Radiation of Ultrarelativistic Electron with Non-Equilibrium Own Coulomb Field

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1994: SLAC experiment E-146

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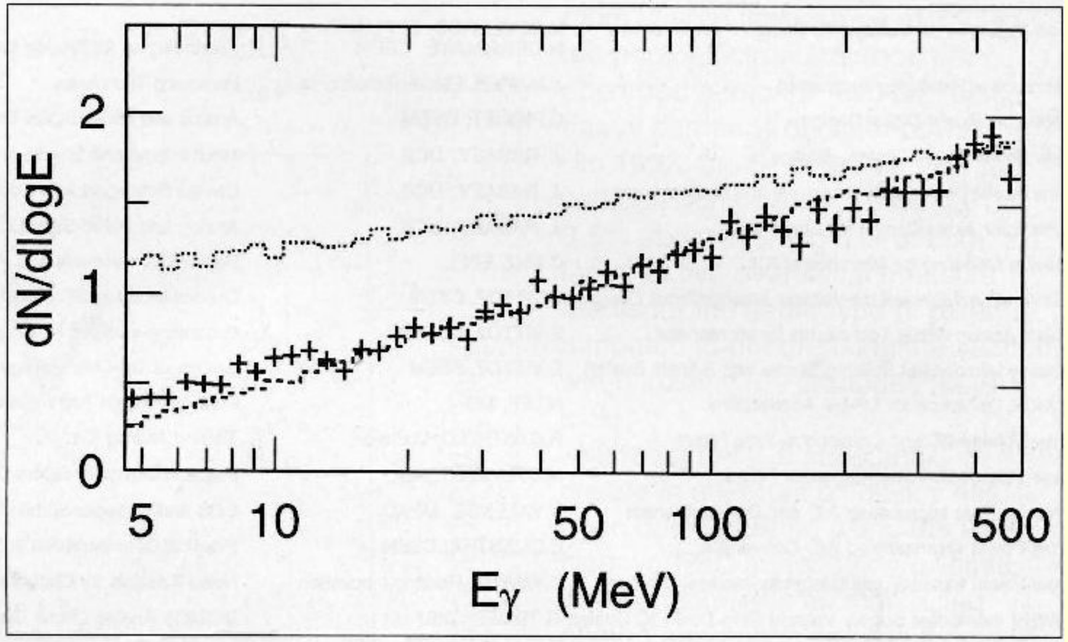
STANFORD (SLAC)
Photon theory verified after 40 years

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.

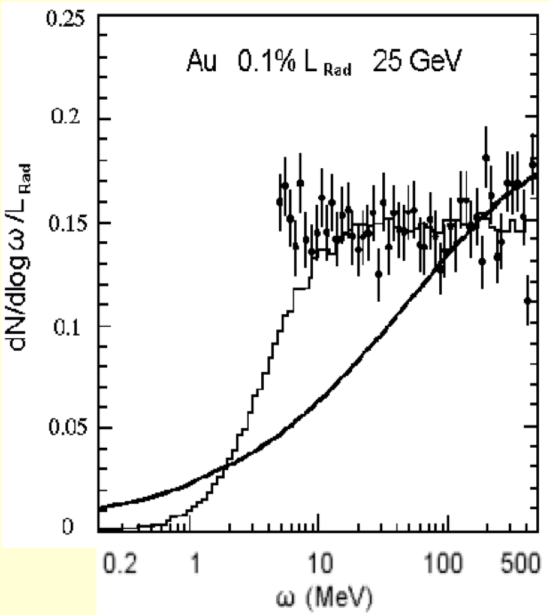
In SLAC experiment E-146, 25 GeV electrons passed through slim targets of carbon, aluminum, iron, gold, lead, tungsten and uranium — as well as a very thin gold target. After traversing the target, the electrons were de-

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-

SLAC experiment E-146

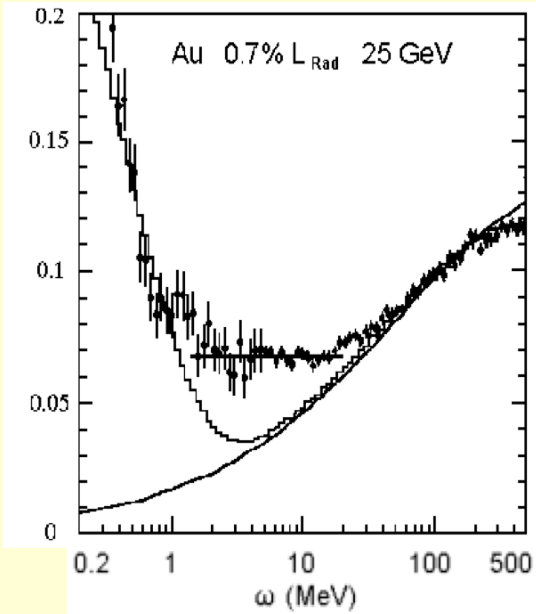
Klein S., Rev. Mod. Phys. **71** (1999) 1501.

Bethe-Heitler



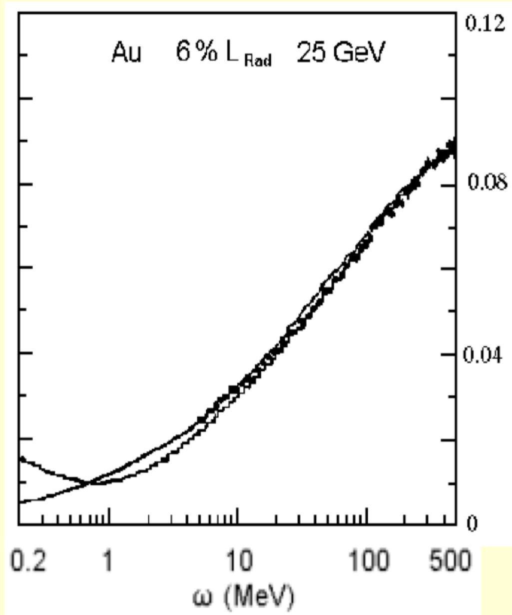
$$\gamma^2 \overline{\vartheta^2} < 1$$

? ? ?



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

LPM effect



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

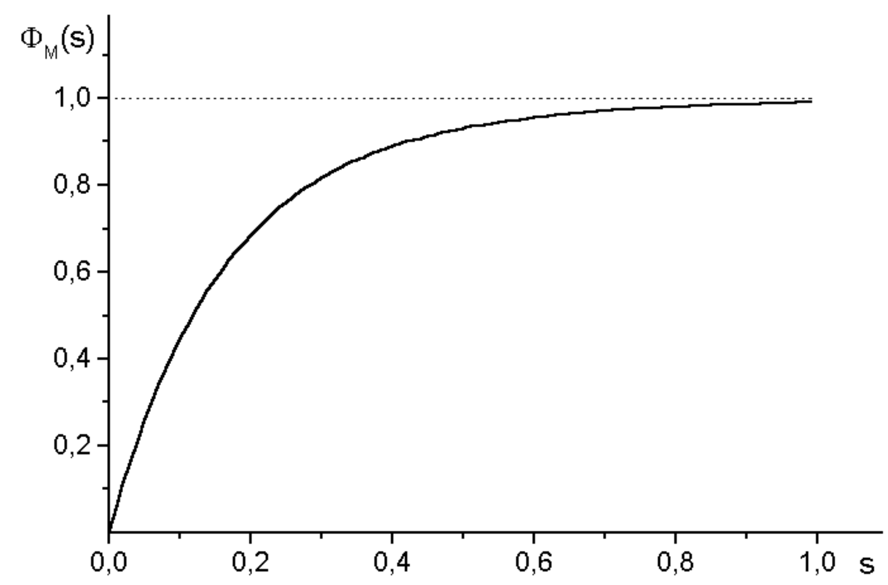
F.F. Ternovsky, JETP **39** (1961) 171**.**

Quantitative theory of the LPM effect in a boundless amorphous medium:

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

$$\frac{dE_{LPM}}{d\omega} = \frac{dE_{BH}}{d\omega} \cdot \hat{O}_M(s) \qquad \frac{dE_{\hat{A}H}}{d\omega} = \frac{4}{3}\frac{T}{X_0} \qquad X_0^{-1} = \frac{4Z^2 e^6 n}{m^2} \ln(mR)$$

$$\omega << \varepsilon \qquad \hat{O}_M(s) = 24s^2 \left\{ \int_0^\infty dt\, cth\, t \quad e^{-2st} \sin 2st - \frac{\pi}{4} \right\} \qquad s = \frac{1}{2\sqrt{2}} \sqrt{\frac{\omega}{\omega_{LPM}}}$$



$$\omega_{LPM} = 2q\gamma^4 \sim \gamma^2 \qquad q = \frac{\varepsilon_s^2}{\varepsilon^2}\frac{1}{X_0}$$

$$\boxed{\overline{\vartheta}_{l_c} > \gamma^{-1}} \qquad l_c = 2\gamma^2/\omega$$

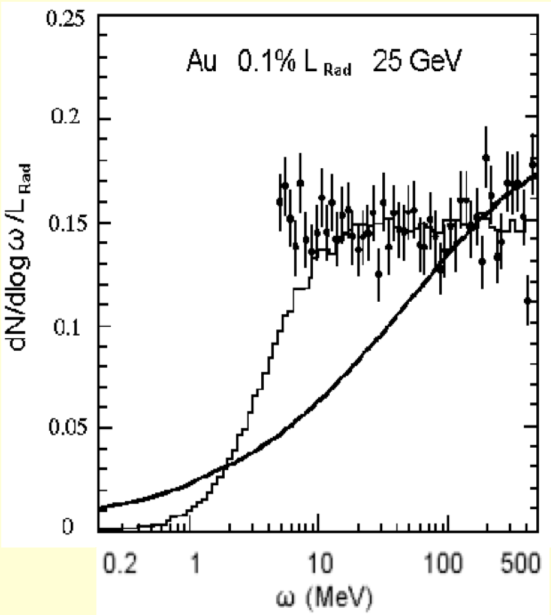
$$\frac{dE_{LPM}}{d\omega} \sim \sqrt{\omega}$$

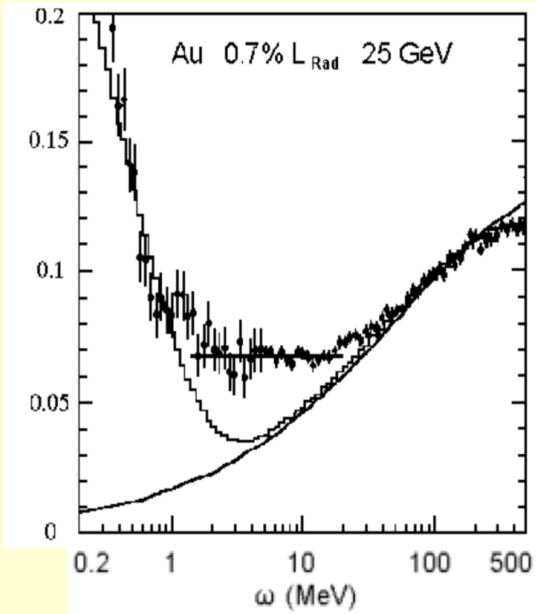
$$T >> l_c$$

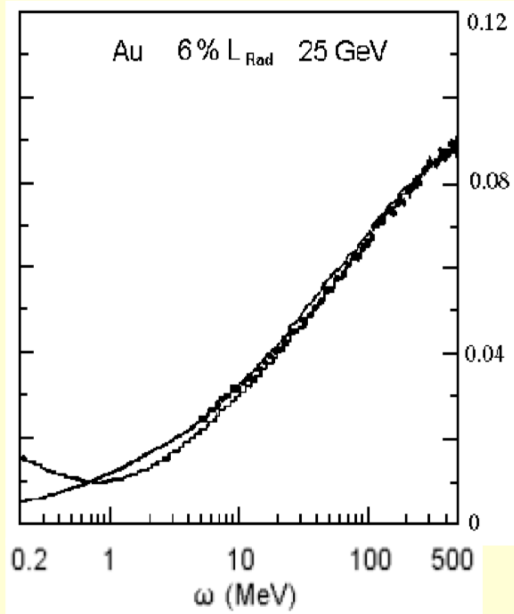
SLAC experiment E-146

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

Bethe-Heitler | **? ? ?** | **LPM effect**







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

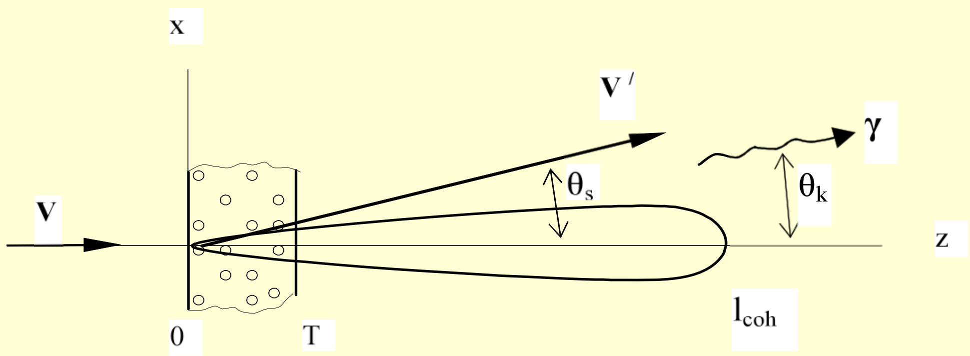
$\gamma^2 \overline{\vartheta^2} > 1$, but T < l_c

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

F.F. Ternovsky, JETP **39** (1961) 171**.**

Radiation in a thin layer of matter $l_c \gg T$

Shul'ga N.F., Fomin S.P., JETP Letters **27** (1978)126; Physics Letters **A114** (1986)148.



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

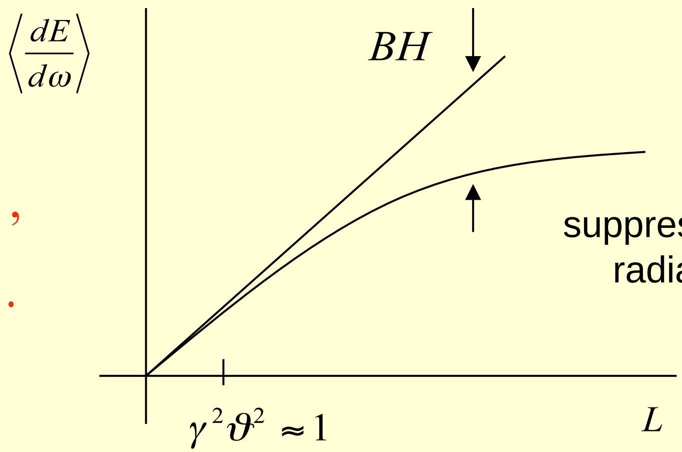
$$\vec{I} = i\int_{-\infty}^{\infty} dt\, e^{i\left(\omega t - \vec{k}\vec{r}(t)\right)}\frac{d}{dt}\frac{\vec{v}}{\omega - \vec{k}\vec{v}}$$

$l_c \gg T$ $$\vec{I} \approx i\left(\frac{\vec{v}\,'}{\omega - \vec{k}\vec{v}\,'} - \frac{\vec{v}}{\omega - \vec{k}\vec{v}}\right)$$

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

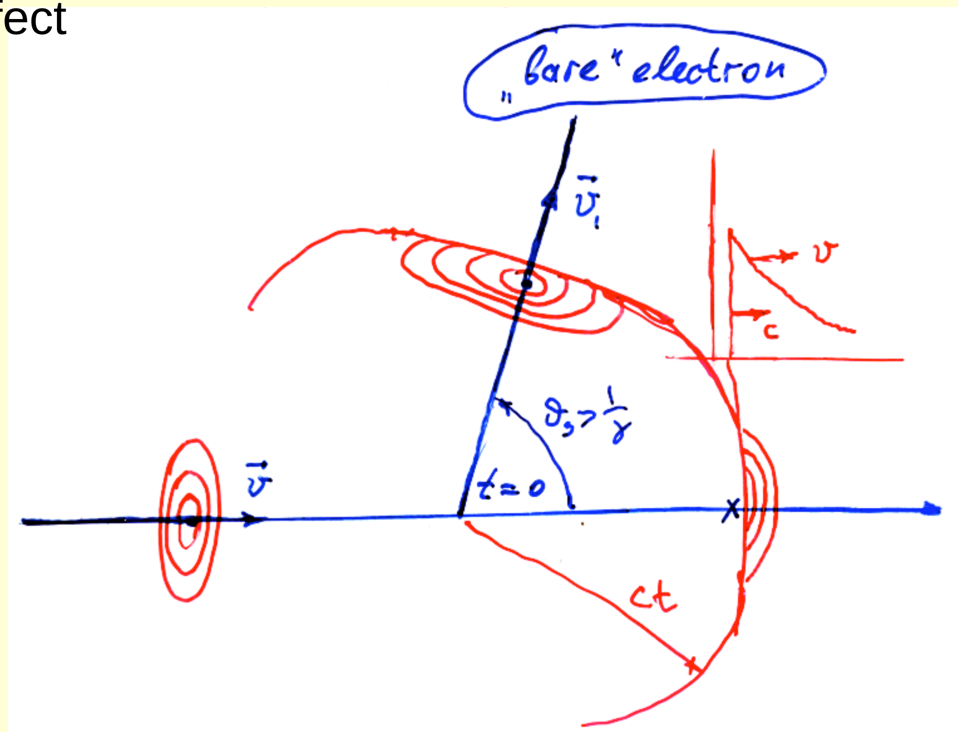
$$\frac{dE}{d\omega} \approx \begin{cases} \dfrac{3e^2}{\pi}\xi^2, & \xi^2 \ll 1, \\ \dfrac{2e^2}{\pi}\ln(4\xi^2), & \xi^2 \gg 1. \end{cases}$$

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



Electromagnetic field of electron at scattering

Qualitative explanation of supression effect



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

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

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

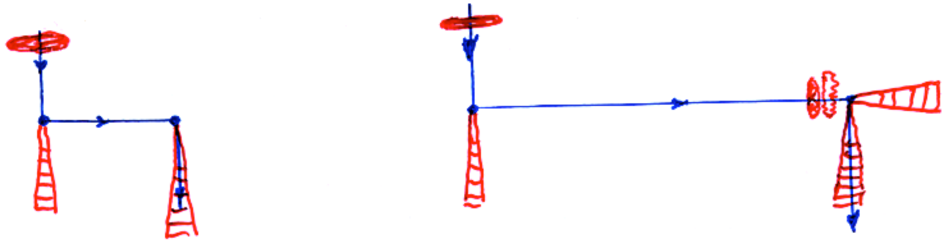
$$= \Theta(t - r)\varphi_{v_1}(\vec{r},t) + \Theta(r - t)\varphi_v(\vec{r},t)$$

$$\Delta t \ll \left(k - kv_1\right)^{-1} \approx 2\gamma^2 / v = l_c$$

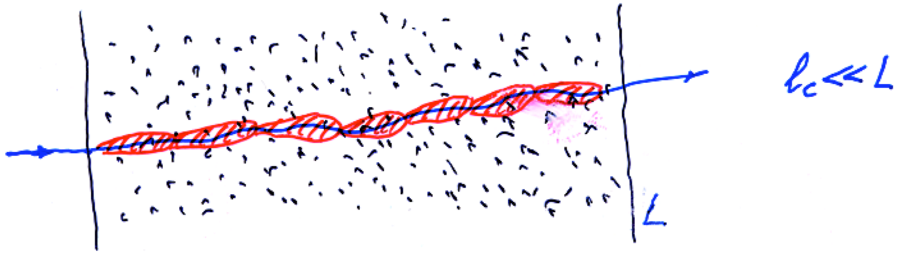
E.Feinberg JETP 50(1966)202,

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)

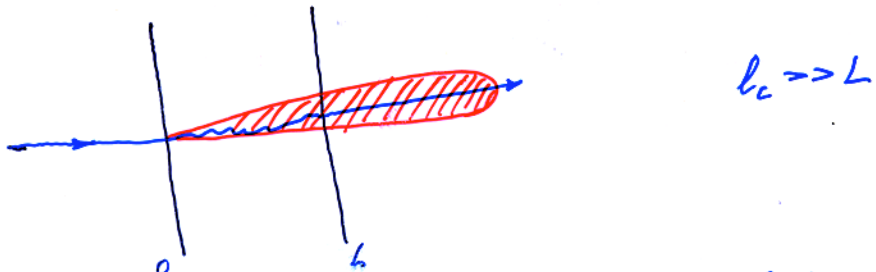


LPM case



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

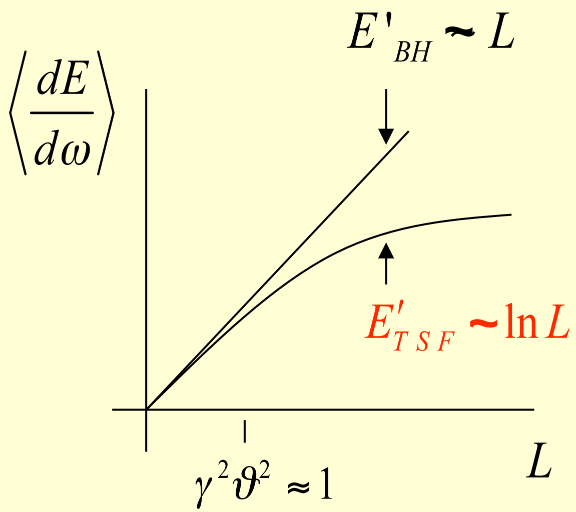
N. Shul'ga, S. Fomin (1978)



Electron is "bare" for all collisions !!!

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

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



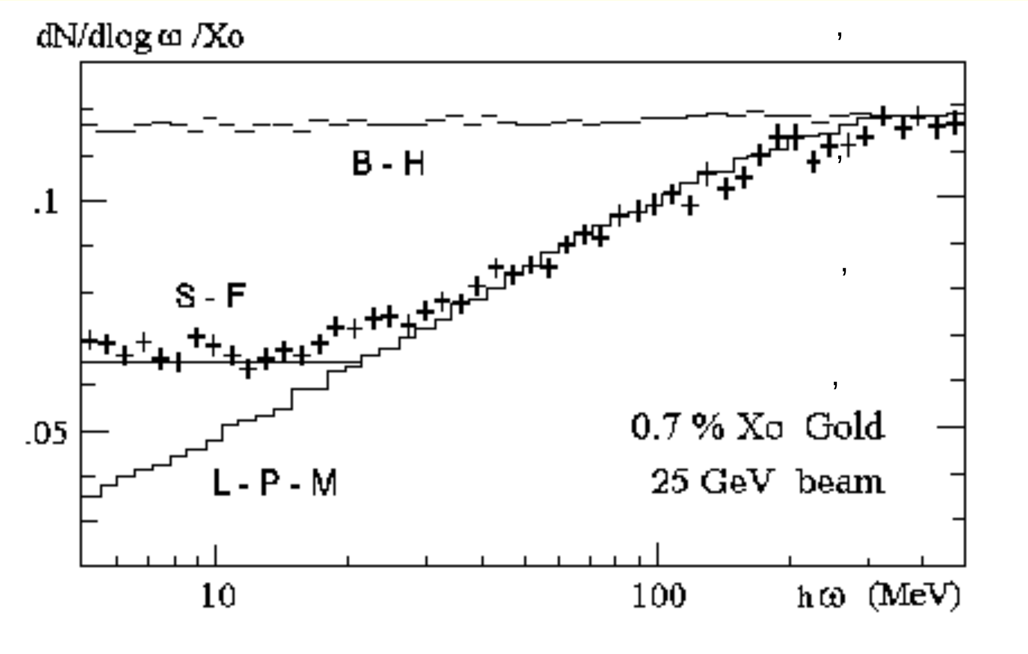
Quantitative theory of radiation in a thin layer of matter

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

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

:

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



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

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

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

$$C = 0,577$$

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.

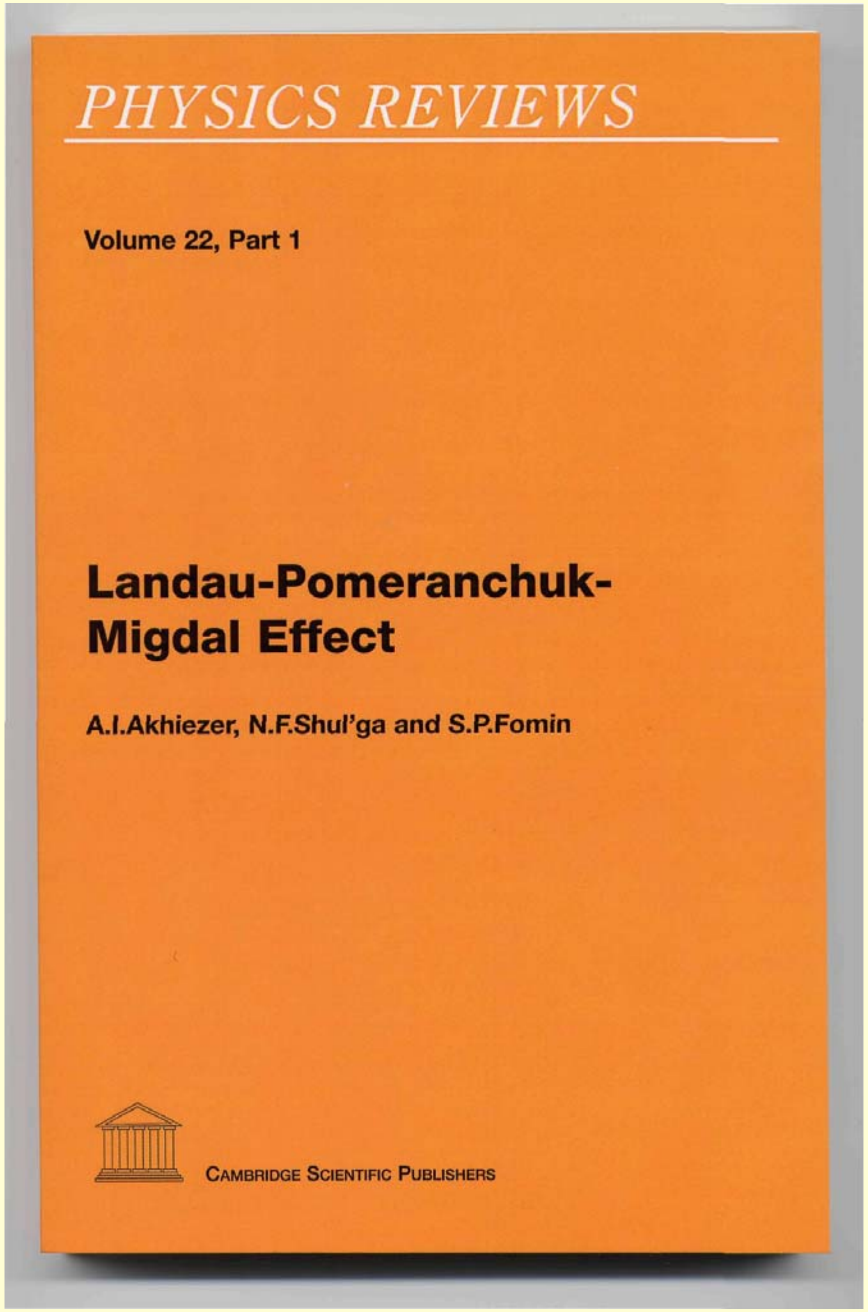
B.G. Zhakharov. Structured targets and Landau-Pomeranchuk-Migdal effect for finite-size targets. *JETP Lett.* 1996, v. 64, p. 781-787.

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.

. . . .



2005

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

Cambridge, UK, 2005, 215 p.

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]

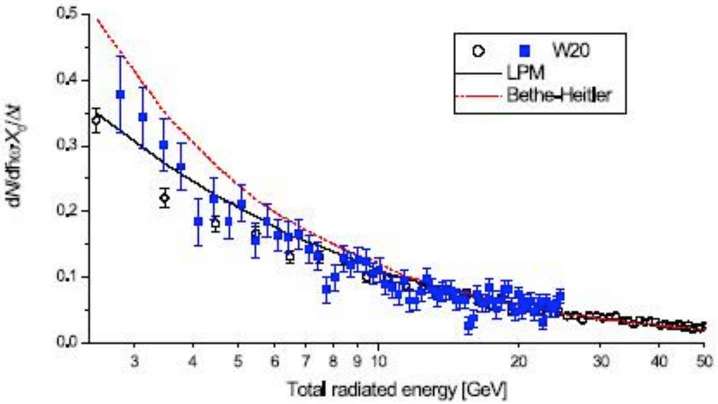


FIG. 5: *Normalized bremsstrahlung spectrum, $dN/d\hbar\omega \cdot X_0/\Delta t$, for 178 GeV positrons on 4 layers of 20 μm W with 100 μm LDPE spacers. The vertical scale is normalized to the number of incoming positrons and the thickness in units of the radiation length. The meaning of the symbols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

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

CERN NA63 experiment 2008

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

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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]

[a] *Department of Physics and Astronomy, University of Aarhus, Denmark*
[b] *University of Florence, Florence, Italy*
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[d] *Free University, Amsterdam, The Netherlands*
[e] *University of Istanbul, Istanbul, Turkey*
[f] *University of Johannesburg, Johannesburg, South Africa*

A R T I C L E I N F O

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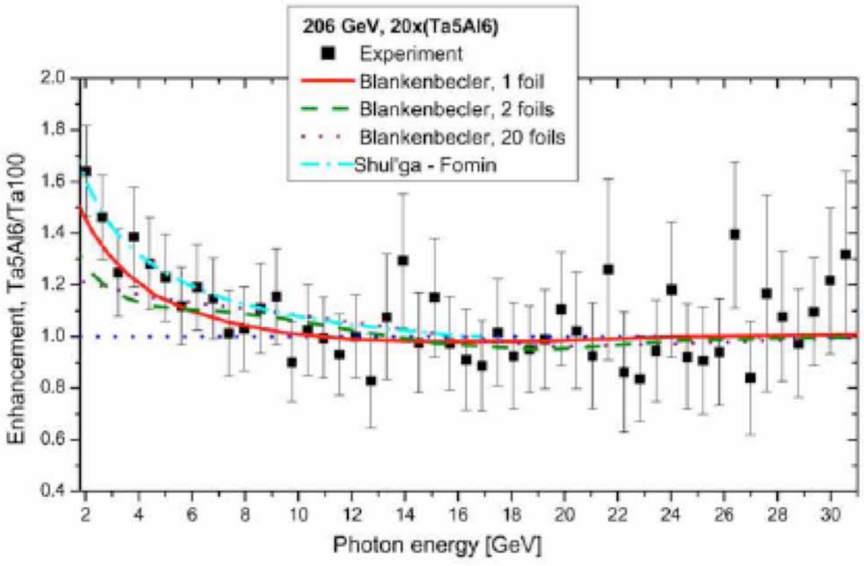
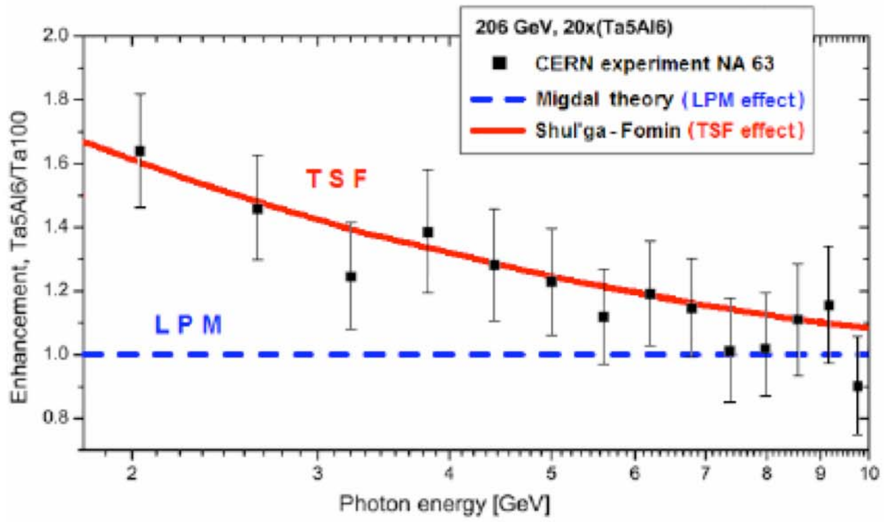
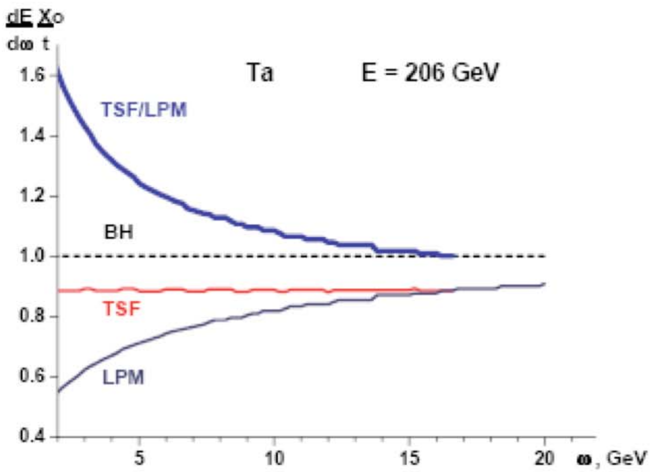
95.30.Gv

A B S T R A C T

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.

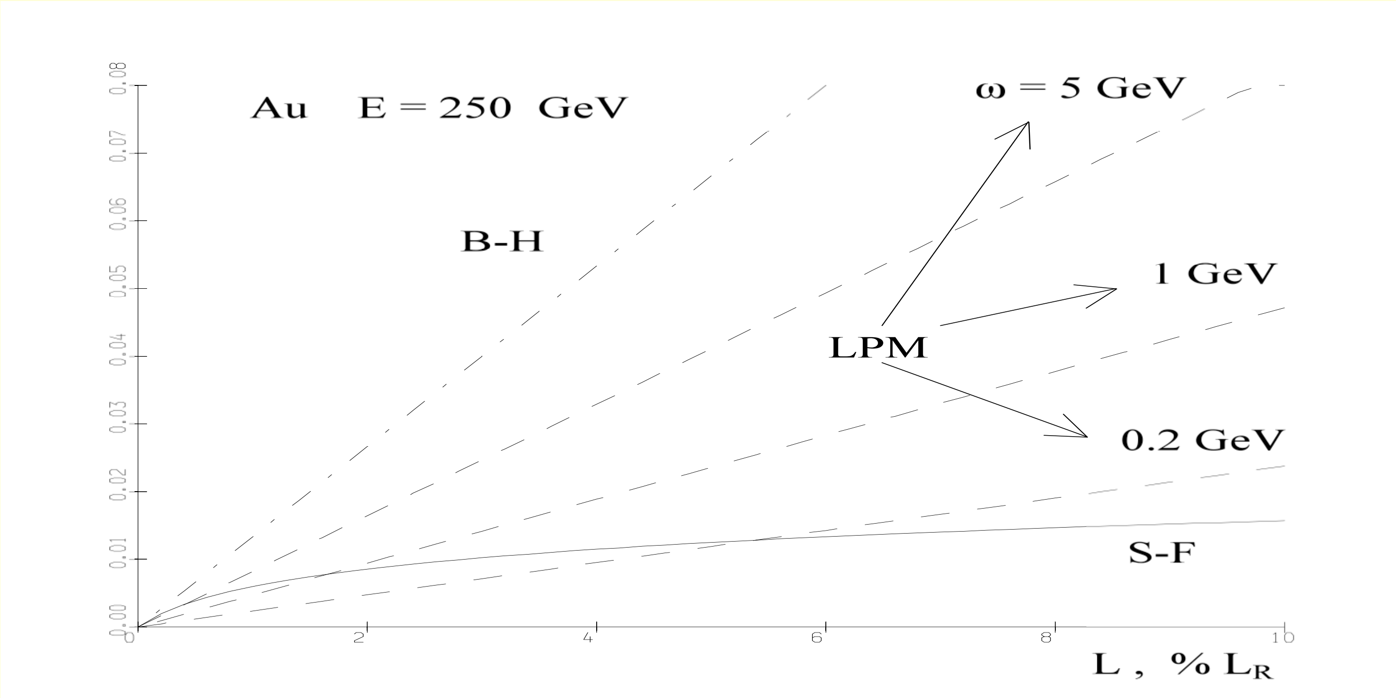

206 GeV, 20x(Ta5Al6)
Experiment
Blankenbecler, 1 foil
Blankenbecler, 2 foils
Blankenbecler, 20 foils
Shul'ga - Fomin
Enhancement, Ta5Al6/Ta100
Photon energy [GeV]


206 GeV, 20x(Ta5Al6)
CERN experiment NA 63
Migdal theory (LPM effect)
Shul'ga - Fomin (TSF effect)
TSF
LPM
Enhancement, Ta5Al6/Ta100
Photon energy [GeV]


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

Thickness dependence

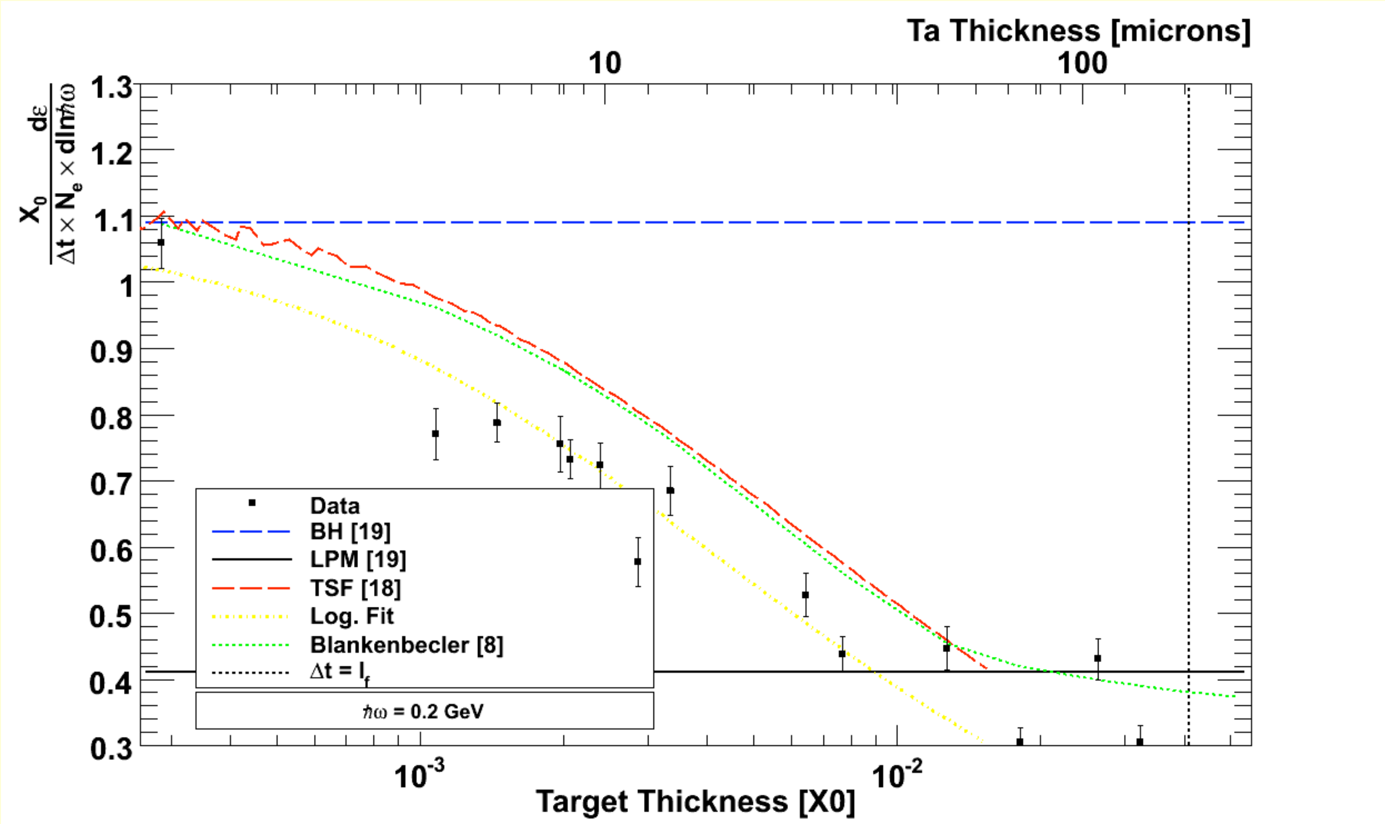
Shul'ga N.F., Fomin S.P., JETP **86** (1998) 32



CERN experiment NA63 June 2009

SPS secondary electron beam E = 149 GeV, Ta target thickness: 2 - 200 μm

hω = 0.2 – 3 GeV



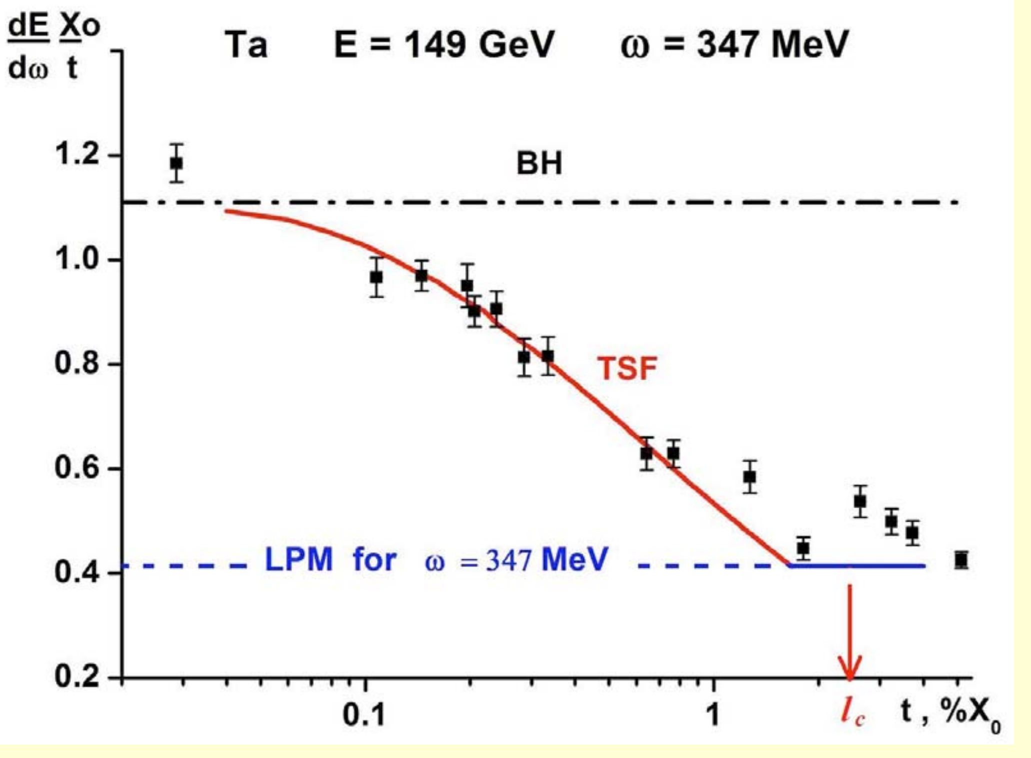
"Distorted Coulomb field of the scattered electron"

H.D.Thomsen, J. Esberg, K.K. Andersen. M.D. Lund, H. Knudsen, U.I. Uggerhoj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar and S. Ballestrero, S.H. Connell

Phys. Rev. D 81 (2010) 052003.

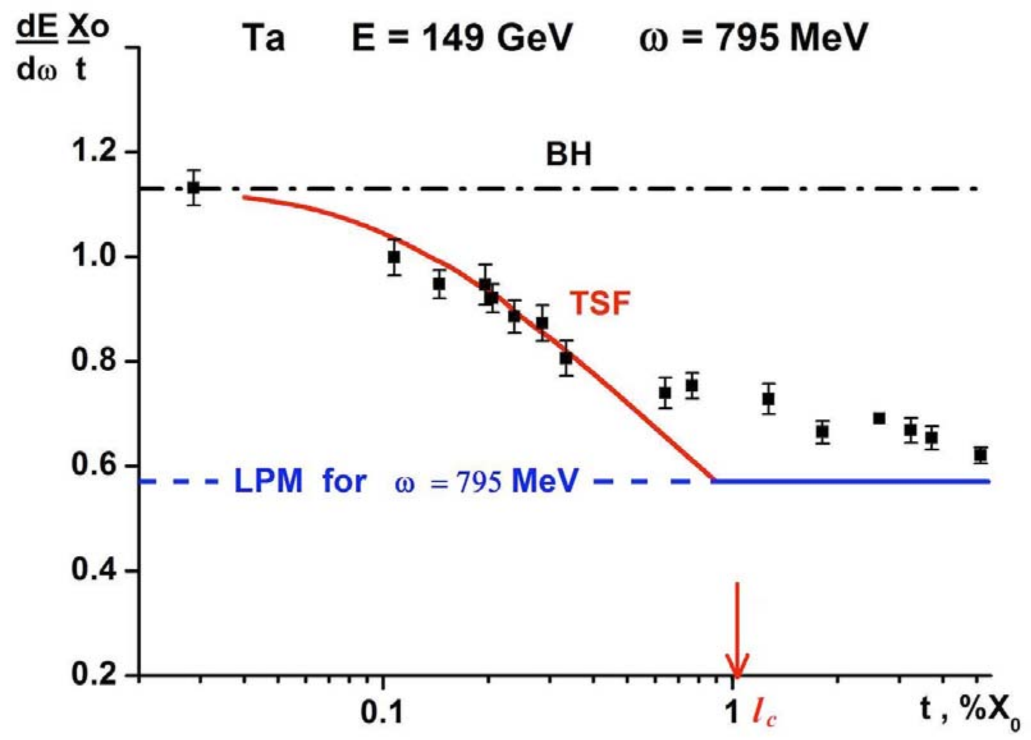
TSF Theory & CERN experiment NA63 June 2009

Thickness dependence of radiation spectral density



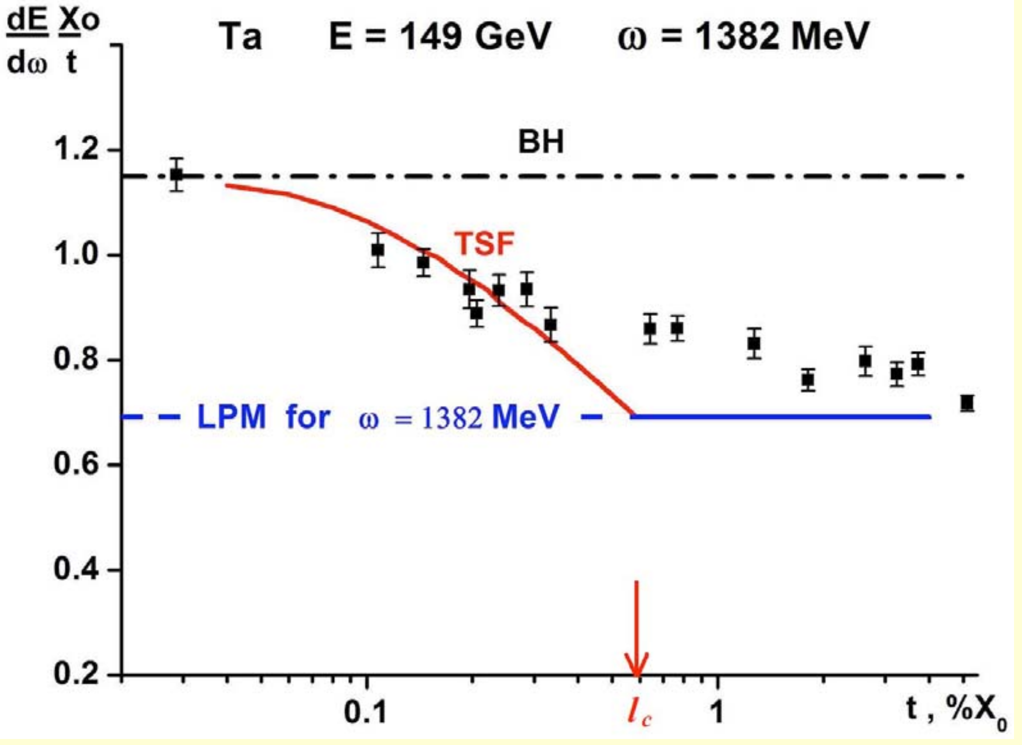
TSF Theory & CERN experiment NA63 June 2009

Thickness dependence of radiation spectral density



TSF Theory & CERN experiment NA63 June 2009

Thickness dependence of radiation spectral density

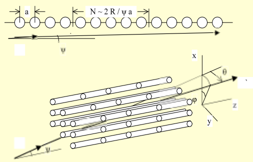


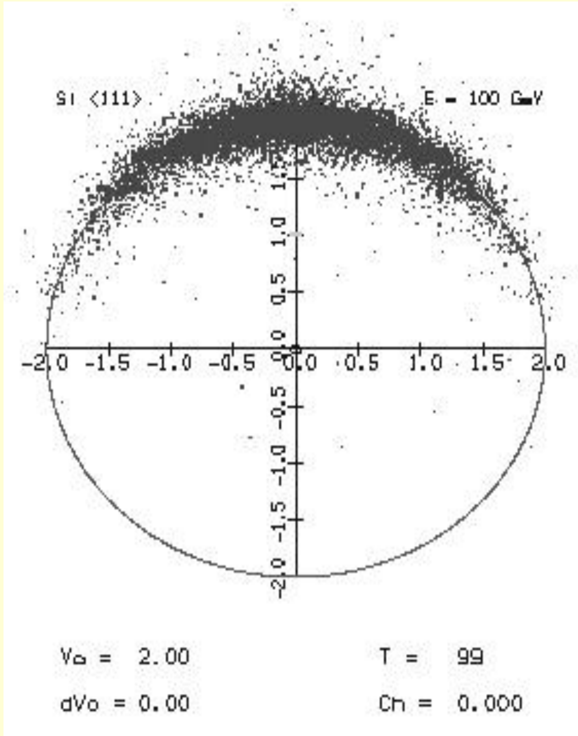
LPM and TSF effects in a crystal

Shul’ga N., Fomin S., JETP Letters **27** (1978)126; Phys. Lett. **A114** (1986)148.
Laskin N., Mazmanishvili A., Shul’ga N., Phys. Lett. **A112** (1985) 240.

Multiple scattering on crystal atomic strings

Shul’ga N., Truten’ V., Fomin S., J. Techn. Phys. **52** (1982) 2279.

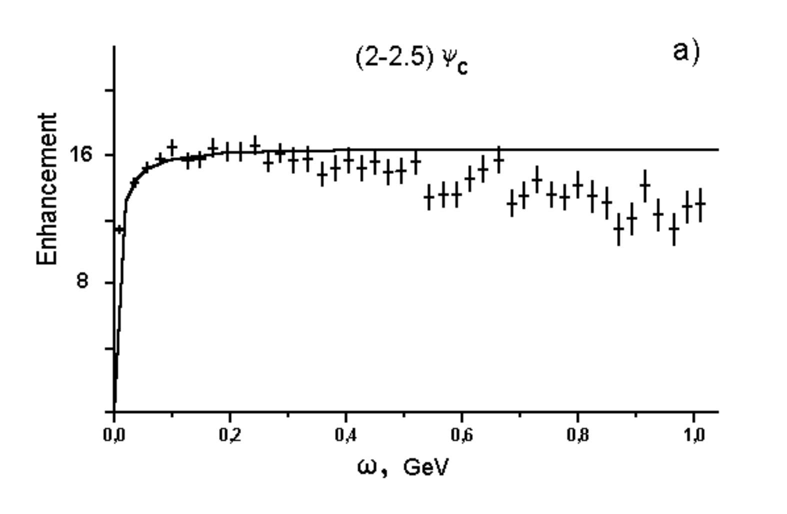


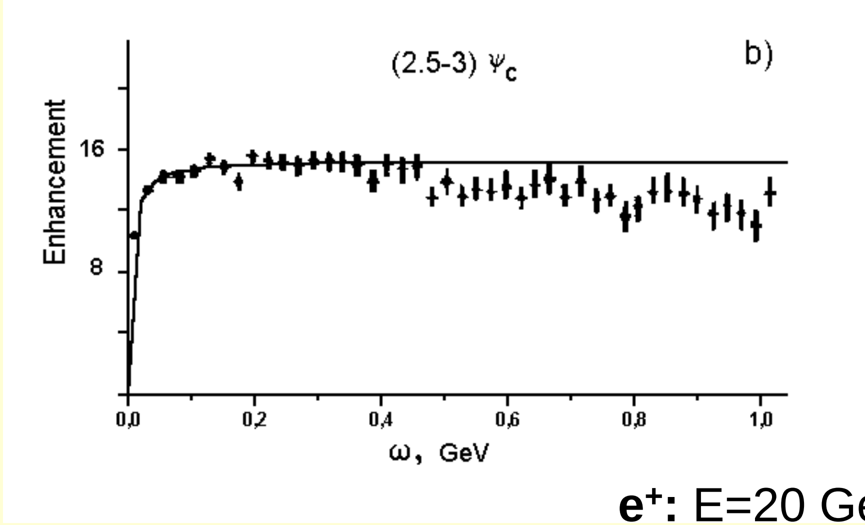


CERN experiment: **Bak J.F. et al.** Nucl. Phys., **B302** (1988) 525.

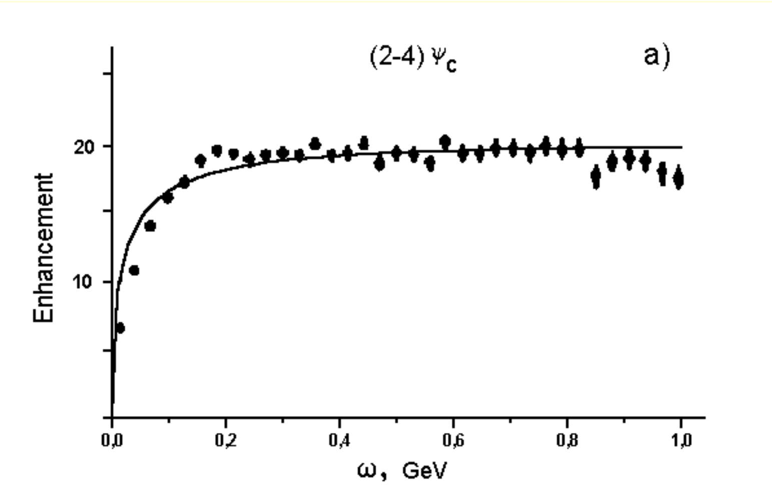
Theory: **Laskin N., Shul'ga N.,** Phys.Lett. **A135** (1989) 147.

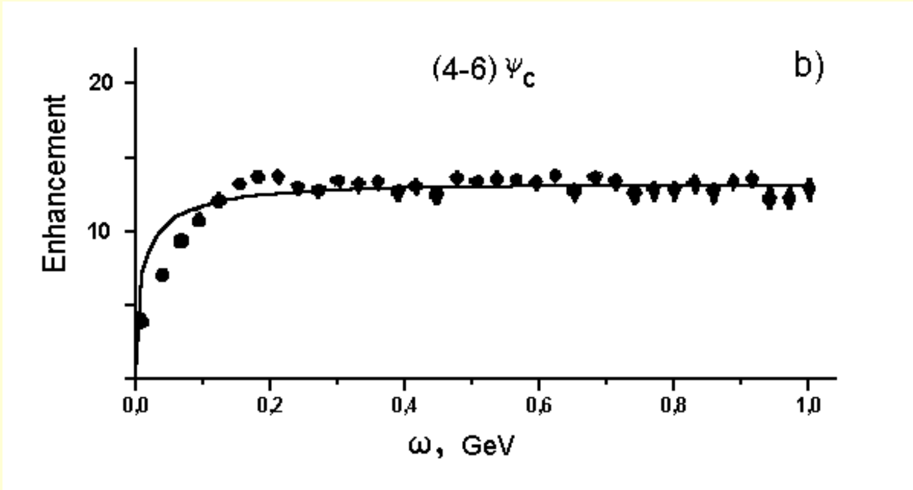
e^- : E=10 GeV





e^+: E=20 GeV





Angular Dirtribution of Radiation in Non-Dipole Case

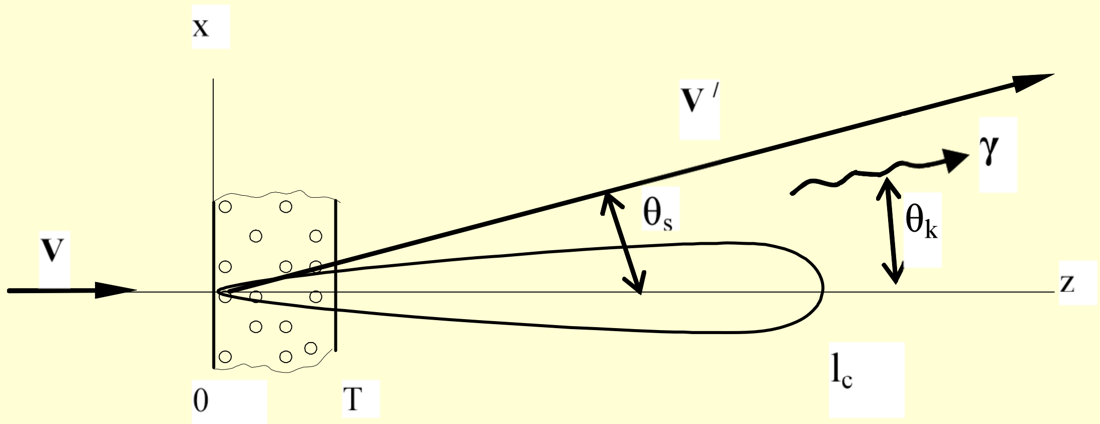
$$\frac{d^2E}{d\omega\, do} = \frac{e^2\omega^2}{4\pi^2}\left[\vec{n}\times\vec{I}\right]^2, \quad \vec{I} = i\int_{-\infty}^{\infty} dt\, e^{i\left(\omega t - \vec{k}\vec{r}(t)\right)} \frac{d}{dt}\frac{\vec{v}}{\omega - \vec{k}\vec{v}} \approx i\left(\frac{\vec{v}'}{\omega - \vec{k}\vec{v}'} - \frac{\vec{v}}{\omega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

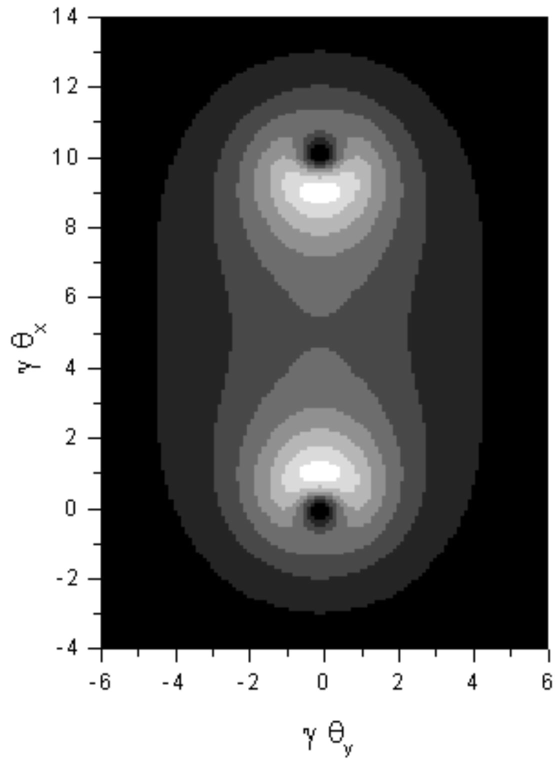
$$l_c >> T$$

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

$$\gamma\vartheta_e = 10$$

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





Fomin S.P., Shul'ga N.F., Shul'ga S.N., Yad.Fiz. 66 (2003) 421

Polarization of Radiation in Non-Dipole Case

A.S. Fomin, S.P. Fomin, N.F. Shul'ga, Proc. SPIE **5974** (2005) 177; Proc. SPIE **6634** (2007) 663406.

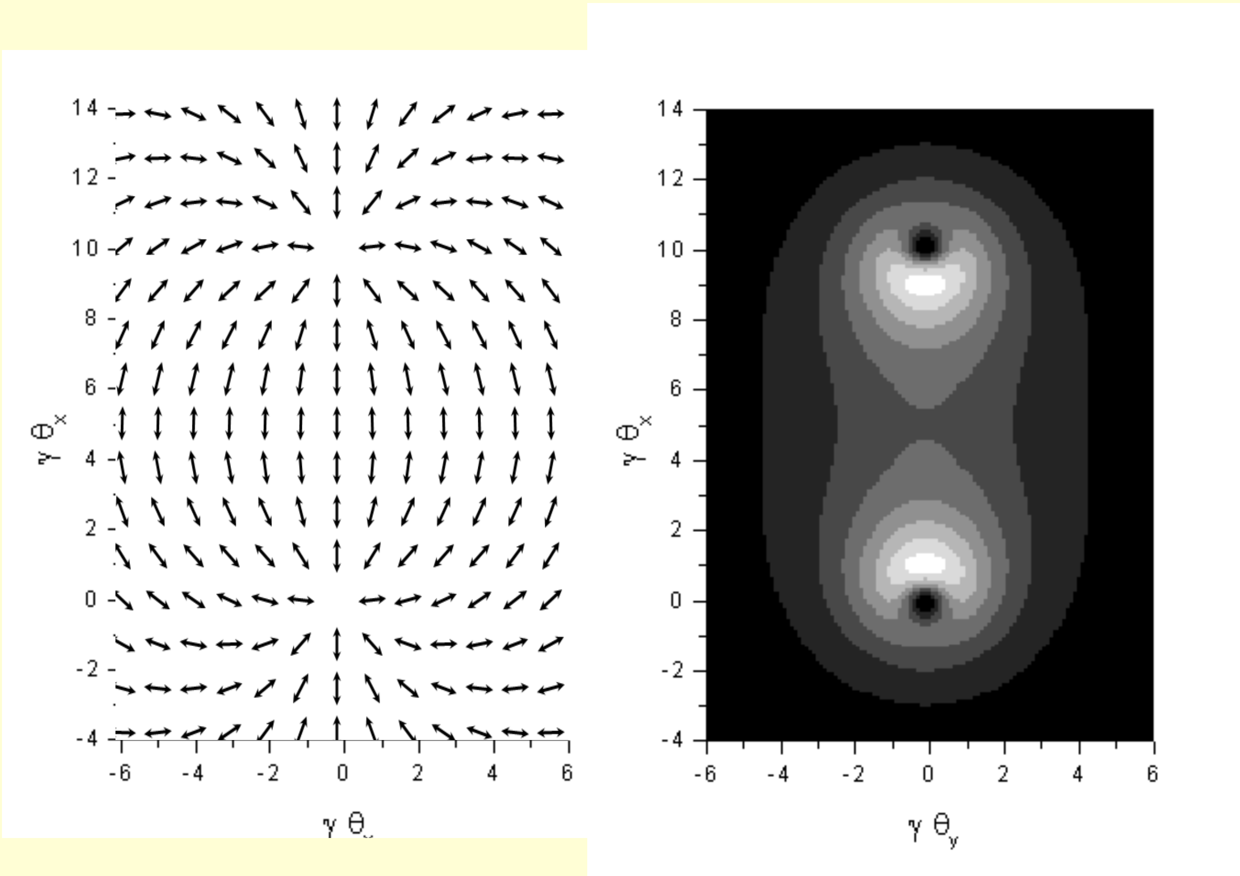
Polarization matrix: $J_{ik} = \dfrac{e^2\omega^2}{4\pi^2}\left(\vec{e}_i \vec{I}\right)\left(\vec{e}_k \vec{I}\right)$, where $\vec{e}_{i,k}\vec{n} = 0,\ \vec{e}_i\vec{e}_k = \delta_{ik}$.

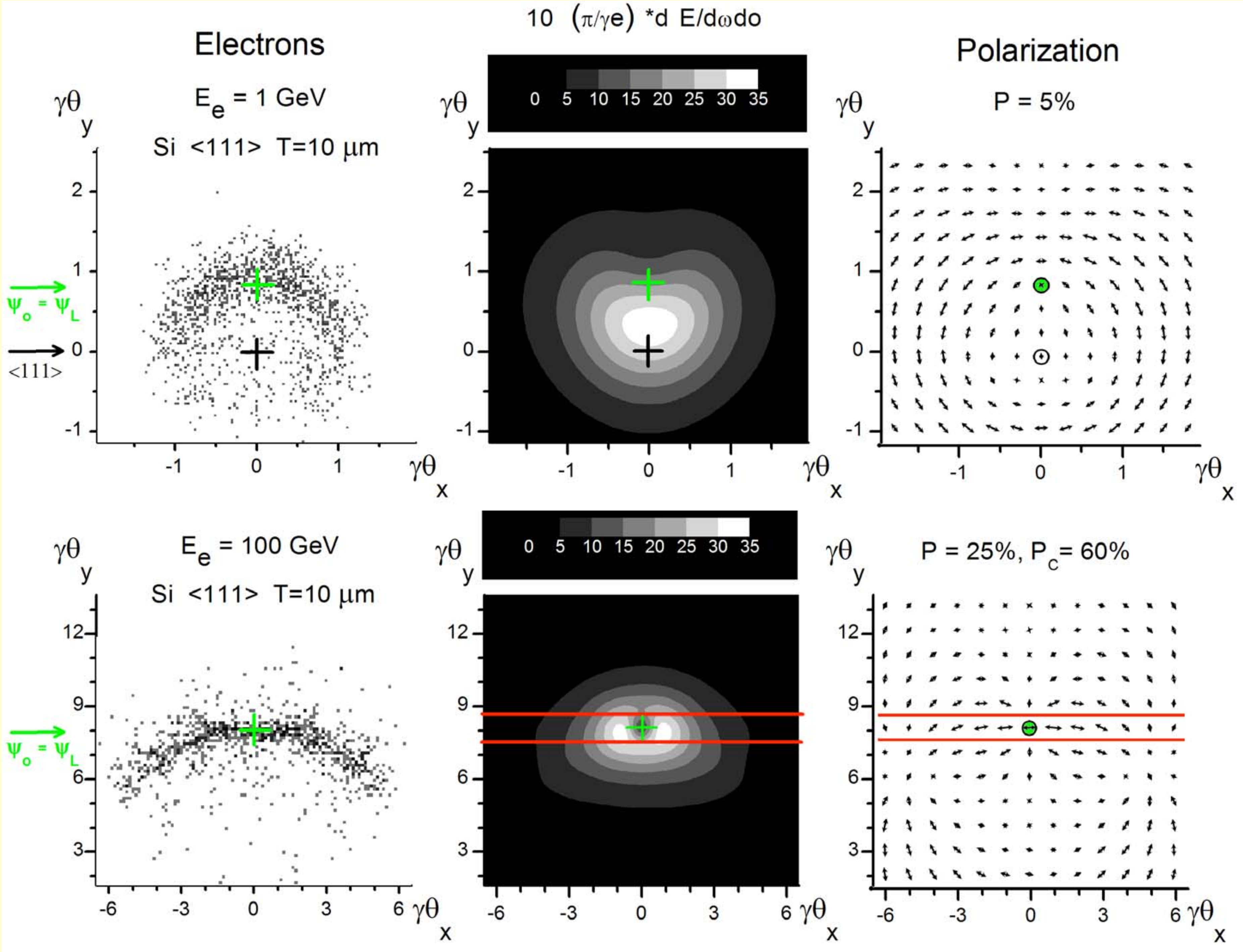
Circular polarization: at $l_{coh} \ggg T$: $J_{ik} = J_{ki} \Rightarrow P_c = 0$ for all observation angles

$$P_c = \frac{J_{12} - J_{21}}{J_{11} + J_{22}}$$

Linear polarization:

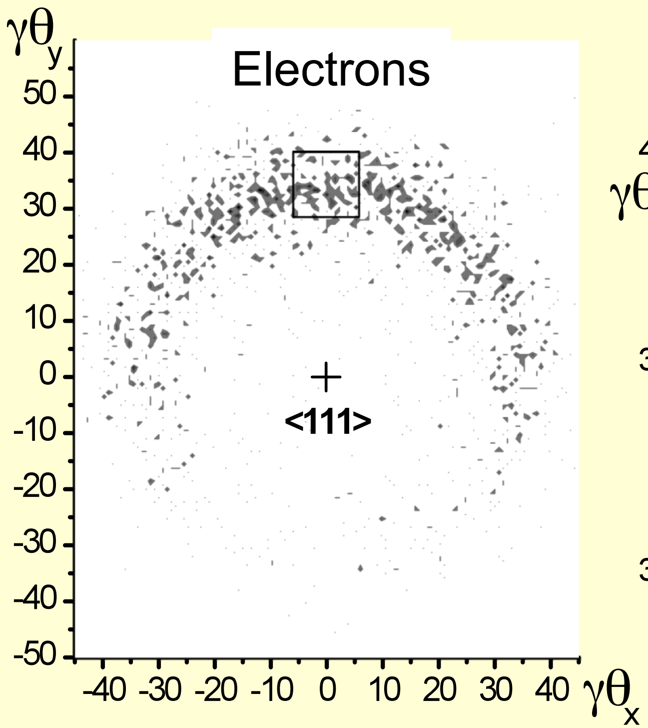
$$P = \frac{J_{11} - J_{22}}{J_{11} + J_{22}}$$

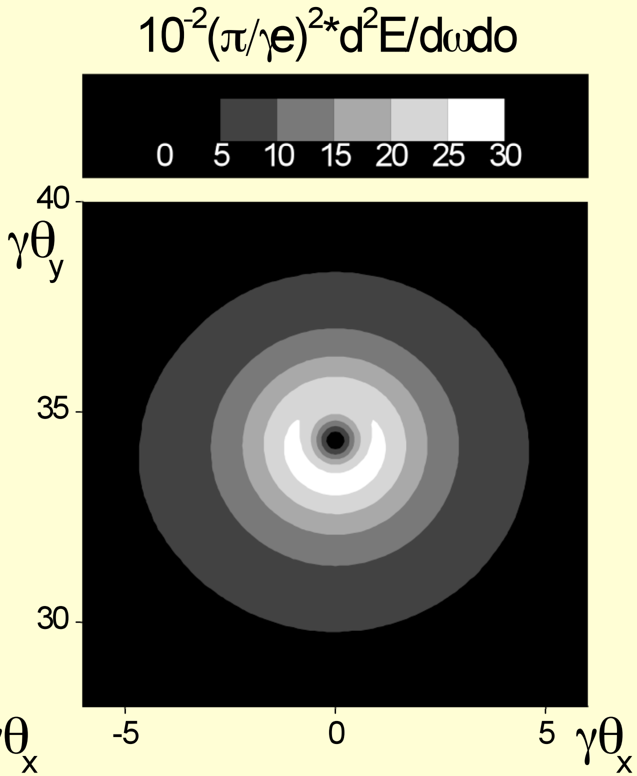


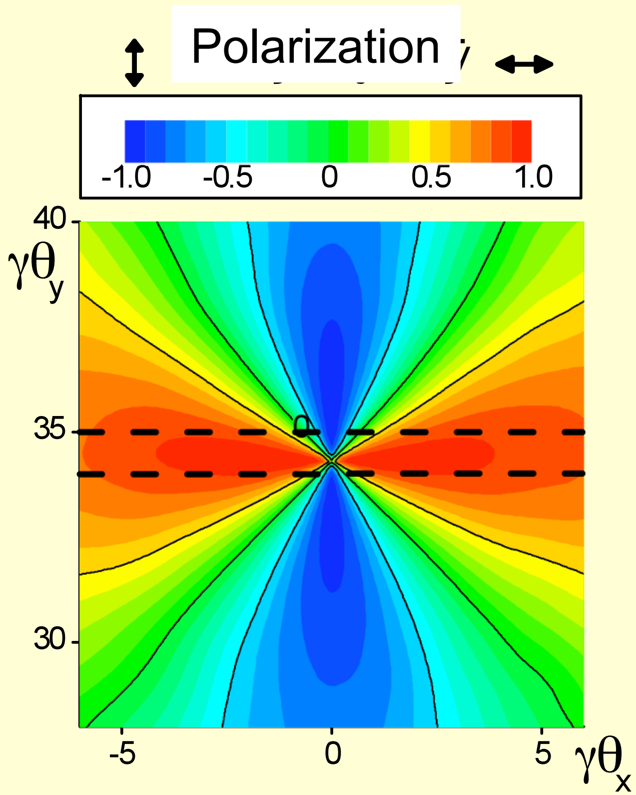

Electrons
10 (π/γe) *d E/dωdo
Polarization
E_e = 1 GeV
Si <111> T=10 μm
P = 5%
$\psi_o = \psi_L$
<111>
E_e = 100 GeV
Si <111> T=10 μm
P = 25%, P_C = 60%
$\gamma\theta_x$
$\gamma\theta_y$
0 5 10 15 20 25 30 35

Strong Non-Dipole Regime of Radiation (High energy)

E_e = 200 GeV   W <111>   T = 20 μm $\psi = \psi_L$ $\gamma\,\psi_L = 35$

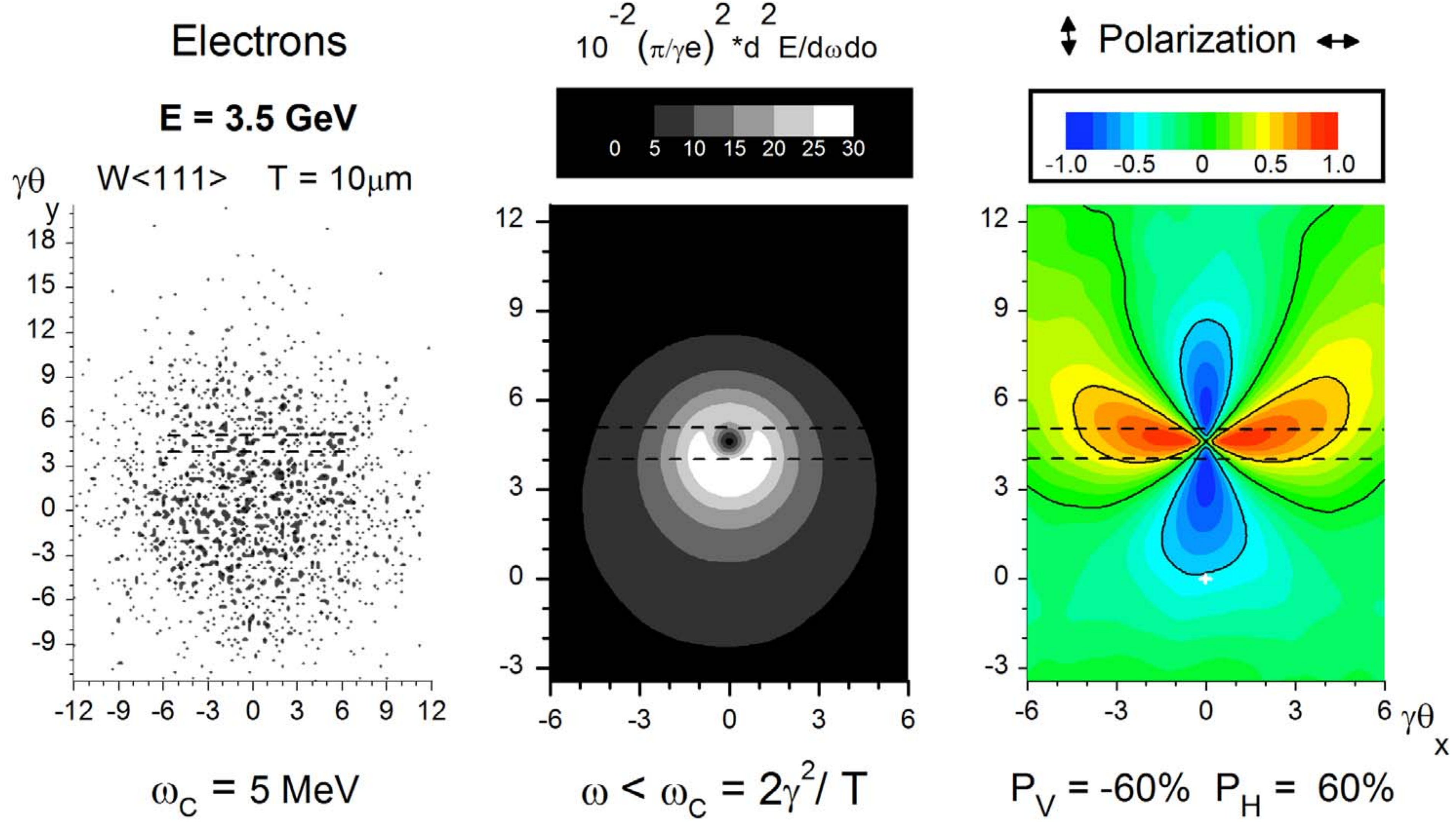






Pc ~ 80%

Non-Dipole Regime of Radiation
(Low Energy)



S U M M E R Y

- 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 logarithmic thickness dependence** of radiation spectrum of ultrarelativistic electrons in a thin layer of matter **was observed for the first time (!) in CERN experiment NA63** for electron energies 149 GeV.

- A new possibility of **high degree linear polarized photon production** based on special features of non-dipole regime of radiation is proposed.

- The **optimization of experimental conditions** for the first observation of mentioned above effect is carried out.

Thank You for Your Attention!