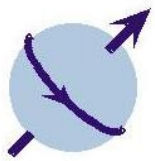


Suggestions for experiments with high-energy electron-photon beams and crystals

Victor Tikhomirov

Institute for Nuclear Problems Minsk, Belarus

Outline

• ***Strong Field Electrodynamics*** in crystals: respectable past and challenging future

Synchrotron-like (**uniform field**) **dichroism**
and **birefringence** in very hard γ -region

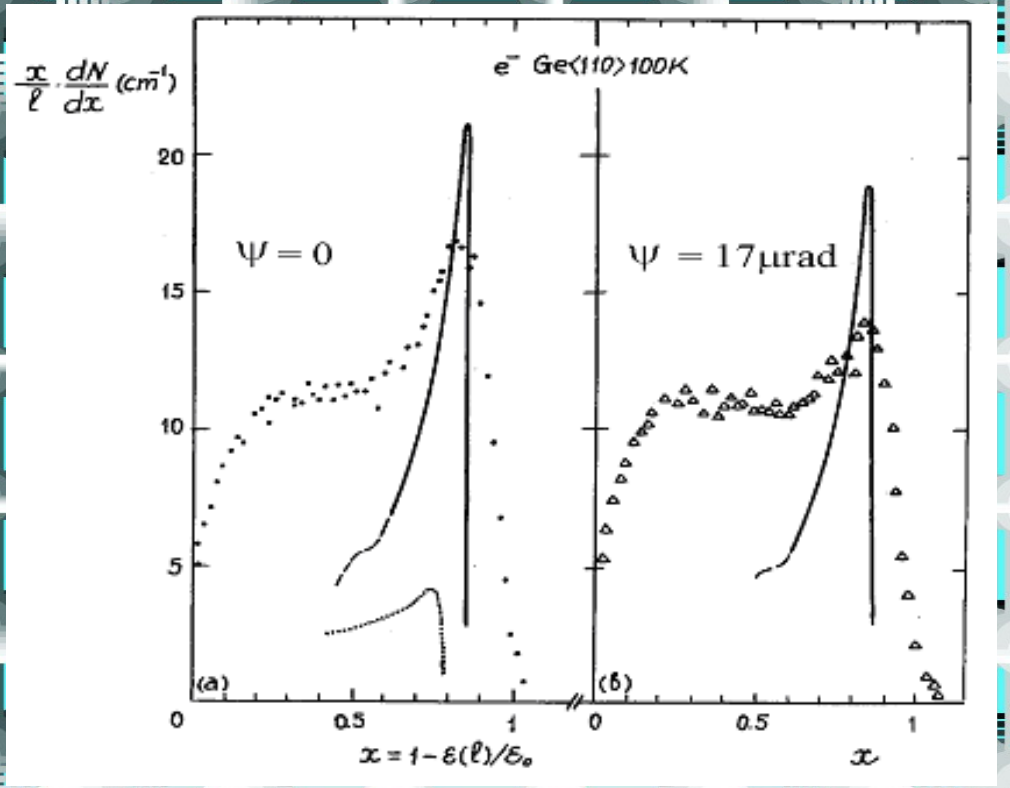
Spin effects in bent crystal:
Radiative ***self-polarization*** in bent crystals
Production of transversely ***polarized e±***
by γ-quanta in bent crystals
Positron *magnetic* ***moment modification***

• Existence and observation possibilities of **electron chirality**

•Conclusions

Electron radiative cooling in crystals

Tikhomirov V.V. Phys. Lett. A. 125(1987) 411; NIM B36(1989)282.



Electron radiative loss spectrum expressed in units of electron initial energy **150 GeV** at the angle of incidence Ψ = 0 and 17 μrad on the Ge crystal plane <110> cooled to 100K. Dotted curve is calculated without taking into account the radiation cooling.

Manifestation of e^+e^- pair production in semi-uniform field crystal field

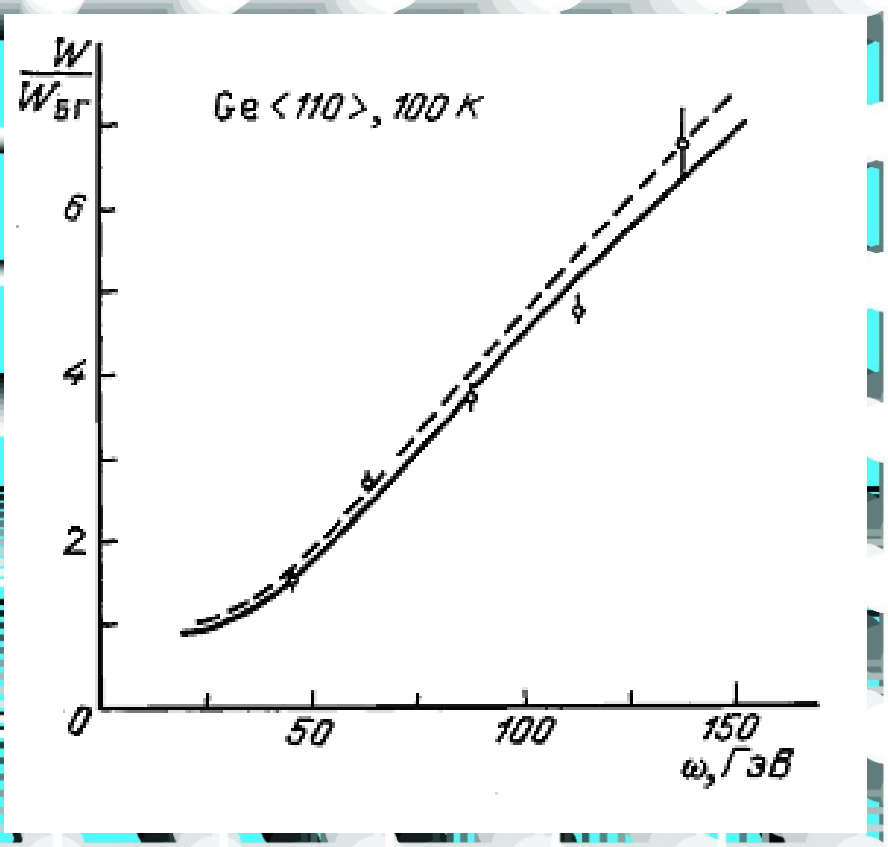
Baryshevskii V.G., Tikhomirov V.V.

Phys. Lett. 90A(1982); Yad. Fiz. 36(1982)697.

Energy dependence of e^+e^- pair production probability by high-energy gamma-quanta

in the field of <110> axes of a Ge crystal at T=100K expressed in units of the Bethe – Heitler probability.

Dots – **experimental data**. The solid and dotted curves are respectively calculated with and without taking into account of the energy dependence of the probability of incoherent PP.



Much more ***Strong Field QED*** effects will be possible to observe at the ***LHC energy***

Positron (electron) anomalous magnetic moment modification influencing spin rotation

V. G. Baryshevsky, *Pis'ma Zh. Tekh. Fiz.* **5**, 182 (1979) [*Sov. Tech. Phys. Lett* **5**, 73 (1979)].

V. G. Baryshevsky and A. O. Grubich, *Yad. Fiz.* **44**, 1114 (1986) [*Sov. J. Nucl. Phys.* **44**, 721 (1986)].

V. V. Tikhomirov, *Sov. J. Nucl. Phys.* **61**, 1188 (1996).

Electron spin rotation in a circularly polarized crystal field harmonics

V. V. Tikhomirov, *Pis'ma v Zh. Eksp. Teor. Fiz.* **61**, 177 (1995).

V. V. Tikhomirov, *Phys. Rev. D* **53**, 7213 (1996).

V. V. Tikhomirov, *Sov. J. Nucl. Phys.* **62**, 664 (1999).

V. V. Tikhomirov, *Zh. Eksp. Teor. Fiz.* **109**, 1188 (1996).

Vacuum dichroism and birefringence

V. G. Baryshevsky and V. V. Tikhomirov, *Usp. Fiz. Nauk* **159**, 529 (1989) [*Sov. Phys. Usp* **32**, 1013 (1989)].

V. G. Baryshevsky and V. V. Tikhomirov, *Yad. Fiz.* **36**, 697 (1982) [*Sov. J. Nucl. Phys.* **36**, 408 (1982)];*Phys. Lett. A* **90**, 153 (1982).

V. G. Baryshevsky and V. V. Tikhomirov, *Nucl. Instr. Meth. A* **234**, 430 (1985).

V. V. Tikhomirov, *Sov. J. Nucl. Phys.* **53**, 338 (1991).

Electron radiative self-polarization in crystals

V. G. Baryshevsky, A.O. Grubich *Pis'ma Zh. Tekh. Fiz.* **5**, 1529 (1979).

V. V. Tikhomirov, *Pis'ma v Zh. Eksp. Teor. Fiz.* **58**, 168 (1993).

Polarized electron-positron pair production by gamma-quanta

V. G. Baryshevsky and V. V. Tikhomirov, *Zh. Eksp. Teor. Fiz.* **85**, 232 (1983) [*Sov. Phys. JETP* **58**, 135 (1983)];*Phys. Lett. A* **96**, 215 (1983).

V. G. Baryshevsky and V. V. Tikhomirov, *Yad. Fiz.* **48**, 670 (1988) [*Sov. J. Nucl. Phys.* **48**, 429 (1988)].

Both strong crystal fields and high γ - quantum energies allow to reach the CRITICAL FIELD

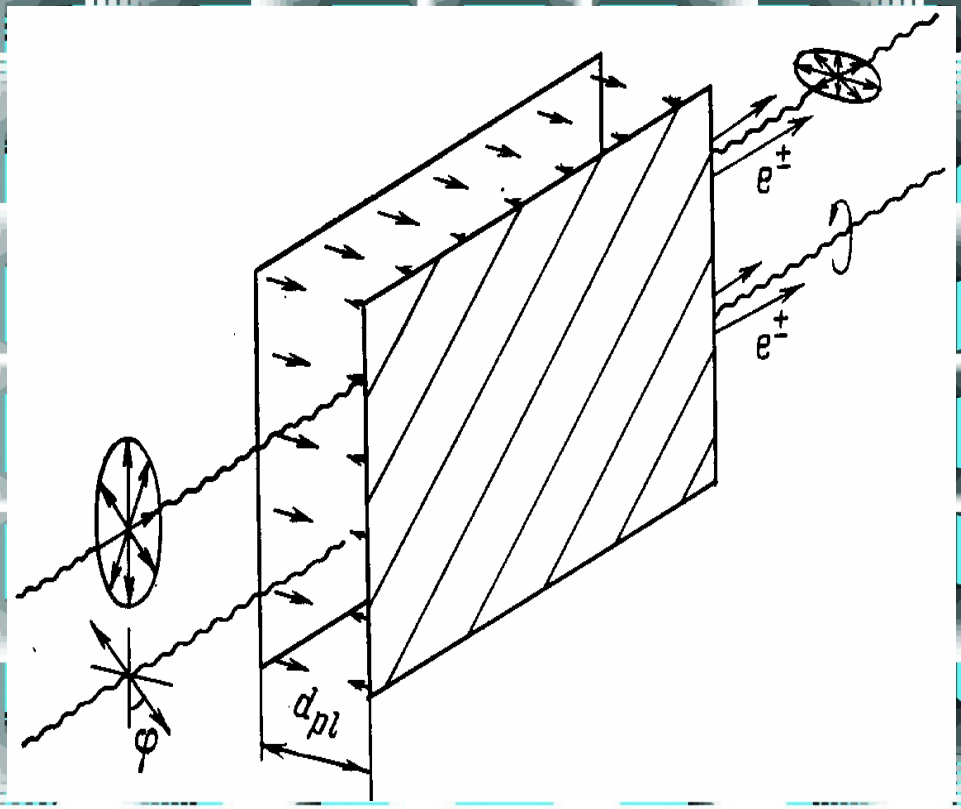
$$E_0 = \frac{m^2 c^3}{e\hbar} = 1.32 \cdot 10^{16} \frac{\mathrm{V}}{cm}$$

Table: *Maximum electric fields and critical energies for some crystals*

Crystal	***(plane) or <Axis>***	$E_{\max}$ ***GV/cm***	$\omega_{th} = \frac{2E_0}{E_{\max}} mc^2$ * ***TeV***
Diamond	(110)	7.7	1.78
	<110>	75	0.20
Si	(110)	5.7	2.39 (1.7)
	<110>	4.6	0.29
Ge	**(110)**	**9.9**	**1.37 (0.9)**
	<110>	**78**	**0.174(0.11)**
W	(110)	43	0.316
	<111>	500	0.027

* *Electric field reaches* E_0 *in ref. frame of* e^+e^- *pair produced at* $\omega = \omega_{th}$

The averaged field of crystal planes



A crystal is *similar* to a region of space occupied by a **uniform electric field** and possesses the properties of **dichroism** *and* **birefringence** in very hard γ -region

Pair production probabilities by γ-quanta polarized along (x) and normal (y) to transverse electric field

$$W_{x,y}(\kappa) = \frac{\alpha m^2}{\sqrt{\pi}\,\omega^2}\int_0^{\omega} d\varepsilon_+ \left[\int_{\zeta}^{\infty} \Phi(y)dy + \left(2 \pm 1 - \frac{\omega^2}{\varepsilon_+\varepsilon_-}\right)\frac{\Phi'(\zeta)}{\zeta}\right],$$

$$\Phi(\zeta) = \frac{1}{\sqrt{\pi}}\int_0^{\infty} \cos\left(\zeta t + \frac{t^3}{3}\right)dt, \qquad \zeta = \left(\frac{E_0 m\,\omega}{E\,\varepsilon_+\varepsilon_-}\right)^{2/3}$$

Coherent pair production probabilities by γ-quanta polarized along (II) and normal (Υ) to crystal planes

$$W_{\text{II},\perp}^{coh} = \int_0^{d_{pl}} W_{y,x}\left(\kappa(E(x))\right)\frac{dx}{d_{pl}}, \qquad \kappa = \frac{E\,\omega}{E_0 m}$$

Incoherent pair production probabilities by γ_0-quanta polarized along (II) and normal (Υ) to crystal planes

$$W^{inc}_{II(\perp)} = \frac{1}{15 L_{rad}\,\omega^3}\int_0^{d_{pl}} \frac{n(x)}{n_0}\frac{dx}{d_{pl}}\int_0^{\omega} d\varepsilon_+\left[1-\theta(1-\zeta)\,\frac{\ln\zeta}{2\ln(183\,Z^{-1/3})}\right]\times$$

$$\times[[\omega^2[1\pm1]\zeta^4\mathrm{Y}\mp6\zeta\mathrm{Y}-(3\pm4)\zeta^2\mathrm{Y}'-(1\pm1)\zeta^3]+$$

$$+(\varepsilon_+^2+\varepsilon_-^2)[(1\mp1)\zeta^4\mathrm{Y}+(3\pm6)\zeta\mathrm{Y}-(5\mp4)\zeta^2\mathrm{Y}'-(1\mp1)\zeta^3]],$$

$$\mathrm{Y}=\mathrm{Y}(\zeta)=\int_0^{\infty}\sin\left(\zeta t+\frac{t^3}{3}\right),$$

$$n(x)=\frac{n_0\,d_{pl}}{\sqrt{2\pi}\,u}\exp\left(-\frac{x^2}{2u^2}\right), \qquad \frac{1}{L_{rad}}=4\alpha\,n_0\left(\frac{Z\alpha}{m}\right)^2\ln(183\,Z^{-1/3})$$

Total pair production probabilities by polarized γ_0-quanta in crystals

$$W_{\text{II}(\perp)} = W^{coh}_{\text{II}(\perp)} + W^{inc}_{\text{II}(\perp)}$$

Pair production asymmetry

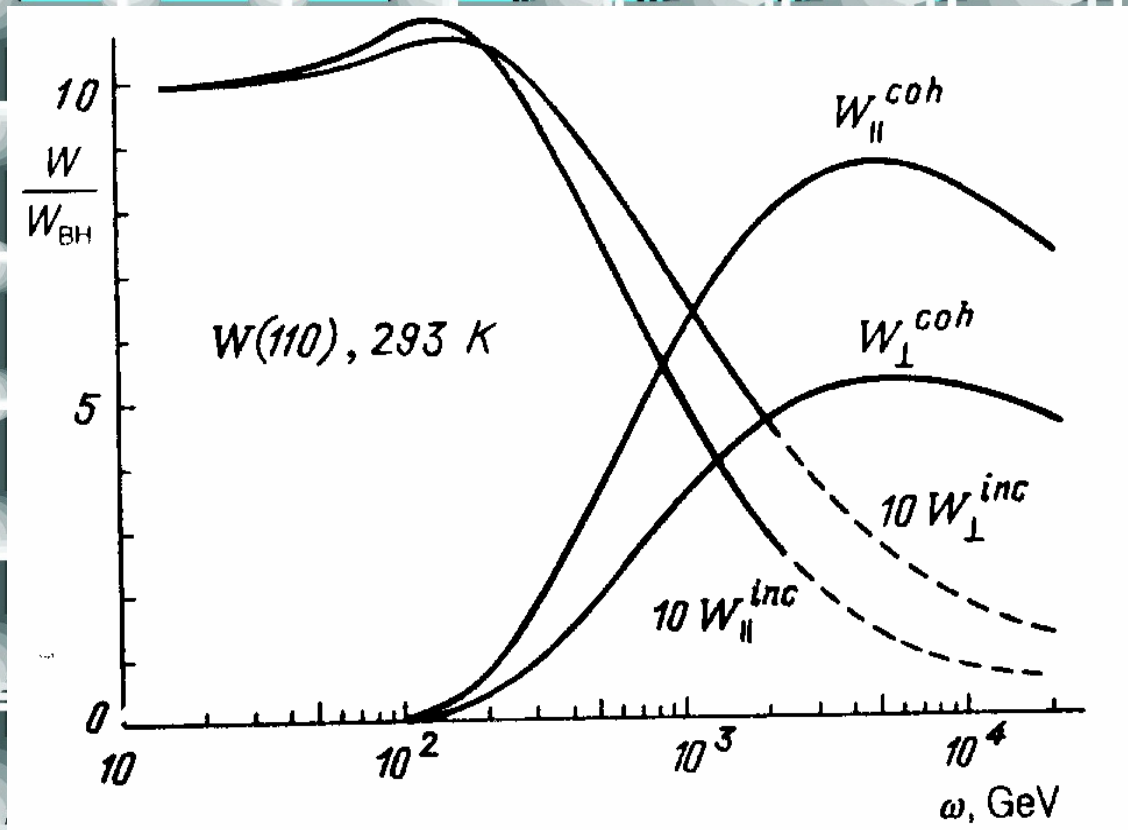
$$\frac{W_{\text{II}} - W_{\perp}}{W_{\text{II}} + W_{\perp}}$$

Synchrotron-like crystal ***dichroism***

Energy dependence of the coherent and incoherent contributions to the probability of

e^+e^- pair production

by γ-quanta **polarized** parallel and normal to the <110> planes of tungsten, along which these γ - quanta are propagating.



Dichroic crystal polarizer

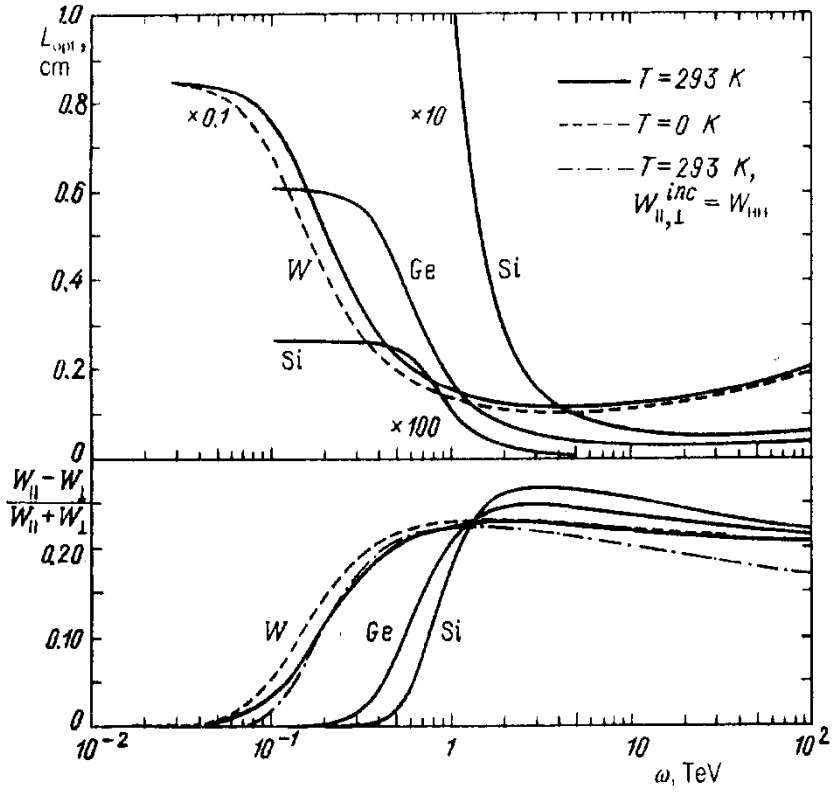
Optimal

polarizator length

and

pair production asymmetry

for <110> planes of crystals of Si,Ge and W at T=293K (below). Dotted curves - for W at T=0K, dot-dash – also for W, but neglecting the energy and polarization dependence of the incoherent contribution of PP at T=293K.



Synchrotron-like crystal ***birefringence***

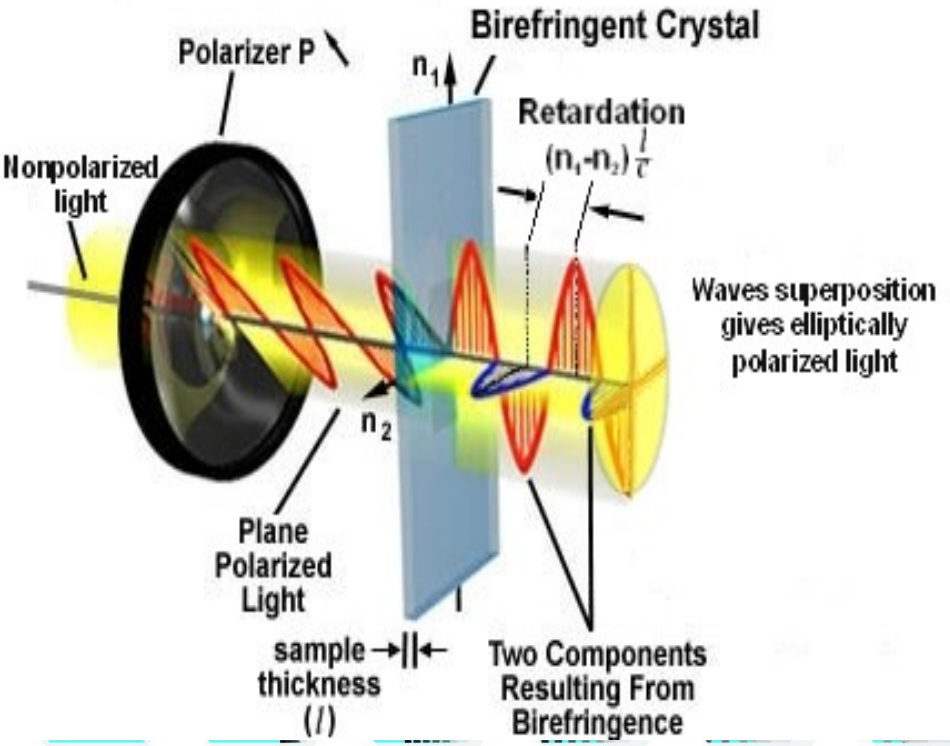
$$L_{\lambda/4}\,\frac{\omega}{c}(n_{\parallel}-n_{\perp})=\frac{\pi}{2}$$

For visible light

$$\Delta t = 10^{-15}\,\mathrm{s}$$

For γ - quanta

$$\Delta t = 10^{-28}\,\mathrm{s}$$

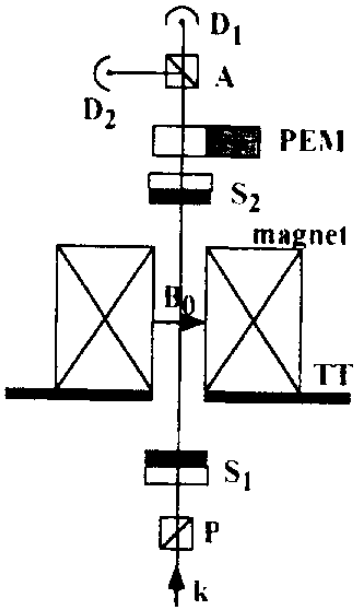


– determines polarization of Neutron Star gamma radiation

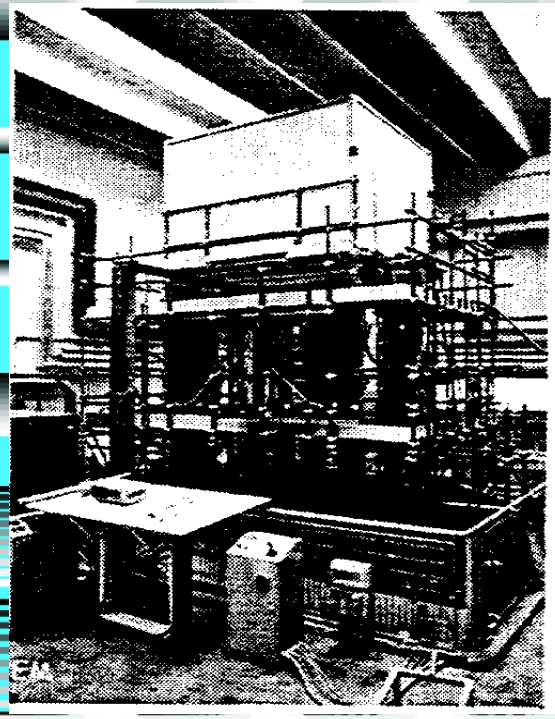
– is experimentally searched for a long time

Light phase velocity anisotropy in vacuum due to static magnetic field

Polarizzazione del Vuoto con LASer (PVLAS)
Laboratori Nazionali di Legbaro of INFN, Padova



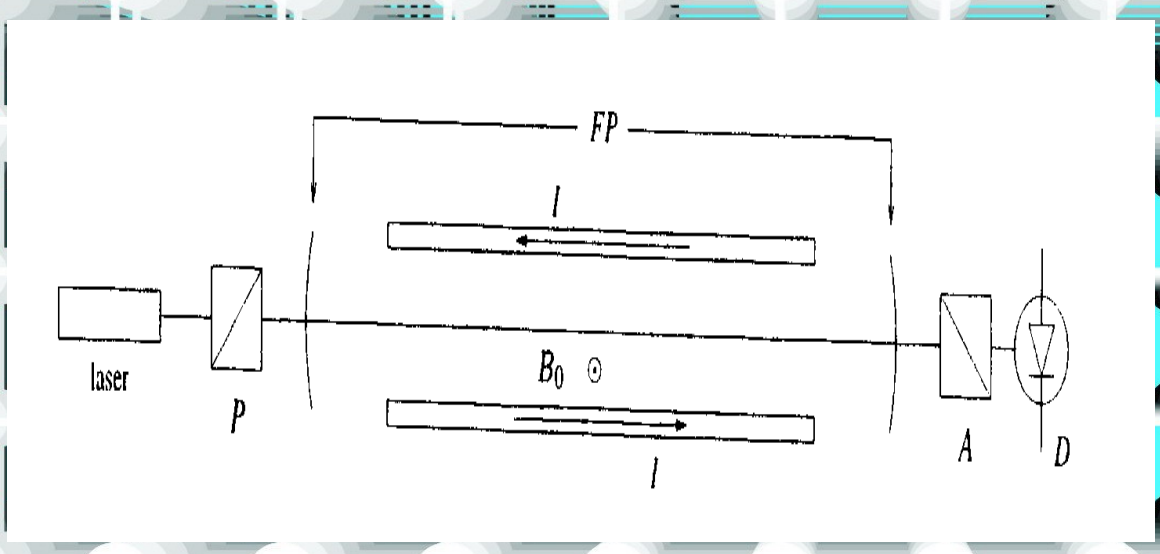
schematic layout



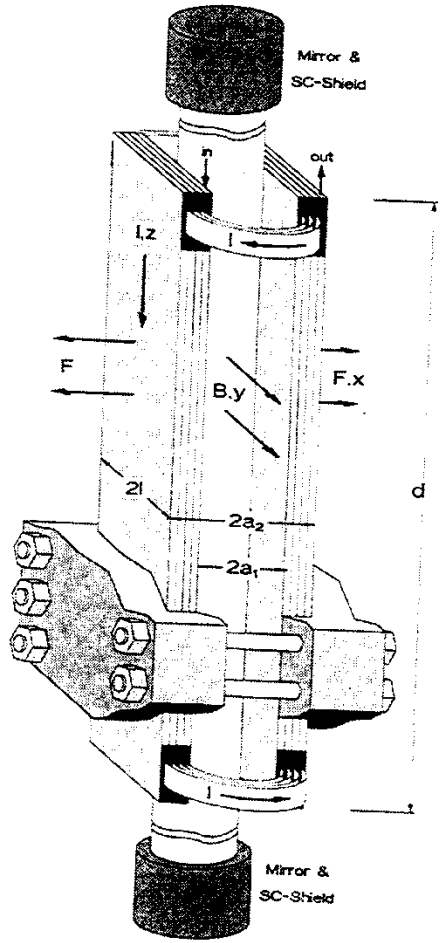
apparatus view

Birefringence Magnetique du Vide (BMV)

Laboratoire National das Champs Magnetique Pulses, Toulouse



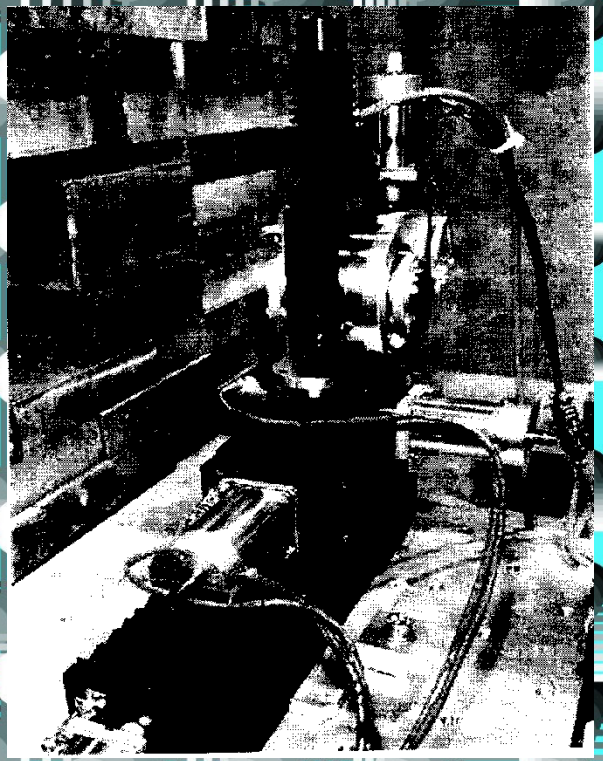
Sketch of the optical apparatus



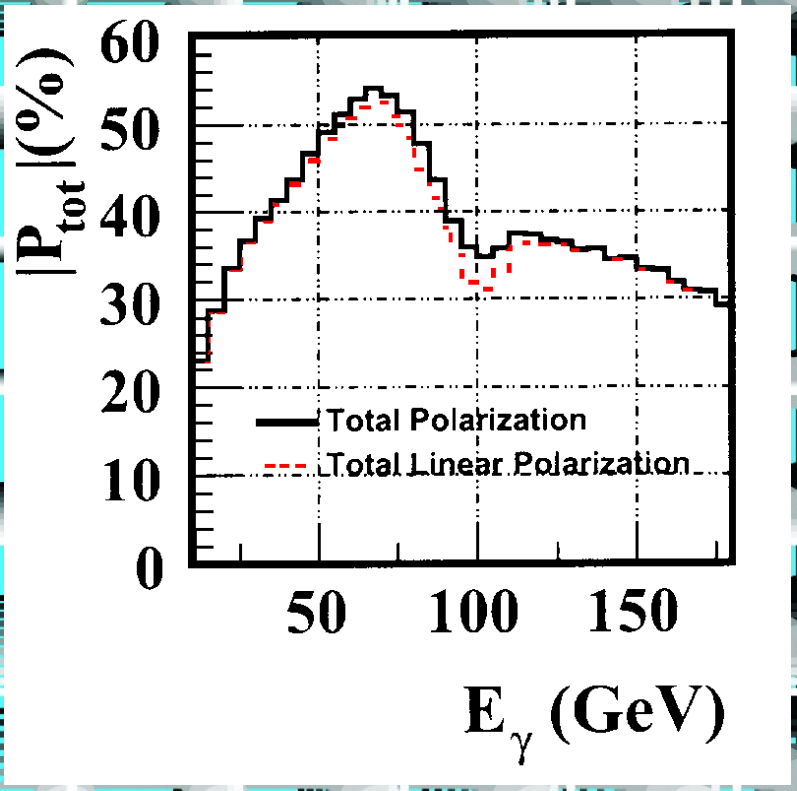
Magnet design →

Crystal birefringerence *(Cabibbo, 1962)*

CERN (Armenia-Sweden-Italy-Switzerland-USA-South Africa-France-Netherlands-Russia-Spain-Danmark)



Birefringent (quarter wave plate) Si crystal and goniometer



Stokes parameters after the quarter wave crystal

Refraction indexes of γ-quanta polarized along (II) and normal (γ) to crystal planes

$$n_{\text{II}(\perp)} = n^{coh}_{\text{II}(\perp)} + n^{inc}_{\text{II}(\perp)}$$

$$n^{coh}_{\text{II}(\perp)}(\omega) = \int_0^{d_{pl}} n_{y(x)}(\kappa(x))\,\frac{dx}{d_{pl}}$$

$$n_{x(y)}(\kappa) = \frac{1}{2}\Re\varepsilon_{x(y)} = 1 - \frac{\alpha}{3\pi}\left(\frac{E}{\kappa E_0}\right)^2 \int_0^{\omega} \frac{\Upsilon'(\zeta)}{\zeta}\left(\frac{\omega^2}{\varepsilon_+\varepsilon_-} + \frac{1\mp 3}{2}\right)\frac{d\varepsilon_+}{\omega}$$

$$n^{inc}_{\text{II}(\perp)} = n_{\omega<<\omega_{\kappa=1}} - \frac{\sqrt{\pi}}{30\,L_{rad}\omega^4}\int_0^{d_{pl}} \frac{n(x)}{n_0}\,\frac{dx}{d_{pl}} \times$$

$$\times \int_0^{\omega} d\varepsilon_+ \left(\omega^2[(1\pm 1)\zeta^4\Phi \mp 6\zeta\Phi - (3\pm 4)\zeta^2\Phi'] + \right.$$

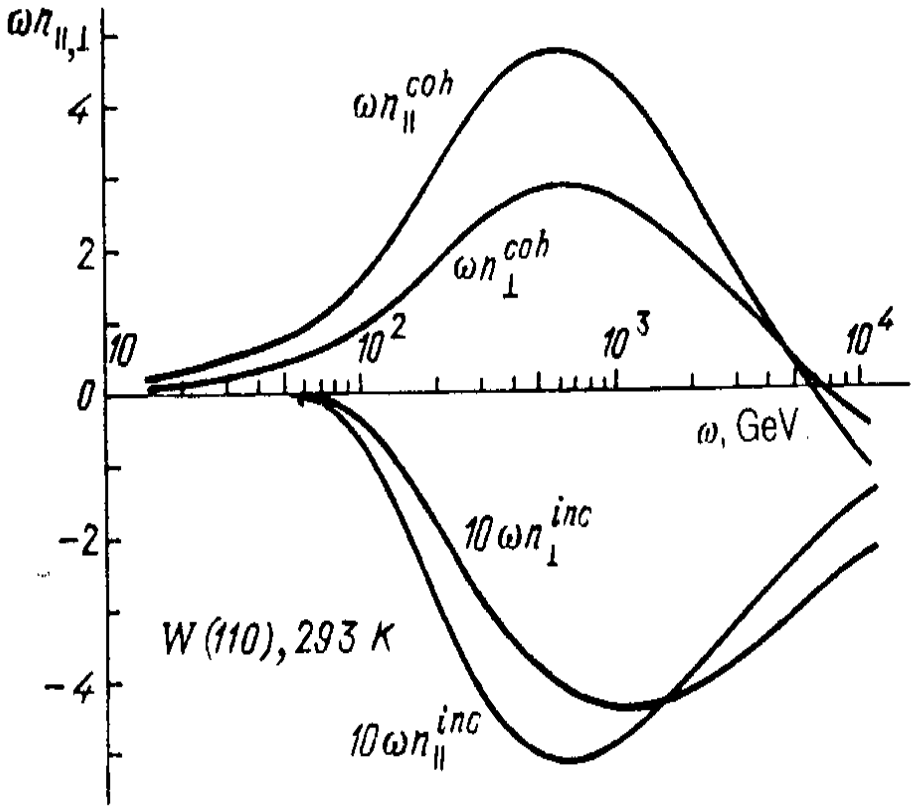
$$\left. + (\varepsilon_+^2 + \varepsilon_-^2)[(1\mp 1)\zeta^4\Phi + (3\pm 6)\zeta\Phi - (5\mp 4)\zeta^2\Phi']\right)$$

The LHC energy is really optimal:

multiplied by energy coherent and incoherent contributions to the

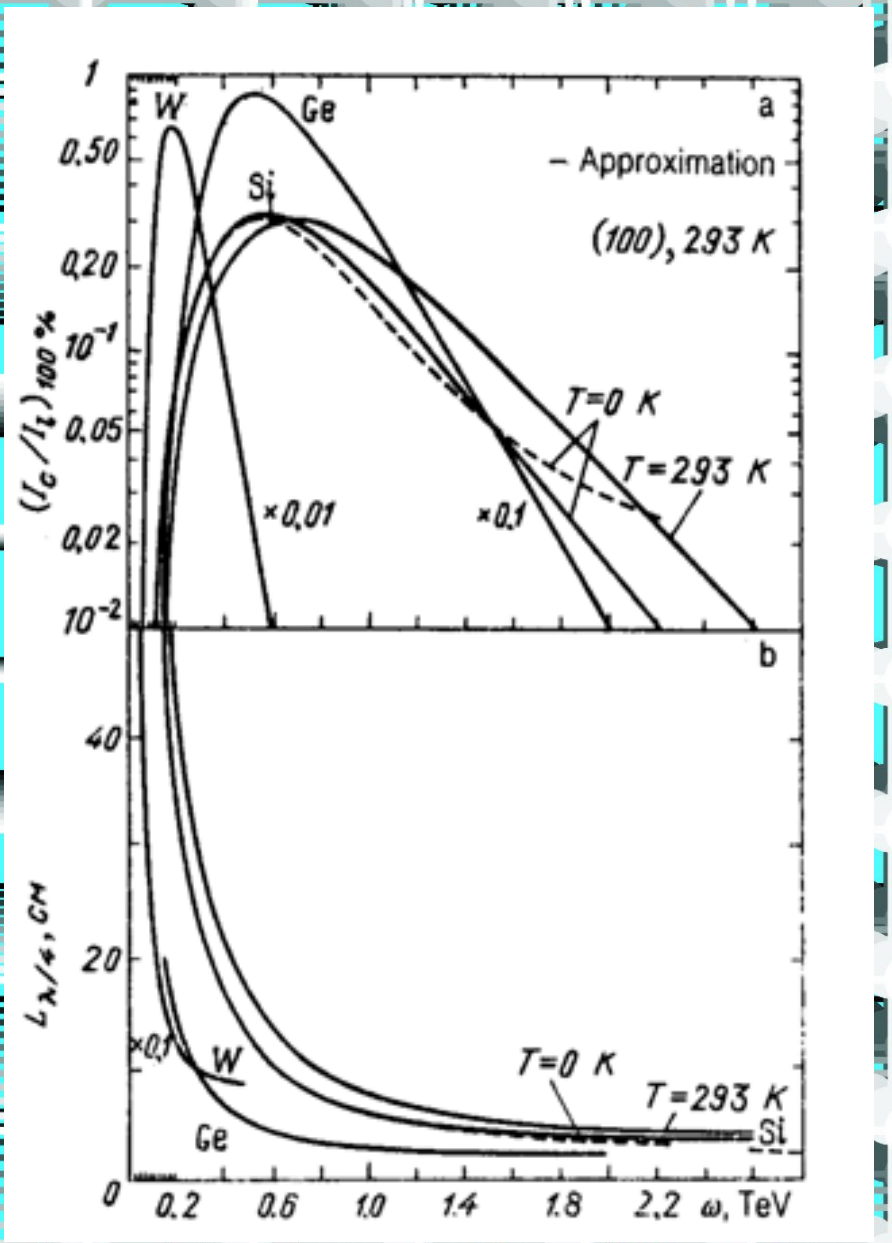
refractive indexes

of γ -quanta linearly polarized parallel and perpendicular to the <110> planes of a tungsten crystal at T=293K.



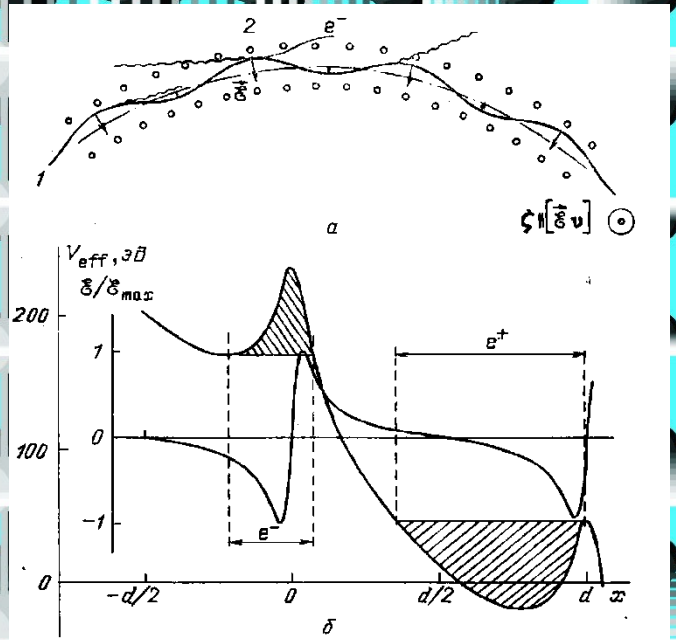
Energy dependence of **attenuation coefficients** of a completely polarized beam and **lengths** of **quarter-wave plates** based on using the birefringence property of the fields of the <110> planes of Ge and W crystals at T=293K, and also Si at 0 and 293K

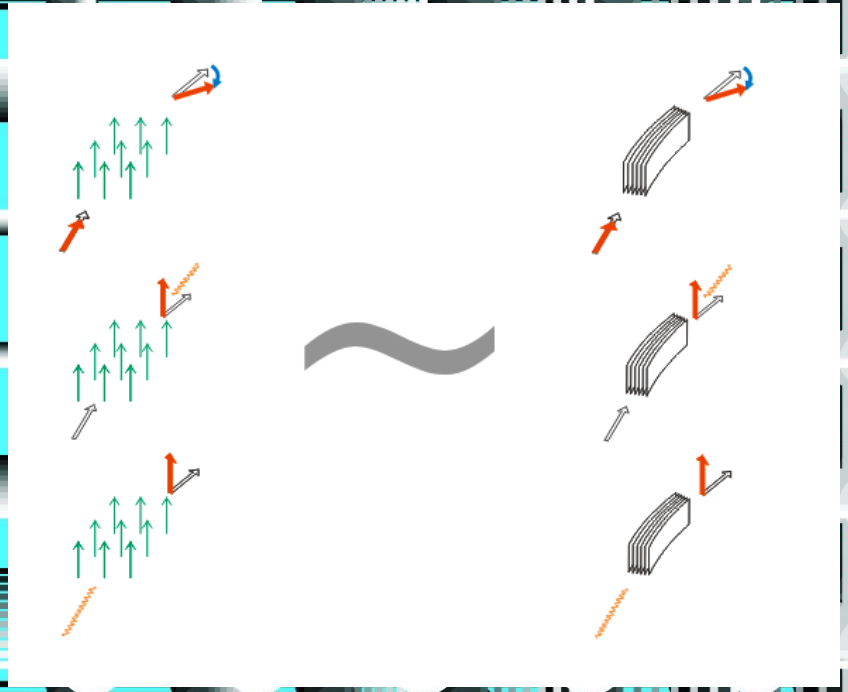
Dotted curves are calculated by using the simplified description of the refraction and the absorption by the Bethe – Heitler probability.



Spin effects in bent crystal

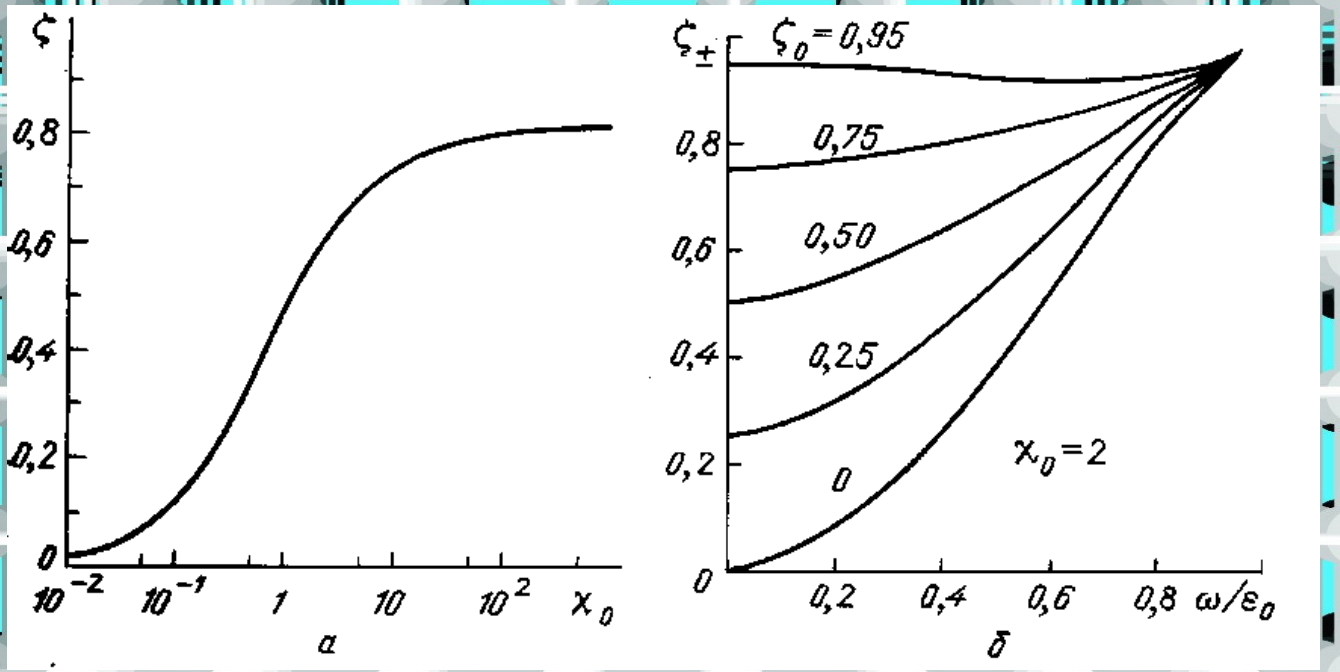
V. G. Baryshevsky, Pis'ma Zh. Tekh. Fiz. 5(1979)182; 5(1979)1529.





Channeled e^+ and e^- move or are produced by gamma-quanta in bent crystals in the regions with dominating direction of the planar electric field, which represents itself an origin of a number of spin effects.

Radiative self-polarization in the uniform field

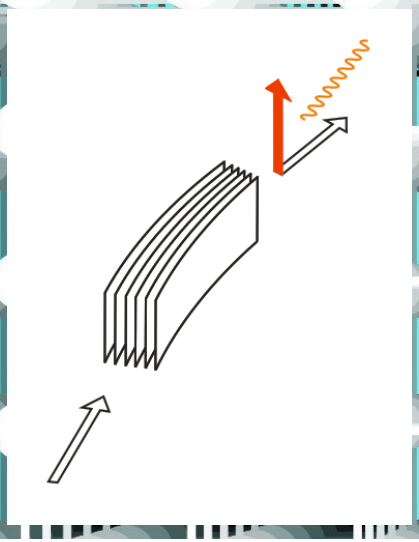


Maximal polarization attained by $e^{\pm}$ losing all their energy for radiation the initial value of the χ.

Final $e^{\pm}$ polarization vs the energy of emitted γ-quantum at different initial polarizations and $\chi_0 = 2$.

$$\chi = \frac{E}{1.32 \cdot 10^{16} eV/cm} \frac{\varepsilon}{mc^2}$$ – the main parameter of quantum electrodynamics

Radiative self-polarization in bent crystals at purely planar channeling



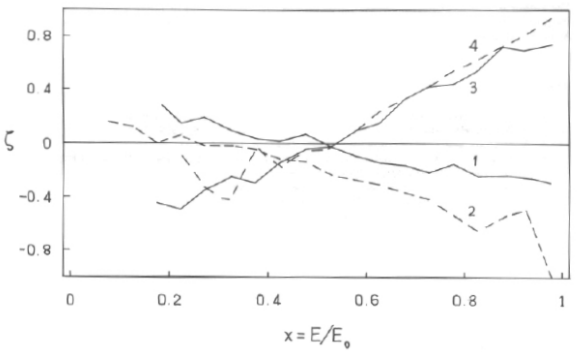


FIGURE 2 Electron and positron polarization gained in Si(110) crystal at $T = 293$ K versus final energy, expressed in units of initial energy $E_0 = 1$ TeV. Curves 1 and 2—for electrons, 3 and 4—for positrons. Curves 1 and 3—for constant radius $R = 5.3$ m of crystal bent, curves 2 and 4—for crystal curvature increasing along the crystal (for details see the text). The crystal lengths were 0.1, 0.07, 0.45 and 0.2 for curves 1–4, respectively.

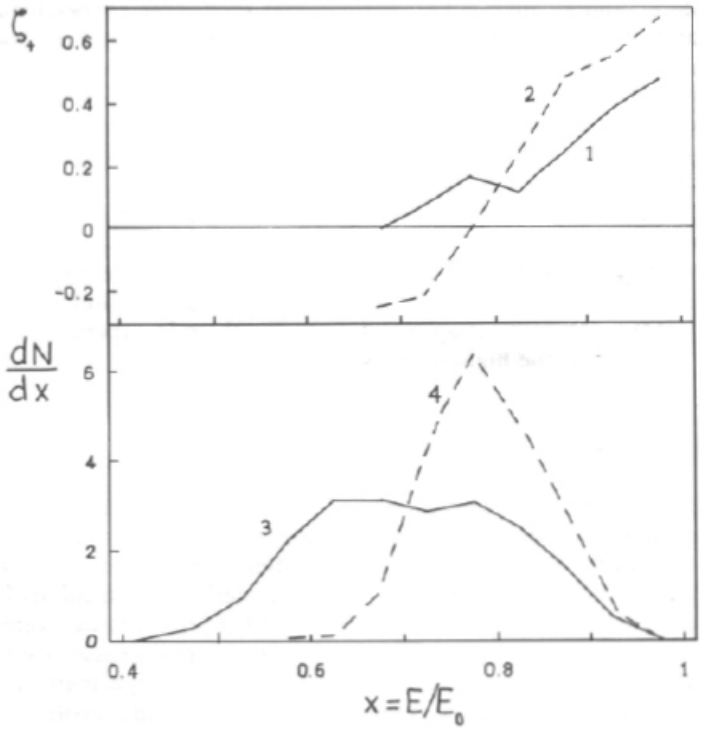
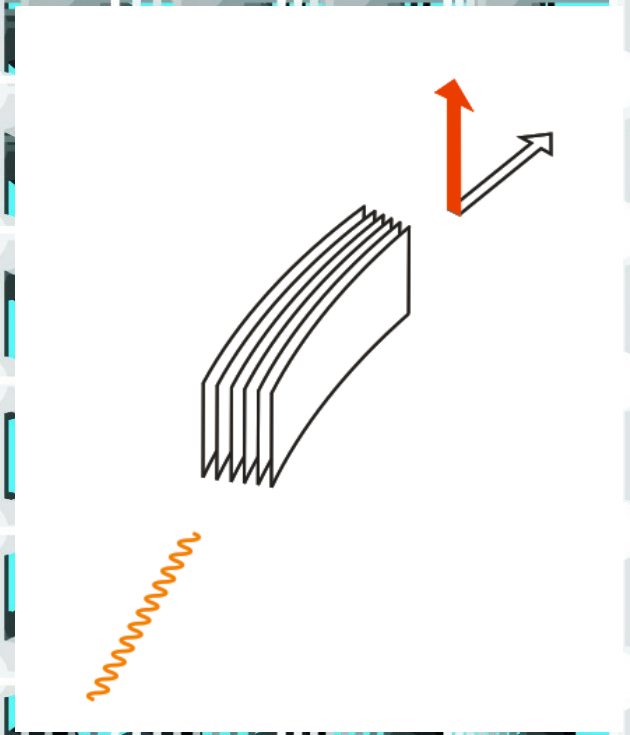
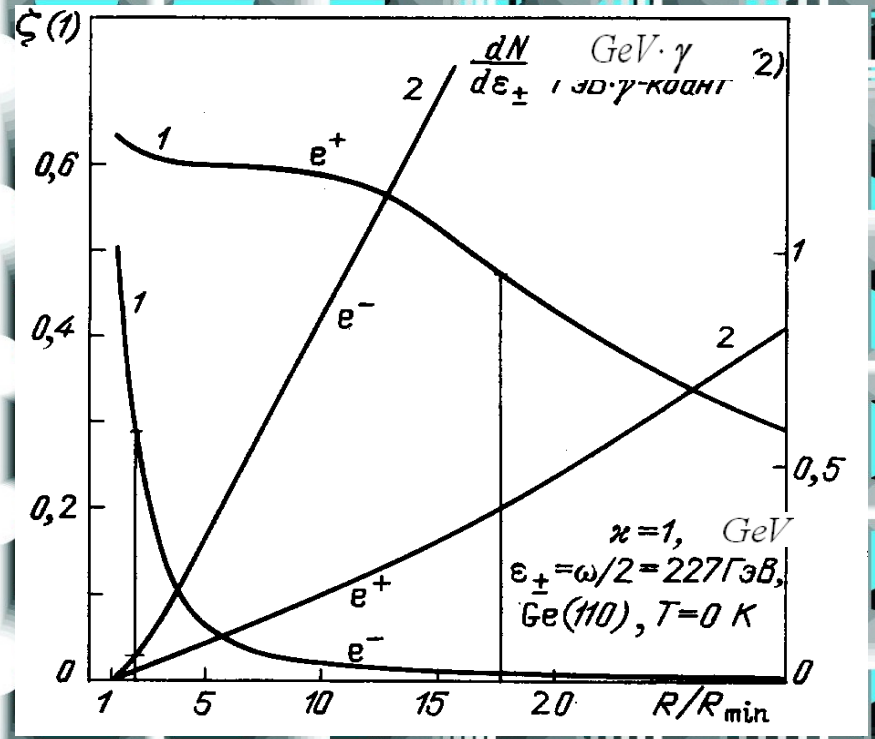


FIGURE 1 Polarization (curves 1 and 2) and energy distribution (curves 3 and 4) gained by positrons with initial energy $E_0 = 287$ GeV in the bent Ge(110) crystal at $T = 100$ K. Curves 1 and 3—for constant radius of crystal bent $R = R_0 = 1$ m, curves 2 and 4—for crystal radius $R(z) = R_0/3^{z/l}$ decreasing along the crystal of length $l = 1$ cm.

Production of transversely polarized $e^{\pm}$ by γ-quanta in bent crystals

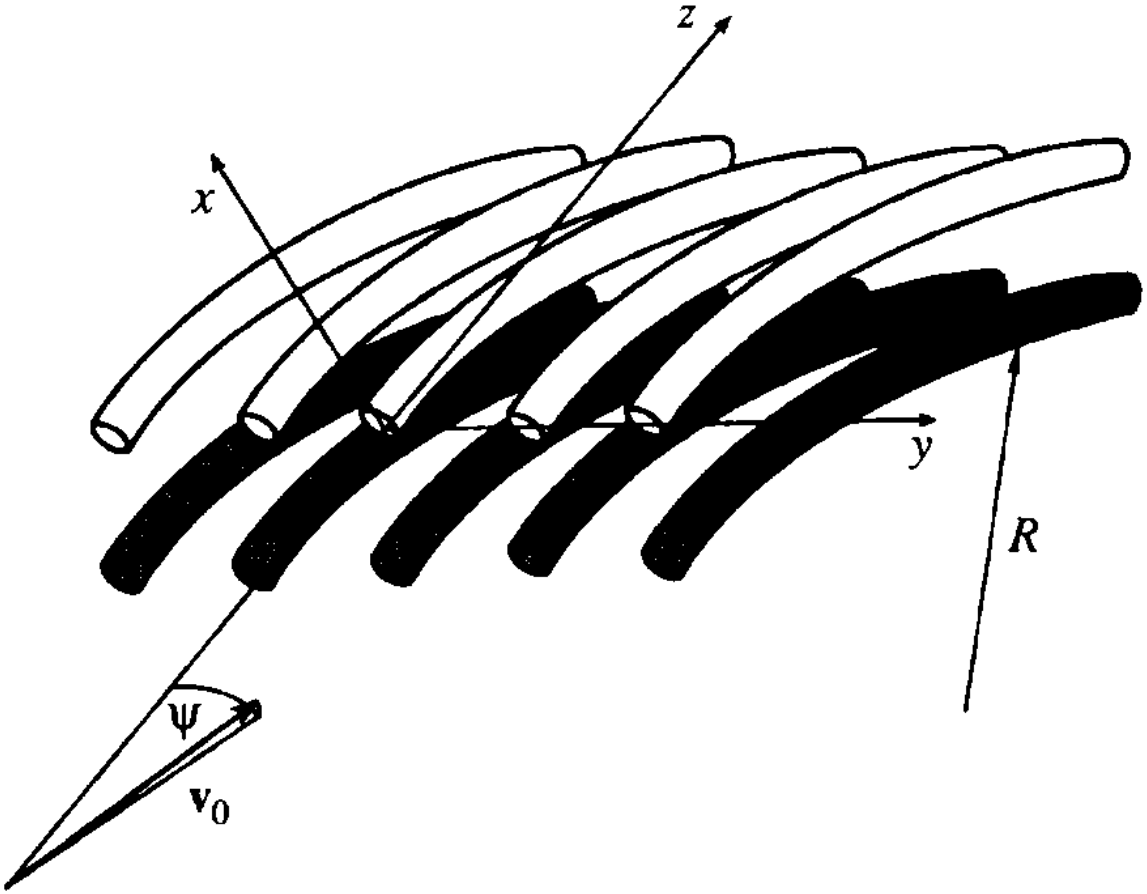




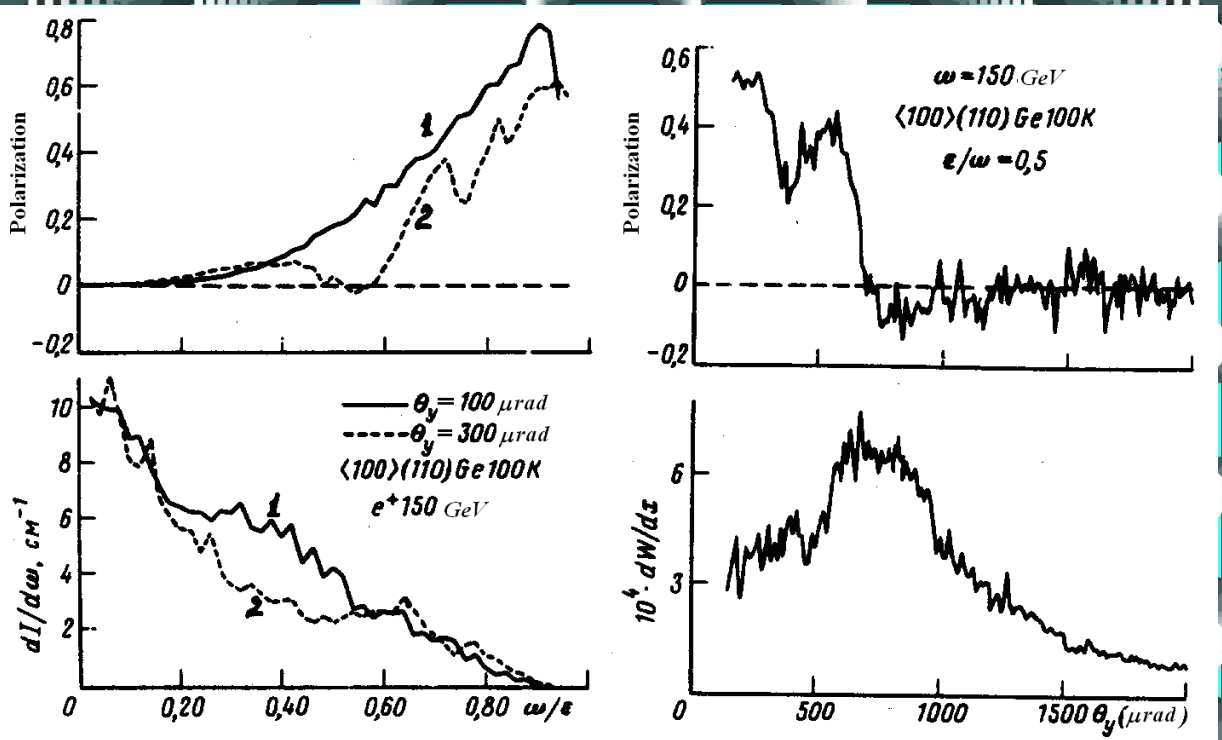
Differential number and polarization of $e^{\pm}$, produced with energy of 227 GeV *vs* the Ge(110), T = 0K, crystal bending radius. Vertical lines indicate the optimal bending radius values.

All these effects need the LHC energies for their observation

Stronger axial field allows to facilitate the Strong Field QED effect manifestation



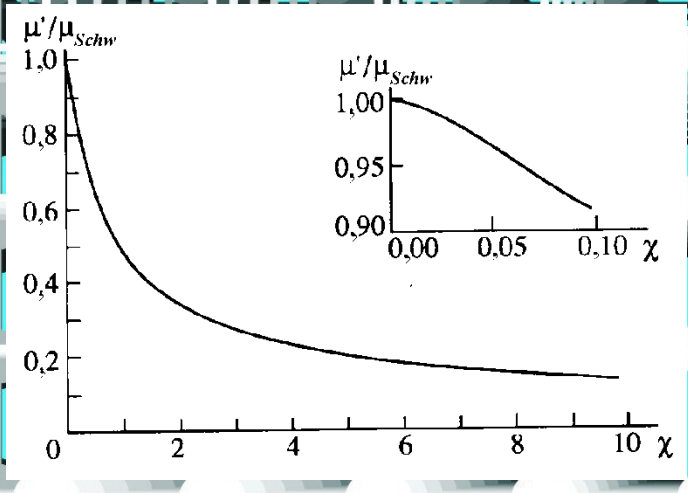
Self-polarization and polarized pair production enhanced by crystal axes



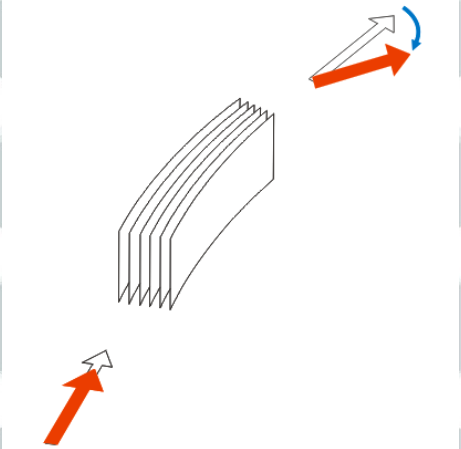
Spectral dependence of final polarization and radiation intensity of γ-quantum emission by 150 GeV positron.

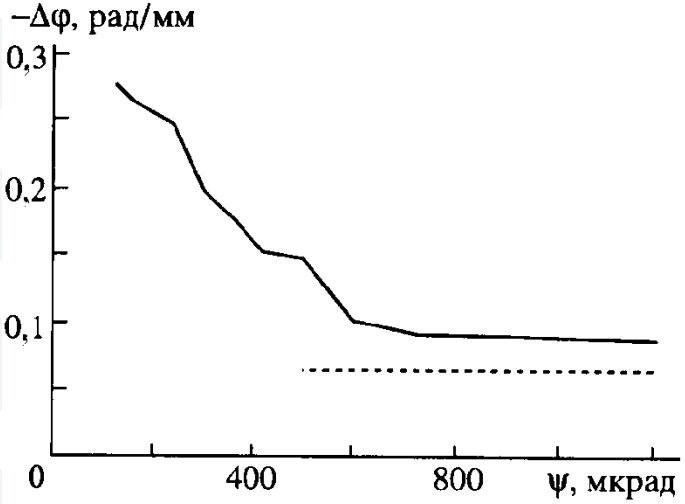
Angular dependence of differential probability and polarization of channeled positron production by 150 GeV γ-quantum.

Positron magnetic moment modification



Anomalous magnetic moment dependence on $\chi = E'/E_0$ in the uniform field, $\mu_{Schw} = (\alpha/2\pi)\mu_0$.





Angular dependence of 150GeV positron spin rotation angle revealing its magnetic moment modification.

Circularly polarized Coherent

Bremsstrahlung and Pair Production

→ talk

Radiation from leptons
in crystals, theory

A new property of electron

Electron possesses:

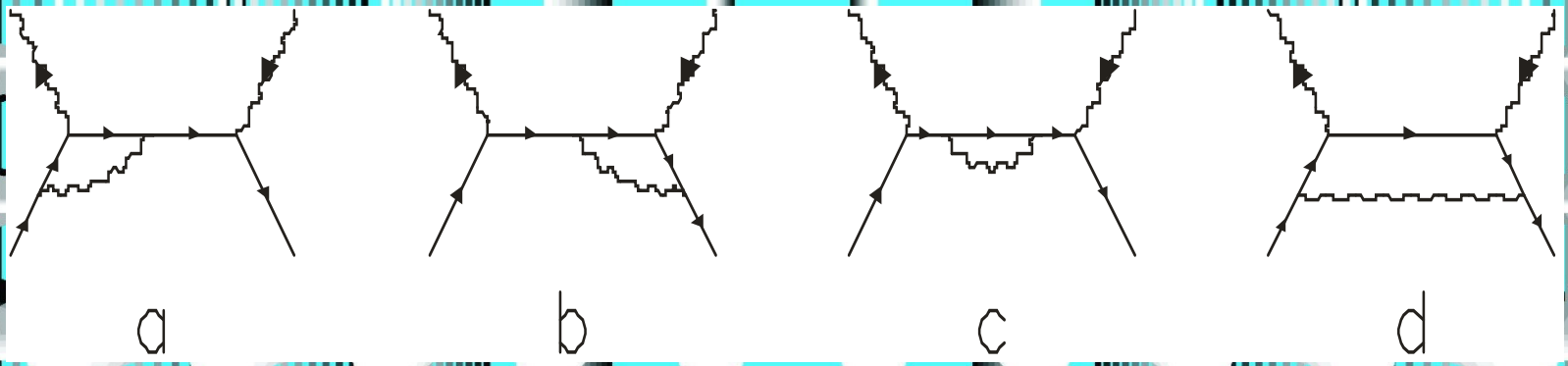
$m,$ $e,$ $\mu,$ l

and χ *(chirality)!*

+ non-applicability of the Bargmann-Michel-Telegdi equation

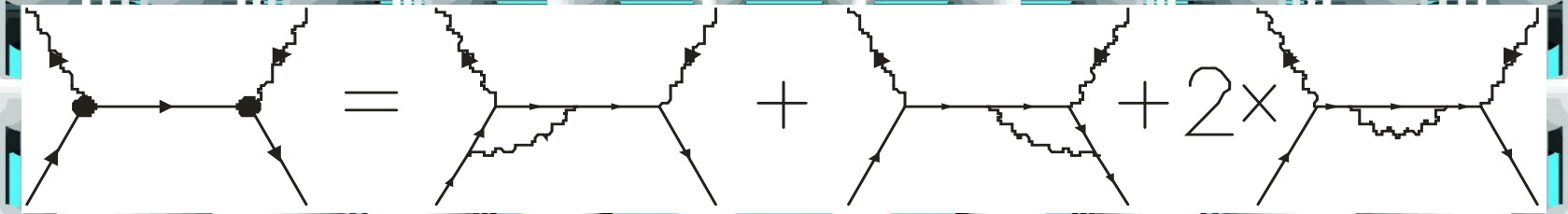
in a ***C***ircularly ***P***olarized electromagnetic ***W***ave

First-order correction to Compton Scattering



What does it describe?

Magnetic moment precession in a CPW



$$\Omega_{\mathrm{CPW}}^{\mathrm{BMT}} \simeq 4\lambda_2 \frac{H^2}{\omega_0}\left[(\mu' + \mu_0/\gamma)^2 - 2\mu' \frac{\mu_0}{\gamma} - \frac{\mu_0^2}{\gamma^2}\right]$$

$$= 4\lambda_2 \mu'^2 \frac{H^2}{\omega_0} = \left(\frac{\alpha}{2\pi}\right)^2 \lambda_2 \omega_0 \xi_0^2 \qquad (5)$$

$$\Omega^{(3)} = \left(\frac{\alpha}{2\pi}\right)^2 \lambda_2 \omega_0 \xi_0^2 \qquad (24)$$

Corresponds to the predictions of Bargmann-Michel-Telegdi equation

Chirality manifestation in a CPW

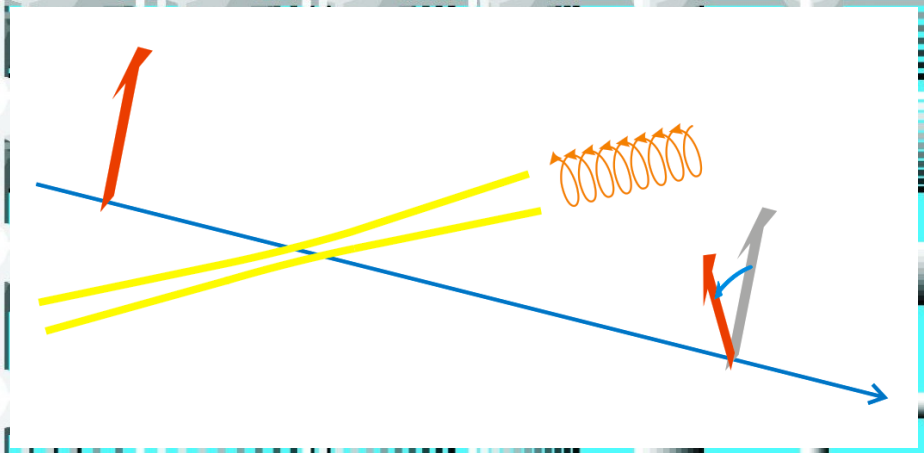
$$\Omega^{(2)} = -\frac{2H^2}{\varepsilon\omega_0}\lambda_2 f_2^{(2)}(\varepsilon) = -\frac{mH^2}{\varepsilon\omega_0^2}\lambda_2 f_2^{(2)}(\omega) \tag{25}$$

$$= \frac{\alpha}{\pi}\lambda_2\omega_0\xi_0^2\frac{1}{x}\left\{\left(\frac{2}{x}-1\right)\left[F(x-1)+\frac{\pi^2}{6}\right]-\left(\frac{2}{x}+1\right)[F(x)-\ln x\ln(1+x)]+\frac{x}{1-x^2}+\frac{2x^3\ln x}{(1-x^2)^2}\right\}$$

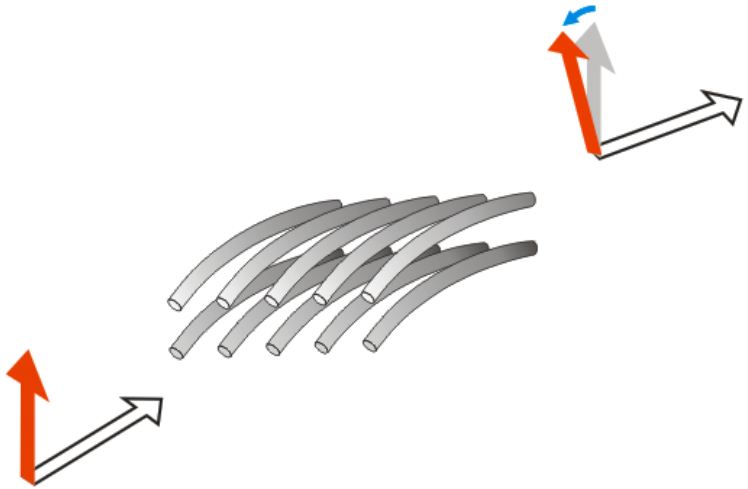
$$x \simeq 4\varepsilon\omega_0/m^2 \simeq 0.0153\varepsilon(\mathrm{GeV})\omega_0(\mathrm{eV}) \simeq 0.019\varepsilon(\mathrm{GeV})/\lambda(\mu\mathrm{m}).$$

Does not correspond to the predictions of the Bargmann-Michel-Telegdi equation***!***

Chirality can be easily observed



both in laser field



and bent crystal

Chirality can be observed both in a laser field and bent crystal

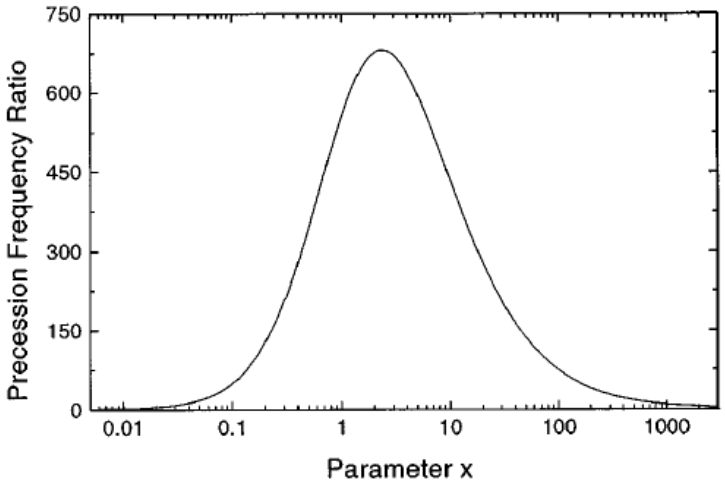


FIG. 2. The dependence on the parameter x of the ratio $R=-\Omega^{(2)}/\Omega^{(3)}$ of the contribution (25) of order α^2 to the electron spin precession frequency in a CPW in the limit of $\xi_0^2 \ll 1$, to the contribution (24) of order α^3 equal to the spin precession frequency (5), following from the BMT equation.

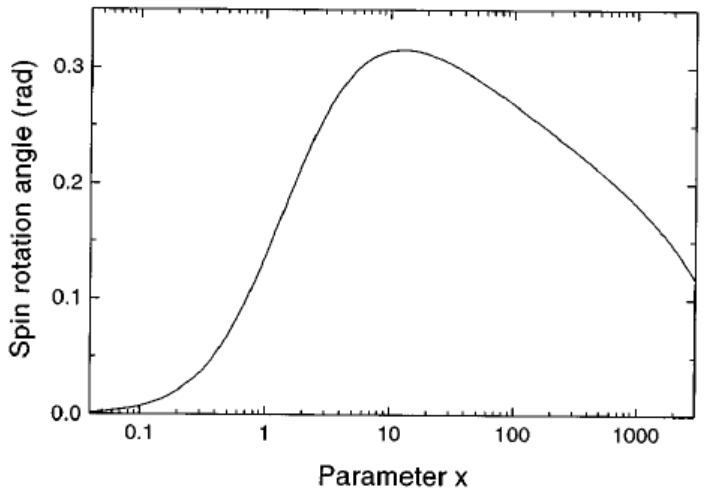


FIG. 3. The dependence on the parameter x of the rotation angle of transverse electron spin component in a CPW on a typical length of the inverse Compton scattering in the limit $\xi_0^2 \ll 1$ of nonrelativistic transverse electron motion.

$$x \simeq 4\varepsilon\omega_0/m^2 \simeq 0.0153\varepsilon(\mathrm{GeV})\omega_0(\mathrm{eV}) \simeq 0.019\varepsilon(\mathrm{GeV})/\lambda(\mu\mathrm{m}).$$

What is suggested to observe:

e^+e^- pair production in semi-uniform field crystal field
Electron radiative cooling

Strong Field QED effects observable only at the ***LHC energy:***

Synchrotron-like (**uniform field**) **dichroism**
and **birefringence** in very hard γ -region

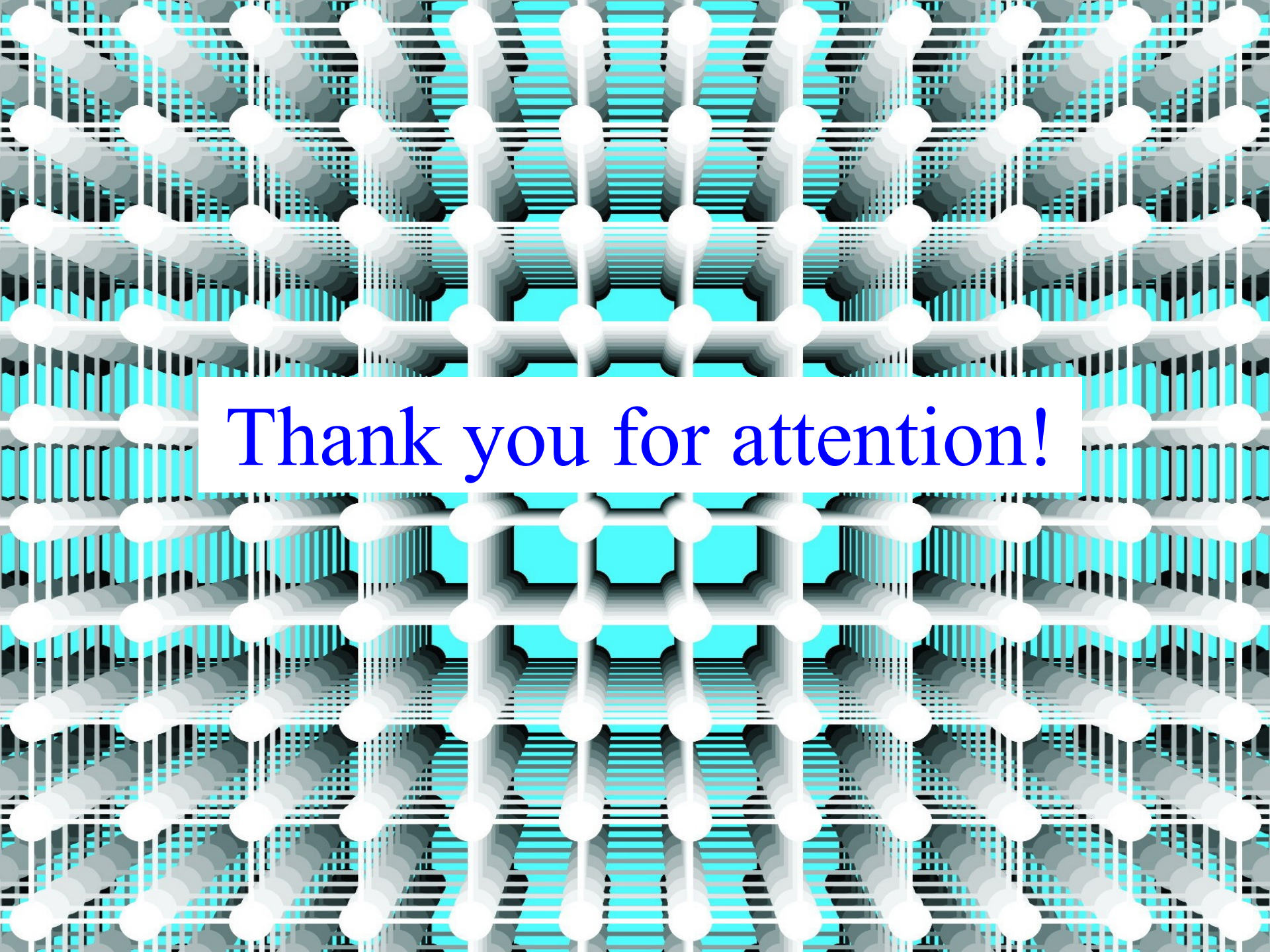
Spin effects in bent crystal:
Radiative ***self-polarization*** in bent crystals
Production of transversely ***polarized*** $e^{\pm}$
by γ-quanta in bent crystals
Positron *magnetic* ***moment modification***

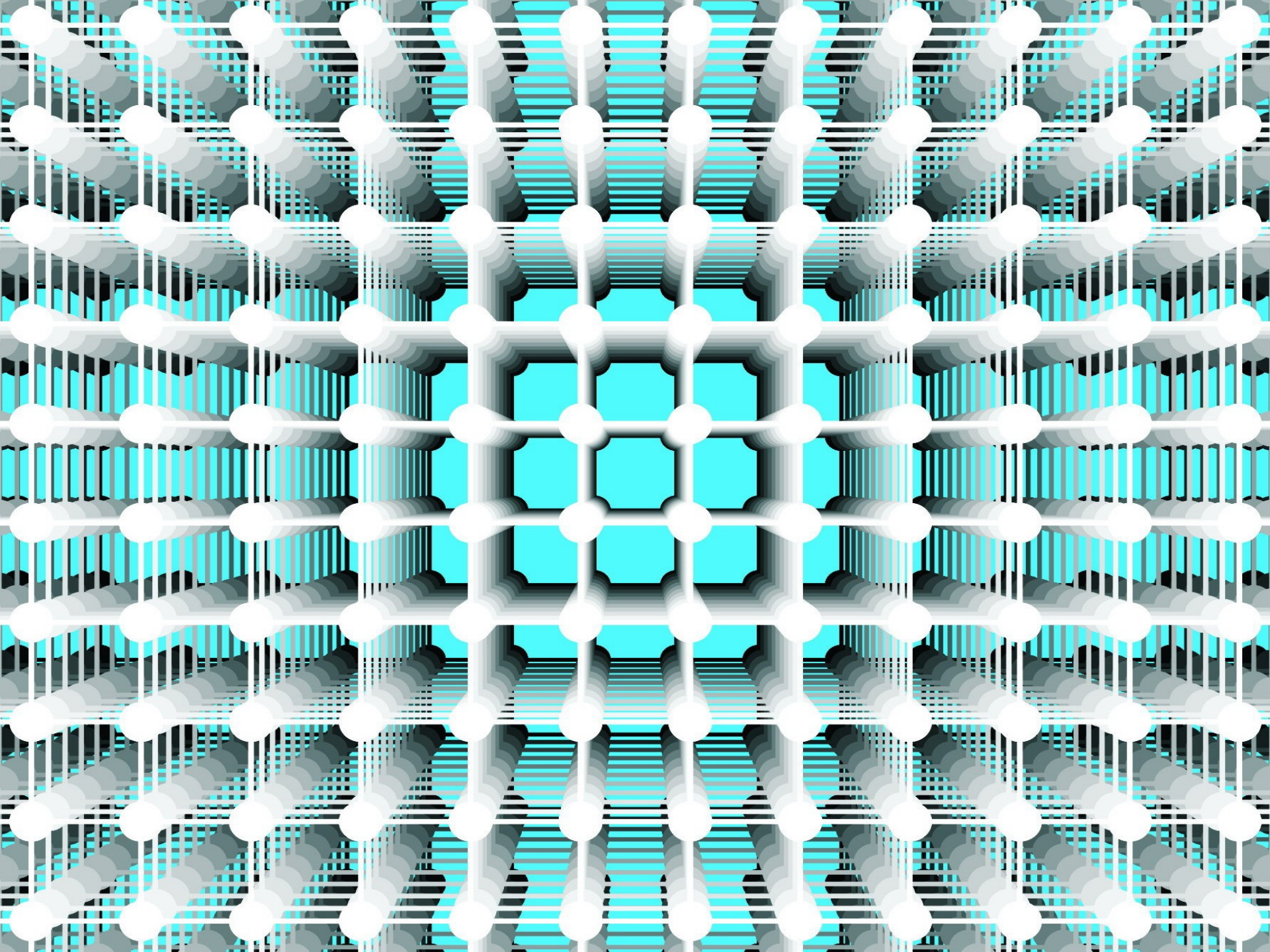
Circularly polarized Coherent Bremsstrahlung
and Pair Production.
Allow to generate:
circularly polarized gamma-quanta,
longitudinally polarized positrons,
longitudinally polarized *electrons.*
Allow to measure:
gamma circular polarization,
longitudinal positron polarization.

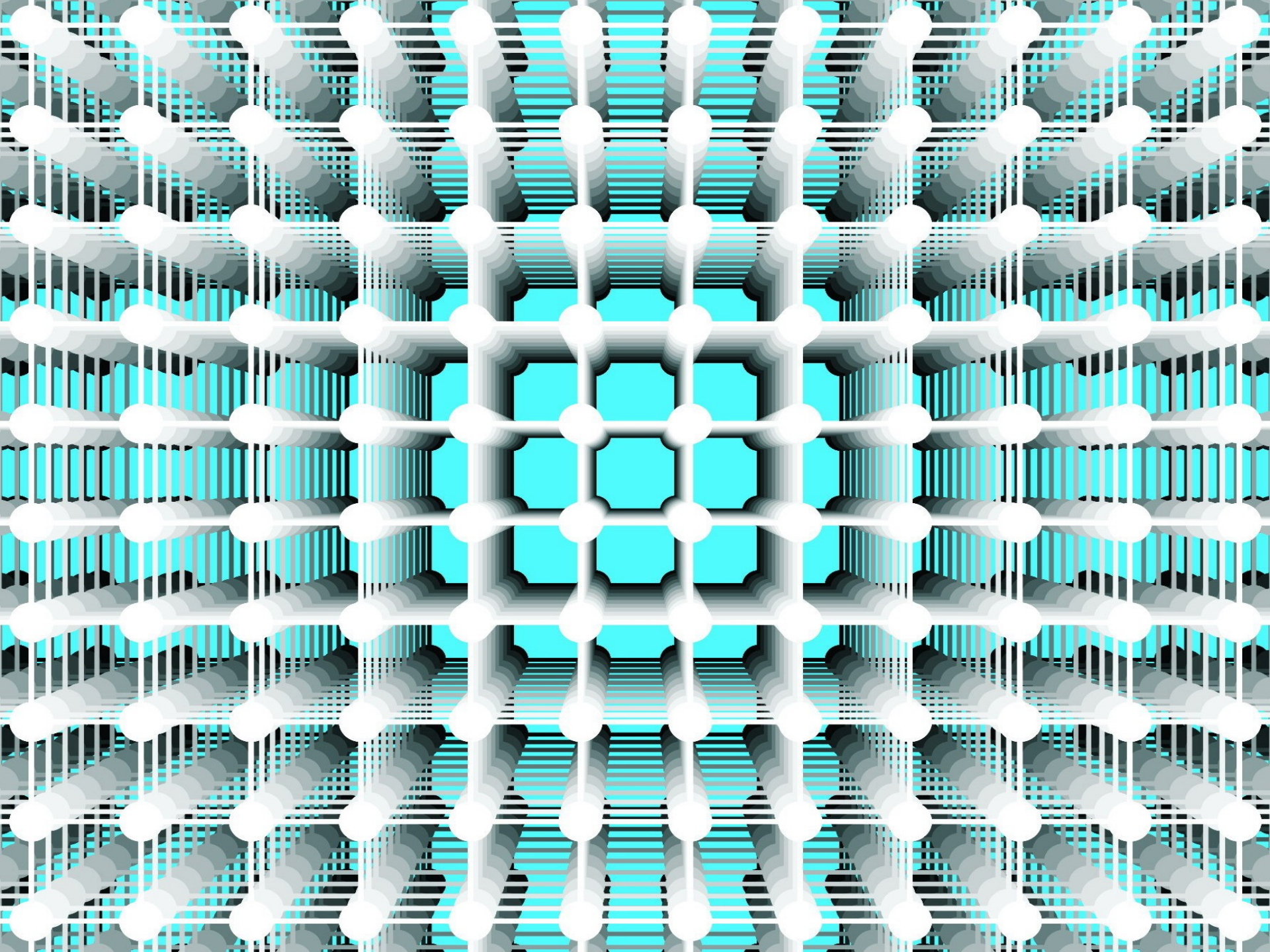
Chirality, *a* new property of electron
Can be observed in both laser field and bent crystals.

Radiation in MVROC conditions.

Incoherent radiation **suppression by crystal cut…**


Thank you for attention!





Both strong crystal fields and high γ - quantum energies allow to reach the CRITICAL FIELD

$$E_0 = \frac{m^2 c^3}{e\hbar} = 1.32 \cdot 10^{16} \frac{\mathrm{V}}{cm}$$

Table: *Maximum electric fields and critical energies for some crystals*

Crystal	***(plane) or <Axis>***	$E_{\max}$ ***GV/cm***	$\omega_{th} = \frac{2E_0}{E_{\max}} mc^2$ * ***TeV***
Diamond	(110)	7.7	1.78
	<110>	75	0.20
Si	(110)	5.7	2.39 (1.7)
	<110>	4.6	0.29
Ge	**(110)**	**9.9**	**1.37 (0.9)**
	<110>	**78**	**0.174(0.11)**
W	(110)	43	0.316
	<111>	500	0.027

* *Electric field reaches* E_0 *in ref. frame of* e^+e^- *pair produced at* $\omega = \omega_{th}$

The Mir castle

LHC opens up the possibilities to observe the strong field QCD effect of uniform field dichroism and birefringence in crystals

in optimal energy region

Also can be observed:

Strong electron magnetic moment modification

Production of polarized electrons and positrons

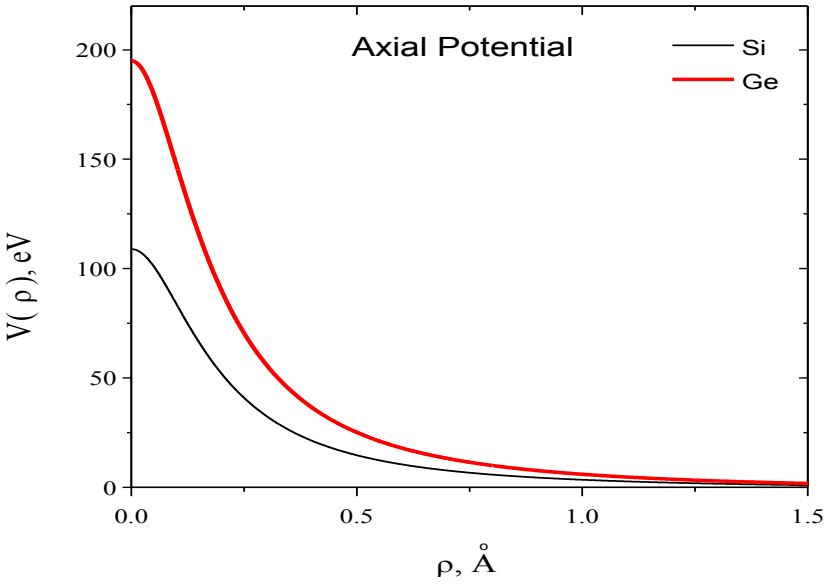
Electron radiative self-polarization

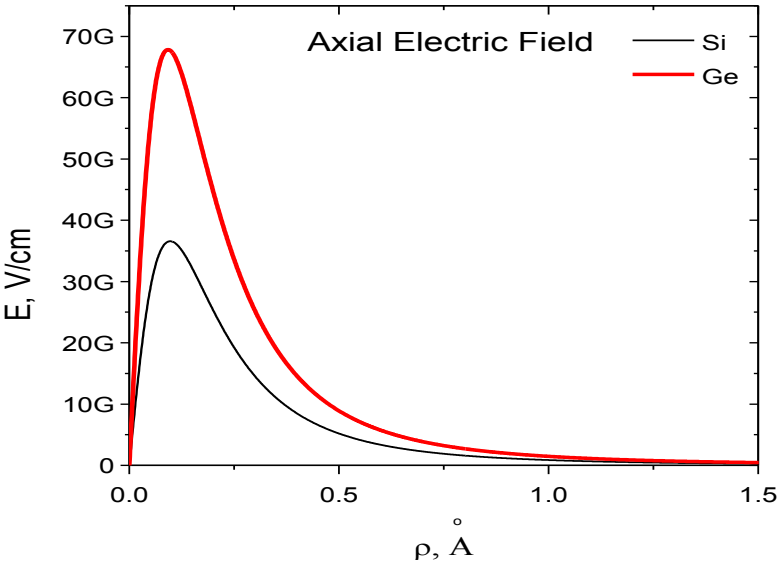
...

Outline

- Coherent bremmstrahlung and its linear polarization
- String-of-strings crystal orientation
- Polarization of crystal field harmonics
- Circular polarization of radiation of positrons channeled in bent crystals with string-of-strings orientation
- Polarization asymmetry of channeled positron production
- Other manifestations of circular polarization of the crystal field harmonic
- Conclusions

Comparison of axial potential and field strength in Si and Ge





Both potential and field strength are nearly **twice as larger** in Si than in Ge

Comparison averaged potentials and field strengths of Ge and Si planes and axes

		Si(293K)	Ge(293K)		Ge(100K)	
<110>	V_0, eV	**133**	**229**	172%	**309**	232%
<110>	E_{max},GV/cm	**46**	**78**	170%	**144**	313%
		Si(293K)	Ge(293K)		Ge(0K)	
(110)	V_0, eV	**21.5**	**37.7**	175%	**44.0**	205%
(110)	E_{max},GV/cm	**5.7**	**9.9**	1.74	**14.9**	261%

u(293K)=0.085Å, u(100K)=0.054Å, u(0K)=0.036Å

Ge cooling is very productive!

Investigating Strong Field QED effects

$$\chi = \frac{E}{1.32 \cdot 10^{16} eV/cm} \frac{\varepsilon}{mc^2}$$ – the main parameter of quantum electrodynamics

		Si(293K)	Ge(293K)		Ge(100K)	
<110>	E_{max},GV/cm	**46**	**78**	170%	**144**	313%
	χ(120GeV)	**0.82**	**1.39**		**2.56**	

$$I(\chi \ll 1) \propto E^2,$$
$$I(\chi \sim 1) \propto E,$$
$$I(\chi \gg 1) \propto E^{2/3}$$

Radiation intensity will grow like $E \div E^2$