Channeling-2012

ON THE INFLUENCE OF A PARTICLE'S FIELD EVOLUTION ON ITS IONIZATION ENERGY LOSSES IN THIN LAYERS OF SUBSTANCE

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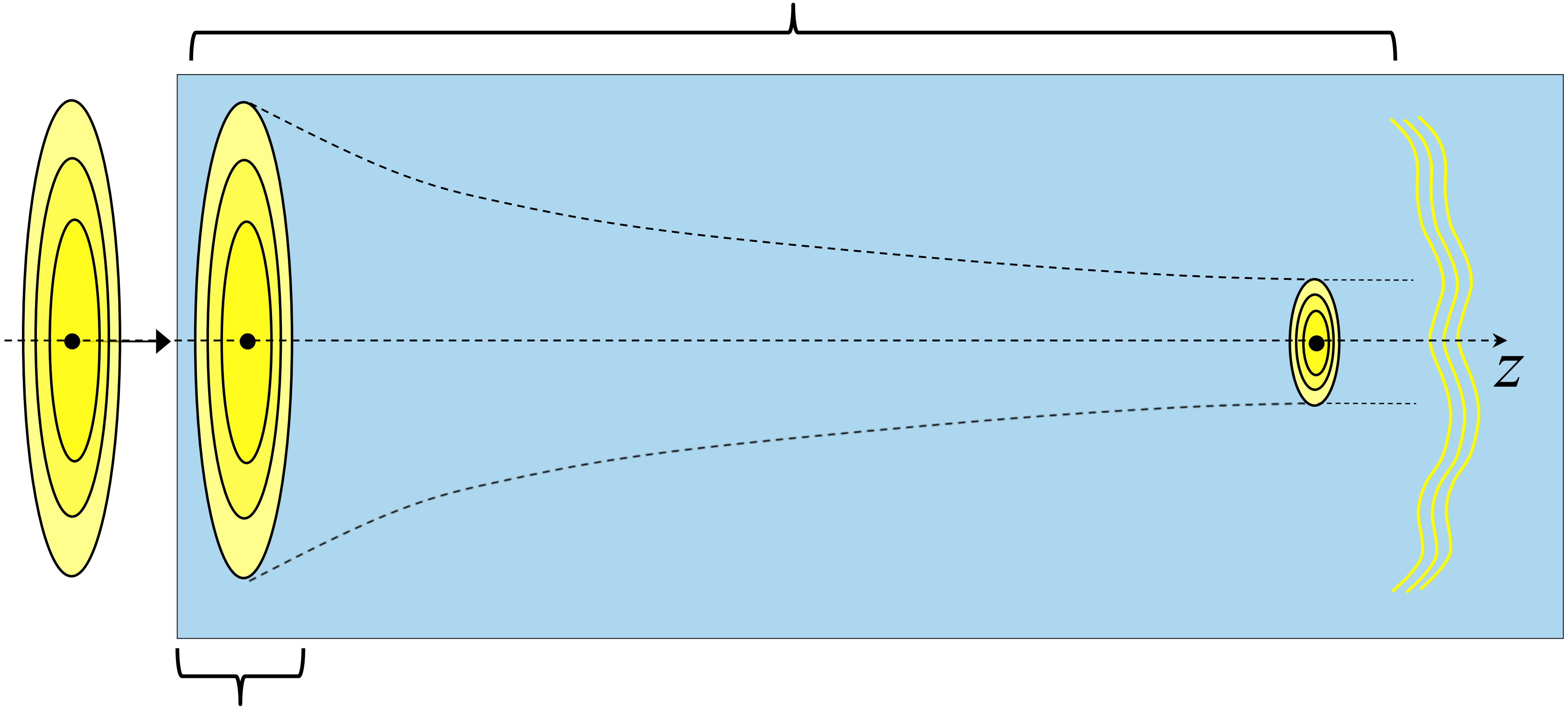
- Energy losses in infinite medium (Bethe-Bloch, Fermi)
- Energy losses in thin plates (Garibian)
- Field structure after electron emergence from substance
- Energy losses of half-bare electron in thin plate

RECONSTRUCTION OF THE FIELD AND IONIZATION ENERGY LOSSES

Field reconstruction $L \approx \gamma^2 / I$



Ionization losses reconstruction

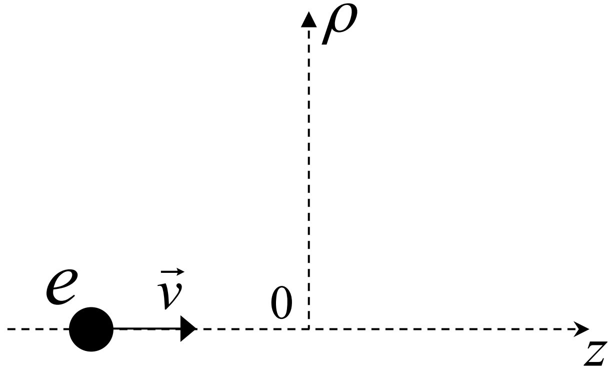
$L \approx I / \omega_p^2$ ≈ **absorption length**

I – mean ionization potential

G. Garibian, 1959

BETHE-BLOCH FORMULA

Infinite substance

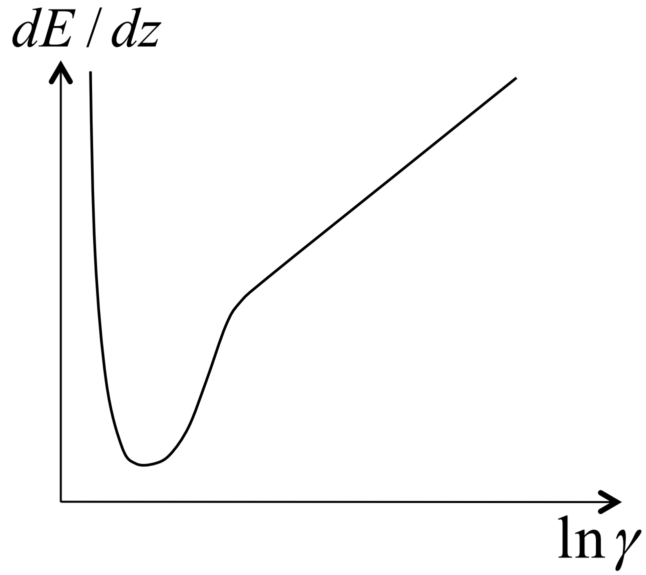


We consider ionization losses with the momentum transfer less than q_0 **(the collisions with impact parameter** $\rho > b = 1/q_0$ **)**

For $1 \le \gamma \le I/\omega_p$**:**

$$\frac{dE}{dz} = \frac{\omega_p^2 e^2}{v^2} \ln \frac{\gamma}{bI}$$

$$\varphi_{Coul} = e/\sqrt{\rho^2\gamma^{-2} + (z - vt)^2}$$

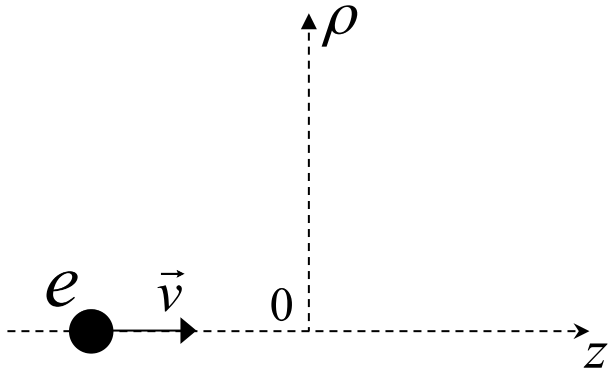


FERMI FORMULA

For $\gamma > I / \omega_p$

The influence of medium polarization:

$$\varphi(\vec{r},t) = \varphi_{Coul} e^{-\omega_p \sqrt{\rho^2 + \gamma^2 (z - vt)^2}}$$

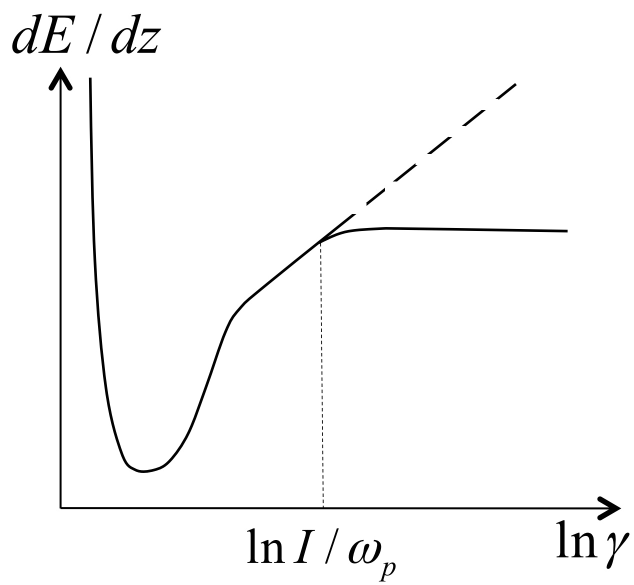


Screening of the field for:

$$\rho > 1 / \omega_p$$

Ionization energy losses:

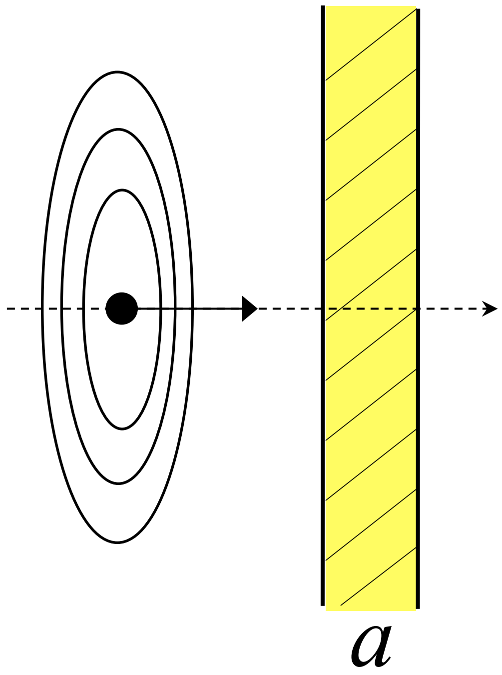
$$\frac{dE}{dz} = \frac{\omega_p^2 e^2}{v^2} \ln \frac{v}{b\omega_p}$$



THIN LAYER OF SUBSTANCE

Bethe-Bloch and Fermi formulae are valid in boundless homogeneous substance

Garibian G.M.// JETP, 1959



Total absence of the density effect in thin plates:

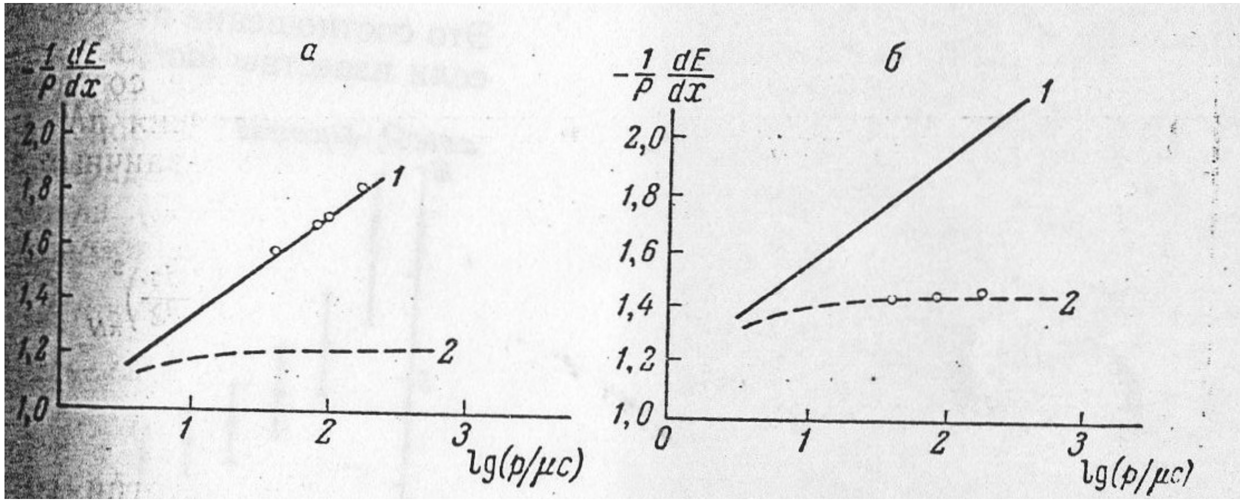
$$a \leq I / \omega_p^2$$

Particle energy loss:

$$\Delta E = \frac{\omega_p^2 e^2}{v^2} a \ln \frac{\gamma}{bI} \quad \begin{cases} 1 \leq \gamma \leq I / \omega_p \\ \gamma > I / \omega_p \end{cases}$$

FIRST EXPERIMENT (Kharkov, 1963)

A.I. Alikhanian, G.M. Garibian, M.P. Lorikian, A.K. Walter, I.A. Grishaiev, V.A. Petrenko, G.L. Fursov // JETP, 1963



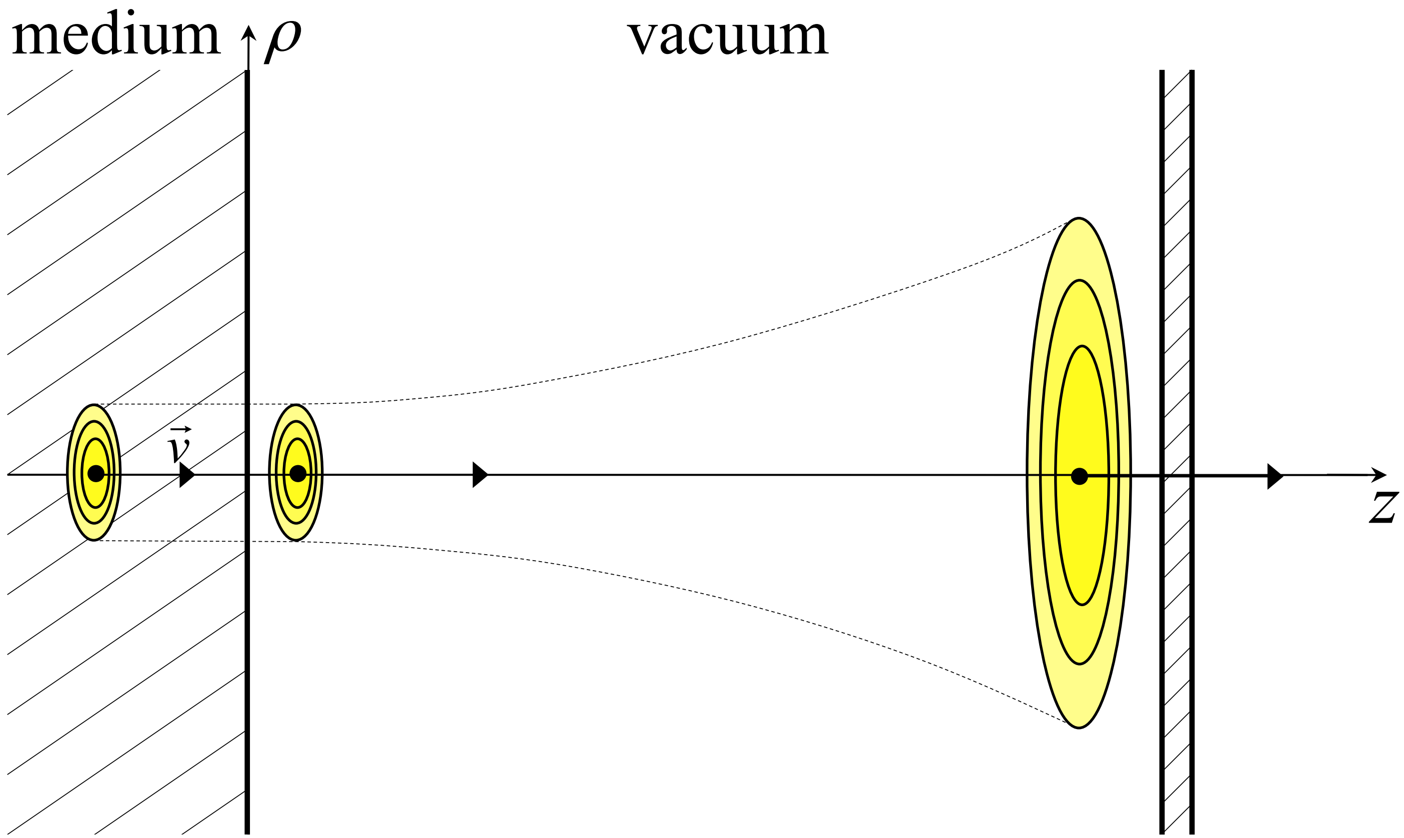
Electron energy losses in thin films of polystyrene of thicknesses $10^{-6}\,cm$ (a) and $2\times10^{-3}\,cm$ (б)

1 – theoretical curve without density effect

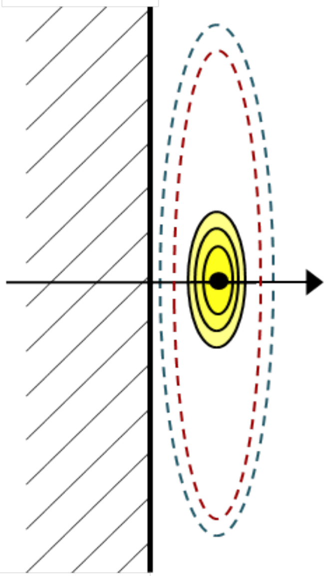
2 – theoretical curve with density effect

circles show the measurement results

EVOLUTION OF THE FIELD AROUND THE ELECTRON IN VACUUM AT ULTRA HIGH ENERGIES



EVOLUTION OF THE FIELD AROUND THE ELECTRON IN VACUUM AT ULTRA HIGH ENERGIES



Total field:

$$\vec{E} = \vec{E}^C + \vec{E}^F$$

Boundary conditions:

$$\left.\begin{aligned} \left(E_\rho^C + E_\rho^F\right)^{diel}\Big|_{z=0} &= \left(E_\rho^C + E_\rho^F\right)^{vac}\Big|_{z=0} \\ \left(E_z^C + E_z^F\right)^{diel}\Big|_{z=0} &= \hat{\varepsilon}\left(E_z^C + E_z^F\right)^{vac}\Big|_{z=0} \end{aligned}\right\} \quad + \quad div\vec{E}^F = 0$$

Fourier expansion of the free field:

$$E_\rho(\vec{r},t) = \frac{e}{\pi\ v}\int_0^\infty dq q^2 J_1(q\rho) \times$$

$$\times \int_{-\infty}^{+\infty} d\omega \frac{\sqrt{\omega^2 - q^2}}{\sqrt{\omega^2\varepsilon - q^2} + \varepsilon\sqrt{\omega^2 - q^2}} \left[\frac{1 + \frac{v}{\omega}\sqrt{\omega^2\varepsilon - q^2}}{q^2 + \frac{\omega^2}{v^2} - \varepsilon\omega^2} - \frac{\varepsilon + \frac{v}{\omega}\sqrt{\omega^2\varepsilon - q^2}}{q^2 + \frac{\omega^2}{v^2} - \omega^2} \right] e^{i\sqrt{\omega^2 - q^2}z - i\omega t}$$

$\vec{q}$ – component of vector $\vec{k}$ orthogonal to z axis

THE STRUCTURE OF THE FIELD IN VACUUM

$\varepsilon(\omega) = 1 - \omega_p^2 / \omega^2$ ω_p – plasma frequency of the first substance

For $\gamma >> 1$ **characteristic values:** $\omega_p / \omega << 1$ **and** $q / \omega << 1$

Free field:

$$E_\rho^F(\vec{r},t) = \frac{e}{\pi\ v}\int_0^\infty dq q^2 J_1(q\rho)\int_{-\infty}^{+\infty} d\omega \left[\frac{1}{q^2 + \omega_p^2 + \frac{\omega^2}{v^2\gamma^2}} - \frac{1}{q^2 + \frac{\omega^2}{v^2\gamma^2}}\right]\exp\left\{i\omega(z-t) - i\frac{q^2}{2\omega}z\right\}$$

Total field:

$$E_\rho = E_\rho^C + E_\rho^F$$

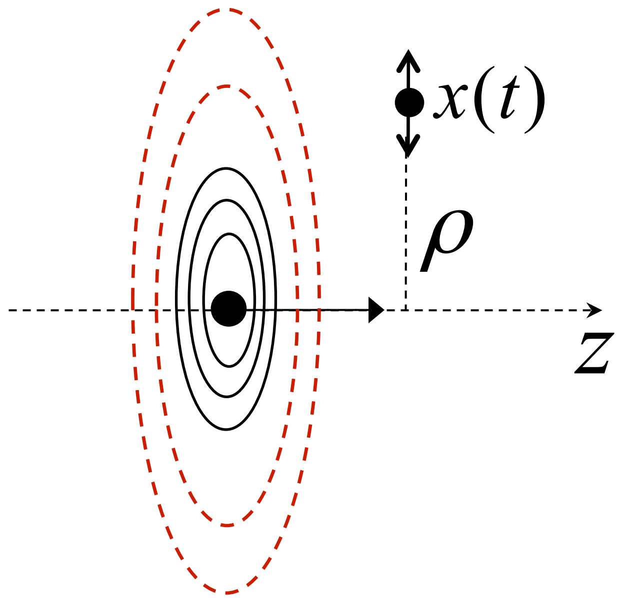
Particle's own Coulomb field:

$$E_\rho^C(\vec{r},t) = -\frac{\partial}{\partial\rho}\frac{e}{\sqrt{\rho^2\gamma^{-2} + (z - vt)^2}} = \frac{e}{\pi\ v}\int_{-\infty}^{\infty} d\omega \int_0^{+\infty} dq \ \frac{q^2 J_1(q\rho)}{q^2 + \frac{\omega^2}{v^2\gamma^2}} e^{i\frac{\omega}{v}z}$$

IONIZATION OF SUBSTANCE BY EXTERNAL FIELD

$$\omega_0 = I$$

$$\ddot{x} + \beta\dot{x} + \omega_0^2 x = \frac{e}{m}\left(E_\rho^C + E_\rho^F\right)$$



Energy transfer to a harmonic oscillator by external field:

$$\Delta\mathcal{E} = \frac{e^2}{2m}\left|E_{\omega_0}(\vec{r})\right|^2$$

$$E_{\omega_0}(\vec{r}) = \int_{-\infty}^{+\infty} E(t)e^{-i\omega_0 t}dt$$

ω_0 – oscillator's own frequency

J.D. Jackson // Classical electrodynamics, 1999

IONIZATION ENERGY LOSSES BY HALF-BARE ELECTRON

$$\omega = \omega_0$$

Total field Fourier-component:

$$E_{\omega}^{\rho}(\vec{r}) = 2\frac{e}{v}\int_0^{\infty} dq q^2 J_1(q\rho)\left\{\left[\frac{1}{q^2+\omega_p^2+\frac{\omega^2}{v^2\gamma^2}} - \frac{1}{q^2+\frac{\omega^2}{v^2\gamma^2}}\right] e^{i\omega z - \frac{q^2 z}{2\omega}} + \frac{e^{i\frac{\omega}{v}z}}{q^2+\frac{\omega^2}{v^2\gamma^2}}\right\}$$

Total energy loss per unit path:

$$\frac{d\mathcal{E}}{dz} = n\frac{e^2}{2m}\int_0^{\infty} d\rho 2\pi\rho \left|E_{\omega_0}^{\rho}(\vec{r})\right|^2$$

IONIZATION ENERGY LOSSES BY HALF-BARE ELECTRON

$$\omega = \omega_0$$

After integration over ρ :

$$\frac{d\mathcal{E}}{dz} = \frac{\mathbf{\Omega}_p^2 e^2}{v^2} \int_0^{q_0} dq\, q^3 \left\{ \left(\frac{1}{q^2 + \frac{\omega^2}{v^2\gamma^2}} \right)^2 + \left(\frac{1}{q^2 + \omega_p^2 + \frac{\omega^2}{v^2\gamma^2}} - \frac{1}{q^2 + \frac{\omega^2}{v^2\gamma^2}} \right)^2 + \right.$$

$$\left. + \left(\frac{1}{q^2 + \omega_p^2 + \frac{\omega^2}{v^2\gamma^2}} - \frac{1}{q^2 + \frac{\omega^2}{v^2\gamma^2}} \right) \frac{1}{q^2 + \frac{\omega^2}{v^2\gamma^2}} 2\cos\left(\frac{\omega\, z}{2v^2\gamma^2} + \frac{q^2 z}{2\omega} \right) \right\}$$

$\mathbf{\Omega}_p$ – plasma frequency of the plate

IONIZATION ENERGY LOSSES BY HALF-BARE ELECTRON

Assumption: $q_0 >> \omega_p >> I/\gamma$

For $z \to 0$

$$\frac{d\mathcal{E}}{dz} = \frac{\Omega_p^2 e^2}{v^2} \ln \frac{q_0}{\omega_p}$$

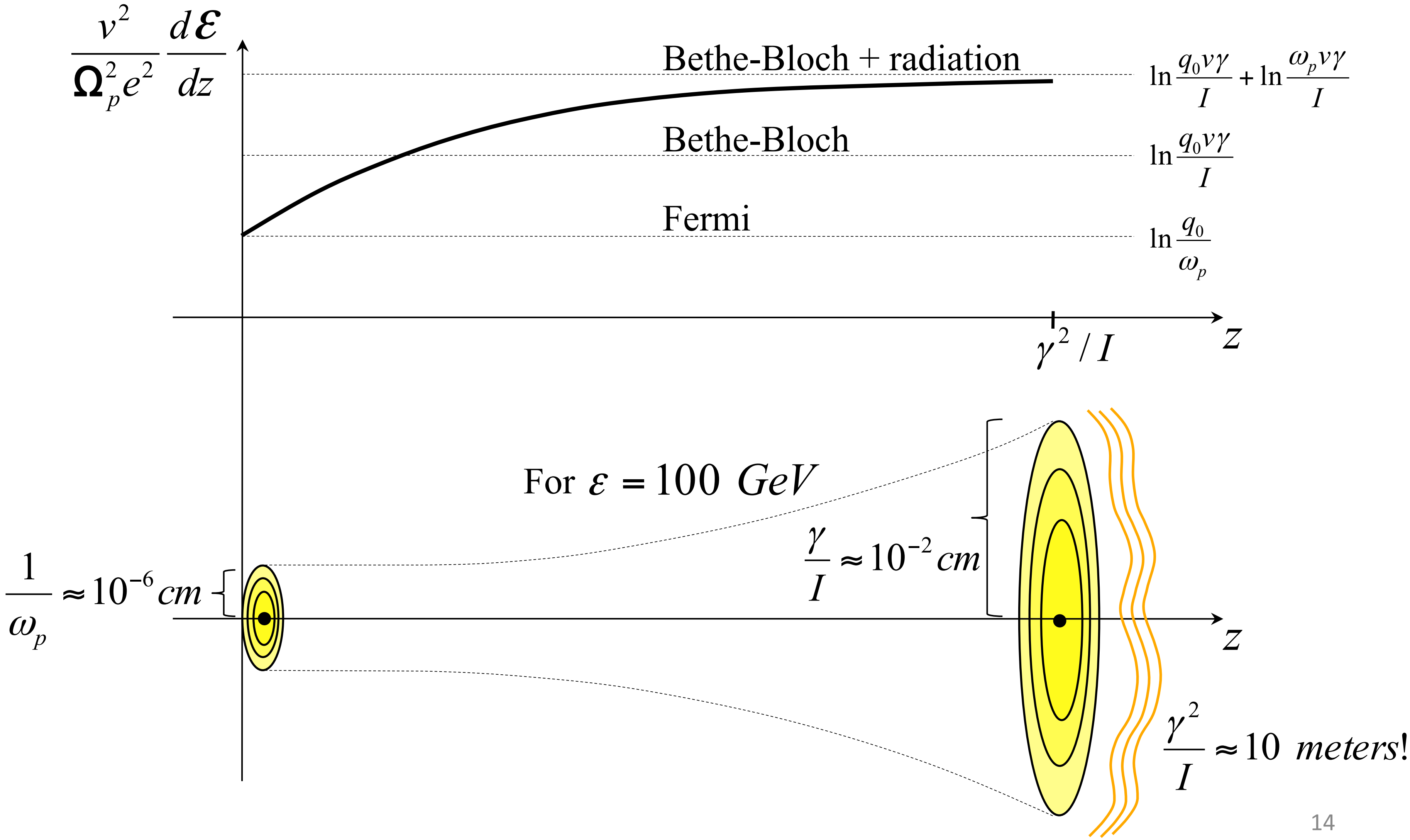
For $I/\omega_p^2 << z << 2\gamma^2/I$

$$\frac{d\mathcal{E}}{dz} = \frac{\Omega_p^2 e^2}{v^2} \ln \frac{q_0 z \omega_p}{2I}$$

For $z \geq 2\gamma^2/I$

$$\frac{d\mathcal{E}}{dz} = \frac{\Omega_p^2 e^2}{v^2} \left\{ \ln \frac{q_0 v \gamma}{I} + \ln \frac{\omega_p v \gamma}{I} \right\}$$

IONIZATION ENERGY LOSSES BY HALF-BARE ELECTRON (from Fermi to Bethe-Bloch formula)



CONCLUSIONS

❖The existence of a transition process in which the ionization energy losses of a particle are defined by the mechanism of reconstruction of the field around it into radiation (not by the absorption of the free field)

❖ Gradual change of particle ionization energy losses from Fermi to Bethe-Bloch mode (if taking into account residual ionization by transition radiation) in the considered process

THANK YOU!