ADVANCES in COHERENT BREMSSTRAHLUNG and LPM – EFFECT STUDIES

(in commemoration of the 100th anniversary from the birth of L. D. Landau)

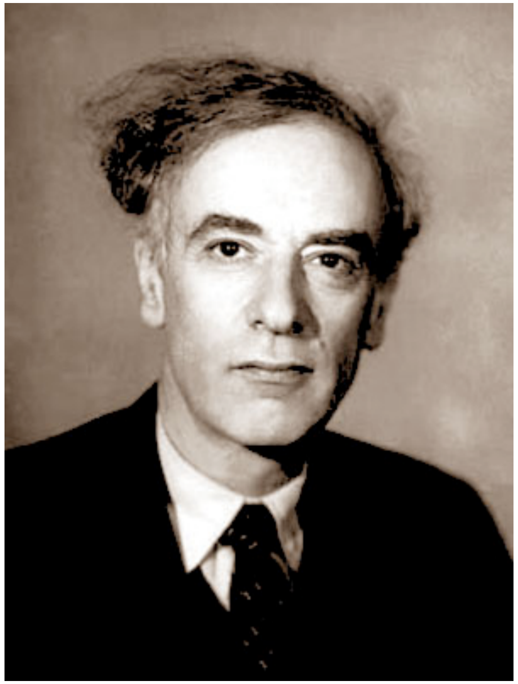
N. F. Shul'ga

Akhiezer Institute for Theoretical Physics
of National Science Center "Kharkov Institute of Physics and Technology"
Kharkov, Ukraine
e-mail: shulga@kipt.kharkov.ua

- **Landau in Kharkov (1932-1937)**
- **CB theory and its problems**
- **Semiclassical and classical theory of CB and experiment**
- **LPM-effect in amorphous media and in crystals**
- **CB at high energy**
- **CB in deformed crystals**

LEV LANDAU (1908-1968)

(in commemoration of 100th anniversary from the birth)



- Nobel prize 1962
- The head of the theoretical department in Ukrainian Physical Technical Institute (Kharkov) from 1932 to 1937

Ukrainian Physical-Technical Institute UPhTI was founded 30 October 1928.

(Now National Science Center "Kharkov Institute of Physics and Technology")

prof. I.Obreimov was the first director of UPhTI. (1928-1931).
He organized the first theoretical department in the USSR (1928).

Prof. D.Ivanenko

He was the first head of Theoretical Department UPhTI (1928-1931)

Prof. D.Ivanenko

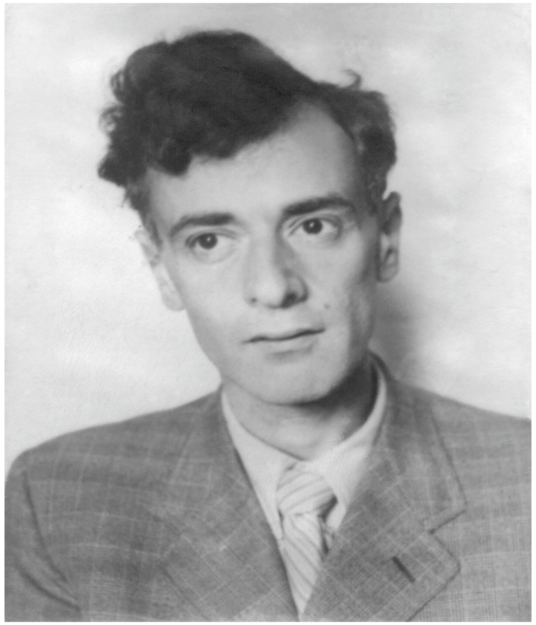
He was arrested in 1935 as a “socially dangerous element”
“… They remembered him his non-proletarian origin… accused him of contacts with foreigners, knowledge of foreign languages… “

(Ivanenko’s wife)

In 1931, I.Obreimov proposed to lead the theoretical department of UPhTI to P.Dirac, then to P.Ehrenfest…

They agreed to be the members of the academic council of UPhTI and proposed for this position L.Landau, who was unemployed in that time for about one year

Lev Landau
The head of theoretical department UPhTI from 1932 to 1937.



- Creation of the school for theoretical physics
- Creation of the course of theoretical physics since 1935

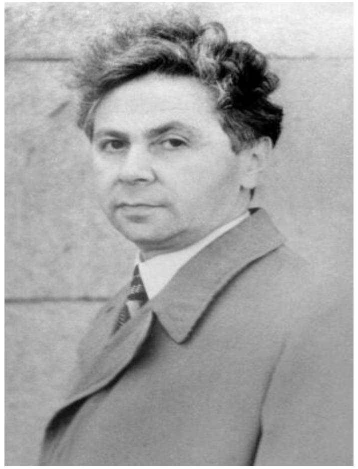
  Mechanics (with L.Pyatigorskii)

  Statistical physics (with E.Lifshitz)

  Electrodynamics (started with L.Pyatigorskii)

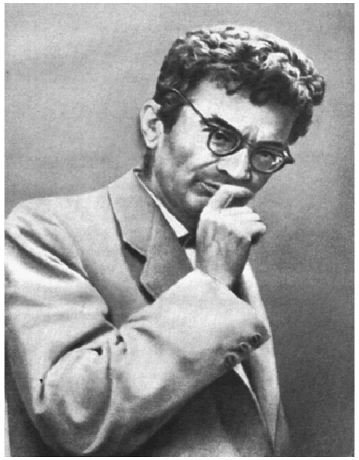
- Third international Theoretical Physics Conference (1934)
- Revision of the system of teaching the course of physics

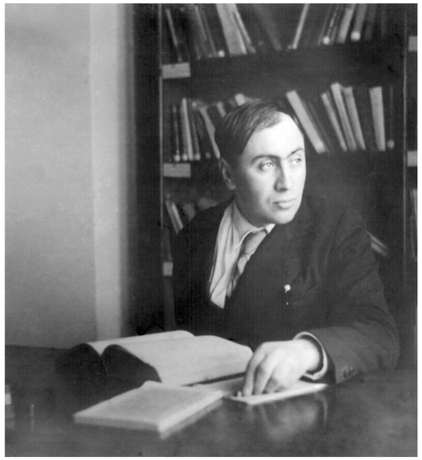
School of Landau (UPhTI -1934)


A.Kompaneetz


E.Lifshitz


A.Akhiezer


I.Pomeranchuk


L.Pyatigorskii


L.Tisza

E.Teller recommended him
to work in Kharkov

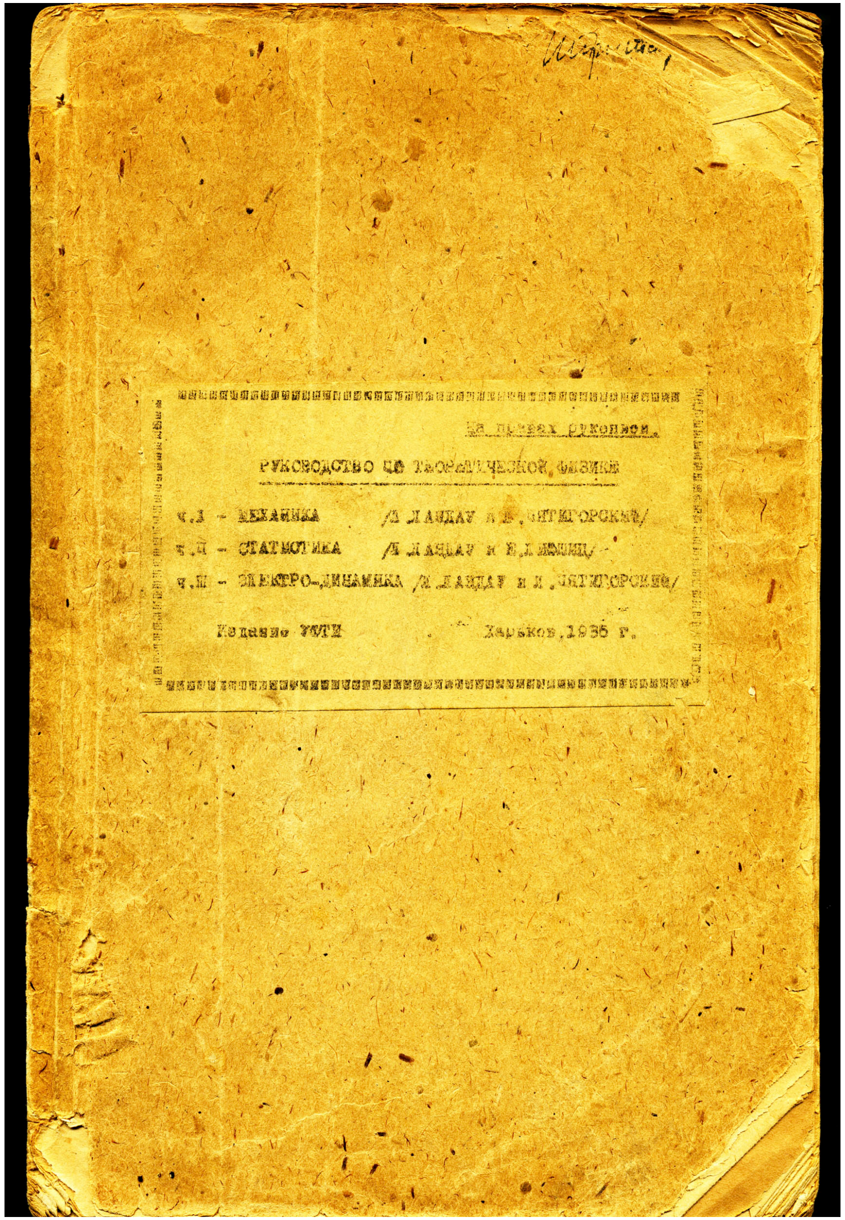
Kharkov, UPhTI (1930’s)

P.Dirac – member of the scientific council of UPhTI
P.Kapitza, G.Gamov, P.Erenfest – scientific consultants of UPhTI
F.Hautermans – staff of UPhTI (30-е годы)
W.Weisskopf – staff of UPhTI (1933-1934)

«I could not get a job in England, neither in France. 1933 I leaved… for Kharkov, where it was possible to get a job, which provided me with means of subsistence.».

W.Weisskopf

N.Bohr, R.Peierls, V.Fock, B.Podolskii, Yu.Rumer,… .
also came to Kharkov and worked in UPhTI for a long time



Course of theoretical physics. Kharkov, 1935

III International Conference on theoretical Physics

(Kharkov, 1934)

«Осторожно, кусается!»
(Be careful, bites!)

L.Landau and N.Bohr

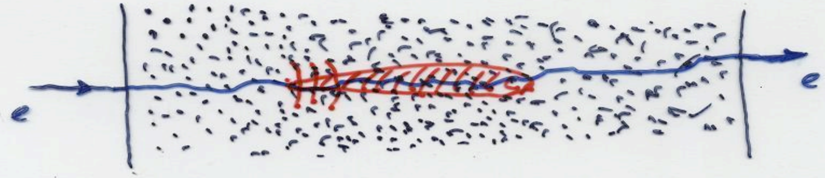
Thick books are a cemetery where ideas of the past which had served their time are buried

L.Landau

(Господи, прости им, не ведают, что творят)
«God, absolve them ‘cause they know not what they do

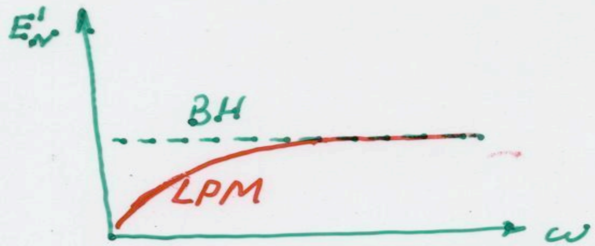
L.Landau

LPM – effect (1953)



$$\frac{dE^{(N)}_{BH}}{d\omega} = N\,\frac{dE^{(1)}}{d\omega}$$

Landau – Pomeranchuk 1953



Discussion: E.Feinberg and M.Ter- Mikaelian with L.Landau and I. Pomeranchuk (1952)

T. - M. – Interference radiation by ultrarelativistic electrons in crystals.

Landau – That is impossible because the interference effect is possible only for

$\lambda = \frac{\hbar}{p} \geq a$ **, but not for** $\lambda \ll a$

The discussion was stopped.

Coherent length (Ter-Mikaelian, 1953)

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

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

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

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

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

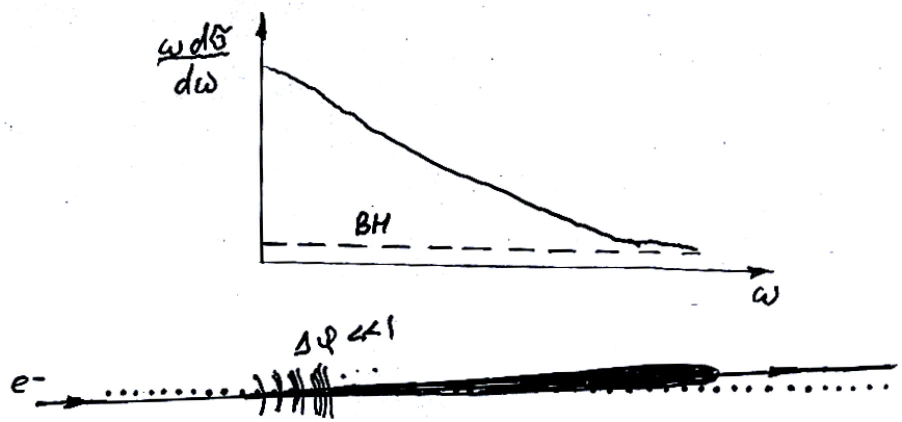
$$r_{\perp eff} \approx {1}/{q_{\perp eff}} \approx R$$

$$\varepsilon = 100 Mev \quad \omega = 100 kev \quad l_c \approx 10^{-4} cm$$

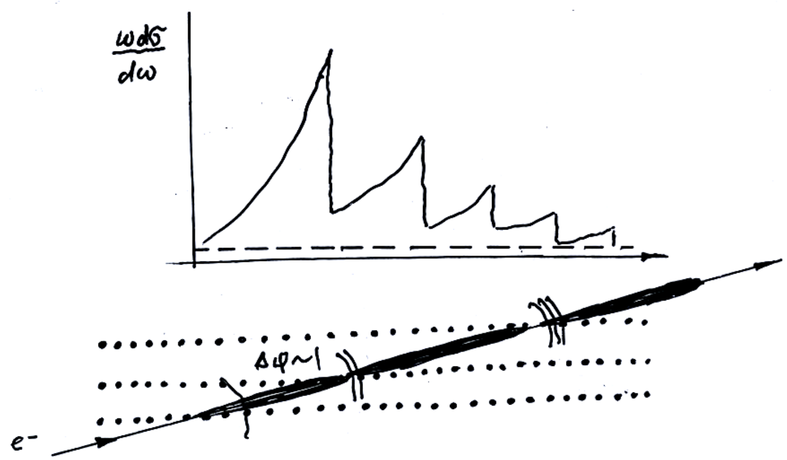
$$\varepsilon = 100 Mev \quad \lambda \approx 1 cm \quad l_c \approx 10^3 m!!!$$

Coherent length

(Ter-Mikaelian 1953 – crystal, Landau-Pomeranchuk 1953 – amorphous media)



Coherent effect



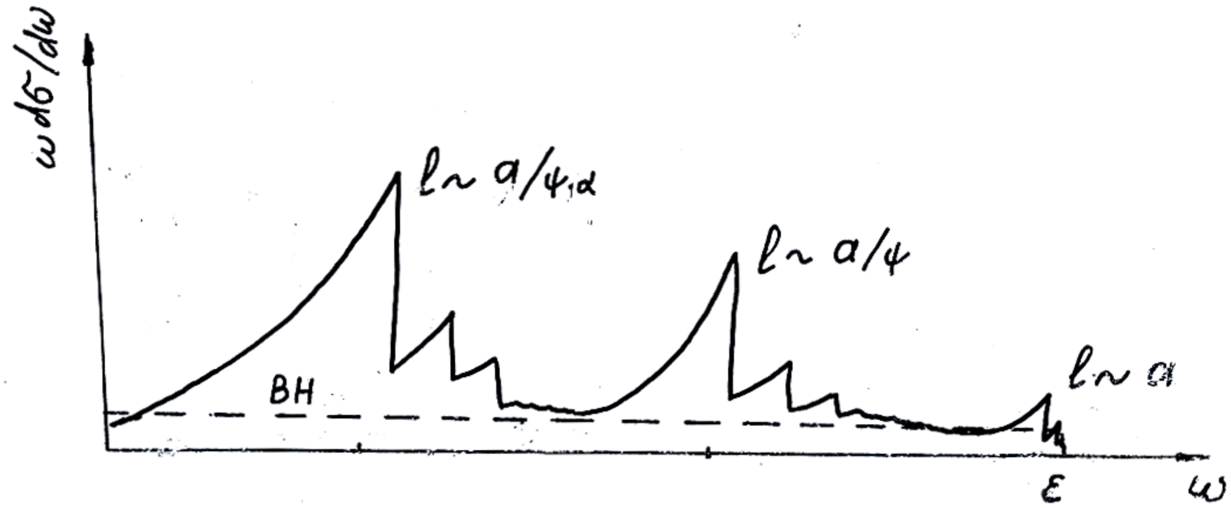
Coherence + Interference

Landau was agreed that Ter-Mikaelian's results were correct, but he said that it is needed to use another way for describing this effect

Coherent Bremsstrahlung Theory

(Ferretti 1950, Ter-Mikaelian 1952, Überall 1956, 1960)

$$d\sigma_{atom} \sim \cdots \int d^3q \cdots \longrightarrow d\sigma_{crystal} \sim \cdots \sum_{\vec{g}} \cdots$$



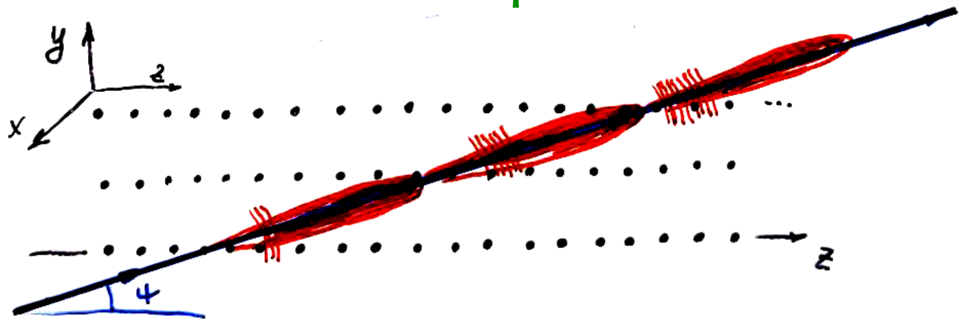
Akhiezer, Shul'ga 1982

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

CB – type B

$$g_z = \frac{2\pi}{a} = \frac{\omega m^2}{2\varepsilon\varepsilon'}$$

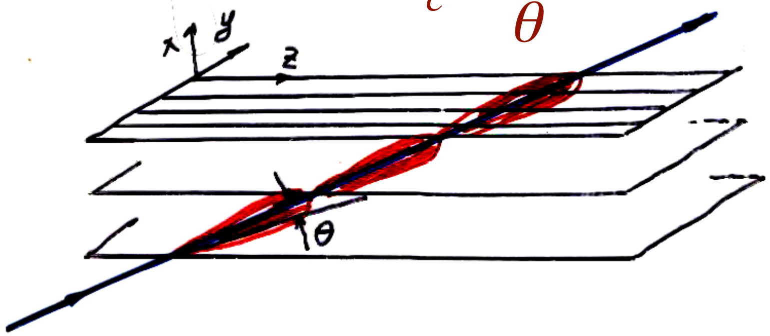
$$l_c = \frac{a}{\psi}$$



CB – row effect

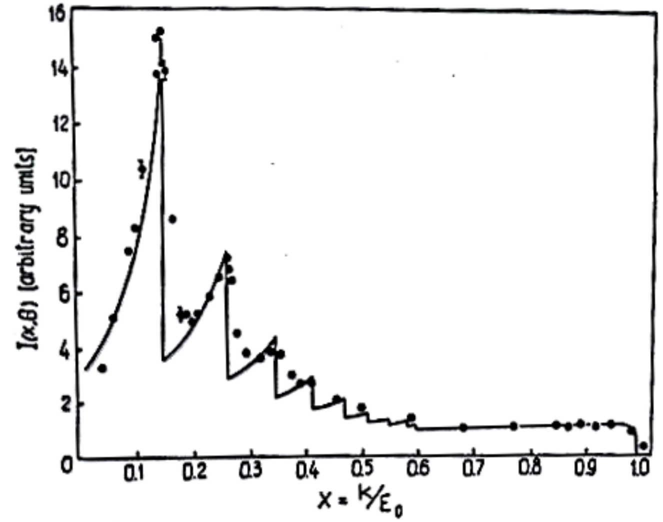
$$\psi\frac{2\pi}{a} = \frac{\omega m^2}{2\varepsilon\varepsilon'}$$

$$l_c = \frac{a}{\theta}$$



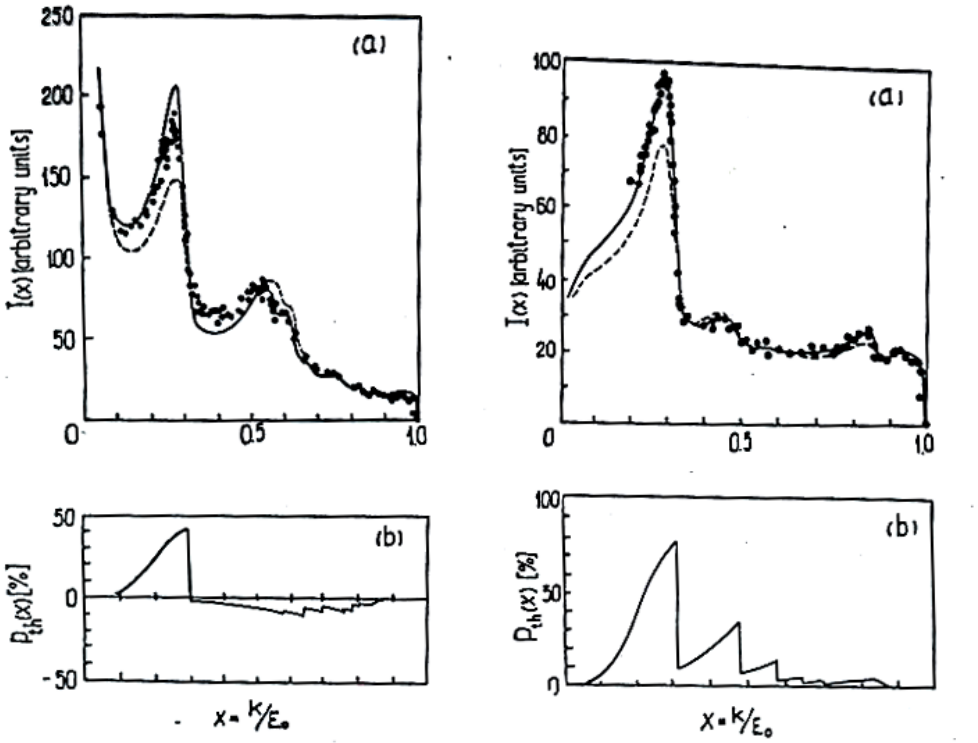
CB – point effect

$$\theta\frac{2\pi}{a} = \frac{\omega m^2}{2\varepsilon\varepsilon'}$$



Frascati

ε=1GeV, θ =4,6 mrad



DESY

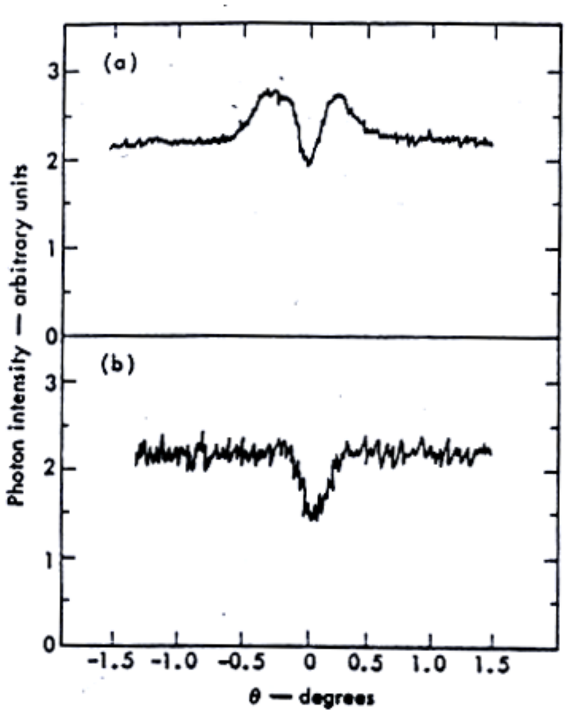
ε=4,8 GeV, θ =3,4 mrad

Problems of CB theory

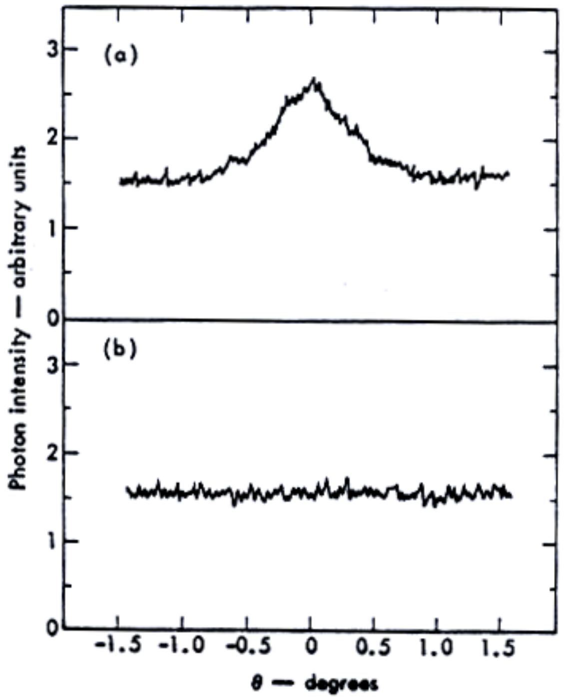
- e^+e^- - dependence
- second and higher Born approximations are increased quickly
- The validity conditions of F – T - Ü method
- Ter-Mikaelian - Überall methods
- $dE/d\omega \rightarrow \infty$ for $\psi \rightarrow 0$ at $\omega \simeq \omega_{max}$

Channeling and Coherent Bremsstrahlung for relativistic positrons and electrons

(USA Lawrence lab, Livermore lab, 1970)



positrons



electrons

$$\varepsilon = 28 MeV, \qquad Si - \langle 110 \rangle, \qquad L = 53 \mu m$$

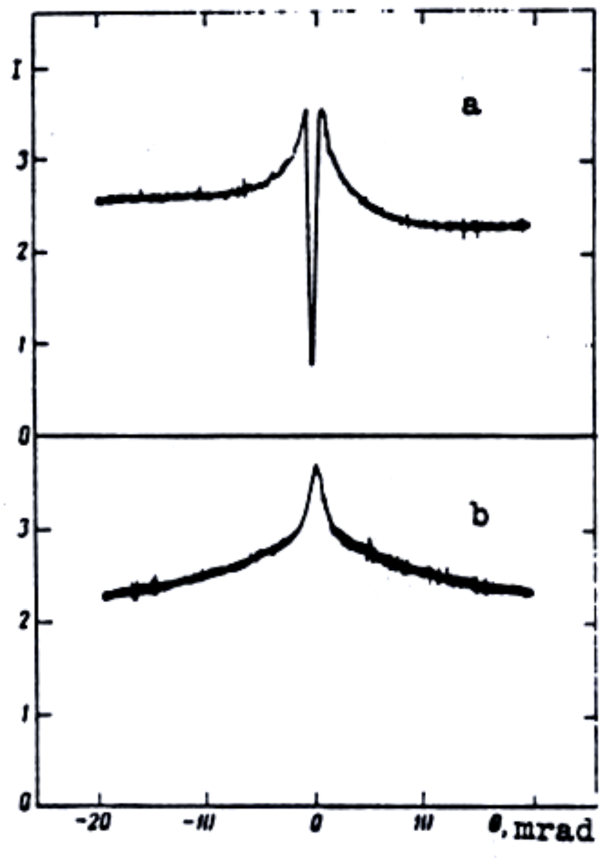
Channeling and Coherent Bremsstrahlung and Scattering for 1 GeV positrons and electrons

(Ukraine, Kharkov, 1972)

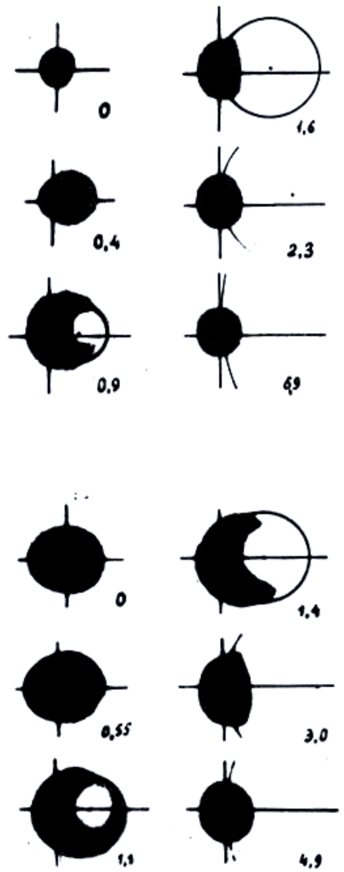
Orientation dependence of the radiation intensity

e^+

e^-



Angular distribution of scattering

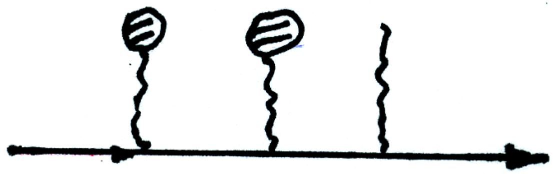


e^+

e^-

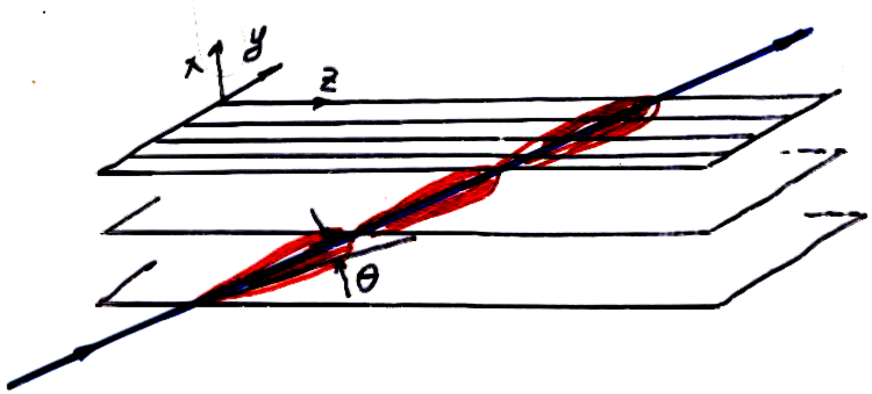
Second Born approximation in CB theory

A.Akhiezer, P.Fomin, N.Shul'ga (1970)



$$d\sigma_c = d\sigma_{coh}^{Born} \cdot \left(1 \pm \eta \frac{\theta_c^{\,2}}{\theta^2}\right), \qquad \hbar\omega \ll \varepsilon$$

$\eta \sim 1$ $\qquad \theta_c$ – *crytical channelling angle*



Higher Born Approximation in the CB Theory

A.Akhiezer, N.Shul'ga (1975)

$$N_{coh} \sim \min\left(\frac{l_{coh}}{a}, \quad \frac{R}{\psi_a}\right)$$

$$\frac{Ze^2}{\hbar c} \ll 1 \quad \rightarrow \quad N_{coh}\frac{Ze^2}{\hbar c} \sim \frac{R}{\psi a}\frac{Ze^2}{\hbar c} \ll 1$$

Quickly destroys for $\psi \rightarrow 0$

PARADOX

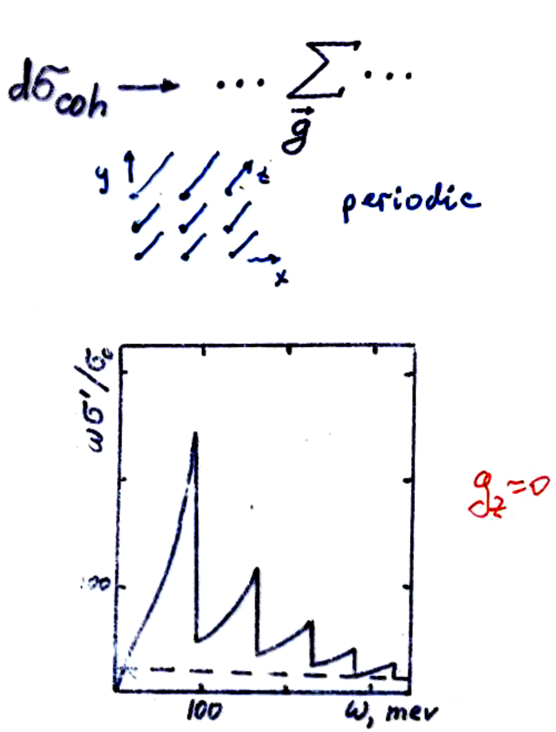
This condition did not fulfill practically for experiments (1960-1970) on verification of F – T – Ü theoretical results.

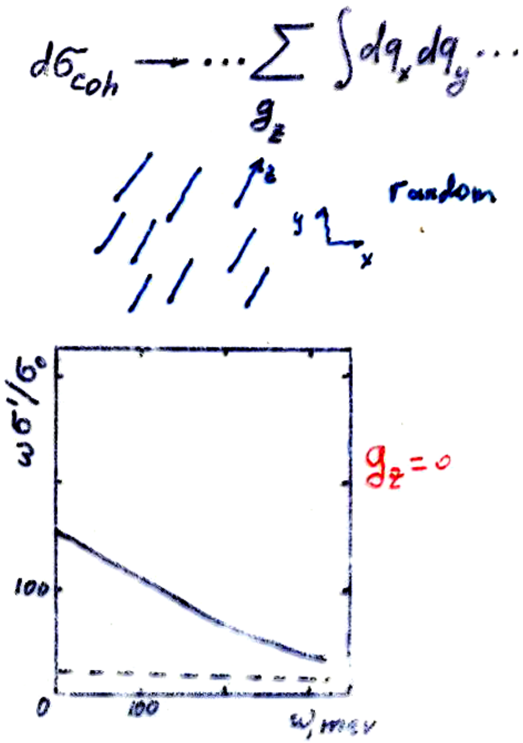
But the experiments were in good agreement with this theory !!!
Why ???

Problem

M. Ter-Mikaelian – 1952
H. Überall – 1960

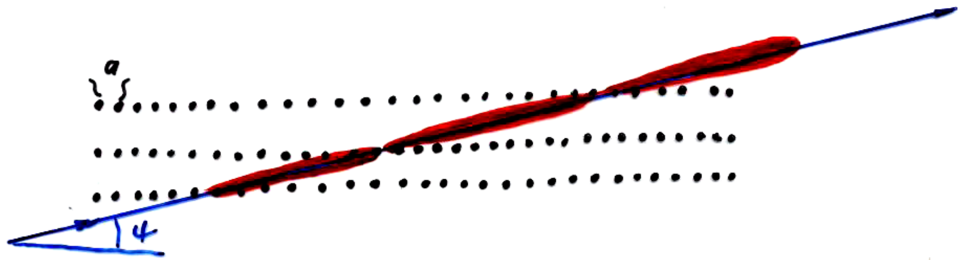
H. Überall – 1956





$\varepsilon = 1\,GeV$, $Si - \langle 100 \rangle$, $\psi = 2\,mrad$

Eikonal, Semiclassical, Classical CB Theory



Semiclassical approximation

$$\boxed{\frac{N_c Z e^2}{\hbar c} = \frac{R}{\psi a}\frac{Ze^2}{\hbar c} \gg 1}$$

!!!

Classical Electrodynamics

$$N_c \frac{Ze^2}{\hbar c} \gg 1, \quad \hbar\omega \ll \varepsilon$$

$$d\sigma^{(WKB)} = d\sigma\left\{\vec{r}_{cl}(t)\right\}$$

- Radiation is determined by the classical trajectory !!!
- It is necessary to know the types of particles' motion in crystal
- Same methods for description of CB and LPM effects !!!

Semiclassical Theory of CB in Crystals
A.Akhiezer, N.Shul'ga (1982)

$$d\sigma_{coh}^{(WKB)} = d\sigma_{coh} \cdot \left(1 + O\left(\frac{\psi_c^2}{\psi^2}, \gamma\theta_{scatt}\right)\right)$$

1. Trajectory is close to rectilinear
2. Dipole approximation

1. $\psi \le \psi_c$ – Channeling and above - barrier motion

2. $\gamma\theta_{scatt} \gg 1$ + $\begin{cases} l_c \ll R/\psi & \text{synchrotron approx. (constant field approx.)} \\ l_c \gg R/\psi & \text{LPM - like effects} \end{cases}$

N.Shul'ga (1980)

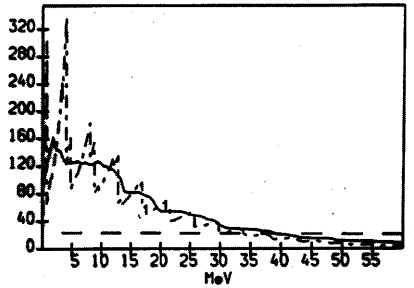
Semiclassical Theory: V.N. Baier et al. (1990)…

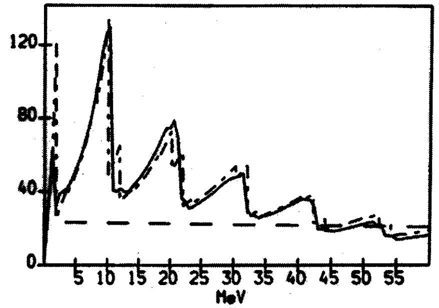
CB for real trajectories of electrons and positrons in crystals

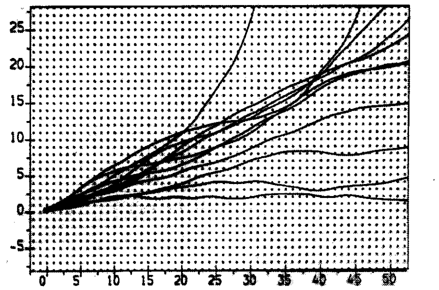
(V.Truten', N.Shul'ga, 1995 -…)

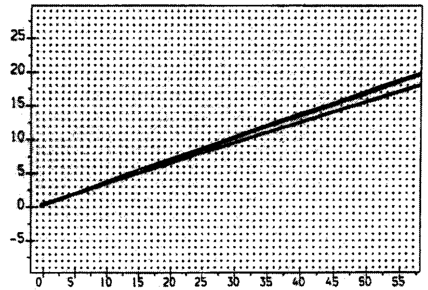
e^{-} $\psi = 2\psi_c$

e^{+} $\psi = 5\psi_c$



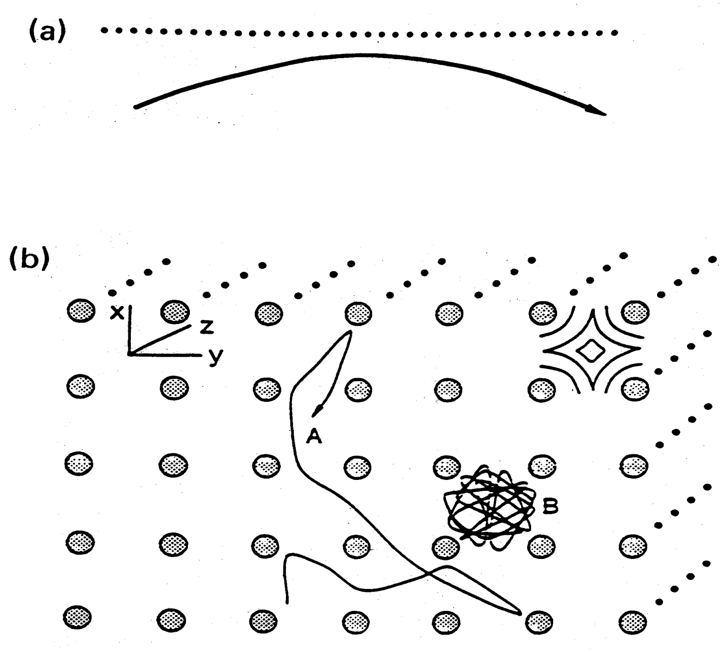


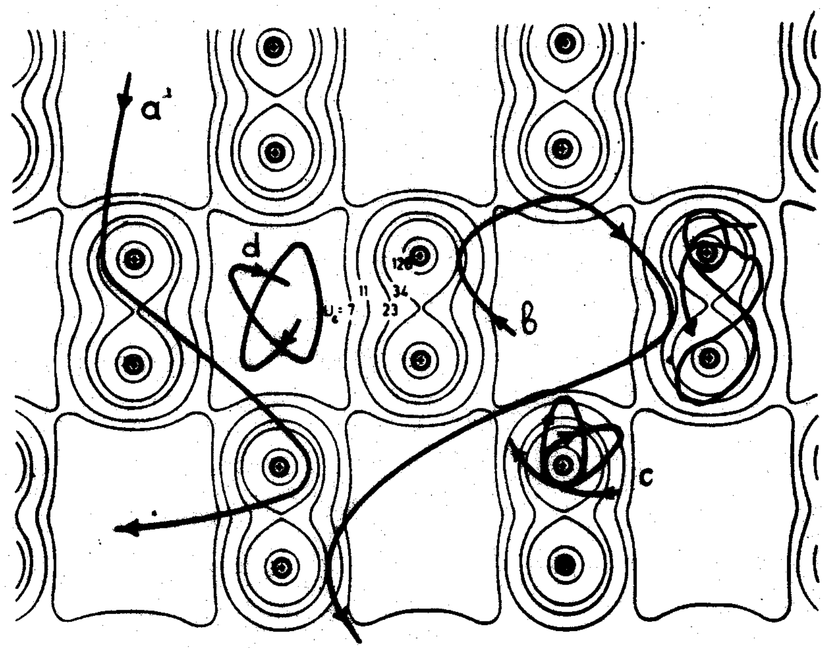


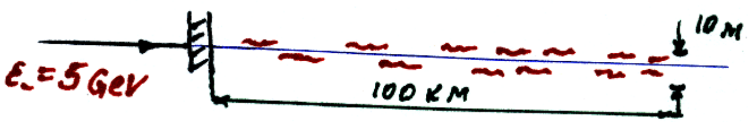


H.Überall

The motion along crystal axis



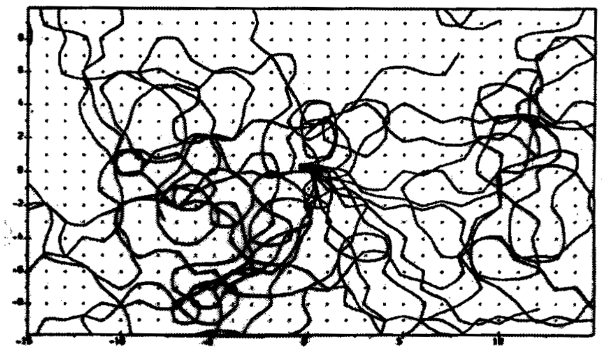




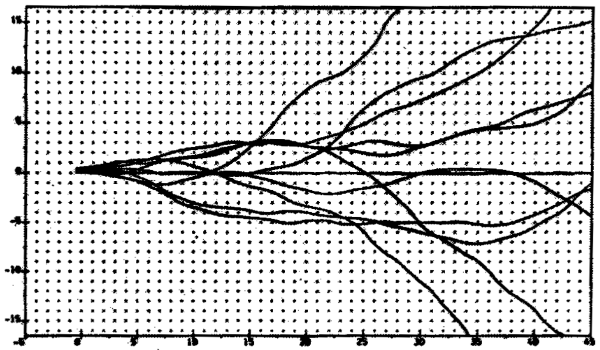
for thick crystals $\frac{I^{ch}_{\omega,\vartheta}}{I^{am}_{\omega,\vartheta}} \sim 25.000$

Dynamical chaos phenomenon
(Yu.Bolotin, V.Gonchar, N.Shul'ga 1985)

$\psi = 0{,}5\ \psi_c$

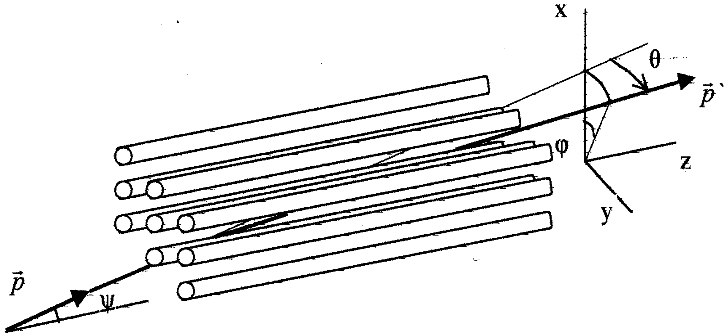


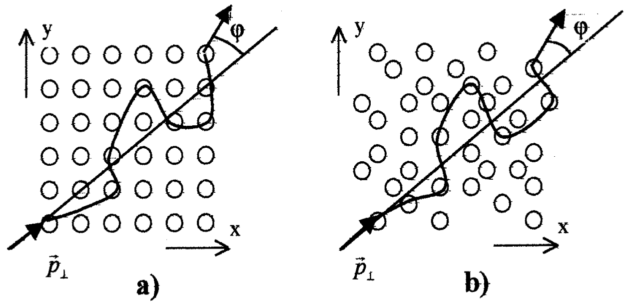
e^-



$\psi = 1{,}5\psi_c$

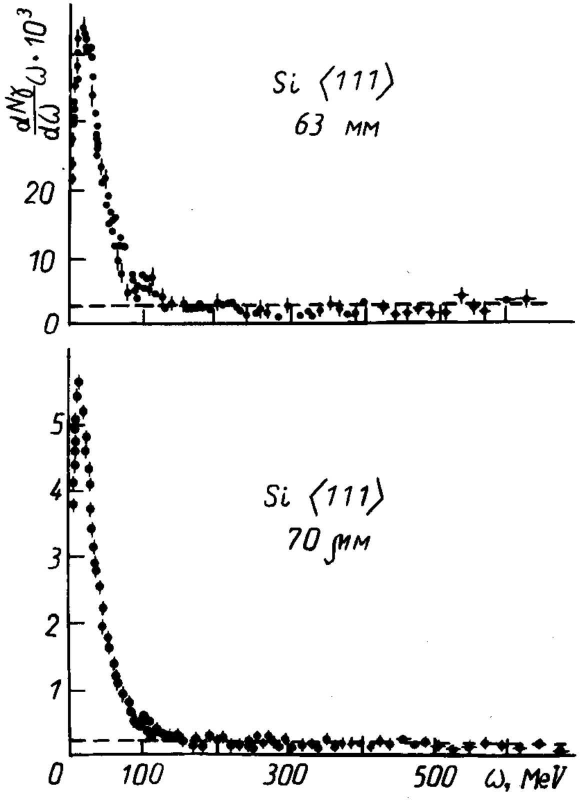
Dynamical chaos



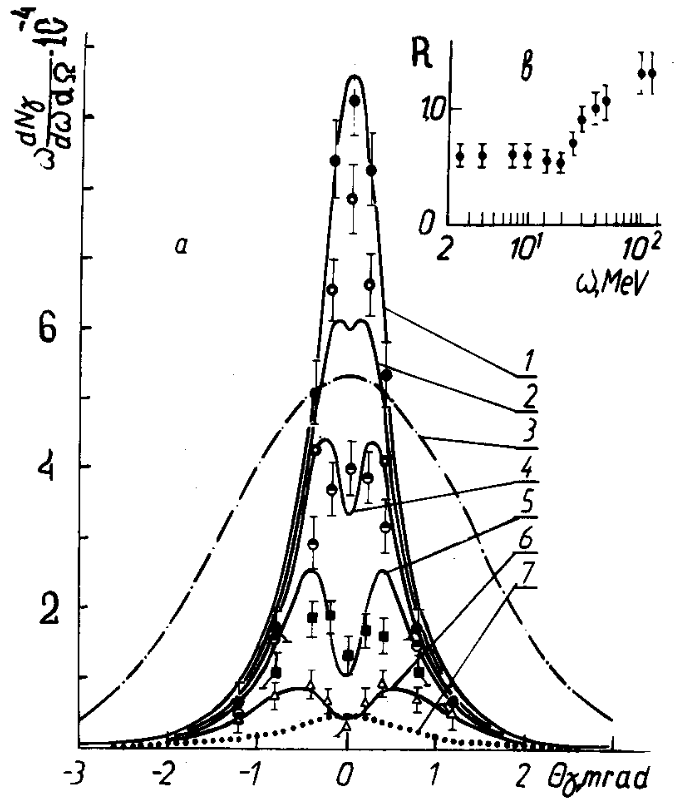


Multiple scattering

Theory (Dynamical Chaos Approx.) and Experiment for 1,2 GeV electrons Kharkov 1990 – … (Phys.Lett.A, 1991, v.158, 177)



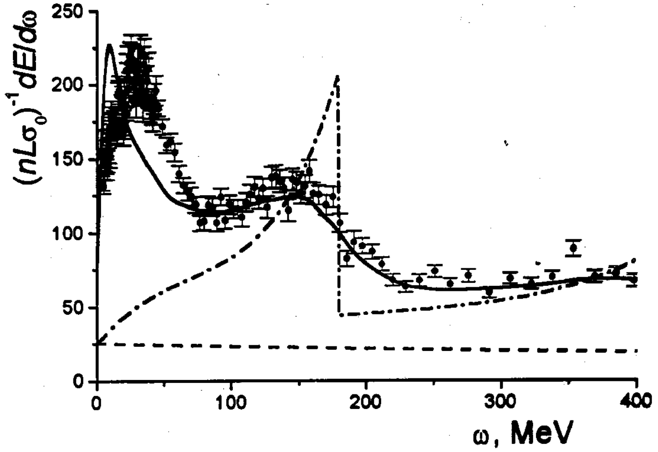
spectrum

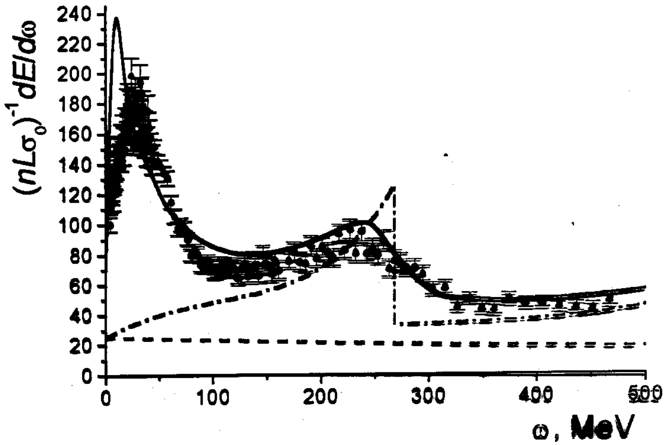


spectral-angular

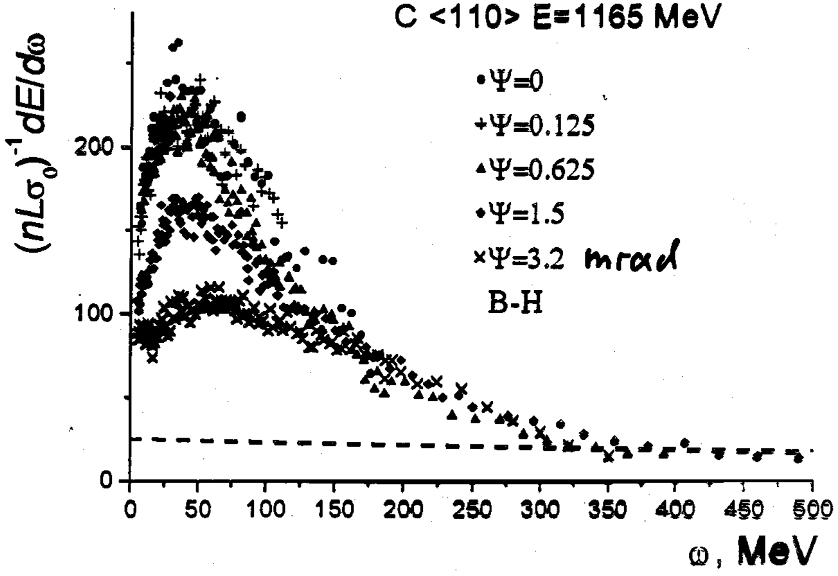
Theory (real particles' trajectories) – experiment.
Kharkov 1990 – …

$L = 300\mu$



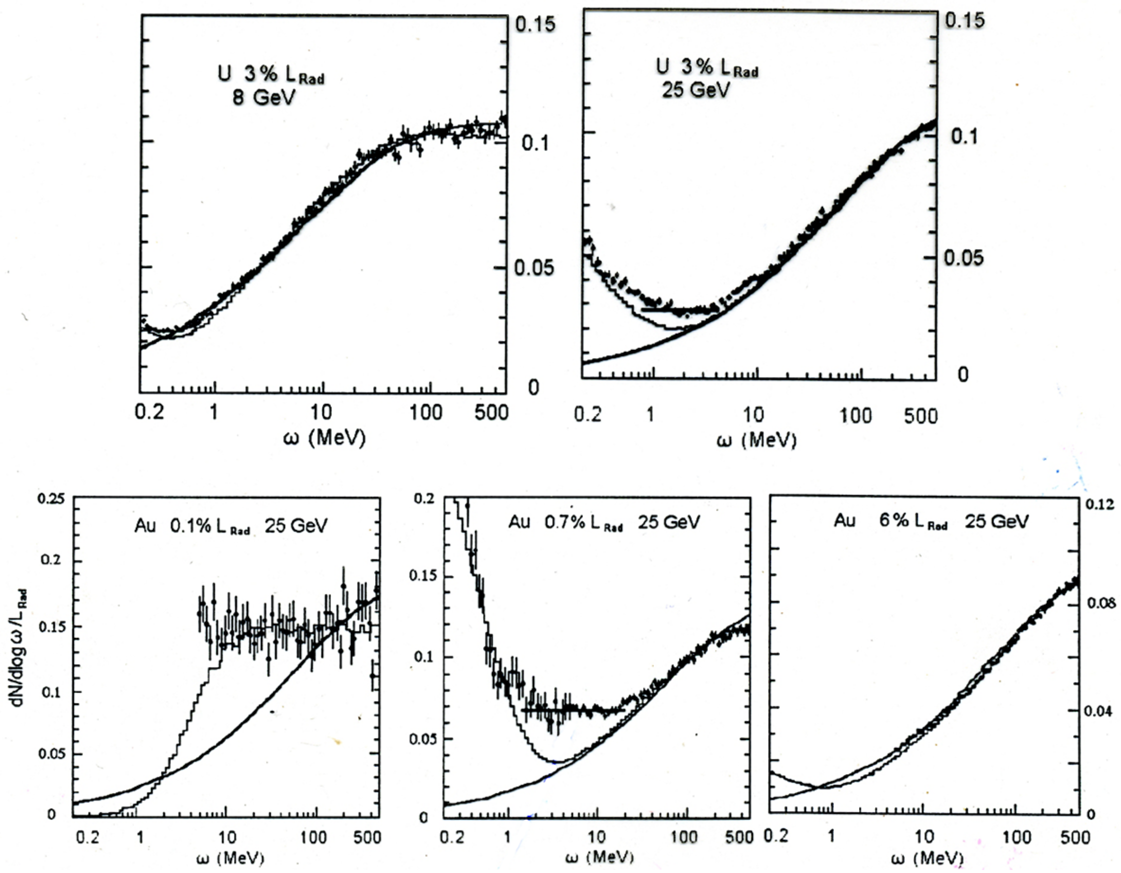


$L = 2cm$

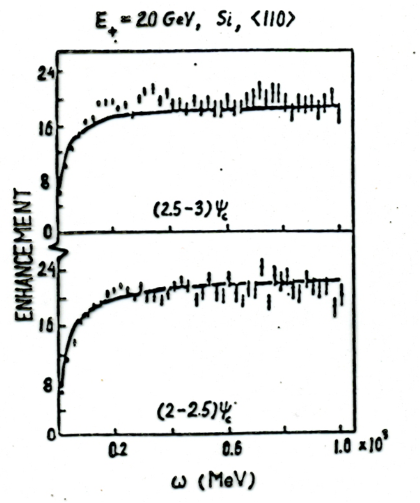


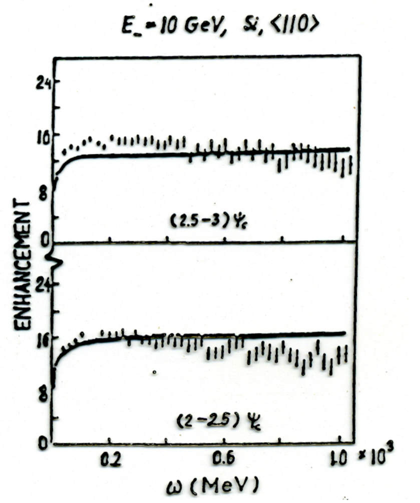
$\varepsilon_- = 1,2GeV$, diamond $\langle 110 \rangle$

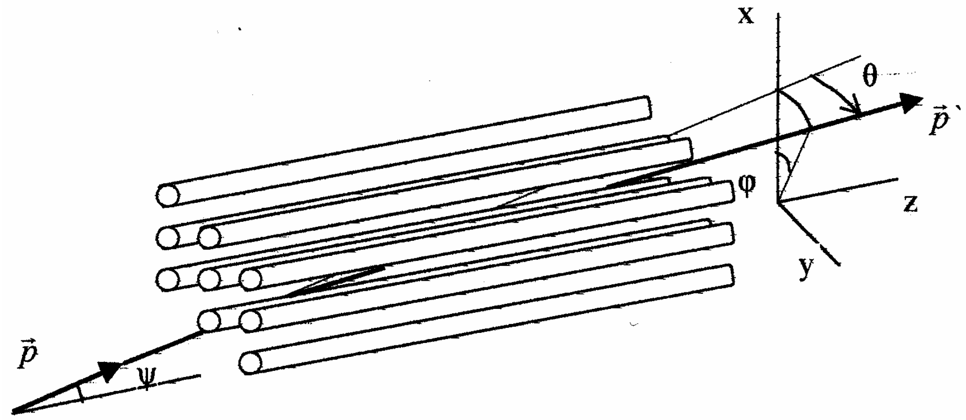
LPM-effect
Effect which was confirmed after 40 years!
SLAC experiment – 1995



Influence of Multiple Scattering on CB in Crystals
Analogue of LPM-effect

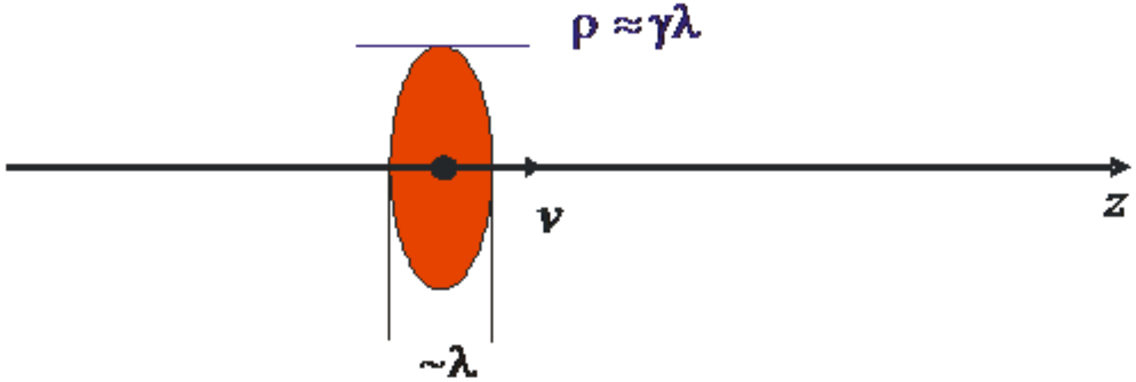






Experiment - J.Bak et al. Nucl.Phys. 1998
Theory – N. Laskin, N.Shul'ga, Phys.Lett.A, 1989

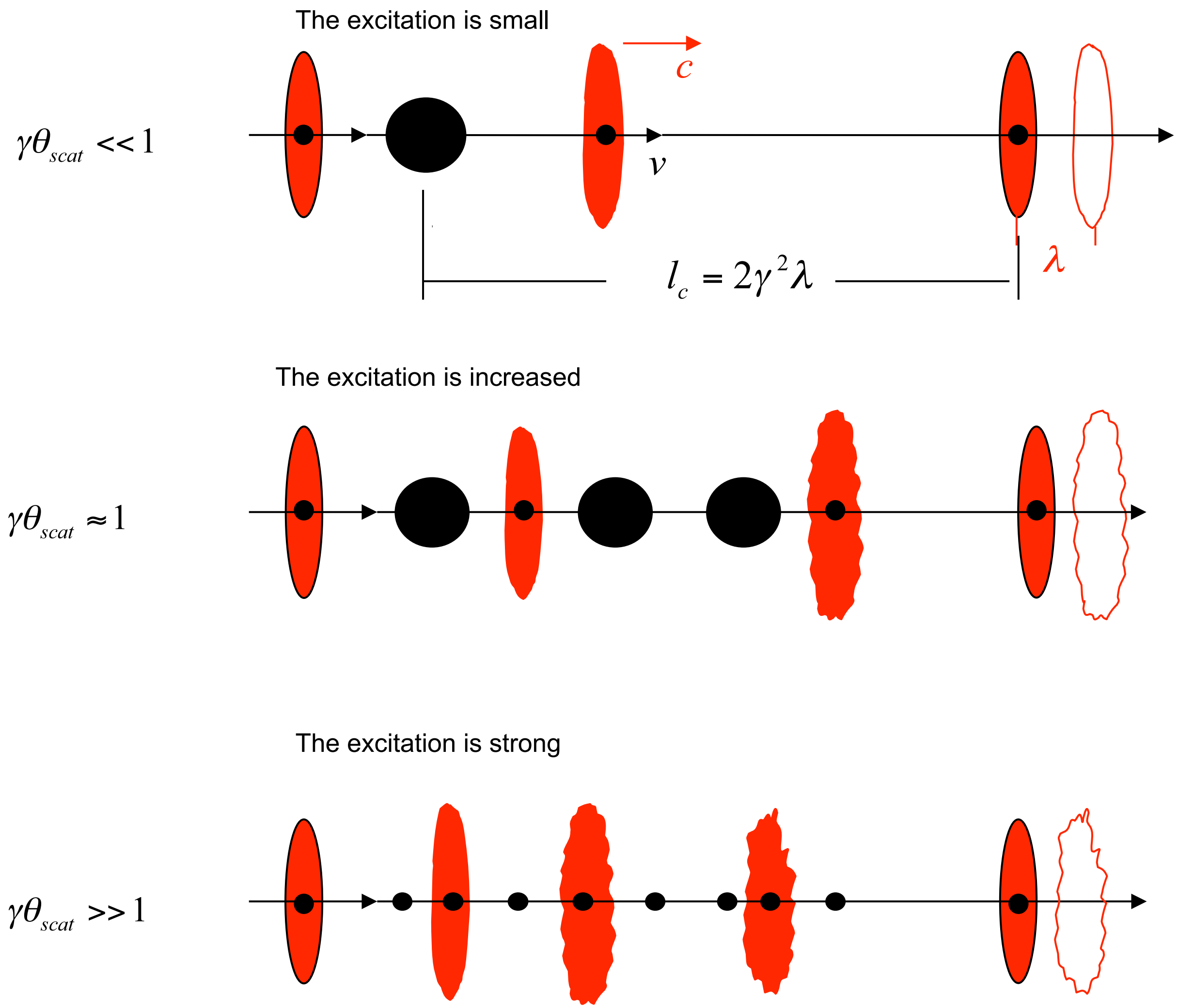
Relativistic Electron Field Potential



$$c_{\vec{k}} = e^{-ik_z vt} \int d^3 r e^{i\vec{k}\vec{r}} \frac{e}{\sqrt{z^2 + \rho^2 / \gamma^2}} =$$

$$= \frac{4\pi\gamma e}{k_\perp} e^{-ik_z vt} \int_0^\infty dz \cos k_z z e^{-\gamma k_\perp z} = 4\pi e \cdot e^{-ik_z vt} \int_0^\infty \rho \, d\rho \;\; J_0 \left(k_\perp \rho \right) K_0 \left(k_z \rho / \gamma \right)$$

How Does Electron Radiate?



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

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

$$l_c = 2\gamma^2\lambda$$

$$\varepsilon = 5GeV$$

$$l_c \sim 10^{-3}cm \quad for\ \omega \sim 1\ MeV$$

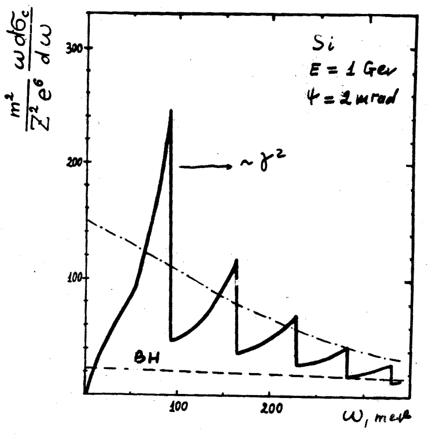
$$l_c \sim 1cm \quad for\ \omega \sim 1\ KeV$$

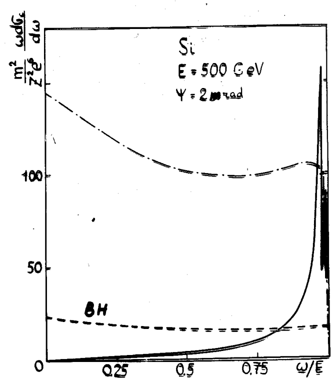
CB for High Energies

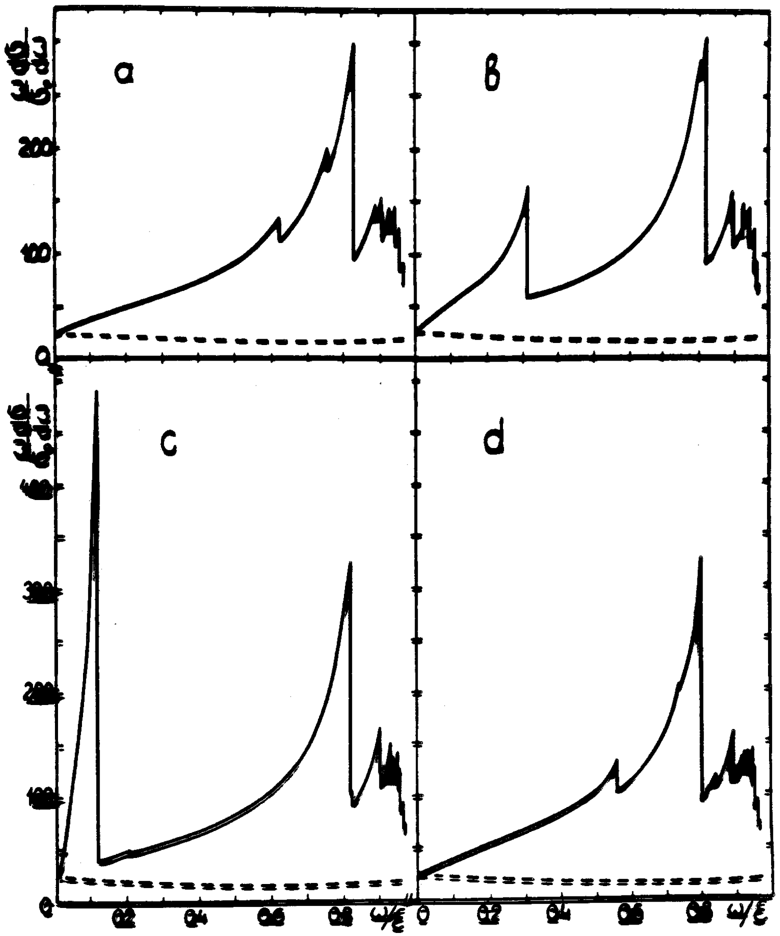
(N.Shul'ga, V.Truten', 1992)

fine structure of CB

CB



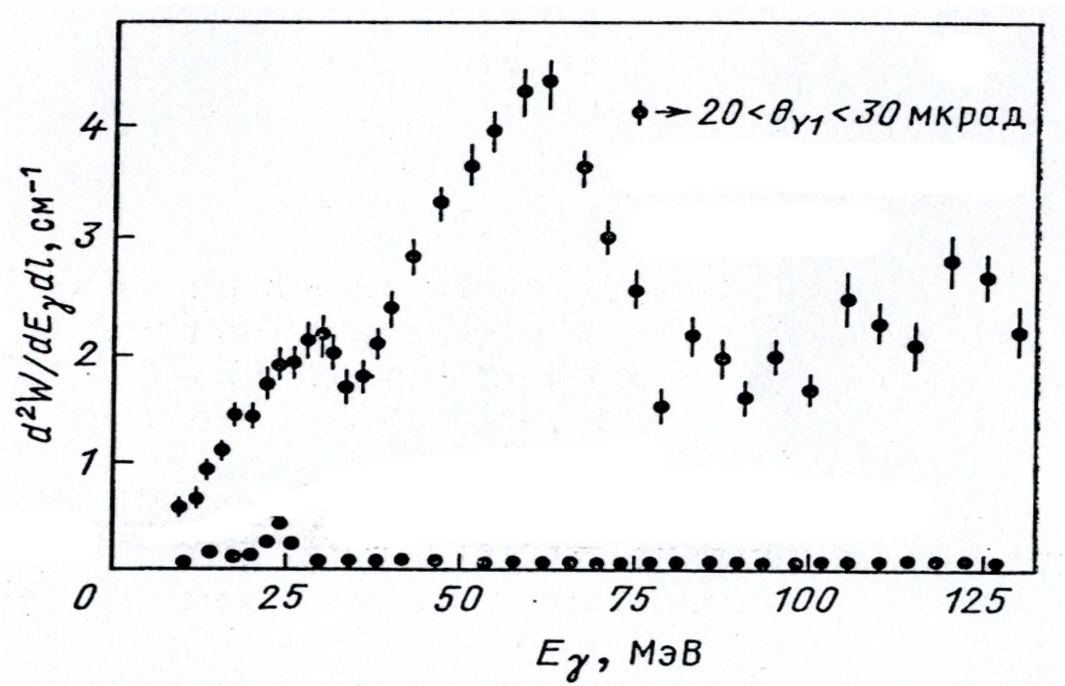




H.Bilokon et al. NIM, 1983

ε=150 GeV

IPHE experiment
E.Tsyganov et al, 1982



$$\varepsilon_+ = 10GeV, plane\ chanelling$$

CB for 150 MeV electrons
2008 Experiment at Max lab (Sweden)

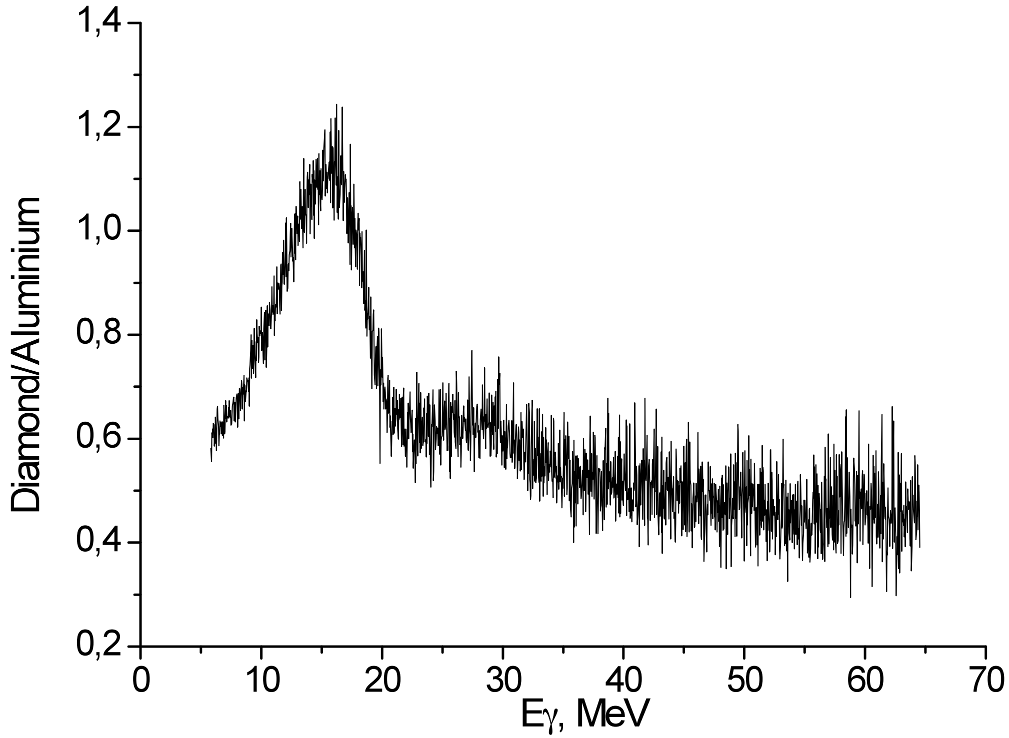
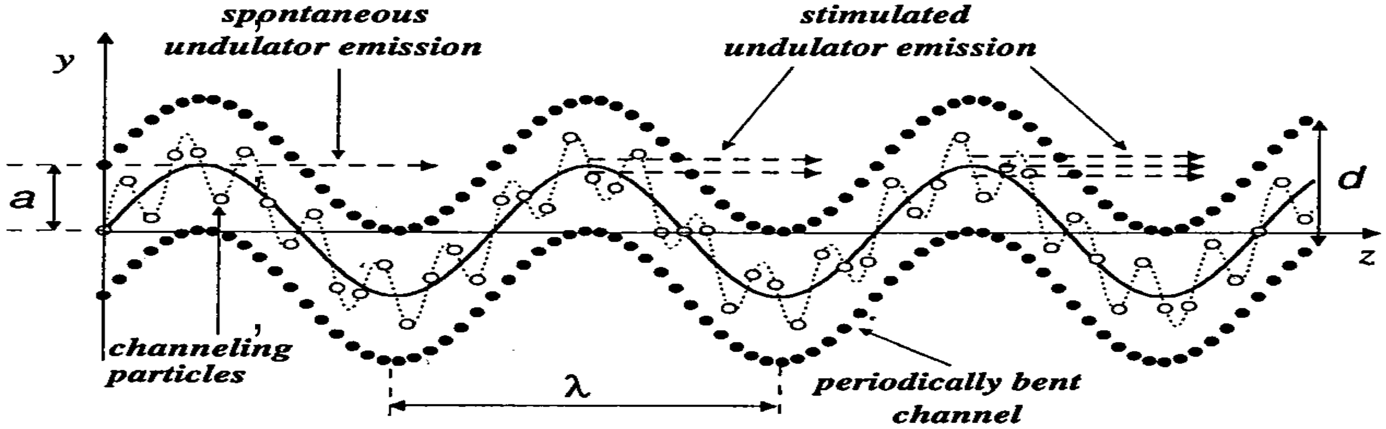
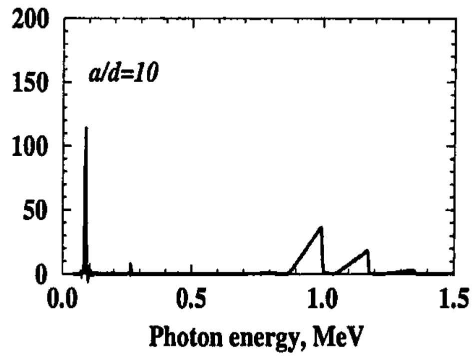


Fig.10. Spectra of the CB from a diamond crystal of thickness 0.1 mm normalized to the bremsstrahlung spectrum from amorphous Al target. Collimation angle $\theta c \sim 0.73 \gamma \theta$. Electron energy is 143.9 MeV.

Radiation in the Field of Periodically Deformed Crystal Planes of Atoms at the Channeling

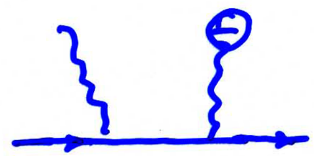


$$d << a << \lambda \qquad d \sim 10^{-8}\,cm \qquad a \sim 10..10^{2}\,d \qquad a \sim 10^{-5}..10^{-4}\,\lambda$$



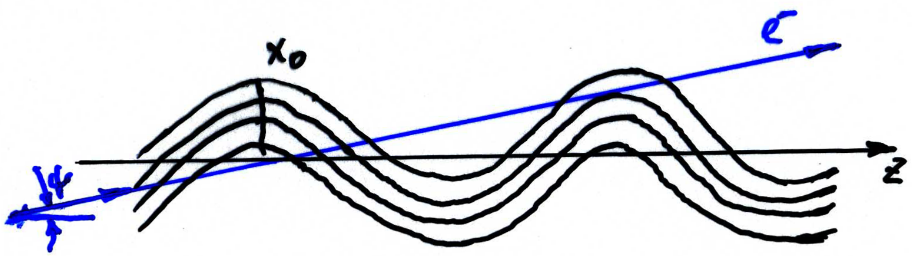
1.L.Sh.Grigoryan, A.R.Mkrtchyan, A.H.Mkrtchyan et al, Nucl. Instr. and Meth. in Physics Research B **173**, 132 (2001).
2.A.V.Korol, A.V.Solov`yov and W.Greiner, Int. J. Mod. Phys. E **13**, 867 (2004).

Coherent Radiation in Periodically Deformed Crystal Planes



$x_0 \sim a$

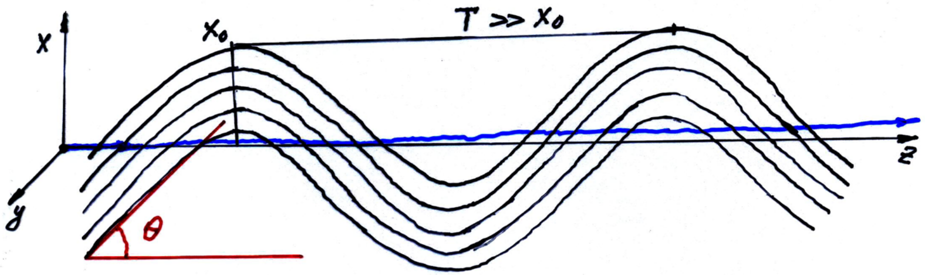
A.Saharian, A. Mkrtchyan
et al. (2004)

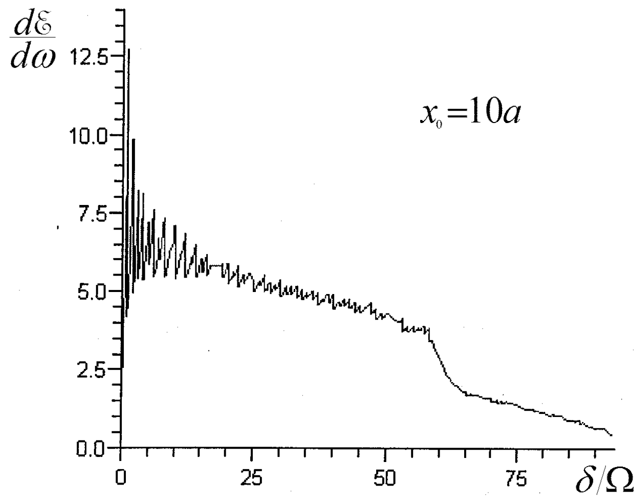


$x_0 >> a$

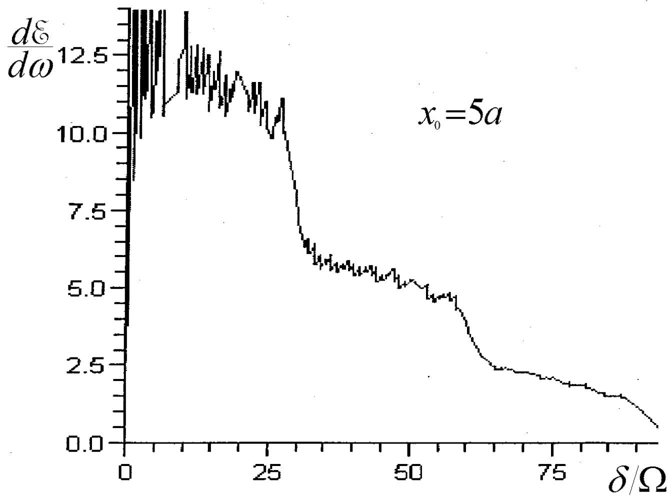
Born & Semiclassical Approx.
N.Shul'ga, V. Boyko JETP Lett, 2006

Coherent Radiation Spectrum by Relativistic Electrons in Periodically Bent Crystal Planes





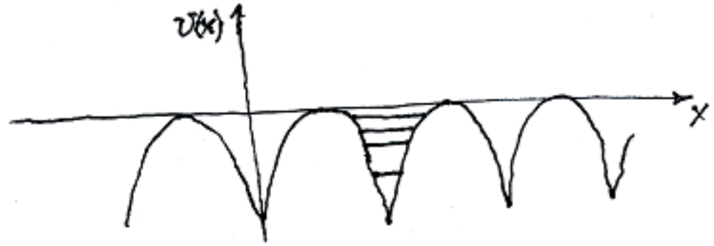
$$\frac{d\mathcal{E}_c}{d\omega} = N\frac{32\pi^2 Z^2 e^6}{a^3}\frac{\delta}{m^2}\sum_{\Omega n\geq\delta}\sum_{g_x}\frac{g_x^2 J_n^2(g_x x_0)}{\left(g_x^2+R^{-2}\right)^2}\frac{1}{(\Omega n)^2}\left\{1-2\frac{\delta}{\Omega n}\left(1-\frac{\delta}{\Omega n}\right)\right\}$$



N. Shul'ga, V. Boyko Phys. Lett, 2008

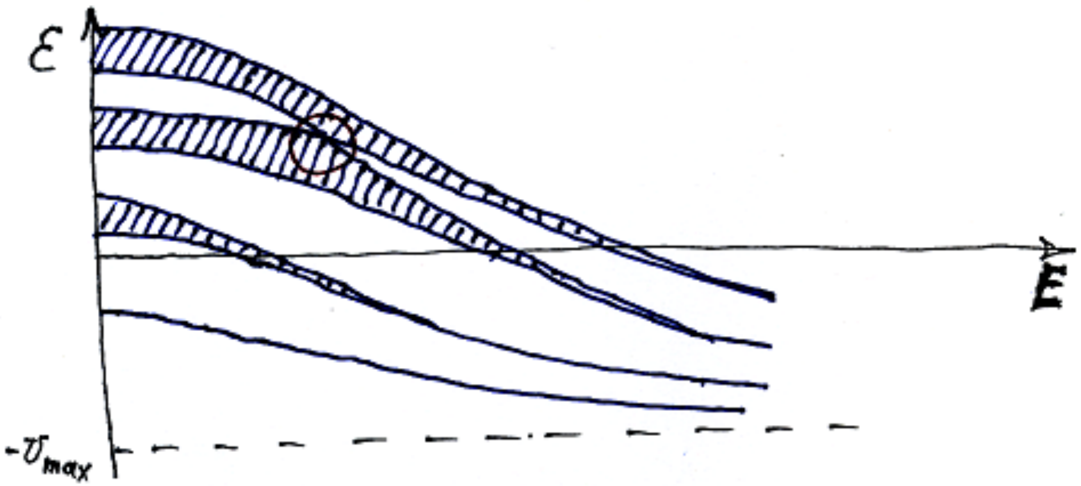
Energy levels at plane chanelling

$$\left[\frac{\hat{p}_x^2}{2E} + U(x) \right] \psi(x) = \varepsilon \psi(x)$$



ε_n from $\oint p(x)\,dx = 2\pi n \hbar$

$$n_{max} \sim \sqrt{E_{MeV}}$$



Conclusions