ISSN 1561-2430 (print)
UDC 539.1

Received 16.10.2017
Поступила в редакцию 16.10.2017

**V. G. Baryshevsky, V. V. Tikhomirov**

*Institute for Nuclear Problems of the Belarusian State University, Minsk, Belarus*

# CRYSTAL APPLICATIONS IN HIGH ENERGY PHYSICS FOR NEW PHENOMENA OBSERVATION AND ACCELERATION TECHNOLOGY DEVELOPMENT

**Abstract.** When high energy particles move along the crystal axis or plane, they experience the action of an extended effective field, the strength of which by orders of magnitude exceeds that of any stationary magnet. These fields give rise to wide possibilities of new phenomena observation, particle properties measurement, high energy beam control, generation and polarization. Many of their possibilities have been predicted by Belarusian scientists and observed at CERN, FNAL, IHPEP, etc. The revealed effects of channeling efficiency increase by crystal cutting and multiple volume reflection from different atomic planes of the same bent crystal make it possible to improve the radiation protection of superconducting magnets of both the high luminocity Large hardron collider phase and the Future circular collider. A drastic enhancement of both radiation and pair production processes in crystals can influence the functioning of both the existing Compact muon solenoid electromagnetic calorimeter at CERN and Fermi gamma-telescope as well as can be applied to devise more effective calorimeters and gamma-telescopes in future. A remarkable effect of channeling particle spin rotation in bent crystals enables one to measure both magnetic and electron dipole moments of short-lived charm and beauty hyperons as well as to observe electron magnetic moment modification.

**Keywords:** crystal, high energies, electron, positron, gamma-quantum, strong field, quantum electrodynamics, collimation, radiation, pair production, magnetic moment

**For citation.** Baryshevsky V. G., Tikhomirov V. V. Crystal applications in high energy physics for new phenomena observation and acceleration technology development. *Vestsi Natsyianal'nai akademii navuk Belarusi. Seryia fizika-matematychnykh navuk = Proceedings of the National Academy of Sciences of Belarus. Physics and Mathematics series*, 2017, no. 4, pp. 20–32.

**В. Г. Барышевский, В. В. Тихомиров**

*Институт ядерных проблем Белорусского государственного университета, Минск, Беларусь*

## ИСПОЛЬЗОВАНИЕ КРИСТАЛЛОВ В ФИЗИКЕ ВЫСОКИХ ЭНЕРГИЙ ДЛЯ НАБЛЮДЕНИЯ НОВЫХ ЯВЛЕНИЙ И РАЗВИТИЯ УСКОРИТЕЛЬНЫХ ТЕХНОЛОГИЙ

**Аннотация.** При движении частиц высоких энергий вдоль осей или плоскостей кристалла они испытывают действие протяженного эффективного поля, напряженность которого на порядки превосходит величины, создаваемые любыми стационарными магнитами. Столь сильные поля открывают широкие возможности наблюдения новых явлений, измерения характеристик частиц, управления их пучками, а также генерации и поляризации последних. Многие из этих возможностей были предсказаны белорусскими учеными и наблюдались в ЦЕРН, ФНАЛ, ИФВЭ и других ускорительных центрах. Предложенные эффекты увеличения эффективности захвата частиц в режим каналирования при помощи выреза в кристалле и усиления их отклонения вследствие отражения от различных плоскостей одного кристалла позволяют усилить защиту сверхпроводящих магнитов Большого адронного коллайдера и проектируемого адронного коллайдера Будущего. Значительное усиление процесса излучения и рождения пар в кристаллах может оказывать влияние на функционирование калориметра Компактного мюонного соленоида (CSM) гамма-телескопа «Ферми», а также быть использовано при разработке более эффективных калориметров и гамма-телескопов в будущем. Эффект вращения спина каналированных частиц в изогнутых кристаллах делает возможным измерения магнитных и электрических дипольных моментов короткоживущих очарованных и бьюти-гиперонов, а также наблюдать изменение магнитного момента электрона.

**Ключевые слова:** кристалл, высокие энергии, электрон, позитрон, гамма-квант, сильное поле, квантовая электродинамика, коллимация, излучение, рождение пар, магнитный момент

**Для цитирования.** Барышевский, В. Г. Использование кристаллов в физике высоких энергий для наблюдения новых явлений и развития ускорительных технологий / В. Г. Барышевский, В. В. Тихомиров // Вес. Нац. акад. навук Беларусі. Сер. фіз.-мат. навук. – 2017. – № 4. – С. 20–32.

Both the perspectives of Large hadron collider (LHC) energy and luminosity upgrades and the start of Future circular collider (FCC) project aimed to reach the 50 TeV energy at CERN, call for the development of the physical research programme for these accelerators, spanning from the coming years to the much

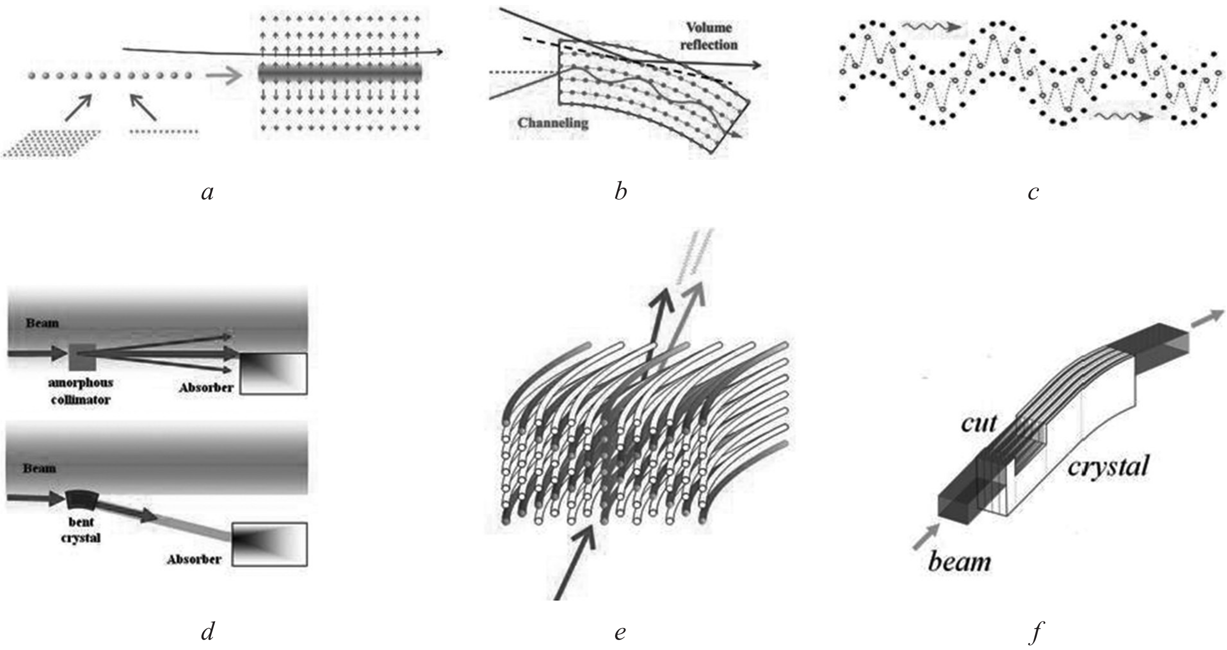



Fig. 1. The effective intra-crystal field origin (*a*) and manifestations through the coherent particle deflection (*b*), the crystal undulator (*c*), particle beam collimation enhancement by crystal application (*d*), multiple volume reflection (*e*) and the crystal cut idea (*f*). For details see the text

more distant future. The results of our more than 40-y year study of high-energy particles interaction with crystals [1–5], most of which have already been verified experimentally at CERN and other accelerator centers, constitute themselves a core of such a long-term research program for both LHC and FCC.

Intensive electromagnetic fields are crucial for many important applications. They are also the source of numerous fundamental physical phenomena, giving rise to the $e^+e^-$ pair production by γ-quanta, γ-quanta birefringence and splitting, intense synchrotron-type radiation and both electron mass and magnetic momentum modification, greatly widening the understanding of the nature of electromagnetic field, electromagnetic interaction and particle structure [6–9]. Normally these effects are discussed only in connection with the atmospheres of neutron stars. On the Earth the accessible permanent magnet field strength determines the dimensions of tokamaks, high-energy particle detectors and circular accelerators as well as the highest available particle energies [10]. The undulator field strength limits both the spectrum and brightness of synchrotron and free electron laser x-ray sources [11]. On the other hand, a small extent of the strong atomic field limits the Bethe-Heitler radiation and pair production, making it necessary to use too bulky scintillator crystals for particle detection in both high-energy physics and astrophysics.

The long-term investigation of high energy particle interaction with crystals [1–5, 12–17] revealed that the latter can serve a unique source of strong stationary electric field, unreachable in the Earth conditions and having various applications both in fundamental science and accelerator technology. Such fields exert their influence upon fast particles moving close to parallel to atomic strings and planes – see Fig. 1 *a*–*c*. Since any considerable deflection of sufficiently energetic particles occupies hundreds and more interatomic spaces, strongly correlated particle collisions with individual atoms of an oriented crystal merge in a continuous deflection process, described by a slowly varying effective intracrystal field. The latter both exceeds an electric field atomic unit of $5.14{\cdot}10^9$ V/cm [1–3,14–17] (see table) and extends in space to hundreds, thousands and more interatomic spaces, depending on particle energy.

**Typical values of effective crystal field and critical $e^\pm$ and photon energies**

| Crystal element | Z | *plane / axis* | $E_{eff}$ (GV/cm) | $H_{eff}$ (kilotesla) | $\varepsilon_{cr} = \hbar\omega_{cr}$ (GeV) |
|---|---|---|---|---|---|
| Si | 14 | *plane* (110) | 5.7 | 1.9 | 1200 |
| Ge | 32 | *axis* ‹110› | 144 | 48 | 47 |
| W | 74 | *axis* ‹111› | 500 | 167 | 13.6 |

The strong effective fields, describing correlated particle collisions with atoms in oriented crystals, readily explain the origin of the channeling phenomenon [12], the high intensity of both coherent bremsstrahlung [13, 17], *X*-ray and gamma-ray channeling radiation [18, 19], as well as the possibility of extremely fast high energy particle deflection by bent crystals, predicted by E. N. Tsyganov [20]. Below we will dwell upon the subsequent studies of crystal application for measurement of particle fundamental characteristics, narrow spectrum x- and gamma-ray generation, high energy particle beam collimation, deflection, polarization, acceleration to the highest energies and registration by both accelerator detectors and gamma-telescopes.

**1. Crystal assisted high energy particle beam collimation.** Starting from the time of the Superconducting super collider project in 1980-th [21] it became clear that an effective beam collimation system is necessary to protect the superconducting magnets. In particular, the latter will be crucial for both the High Luminosity LHC and FCC [22] projects.

A collimation system has to remove the beam halo which inevitably builds up due to the particle scattering in interaction points (IPs), intro-beam scattering and scattering on resudual gas, non-linearities of magnetic field, RF noise, accelerator elements imperfections, etc. [23]. Each of these effects can increase the particle amplitude of betatron and some of them − of synchrotron oscillations. Further continuous diffusional boil up of the particle ascillation amplitude bring them to the collisions with magnets, detectors, quadrupokes, etc. At that the irradiation of superconducting magnets is most dangerous since it can easily induce their quenching.

At present amorphous collimators are used at the LHC which deflect halo particles only − see the up part of Fig. 1, *d*. The amplitude build up induced therewith is stochastic in nature and needs a considerable number of the collimator hits by particles to reach the absorber aperture. Most of the halo sources [23] intensify with the beam current rise, strengthening the requirements imposed on the collimation system. It is recognized for a long time that the latter can be more easily met using the effects of particle correlated scattering in crystals (see Fig. 1, *d*). Of them the most widely known is the channeling particle deflection in bent crystals [20], which also provides an alternating particle deflection in crystal undulators [25, 26] (see Fig. 1, *c*). Besides channeling, the volume reflection effect in bent crystals [24] is also important, which both provides for a considerable coherent particle deflection in a sequence of bent crystals [27] and intensifies the random particle deflection in the channeling collimation mode.

However, both of the effects from Fig. 1, *b*, widely used by the latter, possess considerable shortcomings. Namely, channeling is characterized by the limited capture efficiency of 85 % or less, while volume reflection is able to deflect particles by the angles which do not exceed the critical channeling angle much. To overcome these limitations, the ideas of crystal cut [4] (Fig. 1, *f*) and multiple volume reflection in one crystal (MVROC) [5] (Fig. 1, *e*) have been introduced, respectively. The first allows the planar field of a less than a quarter channeling period crystal plate (see Fig. 1, *f*) to redirect incident particles to the center regions of the inter-planar channels providing for the channeling efficiency rise from 85 to 98–99 % (see Fig. 2). The MVROC effect, which has been already observed in a number of experiments [28–30], originates from the possibility of volume reflection from different planes

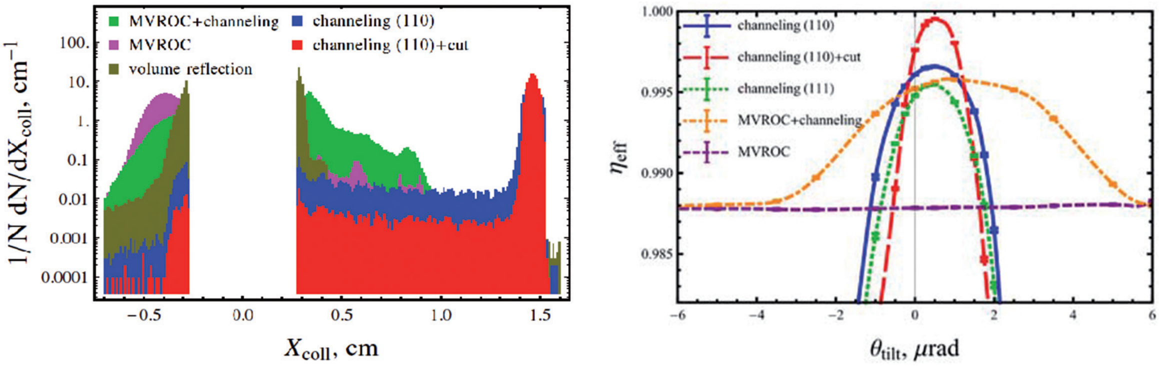



Fig. 2. Collimated particle distribution in transverse coordinate (left) and collimation efficiency dependence on crystal collimator misalignment (right) for the different types of suggested crystal collimators

of the same bent crystal resulting in about five-fold increase of the deflection angle. Additional MVROC advantage consists in the possibility of its realization in parallel with the channeling by either "vertical" or some skew plane [31] in the same crystal.

Fig. 2 compares different crystal assisted collimation approaches. Its left hand side shows corresponding transverse coordinate distributions while the right one − the orientational dependence of different collimation method efficiency. The former demonstrates both the deflection amplification by MVROC and decrease of non-channeling particle fraction by the cut, while the latter − both the extremely high collimation efficiency of the crystal cut and the large acceptance of the collimator using MVROC effect. An empty space on the left hand side corresponds to the small particle deflection leaving the latter on a stable orbit.

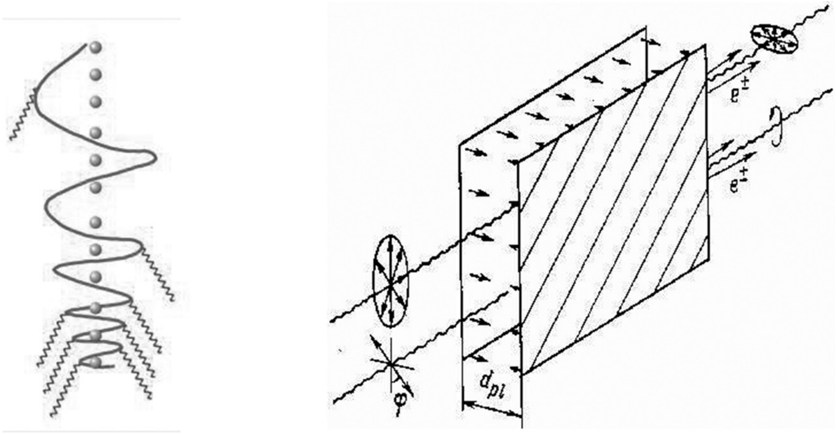
**2. Radiation and pair production enhancement in crystals and its applications.** Lorenz boost magnifies the transverse effective crystal field [1–3, 14–17] up to the critical Schwinger one $m^2c^3/e\hbar = 1.32{\cdot}10^{16}$ V/cm (or $4.4{\cdot}10^9$ tesla) in the reference frame of radiating or being produced $e^\pm$ with the critical energy $\varepsilon_{cr} = \hbar\omega_{cr}$ of tens of GeV (see table). The secondary electron-photon beams of up to 300 GeV the energy, being available since 1970-th at Super proton synchrotron at CERN, were used to observe experimentally the effects inherent to the atmospheres of neutron stars at CERN in 1980-th [1–3, 14–17].

A possibility of increase of both the intensity of gamma-quantum radiation by electrons (positrons) and the rate of $e^\pm$ pair production (PP) by gamma-quanta, induced by the coherent particle interaction with coordinated atoms in crystals, was predicted in 50-th and widely explored experimentally [13, 17]. However, the "Coherent Bremsstrahlung theory" [13] (see also [15, 17]) was based on Born approximation, which described all the particles in terms of plane waves, completely neglecting the crystal field influence on particle motion, on channeling process in particular. As a consequence, the Coherent Bremsstrahlung theory [13] incorrectly predicted both the unphysical growth of the probabilities of radiation and PP with energy and a complete suppression of both of the latter at any energy at zero angle of particle incidence with respect to crystal planes and axes.

Both the correct energy and orientational dependencies of the coherent processes in crystals at high energies were predicted by the theory [32, 1–3], based on the consistent consideration of particle interaction with the averaged field of atomic planes and strings [12], instead of plane wave approximation. In particular, it was demonstrated in [32] and, later, in [14–16] that, starting from the particle energies from several tens to hundreds of GeV, depending on the crystal chemical element and axis or plane choice, both radiation and PP processes shift to the smallest particle incidence angles, becoming more and more similar to that in the uniform electromagnetic field, justifying thus the name of synchrotron-type radiation and PP processes [1–3, 14–17]. Essential predictions for the synchrotron-type processes in crystals are saturation of their intensity, reached after one-two order growth in the TeV-energy region at the smallest particle incidence angles, as well as the large number of accompanying polarization and spin effects [1–3, 32].

Some of the predicted features of synchrotron-type processes in crystals have been already observed in the large number of experiments, the most significant results of which were the 7–8 time increase of PP probability at zero incidence angle [33, 34] as well as a sudden observation [35] and immediate explanation [36–38] of the radiative cooling effect. The nature of the latter, illustrated by Fig 3, *a*, consists in the electron orbit shrinking to the region of the highest axial field, induced by the electron radiative energy loss. In its turn, the latter is further enhanced by the orbit shrinking making the cooling process self-accelerating and influencing the channeling particle dynamics stronger, than the ubiquitous Coulomb multiple scattering process. The radiative cooling effect was further observed in C, Si, Ge and W crystals of different thickness [39, 40]. Its role will increase for long with the electron energy rise.

Radiative cooling effect is essential for futuristic schemes of muon and proton acceleration to petaelectronvolt and higher energies [10]. The point is that channeling effect is supposed to be used both in the future circular accelerator version for particle deflection and in the linear one for particle motion control. In both of them radiative cooling role consists in suppressing the dechanneling. It should be pointed out, that, contrary to electrons, the radiative cooling of both muons and protons proceeds in the dipole regime of channeling radiation for which a practically complete transverse oscillatory motion damping is possible without considerable loss of total (longitudinal) energy.




*a* *b*

Fig. 3. Synchrotron-type radiation and pair production manifestation through the radiative cooling (*a*) and crystal dichroisam and birefringence (*b*). For details see the text

**3. Electromagnetic shower acceleration in high energy particle detectors.** A number of homogeneous electromagnetic calorimeters (BELLE, BaBar, CMS ECAL, KTeV, PANDA, etc.) and some existed and designed gamma-telescopes use crystalline scintillators for high-energy electron (positron) and gamma-quantum total energy measurements. The structure of scintillator crystals clearly has to influence the performance of the existing devises. In fact, both the discrepancy of shower development in different crystals and disagreement between the data and the simulations in the lateral dimensions of the electromagnetic showers have been observed in PWO already in the test beam experiments in 1990-th. To clarify the scale of crystal structure influence on the CMS ECAL performance and on the Higgs boson mass measurement in particular, we simulated recently the profile of energy deposition by electromagnetic showers induced by detected $e^{\pm}$, $\gamma$ in a 23 cm long ECAL lead tungstate (PWO) crystals combining the power of radiation and pair production probability evaluation by Baier − Katkov formula with that of the extended electromagnetic shower simulation by GEANT4 [41].

The first realistic simulation [38] of the electron radiation in a quite thin 185 μm Ge crystal, despite they have been conducted on a supercomputer, yielded quite a modest statistics. The present simulations of radiation in 1–2 mm crystals [42–45] still remain time consuming for a PC. This made it clear [41] that the simulations of electromagnetic shower development in much thicker 23 cm PWO crystals of ECAL CMS would be impossible without drastic simplifications. In order to estimate the maximal possible effect of crystal structure influence on electromagnetic shower development as well as to accelerate the simulation procedure, one can consider the case of zero angle particle incident with respect to a crystal axis having in mind that at high particle energy, say, above 5–10 GeV, for which the crystal structure influence is most significant, the angles of particle deflection from the initial particle momentum direction will not exceed the typical angle of synchrotron-type radiation and PP, which reaches a milliradian for PWO [2]. To neglect the rear and difficult-to-treat processes of channeled particle radiation [36–38] and PP, particle incidence angles were limited from below in [41]. Both the radiation and PP probabilities were simulated in a 10 μm PWO crystal at some discrete initial particle energies. Initial particles were directed at the incidence angles of 0.2÷0.5 mrad with respect to <100> (equivalent to <010>) PWO crystal axis when their trajectories were simulated. For that, as in [42–45], the particle stepwise motion in the averaged potentials of PWO crystal atom strings was evaluated by integration of relativistic mechanics equation and the particle incoherent scattering sampled at each trajectory step. The obtained realistic electron (positron) trajectories, along with Baier−Katkov method, were used, as in [42–45], to evaluate both the radiation intensity and PP rates.

To take advantage of the power of simulations of energy deposition by electromagnetic showers by GEANT4 at the minor modifications of the latter, the integral PP probability and radiation intensity were introduced to GEANT4 as the multipliers of Bethe-Heitler cross sections of PP and radiation respectively. The key feature of both PP probability and radiative energy loss rate was the saturation of their growth at practically the same level of a 7–7.5-time excess over the Bethe-Heitler values at the energies of about 1 and 0.4 TeV, respectively. It should be mentioned that, introducing only the integral PP probability and radiation intensity into GEANT4, we neglected all the specific features of the secondary particle spectra of synchrotron-type radiation and PP processes, assuming their Bethe-Heiler behavior. Both the number and severity of all the undertaken approximations demonstrate the real complexity of the direct simulation of extended electromagnetic showers in crystals, which should be considered as a long-term general investigation goal. of this. Nevertheless, the simplified simulation method described above allows one to reveal the scale of crystal structure influence of the electromagnetic shower development in a typical ECAL barrel PWO crystal cell, having 22×22 mm$^2$ front face and 23 cm length, equal to 25.8 radiation lengths, illustrated by Fig. 4, which compares the energy deposition profiles by the electromagnetic showers simulated through both the standard and modified GEANT4 applications, designated as "Geant4" and "mod Geant4". One can see that the main consequences of the modification of both the radiation and PP processes by the PWO crystal structure are the shift of the electromagnetic shower maximum towards the crystal entrance by 2 cm (2.3 radiation lengths $X_0$) and 3.6 cm (4.0 $X_0$); the acceleration of the shower development rate at the crystal entrance by about 5 and 7 times and the reduction of longitudinal energy leaks through the rear crystal face from 1–1.5 % to 0.1–0.2 % at 100 GeV and 1 TeV, respectively.

The demonstrated significant modification of electromagnetic shower development make it possible to discuss the influence of the PWO crystal structure on the CMS ECAL performance in general. During CMS ECAL operation, the contributions to the resolution due to the channel-to-channel response spread must be kept to within 0.4 %, in order to retain the necessary ECAL intrinsic resolution [46]. The dominating contribution to the standalone channel energy resolution for high-energy electron and photon showers is given by the constant term of the energy resolution parameterization. Though the contributions of non-uniformity of the longitudinal light collection, energy leakage from the rear side of the calorimeter, single-channel response uniformity and stability to the constant term had been taken into consideration, the observed energy resolution was not correctly described by the Monte Carlo simulations and additional Gaussian smearing was found has to be applied upon a detailed simulation of the readout stage [46]. Also the enhanced fluctuations of the depth of the longitudinal centre of gravity can influence the photon coordinate reconstruction.

We conjecture that the discrepancy of the GEANT4 predictions with the experimentally observed ECAL energy resolution may be ascribed to the crystal structure influence on both the radiation and pair production processes which has modified the shower development in PWO crystals. First, the dependence of the "crystal structure effect" on the orientation of particle incidence direction with respect to the PWO crystal structure has to violate the main assumption of the φ-symmetry method, which originates from the reason that the total deposited transverse energy should be the same in all the crystals at the same pseudorapidity. Second, the dependence on the particle energy will be the origin of the nonequivalence of the calibration methods using invariant masses of the photon pairs from the $\pi^0$- or η-mesons and

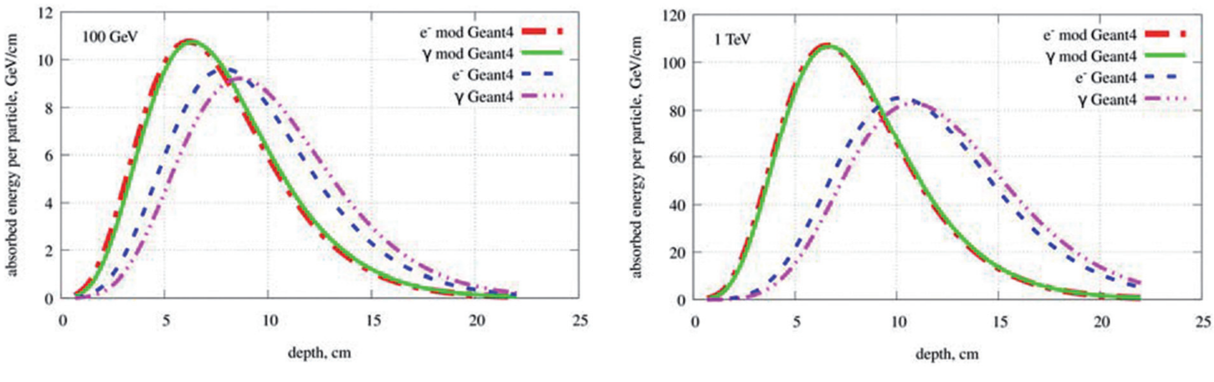



Fig. 4. Dependence of the energy absorbed per incident particle per unit PWO crystal length on the depth of the development of the electromagnetic shower initiated by 100 GeV (left) and 1 TeV (right) electron and gamma-quantum. One pair of curves was simulated by the direct GEANT4 application while another − by GEANT4 supplied by the radiation and PP probabilities multiplied by the normalization coefficients reflecting the probability increase in crystals

the isolated electrons from both *W*- and *Z*-boson decays. That is why the application of the intercalibration constants, obtained using both the φ-symmetry method and the $\pi^0$, η, *W* and *Z* decay products, was accompanied by neglecting the channel response dispersion induced by the PWO structure influence on the shower development in PWO crystals, which stipulated the additional Gaussian smearing necessity reported in [46]. The only way both to understand the origin of the real ECAL CMS energy resolution and to clarify the possibilities of its improvement is to start a direct study of the role of the PWO crystal structure influence on the ECAL CMS performance.

In future the acceleration of electromagnetic shower development in crystals can be applied for the thickness reduction of both electromagnetic calorimeters and gamma-telescopes intended for application in the TeV-energy region. The same can be also used to increase the signal from the earliest stage of high-energy $e^\pm$ and γ registration. The strong orientation dependence of the radiation and pair production can be used for the construction of gamma-telescopes with sub-milliradian angular resolution.

The simple formulae of the radiation and PP processes in a uniform field, even after a considerable improvement, can be applied at the smallest incidence angles only. Since the quantum features of particle motion in the averaged crystal field become negligible at such $e^\pm$ energies and since the radiated photon energy becomes comparable with that of emitting $e^\pm$, Baier – Katkov semi-classical method proves to be the most suitable tool for both synchrotron-type radiation and PP process treatment [8, 15]. A direct numerical integration of Baier – Katkov formula, which was both practically implemented and compared with experiments in [42–45], now allows one to extend the study of the role of radiation and PP enhancement to the real conditions in crystal calorimeters and gamma-telescopes. Fig. 5 illustrates the orientational dependence of PP probability in Si crystal which can be used to provide a sub-milliradian angular resolution of the space gamma-telescope [47].

According both to the prediction of QED of phenomena in strong electromagnetic field [6–9] and the theory [1–3, 32] of PP process in crystals, synchrotron-type PP is accompanied by strong dichroism and birefringence phenomena. On the strength of effective crystal field symmetry, the latter can be freely observed in the field of crystal planes only – see Fig. 3, *b*. Since the strength of the effective field of the latter is nearly one order of magnitude lower than that of atomic strings, the threshold energy of synchrotron-type PP is respectively higher and could not be reached in first experiments [33, 34] on synchrotron-type PP – see table and Fig. 6. However an observation of the synchrotron-type dichroism and birefringence phenomena will become possible at the LHC gamma-beams, the energies of which will definitely exceed one TeV. Synchrotron-type crystal dichroism and birefringence phenomena make it possible to generate polarized high energy gamma-beams and to furnish both high energy electromagnetic calorimeters and gamma-telescopes with the polarization measurement ability.

**4. Crystal undulators.** Both the atomic strength and sub-atomic transverse scale of variation of the effective field of crystal planes result in one another perspective crystal applications for the development of quasi-monochromatic sources of *X*- and gamma-radiation. High-intensity semi-monochromatic *X*-ray beams are important for both fundamental and applied research. Nowadays, intense *X*-ray beams

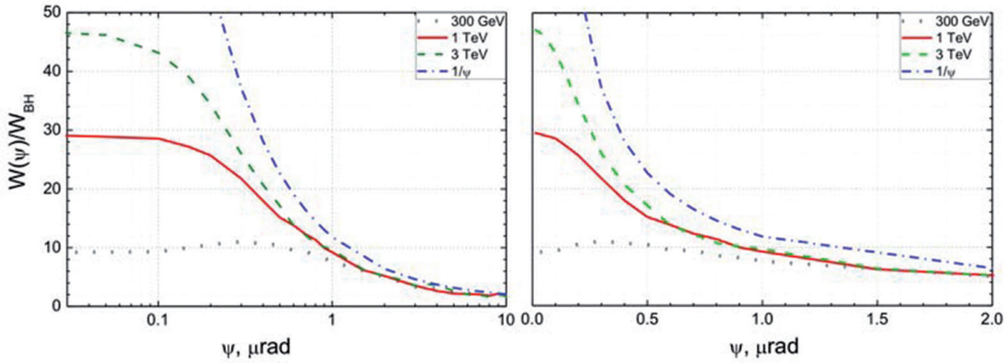



Fig. 5. PP probability dependence on the γ-quantum angle of incidence on the <110> Si axis for 0.3, 1 and 3 TeV γ-quantum energies. PP probability is measured in the units of Bethe-Heitler probability. The curves marked by 1/ψ demonstrate the asymptotic large incidence angle PP probability behavior

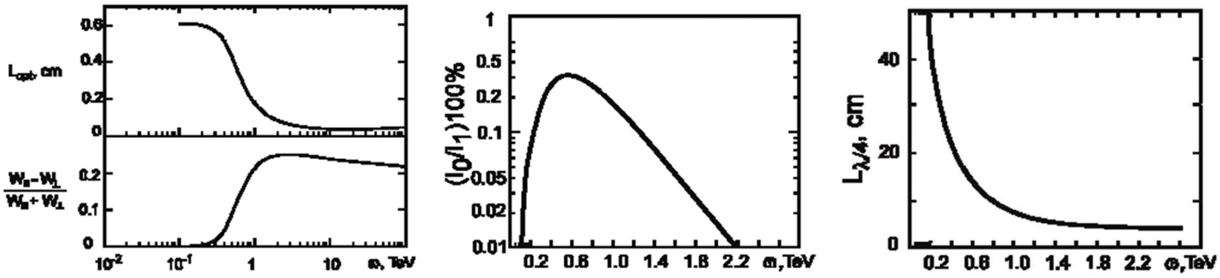



Fig. 6. Optimal length of the dichroic synchrotron-type polarizer (up, left) and the corresponding pair production asymmetry (bottom, left), quarter-wave attenuation coefficient (middle) and thickness (right)

are produced at synchrotrons by electron radiation in magnetic undulators [11], forcing electrons to a periodic oscillatory motion, resulting in semi-monochromatic electromagnetic radiation. With currently available magnetic undulators, the minimum achievable oscillation period of the order of centimeters limits the generated *X*-ray energy to a few tens of keV at the highest synchrotron electron energies [11].

An availability of the harder *X*-ray or even γ-ray sources will pave the way to the development of innovative applications [48, 49]. For instance, a γ-ray beam can induce nuclear reactions through photo-transmutation, i. e., it can be applied for changing the atomic numbers of nuclei. This technique can be employed for eliminating nuclear waste by transmuting the contained ultra-short-lived nuclei to the isotopes used in medicine. Another possible application lies in the field of photo-induced nuclear fission to induce the fragmentation of heavy nuclei resulting in the production of medium mass neutron-rich nuclei.

In order to produce photons with the energies most suitable for many applications, undulators with a shorter periods, than that of the currently available FELs, are needed. Various constructions of mm-period undulators have been proposed suffering from low magnetic field strength, need of expensive cooling system and strict requirements on beam quality [48].

A more promising solution for reaching higher photon energies is the usage of a crystalline undulator (CU) [25, 26, 3] − see Fig. 1, *c*. In the latter, the electrons (positrons) are forced to an oscillatory motion by the strong effective field, generated by the atoms of aligned crystal planes or axes. For instance, the Si (110) planes act on charged particles with an effective electric field of about 6 GV/cm (see table), which is equivalent to a 2 kT magnetic one. CUs can be formed [25, 26, 48–50] by ultrasonic or electromagnetic waves, by periodic modulation of Ge content $x$ in the $Si_{1-x}Ge_x$ super-lattice, by periodic micro-scratches on the crystal surface, by thin strips producing periodic surface strain through the grooving method.

Though CUs were proposed quite long ago [25, 26], reliable realistic description of their functioning has become possible only after the development and wide experimental validation of the corresponding simulation tool [42–45]. The latter was applied for an extended analysis of both conducted and suggested experiments in [50, 51]. In particular, limited perspectives of any electron CU was demonstrated [50] as well as an "optimal positron CU" construction was elaborated [51]. First of all, trying to assure both the maximum intensity and minimum spectral width of the positron CU radiation, we concluded that the "optimal CU" should work at the positron energy of a few GeV. Than, fixing the latter at 1.5 GeV, the "optimal CU" period, amplitude and length of, respectively, 12 μm, 0.4 nm and 0.48 mm as well as the radiation spectrum width of 3 % (see Fig. 7) and quantum yield of $10^{-3}$ $\gamma/e^{+}$ were establish by means of thorough optimization.

**5.1. High energy particle spin rotation.** The phenomena [1–3, 52] of spin rotation and depolarization of high-energy particles in crystals provide unique possibilities of measuring anomalous magnetic momenta of short-lived charm and beauty hyperons as well as of quadrupole moment of Ω-hyperon in the energy range of both LHC and FCC. In addition, crystals with polarized nuclei make it possible to measure polarization of the short-living particles as well as the characteristics of spin-dependent strong and, both parity and time symmetry violating weak interaction of the same with nuclei.

Though magnetic momenta are important characteristics of elementary particles, their values have not been measured for many of them, as for charm and beauty baryons and τ-lepton. The problem is the small

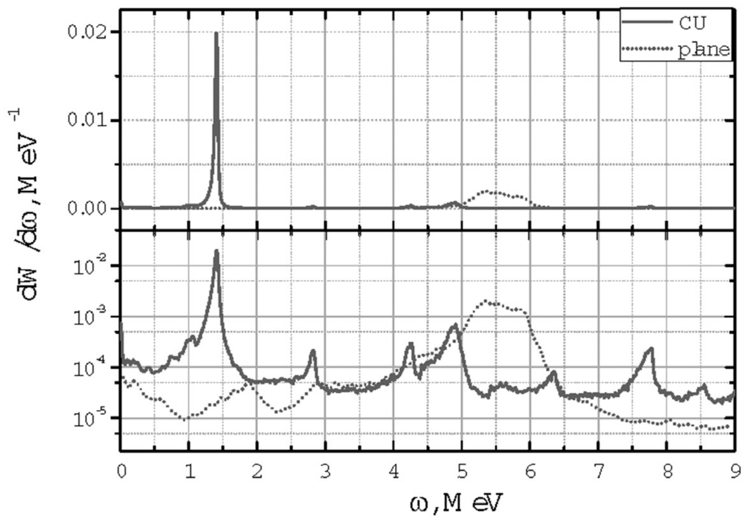



Fig. 7. Spectral distribution of the radiation emitted by a 1.5 GeV positron in the linear (top) and logarithmic (bottom) scale: solid line − in the Si (110) CU and dotted line − in a plane 0.48 mm Si (110) crystal. Positron beam incidence angle equals zero, its angular divergence is 10 μrad and radiation collimation semi-apex angle is 42.6 μrad

lifetime of both charm ($\tau = 2\cdot 10^{-13}$ s for $\Lambda_c^+$, $3.5\cdot 10^{-13}$ s for $\Xi_c^+$) and beauty baryons, produced by TeV energy protons, results in a few-cm decay length, making it impossible to measure their anomalous magnetic momenta by the conventional method. However, an application of the strong crystal field can change the situation essentially for the better.

Indeed, the phenomenon of spin rotation of particles channeling in bent crystals (see Fig. 8) was predicted in [52] and successfully tested on $\Sigma^+$ hyperon at Fermilab [53]. The point is that a particle channeling in a bent crystal is, in average, deflected by the action of an atomic-scale effective electric field $E$ (see table). The latter induces the spin preseccion with the angular frequency [52]

$$\omega = 2\mu' E / \hbar,$$

proportional to the particle anomalous magnetic moment $\mu'$. The high crystal field strength results in the radian-scale spin rotation angle per the decay length of charm and beauty baryons produced at either the LHC or FCC [54]. In addition, it was also shown in [54], that despite the decrease of the Lindhard angle at high particle energy, the necessary statistisc acquisition time remains limited to 10−100 hours, acceptable for the future fixed-target experiments at both the LHC and FCC.

The preparations for the experiment on $\Lambda_c^+$ magnetic moment measurement using the spin rotation in a bent crystal [55] has resently been started by UA9 CERN collaboration [55], while nother group [56] has recently proved that the same makes it possible to tighten the limitations on the $\Lambda_c^+$ electric dipole moment up to the level of $d < 10^{-17}\,\mathrm{e}\cdot\mathrm{cm}$.

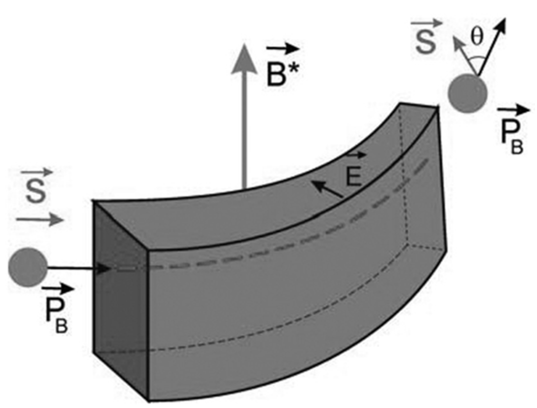



Fig. 8. Spin rotation in a bent crystal

The efficiency of the spin rotation effect [52] in a bent crystal is assured by the stability of channeling motion inherent to positively charged particles only. However, along with the positively charged short-lived hyperons, a family of negatively charged ones also exists, bottom baryons $\Xi_b^-\left(\tau = 1.56\cdot 10^{-12}\,\text{s}\right)$ and $\Omega_b^-\left(\tau = 1.1\cdot 10^{-12}\,\text{s}\right)$ in that number. The strong dechanneling processes of the latter makes it neccesary to search for an alternative method of their magnetic moment measurement.

**5.2. Spin depolarization of both charged and neutral particles in crystals.** When a particle travels through a crystal at some angles to its axis, effective crystal field of atomic strings changes randomly on the particle trajectory [17]. These fluctuations of the strong effective crystal field induce stochastic spin rotations, resulting in a dispersion of the particle polarization directions behind the crystal [3, 57]. Since the polarization rotation angles are also proportional to the particle anomalous magnetic momentum, the latter can be extracted from the result of simulataneous measurement of the mean-square scattering angle and depolarization degree. This alternative method [3, 57] of anomalous magnetic momentum measurement can be realised in stright crystals and applied to both positively and negatively charged short-lived baryons, to the number, for bottom baryons.

Among the hyperons, there is also a family of short living neutral ones: $\Xi_c^0$ hyperon has a lifetime $\tau \approx 1.1\cdot 1^{-13}\,\text{s}$, $c\tau \approx 33.6\ \mu m$, $\Omega_c^0 - \tau \approx 7\cdot 10^{-14}\,\text{s}$, $c\tau \approx 21\ \mu m$, and $\Lambda_b^0 - \tau \approx 10^{-12}\,\text{s}$, $c\tau \approx 427\mu\text{m}$. It has been revealed [57] that depolatization of the neutral particles increases sharply in crystals as well. The estimates show that the time for observation of this effect for the neutral charm hyperons is of the same order as that of the spin rotation effect for charged $\Lambda_c^+$ hyperons in a bent crystal. Though the production rate for the neutral bottom baryons is noticeably smaller than that for the charged ones, the increase of the proton energy in future will make it possible to measure their anomalous magnetic momenta for about 200 hours.

It should be also mentioned that, as reported in [1−3], the experiments on electron and positron spin rotation in bent crystals provide a unique possibility for studying the effects of quantum electrodynamics of a strong field [6–9], namely, the dependence of the anomalous magnetic moment on both the electric field strength and particle energy [6, 8]. The same possibility exists in observation of both electron and positron spin depolarization.

More detailed consideration of the diverse new possibilities of measurement of particle proper and interaction characteristics can be found in [1–5, 57].

## References

1. Baryshevsky V. G. *Channeling, Radiation and Reactions in Crystals at High Energies.* Minsk, Belarusian State University, 1982. 256 p. (in Russian).

2. Baryshevskii V. G., Tikhomirov V. V. Synchrotron-type radiation processes in crystals and polarization phenomena accompanying them. *Soviet Physics Uspekhi*, 1989, vol. 32, no. 11, pp. 1013–1032. Doi: 10.1070/pu1989v032n11abeh002778

3. Baryshevsky V. G. *High-Energy Nuclear Optics of Polarized Particles.* World Press, 2012. 640 p. Doi: 10.1142/9789814324847

4. Tikhomirov V. V. A technique to improve crystal channeling efficiency of charged particles. *Journal of Instrumentation,* 2007, vol. 2, no. 8, p. 08006. Doi: 10.1088/1748-0221/2/08/P08006

5. Tikhomirov V. V. Multiple volume reflection from different planes inside one bent crystal. *Physics Letters B,* 2007, vol. 655, no. 5-6, pp. 217–222. Doi: 10.1016/j.physletb.2007.09.049

6. Ritus V. N. Quantum electrodynamics of the phenomena in a strong field. *Trudy FIAN* [Proc. P.N. Lebedev Physical Institute], 1979, vol. 111, pp. 3–151 (in Russian).

7. Erber T. High energy conversion processes in intense magnetic field. *Reviews of Modern Physics*, 1966, vol. 38, no. 4, pp. 626–659. Doi: 10.1103/revmodphys.38.626

8. Baier V. N., Katkov V. M., Fadin V. S. *Radiation From Relativistic Electrons.* Moscow, Atomizdat Publ., 1973. 376 p. (in Russian).

9. Berestetskii V. B., Lifshitz E. M., Pitaevskii L. P. Electrodynamics of hadrons. *Quantum Electrodynamics.* Second Edition. Butterworth-Heinemann, 1982, pp. 624–647. Doi: 10.1016/b978-0-08-050346-2.50020-9

10. Zimmermann F. High-energy physics strategies and future large-scale projects. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2015, vol. 355, pp. 4–10. Doi: 10.1016/j.nimb.2015.03.090

11. Elleaume P., Ropert A. The ultimate hard X-ray storage-ring-based light source. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2003, vol. 500, no. 1–3, pp. 18–24. Doi: 10.1016/s0168-9002(03)00737-x

12. Lindhard J. Influence of crystal lattice on motion of energetic charged particles. *Matematisk-fysiske Meddelelser. Det Kongelige Danske Videnskabernes Selskab.* København, 1965. vol. 34, no. 14. 64 p.

13. Ter-Mikaelian M. L. *High-energy Electromagnetic Processes in Condensed Media.* New York, Wiley, 1972. 466 p.

14. Kimball J.C., Cue N. Quantum electrodynamics and channeling in crystals. *Physics Reports,* 1985, vol. 125, no. 2, pp. 69–101. Doi: 10.1016/0370-1573(85)90021-3

15. Baier V. N., Katkov V. M., Strakhovenko V. M. *Electromagnetic Processes at High Energies in Oriented Single Crystals.* Singapore, World Scientific, 1998. 568 p. Doi: 10.1142/9789812817532

16. Sorrensen A. H., Uggerhoj E. Channeling and channeling radiation. *Nature,* 1987, vol. 325, no. 6102, pp. 311–318. Doi: 10.1038/325311a0; Sorrensen A. H., Uggerhoj E. The channeling of electrons and positrons. *Scientific American,* 1989, vol. 260, no. 6, pp. 70–77.

17. Akhiezer A. I., Shul'ga N. F. *High Energy Electrodynamics in Matter.* New York, Gordon and Breach, 1996. 400 p.

18. Baryshevsky V. G., Dubovskaya I. Ya. Complex and anomalous Doppler effect for channeling positrons (electrons). *Doklady Physics,* 1976, vol. 21, pp. 711–714.

19. Kumakhov M. A. On the theory of electromagnetic radiation of charged particles in a crystal. *Physics Letters A,* 1976, vol. 57, no. 1, pp. 17–18. Doi: 10.1016/0375-9601(76)90438-2

20. Tsyganov E. N. *Some aspects of the mechanism of a charge particle penetration through a monocrystal*. Technical report. FermilabTN-683, 1976. Available at: http://lss.fnal.gov/archive/test-tm/0000/fermilab-tm-0682.pdf

21. Maslov M. A., Mokhov N. V., Yazynin I. A. *The SSC Beam Scraper System*. Superconducting Super Collider Laboratory SSCL-484. Dallas U.S.A, 1991. Available at: http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/23/011/23011739.pdf

22. Ball A., Benedikt M., Bottura L., Dominguez O., Gianotti F., Goddard B., Lebrun P., Mangano M., Schulte D., Shaposhnikova E., Tomas R., Zimmermann F. *Future circular collider study hadron collider parameters*. Tech. Rep. FCC-1401101315-DSC, 2014. Available at: https://indico.cern.ch/event/282344/attachments/519300/716459/FCC-1401101315-DSC_HadronColliderParameters_V1.0_ForIndico.pdf

23. Lamont M. *Estimates of annual proton doses in the LHC*. LHC Project Note 375, 2005. Available at: http://cds.cern.ch/record/893060/files/project-note-375.pdf

24. Taratin A. M., Vorobiev S. A. "volume reflection" of high-energy charged particles in quasi-channeling states in bent crystals. *Physics Letters A*, 1987, vol. 119, no. 8 pp. 425–427. Doi: 10.1016/0375-9601(87)90587-1

25. Baryshevsky V. G., Dubovskaya I. Ya., Grubich A. O. Generation of γ-quanta by charged particles in the presence of a variable external field. *Physics Letters A*, 1980, vol. 77, no. 1, pp. 61–64. Doi: 10.1016/0375-9601(80)90637-4

26. Kaplin V. V., Plotnilov S. V., Vorobiev S. A. Radiation by charged particles channeled in deformed crystals. *Zhurnal Tekhnicheskoi Fiziki = Journal of Applied Physics,* 1980, vol. 50, pp. 1079–1081 (in Russian).

27. Scandale W. Use of crystals for beam deflection in particle accelerators. *Modern Physics Letters A,* 2012, vol. 27, no. 6, p.1230007. Doi: 10.1142/s0217732312300078

28. Vomiero A., Bagli E., Baricordi S., Dalpiaz P., Fiorini M., Guidi V., Mazzolari A., Vincenzi D., Milan R., Gianantonio Della Mea, Vallazza E., Afonin A. G., Chesnokov Yu. A., Maisheev V. A., Yazynin I. A., Golovatyuk V. M. Tikhomirov V. V. First observation of multiple volume reflection by different planes in one bent silicon crystal for high-energy protons. *Physics Letters B,* 2009. vol. 682, no. 3 pp. 274–277. Doi: 10.1016/j.physletb.2009.11.026

29. Scandale W., Vomiero A., Bagli E., Baricordi S., Dalpiaz P., Fiorini M., Guidi V., Mazzolari A., Vincenzi D., Milan R., Della Mea G., Vallazza E., Afonin A. G., Chesnokov Yu. A., Maisheev V. A., Yazynin I. A., Kovalenko A. D., Tikhomirov V. V. Observation of multiple volume reflection by different planes in one bent silicon crystal for high-energy negative particles. *EPL (Europhysics Letters)*, 2011, vol. 93, no. 5, p. 56002. Doi: 10.1209/0295-5075/93/56002

30. Guidi V., Mazzolari A., Tikhomirov V. On the observation of multiple volume reflection from different planes inside one bent crystal. *Journal of Applied Physics*, 2010. vol. 107, no. 11, p. 114908. Doi: 10.1063/1.3407526

31. Tikhomirov V. V., Sytov A. I. Multiple Volume Reflection as an Origin of Significant Scattering Intensity and Radiation Power Increase. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* 2013. vol. 309. pp. 109–114. Doi: 10.1016/j.nimb.2013.01.068

32. Baryshevsky V. G., Tikhomirov V. V. Birefringence of the high-energy γ-quanta in monocrystals. *Sov. J. Nucl. Phys.*, 1982, vol. 36, pp. 408–416.; Baryshevsky V. G., Tikhomirov V. V. Birefringence of the high-energy γ-quanta in monocrystals. *Physics Letters A*, 1982, vol. 90, no. 3, pp. 153–155. Doi: 10.1016/0375-9601(82)90722-8

33. Belkacem A., Bologna G., Chevallier M., Cue N., Gaillard M. J., Genre R., Kimball J. C., Kirsch R., Marsh B., Peigneux J. P., Poizat J. C., Remillieux J., Sillou D., Spighel M., Sun C. R. Study of $e^+e^-$ pair creation by 20-150 GeV photons incident on a germanium crystal in alignment conditions. *Physical Review Letters*, 1987, vol. 58, no. 12, pp. 1196–1199. Doi: 10.1103/physrevlett.58.1196

34. Bak J. F., Barberis D., Brodbeck T. J., Doyle A. T., Ellison R. J., Elsener K., Hughes-Jones R. E., Kolya S. D., Mercer D., Møller S. P., Newton D., Ottewell P. J., Petersen J. B. B., Siffert P., Sørensen A. H., Thompson R. J., Uggerhø E., Wilson G. W. $e^+e^-$ pair creation by 40–150 GeV photons incident near the <110> axis in a germanium crystal. *Physics Letters B*, 1988, vol. 202, no. 4, pp. 615–619. Doi: 10.1016/0370-2693(88)91874-6_

35. Belkacem A., Bologna G., Chevallier M., Cue N., Gaillard M. J., Genre R., Kimball J. C., Kirsch R., Marsh B., Peigneux J. P., Poizat J. C., Remillieux J., Sillou D., Spighel M., Sunet C. R. New channeling effects in the radiative emission of 150 GeV electrons in a thin germanium crystal. *Physics Letters B,* 1986, vol. 177, no. 2, pp. 211–216. Doi: 10.1016/0370-2693(86)91059-2

36. Tikhomirov V. V. The position of the peak in the spectrum of 150 GeV electron energy losses in a thin Germanium crystal is proposed to be determined by radiation cooling. *Physics Letters A*, 1987, vol. 125, no. 8. pp. 411–415. Doi: 10.1016/0375-9601(87)90173-3

37. Tikhomirov V. V. Simulation of multi-GeV electron energy losses in crystals. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 1989, vol. 36, no. 3, pp. 282–285. Doi: 10.1016/0168-583x(89)90670-8

38. Artru X. A simulation code for channeling radiation by ultrarelativistic electrons or positrons. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 1990, vol. 48, no. 1-4, pp. 278–282. Doi: 10.1016/0168-583x(90)90122-b

39. Baurichter A. A. Baurichter, K. Kirsebom, Yu. V. Kononets, R. Medenwaldt, U. Mikkelsen, S. P. Møller, E. Uggerhøj, T. Worm, K. Elsener, S. Ballestrero, P. Sona, J. Romano, S. H. Connell, J. P. F. Sellschop, R. O. Avakian, Avetisian A. E., Taroian S. P. Radiation emission and its influence on the motion of multi-GeV electrons and positrons in strong crystalline fields. *Physical Review Letters*, 1997, vol. 79, no. 18, pp. 3415–3419. Doi: 10.1103/physrevlett.79.3415

40. Kirsebom K., Mikkelsen U., Uggerhøj E., Elsener K., Ballestrero S., Sona P., Connell S. H., Sellschop J. P. F., Vilakazi Z. Z. Radiation emission and its influence on the motion of multi-GeV electrons and positrons incident on a single diamond crystal. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2001, vol. 174, pp. 274–296. Doi: 10.1016/s0168-583x(00)00517-6

41. Baryshevsky V. G., Haurylavets V. V., Korjik M. V., Lobko A. S., Mechinsky V. A., Sytov A. I., Tikhomirov V. V., Uglov V. V. On the influence of crystal structure on the electromagnetic shower development in the lead tungstate crystals. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 1989, vol. 402, pp. 35–39. Doi: 10.1016/j.nimb.2017.02.066

42. Guidi V., Bandiera L., Tikhomirov V. V. Radiation generated by single and multiple volume reflection of ultrarelativistic electrons and positrons in bent crystals. *Physical Review A,* 2012, vol. 86, no. 4, p. 042903. Doi: 10.1103/physreva.86.042903.

43. Bandiera L., Bagli E., Guidi V., Mazzolari A., Berra A., Lietti D., Prest M., Vallazza E., De Salvador D., Tikhomirov V. Broad and intense radiation accompanying multiple volume reflection of ultrarelativistic electrons in a bent crystal. *Physical Review Letters,* 2013, vol. 111, no. 25, p. 255502. Doi: 10.1103/physrevlett.111.255502

44. Mazzolari A, Bagli E., Bandiera L., Guidi V., Backe H., Lauth W., Tikhomirov V., Berra A., Lietti D., Prest M., Vallazza E., De Salvador D. Steering of a sub-GeV electron beam through planar channeling enhanced by rechanneling. *Physical Review Letters,* 2014, vol. 112, no. 13. p. 135503. Doi: 10.1103/physrevlett.112.135503

45. Bandiera L., Bagli E., Germogli G., Guidi V., Mazzolari A., Backe H., Lauth W., Berra A., Lietti D., Prest M., De Salvador D., Vallazza E., Tikhomirov V. Investigation of the electromagnetic radiation emitted by sub-GeV electrons in a bent crystal. *Physical Review Letters,* 2015, vol. 115, no. 2, p. 025504. Doi: 10.1103/physrevlett.115.025504.

46. Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s}$ = 7 TeV. *Journal of Instrumentation*, 2013, vol. 8, no. 09, P09009. Doi: 10.1088/1748-0221/8/09/p09009

47. Tikhomirov V. V. On the possibility of crystal use in gamma-telescopes. *Doklady Natsional'noi akademii nauk Belarusi = Doklady of the National Academy of Sciences of Belarus,* 2015, vol. 59, no. 1, pp. 41–47 (in Russian).

48. Bagli E., Bandiera L., Bellucci V., Berra A., Camattari R., De Salvador D., Germogli G., Guidi V., Lanzoni L., Lietti D., Mazzolari A., Prest M., Tikhomirov V., Vallazza E. Experimental evidence of planar channeling in a periodically bent crystal. *The European Physical Journal C*, 2014, vol. 74, no. 10, p. 3114. Doi: 10.1140/epjc/s10052-014-3114-x

49. Korol A. V., Solov'yov A. V., Greiner W. *Channeling and Radiation in Periodically Bent Crystals*. Springer-Verlag, Berlin, Heidelberg, 2014. 284 p. Doi: 10.1007/978-3-642-31895-5

50. Baryshevsky V. G. Tikhomirov V. V. Crystal undulators: from the prediction to the mature simulations. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, B. 2013, vol. 309, pp. 30–36. Doi: 10.1016/j.nimb.2013.03.013

51. Tikhomirov V. V. *A benchmark construction of positron crystal undulator*. 2015. Available at: http://inp.bsu.by/personal/tikhomirov/1502.06588.pdf

52. Baryshevsky V. G. Spin rotation of ultrarelativistic particles passing through a crystal. *Pis'ma v zhurnal tekhnicheskoi fiziki = Applied Physics Letters*, 1979, vol. 5, pp. 182–184 (in Russian).

53. Baublis V. V. (et al.) First observation of spin precession of polarized Σ+ hyperons channeled in bent crystals. LNPI Research Report (1990–1991) E761 Collaboration. St. Pertersburg, 1992, pp. 24–26.

54. Baryshevsky V. G. The possibility to measure the magnetic moments of short-lived particles (charm and beauty baryons) at LHC and FCC energies using the phenomenon of spin rotation in crystals. *Physics Letters B*, 2016, vol. 757, pp. 426–429. Doi: 10.1016/j.physletb.2016.04.025

55. Fomin A. S., Korchin A. Yu., Stocchi A., Bezshyyko O. A. , Burmistrov L., Fomin S. P., Kirillin I. V., Massacrier L., Natochii A., Robbe P., Scandale W. , Shul'ga N. F. Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals. *Journal of High Energy Physics*, 2017, vol. 2017, no. 8. Doi: 10.1007/jhep08(2017)120

56. Botella F. J., Garcia Martin L. M., Marangotto D., Martinez Vidal1 F., Merli A., Neriz N., Oyanguren A., Ruiz Vidal J. On the search for the electric dipole moment of strange and charm baryons at LHC. *The European Physical Journal C*, 2017, vol. 77, no. 3. Doi: 10.1140/epjc/s10052-017-4679-y

57. Baryshevsky V. G. Spin rotation and depolarization of high-energy particles in crystals at LHC and FCC energies. The possibility to measure the anomalous magnetic moments of short-lived particles and quadrupole moment of Ω-hyperon. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* 2017, vol. 402, pp. 5–10. Doi: 10.1016/j.nimb.2017.02.081

## Information about the authors

**Vladimir G. Baryshevsky** – D. Sc. (Physics and Mathematics), Professor, Honorary Director, Principal Research Scientist, Research Institute for Nuclear Problems of Belarusian State University (11, Bobruiskaya Str., 220030, Minsk, Republic of Belarus). E-mail: bar@inp.bsu.by

**Viktor V. Tikhomirov** – D. Sc. (Physics and Mathematics), Professor, Head of the Laboratory of Nuclear Optics and Astroparticle Physics, Research Institute for Nuclear Problems of Belarusian State University – INP (11, Bobruiskaya Str., 220030, Minsk, Republic of Belarus). E-mail: tikh@inp.bsu.by

## Информация об авторах

**Владимир Григорьевич Барышевский** – доктор физико-математических наук, профессор, почетный директор, главный научный сотрудник Института ядерных проблем Белорусского государственного университета (ул. Бобруйская, 11, 220030, г. Минск, Республика Беларусь). E-mail: bar@inp.bsu.by

**Виктор Васильевич Тихомиров** – доктор физико-математических наук, профессор, заведующий лабораторией ядерной оптики и космомикрофизики Института ядерных проблем Белорусского государственного университета (ул. Бобруйская, 11, 220030, г. Минск, Республика Беларусь). E-mail: tikh@inp.bsu.by