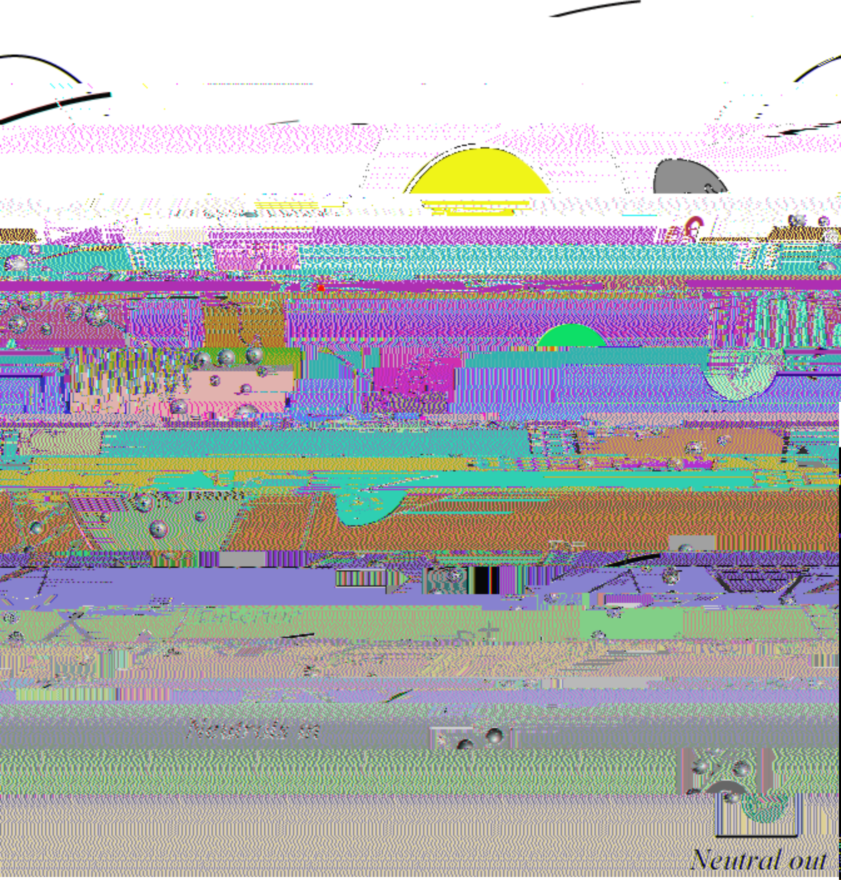
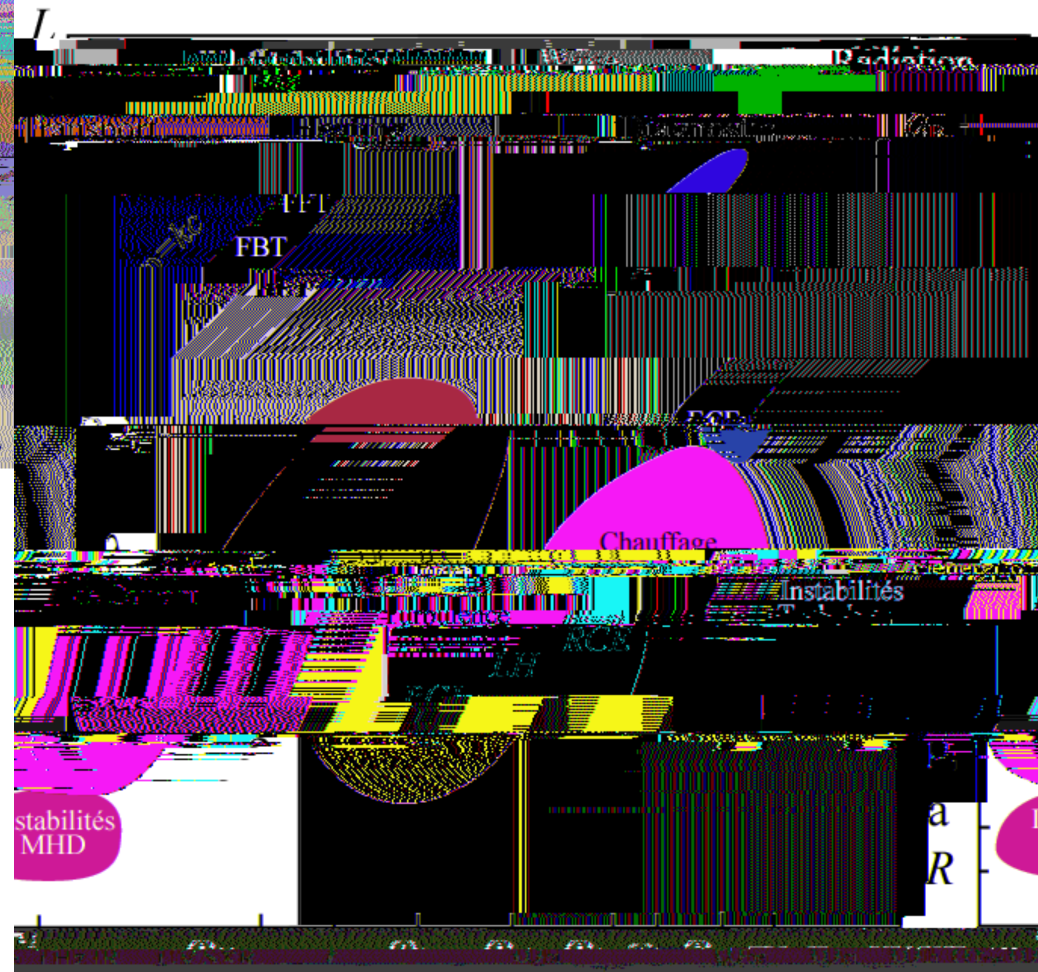
ÉCOLE

Tech

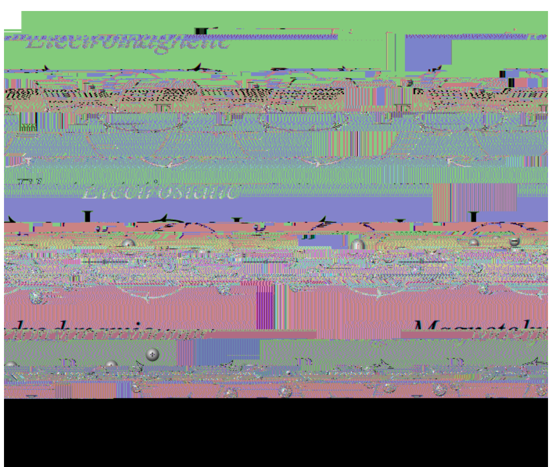

Neutral out


FBT
Chauffage
Instabilités
stabilités
MHD

Physics of Landau and Cyclotron Resonances :

- Active and reactive power
- Plasma resonances
- Resonant interaction
- Random phase approximation RPA
- Quasi linear equation
- Landau absorption
- Cyclotron absorption
- Current generation 1D
- Current generation 2D
- Free energy extraction


Electrons, ions
Absorption
Electric field
Coupling
Antenna
Propagation



Reactive power exchange

$$\frac{d\mathbf{v}}{dt} = \frac{q}{\ldots} \ldots \frac{q}{\ldots}$$

Active power exchange

$$\frac{d\mathbf{v}}{dt} = -\nu\mathbf{v} + \frac{q}{m}\mathbf{E}\exp(-j\omega t) \qquad \langle \mathbf{v}\cdot\mathbf{E}\rangle_t \neq 0$$

$k_\parallel v_\parallel - \omega \ll 0$

$k_\parallel v_\parallel - \omega \gg 0$

Resonant collisionless power exchange

$k_\parallel v_\parallel - \omega \approx 0$

$$\frac{dv_\parallel}{\ldots} = \frac{q}{\ldots} E \ldots \frac{q}{\ldots} \frac{E}{\ldots} \ldots$$

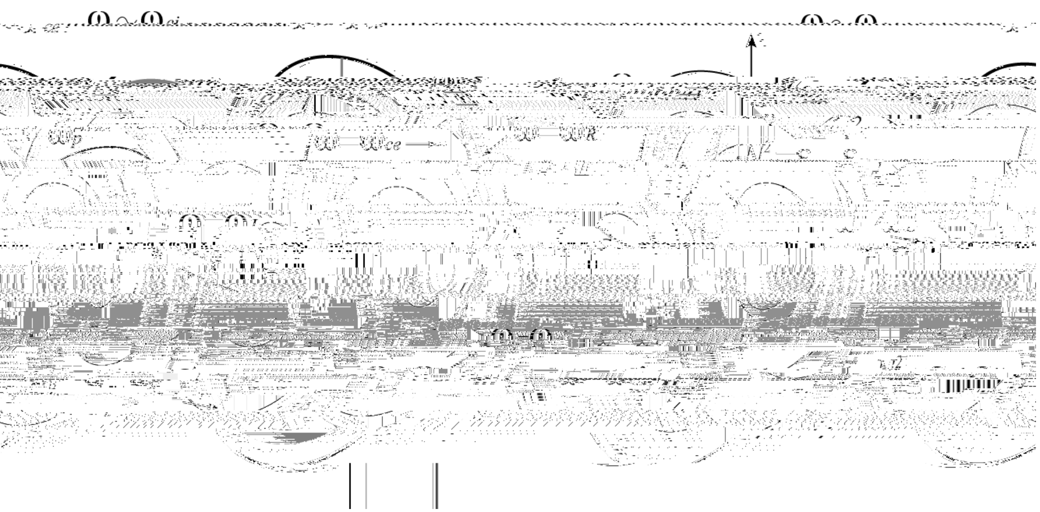
Cold Plasma Resonances

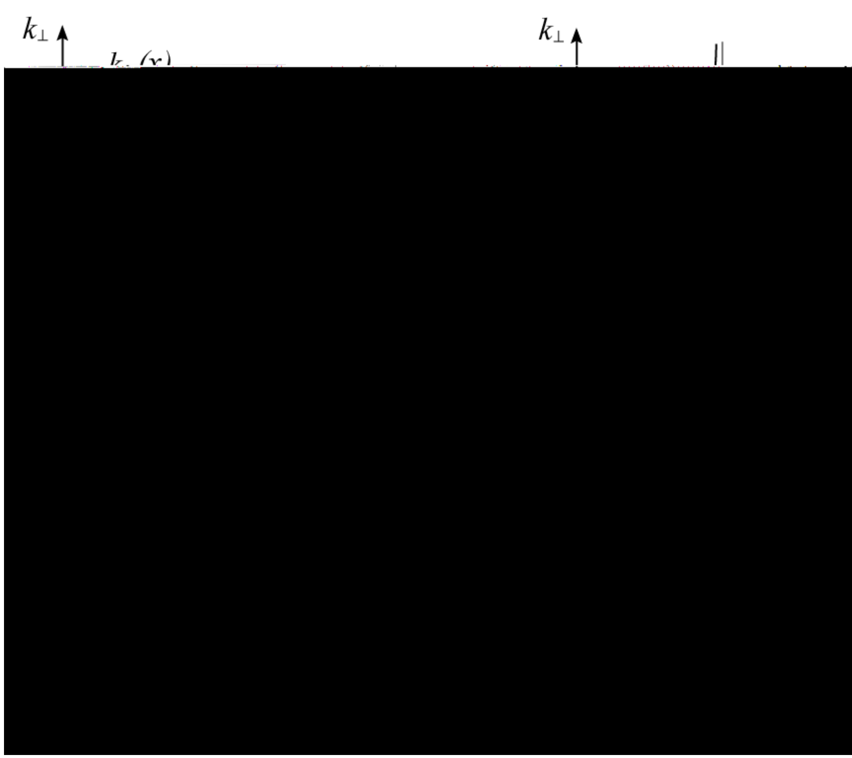
$$\begin{vmatrix} \varepsilon_\perp - N_\parallel^2 & -j\varepsilon_\times & N_\perp N_\parallel \\ j\varepsilon_\times & \varepsilon_\perp - N_\parallel^2 - N_\perp^2 & 0 \\ \dots & \dots & \dots \end{vmatrix} = 0$$

$$\left(\varepsilon_\perp + \varepsilon_\parallel\right)\left(\varepsilon_\perp - N_\parallel^2\right) - \varepsilon \dots$$

Cutoffs: ... = 0 — Resonances: ... = 0

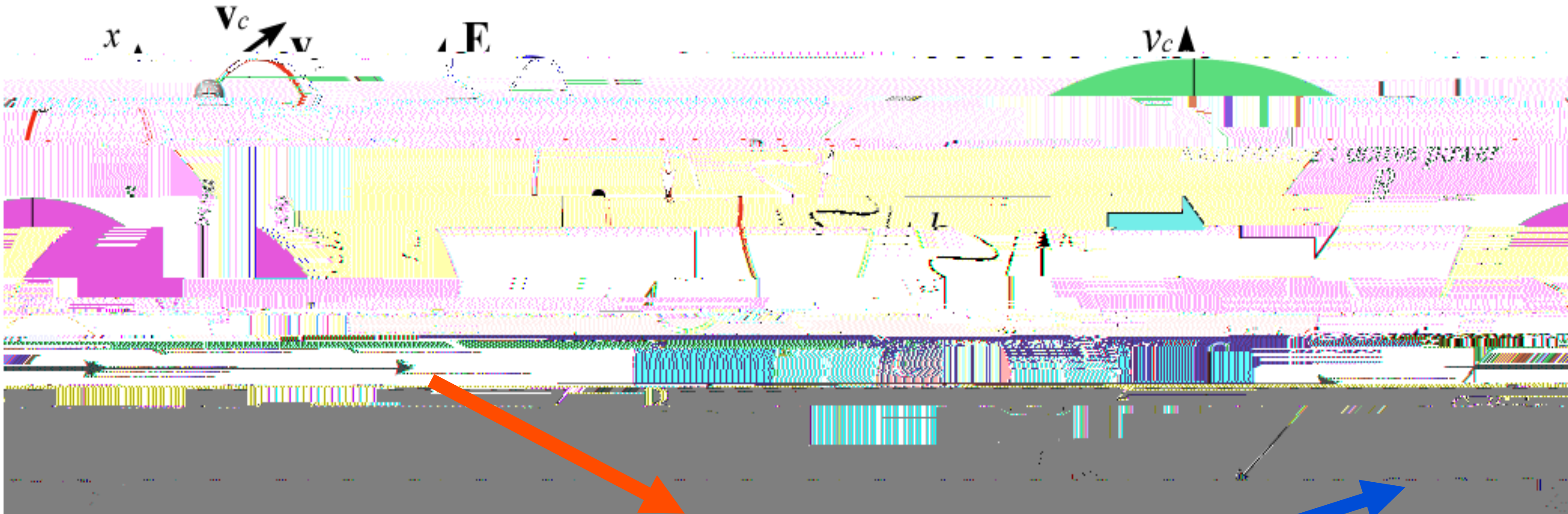
Conversion of active power — Localisation of reactive power





Resonant Absorption

Waves - Particles Resonances



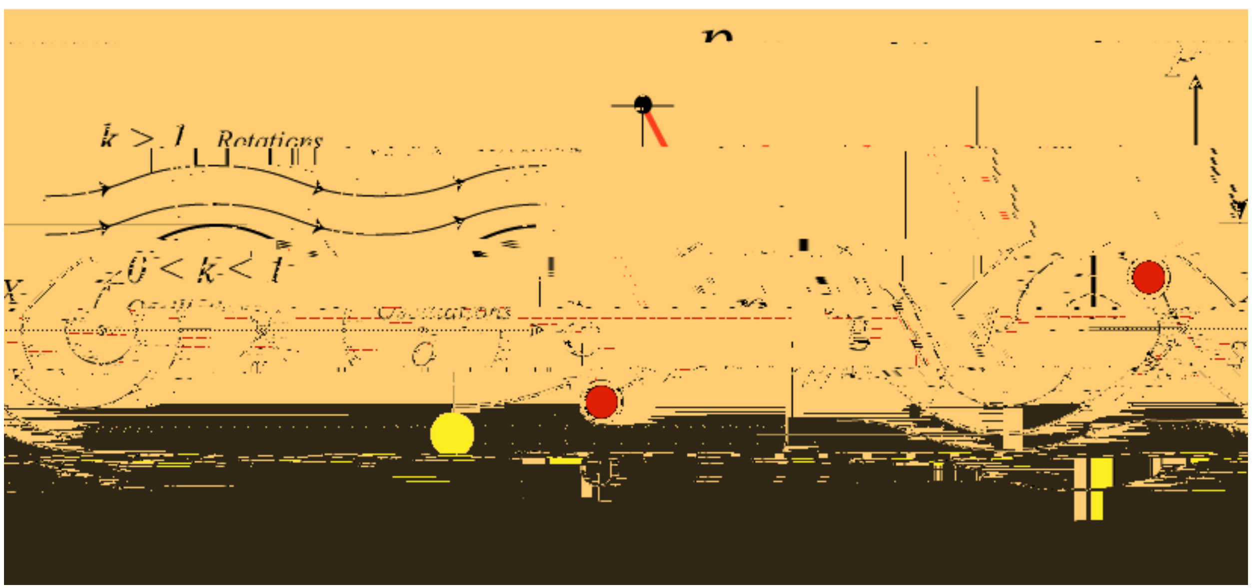
Landau Resonances $\omega = k_{\|} v_{\|}$

Cyclotron Resonances $\omega - k_{\|} v_{\|} = n\omega_c$

$$\frac{d\varphi}{dt} = I - \omega_0$$

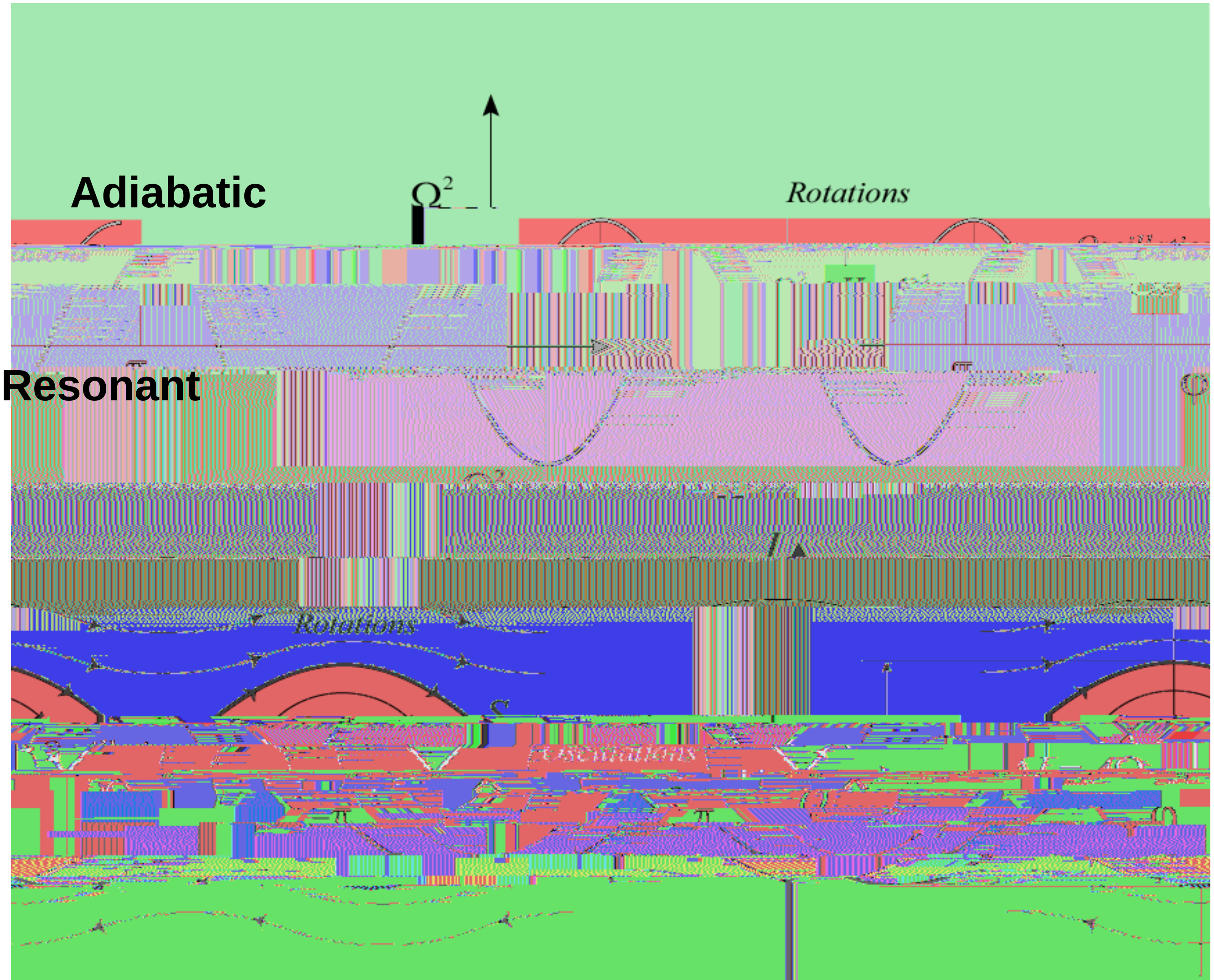
Potential : $E = \Omega^2 \cos\varphi$ Kinetic : $E = (I - \omega_0)^2$

Nonlinear pendulum



Nonlinear pendulum

Potential : $E = \Omega^2 \cos\psi$ Kinetic : $E = (I - \omega_0)^2$

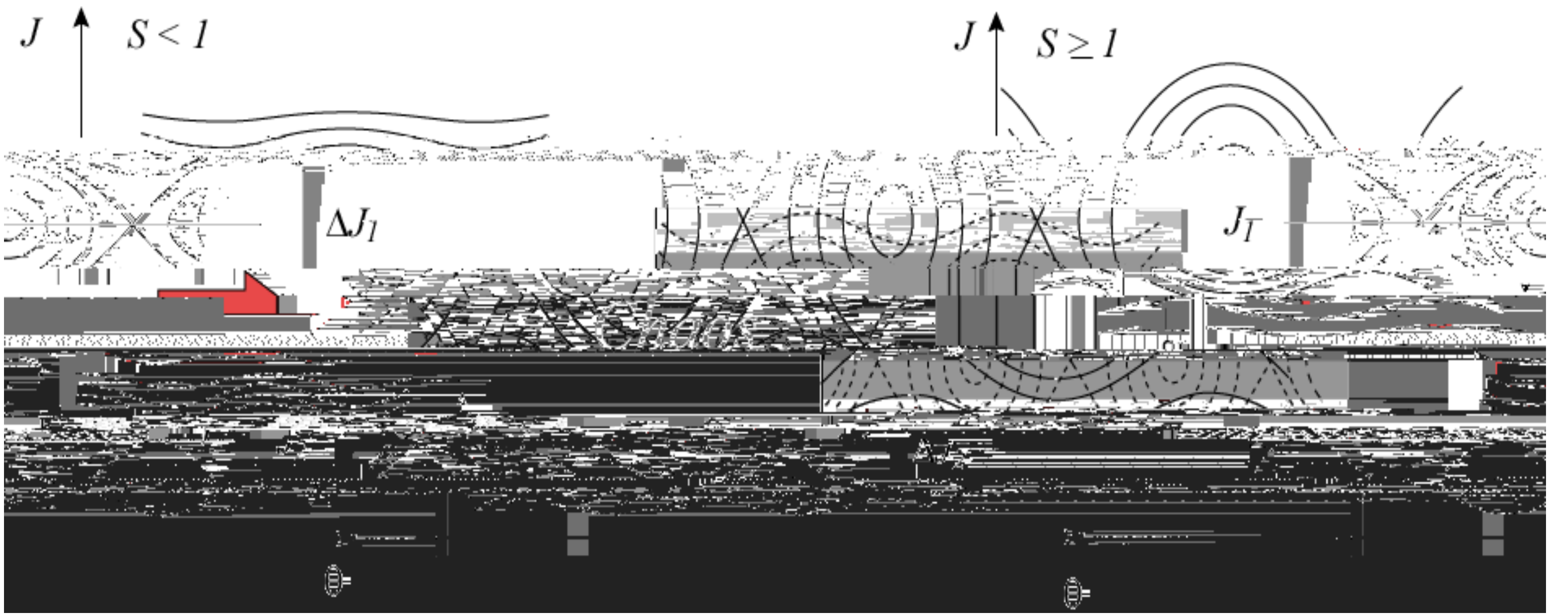


[redacted]

1st order

[redacted]

2nd order



Resonance

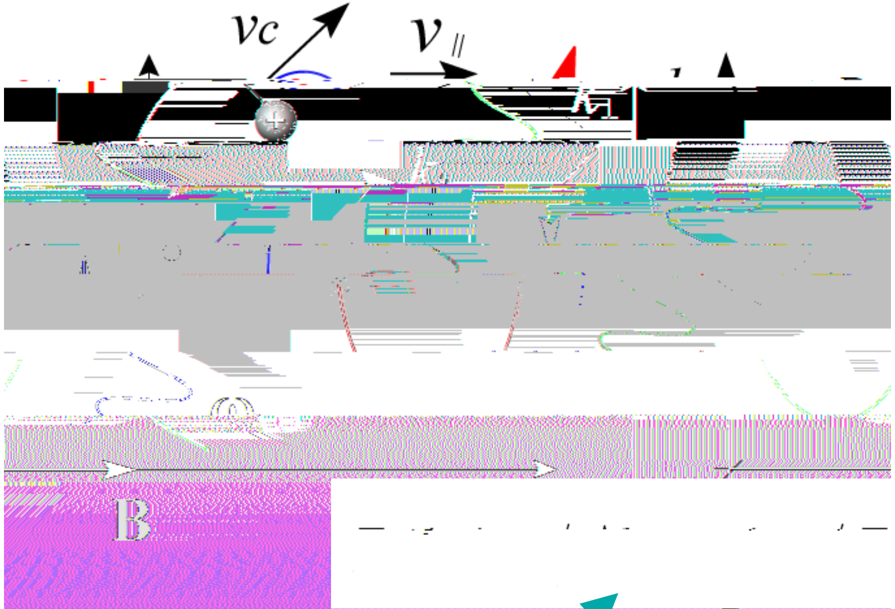
Resonances

Chaos

Random Walk

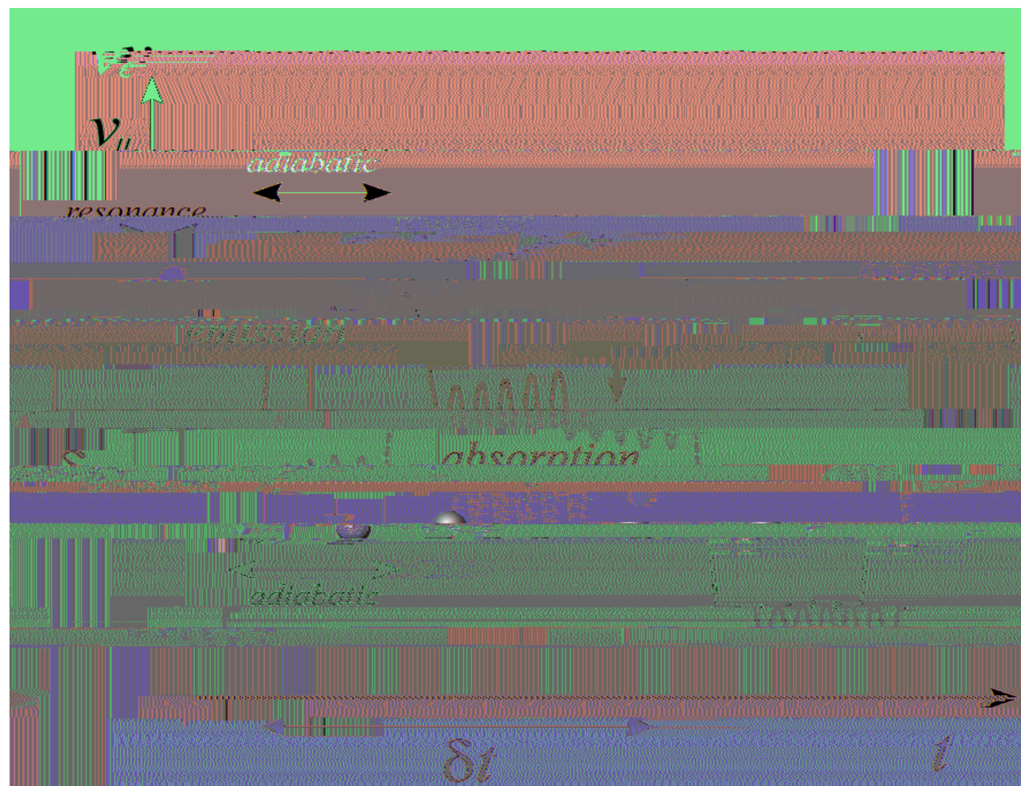
RPA

Quasilinear theory

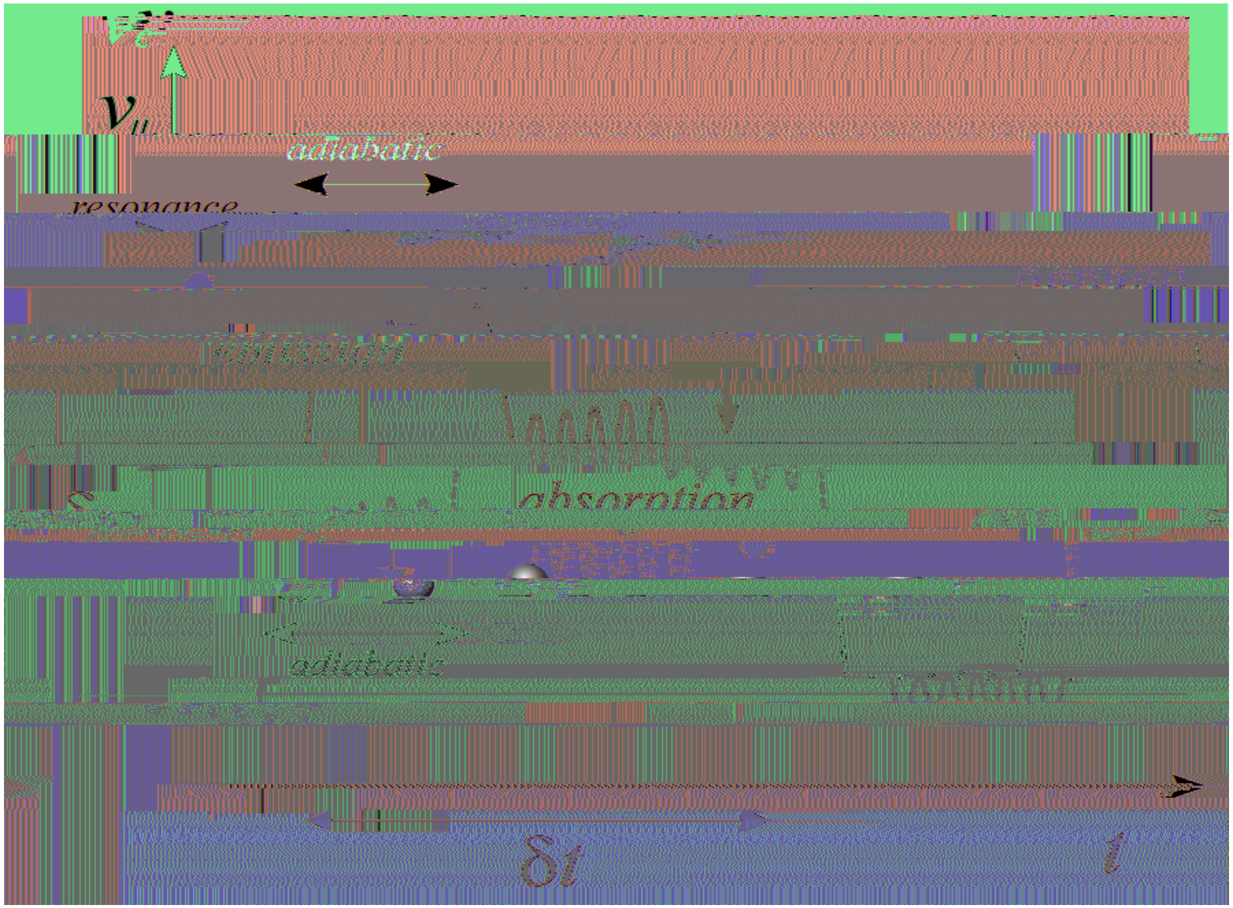


v_c
$v_{\parallel}$
B

RPA

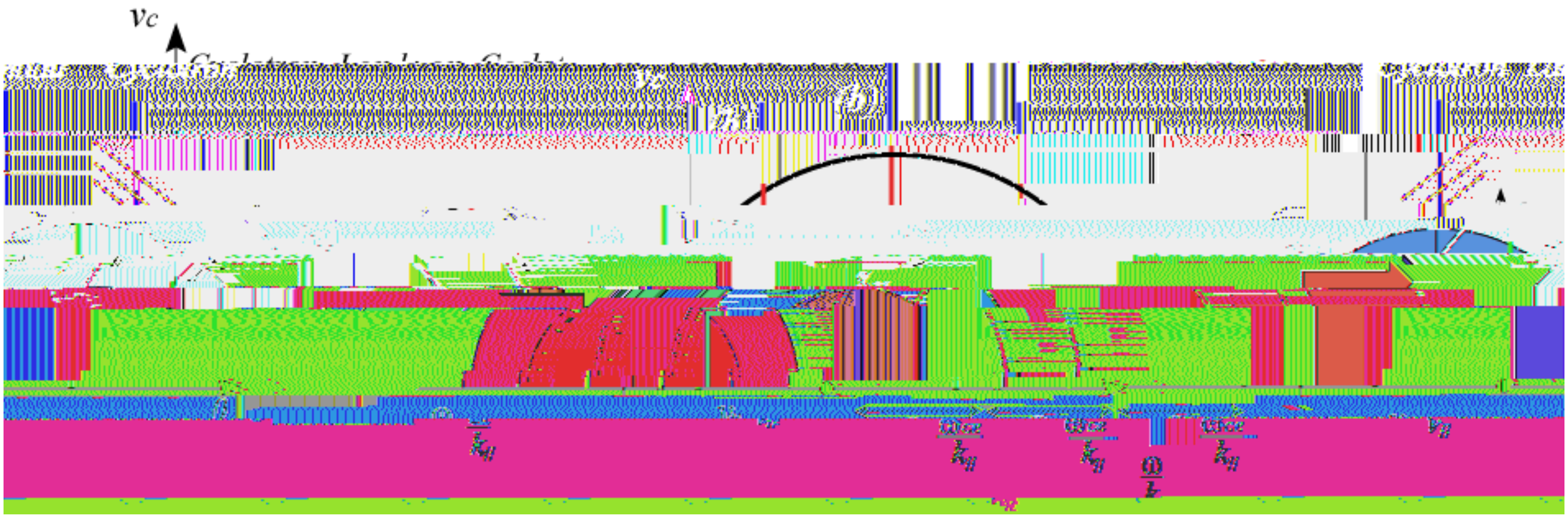


$v_{\parallel}$
adiabatic
resonance
emission
absorption
adiabatic
δt
t

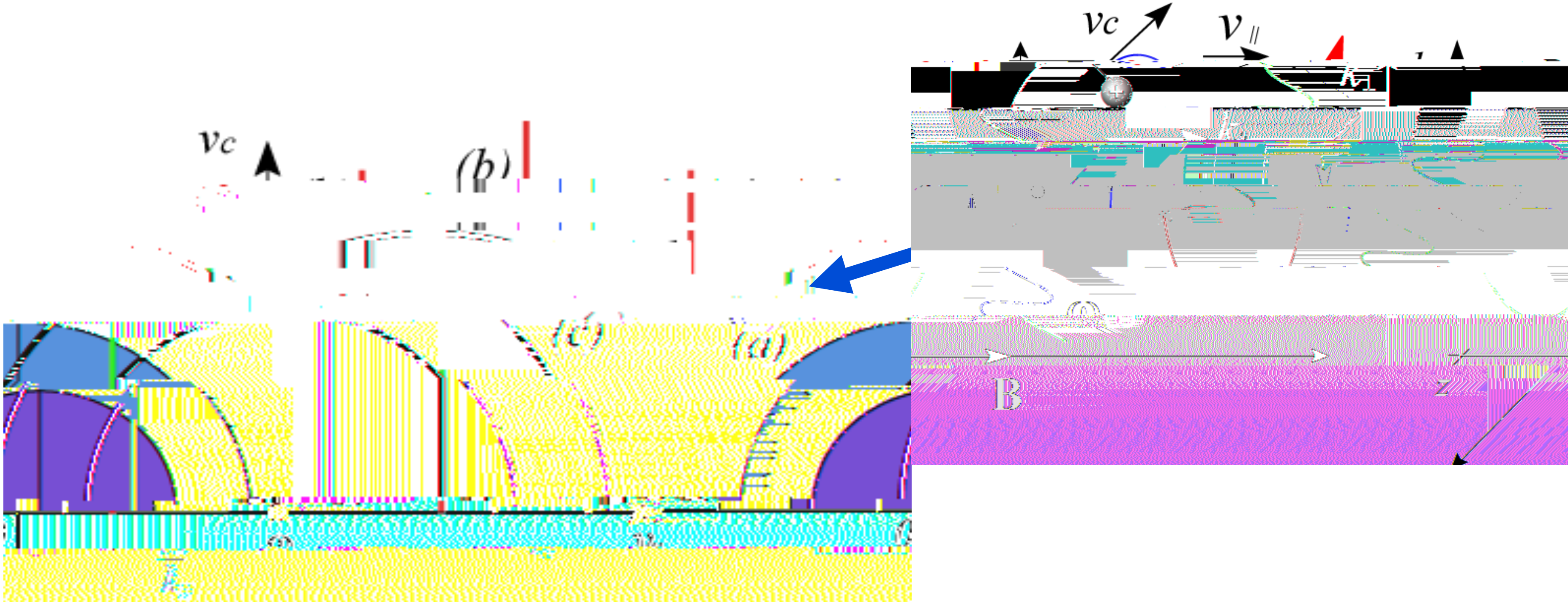


$v_{\parallel}$
adiabatic
resonance
emission
absorption
adiabatic
δt
t

RPA



vc



Resonance curves (b): $\omega = N\omega_c + k_\parallel v_\parallel$

Quasi linear equation

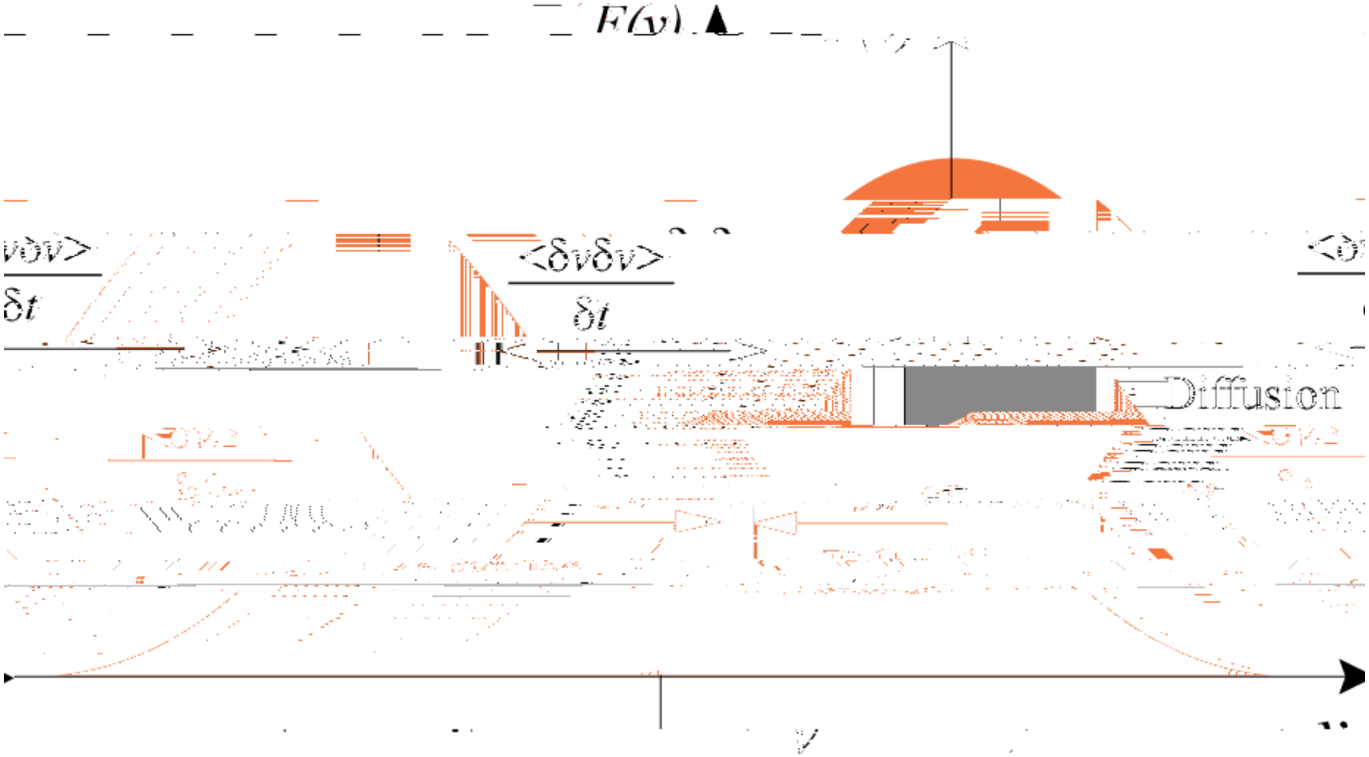
$$\frac{\partial F(\mathbf{v},t)}{\partial t} = \int \left[w(\mathbf{v} \leftarrow \mathbf{v}+\mathbf{x}) F(\mathbf{v}+\mathbf{x},t) - w(\mathbf{v}+\mathbf{x} \leftarrow \mathbf{v}) F(\mathbf{v},t) \right] d\mathbf{x}$$

$$\frac{\partial F(\mathbf{v},t)}{\partial t} = \int \left[w(\mathbf{v} \leftarrow \mathbf{v}+\mathbf{x}) F(\mathbf{v}+\mathbf{x},t) - w(\mathbf{v}+\mathbf{x} \leftarrow \mathbf{v}) F(\mathbf{v},t) \right] d\mathbf{x}$$

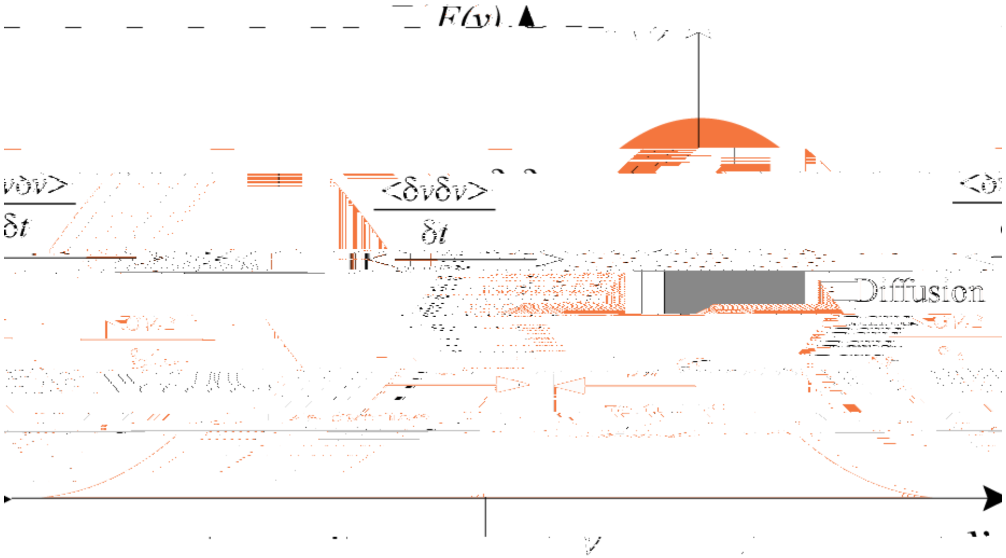
$$w(\mathbf{v} \leftarrow \mathbf{v}+\mathbf{x}) F(\mathbf{v}+\mathbf{x}) = w(\mathbf{v}-\mathbf{x} \leftarrow \mathbf{v}) F(\mathbf{v}) \ldots$$

Taylor : Kramer-Moyal

$$\int d\mathbf{x} \left[w(\mathbf{v}-\mathbf{x} \leftarrow \mathbf{v}) - w(\mathbf{v}+\mathbf{x} \leftarrow \mathbf{v}) \right] = 0$$



$$\frac{\partial F(v,t)}{\partial t} = \frac{\partial}{\partial v}\left[\langle \delta v \rangle \; [illegible] \; \frac{\partial}{\partial v} \langle \delta v \delta v \rangle \; [illegible] \right]$$

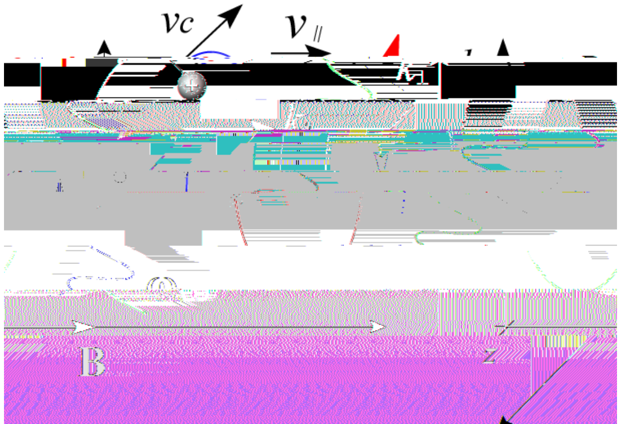


$$Microreversibility:\ w(\mathbf{v}+\mathbf{x}\leftarrow\mathbf{v}) = w(\mathbf{v}\leftarrow\mathbf{v}+\mathbf{x})$$

$$\frac{1}{2}\int \mathbf{x}w(\mathbf{v}+\mathbf{x}\leftarrow\mathbf{v})\,d\mathbf{x}-\frac{1}{2}\int \mathbf{x}w(\mathbf{v}-\mathbf{x}\leftarrow\mathbf{v})\,d\mathbf{x} \qquad \frac{\langle\delta\mathbf{v}\rangle}{\delta t} =$$

$$1 \int \quad \partial w(\mathbf{v}-\mathbf{x}\leftarrow\mathbf{v})$$

$$\textit{Einstein Relation:}\ \frac{\partial}{\partial \mathbf{v}} \cdot \frac{\langle \delta \mathbf{v} \delta \mathbf{v} \rangle}{2 \delta t} = \frac{\langle \delta \mathbf{v} \rangle}{\delta t}$$

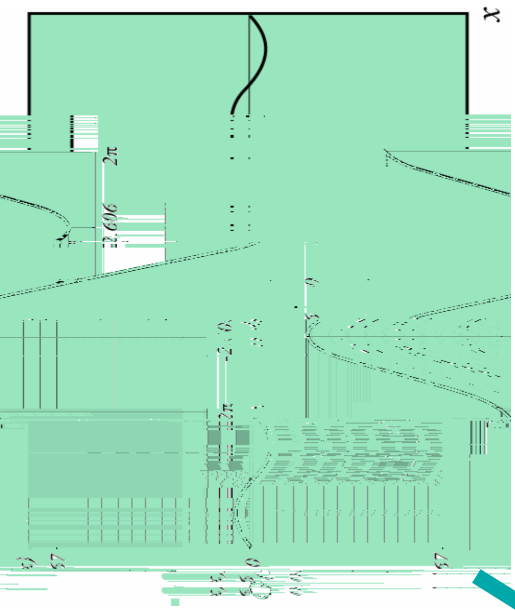


RPA

$$\frac{dv_\parallel}{\;} \qquad q \;\; d$$

$$v' = v_\parallel - \omega/k_\parallel$$

$$v' = v_\parallel - \omega/k_\parallel$$

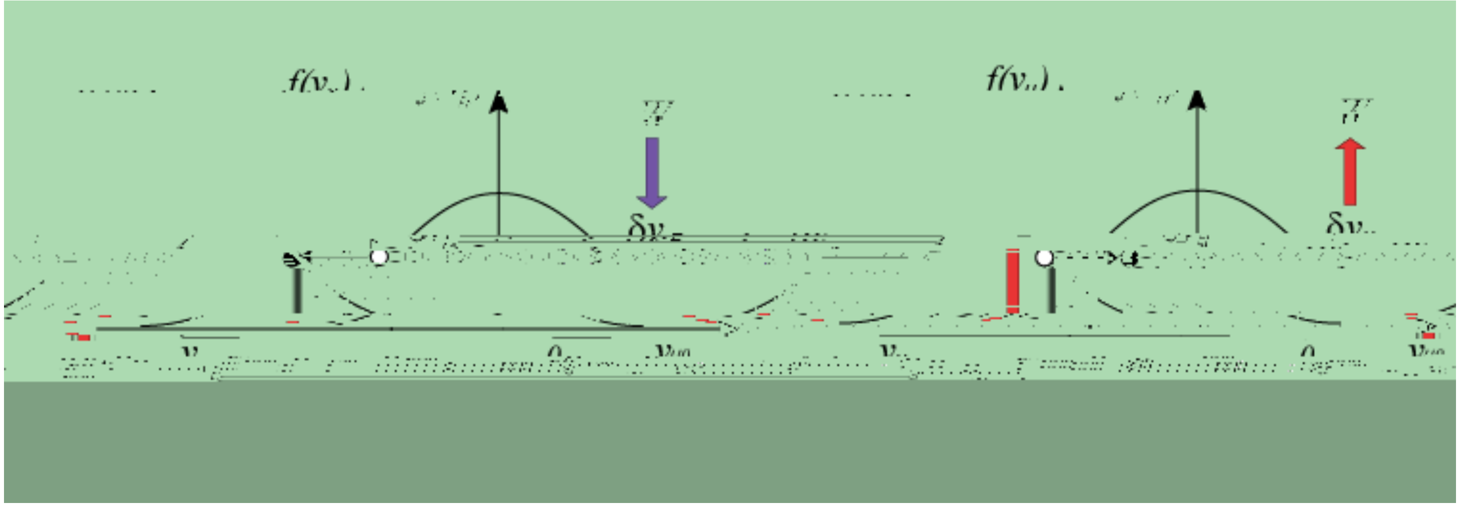


$k_\parallel v_\parallel - \omega \gg$

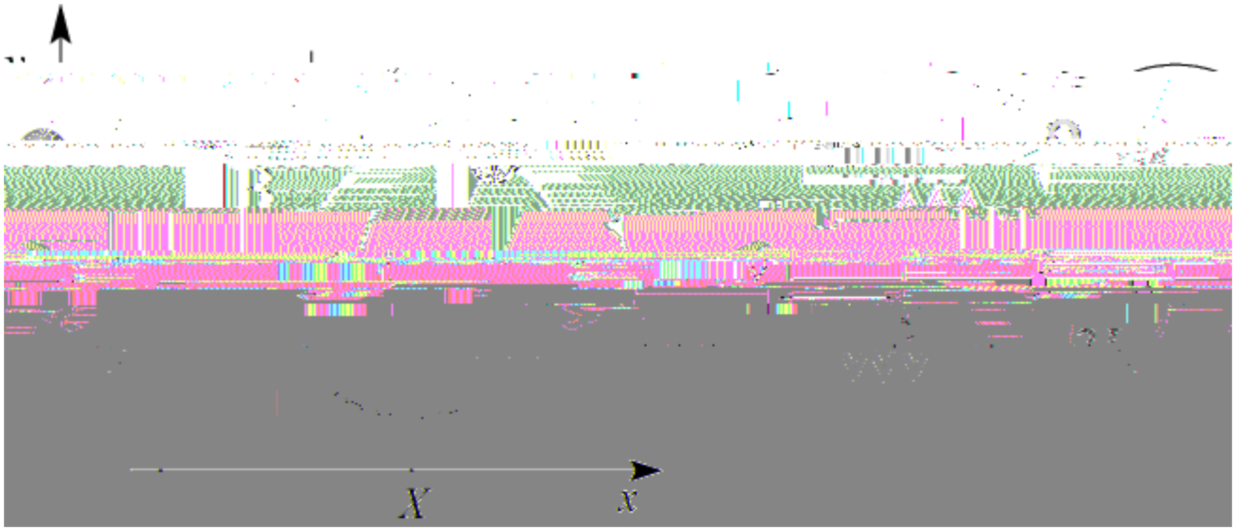
$k_\parallel v_\parallel - \omega \approx 0$

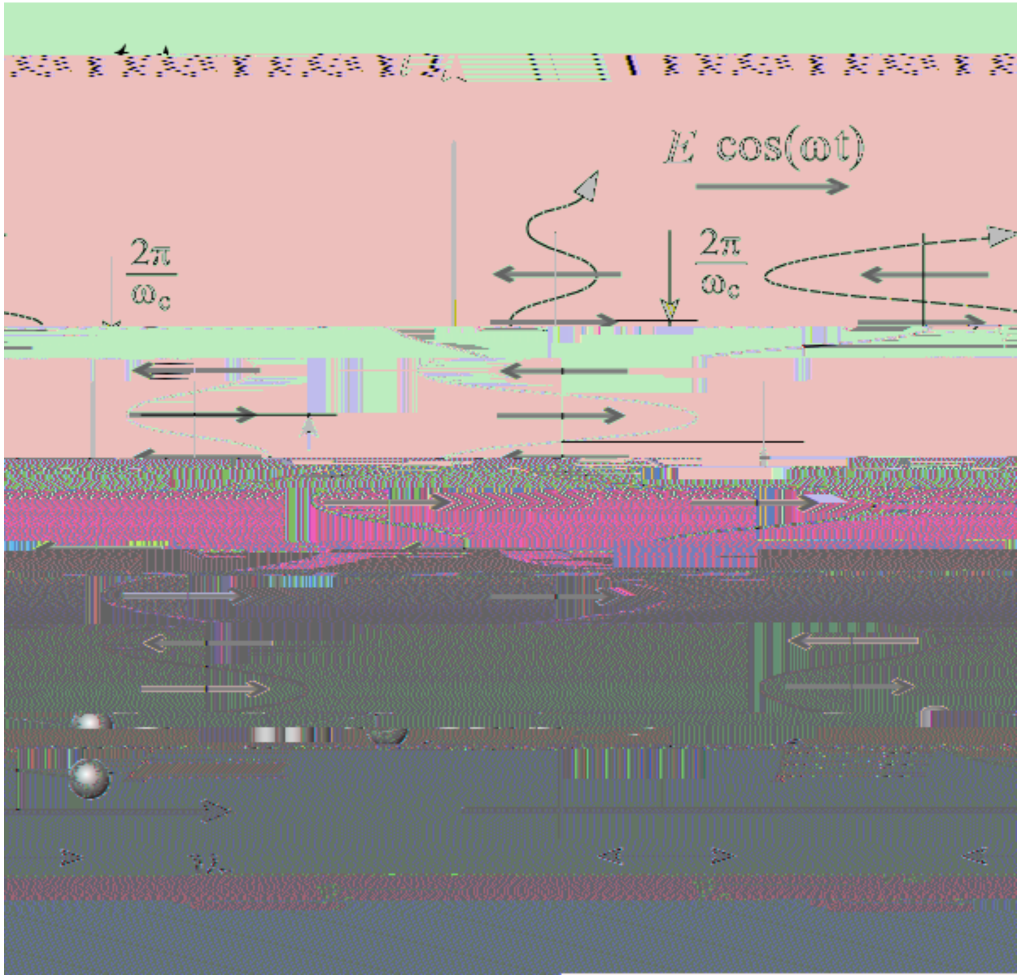
$k_\parallel v_\parallel - \omega \ll 0$

$\epsilon \sin^2(x/\epsilon)/x^2 \xrightarrow{\epsilon \to 0} \pi\delta(x)$



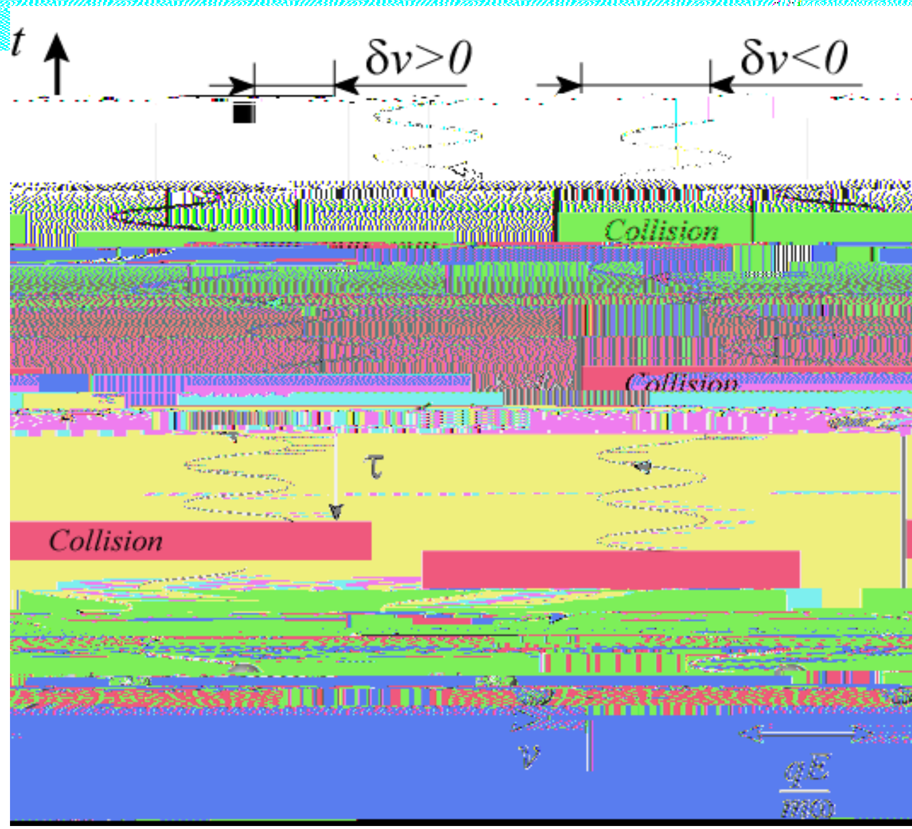
Cyclotron absorption




E cos(ωt)
2π/ωc
2π/ωc

Inverse Bremsstrahlung

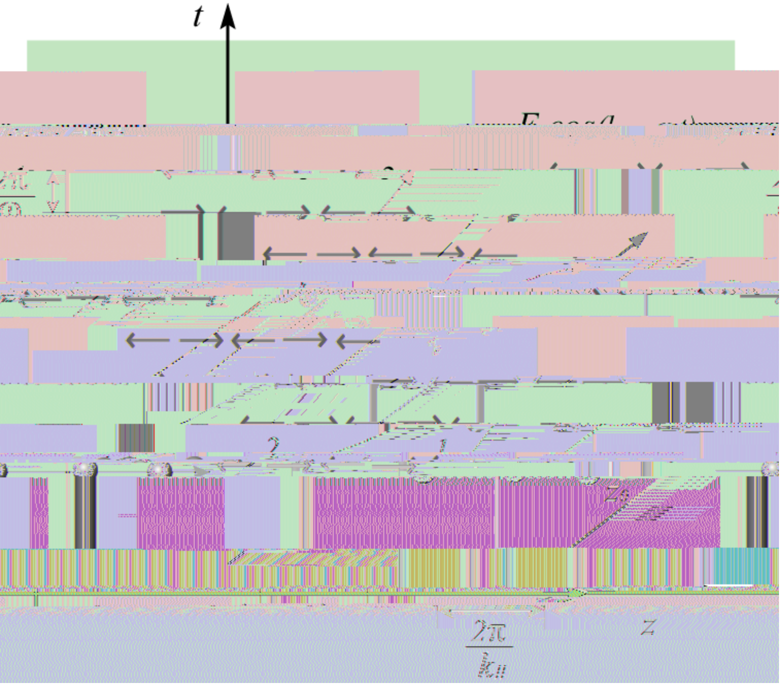
$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}\mathbf{E}\sin(\omega t) + \sum_n \delta(t-\tau_n)\,\delta\mathbf{v}$$

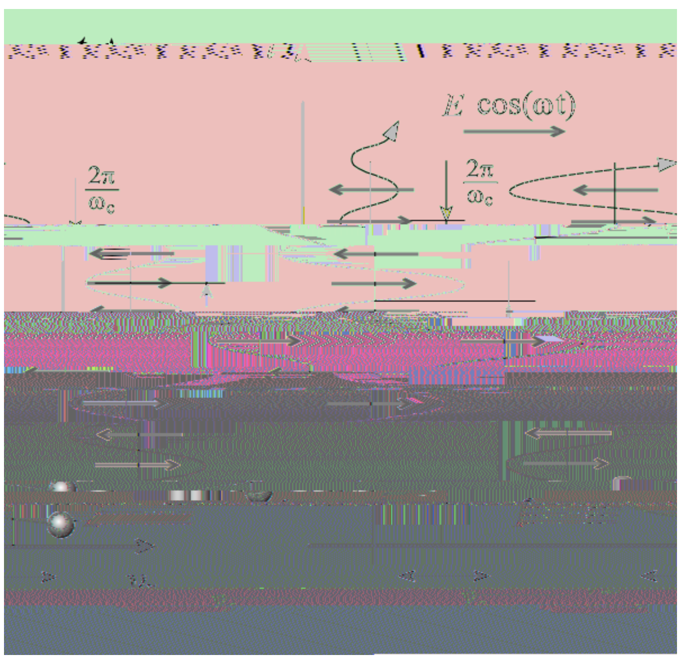


$$\frac{d\mathbf{v}}{dt} = \gamma \mathbf{F}\sin(\omega t) + \sum_n \delta(t-\tau_n)\,\delta\mathbf{v}$$

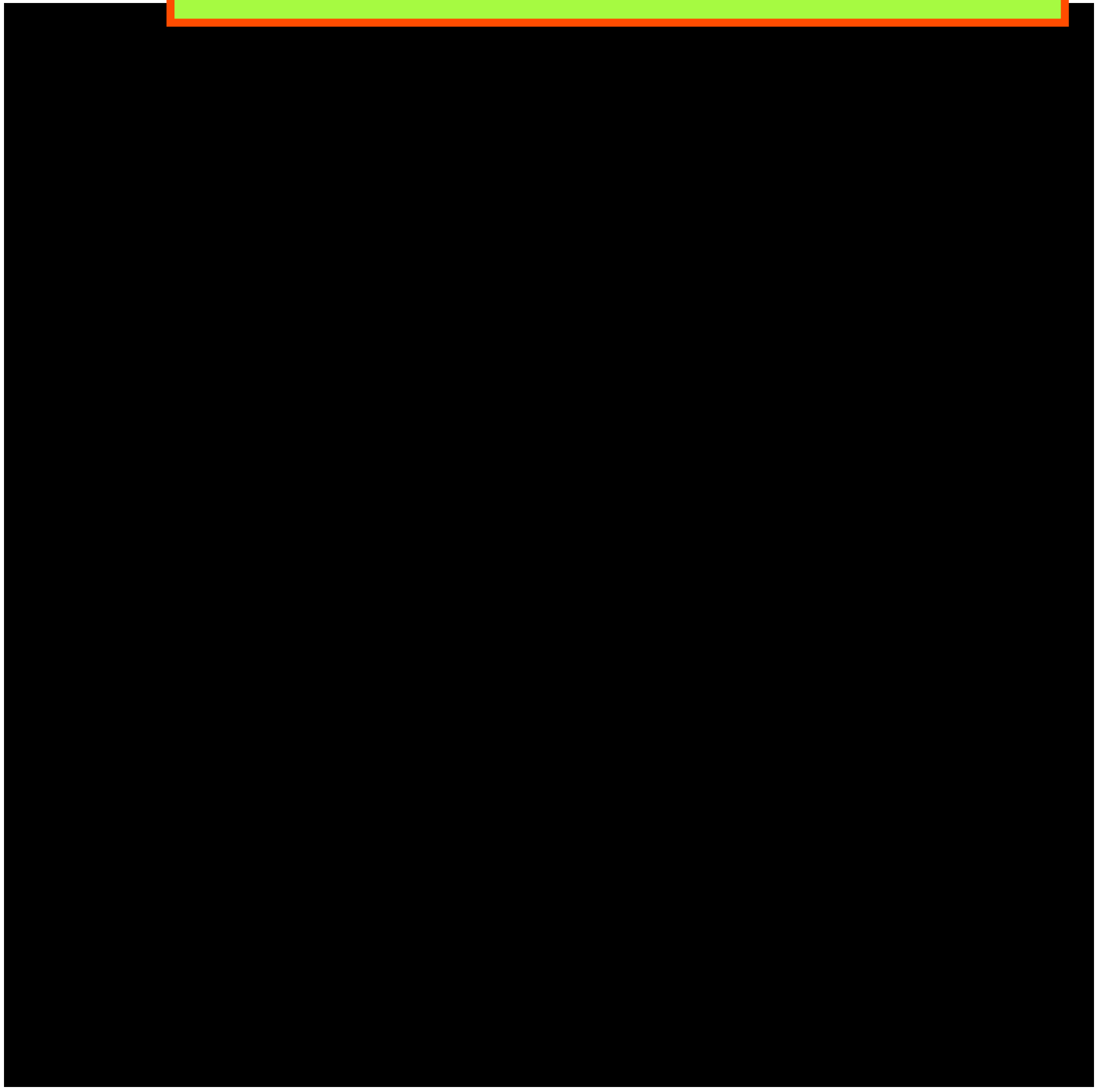
[redacted]

$\cos a - \cos b =$

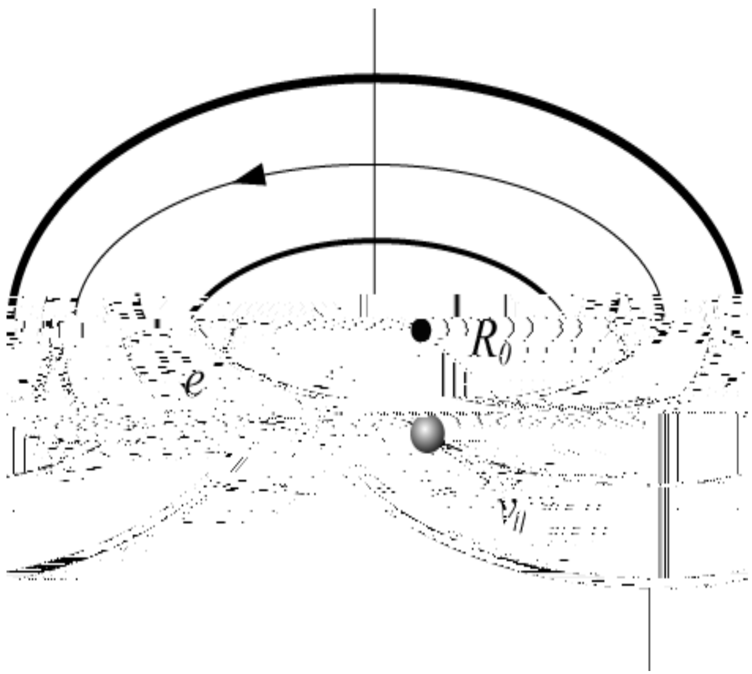




Finite Larmor radius effect :



Current Generation



$$\frac{ev_{\|}}{2\pi R}$$

Thermoélectric effect

Spitzer Conductivity

$$\mu_{\|} = \left| \frac{e}{m_e \nu_e} \right|$$

$T^{\frac{3}{2}}$

[redacted]

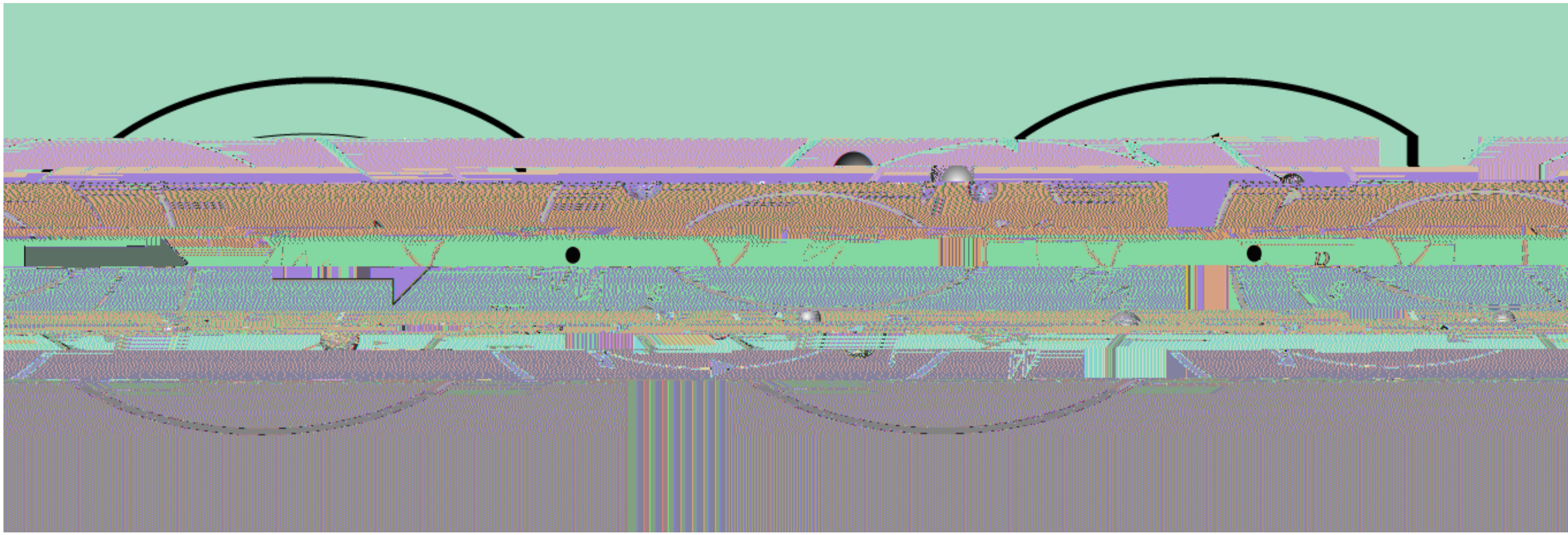
$\left[\quad \left(s \right) \right]$

$\oint \quad T_e^{\frac{5}{2}} \nabla_{\parallel} \ln n_e ds \quad 5T_e^{\frac{5}{2}}$

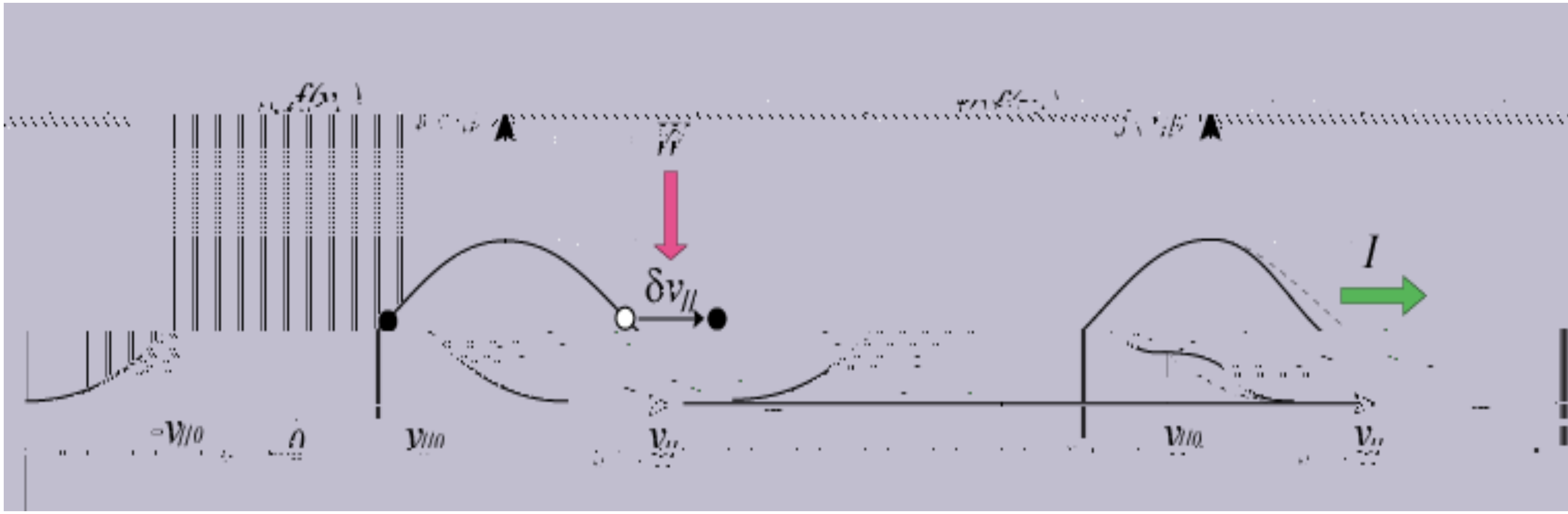
[illegible]

[illegible]

[illegible]

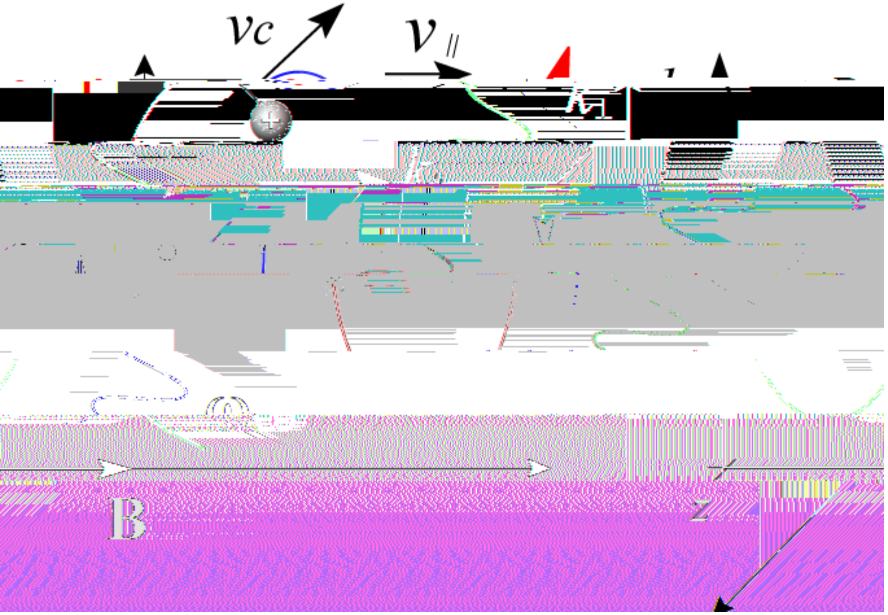


Toroidal current : $I\,[\mathrm{A}] = e\,[\mathrm{C}]\, v_{\parallel}\,[\mathrm{m/s}] \ldots \quad I = e\langle v_{\parallel}\rangle \ldots$

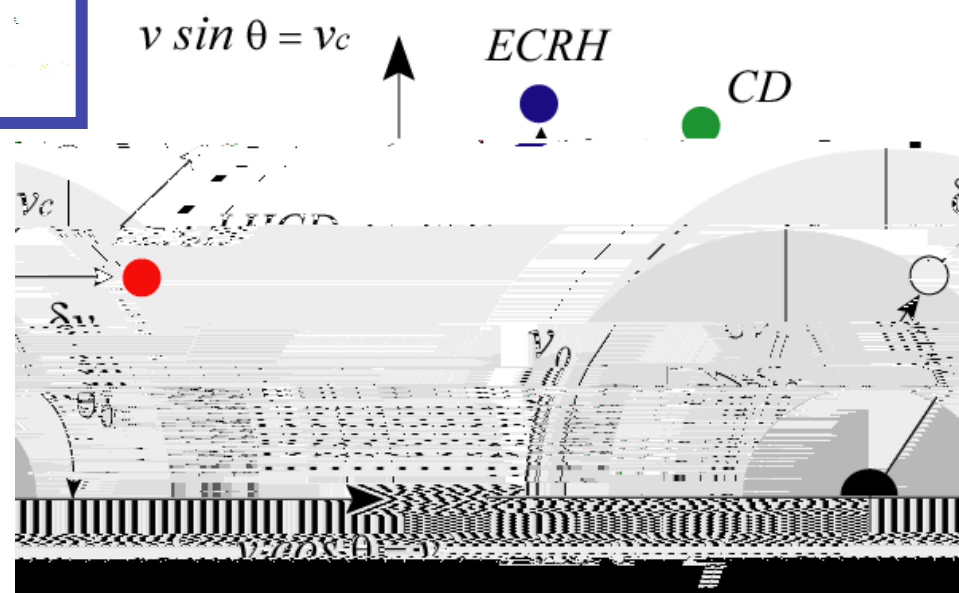


$dv_{\parallel}$

$e\langle v_{\parallel}\rangle \quad eA(t)$



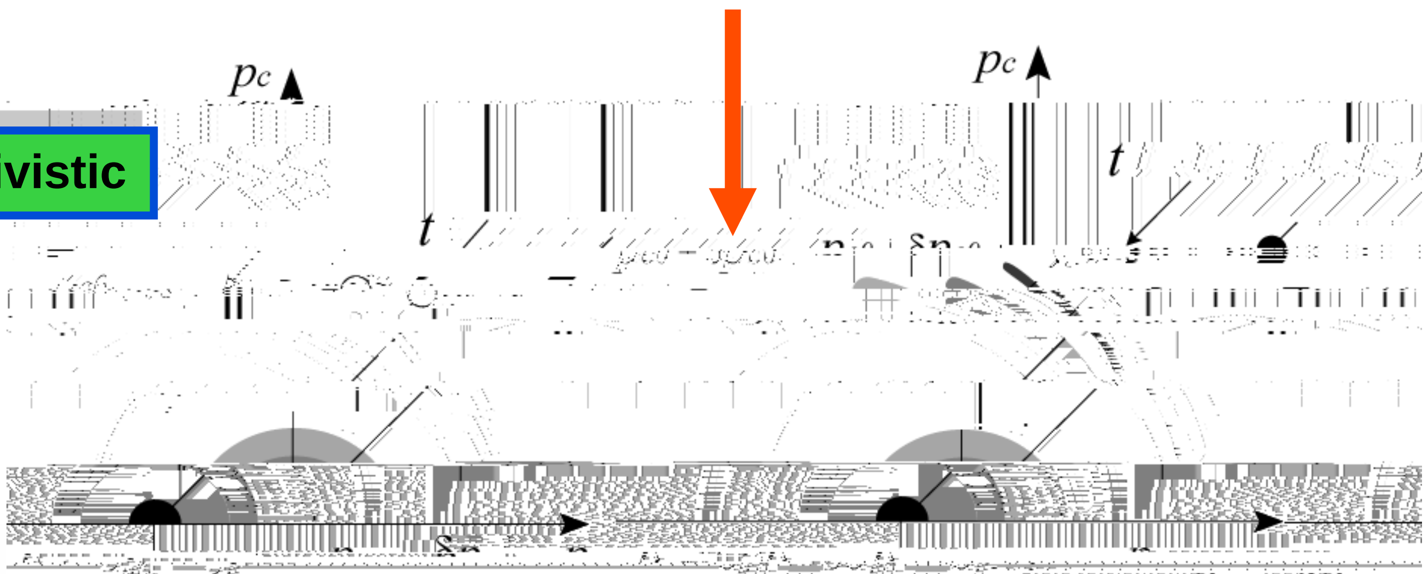
Resonance curves (b) ... $\omega = N\omega_c + k_\parallel v_\parallel$



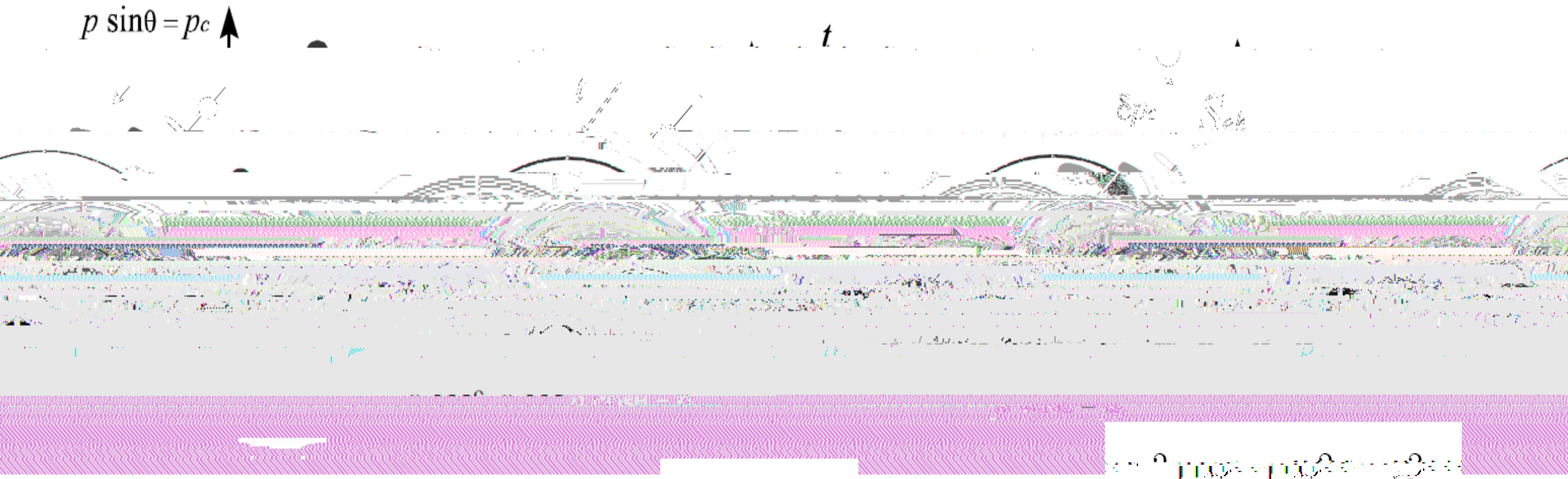
Current generation I : 2D response

1D classical

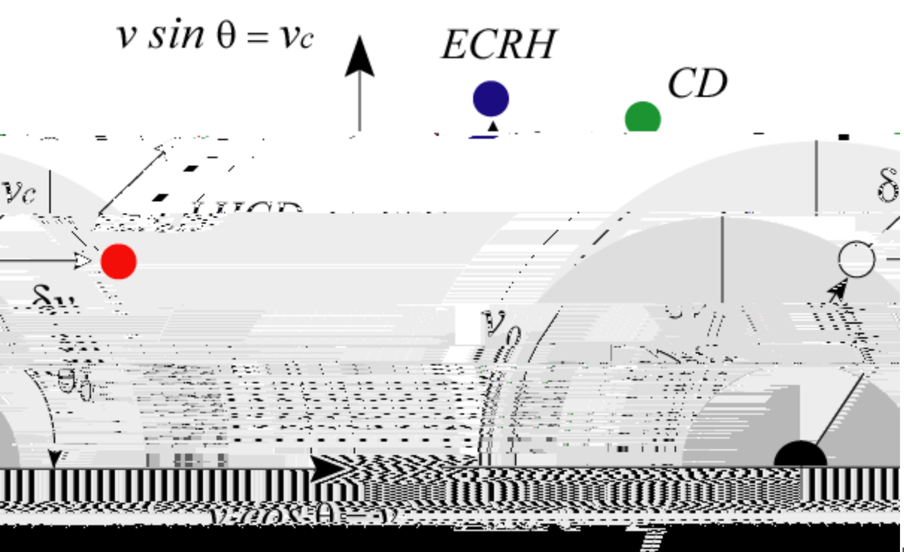
2D relativistic



2 D Model

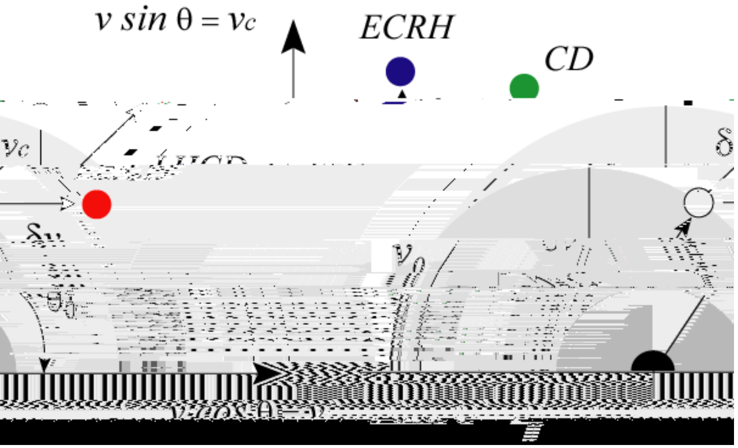


$$\gamma\omega - k_{\parallel}\gamma v_{\parallel} = n\omega_c \quad \longrightarrow \quad \delta p_{\parallel} = \hbar k_{\parallel}$$

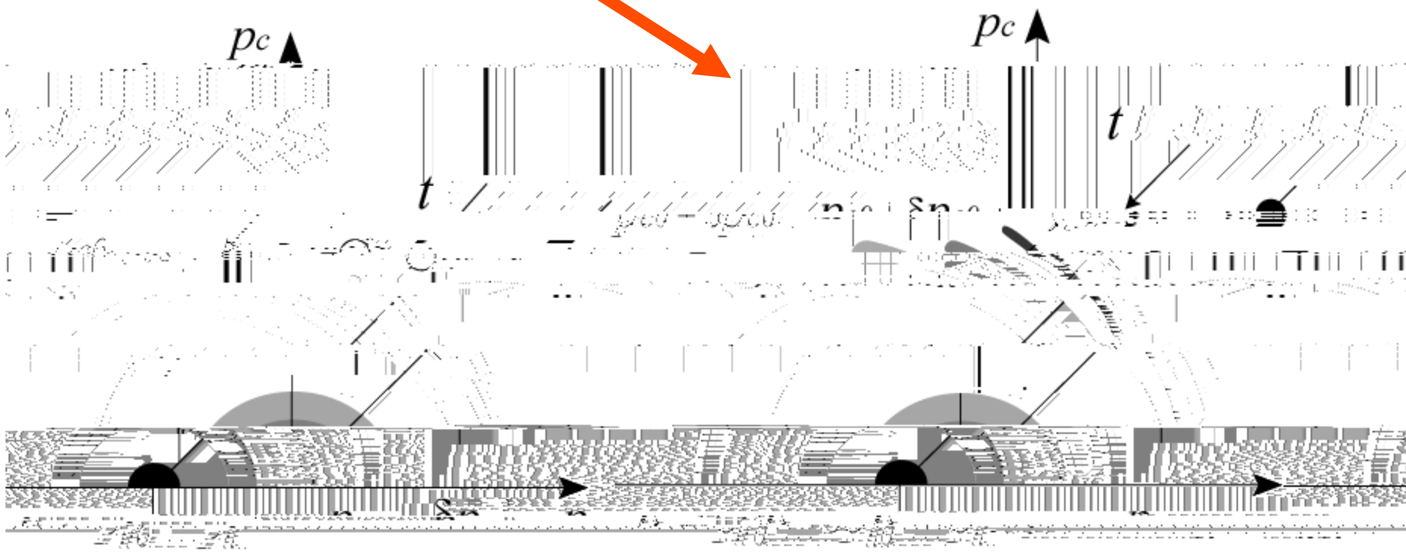


Photon absorption

[redacted]



Electron-hole collisional relaxation

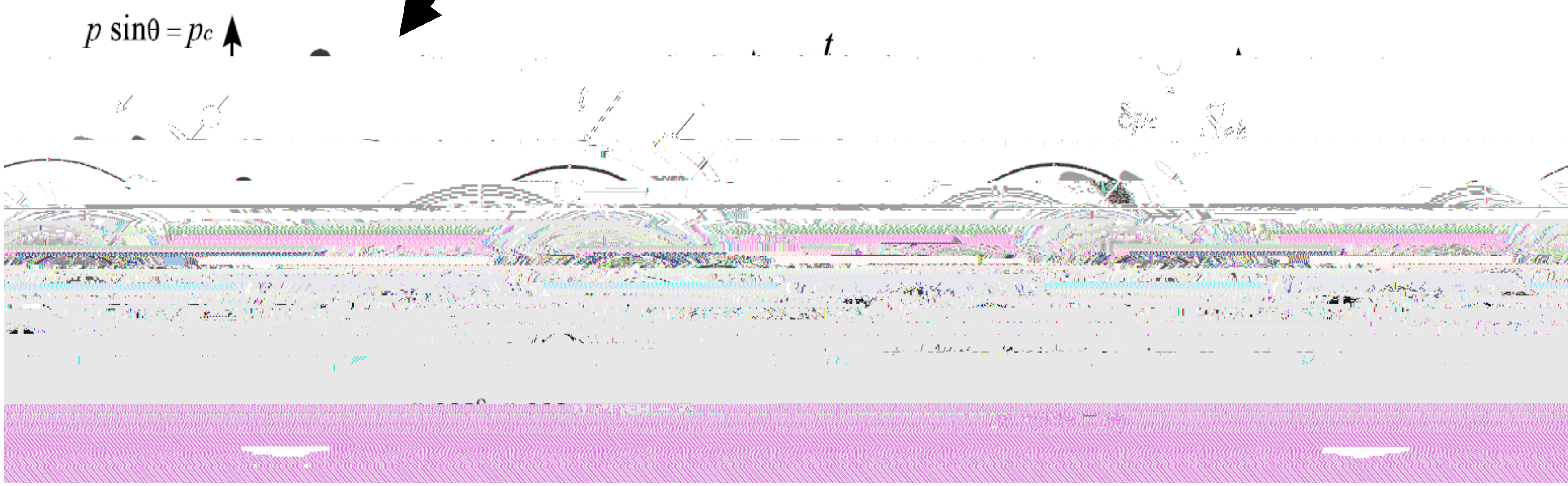


[redacted]

Evolution **Collisions** **Photons Absorption**

Excitation - Relaxation

$$\delta(\mathbf{p} - \mathbf{p}_0 - \delta\mathbf{p}_0) = \delta(\mathbf{p} - \mathbf{p}_0)$$



Excitation - Relaxation

$$\delta U(k_{\parallel}, \omega) = N\hbar\omega$$

$$\partial f$$

$$\exp Ct = 1 + Ct + \frac{Ct \cdot Ct}{\ldots} + \frac{Ct \cdot Ct \cdot Ct}{\ldots} + \ldots$$

[redacted]

$$f(\mathbf{p}, \mathbf{p}_0, t, t_0) = \theta(t - t_0) \exp[C(\mathbf{p})(t - t_0)] \cdot U(k_{\parallel}, \omega) \, S(\mathbf{p}_0) \cdot \delta(\mathbf{p} - \mathbf{p}_0)$$

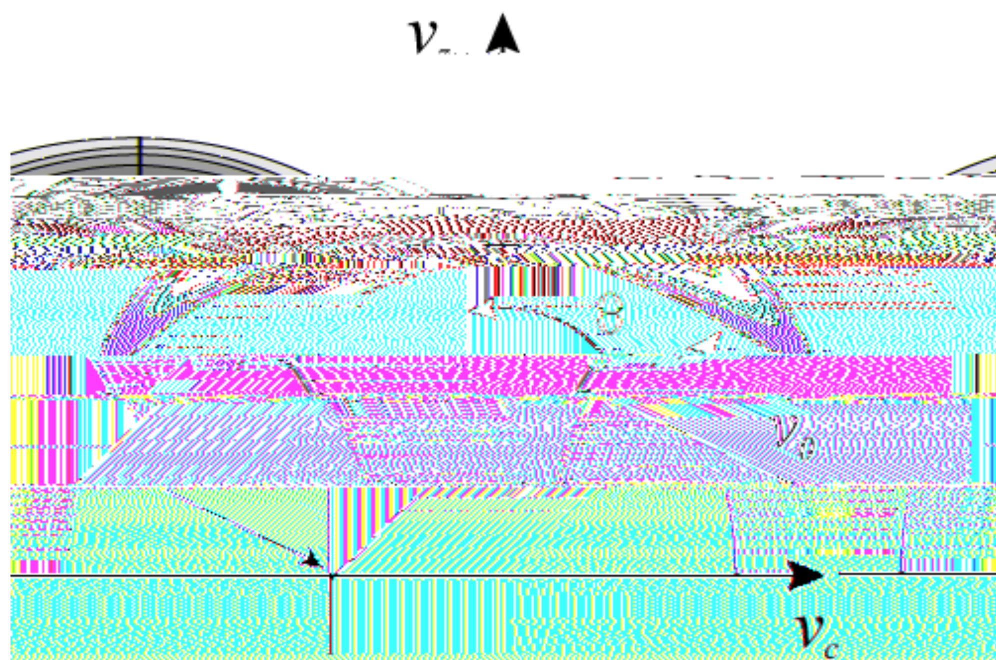
Toroidal current : $I\,[\mathrm{A}] = \frac{e\,[\mathrm{C}]\, v_{\parallel}\,[\mathrm{m/s}]}{\ldots} \ldots I \frac{e \langle v_{\parallel} \rangle}{\ldots}$

$$\delta U \left(k_{\parallel}, \omega\right) = W \left(k_{\parallel}, \omega\right) \delta t$$

$I \left[\mathrm{A} \right] \ldots \Omega^2 \ldots 2$

$\ldots \frac{n\omega_c}{\ldots} \frac{\partial}{\ldots} + k_{\parallel} \frac{\partial}{\ldots}$

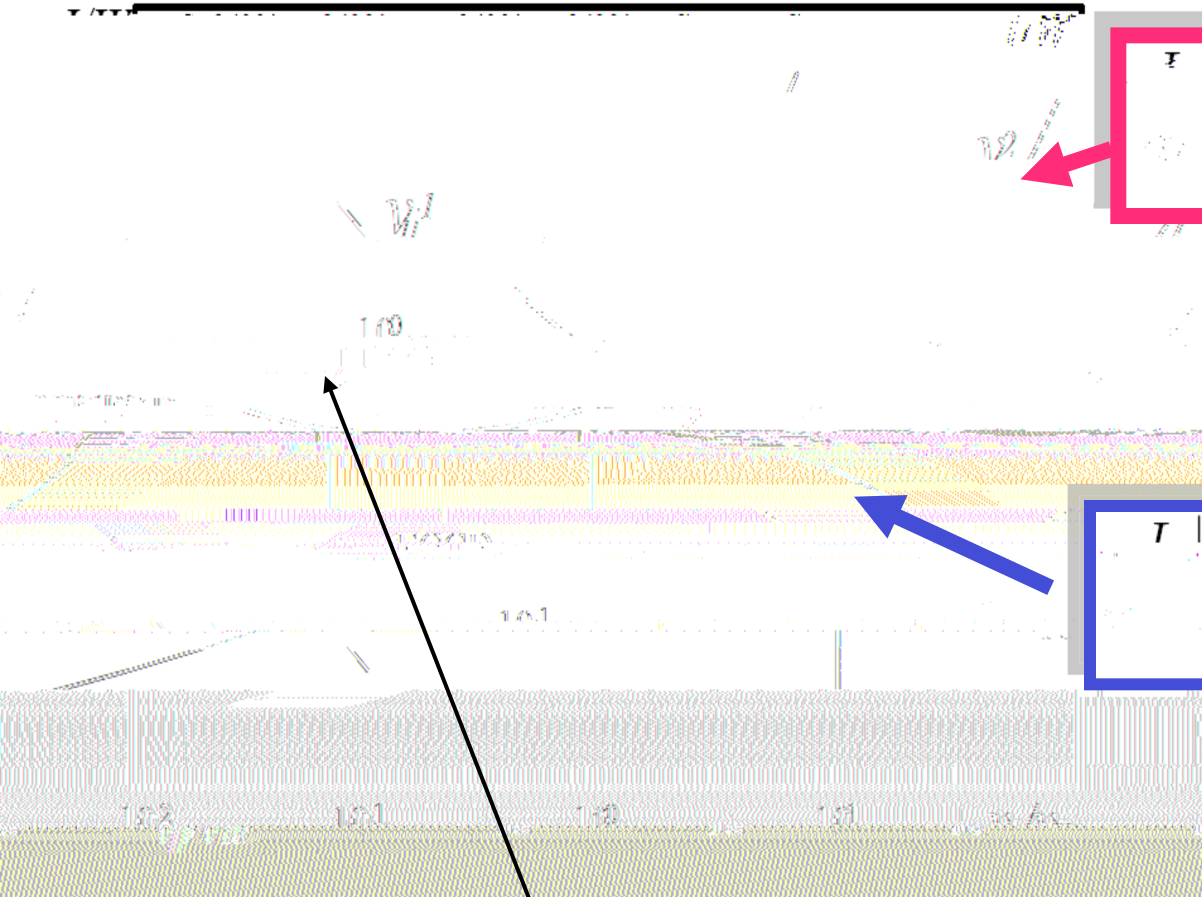
$$\sum^{l=+\infty} (2l+1) \left[\ldots \right]^{\frac{(Z+1)l(l+1)}{2}}$$



$$l=+\infty \quad (2l+1) \quad \left[\quad \right]^{\frac{(Z+1)l(l+1)}{2}}$$

$$\left[\frac{k_\parallel}{} \frac{\partial}{} \quad \frac{n\omega_c}{} \frac{1}{} \frac{\partial}{} \right]$$

$$\frac{2\varepsilon_0^2 m_e c^2}{} \quad [\mathrm{A}] \quad [10^{20}\,\mathrm{m}^{-3}]$$



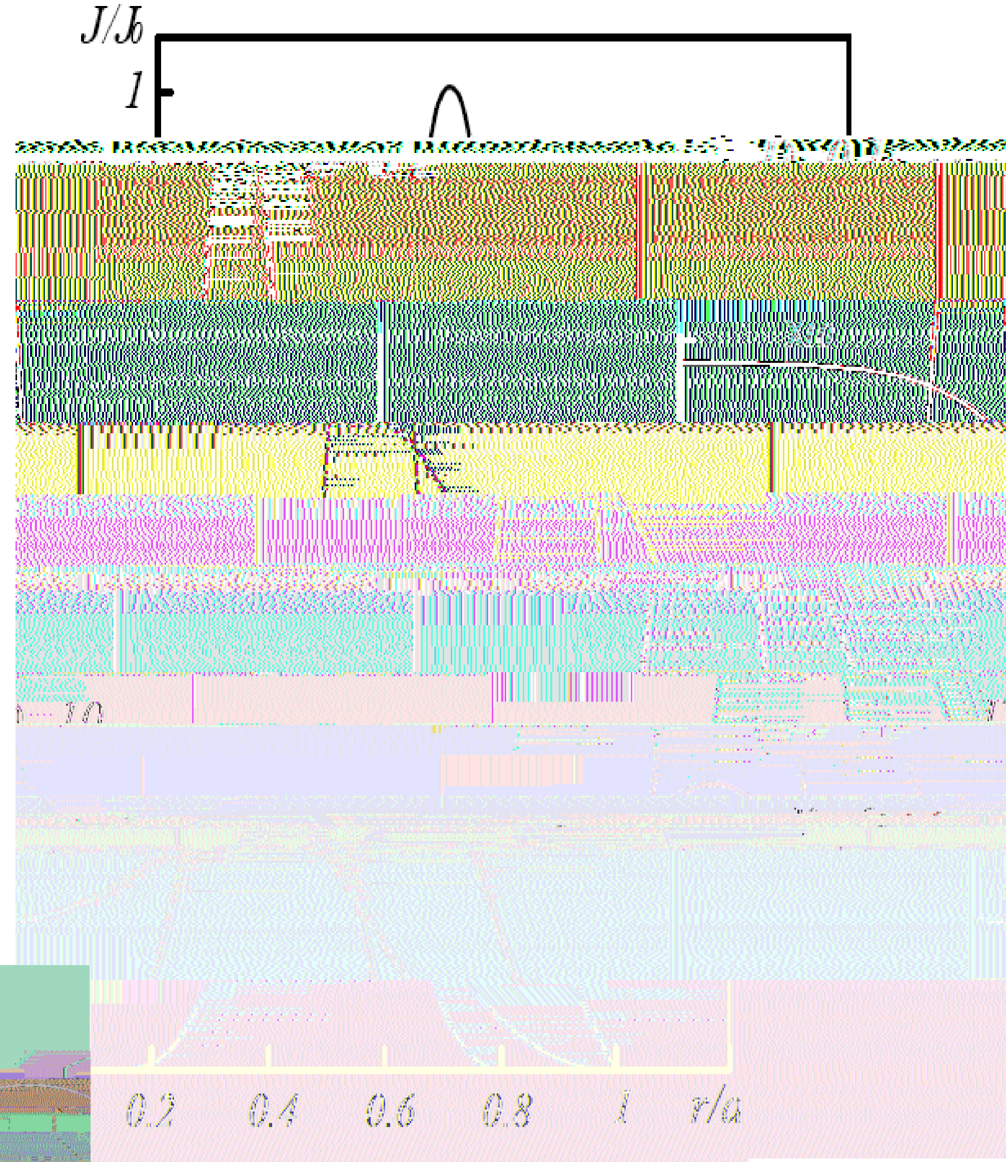
RF Current Transport

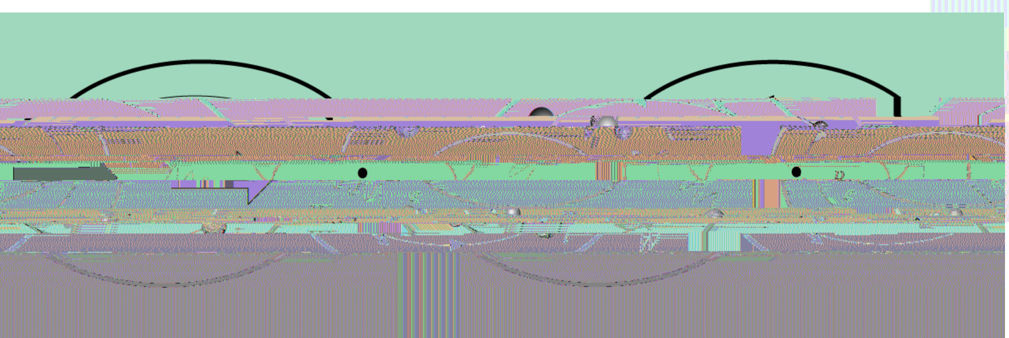
Collisions *Transport radial*

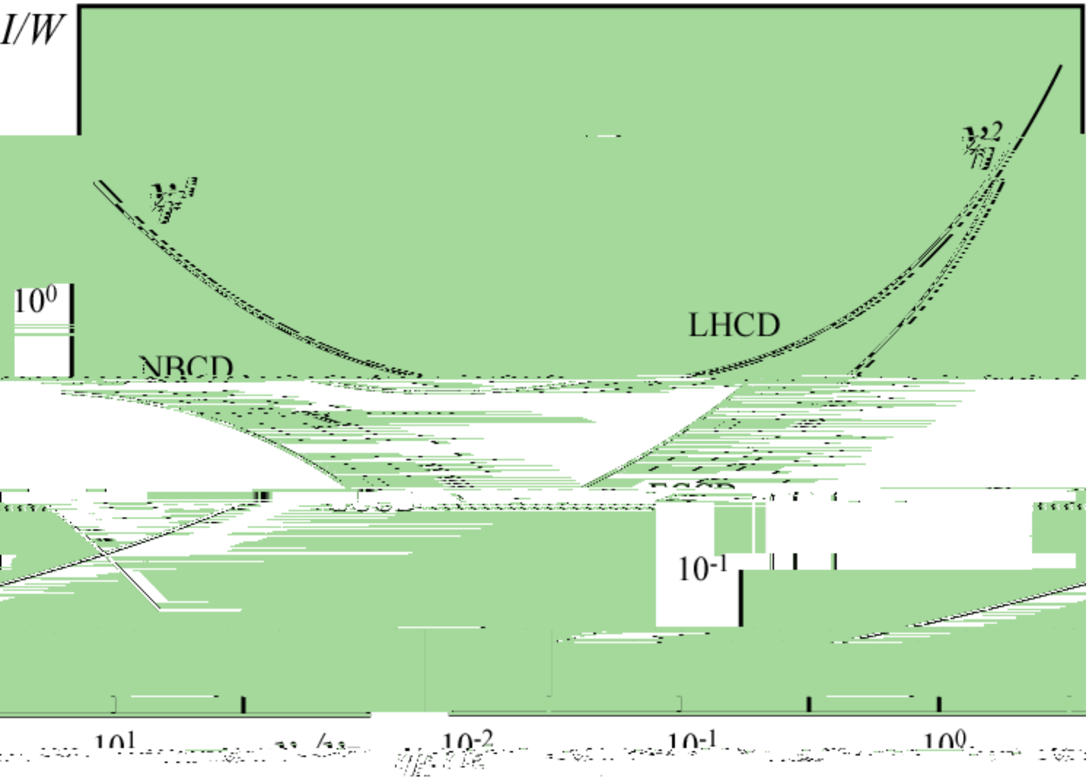
$$\delta\left(\cos\theta - \cos\theta_0\right)\frac{\delta\left(p - p_0\right)}{p^2}\frac{\delta\left(r - r_0\right)}{r}$$

$l=+\infty$

$$D = \frac{a^2}{\tau_d}$$


J/J0
1
0.2
0.4
0.6
0.8
1
r/a

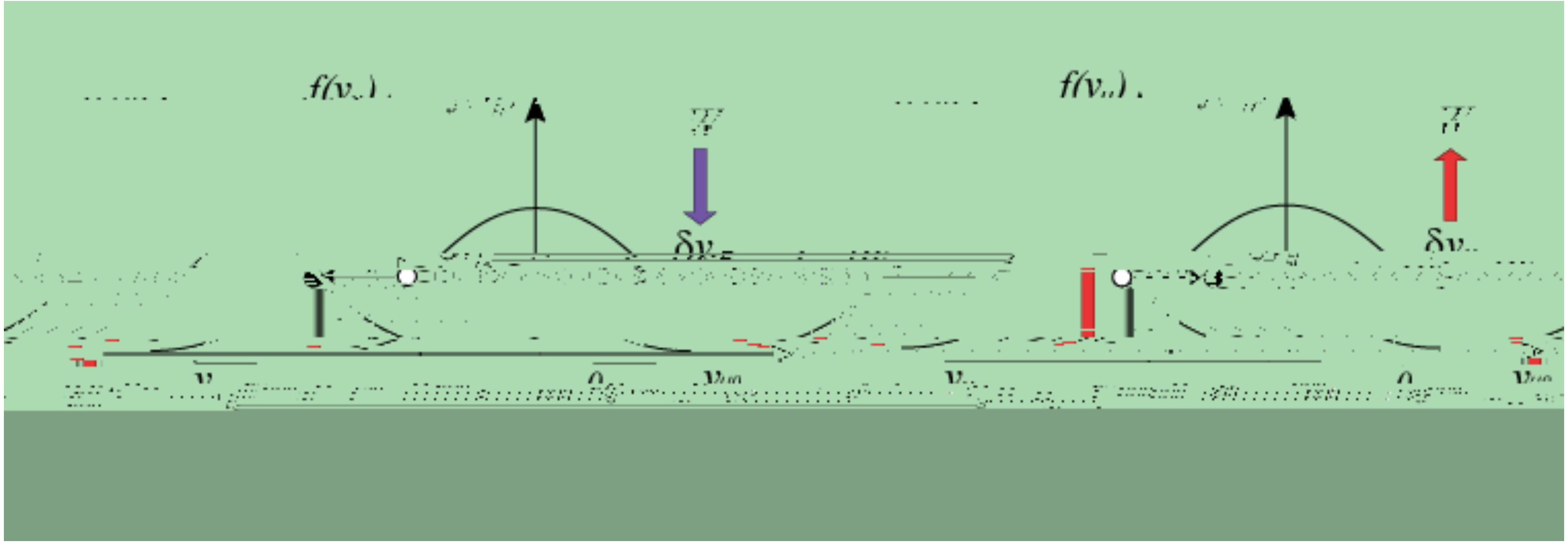


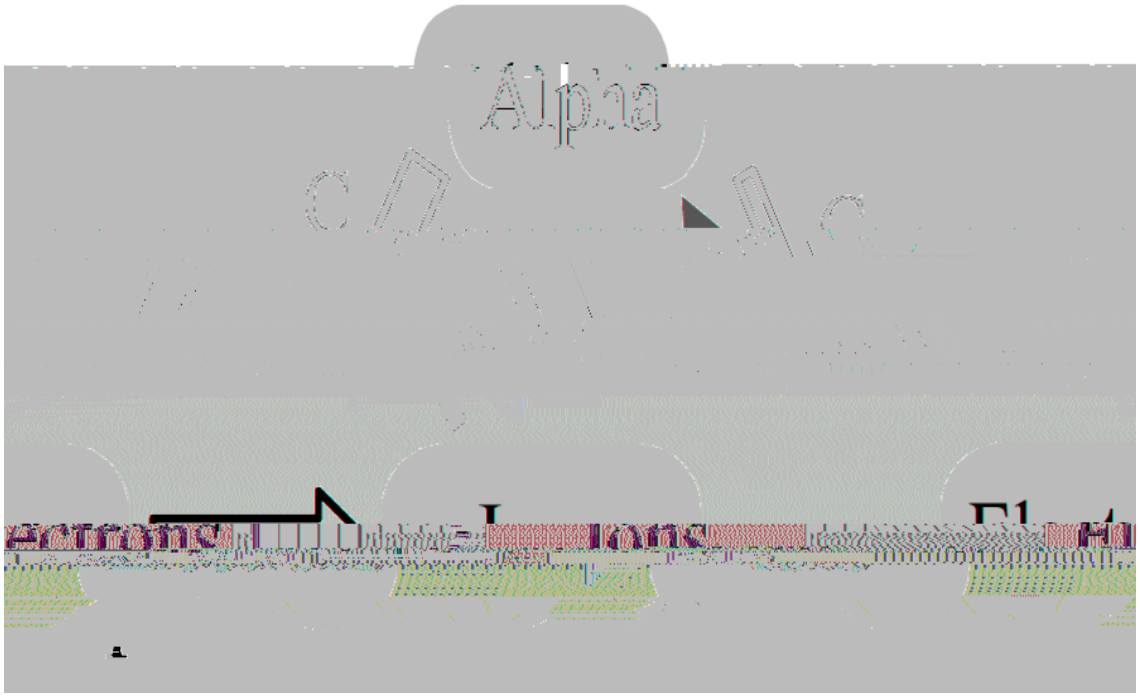


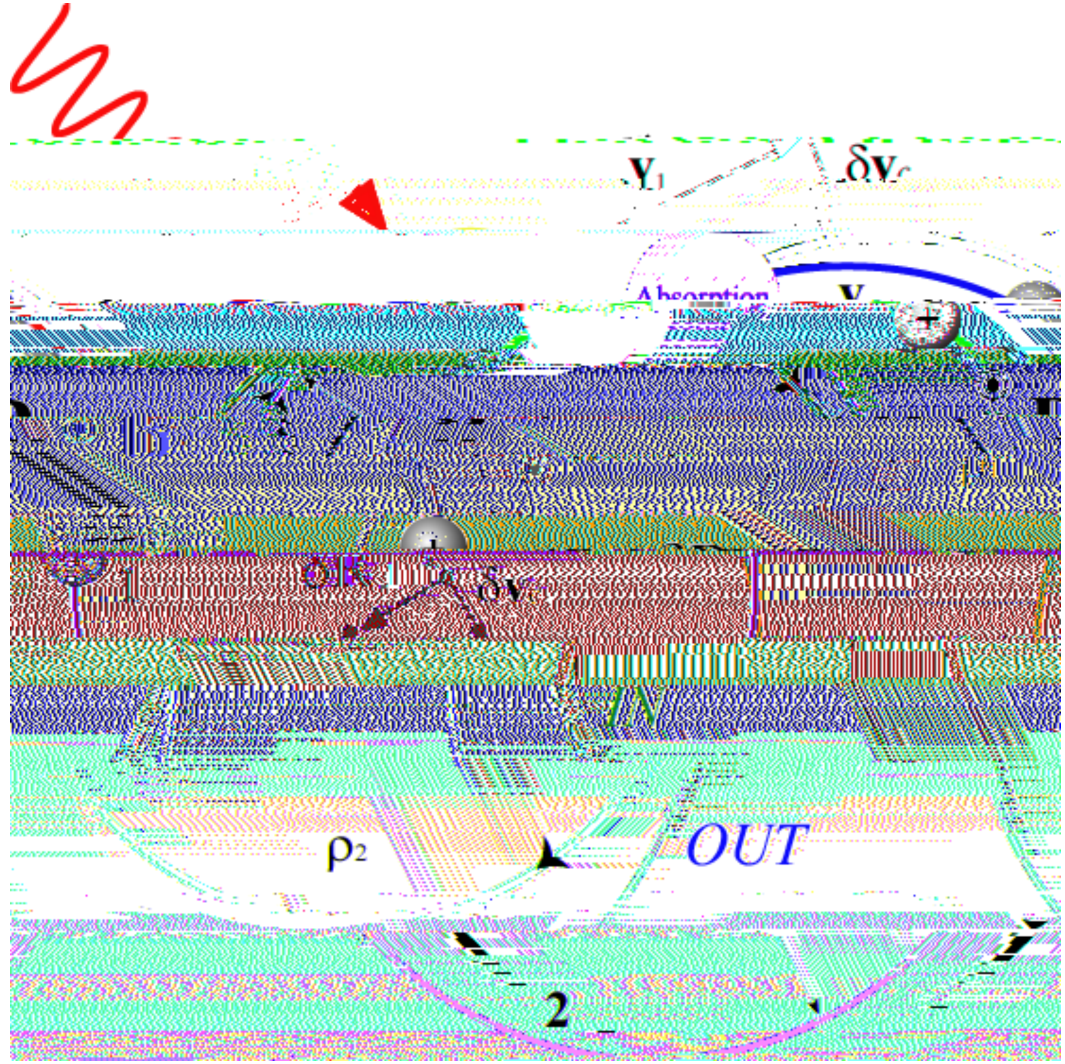
$I_{\|}$ [A] $2\varepsilon_0^2 m_e c^2$ $4N_{\|}^{-2}$ [illegible]

I [A] $2\varepsilon_0^2 m_e c^2$ $3N_{\|}^{-2}$ [illegible]

Free Energy Extraction

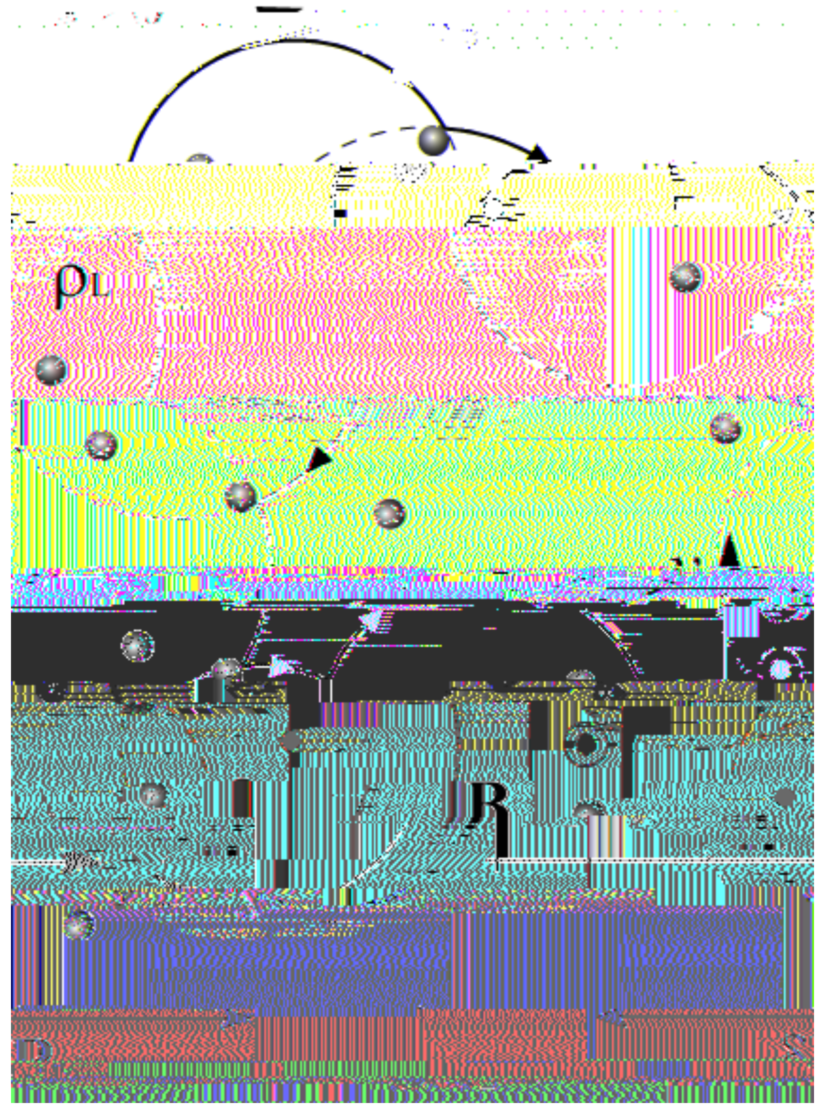



Alpha



$$\delta \mathbf{R}_{\perp} = \frac{\delta \mathbf{v}_c \times \mathbf{b}}{\omega_c}$$

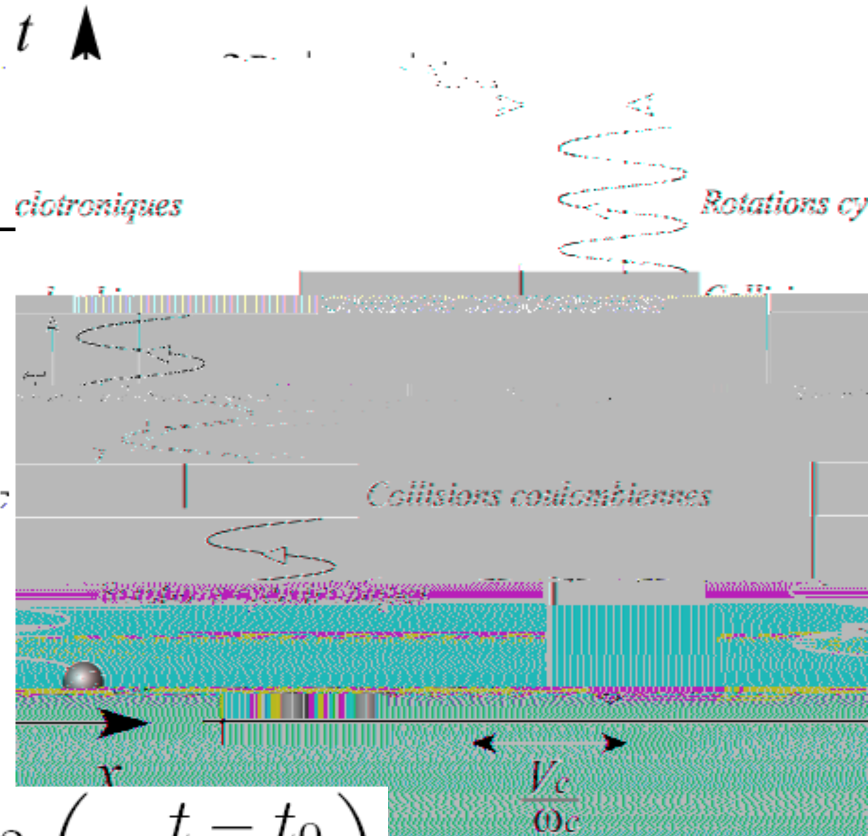
$$\langle \delta v^2 \rangle + \langle \delta v^2 \rangle$$



$d\mathbf{v}$ q

[redacted]

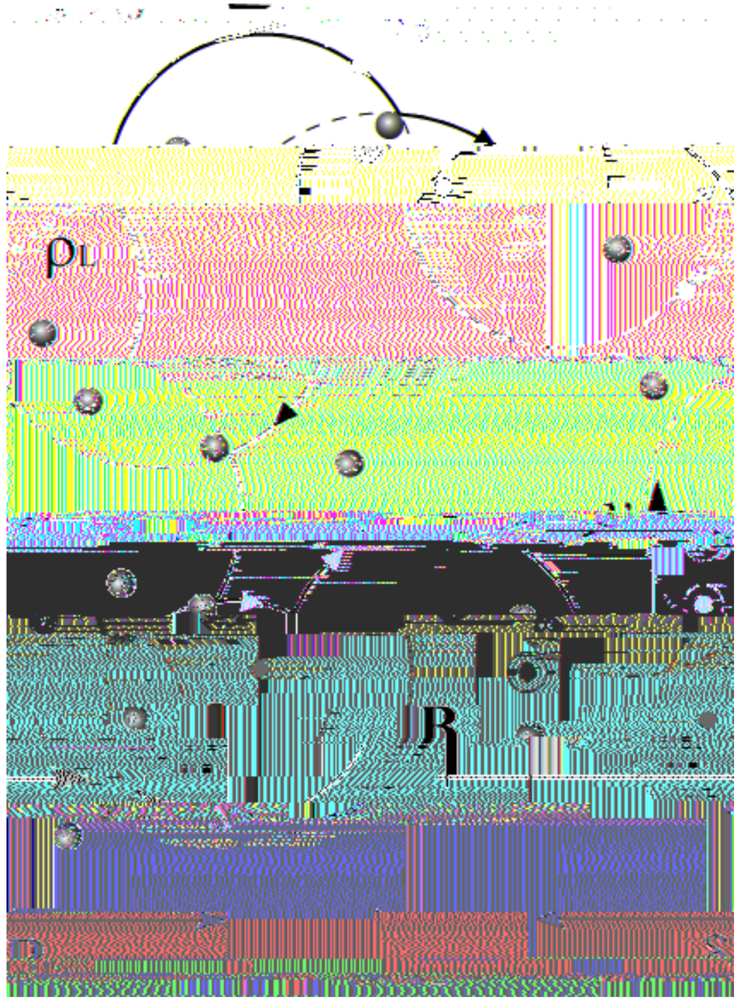
τ_0 t t



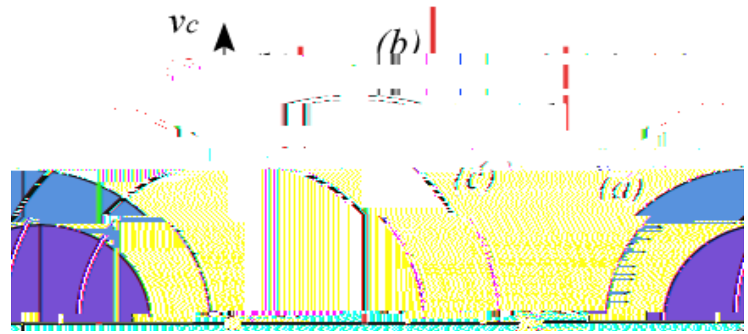
$t - t_0$

$$dP(\tau) = \nu \exp(-\nu\tau)\, d\tau$$

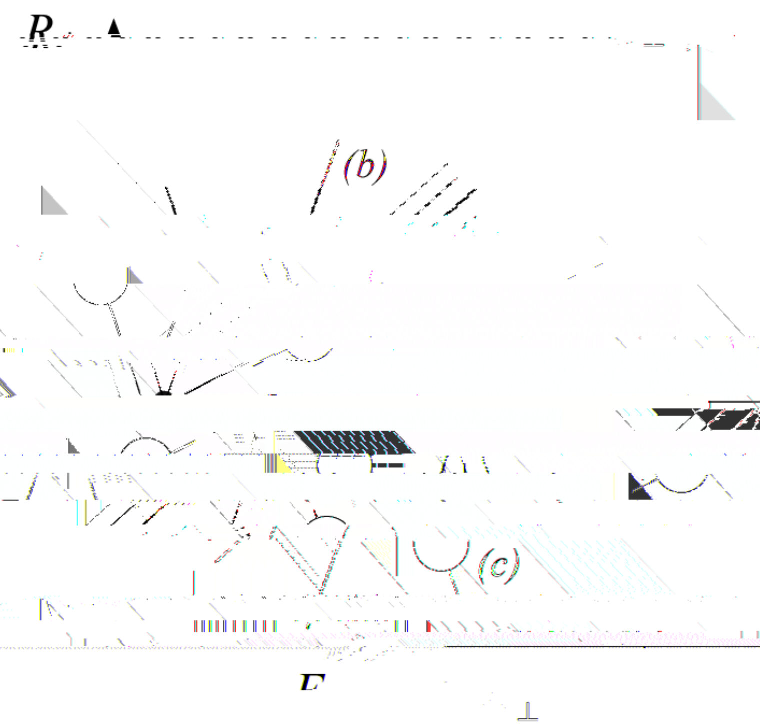
$$2v_c^2 \frac{\nu}{\nu^2 + \omega^2}$$

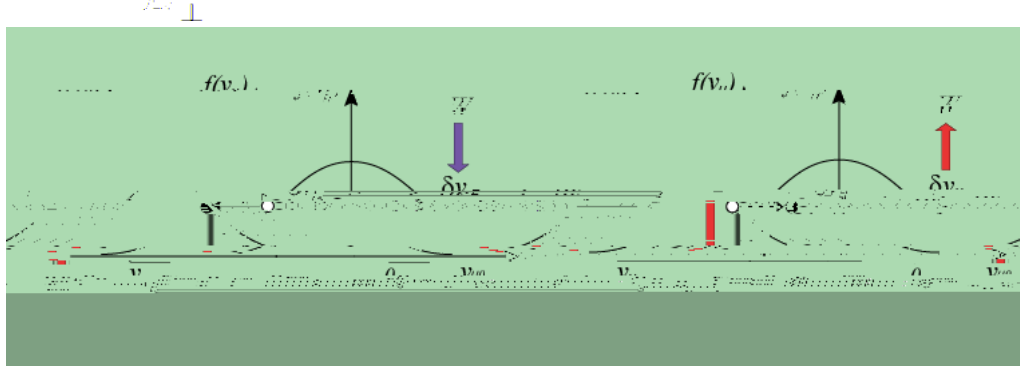


$\langle \delta R^2 \rangle$	$\langle \delta R^2 \rangle$	$D_{\parallel}$


(b)
(c)
(a)


(a)
(b)
(c)


(b)
(c)



$F \; k \; \phi \cos\theta$

[redacted]

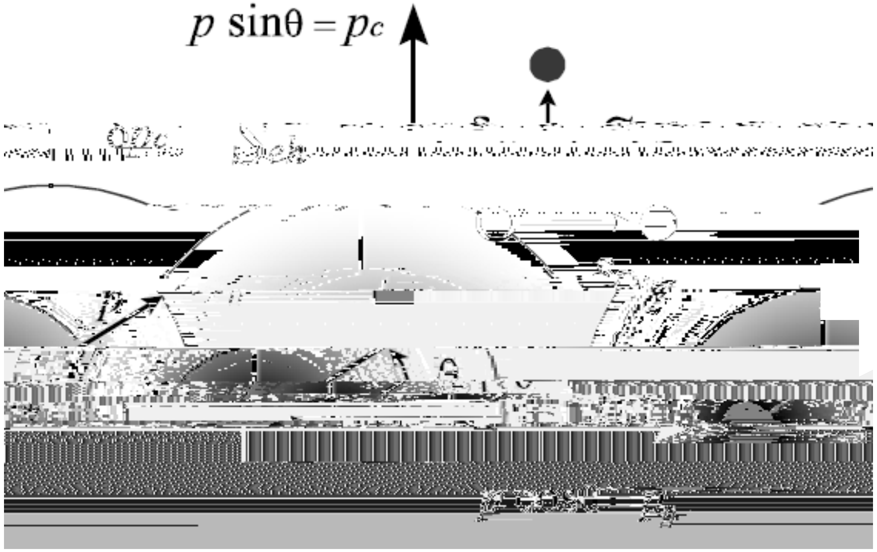
$\langle \delta v_c^2 \rangle \quad \pi \; e^2$

[redacted]

Physics of Landau and Cyclotron Resonances :

- Active and reactive power
- Plasma resonances
- Resonant interaction
- Random phase approximation RPA
- Quasi linear equation
- Landau absorption
- Cyclotron absorption
- Current generation 1D
- Current generation 2D
- Free energy extraction

Transfert d’impulsion



dv_u [illegible]

[illegible]

Suprathermique $\nu = \frac{n_e Z e^4 \Lambda}{\ldots}$ $\frac{I}{\ldots}\left[\mathrm{A}\right] = \frac{2\varepsilon_0^2 m_e}{\ldots} v^2$

$\frac{n_e Z e^4 \Lambda}{\ldots}$ $I\left[\mathrm{A}\right] \ldots 2\pi^{\frac{1}{2}}\varepsilon^2 m \ldots v^3$