National Academy of Sciences of Ukraine

National Science Center
“Kharkiv Institute of Physics and Technology”

Electrodynamic Processes at High Energies with “Half-Bared” Electrons: LPM, TSF effects and their Analogues

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DESY 10 May 2022 Hamburg, Germany

Outline:

- Brief information about NSC KIPT
- Bremssrahlung of high energy particles & coherence length of radiation process
- Landau-Pomeranchuk-Migdal effect and radiation length
- SLAC experiment E-146 on LPM effect and thin target problem
- Radiation in a thin layer of substance
- CERN experiment NA63 and radiation of “half-bared” electron
- Spectral-angular distribution and polarization of radiation at non-dipole regime
- Others effects with “half-bared” particles
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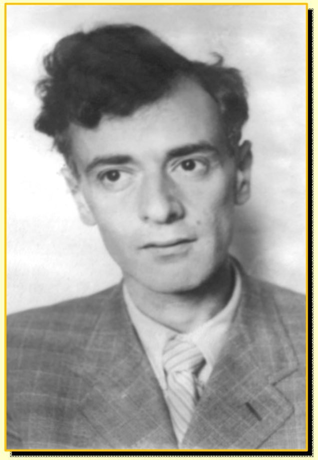
"Kharkiv Institute of Physics and Technology" - History

- 1928 Creation of the "Ukrainian Institute of Physics and Technology"
- 1931 First cryogenic laboratory in the USSR (Lev Shubnikov)
  (first liquid hydrogen and helium in the USSR)
- 1932 First destruction of lithium atomic nucleus in the USSR
  (A. Val'ter, K. Sinel'nikov, A. Lejpunsky, G. Latyshev)
- 1932-37 Landau's School and world-known Course of Theoretical Physics
  (Lev Landau, E. & I. Lifshiz, I. Pomeranchuk, A. Akhiezer, …)
- 1946 First monographia on Reactor Theory in the world (printed in 2001)
  (A. Akhiezer, I. Pomeranchuk - Lab #1 in USSR Atomic project),
- 50th- p.t. A line of electron and ion accelerators were constructed
  A family of thermonuclear installations – stellarator-torsatrons "Uragan"
  Radiation and reactor material science
- 60th Quantum Birth of the Universe from Vacuum (Piotr Fomin)
- 70th - Discovery of Supersymmetry and Supergravity (Dmitrii Volkov)
- 70th- p.t. - First observation of channelling radiation of relativistic electrons
  & positrons (V. Morokhovskii et al.) and development of the theory of
  High Energy Electrodynamics in Matter (A. Akhiezer, N. Shul'ga, ...)



Lev Landau, Nobel Prize 1962

Dmitrii Volkov

National Academy of Sciences of Ukraine
Nuclear Physics and Power Division

National Science Center
“Kharkov Institute of Physics & Technology”

Academician **Nikolai Shul’ga**, Head of NPPD & Director General of NSC KIPT

- *Institute of Solid-state Physics, Materials Science and Technologies* (physics of radiation effects, radiation materials science and technologies)
- *Institute of Plasma Physics* (plasma physics and controlled fusion)
- *Institute of High Energy Physics and Nuclear Physics*
- *Institute of Plasma Electronics and New Methods of Acceleration*
- *Akhiezer Institute for Theoretical Physics* (All branches of Physics)
- *R&D Complex "Accelerator"* (physics and engineering of accelerators)
- *Technological Complex "Nuclear Fuel Cycle“*
- *Research Facility “Neutron Source" (ADS)*

Nearly 300 PhD and 80 Doctors of Science work in NSC KIPT


National Science Center
“Kharkiv Institute of Physics and Technology”
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NSC "Kharkov Institute of Physics and Technology" some days ago

NSC “Kharkov Institute of Physics and Technology” some days ago

Participants of French-Ukraine Winter School on HEP (March 2016) at School of Physics & Technology of V.N. Karazin National University

The building of the School of Physics & Technology of V.N. Karazin Kharkiv National University (March 2022)

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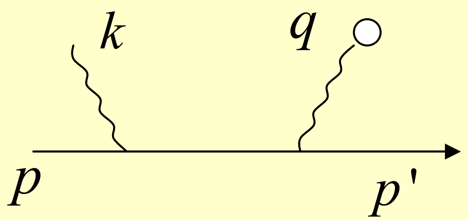
Coherence length of Bremsstrahlung



$$l_c = {2\varepsilon\varepsilon'}/{m^2\omega}$$

$$c = \hbar = 1 \quad !!!$$

$$\varepsilon = \varepsilon' + \omega, \qquad \mathbf{p} = \mathbf{p}' + \mathbf{k} + \mathbf{q}$$

$$q_{\parallel eff} = q_{\parallel \min} = \omega m^2 / 2\varepsilon\varepsilon'$$

$$d\sigma \approx \int d^2 q_\perp \int_{q_{\min}}^{\infty} dq_\parallel \frac{q_\perp^2}{q_\parallel^2} \left|U_q\right|^2$$

$$r_{\parallel eff} \approx q_{\parallel eff}^{-1} \approx l_c = {2\varepsilon\varepsilon'}/{m^2\omega}$$

$$l_c = \frac{2\varepsilon\varepsilon'}{m^2\omega}$$

$$\omega \ll \varepsilon: \quad l_c = 2\gamma^2 / \omega$$

$$\gamma = \varepsilon / m$$

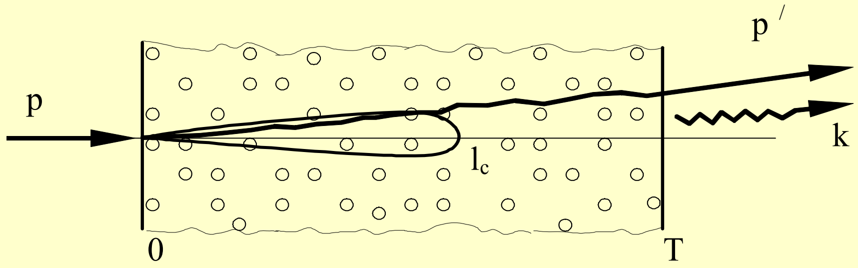
$$r_{\perp eff} \approx {1}/{q_{\perp eff}} \approx R$$

$$U(r) = \frac{Z|e|}{r} e^{-r/R}$$

$$\varepsilon = 100\ \text{GeV} \qquad \omega = 10\ \text{MeV} \qquad l_c \approx 1\ \text{mm}$$

1934: Bethe-Heitler theory of Bremsstrahlung

H. Bethe and W. Heitler, *Proc. Roy. Soc.* **A 146** (1934) 83.



$$q_{\min} = \frac{\omega m^2}{2\varepsilon\varepsilon'} = \frac{1}{r_{\max}} \qquad r_{\max} = l_{coh} = \frac{2\varepsilon\varepsilon'}{\omega m^2}$$

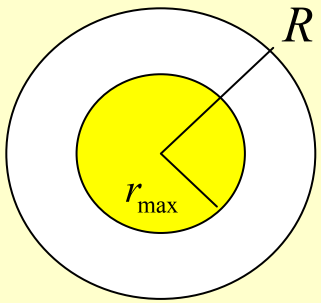
screening effect

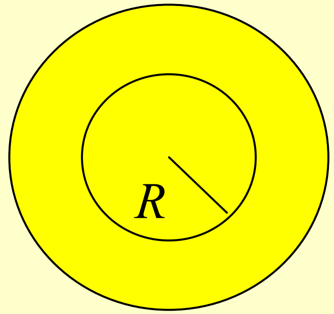
$$\frac{Z|e|}{r} \rightarrow \frac{Z|e|}{r} e^{-r/R}$$

$$\frac{dE_{BH}}{d\omega} \sim \vartheta^2 \qquad \left\langle \frac{dE_{BH}}{d\omega} \right\rangle \sim \left\langle \vartheta^2_{ms} \right\rangle \sim T$$

$$\frac{dE_{BH}}{d\omega} = \frac{2T}{3X_0}\left[\left(1+\frac{\varepsilon'^2}{\varepsilon^2}\right)+\frac{\omega^2}{\varepsilon^2}\right]$$

$$\varepsilon' = \varepsilon - \omega$$





and if $\omega \ll \varepsilon$: $\dfrac{dE_{BH}}{d\omega} = \dfrac{4}{3}\dfrac{T}{X_0} \neq f(\omega)$

$$r_{eff} \approx r_{\max} \rightarrow r_{eff} \approx R$$

where $X_0 = \left(\dfrac{4Z^2 e^6 n}{m^2} \ln mR\right)^{-1}$ is the Radiation length = *f*(Z,n), but not ε **!!!**

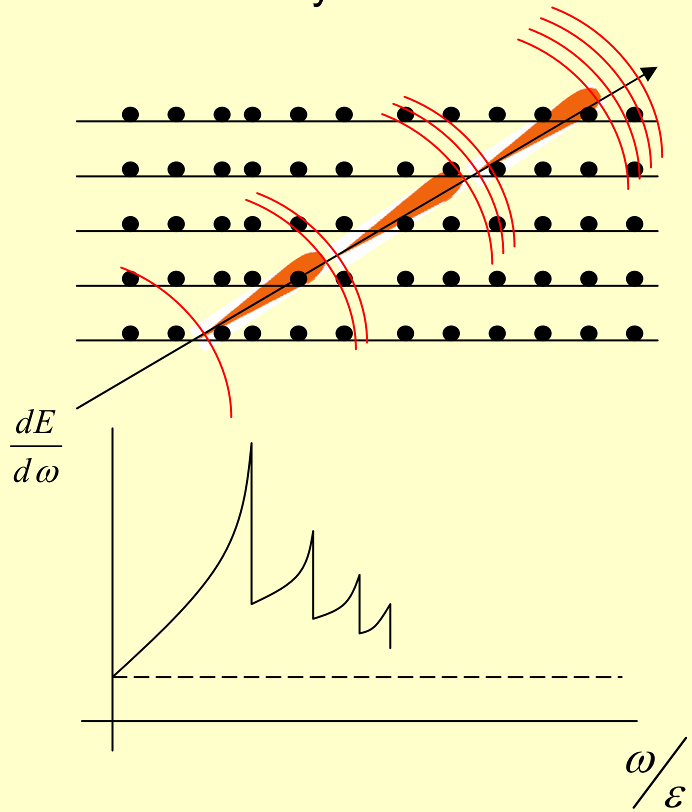
Coherence Length (M.Ter-Mikaelian, 1953)

Mikael Ter-Mikaelian

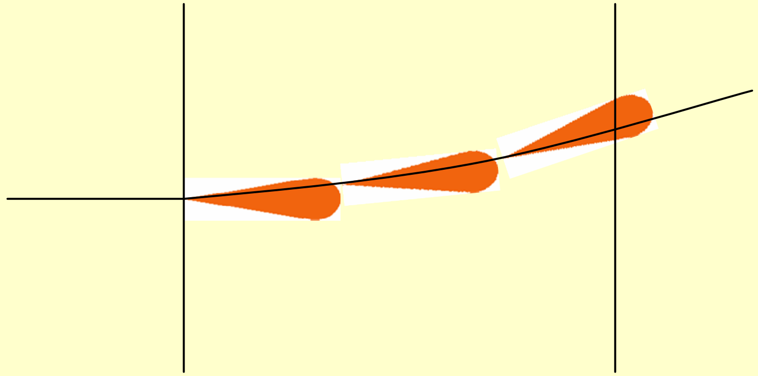
M.L.Ter-Mikaelian, High-Energy Electromagnetic Processes in Condensed Media, Wiley-Interscience, New York, 1972

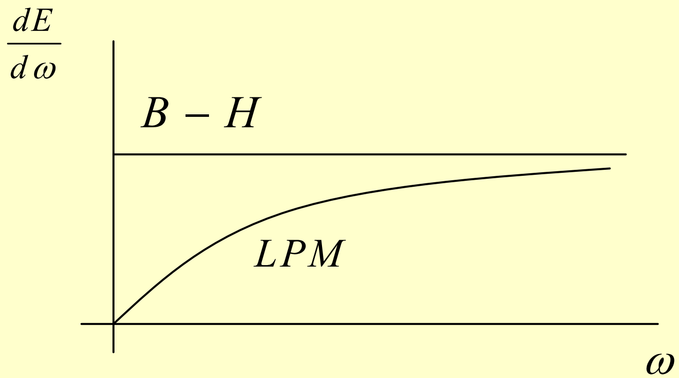
$$l_c = 2\gamma^2 / \omega$$

crystal



amorphous media





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Multiple Scattering Effect on Radiation in Amorphous Medium

L. Landau and Ya. Pomeranchuk (1953)

$$\frac{dE}{d\omega do} = \frac{e^2}{4\pi^2}\left|\vec{k}\times\int_{-\infty}^{\infty} dt\,\vec{\upsilon}(t)\,e^{i\left(\omega t-\vec{k}\vec{r}(t)\right)}\right|^2 \qquad \omega = \frac{c}{\sqrt{\varepsilon}}k$$

$$\Delta\varphi = \omega\Delta t - \vec{k}\vec{r}\left(\Delta t\right) <\sim 1 \qquad i(\omega t - \vec{k}\vec{r}) = i\omega t(1-\sqrt{\varepsilon}\frac{v}{c}\cos\theta\cos\vartheta_s)$$

If $\varepsilon \gg mc^2$ $\quad \Delta t \sim \frac{2\gamma^2}{\omega}\frac{1}{1+\gamma^2\overline{\vartheta_s^2}}$ $\qquad l_c^* = \frac{2\gamma^2/\omega}{1+\gamma^2\theta^2+\gamma^2\overline{\vartheta_S^2}+\gamma^2\omega_p^2/\omega^2}$

$$\Delta t \sim \begin{cases} 2\gamma^2/\omega\,, & \gamma^2\overline{\vartheta_s^{\,2}} \ll 1 \\ \ll 2\gamma^2/\omega, & \gamma^2\overline{\vartheta_s^{\,2}} \gg 1 \end{cases} \qquad \overline{\vartheta_s} \gg \gamma^{-1} \qquad \omega_p = \sqrt{4\pi\, n\, Ze^2/m}$$

Landau and Pomeranchuk method

$$\frac{dE}{d\omega}=\frac{e^2\omega}{\pi c^2}\int dt\int d\tau\, e^{i\omega\tau}\left[\vec{\upsilon}(t)\vec{\upsilon}(t+\tau)-\frac{c^2}{\omega^2}\left(\vec{\upsilon}(t)\nabla_1\right)\left(\vec{\upsilon}(t+\tau)\nabla_2\right)\right]\times$$

$$\times\frac{\sin\frac{\omega}{c}\left|\vec{r}_2(t+\tau)-\vec{r}_1(t)\right|}{\left|\vec{r}_2(t+\tau)-\vec{r}_1(t)\right|}$$

$$\vec{\upsilon}(t+\tau)\approx\vec{\upsilon}(t)\left[1-\frac{1}{2c^2}\upsilon_\perp^2(\tau)\right]+\vec{\upsilon}_\perp(\tau)\qquad\qquad \upsilon_\perp\ll\upsilon$$

$$\frac{dE}{d\omega}=-\frac{e^2\omega}{\pi c\gamma^2}\int dt\int\frac{d\tau}{\tau}e^{i\omega\tau}\cdot\left[\gamma^2\upsilon_\perp r_\perp-\frac{r_\perp^2(\tau)}{\tau^2}\right]\cdot\sin\frac{\omega}{c}\left|\upsilon\tau-\int_0^\tau d\tau'\upsilon_\perp^2(\tau')+\frac{1}{2c\tau}\vec{r}_\perp^2(\tau)\right|$$

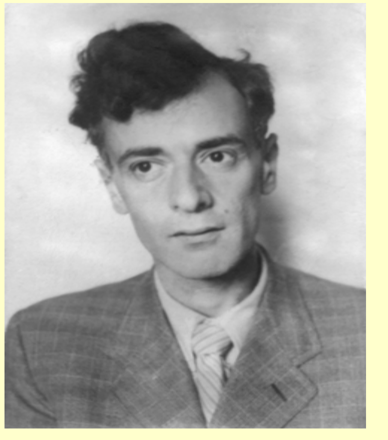
$$\left[1+\frac{1}{2c^2}\gamma^2\upsilon_\perp^2(\tau)\right]$$

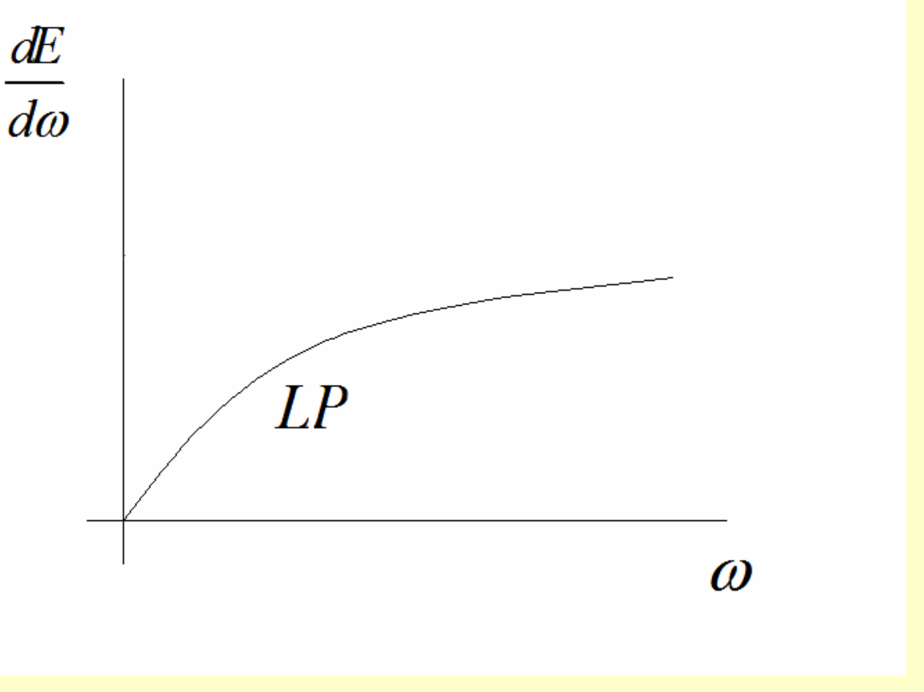
A.Akhiezer, N.Shul'ga, Sov. Phys. Usp., 1982
S.Drell, R.Blankenbecler, Phys.Rev., 1995

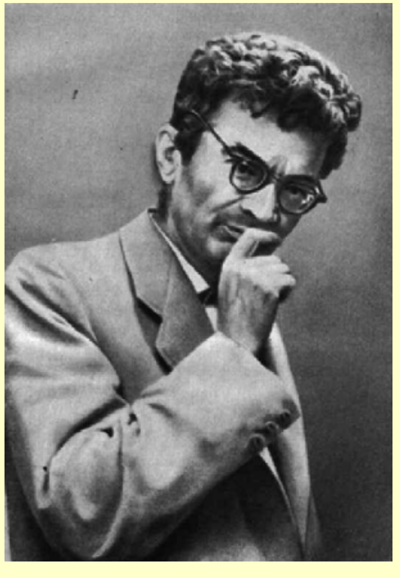
Landau-Pomeranchuk effect (at $\omega \to 0$)

$$\left\langle \frac{dE}{d\omega} \right\rangle \sim \ldots \left\langle \left[1 + \frac{1}{2c^2} \gamma^2 \upsilon_\perp^2(\tau) \right] \cdot \sin(\ldots) \right\rangle \longrightarrow \ldots \langle\, [\ldots]\, \rangle \cdot \langle\, \sin(\ldots)\, \rangle$$

$$\frac{dE_{LP}}{d\omega} \approx \frac{L}{X_0} \sqrt{\frac{2\pi}{3} \frac{\omega E_0}{E}}$$





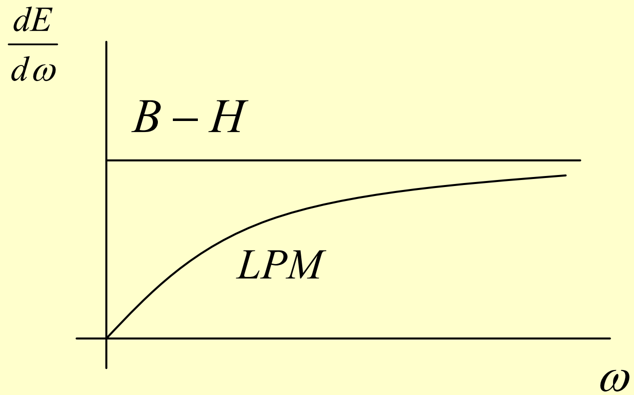


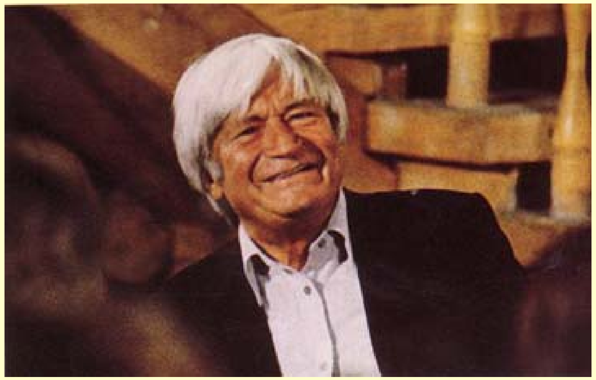
Kinetic equation method (A. Migdal, 1954)

$$\frac{dE}{d\omega do} = \frac{e^2}{4\pi^2}\int dt \int d\tau\, e^{i\omega\tau} \left\langle \vec{k}\times\vec{\upsilon}'\cdot\vec{k}\times\vec{\upsilon}\cdot e^{i\vec{k}\left(\vec{r}'-\vec{r}\right)} \right\rangle$$

$$\langle \ldots \rangle = \int d^3r'\, d^3\upsilon'\, d^3r\, d^3\upsilon\, W_1\left(\vec{r},\vec{\upsilon},t\right) W_2\left(\vec{r}',\vec{\upsilon}';\vec{r},\vec{\upsilon};\tau\right)\ldots$$

$$\partial_t W + \vec{\upsilon}\cdot\vec{\nabla} W = n\int d^3\upsilon'\,\sigma\left(\vec{\upsilon}'-\vec{\upsilon}\right)\left[W\left(\vec{r}',\vec{\upsilon}',t\right) - W\left(\vec{r},\vec{\upsilon},t\right)\right]$$



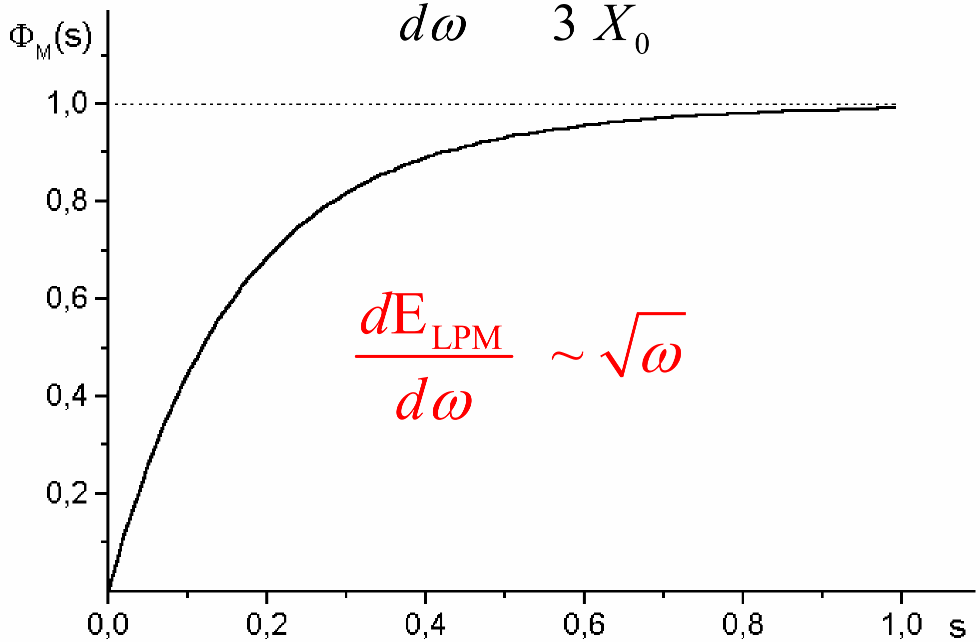


Quantitative theory of the effect in a boundless amorphous medium:

A.B. Migdal, Dokl. Akad. Nauk SSSR **96** (1954) 49; JETP **32** (1957) 633.

$$\frac{dE_{LPM}}{d\omega} = \frac{dE_{BH}}{d\omega} \cdot \Phi_M(s) \qquad \Phi_M(s) = 24s^2 \left\{ \int_0^\infty dt\, cth\, t \quad e^{-2st} \sin 2st - \frac{\pi}{4} \right\}$$

$$\frac{dE_{BH}}{d\omega} = \frac{4}{3}\frac{T}{X_0}$$



$$\frac{dE_{LPM}}{d\omega} \sim \sqrt{\omega}$$

$$s = \frac{1}{2\sqrt{2}}\sqrt{\frac{\omega}{\omega_{LPM}}}$$

$$\omega_{LPM} = 2q\gamma^4 \sim \gamma^2$$

$$q = \frac{\varepsilon_s^2}{\varepsilon^2}\frac{1}{X_0}$$

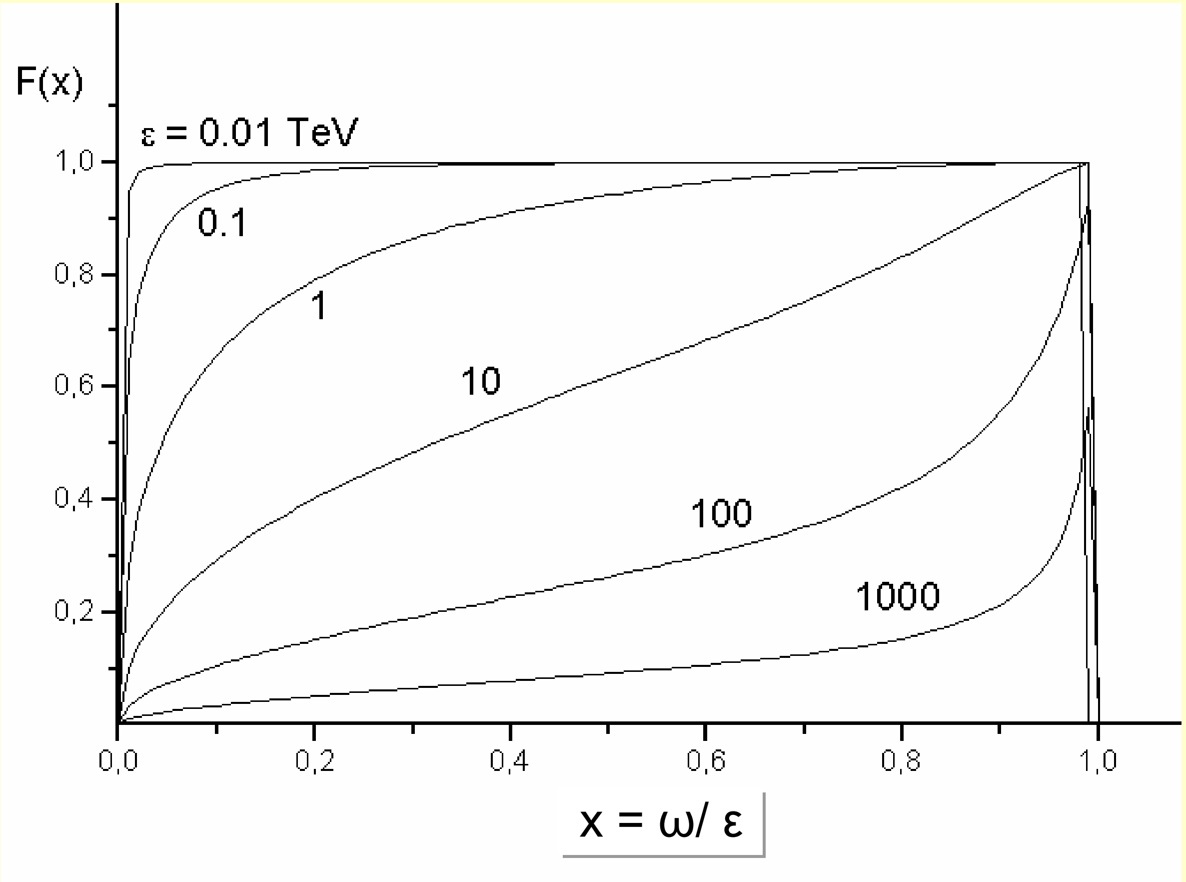
Cosmic ray experiments: **M.Miesowicz, O.Stanisz, W.Wolther. *Novo Cimento* 5 (1957) 513.**
A.Varfolomeev et al. *Sov. Phys. JETP* 11 (1960) 23.

LPM effect for very high energy

F(x) = E'$_{LPM}$ / E'$_{BH}$

$\omega_{LPM} \sim \gamma^2$

$X_0 = f(\varepsilon)$!!!



Increasing of Radiation length !!! GEANT, …

Detector design and Radiation shielding calculation …

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1994: SLAC experiment E-146

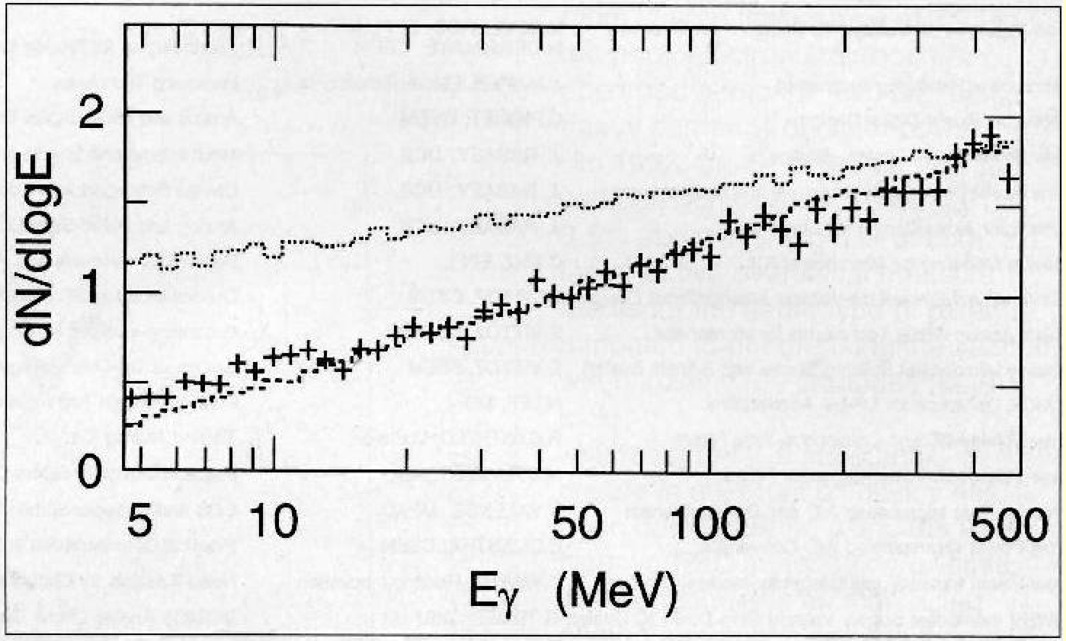
Volume 34
No. 1
January/February
1994

CERN COURIER

Covering current developments in high energy physics and related fields worldwide

STANFORD (SLAC)
Photon theory verified after 40 years

Developed by Landau, Pomeranchuk, and Migdal forty years ago, the LPM effect predicts that the production of low energy photons by high energy electrons should be suppressed in dense media.
In 1993 this was finally verified at Stanford (SLAC). The diagram compares data (crosses) with Monte Carlo simulations - one (dashed line) including LPM suppression and the other (dotted line) ignoring it - for 25 GeV electrons on uranium. Data recorded with two different targets were subtracted to remove edge effects.



A collaboration of physicists from the University of California at Santa Cruz (UCSC), the Stanford Linear Accelerator Center (SLAC), American University and Livermore has verified a theory that is almost forty years old.

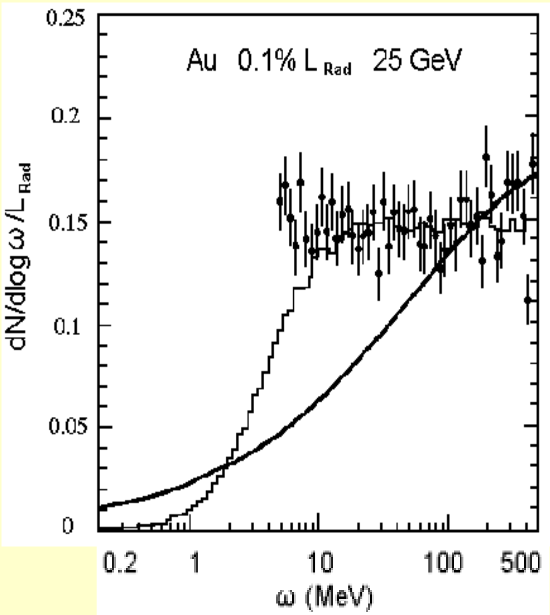
In SLAC experiment E-146, 25 GeV electrons passed through slim targets of carbon, aluminum, iron, gold, lead, tungsten and uranium — as well as a very thin gold target. After traversing the target, the electrons were de-

The E-146 data confirm that the LPM effect exists. The magnitude of the suppression in dense media such as uranium is consistent with Migdal's prediction. Lighter targets such as carbon show little suppres-

SLAC experiment E-146

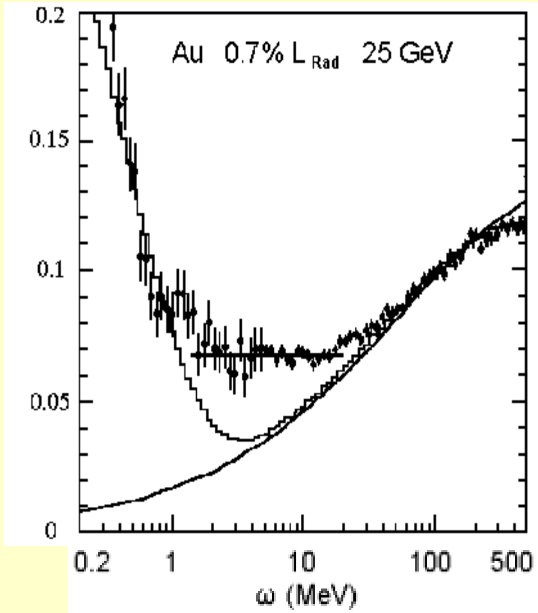
Anthony P.L. et al., Phys. Rev. Lett. **75** (1995) 1949.
Klein S., Rev. Mod. Phys. **71** (1999) 1501.

Bethe-Heitler



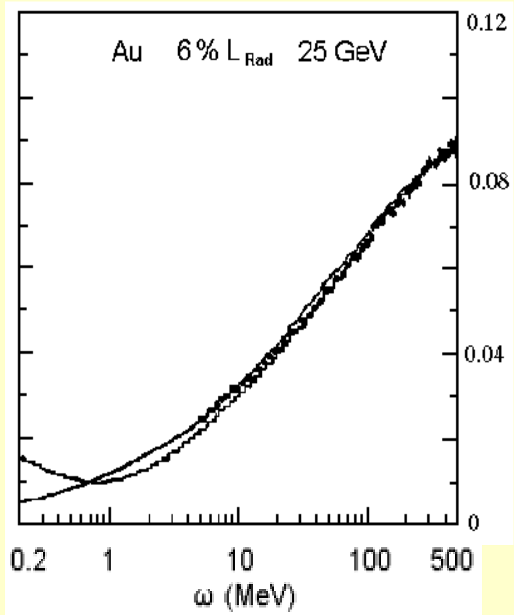
$\gamma^2 \overline{\vartheta^2} < 1$

? ? ?



$\gamma^2 \overline{\vartheta^2} > 1$, but T < l_c

LPM effect



$\gamma^2 \overline{\vartheta^2} > 1$ and T > l_c

F.F. Ternovskii. *JETP* 12 (1961) 123.

$$\overline{\vartheta^2_{ms}} = \frac{\varepsilon_s^2}{\varepsilon^2}\frac{T}{X_0} \times \left(1 + 0.038 \ln\frac{T}{X_0}\right)$$

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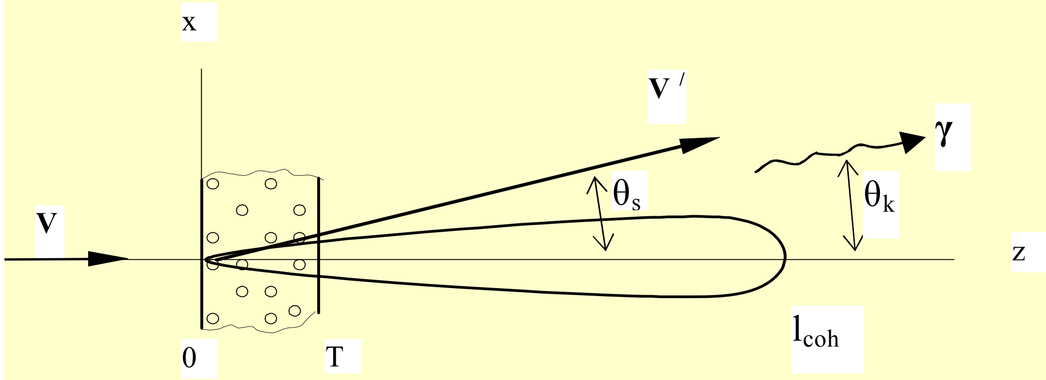
Radiation in a thin layer of matter : $l_c >> T$

Shul'ga N.F. and Fomin S.P., JETP Lett. 27 (1978)126;
Fomin S.P. and Shul'ga N.F., Phys. Lett. A114 (1986)148.

$$\frac{d^2E}{d\omega do} = \frac{e^2\omega^2}{4\pi^2}\left[\vec{n}\times\vec{I}\right]^2$$



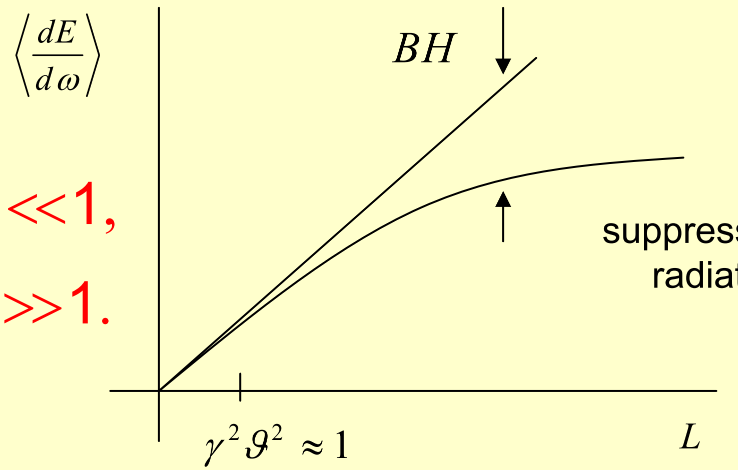
$$\vec{I} = i\int_{-\infty}^{\infty} dt\, e^{i\left(\omega t-\vec{k}\vec{r}(t)\right)}\frac{d}{dt}\frac{\vec{v}}{\omega-\vec{k}\vec{v}}$$

$$\vec{I} \approx i\left(\frac{\vec{v}'}{\omega-\vec{k}\vec{v}'}-\frac{\vec{v}}{\omega-\vec{k}\vec{v}}\right)$$

$$\frac{dE}{d\omega} = \frac{2e^2}{\pi}\left[\frac{2\xi^2+1}{\xi\sqrt{\xi^2+1}}\ln\left(\xi+\sqrt{\xi^2+1}\right)-1\right], \quad \xi = \frac{1}{2}\gamma\vartheta$$

$$\frac{dE}{d\omega} \approx \begin{cases} \dfrac{3e^2}{\pi}\xi^2, & \xi^2 << 1, \\ \dfrac{2e^2}{\pi}\ln(4\xi^2), & \xi^2 >> 1. \end{cases}$$

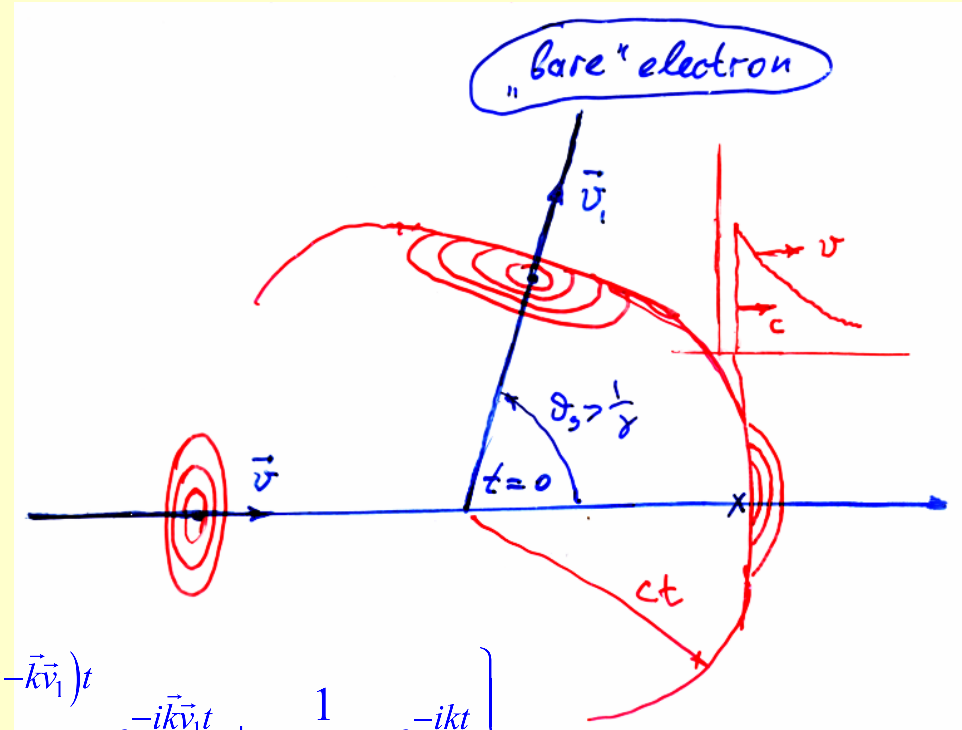
$$\frac{dE}{d\omega} \approx \begin{cases} T, & \xi^2 << 1, \\ \ln T, & \xi^2 >> 1. \end{cases}$$



Electromagnetic field of electron at scattering

$$\left(\Delta - \frac{\partial^2}{\partial t^2}\right)\varphi = 4\pi e \delta\left(\vec{r} - \vec{r}(t)\right)$$

$$\varphi_v(\vec{r},t) = \frac{e}{\sqrt{(z-vt)^2 + \rho/\gamma^2}}, \qquad t<0$$



$$\varphi_{ret}(\vec{r},t)\Big|_{t>0} = \frac{e}{2\pi^2}\mathrm{Re}\int\frac{d^3k}{k}e^{i\vec{k}\vec{r}}\left\{\frac{1-e^{-i\left(k-\vec{k}\vec{v}_1\right)t}}{\omega-\vec{k}\vec{v}}e^{-i\vec{k}\vec{v}_1 t} + \frac{1}{k-\vec{k}\vec{v}}e^{-ikt}\right\} =$$

$$= \Theta(t-r)\varphi_{v_1}(\vec{r},t) + \Theta(r-t)\varphi_v(\vec{r},t)$$

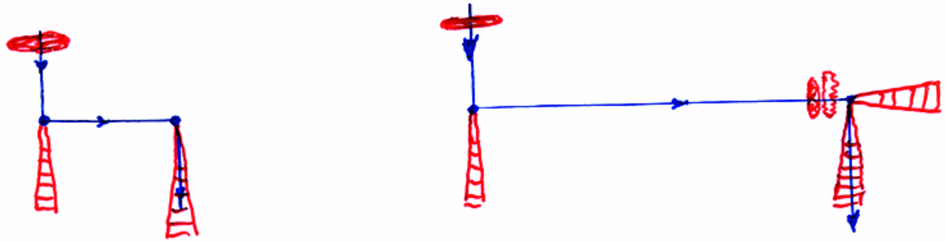
$$\Delta t \ll \left(k - kv_1\right)^{-1} \approx 2\gamma^2/\omega = l_c \qquad \text{For} \quad \varepsilon = 25\,\text{GeV}, \quad \omega = 10\,\text{MeV}, \quad l_c = 0.1\,\text{mm}$$

E.Feinberg, *JETP* 50 (1966) 202.

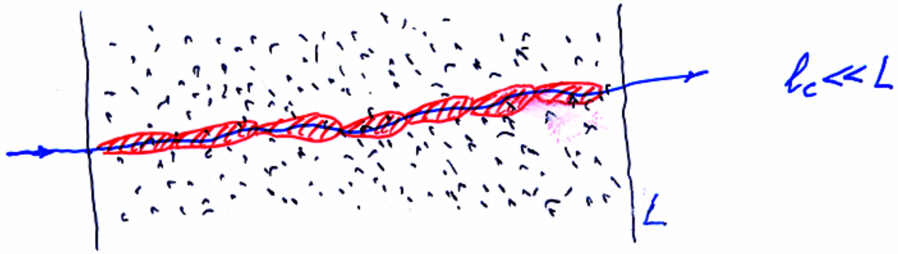
S.P. Fomin, N.F. Shul'ga, *Phys. Let. A* 114 (1986) 148

A.I. Akhiezer, N.F. Shul'ga, *Sov.Phys.Usp.* 30 (1987) 197

E. Feinberg (JETP, 1966, v. 50, 202)

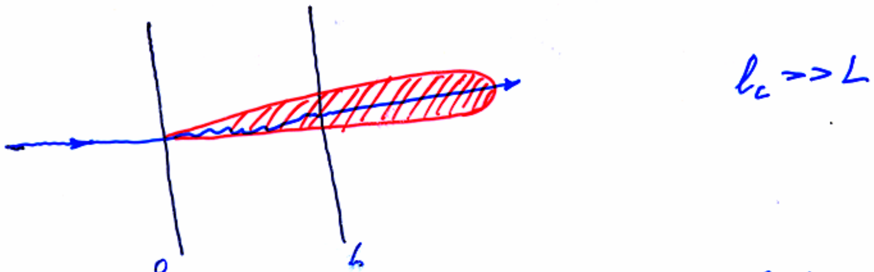


LPM case



Balance = e^- is undressed + e^- is dressed

N. Shul'ga, S. Fomin (1978)

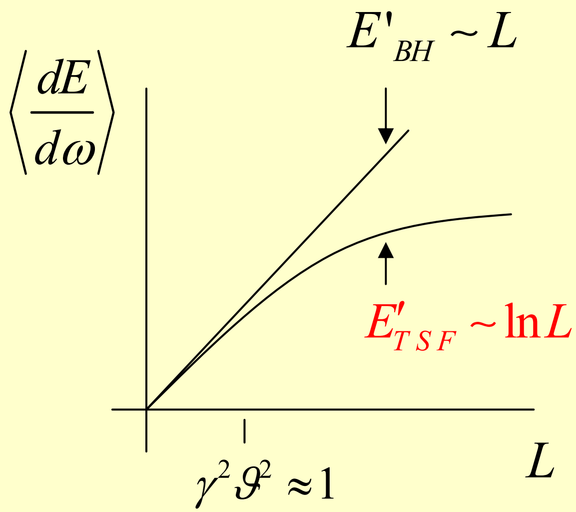


Electron is "bare" for all collisions !!!

$$\gamma^2 \overline{\vartheta^2} > 1$$

$$\sqrt{\overline{\vartheta^2}} > \gamma^{-1}$$

$$\frac{dE_{LP}}{d\omega} \approx \frac{L}{X_0} \sqrt{\frac{2\pi}{3} \frac{\omega E_0}{E}}$$

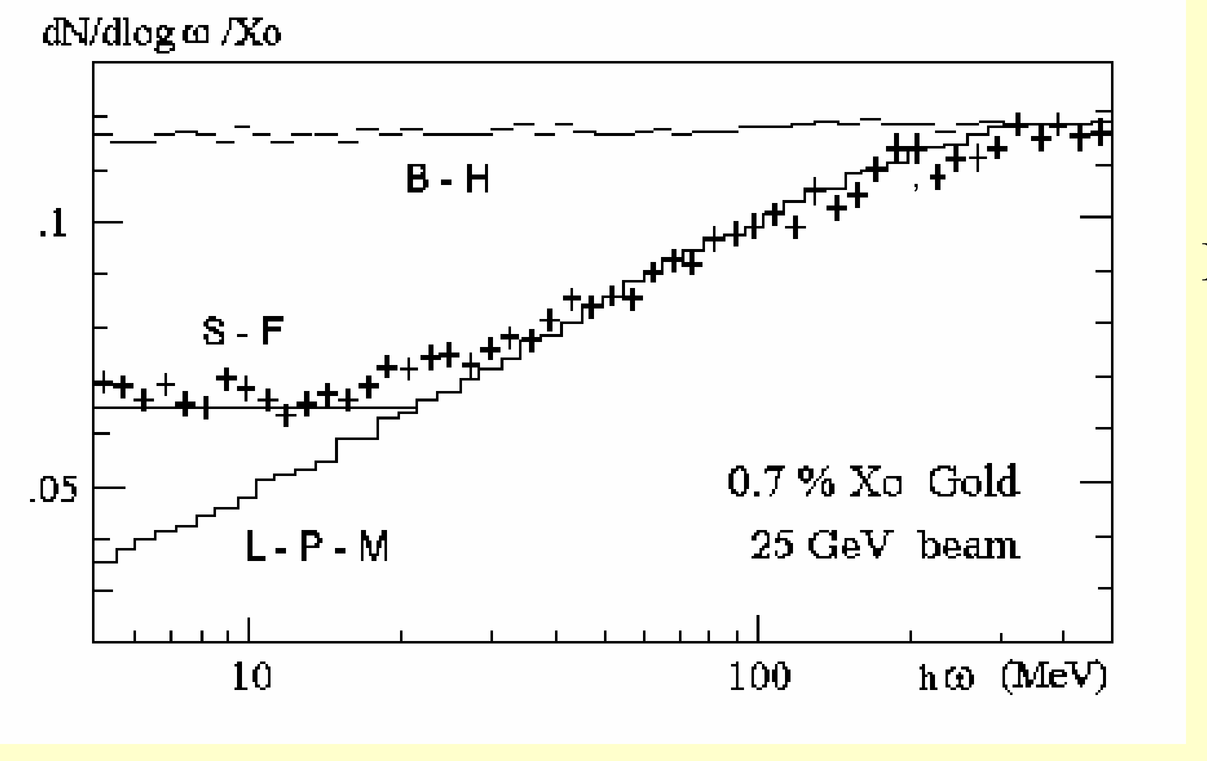


Quantitative theory of radiation in a thin layer of matter

Shul'ga N.F., Fomin S.P., JETP Lett. 63 (1996) 873; JETP 86 (1998) 32; NIM B145 (1998) 73.

$$\left\langle \frac{dE}{d\omega} \right\rangle = \int d\vec{\vartheta}_s \, f(\vec{\vartheta}_s) \frac{dE}{d\omega}, \qquad f_{B-M}(\vartheta) = \frac{1}{2\pi} \int_0^\infty \eta \, d\eta \, J_0(\eta\vartheta) \exp\left\{ -2\chi_c^2 \int_0^\infty \chi \, d\chi \, q(\chi) \chi^{-4} [1 - J_0(\eta\chi)] \right\}$$

$$\gamma^2 \overline{\vartheta^2} > 1 \qquad \frac{dE_{SF}}{d\omega} = \frac{2e^2}{\pi} \left[\left(\ln a^2 - C \right) \left(1 + \frac{2}{a^2} \right) + \frac{2}{a^2} + \frac{C}{B} - 1 \right] \qquad a^2 = \gamma^2 \overline{\vartheta^2}$$



$$\overline{\vartheta^2} = \chi_c^2 B$$

$$B - \ln B = \ln(\varepsilon^2 R^2 \chi_c^2) + 1 - 2C$$

$$\chi_c^2 = 4\pi \, nLZ^2 e^4 / \varepsilon^2$$

$$C = 0,577$$

Other publications on this subject:

R. Blankenbacler, S.D. Drell. The Landau-Pomeranchuk-Migdal effect for finite targets. *Phys.Rev.* 1996, v. D53, p. 6265-6281.

R. Blankenbacler. Structured targets and Landau-Pomeranchuk-Migdal Effect. *Phys. Rev.* 1997, v. D55, p. 190-195.

B.G. Zhakharov. Structured targets and Landau-Pomeranchuk-Migdal effect for finite-size targets. *JETP Lett.* 1996, v. 64, p. 781-787.

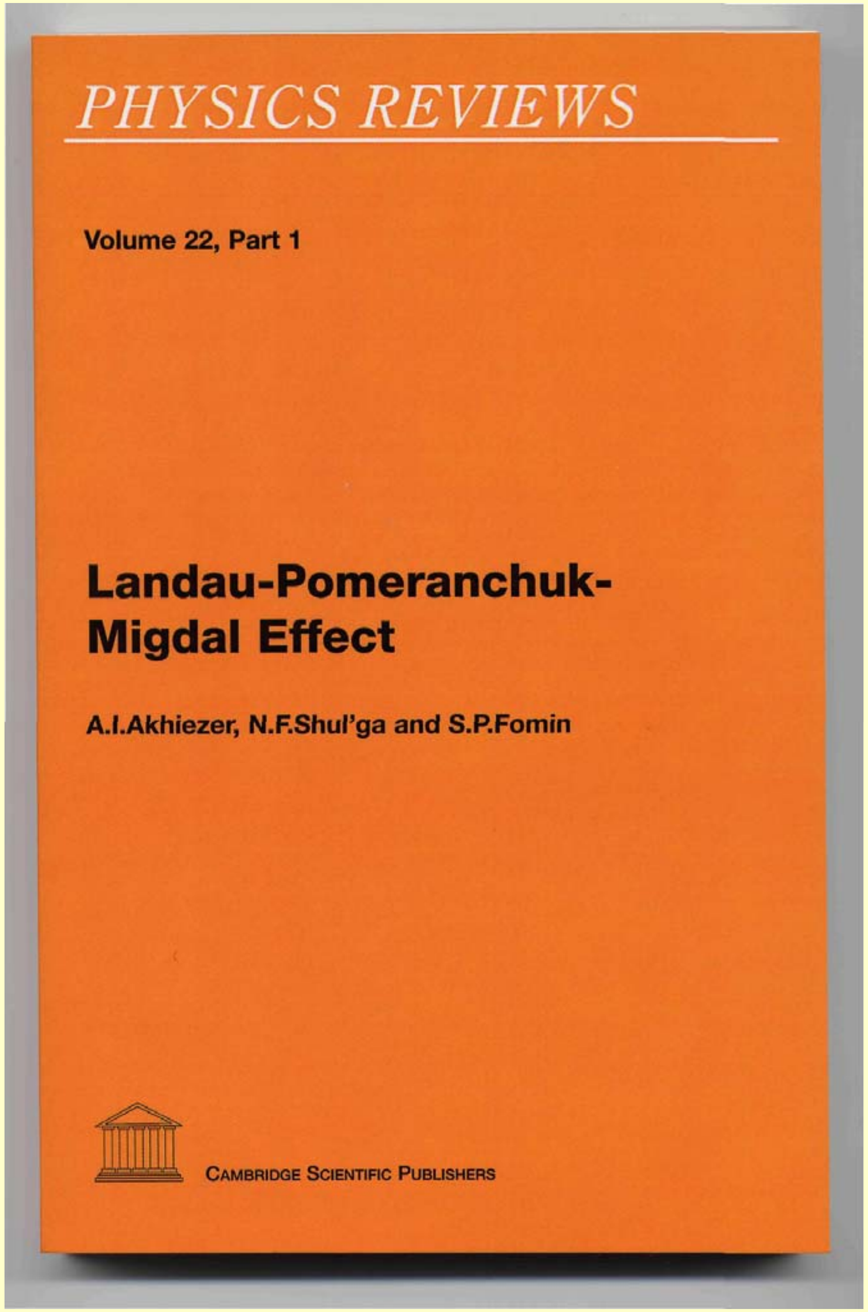
B.G. Zhakharov. Light-cone path integral approach to the Landau-Pomeranchuk-Migdal effect. *Yadernaya Fiz.* 1998, v. 61, p. 924-940.

R.Baier, Yu.L.Dokshitser, A.H.Mueller, S.Peigne, D.Schiff. The Landau-Pomeranchuk-Migdal effect in QED. Nucl. Phys. 1996, v. B478, p. 577-597.

V.N. Baier, V.M. Katkov. Landau-Pomeranchuk-Migdal effect and transition radiation in structured targets. *Phys. Rev.* 1999, v. D60, 076001, 12 p.

X. Artru. Classical spectral sum rules and “half-naked” electron effects in radiation from relativistic electrons in external field. *Journal of Instrum.,* 2020, v. 15, C04042.

. . . .



2005

A.I. Akhiezer, N.F. Shul'ga, S.P. Fomin.
***The Landau-Pomeranchuk-Migdal Effect*.**
Cambridge Scientific Publishers,
Cambridge, UK, 2005, 215 p.

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CERN NA63 experiment 2005

SPS secondary positron beam E = 178 GeV, target thickness: 2, 10, 20 μm

PHYSICAL REVIEW D **72**, 112001 (2005)

Formation length effects in very thin targets

U. I. Uggerhøj,[1] H. Knudsen,[1] S. Ballestrero,[2] P. Sona,[2] A. Mangiarotti,[3] T. J. Ketel,[4] A. Dizdar,[5] S. Kartal,[5] and C. Pagliarone[6]

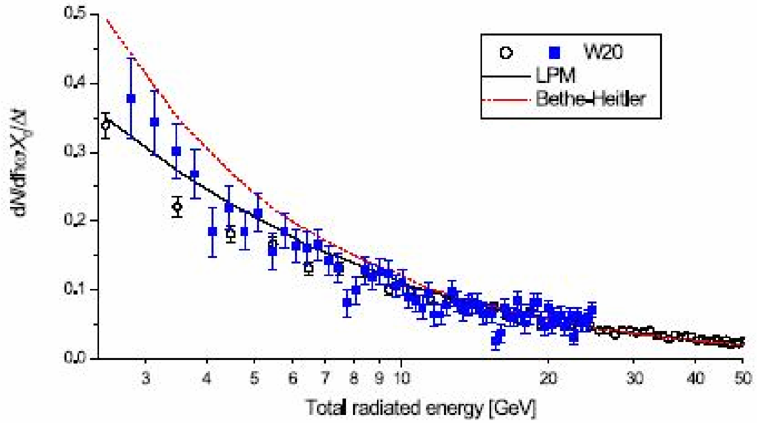

FIG. 5: *Normalized bremsstrahlung spectrum, $dN/d\hbar\omega \cdot X_0/\Delta t$, for 178 GeV positrons on 4 layers of 20 μm W with 100 μm LDPE spacers. The vertical scale is normalized to the number of incoming positrons and the thickness in units of the radiation length. The meaning of the symbols is as in figure 2.*

B. Thin target—Ternovskii-Shul'ga-Fomin effect

Because the formation length for radiation emission increases with decreasing photon frequency, at a certain point the formation zone extends beyond the thickness of the foil. In this case, the radiation yield also becomes suppressed. Theoretical studies of this effect were first performed by Ternovskii [6] and later extended by Shul'ga and Fomin [5,7–11]. The phenomenon is also of substantial interest in QCD [16–19].

For the Ternovskii-Shul'ga-Fomin (TSF) effect, the analysis is applicable for target thicknesses $l_\gamma \ll \Delta t < l_f$, see e.g. [10]. Combining the formation length and the target thickness parametrized by $k_f > 1$, $\Delta t = l_f/k_f$, the effect becomes appreciable for photon energies

$$\hbar\omega < \hbar\omega_{TSF} = \frac{E}{1 + \frac{\Delta t}{2\gamma\lambda_c}}, \qquad (2)$$

CERN NA63 experiment 2008

SPS secondary electron beam E = 206 & 234 GeV, target thickness: 5-10 μm

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ELSEVIER

On the macroscopic formation length for GeV photons

CERN NA63 Collaboration

H.D. Thomsen [a], J. Esberg [a], K. Kirsebom [a], H. Knudsen [a], E. Uggerhøj [a], U.I. Uggerhøj [a,*], P. Sona [b], A. Mangiarotti [c], T.J. Ketel [d], A. Dizdar [e], M.M. Dalton [f], S. Ballestrero [f], S.H. Connell [f]

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[b] University of Florence, Florence, Italy
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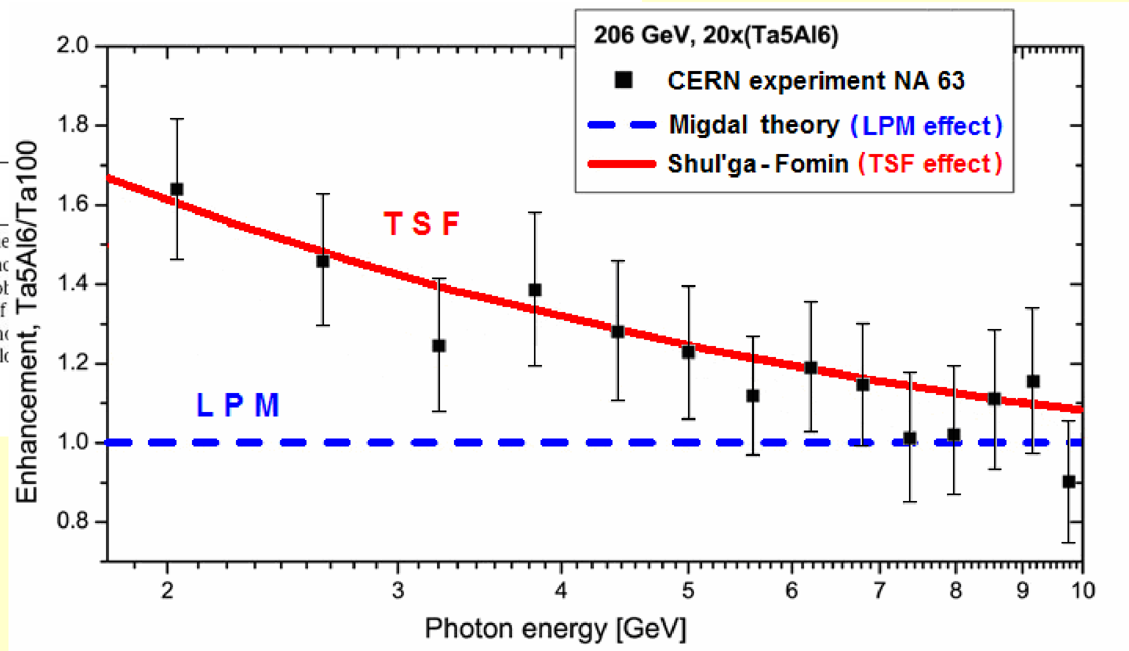
ARTICLE INFO

Article history:
Received 18 April 2008
Received in revised form 9 January 2009
Accepted 23 January 2009
Available online xxxx
Editor: M. Doser

PACS:
41.60.-m
95.30.Gv

ABSTRACT

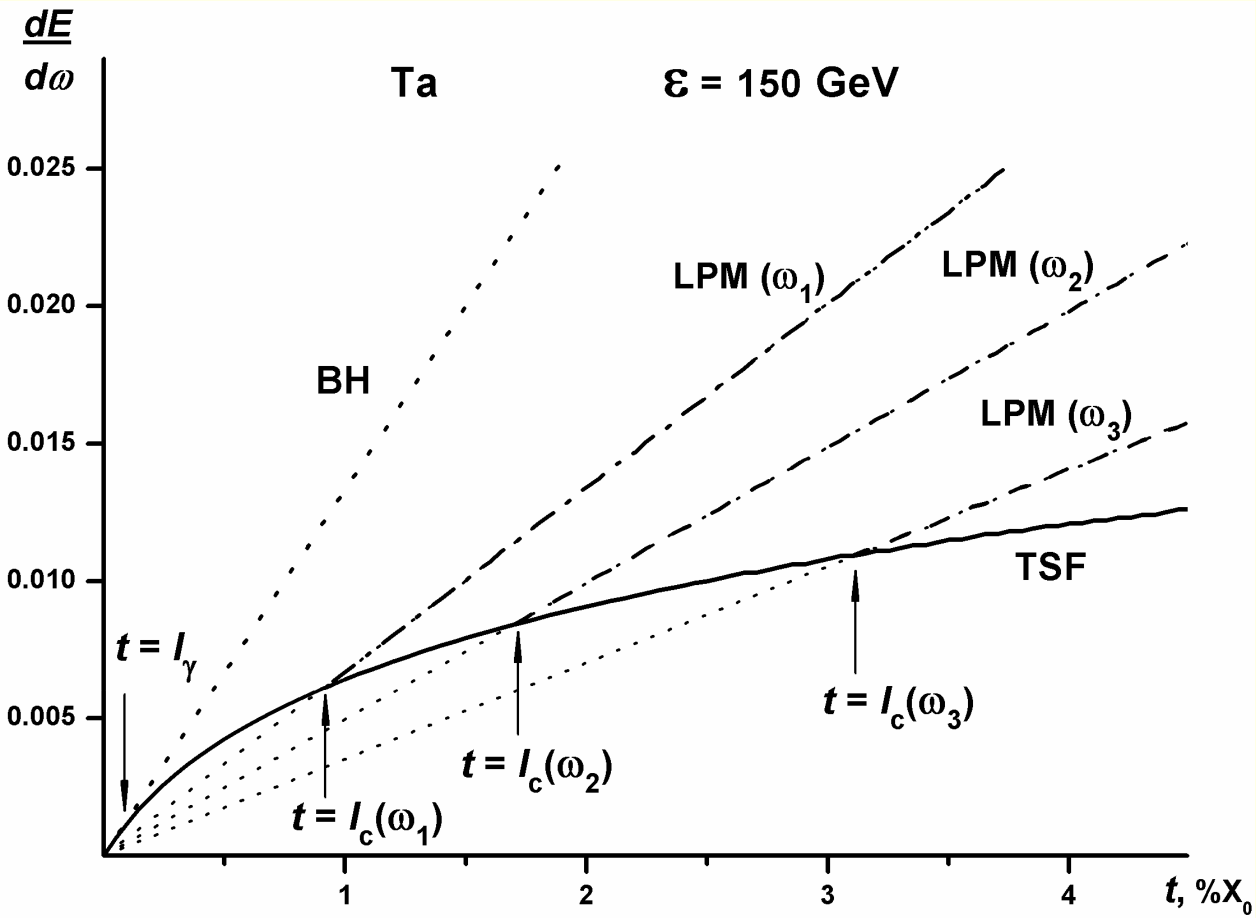
Experimental results for the
targets are presented. An inc
a 100 μm thick target is ol
exceeding the thickness of
formation length of GeV ph
directly to be a factor 10^{10} l



Thickness dependence !!!

N. Shul'ga, S. Fomin: JETP Lett. **27**(1978)126. Phys.Let.A **114**(1986)148; JETP **86**(1998)32

$$\omega_{TFS} = \frac{\varepsilon}{1+\varepsilon_{TSF}/\varepsilon} \qquad \varepsilon_{TSF} = m^2 t / 2 \approx 6.6 \text{ PeV} \cdot t \text{ (cm)}$$



If $\varepsilon << \varepsilon_{TSF}$:

$\omega_{TSF} \approx 2\gamma^2/t$

$t \approx l_c(\omega)$

ω_1 = 800 MeV

ω_2 = 350 MeV

ω_3 = 150 MeV

CERN experiment NA63 - June 2009

June 5, 2009

Dear Nikolai and Serguei,

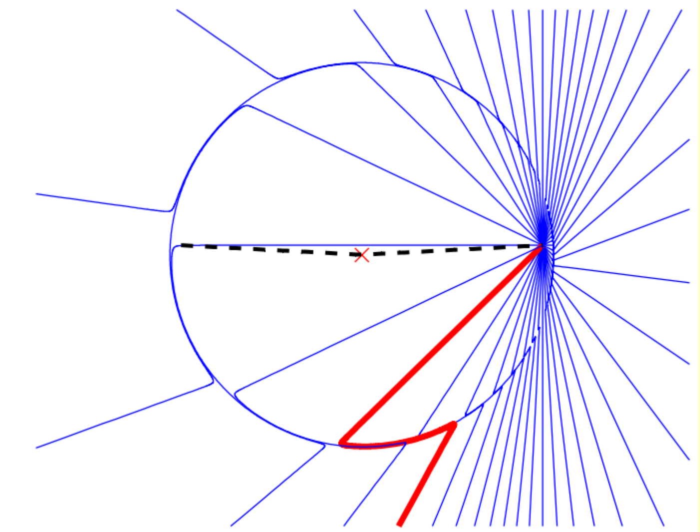
It is a pleasure for me to tell you that in the CERN experiment we are running these days, we have confirmed the logarithmic thickness dependence that your theory for thin targets has predicted, …

… we are certain that the effect is there, and we thought we would let you know that we have 'seen' the 'half-bare' electron :-)

Best regards from all of us at NA63,

Ulrik Uggerhoj

Spokesman of CERN NA63 collaboration
Professor, Aarhus University, Denmark

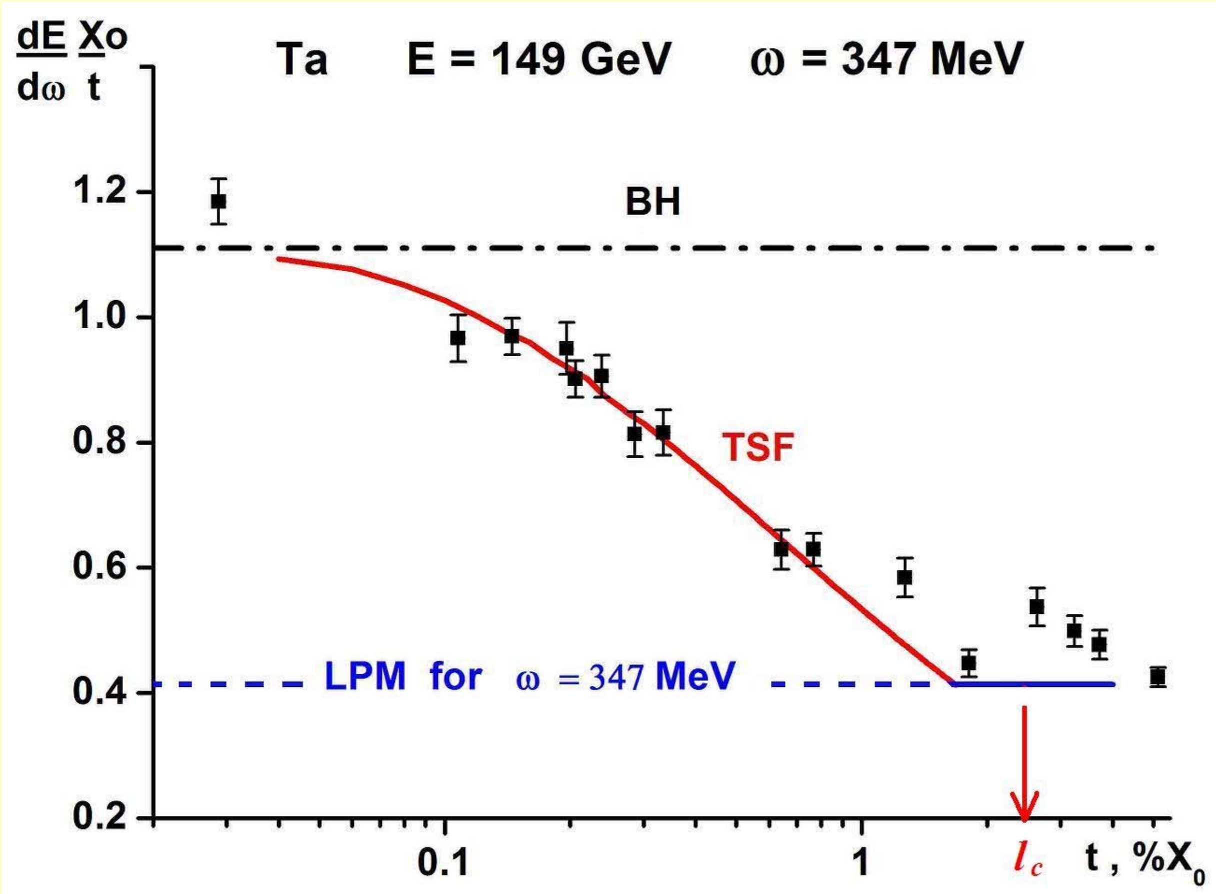


(a) *Single Scattering.*

TSF Theory & CERN experiment NA63 June 2009

H.D.Thomsen et al., Phys. Rev. D 81 (2010) 052003

A.S.Fomin, S.P.Fomin, N.F.Sul'ga, *Nuovo Cimento 34C (2011) 45.*



BH, LPM and TSF effects at high energy (ε=200 GeV)

Thickness dependence of radiation spectral density

(from H.D.Thomsen PhD thesises)

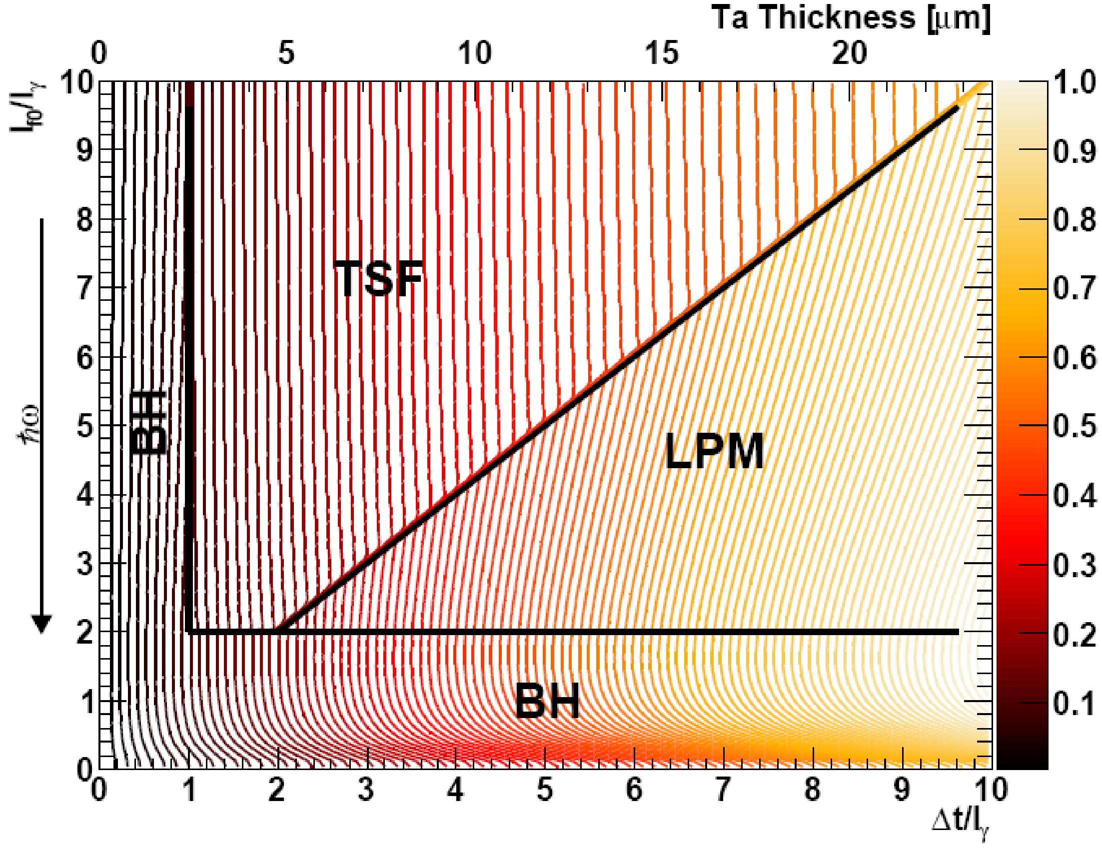


Figure 4.8: The bremsstrahlung power spectrum level (in arbitrary units) in a small part of the $(\Delta t, \ell_{f0}, \ell_\gamma)$ parameter space. The contour lines trace lines of equal bremsstrahlung yield. Upper horizontal axis shows the equivalent tantalum thickness. For the calculation, $E_0 = 200$ GeV and tantalum have been assumed.

$$\vartheta_{ms}(l_\gamma) = 1/\gamma$$

$$l_\gamma = \frac{e^2}{2\pi} X_0$$

$$T = l_c$$

$$l_c = \frac{2\varepsilon\varepsilon'}{m^2\omega}$$

$$X_0 = \left(\frac{4Z^2 e^6 n}{m^2} \ln mR \right)^{-1}$$

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Angular Dirtribution of Radiation in Non-Dipole Case

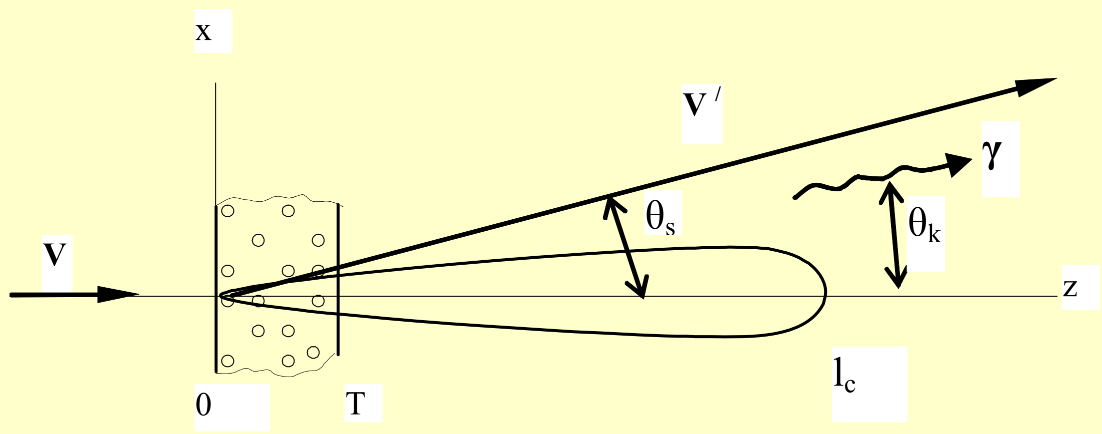
S.P. Fomin, N.F. Shul'ga, S.N. Shul'ga, Phys. Atom. Nucl. 66 (2003) 421

$$\frac{d^2E}{d\omega\, do} = \frac{e^2\omega^2}{4\pi^2}\left[\vec{n}\times\vec{I}\,\right]^2, \quad \vec{I} = i\int_{-\infty}^{\infty} dt\, e^{i\left(\omega t - \vec{k}\vec{r}(t)\right)} \frac{d}{dt}\frac{\vec{v}}{\omega - \vec{k}\vec{v}} \approx i\left(\frac{\vec{v}'}{\omega - \vec{k}\vec{v}'} - \frac{\vec{v}}{\omega - \vec{k}\vec{v}}\right)$$

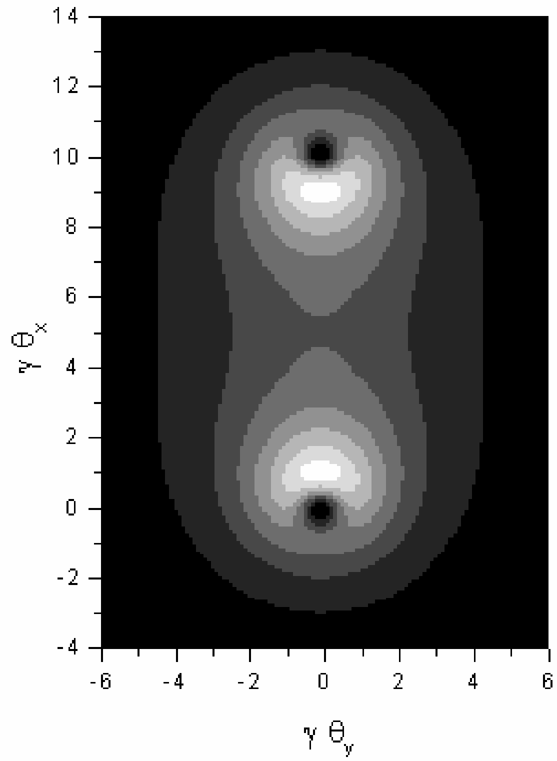
$l_c >> T$

$$\frac{d^2E}{d\omega\, do} = \frac{e^2\gamma^2}{\pi^2 G}\left\{\frac{1+\alpha^2+\alpha^2\beta^2+2\alpha\beta\cos\varphi}{\left(1+\alpha^2\right)^2} - \frac{1}{G}\right\}$$

$$G = 1+\alpha^2+\beta^2-2\alpha\beta\cos\varphi \qquad \alpha = \gamma\vartheta_k \qquad \beta = \gamma\vartheta_e$$



$\gamma\vartheta_e = 10$



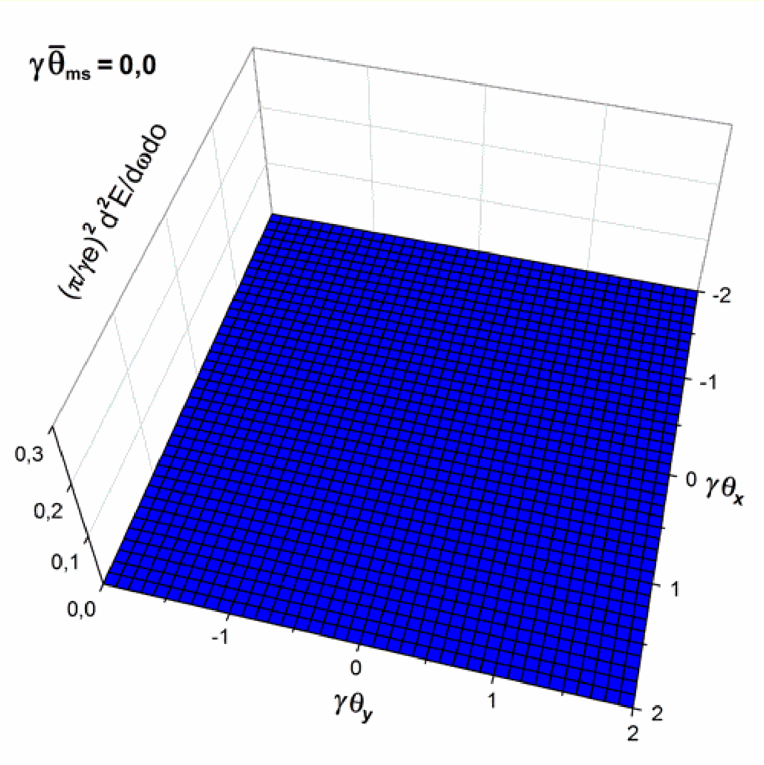
Angular Distribution of Radiation at Non-Dipole Mode

Bethe-Heitler theory of Bremsstrahlung is valid if $\gamma\bar{\vartheta}_{ms}(l_c) < 1$

At high energy $\gamma\bar{\vartheta}_{ms}(l_c) > 1$ **- non-dipole mode of radiation**

If T > l_c - LPM effect (SLAC experiment E-146, S. Klein et al. 1993-1999)

If T < l_c - TSF effect (CERN experiment NA63, U. Uggerhoj et al. **2005-2010)**



New CERN experiment proposal

Spectral-angular distribution of radiation at transition from dipole to non-dipole mode

Theory predicts radical changes of angular distribution at

$$\gamma\bar{\vartheta}_{ms}(l_c) \approx 1$$

The Main goal: Experimental check and including into GEANT !

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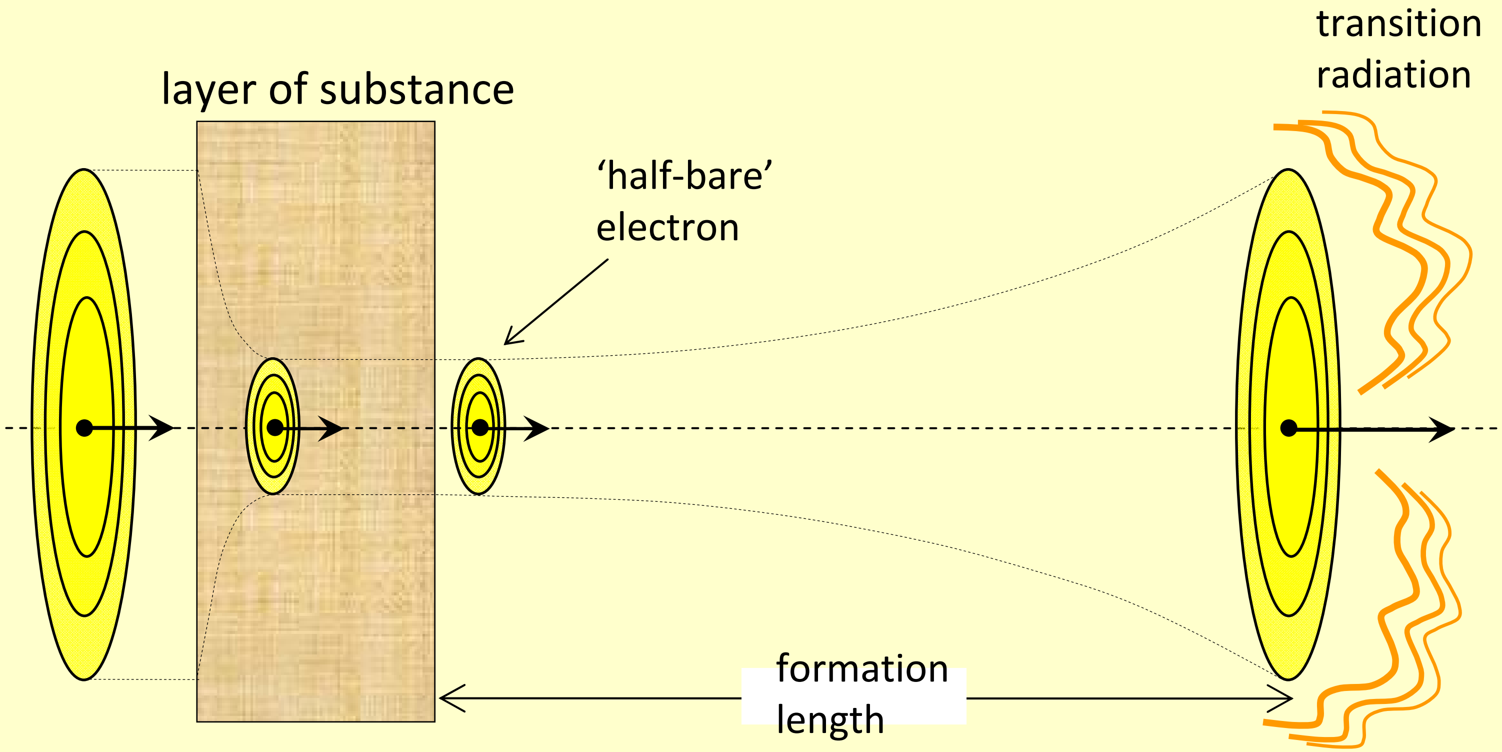
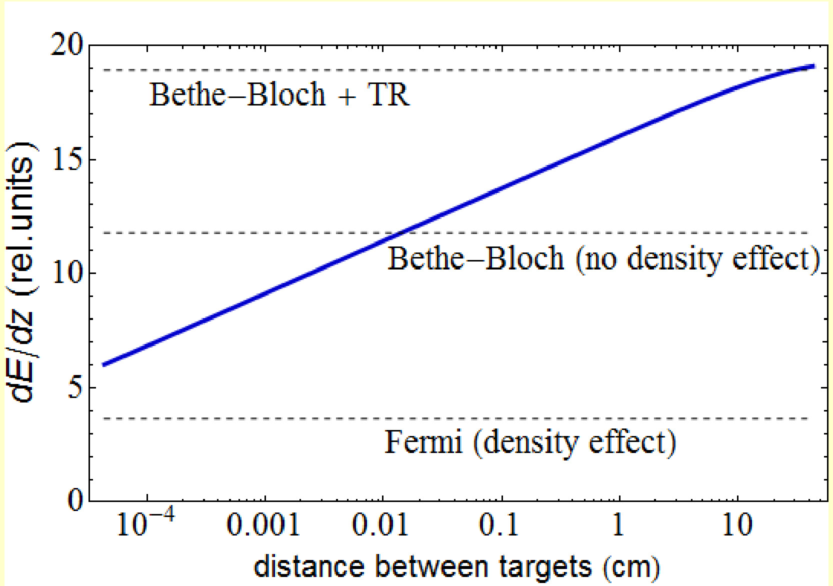
ELECTRON 'UNDRESSING' AS A RESULT OF ITS PENETRATION THROUGH A LAYER OF SUBSTANCE (S. Trofymenko & N. Shulga)



Electron 'half-bare' state in the result of its interaction with substance, can dramatically influence upon further electron interactions with substance within the formation length

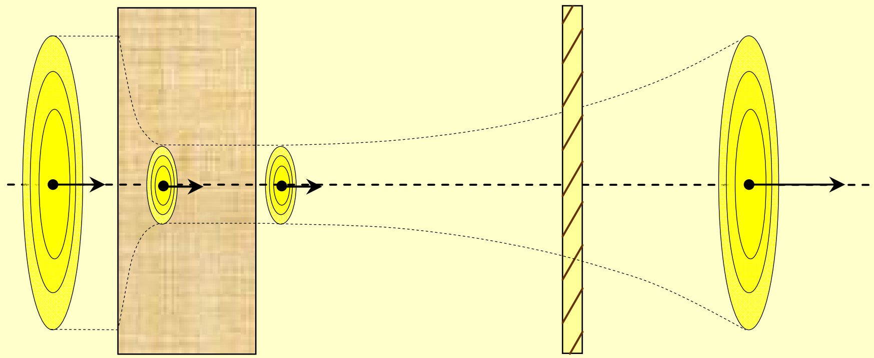
IONIZATION LOSS OF 'HALF-BARE' ELECTRON AND ULTRASHORT BUNCH IN THIN TARGET

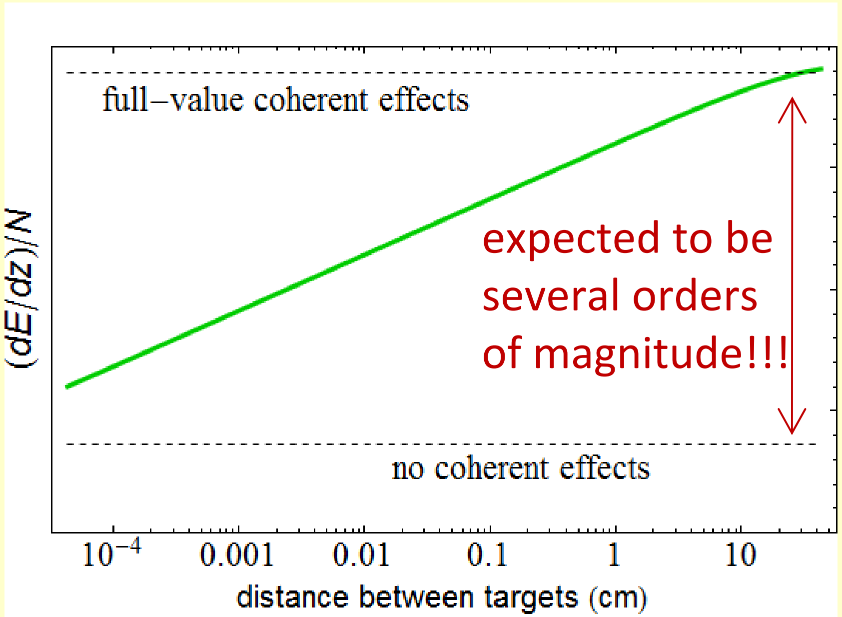


single electron

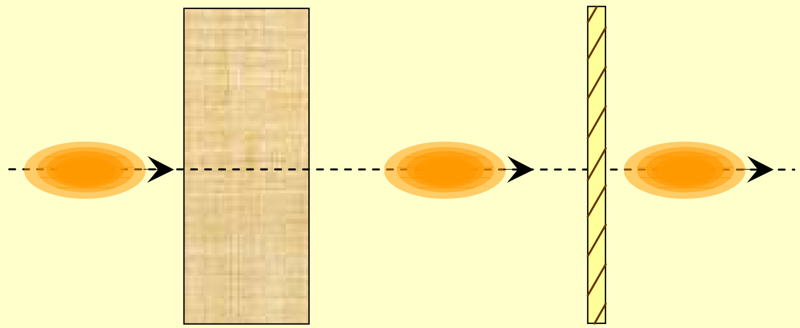
N.F. Shul'ga, S.V. Trofymenko // Phys.Lett.A (2012)

S.V. Trofymenko, N.F. Shul'ga // Phys.Rev.Accel.Beams (2016)





ultrashort electron bunch



for small distances – no coherent effects; for large distances – full-value coherent effects □ huge difference between ionization loss values

COHERENT EFFECT IN IONIZATION LOSS

S.V. Trofymenko, N.F. Shul'ga // Phys. Lett. A (2019)

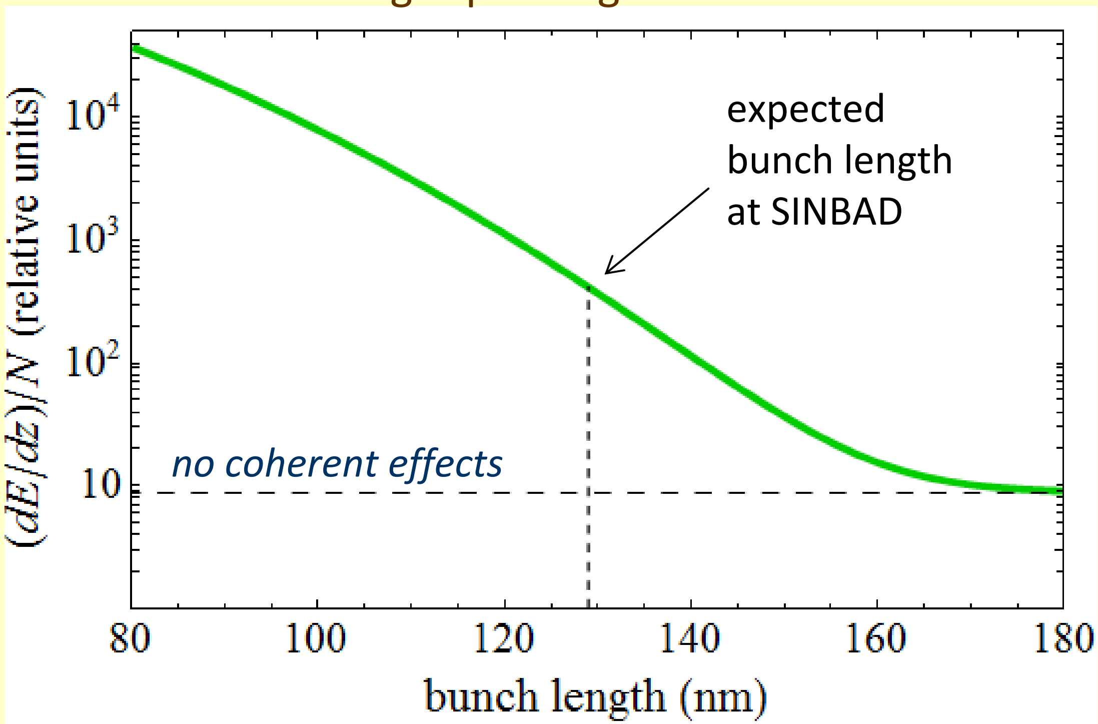
Bunch ionization loss taking into account coherent effects:

$$\frac{dE}{dz} = \frac{2nNe^4}{m} \sum_i s_i \int \frac{d^2 q q^2}{(q^2 + \omega_{0i}^2 / \gamma^2 + \omega_p^2)^2} \{ 1 + (N-1) F_\perp F_\parallel \}$$

incoherent term (Bethe-Bloch formula)

coherent term (depends on the bunch form-factors $F_{\square}$ and $F_{||}$)

Dependence of the ionization loss on the bunch length per single electron



estimation for **SINBAD** facility (thin solid targets or gaseous targets)

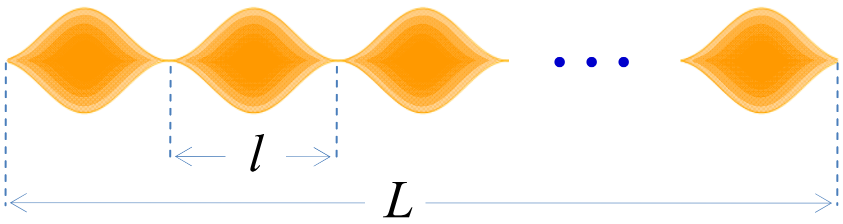
possibility of longitudinal and transversal bunch size diagnostics

RESONANCE EFFECT IN THE IONIZATION LOSS OF A MICROBUNCHED BEAM

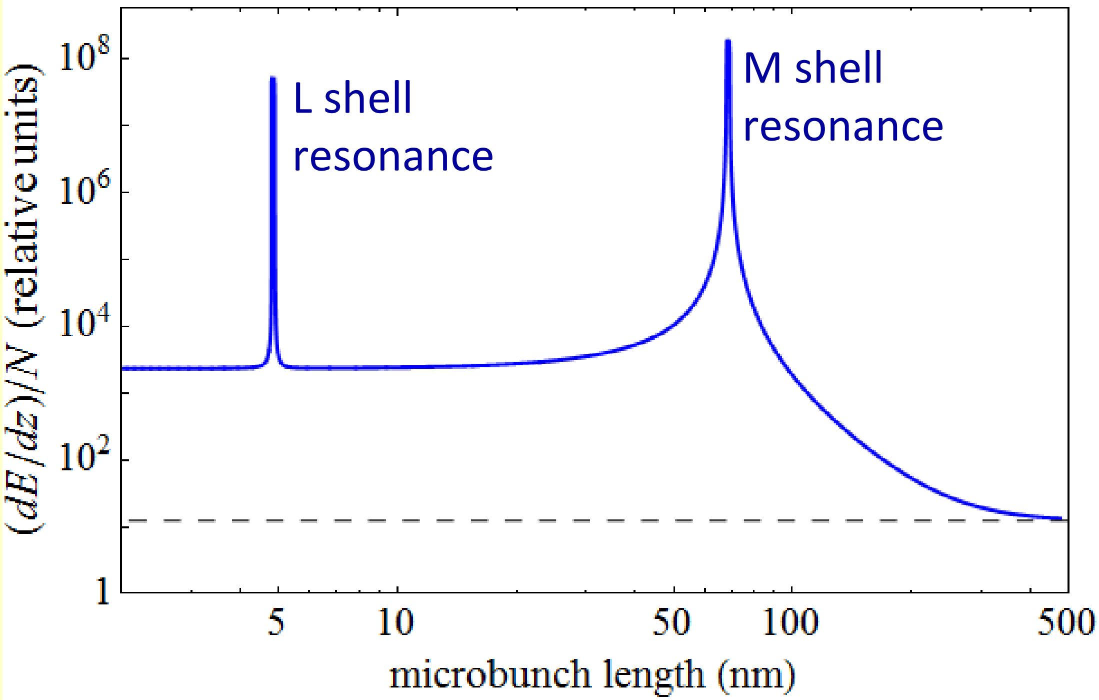
S.V. Trofymenko, N.F. Shul'ga // Phys. Rev. Accel. Beams (2020)

L – beam length

l – microbunch length



Dependence on the microbunch length in thin Si target :



Estimation for **European XFEL** (L =24 □m, Q □ 1 nCl, E= 17.5 GeV)

possibility of studying of microbunching process and controlling of microbunching period

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Conclusion

1. The effect of suppression of ultrarelativistic electron radiation due to a multiple scattering on atoms in a thin amorphous target (TSF effect) was finally confirmed in the CERN experiment NA63 by observation of logarithmic dependence of the radiation spectral density on the target thickness.
2. It is theoretically shown that this effect leads to essential changing not only spectral density of radiation, but also its angular distribution and polarization, that can be verified by future experiments.
3. The analogous of the LPM and TSF effects have to take place in others in Electrodynamics‘ processes, such as transition radiation, ionization losses, as well as in QCD at quark-gluon interaction.

Thank you for attention!