BREMSSTRAHLUNG IN A THIN LAYER OF MATTER AT HIGH ENERGY

S.P. Fomin, A.S. Fomin, N.F. Shul'ga

Akhiezer Institute for Theoretical Physics

National Science Center "Kharkov Institute of Physics & Technology"

Kharkov 61108, Ukraine, e-mail: sfomin@kipt.kharkov.ua

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1. SLAC experiment E-146

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CERN COURIER

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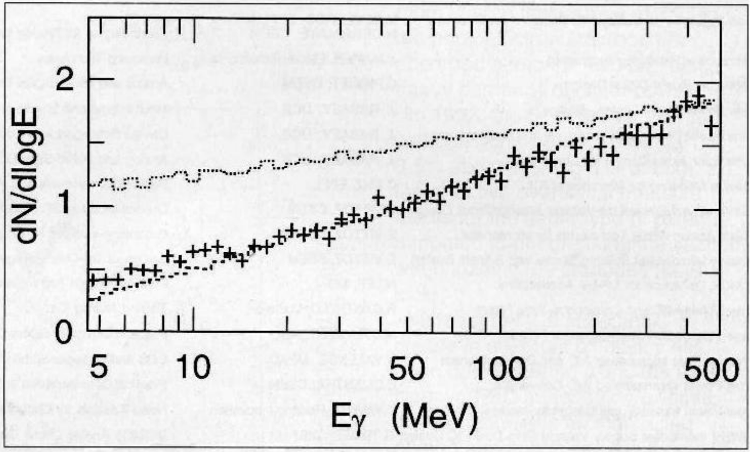
STANFORD (SLAC) Photon theory verified after 40 years



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.

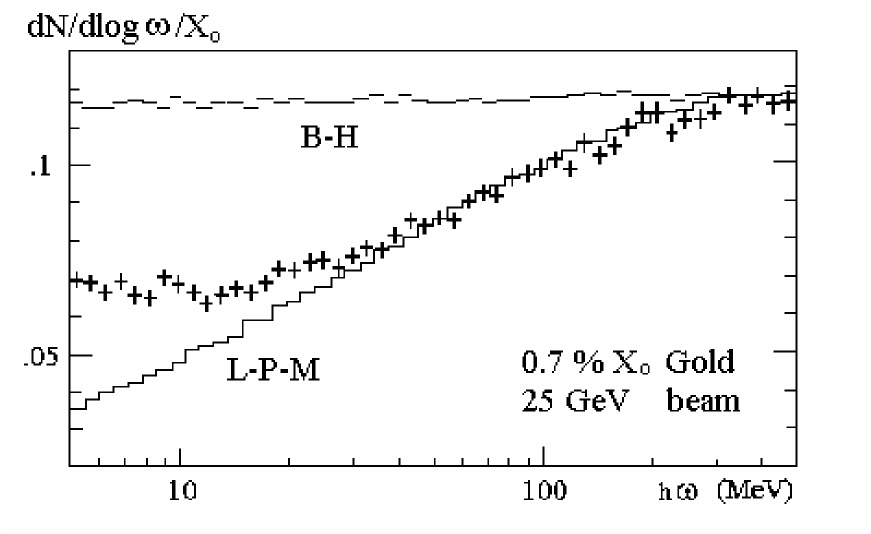
A collaboration of physicists from the University of California at Santa Cruz (UCSC), the Stanford Linear Accelerator Center (SLAC), American University and Livermore has verified a theory that is almost forty years old.

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-

1. SLAC experiment E-146

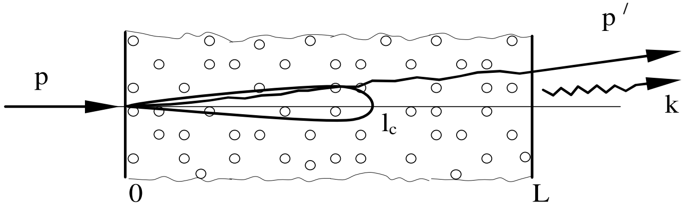
Anthony P.L. et al., Phys. Rev. Lett. **75** (1995) 1949.



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

2. Theory of the LPM effect

Multiple scattering effect on radiation of relativistic electron in amorphous medium



L.D. Landau, I.Yu. Pomeranchuk, Dokl. Akad. Nauk SSSR **92** (1953) 735

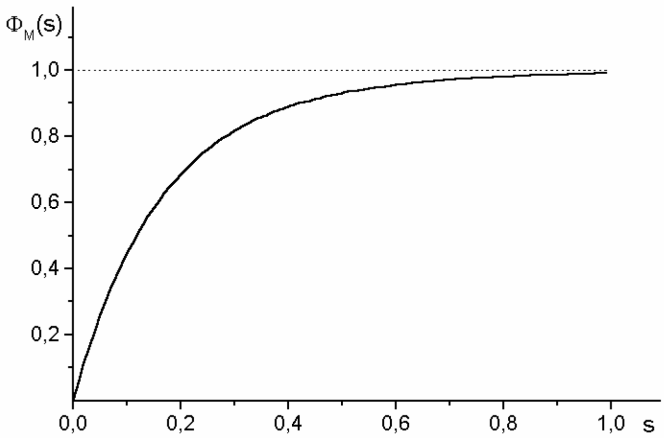
$\overline{\vartheta}_{l_c} > \gamma^{-1}$: suppression of radiation : $\frac{dE_{LP}}{d\omega} < \frac{dE_{BH}}{d\omega}$

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

Quantitative theory of the effect in a boundless amorphous medium:

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

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



$$\frac{d\mathrm{E}_{BH}}{d\omega} = \frac{4}{3}\frac{T}{L}$$

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

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

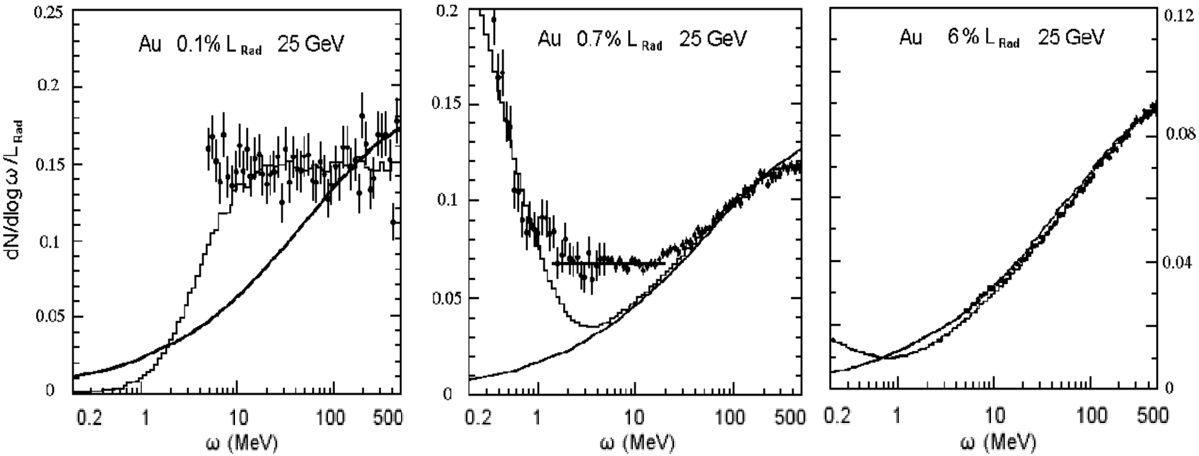
$$q = \frac{\varepsilon_s^2}{\varepsilon^2}\frac{1}{L}$$

$$\frac{d\mathrm{E}_{\mathrm{LPM}}}{d\omega} \sim \sqrt{\omega}$$

SLAC experiment E-146

Klein S., Rev. Mod. Phys. **71** (1999) 1501.

???



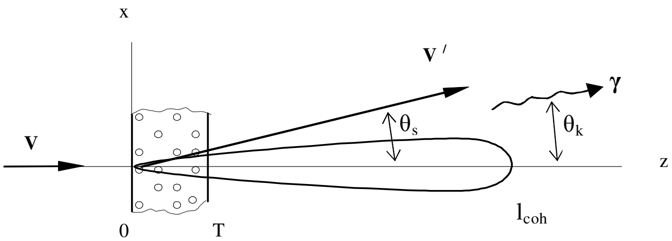
$\gamma^2 \overline{\vartheta^2} < 1$ 　 $\gamma^2 \overline{\vartheta^2} > 1$, but $T < l_c$ 　 $\gamma^2 \overline{\vartheta^2} > 1$ and $T > l_c$

3. Radiation in a thin layer of matter

$l_c >> T$

Shul'ga N.F., Fomin S.P., JETP Letters **27** (1978)126.

Fomin S.P., Shul'ga N.F., Physics Letters **A114** (1986)148.



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

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

$l_c >> T$: $\vec{I} \approx i\left(\frac{\vec{v}'}{\omega - \vec{k}\vec{v}'} - \frac{\vec{v}}{\omega - \vec{k}\vec{v}}\right)$; $\frac{dE}{d\omega} = \frac{2e^2}{\pi}\left[\frac{2\xi^2+1}{\xi\sqrt{\xi^2+1}}\ln(\xi+\sqrt{\xi^2+1}) - 1\right]$, $\xi = \frac{1}{2}\gamma\vartheta$

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

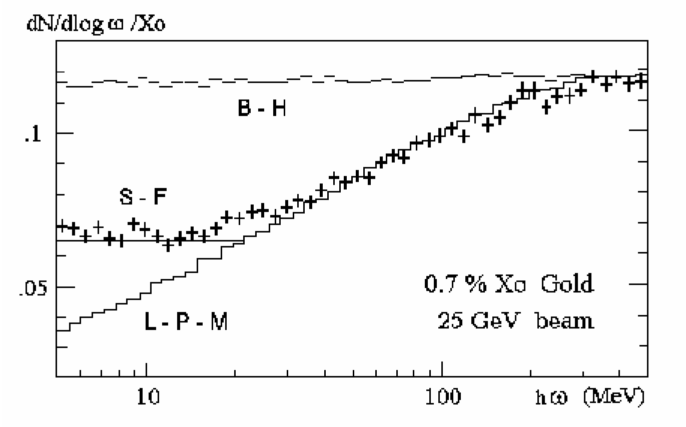
Quantitative theory of radiation in a thin layer of matter:

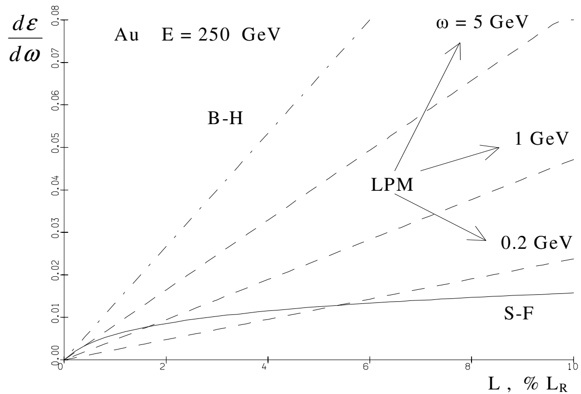
Shul'ga N.F., Fomin S.P., JETP Lett. **63** (1996) 873; JETP **86** (1998) 32; NIM **B145** (1998) 73.

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

$$\gamma^2 \overline{\vartheta^2} > 1: \quad \frac{dE}{d\omega} = \frac{2e^2}{\pi} \left[\left(\ln a^2 - C \right) \left(1 + \frac{2}{a^2} \right) + \frac{2}{a^2} + \frac{C}{B} - 1 \right], \quad a^2 = \gamma^2 \overline{\vartheta^2}, \quad \overline{\vartheta^2} = \chi_c^2 B,$$

$$B - \ln B = \ln(\varepsilon^2 R^2 \chi_c^2) + 1 - 2C, \quad \chi_c^2 = 4\pi\, nLZ^2 e^4 / \varepsilon^2, \quad C = 0,577$$





Other publications:

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Phys.Rev. 1996, v. D53, p. 6265-6281.

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Phys. Rev. 1997, v. D55, p. 190-195.

B.G. Zhakharov. Structured targets and Landau-Pomeranchuk-Migdal effect for finite-size targets.
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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.

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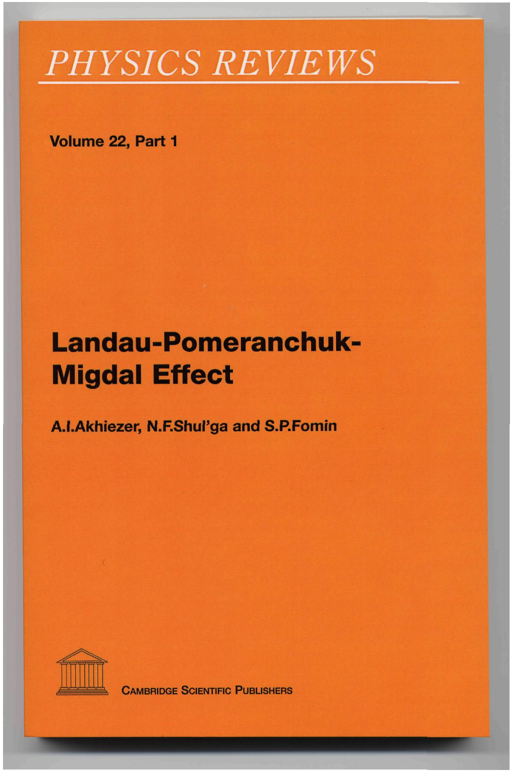
Reviews:



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

S. Klein. ***Suppression of bremsstrahlung and pair production due to environmental factors.***
Rev. of Mod. Phys. 1999, v. 71, p. 1501-1538.

A.I. Akhiezer, N.F. Shul'ga.
High-energy electrodynamics in matter.
Amsterdam: "Gordon and Breach", 1996, 388 p.

A.I. Akhiezer, N.F. Shul'ga. ***The effect of multiple scattering on relativistic particle radiation in amorphous and crystal media.***
Sov.Phys.Uspekhi. 1987, v.30, p.197-218.

M.L. Ter-Mikaelian.
High-energy electromagnetic processes in condensed matter.
New York: "Wiley Interscience", 1972, 457 p.

4. CERN experiment NA63 (2005)

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]

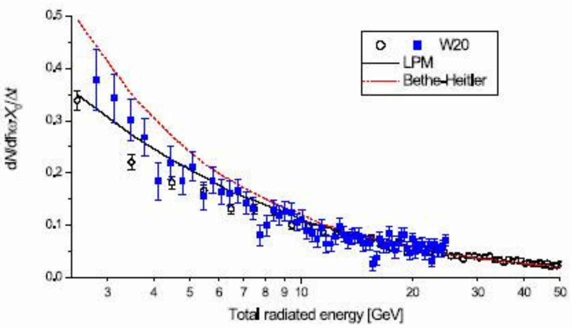


FIG. 5: *Normalized bremsstrahlung spectrum, $dN/d\hbar\omega \cdot X_0/\Delta t$, for 178 GeV positrons on 4 layers of 20 μm W with 100 μm LDPE spacers. The vertical scale is normalized to the number of incoming positrons and the thickness in units of the radiation length. The meaning of the symbols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

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

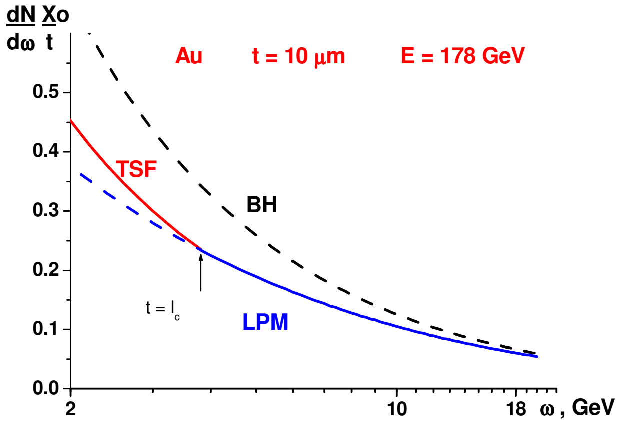
Because the formation length for radiation emission increases with decreasing photon frequency, at a certain point the formation zone extends beyond the thickness of the foil. In this case, the radiation yield also becomes suppressed. Theoretical studies of this effect were first performed by Ternovskii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

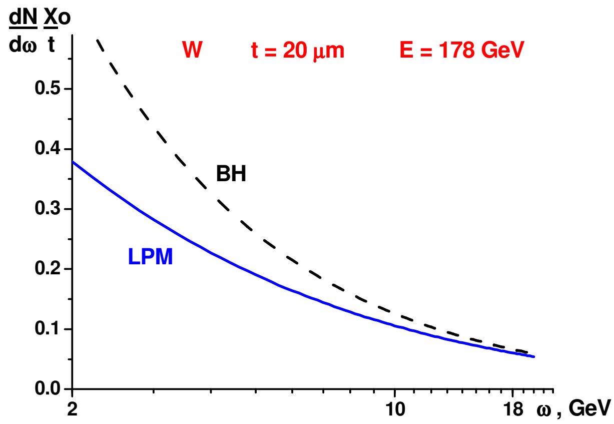
For the Ternovskii-Shul'ga-Fomin (TSF) effect, the analysis is applicable for target thicknesses $l_\gamma \ll \Delta t < l_f$, see e.g. [10]. Combining the formation length and the target thickness parametrized by $k_f > 1$, $\Delta t = l_f/k_f$, the effect becomes appreciable for photon energies

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

4. CERN experiment NA63 (2005)

Results of our calculations:





4. CERN experiment NA63 (2008)

Phys.Lett.B 2008 (in print)

On the macroscopic formation length for GeV photons

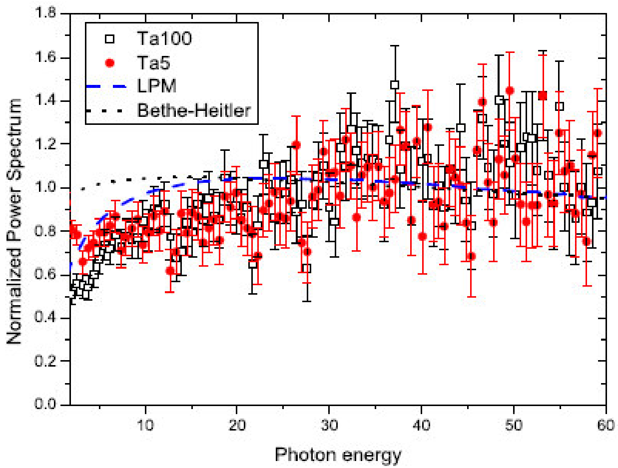
H.D. Thomsen, J. Esberg, K. Kirsebom, H. Knudsen, E. Uggerhøj, U.I. Uggerhøj,[1] P. Sona,[2] A. Mangiarotti,[3] T.J. Ketel,[4] A. Dizdar,[5] and M.M. Dalton, S. Ballestrero, S.H. Connell[6]

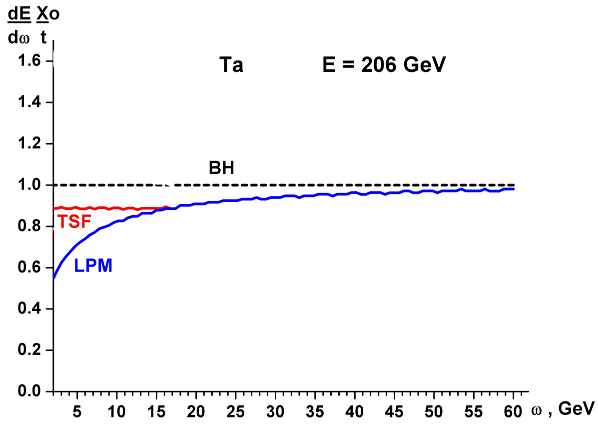
Abstract

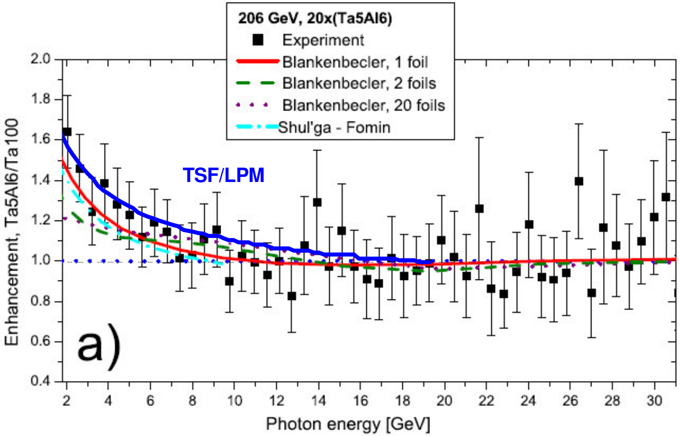
Experimental results for the radiative energy loss of 206 and 234 GeV electrons in 5-10 μm thin Ta targets are presented. An increase in radiation emission probability at low photon energies compared to a 100 μm thick target is observed. This increase is due to the formation length of the GeV photons exceeding the thickness of the thin foils, the so-called Ternovskii-Shul'ga-Fomin (TSF) effect. The formation length of GeV photons from a multi-hundred GeV projectile is through the TSF effect shown directly to be a factor 10^{10} longer than their wavelength.

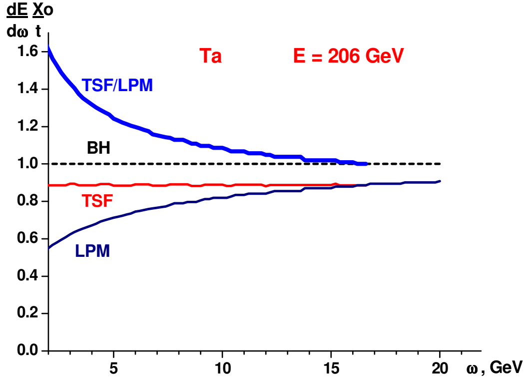
4. CERN experiment NA63 (2008)

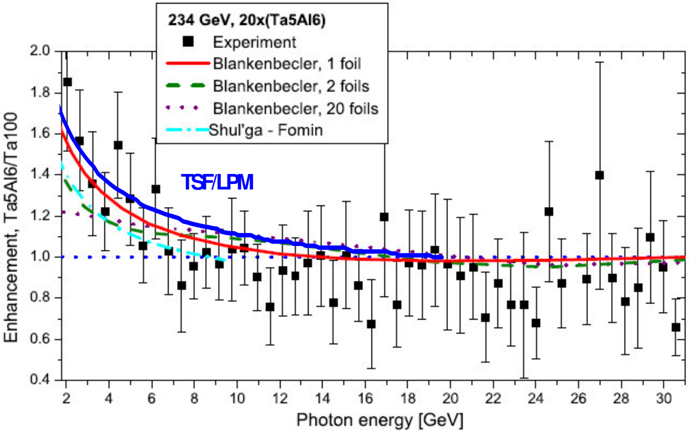
D.H.Thomsen et al. Phys.Lett.B 2008 (in print)

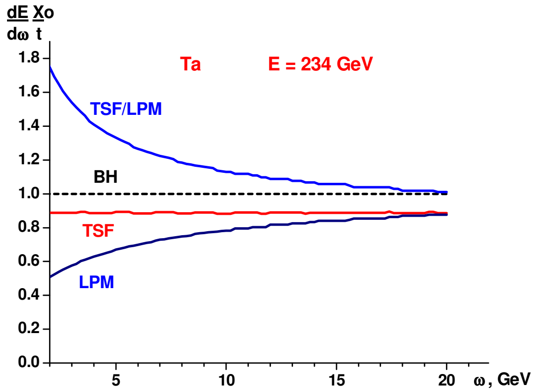





206 GeV, 20x(Ta5Al6)
Experiment
Blankenbecler, 1 foil
Blankenbecler, 2 foils
Blankenbecler, 20 foils
Shul'ga - Fomin
TSF/LPM
a)
Enhancement, Ta5Al6/Ta100
Photon energy [GeV]


dE Xo
dω t
Ta
E = 206 GeV
TSF/LPM
BH
TSF
LPM
ω , GeV


234 GeV, 20x(Ta5Al6)
Experiment
Blankenbecler, 1 foil
Blankenbecler, 2 foils
Blankenbecler, 20 foils
Shul'ga - Fomin
TSF/LPM
Enhancement, Ta5Al6/Ta100
Photon energy [GeV]

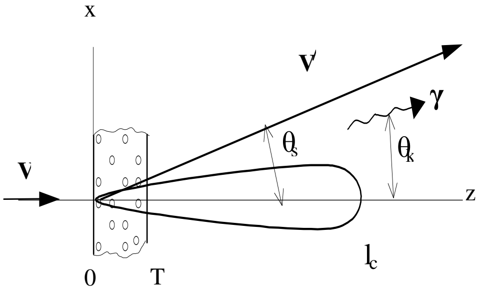

dE Xo
dω t
Ta
E = 234 GeV
TSF/LPM
BH
TSF
LPM
ω , GeV

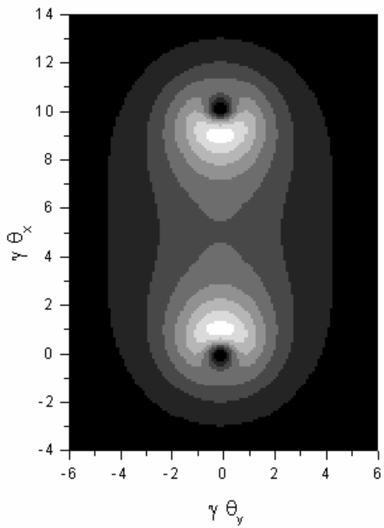
5. Spectral-angular distribution of radiation $l_{coh} \gg T$

Fomin S.P., Shul'ga N.F. and Shul'ga S.N., Phys. of Atomic Nuclei **66** (2003) 396.

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

$$\alpha = \gamma\vartheta_k, \qquad \beta = \gamma\vartheta_e$$





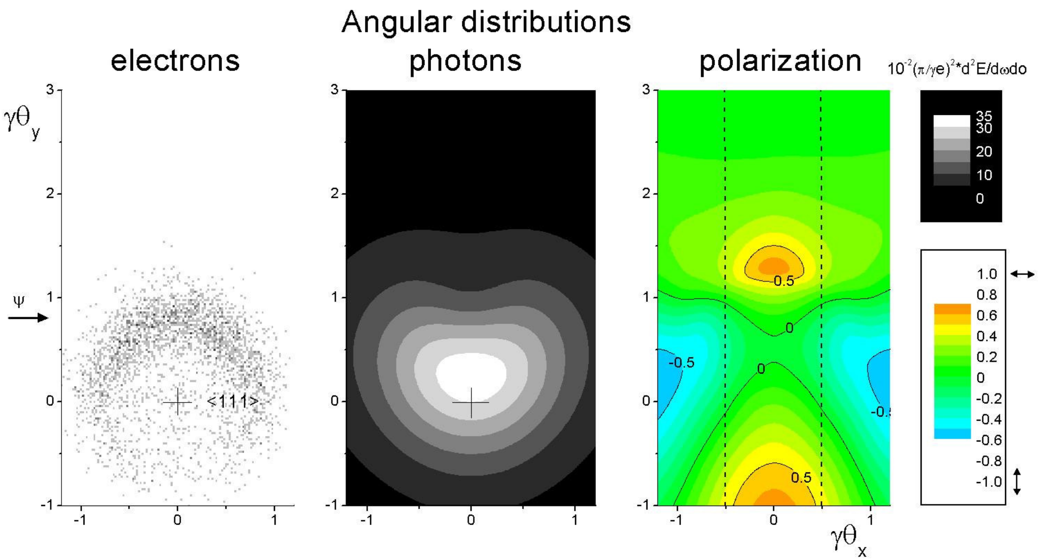
6. Polarization at non-dipole regime of radiation $\overline{\vartheta}_{l_c} > \gamma^{-1}$

Polarization matrix: $J_{ik} = \frac{e^2\omega^2}{4\pi^2}\left(\vec{e}_i \vec{I}\right)\left(\vec{e}_k \vec{I}\right)$, где $\vec{e}_{i,k}\vec{n} = 0, \; \vec{e}_i\vec{e}_k = \delta_{ik}$.

Linear polarization: $P = \frac{J_{11} - J_{22}}{J_{11} + J_{22}}$ **Circular polarization:** $P_c = \frac{J_{12} - J_{21}}{J_{11} + J_{22}}$.

$l_{coh} \gg T$: $J_{ik} = J_{ki}$ => $P_c = 0$ **for any angles of observation**.

Dipole regime of radiation: $\overline{\vartheta}_{l_c} < \gamma^{-1}$

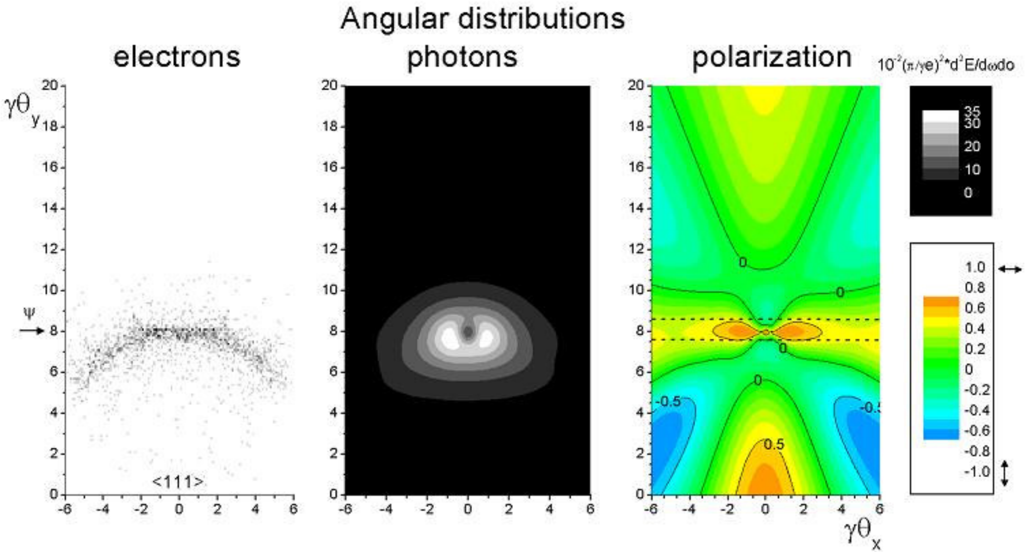


Si <111> T = 10 μm E = 1 GeV $\psi = \psi_C$

P = 0.08

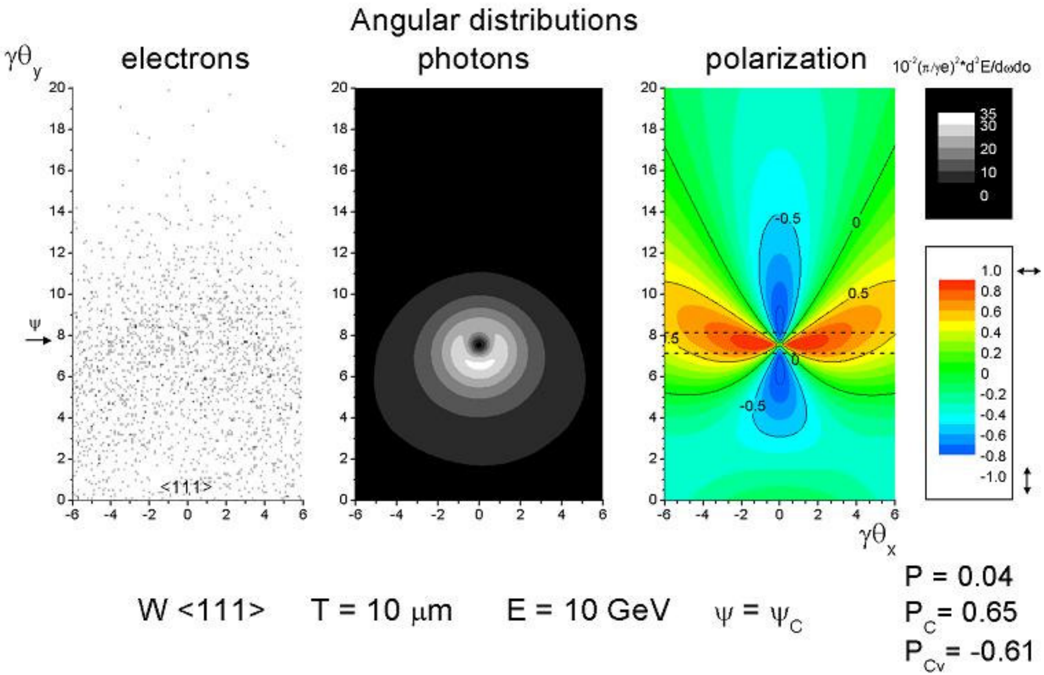
P_C = 0.14

Non-dipole regime of radiation: $\overline{\vartheta}_{l_c} > \gamma^{-1}$



Si <111> T = 10 μm E = 100 GeV $\psi = \psi_C$

P = 0.09
P_C = 0.48


Angular distributions
γθy
electrons
photons
polarization
10^-2(π/γe)^2*d^2E/dωdo
<111>
γθx
W <111> T = 10 μm E = 10 GeV ψ = ψC
P = 0.04
PC = 0.65
PCv = -0.61

Conclusion

- **The multiple scattering effect on radiation spectrum of ultra-relativistic electrons in a thin layer of matter (TSF effect) was observed successfully at CERN experiment NA63 for electron energies 206 and 234 GeV.**
- **The multiple scattering effects significantly the spectral-angular distribution of radiation of ultra-relativistic electrons in a thin amorphous target and in aligned crystal.**
- **The special features of non-dipole regime of ultra-relativistic electron radiation in aligned crystals can be used to obtain the linear polarized high intensity photon beam with "vertical" and "horizontal" direction of polarization simultaneously.**
- **It is necessary to carry out the corresponding experimental investigation to verify mentioned above effects in spectral-angular distribution of radiation and its polarization.**

THANK YOU FOR ATTENTION !