DESY-KIPT Seminar on the DFG project “Pilot Study of a Crystal-based Extraction for 6 GeV Electrons at DESY” in the memory of Nikolai Shul’ga

June 20, 2024, DESY, Hamburg

Development of the theory of high energy particle interaction with matter by Nikolai Shul’ga

Nikolai Fedorovich Shul’ga

15.09.1947 - 23.01.2024

1971: graduated from the School of Physics and Technology in Kharkiv State University

(Diploma with honors)

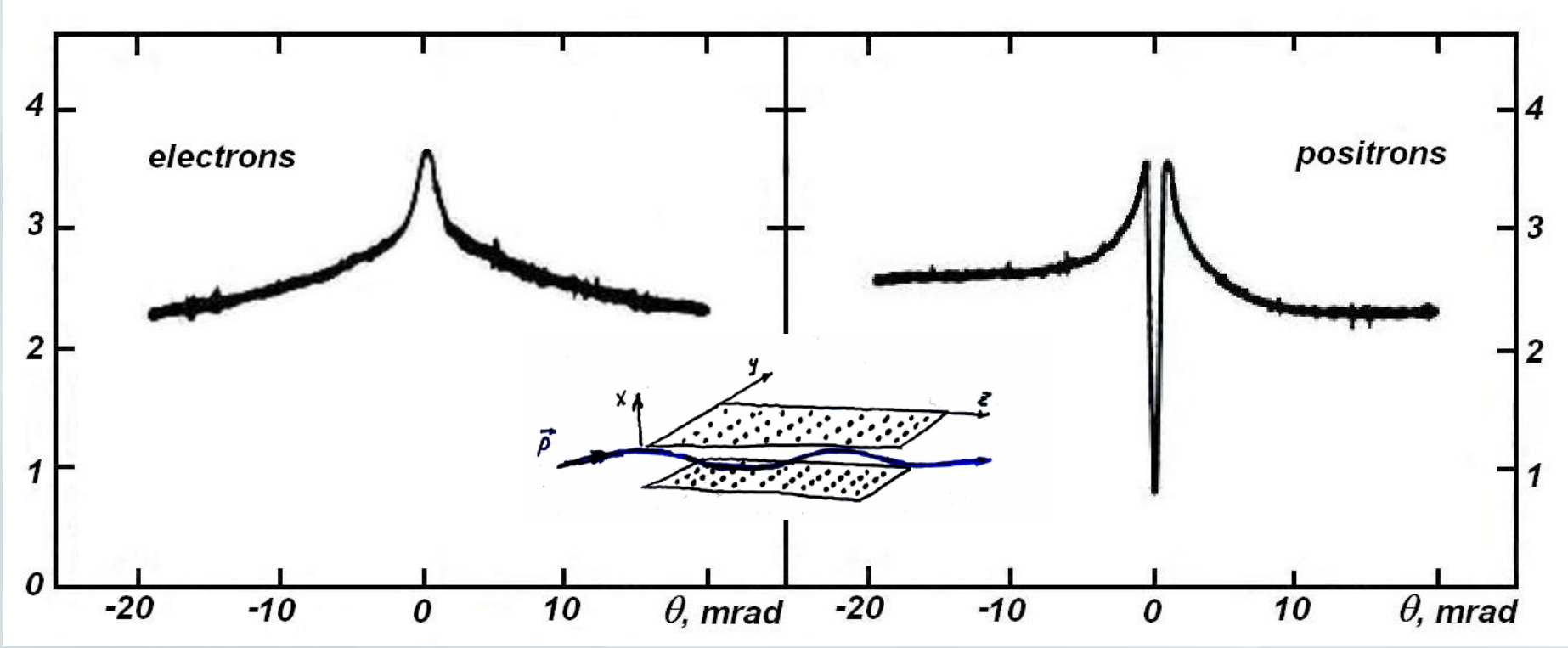
Theoretical Physics Group

Experimental discovery of relativistic positrons and electrons channeling phenomenon on the accelerator Electron Linac 2 GeV (KIPTI, 1968-1971)

Master thesis (1971) : Coherent bremsstrahlung of electrons and positrons of ultrarelativistic energy in crystals.

A.I.Akhiezer, P.I.Fomin, N.F.Shulga, JETP Letters, 1971, v.13, p.713.

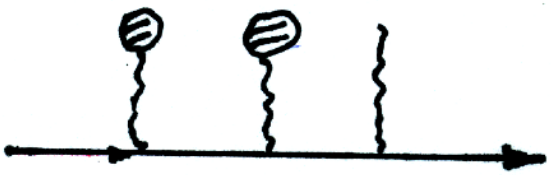
Experimental discovery of the phenomenon of channeling of relativistic electrons and positrons in a crystal at LUE-2 GeV (KIPT, 1968-1971)



I.A.Grishaev, V.L.Morokhovsky, V.I.Kasilov, G.D.Kovalenko, B.I.Shramenko et al. Ukrainian Physical Journal, 15 (1971) 1548; JETP Letters, 16 (1972) 162.

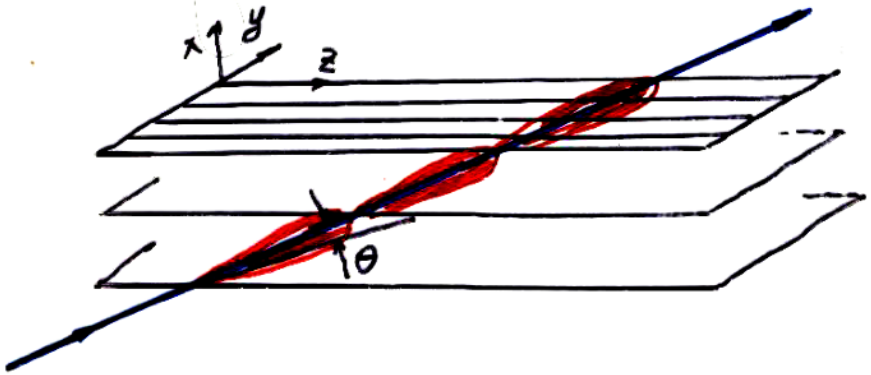
Second Born approximation in CB theory

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



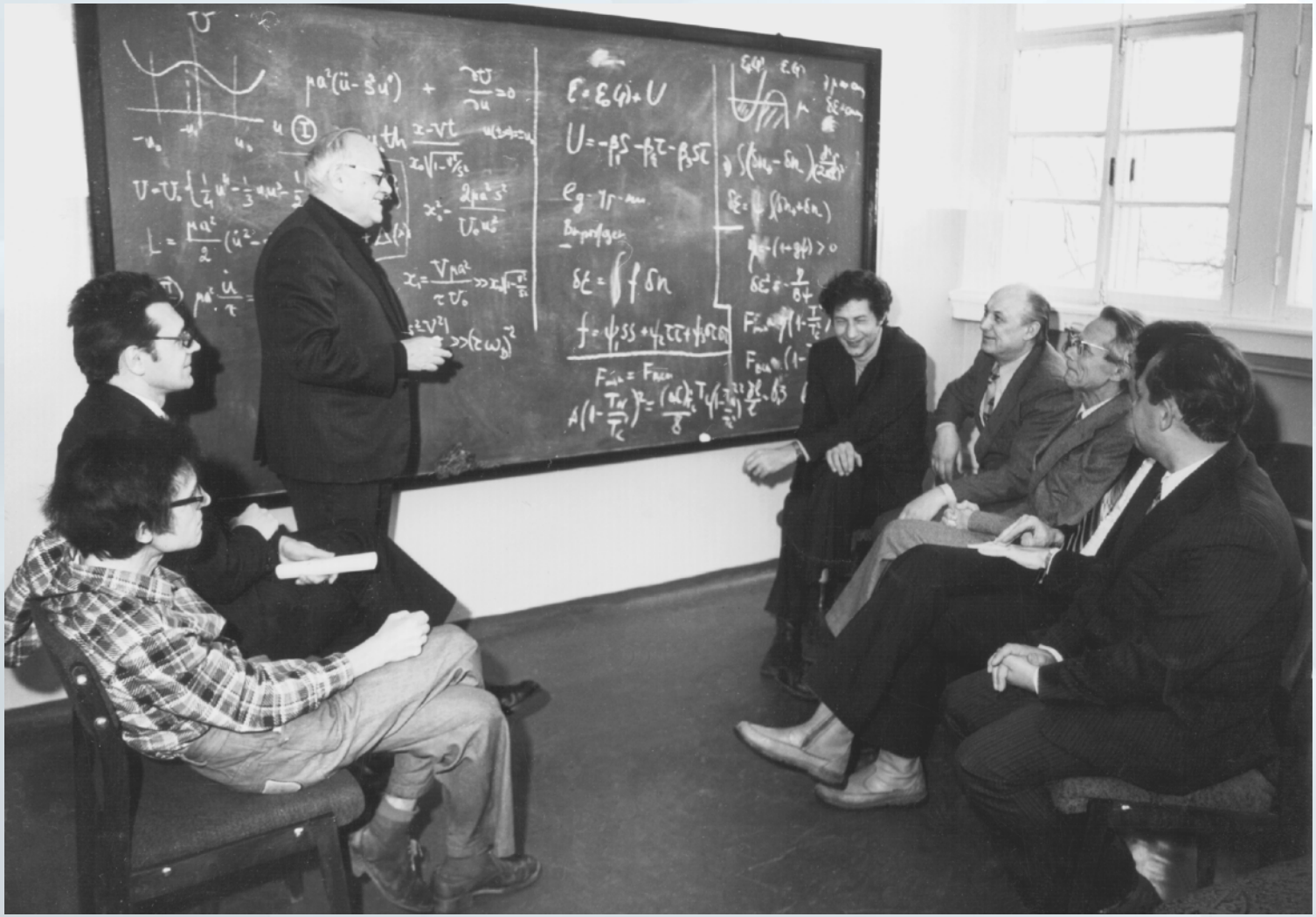
$$d\sigma_c = d\sigma_{coh}^{Born} \cdot \left(1 \pm \eta \frac{\theta_c^{\,2}}{\theta^2}\right),$$

η [?] θ_c – *crytical channelling angle*



1971-1973: Military service

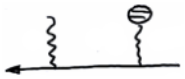
1973 - 2024 : Work at KIPT



At the seminar of A.I. Akhiezer

The main idea (1969)

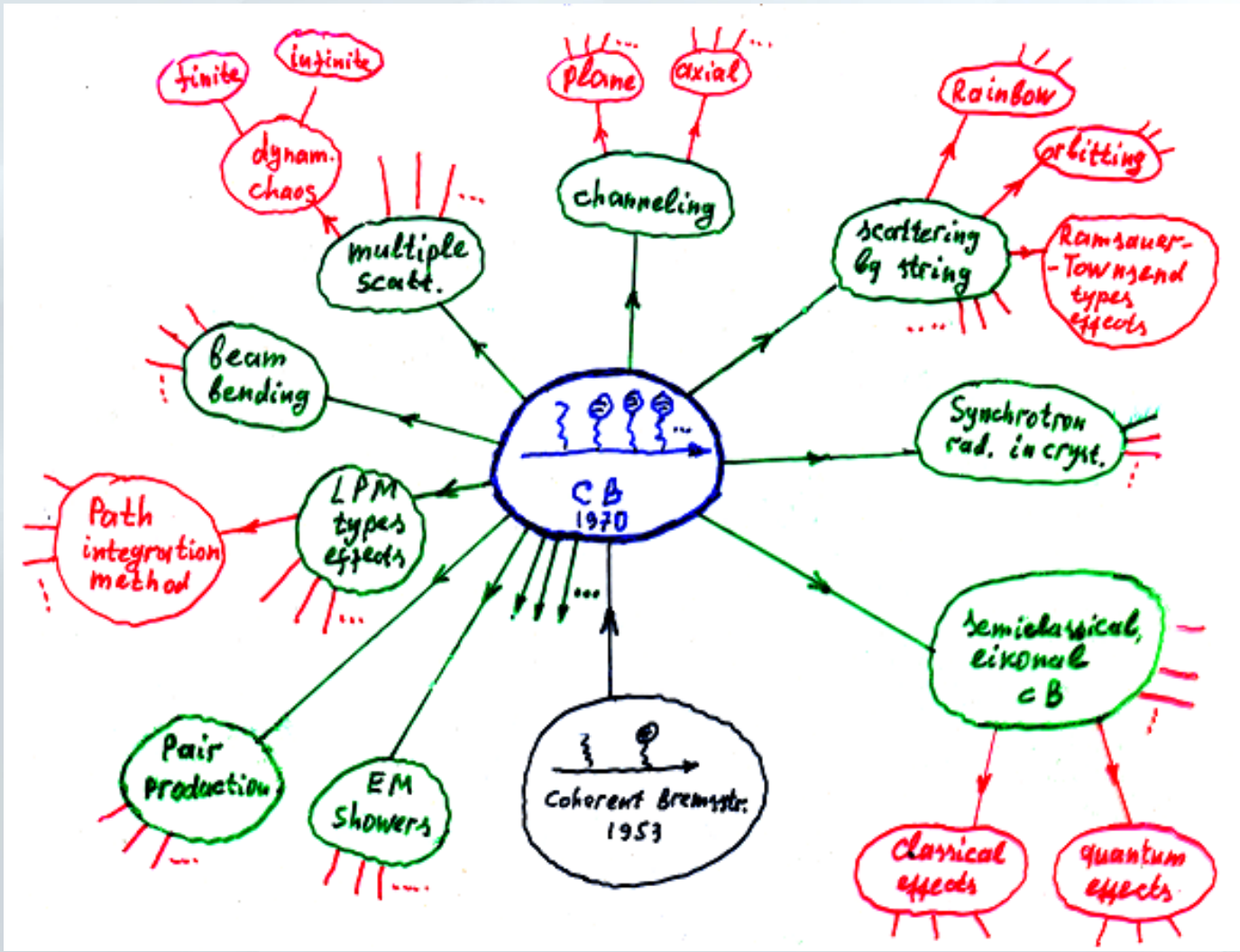
- For coherent bremsstrahlung



$$d\sigma_{coh} >> d\sigma_{BH}$$

- The idea: relative contribution of higher Born approximation can also be large!!!

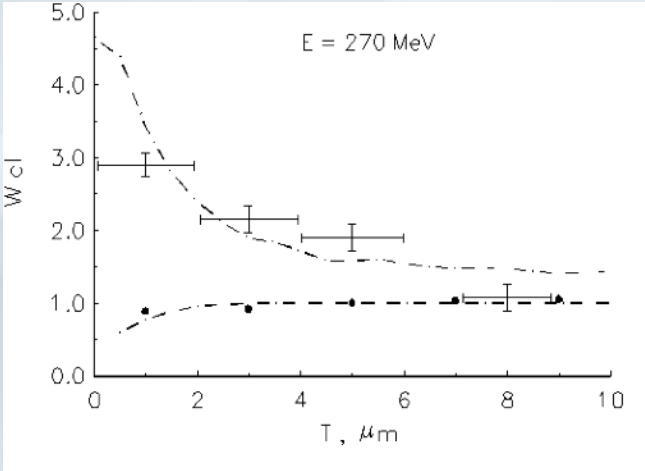
New directions in the theory of coherent effects in the interaction of fast charged particles with crystals

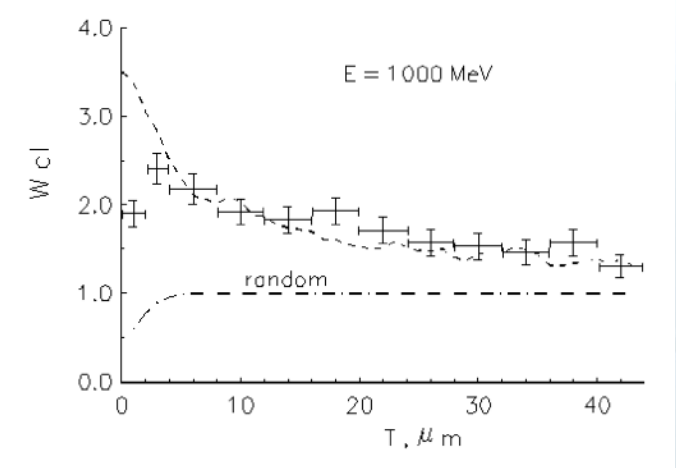


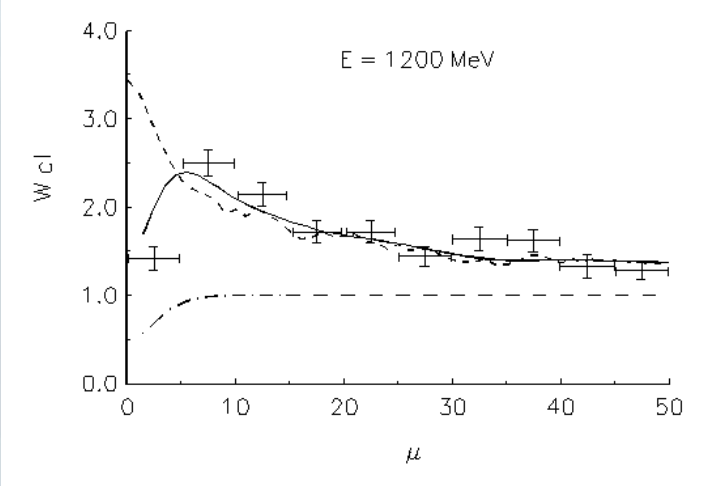
1986 – 1996: Нач. целевого отд. 32-00

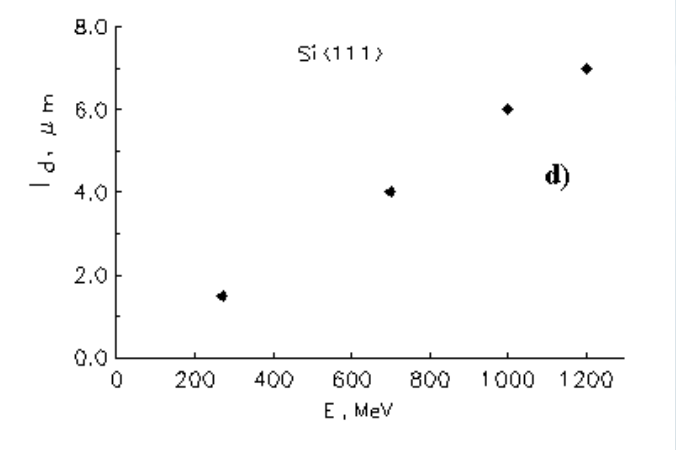
Study of the dynamics of beams of relativistic positrons and electrons in the crystal (by nuclear reactions)

S.P. Fomin, A. Jejcic, V.I. Kasilov et al., NIM B129 (1997) 29.

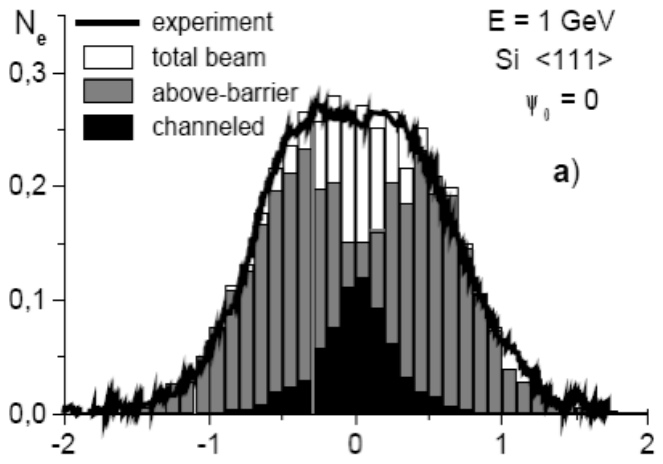


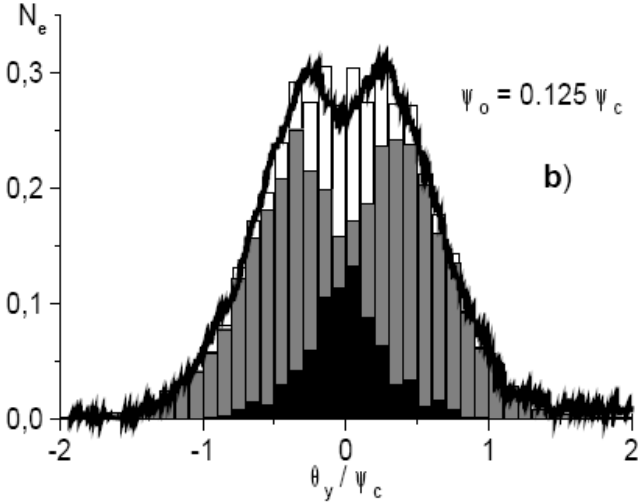


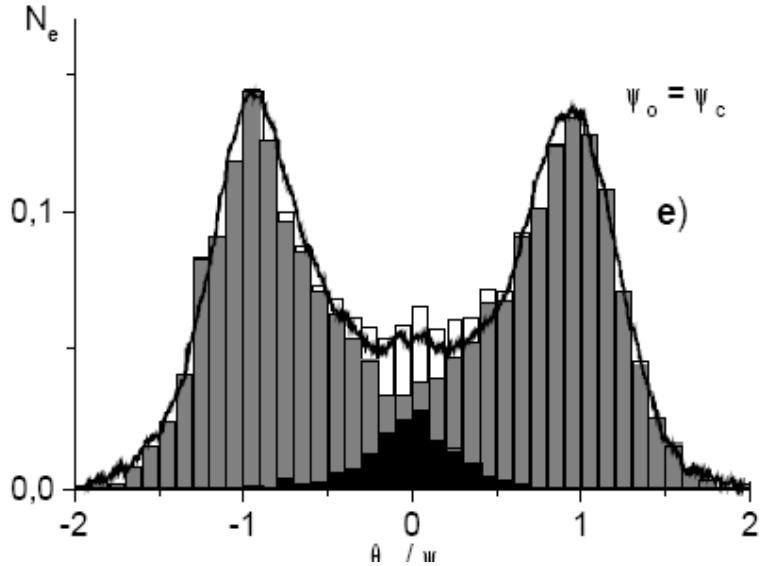


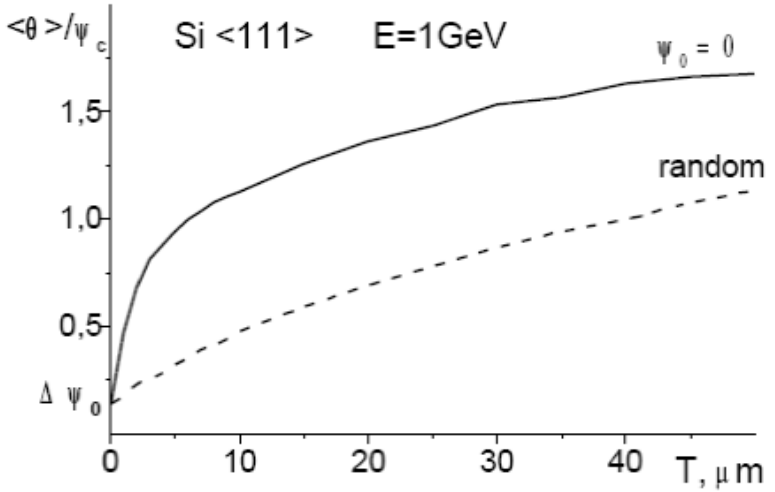


Experimental Results of GeV Electron Channeling in Thin Silicon Crystals



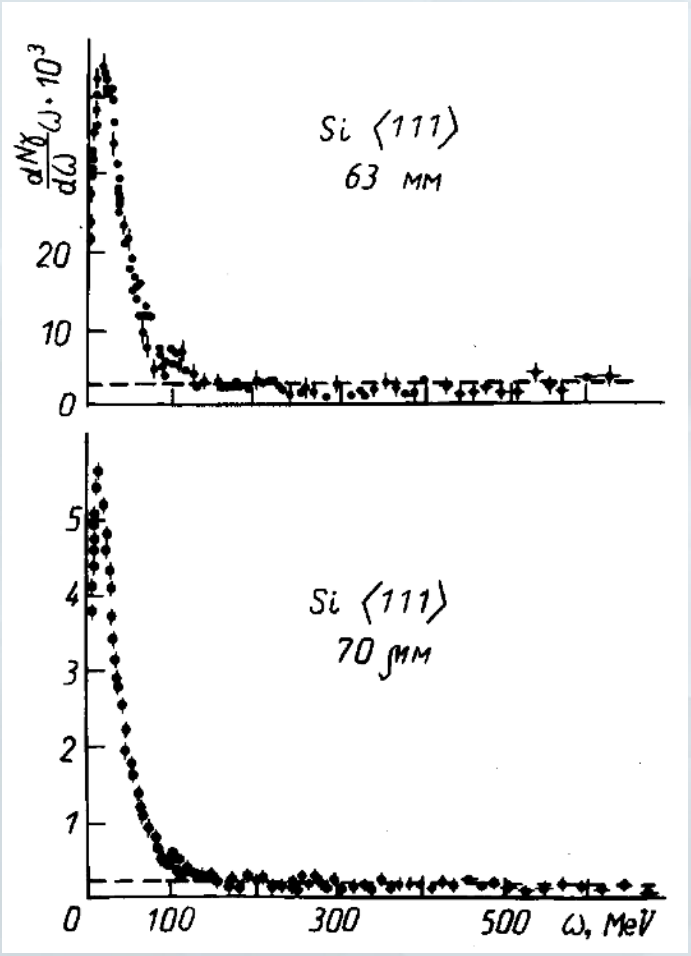


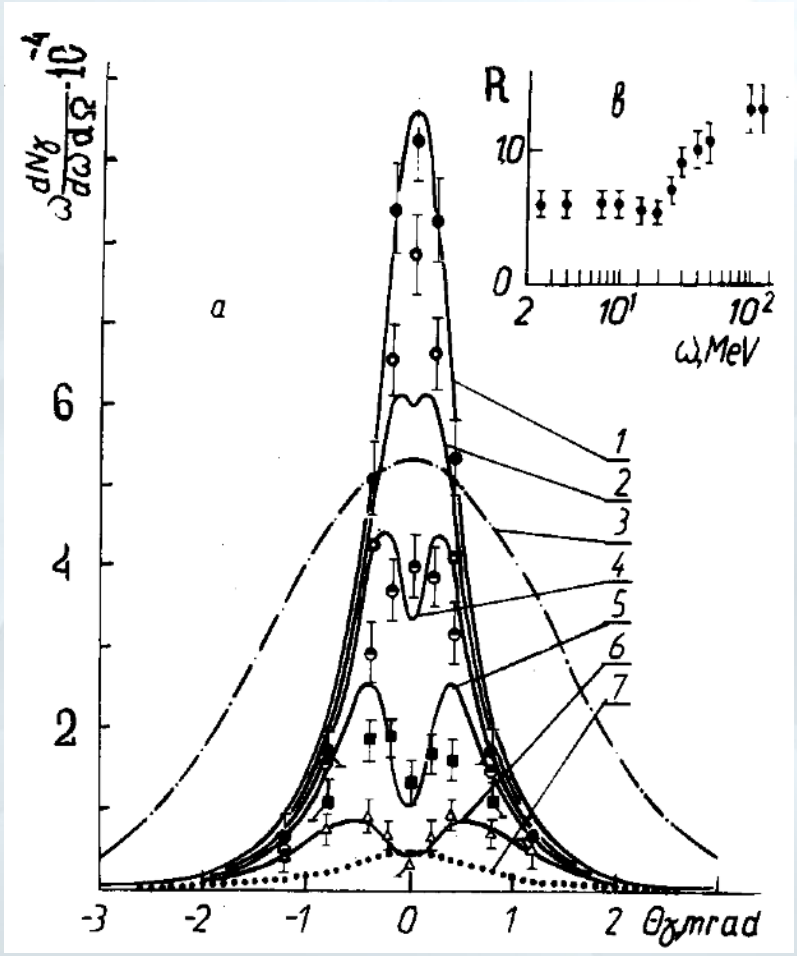




S.P. Fomin et al., "Features of Angular Distributions of 1 GeV Electrons Scattered by Thin Silicon Monocrystals" Problems of Atomic Science and Technology. 2001, pp. 138-143

Theoretical and experimental studies of the basic mechanisms of emission of relativistic electrons in crystals: development of a source of intense gamma radiation





Spectral and spectral-angular characteristics of gamma radiation in crystals

SLAC experiment E-146 (1994-1999)

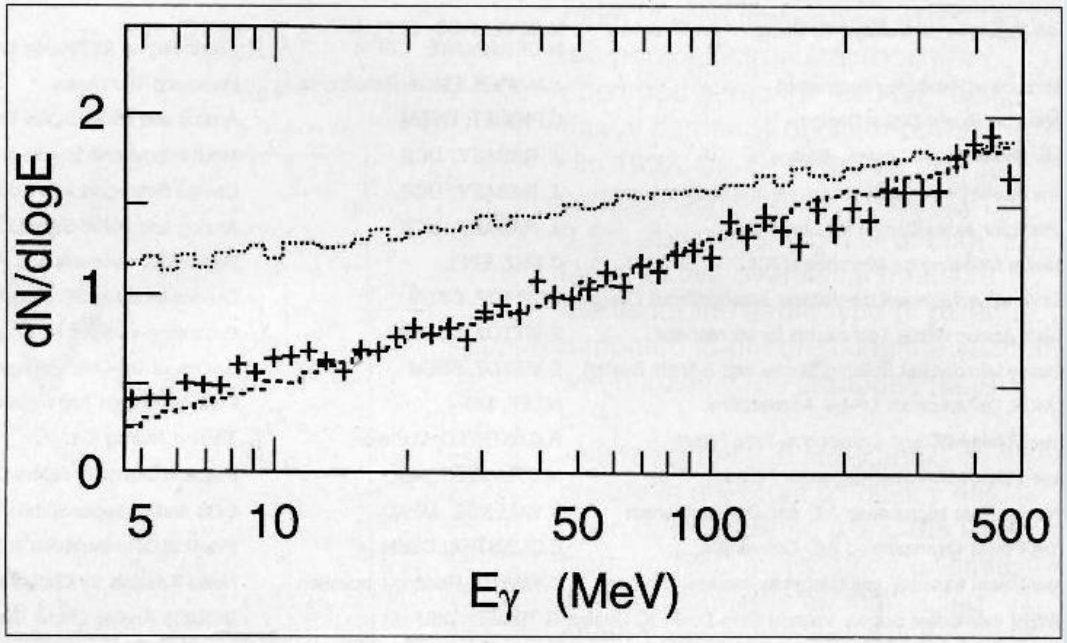
Volume 34
No. 1
January/February
1994

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.

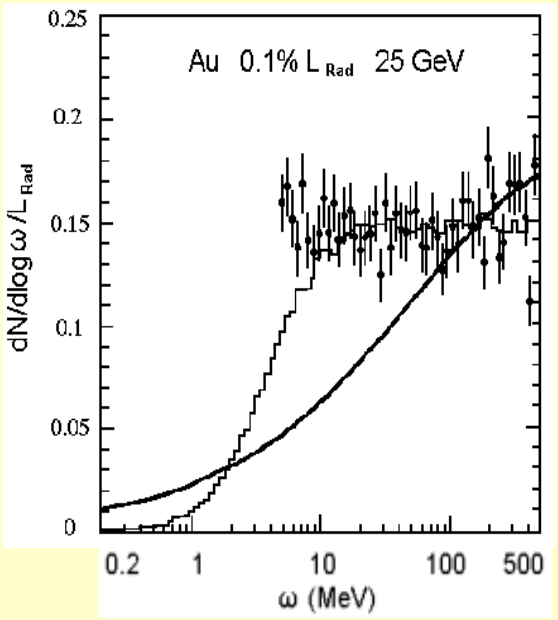
In SLAC experiment E-146, 25 GeV electrons passed through slim targets of carbon, aluminum, iron, gold, lead, tungsten and uranium — as well as a very thin gold target. After traversing the target, the electrons were de-

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

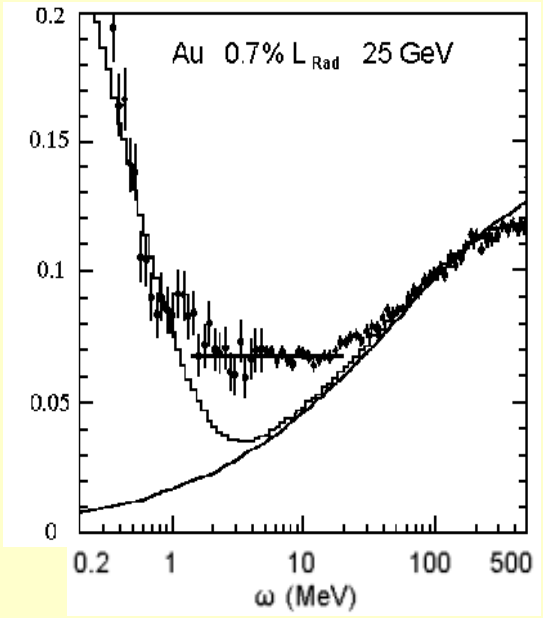
Anthony P.L. et al., Phys. Rev. Lett. **75** (1995) 1949.
Klein S., Rev. Mod. Phys. **71** (1999) 1501.

Bethe-Heitler



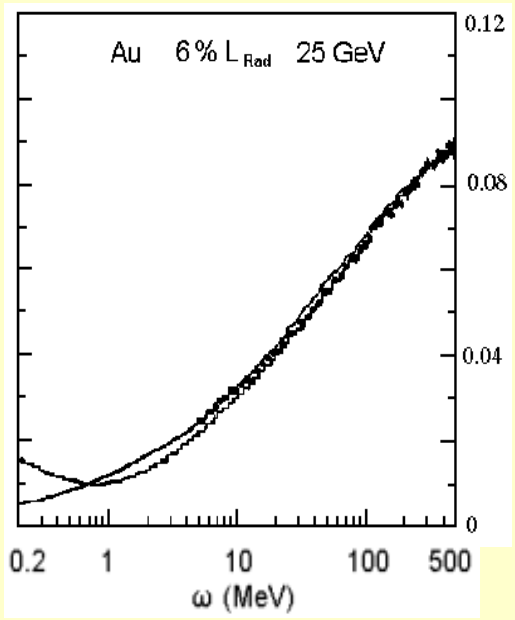
$\gamma^2\overline{\vartheta^2} < 1$

? ? ?



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

LPM effect



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

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

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

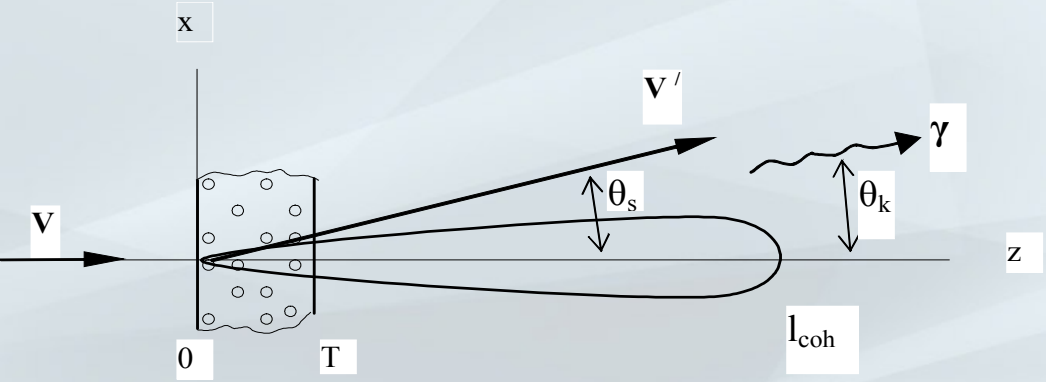
Radiation in a thin layer of matter :

$l_c >> T$

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.

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



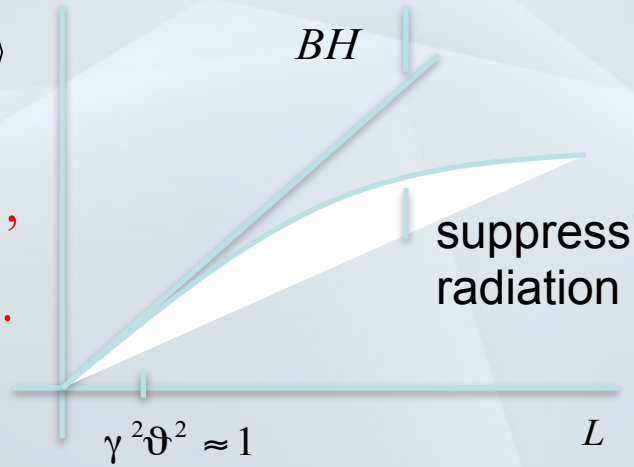
$$\vec{I} = i\int_{-\infty}^{\infty} dt\, e^{i(\omega t-\vec{k}\cdot\vec{r}(t))}\frac{d}{dt}\frac{\vec{v}(t)}{\omega-\vec{k}\cdot\vec{v}(t)}$$

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

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

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

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



suppression of radiation

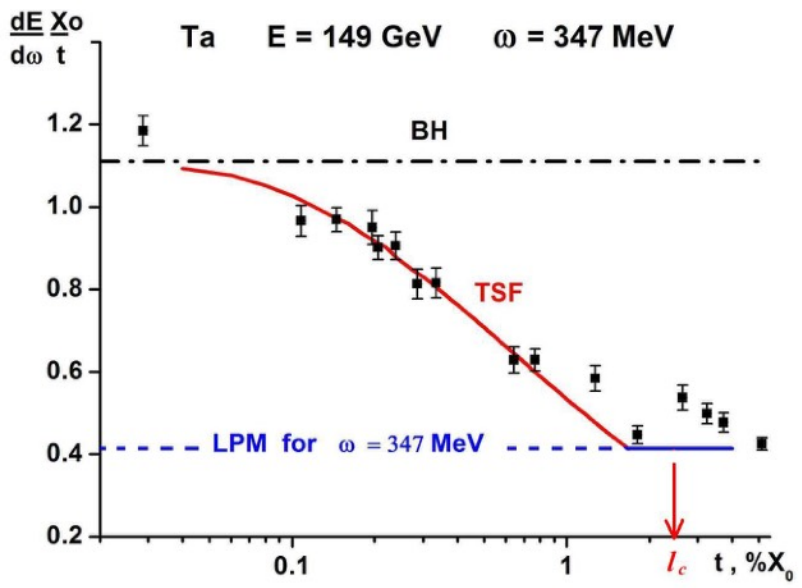
Ternovsky-Shul'ga-Fomin effect of suppressing the radiation of relativistic electrons in a thin layer of matter (TSF effect)

Predicted in KIPT: Letters to ZhETF, 27 (1978) 126.

Confirmed at CERN: Phys. Lett. B 672 (2009) 323; Phys. Rev. D 81 (2010) 052003.

Ulrik Uggerhøj (spokesman of the CERN collaboration NA63):

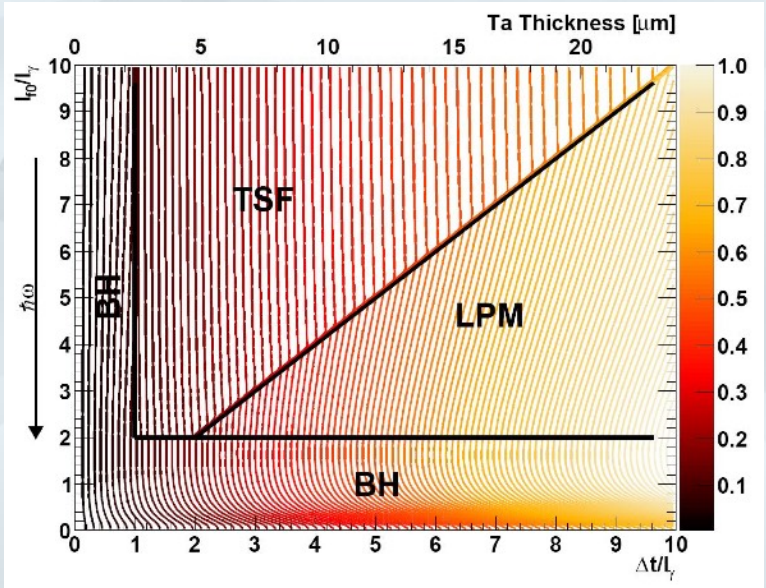
"… we have 'seen' the 'half-bare' electron " !!!



Теория Бете-Гайтлера (BH),

Эффект Терновского-Шульги-Фомина (TSF),

Эффект Ландау-Померанчука-Мигдала (LPM)



Scope of applicability of theories

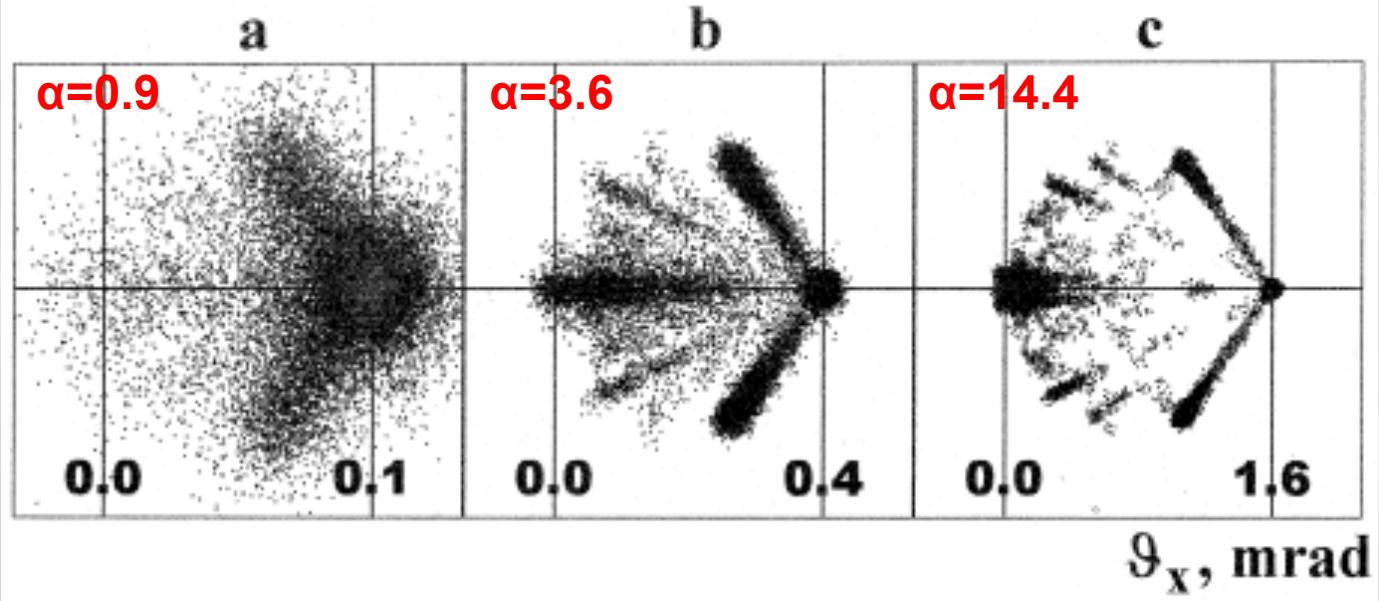
Diagram from PhD thesis of Heine Thomsen, CERN , 2010

Greenenko-Shul'ga condition

A.A. Greenenko, N.F. Shul'ga, NIM B **173** (2001) 178

$$\alpha = \frac{l_\perp}{R\psi_c}\frac{l}{R\psi_c} < 1$$

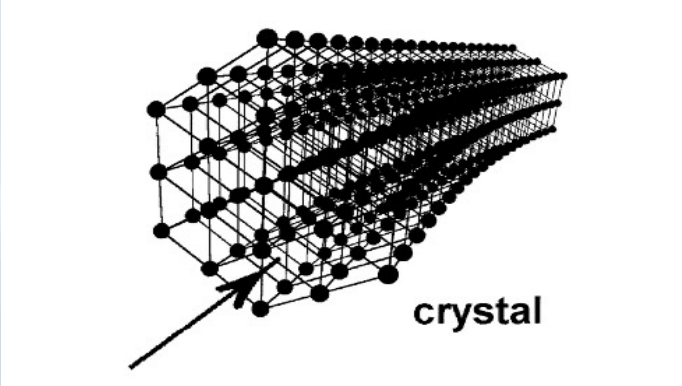
l=crystal lenght along the beam
$l_\perp$=equalization length
R=bending radius
Ψ_c=axial-channeling critical angle



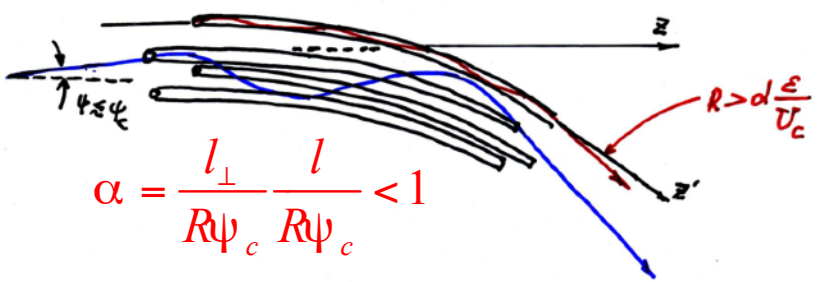
450GeV proton beam angular distribution at the exit of a bent silicon crystal with the curvature radius R=30 m near (110) axis: (a) l=3 mm; α=0.9; (b) l=12 mm; α=3.6; (c) l=48 mm; α=14.4

Stochastic mechanism of deflection of high-energy charged particle beam in a bent crystal

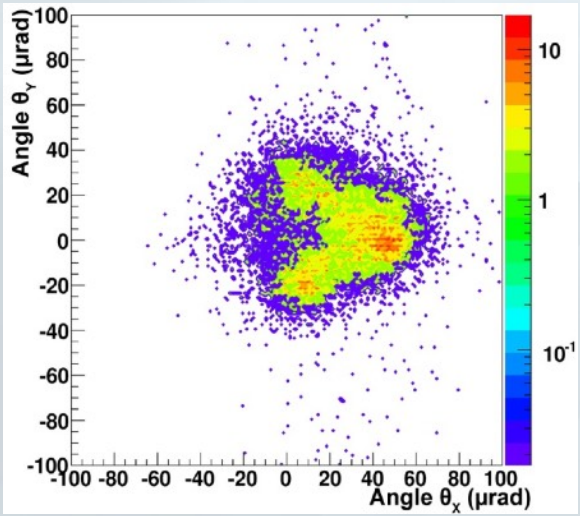
A.A. Greenenko, N.F. Shul'ga, JETP Lett., 54 (1991) 520; NIM B 173 (2001) 178.



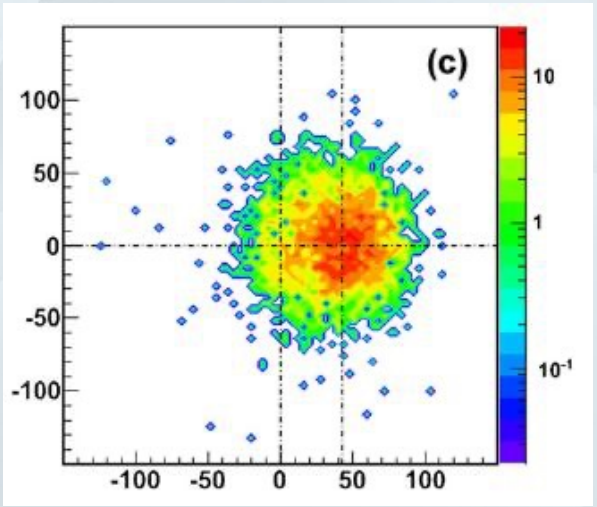
Grinenko-Shul'ga condition



CERN experiment UA9: W. Scandale et al. Phys. Rev. Lett. 101 (2008) 164801; Phys. Lett. B 680 (2009) 301

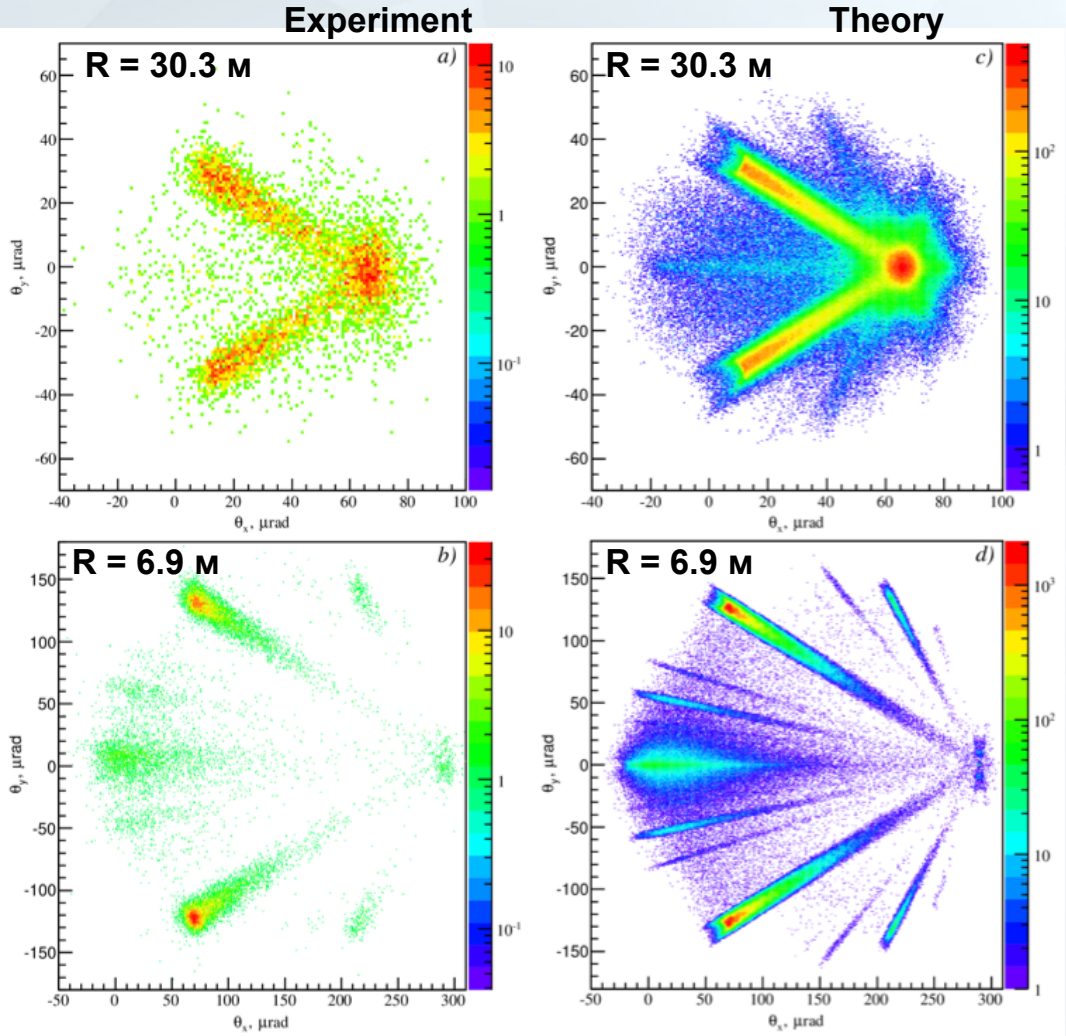


p - protons with energy 400 Gev,



π - mesons with energy 150 GeV

Splitting of the proton beam by a bent crystal on the SPS CERN accelerator (2010-2016)



E = 400 GeV
protons
Si, axis <111>

V. Guidi, I. V. Kirillin, N. F. Shul'ga et al. // Eur. Phys. J. C (2016) 76:80.

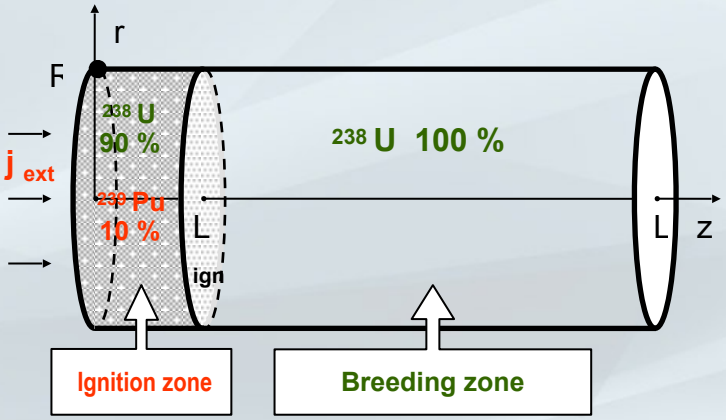
Scientific works: more than 300 articles + 12 monographs and reviews

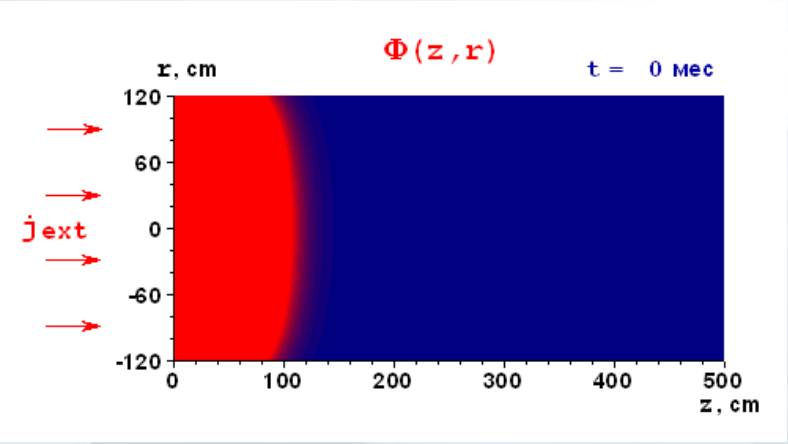
1997: Organization of the A.I. Akhiezer Institute for Theoretical Physics of NSC KIPT

At the seminar of the A.I. Akhiezer Institute for Theoretical Physics of NSC KIPT

PHYSICAL FOUNDATIONS OF A PROMISING FAST REACTOR, OPERATING IN THE MODE OF NUCLEAR COMBUSTION WAVE

S. Fomin, M. Malovytsia, Yu. Mel'nik,V. Pilipenko, N. Shul'ga





Articles: *Annals of Nucl. Energy* (2005, 2020), *Progress in Nucl. Energy* (2008, 2011), ...
Conferences: IAEA-RCM ADS (India); PINP WS (Russia); TWGFR (Belgium); NPAE (Kiev); ICAPP (USA); INES (Japan); IAEA-TWGFR (China); FR-13 (France); WGFR (Argentina); Global (France), …

The Evolution of the Traveling-Wave Concept

TERRAPOWER

1958 Saveli M. Feinberg proposes a "breed-burn" reactor in which unenriched fuel is moved around the core to sustain fission

1979 Michael J. Driscoll and others at MIT further evaluate breed-burn reactor ideas

1988 Lev Feoktistov works on the concept in Russia and publishes an analysis of a concept of a physically safe reactor

1996 Edward Teller, Lowell Wood (now at Intellectual Ventures), and others at Lawrence Livermore Lab detail ways to make breed-burn waves travel through a stationary fuel supply

2000 Hugo van Dam publishes mathematical analyses of waves of fission moving inside nuclear fuels

2001 Hiroshi Sekimoto begins a series of conceptual studies of various kinds of TWRs

Early 2000s Sergii Fomin and N. Shul'ga study the burning wave in fast reactors in the Ukraine

2006 Intellectual Ventures begins detailed physics and engineering studies of the feasibility, cost, and features of various TWR designs

2016: Director General of the National Science Center "Kharkiv Institute of Physics and Technology"

NEUTRON SOURCE BASED ON SUB-CRITICAL ASSEMBLY, CONTROLLED BY AN ELECTRON ACCELERATOR

Scientific career of Nikolai Shul'ga

1973 – Junior researcher at the Kharkiv Institute of Physics and Technology (KIPT)

1977 – PhD thesis

1981 – Senior researcher at KIPT

1985 – Doctor of Science thesis

1986 – Head of Department at KIPT

1999 – Professor of V.N. Karazin KNU

2000 – A.S.Davydov Prize of the National Academy of Science of Ukraine

2002 – State Prize of Ukraine in the field of science and technology

2003 – Corresponding member of the National Academy of Science of Ukraine

2009 – Full member of the National Academy of Science of Ukraine (NAS of Ukraine)

2014 – Honoris Causa Doctor of V.N. Karazin Kharkiv National University

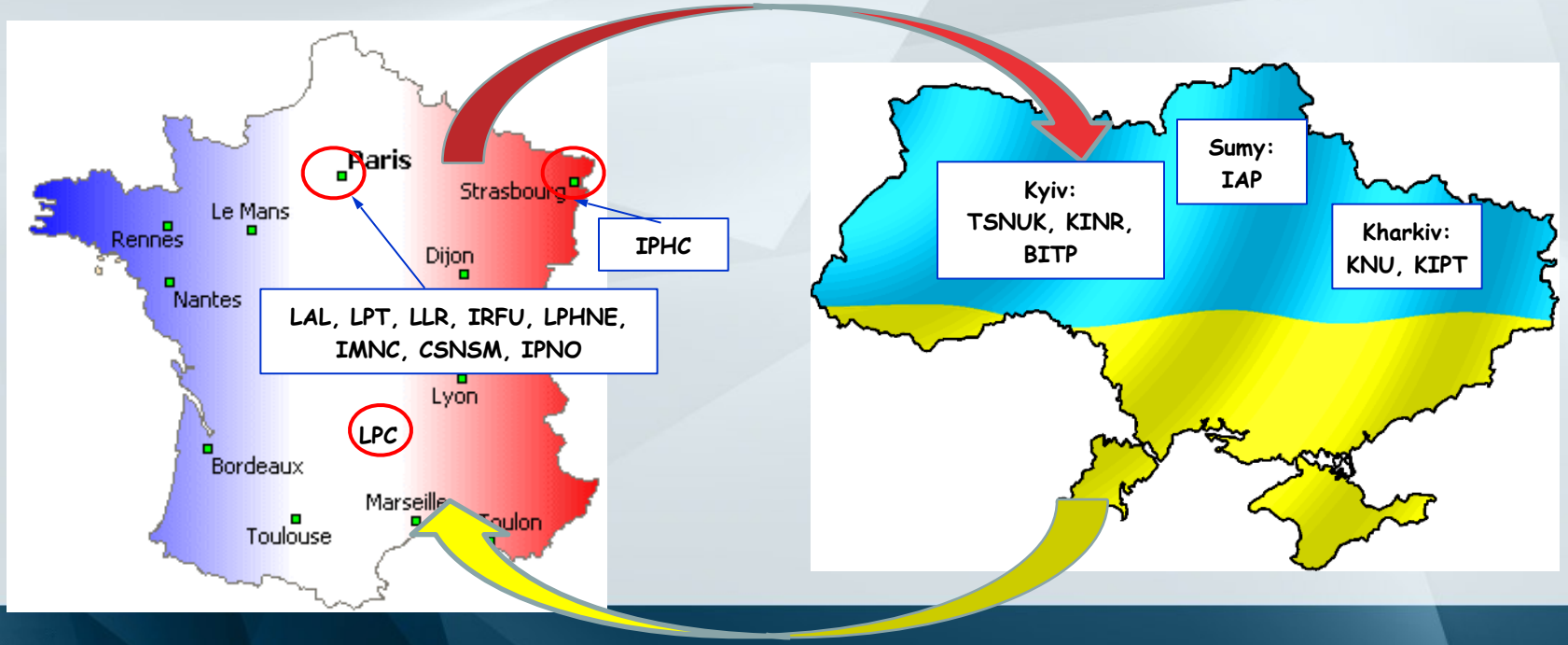
2015 – Honoris Causa Doctor of N.N. Bogolyubov Institute for Theor. Physics

2016 – Head of the Department of Nuclear Physics and Energy of the NAS of Ukraine

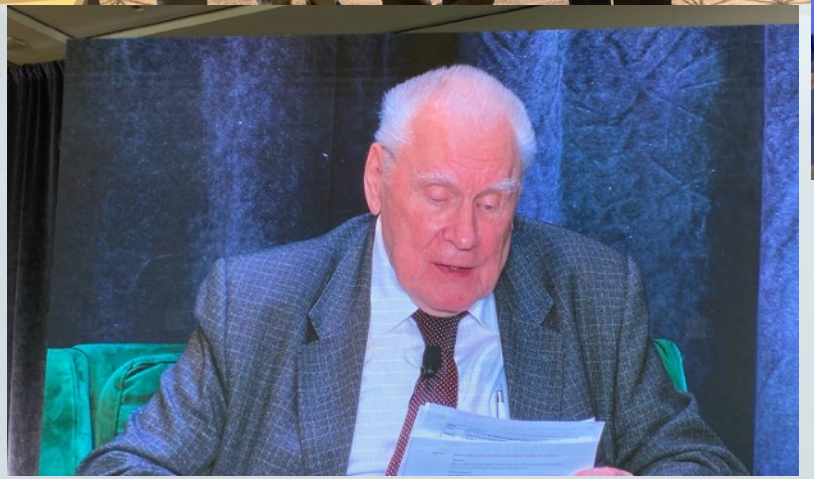
2016 – Director General of NSC KIPT

International cooperation

In 2015 Nikolai Shul'ga became one of the founders and leaders of the International Associated Laboratory (France-Ukraine) "Development of detector systems for experiments on accelerators and technologies for the physics of accelerators" (LIA IDEATE)



The Transatlantic Big Science Conference 2022



3rd French-Ukrainian workshop on the instrumentation developments for HEP

October 15-16, 2015, LAL, Orsay, France

Participants of the workshop, LAL, 16 October 2015

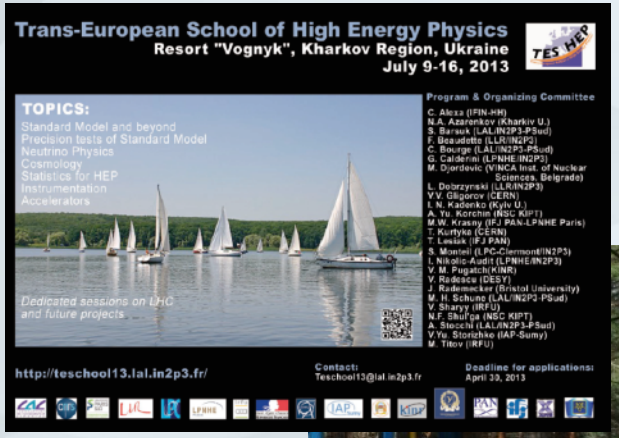
Chairman and member of the Organizing Committees of a number of international conferences: QEDSP, ФВЗЧК, ICACS, RREPS, “Channeling”, ...

Pedagogical activities of Professor N. Shul'ga

Head of the Department of Theoretical Physics at the School of Physics and Technology at the V.N. Karazin KNU

N. Shul'ga was supervisor of 11 PhD and 7 Doctor thesis

2013: Trans-European Summer School in High Energy Physics, Old Saltov



Succession of generations:
Sergii Nikolaevich and Nikolai Fedorovich

Thank you for attention !

Blessed memory of the outstanding Scientist and wonderful Teacher - Nikolai Shul'ga!