Lecture Notes – Plasma Physics

Key plasma properties:

- Particle Density
- Ionization Degree – quasi neutrality
- Debey Length
- Plasma Oscillation
- Free electrons and ions – particles are dom. by mag. and elct. forces
- needs a source of energy to be sustained

Plasma: – ionized gas

contains: positive ions, neutrals, electrons
(negative ions)

quasi neutral

$$\boxed{n_e = \sum_q q\, n_q}$$

(not the case for EBIT, EBIS)

typically electrons are heated (in ion source plasmas, ions can be heated in fusion plasma)

Key property: electron temperature – typically

- expressed in eV $\propto kT_e$ ([Energy])
- electrons do not transfer a lot of heat to the wall but plasmas have thousands of degree temperature

1eV $\propto$ equivalent to 11600K

Plasma density n_e/n_i $= \dfrac{\text{number of electrons/ions}}{\text{Volume}}$

(1a)

Degree of ionization: $\eta_i = \frac{\sum_q n_q}{n_{atoms} + \sum_q n_q}$

typically the degree of ionization is low for ion sources $\eta_i \ll 1$ (10^{-5} to 10^{-3})

↓

not the case for ECR ion sources!

→ degree of ionization gives a measure of the ionization efficiency for an ion source

Debey Length

Neutrality is intrinsic to plasmas → otherwise an electric field would arise that drives the plasma back to neutrality, but local variations arise

↓

- fluctuation, noise, oscillations
- Plasma sheath ...

- Neutrality is a dynamic ~~eq~~ equillibrium state

Qualitative Derivation of the Debey Sphere / Length

- Suppose within a small sphere δ_x we have charge separation

$$\Rightarrow E_{field} = \frac{e \cdot n_i \delta_x}{\varepsilon_0} \Rightarrow$$ field created between the two charge separated regions

$$\Rightarrow W_{pot} = \int_0^{\delta x} e E_x \, dx = \int_0^{\delta x} \frac{e^2 n_i \delta x}{\varepsilon_0} dx = \frac{e^2 n_i}{2\varepsilon_0} \delta x^2$$

$W_{pot} = \frac{1}{2} k_B T_e \Leftrightarrow$ defines the mobility in the plasma (ions are ignored as they are tooo slow)

$$\frac{1}{2} k_B T_e = \frac{e^2 n_i}{2 \varepsilon_0} \delta x^2$$

movement into one degree of freedom

$$\delta_x = \sqrt{\frac{\varepsilon_0 \cdot k_B T_e}{n_i e^2}} = \lambda_D \text{ Debey Length}$$

The Debey length defines the sphere in which electric fields have an influence ~~and~~.
Outside this sphere electric charges are screened ⟶ important geometric factor for extraction simulations

order of magnitude: mm to 0.01mm | $\lambda_D = 743 \sqrt{\frac{U_e[eV]}{n_e[cm^{-3}]}}$ [cm]

2a

Plasma Oscillation — Plasma Frequency

$$E = \frac{e \cdot n \cdot x}{\varepsilon_0}$$ x.... separation length of charge

↓ causes a restoring force ⟺ oscillations

$$F = -eE = -\frac{e^2 n \cdot x}{\varepsilon_0} = m_e \frac{d^2x}{dt^2}$$

$$m_e \frac{dx^2}{dt^2} + \left(\frac{e^2 n}{\varepsilon_0}\right)^{k} x = 0$$ ⟺ classic harmonic oscillator

↓ solution

$$x(t) = A\cos(\omega t + \phi) \qquad \omega = \sqrt{\frac{k}{m}}$$

Plasma Frequency

$$\omega_{P_e} = \sqrt{\frac{e^2 n}{\varepsilon_0 m_e}}$$ ⟺ Plasma Frequency

$\omega_{P_e} = 2\pi \cdot 8.9 \sqrt{n_e [m^{-3}]}$ ~ plasma density $10^{10}/m^3$

$\omega_P = 2\pi \cdot 8.9 \cdot 10^8$ (GHz regime) } ECR heating! $\sim 10^{16}/m^3$

qualifies wave propagation in a plasma

electromagnetic waves with frequency higher than the critical frequency can propagate, lower they get rejected.

ions: $$\omega_{p_i} = \frac{Q^2 e^2 n_i}{\varepsilon_0 m_i}$$

$$f_{p_i} = 210 \cdot Q \sqrt{\frac{n_i}{A}} \ (\text{Hz}) \quad f\,[\text{MHz}]$$

Magnetic Fields

a) Cyclotron frequency

$$m r \omega^2 = e Q v \times B$$

$$\omega = \frac{eQB}{m}$$ ⟷ frequency of rotation of the particles in the magn. field.

$$f_{ce} = 28 GHz \cdot B(T)$$

$$f_{ci} = 15.2 \frac{QB}{A} [MHz]$$

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b) Cyclotron Radius (GyroRadius)

$$\frac{mv^2}{r} = eQvB$$

$$r = \frac{mv}{eQB} \quad \text{or} \quad Br = B\,roh = \frac{mv}{eQ} = \frac{p}{eQ}$$

→ stiffness of an ion/electron beam in an external field

$$\rho_i = 0.0014 \frac{\sqrt{A T_i}}{QB} (m) \quad \rho_e = 0.00033 \frac{\sqrt{T_e}}{B} (m)$$

Magnetic and Plasma Pressure

Magnetic field contains an energy density ≙ $[J/m^3]$ ⟺ equivalent to a pressure

pressure is transverse to the magnetic field

$$P_{mag} = \frac{B^2}{2\mu}$$ (magnetic field creates a force in a current carrying conductor)

(2c)

Pressure by the gas

$P = nkT$ n.... particle density

Pressure of the plasma then is

$P_{plasma} = n_e k T_e + n k T_i$

$$\frac{B_{int}^2}{2\mu} + (n_e k T_{e\perp} + n_i k T_{\perp}) = \frac{B_{ext}^2}{2\mu}$$

steady state in the plasma

$B_{int} < B_{ext}$

difference for a steady state plasma is small

But for some ion sources (Laser, Arc...) with a dynamic plasma creation process

→ plasma is rapidly expanding

→ highly dynamic → problem is the ~~x~~ reproducibility of each pulse.

Particle transport in plasmas

Drift and diffusion ⟶ important phenomenas for ion source plasma/characterization

Key words: mobility b
conductivity σ
diffusion coefficient D

under the influence of an electric field E + friction added due to collissions one can define a drift velocity

$$\vec{V_D} = \underset{\text{mobility}}{b} \cdot q \cdot \vec{E}$$

$$j_e = q \cdot n_q \cdot \vec{V_D} \quad \text{current carried by drifting particles}$$

$$= q \cdot n_q b q \cdot \vec{E} = \underbrace{q^2 n_q b}_{\sigma} \cdot \vec{E} = \sigma \vec{E}$$

$$b = \left(\frac{1}{m_e \nu_{en}} \right) \propto \frac{1}{\sqrt{m_e}}$$

ν_{en} ← collission frequency

$\nu_e = \sigma_{en} \cdot v_e$ (σ_{en} – cross section; collissions between electron + neutrals)

↳ weakly ionized plasma (friction is due to collission between electron and neutrals)

→ highly ionized plasma the friction is due to collissions between electrons and ions

→ equillibrium is possible if the friction force decreases slowly with increasing v_{eD} (electron velocity)

(collission freq. decreases with increasing electron energy (Coulomb cross section decreases)

⇓

"run away electrons"

3a

Diffussion ∝ mass

⇓

$$\frac{D_e}{D_i} \approx \sqrt{\frac{m_i}{m_e}}$$ → electrons diffuse much faster than ions

↳ in magnetized plasmas the particles are bound to the field lines

↳ → diffusion is very diff. from neutr. gas.

↳ magneto plasma diffusion is dominated through

collissions between particles = Coulomb interaction

$= \frac{\text{scattering}}{\text{time between scattering}} - \frac{r_L^2}{\tau_{90}}$ } // → losses into the magnetic bottle

} transverse → jumps one Larmor radius

↳ confinement / diffusion processes in magnetized plasmas are quite complex – depends on plasma condition ⟷ ~~pt~~ description of the plasma confinement time is ~~also~~ dep. on description of collissions in the plasma.

// to the field: Collission frequency govern confinement time (similar to non magnetized plasma)

$$\frac{D_{\parallel e}}{D_{\parallel i}} = \sqrt{\frac{m_i}{m_e}}$$ transport // fieldline is faster for electrons

⊥ gyrotron motion + Coulomb collissions

if $f_{cyc} \gg f_{coul}$ → particles hops from one fieldline to the next $D_\perp \sim \nu \langle r_c \rangle^2 \propto m \rightarrow \frac{D_{\perp e}}{D_{\perp i}} = \sqrt{\frac{m_e}{m_i}}$

Sheath formation and Plasma Walls / objects in the plasma

- ion source plasma is closed by a vessel → interaction ~~of~~ between the wall and the plasma particles → can be very important for the operation of ion sources / performance (also critical for fusion devices)

ions → stick to the wall
→ re-emitted as neutrals
→ desorpt at a later time (impurities)
→ create secondary particles
→ sputtering

electrons: stick to the wall
absorbed
secondary particles

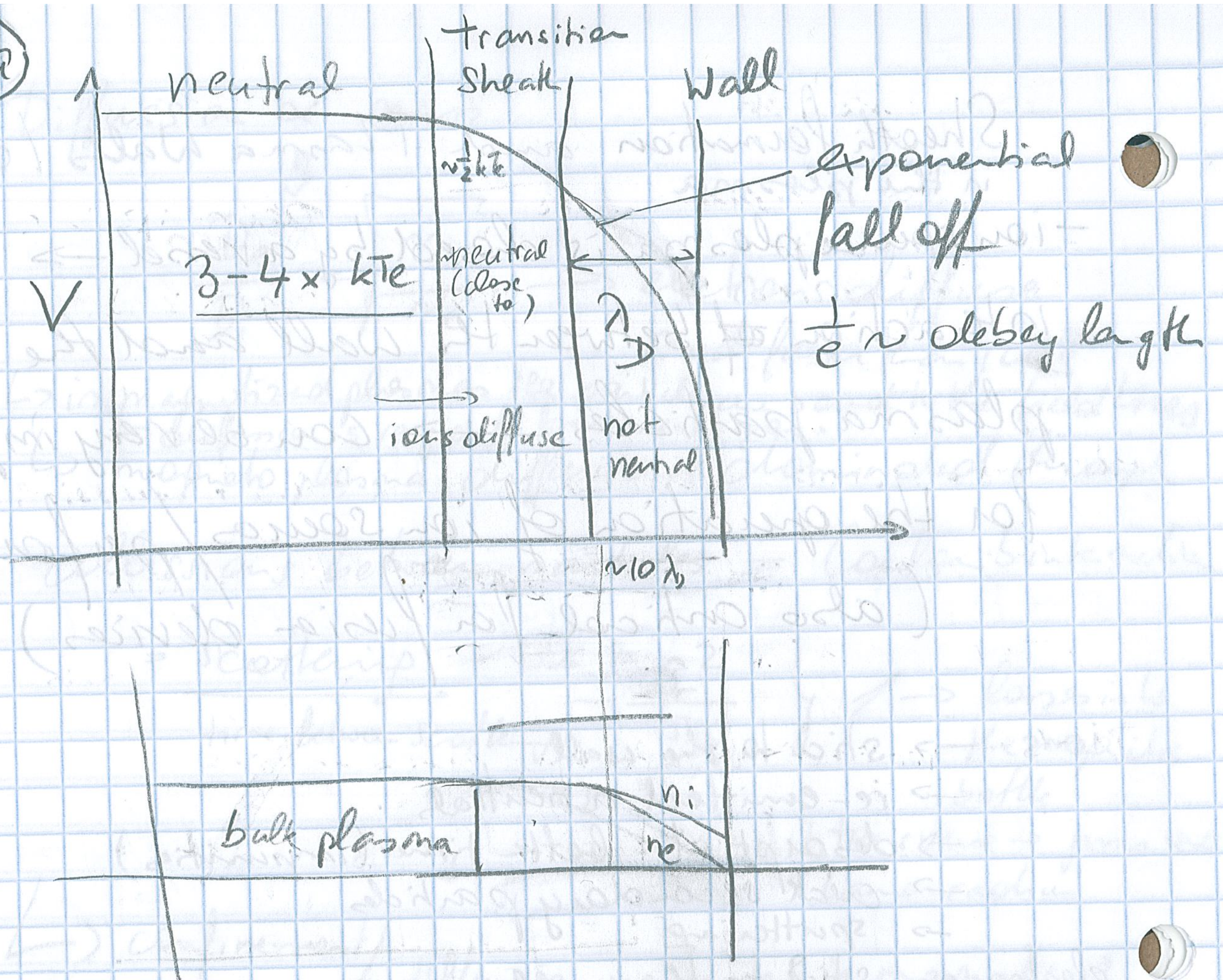
Plasma sheath:

Between the plasma and the wall a positive potential is created to maintain plasma neutrality.

Qualitative explanation: ~~(~~(neglect any second. particles)

e^- have much higher mobility than ions
↓
more electrons hit the wall than ions –
plasma develops a positive plasma potential so the net current to the wall = 0 and the bulk plasma remains neutral.

4a



plasma potential usually has a few Volts →

→ measure of the energy spread of the beam

Homework: Calculate Debey Length, plasma sheet thickness
make a graph?
get a feel for λ_D

extraction Systems

Sheath thickness with an external voltage

$$d_{Sheath} \sim \lambda_D \sqrt{\frac{eV}{kT}}$$

10kV, 5eV

$10^{10}/cm^3$

~ 44 debey length

Ionization

- electron impact ioniz.
- photo ioniz.
- field ioniz.
- Surface ionization

X Recombination, charge exchange

electron impact ionization (single/multiple)

↳ has a threshold energy $E_e \geq e\phi_i$ ← ionization potential

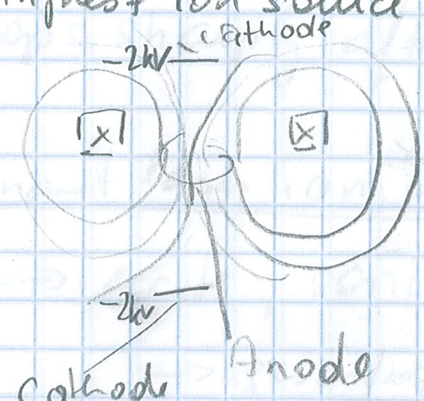
$$e^- + A \rightarrow e^- + A^+ + e^-$$

Electron impact ionization cross section increases with energy: peaks ~ $3-4 \times \phi_i$

then decreases $\frac{1}{E_e}$

enhance chance of ionization by increasing the electron path in the source (electron confinement)

→ simplest ion source: Penning discharge Ion Gauge (PIG)



Salzborn / Müller

$$\sigma = \frac{A}{E_e \phi_i} \ln \frac{E_e}{\phi_i}$$

$A = 1.4 \times 10^{-3}\ cm^2 (eV)^2$

→ strongly decreases with charge state ϕ_i ... Ionization Energy

(5a)

— show Ar ionization cross section

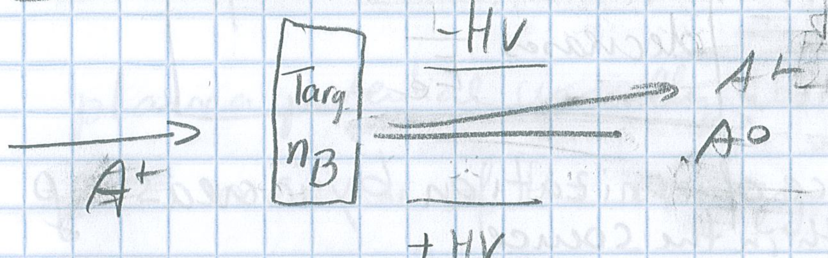
—> step wise ionization is ~~most~~ more likely
(increase e^- confinement time!)

estimate: $\tau_i(Q)$ needed for stripping

$$\tau_i(Q) = \sum_{k=0}^{Q-1} \frac{1}{n_e \cdot (\sigma_{k,k+1})\, v_{eT}}$$

n_e: electron density; $\sigma_{k,k+1}$: cross section; v_{eT}: electron velocity

(—> show earlier!)
What is a cross section: Probability of something to happen



$$\frac{dI_{A^+}}{dx} = -\sigma\, n_B \cdot I_{A^+}$$

$$dI_{A^+} = -\sigma\, n_B\, I(x)\, dx$$

$$\frac{dI}{I(x)} = -\sigma\, n_B\, dx$$

$$I(x) = I_0\, e^{(-\sigma_T n_B x)}$$

average mean free path $\lambda = \frac{1}{\sigma n_B}$ $\quad f = \frac{v}{\lambda} = \sigma v_A n_B$

$$R = \langle f \rangle = n_B \langle \sigma v \rangle$$

Homework:

→ go to NIST : get data for the ionization potential – Why are there sharp drops in the potentials

→ calculate Salzborn Müller cross sections for $Ar^{+} \rightarrow Ar^{18+}$
What is the minimum confinement time to reach Ar^{18+} (ignoring charge exchange)

Photoionization:

→ the absorption of a photon will result in ejection of an electron.

$h\nu > e\phi$ $1 eV \hat{=} 12400 Å$ soft x-rays to UV

The cross section minimizes sharply at a photon energy just slightly above the ionization energy and drops sharply after that

Resonant laser ionization

→ excite, ionize : 2 step process

→ resonant process ⟷ ~~very~~ selective

way of ionization ⟷ link to Isolde paper!

(6a)

Ion impact ionization

- charge transfer or charge exchange collissions

- resonant charge exchange (between the same atomic sp.)
- energy requiered for this ionization process req. higher energies : $A^0 + Q^{n+} \rightarrow A^+ + Q^{n-1}$

Since the ion velocity must ~~be~~ match the orbitel electron velocity → important loss mechanism for highly charged ions in the source plasma and beam transport.

σ ~~∝~~ Q of ion ↔ Homework for vacuum section!

Negative ion production

→ Daniel's lecture

- double charge exchange or two step process

$D^+ + Ba^0 \rightarrow D^- + Ba^{2+}$

$D^+ + Cs^0 \rightarrow D^0 + Cs^+$

$D^0 + Cs^0 \rightarrow D^- + Cs^-$

+ volume production within the plasma

H_2 detachment (↔ lookup)

Field ionization

→ sharp needle - intense electric field to extract electrons or ions from the solid or lq. state

Lq metal ion sources → one of the brightest sources

<u>Surface ionization</u>

ions get extracted from an heated substrate or ionized ~~after the vapor~~ through contact with an hot tube/mesh (Tantalum)

→ Alkali metals Li, Na, ...