Channeling-2012

LPM and TSF-effects

(Features of non-dipole radiation by relativistic electron in thin crystal)

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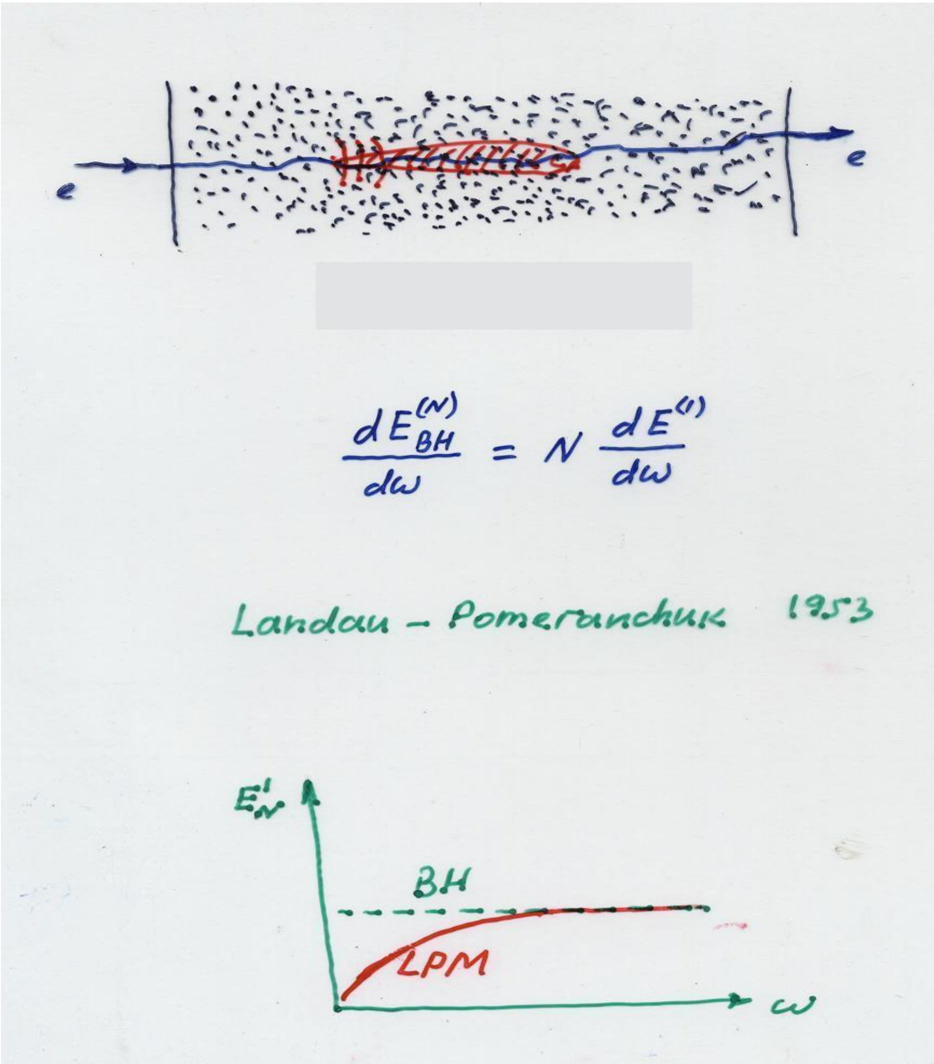
LPM – effect (1953)



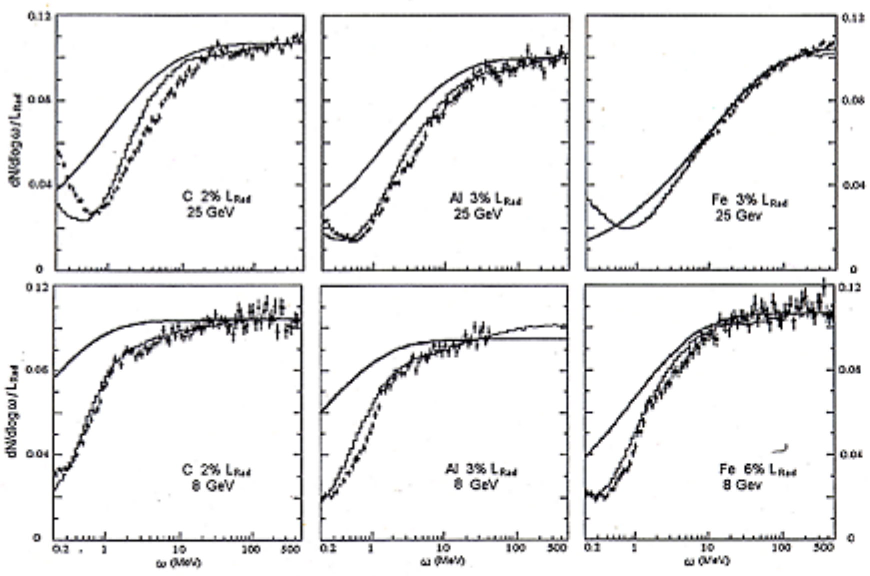
$$\frac{dE_{BH}}{d\omega} = \frac{4}{3}\frac{L}{X_0}\frac{E'}{E}\left(1 + \frac{\omega^2}{EE'}\right)$$

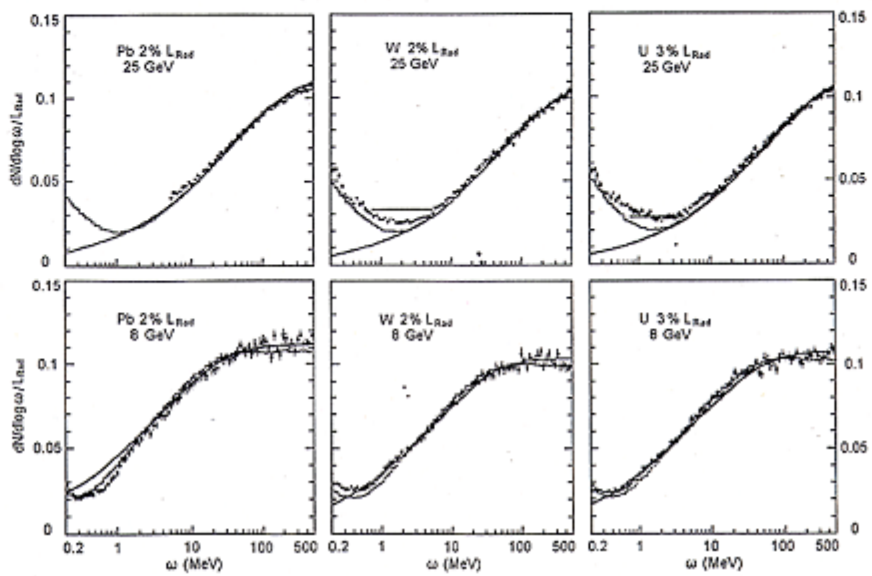
$$X_0^{-1} = \frac{4Z^2 e^6 n}{m^2}\ln(mR)$$

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

An effect confirmed after 40 years!

(SLAC – experiment   Phys.Let. (1995); Rev.Mod.Phys. (1999)





LPM

CERN Courier 1994

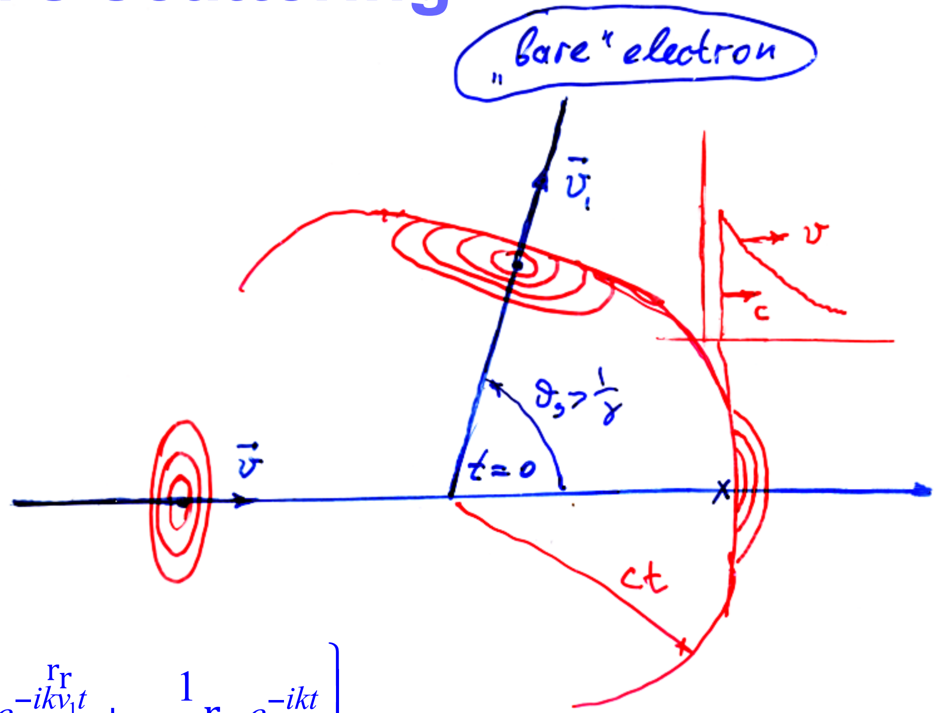
E. Feinberg Природа 1994

TSF

Evolution of electromagnetic field at electron's scattering

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

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



$$\varphi_{ret}(\vec r, t)\Big|_{t>0} = \frac{e}{2\pi^2}\mathrm{Re}\int \frac{d^3k}{k} e^{i\vec k\vec r}\left\{\frac{1 - e^{-i(k - \vec k\vec v_1)t}}{\omega - \vec k\vec v} e^{-i\vec k\vec v_1 t} + \frac{1}{k - \vec k\vec v} e^{-ikt}\right\} =$$

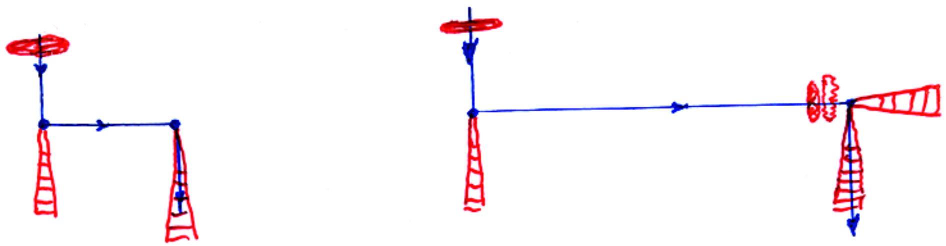
$$= \Theta(t - r)\varphi_{v_1}(\vec r, t) + \Theta(r - t)\varphi_v(\vec r, t)$$

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

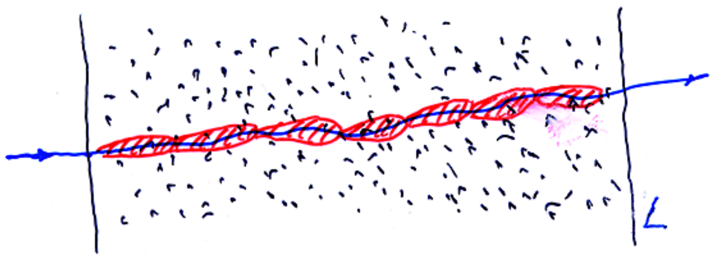
For $\varepsilon = 50 MeV$, $\lambda = 1 cm$, $l_c = 200\ m$

E.Feinberg JETP 50(1966)202, A. Akhiezer, N.Shul'ga, S.Fomin Sov.Phys.Usp. 30(1987)197 Phys.Lett.A 114(1986)148

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



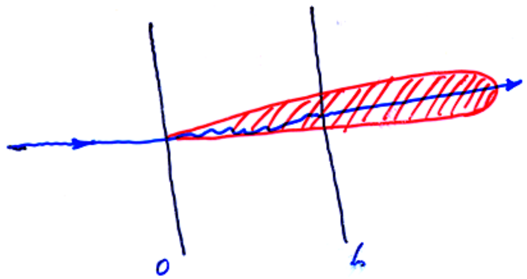
LPM case



$l_c \ll L$

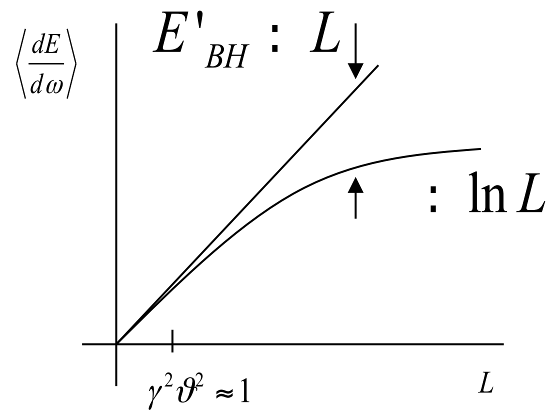
balance = e^- is undressed + e^- is dressed

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



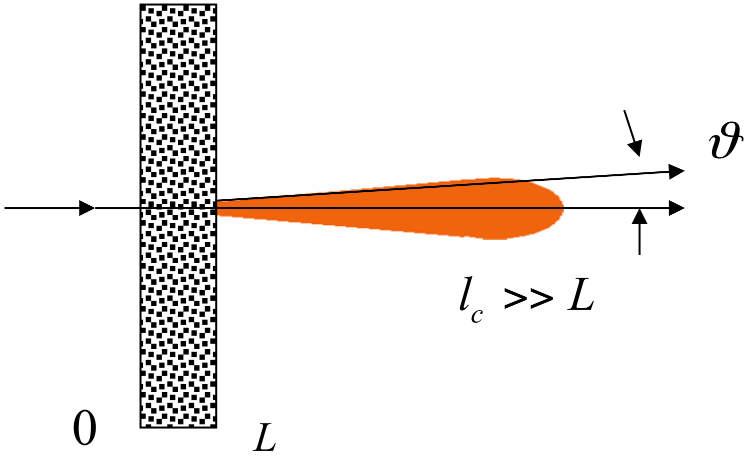
$l_c \gg L$

Electron is "bare" for all collisions !!!



Radiation in thin target (**TSF**-effect)

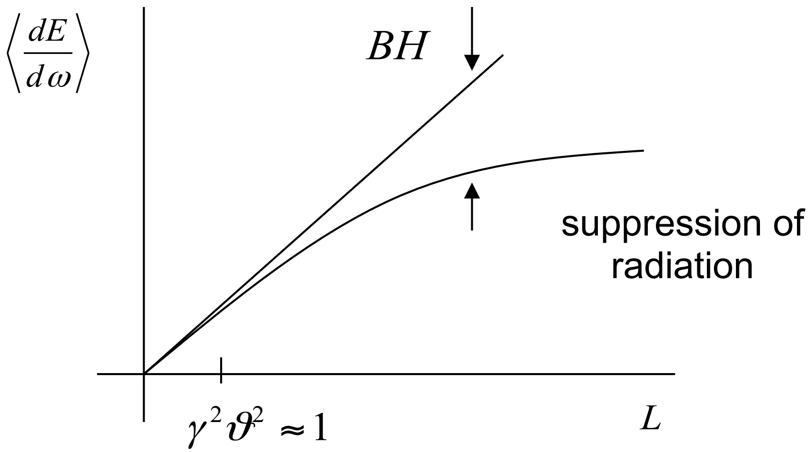
F. **T**ernovskii, JETF 1960, N. **S**hul'ga, S. **F**omin JETP Lett. 1978, 1996



$$l_c = \frac{2\gamma^2}{\omega} \; ? \; L$$

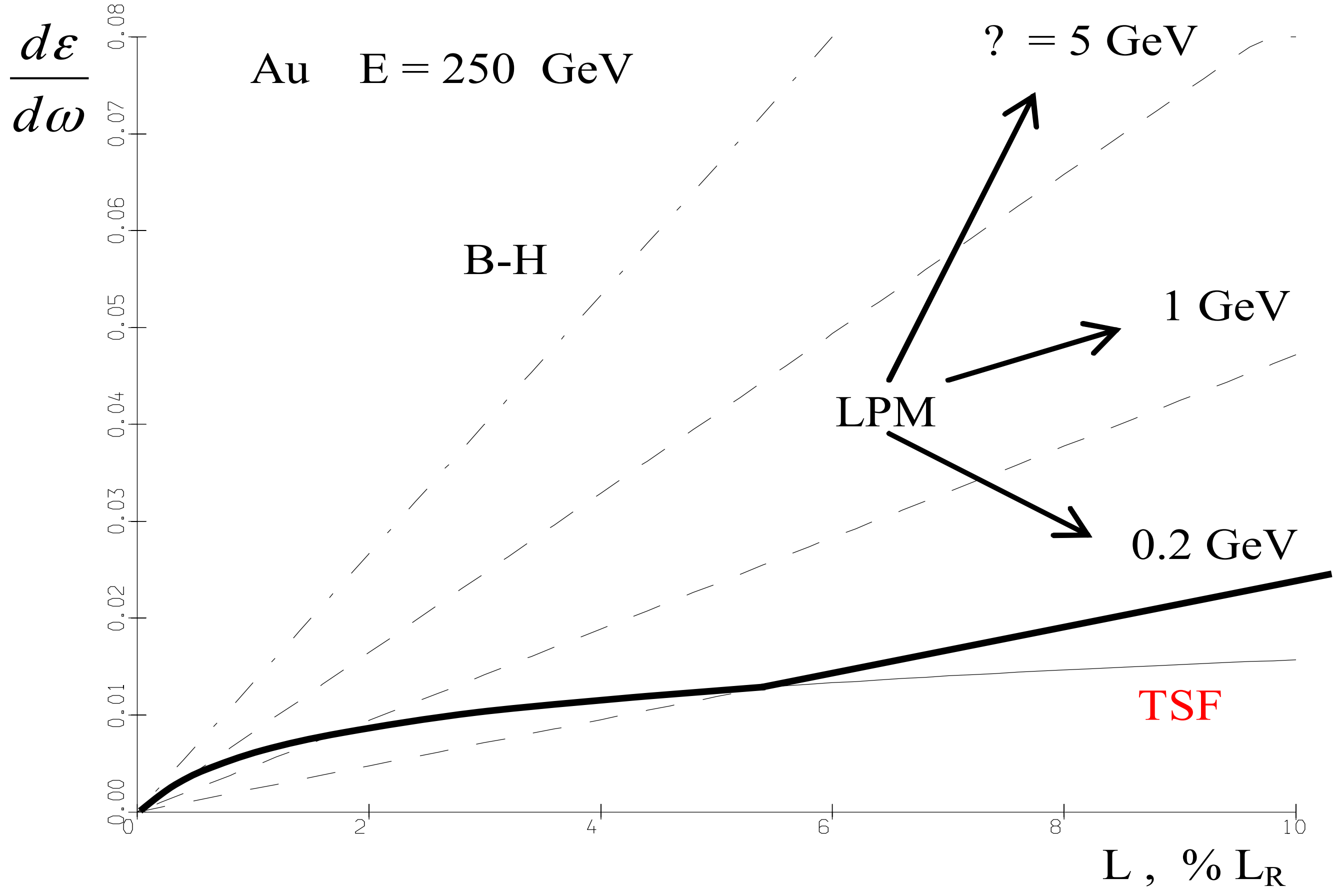
$$\left\langle \frac{dE}{d\omega} \right\rangle = \frac{2e^2}{\pi} \left\langle \left[\frac{2\xi^2+1}{\xi\sqrt{\xi^2+1}} \ln\left(\xi + \sqrt{\xi^2+1}\right) - 1 \right] \right\rangle \approx$$

$$\approx \frac{2e^2}{3\pi} \begin{cases} \gamma^2 \overline{\vartheta^2} \\ 3\ln \gamma^2 \overline{\vartheta^2} \end{cases} \approx \begin{cases} E'_{BH} \\ < E'_{BH} \end{cases}$$



$$\xi = \frac{\gamma\vartheta}{2}$$

Dependence on thickness



Suppression of radiation by relativistic electrons in a thin layer of matter (TSF effect)

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

Confirmed at CERN - 2009 - ***H.D.Thomsen et al., Physics Letters B 672 (2009) 323.***

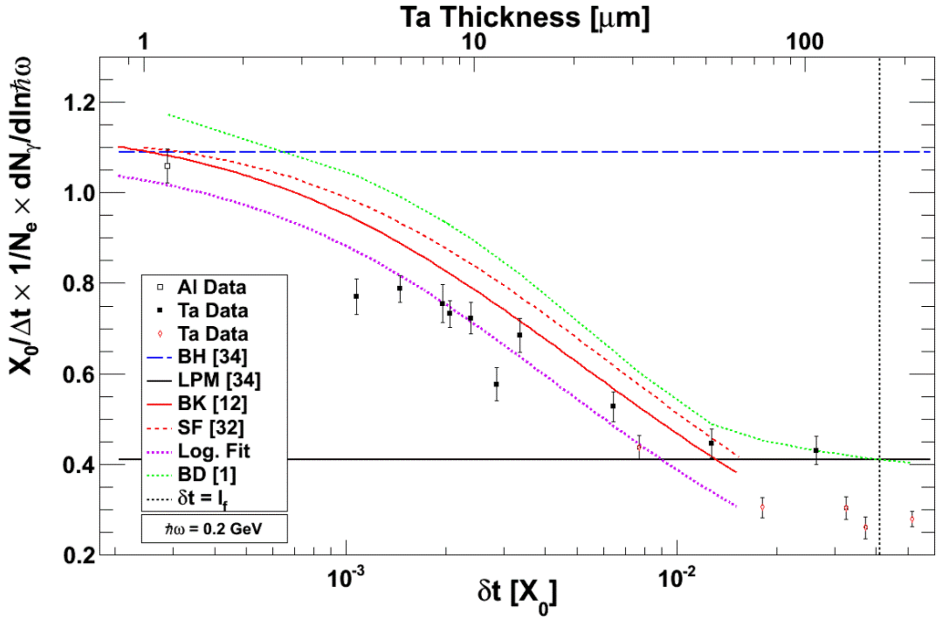
H.D.Thomsen et al., Physical Review D 81 (2010) 052003.

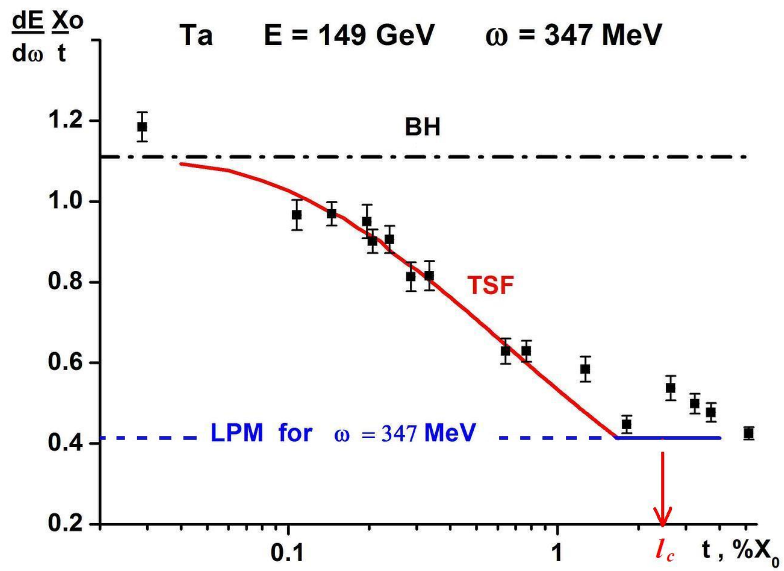
CERN NA63 SPS E = 149 GeV

"Channeling 2010", Ferrara, Italia

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

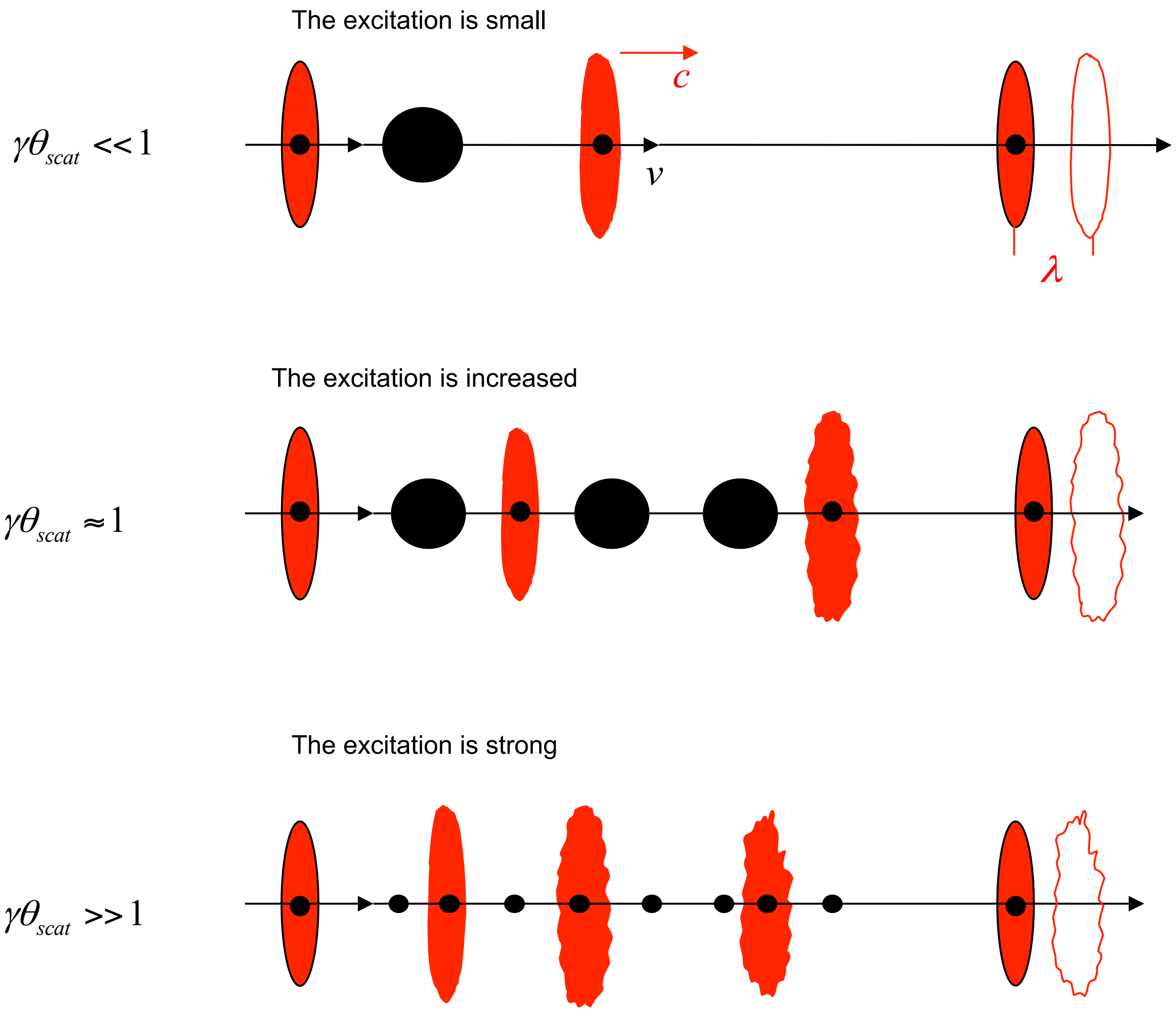
Nuovo Cimento (2011), in press





U. Uggerhoj : … we have seen the half - bare electron !

HOW DOES ELECTRON RADIATE?



$$v_{rel} = c - v$$

$$\lambda = (c - v)\Delta t_c \rightarrow \Delta t_c \approx 2\gamma^2 \lambda$$

Analogs for LPM and TSF-effects

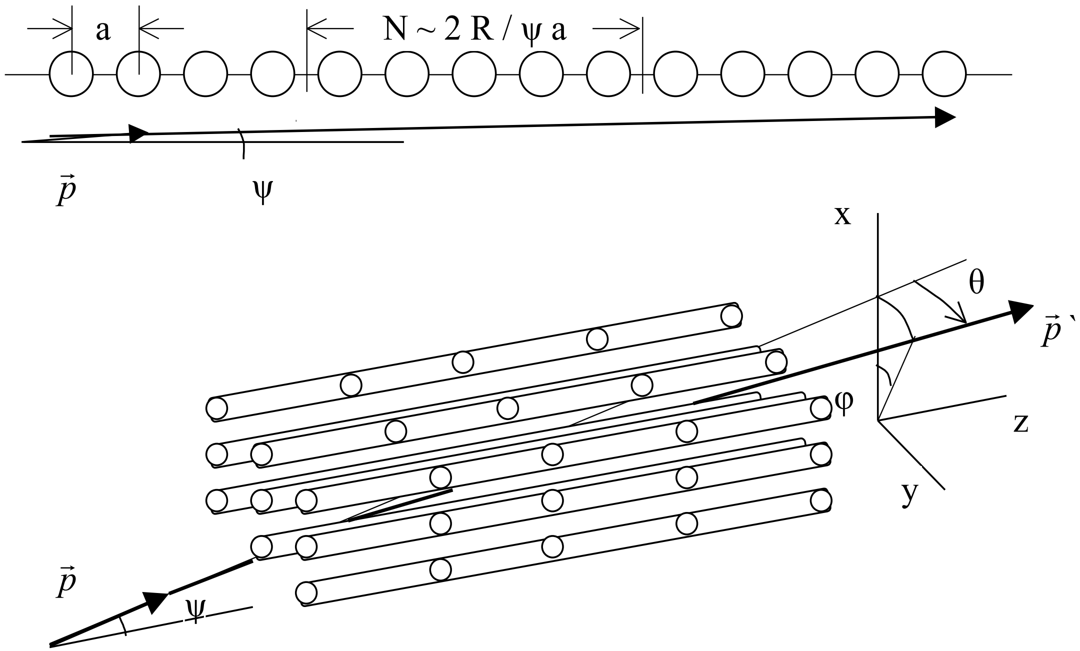
- ***Coherent bremsstrahlung, dynamical chaos***
- ***Volume reflection***
- ***Beam-beam coherent bremsstrahlung***

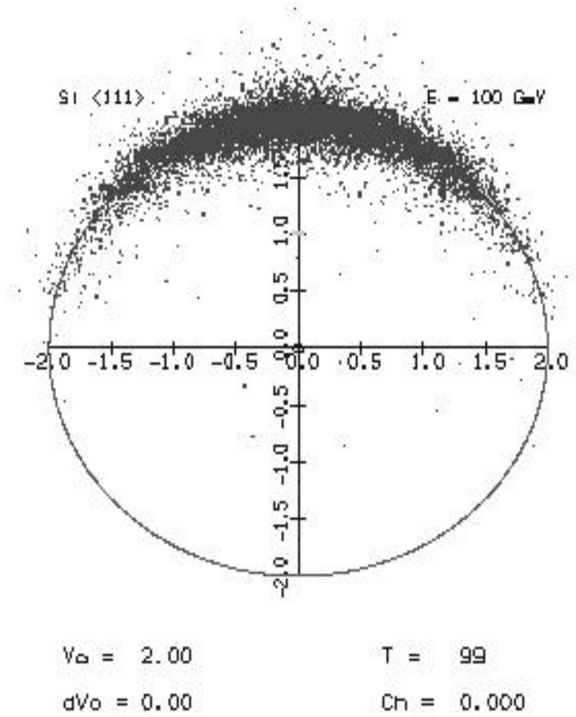
LPM effect in crystal

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

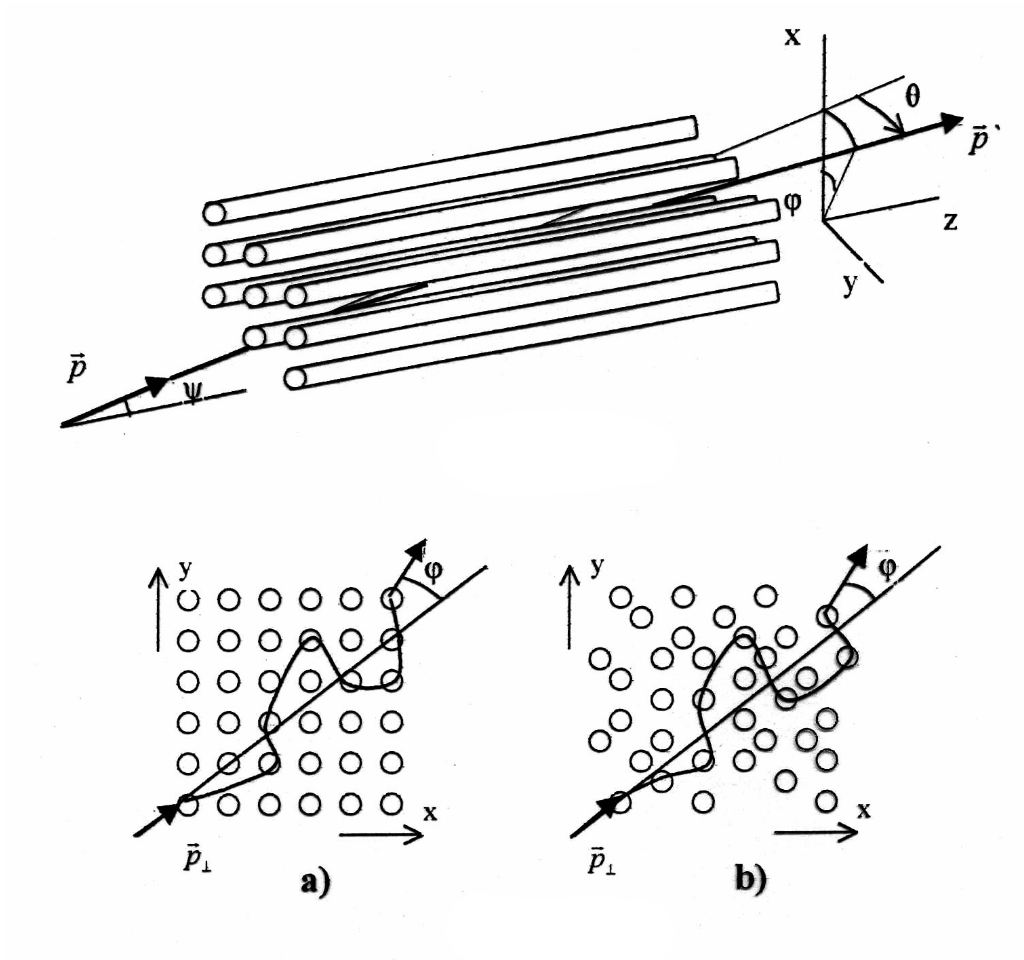
Multiple scattering in crystal

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





Multiple Scattering on Atomic strings



$$\psi : \psi_c$$

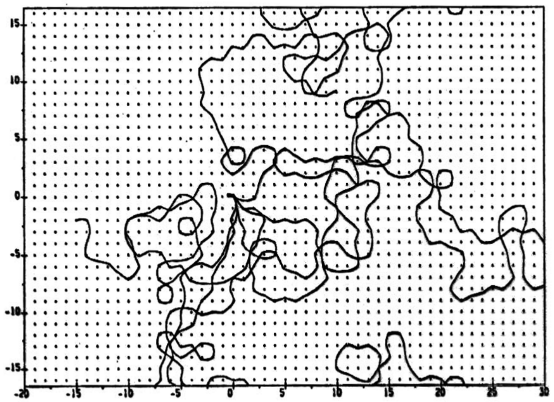
$$\psi_c = \sqrt{2U_0/\varepsilon}$$

V. Beloshitskii, M. Kumakhov (1973), $\psi < \psi_c$

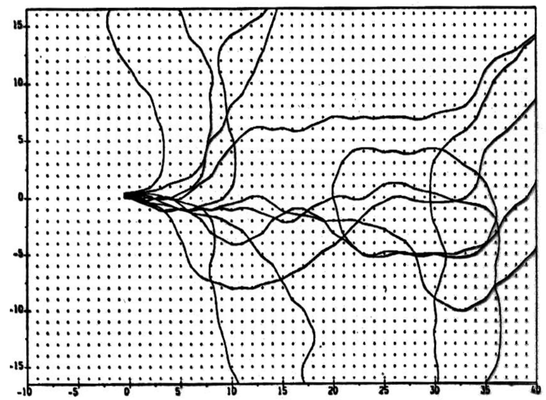
N. Shul’ga, V. Truten’, S. Fomin (1982), $\psi > \psi_c$

Dynamical Chaos at Multiple Scattering

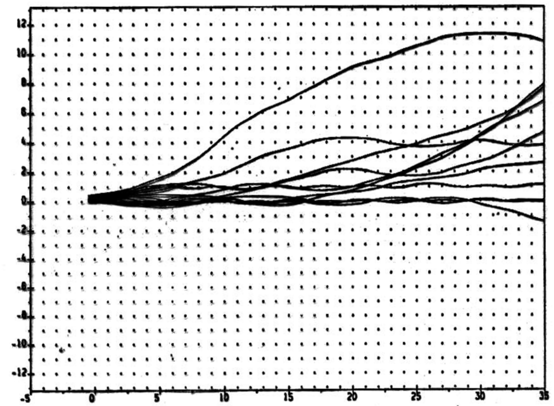
$$z = \psi / \psi_c$$



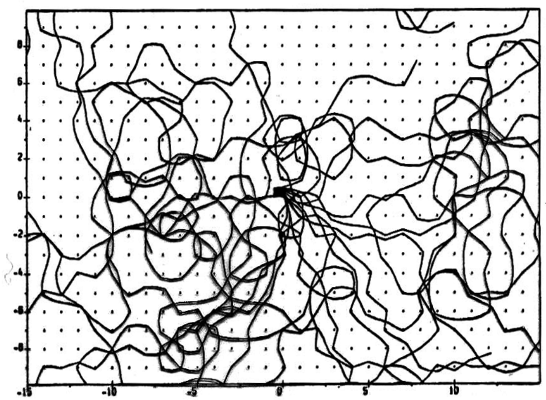
Z=0.5

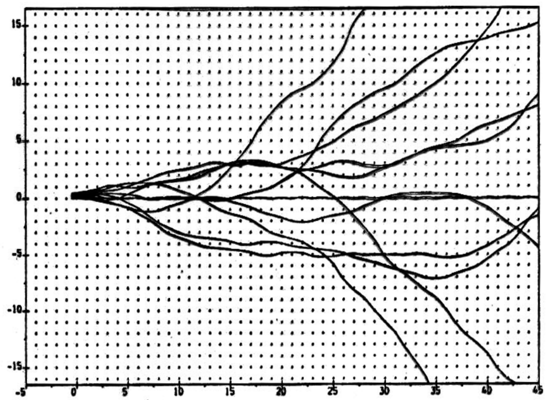


Z=1

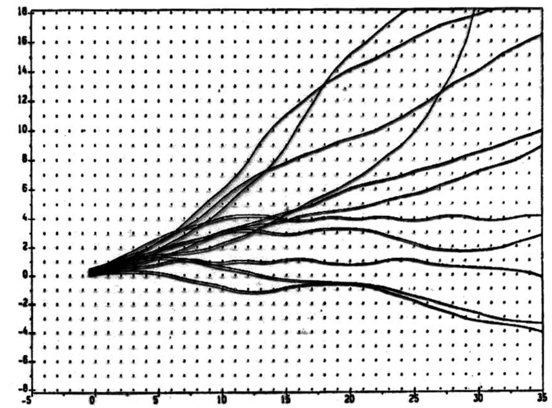


Z=2 $\alpha = 6^0$





Z=1.5



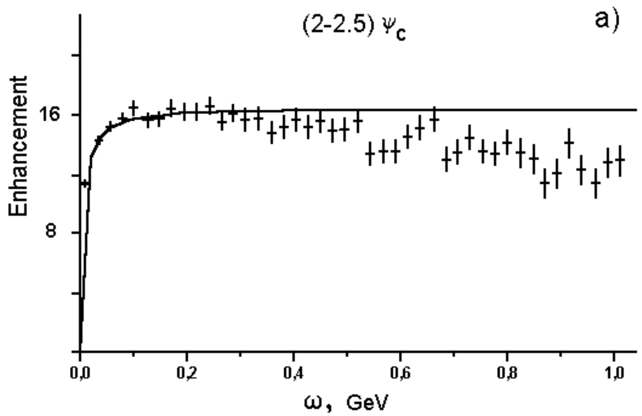
Z=2 $\alpha = 15^0$

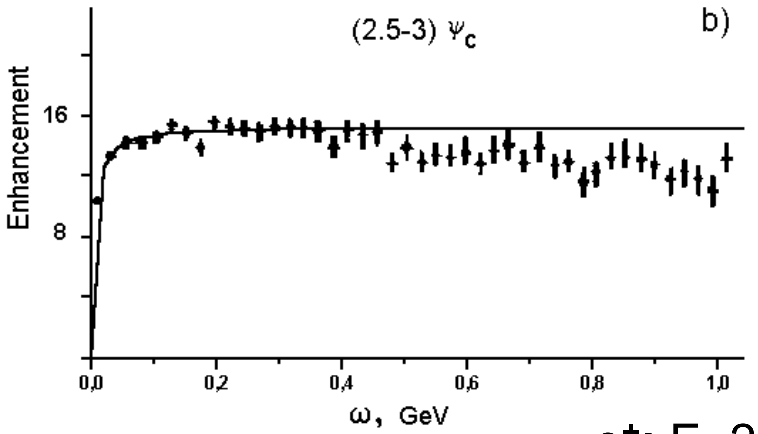
A. Akhiezer, N Shul'ga, V. Truten', Physics Reports, 1991

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

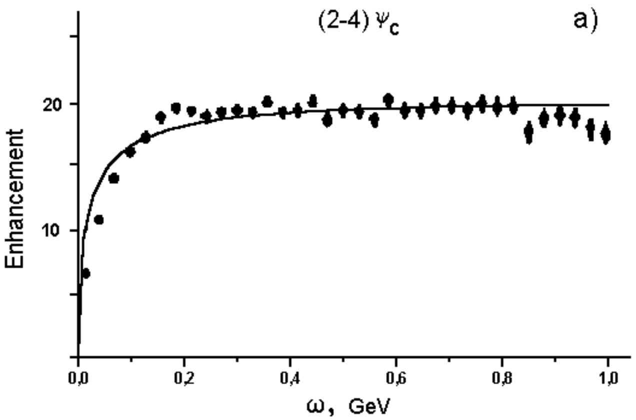
Theory: **Laskin N., Shul'ga N.,** Phys.Lett. **A135** (1989) 147.

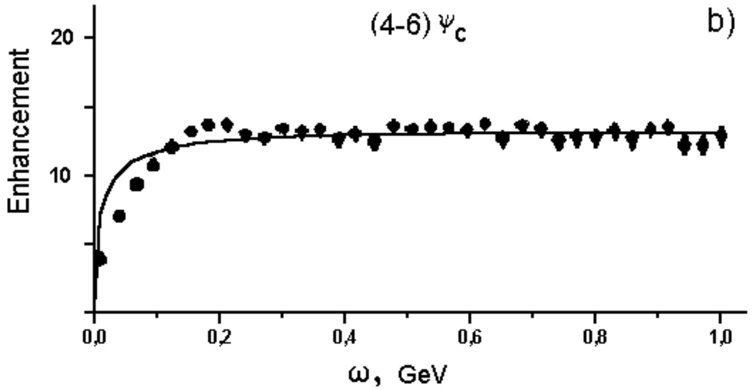
e^- : E=10 GeV





e^+: E=20 GeV





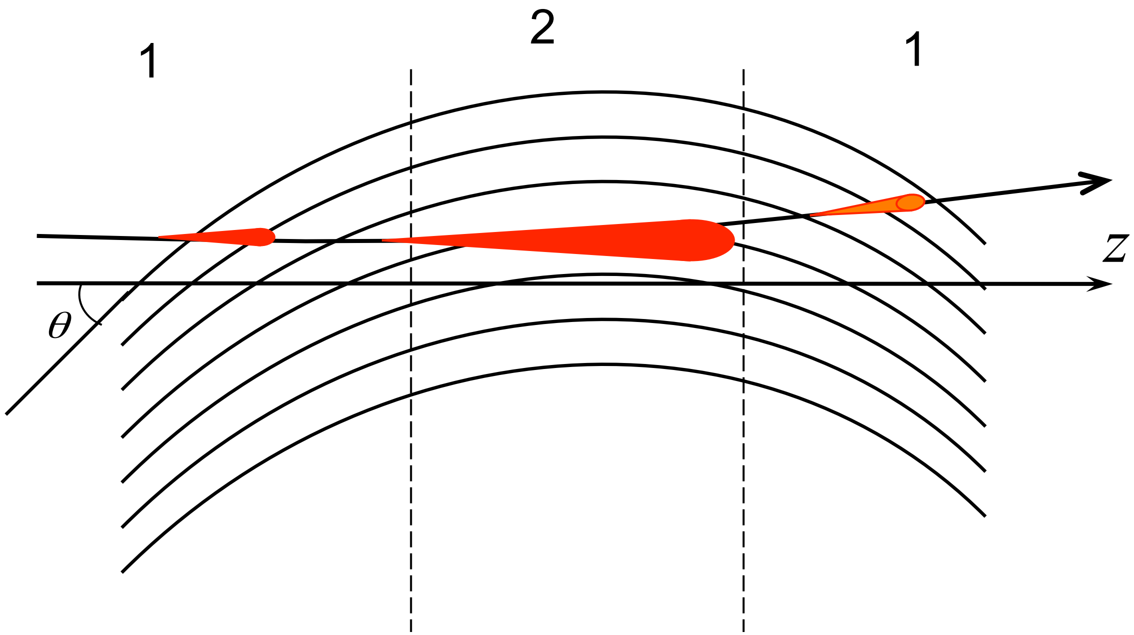
New proposals

LPM: 10 GeV → 100 GeV

TSF: thin crystal

Coherent Radiation in Bent Crystal Planes

N. Shul'ga, V. Boyko, V, Truten', 2008



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

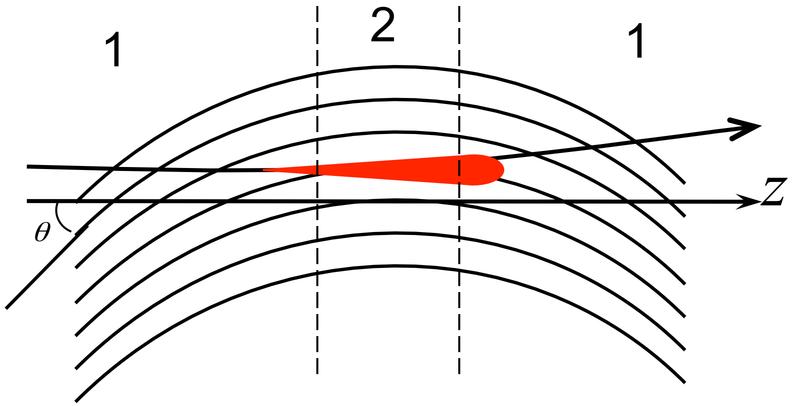
$$\theta_c = \sqrt{2U_0 / \varepsilon}$$

$I \qquad l_c < a/\theta_c, \qquad \gamma\theta_c < 1 \qquad \Rightarrow \dfrac{dE}{d\omega} = \dfrac{dE_{coh}(\theta(z))}{d\omega} \quad \theta = \theta(z)$!!!

$II \qquad l_c >> a/\theta_c \qquad \left.\begin{matrix}\gamma\theta_c < 1 \\ \gamma\theta_c > 1\end{matrix}\right\}$ type angle trajectory approximation $\quad \vartheta_{scatt} \sim \theta_c$

$l_c << a/\theta_c \qquad \gamma\theta_c > 1$ synchrotron (constant field) approximation

Low frequency Radiation in Bent Crystal Planes



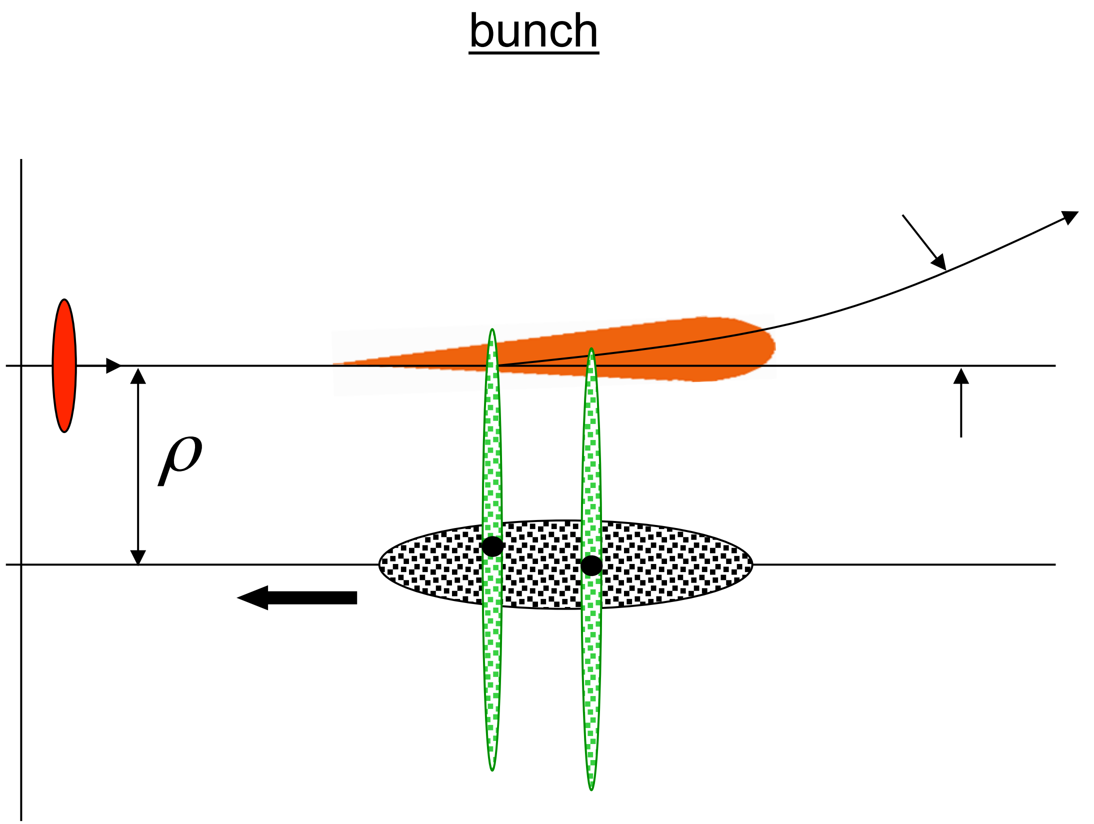
$$\left\langle \frac{dE}{d\omega} \right\rangle = \frac{1}{L_x} \int_R^{R+L_x} db \; \frac{dE(\vartheta_e(b))}{d\omega}$$

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

$$\frac{\langle E' \rangle}{E'_{BH}} \sim \frac{3e^2}{\pi} \frac{L_R}{L} \ln\left(\gamma\vartheta_e / 2\right)$$

$$\frac{\langle E' \rangle}{E'_{BH}} \sim 1 \qquad \text{for } \varepsilon\text{=100 GeV}, \; L = 1\,\text{mm}, \; L_R = 10\text{ cm}, \; \ln\left(\gamma\vartheta_e / 2\right) \sim 1$$

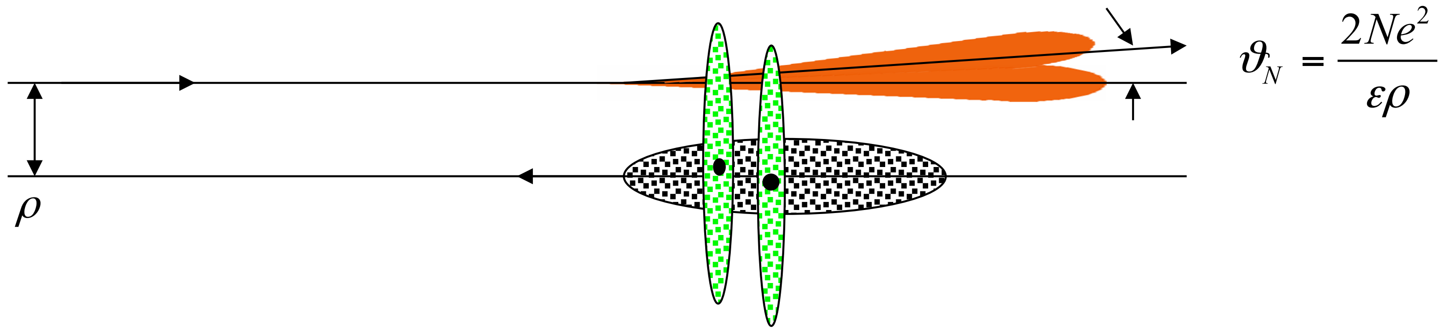
Coherent radiation at electron collision with a short bunch



$$\vartheta_N = \frac{2Ne^2}{\varepsilon\rho}$$

N. Shul'ga, D. Tyutyunnik, JEPT Lett. 78(2003)700., Proc. of SPIE, v. 5974(2005)60.

Suppression of coherent radiation (analog of LPM-effect)



$$\vartheta_N = \frac{2Ne^2}{\varepsilon\rho}$$

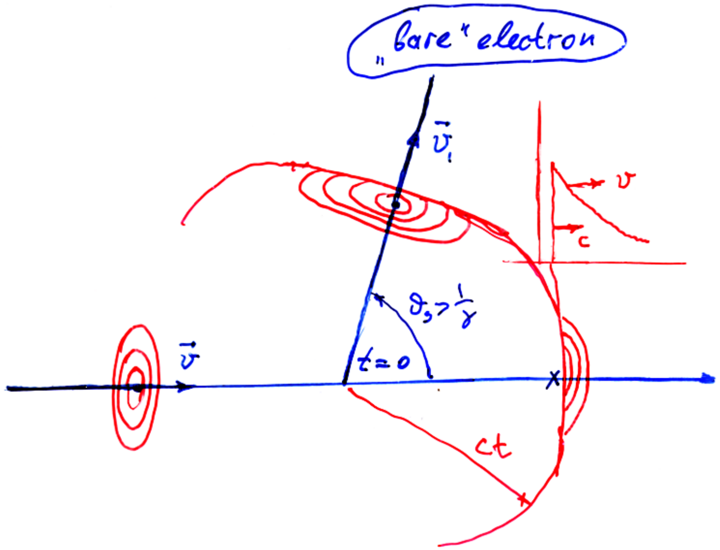
$$\frac{dE_N}{d\omega} = \frac{2e^2}{\pi}\left[\frac{2\xi^2+1}{\xi\sqrt{\xi^2+1}}\ln\left(\xi+\sqrt{\xi^2+1}\right)-1\right], \qquad \xi = \frac{\gamma\vartheta_N}{2}$$

$$\frac{dE_N}{d\omega} \approx \begin{cases} N^2 \dfrac{e^6}{m^2\rho^2} & \gamma\vartheta_N << 1 \\ 4e^2 \ln\left(\dfrac{Ne^2}{m\rho}\right) & \gamma\vartheta_N >> 1 \end{cases}$$

ε=5 Gev, L=0.1 cm, ρ=0.01 cm, $N=10^{10}$, $\omega_c = 4\gamma^2/L \approx 50 kev$, $\gamma\vartheta_N \approx 1$

N. Shul'ga, D. Tyutyunnik. JETP Lett. 78 (2003) 700.
NiM B227 (2005) 152

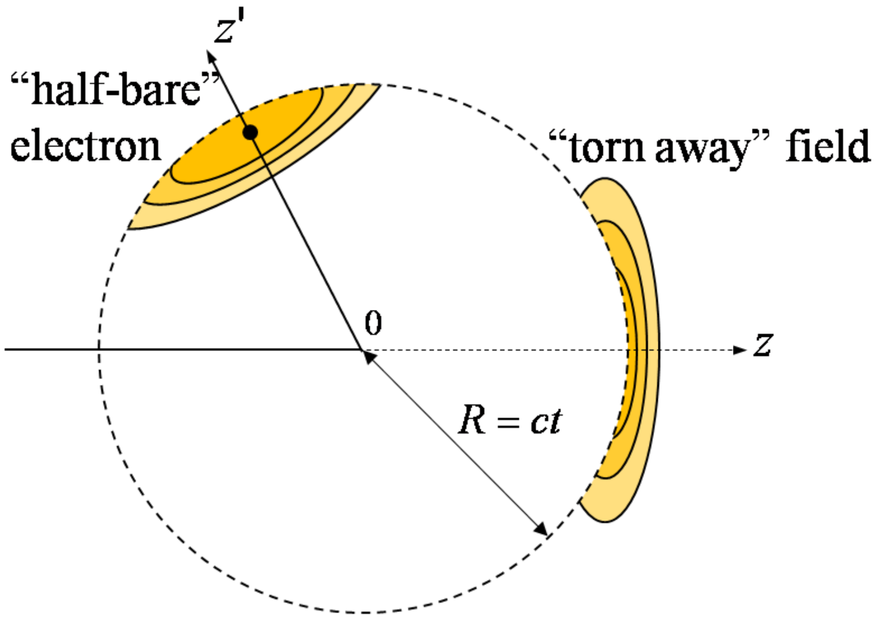
FOURIER TRANSFORMATION OF ELECTRON'S FIELD
COHERENT LENGTH, WAVE ZONE



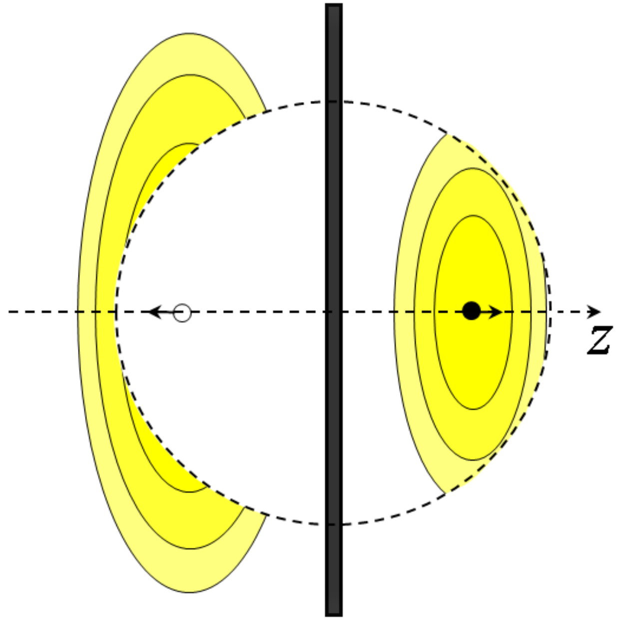
$$\varphi(\vec{r},t) = \frac{e}{2\pi^2} \mathrm{Re} \int \frac{d^3k}{k} e^{i\vec{k}\vec{r}} \left\{ \frac{1 - e^{-i\left(k - \vec{k}\vec{v}_1\right)t}}{\omega - \vec{k}\vec{v}_1} e^{-ikv_1 t} + \frac{1}{k - \vec{k}\vec{v}} e^{-ikt} \right\}$$

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

THE ANALOGY IN BREMSSTRAHLUNG



Bremsstrahlung



Transition radiation

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. Akhiezer, N. Shul’ga *High Energy Electrodynamics in Matter*, 1996
N. Shul’ga, V. Syshchenko, S. Shul’ga // Phys. Lett. A, 2009

APPROXIMATION OF THE COULOMB FIELD BY THE PACKET OF PLANE WAVES (EQUIVALENT PHOTON METHOD)

$$\varphi_{free}\left(\vec{r},t\right) = \mathrm{Re}\int \frac{d^3k}{\left(2\pi\right)^3} e^{i\left(\vec{k}\vec{r}-kt\right)} C_k$$

$$C_k = \frac{8\pi\, e\, \Theta\left(k_z\right)}{k_\perp^2 + k_z^2/\gamma^2}$$

$$\varphi_{free}\left(\vec{r},t\right) = \mathrm{Re}\int dk \varphi_k\left(\vec{r},t\right)$$

$$\varphi_k\left(\vec{r},t\right) = \frac{2}{\pi} e^{ik(z-t)} \int_0^\infty \frac{\theta d\theta}{\theta^2 + \gamma^{-2}} J_0\left(k\rho\theta\right) e^{-ikz\theta^2/2}$$

WAVE AND PRE-WAVE ZONES

$$\varphi_k\left(\vec{r},t\right)=\frac{2}{\pi}e^{ik(z-t)}\int_0^\infty\frac{\theta\,d\theta}{\theta^2+\gamma^{-2}}J_0\left(k\rho\theta\right)e^{-ikz\theta^2/2}$$

pre-wave zone

$$\varphi_k\left(\vec{r},t\right)\approx\frac{2}{\pi}K_0\left(k\rho/\gamma\right)e^{ik(z-t)} \qquad kz\vartheta^2/2<<1$$

$$\varphi\left(\vec{r},t\right)=\frac{e}{\sqrt{(z-t)^2+\rho^2/\gamma^2}} \qquad z<<l_c$$

wave zone

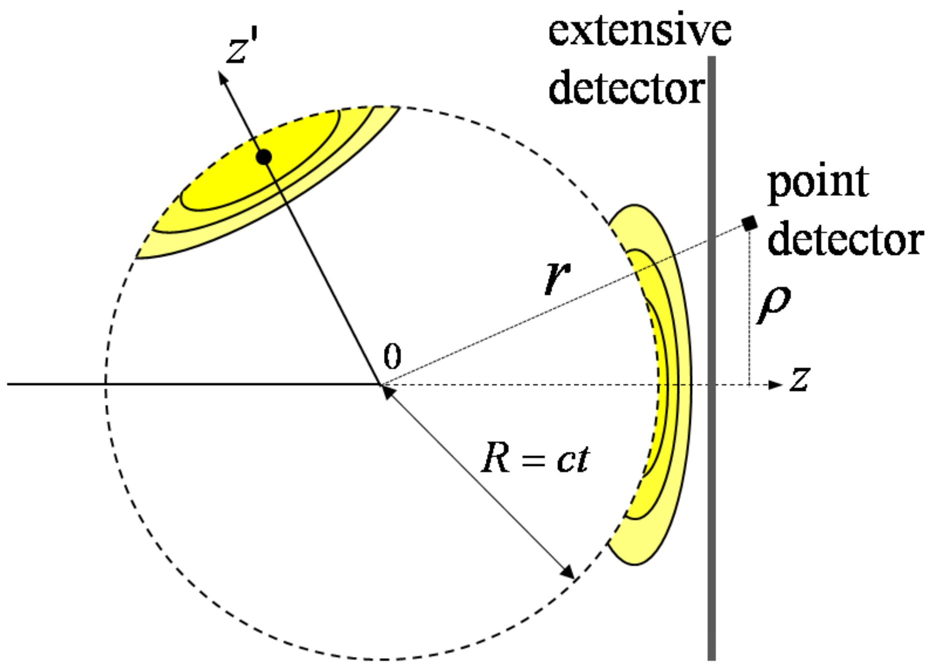
$$\varphi_k\left(\vec{r},t\right)=-\frac{2i}{\pi}\frac{1}{\vartheta_0^2+\gamma^{-2}}\frac{1}{kr}e^{ik(r-t)} \qquad kz\vartheta^2/2>>1$$

$$\vartheta_0=\rho/z \qquad z>>l_c$$

N.Shul'ga, V. Syshchenko, S. Shul'ga. Phys. Lett. A 374 (2009) 331

The Problem of Bremsstrahlung Radiation Measurement

N.Shul'ga, S. Trofymenko, V. Syshchenko JETP Lett., 93 (2011) 1



Point detector: $\Delta\rho \ll \gamma/\omega$

$|z| \gg l_c$:

$$\frac{d\mathcal{E}}{d\omega do} = \frac{e^2}{\pi^2}\frac{\vartheta^2}{\left(\gamma^{-2}+\vartheta^2\right)^2}$$

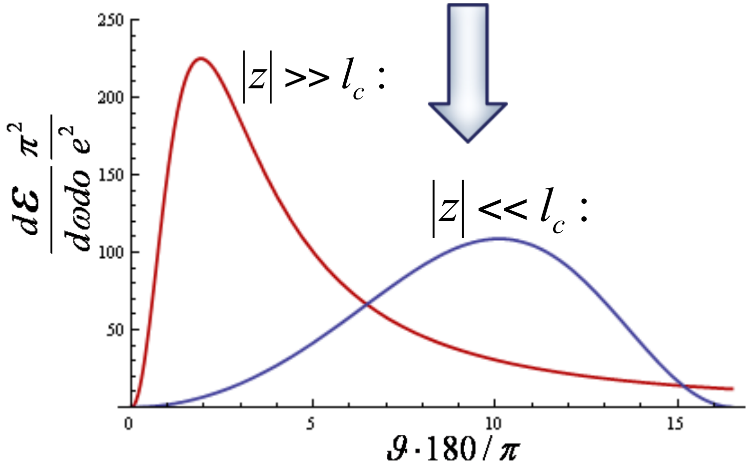
$|z| \ll l_c$:

$$\frac{d\mathcal{E}}{d\omega do} = \frac{4e^2}{\pi^2}\frac{1}{\vartheta^2}\sin^2\left(\frac{\omega\,|z|\,\vartheta^2}{4}\right)$$

Extensive detector: $\Delta\rho \gg \gamma/\omega$

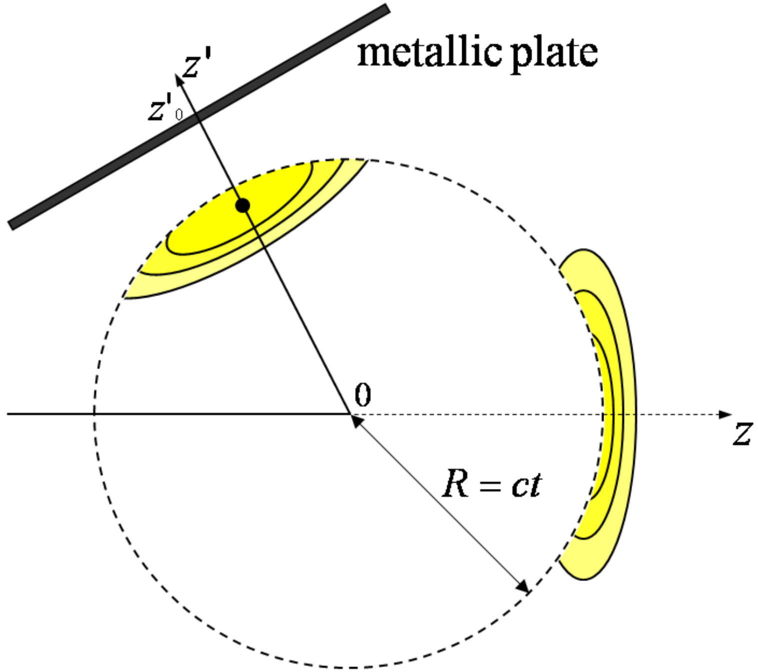
any Z:

$$\frac{d\mathcal{E}}{d\omega do} = \frac{e^2}{\pi^2}\frac{\vartheta^2}{\left(\gamma^{-2}+\vartheta^2\right)^2}$$



TRANSITION RADIATION BY ELECTRON WITH NONEQUILIBRIUM FIELD

N.Shul'ga, S. Trofymenko, V. Syshchenko JETP Lett., 93 (2011) 1



Transition radiation by "torn away" field :

$$\frac{d\mathcal{E}}{d\omega do} = \frac{e^2}{\pi^2}\frac{\vartheta^2}{\left(\gamma^{-2}+\vartheta^2\right)^2}$$

does not depend on z_0

Transition radiation in wave zone by electron with nonequilibrium field :

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

CONCLUSIONS

- Analogs of LPM and TSF – effects
  - thick crystals 10 GeV → 100 GeV
  - thin crystals
  - volume reflection from bent crystal planes
  - beam-beam coherent radiation

- Pre-wave zone for bremsstrahlung

- Transition radiation by half-bare electron

THANK YOU FOR ATTENTION!