Part II

Ion Sources Physics

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A survey of physics occuring in Ion Sources. To introduce better The Ion Source presentations

- Reminder of some microscopic quantities
- The Paschen Law
- The Glow Discharge (Crooks tube)
- Basics of plasma physics
- Process of ionization in a plasma
- Motion of particles in a magnetic field
- Introduction to Electron Cyclotron Resonance (ECR)

Reminder of some microscopic processes

Cross section:

- The cross section σ is the effective area which governs the probability of a specific physical interaction between two particles. Unit is usually cm^{-2}.

Mean free path

- It is the mean distance λ covered by a particle between two interactions with a target of the same type. The probability to have an interaction is proportional to the target density n (in cm^{-3}). So, Probability of collision=1=$n.\sigma.\lambda$

$$\lambda = \frac{1}{n\sigma}$$

Collision frequency

- It is the number of collision ν pers second associated to the processed described by the cross section σ. It is proportionnal to the velocity of the particle v and to the number of targets n. Unit is Hz or [s]$^{-1}$.
-

$$\nu = n\sigma v$$

Collision time

- It is the duration τ inverse of the collision frequency. Unit is [s]

$$\tau = \frac{1}{\nu} = \frac{\lambda}{v}$$

The Paschen Law

The Paschen Law describes the condition to initiate a breakdown in a gas, as a function of:

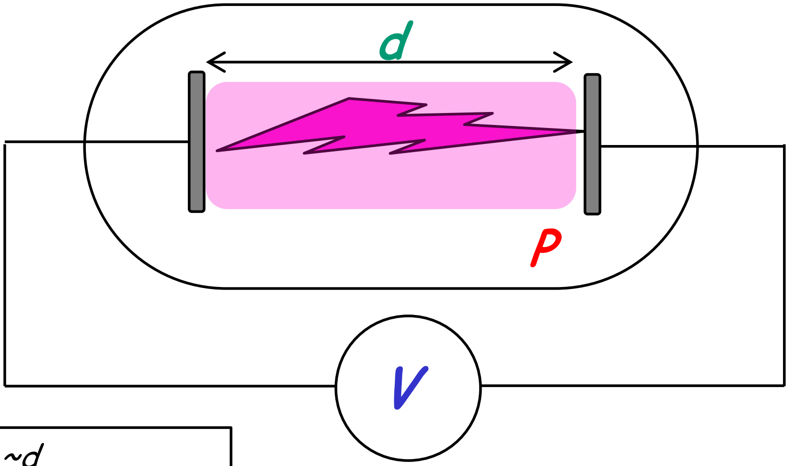
- The pressure *P*
- The voltage *V* between 2 electrodes
- The distance *d* between 2 electrodes
- α, β constants for one gas

Why is there a disuption?

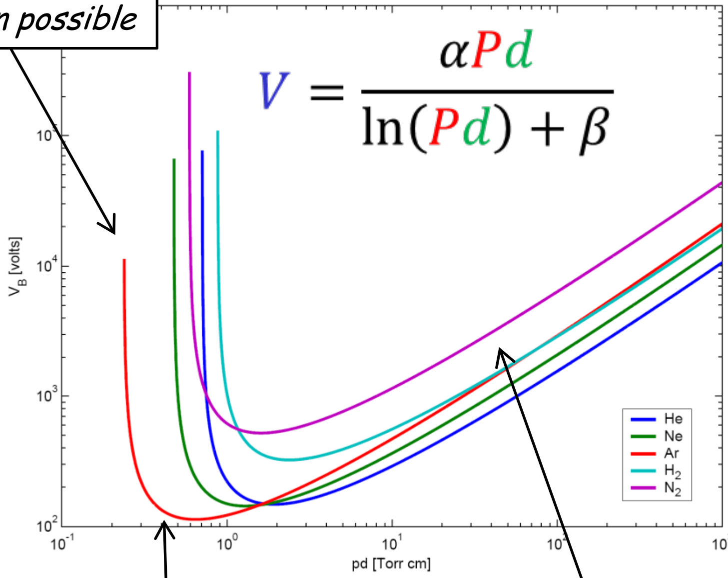
- A single free electron is accelerated by the electric field E=V/d
- The distance between 2 collisions with gas molecule is the mean free path Λ.
- If the energy gained between 2 collisions is greater than the ionization potential of the gas, a second electron is created => avalanche=> breakdown of a plasma

Asymptotic behaviour

- The higher the pressure, the lower Λ and the higher the necessary voltage V to make a disruption. The curve increases.
- At low pressure, Λ ~d and no more chain reaction is possible, the breakdown is no more possible.



Λ ~d
⇒ No chain reaction possible



$$V = \frac{\alpha P d}{\ln(Pd) + \beta}$$

Paschen Minimum

Λ decreases
⇒ V must increase
To keep disruption

The Direct Current Glow Discharge (1/3)

An example of how non linear is plasma physics

- Stage 1 : The Dark Discharge

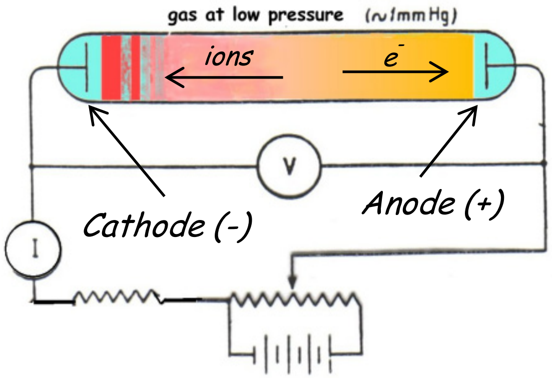
(5)The Breakdown voltage (transition):
Secondary electrons emitted by impact of e^- on cathode and ions on anode increase current enough to breakdown the plasma which starts to emit light.
See Paschen Law slide!

(4)The Corona Discharge:
Additional Corona discharge occur in regions of high electric field near sharp points, edges in gases prior to electrical breakdown (see FE GUN slides!)

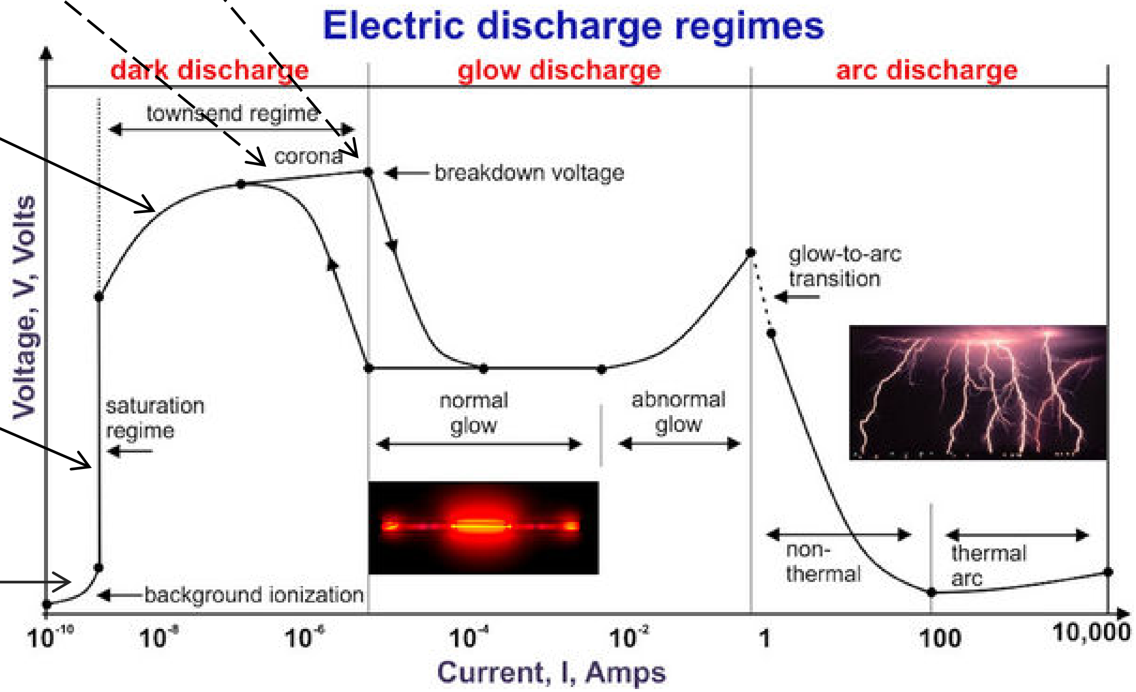
(3)The Townsend regime:
The free e- gain enough energy on λ to ionize atoms of gas=> avalanche.
Exponential rise of current with V.
(regime of wire chambers detectors!)

(2)The saturation regime:
Electric field is high enough to collect all the charges produced by cosmic rays. => I saturates while V is increased (like a radiation counter!)

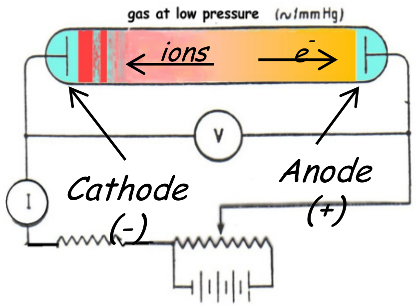
(1)The background ionization:
Energetic Cosmic rays induce a residual Ionization near to the electrodes.
The weak local electrical field enables To collect the charges



Tube filled up with Ne or Ar gas with P~0.1-10 mbar



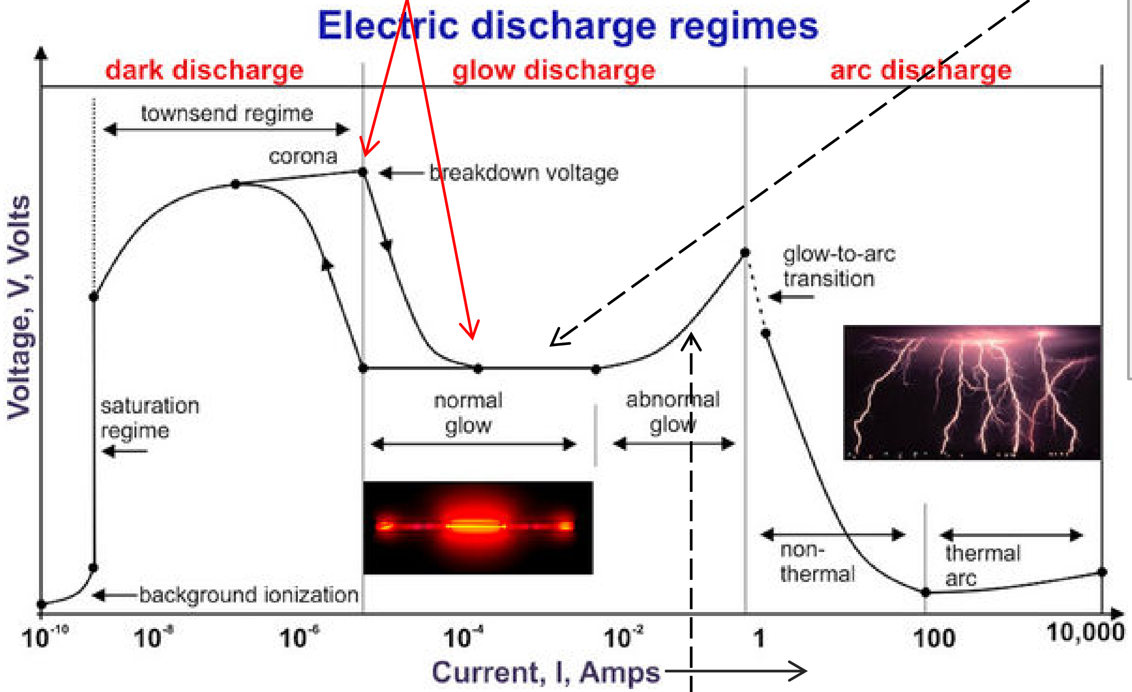
The Direct Current Glow Discharge (2/3)



…An example of how non linear is plasma physics

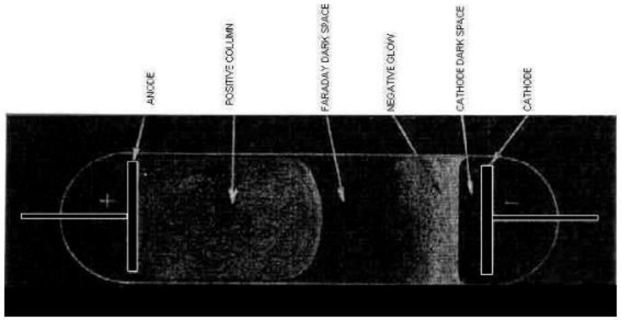
- Stage (2): The Glow Discharge (above breakdown)

(5)The Breakdown voltage (transition):
At the breakdown stage, the current may increase exponentially by a factor of 10^4 to 10^8 . Then, the plasma naturally evoluateds toward the glow discharge regime

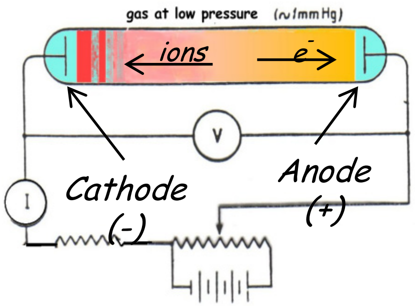


(6)The Normal Glow Discharge:
The plasma glows because the electron density and electron energy are high enough to generate visible light by excitation collisions.
At low current, glow is only visible on one part of the tube. The electrode current density in ***independent*** *of the total current here. It means that the total current is proportional to the area of contact between plasma and electrode.*
At Higher current; the glow is extended to the whole tube and plasma intercepts the whole electrodes surface.
(e.g. Neon tubes on the ceiling!)

(7)The Abnormal Glow Discharge:
In the abnormal glow regime, the voltage increases significantly with the increasing total current in order to force the cathode current density above its natural value and provide the desired current.



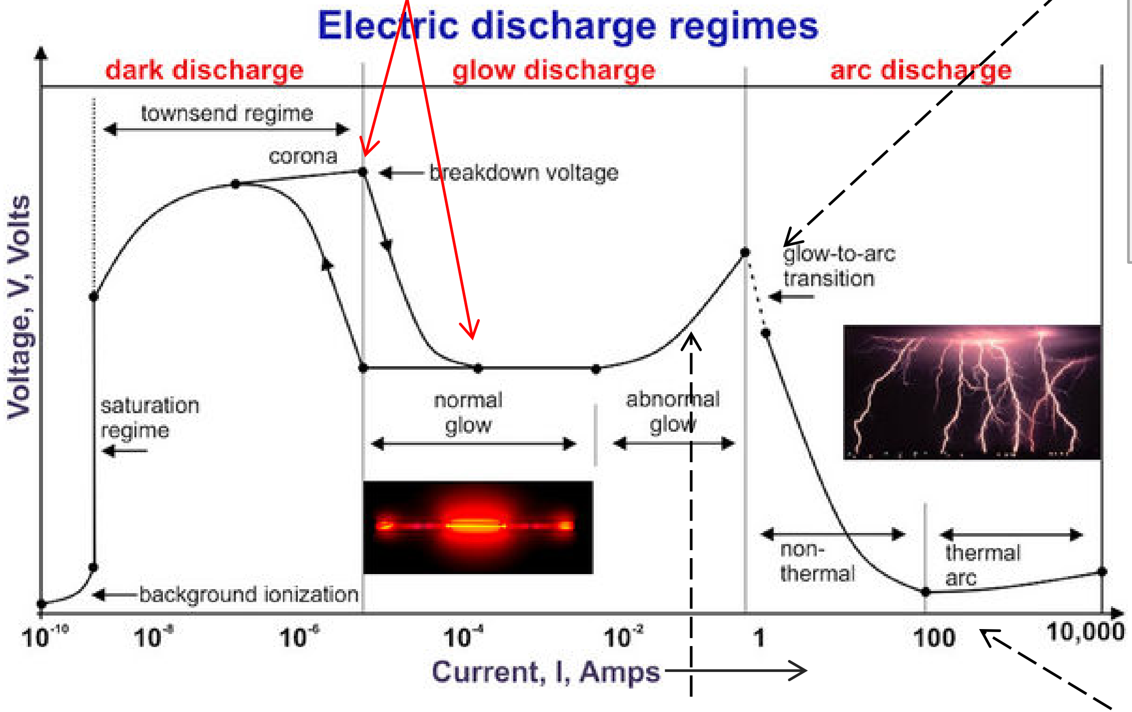
The Direct Current Glow Discharge (3/3)



…An example of how non linear is plasma physics

- Stage (3): The Arc Discharge (to be avoided…)

(5)The Breakdown voltage (transition):
At the breakdown stage, the current may increase exponentially by a factor of 10^4 to 10^8 . Then, the plasma naturally evoluateds toward the glow discharge regime



(8)The Glow to Arc Transition:
The electrodes become hot, the cathode starts to emit electrons thermionically. If the DC power supply has a sufficiently low internal resistance, the discharge will undergo a glow-to-arc transition. The arc regime, from I through K is one where the discharge voltage decreases as the current increases, until large currents are achieved at point J, and after that the voltage increases slowly as the current increases.

(9)The Arc Discharge (destructive!):
In the arc regime, first the discharge voltage decreases as the current increases, electrons are hot with respect to ions, until large currents are achieved. Above, ions are heated by collisions and Ti=Te , the voltage increases slowly as the current increases (increase of resistance with the plasma temperature).

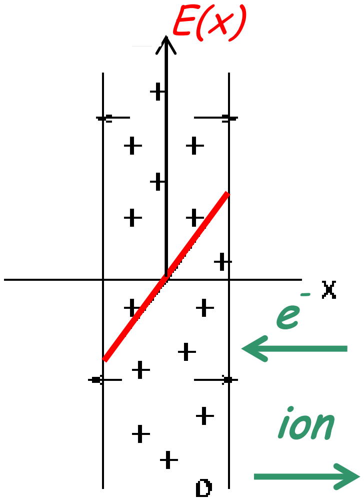
Basics of plasma physics - generalities

- Plasma is considered as the 4th state of matter
- It can be considered as a ionized gas, composed of ions and electrons and possibly of neutral atoms.
  - → The degree of ionization of a plasma is $\alpha = \frac{n_i}{n_i+n}$, n is the density of neutral, and n_i is the ion density
- A plasma is always neutral taken as a whole
  - → $n_i \times e + n_e \times (-e) = 0$ (n_i= ion density of single charge state, n_e= electron density)
- Plasma exists on a wide range of density, pressure and temperatures
  - → a Hot (Thermal) Plasma is such that it approaches a state of local thermodynamic equilibrium where Ti=Te (Ti ion temperature, Te electron temperature).
  - → a Cold Plasma is such that the move of ions can be neglected with respect to electrons, so Te>>Ti. A cold plasma is out of local thermodynamic equilibrium.
- Usual laboratory plasmas are created under vacuum and sustained by injecting electromagnetic power.

- Plasma applied to particle source are mainly COLD PLASMAS, since their goal is to create low emittance beam, and the lower the ion temperature, the smaller the beam emittance.

Basics of plasma physics – Quasi neutrality – Debye Length

- Any local difference between n_i and n_e gives rise to a huge electromagnetic force that tends to reduce it, to tend back to neutrality. One talks about collective behaviour of a plasma.
  - → If $n_i \neq n_e$, then a local space charge appears: $\rho = e(n_i - n_e)$
  - → A local electric field appears: $div(\vec{E}) = \frac{\rho}{\varepsilon_0}$
  - → Let's consider a one dimension slab of plasma with a n_i excess
  - → $\frac{dE}{dx} = \frac{\rho}{\varepsilon_0}$ => $E(x) = \frac{\rho}{\varepsilon_0} x$
  - → The resulting force $F_x(x) = (\pm e)\frac{\rho}{\varepsilon_0} x$ expells ions and attracts ne= arby electrons, tending eventually to reduce the space charge $\rho = e(n_i - n_e) \rightarrow 0$



- So plasma ar also locally neutral
- The smallest dimension scale at which the plasma is quasi-neutral is called the Debye Length

$$\rightarrow \lambda_D \sqrt{\frac{\epsilon_0 k T_e}{n e^2}}$$

, k is the Boltzmann constant, n plasma density

Basics of plasma physics – electron an ion mobility

- The mean velocity of a particle in a plasma at temperature T is expressed as:

$$\frac{1}{2}\mathrm{m}v^2 = \frac{3}{2}kT$$

- For a plasma with T_i=T_e=T, the electrons are moving faster than ions:

$$\frac{v_i}{v_e} = \sqrt{\frac{m_e}{m_i}} \ll 1$$

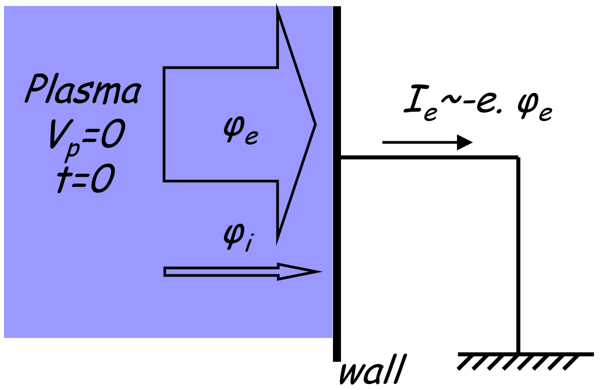
- Electrons are also more sensitive than ions to any electric field E:

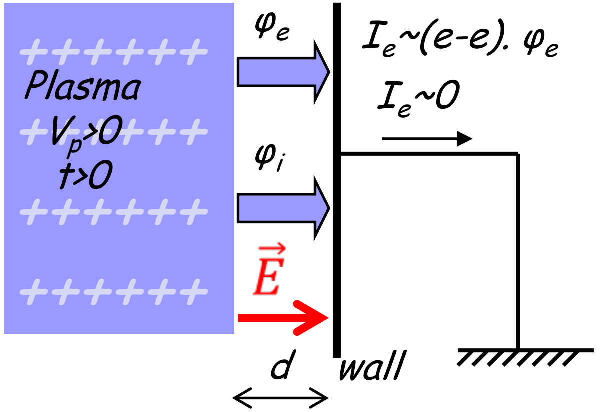
$$F_x = m\frac{dv}{dx} = qE \Rightarrow \left|\frac{dv_i}{dv_e}\right| = \frac{m_e}{m_i} \ll 1$$

- In a cold plasma with T_e>>T_i, it is assumed that the movement of ions is negligible with respect to the one of electrons.
  - → Simplification of theory and calculations
  - → Case of Many Ion Sources

Basics of Plasma Physics - The plasma Potential V_p

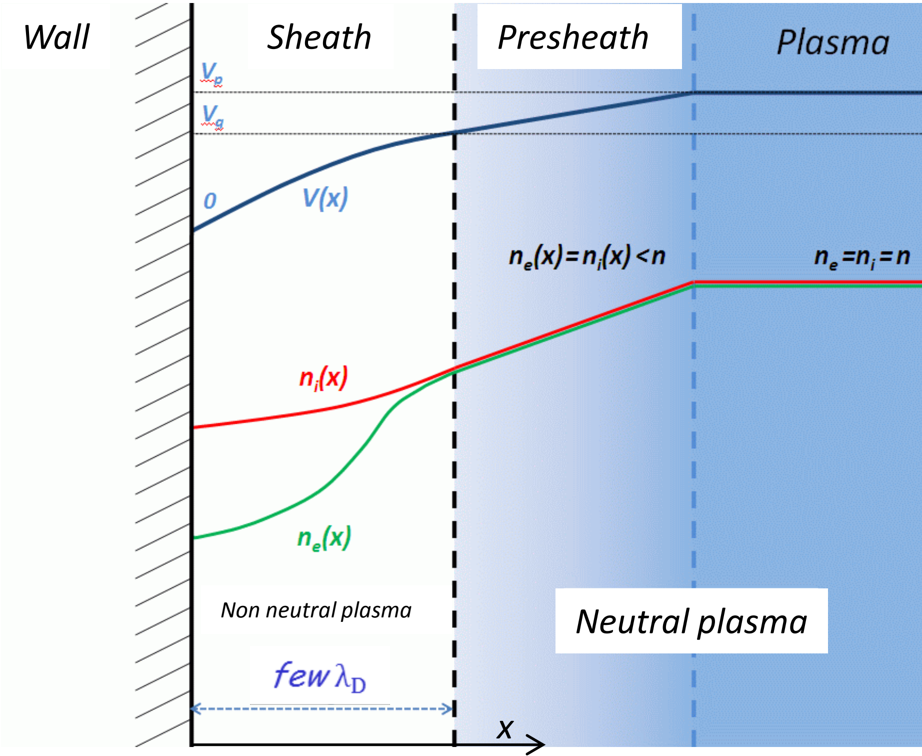
- **What happens when the voltage at the boundary of a plasma is fixed?**
  - The plasma immediately reacts to keep as much as possible its global neutrality…
- **It auto-sets its voltage to the plasma potential $V_p > 0$**
  - Imagine we just created a plasma in a box at t=0 with a voltage $V_p=0$. It is naturally expanding in space and finally reaches the wall fixed to V=0 potential.
    - → The flux of electrons to wall is $\phi_e = n_e v_e$
    - → The flux of ions to wall is $\phi_i = n_i v_i$
  - Since $\phi_e \gg \phi_i$, the net current to the wall is negative
    - → The loss of electrons charges positively the plasma , => V_p starts to increase
  - Consequently, a local electric field E=(Vp-0)/d appears near to the wall
    - → The plasma screens the electric field for distance d> λ_D
    - → The local E decelerates electrons toward the wall
    - → The local E accelerates ions toward the wall
  - Eventually the equilibrium is reached for the plasma potential V_p such that $\phi_e = \phi_i$





Basics of Plasma Physics - The plasma Sheath

- The sheath formation is, like the plasma potential, a consequence of the quasi-neutrality conservation of the whole plasma.
  - The sheath width is ~ a few λ_D
  - The plasma in the sheath is not neutral
  - The cold electrons from the plasma with a kinetic energy E<eVp are repelled back by the sheath which provides an electrostatic confinement.
  - Physical properties of the sheath:
    - $\rightarrow \mathrm{n_e}(x) \ll \mathrm{n_i}(x)$
    - $\rightarrow \mathrm{n_i}(x) v_i(x) = \mathrm{n_e}(x) v_e(x) = Constant$
    - $\rightarrow \mathrm{n_e}(x) = \mathrm{n_e} e^{-\frac{eV(x)}{kT_e}}$
    - $\rightarrow \Delta \mathrm{V(x)} = e\frac{n_e(x)-n_i(x)}{\epsilon_0}$



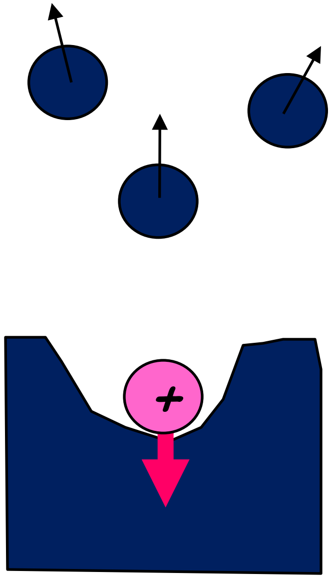
- Bohms Criterion
  - A Presheath is present between the sheath and the plasma
  - The presheath is neutral
    - $\rightarrow \mathrm{n_e}(x) = \mathrm{n_i}(x) < n$
  - The densities decrease linearly with x due to a potential drop in the presheath
    - $\rightarrow V_p - V_g = kT_e/2e$, where V_g is the potential between sheath and presheath
  - The Bohm criterion defines the ultimate ion velocity v_g at the entrance of the sheath to allow the whole plasma equilibrium: $v_g \geq \sqrt{kT_e/m_i}$
- To be used when one wants to simulate a beam extraction from a plasma!

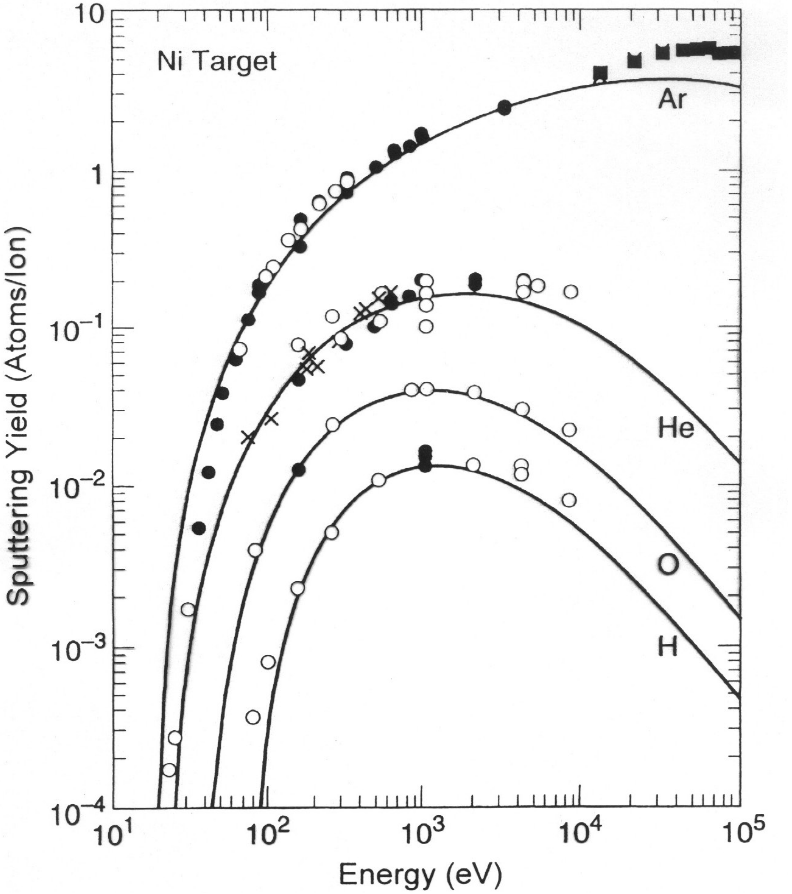
Plasma/ wall interaction: SPUTTERING

- The ions are accelerated in the sheath toward the wall with a kinetic energy $E_i = Z.e.V_p$, where Z is the charge state of the ion and V_p the plasma potential. This energy is sufficient to sputter the wall.

		Ions			
	E_p (eV)	Ne+	Ar+	Kr+	Xe+
Targets	Al	13	13	15	18
	Ti	22	20	17	20
	Ni	23	21	25	20
	Cu	17	17	16	15
	Ag	12	15	15	17
	Au	20	20	20	18
	W	35	33	30	30

Kinetic energy threshold to start sputtering



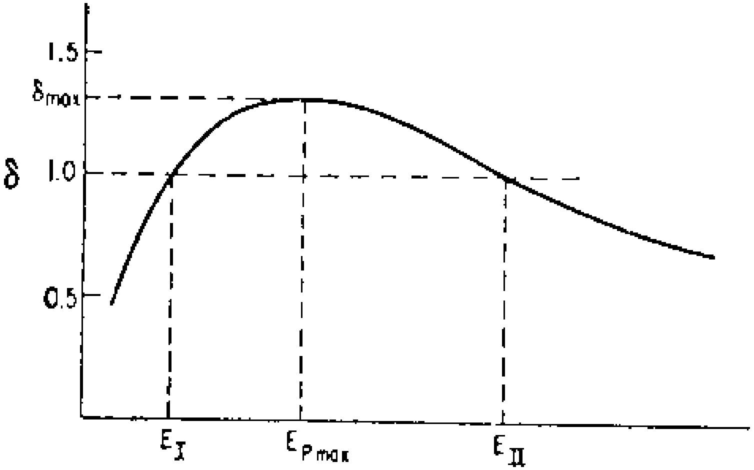


- sputtering Yield depends on target mass
- sputtering ⇔ slow matter destruction
- Induces a plasma contamination

=> one of the major difficulty in high density Tokamak…

Plasma/Wall Interaction: Secondary Electron Emission

- Impinging energetic electrons on walls can generate several secondary electrons (SE) which are accelerated in the sheath toward the plasma
- The SE Yield depends on the primary electron kinetic energy and on the material comosing the wall
- The SE emission can deeply change the plasma equilibrium (plasma potential, plasma density, electron temperature)
- A well selected material can improve the plasma performance (eg Aluminum)



Typical dependance of SE Yield with energy

Element	δ_{max}	E_p (eV)	E_I (eV)	E_{II} (eV)
Cu	1.3	600	200	1500
Fe	1.3	600	200	1500
Pt	1.8	700	350	3000
Ta	1.3	600	250	>2000
W	1.4	650	250	>1500
Compounds	δ_{max}	E_p (eV)		
NaI (crystal)	19	1300		
Al2O3 (layer)	2 to 9			
MgO (crystal)	20 to 25	1500		

Characteristic of SE emission for various elements and compounds

Basics of Plasma Physics - Plasma Oscillation

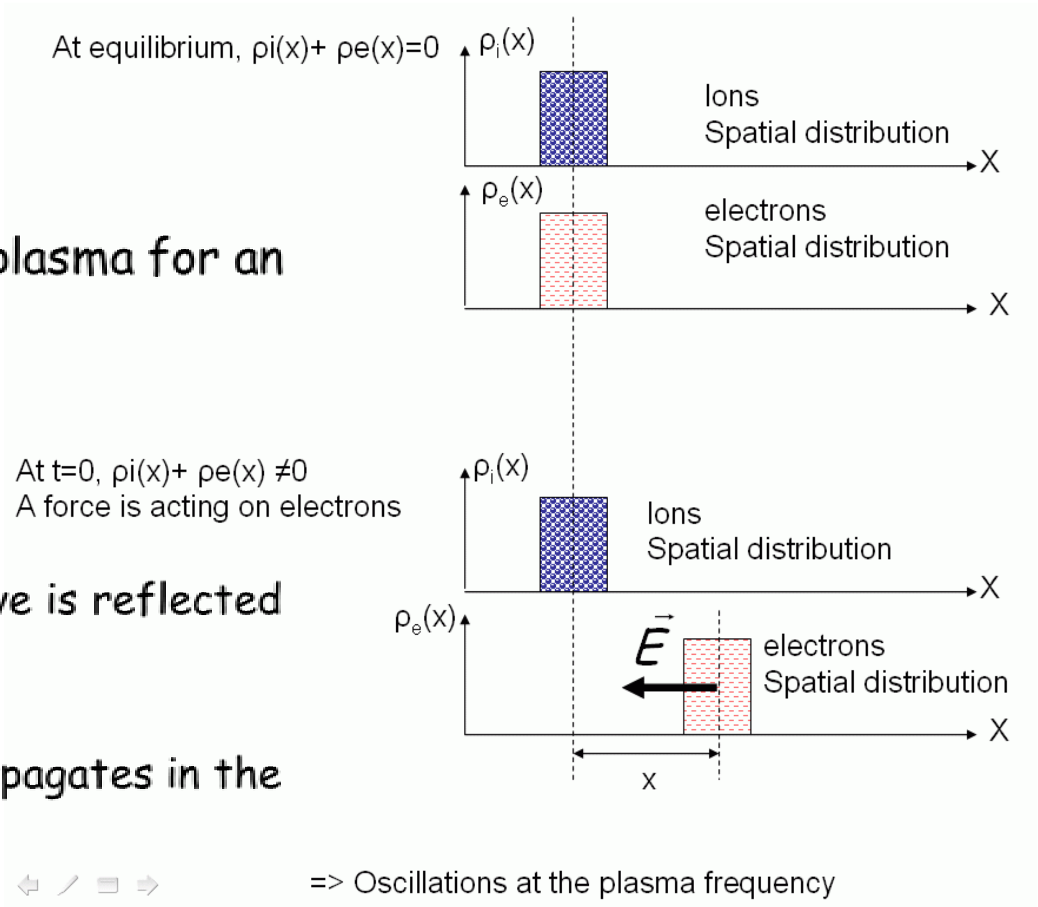
- The plasma (angular) frequency ω_p (or Langmuir frequency) is the natural frequency of oscillation of the electrons in the plasma

$$\rightarrow \omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

- The dispersion relation in the plasma for an electromagnetic light wave is

$$\rightarrow \omega^2 = {\omega_p}^2 + k^2 c^2$$

- If $\omega < \omega_p$, k is imaginary and the wave is reflected out of the plasma
- If $\omega > \omega_p$, k is real and the wave propagates in the plasma



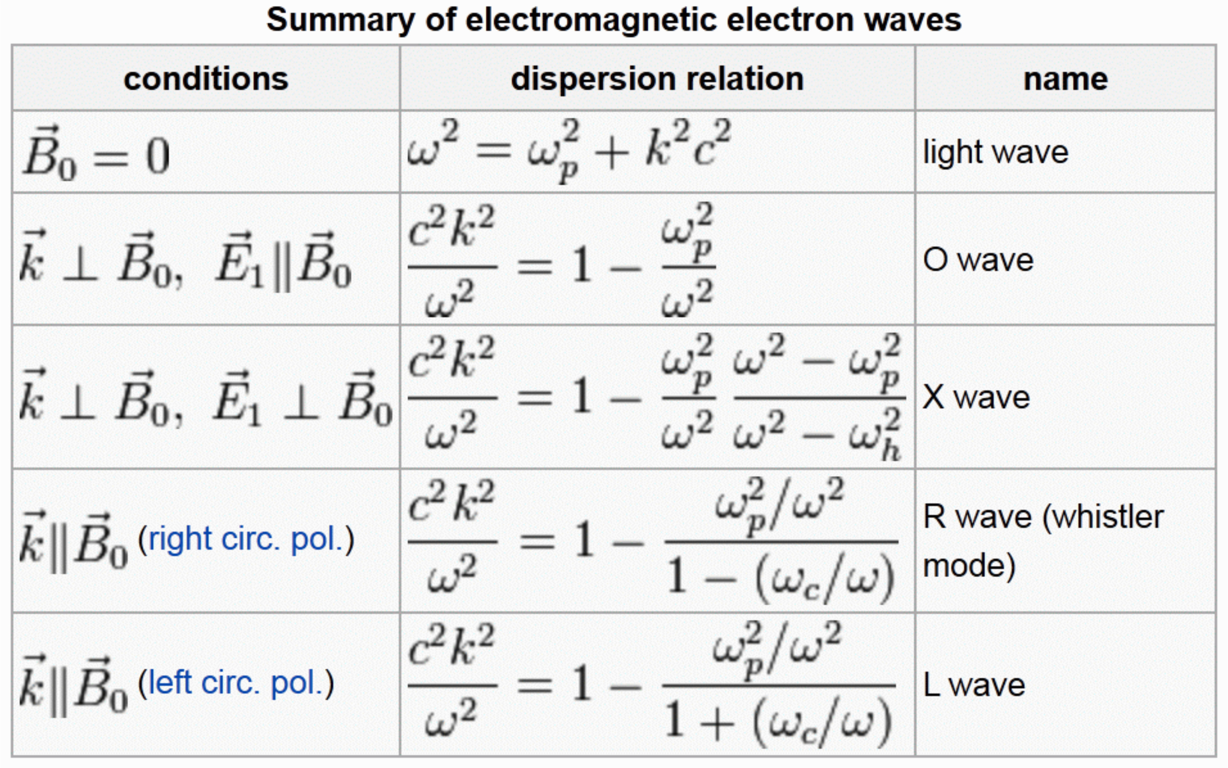
At equilibrium, ρi(x)+ ρe(x)=0

At t=0, ρi(x)+ ρe(x) ≠0
A force is acting on electrons

=> Oscillations at the plasma frequency

Electromagnetic Electron Waves in Plasma

- The interaction of an electromagnetic electron wave with plasma is very complicated. A list of dispersion relation as a function of the type of wave propagating in a plasma is presented for completion
    - An electromagnetic electron wave is a wave in a plasma which has a magnetic field component and in which primarily the electrons oscillate



Summary of electromagnetic electron waves

conditions	dispersion relation	name
$\vec{B}_0 = 0$	$\omega^2 = \omega_p^2 + k^2c^2$	light wave
$\vec{k} \perp \vec{B}_0,\ \vec{E}_1 \parallel \vec{B}_0$	$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$	O wave
$\vec{k} \perp \vec{B}_0,\ \vec{E}_1 \perp \vec{B}_0$	$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2}$	X wave
$\vec{k} \parallel \vec{B}_0$ (right circ. pol.)	$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 - (\omega_c/\omega)}$	R wave (whistler mode)
$\vec{k} \parallel \vec{B}_0$ (left circ. pol.)	$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 + (\omega_c/\omega)}$	L wave

Microscopic processes in a plasma: charged particle interaction

- **Elastic Collisions in the plasma**
  - The electromagnetic interaction between charged particles only occurs in distances < Debye Length λ_D
  - The interaction is done at distance and its intensity depends on the sum of all the neighbour charged particles positions
  - The interaction is modelized by the mean time to deviate the initial trajectory by 90°

=> **The Spitzer formulas** : (~90° deflection)

→ Electron/Electron collision : $\nu_{ee}^{90^\circ} = 5.10^{-6}\dfrac{n\ln\Lambda}{T_e^{3/2}}$

→ Electron-Ion collision : $\nu_{ei}^{90^\circ} = 2.10^{-6}\dfrac{zn\ \ln\Lambda}{T_e^{3/2}}$

→Ion/Ion Collision : $\nu_{ii}^{90^\circ} = z^4\left(\dfrac{m_e}{m_i}\right)^{1/2}\left(\dfrac{T_e}{T_i}\right)^{3/2}\nu_{ee}^{90^\circ}$

- *T* in eV, *n* in cm^{-3}, z = ion charge state, ln(Λ)~10

Microscopic processes in a plasma: Electron Impact Ionization

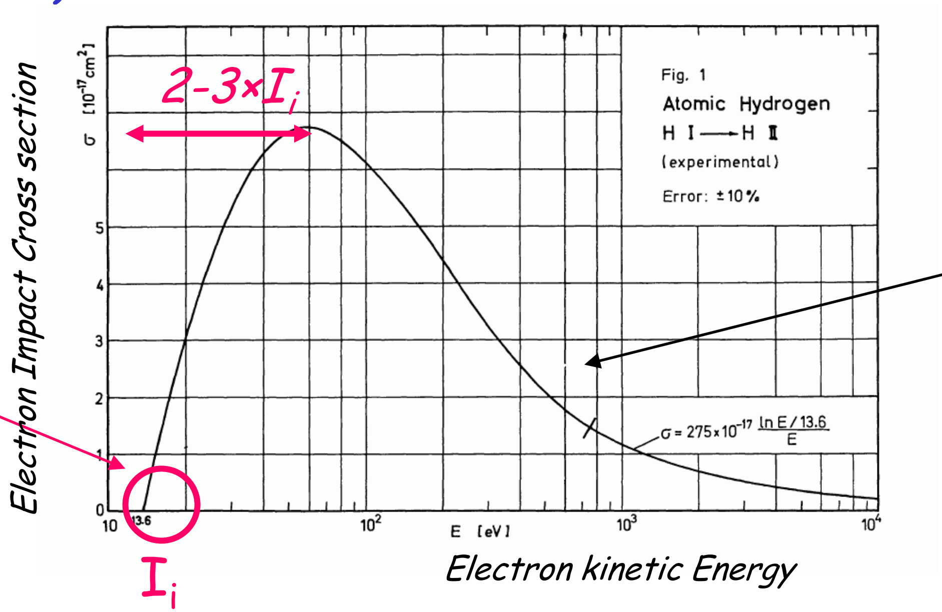
- Inelastic Collisions in a plasma can create or destroy ions. The main way to create an ion is through the:

  - Electron impact Ionisation

$$e^- + A^{i+} \xrightarrow{I_i} e^- + e^- + A^{(i+1)+}$$

→ an energetic electron expells a shell electron from an ion (or an atom)

Threshold energy= binding energy Of the shell electron



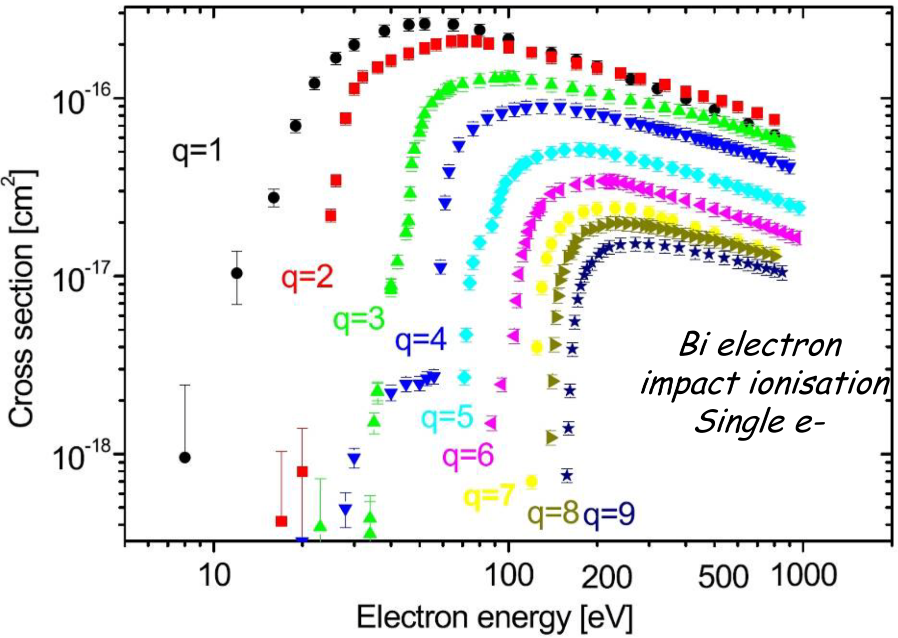
High energy tail

Microscopic processes in a plasma: Electron Impact Ionization

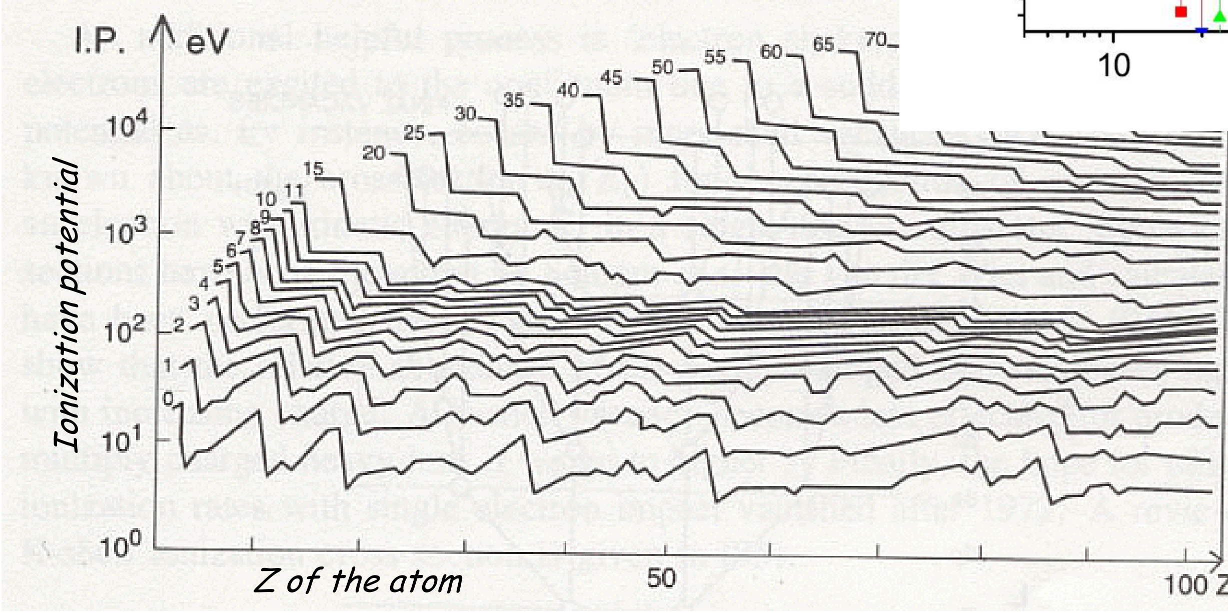
- Electron Impact ionization cross section can be approximated by the Lotz formula:

$$\sigma_{i\rightarrow i+1} \sim \frac{\ln\left(\frac{T_e}{I_{i+1}}\right)}{T_e I_{i+1}}$$

- o T_e= electron kinetic energy
- o I_i= ionisation potential #i



Bi electron impact ionisation Single e-



Ionization potential

Z of the atom

σ decreases while Ii increases

=> The Higher the Z, the lower the σ

Microscopic processes in a plasma: Charge Exchange

- The main term to loose ions is through the:
  - Charge exchange (CE) process

$$A^{0}+B^{i+} \quad \longrightarrow \quad A^{1+}+B^{(i\text{-}1)+}$$

$\downarrow$

Radiative transitions

$$\sigma_{CE}(i \rightarrow i+1) \approx 1.43\,10^{11}\, i^{1.17}\, I_0^{22.7} \ (\mathrm{cm}^2)$$

→ I_O = first ionisation potential

→ i = charge state number of the ion

→ σ_{CE} ~10^{-14} cm^2

→ CE is the dominant process at high pressure

→ making multicharged ions requires secondary vacuum and low neutral density (=> less low charge targets)

Multi-charged ion balance equations in a plasma

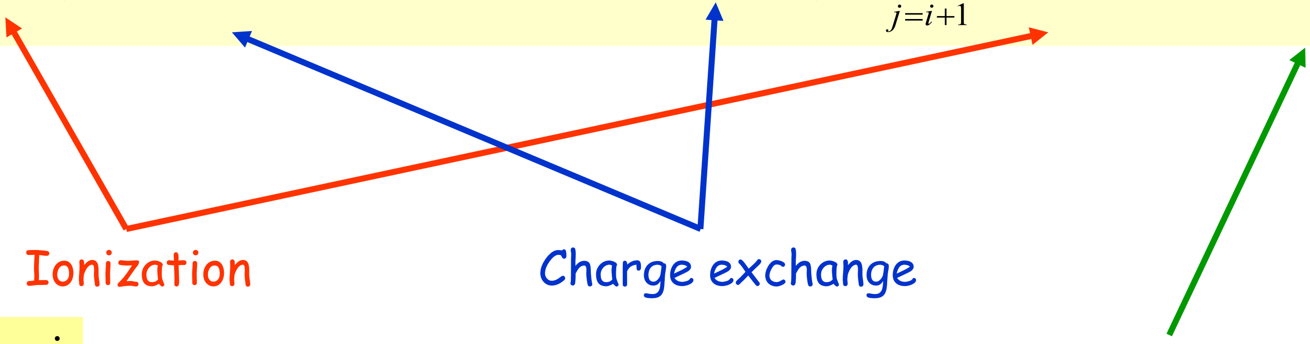
- The population of multicharged ions in a plasma can be described by a set of 0-dimension balance equations:

Creation

Destruction

0 dimension simplified system of equations

$$\frac{\partial n_i}{\partial t} = \sum_{j_{\min}}^{i-1} n_e n_j \left\langle \sigma_{j\to i}^{ioni} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma_{i+1\to i}^{exc} v_i \right\rangle - n_0 n_i \left\langle \sigma_{i\to i-1}^{exc} v_i \right\rangle - \sum_{j=i+1}^{j_{\max}} n_e n_j \left\langle \sigma_{j\to i}^{ioni} v_e \right\rangle - \frac{n_i}{\tau_i}$$



Ionization

Charge exchange

Magnetic Confinement Losses (semi-empirical)

n_i = ions density charge i

n_0= neutral density

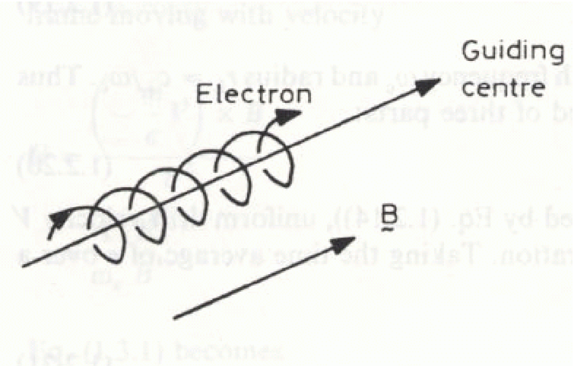
n_e= electronic density

τ_i= confinement time

Motion of particles in a magnetic field

- Magnetic fields are used to confine particles in plasmas.

$$m\frac{d\vec{v}}{dt} = q\,\vec{v}\times\vec{B}$$



$$\vec{v} = \vec{v}_{//} + \vec{v}_{\square}$$

=> $v_{//} = \mathrm{const}$

=> $v_{\square} = \rho_L\,\omega_c$ & $\omega_c = \dfrac{qB}{m}$ Cyclotronic Frequency

Larmor Radius

- ω_c independant of $V_\perp$
- $V_\perp$ increases => ρ_L increases
- The particle follows the local magnetic field line if $\dfrac{\vec{\square}\vec{B}}{B} << 1$

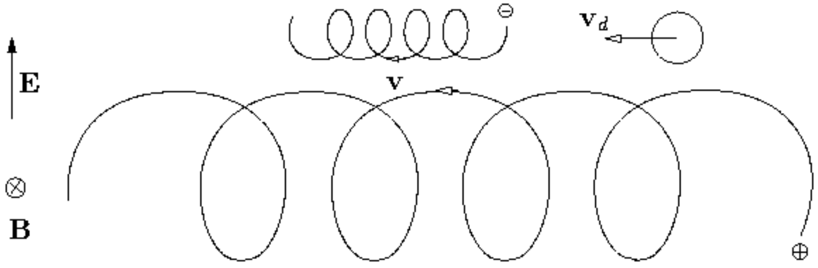
Motion of particles in a E + B Field

- Motion of a charged particle with E//B

$$m\frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v}\times\vec{B})$$

  - $V_{//}$ increases linearly with time
  - Helical trajectory with an increasing thread

- Motion of a charged particle with $E \perp B$
  - Cycloid trajectory



  - No Mean acceleration due to E !
  - Drift velocity : $\vec{v}_D = \frac{\vec{E}\times\vec{B}}{B^2}$

- The motion in a magnetic gradient also induces a drift velocity

Motion of charged particle: The Magnetic Moment

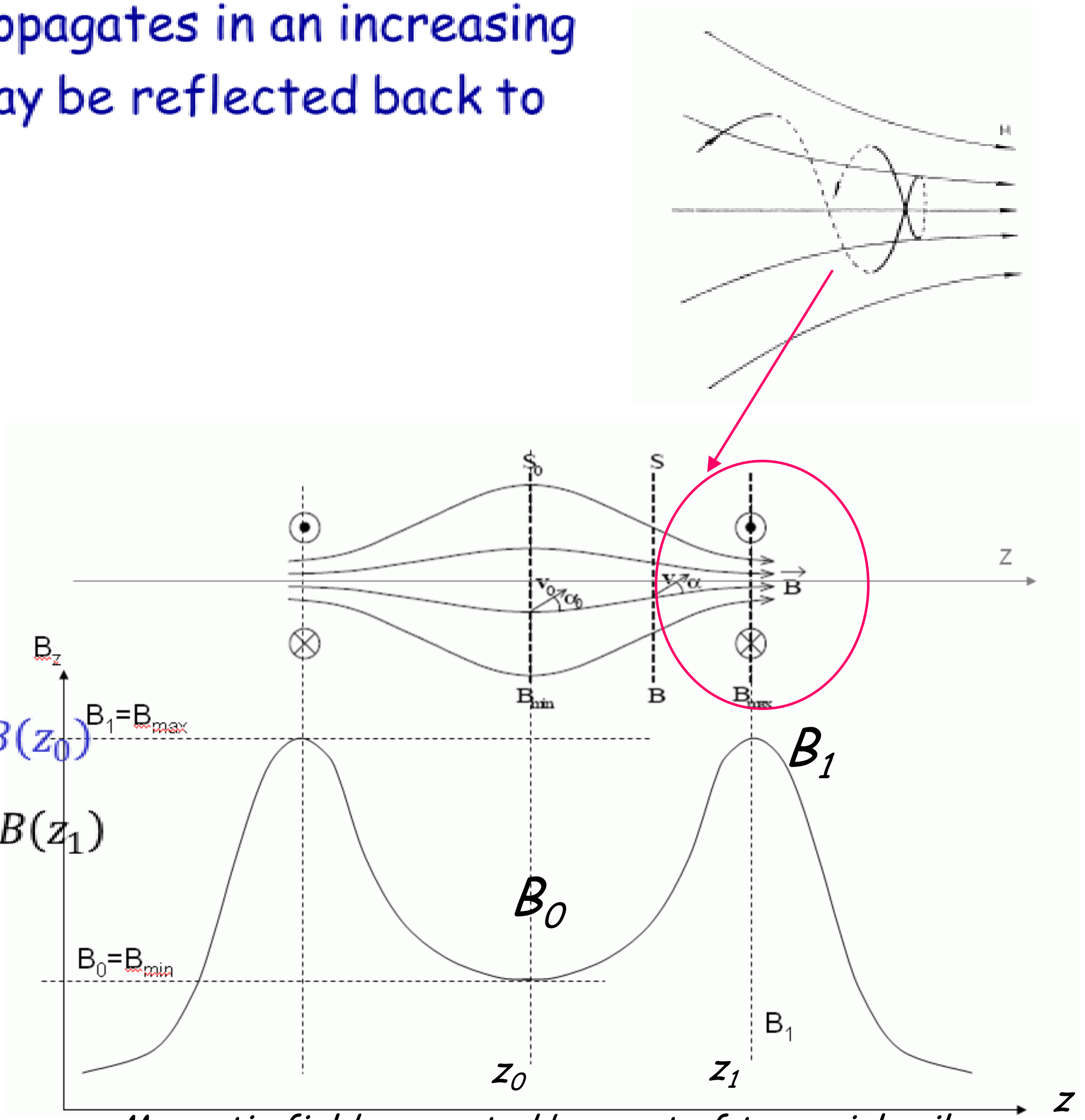
- μ =current loop × area of loop
- $\mu = \frac{mv_{\perp}^{2}}{2B}$
- μ is an <u>adiabatic invariant</u> of the motion

⇔ μ≈constant for E and B slowly varying in space and time

- complicated demonstration (can be found in plasma physics books)

Motion of charged particle: The Magnetic Mirror Effect

When a charged particule propagates in an increasing magnetic field gradient, it may be reflected back to where it comes



Magnetic field generated by a set of two axial coils

kinetic energy:

$$\rightarrow T = \frac{1}{2}m{v_{||}}^2 + \frac{1}{2}m{v_{\perp}}^2 = \text{cst}$$

magnetic moment:

$$\rightarrow \mu = \frac{m{v_{\perp}}^2}{2B} = cst$$

so T can be expressed as:

$$\rightarrow T = \frac{1}{2}m{v_{||}}^2(z) + \mu B(z)$$

At $z=z_0$: $T = \frac{1}{2}m{v_{||}}^2(z_0) + \mu B(z_0)$

At $z=z_1$: $T = \frac{1}{2}m{v_{||}}^2(z_1) + \mu B(z_1)$

If $B_1 > T/\mu$:

$$\exists\, z < z_1 \;/\; \frac{1}{2}m{v_{||}}^2(z) \rightarrow 0$$

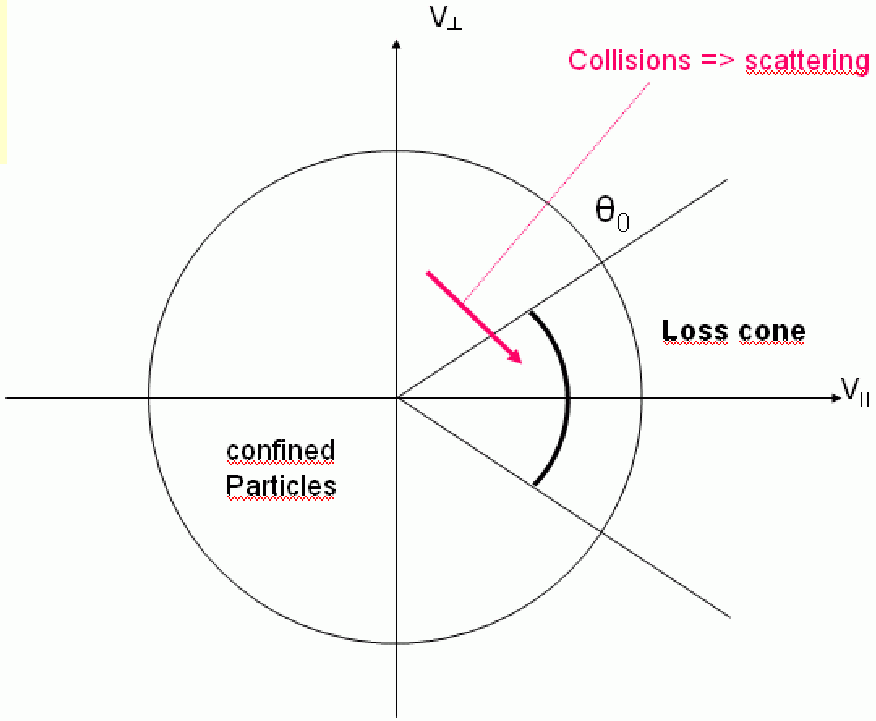
And $T = \mu B(z)$

Motion of charged particle: The Magnetic Mirror Effect

- The Mirror effect is used to magnetically confine particles in plasmas

  - Pitch angle θ = angle between local B and v $v_{||} = v\cos\theta$
  - Magnetic Mirror condition fulfilled for $\theta > \theta_0$ $v_\perp = v\sin\theta$
  - Mirror Ratio : $R = \sqrt{\frac{B_1}{B_0}}$
  - Loss Cone for $\theta < \theta_0$

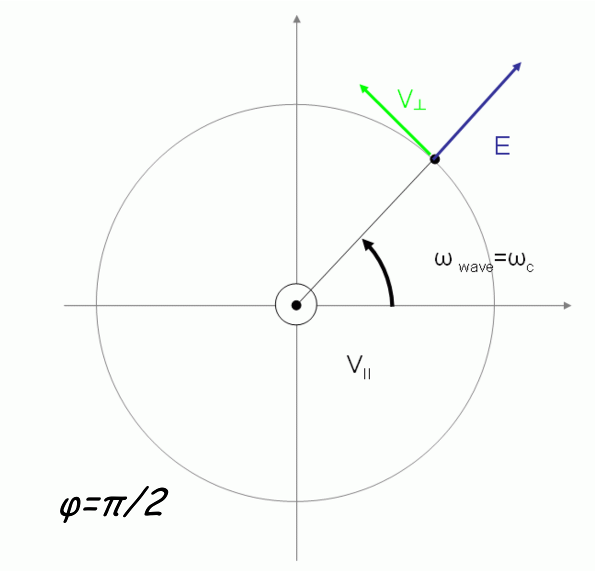
$$\sin\theta_O = \frac{1}{\sqrt{R}}$$



Electron Cyclotron Resonance (ECR)

- The electron cyclotron resonance enables to heat electrons in a magnetized plasma
  - Electromagnetic wave **E**, with angular frequency ω
  - Electron gyrating with cyclotronic frequency $\omega_c = \frac{qB}{m}$
  - Resonant energy transfer from the wave to the electron if :

$$\omega = \omega_c = \frac{qB}{m}$$



  - Increase of $v_\perp$ only
  - Example for $\varphi=(E,v_\perp)=\pi/2$ ->
  - It works because ω_c is independant of $v_\perp$

Electron Cyclotron Resonance (ECR)

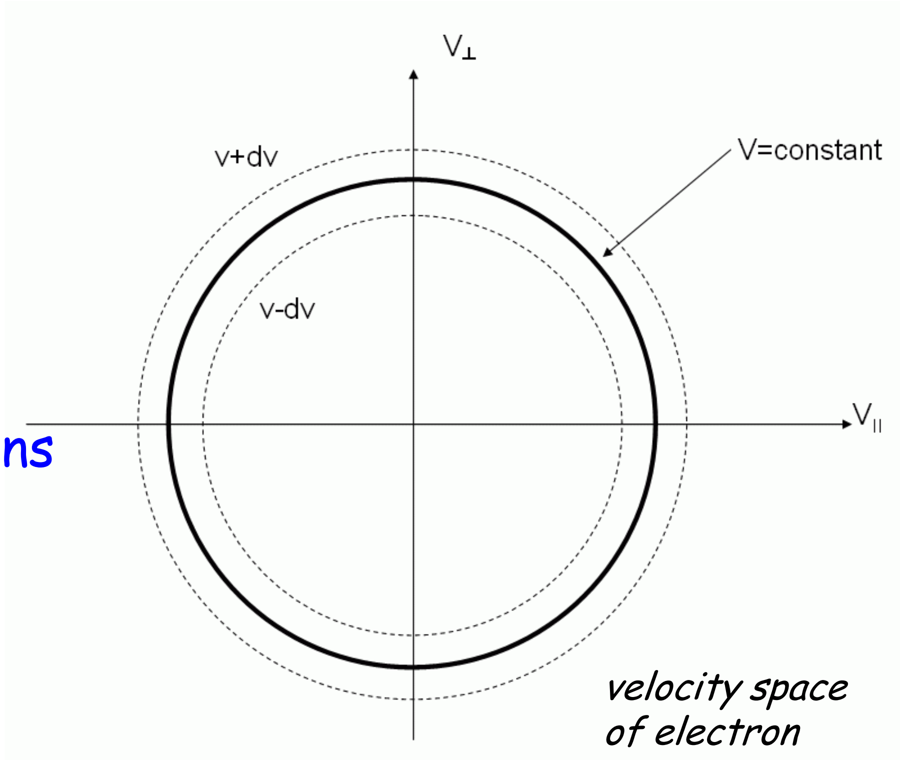
- And what happens when φ=-π/2 ?
  - The particle will loose energy !!!
  - But experimentally, a systematic mean energy increase is observed…

→ECR is a stochastic Heating

- Assumptions :

1) individual particles Have equiprobability to gain dv or loose dv during resonance

2) Coulomb scattering => electrons velocities are distributed on a circle (θ=random)



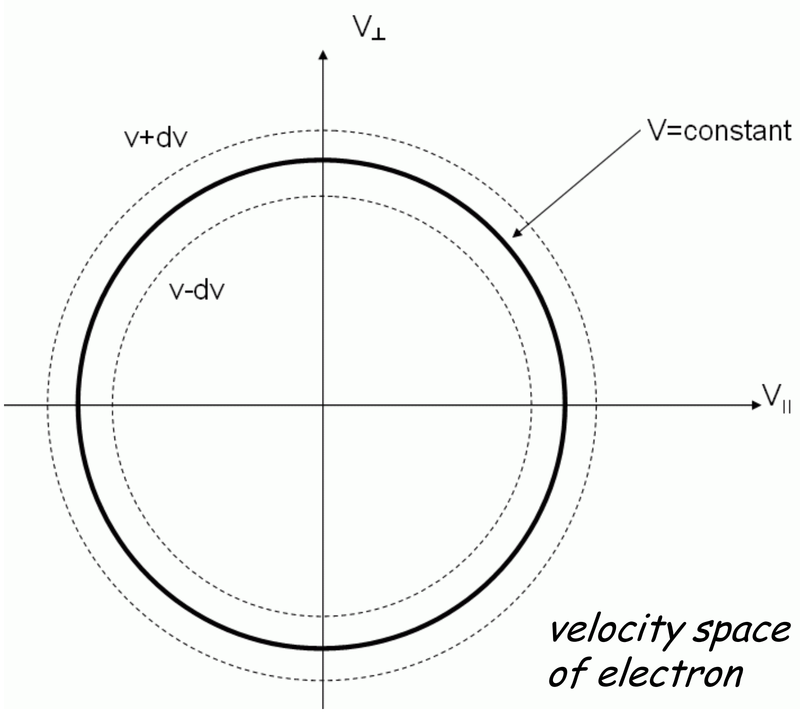
velocity space of electron

Electron Cyclotron Resonance (ECR)

ECR Stochastic Heating of electrons

- Ring [v,v+dv] : $\delta R_{\text{gain}} = \pi(v+dv)^2 - \pi v^2 = \pi(2vdv + dv^2)$
- Ring [v,v-dv] : $\delta R_{\text{loose}} = \pi(v-dv)^2 - \pi v^2 = \pi(-2vdv + dv^2)$
- $\delta R_{gain} - \delta R_{loose} = 4\pi v dv > 0$

So the Probability for an electron to Gain Energy is larger than the one to loose energy!



velocity space of electron