IONIZATION AND TRANSITION RADIATION PROCESSES BY HIGH-ENERGY 'HALF-BARE' ELECTRON

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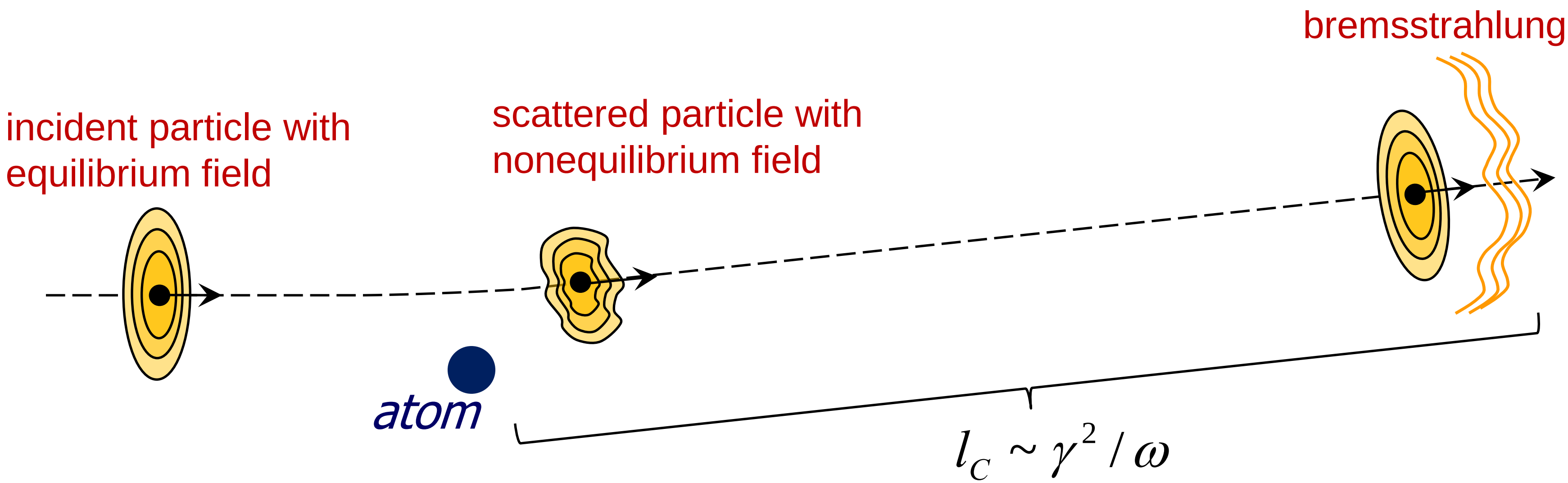
- *N.F. Shul'ga, S.V. Trofymenko, V.V. Syshchenko // JETP Lett. (2011)*
- *N.F. Shul'ga, S.V. Trofymenko // Invited Chapter in the Book "Solutions and Applications of Scattering, Propagation, Radiation and Emission of Electromagnetic Waves", InTech (2012)*
- *N.F. Shul'ga, S.V. Trofymenko // Phys. Lett. A. (2012)*

COHERENCE LENGTH. 'HALF-BARE' ELECTRON



γ – Lorentz-factor

ω – radiated frequency

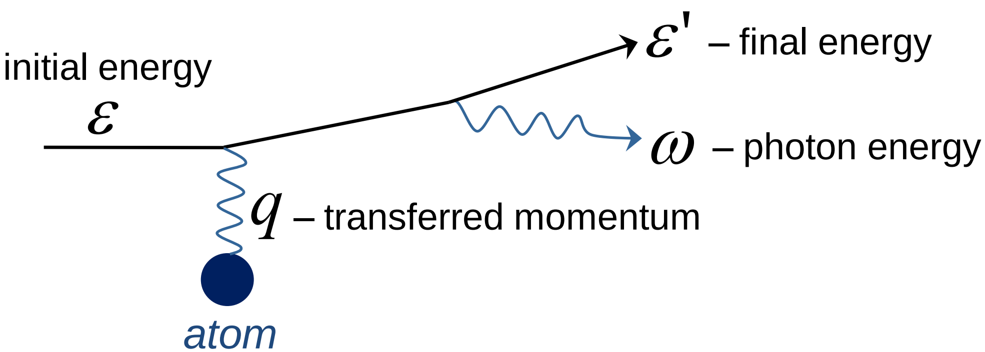
the frequency ω appears
on distance $l_C \sim \gamma^2 / \omega$
from the interaction area

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

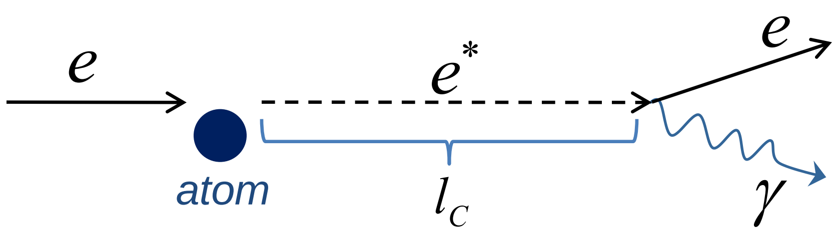
(*M.L. Ter-Mikaelyan // Sov.Phys.JETP, 1953*)



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

For $\omega \ll \varepsilon$ **:**

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

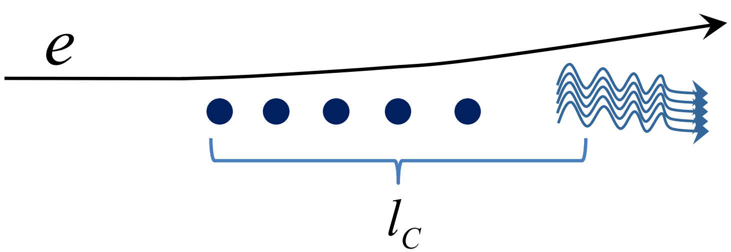


E.L. Feinberg // Sov.Phys.Usp, 1980

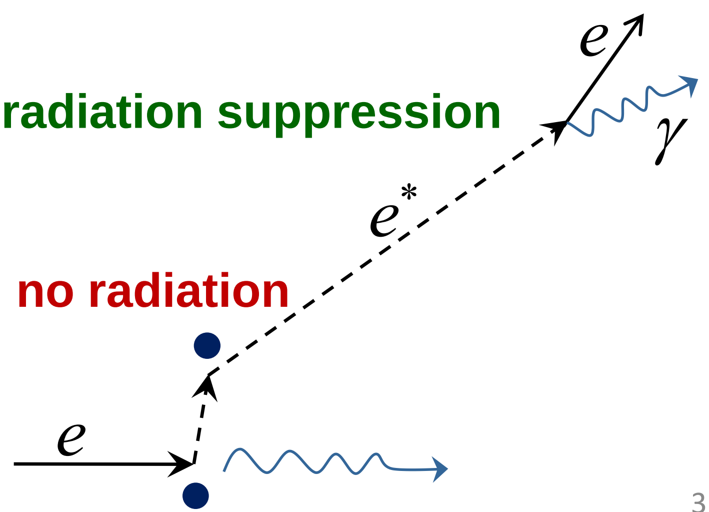
$$T^* >> T_{\text{int}}$$

radiation suppression

coherent radiation

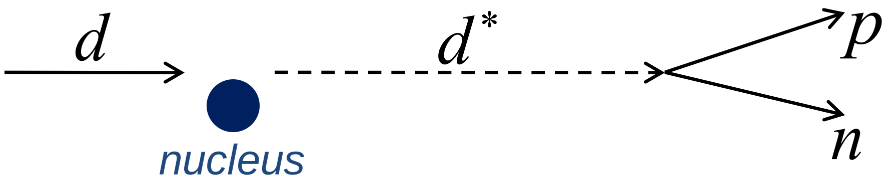


no radiation



ANALOGIES IN HADRONIC INTERACTIONS

deuteron diffractive dissociation

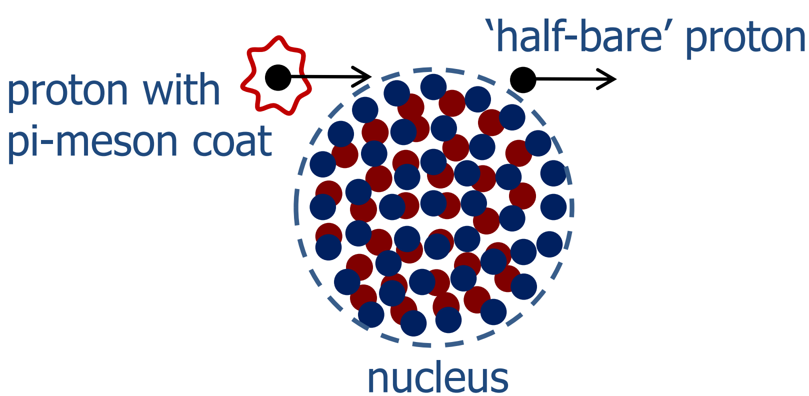


in CMS:

$$T^* \sim \gamma\, r_0 \qquad T_{\rm int} \sim r_0 / \gamma \qquad \Bigg\} \quad \frac{T^*}{T_{\rm int}} \sim \gamma^2 >> 1$$

$$r_0 \sim 1 fm$$

independence (almost) of proton energy loss in proton-nucleus collision on nucleus mass

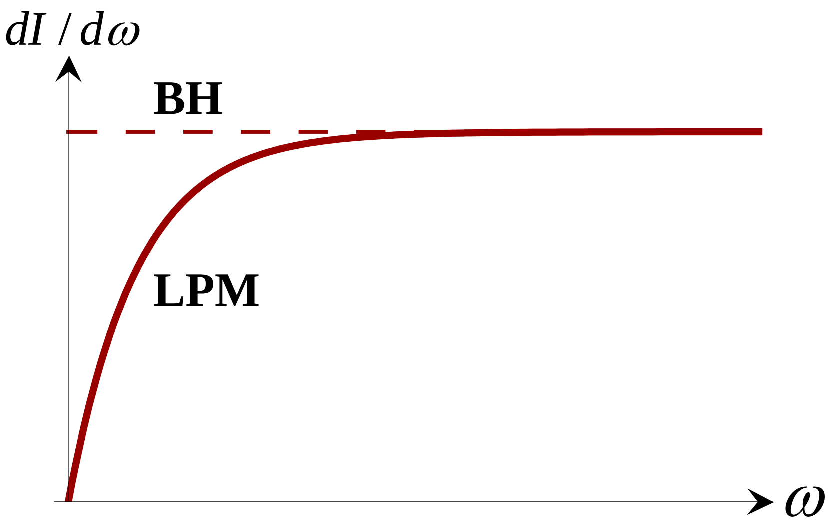


MANIFESTATION OF 'HALF-BARE' STATE IN BRAMSSTRAHLUNG

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 !'

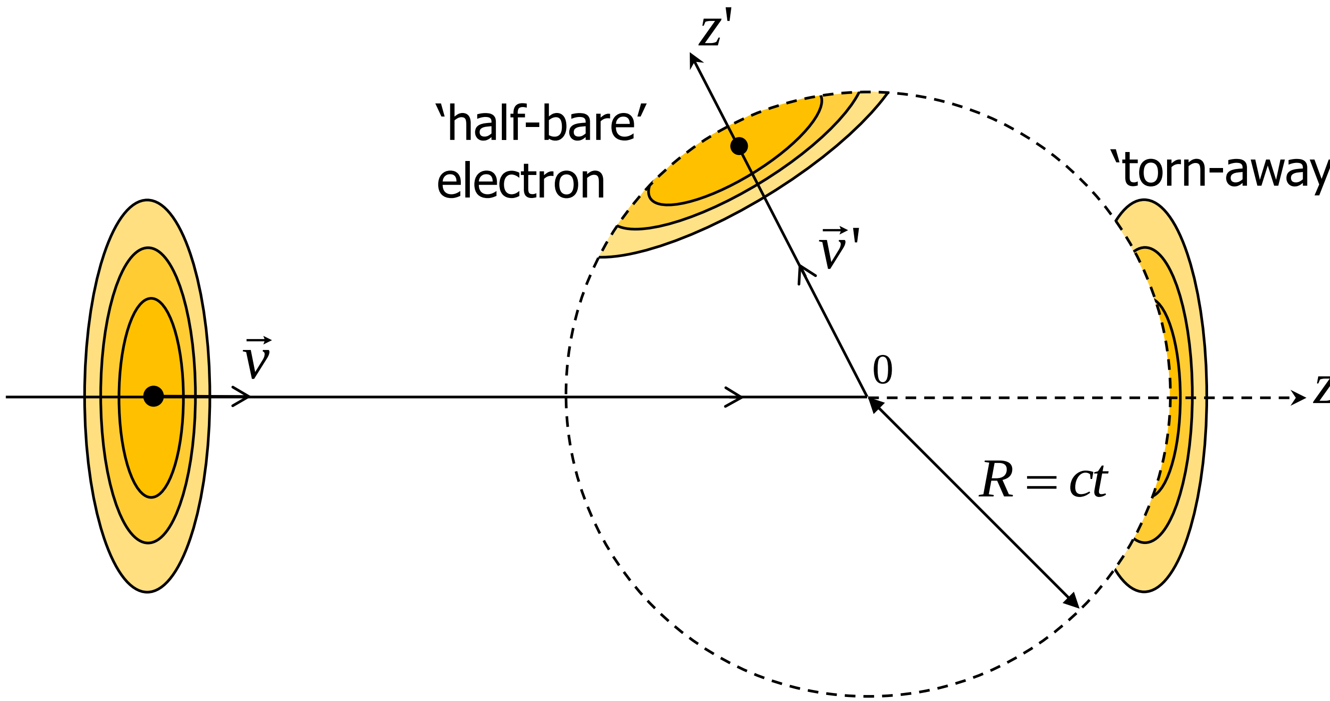
AIM OF THE PRESENT WORK

Search for manifestation of ‘half-bare’ state of electron in its:

1) Transition radiation

2) Ionization energy loss

ELECTRON 'UNDRESSING' BY SHARP SCATTERING

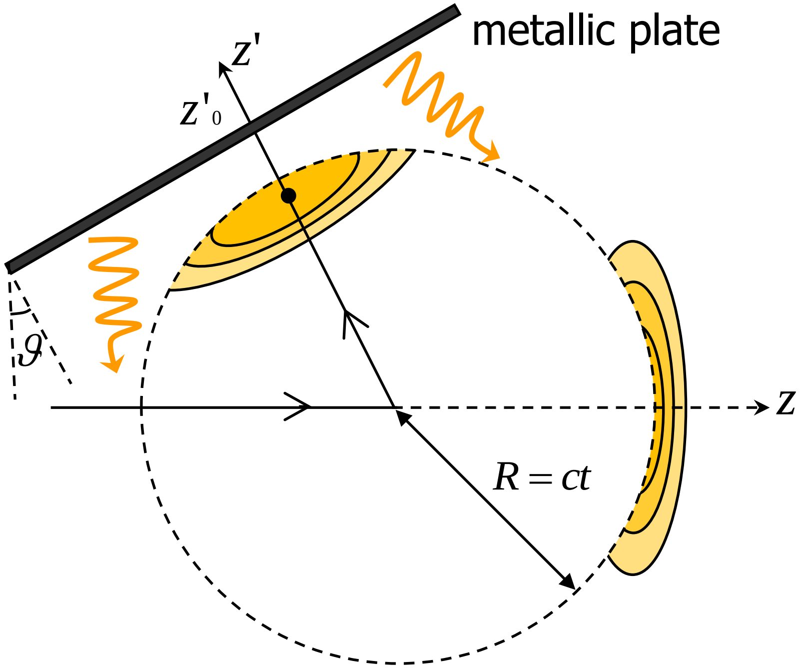


The total field for $t > 0$:

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

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

TRANSITION RADIATION BY 'HALF-BARE' ELECTRON



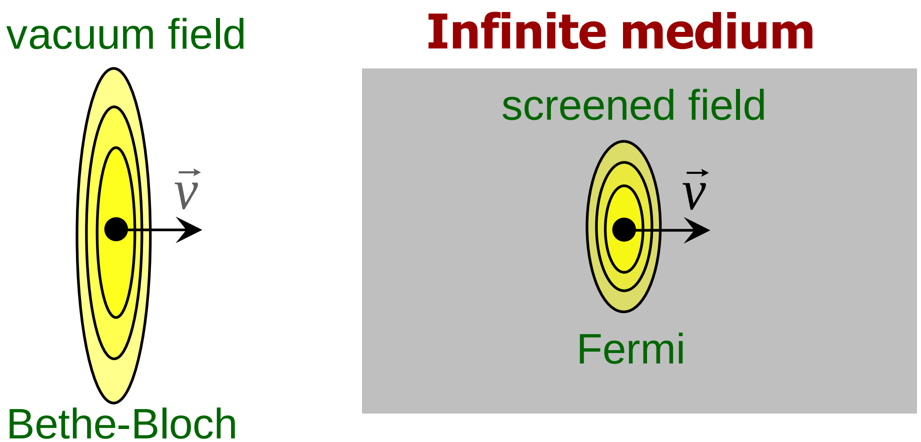
- suppression of radiation for $z'_0 << 2\gamma^2/\omega$
- period of oscillations $\Lambda = \dfrac{4\pi}{\omega(\vartheta^2+\gamma^{-2})}$
- the oscillations can be observed for $z'_0 < \dfrac{2\pi}{\Delta\omega(\vartheta^2+\gamma^{-2})}$

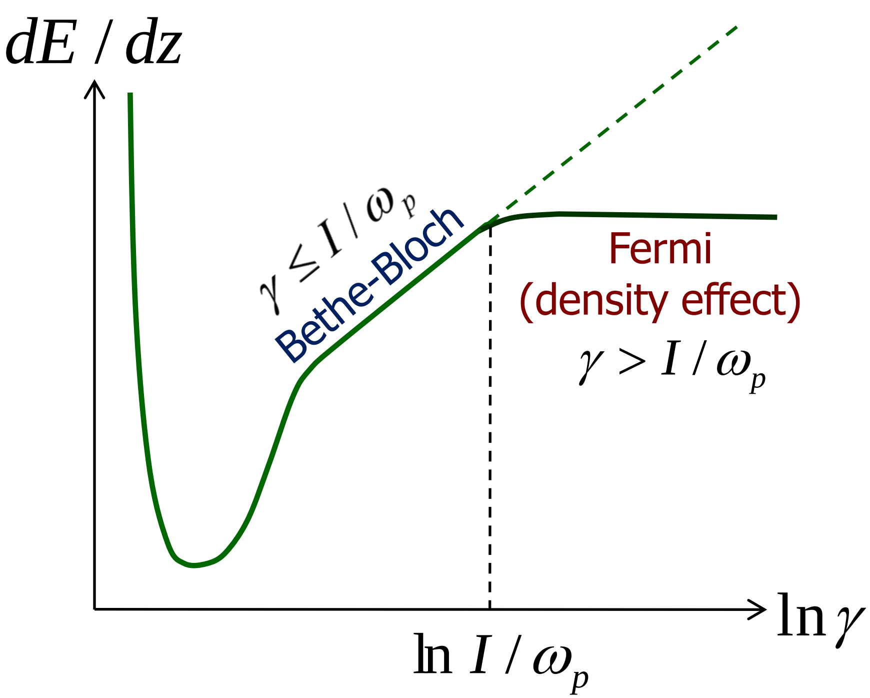
$\omega/\Delta\omega$ – detector resolution

Transition radiation by 'half-bare' electron:

$$\frac{d\mathcal{E}}{d\omega do} = \frac{e^2}{\pi^2}\frac{\vartheta^2}{\left(\vartheta^2+\gamma^{-2}\right)^2}2\left\{1-\cos\left[\frac{\omega z'_0}{2}\left(\gamma^{-2}+\vartheta^2\right)\right]\right\}$$

FERMI AND BETHE-BLOCH FORMULAE





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

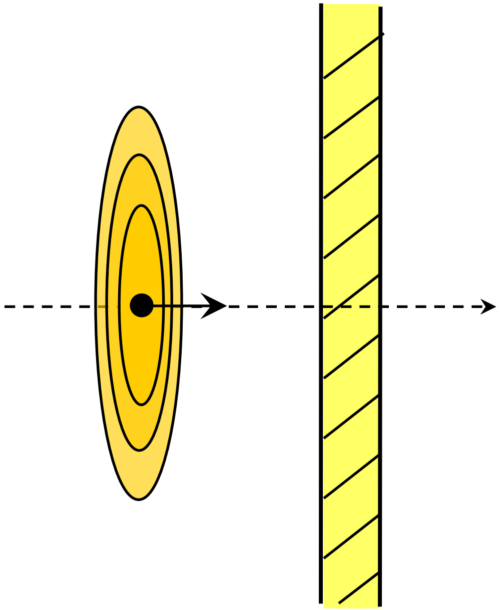
I – mean ionization potential

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



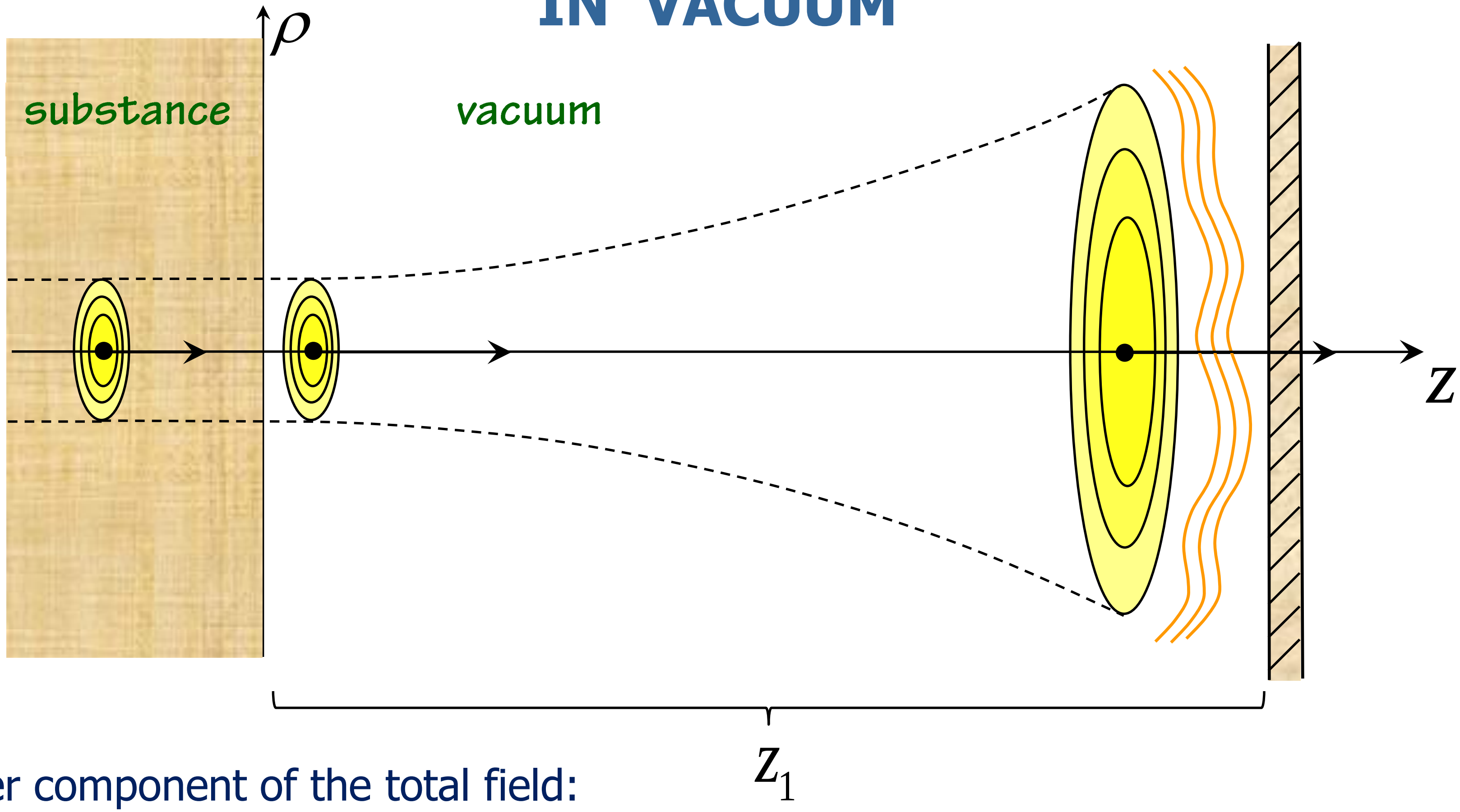
Total absence of the density effect in thin plates:

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

Particle energy loss:

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

EVOLUTION OF THE FIELD AROUND THE ELECTRON IN VACUUM



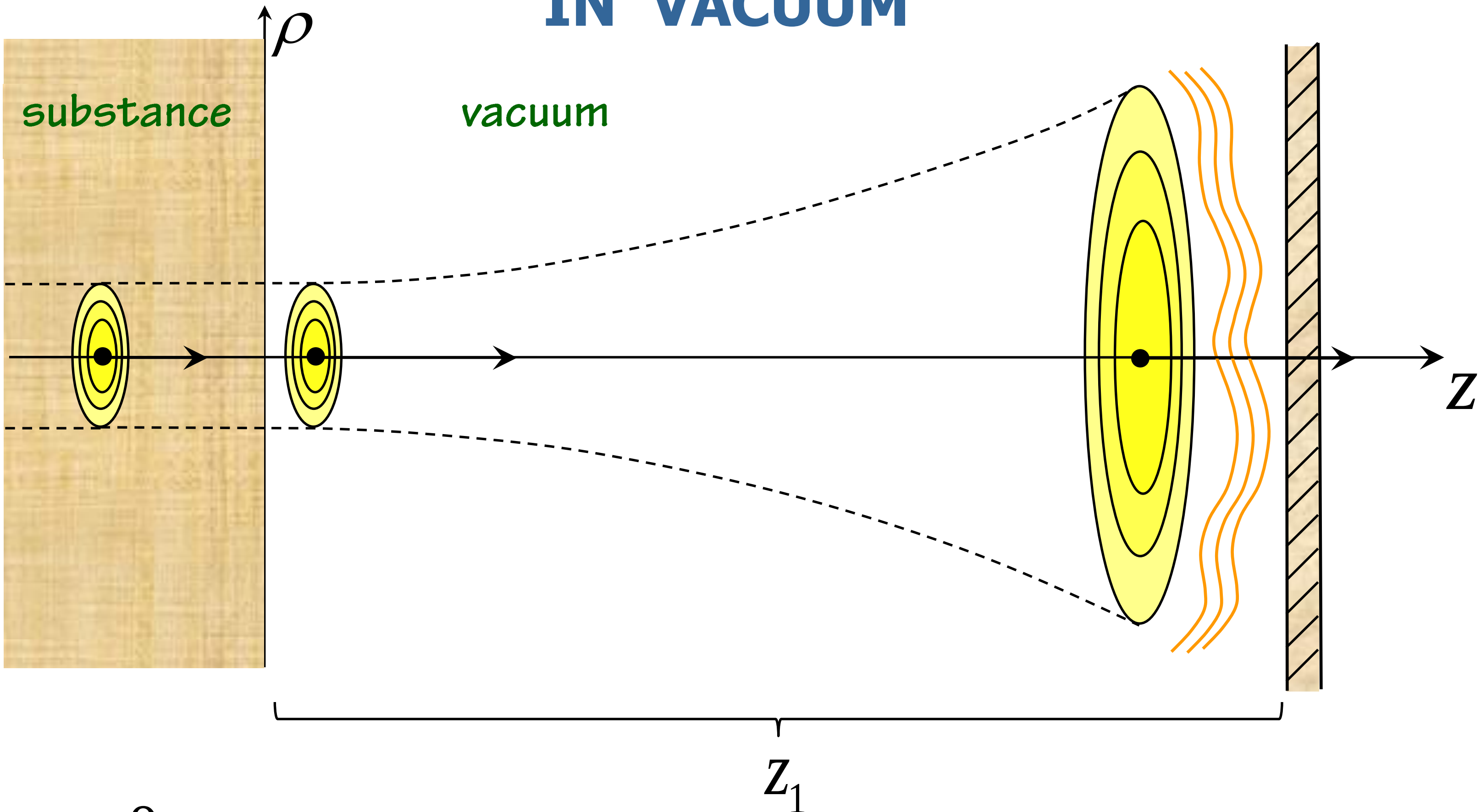
Fourier component of the total field:

$$E_\omega^\rho(\vec{r}) = 2\frac{e}{v}\int_0^\infty dq\, q^2 J_1(q\rho)\left\{ \underbrace{\left[\frac{1}{q^2+\omega_p^2+\omega^2/\gamma^2} - \frac{1}{q^2+\omega^2/\gamma^2}\right] e^{iz\omega - \frac{zq^2}{2\omega}}}_{\text{packet of free waves (transition radiation)}} + \underbrace{\frac{e^{i\frac{\omega}{v}z}}{q^2+\omega^2/\gamma^2}}_{\text{coulomb field}} \right\}$$

packet of free waves (transition radiation)

coulomb field

EVOLUTION OF THE FIELD AROUND THE ELECTRON IN VACUUM



For $z \to 0$:

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

suppressed frequencies $\omega \le \gamma\omega_p$

electron is 'half-bare'

$K_1(x)$ – Macdonald function

IONIZATION ENERGY LOSS OF 'HALF-BARE' ELECTRON

Total ionization per unit path:

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

$$+ Ci(\lambda_\gamma) - \cos\lambda_p Ci(\lambda_p+\lambda_\gamma) - \sin\lambda_p Si(\lambda_p+\lambda_\gamma) +$$

$$\left. + \lambda_\gamma Si(\lambda_\gamma) + \cos\lambda_\gamma \right\}$$

where:

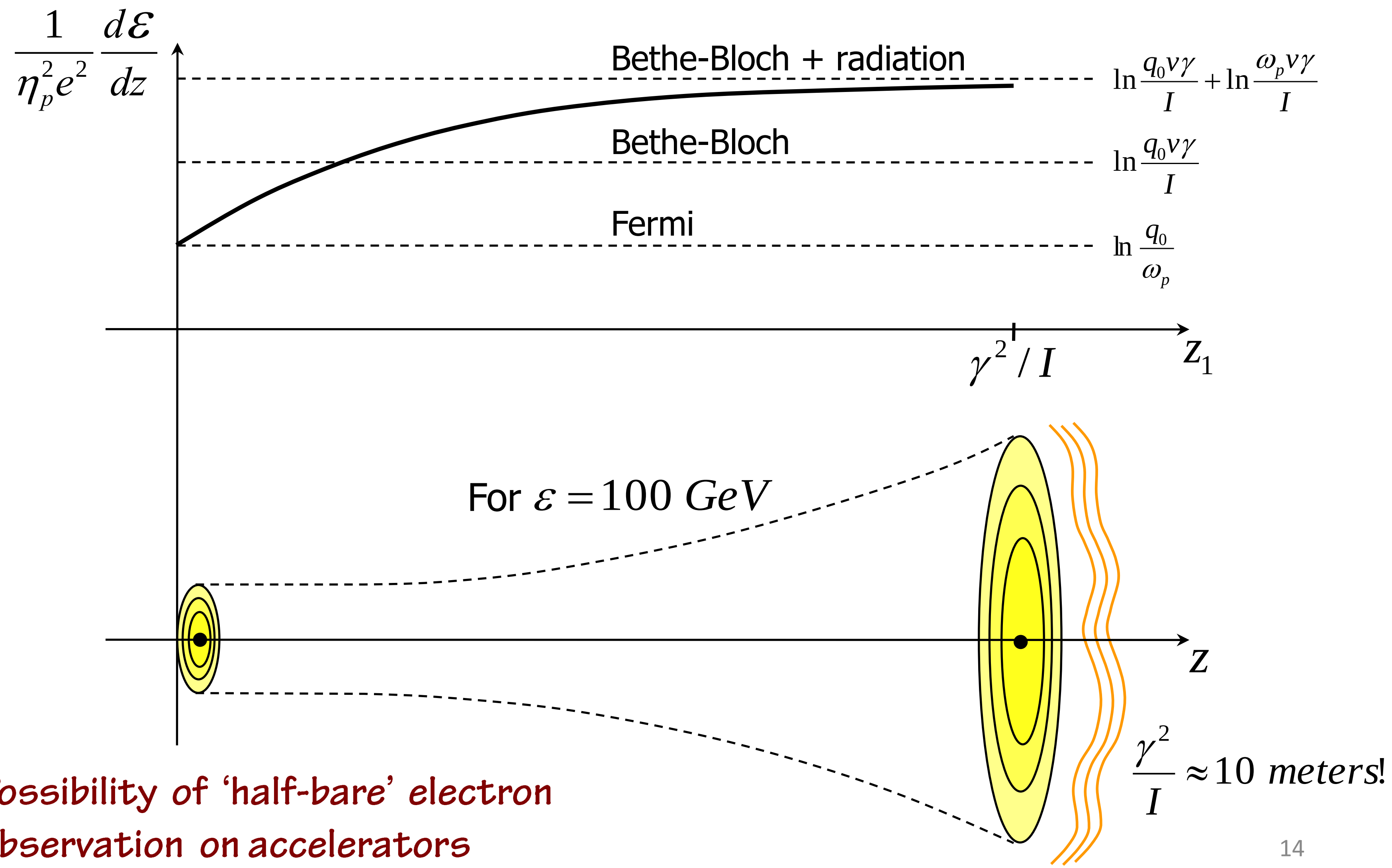
$$\lambda_p = z_1\omega_p^2/2I \qquad \lambda_\gamma = Iz_1/2\gamma^2$$

η_p – plasma frequency of the plate

I – mean ionization potential

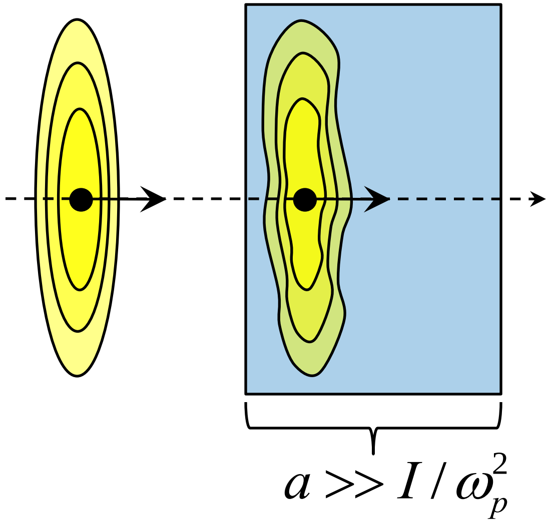
$Si(x)$ and $Ci(x)$ – Sine and Cosine integrals

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

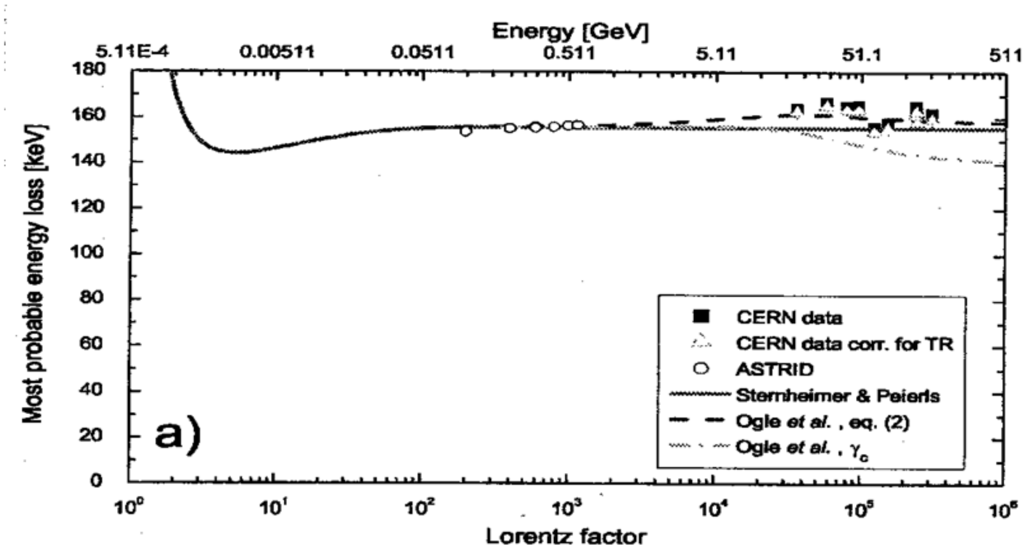


Possibility of 'half-bare' electron observation on accelerators

CERN NA63 EXPERIMENT (2010)



opposite problem statement: field restoration occurs in substance, not in vacuum $\Rightarrow$ absorption destroys the effect



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

CONCLUSIONS

'Half-bare' state of electron should be manifested in its transition radiation and ionization losses as well as in bremsstrahlung:

- ❖Dependence of electron transition radiation characteristics on distance between the plate and the scattering point

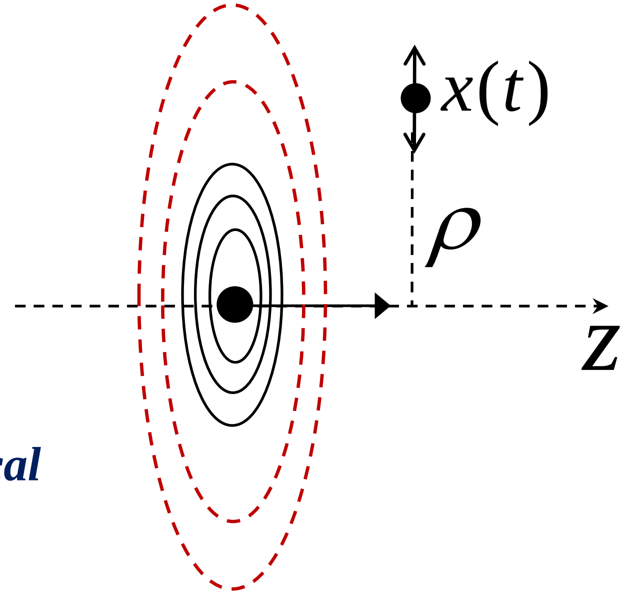
- ❖Existence of transition process in which ionization loss is defined by the mechanism of restoration of the field around the particle within large macroscopic domain of space

- ❖ Gradual increase of electron ionization loss in thin plate from the value with density effect (Fermi formula) to the value without it (Bethe-Bloch formula) supplemented by contribution to ionization from transition radiation

IONIZATION OF SUBSTANCE BY EXTERNAL FIELD

$$\omega_0 = I$$

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



Energy transfer to a harmonic oscillator by external field:

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

J.D. Jackson // Classical electrodynamics, 1999

ω_0 – oscillator's own frequency

Total ionization per unit path:

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

ИОНИЗАЦИОННЫЕ ПОТЕРИ ЭНЕРГИИ «ПОЛУГОЛОГО» ЭЛЕКТРОНА

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

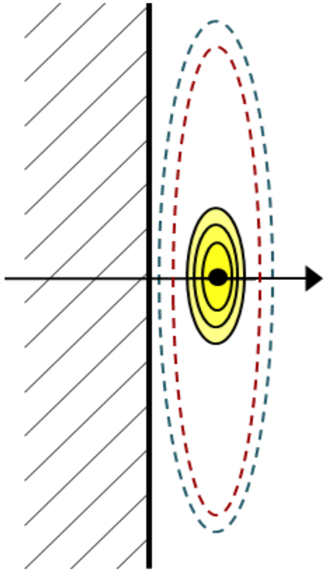
$$\frac{d\mathcal{E}}{dz} = \frac{\Omega_p^2 e^2}{v^2} \ln \frac{q_0 z \omega_p}{2I}$$

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

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

$$F(\vartheta) = \frac{\omega_p^2}{\omega^2} \frac{\vartheta}{(\vartheta^2 + \omega_p^2/\omega^2 + 1/v^2\gamma^2)(\vartheta^2 + 1/v^2\gamma^2)}$$

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

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

Own Coulomb field of the particle:

$$E_{\rho}^{C}(\vec{r},t) = -\frac{\partial}{\partial\rho}\frac{e}{\sqrt{\rho^{2}\gamma^{-2}+(z-vt)^{2}}} = \frac{e}{\pi\, v}\int_{-\infty}^{\infty} d\omega \int_{0}^{+\infty} dq\ \frac{q^{2}J_{1}(q\rho)}{q^{2}+\frac{\omega^{2}}{v^{2}\gamma^{2}}}\, e^{i\frac{\omega}{v}z}$$

Total field:

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

For $z > 2\gamma^{2}/\omega$ **:**

$$E_{\omega}^{\rho}(\rho,z) = \frac{2e}{v}\left\{ \frac{\omega}{\gamma}K_{1}\left(\frac{\omega}{\gamma}\rho\right)e^{i\frac{\omega}{v}z} + \frac{e^{i\omega\, r}}{r}F(\rho/z) \right\}$$

F – definite function of ρ/z

$$r = \sqrt{\rho^{2}+z^{2}}$$

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