Dottorato in FISICA DEGLI ACCELERATORI

INTRODUCTION TO PLASMA PHYSICS AND HEATING PHENOMENA IN ELECTRON CYCLOTRON RESONANCE ION SOURCES

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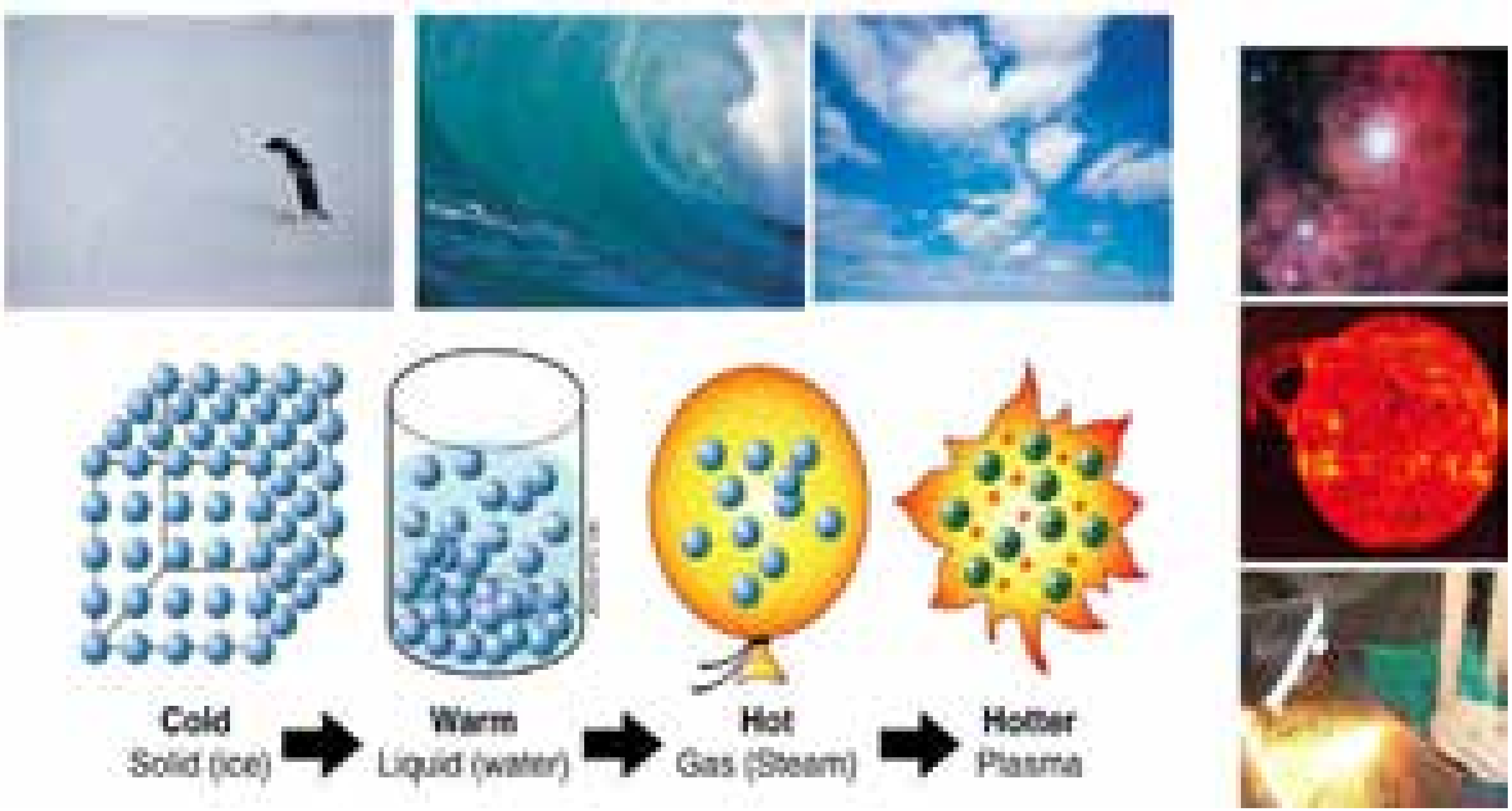
OUTLINE

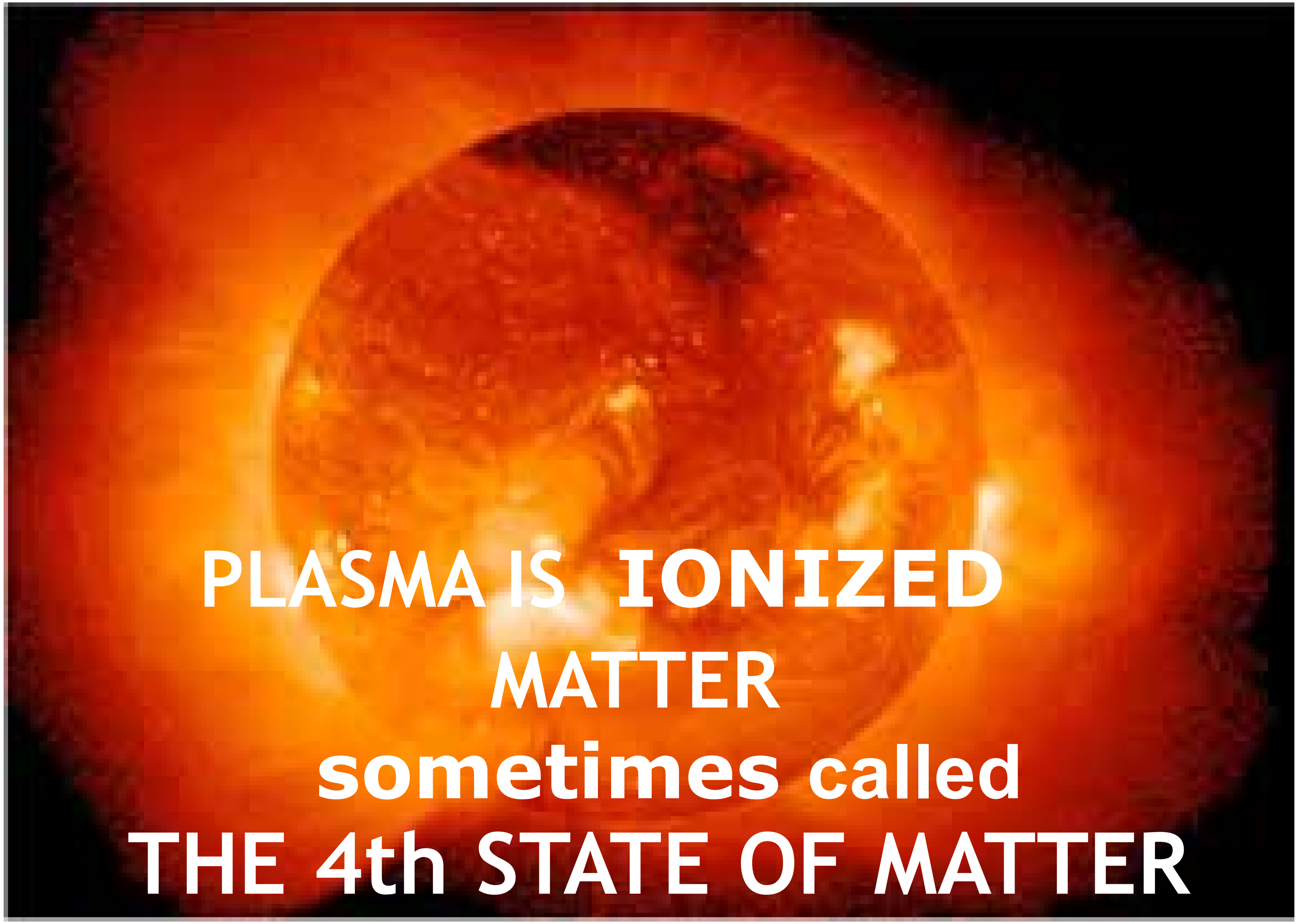
INTRODUCTION TO PLASMA PHYSICS AND HEATING PHENOMENA IN ELECTRON CYCLOTRON RESONANCE ION SOURCES

- Introduction
- Plasma, its constituents and main paramenters
- Particle motion in plasma
- Principles of magnetic confinement
- Atomic physics background in plasma
- ECR heating
- Geller Scaling Law and ECRIS Standard Model

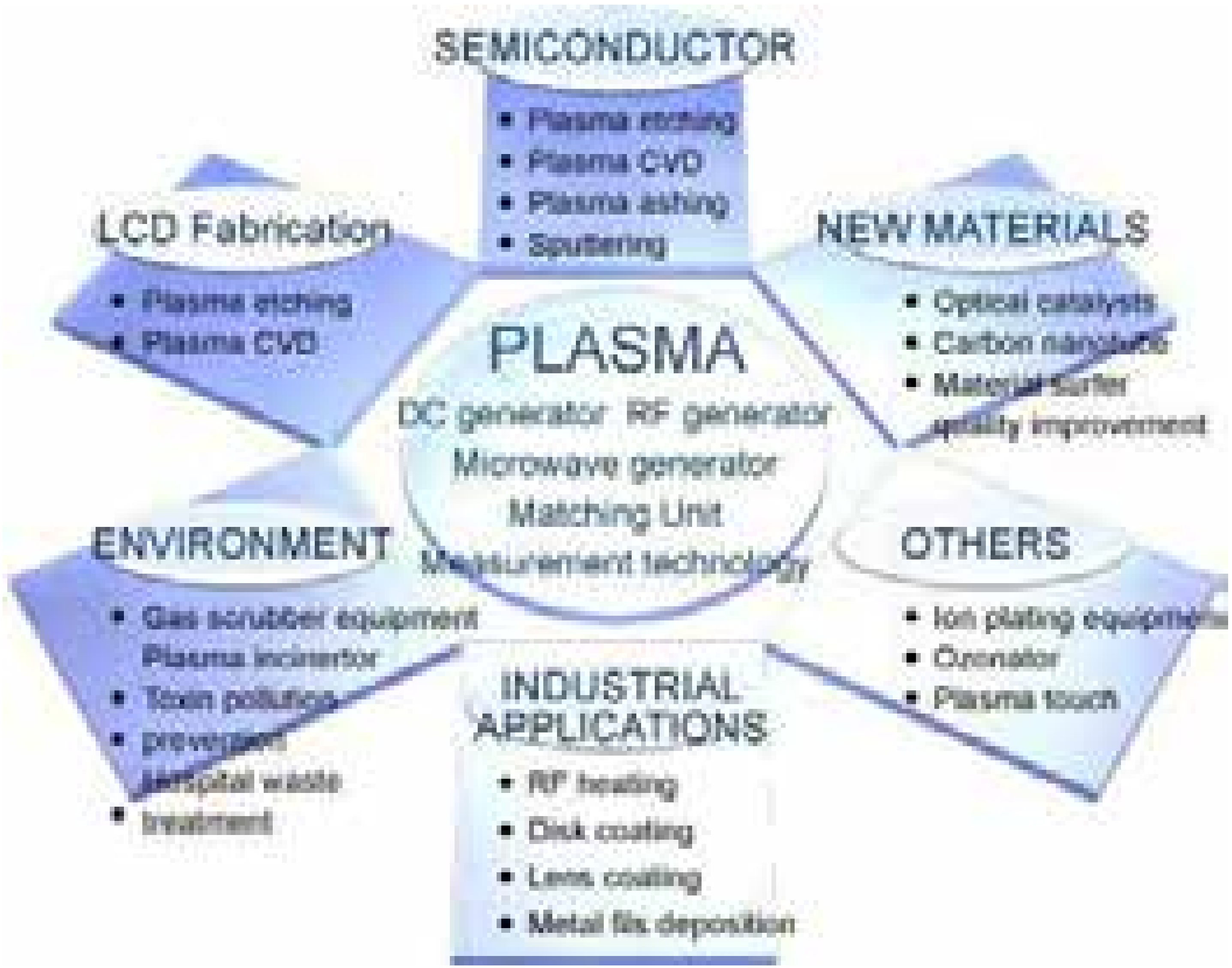
What is plasma? A state of the matter!



What is plasma?



Applications



Main Constituents and Key Properties

- positively (and negatively) charged ions
- electrons
- neutrals

Because of its charged components plasma is sensitive to electromagnetic fields

- quasineutrality within bulk
- screening electric fields by sheath formation (e.g. at walls and electrodes)
- collective phenomena (e.g. plasma waves, drift)

Main quantities characterizing a Plasma

- temperatures of the constituents: Te,Ti,To
- number densities of the constituents: ne, ni, no
- ionization degree η
- Debye length λ_D
- plasma frequency ωpl

Temperature

Weakly ionized plasma is a mixture of different gases:

neutral gas, ion gas and electron gas.

Under the action of electromagnetic fields electrons gain much more energy from the EM-field than ions. Their mean energy exceeds by far the mean energy of the ions and the neutrals. Thus

$$T_e >> T_i, T_n$$

In plasma temperatures are measured in eV:

kT = 1eV corresponds to T = 11600 K

Typical values: kT_e = 1… 10^4 eV for electrons (i.e. 10^4 – 10^8 °K !!)

kT_i = 0.03…1eV for *ions*

It has become international usage to use the symbol
T not for the thermodynamic temperature measured
in Kelvin, but instead for the characteristic energy
k T (k Boltzmann constant) measured in eV.

Quasi-neutrality

For plasma with singly charged ions only

$$n_i \approx n_e$$

For plasma with multiply charged ions

(z charge number of the ions)

$$n_e \approx \sum_z z \cdot n_z$$

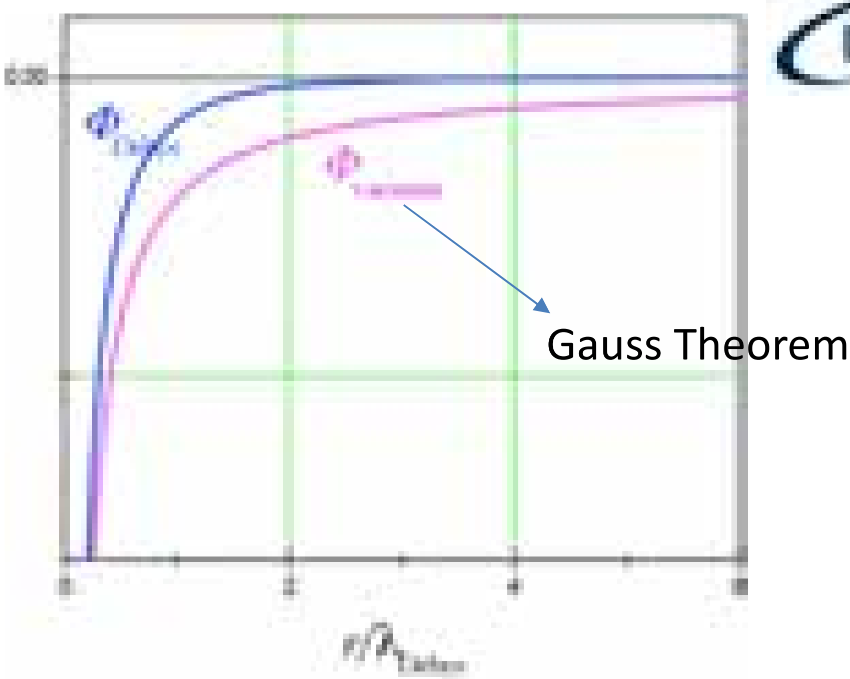
Ionisation degree

$$\eta = \sum_z n_z \bigg/ \left(n_0 + \sum_z n_z \right)$$

n_0 neutral particle density

η << 1 “weakly ionised plasma”
η ≈ 1 “strongly” or “fully ionised plasma”

Debye length – screening effect



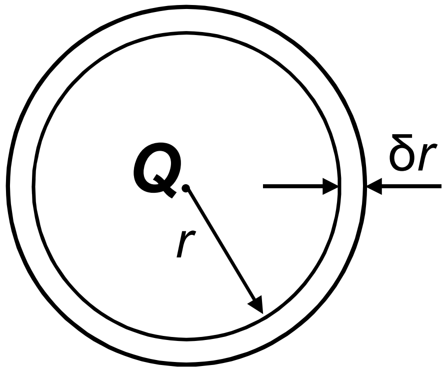
In plasma physics, the Debye length is the scale over which mobile charge carriers screen out electric fields in plasmas and other conductors. In other words, the Debye length is the distance over which significant charge separation can occur.

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k / q_e^2}{n_e/T_e + \sum_{ij} j^2 n_{ij}/T_i}}$$

Every Debye-length λ_D, the electric potential will decrease in magnitude by 1/e.

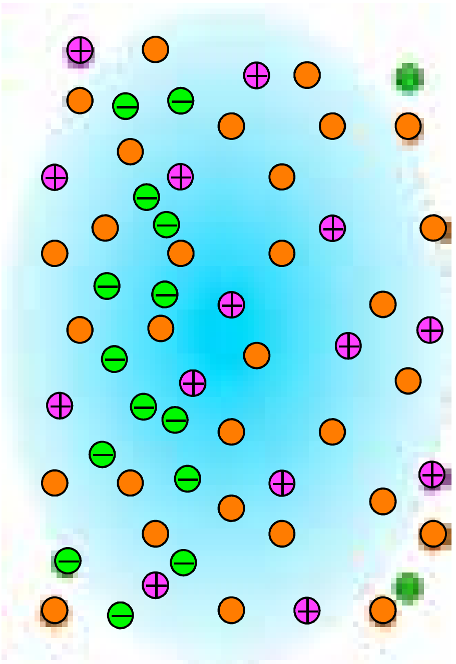
Ionic term is usually dropped:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e q_e^2}}$$



A Debye sphere is a volume whose radius is the Debye length, in which there is a sphere of influence, and outside of which charges are screened.

Quasineutrality



Restoring electric field E due to charge separation $E = \frac{en\Delta x}{\varepsilon_0}$

Example: Fluorescent tube

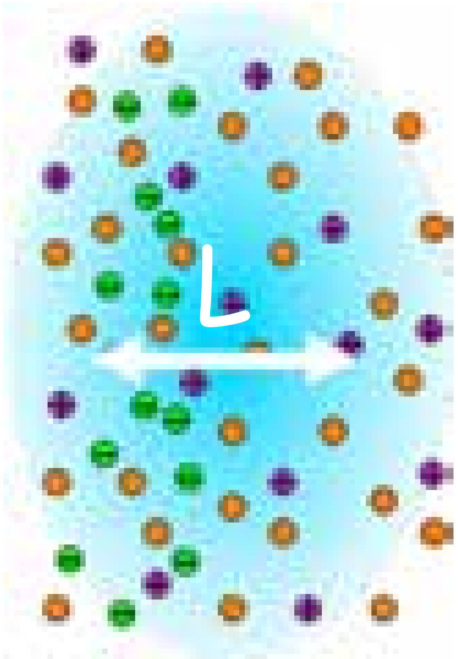
$n_e = 10^{16} m^{-3}$; Δx = 1mm

E_{max} = 180 kV/m; U = (EΔx) = 180V

Potential energy of an ion traversing a space charge sheath

$$W_{pot} = \int_0^{\Delta x} eE dx = \frac{e^2 n_e (\Delta x)^2}{2\varepsilon_0}; \quad \frac{1}{2} k_B T = W_{pot} \Rightarrow \Delta x = \left(\frac{\varepsilon_0 k_B T}{e^2 n_e}\right)^{\frac{1}{2}} = \lambda_D$$

Quasineutrality



What amount of deviation from neutrality can exist over a length L?

The increase in potential energy must not surmount k_B T/2

$$\frac{1}{2} k_B T \approx \frac{1}{2} \frac{e^2 \Delta n L^2}{\varepsilon_0}$$

Substituting $k_B T$ by λ_D yields

$$\Delta n / n \approx (\lambda_D / L)^2$$

Ionized gas is plasma only, if its extension is much larger than the Debye-length

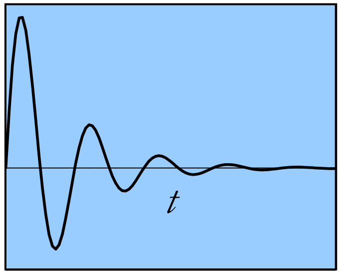
Plasma Oscillations

Equation of motion for electrons moving under the action of the electric field generated by charge separation

$$F = eE = e^2 nx / \varepsilon_0 = m_e \mathrm{d}^2 x / \mathrm{d}t^2$$

This is the equation of a harmonic oscillator with the so-called ***electron plasma frequency*** as natural frequency

$$\omega_{\mathrm{pe}} = \sqrt{e^2 n / \varepsilon_0 m_{\mathrm{e}}}$$



$$\omega_{\mathrm{pe}} / \mathrm{s}^{-1} = 2\pi \cdot 8.98 \cdot \sqrt{n_e / \mathrm{m}^{-3}}$$

Typical value: for n_e=10^{15}m^{-3} we have ω_{pe}=2π*0.28 GHz

Ion plasma frequency

By replacing the electron charge and mass with the ion charge and mass we obtain the ***ion plasma frequency***:

$$\omega_{\mathrm{pi}_{\mathrm{z}}} = \sqrt{(ze)^2 n_{\mathrm{z}} / \varepsilon_0 m_{\mathrm{z}}}$$

❖No effect on ion motion by electromagnetic fields varying with frequencies well above ω_{pi}

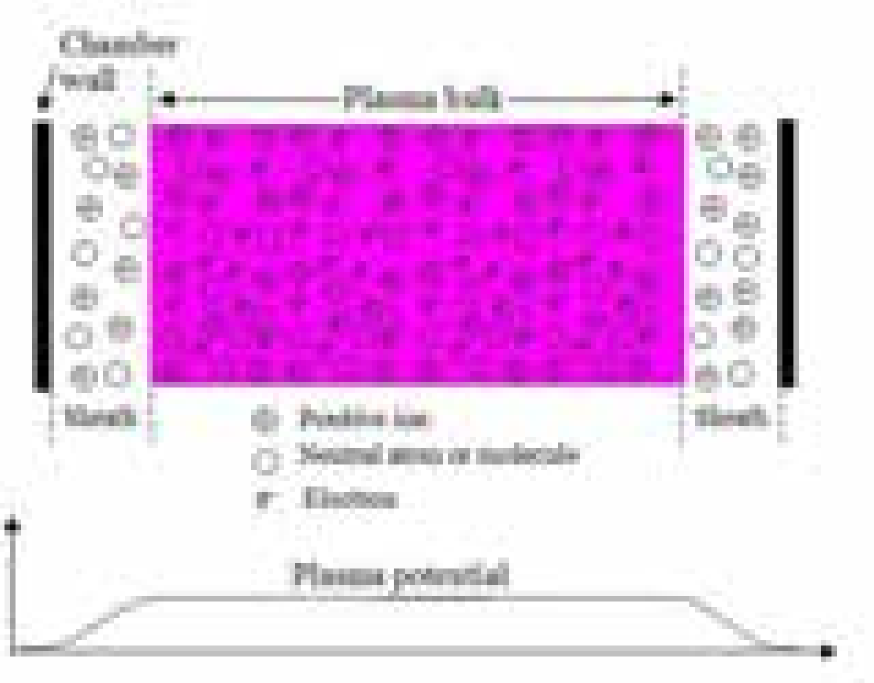
❖Typical values of ω_{pi} are in the $10^6 s^{-1}$ range. Thus ionic RF currents are very small when working with frequencies in the 10 MHz range. In this case ions follow the avaraged (DC) fields only

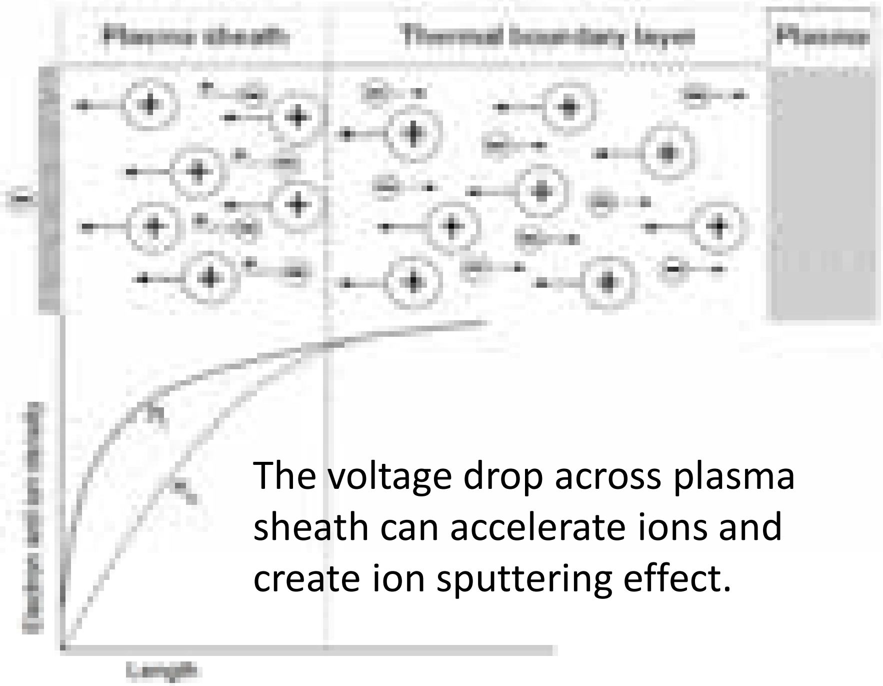
Sheath formation in front of a wall

Charged particles are transported from plasma to enclosing walls at different speeds.
In weakly ionized, nonmagnetized plasma **electron transport is fast**, **ion transport is slow**.

Electrons escape from plasma at much faster speed than ions. Once electrons are mostly depleted from the boundary interface between plasma and electrodes, a region with only positive ions and neutrals will be formed. This usually dark boundary region is called **plasma sheath**.

Positive charges in plasma sheath can push more ions to diffuse out of plasma. It also creates a potential barrier to prevent electrons from diffusing out of plasma. **Plasma sheath also creates a positive plasma potential with respect to the grounded chamber walls**.





The voltage drop across plasma sheath can accelerate ions and create ion sputtering effect.

General picture

Plasma is therefore an ionized gas phase substance that consists of ions, electrons and neutral atoms and/or molecules that grossly maintain charge neutrality.

Electrons and ions should be close enough so that each of them can influence many nearby charged particles within a radius called Debye screening length. As a result, charged particles in plasma ***response collectively*** to external electromagnetic field.

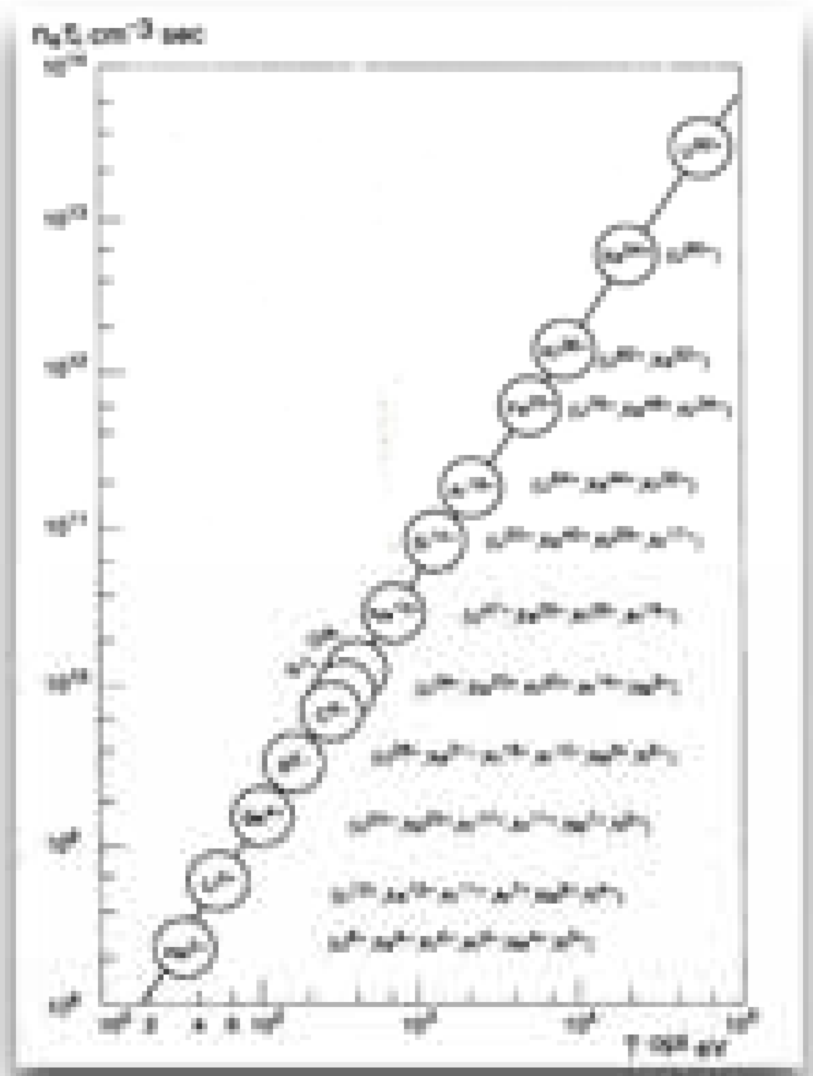
With high density of free moving ions and electrons, plasma is highly electrically conductive. Except boundary regions between plasma and electrodes, plasma contains same amount of positive and negative charges. There is no space charge within the bulk of plasma.

Why are magnetic fields applied to plasmas?

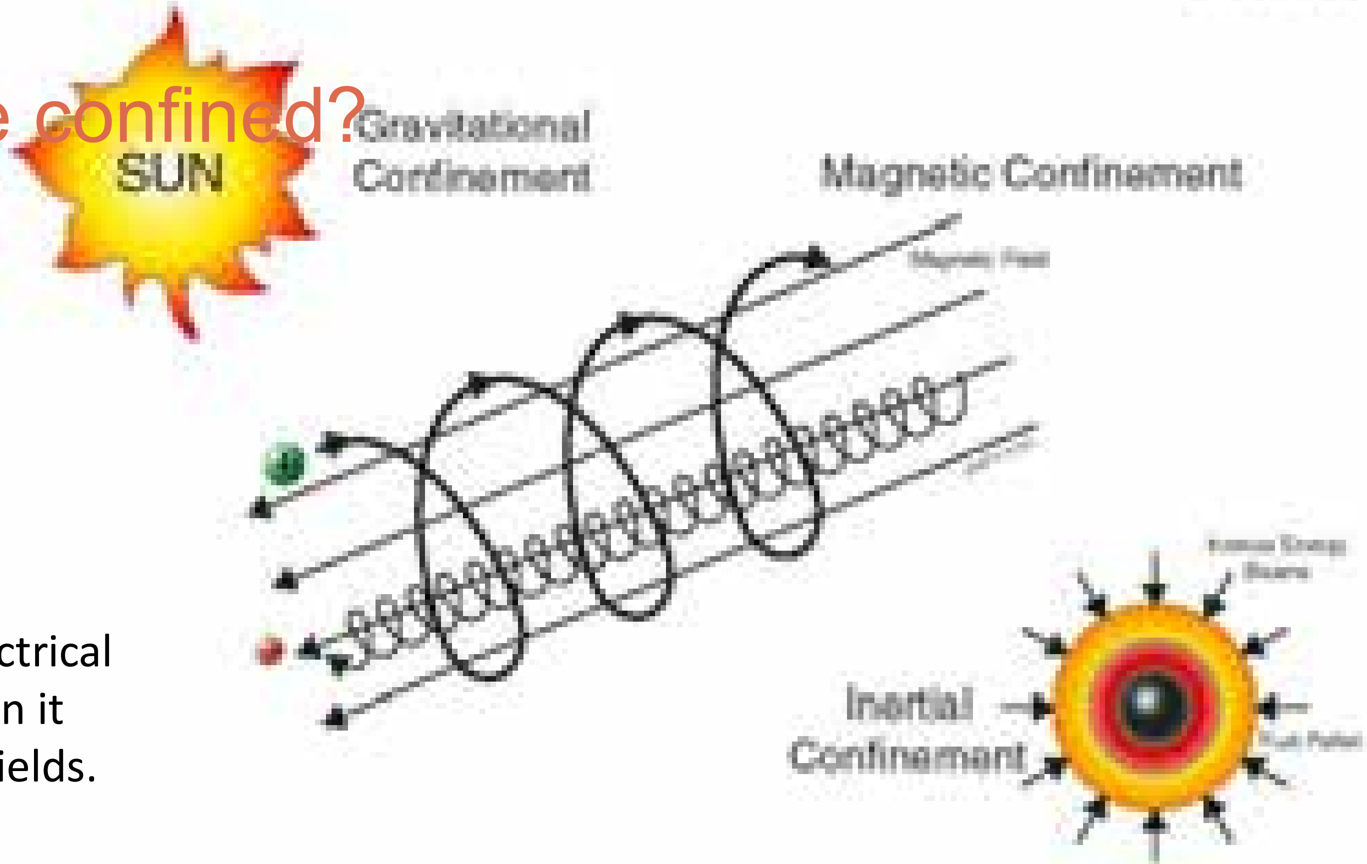
Stabilization of electron and ion confinement is mandatory for plasma ignition or multicharged ions production!

$$I_{ext} \propto \frac{n_e}{\tau_i} \; ; \qquad < q > \propto n_e{}^{*}\tau_i$$

Plasmas at high electron density and characterized by long ion lifetimes are specifically required. They can be produced by high intensity electron beams or sustained by microwaves



How Plasmas can be confined?



Confinement is due their **gravitational field** that creates sufficiently high pressure.

Magnetic confinement uses the electrical conductivity of the plasma to contain it through interaction with magnetic fields.

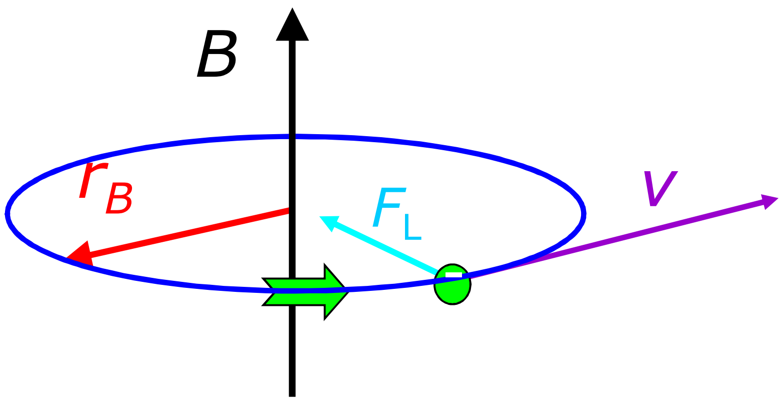
Powerful laser beams compress and heat the hydrogen isotopes to the point of fusion, a technique called inertial confinement fusion (ICF). In the “direct drive” approach to ICF, powerful beams of laser light are focused on a small spherical pellet containing micrograms of deuterium and tritium. The rapid heating caused by the laser “driver” makes the outer layer of the target explode, the remaining portion of the target is driven inwards in a rocket-like implosion, causing compression of the fuel inside the capsule and the formation of a shock wave, which further heats the fuel in the very center and results in a self-sustaining burn. The fusion burn propagates outward through the cooler, outer regions of the capsule much more rapidly than the capsule can expand. Instead of magnetic fields, the plasma is confined by the inertia of its own mass—hence the term inertial confinement fusion.

Gyration of ions and electrons under the action of a static magnetic field

❖The Lorentz force $\boldsymbol{F}_L$ exerted by a static magnetic field of induction B on particles of mass m bearing an elementary charge e causes a circular motion.

❖The radius (cyclotron radius) r_B of the circular trajectory is given by $r_B=mv/eB$

❖The corresponding cyclotron frequency ω_B does not depend on the particle velocity v: $\omega_B=eB/m$

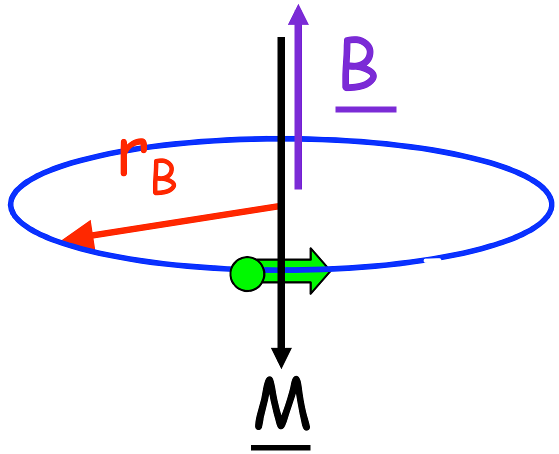


$$\vec{F}_L = q\vec{v}\times\vec{B}$$

Magnetic moment

The magnetic moment is the magnetic strength and orientation of a magnet that produces a magnetic field.

Gyrating particle as a pseudo particle with a magnetic moment M



$$I = q/\tau_B = q\omega_B/2\pi$$ circular current

$$A = r_B^2\pi$$ area of current loop

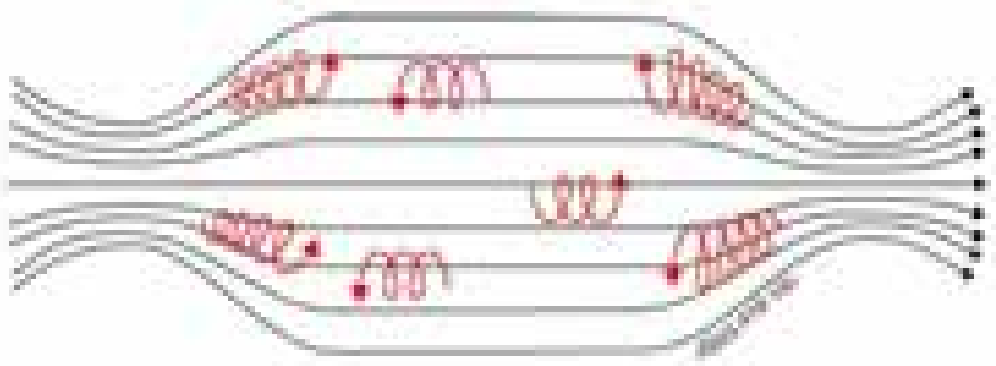
$$M = IA = \frac{q^2B}{2\pi m}\frac{\pi m^2 v_\perp^2}{q^2B^2} = \frac{\frac{1}{2}mv_\perp^2}{B} = \frac{W_\perp}{B}$$ "adiabatic invariant"

$$M = const \qquad W = W_\perp + W_\parallel = const$$

Principles of magnetic confinement

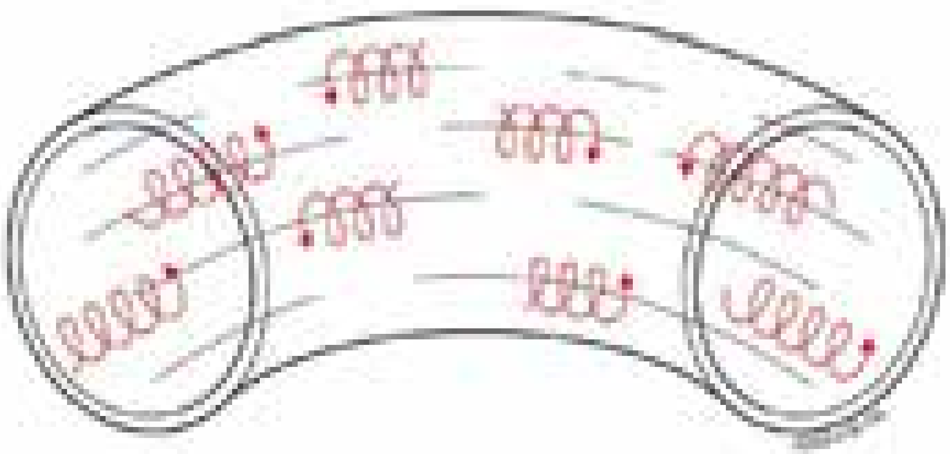
Stabilization of electron and ion confinement is mandatory to achieve ignition (*FUSION*) or highly charged ions (*INJECTORS FOR ACCELERATORS*)

Magnetic fields intrinsically force charged particles to reduce freedom degrees: electrons spiralyze around the field lines and can be trapped for several ms in mirror machines or toroidal structures.



MIRROR STRUCTURES

have axial symmetry and can be produced by sequences of room temperature or SC coils. They are commonly used in ion sources field



TOROIDAL CONFINEMENT

is typical of Fusion Machines like TOKAMAKS or STELLARATORS

Magnetohydrodynamics (MHD) equilibrium

In **MHD**, the plasma is considered as an electrically conducting fluid. Governing equations are equations of fluid dynamics and Maxwell's equations.
A self-consistent set of MHD equations connects the plasma mass density ρ, the plasma velocity V, the thermodynamic (also called gas or kinetic) pressure P and the magnetic field B. The set of MHD eq. is:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{V}) = 0, \qquad \text{Mass Continuity Eq.,}$$

$$\frac{d}{dt}\left(\frac{P}{\rho^{\gamma}}\right) = 0, \qquad \text{Energy Eq.,}$$

$$\rho \frac{d\mathbf{V}}{dt} = -\nabla P - \frac{1}{\mu_0}\mathbf{B} \times (\nabla \times \mathbf{B}), \qquad \text{Euler's Eq.,}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}), \qquad \text{Induction Eq.}$$

The equations are **ideal**, which means that all **dissipative processes** (finite viscosity, electrical resistivity and thermal conductivity) were **neglected**.

The magnetic field is also subject to the condition:

$$\nabla \cdot \mathbf{B} = 0.$$

The ***static equilibrium*** conditions are: $\mathbf{V} = 0, \quad \frac{\partial}{\partial t} = 0.$

These conditions identically satisfy the continuity, energy and induction equations.

Euler equation can be rewritten as: $-\nabla P - \frac{1}{\mu_0} B \times (\nabla \times B) = 0 \quad \rightarrow \quad -\nabla P - \frac{1}{\mu_0}\left[(B \cdot \nabla)B - \frac{1}{2}\nabla B^2\right] = 0$

$$-\nabla\left(P + \frac{B^2}{2\mu_0}\right) - \frac{1}{\mu_0}(B \cdot \nabla)B = 0$$

Total pressure   Magnetic Tension

Conditions for plasma equilibrium and stability

Therefore the plasma confinement and its equilibrium and stability can be investigated by looking to the equilibrium between the plasma kinetic pressure and the magnetic (confining) field pressure.

$$-\nabla\left(\underbrace{P}_{\text{Plasma Kinetic pressure}}+\underbrace{\frac{B^2}{2\mu_0}}_{\text{Magnetic pressure}}\right)-\frac{1}{\mu_0}(B\cdot\nabla)B=0$$

Total pressure

Magnetic Tension

In case B is smoothly variable along its own direction, this term can be neglected.

Therefore the condition for stability become:

$$\boxed{p+\frac{B^2}{2\mu_0}=costante}$$

The stability of the confinement can be studied as a function of the ***β parameter, which is the ratio between the kinetic and magnetic pressures***.

$$\boxed{\beta\equiv\frac{\sum nkT}{\frac{B^2}{2\mu_0}}}$$

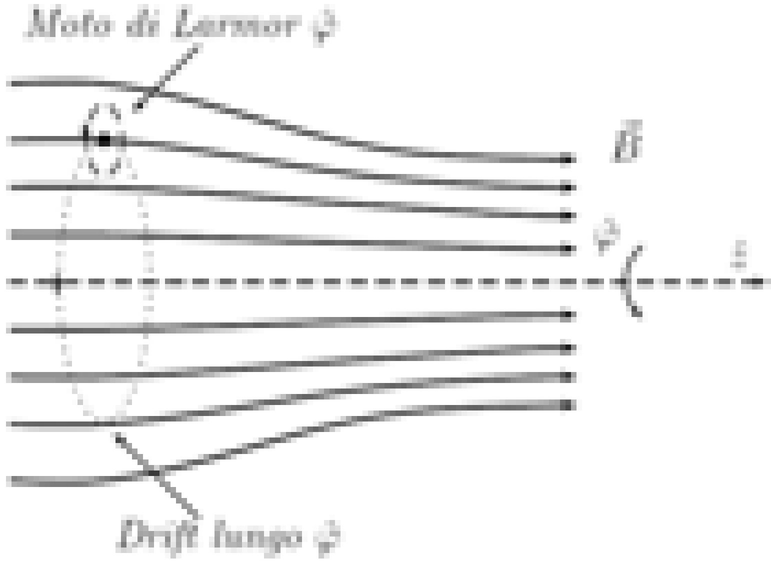
In ECRIS plasmas

$$\sum nkT \sim n_e kT_e$$

The condition for a magnetically stable plasma is that β<<1

Magnetic mirrors

In a magnetic mirror, a configuration of electromagnets is used to create an area with an increasing density of magnetic field lines at either end of the confinement area. Particles approaching the ends experience an increasing force that causes them to reverse direction and return to the confinement area.



Assume adiabatic invariance of the magnetic moment, i.e. that the particle's magnetic moment and total energy do not change. The magnetic moment can be expressed as:

$$\mu = \frac{mv_\perp^2}{2B}$$

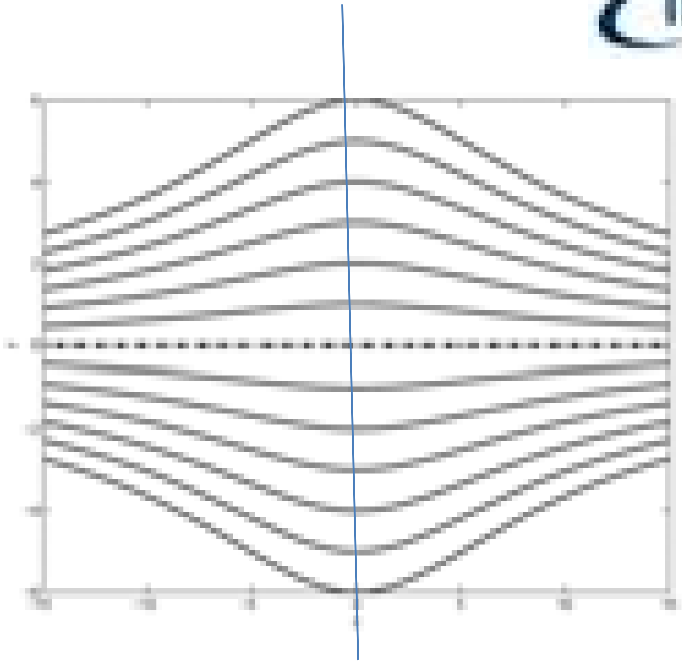
It is assumed ***that μ will remain constant*** while the particle moves into the denser magnetic field. Mathematically, for this to happen **the velocity perpendicular to the magnetic field $v_\perp$ must also rise**. The total energy of the particle can be expressed as:

$$W = W_\perp + W_{\parallel} = \frac{1}{2}mv_\perp^2 + \frac{1}{2}mv_{\parallel}^2$$

In regions with no electric field, if the total energy remains constant then the velocity parallel to the magnetic field must drop. If it can go negative then there is a motion repelling the particle from the dense fields.

When B increases the velocity is adiabatically transferred from $v_\perp$ to $v_{\parallel}$

Magnetic mirrors – Loss cone



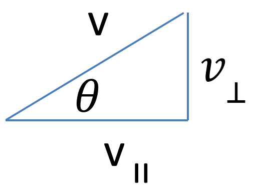
This mirror effect will only occur for particles within a limited range of velocities and angles of approach, those outside the limits will escape form confinement.

The mirror ratio is defined as: $$R = \frac{B_{max}}{B_{min}}$$

At the same time, particles within the mirror have a ***pitch angle***. This is the angle between the particles' velocity vector and the magnetic field vector.

The particles with the small pitch angle can escape the mirror and these particles are usually said to be in the loss cone.

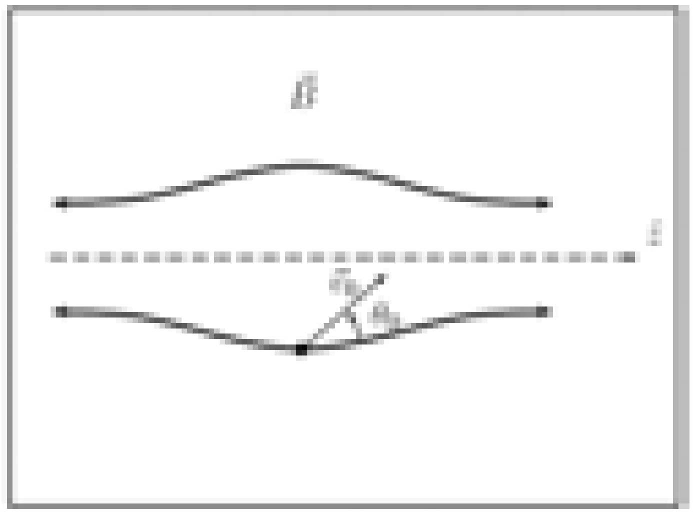
$$\mu = \frac{mv_\perp^2}{2B}$$ INVARIANT



$$\mu = \frac{mv^2 sin^2\theta}{2B} = constant$$

Being the total kinetic energy constant: $$W = \frac{1}{2}mv^2$$

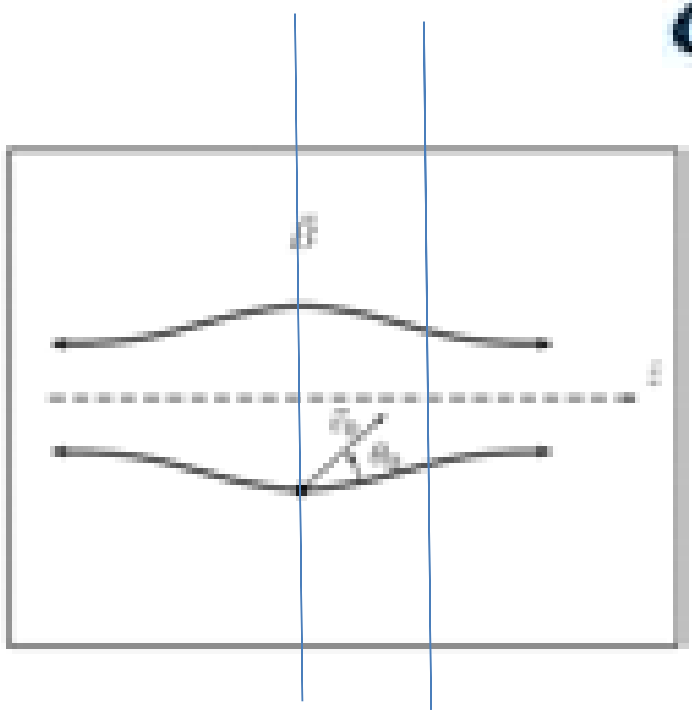
therefore: $$\frac{sin^2\theta}{B} = \boldsymbol{constant}$$



Magnetic mirrors – Loss cone

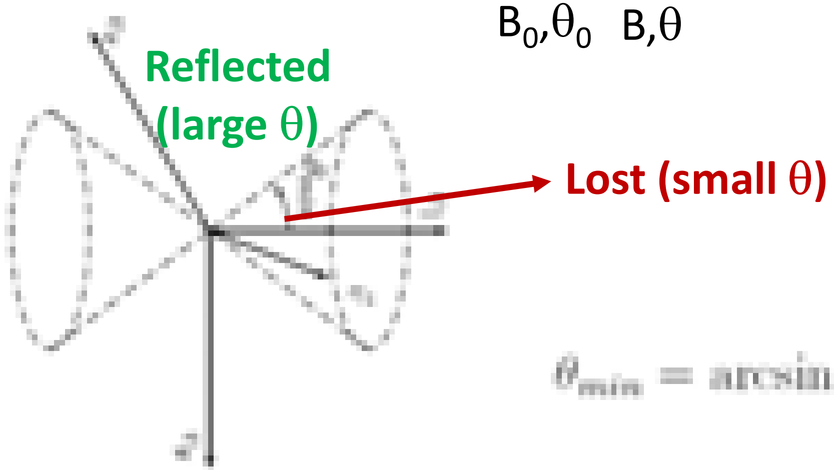
$$\frac{sin^2\theta}{B} = \boldsymbol{constant} \qquad \frac{sin^2\theta_0}{B_0} = \frac{sin^2\theta}{B}$$

If B= Bmax position then if $\begin{cases} \theta > 90° \; particle \; reflected \\ \theta < 90° \; particle \; lost \end{cases}$



Substituting B=Bmax and θ=90° in the conservation equation:

$$sin^2\theta_0 = \frac{B_0}{B_{max}} = \frac{1}{R}$$



$$\theta_{min} = \arcsin\sqrt{\frac{B_0}{B_m}}$$

$$sin^2\theta_0 \geq \frac{B_0}{B_{max}}$$ REFLECTED

$$sin^2\theta_0 \leq \frac{B_0}{B_{max}}$$ LOST

The reflected particles meet the following criteria: $\frac{v_\perp}{v} > \sqrt{\frac{1}{R}}$

Where $v_\perp$ is the particle velocity perpendicular to the magnetic field and v is the particle speed.

Effects of the magnetic field

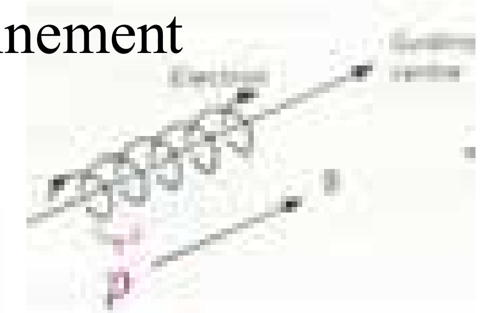
The individual motion of a charged particle in a magnetic field is ruled by: $m\frac{d\vec{v}}{dt} = q\vec{v}\times\vec{B}$

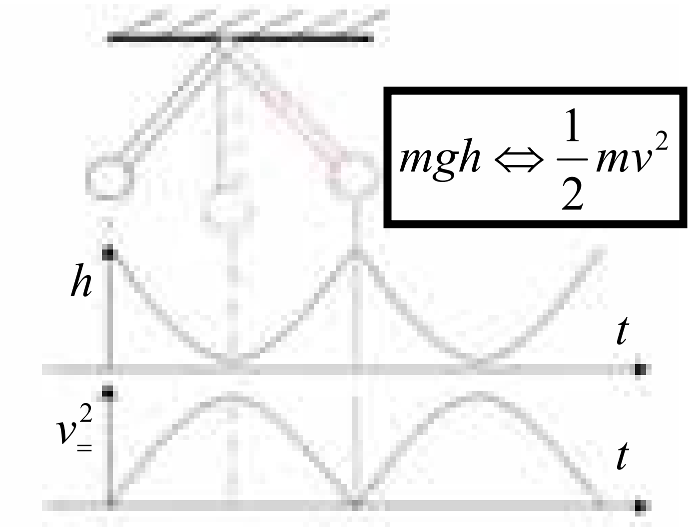
We can decompose the velocity in the two components: parallel (along mirror trap axis) and perpendicular

$$\vec{F}_{\perp} = q\vec{v}\times\vec{B} = qv_{\perp}B \Rightarrow \textit{precession around } B \text{ field}$$

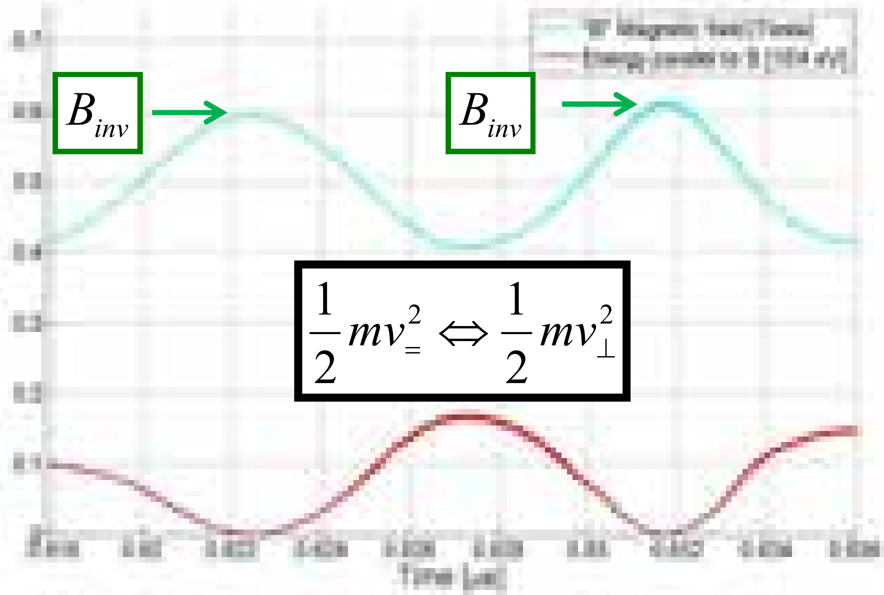
$$\vec{F}_{=} = -\mu\nabla\vec{B} = -\frac{1}{2}mv_{\perp}^{2}\frac{\nabla\vec{B}}{B} \Rightarrow \text{confinement}$$

The particle trajectory is an helix with radius ρ and pitch $p = \frac{2\pi v_{\parallel}}{\omega}$





$$mgh \Leftrightarrow \frac{1}{2}mv^{2}$$



$$\frac{1}{2}mv_{=}^{2} \Leftrightarrow \frac{1}{2}mv_{\perp}^{2}$$

$$E_{tot} = mgh + \frac{1}{2}mv^{2}$$

$$E_{tot} = \frac{1}{2}mv_{=}^{2} + \frac{1}{2}mv_{\perp}^{2}$$

The Electron Cyclotron Resonance

Motion of an electron in a constant Magnetic Field B and a perpendicular time varying Electric Field $E_x(t)$:

$$m\frac{d\vec{v}}{dt} = -e\vec{v}\times\vec{B} - e\vec{E}(t)$$

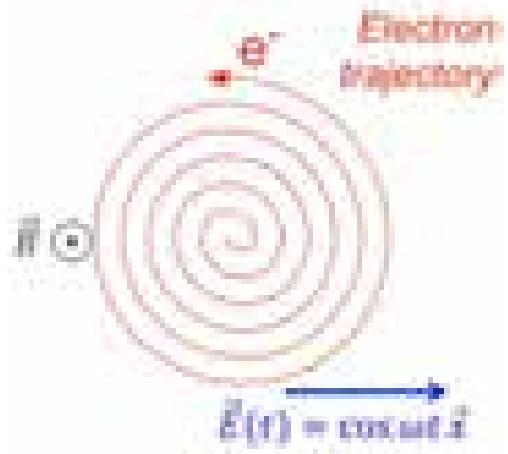
Assuming zero the initial electron velocity of the electron and that:

$\vec{B} = B\vec{z}$ $\quad$ $\vec{E}(t) = E cos\omega_{HF} t\vec{x}$ $\quad$ where: $\boldsymbol{\omega_{HF} = \omega = \frac{eB}{m}}$ $\quad$ **ECR CONDITION**

It can be shown that:

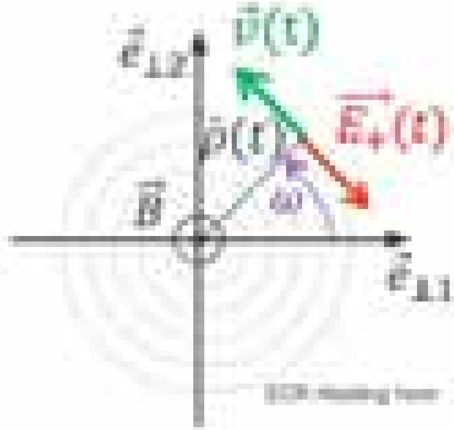
$$\vec{v} = \frac{-eEt}{2m}(cos\omega t\vec{x} + sin\omega t\vec{y}) + \frac{eE}{2m\omega} sin\omega t\vec{x}$$

The electrons gain energy with time and describe a spiral



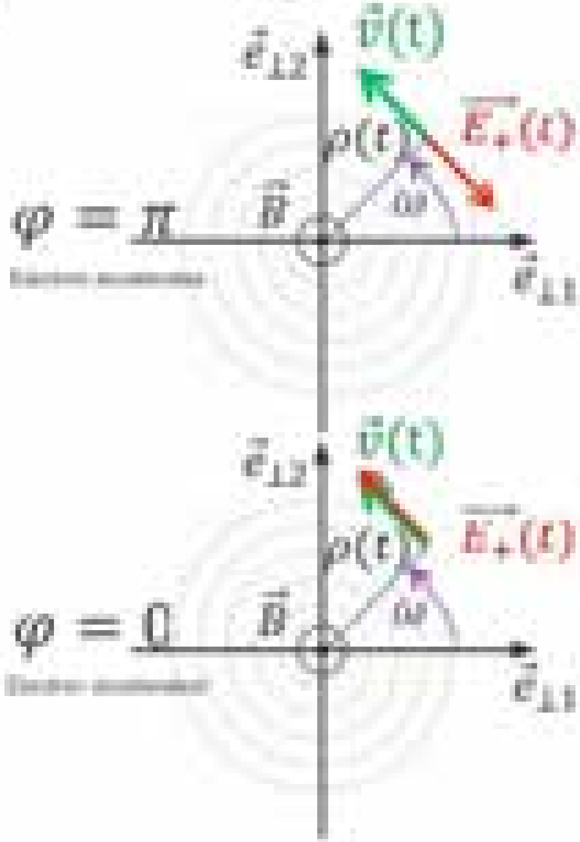
ECR heating in general transverse electric field

- **Static linear polarization time varying Electric field:**
  - for $\vec{E}_x(t) = E\cos\omega t\,\vec{x}$:
  - $\vec{v_1}(t) = \frac{(-e)Et}{2m}(\cos\omega t\,\vec{x} + \sin\omega t\,\vec{y}) + \frac{eE}{2m\omega}\sin\omega t\,\vec{x}$ => ECR HEATING
  - Now for $\vec{E}_y(t) = E\sin\omega t\,\vec{y}$, applying the same reasoning, one can find the same result:
  - $\vec{v_2}(t) = \frac{(-e)Et}{2m}(\cos\omega t\,\vec{x} + \sin\omega t\,\vec{y}) + \frac{eE}{2m\omega}\sin\omega t\,\vec{x}$ => ECR HEATING
- **Static Rotating time varying electric field:**
  - Clockwise rotation case :
  - The electric field turns in the opposite direction of the electron
  - $\vec{E}_-(t) = \vec{E}_x(t) - \vec{E}_y(t) = E\cos\omega t\,\vec{x} - E\sin\omega t\,\vec{y}$
  - $\vec{v_-}(t) = \vec{v_1} - \vec{v_2} = \vec{0}$ => NO ECR HEATING
  - Counter-Clockwise rotation case:
  - Electron and electric field turn in the same direction
  - $\vec{E}_+(t) = \vec{E}_x(t) + \vec{E}_y(t) = E\cos\omega t\,\vec{x} + E\sin\omega t\,\vec{y}$
  - $\vec{v_+}(t) = \vec{v_1} + \vec{v_2} = \frac{(-e)Et}{m}(\cos\omega t\,\vec{x} + \sin\omega t\,\vec{y}) + \frac{eE}{m\omega}(\sin\omega t\,\vec{x})$ => ECR HEATING



ECR Stocastic Heating

- In the former slides, we studied the ECR heating starting from an electron at rest (v_0=0)
- In reality, the electron always has an **initial velocity $v_0 \neq 0$**
- Let's look at the influence of v_0 on the ECR heating, introducing the Phase shift between $\vec{E}$ and $\vec{v}_0$:
  - $\varphi = (\widehat{\vec{E}(0), \vec{v}_0})$
- When $\varphi = \pi$, $\vec{E}(0) \parallel \vec{v}_0$, acceleration is maximum: it is the ideal case studied previously → electron gains energy
- When $\varphi = 0$, acceleration is now in the opposite direction, the electron is decelerated → electron loses energy!
- **So, how does it work???**



ECR Stocastic Heating

Solving again the equation of motion, but with initialelectron velocity different from zero it can be shown that:

$$m\frac{d\vec{v}}{dt} = -e\vec{v}\times\vec{B} - e\vec{E}(t)$$

$$\vec{v} = \left.\begin{array}{l}\dfrac{(-e)Et}{2m}(\cos\omega t\,\vec{x} + \sin\omega t\,\vec{y}) + \dfrac{eE}{2m\omega}\sin\omega t\,\vec{x} +\end{array}\right\}\text{Former solution } (v_0=0)$$

$$\left.\boxed{v_0(\cos(\omega t+\varphi)\,\vec{x} + \sin(\omega t+\varphi)\,\vec{y})}\right\}\text{Initial condition } (v_0\neq 0)$$

Expression of kinetic energy is given by:

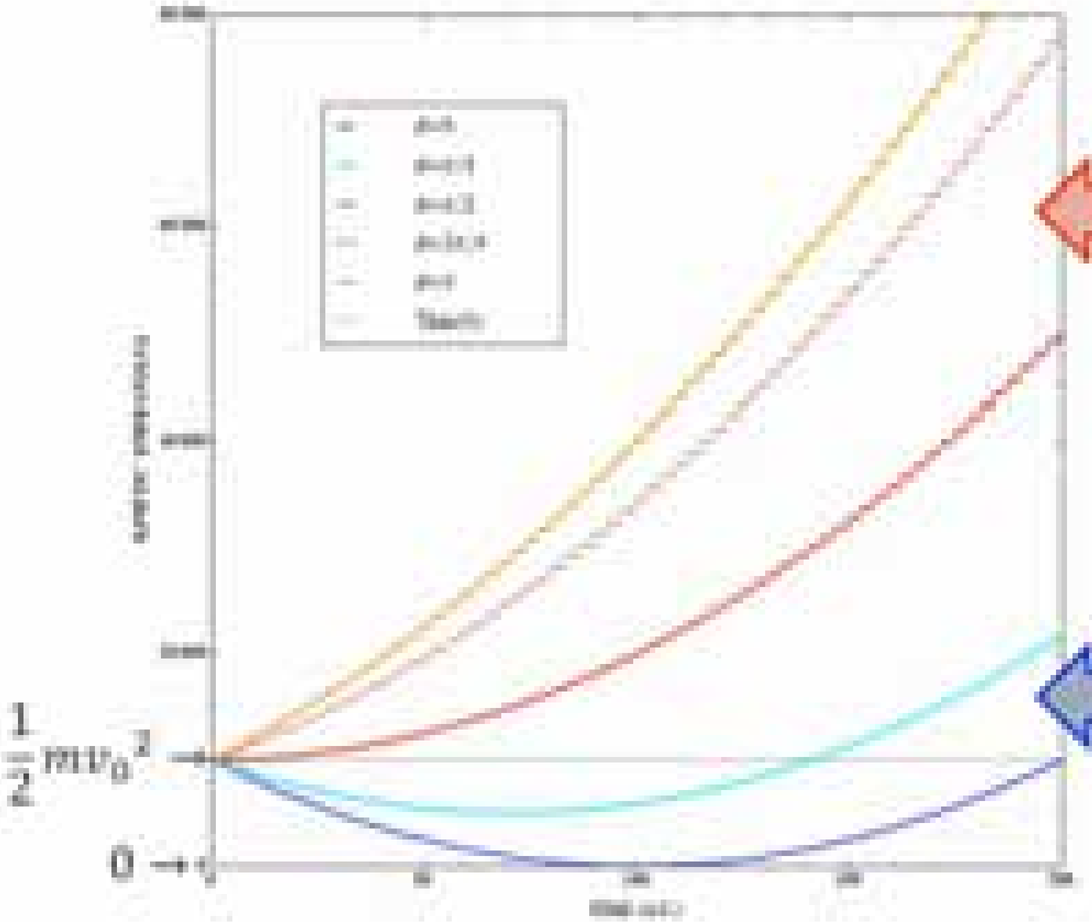
$$T_{kin}(t,\varphi) = \left.\frac{e^2E^2}{2m\omega^2}\left((\omega t)^2 - \omega t\sin 2\omega t + \sin^2\omega t\right)\right\}\text{Increases with time } (\sim t^2)$$

$$\left.+\frac{eEv_0}{\omega}(\sin\omega t\cos(\omega t+\varphi) - \omega t\cos\varphi)\right\}\text{Phase term, may be } <0\ (\sim t)$$

$$\left.+\frac{1}{2}m{v_0}^2\right\}\text{Constant term}$$

ECR Stocastic Heating

- electron Kinetic energy plot as a function of time t and phase φ:



HEATING

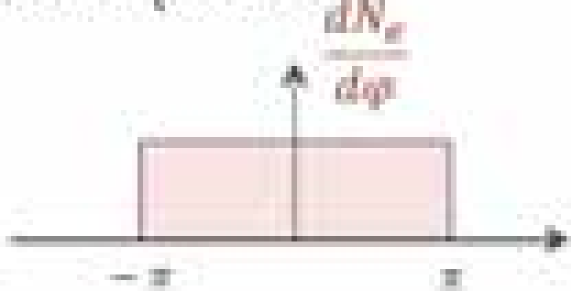
For $\frac{\pi}{2} \leq \varphi \leq 3\frac{\pi}{2}$, $T_{kin}(t)$ increases since $t = 0$

COOLING!

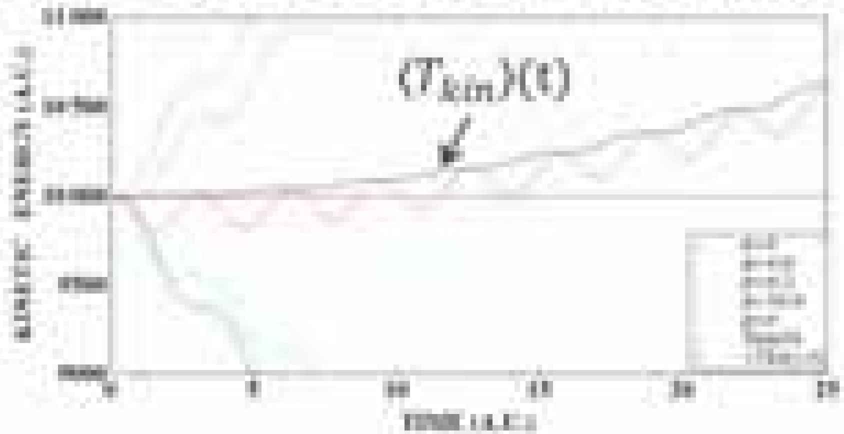
For $-\frac{\pi}{2} < \varphi < \frac{\pi}{2}$, $T_{kin}(t)$ decreases until a minimum, then the electron is accelerated again

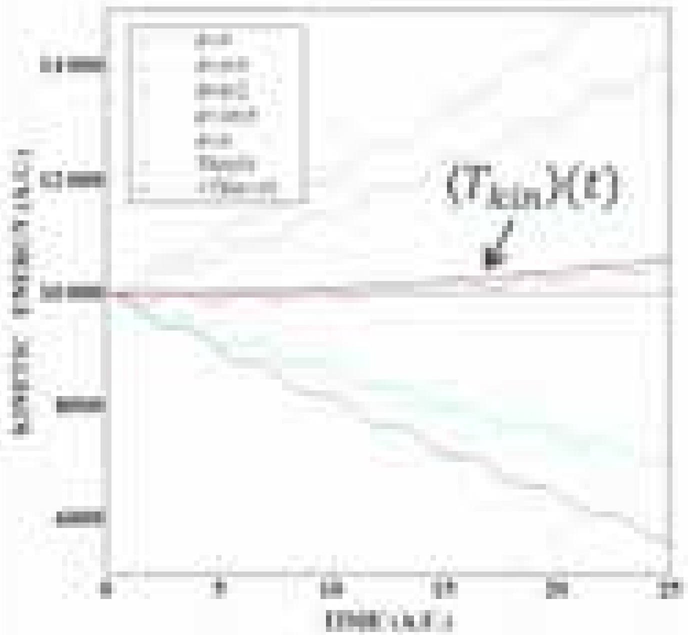
ECR Stocastic Heating

- If we assume that a population of N_e electron with velocity v_0 is **randomly distributed** in its velocity phase space (random phase with the wave), the mean kinetic energy evolution of the population is:



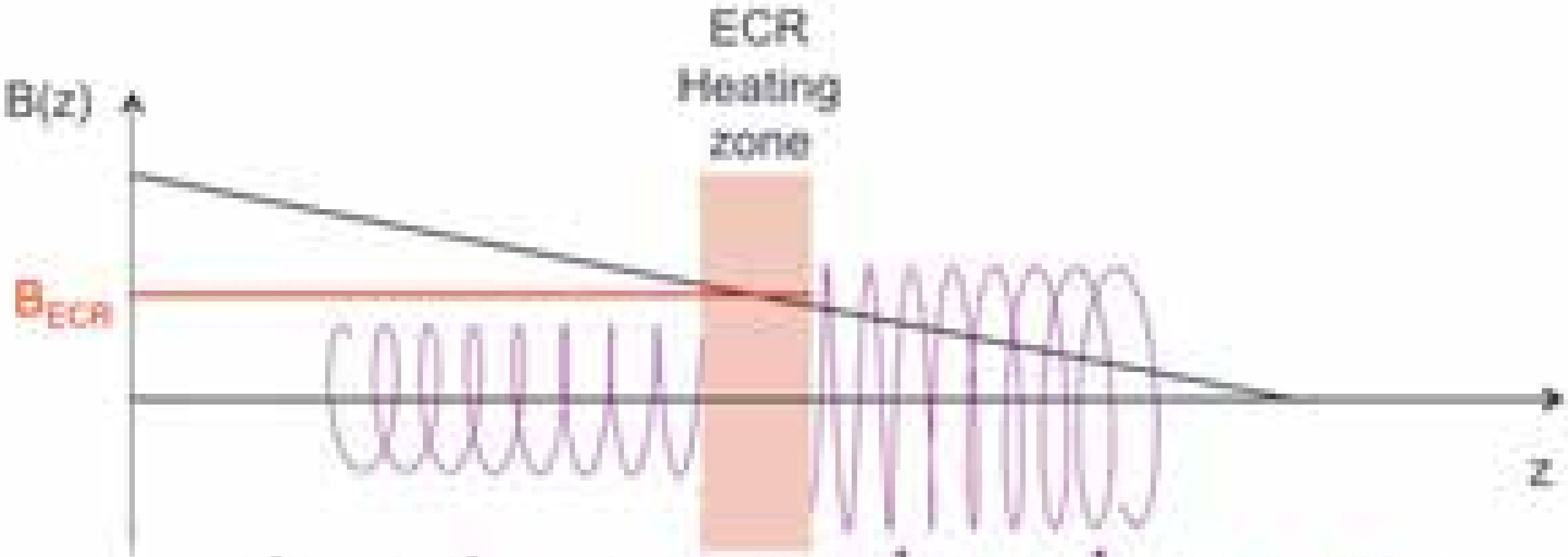
- $\langle T_{kin}\rangle_{\varphi}(t) = \frac{1}{2\pi}\int T_{kin}(t,\varphi)\,d\varphi$
- And we find… $\frac{d}{dt}\langle T_{kin}\rangle_{\varphi}(t) > 0$
- That's the ECR stochastic Heating!





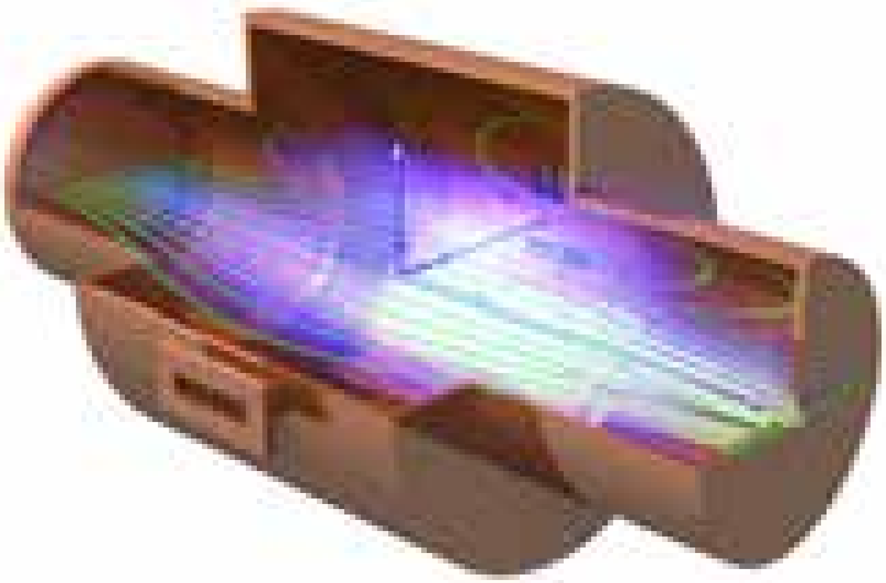
ECR Heating in a magnetic gradient

- In ECR Ion Sources, the ECR zone is usually reduced to a surface, inside a volume, where B is such that $\omega_{HF} = \omega = \frac{eB}{m}$
  - When electrons pass through the ECR surface they are slightly accelerated (in mean) and may gain few eV of kinetic energy
  - The parallel velocity $v_\parallel$ is unchanged, while $v_\perp$ increases
  - The ECR zone thickness is correlated to the local magnetic field slope



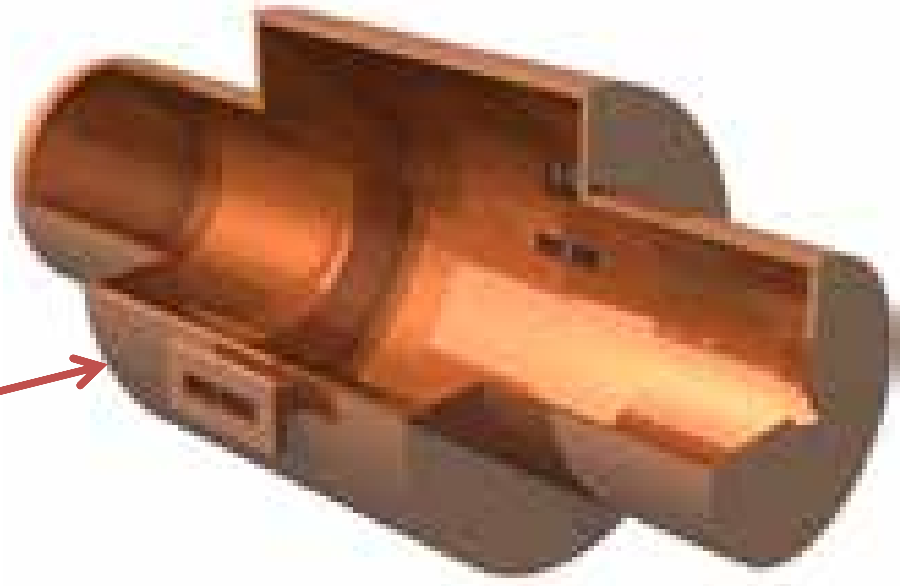
$$\frac{1}{2}mv_\parallel^2 + \frac{1}{2}mv_\perp^2 \Rightarrow \frac{1}{2}mv_\parallel^2 + \frac{1}{2}m(v_\perp + \delta v_\perp)^2$$

Principle of magnetic mirrors

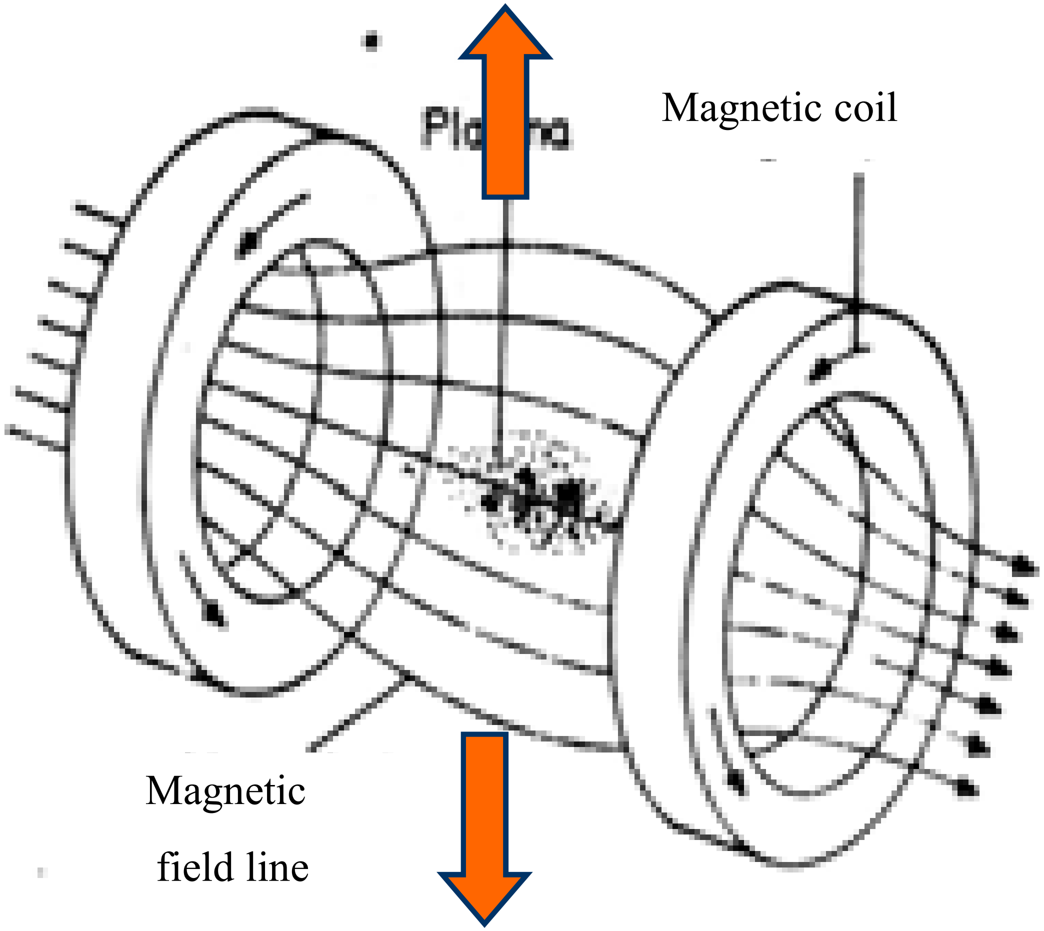


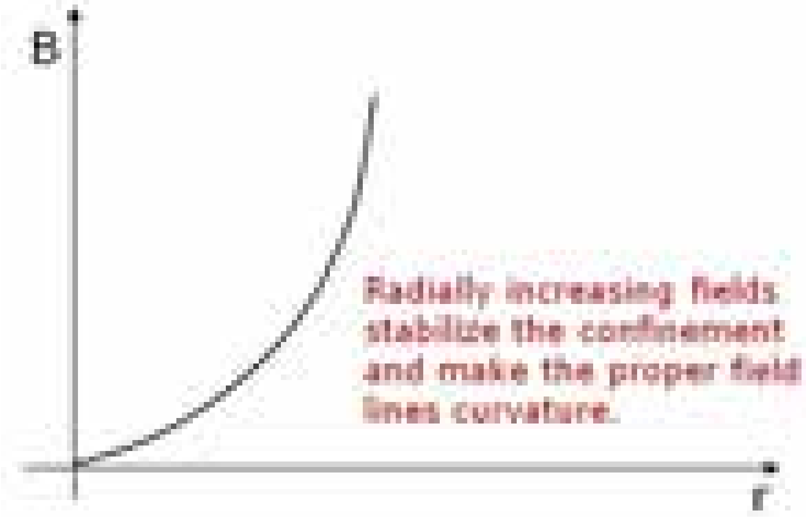
Particles trajectories in plasmas are affected by several drifts, due to spontaneous or induced E fields, B lines curvature, B gradient, gravity, etc…

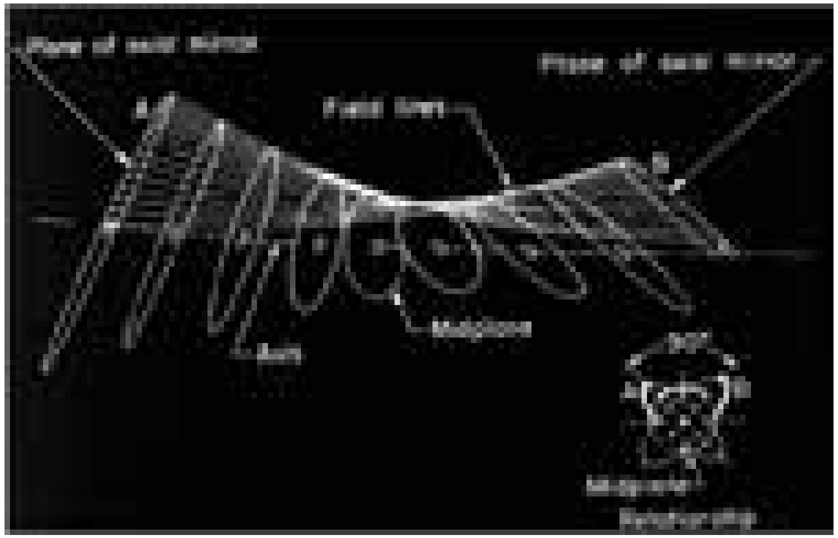
Particles rebounce inside the trap and are contemporaneously affected by the “phi” drift around the magnetic axis, due to the B curvature and axial gradient



The need of the minimum B structure

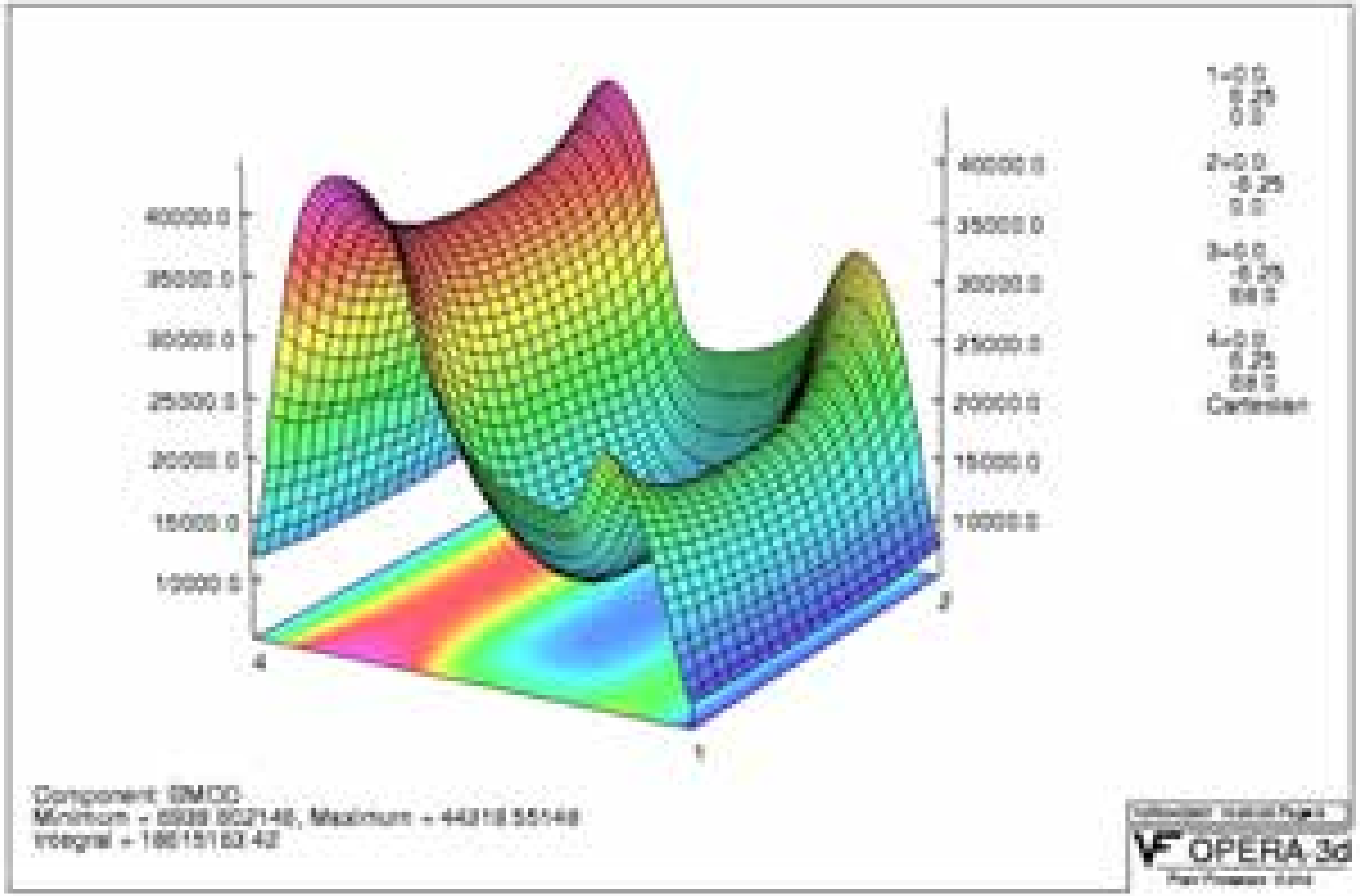






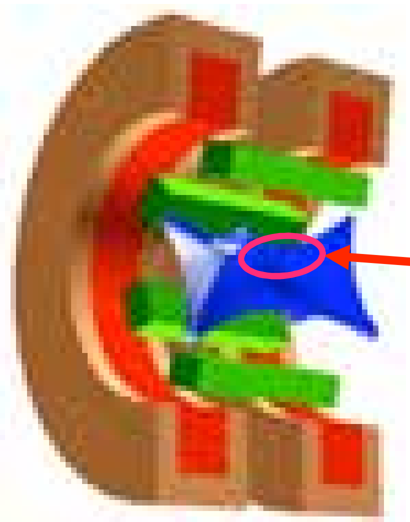
Fluid instabilities generate lateral flows which reduce the plasma lifetime

The need of the minimum B structure



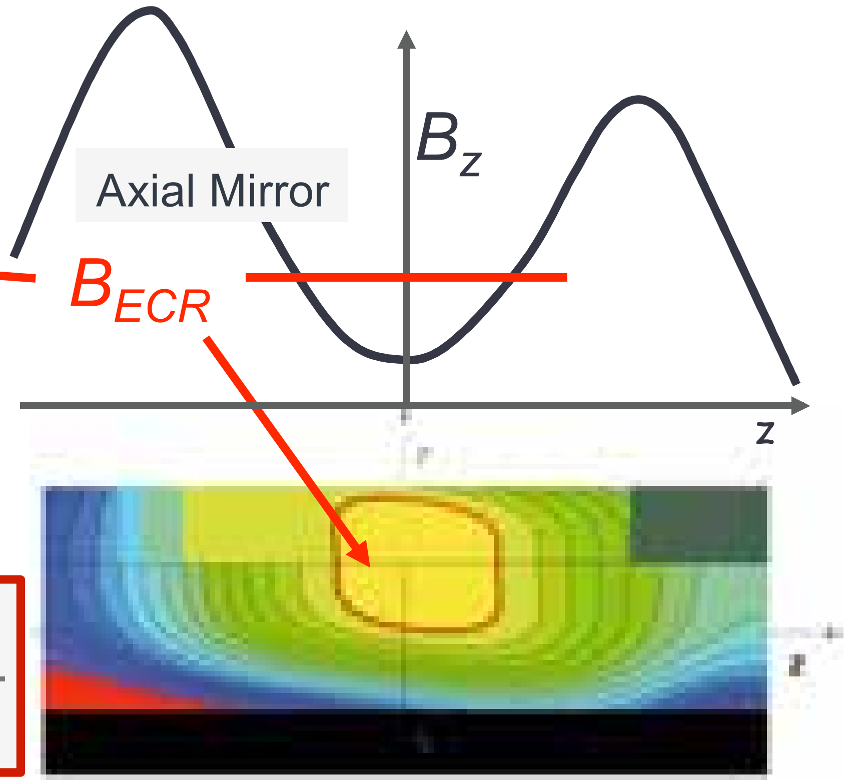
ECRIS Magnetic confinement - Bmin structure

- ECR ion sources features a sophisticated magnetic field structure to optimize charged particle trapping
  - Superimposition of axial coils and hexapole coils
  - The ECR surface ($|B|=B_{ECR}$) is closed



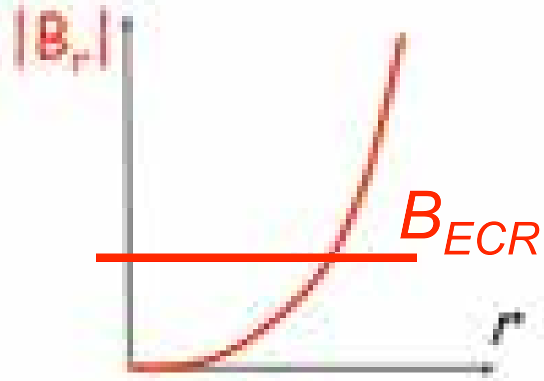
Source LBNL

$$\omega = \omega_{ce} = \frac{qB_{ECR}}{m}$$

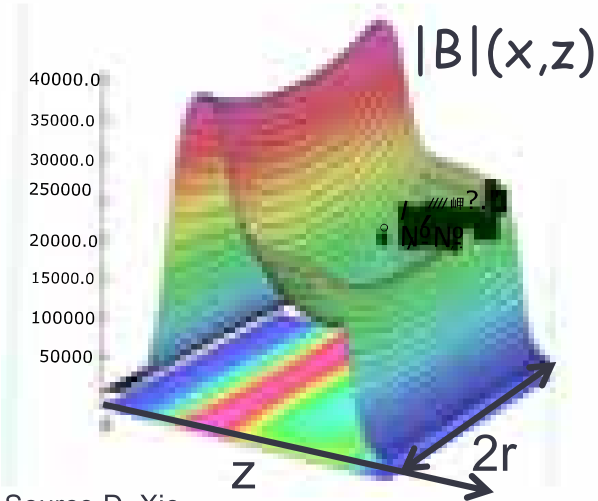


Iso B lines

Source RIKEN, Nakagawa



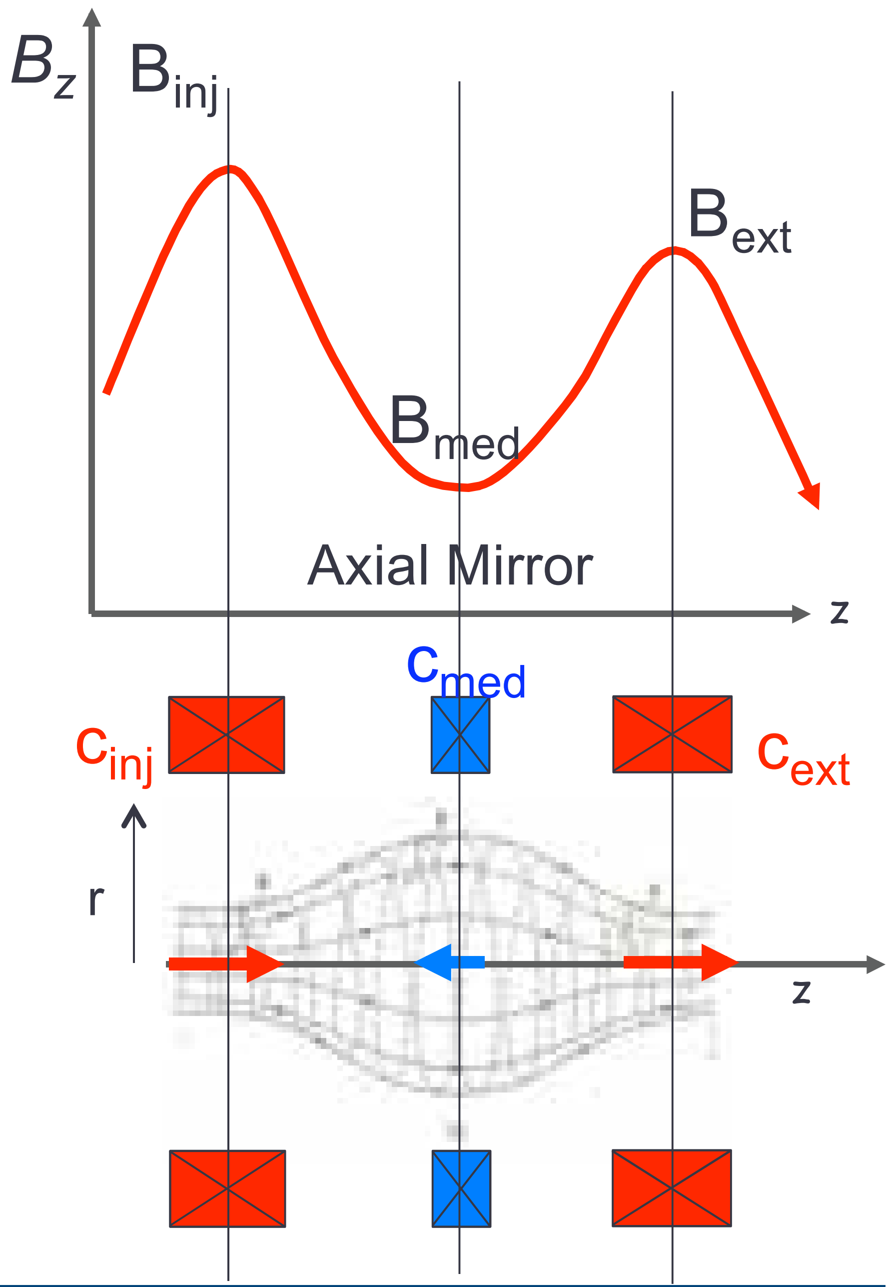
Hexapolar Field



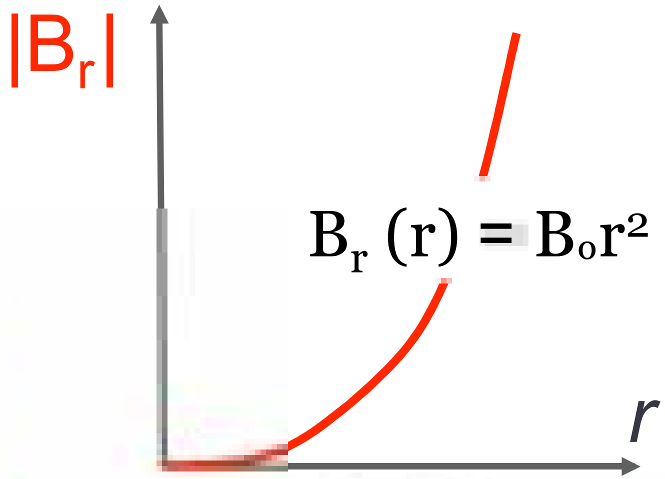
Source D. Xie

Axial magnetic confinement

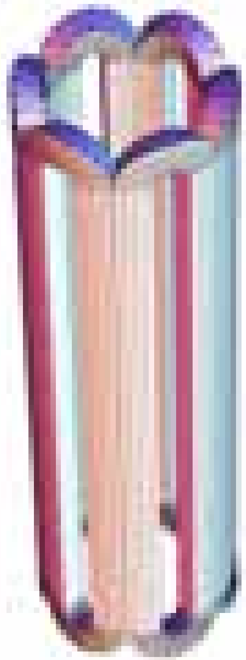
- The axial magnetic confinement in a multicharged ECRIS is usually done with a set of 2 or 3 axial coils.
  - Either room temperature coils + iron to boost the magnetic field
  - Or superconducting coils
- In the case of 3 coils, the current intensity in the middle one is opposed to the others so that it helps digging B_{med}
- Usually Binj, Bext respectively stand for the magnetic field at injection (of RF, atoms…) and (beam) extraction
- Bext should be the smaller magnetic field in the ECR to favor Ion extraction there!



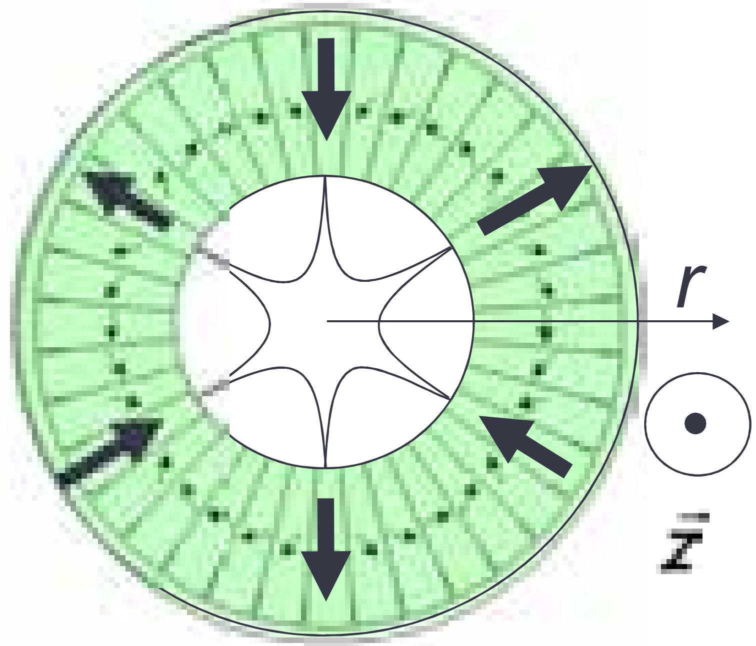
Radial Magnetic Confinement



- The radial magnetic confinement is usually built with a hexapole field
- Either with permanent magnets
  - Br Up to 1.6 T maximum possibly 2T with some tricks
  - Advantage : economical
  - Inconvenient: not tunable
- Either with a set of superconducting coils
  - Br>1.6 T-2 T
  - Advantage: tunable online to optimize a population of ion in the source.
  - Inconvenient: expensive, complicated design and building

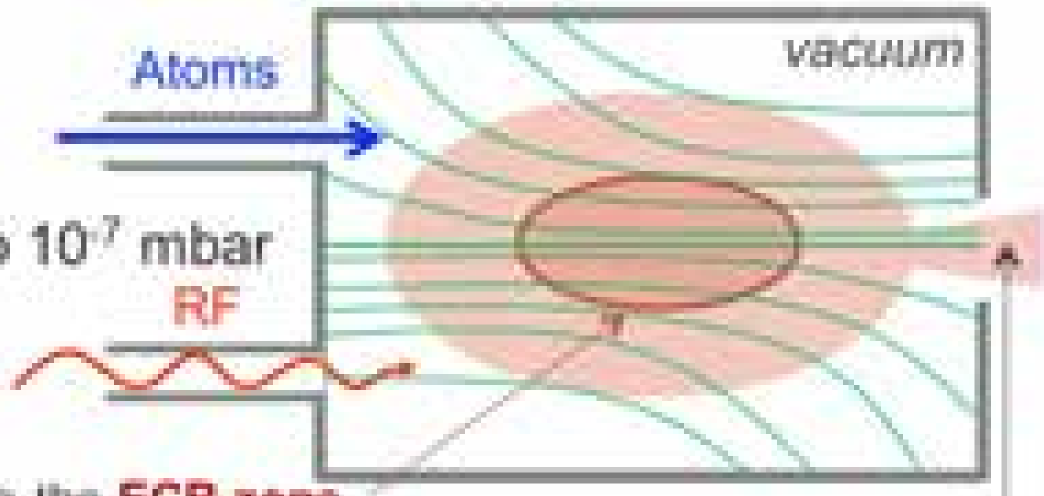


Superconducting hexapolar coil



(HallBach Hexapole
With 36 permanent magnets
30° rotation/magnet)

ECR Plasma build up

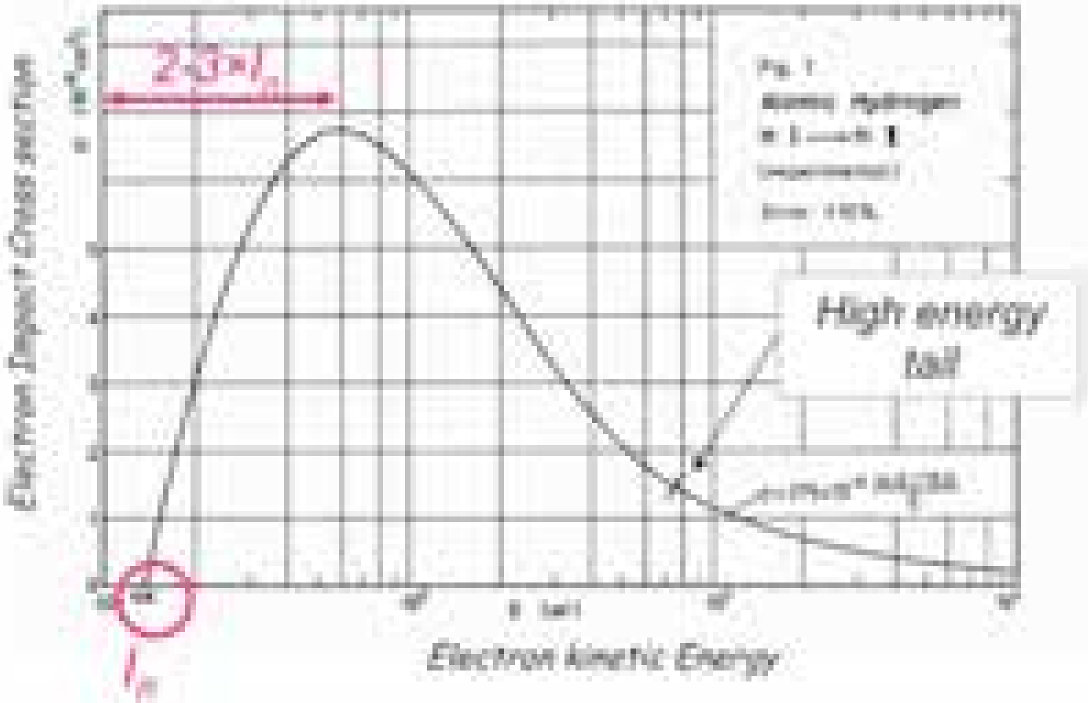


- Pumping & Gas Injection to reach $P \sim 10^{-6}$ to 10^{-7} mbar in the source
- Microwave injection from a waveguide
- Plasma breakdown
  - 1 single electron is heated by a passage through the **ECR zone**
  - The electron bounces thousands of time in the trap and kT_e increases
  - When $kTe > I_1^+$, a first ion is created and a new electron is available
  - Fast Amplification of electron and ion population (~100 μs)
  - =>plasma breakdown

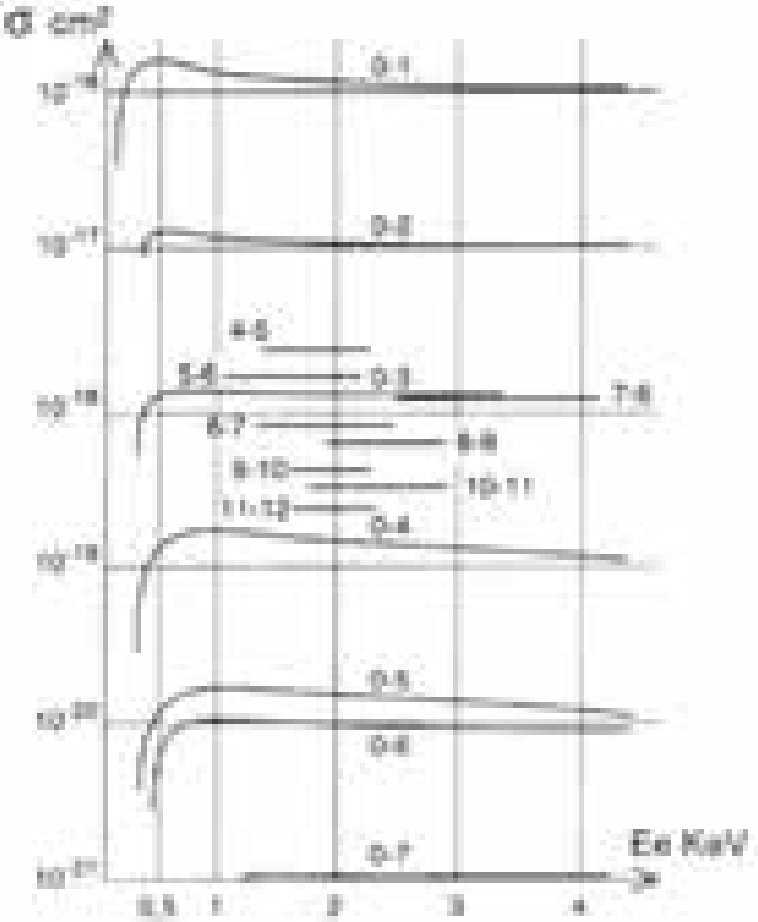
- Multicharged ion build up
  - When Te is established ($kT_e \sim 1$-5 keV), multicharged ions are continuously produced and trapped in the magnetic bottle
  - Ions remains cold in an ECR: $kT_i \sim 1/40$ eV, ($m_e \ll m_i$)
- Population of the loss cone through particle diffusion (coulombian interaction)=> constant change in the particle trajectory=> random redistribution of $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$

Ion creation through Electron Impact Ionization (in gas or plasma)

- Ions are produced through a direct collision between an atom and a free energetic electron
  - $e^- + A^{n+} \rightarrow A^{(n+1)+} + e^- + e^-$
  - Kinetic energy threshold E_e of the impinging electron is the binding energy I_n of the shell electron: $E_e > I_n$
  - Optimum of cross-section for $E_e \sim 2 - 3 \times I_n$
  - Higher energy electron can contribute significantly
  - Double charge electron impact ionization may also occur…



Atomic physics in ECRIS - Step by step ionization



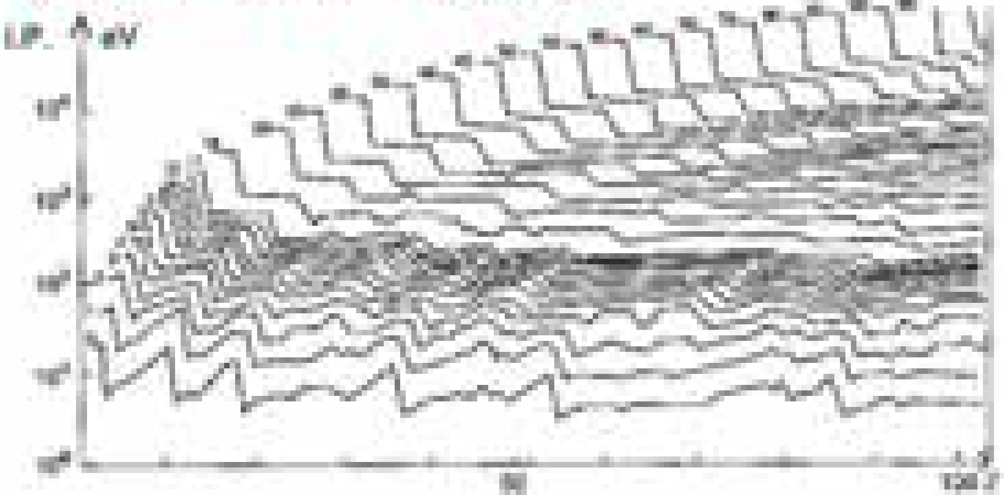
The cross section for ionizing processes like z → z+x as a function of energy features a maximum value when x=1. This means that the ionization proceeds expelling one by one electrons from atomic shells.

The ionization mechanism is therefore a slow process which requires long plasma lifetime to produce highly charged ions

Ion creation through Electron Impact Ionization (in gas or plasma)

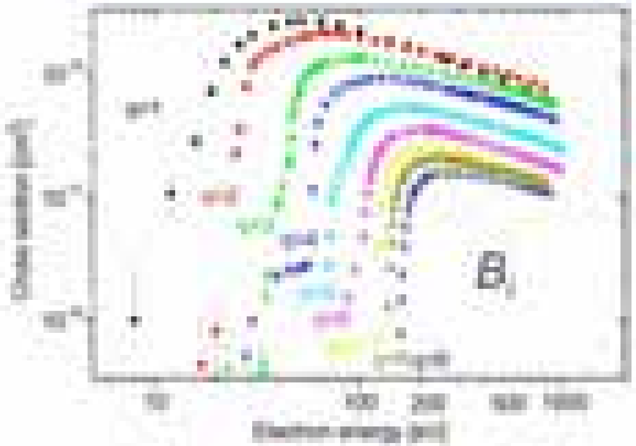
- Electron impact ionization cross section can be approximated by the semi-empirical Lotz Formula:
  - $\sigma_{n \to n+1} \sim 1.4 \times 10^{-13} \dfrac{\ln\left(\frac{E}{I_{n+1}}\right)}{E I_{n+1}}$, E electron kin. energy
    - High charge state production requires hot electrons
    - $Max(\sigma_{n \to n+1}) \sim \dfrac{1}{I_{n+1}^{2}}$ => the higher the charge state, the lower the probability of ionization

I_{n+1} n^{th} Ionization Potential



Example for Bismuth

Z	I_i (eV)	σ_{max} (cm²)
1+	7.2	~2.4×10[illegible]
22+	159	~4.9×10[illegible]
54+	939	~1.4×10[illegible]
72+	3999	~7.8×10[illegible]
82+	90526	~1.5×10[illegible]



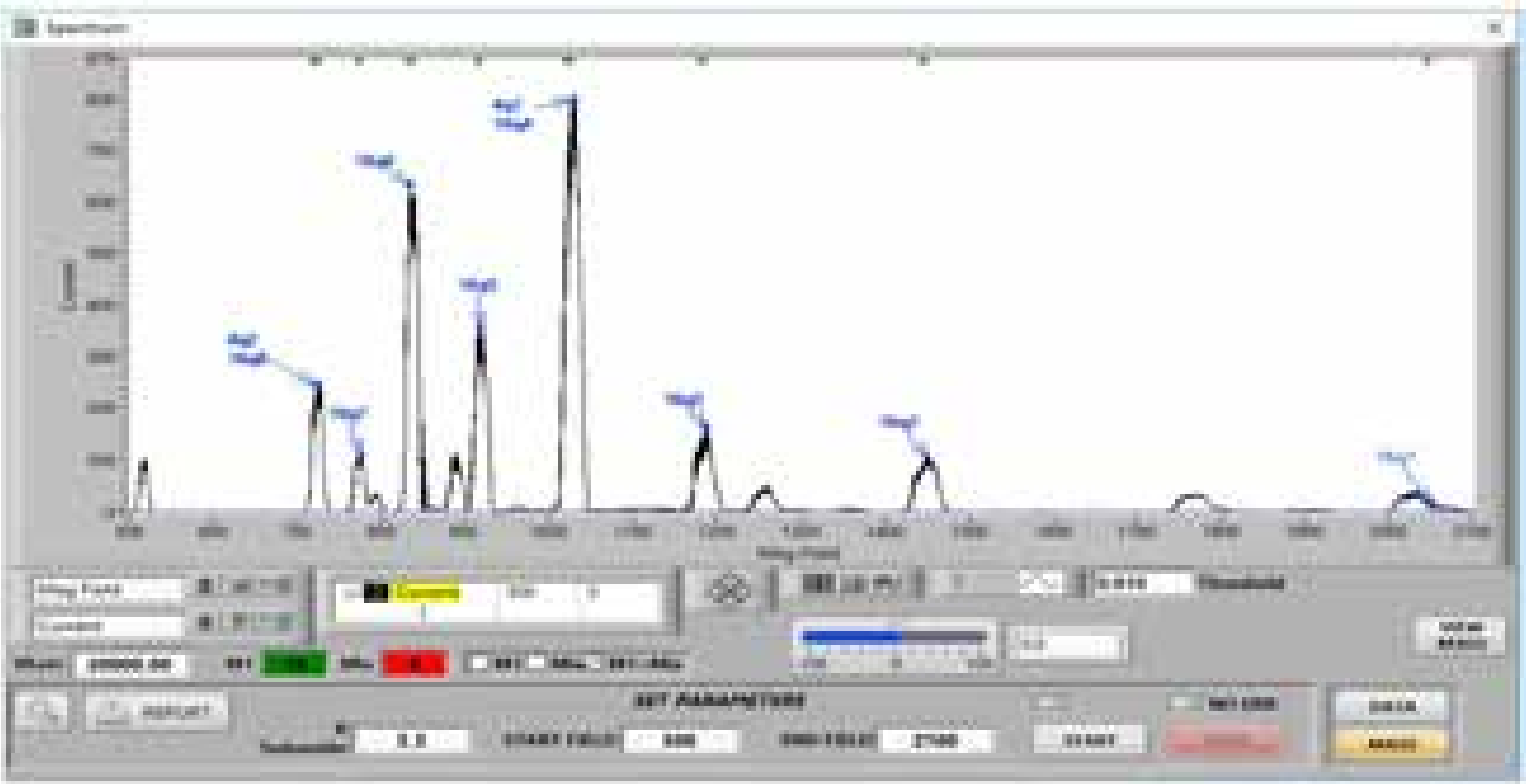
Ion loss through Charge-Exchange (in gas or plasma)

- The main process to reduce an ion charge state is through atom-ion collision e^-
  - $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^{1+}$ (+radiative transitions)
    - Long distance interaction: the electric field of the ion sucks up an electron from the atom electron cloud
    - Any ion surface grazing signs the death warrant of a high charge ion
  - semi-empirical formula :
    - $\sigma_{CE}(n \rightarrow n-1) \sim 1.43 \times 10^{-12} n^{1.17} I_0^{-2.76}\ (cm^2)$ (A. Müller, 1977)
    - I_0 1st ionization potential in eV, n ion charge state

Example :
Bismuth with O_2

Z	1+	22+	54+	72+	82+
σ_{CE} (cm2)	1.5×10^{-15}	5.6×10^{-14}	1.6×10^{-13}	2.2×10^{-13}	2.6×10^{-13}

Charge State Distribution



Zero dimensional modelisation

- The ion charge state distribution in an ECRIS can be reproduced with a 0 Dimension model including a set of balance equations:

$$\frac{\partial n_i}{\partial t} = \underbrace{\sum_{j=j_{min}}^{i-1} n_e n_j \left\langle \sigma^{EI}_{j\to i} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma^{CE}_{i+1\to i} v_{i+1} \right\rangle}_{\text{creation}} \underbrace{- n_0 n_i \left\langle \sigma^{CE}_{i\to i-1} v_i \right\rangle - \sum_{j=i+1}^{j_{max}} n_e n_i \left\langle \sigma^{EI}_{i\to j} v_e \right\rangle}_{\text{destruction}} \underbrace{- \frac{n_i}{\tau_i}}$$

Losses
(ion extraction,
wall,..)

- n_i ion density with charge state i
- σ , cross section of microscopic process
  - Electron impact or charge exchange here
- τ_i is the confinement time of ion in the plasma
- $-\frac{n_i}{\tau_i}$ represents the current intensity for species i (in fact losses)
- Free Parameters: ne, f(ve), τ_i
- Model can be used to investigate ion source physics

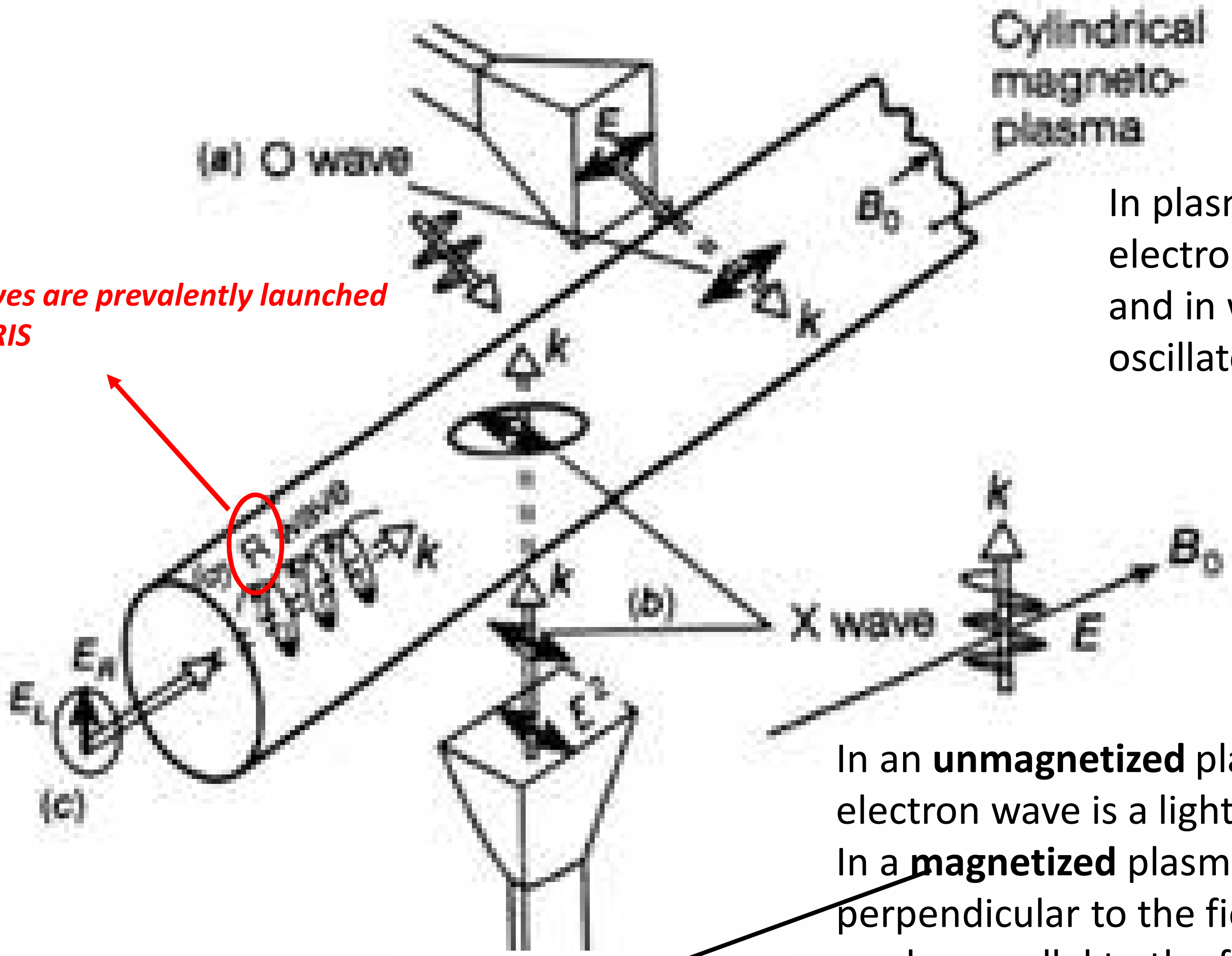
Elastic collision in plasma

- The electromagnetic interaction between charged particles only occurs in distances shorter than the Debye Length λ_D (mm to µm).
- The e-e and e-ion electromagnetic interaction in the Debye sphere (radius~ λ_D) generate a mean force acting on individual charged particles that continuously, and little by little, change their mean velocity direction
- The Elastic interaction is modelized by **the mean time to deviate the initial trajectory by 90°. They are known as the Spitzer formulas:**

- Electron/Electron collision (Hz) : $\nu_{ee}^{90^\circ} = 5.10^{-6}\dfrac{n\ln\Lambda}{T_e^{3/2}}$
- Electron-Ion collision (Hz) : $\nu_{ei}^{90^\circ} = 2.10^{-6}\dfrac{zn\ \ln\Lambda}{T_e^{3/2}}$
- Ion/Ion Collision (Hz) : $\nu_{ii}^{90^\circ} = z^4\left(\dfrac{m_e}{m_i}\right)^{1/2}\left(\dfrac{T_e}{T_i}\right)^{3/2}\nu_{ee}^{90^\circ}$
- T in eV, n in cm-3, z = ion charge state, ln(Λ)~10
- **One should note that these perpetual interaction tends to randomize the velocity direction of a particle inside the plasma**

Waves in plasmas

Plasma-wave interaction is a crucial task of plasma physics, since most of ionized gases are excited and sustained by radiofrequency radiation



R waves are prevalently launched in ECRIS

Anisotropic medium

In plasma physics, an electromagnetic electron wave is a wave in a plasma and in which primarily the electrons oscillate.

In an **unmagnetized** plasma, an electromagnetic electron wave is a light wave modified by the plasma. In a **magnetized** plasma, there are two modes perpendicular to the field, the **O** and **X** modes, and two modes parallel to the field, the **R** and **L** waves.

Plasma Oscillations – Cut off frequency

- The plasma Frequency ω_p is the natural oscillation frequency of a plasma, as a response to a perturbation
  - Oscillations driven by electrons
  - $\omega_p = \sqrt{\dfrac{n_e e^2}{m_e \varepsilon_0}}$
- The simplest dispersion relation of an EM wave in a plasma is:
  - $\omega^2 = {\omega_p}^2 + k^2 c^2$
  - EM wave propagates if $\omega > \omega_p$
- ECR Cut-off density:
  - $\omega > \omega_p \Rightarrow n_e < \dfrac{m_e \varepsilon_0 \omega^2}{e^2}$
  - At a given ECR frequency, the plasma density is limited
    - $n_e \propto \omega^2{}_{ECR}$

=> Oscillations at the plasma frequency

Above cut off:
RF is reflected
=> no more ECR heating!

The cutoff density and Geller's scaling laws

The plasma frequency is connected to self-generated plasma oscillations which affect the wave propagation.

$$\omega_p^2 = \frac{4\pi n_e e^2}{m_e} \rightarrow n_{cutoff} = 4\pi^2 \frac{m\epsilon_0}{e^2} f_p^2$$

Above the cutoff the wave cannot propagate

Plasma density	**$N_e \sim f^2_{ECR}$**
Beam current	**$I \sim N_e \sim f^2_{ECR}$**

High frequency is needed In order to increase the plasma density and current extracted, **BUT**…

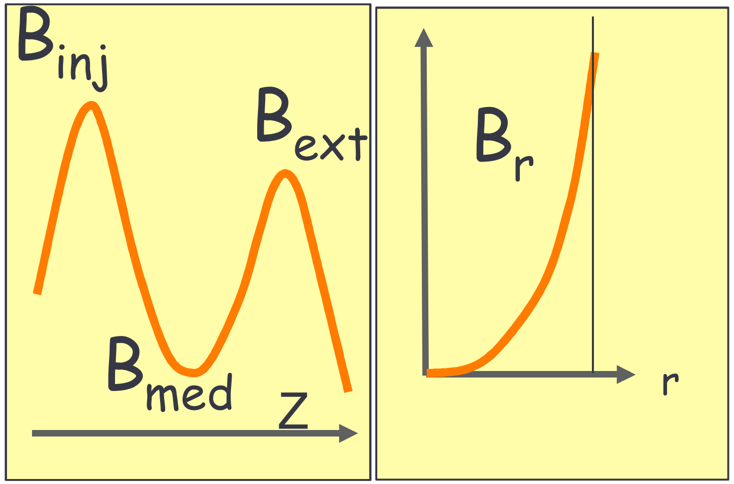
$$B_{ECR} = \frac{f_{ECR}[GHz]}{28}$$

f_{ECR} [GHz]	λ_{ECR} [cm]	n_e [cm^{-3}]	$\Lambda_{0\to1+}$ [cm]	$\tau_{0\to1+}$ [μs]	B_{ECR} [T]
2.45	~12	7.4×10^{10}	~7	~10	0.09
14	~2	2.5×10^{12}	0.2	3	0.5
28	~1	$\sim10^{13}$	0.05	0.7	1
60	~0.5	4.4×10^{13}	0.01	0.17	2

ECRIS Standard Model

- Optimum high charge state ion production and extraction have been experimentally studied as a function of ECR frequency.
- General Scaling laws for the magnetic field have been established

$$B_{ECR} = \frac{f_{ECR}[GHz]}{28}\ Tesla$$



Axial Mirror Radial Mirror

f_{ECR} [GHz]	14	28	56
B_{ECR} [T]	0.5	1	2
$B_{rad} \sim 2 \times B_{ECR}$	1	2	4
$B_{inj} \sim 3\text{-}4 \times B_{ECR}$	2	3.5	7
$B_{med} \sim 0.5\text{-}0.8 \times B_{ECR}$	0.25	0.5	1
$B_{ext} \leq B_{rad}$	1	2	4

~1990 2003 VENUS ?