CERN ACCELERATOR SCHOOL 2012:

ELECTRON CYCLOTRON RESONANCE ION SOURCES - I

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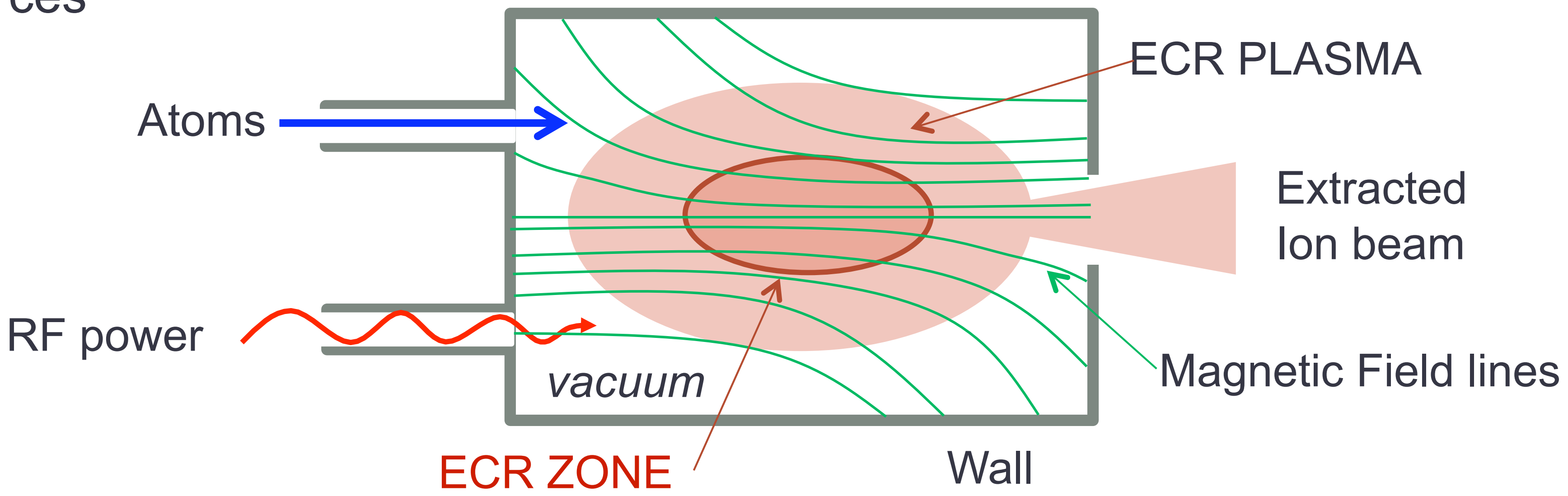
OUTLINE

- **Electron Cyclotron Resonance Ion Source - I**
  - **Introduction**
  - **Summary of the main microscopic processes occuring in an ECRIS**
  - **Electron Cyclotron Resonance Mechanism**
  - **Magnetic confinement and ECR plasma generation**
  - **Geller Scaling Law and ECRIS Standard Model**

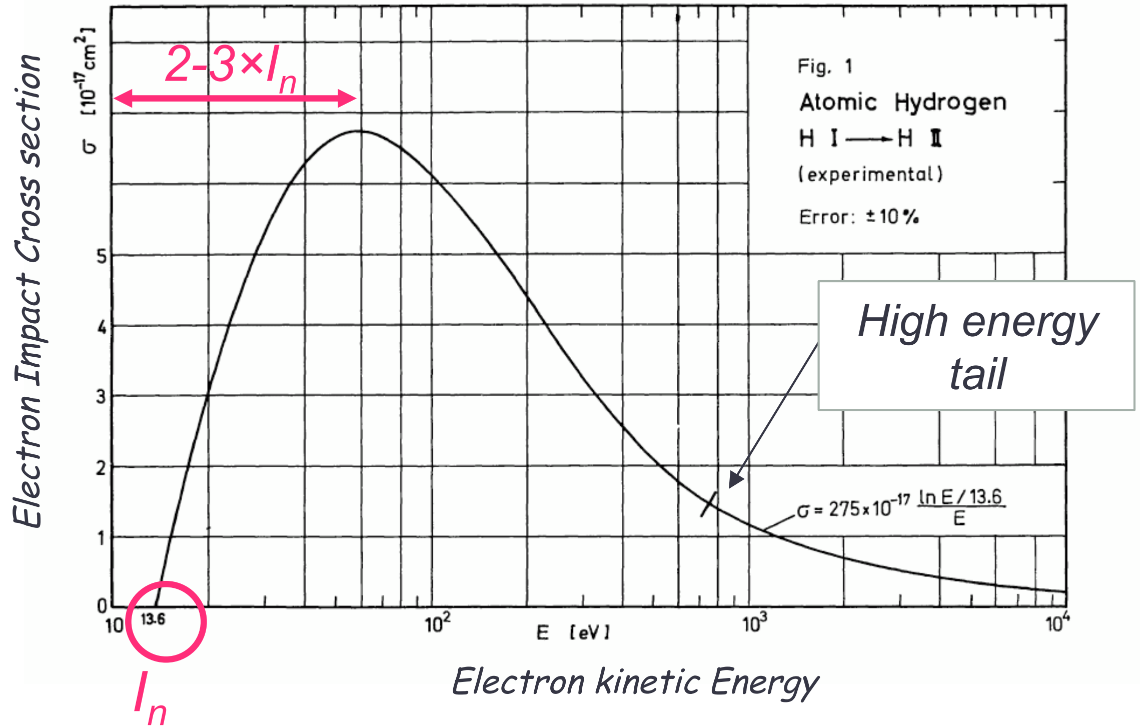
Ingredients of Electron Cyclotron Resonance Ion Source

- An ECR ion source requires:
  - A secondary vacuum level to allow multicharged ion production
  - A RF injection in a metallic cavity (usually multimode)
  - A sophisticated magnetic Field structure that enables to:
    - Transfer RF power to electrons through the ECR mechanism
    - Confine long enough the (hot) electrons to ionize atoms
    - Confine long enough ions to allow multi-ionization ions
    - Generate a stable CW plasma
  - An atom injection system (gas or condensables) to sustain the plasma density
  - An extraction system to accelerate ions from the plasma
- In the following, we will try to detail these points to provide an overview of ECR ion sources



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…



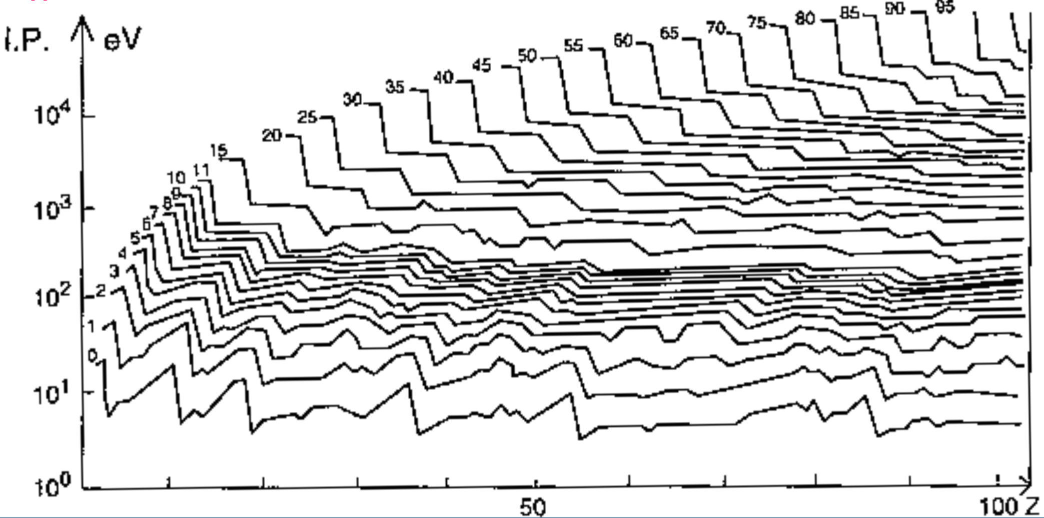
Ion creation through Electron Impact Ionization (in gas or plasma)

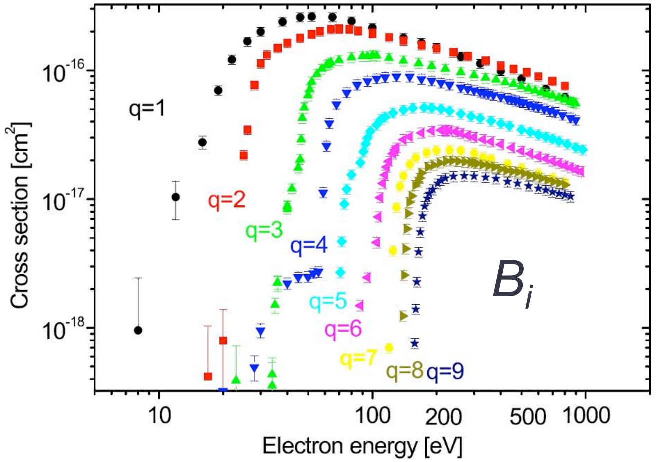
- Electron impact ionization cross section can be approximated by the semi-empirical Lotz Formula:
  - $\sigma_{n \to n+1} \sim 1.4 \times 10^{-13} \frac{\ln(\frac{E}{I_{n+1}})}{E I_{n+1}}$, *E electron kin. energy*
    - High charge state production requires hot electrons
    - $Max(\sigma_{n \to n+1})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

Example for Bismuth

Z	I_n (eV)	σ_{max} (cm^2)
1+	7.2	~2.4×10^{-16}
22+	159	~4.9×10^{-19}
54+	939	~1.4×10^{-20}
72+	3999	~7.8×10^{-22}
82+	90526	~1.5×10^{-24}

$I_{n=}$ n^{th} Ionization Potential





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}

Zero Dimension Modelization

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

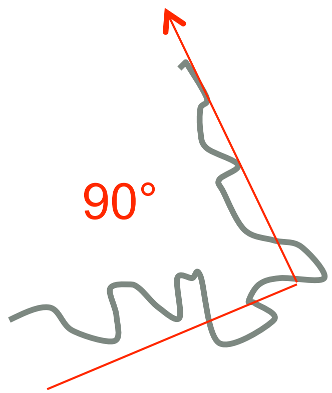
$$\frac{\partial n_i}{\partial t} = \underbrace{\sum_{j=j_{\min}}^{i-1} n_e n_j \left\langle \sigma_{j\to i}^{EI} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma_{i+1\to i}^{CE} v_{i+1} \right\rangle}_{\text{creation}} \underbrace{- n_0 n_i \left\langle \sigma_{i\to i-1}^{CE} v_i \right\rangle -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

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 an ECRIS plasma

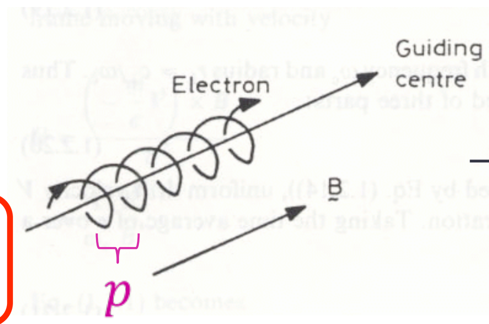
- The electromagnetic interaction between charged particles only occurs in distances shorter than the Debye Length λ_D (mm to µm).
- The e-e and e-ion electromagnetic interaction in the Debye sphere (radius~ λ_D) generate a mean force acting on individual charged particles that continuously, and little 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:**

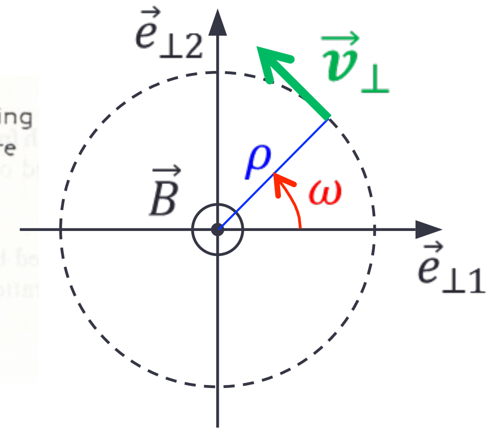


- Electron/Electron collision (Hz) : $\nu_{ee}^{90^\circ} = 5.10^{-6}\dfrac{n\ln\Lambda}{T_e^{3/2}}$
- Electron-Ion collision (Hz) : $\nu_{ei}^{90^\circ} = 2.10^{-6}\dfrac{zn\ \ln\Lambda}{T_e^{3/2}}$
- Ion/Ion Collision (Hz) : $\nu_{ii}^{90^\circ} = z^4\left(\dfrac{m_e}{m_i}\right)^{1/2}\left(\dfrac{T_e}{T_i}\right)^{3/2}\nu_{ee}^{90^\circ}$
- 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**

Motion of a charged particle in a constant magnetic field

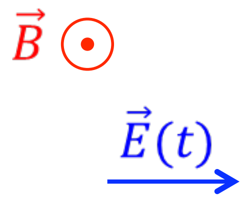
- The Individual motion of a charged particle in a magnetic field is ruled by:
- $m\frac{d\vec{v}}{dt} = q\vec{v} \times \vec{B}$
- Velocity is decomposed as $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$ with $\vec{v}_{\perp}.\vec{B} = 0$ and $\vec{v}_{\parallel} \parallel \vec{B}$
  - We define the space vectors $\vec{e}_{\parallel} = \frac{\vec{B}}{B}$, $\vec{e}_{\perp 1} = \frac{\vec{v}_{\perp}}{v_{\perp}}$ and $\vec{e}_{\perp 2} = \vec{e}_{\parallel} \times \vec{e}_{\perp 1}$
- General solution for the velocity is:
- $\begin{cases} v_{\parallel} = const \\ \vec{v}_{\perp} = \rho\omega(\sin\omega t\,.\vec{e}_{\perp 1} + \cos\omega t\,.\vec{e}_{\perp 2}) \end{cases}$
- $\omega = \frac{qB}{m}$ is the cyclotronic frequency
- ρ is the Larmor radius (constant)
- The particle trajectory is an helix with radius ρ and pitch $p = \frac{2\pi v_{\parallel}}{\omega}$





The Electron Cyclotron Resonance (1/3)

- Motion of an electron in a constant Magnetic Field B and a perpendicular time varying Electric Field $E_x(t)$
  - Assume $\vec{B} = B\vec{z}$; $\vec{E}(t) = E\cos\omega_{HF}t\,\vec{x}$
  - Assume initial particle velocity $\vec{v}_0 = \vec{0}$, and $q = -e$ with $e > 0$
  - Assume $\omega_{HF} = \omega = \frac{eB}{m}$ (ECR resonance condition)

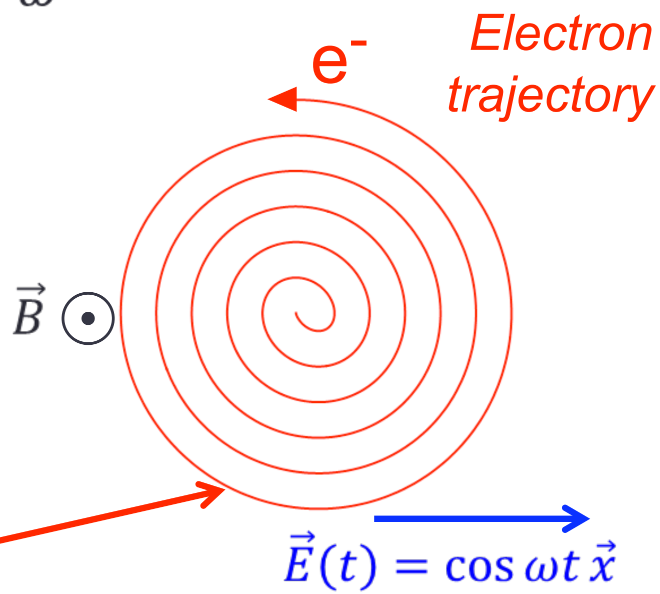


- Let's solve $m\frac{d\vec{v}}{dt} = -e\vec{v}\times\vec{B} - e\vec{E}(t)$! (1)
  - Complex notation: $\vec{\tilde{E}}(t) = Ee^{i\omega t}\vec{x}$
  - We look for velocity solution of type: $\vec{\tilde{v}} = \begin{cases} a(t)e^{i\omega t} \\ b(t)e^{i\omega t} \\ 0 \end{cases}$
- Let's substitute in (1):
- $$\vec{\tilde{v}} = \frac{d}{dt}\begin{vmatrix} ae^{i\omega t} \\ be^{i\omega t} \\ 0 \end{vmatrix} = -\omega e^{i\omega t}\begin{vmatrix} a \\ b \\ 0 \end{vmatrix} \times \begin{vmatrix} 0 \\ 0 \\ 1 \end{vmatrix} - \begin{vmatrix} \frac{eE}{m} \\ 0 \\ 0 \end{vmatrix} e^{i\omega t} \rightarrow \begin{cases} \dot{a} + i\omega a = -b\omega - \frac{eE}{m} \\ \dot{b} + i\omega b = a\omega \end{cases}$$

The Electron Cyclotron Resonance (2/3)

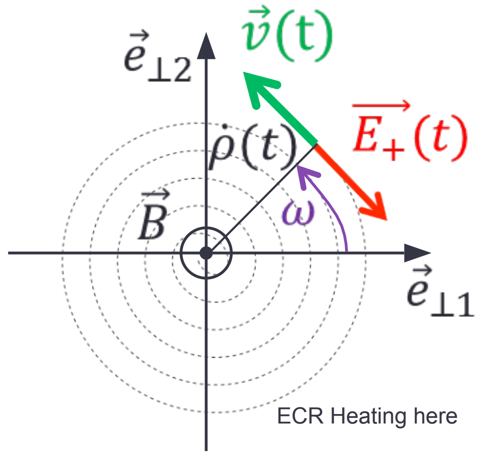
- (*) $\begin{cases} \dot{a} + i\omega a = -\omega b - \frac{eE}{m} \ (1) \\ \dot{b} + i\omega b = a\omega \ (2) \end{cases}$; $(2) \rightarrow \ i\omega a = i\dot{b} - \omega b$; $(\dot{2}) \rightarrow \dot{a} = \frac{\ddot{b}}{\omega} + i\dot{b}$
- $(\dot{2})\&(2) \text{ in } (1) \rightarrow \frac{\ddot{b}}{\omega} + 2i\dot{b} - \omega b = -\omega b - \frac{eE}{m}$
- Assume that $\ddot{b} = 0 \rightarrow \dot{b} = \frac{ieE}{2m} \rightarrow b(t) = \frac{ieE}{2m} t$
- Substitute: $a(t) = \frac{\dot{b}}{\omega} + ib = \frac{eE}{2m\omega}(-\omega t + i)$
- So $\vec{\tilde{v}} = \frac{eE}{2m\omega}(-\omega t + i)e^{i\omega t}\vec{x} + \frac{ieE}{2m\omega}\omega t e^{i\omega t}\vec{y}$
- And finally:

  $\vec{v} = Re(\vec{\tilde{v}}) = \frac{(-e)Et}{2m}(\cos\omega t\,\vec{x} + \sin\omega t\,\vec{y}) + \frac{eE}{2m\omega}\sin\omega t\,\vec{x}$
- The electron gains energy with time & describes a spiral



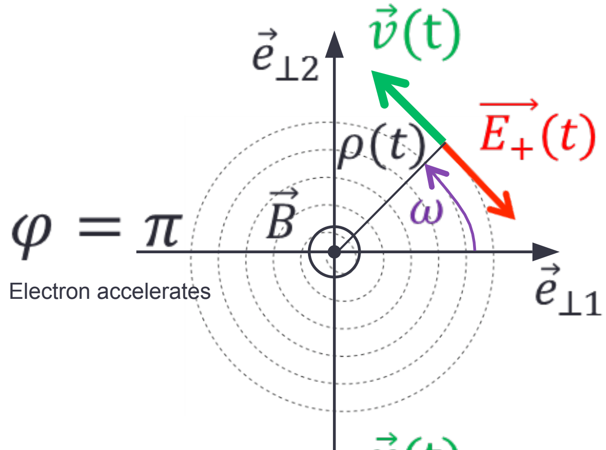
The Electron Cyclotron Resonance (3/3)

- ECR heating in a general transverse Electric Field (with $\vec{B} = B\vec{z}$)
  - **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

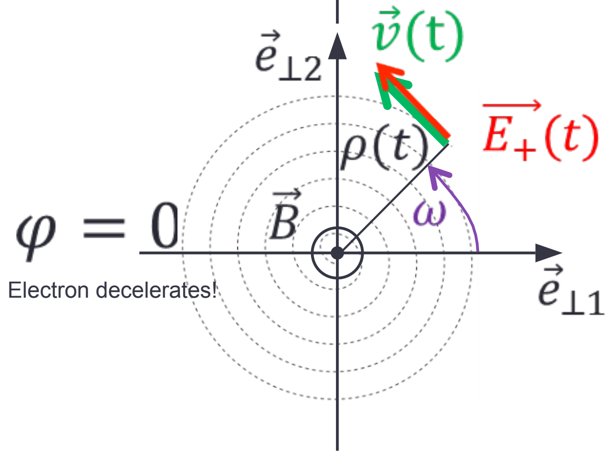


ECR Stochastic Heating (1/5)

- 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 Stochastic Heating (2/5)

- Let's solve again (1): $m\frac{d\vec{v}}{dt} = -e\vec{v}\times\vec{B} - e\vec{E}(t)$, still using complex notations, but with the **initial condition $v_0 \neq 0$**
  - $\vec{v}(t) = a(t)e^{i\omega t}\vec{x} + b(t)e^{i\omega t}\vec{y}$
  - $\vec{v_0} = \vec{v}(0) = v_0(\cos\varphi\,\vec{x} + \sin\varphi\,\vec{y})$
  - so $\mathrm{Re}\big(\mathrm{b}(0)\big) = \mathrm{Re}\big(-v_0 \mathrm{i} e^{i\varphi}\big) = v_0\sin\varphi$ and $\mathrm{Re}\big(a(0)\big) = \mathrm{Re}\big(v_0 e^{i\varphi}\big) = v_0\cos\varphi$
  - and still $\vec{E}_x(t) = E\cos\omega t\,\vec{x}$
- Same solving, but now: $\dot{b} = \frac{ieE}{2m} \rightarrow b(t) = \frac{ieE}{2m}t + b(0)$
- The velocity expression is now :
- $\vec{v} =$

$$\frac{(-e)Et}{2m}(\cos\omega t\,\vec{x} + \sin\omega t\,\vec{y}) + \frac{eE}{2m\omega}\sin\omega t\,\vec{x} +$$ Former solution ($v_0=0$)

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

ECR Stochastic Heating (3/5)

- Finally, the general solution for a counter-clockwise Electric Field $\vec{E}_+(t) = \vec{E}_x(t) + \vec{E}_y(t)$ can be calculated to be :
- $\vec{v} = \frac{(-e)Et}{m}(\cos\omega t\,\vec{x} + \sin\omega t\,\vec{y}) + \frac{eE}{m\omega}\sin\omega t\,\vec{x} + v_0(\cos(\omega t+\varphi)\,\vec{x} + \sin(\omega t+\varphi)\,\vec{y})$

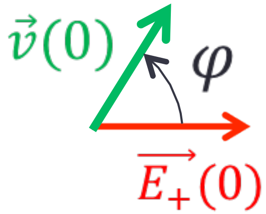
- Expression of the Kinetic Energy of the electron as a function of time t and phase φ :
- $T_{kin}(t,\varphi) = \frac{e^2E^2}{2m\omega^2}((\omega t)^2 - \omega t\sin 2\omega t + \sin^2\omega t)$ — Increases with time $(\sim t^2)$

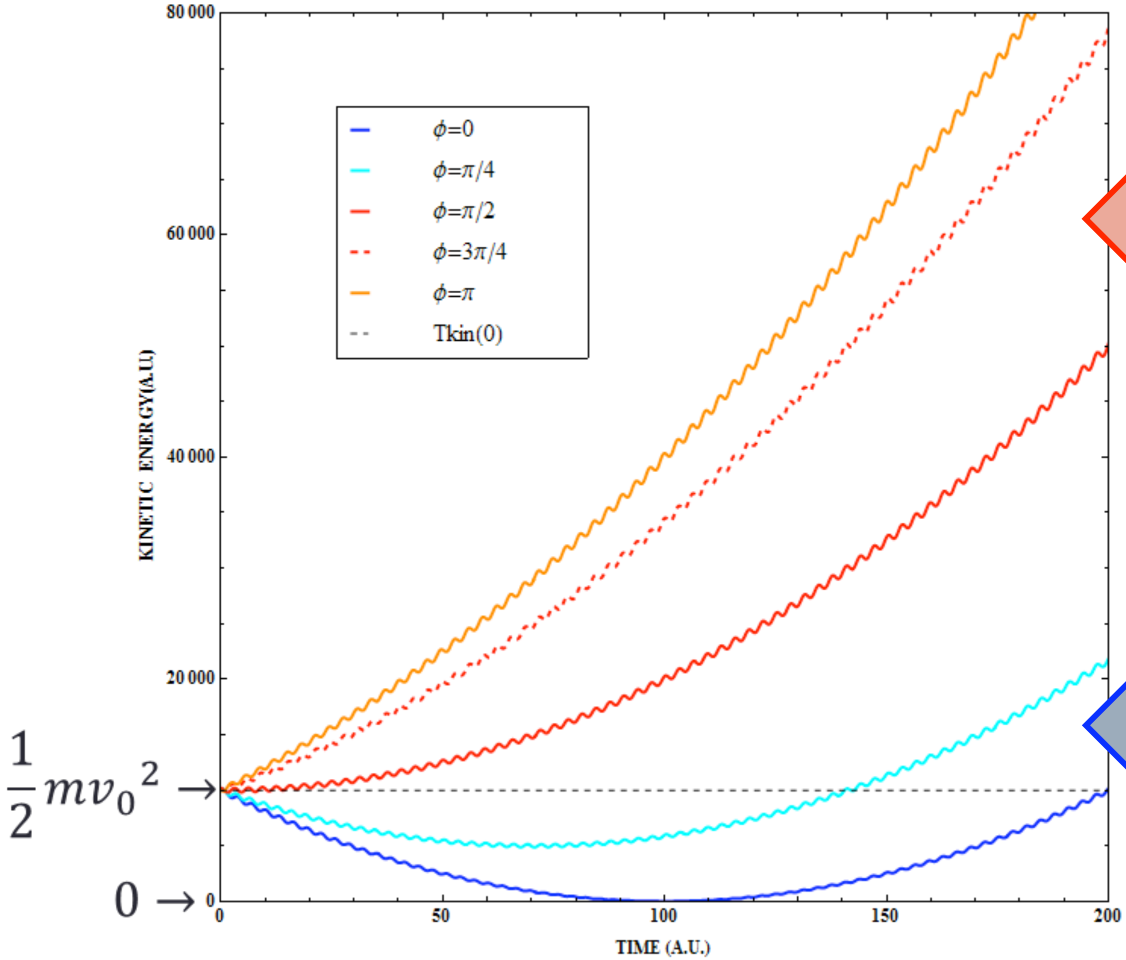
$+\frac{eEv_0}{\omega}(\sin\omega t\,cos(\omega t+\varphi) - \omega t\,cos\,\varphi)$ — Phase term, may be <0 $(\sim t)$

$+\frac{1}{2}m{v_0}^2$ — Constant term

ECR Stochastic Heating (4/5)

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





HEATING

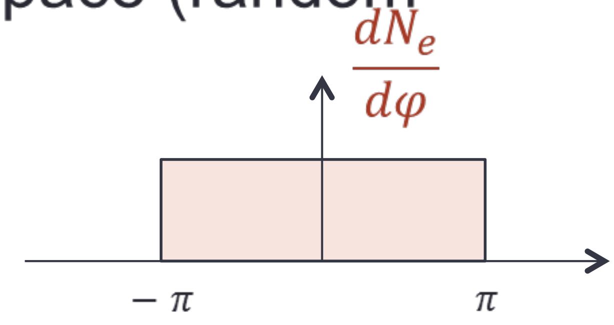
For $\frac{\pi}{2} \leq \varphi \leq 3\frac{\pi}{2}$, $T_{kin}(t)$ increases since $t = 0$

COOLING!

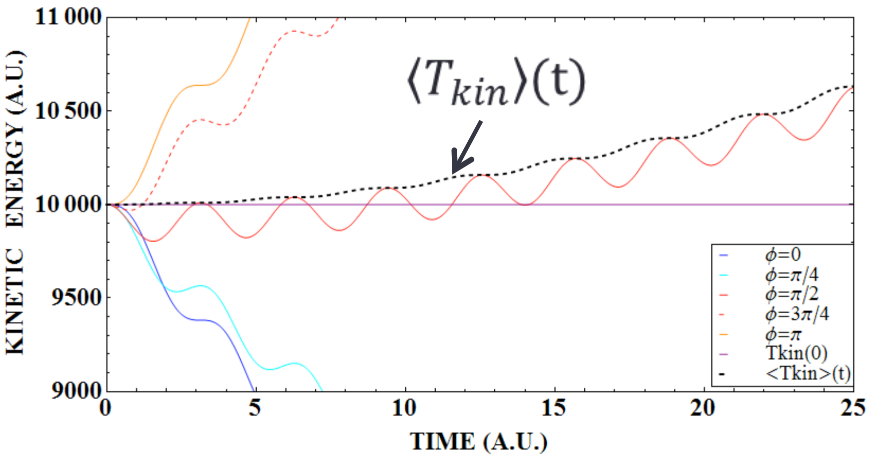
For $-\frac{\pi}{2} < \varphi < \frac{\pi}{2}$, $T_{kin}(t)$ decreases until a minimum, then the electron is accelerated again

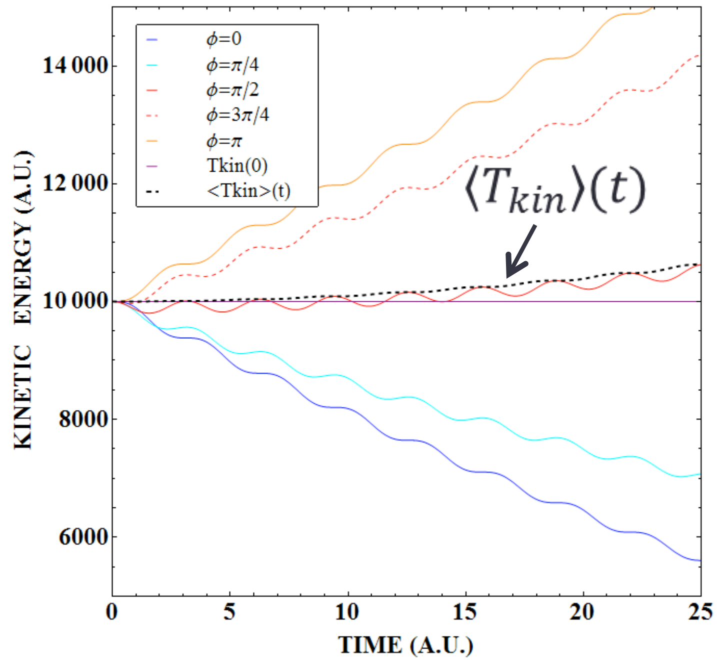
ECR Stochastic Heating (5/5)

- 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:



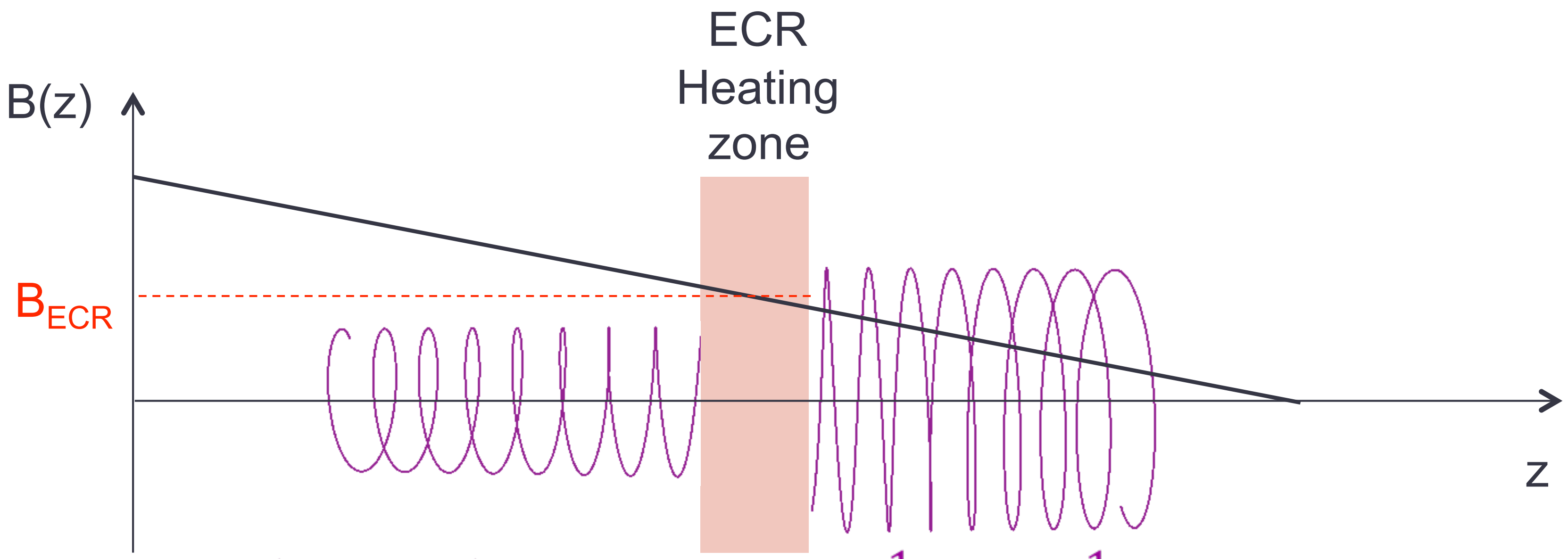
- $\langle T_{kin}\rangle_\varphi(t) = \frac{1}{2\pi}\int T_{kin}(t,\varphi)\,d\varphi$
- And we find… $\frac{d}{dt}\langle T_{kin}\rangle_\varphi(t) > 0$
- That's the ECR stochastic Heating!





ECR Heating in a Magnetic Gradient

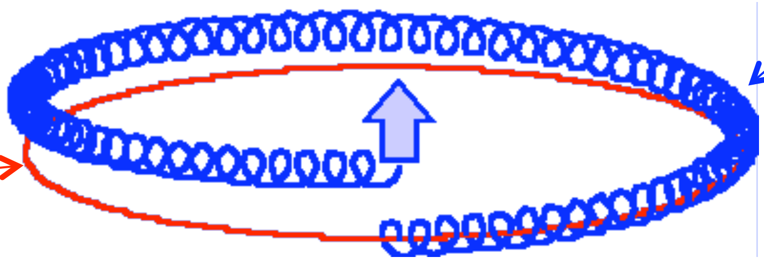
- In ECR Ion Sources, the ECR zone is usually reduced to a surface, inside a volume, where B is such that $\omega_{HF} = \omega = \frac{eB}{m}$
  - When electrons pass through the ECR surface they are slightly accelerated (in mean) and may gain few eV of kinetic energy
  - The parallel velocity $v_{\parallel}$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



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

Properties of particle motion in a magnetic field (1/2)

- $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$ with $\vec{v}_{\perp} . \vec{B} = 0$
- $\left.\begin{matrix} v_{\parallel} = const \\ v_{\perp} = \rho\omega = const \end{matrix}\right\} \rightarrow \boxed{T_{kin} = W_{\parallel} + W_{\perp} = \frac{1}{2}mv_{\parallel}{}^{2} + \frac{1}{2}mv_{\perp}{}^{2} = const}$
- The kinetic energy of a charged particle is constant in a pure magnetic field
- The particle roughly follows the local magnetic field line, even if the field line is bended
  - Provided the magnetic field change per cyclotronic turn to be small ($\nabla B/B \ll 1$)

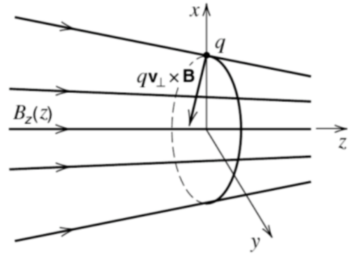


http://www-fusion-magnetique.cea.fr

Properties of particle motion in a magnetic field (2/2)

- The Magnetic Moment of a charged particle in a slowly varying magnetic field is an adiabatic constant of the movement

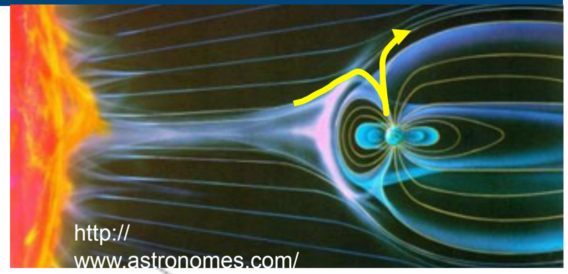
$$\mu = \frac{m{v_\perp}^2}{2B} = \frac{W_\perp}{B} \sim cst$$



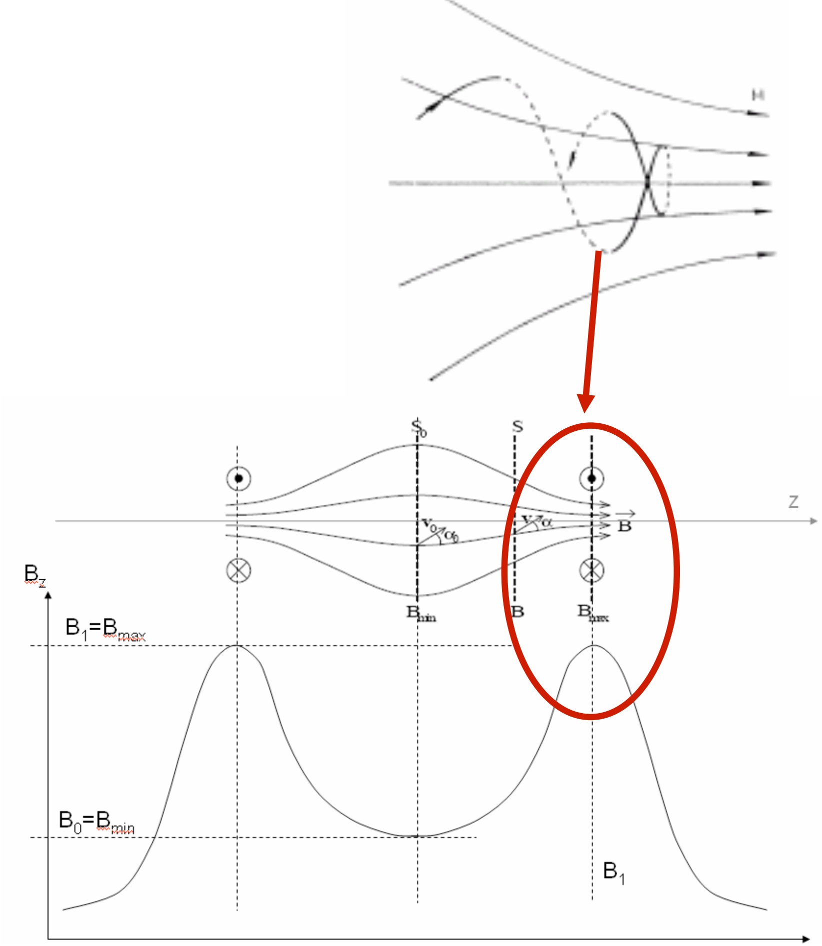
- Demonstration:
  - We assume a local axi-symetric magnetic field which converges toward the z axis with $B_z(z,r) \sim B_z(z)$
    - From $div(\vec{B}) = 0 \rightarrow \frac{1}{r}\frac{\partial(rB_r)}{\partial r} + \frac{\partial B_z(z)}{\partial z} = 0$ (cylindrical coordinate)
    - $\rightarrow d(rB_r) = -\frac{\partial B_z(z)}{\partial z} rdr \rightarrow B_r = -\frac{r}{2}\frac{\partial B_z(z)}{\partial z}$
  - The force acting on a particle rotating around z axis with a Larmor radius $r = \frac{v_\perp}{\omega}$ is:
    - $\vec{F} = q(-v_\perp \vec{e_\theta} + v_\parallel \vec{e_z}) \times (B_r \vec{e_r} + B_z \vec{e_z}) \rightarrow F_z = qv_\perp B_r \rightarrow F_z = -qv_\perp \frac{r}{2}\frac{\partial B_z(z)}{\partial z}$
    - $F_z = -qv_\perp \frac{v_\perp}{2\omega}\frac{\partial B_z(z)}{\partial z} = -\frac{qm}{2qB}{v_\perp}^2 \frac{\partial B_z(z)}{\partial z} = -\frac{m{v_\perp}^2}{2B}\frac{\partial B_z(z)}{\partial z} = -\mu \frac{dB_z(z)}{dz}$
  - The elementary work associated with F_z is $dW_z = dW_\parallel = F_z dz = -\mu dB_z = -\frac{W_\perp}{B_z} dB_z$
  - The kinetic energy constancy implies: $T_{kin} = W_\perp + W_\parallel = const \rightarrow dW_\perp = -dW_\parallel$
- $\frac{dW_\perp}{W_\perp} = \frac{dB_z}{B_z} \rightarrow \mu = \frac{W_\perp}{B_z} = Const$

The Magnetic Mirror Effect

Solar wind reflection by the Earth magnetosphere



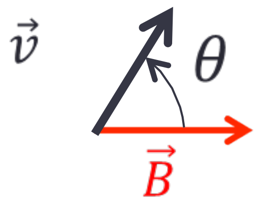
- When a charged particle propagates along z toward a higher magnetic field region, it may be reflected back
  - $T_{kin} = W_{\parallel} + W_{\perp} = \frac{1}{2} m v_{\parallel}^2 + \frac{1}{2} m v_{\perp}^2 = const$
  - $\mu = \frac{m v_{\perp}^2}{2B} = \frac{W_{\perp}}{B} \sim const$
- $T_{kin}(z) = \frac{1}{2} m v_{\parallel}^2(z) + \mu B(z) = const$
  - When B increases, then the velocity is adiabatically transferred from $v_{\parallel}$ to $v_{\perp}$
- The particle is stopped at $z = z_1$ where$(v_{\parallel} = 0)$ and $B(z_1) = \frac{T_{kin}}{\mu}$
  - $T_{kin}(z_1) = \frac{1}{2} m v_{\perp}^2$
- Any perturbation induced by the surrounding particles on the stopped particle will make it go back to where it came from
  => Mirror Effect

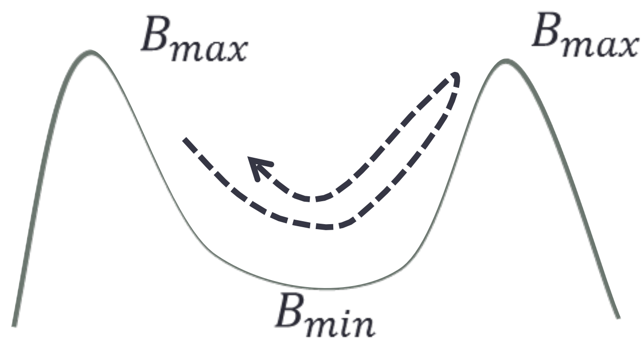


Axial mirror done with a set of 2 coils

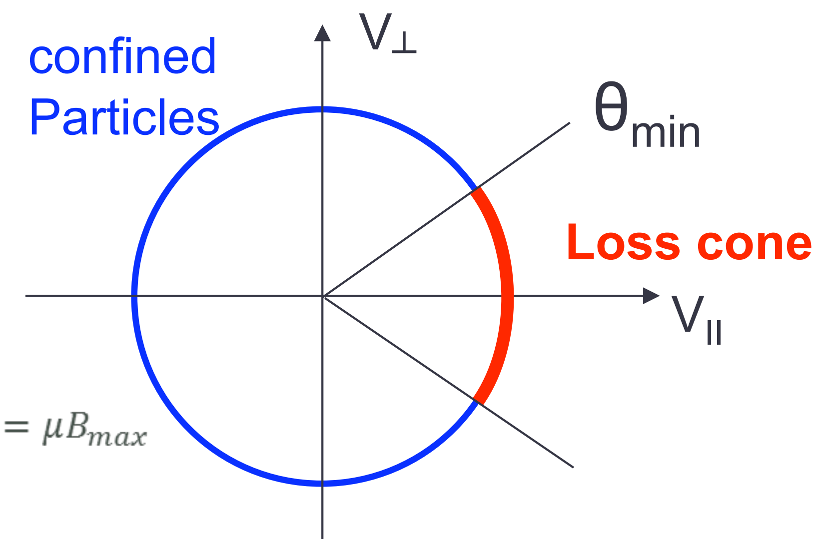
Corrolary of Magnetic Mirroring: The Loss Cone

- The pitch angle θ
  - $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$
  - $v_{\parallel} = v\cos\theta$
  - $v_{\perp} = v\sin\theta$
- $T_{kin} = \frac{1}{2} m {v_{\parallel}}^2 + \mu B$





- The condition to trap a particle in a magnetic mirror from $B = B_{min}$ with a maximum peak at $B = B_{max}$ can be expressed as a function of the mirror ratio R:
- $\begin{cases} \theta \geq \theta_{min} \\ or\ \sin\theta \geq \frac{1}{\sqrt{R}} \\ R = \frac{B_{max}}{B_{min}} \end{cases}$
  - Demonstration:
  - $T_{kin} = \frac{1}{2} m v^2 \cos^2\theta_{min} + \mu B_{min} = \mu B_{max}$
  - $\rightarrow \frac{\cos^2\theta_{min}}{\sin^2\theta_{min}} + 1 = \frac{B_{max}}{B_{min}}$

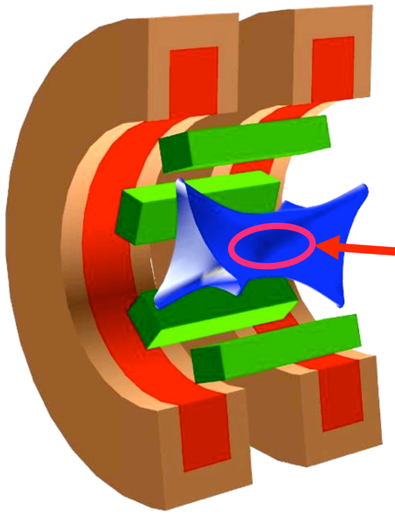


In an ECRIS plasma, The loss cone is perpetually populated By particles interaction (Spitzer)

- Magnetic confinement is not perfect, and it is used to EXTRACT ION BEAMS!

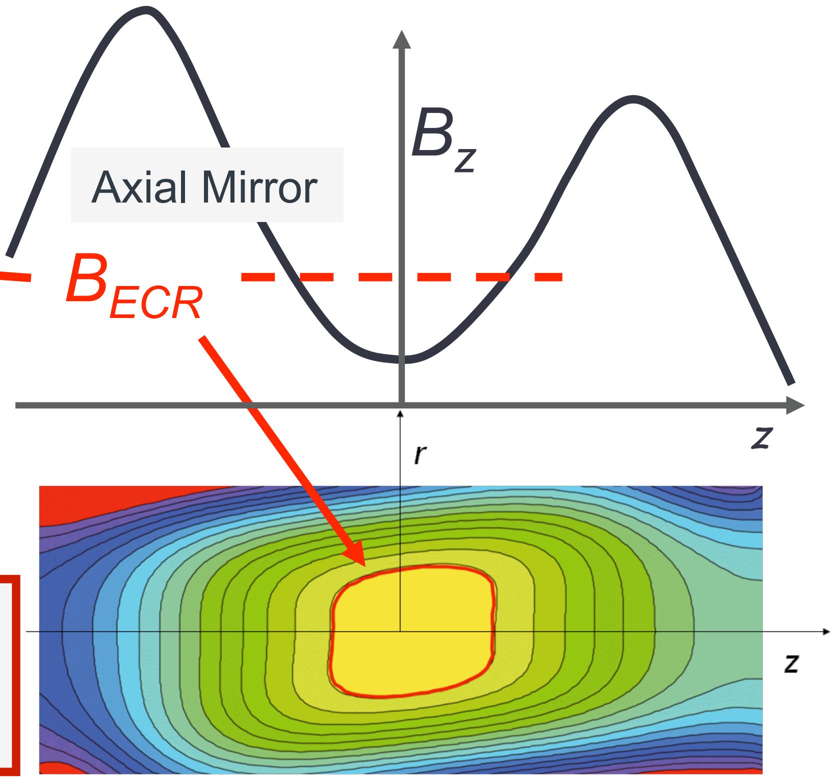
ECR Magnetic confinement: Minimum |B| structure

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



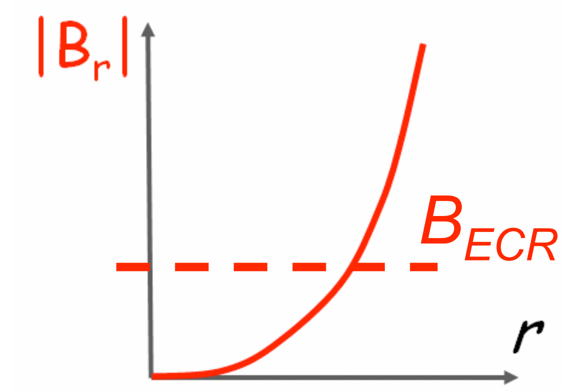
Source LBNL

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

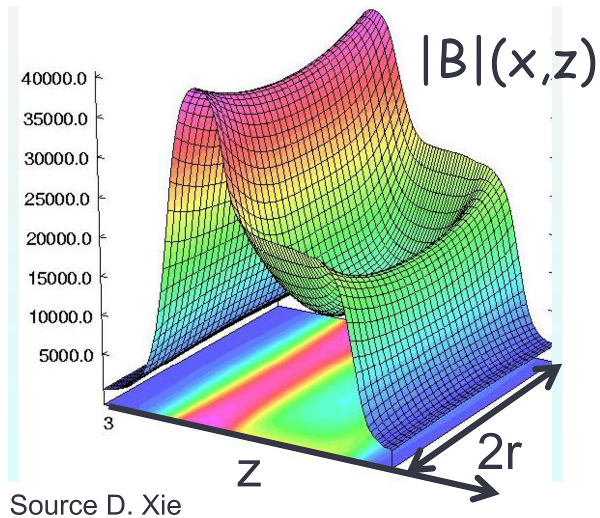


Iso B lines

Source RIKEN, Nakagawa



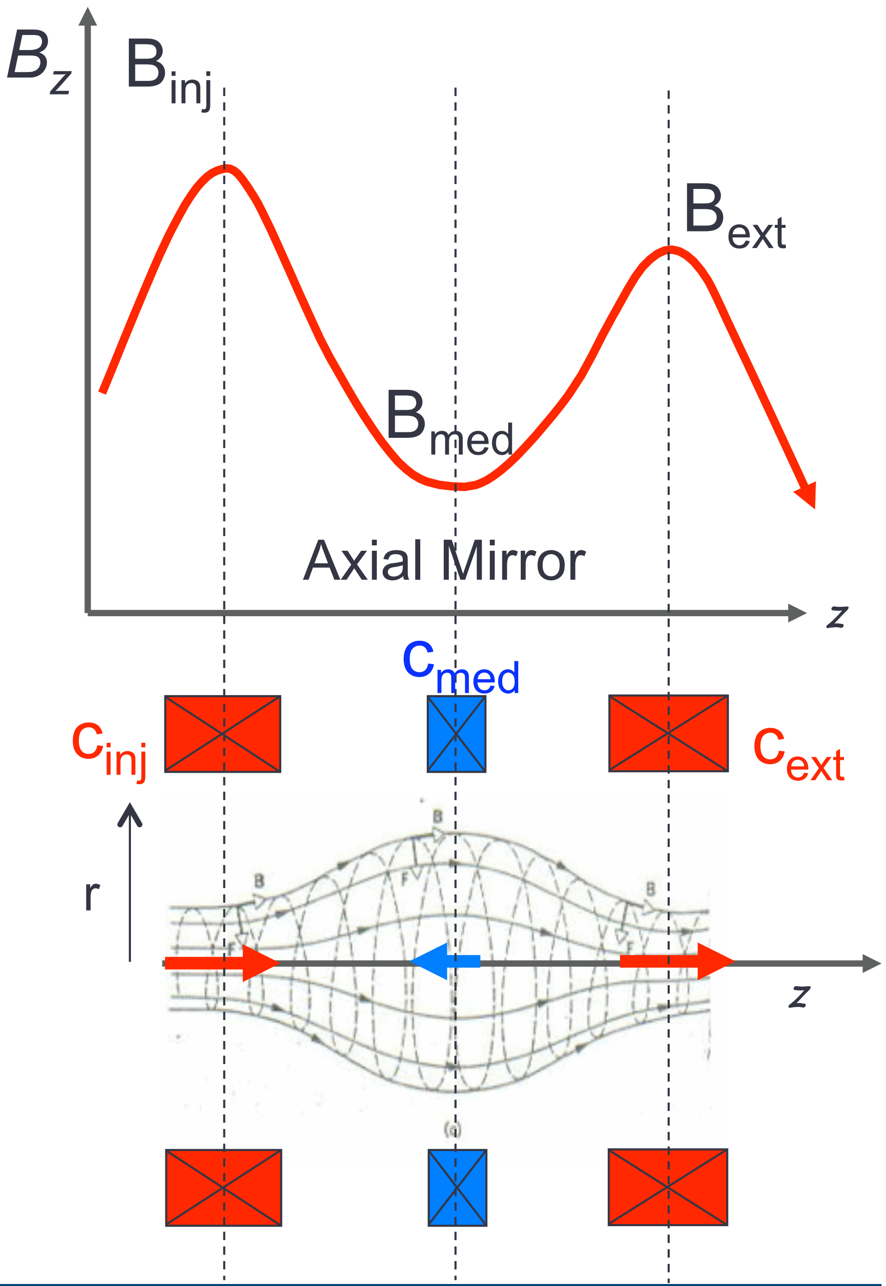
Hexapolar Field



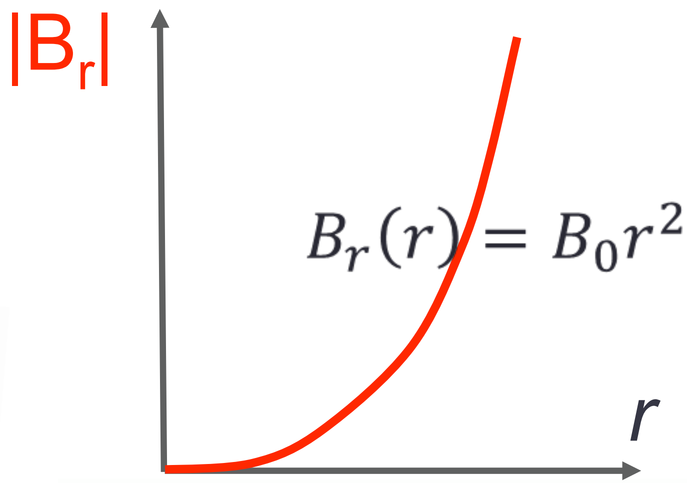
Source D. Xie

Axial Magnetic Confinement

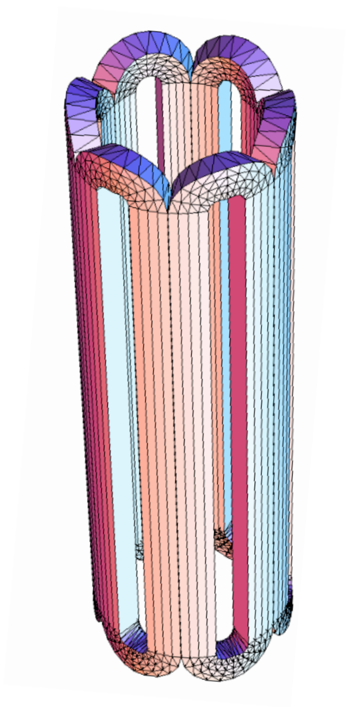
- The axial magnetic confinement in a multicharged ECRIS is usually done with a set of 2 or 3 axial coils.
  - Either room temperature coils + iron to boost the magnetic field
  - Or superconducting coils
- In the case of 3 coils, the current intensity in the middle one is opposed to the others so that 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!



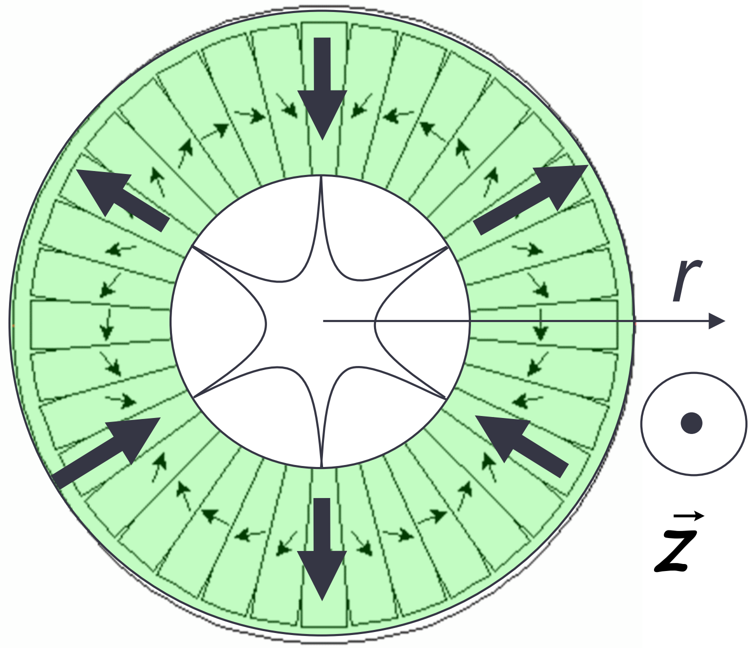
Radial Magnetic Confinement



- 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

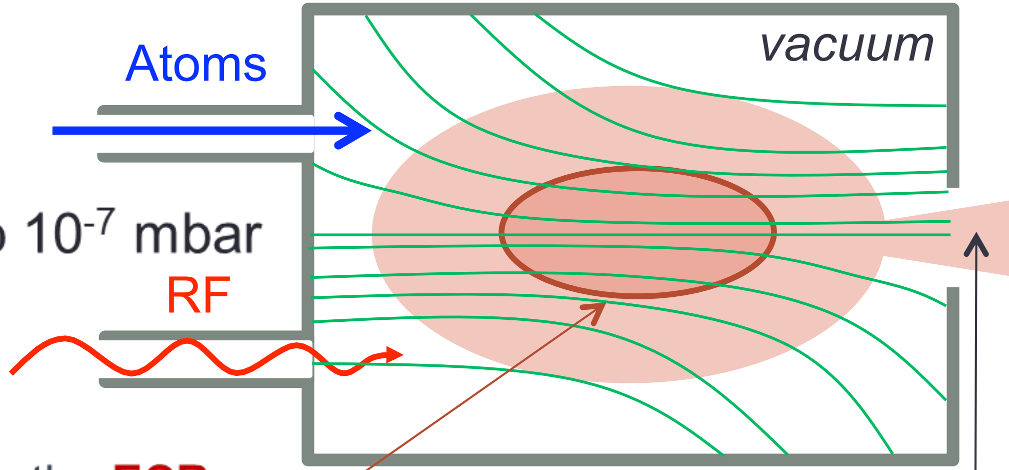


Superconducting hexapolar coil

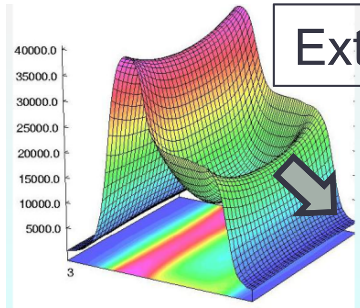


(HallBach Hexapole
With 36 permanent magnets
30° rotation/magnet)

ECR Plasma build up



- Pumping & Gas Injection to reach P~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~1-5 keV), multicharged ions are continuously produced and trapped in the magnetic bottle
  - Ions remains cold in an ECR: kT_i~1/40 eV, (m_e<<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 extraction through the magnetic **loss cone** on the side of the source presenting the minimum magnetic field intensity

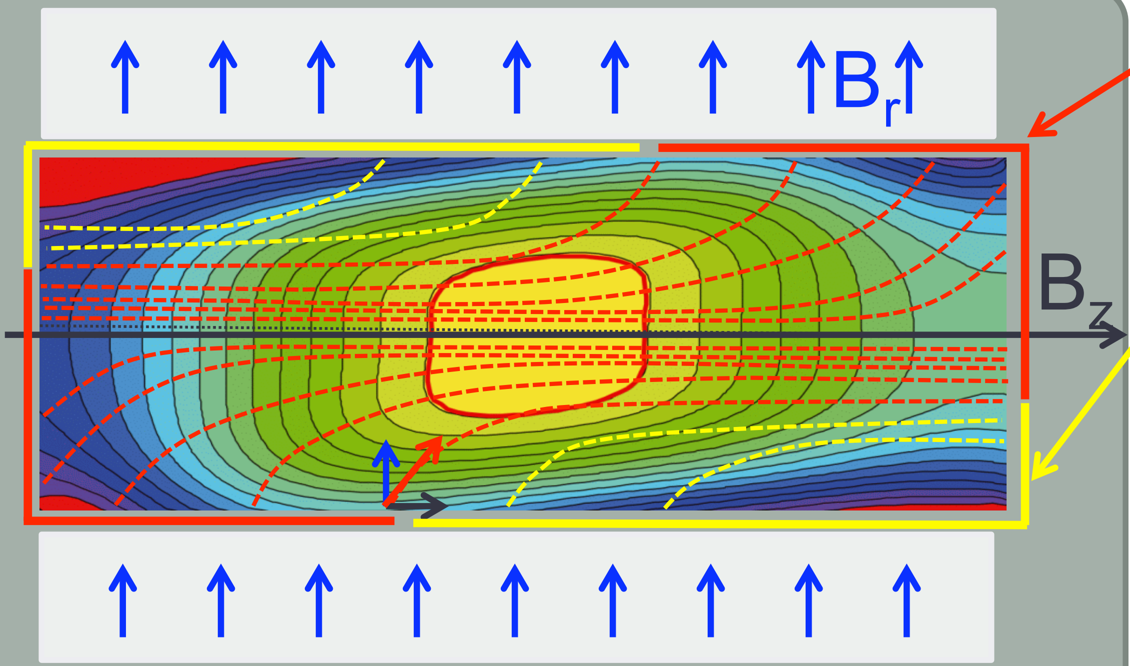
The Famous plasma shape in an ECR Ion Source

- To understand why the ECR plasma ends with 3 lines only, one needs to follow the heated electron through the ECR zone

Photo of ECR plasma from injection (all thickness is superimoosed=> 6 lines) 10+14 GHz heating

HOT ECR ELECTRONS
⇒ High density Plasma
⇒ LIGHT emission
⇒ Tracks on walls

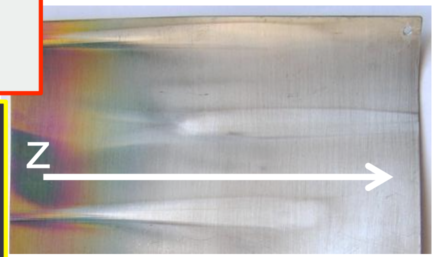
No hot electrons
⇒ Low density Plasma
⇒ No Light emission
⇒ No Tracks on walls



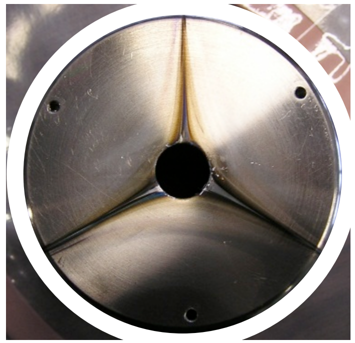
$\vec{B}(r,z) \sim \vec{B}_r(r) + \vec{B}_z(z)$ Near to the wall

$\vec{B}(r,z) \sim \vec{B}_z(z)$ Near to the axis: axial field only

Elevation view from an ECRIS chamber along 2 hexapole poles



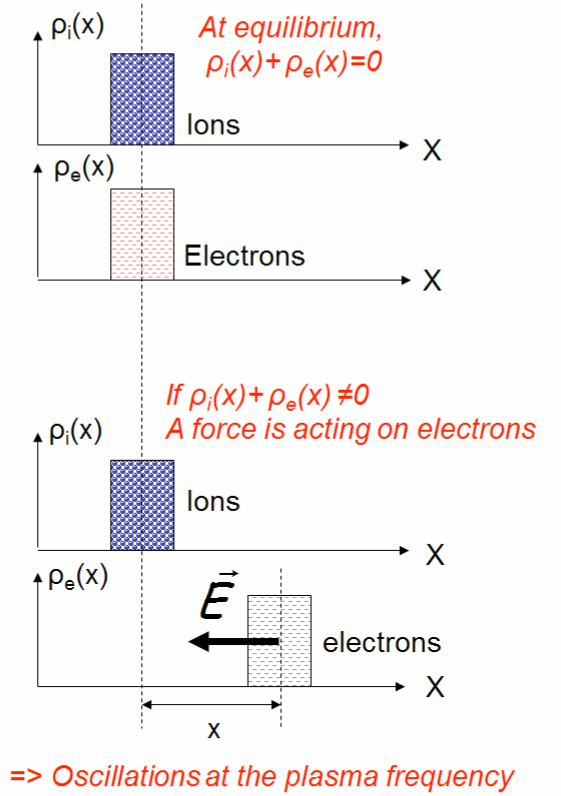
Half unrolled Liner with plasma marks
(3 poles= π only)



Plasma shape at injection (L) and Extraction (R)

Plasma Oscillations – ECR cut off density

- The plasma Frequency ω_p is the natural oscillation frequency of a plasma, as a response to a perturbation
  - Oscillations driven by electrons
  - $\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$
- 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:
  - $\omega > \omega_p \Rightarrow n_e < \frac{m_e \varepsilon_0 \omega^2}{e^2}$
  - At a given ECR frequency, the plasma density is limited
    - $n_e \propto \omega^2{}_{ECR}$



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

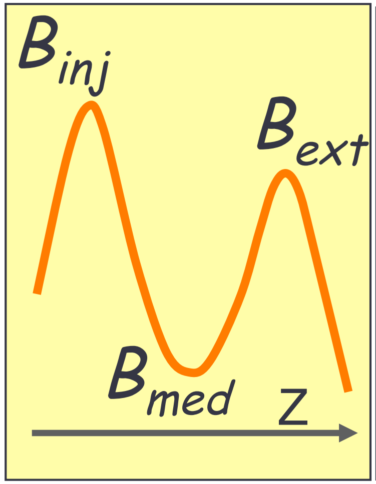
The ECR Scaling law (R. Geller, 1987)

- The higher the frequency, the higher the beam current
- Plasma density $n \sim f^2_{ECR}$
- Beam current $I \sim n \sim f^2_{ECR}$
- But the higher the ECR magnetic field required…
- ECR Magnetic Field $B_{ECR} = \frac{f_{ECR\,[GHz]}}{28}\ Tesla$

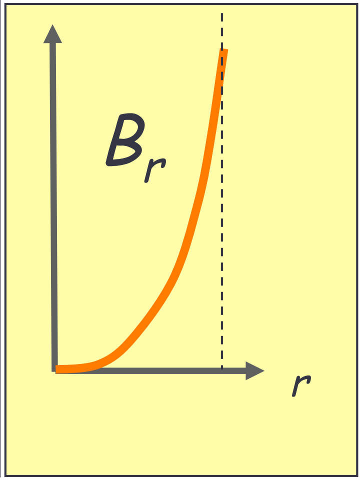
f_{ECR} [GHz]	λ_{ECR} [cm]	n_e [cm^{-3}]	$\Lambda_{0\to1+}$ [cm]	$\tau_{0\to1+}$ [µs]	B_{ECR} [T]
2.45	~12	7.4×10^{10}	~7	~10	0.09
14	~2	2.5×10^{12}	0.2	3	0.5
28	~1	$\sim10^{13}$	0.05	0.7	1
60	~ 0.5	4.4×10^{13}	0.01	0.17	2

The ECR 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



Axial Mirror



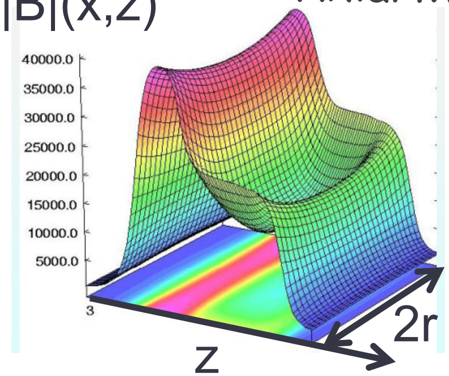
Radial Mirror

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

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 | ?

|B|(x,z)



Source D. Xie