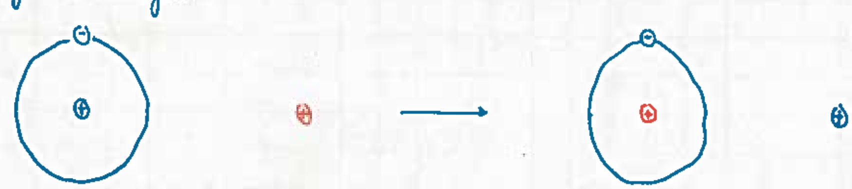


2. T_i

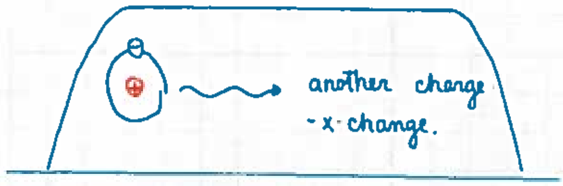
 (i) Charge X-change.



Neutral Particle Detector → can reconstruct T_i



* limitations of the charge x-change method.



multiple charge x-change
→ optically thick

in high density : need Doppler broadening of line-radiation.

222 Reading Notes.

(i) Plasma parameter (g) (p. 57)

$$g = \frac{1}{n_0 \lambda_D^3}$$

when g is small, $\exists$ many particles in a Debye sphere.

$$\langle PE \rangle \ll \langle KE \rangle \qquad (g \ll 1)$$

and the interaction can be neglected., i.e., plasma acts like ideal gas.

2. Gibbs distribution (N = total # of particles, $N/2$ ions, $N/2$ electrons)

$$\boxed{D(\vec{x}_1, \vec{x}_2, \ldots \vec{x}_N) = \frac{1}{(Z)} \exp\left(-\frac{\sum_k \sum_{i>k} W_{ik}}{kT}\right)}$$

$$W_{ik} = \frac{q_i q_k}{|\vec{x}_i - \vec{x}_k|} + \phi_{ext}$$

Z = partition fcn.

$$\boxed{* \; F_1(\vec{x}_1) = \int D \, d^3\vec{x}_2 \, d^3x_3 \cdots d^3x_N}$$

where $F(\vec{x}_1)$ = probability density of finding particle 1 @ $\vec{x} = \vec{x}_1$

* special case $\boxed{W_{ik} \ll kT}$

$$\boxed{F_1(\vec{x}_1) = \frac{1}{V} \rightarrow \text{ i.e., } \exists \text{ no preference}}$$

$$F_2(\vec{x}_1, \vec{x}_2) = \{1 + \underline{P_{12}(\vec{x}_1, \vec{x}_2)}\} F_1(\vec{x}_1) F_1(\vec{x}_2)$$

2-particle correlation function.

$$F_3(\vec{x}_1, \vec{x}_2, \vec{x}_3) = \{1 + P_{12}(\vec{x}_1, \vec{x}_2) + P_{12}(\vec{x}_2, \vec{x}_3) + P_{12}(\vec{x}_1, \vec{x}_3) + T_{123}\} F_1(\vec{x}_1) F_1(\vec{x}_2) F_1(\vec{x}_3)$$

* $T_{123} \ll P_{12} \ll 1$

3. Correlation fcn. (P_{12})

(i) we assume $P_{12} \gg T_{123}$, i.e., only consider 2 particle correlation.

4 Plasma density.

$$n_\alpha(\vec{x}_i) = \bar{n}_\alpha \exp\left(-\frac{q_\alpha \Phi_p + q_\alpha \phi_{ext} + W_{others}}{kT}\right) \quad \text{---} \quad (*)$$

* Ideal plasma : if plasma is divided in P pieces (p. 68)

$$n^* = P\, n_0 \quad , \quad q^* = \frac{1}{P} q_0$$

$$m^* = \frac{m_0}{P} \quad \quad T^* = \frac{T_0}{P}$$

$$\lambda_D^* = \lambda_{D0} \quad \quad \omega_p^* = \omega_{p0}$$

$$g^* = g_0 \cdot \frac{1}{P} \quad \quad P_{12}^* = (P_{12})_0 \cdot \frac{1}{P}$$

$$\rho^* = \rho_0$$

as $P \longrightarrow \infty$

$$\boxed{\begin{array}{l} P_{12}^* \longrightarrow 0 \\ g^* \longrightarrow 0 \\ F \longrightarrow F_0 \end{array}} \longrightarrow \text{single - particle properties of plasma}$$

from (*), we have.

$$\nabla^2 \phi = -4\pi \rho_{ext} - 4\pi \sum_\alpha q_\alpha n_\alpha(\vec{x}) \quad \text{---} \quad (2)$$

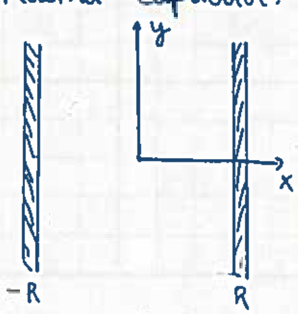
$$\exp\left(-\frac{q\phi}{kT}\right) \approx 1 - \frac{q\phi}{kT}$$

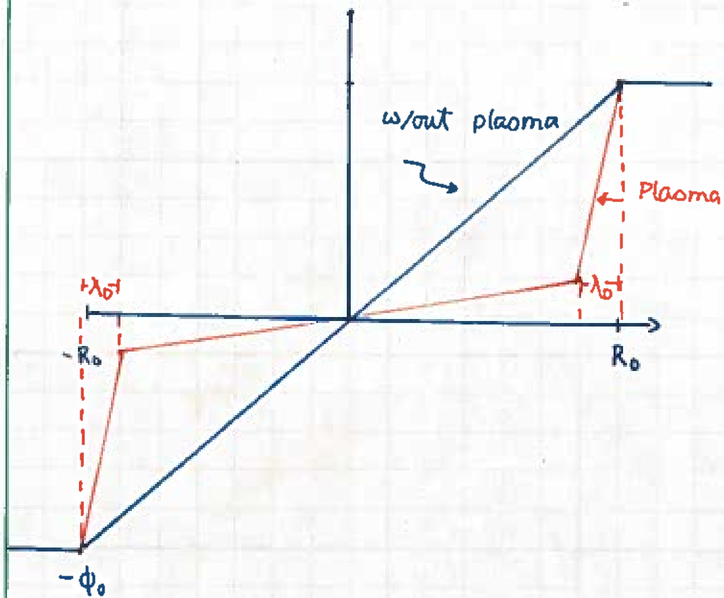
eq. (2) becomes

$$\nabla^2 \phi \approx -4\pi \rho_{ext} - 4\pi \sum_\alpha q_\alpha n_{\alpha 0}\left(1 - \frac{q_\alpha \phi}{kT_\alpha} - \frac{W_{OTHERS}}{kT_\alpha}\right)$$

Neutral plasma $\longrightarrow$ $\boxed{\sum_\alpha q_\alpha n_{\alpha 0} = 0}$

Plasma Capacitor.





(p. 76) The ratio of electrostatic energy to thermo energy is.

$$\boxed{\frac{W\,(\text{Coulomb})}{n_0 kT} = \frac{1}{n_0 \lambda_D^3} = g}$$

$g = 0 \longrightarrow$ ideal gas...

Ch. 3.

Liouville's th.

$$\frac{\partial F}{\partial t} + \sum_i \left(\frac{\partial F}{\partial \vec{x}_i} \cdot \vec{v}_i + \frac{\partial F}{\partial \vec{v}_i} \cdot \vec{a}_i^{\,T} \right) = 0$$

$\boxed{i = 1 \dots N}$ (# of particles)

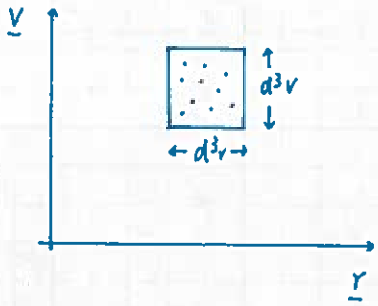
260. 10/7.

Today.

μ-scopic quantities.

1. Most basic quantity. : $f_j(\underline{r}, \underline{v}; t)$

← species.



$dn_j = d^3v\, d^3r\, f_j(\vec{v}, \vec{r}, t)$

- density $n_j(\vec{r}, t) = \int d^3v\, f_j(\vec{v}, \vec{r}, t) \longrightarrow$ in $\dfrac{\#\text{ of particles}}{cm^3}$

(velocity + temperature can be obtained in a similar manner)

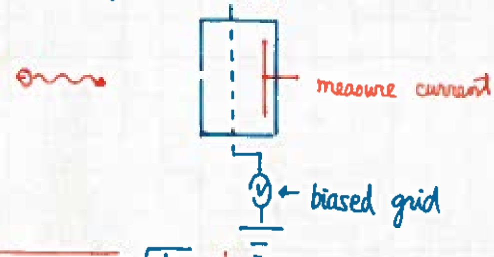
$$\boxed{f \rightarrow f_{maxwell} = \frac{n_0}{(2\pi\, \bar{v}^2)^{3/2}} \exp\left(-\frac{v^2}{2\bar{v}^2}\right)} \longrightarrow \text{Maxwell's distribution.}$$

← Dr. M's convention.

$$\boxed{\bar{v}^2 = \frac{T}{m}} \longrightarrow \text{temp. defined}$$

2. Exp. measurements.

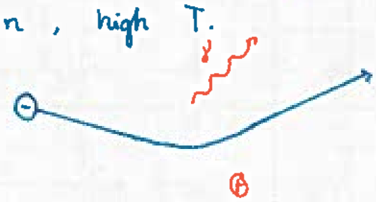
- low temp, low density. → energy analyzer. → a 1-D device.



$$\boxed{I \sim \int_0^{v_{max} \propto \sqrt{\phi_{bias}}} v\, f(v)\, dv}$$

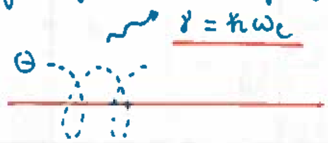
$$\boxed{\frac{dI}{d\,v_{max}} \approx v\, f_e(v)} \longrightarrow \text{Energy Analyzer. Formula.}$$

- for high n, high T.



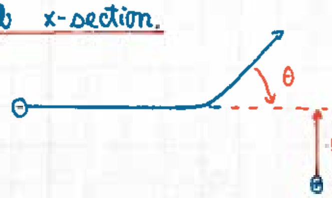
→ from spectrum of γ's, try to find (infer) $f(v)$

- for cyclotrons (magnetized plasma)



- charge x-change (line of sight measurement).

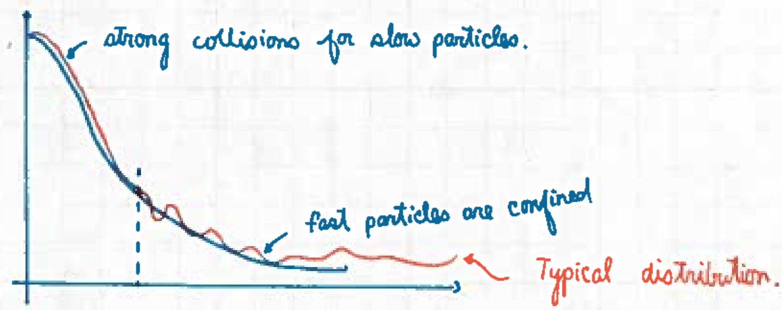
3. Coulomb x-section.



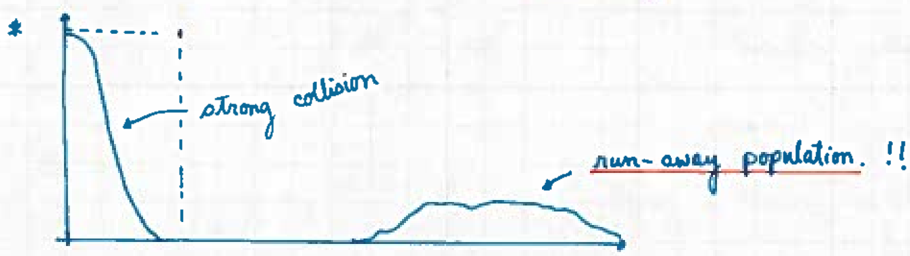
$\sigma_{coul}(\theta = 90°) = \pi \left(\frac{e^2}{m v^2}\right)^2 \sim \frac{1}{v^4}$ (Ask about Deb. Shielding....)

$\boxed{\therefore\ \nu_{coll} \sim v\,\sigma_{coll} \sim \frac{1}{v^3}}$ ← for coulomb collision.

($*$ $\nu_{coll} = n\,v\,\sigma_{coll}$)



$\therefore$ if one applies a force → can develop run-aways.

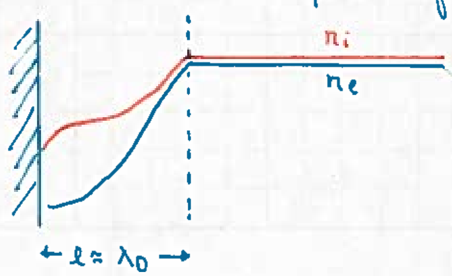


- radiation.
- carries most of the current.
- can be easily dumped by the system → it suffers very little collision.

4. Charge neutralization

$\therefore$ If a plasma is made by ionizing neutrals

$n_e \simeq n_i$ → except @ interfaces.

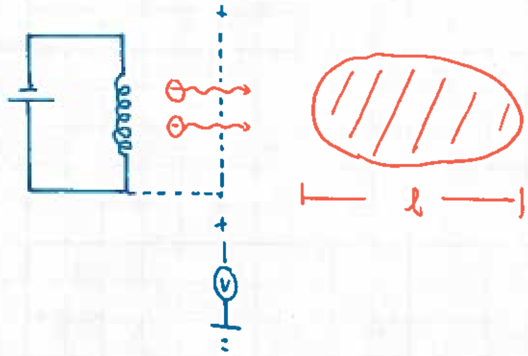


- potential develops such that

$\boxed{T_i = T_e.}$

hence, sheath occurs (hi Ned! ☺)

ii. Plasma can be made of a single species.
e.g. emmitting electron from a filament.



as long as

$$\boxed{\ell \gg \lambda_D, \quad \Gamma \ll 1}$$

we have a plasma

5. Collective parameters.

i. $$\omega_{pj}^2 = \frac{4\pi e^2 n_j}{m_j} \longrightarrow \text{represents collective oscillation.}$$

$\Rightarrow$ harmonic oscillator w/ force $e^2 n$

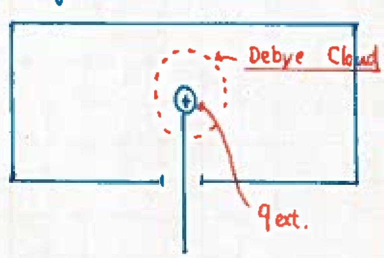
- ω_{pe} : electron plasma frequency. $\longrightarrow$ highest frequency in <u>unmagnetized plasma</u>
- ω_{pi} : ion plasma frequency $\longrightarrow$ $\nexists$ no oscillation @ ω_{pi}. because when we try to excite an ion plasma wave, the electrons will short out the oscillation.

ii. Debye shielding.

$$\lambda_{D,j}^2 = \frac{\overline{V_j}^2}{\omega_{p,j}^2} \longrightarrow \text{mass independent.}$$

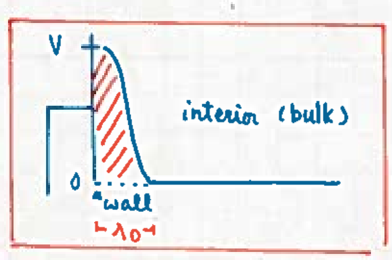
$\overline{V_j}^2 \sim \frac{T}{m}$, $\quad \omega_{p,j}^2 \sim \frac{e^2 n \cdot 4\pi}{m}$

6. Debye shielding.



$$\boxed{\phi(r) = \frac{q_{ext}}{r} e^{-r/\lambda_D}}$$

Yukawa Type

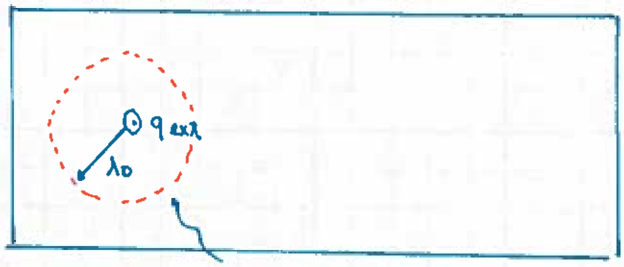


7. <u>Dressed Test Particles</u> (New stuff)

- modify plasma properties

· Test Particle. - its property is not affected by the plasma

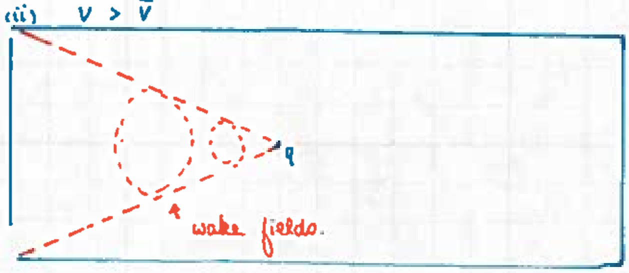
(i) $V = 0$



→ fully dressed test charge.

fully dressed test charge.

(ii) $v > \bar{v}$



if $v_{test} > \bar{v}$ → it leaves a wake field. (Cherenkov radiation)

$$\boxed{\vec{k} \cdot \vec{v} = \omega_p}$$

- In a plasma, each particle can be considered as a test charge.

6. Landau damping

(i) Given: a travelling wave.

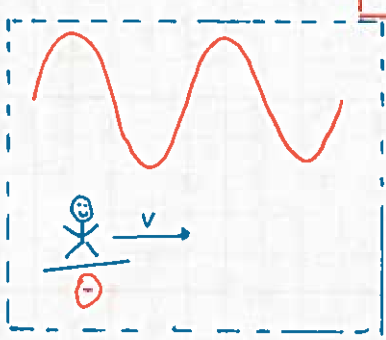
$$E(x,t) \sim \cos(kx - \omega t)$$

(ii) in a particle frame.

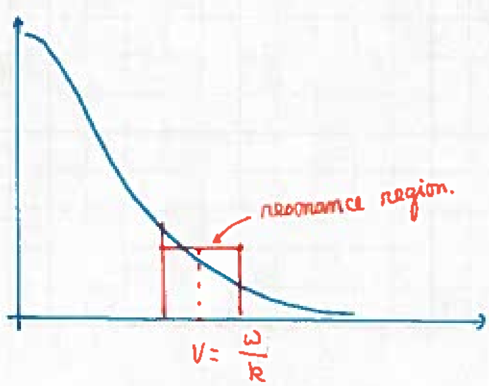
$$x \longrightarrow v(t - t_0)$$

$$E'(x,t) \longrightarrow \cos(kvt - kvt_0 - \omega t)$$

$$\longrightarrow \cos(\boxed{(kv - \omega)}t - kvt_0)$$



if $kv = \omega$ (resonance condition), we can have strong acceleration and / or deceleration (depending on phase) @ $V = \omega/k$



$$E(\vec{x}, t) \sim E_0 \, e^{-|\gamma| t} \cos(\vec{k} \cdot \vec{x} - \omega t)$$

hence. Equilibrium in plasma is a 2-step process.

1. Cherenkov radiation by a dressed charge.
2. Landau Damping by another charge.

* Detuning occurs when $\Delta v \sim \frac{\gamma_L}{k}$.

Today.
Waves in unmagnetized plasma.

1. Given.

$E \sim \exp(i(\vec{k}\cdot\vec{r} - \omega t))$

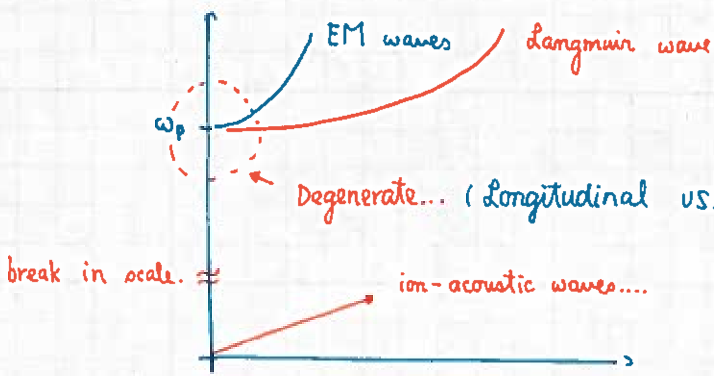
- Linear theory gives....

$k = k(\omega) \longrightarrow$ dispersion relation.

- EM waves: $\omega^2 = \omega_p^2 + k^2 c^2$
- ES waves.
  - Langmuir wave.

    $\omega^2 \approx \omega_p^2 + 3k^2 \bar{v}_e^2$
  - ion acoustic waves.

    $\omega^2 = k^2 c_s^2$ ← sound velocity. $\quad c_s = \sqrt{\dfrac{T_e}{M}}$



- Lamuir wave regime: $\omega < \omega_{pe} \cdot 1.5$
- ion acoustic wave: $\omega < 0.2\,\omega_{pi}$.

2 Roles of the waves.
- Ion Acoustic: Equalize pressure difference....
- Langmuir Wave: Equalize distribution, $f_e(v)$
- EM wave: Commuicate w/ outside.

- @ $\omega = \omega_p \rightarrow$ degeneracy $\rightarrow$ energy transfer between modes.

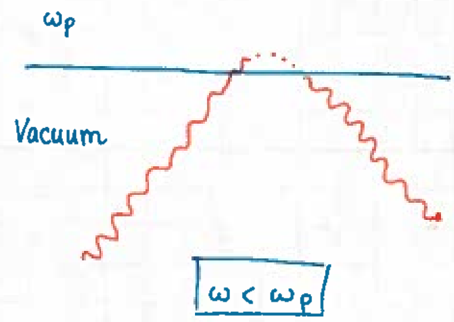
3 for an EM wave.

$k = \sqrt{\dfrac{\omega^2 - \omega_p^2}{c^2}}$

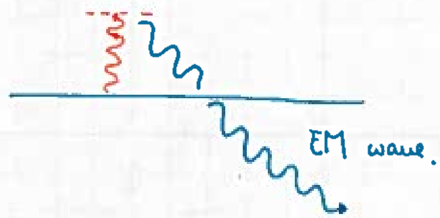
- $\omega > \omega_p \rightarrow$ Propagation.
- $\omega = \omega_p \rightarrow$ cut-off
- $\omega < \omega_p \rightarrow$ Evanescent.

Ex: Ionisphere, again...

- if one works out this problem carefully, we can see the mode conversion process happening @ $\omega = \omega_p$



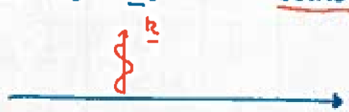
- Conversely, one can generate an ES (Langmuir) wave in a plasma and watch EM emission on the ground.



- Cerenkov condition : $\underline{k} \cdot \underline{v} = \omega$ but $v < c$.
  - → Can excite ES waves but not EM waves.

4. For magnetized plasmas → a lot more structures.

- Medium is bi-refrigent.
  - → 2 EM waves for same ω.
- Propagation $\perp$ to B_0 ⟶ Bernstein modes.



5. Plasma Production.
   - Develop conditions which rate of ionization exceeds rate of recombination.
   - Need to confine plasma for a time. $\boxed{\tau > t_{physics}}$
     - Particle interaction w/ Langmuir wave : $t_{physics} \approx N \cdot \frac{1}{\omega_p}$
     - Plasma transport : $t_{physics} \approx N \cdot \frac{1}{\omega_{i.a.}}$

i. Ionization. → Need energy larger than ionization potential
- Hydrogen : 13.6 eV
- Argon : 15.7 eV
- Cesium : $\boxed{3.9\ eV}$ → low for Alkalite metals

- Methods of ionization
  - electron impact ...

  - Photo- ionization.

- for electron impact. The creation rate.

$$\boxed{\frac{d}{dt} n_- = n_0 \, n_- \, P_{0e}}$$

free electron population

P_{0e} = probability of ionization.

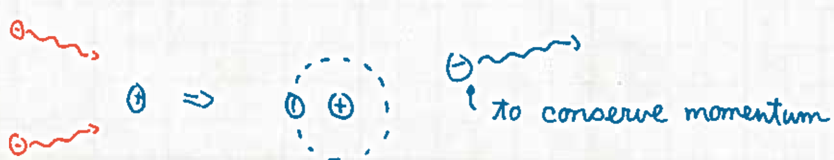
- for photo-ionization, the rate can be found as followed.

$$\boxed{\frac{d}{dt} n_- = n_0 \, \phi \, P_{0\gamma}}$$ → e.g: Ionization in ionisphere.

$P_{0\gamma}$ = photo- ionization cross section.

- Recombination → Several channels, but the 2 most prominent ones are the ~~most prominent~~ a time-reversed creation process.

  - 3- body ~~ra~~ recombination.



$$\frac{d}{dt} n_- \approx - n_-^2 \, n_+ \, P_{e0}$$

$n_+ \approx n_-$

$$\rightarrow \frac{d}{dt} n_- = - n_-^3 \, P_{e0} \propto n^3$$

hence, we'd expect the equilibrium density to be low....

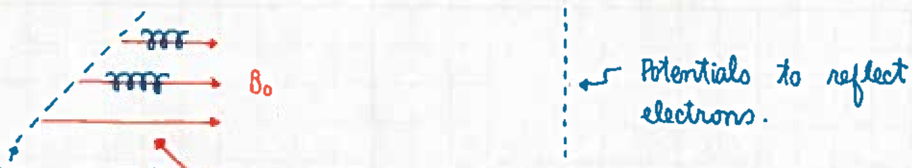
- Radioactive Recombination.

$$\frac{d}{dt} n_- = n_+ n_- \langle P_{\gamma 0} \rangle = \Theta(n_-^2)$$

Recombination Rate...

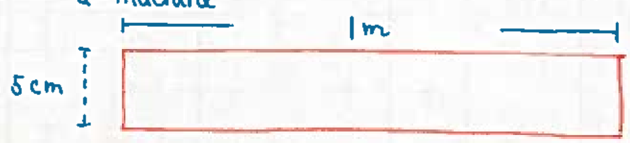
- Confinement time → BIG PROBLEM.

  - Use of Alkali Metal Vapor → Low Ionization Pot (4 eV)
    (Rynn + D'Angelo, → "Q-machine")

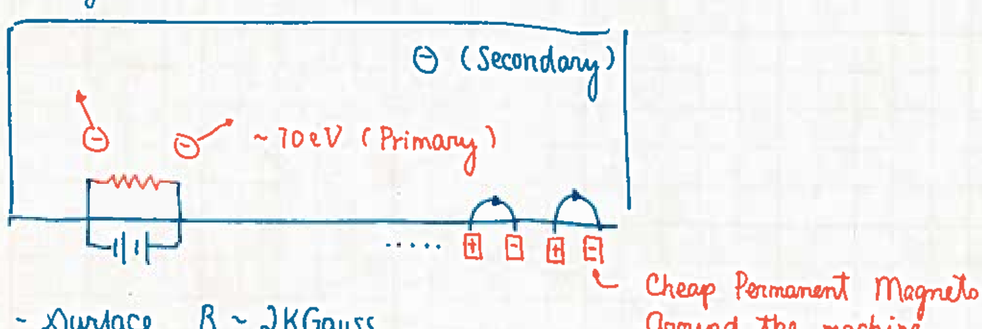


- Fully ionized. (Good)
- Low temperatures (determined by melting point of hot plate)
- $T_i \approx T_e$ (Good)
- small plasma → determined by the size of the beam.

Q-Machine

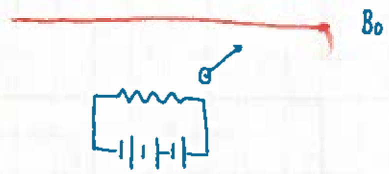


- Mackenzie Bucket (UCLA) → 180E Lab.



- Surface $B \sim 2$ KGauss
- $n \sim 10^{10}\ cm^{-3}$
- $T_e \sim 2\text{-}3\ eV$
  $T_i \sim 0.2\ eV$

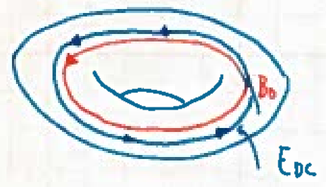
Sidenote:



In a highly magnetized plasma, e^- cannot go across B_0. Then, the filament will acquire a negative potential and stop injecting.

$\tau_{confinement} = \frac{L}{C_s} = \frac{10^2}{10^5} \approx 10^{-3}$ sec. ($*\ C_s = 10^5$ cm/sec)

- Tokamac



- Toroidal Device
- Strong mag field. (~ 10 ~ 50 K Gauss)
- $E_{DC} \rightarrow$ DC electric field.
  - to create 2ndary electrons

- $\tau_{confinement} = 1$ sec.
- Temperature ~ 5 KeV
- Density ~ $10^{14}\ cm^{-3}$
- Volume ~ 20 m^3.

- fusion parameter $n\tau \approx 10^{14}$ (thermo-nuclear range)

222 A. 10/14.

Today
Basic Equations of Plasma.

1. We can have an universal equation

$$\boxed{\frac{D}{Dt} F = 0} \longrightarrow$$ is all and is <u>useless.</u>
↘ too general.

- ask a question → identify τ, l
  τ = time scale
  l = length scale.

- Options
  - Collisionless → Vlasov Equation
  - Collisional + Kinetic → Fokker Planck
  - Fluid description.
  - MHD.

2 Root of all evil → Coulomb force

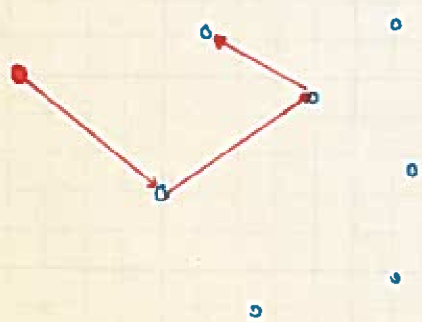
$$|\underline{F}_{12}| = \frac{q_1 q_2}{r^2}$$

(Range is too long)

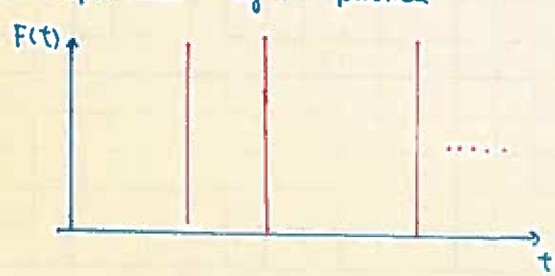
– What is a collision in a plasma?
  - <u>hard sphere</u>

$$F(r) = \begin{cases} 0 & \text{if } \Delta r \geq 2a \\ \infty & \text{if } \Delta r < 2a \end{cases}$$

Test Particle



Force experience by the particle



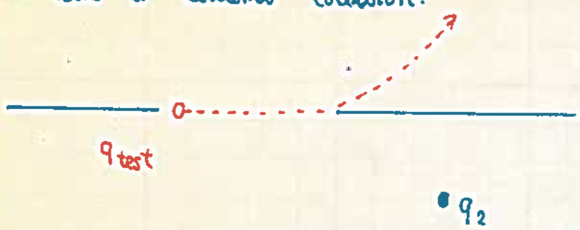
In this case, we have.

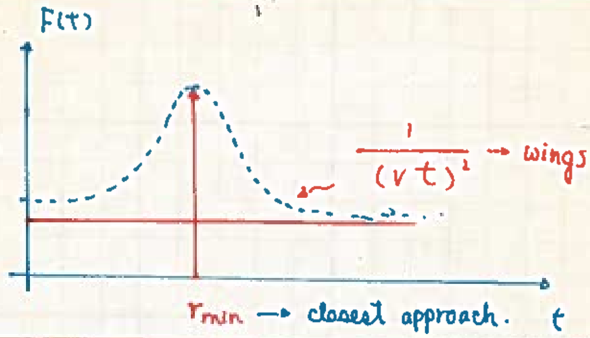
(i) $\sigma = \pi a^2$

(ii) $\nu_c = v n \sigma = \left[n \pi a^2 \right] v$

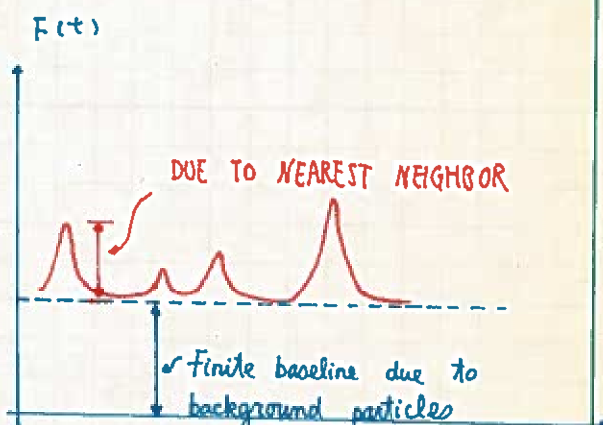
$\boxed{\nu_c \propto v}$ → DIFFERENT THAN COULOMB COLLISION.

- In a Coulomb Collision.

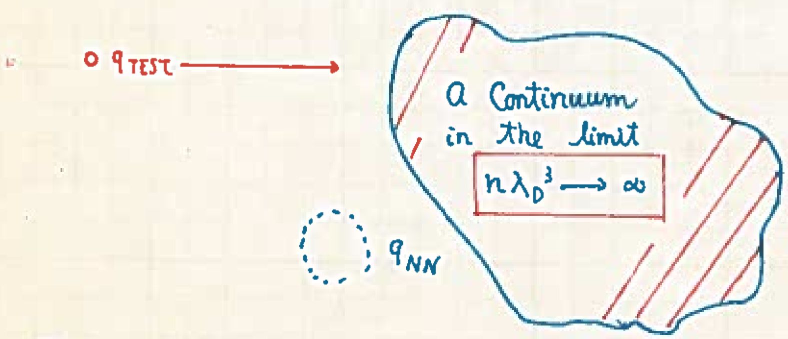




- In a plasma
  - Never any binary interaction.



  - As # of particles increases, the baseline force dominates !!!
  - Ideal limit



- Electric Field.

$$\vec{E} = \vec{E}_{NN} + \langle \vec{E} \rangle$$

Continuum ⟶ smooth charge distribution

$$\boxed{\nabla \langle \vec{E} \rangle = 4\pi\rho}$$