

# **DEVIATIONS FROM GARIBIAN EFFECT FOR IONIZATION LOSS OF HIGH-ENERGY ELECTRONS IN THIN PLATES**

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*N.F. Shul'ga, S.V. Trofymenko // Phys. Lett. A. (2012)*  
*S.V. Trofymenko, N.F. Shul'ga // Phys. Lett. A. (2013)*

# BETHE-BLOCH FORMULA

## Homogeneous infinite medium

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

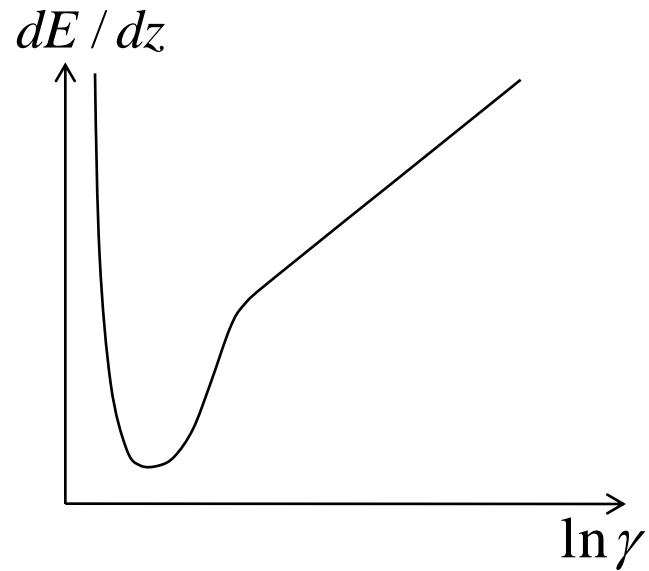
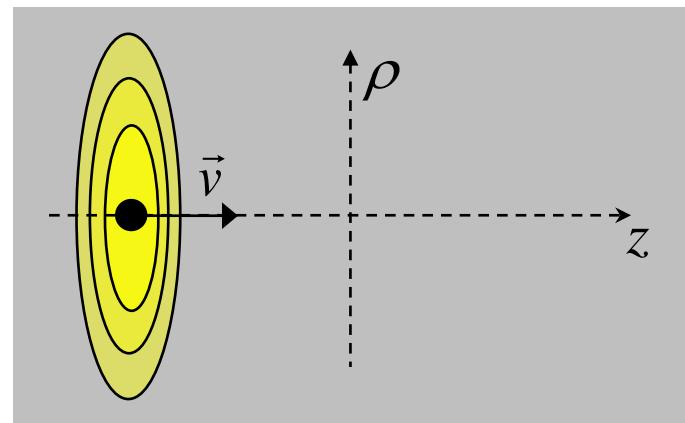
$\gamma$  – particle's Lorentz-factor

$\omega_p$  – plasma frequency

For  $1 \leq \gamma \leq I / \omega_p$ :

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

$I$  – mean ionization potential



# FERMI FORMULA

## Homogeneous infinite medium

For  $\gamma > I / \omega_p$

The influence of medium polarization  
on the particle's field:

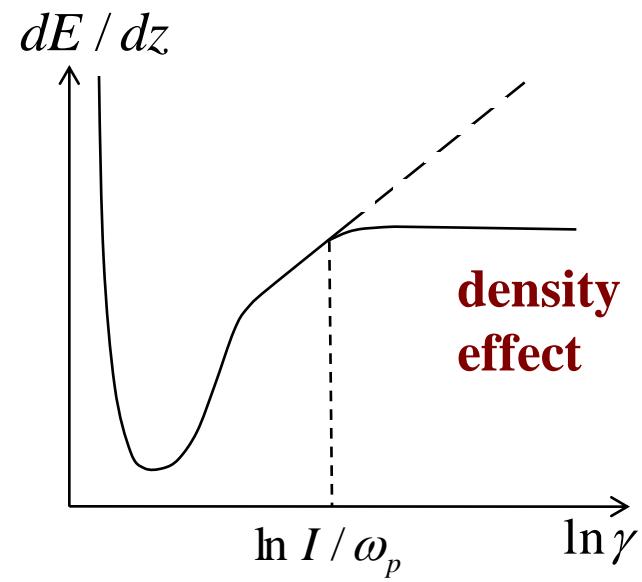
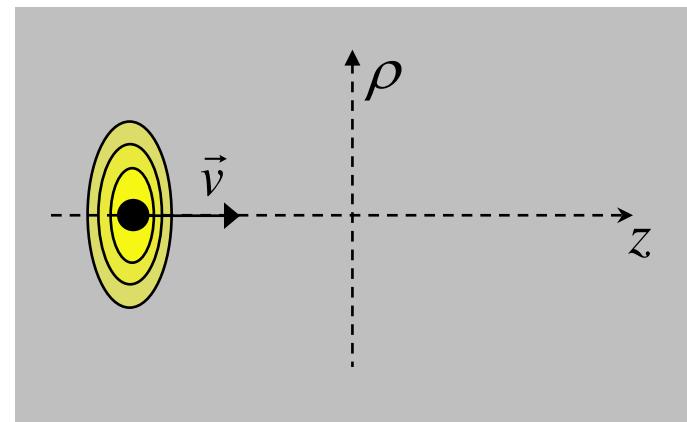
$$\varphi(\vec{r}, t) = \varphi_{Coul} e^{-\omega_p \sqrt{\rho^2 + \gamma^2(z - vt)^2}}$$

Screening of the field for:

$$\rho > 1 / \omega_p$$

Ionization energy loss:

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



# THIN LAYER OF SUBSTANCE

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

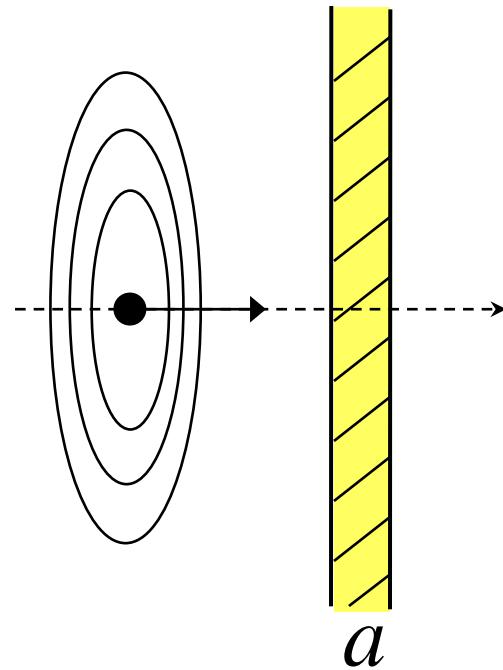
*Garibian G.M.// JETP, 1959*

Total absence of the density effect in thin plates:

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

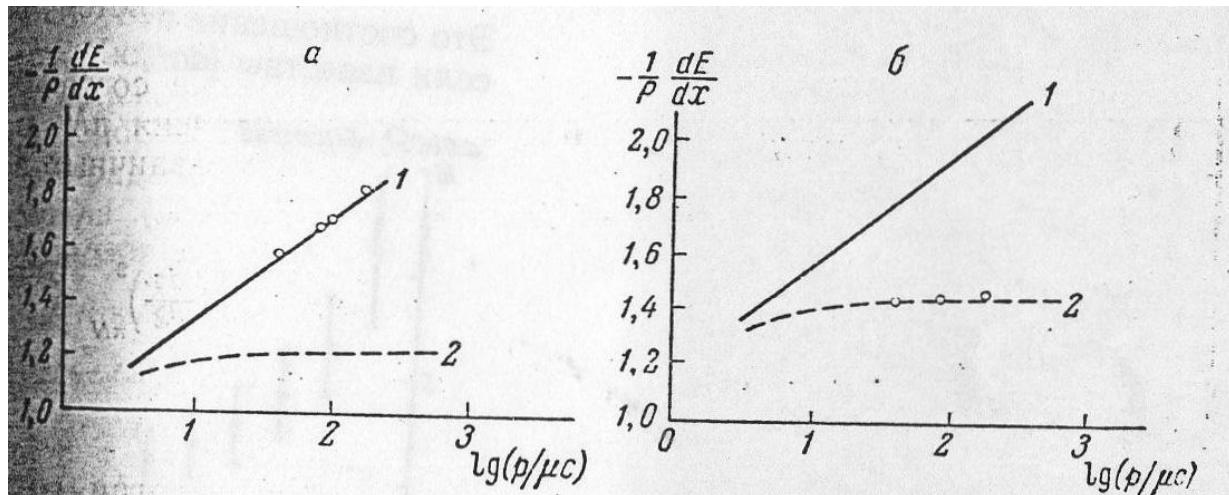
Particle energy loss:

$$\Delta E = \frac{\omega_p^2 e^2}{v^2} a \ln \frac{\gamma}{bI} - \text{arbitrary } \gamma$$



# 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  $10^{-6} \text{ cm}$  (a) and  $2 \times 10^{-3} \text{ cm}$  (b)  
1 – theoretical curve without density effect  
2 – theoretical curve with density effect  
circles show the measurement results

# ANALOGUE IN K-SHELL IONIZATION

**Lack of density effect for inner-shell excitation in thin targets**

## Experiment

*L. Middleman, R. Ford, R. Hofstadter // Phys. Rev. A, 1970*

*G. Dangerfield, B. Spicer // J. Phys. B, 1975*

*K. Ishii et al. // Phys. Rev. A, 1977*

*D. Hoffmann et al. // Z. Phys. A, 1979*

*M. Kamiya et al. // Phys. Rev. A, 1980*

*H. Genz et al. // Z. Phys. A, 1982*

*J. Bak et al. // Phys. Rev. Lett., 1983*

*J. Bak et al. // Phys. Scr., 1986*

*W. Meyerhof et al. // Phys. Rev. Lett., 1992*

*D. Spooner et al. // Z. Phys. D, 1994*

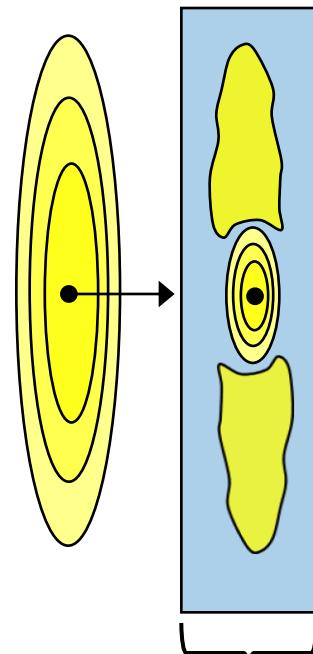
## Theory

*Sørensen A. // Phys. Rev. A, 1987*

*V.K. Yermilova, V.A. Chechin // Z. Phys. D, 1989*

# ELECTRON'S FIELD INSIDE THIN PLATE

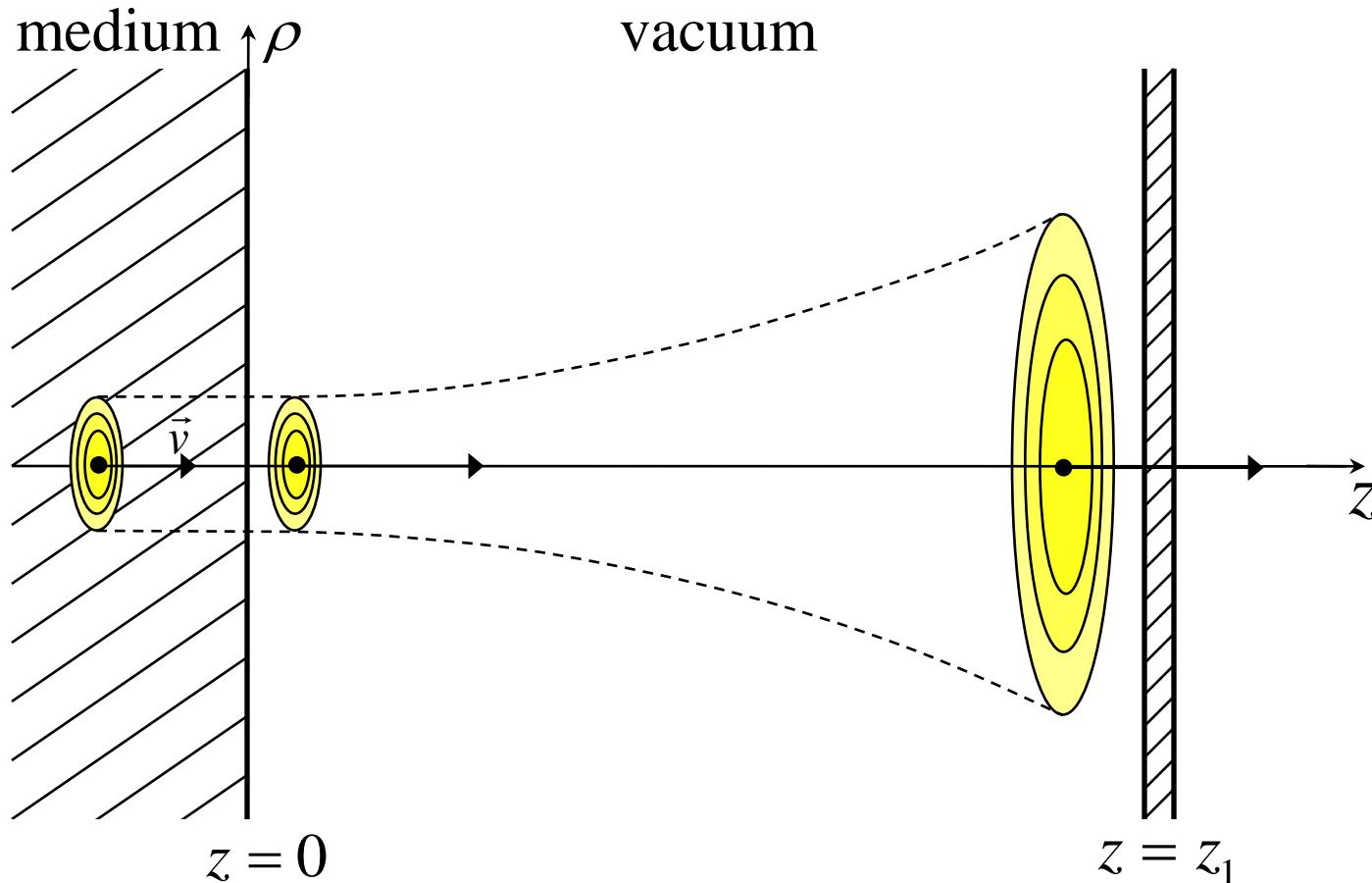
On distances  $z \leq I / \omega_p^2$  from the interface additional ionization is made by transition radiation and the total field around the electron is similar to its field in vacuum



$$a \leq I / \omega_p^2 \approx \text{absorption length}$$

$I$  – mean ionization potential

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



# STRUCTURE OF THE FIELD IN VACUUM

Fourier component of the total field in vacuum ( $\gamma \gg 1, \omega \gg \omega_p$ ):

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

packet of free waves  
(transition radiation)
Coulomb  
field

For  $z \rightarrow 0$ :

$$E_\omega^\rho(\rho) = \frac{2e}{v} \sqrt{\frac{\omega^2}{\gamma^2} + \omega_p^2} K_1\left(\rho \sqrt{\frac{\omega^2}{\gamma^2} + \omega_p^2}\right) e^{i\frac{\omega}{v}z}$$

suppressed frequencies  $\omega \leq \gamma\omega_p$

electron is ‘half-bare’

$K_1(x)$  – Macdonald function

For  $z > 2\gamma^2/\omega$ :

$$E_\omega^\rho(\rho, z) = \frac{2e}{v} \left\{ \frac{\omega}{\gamma} K_1\left(\frac{\omega}{\gamma} \rho\right) e^{i\frac{\omega}{v}z} + \frac{e^{i\omega r}}{r} F(\rho/z) \right\} \quad r = \sqrt{\rho^2 + z^2}$$

# IONIZATION OF SUBSTANCE BY EXTERNAL FIELD

$$\omega_0 = I$$

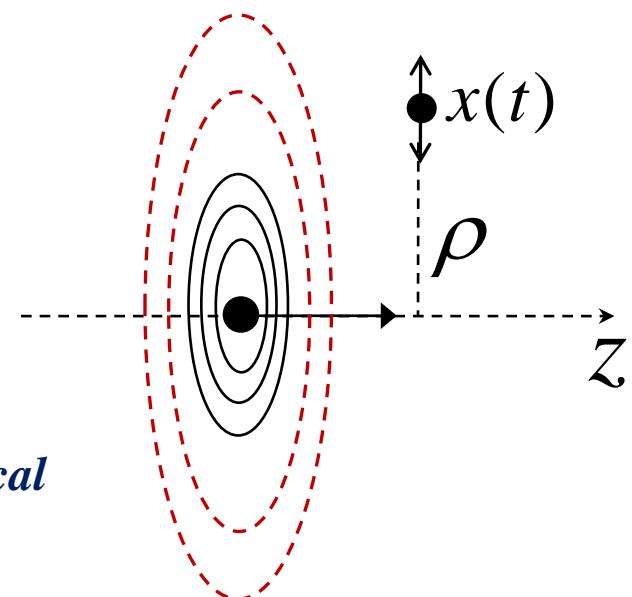
$$\ddot{x} + \beta \dot{x} + \omega_0^2 x = \frac{e}{m} (E_\rho^C + E_\rho^F)$$

Energy transfer to a harmonic oscillator by external field:

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

*J.D. Jackson // Classical electrodynamics, 1999*

$\omega_0$  – oscillator's own frequency



Total ionization per unit path:

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

# IONIZATION LOSS OF ‘HALF-BARE’ ELECTRON

Total ionization per unit path in the plate ( $q_0 \gg \omega_p \gg I/\gamma$ ):

$$\begin{aligned} \frac{d\mathcal{E}}{dz} = & \eta_p^2 e^2 \left\{ \ln \frac{q_0 \gamma}{I} + \ln \frac{\omega_p \gamma}{I} + \right. \\ & + Ci(\lambda_\gamma) - \cos \lambda_p Ci(\lambda_p + \lambda_\gamma) - \sin \lambda_p Si(\lambda_p + \lambda_\gamma) + \\ & \left. + \lambda_\gamma Si(\lambda_\gamma) + \cos \lambda_\gamma \right\} \end{aligned}$$

where:

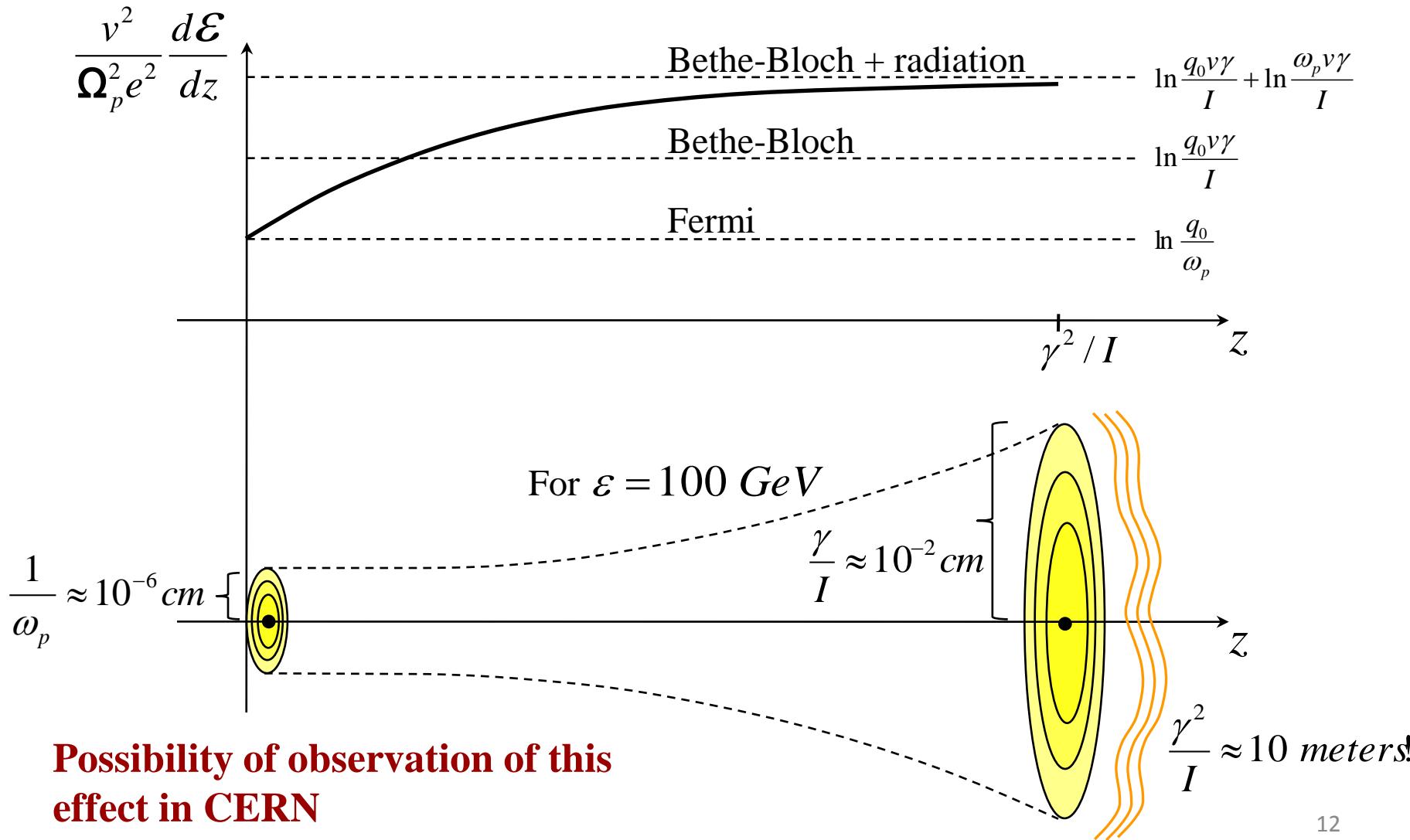
$$\lambda_p = z_1 \omega_p^2 / 2I \quad \lambda_\gamma = Iz_1 / 2\gamma^2$$

$\eta_p$  – plasma frequency of the plate

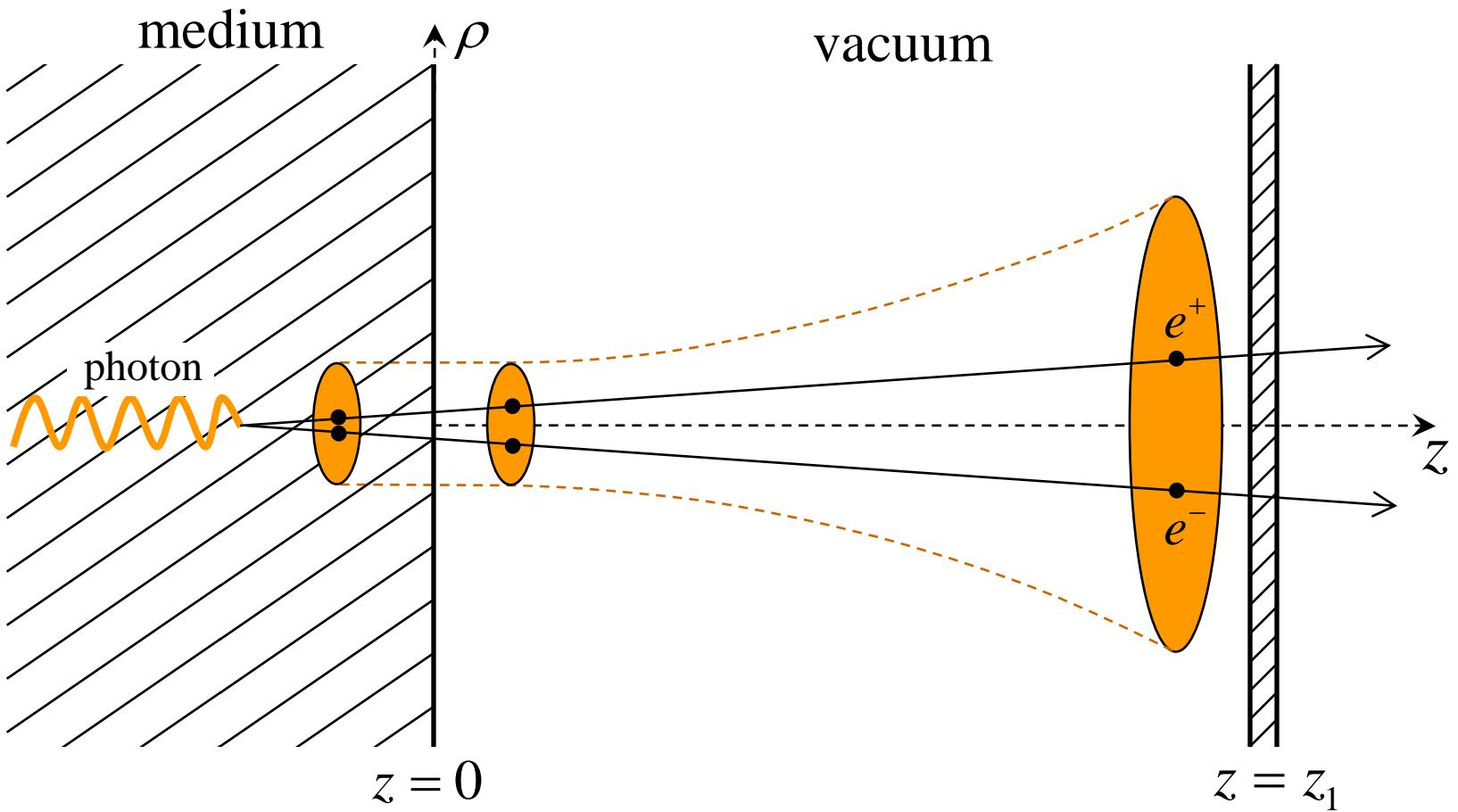
$z_1$  – plate coordinate

$I$  – mean ionization potential

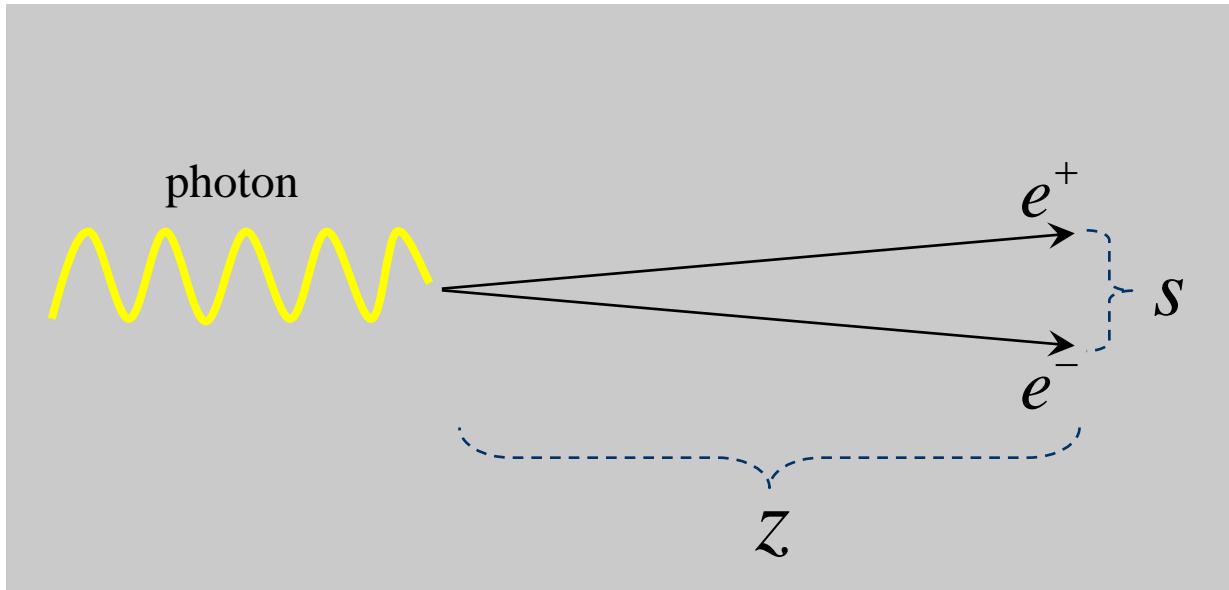
# IONIZATION ENERGY LOSS OF ‘HALF-BARE’ ELECTRON (from Fermi to Bethe-Bloch formula)



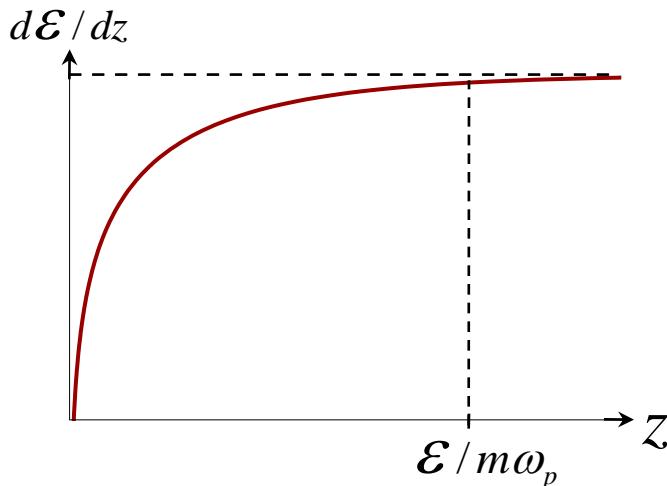
# PAIR IONIZATION LOSS IN THIN PLATE



# CHUDAKOV EFFECT



Dependence of pair ionization loss on distance from pair creation point:

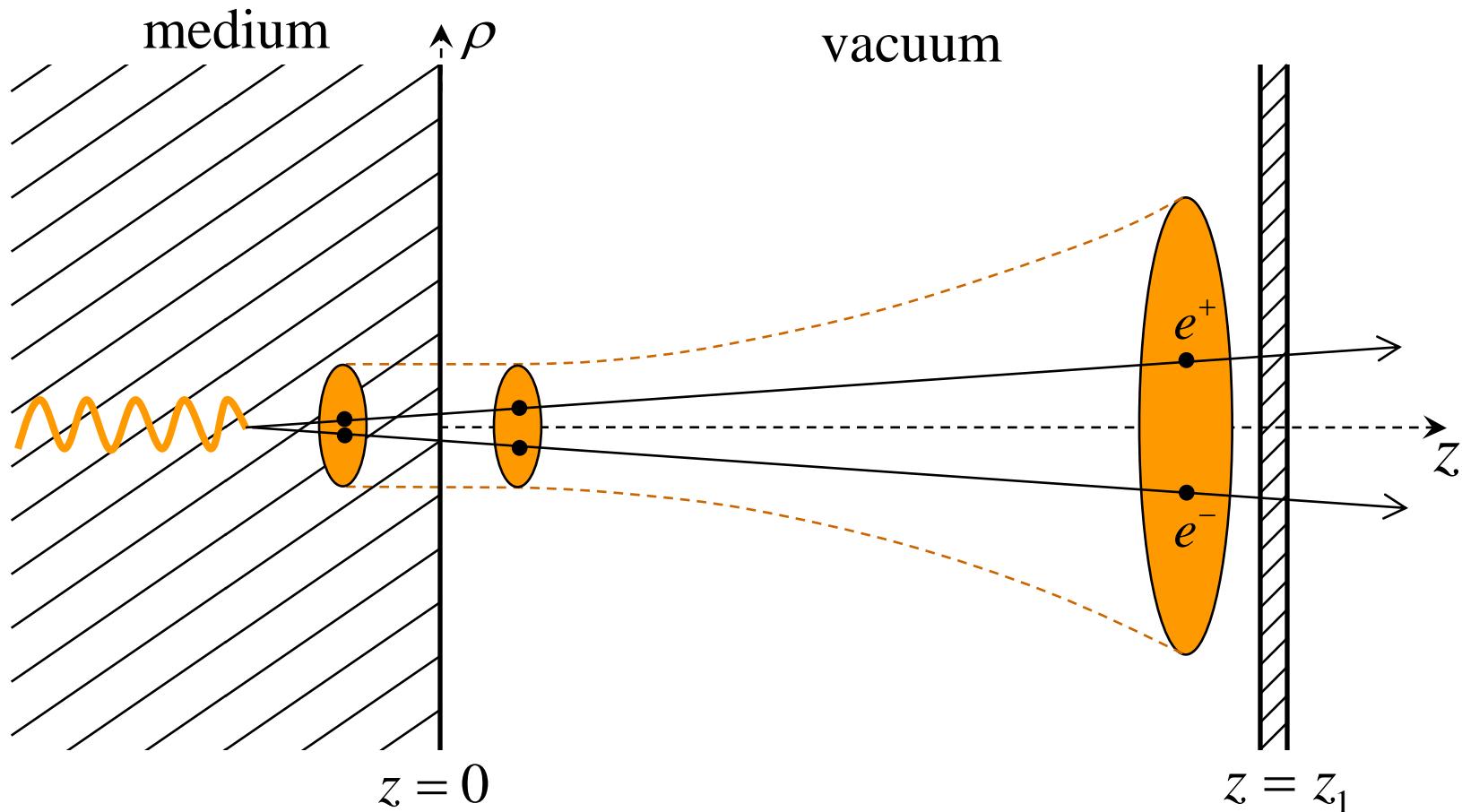


**For  $z < \mathcal{E} / m\omega_p$  (which is for  $s < 1/\omega_p$ ):**

strong suppression of ionization energy losses due to destructive interference of electron's and positron's fields

$\mathcal{E}$  – pair energy

# PAIR IONIZATION LOSS IN THIN PLATE



- Interference influences on ionization loss on much larger distances  $z < \mathcal{E}^2 / m^2 I$
- Possibility of existence of effect opposite to the one of Chudakov

More detailed – in poster

# CONCLUSIONS

- ❖ Modification of the result of Garibian for high-energy particle ionization loss in thin plate in the case when the incident particle has nonequilibrium field
- ❖ Gradual change of particle ionization loss in the plate from Fermi to Bethe-Bloch mode (supplemented by additional ionization by transition radiation) with the increase of distance between the plate and the substance
- ❖ Modification of Chudakov effect in the case of electron-positron pair energy loss in thin plate