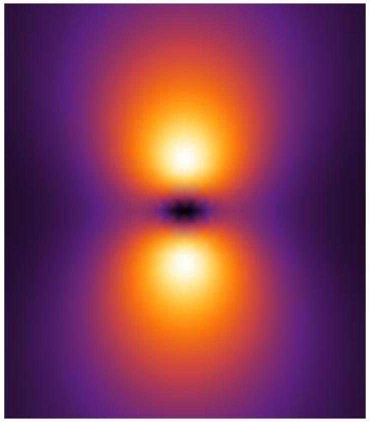
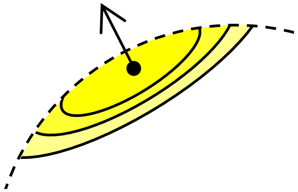
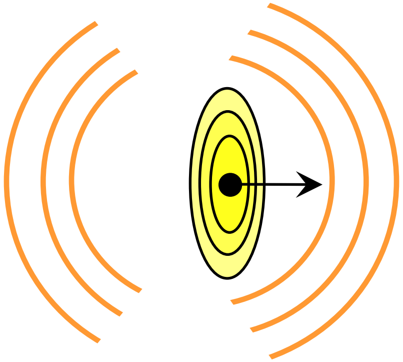
HIGH-ENERGY ELECTRODYNAMIC PROCESSES WITH “HALF-BARE” ELECTRONS

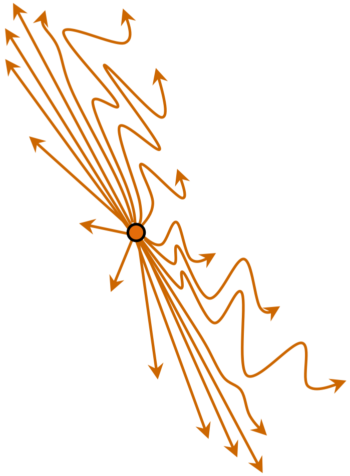


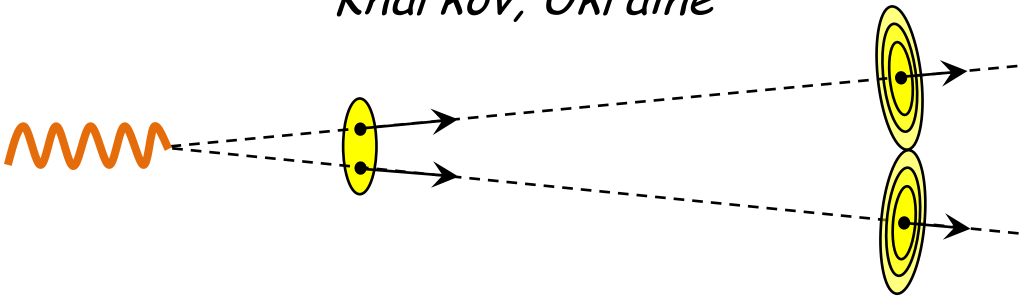


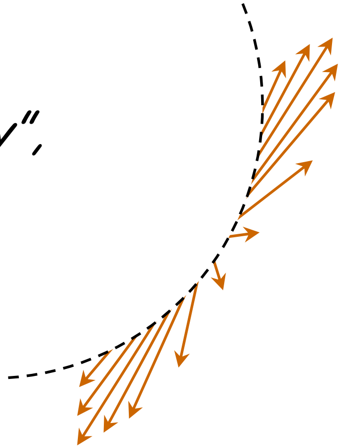


S.V. Trofymenko

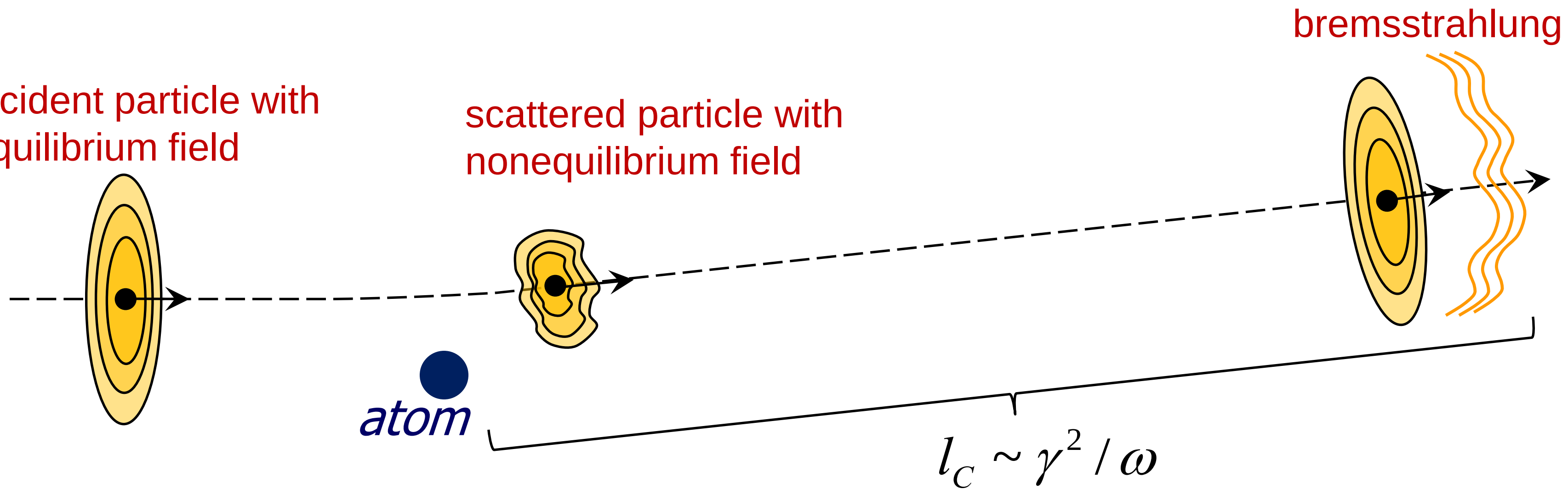
NSC "Kharkov Institute of Physics and Technology",
Karazin Kharkov National University
Kharkov, Ukraine







COHERENCE (FORMATION) LENGTH. ‘HALF-BARE’ ELECTRON



incident particle with equilibrium field

scattered particle with nonequilibrium field

bremsstrahlung

atom

$$l_C \sim \gamma^2 / \omega$$

γ – Lorentz-factor

ω – radiated frequency

$$\mathbf{E}(\mathbf{r},t) = \int_{-\infty}^{+\infty} d\omega \int d^3k \, \underbrace{\mathbf{E}(\mathbf{k},\omega) e^{i(\mathbf{kr}-\omega t)}}_{\text{plane wave (virtual photon)}}$$

the frequency ω appears

on distance $l_C \sim \gamma^2 / \omega$

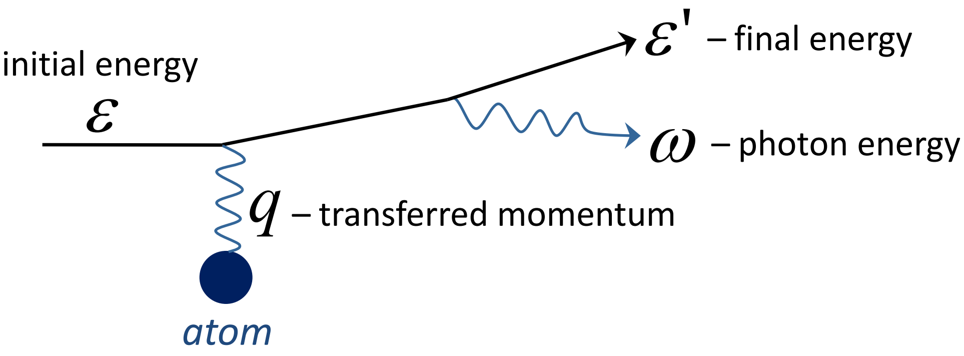
from the interaction area

within coherence length part of Fourier-components is absent in the field around the particle –
the particle is ‘half-bare’

E.L. Feinberg // Sov.Phys.JETP, 1966

COHERENCE LENGTH. QUANTUM POINT OF VIEW

M.L. Ter-Mikaelyan // JETP, 1953



initial energy ε

ε' – final energy

ω – photon energy

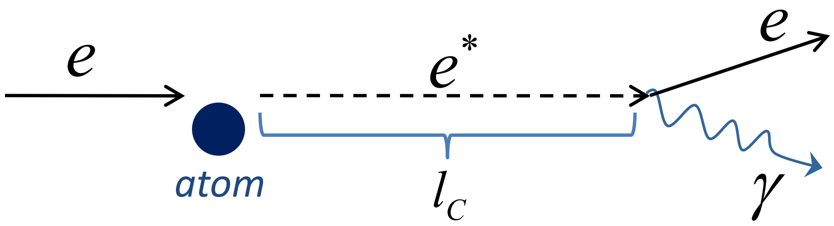
q – transferred momentum

atom

$$l_C \sim \frac{1}{q_\parallel} \approx \frac{2\varepsilon\varepsilon'}{\omega m^2}$$

For $\omega << \varepsilon$:

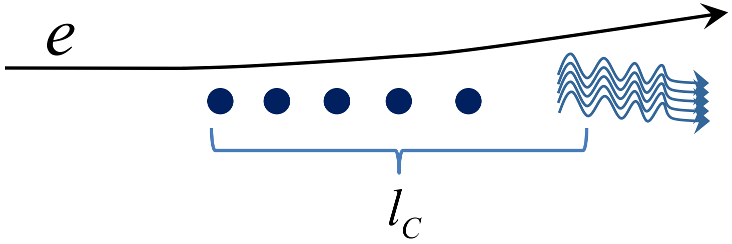
$$l_C \sim \gamma^2 / \omega$$



E.L. Feinberg // Sov.Phys.Usp, 1980

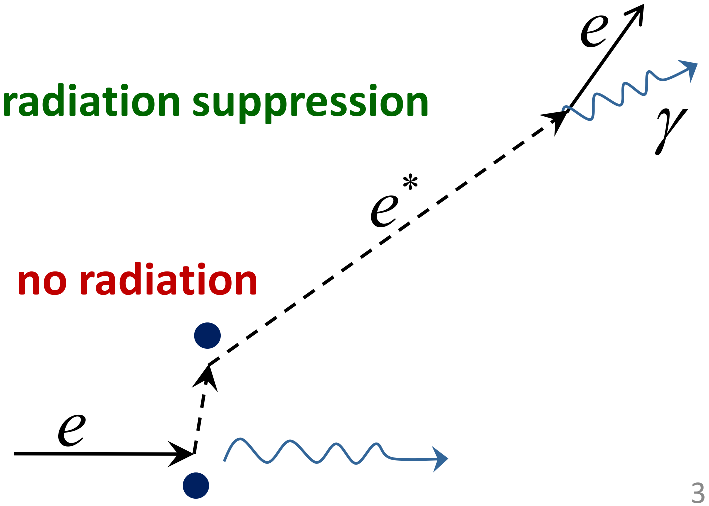
$$T^* >> T_{\text{int}}$$

coherent radiation



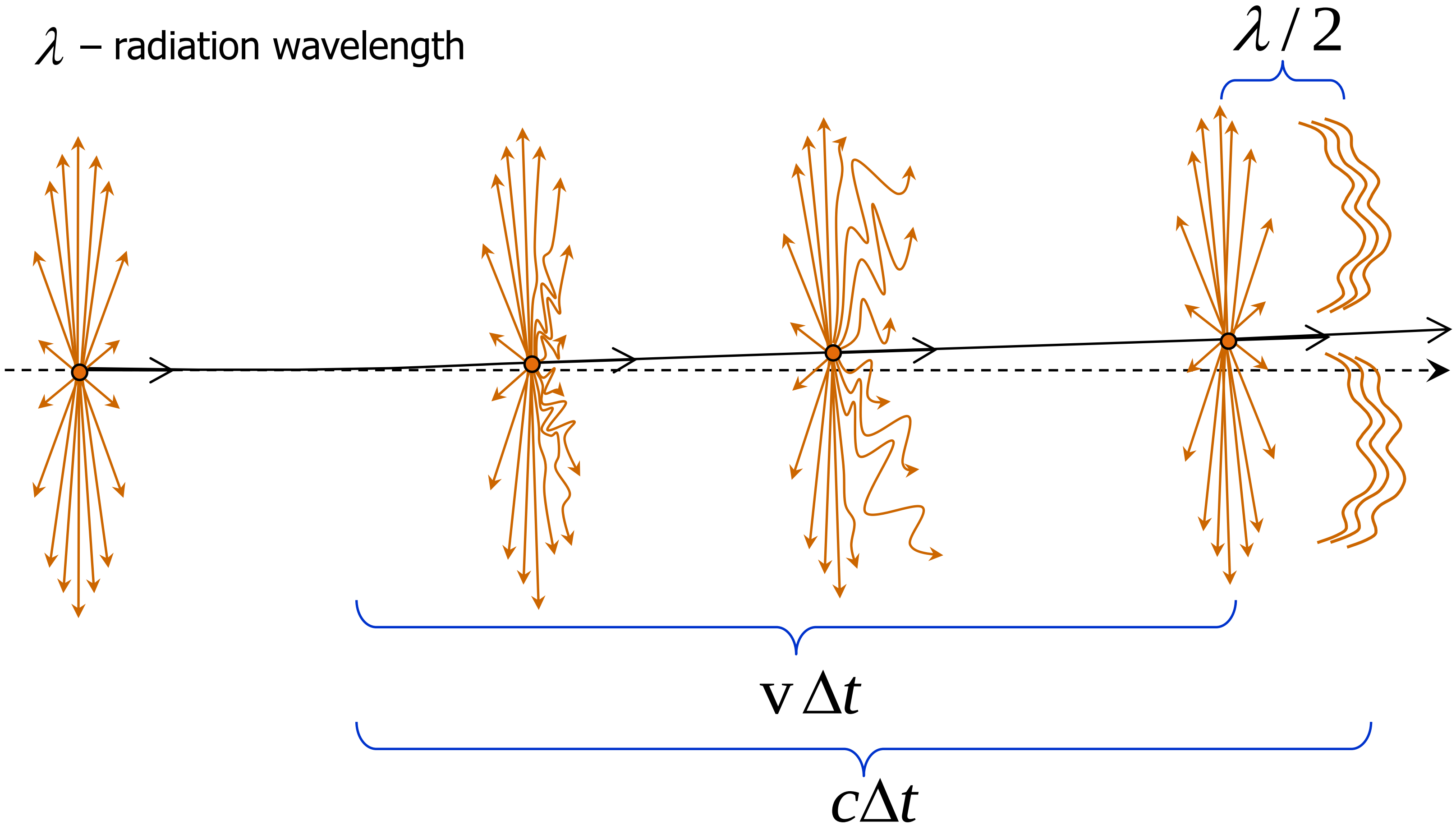
radiation suppression

no radiation



«CLASSICAL» FORMATION LENGTH

λ – radiation wavelength



$$(c-\mathrm{v})\Delta t = \lambda / 2$$

$$c-\mathrm{v} = c(1-\mathrm{v}/c) \approx c\,\frac{1-\mathrm{v}^2/c^2}{2} = \frac{c}{2\gamma^2}$$

$$\Delta t = \gamma^2 \lambda / c$$

$$l_C = c\Delta t = \gamma^2 \lambda$$

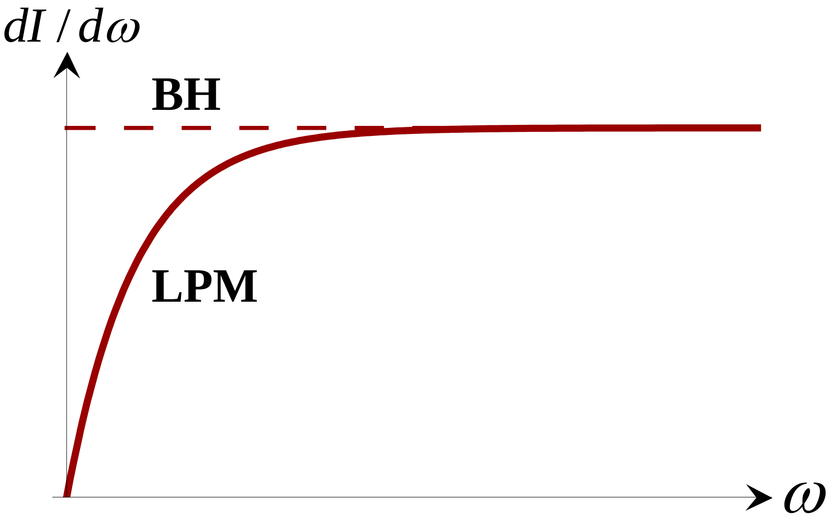
MANIFESTATION OF 'HALF-BARE' STATE IN BRAMSSTRAHLUNG

1) Coherent bremsstrahlung

M.L. Ter-Mikaelyan // JETP, 1953

H. Überall // Phys.Rev., 1956

2) Landau-Pomeranchuk-Migdal effect (suppression of Bethe-Heitler spectrum al low frequencies)
Observed in SLAC (1993)



3) Ternovsky-Shul'ga-Fomin effect (bremsstrahlung suppression in thin layers of substance)

Observed in CERN NA63 experiment:

H.D. Thomsen, K.K. Andersen, J. Esberg, H. Knudsen, M. Lund, K.R. Hansen, U.I. Uggerhøj et. al. // Phys.Lett.B, 2009

U. Uggerhøj : '… we have seen the 'half–bare' electron !'

IN THE PRESENT TALK

Investigation of the influence of half-bare state of electron upon its:

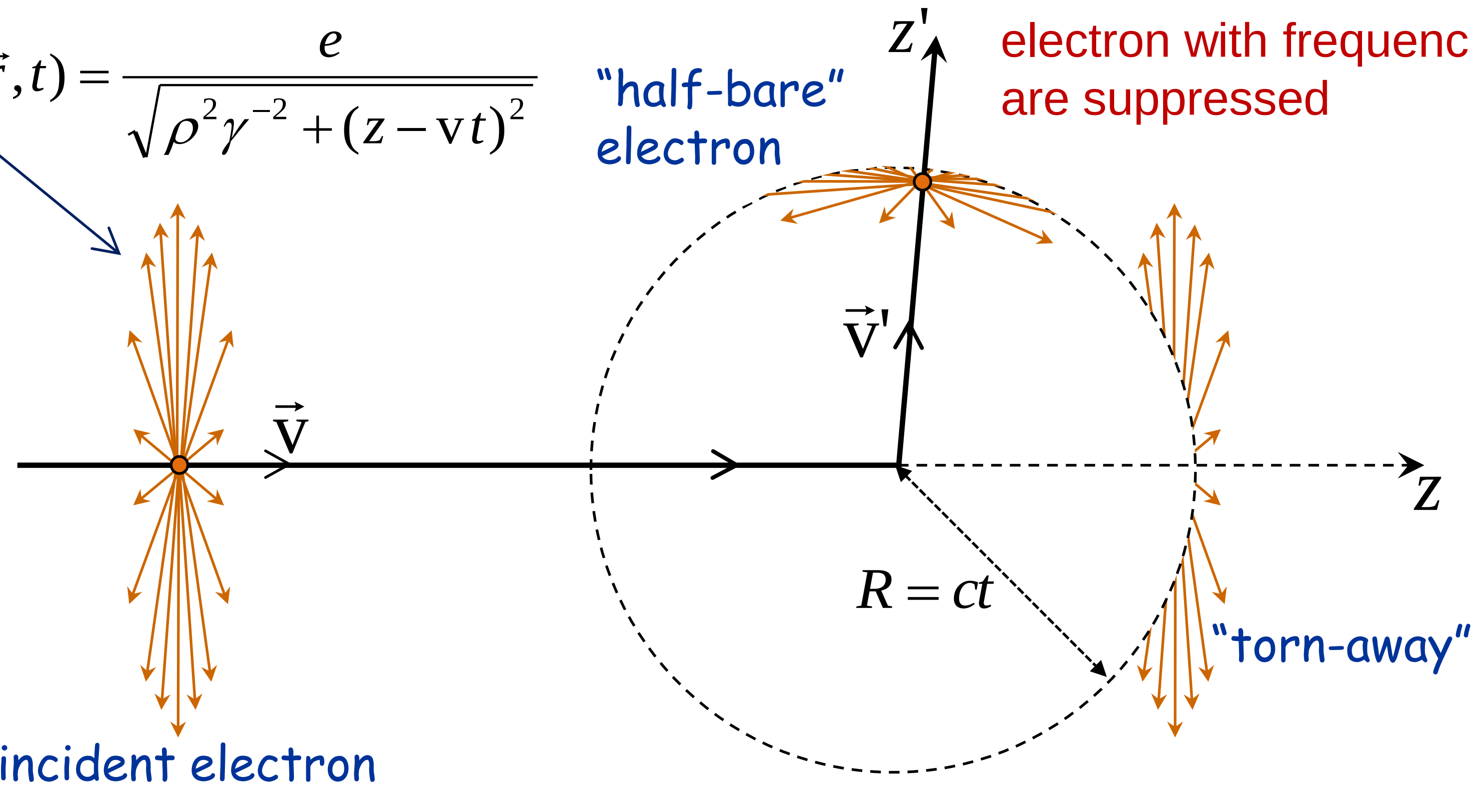
1) Transition radiation

2) Ionization energy loss

3) X-ray emission in crystal

"HALF-BARE" ELECTRON

At $t<2\gamma^2/\omega_0$ Fourier components of the field around the scattered electron with frequencies $\omega < \omega_0$ are suppressed



$$\varphi_{\mathrm{v}}(\vec{r},t) = \frac{e}{\sqrt{\rho^2\gamma^{-2} + (z-\mathrm{v}t)^2}}$$

"half-bare" electron

incident electron

"torn-away" field

Scalar potential of the total field for $t > 0$:

$$\varphi(\vec{r},t) = \theta(r-ct)\varphi_{\mathrm{v}}(\vec{r},t) + \theta(ct-r)\varphi_{\mathrm{v}'}(\vec{r},t)$$

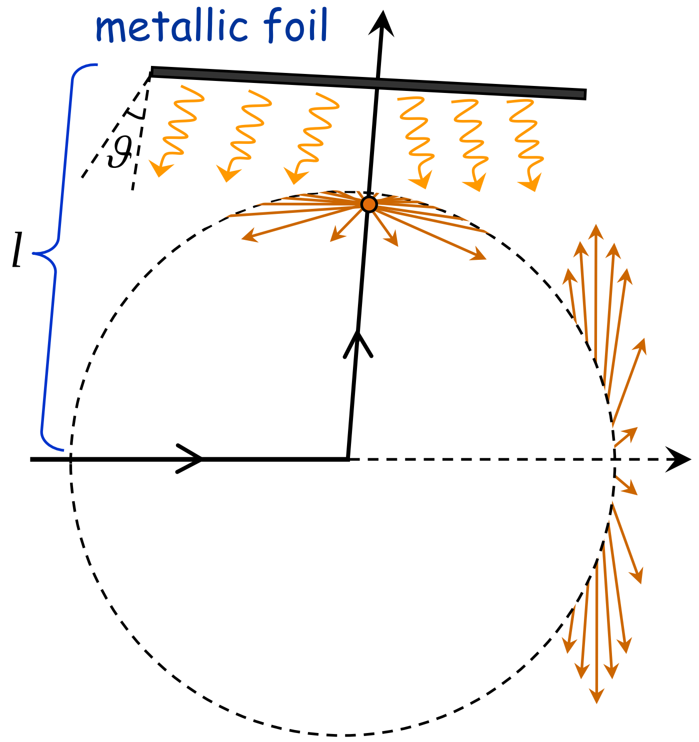
$$\theta(x>0)=1$$

$$\theta(x<0)=0$$

E.L. Feinberg // Sov. Phys. Usp, 1980

A.I Akhiezer, N.F Shul'ga, "High Energy Electrodynamics in Matter", 1996

TRANSITION RADIATION BY HALF-BARE ELECTRON

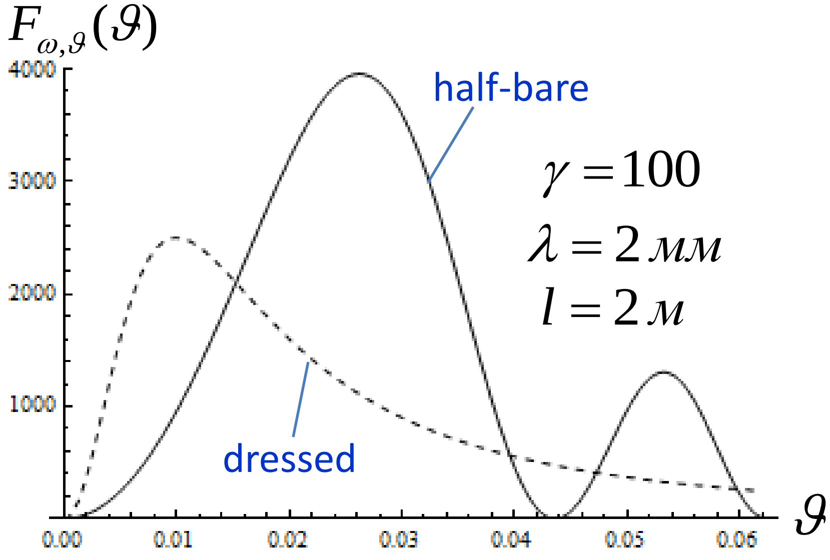


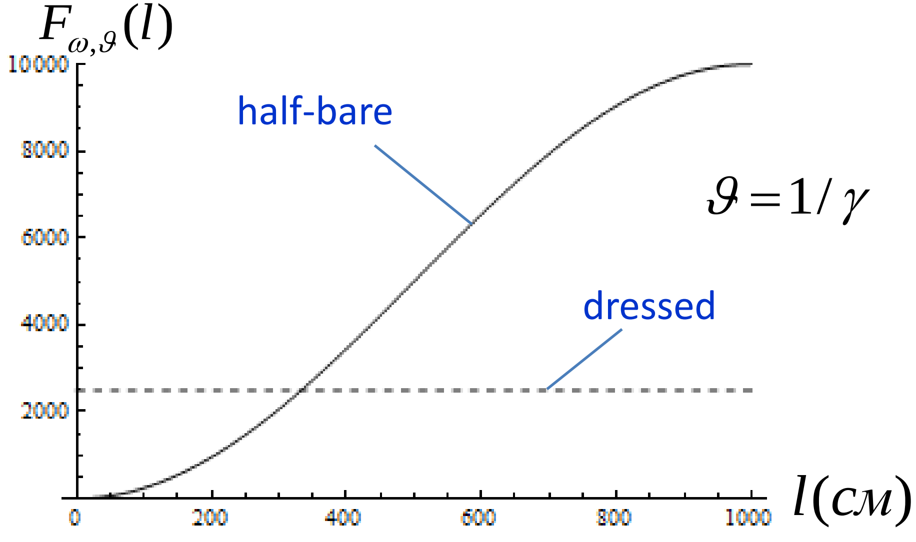
N.F. Shul'ga, S.V. Trofymenko,
V.V. Syshchenko // JETP Lett. (2011)

Spectral-angular density of TR by half-bare electron:

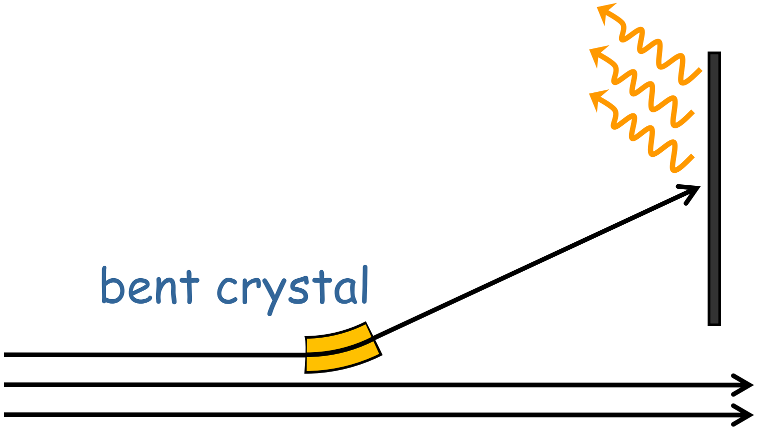
$$\frac{d^2W}{d\omega\, do} = \frac{e^2}{\pi^2}\frac{\vartheta^2}{(\vartheta^2+\gamma^{-2})^2}\, 4\sin^2\left(\frac{l}{2l_C}\right)$$

$$F_{\omega,\vartheta} = \frac{\pi^2}{e^2}\frac{d^2W}{d\omega\, do} \qquad l_C \sim \frac{\lambda}{(\gamma^{-2}+\vartheta^2)}$$

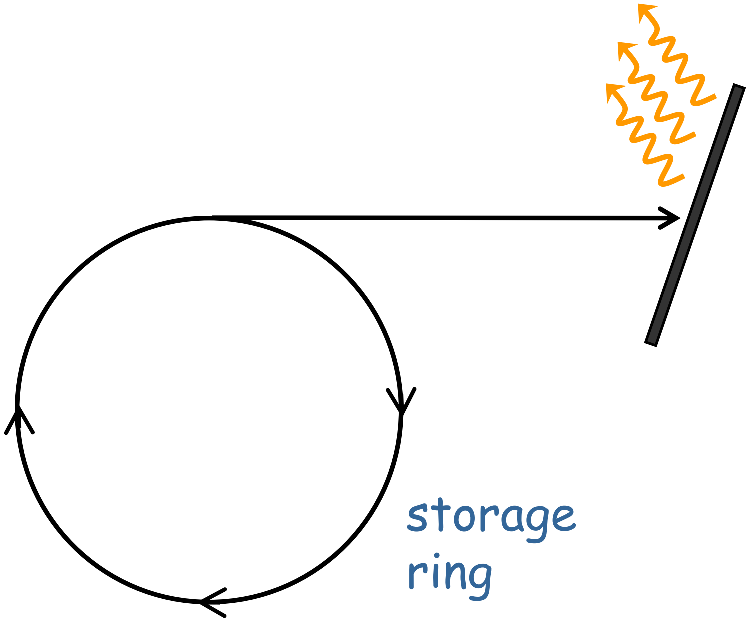




TRANSITION RADIATION BY ‘HALF-BARE’ ELECTRON



Extracted beams may be an example of ‘half-bare’ particle beams



For 10 GeV electrons even in optical region

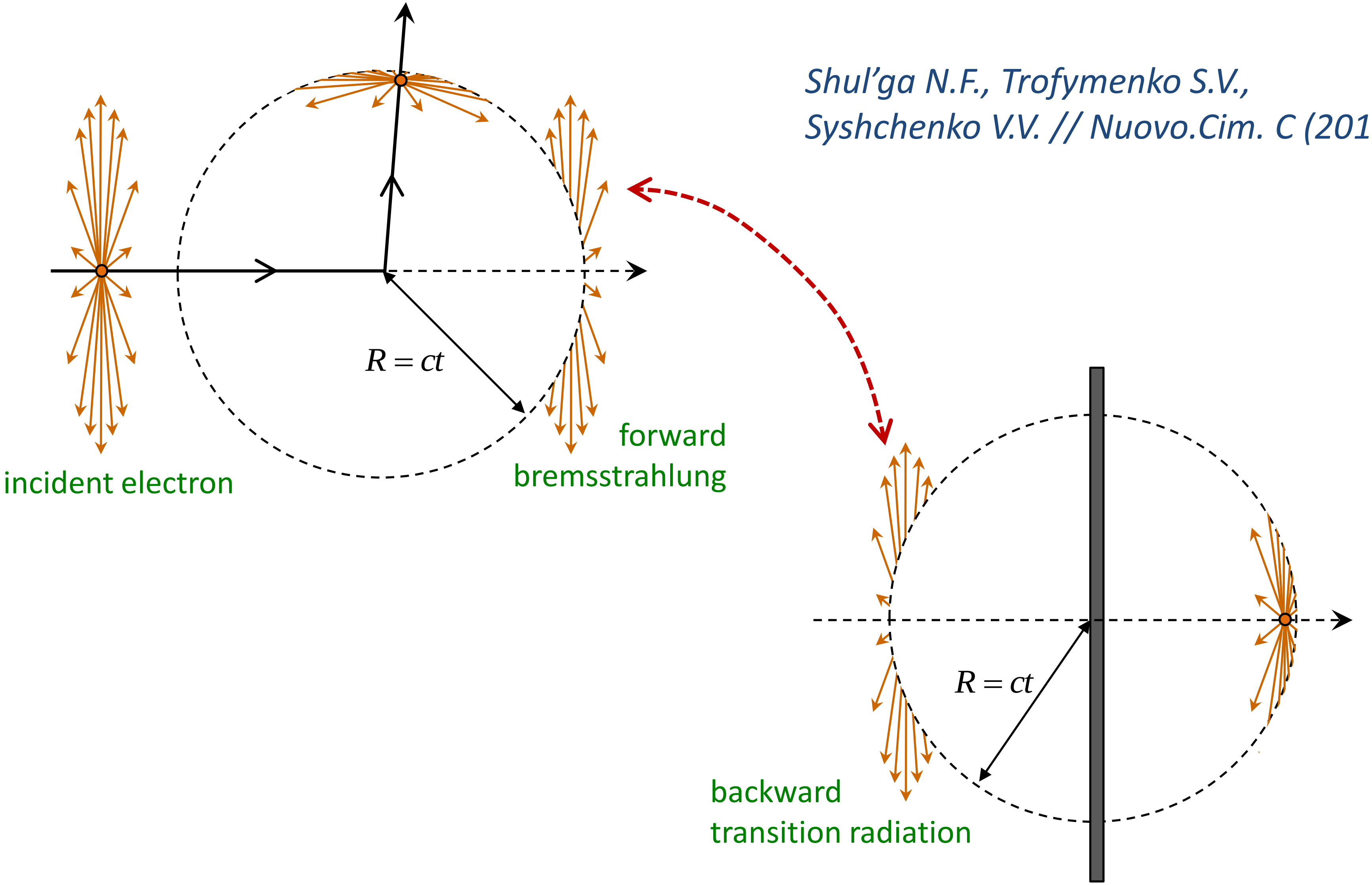
$$l_C \sim \gamma^2 / \omega \sim 200\,m$$

(in millimeter region

$l_C \sim 400\,km$!)

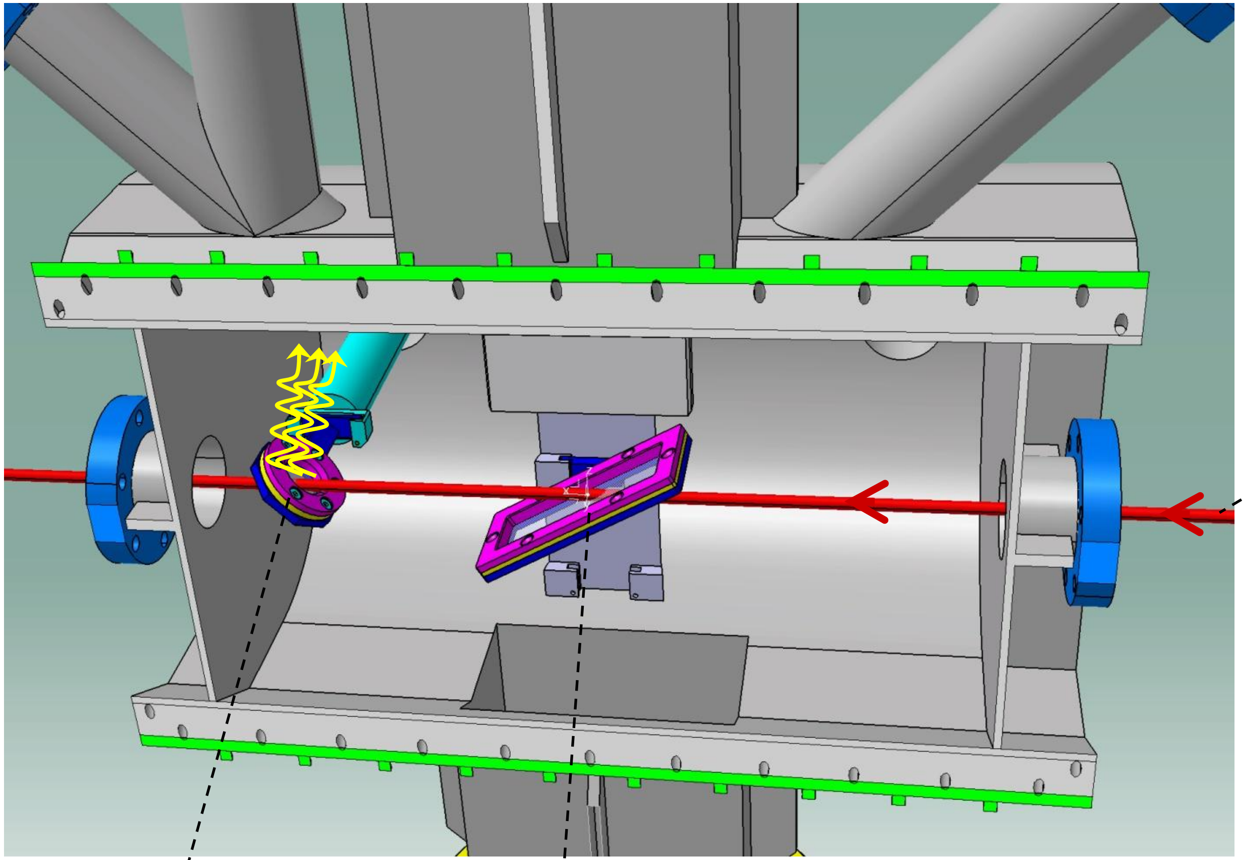
ANALOGOUS FIELD STRUCTURE IN TRANSITION RADIATION AND BREMSSTRAHLUNG PROCESSES

Shul'ga N.F., Trofymenko S.V., Syshchenko V.V. // Nuovo.Cim. C (2011)



EXPERIMENT ON HALF-BARE ELECTRON TR INVESTIGATION BEING PREPARED AT CLIO

S. Trofymenko, N. Shul'ga, N. Delerue, S. Jenzer, V. Khodnevych,
A. Migayron // J. Phys. (2017)



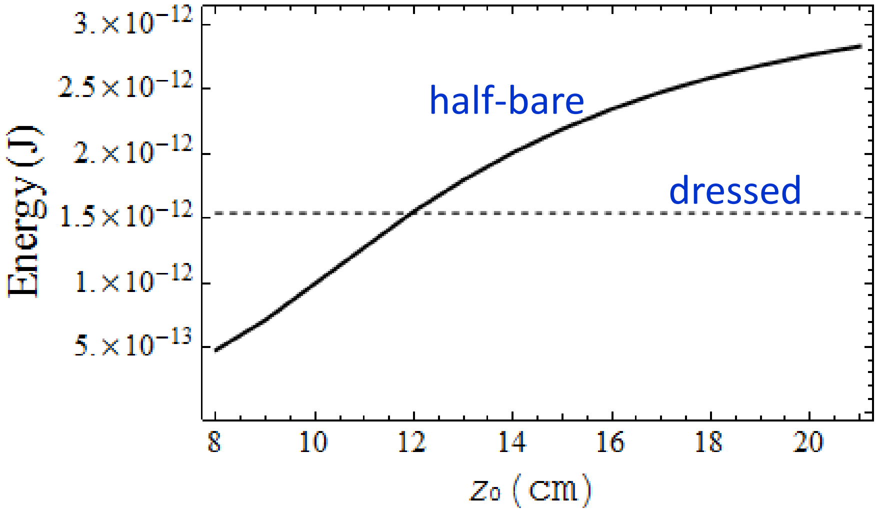
45 MeV electron beam

radiating screen (downstream)

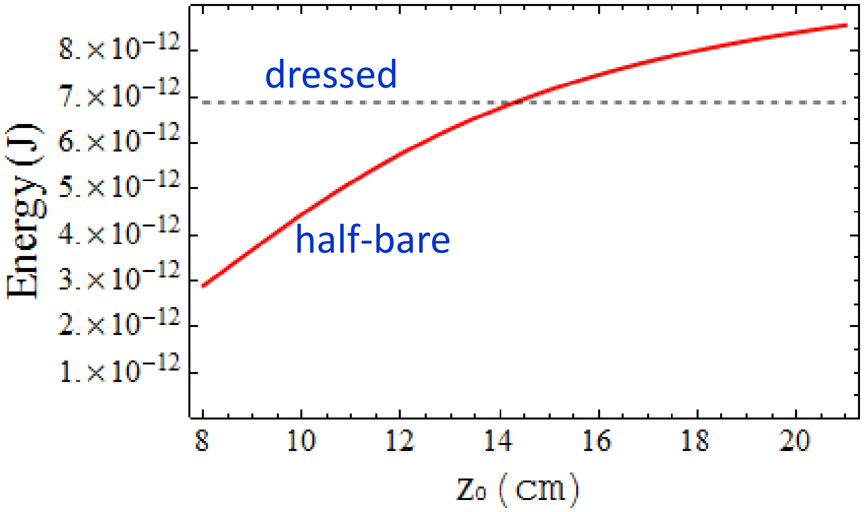
"undressing" screen (upstream)

EXPECTED SIGNAL AT CLIO (single bunch of 10^9 electrons)

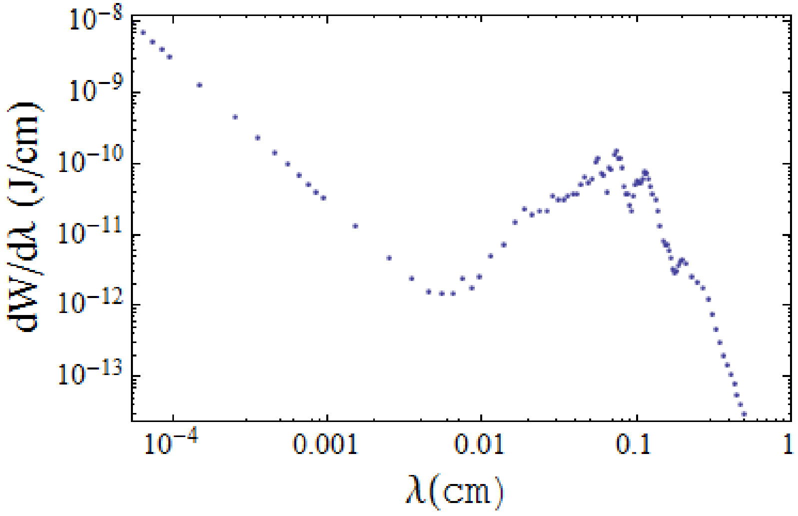
in the range 0.04 cm < λ < 0.06 cm:



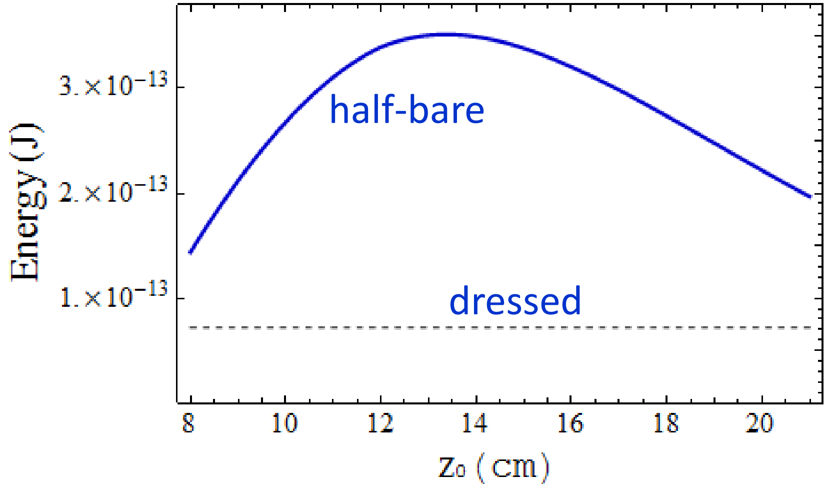
in the range 0.04 cm < λ < 0.5 cm:



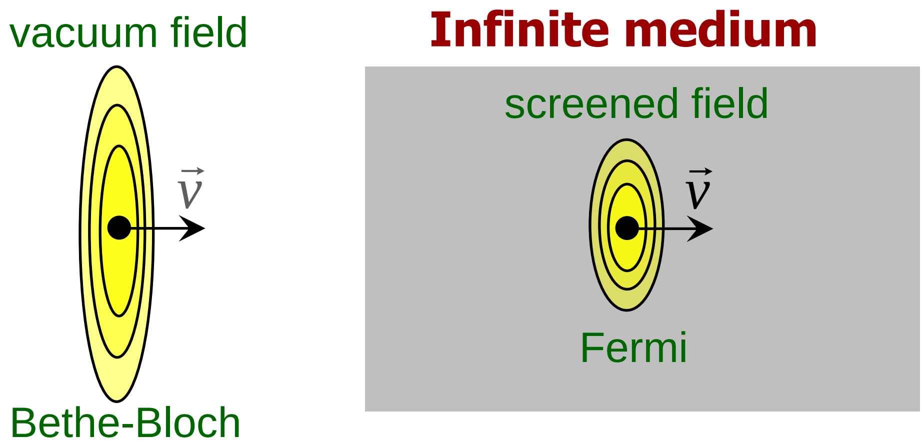
spectrum for "dressed" electron:

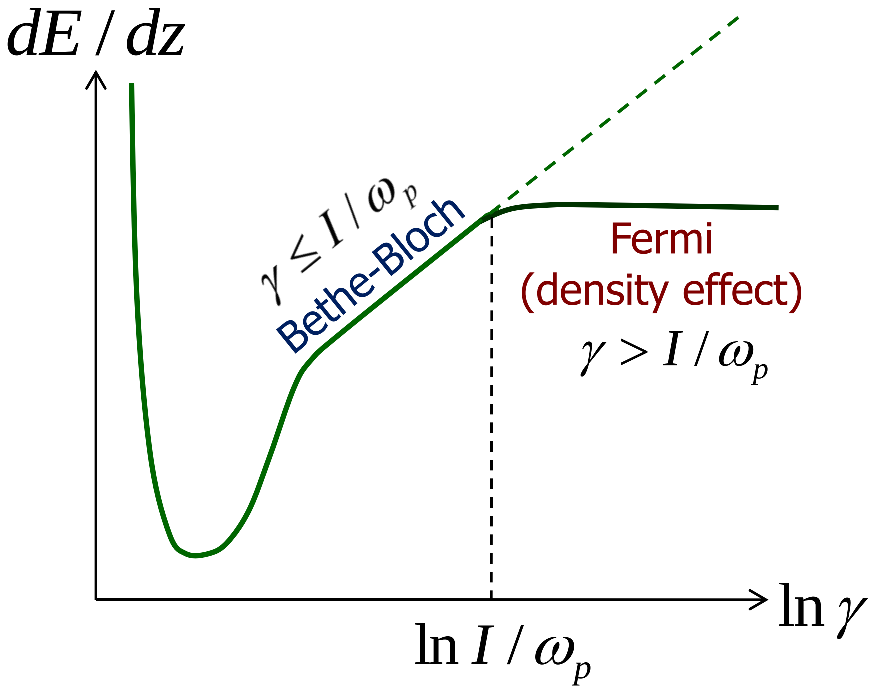


12.5 MeV bunch in the range 0.048 cm < λ < 0.054 cm:



FERMI AND BETHE-BLOCH FORMULAE





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

Bethe-Bloch formula ($\gamma \le I / \omega_p$):

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

Fermi formula ($\gamma > I / \omega_p$):

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

γ – electron Lorentz-factor

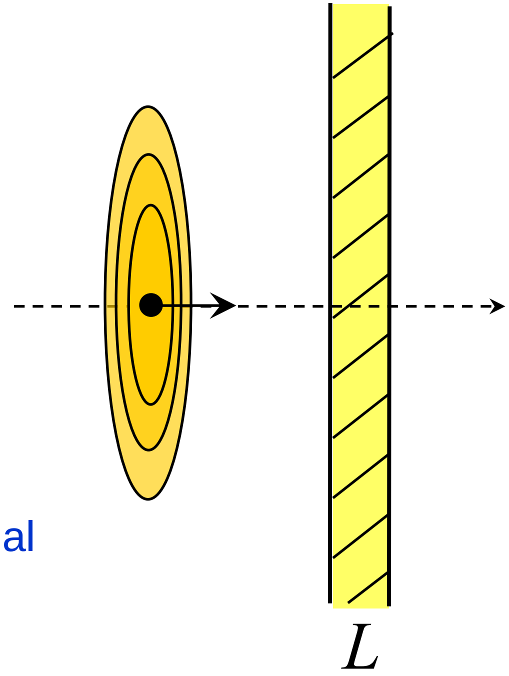
I – mean ionization potential

ω_p – plasma frequency

THIN LAYER OF SUBSTANCE

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

Garibian G.M.// JETP, 1959
Sørensen A. // Phys.Rev.A, 1987



Total absence of the density effect in thin plates:

$$L \le I / \omega_p^2$$

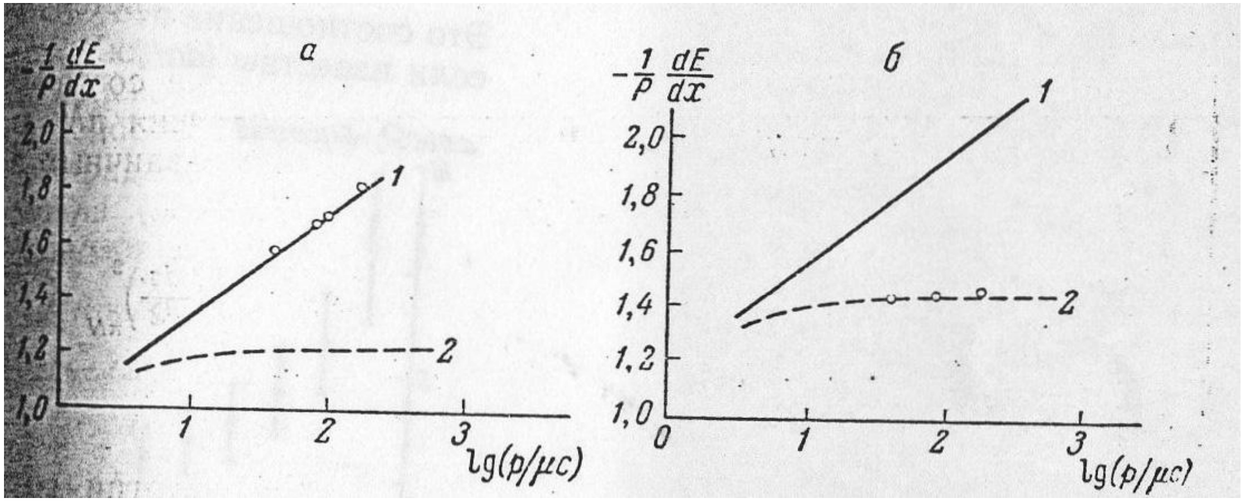
I – mean ionization potential
ω_p – plasma frequency
γ – Lorenz-factor

Particle energy loss:

$$\Delta E = \frac{\omega_p^2 e^2}{v^2} a \ln \frac{\gamma}{bI} \quad \text{for} \quad 1 \le \gamma < \infty$$

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)

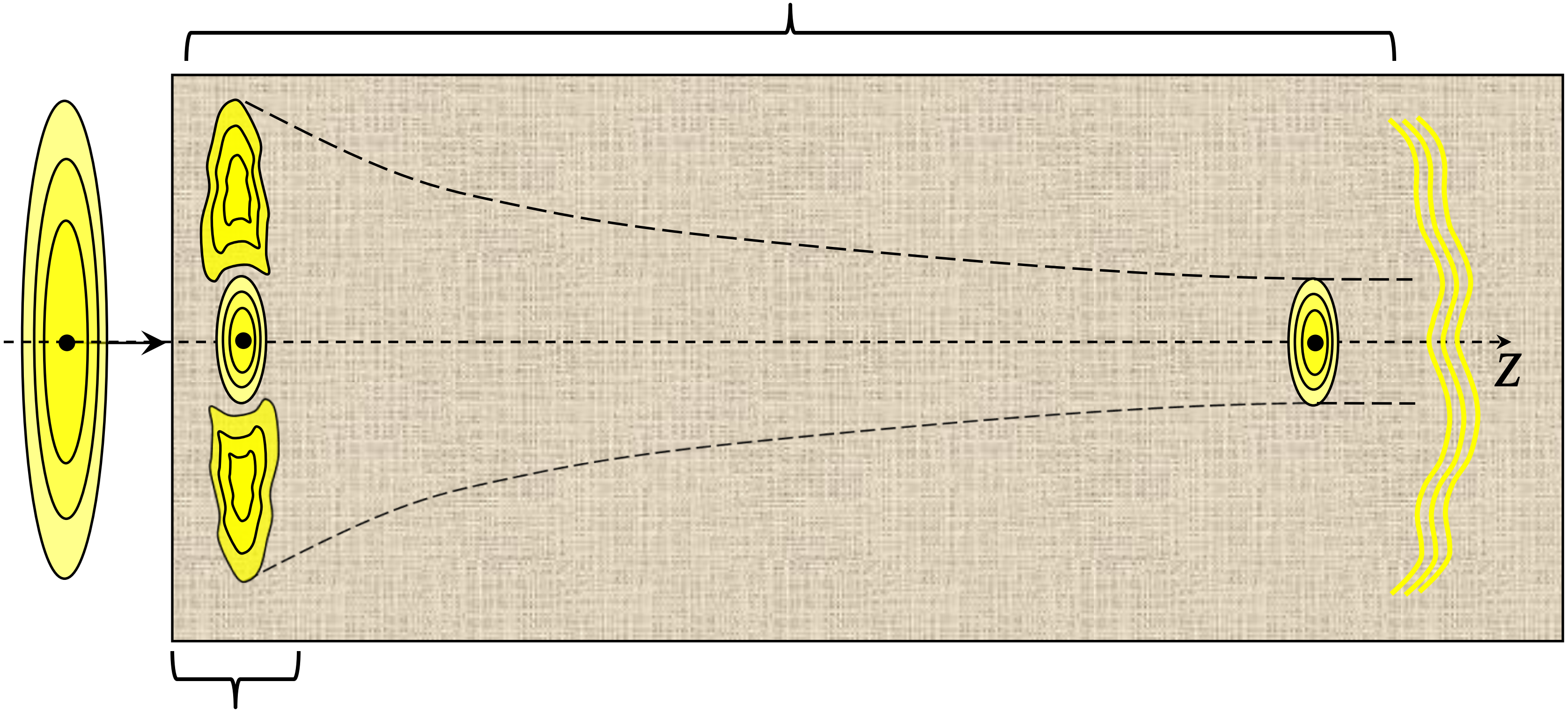
1 – theoretical curve without density effect

2 – theoretical curve with density effect

circles show the measurement results

TRANSFORMATION OF ELECTRON'S FIELD AND IONIZATION LOSS VALUE UPON ENTRANCE INTO THE SUBSTANCE

Field transformation $L \sim \gamma / \omega_p$



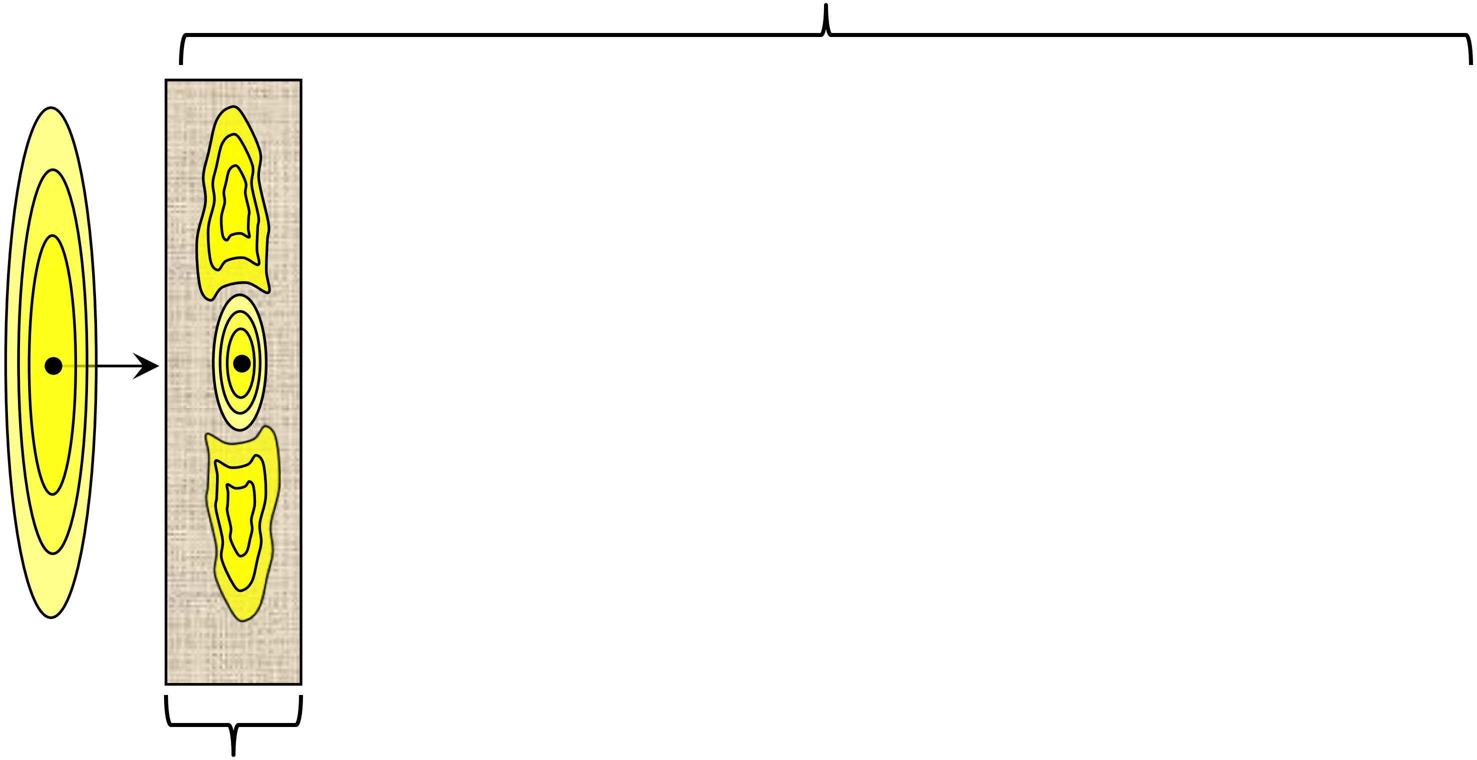
Ionization loss transformation

$L \sim I / \omega_p^2$ ~ absorption length

I – mean ionization potential

TRANSFORMATION OF ELECTRON'S FIELD AND IONIZATION LOSS VALUE UPON ENTRANCE INTO THE SUBSTANCE

Field transformation $L \sim \gamma / \omega_p$



Ionization loss transformation

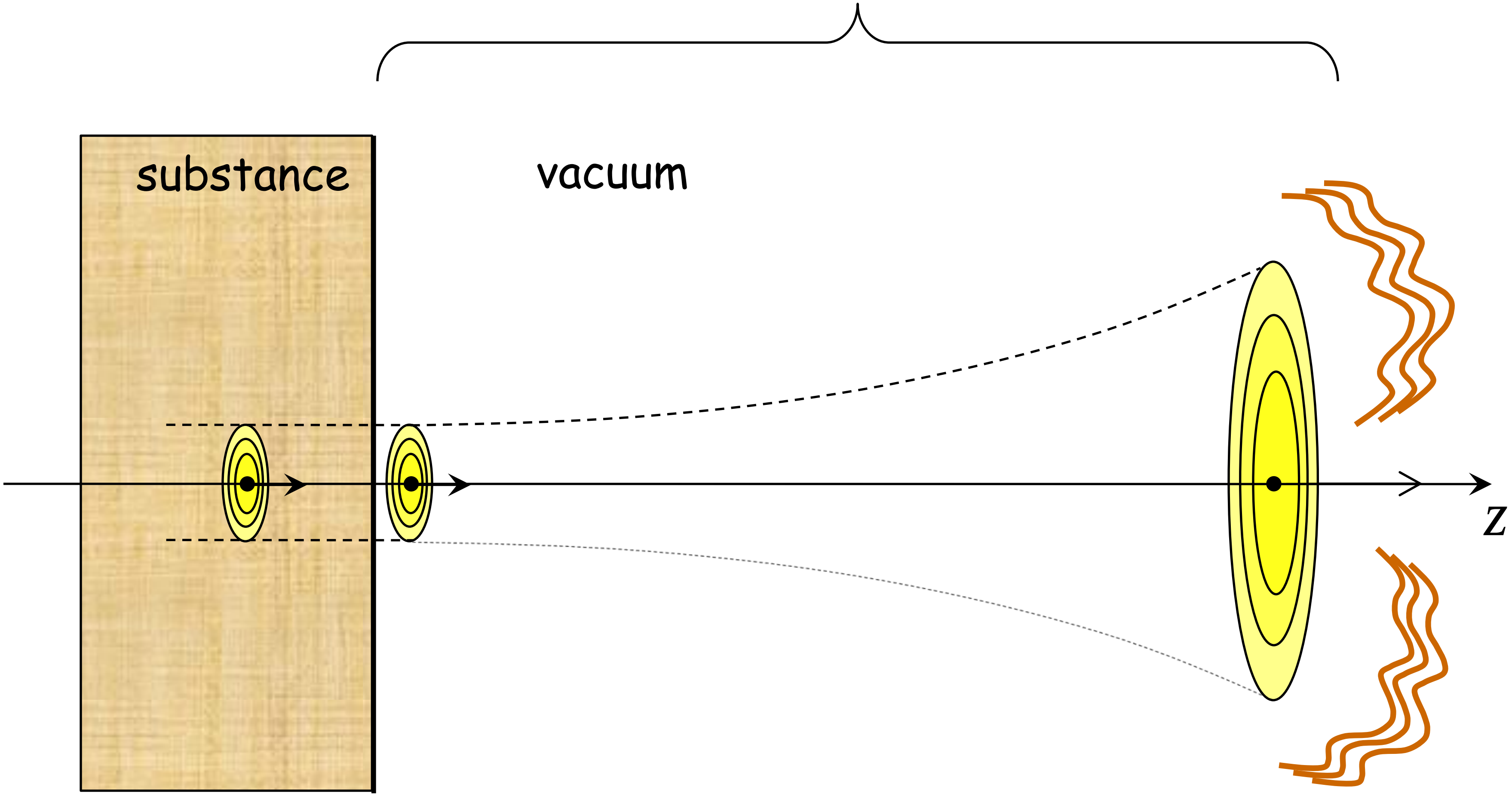
$L \sim I / \omega_p^2$ ~ absorption length

for solids $L \sim 0.1\,\mu m$

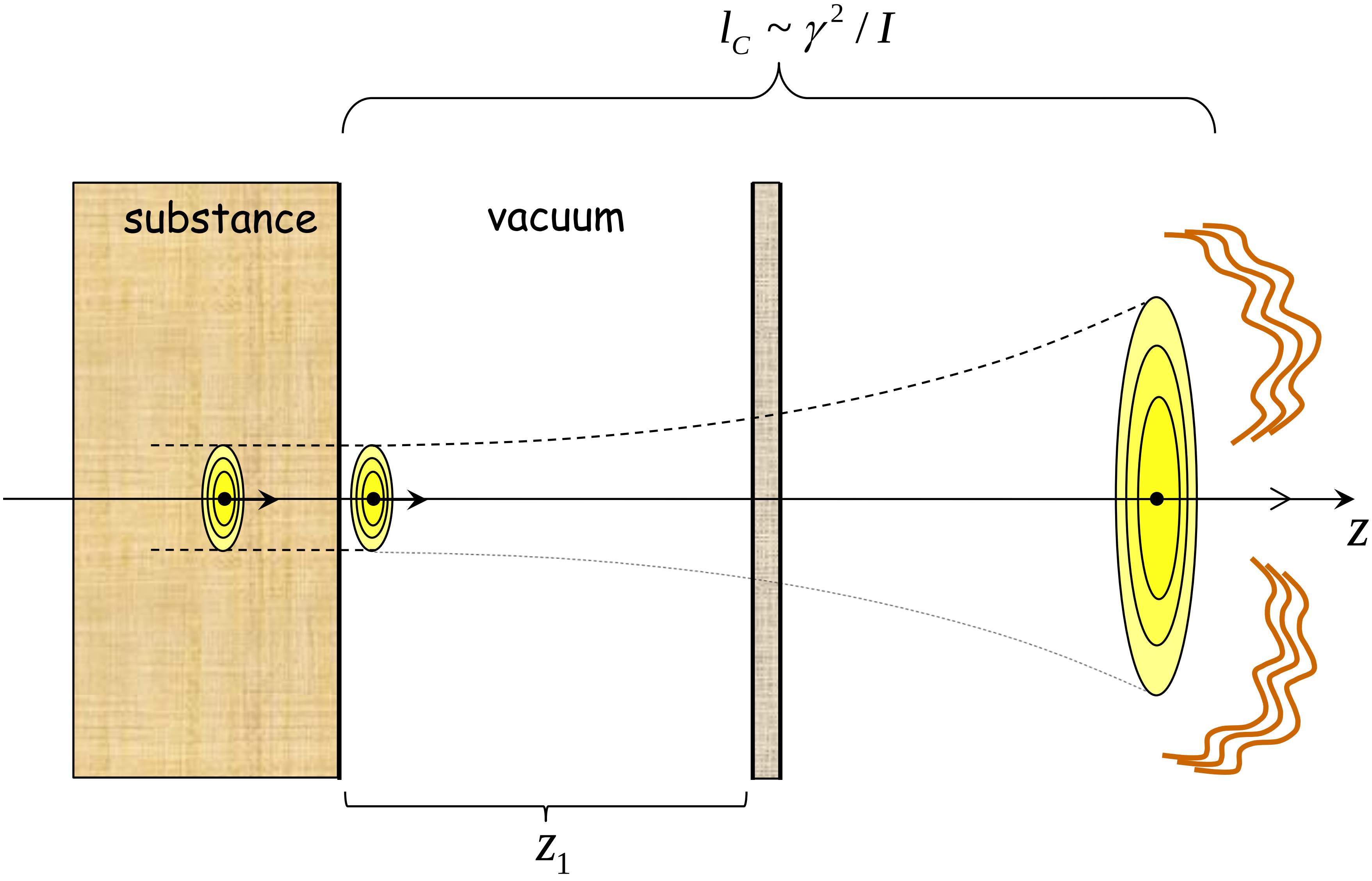
I – mean ionization potential

EVOLUTION OF THE FIELD AROUND THE ELECTRON IN VACUUM

$$l_C \sim \gamma^2 / I$$

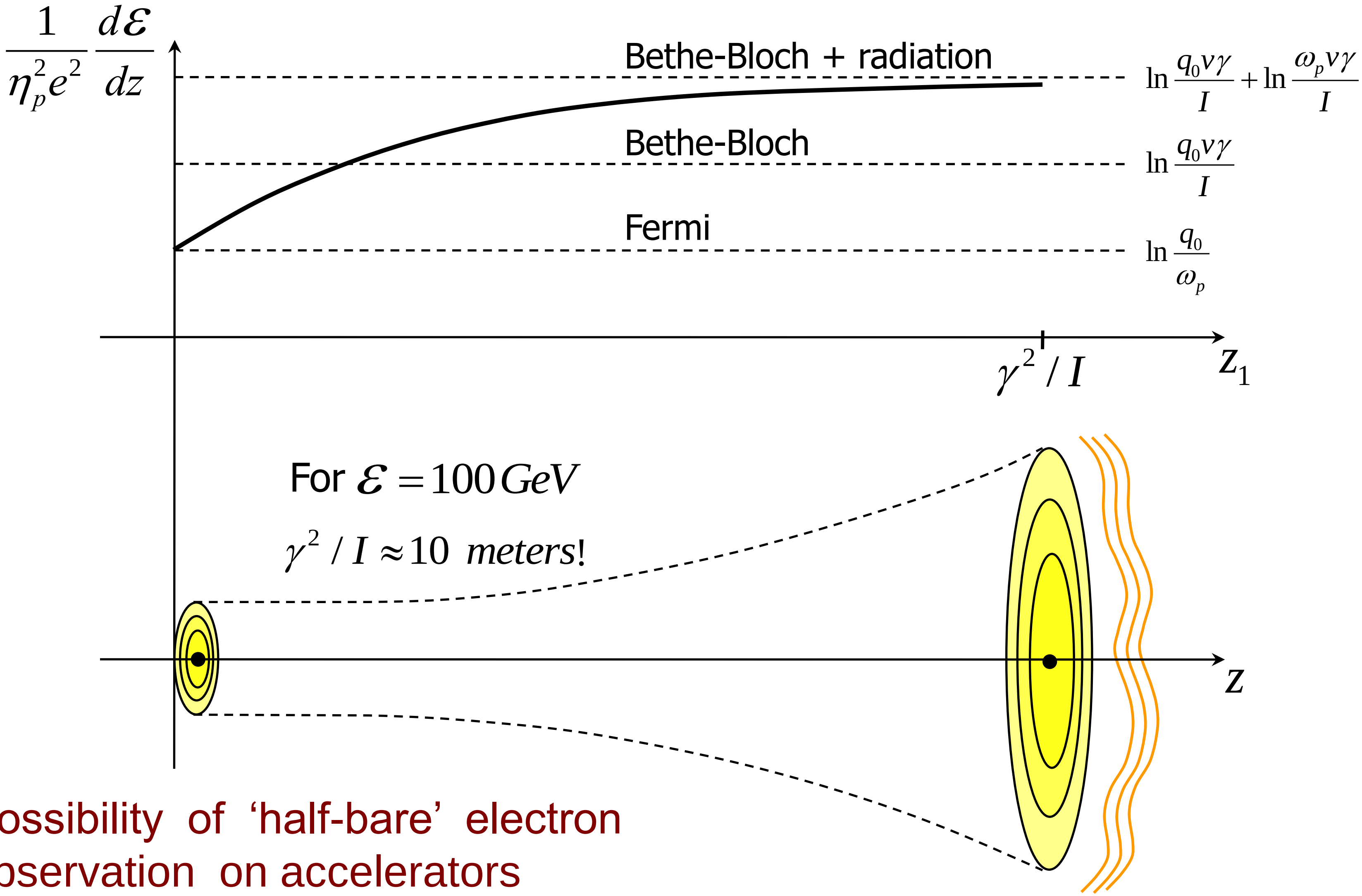


EVOLUTION OF THE FIELD AROUND THE ELECTRON IN VACUUM



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

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

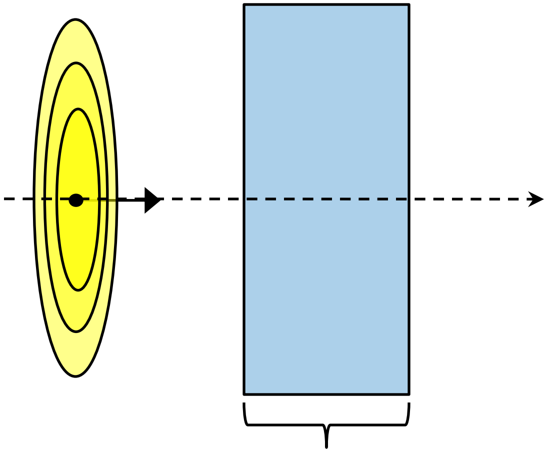


For $\mathcal{E}=100\,GeV$

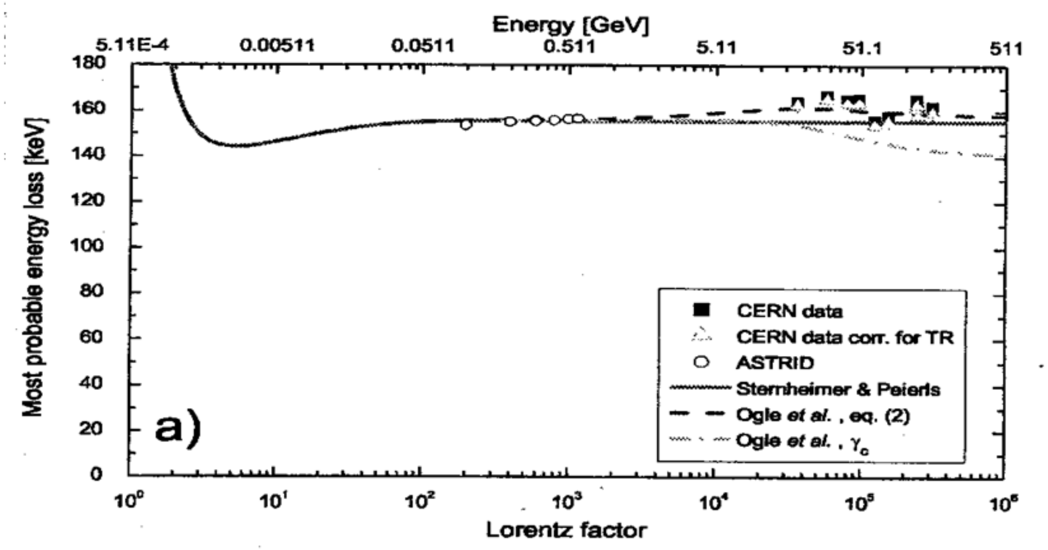
$\gamma^2/I\approx 10\ meters!$

Possibility of 'half-bare' electron observation on accelerators

CERN NA63 EXPERIMENT (2010)

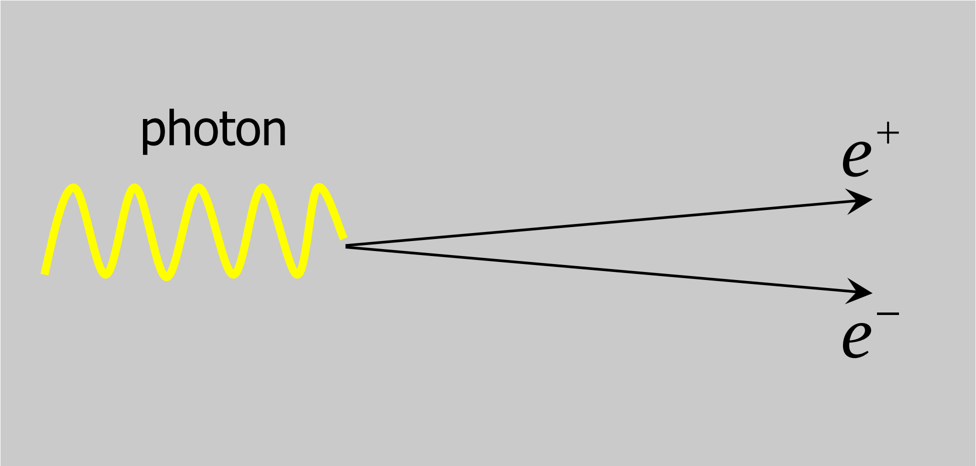


$$L \gg I/\omega_p^2$$



K.K. Andersen, J. Esberg, K.R. Hansen, H. Knudsen, M. Lund, H.D. Thomsen, U.I. Uggerhøj et. al. // NIM B, 2010

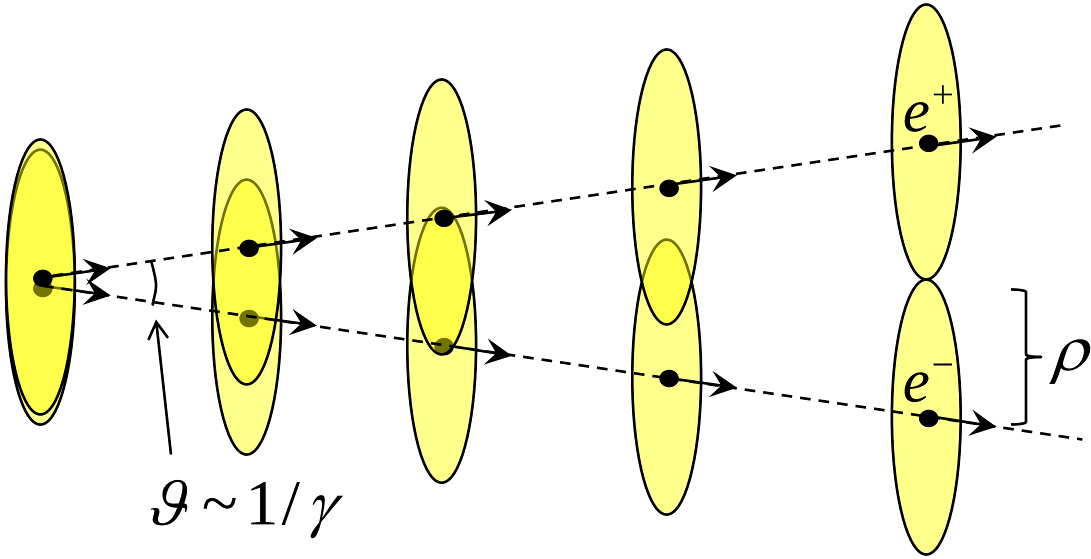
CHUDAKOV EFFECT
(ionization loss in boundless medium)



- *Chudakov A.E. // Izv. AS USSR, 1955*
- *Perkins D. // Phil.Mag., 1955*

Interference distance:

$$L_{\text{int}} \approx \frac{\rho_{\text{int}}}{\vartheta} \sim \frac{\gamma}{\omega_p}$$



$\vartheta \sim 1/\gamma$

$$\rho_{\text{int}} \sim \frac{1}{\omega_p}$$

For $\varepsilon = 100\,GeV$

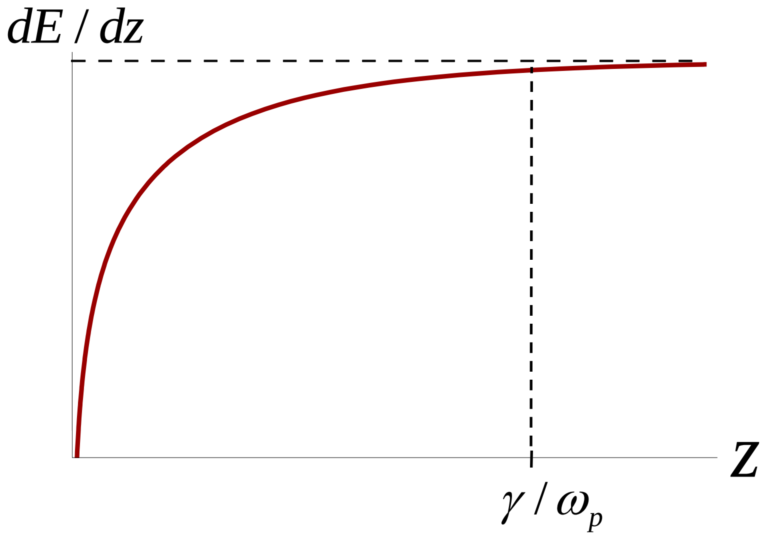
$L_{\text{int}} \sim 1mm$

γ – Lorenz-factor of each particle

ω_p – plasma frequency of substance

CHUDAKOV EFFECT
(ionization loss in boundless medium)

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



For $z<\gamma/\omega_\mathrm{p}$ strong suppression of dE/dz

Theory

- *Berestetskii V.B., Geshkenbain B.V. // JETP, 1956*
- *Yekutieli G. // Nuovo Cim., 1957*
- *Mito I., Ezawa H. // Progr. Theor. Phys., 1957*
- *Burkhardt G.H. // Nuovo Cim., 1958*

Experiment

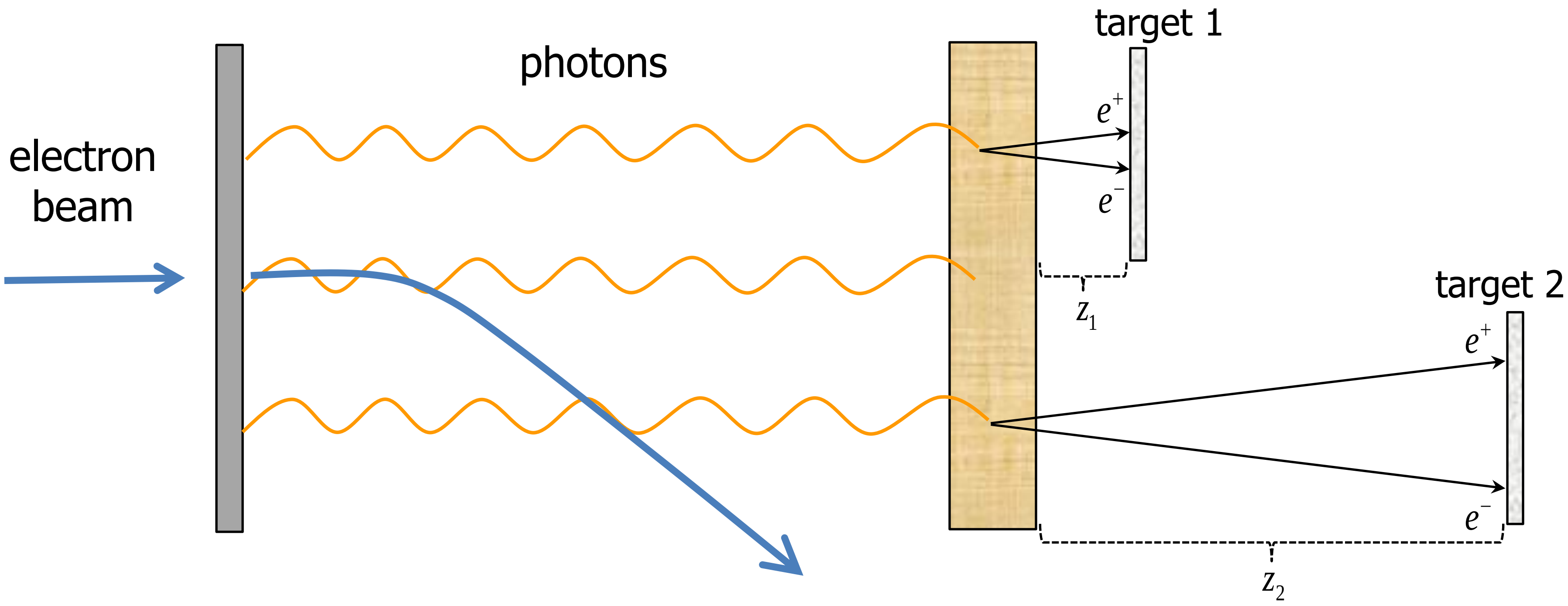
- *Perkins D. // Phil.Mag., 1955*
- *Wolter W., Miesowich M. // Nuovo Cim.,1956*
- *Iwadare J. // Phil.Mag., 1958*

(cosmic ray photons)

CERN (SPS) NA63 EXPERIMENT

T. Virkus, H.D. Thomsen, E. Uggerhøj et al. // Phys. Rev. Lett., 2008

H. D. Thomsen, U. I. Uggerhøj // Nucl. Instrum. Meth. B., 2011



The ratio of pair ionization losses in two plates $\sigma = \Delta\mathcal{E}_1 / \Delta\mathcal{E}_2$ as a function of the pair energy $\mathcal{E}$ was measured in the range $1\,GeV < \mathcal{E} < 100\,GeV$

For $L_{\text{int}} > z_1$ and $L_{\text{int}} > z_2$ $\longrightarrow$ $\sigma < 1$

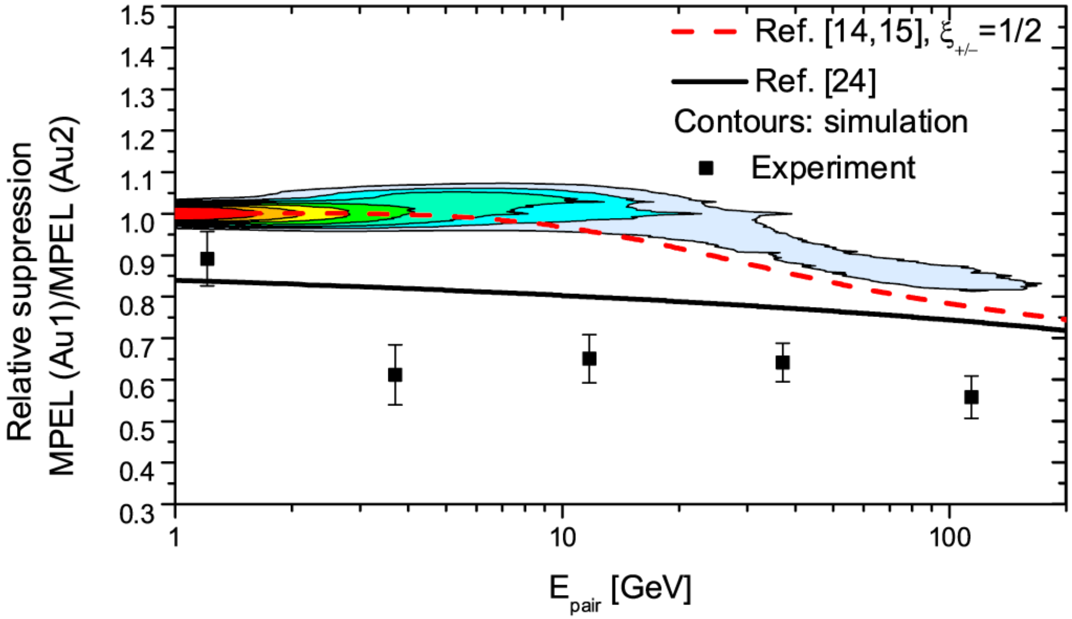
For $L_{\text{int}} << z_1$ and $L_{\text{int}} << z_2$ $\longrightarrow$ $\sigma = 1$

CERN (SPS) NA63 EXPERIMENT

T. Virkus, H.D. Thomsen, E. Uggerhøj et al. // Phys. Rev. Lett., 2008

H. D. Thomsen, U. I. Uggerhøj // Nucl. Instrum. Meth. B., 2011

$\Delta\mathcal{E}_1 / \Delta\mathcal{E}_2$ as a function of the pair energy $\mathcal{E}$



Ref.[14]: V.B. Berestetskii, B.V. Geshkenbain // JETP, 1956

Ref.[15]: P. Sigmund // Particle Penetration and Radiation Effects, 2006

Ref.[24]: G.H. Burkhardt // Nuovo Cim., 1958

PROBLEM STATEMENT

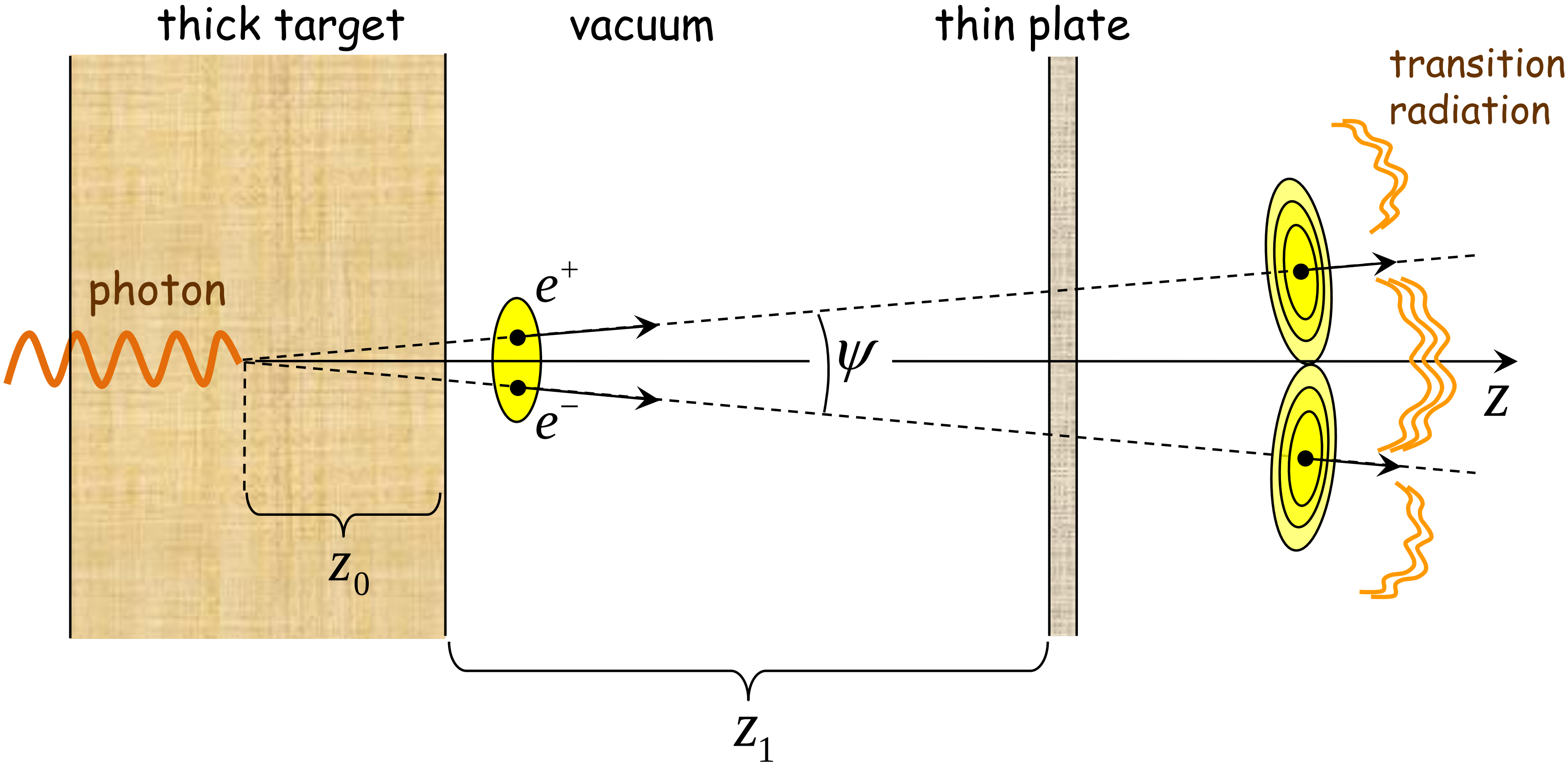


plate thickness $a \leq I / \eta_p^2$

η_p – plasma frequency of the plate

I – mean ionization potential

$l_{form} \sim \gamma^2 / I$

PAIR IONIZATION LOSS IN THE PLATE

(the plate is situated on distance z_1 from the substance)

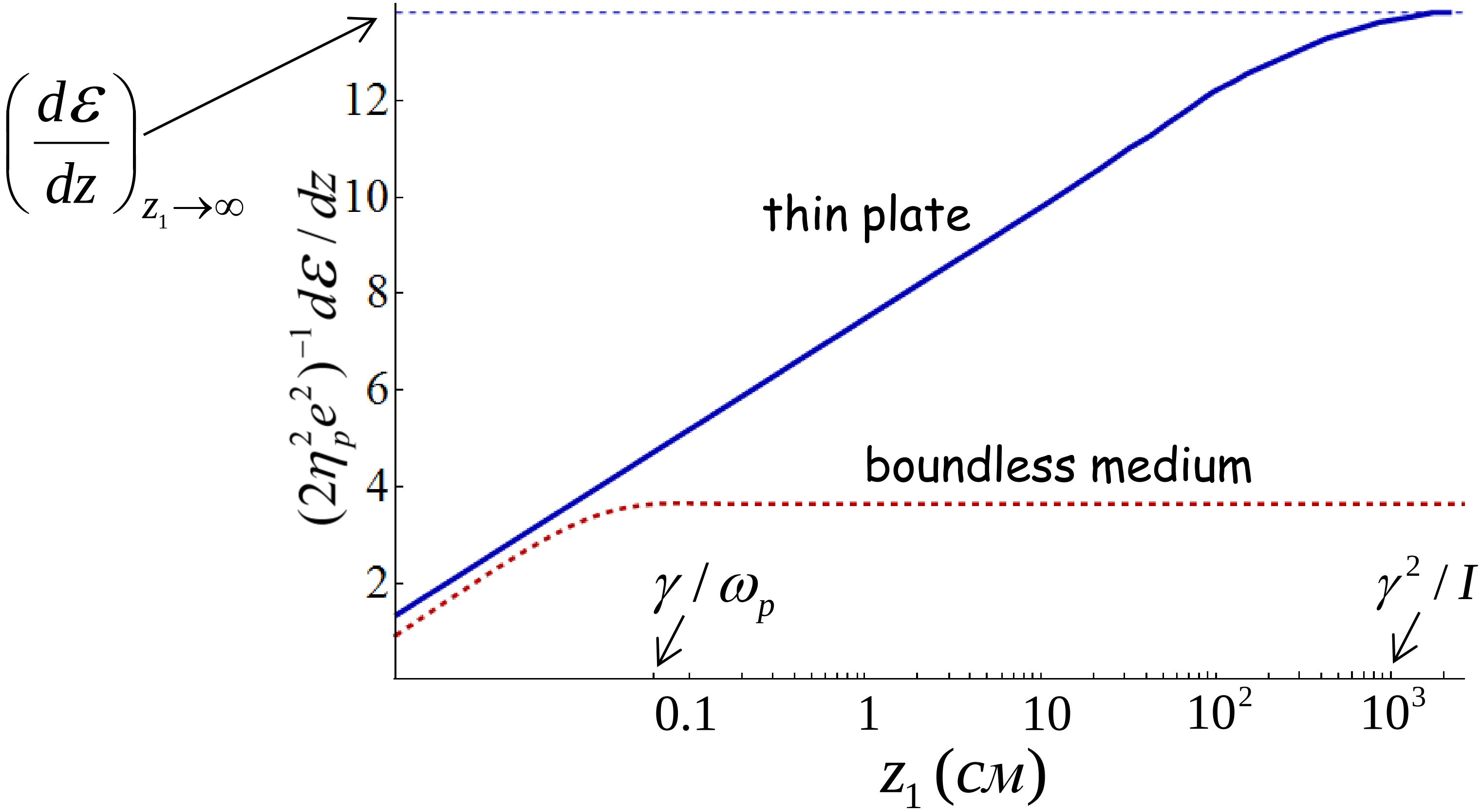
S.V. Trofymenko, N.F. Shul'ga // Phys. Lett. A (2013)

$$\frac{d\mathcal{E}}{dz} = 2\eta_p^2 e^2 \left\{ \underbrace{\ln\frac{q_0 v\gamma}{I} - \frac{1}{2}}_{\text{ionization by particles' proper Coulomb fields}} + \underbrace{\ln\frac{\omega_p v\gamma}{I} - 1}_{\text{ionization by transition radiation field}} + \underbrace{F(z_1)}_{\text{interference effects}} \right\}$$

PAIR IONIZATION LOSS IN THE PLATE

(the plate is situated on distance z_1 from the substance)

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



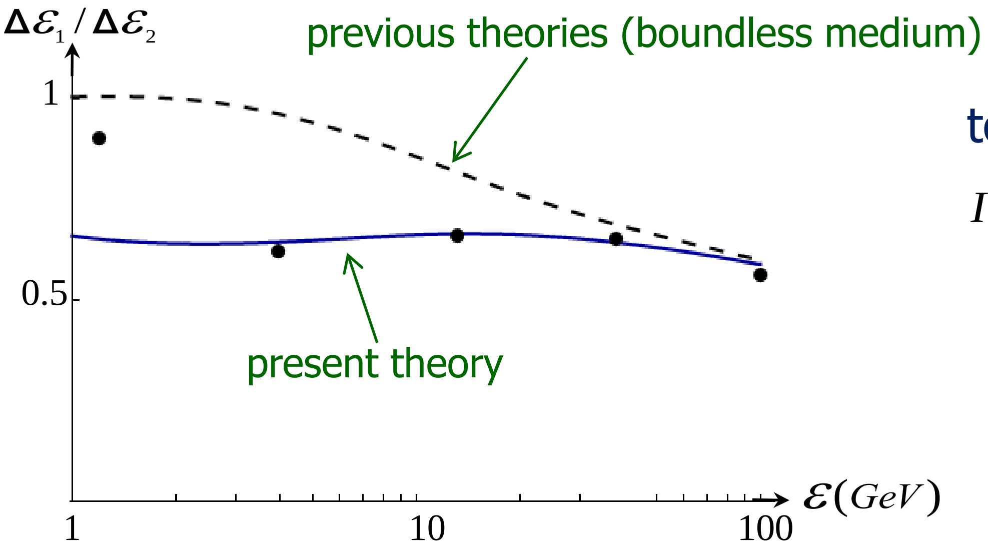
For:

$\mathcal{E} = 100\,GeV$

$\frac{\gamma^2}{I} \sim 10\,m$**!**

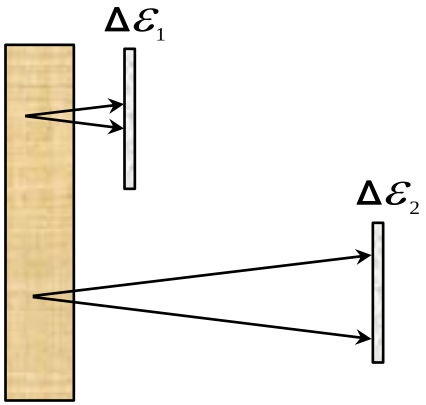
Interference effects are manifested on distances $z_1 \sim \gamma^2/I$, which significantly exceed the corresponding distances $z_1 \sim \gamma/\omega_p$ in the case of pair motion in boundless medium

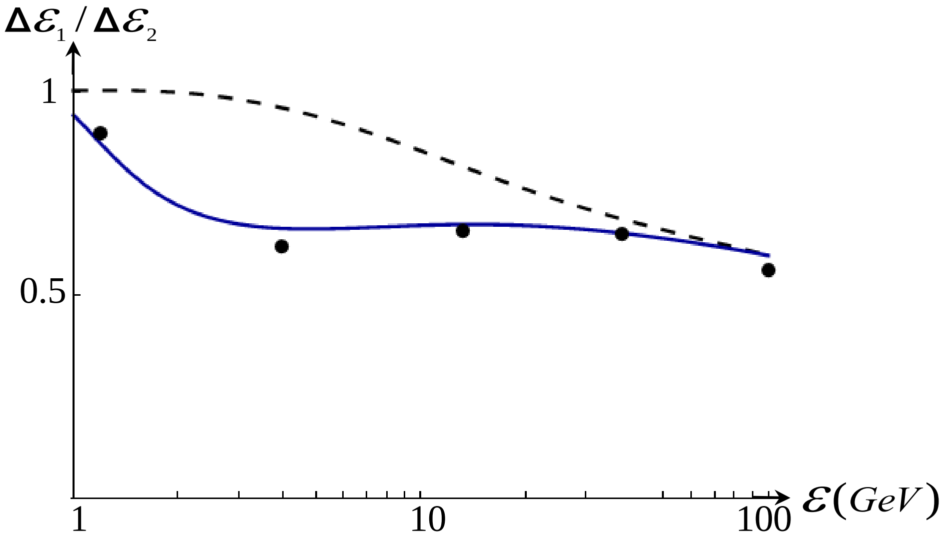
RATIO OF PAIR IONIZATION LOSSES IN TWO TARGETS
(as function of pair energy)



total ionization loss

$I \sim 100\,eV$ (mean ionization potential)



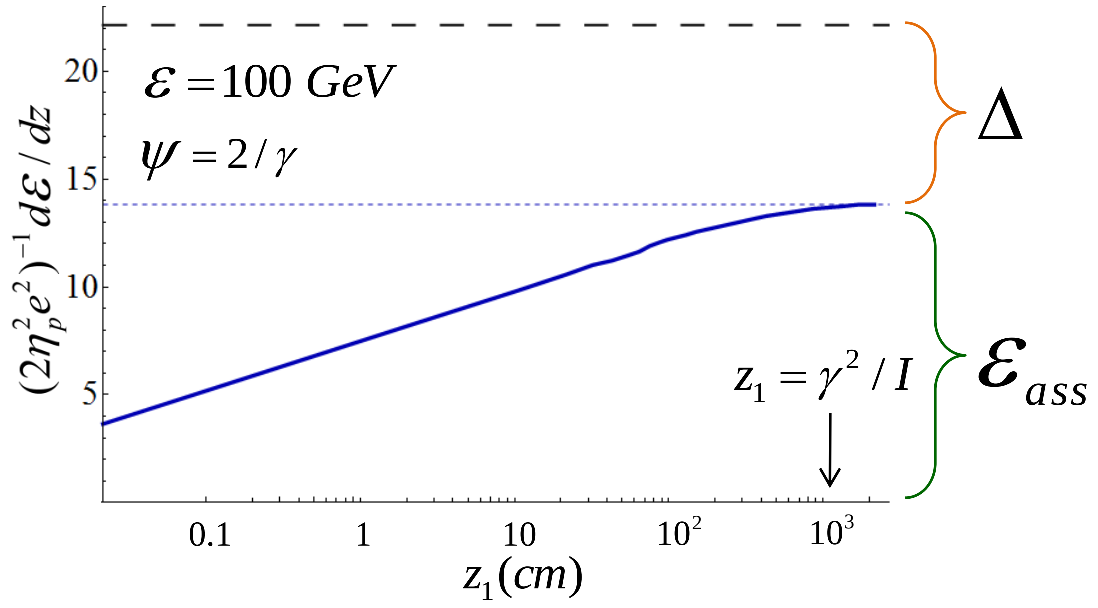


Loss due to excitation of inner atomic shells

$I_{in} \sim 2000\,eV$ (inner shells ionization potential)

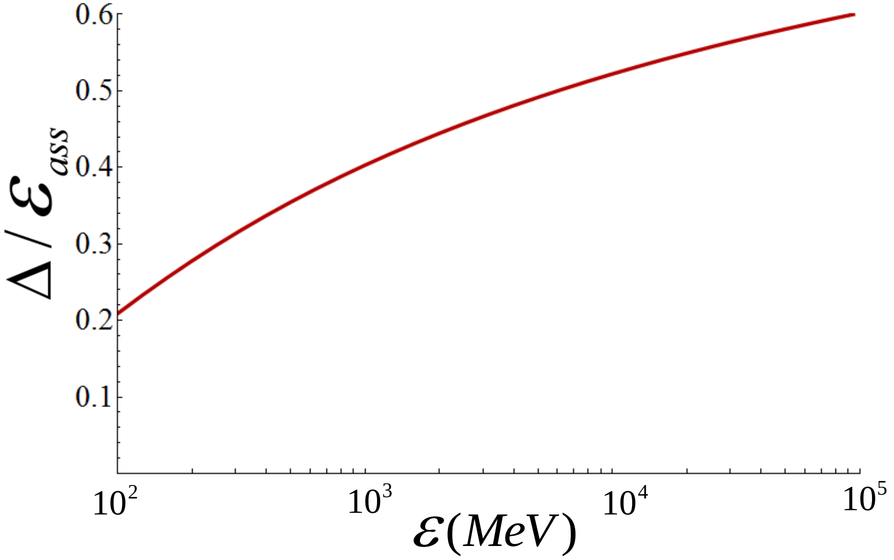
ANOMALOUS ASYMPTOTICAL BEHAVIOR OF PAIR IONIZATION LOSS

S.V. Trofymenko, N.F. Shul’ga // Nucl. Instrum. Meth. B (2017)



dependence of pair ionization loss on distance between the substance and the plate

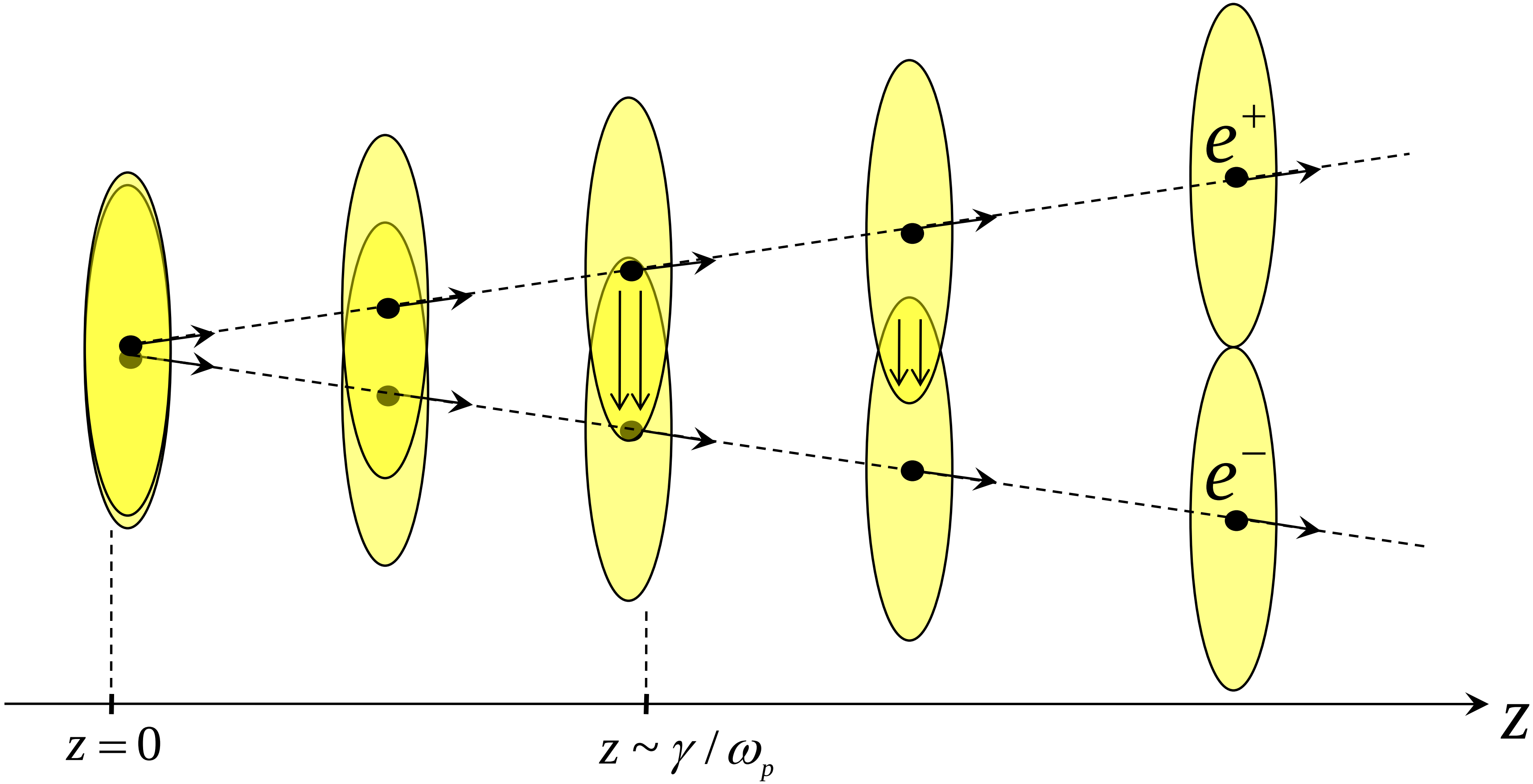
ψ – pair divergence angle



dependence of relative value of ionization loss asymptotic suppression on the energy of the pair

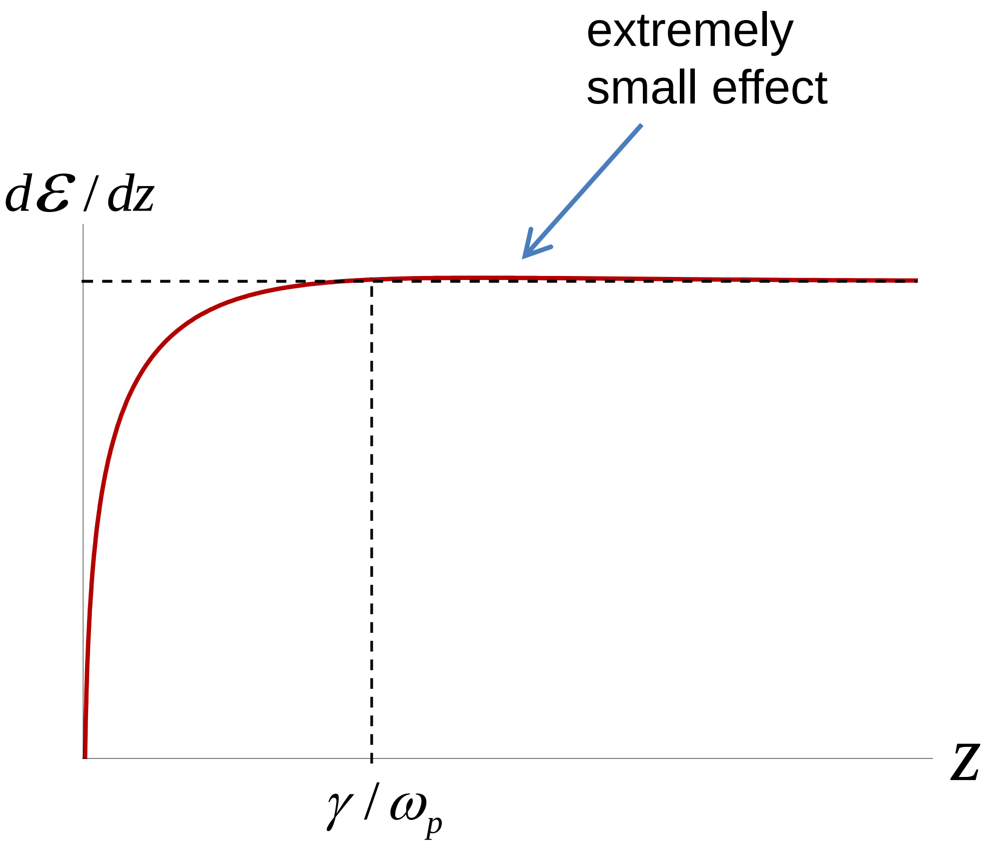
“ANTI-CHUDAKOV” EFFECT

Existence of region on distance $z \sim \gamma/\omega_p$ from the creation point where electron’s and positron’s fields interfere constructively



It is natural to expect increase of ionization loss at $z \sim \gamma/\omega_p$

“ANTI-CHUDAKOV” EFFECT IN BOUNDLESS MEDIUM

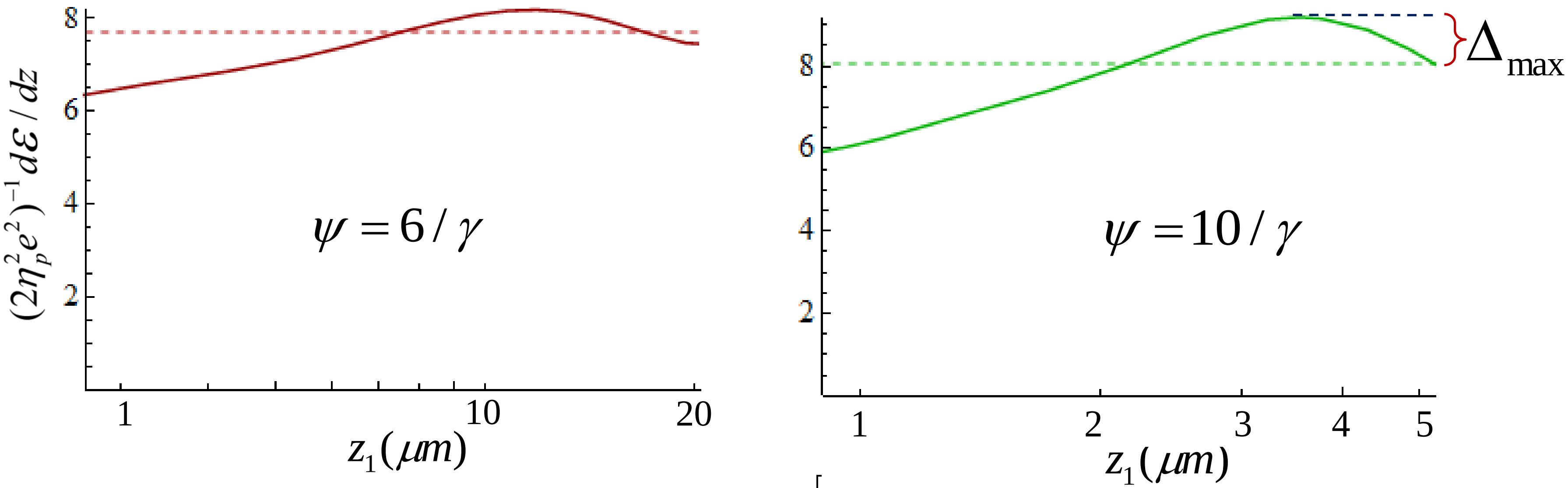


“ANTI-CHUDAKOV” EFFECT IN THIN TARGETS

N.F. Shul’ga, S.V. Trofymenko // Phys. Lett. A (2014)

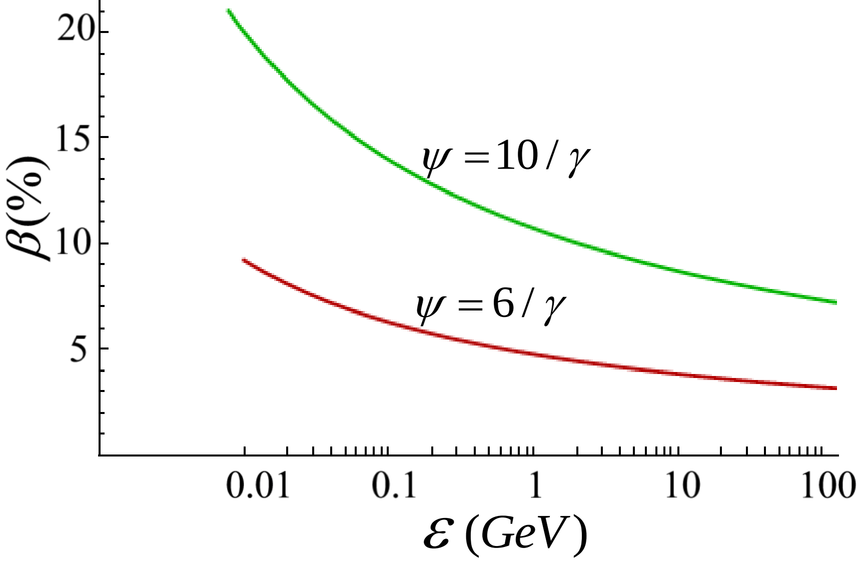
S.V. Trofymenko // Probl. Atom. Sci. Tech. (2017)

Dependence of $d\mathcal{E}/dz$ **on** z_1 **for** $\mathcal{E} = 100\,MeV$ $(\gamma^2/I \sim 11\,\mu m)$ **:**



dependence of the relative value of excess on the pair energy:

$$\beta = \frac{\Delta_{\max}}{(d\mathcal{E}/dz)_{z\to\infty}} \approx \frac{A}{2\ln\gamma + B}$$



γ – particles’ Lorenz-factor

CONCLUSIONS

Influence of large formation lengths and “half-bare” state of electron on its transition radiation, ionization loss and X-ray emission in thin crystals:

- Modification of transition radiation spectral-angular characteristics
- Difference of ionization loss value in thin target from the result predicted by Bethe-Bloch formula within macroscopically large distances
- Manifestation of the effect of e^+e^- pairs ionization loss suppression in thin targets on much larger distances than in the case of “classical” Chudakov effect in boundless medium
- Anomalous asymptotical behavior of pair ionization loss in thin targets
- Existence of the effect opposite to the one of Chudakov