XIII International Symposium

RREPS-19

Radiation from Relativistic Electrons in Periodic Structures

BOOK of ABSTRACTS

September 15-20, 2019, Belgorod, Russian Federation

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"RREPS-19"
Radiation from Relativistic Electrons in Periodic Structures
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Organized by Belgorod State University, Tomsk Polytechnic University, National Research Nuclear University "MEPhI"

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Schedule (preliminary)

Day	Morning	Afternoon	Evening
September 15 Sunday		***Registration***	***Welcome Party***
September 16 Monday	***Registration, Opening and Plenary Session***	***Oral Session***	***Poster Session***
September 17 Tuesday	***Oral Session***	***Oral Session***	***Poster Session***
September 18 Wednesday	***Oral Session***	***Symposium Excursion***	
September 19 Thursday	***Oral Session***	***Oral Session***	***Symposium Dinner***
September 20 Friday	***Oral Session, Closing***	***Departure***	***Departure***

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The Summary

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Section 1

General Properties of Radiation from Relativistic Particles: Day 1

For Notes

Radiative Processes with Twisted Electrons, Photons and Neutrons

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The report will provide an overview of a number of radiation processes involving twisted particles, that is, particles with a non-zero projection of the orbital angular momentum on the direction of motion of a particle. In this talk I review the basic properties of twisted particles and unusual properties of many atomic processes with twisted particles (new selection rules, unusual angular distribution and polarization of the final particles) which were recently considered by our Russian-German group, namely:

the Vavilov-Cherenkov radiation by twisted electrons;
radiation recombination of twisted electrons on protons;
ionization of atoms by twisted photons;
radiation recombination of twisted neutrons.

Collisions of twisted photons, electrons and neutrons may be of interest for investigations in physics of atoms, atomic and nuclear structures because they give us an additional degree of freedom: the orbital angular momentum.

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Electromagnetic Field of a Vortex Electron and Non-paraxial Effects

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Vortex electrons are freely propagating particles that carry orbital angular momentum (OAM) ℓ with respect to a propagation axis and its values, obtained experimentally, already reach $\ell \sim 1000\,\hbar$. In contrast to the ordinary beams, such twisted electrons possess an additional magnetic moment, an electric quadrupole moment, as well as higher multipole moments. These moments can be controlled by varying the packets' width and the OAM and can be made quite large, which influences electromagnetic field of the particles. As a result, interaction of the vortex electrons with external fields and with matter differs from that of the ordinary electrons, which may lead to relatively easily noticeable effects in electromagnetic radiation and scattering.

Here we obtain electromagnetic field of a relativistic vortex electron, described as a generalized Laguerre-Gaussian packet, in a form of a multipole expansion with an electric quadrupole term kept. The quadrupole contribution is attenuated in a paraxial regime, when the electron packet is large compared to its Compton wavelength, but it is enhanced at large OAM as well as at large times (low frequencies), when the packet's spreading is essential. For typical parameters of the available vortex beams, the frequencies for which the contribution of the quadrupole becomes comparable to that of the magnetic moment lie below the optical part of the spectrum– in IR- and THz range. We discuss several possibilities to observe the non-paraxial effects in radiation processes due to these new multipole moments.

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Classical and Quantum Descriptions of Radiation from Relativistic Electrons in External Fields

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We review the process of photon emission by a relativistic electron moving along a classical trajectory in an external field.

In a first part we assume that the emitted photon energy is much smaller than the electron energy. This case can be treated in classical electrodynamics. We briefly review the main radiation characteristics: spontaneous or stimulated emission, dipolar or non-dipolar regime, polarization, spectral sum rules, infrared divergence, coherence length effects (e.g., LPM effect), enhancement in oriented crystals. We end up this part with some considerations on photon impact parameter, radiation damping and the side-slipping effect.

In a second part we consider the case where the photon takes a non-negligible part of the electron energy. This can happen when, in the electron frame, the external field is higher than the critical electric field $1.32\ 10^{18}$ volt/m or varies significantly in a time scale $\lambda_{Compton}/(2\pi c) = 1.2910^{-21}$ s. Then the recoil and spin effects become important and are approximately taken into account by the semi-classical formula of Baïer and Katkov (BK). We show that this formula almost coincides with an exact one when the external field is a plane wave. We state the conditions of validity of the BK formula and review its applications in high-energy coherent and incoherent electromagnetic processes in oriented crystals. Concerning the incoherent processes, we discuss whether the electron trajectory must be calculated with the classical or with the quantum scattering theory.

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Applied Research at the LHEP JINR Accelerator Complex

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Applied research planned at the accelerator complex NICA is discussed. This research includes radiobiology, material research, testing of electronic components, etc. Beam monitoring and methodology of experimetnal studies are discussed. The self-similarity approach is applied to demonstrate the attractiveness of experiments in the intermediate energy range.

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ARIES – Accelerator Research and Innovation for European Science

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Today, third- and fourth-generation synchrotron radiation (SR) sources and X-ray free-electron lasers (FEL's) find many different applications in materials science, molecular biology and biochemistry, biomedical studies, crystallography, spectroscopy, studies of rapid processes and other areas of scientific and applied research. For these applications the crucial problem consists in reaching the diffraction limit for a given beam energy of 3-6 GeV: thereby, an object can be imaged with high contrast and sharpness once its size is comparable with the wavelength of the synchrotron or undulator radiation. It was assumed that transverse emittances below 100 pm rad are necessary for the fourth generation to achieve new horizons in the research using SR. Long years it was assumed than such values of the emittance can be reached only with FEL's driven by high-brightness electron linacs. Few years ago it was demonstrated that storage synchrotrons also enable for reducing the horizontal emittance and first beams with emittances near 100 pm rad were indeed generated by the MAX-IV (Sweden) [1] and Sirius (Brazil) [2] synchrotron light sources commissioned in 2016-2017. Several similar facilities are under the design and construction stages but today's leading trend consists in upgrading the existing SR sources to fourth generation [3-7].

It is proposed that SSRS-4 complex will includes both the 6 GeV storage synchrotron and a FEL(s) [8]. Such layout leads to the complex injection system based on full-energy linear accelerator which will uses both for top-up injection into storage ring and for generation of the high-brightness drive bunches for FEL.

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Coherent Effects in the Ionization Loss of High-Energy Electron Bunches

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Usually the ionization loss of a beam moving in substance is just a sum of independent losses of separate particles constituting the beam. In the present work it is shown that for beams (bunches) of sufficiently high particle density and small spatial size this rule can be considerably violated. In this case the value of the bunch ionization loss can exceed the above sum by several orders of magnitude. Such an effect is similar to the coherent effect in radiation by charged particle bunches. However, extremely large particle density of the bunch is required for manifestation of such an effect in thick targets, where the density effect [1] in the ionization loss takes place. But the condition on the particle density is significantly weakened if consider the ionization loss in sufficiently thin targets (or thin boundary layers of targets of arbitrary thickness), where the density effect is absent. The same holds for the ionization loss in rarefied gases with a much smaller value of the plasma frequency than in solids. In these cases the discussed effect can be manifested for bunch parameters, which are achievable at modern free-electron lasers (e. g., European XFEL [2]), and a series of accelerators presently under construction (e.g., SINBAD [3]). This effect can be of interest for the problems of charge particle beam diagnostics.

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Coherent OTR as a Tool for Transverse Bunch Size Measurements

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Optical Transition Radiation (OTR) is widely used for transverse beam profile diagnostics at electron linear accelerators. But this technique may not be implemented for FEL's[1] or LWPA accelerators[2], the reason is that such machines have ultrashort bunches causing coherent effects in the OTR emission process[3]. An approach to calculate the coherent OTR (COTR) propagation through a standard optical system with a focusing lens has been developed. COTR image of the bunch profile is obtained by the summation of the OTR fields coherently emitted by all electrons from a bunch and then focused in the detector plane. Assuming the bunch transverse profile is a Gaussian type it was shown that the final image has a typical "ring" shape. The characteristics of such image depend on the bunch transverse size and can be determined from the COTR image measurement for known optical system parameters.

This work was supported by the grant of the Russian Ministry of Science # 3/1903.2017.

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Section 6

Coherent Bremsstrahlung and Channelling Radiation

For Notes

Channeling of Relativistic Electrons: from Basics to Applications

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As known channeling of electrons in crystals can be observed for the beam energies starting from several MeV and is observable up to hundred GeV energies. Applying the same phenomenology of channeling physics for description of various behaviors of beam motion in crystals we simplify solution of many tasks that typically are split between high-energy and low-energy physics.

This report aims in reviewing recent results on channeling of relativistic electrons in crys-tals that were obtained by various groups in the world. Fine features of both electron scatter-ing in crystals and radiation by channeled electrons will be considered from the point of view of theoretical and experimental studies. Various extended applications of electron channeling for basic and applied tasks will be reported.

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Channeling and Volume Reflection Radiation Generated by 855 MeV Electrons in Ultrashort Si and Ge Bent Crystals

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The spectral intensity of gamma radiation generated by 855 MeV electrons under the conditions of channeling and volume reflection in silicon and germanium bent crystals was measured at the Mainz Mikrotron MAMI. Both crystals were 15 μm thick and bent along (111) crystal planes [1]. Both crystals were mounted on piezo activated dynamical holder [1, 2], which allowed us to change the crystal curvature online with neither vacuum braking nor any modification of the setup.

The radiation spectra were recorded for different crystal alignment, namely for channeling, volume reflection, random and "anti volume reflection", i.e. opposite to the volume reflection direction. Moreover, this experiment was repeated for 4 different crystal curvatures for Si crystal as well as 3 curvatures for Ge. All of the experimental results were reproduced by our simulations using the CRYSTALRAD simulation code [3].

Radiation under the volume reflection conditions demonstrates lower but comparable radiation intensity w.r.t. the channeling case. At the same time volume reflection possesses considerably higher angular acceptance than channeling. Moreover, the volume reflection angular acceptance as well as the radiation intensity can be balanced by changing of the crystal curvature. The radiation intensity in the Ge bent crystal is roughly twice higher than in the silicon one at the equal conditions.

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Investigation of the Influence of the Periodicity of Crystalline Atomic Strings Arrangement on the Spectral and Spectral-angular Distribution of High-energy Charge Particle Radiation in Crystal

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If a high-energy charged particle penetrates through a crystal having a small angle between its momentum and one of the main atomic axes, correlations between successive collisions of the particle with neighboring atoms may occur. Because of periodic arrangement in the location of atomic strings in crystal such orientational effect as planar channeling is possible. When high-energy charged particle moves in a crystal having a small angle between its momentum and one of the main crystal atomic planes the motion of particle in many cases is determined by the continuous potential of atomic planes. The existence of continuous potential leads to the planar channeling of the particle in the field of neighboring atomic planes. In this work we investigate the influence of the periodicity of crystalline atomic strings arrangement on the spectral and spectral-angular distribution of high-energy charge particle radiation in crystal.

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The Photorecombination Effect of the Ultrarelativistic Channeling Electron

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The photorecombination process of the axial channeling high-energy electrons is considered. The photorecombination probability of an electron with radiation of the hard photon $\hbar\omega$ and an electron transition in the channeling state with energy of the transversal motion $\varepsilon_{\perp n}$ is analyzed. Authors propose to use for considering of this and similar quantum electrodynamics relativistic processes the so called accompanying reference system (ARS), moving parallel to the channeling axis with the velocity, equal to the longitudinal component of the fast particle velocity, $V = \frac{p_{||}c^2}{E}$. In such an accompanying reference system the transversal motion of a particle, entering the single crystal at the angles, not exceeding the critical Lindhard angle $\theta_L \sim \sqrt{U_0/E}$, (where U_0 is the effective depth of the axial channeling potential, $E >> mc^2$ is the relativistic energy of a penetrating particle) can be considered as non-relativistic up to the very high total energies of the incoming particles, (up to $E \sim 10^{11}$ eV for leptons). Considering the electron transversal motion with the non-relativistic energies allows employ the familiar standard results from the atomic physics. In particular the cross section calculation of the radiative recombination of electron with atomic row, which is accompanied by the hard photon emission is presented.

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Regular and Chaotic Motion Domains in the Channeling Electron's Phase Space and Mean Level Density for Its Transverse Motion Energy

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The motion of charged particles in a crystal during axial channeling can be both regular and chaotic [1]. The chaos in quantum case manifests itself in the statistical properties of the energy level set. These properties had been studied in [2] for the electrons channeling along [110] direction of the silicon crystal, in the case when the classical motion is completely chaotic. The case of channeling along [100] direction is of special interest because the classical motion here can be both regualr and chaotic for the same energy, depending on the initial conditions.

The semiclassical energy level density as well as its part that corresponds to the regular motion domains in the phase space is computed for the 10 GeV channeling electrons and positrons. It is demonstrated that the level spacing distribution for both electrons and positrons is better described by Berry-Robnik distribution [3] than by Wigner or Poisson distributions that are related to the completely chaotic and regular situations, respectrively (see, e.g. [4]).

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Positron Source based on Coherent Bremsstrahlung of 10-50 MeV Electrons

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Conventional positron sources are based on the conversion of bremsstrahlung from relativistic electrons into electron-positron pairs.

Reasonably effective approach for a positron source known as a "hybrid" solution [1, 2] is using a multi-GeV electron beam for production of channeling radiation (CR) in a crystalline target (radiator) with its subsequent conversion into electron-positron pairs in amorphous target (convertor).The total yields and energy spectra of positrons produced in both thin [3] and thick [4] amorphous W converters by conversion bremsstrahlung and axial channeling radiation of electrons in a thin W crystalline radiator were calculated using approach proposed in [5], revealing the advantages in the use of channeling phenomenon for getting higher positron fluxes.

On the contrary to channeling radiation from relativistic particles, coherent bremsstrahlung is characterized by higher radiation frequencies at lower energies of charged particles crossing the crystal, the radiation intensity of which exceed those for bremsstrahlung. This feature can be applied for obtaining an effective positron source at much lower electron energies. In this report we consider the radiator-converter approach for calculating total yield and energy spectra of positrons produced by bremsstrahlung and coherent bremsstrahlung (CB) using the formulae of Ref. [6] from 10-50 MeV electrons in Si and Ge crystalline radiators and W amorphous converter. Computer simulations are carried out taking into account positron stopping in a thick convert

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Section 5

Diffraction Radiation and Smith-Purcell Radiation

For Notes

Smith-Purcell Radiation from Active Gratings

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We propose the idea to drive Smith-Purcell effect by changing properties of the elements a diffraction grating consists of. The control of elements composing a diffraction grating is the idea that has already been realised in the active phase gratings, which are, e.g., integral part of modern avionics. In terms of fundamental research such gratings today are very actively investigated in the physics of metamaterials, and particularly in metasurfaces, in which they provide the attractive opportunity to control the characteristics of refracted and reflected light.

In this report we show how to control the characteristics of Smith-Purcell radiation ruling by the properties of the grating's elements and show how it can be realised by the example of the 2D dotted grating consisting of arranged small subwavelength elements. The grating considered is a metasurface comprising dot-like particles each of which is a bunch (bush) of nanotubes, imbedded into a substrate. The operation is supposed to be executed by the external electric potential, which will allow changing the electron density at the ends of nanotubes. General properties of Smith-Purcell effect are calculated and discussed.

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Diffraction Radiation Generation by the Internal Target of the Cyclic Accelerator

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The observation and study of the properties of the diffraction radiation (DR) of relativistic electrons in the ultra-soft X-ray region ($E_{ph} \sim 100$ eV) have troubles with the usage of the extracted charge particle beam because it is necessary to establish the very small impact parameter $b \sim \gamma\lambda/2$ in the experiment. Here b is the distance from the particle trajectory to the target edge,γ is the Lorentz factor of a charged particle, γ is the wavelength of the generated radiation. These values are for electrons with the energy of 25 MeV and $\gamma = 10nm$ $b \cong 0.25\mu m$

However, while using the target set into a cyclic accelerator [3] or a storage ring [4, 5], one can expect the enhanced yield of DR due to the multiple passages of the electron beam near the target's edge and slow decrease of the parameter b, cycle by cycle, up to the moment of the interaction with the body of the target. During the slow transverse drawing together of the beam and the target the contribution of DR can become comparable with the contribution of the transition radiation (TR) from the target.

In this report, we compare the results of TR and DR contributions calculations, taking into account multiple passages of a charged particle near the target's edge and experimental results presented in [4,5]. The calculations of TR and DR were performed using the theory [1,2].

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Pre-bunched Relativistic Electron Beam by Dielectric Capillary

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To date, large variety of a passive dielectric deflectors have been tested with keV electron beam for potential usage in the field of applied biology and medicine. However, there is an attraction to implement the same techniques for deflection and focusing of a low-emittance relativistic pre-bunched electron beam of a modern compact linear accelerator. To verify this possibility we have made initial experimental study at KEK LUCX facility where electron beam bunches with ps rms durations, nC charges and 8 MeV energy were transmitted through a multi-mode dielectric capillary. The 60 mm length capillary is assembled of 4 mm and 4.4 mm alternate inner diameter rings which formed a 250 um longitudinal period of the structure. The capillary is wrapped with a grounded copper tube with an internal diameter of 5.4 mm. It was shown that the shift of capillary axis parallel to the beam axis within the size of the beam cross section lead to the shift of the transmitted beam charge profile as observed at luminescent screen downstream of the capillary. At the same time, we have witnessed increase of the charge density at the screen what can be referred as a beam passive focusing by the dielectric capillary. Further investigations are foreseen to explore applicability of the given deflection/focusing scheme for femtosecond electron bunches and confirm the physics of observed phenomena.

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Observation of Coherent Terahertz Smith-Purcell and Grating Transition Radiation from a Metasurface

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We report the results of experimental and theoretical studies of coherent terahertz radiation generated by a short electron bunch from a metasurface. The metasurface is an array of sub-wavelength copper spherical-like elements placed on a monocrystalline sapphire substrate. The target has two periodicities, along and perpendicular to the electrons trajectory. Experiment was carried out using 8 MeV electron beam of KEK LUCX facility. The target was installed into 5D in-vacuum manipulator so it could be positioned and inclined with respect to the electron beam. Because of that, several types of radiation and its properties were confirmed: Smith-Purcell radiation, Transition radiation, Grating transition radiation, Cherenkov radiation inside a substrate. The main characteristics of the radiation like spectrum, spectral-angular distribution, characteristic angle of emitted radiation, and dispersion relation were calculated. The experimental and theoretical results are compared, and good agreement is demonstrated.

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Focusing of Drive and Witness Bunches in Dielectric Waveguide Filled With Inhomogeneous Plasma

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Here we report the results of PIC numerical simulation of focusing of witness and drive bunches in dielectric waveguide filled with radially inhomogeneous plasma. Wakefield was excited by electron bunch in quartz (permittivity is 3.8) dielectric tube with outer and inner diameters of 1.2 mm and 1.0 mm, respectively, inserted in cylindrical metal waveguide. Energy of drive bunch electrons was 5 GeV, drive bunch charge was 3 nC, its length was 0.2 mm, bunch diameter was 0.9 mm. Witness bunch had the same parameters as drive bunch for exception of the charge equal to 0.3nC. The internal area of dielectric tube was filled by plasma with different transverse density profiles: homogeneous density, density profile created at capillary discharge, inhomogeneous radial density profile with vacuum channel along the waveguide axis. Plasma density for all considered cases was so low that the plasma frequency is less than the frequency of the main dielectric mode. The results of PIC numerical simulation show the drive bunch is focused both in homogeneous, and in inhomogeneous plasma. Acceleration and focusing of witness bunch when using inhomogeneous transverse plasma density can be improved in comparison with homogeneous plasma case.

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Generation of Monochromatic Radiation from a Multilayer Prismatic Target

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In this report, we show the experimental results of angular distribution and spectrum of radiation produced by a multilayer prismatic target, consisting of metallic foils separated by vacuum/air gaps when an electron beam moving near target. Experiment was carried out at TPU microtron, where the 6 MeV electron beam consists of electron bunches with a repetition rate 2.63 GHz determined by RF system. We observe the sharp monochromatic lines in the spectrum of produced radiation and the dependence of the radiation intensity on the tilt angle of target. The obtained results are compared with Smith-Purcell radiation from a grating with the same period and Cherenkov radiation from a teflon prism generated for the same experimental conditions. We expect using this effects to allow increasing the monochromaticity and intensity of radiation when such a target will be designed and employed in THz and sub THz spectral ranges.

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Poster Session I

For Notes

Quantum Approach for Orbital Angular Momentum of Channeling Radiation from 255 MeV Electrons in Thin Si Crystal

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The radiation of relativistic electrons in helical undulator carry orbital angular momentum (OAM). This fact was theoretically predicted [1] and experimentally proved [2]. The undulator radiation from 917 MeV electrons contains the photons with energy of 99 eV and OAM $\pm\hbar$, see [2]. However, charged particles moving along a helical trajectory produce radiation carring OAM [3]. One more example of the trajectory of such a type is the rosette trajectory of a charged particle at axial channeling regime.

Here, using the developed code BCM-2 [4] and the general formula for the probability of radiation of a twisted photon by a classical current derived in [5], we calculate the distribution of photons of channeling radiation over its OAM projection and the density of the average number of photons carrying OAM against the photon energy. The calculations are carried out for the initial electron beam energy 255 MeV (SAGA-LS) and thin 10 μm Si crystal to avoid the dechanneling effects.

The comparison of the results with the ones obtained using the semi-classical approach [6-8] is performed. The proposed scheme for production of radiation carrying the OAM allows one to generate the twisted photons with much higher energies as compared with the scheme based on using the undulator radiation [1, 2].

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The Channeling Radiation from Positron Bunch in Nanotubes Taking to Account the Inhomogeneity of the Medium Polarization

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The problem of channeling radiation of the positron bunch in the system of packed nanotubes investigated. The spectral distribution of the total radiation differs from the analogous value for the planar channeling of positrons. This distribution consists of two parts. The first part represents the contribution of the positrons of which amplitude is less than a certain value, the second part is the contribution of the remaining positrons, the radiation of which is produced in a medium with inhomogeneous polarization. The spectral distribution, taking into account the inhomogeneity of the polarization of the medium, differs significantly from the case when the averaged homogeneous polarization of the medium taken into account.

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Angular Distribution of High Power Radiation from a Charge Rotating Around a Dielectric Ball

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The angular distribution of the radiation from a relativistic charged particle uniformly rotating along an equatorial orbit around a dielectric ball is studied. Earlier it was shown that for some values of the problem parameters and in the case of weak absorption of radiation in the ball material, the radiation intensity can be essentially larger than that for the same charge rotating in a homogeneous transparent medium having the same real part of dielectric permittivity as the ball material. The generation of such high power radiation is due to the fact that electromagnetic oscillations of Cherenkov radiation induced along the trajectory of particle are partially locked inside the ball and superimposed in nondestructive way. In the present paper, the angular distribution of this radiation in the case of a ball made of strontium titanate, melted quartz or teflon is studied in the gigahertz and terahertz frequency ranges. It is shown that during the rotation of electron the high power radiation propagates in all possible directions determined by Cherenkov condition.

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Radiation of Twisted Photons from Planar Channeled Electrons

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Over the last years, a research direction in modern quantum optics is related with so-called "twisted photons". According to [1], such photons can be created from usual laser beams by means of specially designed holograms. Moreover, in Refs.[2] was demonstrated that micron-sized "particles" start to rotate after absorbing twisted photons.

The twisted photon states are the states of a free electromagnetic field with definite energy, the longitudinal projection of momentum, projection of the total angular momentum, and helicity [1]. Despite the number of theoretical and experimental works on twisted photons, some theoretical features of ones are not studied up to date.

Still there is no generally accepted quantum theory of twisted photons emission from charged particles. For example, in the Refs. [3] it was suggested an approach based on the quantum description of emitted photons and classical currents. It is some semiclassical model. Unfortunately, Refs. [3] does not contain sufficient theoretical substantiations of this approach.

Any beam of ordinary photon can be represented as the sum of twisted photons, but due to cylindrical (axial) symmetry number of photons "rotates to the right" (photons with positive longitudinal projection of momentum) is equal to number of photons "rotates to the left" (photons with negative longitudinal projection of momentum). As a result, the total longitudinal projection of momentum of beam is zero. Therefore, in order to obtain a beam of the twisted photons the cylindrical (axial) symmetry of radiation condition should be broken. Such a situation arises for example at electrons (positrons) planar channeling in a crystal.

In the present report, we developed the theory of radiation of twisted photons from planar channeling electrons (positrons) on the base of the approach developed in [1].

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Hertz Tensor as a Basis for Spin Photonics in Terms of the Relativistic Radiation Theory

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Relativistic expressions of Hertz tensor for orbital and spin motion are used to determine potentials and strengths of electromagnetic fields of an arbitrarily moving classical spin particle. It is shown that the thus obtained fields satisfy Maxwell equations in particle radiation convective and wave zones.

Further, based on the covariant definitions of the density tensors of orbital and spin angular momentum of the electromagnetic field, corresponding radiation powers of the angular momentum of the radiation electromagnetic field can be found using the four-dimensional Gauss's theorem. The obtained formulas can also be used to study the characteristics of the angular power distribution of the corresponding angular momentum of the electromagnetic field.

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Development of Yb-based Laser System for Crab Crossing Laser-Compton Scattering

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Laser-Compton scattering is a phenomenon that produces high-quality X-ray by collision between electron beam and laser pulse. The amount of scattered light is largest at head-on collision but the collision often has some certain angle structurally, due to practical issues so that the amount of scattered light decreases. In order to solve this problem, we plan to demonstrate the principle of crab crossing in laser-Compton scattering which creates head-on collision in a pseudo manner. When the electron beam is tilted by half of the collision angle, the amount of scattered X-rays becomes the largest. In crab crossing, the amount of scattered light can be efficiently enhanced by using a collision laser with high intensity, high quality, and especially, ultrashort pulse duration. Thus, we have introduced a regenerative amplifier using ceramics thin-disk which is a disk-shaped gain medium with excellent heat dissipation as collision laser and developed a dedicated laser system. In this laser system, the pulse energy of 10 mJ and pulse duration of 1 ps (FWHM) is targeted using the Chirped Pulse Amplification (CPA) method. At this conference, we will report on the present status of the laser development and the experimental results of crab crossing laser-Compton scattering.

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Radiation of Surface Waves by Fast Electrons Crossing a Metasurface

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Metasurfaces are artificial materials with sub-wavelength thickness. Its main application is to control the electromagnetic properties of radiation like polarization or anomalous reflection [1]. In recent years a particular case of metasurfaces – 1D or 2D plasmonic arrays - attracts interest of physicists all over the word. There are theoretical and experimental studies, the objects of which are not only scattering effects, but also ones caused by interaction between charged particles and metasurfaces [2,3]. The latter include Smith-Purcell effect, local field effects, localized plasmonic resonances, which lead to the promising enhancement of radiation, and surface waves. Such surface waves, radiated by fast electron crossing a periodical metasurface under an arbitrary angle, are a subject of this report. The main characteristics of arising radiation are calculated within first-principle approach. Also, the necessary conditions and dispersion relation of surface waves are defined. The emitted spectrum is calculated. Generation of these waves make them attractive for applications in such areas as near-field microscopy, measurement thickness of thin films and many others [4].

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Feasibility of Optical Cherenkov Radiation for a Detection of Tokamak Runaway Electrons with Energy up to a few MeV

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Recently authors of the work [1] proposed to use Cherenkov detectors to register runaway electrons generated in tokamak installations with energies from tens keV up to a few MeV. In the experiments [2, 3] we have measured Cherenkov radiation (ChR) characteristics generated by 400 keV electrons [2] and 6 MeV electrons [3] from thin quartz, leucosapphire and diamond plates. We have showed that for low energy electrons (less than 400 keV) a geometry of ChR detector can be chosen as traditional one with extraction of the ChR light through a plate surface perpendicular to an electron beam. Nevertheless, for relativistic electrons ($E_e = 6$ MeV) such a geometry doesn't allow to detect ChR and a plate has to be inclined respect to the electron beam. In the former case, a multiple scattering process in a plate leads to a significant "smoothing" of the ChR angular distribution, but for the latter one, this effect is suppressed. In the report we have simulated spectral-angular characteristics of ChR using GEANT4, compared with experimental data, and showed a necessity to choose measurements geometry for the required electron energy range, which depends on the radiator material also.

The experiments were performed within the framework of the project No 18-19-00184 of the Russian Science Foundation. Authors from TPU (A. Potylitsyn, B. Alekseev, A. Vukolov) acknowledge support by the program "Nauka" Ministry of Science of the Russian Federation (project No.3.1903.2017).

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The Probability of Radiation of Twisted Photons in Dispersing Media

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Transition and Vavilov-Cherenkov radiations of plane-wave photons are well studied and find many applications [1,2]. Modern research in this area are aimed at exploring new ef-fects arising from the orbital angular momentum (OAM) of particles [3,4]. One of the possible applications of these studies is to improve the Vavilov-Cherenkov detectors [4]. Furthermore, these types of radiation are employed to produce twisted photons [5]. The use of helical beams allows one to increase the OAM of generated photons [6].

We have developed a general theory of radiation of twisted photons by classical currents in an inhomogeneous dispersive medium. We applied the developed general theory to descrip-tion of radiation of twisted photons produced by a bunch of charged particles passing through a dielectric plate or an ideal conductor plate. The created photons in these cases have a non-zero orbital momentum.

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Radiation Losses of Relativistic Electrons via Cherenkov Diffraction Radiation Mechanism

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For an electron moving in a vacuum near the flat surface of the infinite radiator in which Cherenkov radiation (ChR) is generated [1], radiation losses are estimated. Calculation for such a stationary case were based on the existing model [2].

In the report, we considered the similar case but with a finite length radiator along the trajectory of the charge. Such a radiator possesses input and output planar faces perpendicular to the path of the charge. In this case, the Coulomb field of a relativistic charge with a transverse size of $\sim \gamma\lambda/2\pi$ (γ is the Lorentz-factor, λ - wavelength), interacts with the front entrance face of the dielectric radiator and generates diffraction radiation (DR) [3]. Recently such kind of the radiation mechanism, so-called Cherenkov Diffraction radiation (ChDR), was experimentally observed in the optical range [4]. Obviously, in the case under consideration, radiation losses are generated by the ChDR mechanism (or, in other words, by ChR and DR [5]). We have developed the model to calculate the radiation losses based on the polarization currents method [6]. We have shown that the losses via the ChDR mechanism are higher by 2-3 orders of magnitude compared to charge radiation moving near an infinite radiator.

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Pic-Code Karat Simulation of Coherent Cherenkov Radiation From a Bunch Passing Through a Hollow Conical Target

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Authors of the work [1] have measured spectral and angular characteristics of the Cherenkov radiation generated by a bunch passing along axes of the hollow conical target. They used a complicated optical scheme to measure a transverse profile of the generated beam and, as a result, they observed distribution with a maximum along an axes instead an expected "ring structure".

In the report we present simulation results for an angular distribution of the radiation as well as the spectral distribution obtained by the PiC code KARAT for the condition of the experiment [1].

We show that in strict satisfaction of the condition $\theta_{cone} = \frac{1}{2}\theta_{cn}$ (θ_{cone} is an opening cone angle, $\theta_{cn} = \arccos(1/\beta n)$) is the Cherenkov angle, $\beta = v/c$, n is a refractive index) a propagating radiation beam is retained a hollow structure for distances much larger than a radiator length.

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X-ray Transition Radiation Produced by 2.8-GeV Electrons in a Multilayer Aluminum Target And Diffracted in a Silicon Crystal

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X-ray transition radiation (XTR) by relativistic charged particles is a promising tool for diagnostics of sub-micrometer size beams, required for future linear colliders. Also XTR can be used not only in accelerators. For example, in [1] XTR by 855 MeV electrons from a multilayer structure, diffracted in a Si plate, was investigated for the purpose of its application for X-ray phase contrast imaging. The use of a multilayer target increases the yield of transition radiation and a crystal allows extracting a narrow line with tunable energy from the continuous spectrum.

In the present work we study the XTR generated by 2.8-GeV electrons in a target of 32 Al foils with thickness of 13 um, diffracted on (111) plane of a Si crystal at the Bragg angle of 7.9 degrees, with the aim of applying it for the further study of its focusing by polycapillary X-ray optics. The XTR spectra are measured using Amptek XR-100SDD detector and contain a narrow peak with the energy of 14.4 keV. The study was performed at the Test Beam Facility TB21 of DESY [2]. The obtained results coincide well with the calculations.

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Effect of the Crystal Surface Spinning Relative to an Electron direction at the Output of the Diffracted Transition Radiation

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It is known, see, for example, [1, 2], that the discrepancy between the normal to the target surface and the direction of the electron leads to the appearance of elliptical polarization of transition radiation emitted into the front hemisphere. The dependence of the radiation intensity with parallel and perpendicular polarization components with respect to the selected plane ceases to be a function of only the azimuthal photon emission angle. An additional dependence on the angle of rotation of the target surface and the energy of the particles appears. Within the framework of the development of the method [3], the influence of this effect on the observed angular distributions of the diffracted transition radiation (DTR) is analyzed. It is shown that taking into account the change in radiation intensity due to the discrepancy between the normal to the target surface and the direction of electron motion leads to agreement between the calculated and measured ratios of the yields of parametric X-ray radiation and the diffracted transition radiation for experimental conditions [4].

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On the Problem of Application of Diffracted Transition Radiation for Indication of Relativistic Electron Beam Parameters

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Within the two-wave approximation of the diffraction theory, an expression for the angular density of diffracted transition radiation DTR excited in a thin single-crystal target by a beam of ultrarelativistic electrons is obtained. The inverse problem of reconstructing the angular distribution of the beam electrons from the angular distribution of the DTR with the aim of using it for the beam parameter indication on electron accelerators is investigated.

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Crystalline X-Ray Resonator for Storage of Diffracted Transition Radiation

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Usually, synchrotron or undulator radiation is considered as a source of X-rays for filling in crystalline X-ray resonator [1,2]. Here, we present the idea to fill in the X-ray resonator by diffracted transition radiation (DTR). The DTR at Bragg frequency arises at crystal surface by incident relativistic charged particle crossing the crystal surface [3]. The crystalline resonator can be filled in by the DTR produced in the inner surfaces of crystalline mirrors of a Fabry-Perot resonator by relativistic particles passing through the crystalline mirrors of the resonator. Consequence of bunches of particles can be used for coherent enhancement of the DTR stored in the resonator.

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The Effect of Reflection Asymmetry on the Output of Coherent Radiation of Electrons in Crystals

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Recently, a large number of theoretical papers devoted to the influence of reflection asymmetry on the output of parametric X-ray radiation (PXR) and diffracted transition radiation of fast electrons in crystals have appeared, see, for example, [1,2] and the literature cited there. In the cited papers it is stated that due to dynamic effects in radiation, reflection asymmetry can change the radiation output several times depending on the asymmetry value. This point of view is called into question in the paper [3], where it is stated that the reflection asymmetry does not affect the total radiation output.

Crystals with asymmetric reflection geometry were used in experiments on the investigation of angular distributions of PXR in [4, 5], which makes it possible to use the results of these works for comparison with the predictions of the dynamic [1, 2] and kinematic [6] PXR theory. Comparison shows that the kinematic PXR theory better describes the measurement results in the paper cited then the dynamical one. The measurement geometry, which can give an exact answer to the question about the contribution of dynamic effects to the PXR, is suggested.

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Coherent X-ray Radiation Excited by a Beam of Relativistic Electrons in a Layered Periodic Structure

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The dynamic theory of coherent X-ray radiation, excited in a periodic layered medium by a beam of relativistic electrons in the Bragg scattering geometry, is developed. On the basis of the two-wave approximation of the dynamic theory of diffraction, expressions are obtained describing the spectral-angular and angular distributions of PXR, DTR and the term resulting from their interference, taking into account the multiple scattering of electrons on target atoms. On the basis of the expressions obtained, the possibility of the manifestation of the effects of dynamic diffraction in coherent X-rays was investigated. The influence of the reflection asymmetry of the Coulomb field of the electron with respect to the target surface of the on the spectral-angular characteristics and interference of the radiations PXR and DTR under conditions of multiple scattering is estimated. It is shown that as the angle of electron incidence at a target for a constant Bragg angle decreases, the width of the PXR spectrum increases, which leads to an increase in the PXR angular density (this effect is not related to absorption). In the same conditions the width of the frequency domain of full external reflection and the amplitude of the DTR spectrum also increase, which leads to a significant increase in the angular density of the DTR. The obtained analytical expressions can be used to determine the optimal parameters of the experiment on confirmation of the predicted dynamic effects.

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THz Smith-Purcell Radiation from 1D and 2D Arranged Systems of Microparticles

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Smith-Purcell radiation is investigated widely because of its perspectives as a source of THz radiation. Experiments also proved possibility of electron beam diagnostics based on this effect. In the present research we consider SPR from metamaterial - periodic 1D and 2D structures of small particles. Expressions for spectral-angular distributions were obtained analytically. The results involve arbitrary direction of the moving electron beam above the structures and represent generalization of expressions obtained recently in [1]. The fact that the angle is arbitrary is important i) for the role of conical effect to be manifested [2, 3], and ii) for the divergence of the beam to be taken into account.

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Radiation from a Bunch in a Circular Waveguide with Partly Corrugated Walls

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The possibility of creating new sources of gigahertz and terahertz radiation based on the periodic waveguide systems has been recently widely discussed. However, the main attention has been paid to the investigation of Smith-Purcell radiation [1]. On the other hand, the "long-wave" radiation (the wavelength is much greater than the structure's period) is also of interest [2-4].

This report is devoted to the investigation of the radiation excited by a bunch moving in a circular piecewise regular vacuum waveguide. One part of the waveguide has the smooth wall, and the other possesses the periodic wall. It is assumed that the corrugation period and depth are much less than the waveguide radius and the wavelengths under consideration. The cases of bunches moving from the smooth part of waveguide into the corrugated one and in the opposite direction are analyzed. The analytical approach is based on the replacement of strict boundary conditions on the corrugated walls by the equivalent boundary conditions [5] (this method has been tested for the charge's field in [4]). The main attention was focused on the wave field investigation.

It was obtained that in the case of bunch flying into the corrugated waveguide part, the wave field discrete part exists only in some restricted area behind the bunch. The back front of the wave train moves with the group velocity of the single generated mode. In the case of the bunch flying into the smooth part it was shown that almost all radiation generated in the corrugated waveguide part penetrates into the smooth one. It was also obtained that a decrease in bunch velocity leads to the generation of additional modes in the wave field discrete part, thereby complicating the field structure.

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Eikonal Approximation and the Conical Effect in Smith-Purcell Radiation

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The diffraction and transition radiation under normal incidence of a particle to the semi-infinite dielectric plate had been considered in [1] using the eikonal approximation in the transition radiation theory [2, 3]. This approach is valid for the high radiation frequencies domain (where the dielectric permittivity of the plate material is close to unit), including X-ray domain. In the present report this method is applied to the case of oblique incidence of the particle on the plate (but parallel to the plate's edge) as well as to the periodic set of such plates (Smith-Purcell radiation). The oblique incidence of the particle (both in the case of the single plate and in the case of the periodic grating of such plates) leads to the so called conical effect in the radiation angular distribution recently observed in [4]. We outline that the origin of this effect lies in the superluminal motion along the plate's edge of the disturbance produced by the incident particle's field in the plates. The analogious effects arise in various physical situation [5-7]. Also we compare our results to ones of [8, 9] obtained using different tecnique.

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Muon Source Driven by Channeling Radiation

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The search for novel muon sources is of growing interest in regards with present actual problems such as, for instance, muon-antimuon colliders [1] and muon-catalyzed nuclear fusion [2]. As known for the muon production one can use interaction of high energy proton beams with carbon based media or beryllium targets [3], as well as interaction of high energy electron beams with laser beams [4].

Many times discussed solution [5] for the positron production is based on the use of multi-GeV electron beam as a source of channeling radiation in a crystalline target (radiator) with its subsequent conversion into electron-positron pairs in amorphous target (convertor).

In this work we propose to apply similar scheme for muon production, i.e. a "hybrid" scheme based on channeling radiation by $1 \div 5$ GeV electrons in W crystalline radiator and its successful conversion in amorphous converter has been analyzed as a source of muons.

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Single-photon Annihilation of Planar Channeled Positrons

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It is well known that due to conservation laws of momentums and energies free electron and positron can annihilate only into two or more photons [1]. But in the external field the part of annihilate particles momentum can be absorbed by the field and single-photon annihilation becomes possible [1-4].

he conditions for single-photon annihilation are fulfilled when channeling relativistic positrons in a crystal. For the first time, the possibility of this process in a crystal was highlighted in the article [4]. Unfortunately, in this paper a consistent theory of this process was not developed, the authors confined themselves to simple estimates.

Here in the frame of quantum electrodynamics we develop the theory of single-photon annihilation of relativistic positrons channeled in a crystal. It should be notice that Feynman diagram of the process under consideration is similar to Feynman diagram of the secondary electron emission induced by channeled relativistic electrons in a crystal [5]

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Simulation of Positron Spectra of a Hybrid Positron Source

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In our previous paper [1] we considered the non-dipolarity of axial channeling radiation (CR) generated in a tungsten single crystal at electron-beam energies of several GeV. It was shown that the non-dipole approximation results in a considerable variation of the CR spectrum. In this work we present GEANT4 [2] simulations of a hybrid positron source based on the conversion of axial CR into e^+e^- pairs inside an amorphous tungsten converter and compare the positron spectra obtained from CR calculated in dipole and non-dipole approximation.

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Quantum Features of Radiation at Small-Angle Reflection by Crystals

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In our recent paper [1] in the framework of quantum electrodynamics the theory of a new type of X-ray radiation emitted by relativistic electrons at the quasi-channeling conditions вЃ¥ Electron Radiation at Small-Angle Reflection (ERSAR) was developed beyond the dipole approximation. This radiation arises when the electron is reflected by or crossed the crystal surface which coincides with one of the crystallographic planes. It is shown that in this case one can reveals two kinds of radiation: channeling radiation by reflected particles and diffracted channeling radiation by passed particles.

The ERSAR can be applied for example for investigation of the crystal surface. The advantage of its use is that when the crystal surface does not coincide with the crystallographic plane, ERSAR not disappears (due to the quasi-channeling), but appears the Transition Radiation.

The ordinarily (inside the crystal) Diffracted Channeled Radiation (DCR) [2] is accompanied by parametric X-ray radiation (PXR) and in these conditions, the experimental investigation of DCR is very difficult. But in our case (ERSAR), the PXR is absent and possibly, the use of ERSAR might be decisive to register DCR.

In this work, using the ERSAR-theory formulas we carried out the numerical calculation of ERSAR for one of simple experimental condition.

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Features of The Orientation Motion of Neutral Particles in Chiral Nanotubes

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The report presents the results of investigations initiated in [1] and related to study the channeling of neutral atoms in single-wall carbon nanotubes (CNT) with different chiralities (n, m), where $n > m$ [2]. Based on the methodology [3] and using the "standard" single-particle Lennard-Jones interaction potential, an exact potential of the interaction of a channeled neutral atom with carbon atoms of CNT wall

$$U(\vec{r}) \equiv U(\rho, \varphi, z) = 4\varepsilon \sum_{s=-\infty}^{\infty} \sum_{j=1}^{2} \sum_{p=1}^{n-m} \left[\sigma^{12} / \left|\vec{r} - \vec{r}_{sjp}\right|^{12} - \sigma^{6} / \left|\vec{r} - \vec{r}_{sjp}\right|^{6}\right]$$

is constructed. Here $\vec{r}$ and $\vec{r}_{sjp}$ are, correspondently, the radius-vectors of the channeling atom and concrete carbon atom of nanotube.

On the basis of the expansion of this potential in the angular harmonics $U(\rho, \varphi, z) = \sum\limits_{k,l=-\infty}^{\infty} U_{kl}(\rho) \exp\left[i(2\pi kz/H + l\varphi N)\right]$, where N is the number of spirals covering CNT, the transitions between the quantum states of transverse energy, which occur during channeling of neutral atoms in the average potential $U_{00}(\rho)$ are investigated.

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Investigation of Canneling and Radiation of Charged Particles in Ionic Crystals with a Structure of Type Sodium Chloride

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In papers [1-4] (see also references therein), the channeling of relativistic and weakly relativistic electrons in the main charged (111) planes and main charged axes [110] was studied (in [1, 2], the high-index charged planes were also partially studied) in ionic crystals of LiH, LiD and in lithium halides in order to detect anomalous features in the structures of the interaction potentials, as well as to obtain intense monochromatic short-wave radiation. It was also shown that in these directions in the structures of emerging potential wells, the so-called long-range Coulomb interaction plays a large role, leading (in combination with the temperature factor) to significant changes in the depths of potential wells in negatively and positively charged planes and axes. It is important to note that in some cases (for example, for LiH and LiD crystals) such effects even lead to inversions of potential wells into potential barriers and a fundamental change in the channeling regimes.

This paper presents new results of the study of channeling processes (both in planar and axial modes) of positively and negatively charged particles in many other ionic crystals with a NaCl type structure (see [5]). In particular, the report considers not only charged planes (we will consider them strongly charged) and axes, but also planes whose parameters are close to electrically neutral (due to different amplitudes of thermal vibrations for positively and negatively charged ions, these planes will be weakly charged). The report also presents the results of studies on the influence of the temperature factor on the structure of the interaction potentials in order to detect their anomalous features, including the "sensitivity" of the spectra of channeled radiation to the ionic powers of ionic crystals, as well as to the Debye temperature values in order to clarify these parameters.

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Transport of Accelerated Electrons through Dielectric Nanochannels in PET Films

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The possibility to control beams of Ne7+ ions with a PET film with nanocapillaries formed in it was demonstrated in an experimental work [1]. To describe the observed effect, the authors of this work introduced the term "guiding". Later, the guiding effect was observed for other types of ions with different energies [2]. Similar experiments were also conducted with electrons with energies up to 1 keV. The results of the work performed did not allow to unequivocally assert existence of an effective guiding effect for nanocapillaries, in which the majority of the beam electrons do not lose energy when passing through the PET film.

In the present work, experimental research was carried out on the guiding of electrons with an energy of 10 keV passing through capillaries with diameters of 200, 400 and 800 nm formed in a PET of 10 μm thickness. We want to express our gratitude to Professor R. Schuh (Sweden) and Doctor H.Zhang (China) for the samples and fruitful discussions.

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Section 2

Cherenkov Radiation

For Notes

Application of Cherenkov Diffraction Radiation for Charged Particle Beam Diagnostics

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With over 30 000 accelerator infrastructures around the world, development of beam diagnostics has become a separate area of research in accelerator science. Such unique facilities as the Large Hadron Collider, synchrotron storage ring based light sources and X-ray free electron lasers continuously push the requirements for diagnostics equipment. These days an optimal beam monitoring devise is single shot and non-invasive providing either, detailed information about the structure of the beam or about the beam behaviour. Not all beam parameters can be diagnosed optimally these days.

During the last three years, the emission of Cherenkov Diffraction Radiation (ChDR), appearing when a relativistic charged particle moves in the vicinity of and parallel to a dielectric medium, has been investigated with the aim of providing non-invasive beam diagnostics. Our recent studies [1] of ChDR have revealed its very interesting properties including a large number of photons emitted in a narrow and well-defined solid angle, providing excellent conditions for detection with very little background. This contribution will present a collection of recent beam measurements performed at several facilities such as the Cornell Electron Storage Ring, the Accelerator Test Facility 2 at KEK, Diamond Light Source in the UK, the CLEAR test facility at CERN and the CLARA test facility in Daresbury Laboratory. Those results, complemented with simulations, suggest that the use of both incoherent and coherent emission of Cherenkov diffraction radiation could open up new beam instrumentation possibilities for relativistic charged particle beams.

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High-Frequency Radiation of Relativistic Charged Particle Bunches in Presence of Dielectric Objects: Methods and Examples

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Radiation of charged particles moving in presence of dielectric targets is of interests for various applications in accelerator and beam physics [1, 2]. Typically, the size of the target is much larger than the wavelengths under consideration. This fact gives us an obvious small parameter of the problem (ratio between the wavelength and the target dimension) and allows developing approximate methods of analysis. We have developed two methods: the "ray-optical method" [3, 4] and the "aperture method" [5-8]. These methods can be very effective for all situations where we can find the tangential field components on the "aperture" which is an object's boundary illuminated by Cherenkov radiation. As a rule, this cannot be done rigorously. But for high-frequency (in the aforementioned sense) radiation, this can often be done approximately.

Here we consider several new examples of the use of the developed methods. In particular, the so-called dielectric concentrator of Cherenkov radiation is studied in the situation where the charge moves parallel to the structure axis with a certain displacement from it (a problem without axial symmetry). The influence of the trajectory shift on the effect of radiation focusing is analyzed. Next, we consider the problem of radiation from a dielectric ball with a vacuum channel (the charged particle bunch moves along the channel axis). In this case, both the ray-optical method and the aperture one are used. The main analytical results are obtained. They are compared with simulations in COMSOL Multiphysics. Various physical effects are demonstrated including the effect of radiation concentration in certain small areas and the phenomenon of the "Cherenkov spotlight" in the Fraunhofer zone. Prospects for using the ray-optical and aperture methods are discussed.

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Optical Cherenkov Radiation from an Inclined Plate as a Tool for Angular Beam Diagnostics

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In the paper [1] authors presented results of the measurements of the optical Cherenkov radiation generated by 255 MeV electrons passing through an inclined diamond plate with a thickness 50 micrometers. They showed that intensity of the registered photons (a part only from the whole Cherenkov cone, which is extracted into vacuum from the inclined plate) is high enough for certain detection.

We propose to use such an effect to determine a beam divergence measuring a dependence of the Cherenkov radiation yield on the inclination angle for a fixed detector position.

For electron energy ~ 1 GeV and the quartz plate thickness 4 mm it is possible to measure a divergence at the level 10^{-4} rad.

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BBU Instability in Rectangular Dielectric Resonator

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One of the significant limitations on the amplitude of the accelerating field in a dielectric wakefield accelerator is the head-tail drive bunch beam breakup (BBU) instability. In this report, we analytically and numerically investigate an arising and evolution of the BBU instability in a rectangular dielectric resonator when excited by a sequence of relativistic electron bunches. The dielectric resonator is a metal waveguide R_{26} with transverse dimensions 45x90mm with Teflon dielectric slabs (dielectric constant 2.051) with a thickness of 8.2mm located along the wide side of the resonator. The wavelength of the LM_{21} operating mode having a symmetric profile of the longitudinal component of the electric field is 53.2 mm. The electron energy of bunches is 4.5 MeV, the charge of each bunch is 6.4 nC, the repetition period is equal to twice the wavelength of the LM_{21} mode. By numerical PIC simulations, the charge losses of electron bunches on dielectric plates are investigated depending on the structure length, the initial offset of the drive bunches relative to the cavity axis. It is shown that the charge losses on dielectric slabs due to the BBU instability do not exceed 5%. When the resonance bunch repetition period is changed (a multiple of the LM_{21} mode's wavelength) by a period, a multiple of another eigen wavelength (e.g., the LM_{11} mode), the charge loss of the drive bunches does not change appreciably.

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Noninvasive Longitudinal Beam Profile Diagnostic Using Cherenkov Diffraction Radiation at CLARA Facility

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Production and diagnostics of short electron bunches in modern particle accelerators are fore-front issues. For example, in modern X-ray free-electron lasers the electron bunches are longitudinally compressed down to $<$100 fs to achieve high peak currents which is crucial to drive FEL process. Such a short bunch duration opens the possibility to use effect of coherent radiation for longitudinal beam profile diagnostics. In our work we focus on using the coherent Cherenkov diffraction radiation (ChDR) effect, which is, in comparison with others types of polarization radiation has relatively high intensity, allows us to perform noninvasive diagnostic, and is highly directional providing low background detection possibility.

Experimental part was performed at CLARA accelerator [1], where a 35 MeV, 70 pQ bunch with pulse repetition rate of 10 Hz was used to produced coherent Cherenkov radiation from teflon target. Inside the vacuum chamber we developed a multi-directional manipulation platform where ChDR and transition radiation (TR) targets were mounted. It allowed us to observe both effects during one accelerator run and make relevant comparisons. For spectral analysis we used Martin-Pupplet interferometer as it provides higher signal to noise ratio and allows us to perform self-normalisation.

Theoretical part consists of calculation of Cherenkov emission from a single particle. The model we used can be found in [2], Eq. 18. It takes into account angular acceptance of optical detection line, distance between target surface and electron beam, beam energy, target dimensions and its refractive index. Using this equation with experimental parameters from CLARA we can calculate ChDR single electron spectrum to extract bunch form-factor. Longitudinal charge distribution can be obtained as an inverse Fourier transform of a square root of the form-factor [3].

As a result we will demonstrate a selection of interferograms and spectra obtained during experiments at CLARA (both for TR and ChDR targets), products of single electron spectrum calculation for specific parameters we used, and reconstructed longitudinal beam profile for CLARA machine.

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Section 1

General Properties of Radiation from Relativistic Particles: Day 2

For Notes

Compton and Thomson Inverse Scattering as an X-ray Source: State of the Art and Perspectives

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Compton backscattering is the most promising instrument of radiation generation in the X-ray range. Comparing with modern 4-th generation facilities, Compton sources offer very important for the research laboratories advantages - relative compactness and cheapness, while the main characteristics (number of photons per pulse, energy bandwidth, pulse duration, emittance etc.) can be sufficient for applications in phase contrast and K-edge imaging, cancer therapy, computed tomography and so on. In the present report we give a short review of current state of development of such sources. We discuss the theoretical approach describing the interaction of electron beams with electromagnetic waves, advantages and disadvantages of linear and nonlinear regimes, coherent effects, polarization, as well as the progress and problems in experimental realization.

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Relationships between Parameters of Single Atomic Scattering and Bremsstrahlung

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To characterize fast charged particle scattering on an atom, two parameters are introduced, depending on the atom potential and determining the hard scattering (pre-Rutherford asymptotic behaviour), and one parameter characterizing multiple scattering in atomic matter from such atoms. It is proven that the latter quantity expresses the screening momentum in the Molière's multiple Coulomb scattering theory both in the perturbative and semi-classical regimes. For classical scattering on an atom, the existence of a scaling more general than that of Lindhard-Nielsen-Scharff is proven. A relationship between the Molière angle and the radiation length is obtained, taking into account the Coulomb nature of electron scattering on atoms in the next-to-leading logarithmic approximation.

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Conversion of Relativistic Electron Energy into One Photon when Interacting with Crystal

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Interaction of relativistic electrons with crystal axis or plane is traditionally described in channeling model as a motion in some even, homogeneous averaged potential. However, real crystal axis or plane consists of individual atoms, positioned periodically. Interaction with periodical heterogeneities must be accompanied with quantum transition of discrete portions of momentum $\Delta_{p||} = 2\pi n\hbar/d$, $n = 1, 2, 3, \ldots$, defined by the period of heterogeneities d. In axial case d is equal to the period of crystal lattice along this axis. Transmission of sufficient quantum portion of momentum to the lattice can be accompanied by the emission of photon with correspondingly high energy $\hbar\omega \sim 4\pi\hbar\ E_1^2/dm^2c^3$. In case of energies $E \sim GeV$ or more, up to $\sim 90\%$ of electron's energy may be converted into just one photon in this process.

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Modified Baier-Katkov Method for Twisted Photon Radiation

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Nowadays the Baier-Katkov (BK) semiclassical method [1] is a standard tool to de-scribe radiation of plane wave photons by ultrarelativistic charged particles in external electromagnetic fields of a general form. The BK method is realized in several computer codes [2,3] and proved to be very successful. We use this method to derive the radiation probability of one twisted photon [4] by an ultrarelativistic charged particle with account for the quantum recoil. In the case of negligible quantum recoil, the obtained general formula reduces to the one derived in [5].

The derived formula is used to describe the radiation of twisted photons by charged particles in undulators and laser waves. The explicit formulas for the probability to record a twisted photon are obtained in these cases. The manifestation of the blossoming out rose effect [6] in the nonlinear Compton process in a strong laser wave with circular polarization and in the wiggler radiation is revealed. Several examples are studied: the radiation of MeV twisted photons by 180 GeV electrons in the wiggler; the radiation of twisted photons by 256 MeV electrons in strong electromagnetic waves produced by the CO_2 and Ti:Sa lasers; and the radiation of MeV twisted photons by 51.1 MeV electrons in the electromagnetic wave generated by the FEL with photon energy 1 keV.

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Lobachevsky Space in Analysis of Relativistic Nuclear Interactions. Directed Nuclear Radiation - a new Phenomenon

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The relativistic nature of phenomena is illustrated in terms of the Lobachevsky geometry. The Lobachevsky space is used for description of particle production in relativistic nuclear physics on the basis of experimental data obtained at bubble chambers in π-C, p-C, C-C, n-p reactions in an energy range from units to tens of GeV. The new phenomenon - directed nuclear radiation - is discussed.

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Poster Session II

For Notes

The Origin of Thermal Breakdown of Semiconductor Materials at Electromagnetic Pulse Exposition

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An elementary theory of the thermal breakdown origin in thin films of semiconductor materials, the conductivity of which has a rapidly increasing dependence on temperature from a certain threshold value, is proposed. In the presence of such a dependence, due to the delay in the heat transfer process between inhomogeneously heated areas of the film in comparison with the rapid growth of the Joule heat emission generated by Foucault currents caused by the action of an electromagnetic pulse on the semiconductor material, there is a "locking" of heat in small areas with a linear size r_0 of the 1 μ order. The duration of the time intervals during which such locking occurs is sufficient for a local temperature increase in these areas from its operating values T_0 to the melting temperature T_m of the material. As a result, melted channels with a characteristic linear size r_m appear in the film. The local temperature increase is generated by thermodynamic fluctuations of the temperature distribution in the film which have a typical amplitude about 1-3K in the regions with size r_0.

Within the framework of the described theoretical thermodynamic representations, it is formulated the simple dynamic model of the temporal growth of the linear size r(t) of the melting region together with the temperature T(t) in it. The calculation of the function r(t) based on this model makes it possible to predict the values for experimentally observed some thermal breakdown characteristics. Namely, the dependences of the thermal breakdown time t_m (channel melting time) and the size r_m of the channel on some characteristics of the semiconductor material (its conductivity and thermal conductivity), as well as on the experimental values of the typical spatial sizes of the temperature inhomogeneities in the film and their average amplitude are calculated.

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Crystalline Undulator Radiation in "Water Window" Region

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The researchers have realized a "crystalline undulator" (CU), with periodically bent crystallographic planes. Optical radiation generated by a relativistic positron bunch channeling in CU is considered.

Due to the crystal's medium polarization, both soft and hard boundary photons exist emitting at a zero angle. In the case when the bunch energy crosses the threshold, the wavelength of the boundary soft photons becomes dependent only on the amplitude and spatial period of CU. A certain choice of these control parameters theoretically guarantees a region called the "water window" (2.32-4.36 nm within the soft X-ray regime), where brilliant images of biological materials are available.

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The Spectral Characteristics of the Radiation Channeled Positron Bunch in a Crystalline Sectional Undulator

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The case when the single crystals curved along arcs of a circle is considered. The frequency distribution of radiation, depending on the distance between the sections, received. The optimal value of this parameter revealed, at which the constructive interference of the radiation fields formed in the sections occurs.

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First Observation of Scattering of Sub-GeV Electrons in Ultrathin Si Crystal at Planar Alignment and its Relevance to Crystal-Assisted 1D Rainbow Scattering

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Rainbow Scattering (RS) is a very specific type of scattering, which has been well known for a long time in the three-dimensional (3D) scattering of waves and particles (both classical and quantum), see e.g. [1]. In the theory of crystal rainbows (2D RS) with fast ions [2], the key aspect is the specific dependence of the deflection angle on the impact parameter with a crystal axis. The challenge and motivation appears to answer a question - whether the 1D (one-dimensional) RS by a crystal plane in an ultrathin crystal exist? To observe 1D-RS, the first precise measurements of 255 MeV electron scattering by an ultrathin 0.58 μm Si crystal at angles of incidence less than the Lindhard critical angle between a beam and (111) plane were performed at the SAGA-LS facility. The main results are as follows [3]:

1) 1D-RS of relativistic 255 MeV electrons was observed for the first time.
2) The simulations of electron trajectories revealed the multiple-value connection (as in 3D-RS) between deflection angle and impact parameters (points of incidence into a crystal), which affects the angular distributions of scattered electrons. This connection is dependent on the crystal thickness L, which is the second important parameter that characterizes 1D-RS.
3) The comparison of the experimental and theoretical results showed a fair agreement.

In this work we continue investigation of 1D-RS of relativistic electrons for different crystal and electron energy.

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Half-Wave-Crystal Channeling of Relativistic Heavy Ions at Super-FRS GSI/FAIR and Possible Applications

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A half-wavelength crystal (HWC) is a thin crystal where a channeling particle experiences only one collision with a crystallographic plane ("mirroring" or HWC channeling) during penetration through a crystal. The HWC channeling was observed for 400 GeV protons at CERN-SPS [1] and for 255-MeV electrons at the SAGA-LS Facility [2, 3]. The HWC channeling is explained by computer simulations as a sequence of specific particles trajectories governed by the one-dimensional periodic potential of crystallographic planes. The perspective atomic physics experiments (including crystal targets) with Relativistic Heavy Ion (RHI) beams are the part of the Super-FRS Experiment Collaboration program [4].

Here, we present the results of computer simulations of HWC channeling of high-Z (^{129}Xe, ^{208}Pb, ^{238}U) and low-Z (p,t, d, ^{6}Li, ^{9}Li, ^{11}Li) relativistic ions with kinetic energy $E_k = 300$ MeV/u passing through a (200) tungsten crystal, using the computer code BCM-2.0 [5]. Possible applications of HWC-channeling of RHI are discussed, e.g. as fragments deflectors and splitters and even as the charge Ze and mass number A (isotopes) filters.

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Channeling of Fast Neutrons in Crystalline Structures of Textured CVD Diamond

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The passage of fast neutrons through the crystal structures of a textured CVD diamond was investigated. Polycrystalline and single-crystal samples with (100) crystal orientation were used. Neutrons from the Cf-252 isotope (with an average energy of about 2 MeV) were used as the source. Neutrons were detected by two independent methods: proportional counters with He-3 filling and a paraterphenyl crystal scintillation detector. The measurements showed the dependence of the neutron flux entering the detector on the orientation of the target from the structure of a textured CVD diamond. A possible explanation of the effect is the channeling of deuterium and neutron ions in the channels of a textured CVD diamond.

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Dose-Enhancing Agent for Radiotherapy at Orthovoltage X-Rays Irradiation

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Photon-capture therapy (PCT) or contrast-enhanced radiotherapy (CERT) is a promising development direction of binary radiation therapy, which is applied in order to increase the treatment efficiency that may be caused by the local energy deposition in the tumor [1]. The basic principle of PCT is the generation of a large number of the characteristic X-rays and low-energy Auger-electrons due to interaction between photons and nuclei of heavy elements ($Z \geq 53$). In biological tissue this secondary low-energy radiation ionizes nearby atoms and leads to the occurrence of highly active radical series, which causes the destruction of the macromolecules of DNA and RNA as well as other cell structures[2].

The results of previous radiobiological studies based on orthovoltage X-rays irradiation have shown that the presence of cisplatin (Pt, Z = 78) reduces the survival of the HeLa cells[3].

The purpose of this research is to study and evaluate the dependence of dose increase on DEA concentration at orthovoltage X-rays radiation using Monte-Carlo simulation methods.

As part of this study the simulation of 60, 120, 180, 250 keV photon beams at different concentrations cisplatin in tumor volume was simulated by Geant4 and Computer Lab (PCLab). At the first stage of this research we performed simulation of dose distribution in the water (Blue Phantom) from Xstral300 X-ray tube that was previously measured at Tomsk Regional Oncology Centre. In the second stage we performed simulation of dose depth curves in the presence of cisplatin in the target volume. Cisplatin concentrations from 3 μM to 0.03 M were studied. 3 μM concentration is the minimal concentration, which had a visible effect during the radiobiological experiments [3]. The simulation results showed that the dose escalation can be caused by PCT. There is a dose enhancement in the volume where cisplatin is accumulated. The higher is concentration, the higher is the effect. However, the photon energy increase from 60 to 250 keV and increase of depth of target reduces the effect of PCT due the decrease of the photoelectric effect cross-section.

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Particle Identification on Spin Physics Detector at the NICA Collider

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A new project of Nuclotron-based Ion Collider fAcility (NICA) and Spin Physics Detector (SPD) is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna. NICA will provide a variety of beam species ranged from protons and polarized deuterons to gold ions. High luminosity collisions of polarized protons and deuterons at NICA opens wide opportunities for nucleon spin physics studies. The particle identification system for SPD NICA is discussed. The simulations required to determine the necessary accuracy of the SPD PID system are presented. The simulations include particle motion in a strong uniform magnetic field in an energy range of 0.5 - 10 GeV for electrons / positrons, the separation of hadrons from pions / kaons in the same energy range.

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Detector Simulation for the MPD Experiment

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In the course of the work, a model of the detector of the MPD experiment was created. That's model makes it possible to simulate the passage of charged hadrons, photons and electrons. It's further allows for the calibration of gold beams on new the detector on the base of NICA. The simulation was based on the ROOT software package, which was written on C++ and other programming languages by the CERN. This software package is able to simulate the processes occurring in accelerators during the collision of beams with a further separation of those into pieces and the passage of these parts through various materials.

Since the detector will consist of many different materials of different shapes, it is necessary to add all of them to the model. In addition to a large number of different elements, it was necessary to indicate accurately all sizes and dimensions.

The result of this work is a convenient working model for detector.

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Determination of Wide-Aperture Electron and X-Ray Beams Transverse Sizes

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Radiation sources is widely used in different science and technological applications. Currently many medical centers are equipped with radiation medical setups, such as X-ray tubes and charged particle accelerators. To provide correct operation of these setups in the treatment and diagnosis procedures it is necessary to control spatial parameters of radiation beams. To determine such parameters X-ray and dosimetry films is widely used in medical practice. These approaches intend using of consumables that increases the operating cost of these devices. Two other disadvantages are the necessity of accurate control of the replaceable sensitive elements parameters and impossibility of on-line monitoring of beam parameters. Therefore, it is prospective to create a uniform non-disposable devise for measurement of X-ray and electron beams transverse sizes.

Nowadays, the method for measurement of electron beam sizes based on wire scanning is well studied and widely used. This method implies thin metal wire motion in a plane perpendicular to the beam propagation while detector is located behind the wire. Thus, the beam is partly absorbed and scattered by the metal that causes changing of the detector signal. Besides, to measure the beam with sizes up to tens of microns laser wire scanners is also used.

In this work the sizes of electron and X-ray beams is measured using one uniform scintillation scanner, which is a thin scintillation strip, in which analyzed beam generates light photons. These photons is guided by the optical fiber to photomultiplier. The intensity of light photons is proportional to the quantity of absorbed energy and consequently to the flux of primary radiation passing through it.

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Changes of 3d-Printed Plastic Samples Mechanical Properties Caused by 6 MeV Electron Beam Irradiation

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The number of 3D printing technology applications is crucially rising throughout last two decades. One of the prospective applications is high-energy beam shaping. However, to estimate applicability of this approach it is necessary to investigate mechanical properties degradation of 3D printed plastic samples under high radiation dose. Therefore, this work is aimed to study of 3D printed plastic samples mechanical properties, irradiated by the 6 MeV electron beam.

In a frame of work plastic samples made of ABS, PLA and HIPS are produced by fused deposition method with Ultimaker2 printer with modified printhead. For each plastic and two kind of tests, we produce three samples for control group and three for irradiated one. In accordance to the recommendations for determining of the compressive strength (ISO 604:2002) the samples have a cubic shape with a 2 cm long edge. Other samples is $10 \times 20 \times 80 cm^3$ sized accordingly to the recommendations for static bending tests (ISO 178:2010). The irradiation is carried out with the extracted 6 MeV electron beam of TPU microtron with 1.5 kGy dose value. Mechanical properties investigations of irradiated and control samples is carried out on Instron 5985.

Observed results shows that investigated parameters (compressive modulus and bending stress) do not differ for irradiated and control samples made of ABS, PLA and HIPS plastic within measurement error. Thus, it is possible to conclude that 3D printed plastic samples retain their mechanical properties under radiation dose up to 1.5 kGy for all tested materials.

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Determining of Electron Beam Percentage Depth Dose in Media with Varied Density by Longitudinal Arranged Dosimetry Film: Simulation Results

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It has become a standard to monitor the parameters of clinical electron radiation sources. To increase the accuracy of irregular dose field measurement, it is necessary to measure the percentage depth dose (PDD), for instance, in a 3D printing material with density differs from the 1 g/cm^3. The purpose of this work is to explore the possibility to determine the PDD in media with different densities using dosimetry films.

We use the Monte-Carlo method for simulation. A flat 10×10 cm^2 parallel electron beam with a uniform distribution falls on a water phantom.

Water is a medium for the beam propagation, and we can vary its density in the settings. The density varies from 0.4 to 2.3 g/cm^3 and the chemical composition remains constant. Simulation for each density is carried out in two geometries: 1 - electrons propagate in a homogeneous medium; 2 - flat dosimetry film corresponding to the Gafchromic EBT3 film (1.2 g/cm^3 density) is placed in the path of the beam and oriented along the electron motion.

The results show that tissue-equivalent dosimetry films can be arranged longitudinally to measure the electron beam PDD in media with densities from 0.9 to 1.8 g/cm^3. This can simplify the experimental measurements of the PDD in 3D printing materials with densities close to water.

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Compensating Filter for Computed Tomography of core Samples from Oil and Gas Fields

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The effect of an aluminum compensating filter on the signal-to-noise ratio in core samples tomograms is investigated. When scanning the core, a compensation filter in the form of an aluminum parallelepiped with a hole approximately equal to the diameter of the core was used. The filter is fixed above the stage, the core is placed in the hole and rotates inside the filter. It is shown that the filter provides the maximum contrast of the useful signal over the entire dynamic range of the scintillation flat detector. After the normalization of the core projections to the filter without the core, the obtained projections were used as input data for reconstruction based on the Feldkamp algorithm. The signal-to-noise ratio of the resulting tomograms is improved about two times as compared with the case of a conventional flat aluminum filter.

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Simulation of Cone Beam Computed Tomography of Core Samples from Oil and Gas Taking into Account Spectral Information in Geant4

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With the advent of photon counting matrix detectors it is become possible to take into account spectral infromation in CBCT. It gives benefits of improving contrast, reducing beam hardening artifact and separation of components with similar effective X-ray attenuation. In this study the positive effect of spectral analysis on tomography of core samples from oil and gas fields is estimated by simulating experiment in Geant4. In case of ideal tube focus and experiment geometry, radiogramms of PMMA cylinder with mineral insertions are obtained to perform reconstruction and compare the result with that got by typical CBCT.

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Semiconductor Diode for Heating of Pyroelectrics in Pyroelectric Accelerator of Charged Particles, X-ray, and Neutron Sources

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Pyroelectric accelerators, sources of X-rays and neutrons operate due to variation of the temperature of pyroelectric elements in vacuum. Usually resistors, incandescent lamps, Peltie elements or outer electromagnetic radiation are used for heating of the elements. Here, we propose application of semiconductor diode or transistor for heating of the elements in vacuum. Results of first experiments on heating of $LiNbO_3$ pyroelectric crystal by commercially available Si diode in vacuum and observation of X-ray radiation are presented. Such diodes are compact, low-mass, powerful, operate in vacuum, and have good heat-conducting base. Perspectives for application of semiconductor diodes or transistors for heating of pyroelectric elements in pyroelectric accelerators, X-ray, and neutron generators are discussed.

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Miniature Pyroelectric X-ray Source

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Recently, pyroelectric accelerator and X-ray generator, embedding in vacuum chamber with size 10 cm has been developed in Belgorod State University. The outer pump pumped the chamber out. The energy of characteristic x ray's peak can be changed due to installing corresponding target in the accelerator. Such X-ray generator can be used for calibration of X-ray detectors without using radioactivity elements and outer high voltage power sources.

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Piezoelectric Quartz X-ray Source

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Recently piezoelectric accelerator was proposed [1]. Piezoelectric elements were used for generation of high voltage potential [1]. At the present work we used cylindrical quartz crystal with axis (11) orientated along axis of cylinders. Results of measurements X-ray spectra generated by electrons in such quartz accelerator are presented and discussed in this work. The main properties and perspective applications of the quartz accelerators are discussed.

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Pyroelectric Impulse Accelerator

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Usually, pyroelectric accelerators are based on the pyroelectric crystals [1] or ferroelectric ceramics, which work in the qusy-continues mode. The duration of the accelerator's operation is defined by the duration of the heating or cooling of the pyroelectric element, usually for several minutes. At the present work positive charge appears on the surface of the pyroelectric crystal due to changing temperature, after this grounded electrons sources is activated. As a result, we obtained impulse pyroelectric accelerator. The properties of impulse neutron source and X-ray generator, which is based on such accelerator, are discussed in this work.

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Installation "Rontgen 1" for the Study of Radiation Processes of Interaction of Relativistic Electrons with Matter

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The installation "Rontgen 1" [1] of the Department of High Energy Physics at LPI RAS is designed to study the characteristics of electromagnetic radiation in the spectral range from terahertz to gamma radiation generated within interaction of a beam of 7 MeV electrons with matter. Main feature of the installation is a possibility of carrying out absolute measurements of radiation spectra at observation angles in range of $0 \ldots 180°$ relative to the electron beam axis.

The work presents the main characteristics of developed installation that determine the prospects for using the installation as a test stand.

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Method of Diagnostics of Electron Beams of Femto-, Attosecond Duration

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For the first time, the use of a sampling calorimeter for recording short high-power X-ray pulses was proposed. Studies of the counting characteristics of the prototype on a monochromatic beam from a laboratory setup based on an X-ray tube with a wave dispersion attachment were carried out. Radiation with an energy of 20 keV is incident on a detector assembled from alternating layers of B-418 and Al scintillator, the thickness of each layer is 1 mm. According to the simulation results, the device allows you to register X-ray pulses with an intensity from 10^4 to 10^{20} quanta per second. The results of the experiment are compared with the results of modeling in GEANT4.

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Obtaining Parallel X-Ray Beams with Controllable Quantity and Distances Under the External Acoustic Fields in Quartz Crystals

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The possibility of obtaining parallel X-ray beams and controlling their quantity and distances in a wide range has been experimentally considered. To implement this experiment, a three-crystal scheme was assembled. The first crystal is set to monochromatize an X-ray beam, which provides high resolution. The second quartz crystal with AT - cut is used to obtain parallel X-ray beams with different distances and quantities using the effect of bulk acoustic waves with different frequencies. And the third quartz crystal with asymmetric reflection is used to control the distances of parallel beams in a wide range (from 50 μm to 1 mm).

In the experiments used the MoKα_1 monochromatic X-rays. Acoustic vibrations with frequencies of 2.979, 4.890, 6.933 and 8.836 MHz were excited to the quartz crystal with AT - cut, and X-ray parallel beams were obtained on the front section of the reflected beam. X-rays were recorded using photographic film. The formation of parallel X-ray beams in the frontal section from the second "splitter" crystal, falling on an asymmetric crystal, is reflected and their distance increases more than 20 times.

Thus it is shown that, using such a three-crystal scheme, it is possible to obtain any number of parallel X-ray beams and control their distances in wide ranges.

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Measurement of 1-GeV Electrons Ionization loss Spectra in a CdTe Crystal with a Thickness of 1 mm

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Particle identification systems in accelerator complexes often use detectors that measure the ionization loss by charged particles. In case of using semiconductor detectors, flat Si crystals usually act as an active element (see, e.g., [1]). In the present work the ionization loss of 1-GeV electrons moving in a CdTe crystal are measured. Along with silicon, CdTe crystals are also widely used, for example, for the production of X-ray and gamma-ray detectors.

As a target, we used Amptek XR-100T CdTe electrically cooled X-ray detector with crystal thickness of 1 mm which was installed on the beam of relativistic electrons at the Test Beam Facility TB21 of DESY [2]. The energy resolution of the detector is about 830 eV at X-ray energy 59.5 keV emitted from ^{241}Am. The measured spectra of 1-GeV electrons ionization losses in 1-mm thick CdTe crystal contain a peak with the energy of about 620 keV and the width of about 200 keV. Properties of the observed spectra are discussed.

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Radiation from a Charged Particle Bunch Moving in Presence of a Corrugated Surface with Small Period

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We consider "longwave" radiation of a charged particle bunch moving in the presence of a corrugated planar conductive surface. It is assumed that wavelengths under consideration are much more than the period and the depth of corrugation. In this case, the corrugated structure can be replaced with a smooth surface on which the so-called equivalent boundary conditions (EBC) are fulfilled [1]. In fact, we deal with some anisotropic surface characterized by a certain matrix impedance.

It should be noted that problems, connected with excitation of radiation in such structures, are of essential interest for development of methods to generate microwave and terahertz (THz) radiation. In particular, similar problems were investigated for waveguide with a finely corrugated wall [2,3]. In these works, authors showed that an ultrarelativistic charge moving along an axis of a circular metal waveguide generates "longwave" radiation, the intensity of which is comparable to one in a dielectric waveguide. In the paper [4] authors considered the problem with a charge moving in the presence of a plane wire structure consisting of thin conductors.

Here we investigate the situation when the corrugated surface is planar and has rectangular "cells". Two different cases of motion are examined. In the first one, the thin bunch with an arbitrary longitudinal profile moves along the corrugated surface with a constant velocity which is perpendicular to grooves of the structure. Using the method of EBC we obtain the electromagnetic field components which are presented in form of spectral integrals. It is demonstrated that an ultrarelativistic bunch generates the surface waves, whereas volume radiation is absent. In the second case, the bunch passes through the structure (perpendicularly to it). Fourier transforms of electromagnetic field are obtained and analyzed. It is shown that, in this situation, both volume radiation and the surface waves are excited. Besides the field components, we analyze the energy losses of the bunch for both cases of motion.

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Study on Coherent THz Radiation Using Tilt Control of Electron Beam

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Conventional positron sources are based on the conversion of bremsstrahlung from relativistic electrons into electron-When the velocity of the charged particles is faster than the light velocity in a medium, Cherenkov radiation is produced at an angle dependent on the refractive index of the medium. Coherent Cherenkov radiation can be obtained by matching the tilt of the electron beam with the Cerenkov radiation angle, which is very useful as a high intensity THz pulse source. In order to control the tilt of the electron beam, we use a rf transverse deflecting cavity. TOPAS (cyclic olefin copolymer) which has a constant refractive index in the THz band is used as a target medium. In our previous study, a broadband THz pulse about 0.1 to 1.0 THz was generated by focusing the transverse size of the electron beam using quadrupole magnets. For a more advanced light source, monochromaticity and wavelength tunability are required. The radiation obtained from an electron beam having a periodic structure has an enhanced wavelength corresponding to the period. Therefore, by giving a periodic structure to the electron beam with a multi slit, we tried to generate a quasi-monochromatic THz pulse. At this conference, we will report the experimental results of the generation of coherent Cherenkov radiation and quasi-monochromatization with the periodic electron beam, and future prospects.

Durability Improvement of Cesium Telluride Photocathode for an Rf-gun

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At Waseda University, we have been studying for high quality electron beam generation using 1.6 cell Cesium Telluride (Cs-Te) photocathode rf-gun. We use photocathode as the electron source, which can generate high-quality electron beam such as low emittance, and short bunch. The performance of photocathode is evaluated mainly in terms of quantum efficiency (Q.E.) and lifetime. Cs-Te photocathode used in the rf-gun is known for high Q.E. about 10% with UV light and relatively longer lifetime among semiconductor photocathodes[1].

Since it is a hard environment for photocathode inside the gun, it is necessary to replace the photocathode every several months. In other words, in order to achieve long-term operation of rf-gun, it is necessary to find highly durable photocathode recipe. It has been reported that the Cs-Te photocathode by co-evaporation can produce a photocathode having a longer lifetime as compared with the sequential evaporation[2]. Moreover, we have done studies to improve lifetime and durability of Cs-Te photocathode by coating the cathode surface with CsBr thin film[3]. In this symposium, we report the evaluation results of Cs-Te photocathode by co-evaporation, CsBr coated photocathode performance in an rf-gun and future prospects.

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Section 3

Transition Radiation

For Notes

Radiation of a Bunch in a Waveguide Partly Filled with an Anisotropic Dispersive Medium

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In a series of works so-called reversed (backward) Cherenkov-transition radiation (RCTR) was studied [1,2]. This effect can occur when a charged particle bunch crosses the boundary between a vacuum and a left-handed medium (LHM). RCTR can be perspective for different applications in the domain of the beam diagnostics, evaluation of the medium characteristics and development of new methods of generation of gigahertz and terahertz radiation. Artificial anisotropic materials or metamaterials (MTMs) possessing left-handed properties in the GHz and THz band have been demonstrated recently (see, for example, [3-4]). In such a medium, a moving charged particle generates reversed (backward) Cherenkov radiation (RCR). The RCR can penetrate through the boundary into a vacuum and, as a result, the RCTR can be generated at some condition [5]. Here, we consider the case of waveguide loaded with the semi-infinite anisotropic MTM.

We analyze the electromagnetic field of a bunch that moves uniformly in a circular waveguide and crosses a boundary between a vacuum area and an area filled with MTM. The MTM is characterized by the diagonal dielectric permittivity tensor with components possessing frequency dispersion of plasma types. The investigation of the waveguide mode components is performed analytically and numerically with methods using as well as in papers [2, 6-7]. The cases when the bunch flies into and out of the MTM are under consideration. In compliance with the parameters of the MTM, Cherenkov radiation has direct or reversed direction in relation to the bunch motion.

In the case when the bunch flies into the MTM, intensive radiation (RCTR) can be generated in the vacuum area. The main properties of this radiation are described, and essential differences from the RCTR in the case of isotropic LHM are revealed. The analytical and numerical investigations show that the RCTR in the vacuum area always consists of a finite number of propagating modes. We show that selection of the problem parameters allows obtaining both multimode radiation and monochromatic one.

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Manifestation of the Formation Length Effect for X-ray Transition Radiation by 1-6 GeV Electrons in Periodic Multifoil Radiators

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Formation region effects in X-ray transition radiation are experimentally investigated. The study was performed on the test beam facility TB21 at DESY [1]. The radiation was generated by 1-6 GeV electrons in two multilayer targets of different period, which consisted of thin aluminum foils separated by air gaps. The period of the first target was smaller than the typical size of the radiation formation distance in the gap between the foils, while the period of the second one exceeded this distance. Both the effects of suppression and enhancement of X-ray transition radiation were observed at variation of the incident electron beam energy. The latter effect of radiation enhancement in the small-period radiator compared to the large-period one is a new feature of the discussed emission which was not reported in previous investigations of this kind (see, e. g., [2]). Application of this effect for a noticeable enhancement of the radiation yield is discussed and the conditions required for this are presented. The expression for the spectral density of transition radiation from a multilayer target is derived for the case of an arbitrary transversal particle distribution in the electron beam and the finite size of the detector active area. The experimental results are analyzed and compared to the theoretical estimations.

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Effect of Interference in Angular Distribution and New Opportunities for Transition Radiation Detectors

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Identification of ultra-relativistic hadrons with a good precision is a challenge for the Detector Physics. The only known way to identify multi-TeV hadrons (Pi, K and p) is using Transition Radiation Detectors. This type of detectors, however, also requires improvements to satisfy all modern requirements [1 - 3]. For that to be done, it is necessary to know all features of transition radiation. In this report we present new theoretical results concerning complex interference structure of angular distribution of transition radiation [4]. Also, recent experimental [5 - 7] results are compared with the theory and simulations in GEANT4 [8]; the latter was modified in accordance with recent theoretical and experimental results.

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Application of Timepix Detector for Measurement of X-rays Produced by a Low-intensity Electron Beam Passing Through a Periodic Target

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This report demonstrates initial testing of the high-speed spectral camera ModuPIX based Timepix detector with Si sensor. We present the first results on the measurement of X-rays produced by passing a 2 GeV low-intensity electron beam through a resonant transition radiation target and then diffracted from the HOPG crystal. A test setup was constructed on the test beam line No 21 at DESY (Hamburg, Germany). The results obtained show that the Timepix detector allows separating the low intensity diffracted X-rays from the background caused by charged particles.

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Monochromaticity of Transition Radiation and Diffraction Radiation from Grating

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High interest in developing intense monochromatic THz sources is explained by its unique features, such as ionization absence and weak absorption in dielectric samples.

The linac at ATF KEK (Japan) can provide generation of electron bunches with length less than 0.15 mm. Therefore, it can produce THz/sub-THz radiation via coherent transition/diffraction radiation (TR/DR) mechanism. In order to produce monochromatic radiation, we investigated spectral characteristics of coherent TR/DR in the geometry where bunches interact/pass nearby with a periodical target (grating) instead of a flat metallic foil as for conventional TR/DR. As a result, a continuous spectral distribution, which is typical for TR/DR, is transformed into a spectrum with narrow spectral lines, so-called Grating Transition Radiation (GTR) [1] and Grating Diffraction Radiation (GDR).

We experimentally investigated a GTR/GDR spectral line shape for different grating tilting angle with respect to an electron beam and observed that for orientation angles much more than the inverse Lorentz factor there is some line splitting. In this report, we present spectral measurement results for two polarization components both cases and compare them with the preliminary simulation results.

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Characteristics of Smith-Purcell Radiation and Grating Transition Radiation from Gratings with Variable Profile

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In the report we compare the characteristics of the coherent Smith-Purcell radiation (SPR) and the grating transition radiation (GTR) [1] in the millimeter wavelength range generated by the 6 MeV electron beam from Tomsk microtron. The experiment was performed with the modulated electron beam with RF frequency $\gamma_0 = 2.63$ GHz. The measurements were carried out for two types of gratings, the first one was designed with flat strips separated by vacuum gaps with variable angles of the strip inclination, and the second one was a standard grating with a triangular profile. A sharp spectral and angular discreteness of GTR and SPR were detected. These effects are determined by the resonances between modulated beam periodicity and diffraction orders of the radiation from gratings. We demonstrate a strong dependence of the radiation intensity on the grating strip slope and its profile.

This work was supported by the JSPS-RFBR grant No18-52-50002 and by the Competitiveness enhancement program of Tomsk polytechnic university.

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Section 8

Applications of Monochromatic X-ray, γ-ray and Terahertz Beams Produced at Electron Accelerators

For Notes

Russian Project of 4th Generation Synchrotron Light Source SSRS-4: Main Goals and General Description

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Today, third- and fourth-generation synchrotron radiation (SR) sources and X-ray free-electron lasers (FEL's) find many different applications in materials science, molecular biology and biochemistry, biomedical studies, crystallography, spectroscopy, studies of rapid processes and other areas of scientific and applied research. For these applications the crucial problem consists in reaching the diffraction limit for a given beam energy of 3-6 GeV: thereby, an object can be imaged with high contrast and sharpness once its size is comparable with the wavelength of the synchrotron or undulator radiation. It was assumed that transverse emittances below 100 pm rad are necessary for the fourth generation to achieve new horizons in the research using SR. Long years it was assumed than such values of the emittance can be reached only with FEL's driven by high-brightness electron linacs. Few years ago it was demonstrated that storage synchrotrons also enable for reducing the horizontal emittance and first beams with emittances near 100 pm rad were indeed generated by the MAX-IV (Sweden) [1] and Sirius (Brazil) [2] synchrotron light sources commissioned in 2016-2017. Several similar facilities are under the design and construction stages but today's leading trend consists in upgrading the existing SR sources to fourth generation [3-7].

It is proposed that SSRS-4 complex will includes both the 6 GeV storage synchrotron and a FEL(s) [8]. Such layout leads to the complex injection system based on full-energy linear accelerator which will uses both for top-up injection into storage ring and for generation of the high-brightness drive bunches for FEL.

In this report we present current information about one of the largest Russian scientific projects. Results of the magnetic structure of the SSRS-4 main ring evolution will presented as well as the results of the beam dynamic, dynamic aperture and energy acceptance simulations. The general structure and the beam dynamics for the 6 GeV top-up injection linac will be also shown. Achievable parameters of synchrotron radiation will be discussed as well.

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GEANT4 Modelling of Light Collection in PWO Scintillator Crystal Wrapped by a Retro-reflective Film

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Scintillation light transport and collection at the entrance window of a photodetector in a great extent have effect on the energy and time resolutions of a scintillation detector, especially in the case of high value of the scintillator refraction index and its large size at least on one of dimensions. Now various wrappings are applying to improve light collection and in some cases, its linearity. To control photon capture in oblong scintillator sensors some variants of the photonic crystals are proposed [1]. As was showed [2], retro-reflector also can be successfully used for the effective control of photon transport within a detector.

In the contribution we consider distributions of scintillation photons and evaluations of energy and time resolutions in the CMS type PWO element wrapped by specular reflector (aluminum foil mirror), diffuse reflector (Tyvek), and retro-reflector (3M Scotchlite Reflective Material) irradiated by electrons and gamma-quanta with energy of 1, 10, and 100 GeV. Simulations were performed using Monte-Carlo GEANT4 toolkit supplemented by implementation of the retro-reflector into its optical simulations.

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Pre-bunched Electron Beam Generation and Application for Accelerator-based THz radiation Source

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The motivation for developing of intense THz source at KEK LUCX is coming from the growing interest to THz radiation from various scientific communities worldwide. High gradient photo-cathode RF gun and few tens of femtosecond (Ti:Sa) laser system are now routinely used to generate a pre-bunched electron beam of a few hundred femtoseconds. Also, a new Yb-dopped fiber based laser system with enhanced tunability and stability is under development. We are investigating the production and properties of the intense radiation beams in the range of 0.1-0.6 THz based on Grating Diffraction Radiation (GDR) and Smith-Purcell radiation. These types of EM radiation are generated when a charged particle moves in the vicinity of a periodical pattern or grating. The grating type and period can be chosen to make quasi-monochromatic radiation spectrum. In this reports the status of the KEK LUCX facility and its RF gun laser system upgrade will be presented. Also, consequent enhancements to radiation studies will be discussed.

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Electron and X-ray Source based on a Pyroelectric Single Crystal Driven by a Periodically Varying Temperature

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Nowadays, the possibilities of obtaining compact and safe particle sources and accelerators for a wide range of applications are being actively investigated and considered. One of such possibilities is a pyroelectric effect in single crystals of lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$) can lead to acceleration of electrons to energies of the order of 100 keV and to generation X-rays with broad spectrum. However, electric breakdowns prevent stable particles acceleration.

The sinusoidal mode of changing the temperature of a pyroelectric single crystal leads to oscillations the pyroelectric current with a typical frequency of the order of 1-50 mHz and the amplitude of about 1-10 nA for samples with area of several cm^2. In vacuum condition that current might induce high electric field, which oscillates with the same frequency. Estimated amplitude of electric field is of the order of 105 V/cm. The possibilities and the advantages of using such mode of temperature change to obtain a quasi-stable X-ray and electron pyroelectric source are considered. Preliminary results of measurement of electron and X-ray flux are reported.

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Dose-Enhancing Agent for Radiotherapy at 6 and 10 MV Medical Linac

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Radiation therapy is an important and effective technique of malignant tumors treatment [1]. Actual problem of radiotherapy is increasing effectiveness and reducing side effects of the treatment. Binary technologies of radiation therapy can be used to improve treatment results. One of the most promising technology is contrast-enhanced or "photon-capture" radiotherapy (PCT) [2]. The PCT is effective at low X-ray energies where the photoelectric effect dominates (up to about 200 keV). Accordingly, the energy escalation of photon beams leads to a gradual decrease the effect of the PCT. However, low-energy photons for medium- and deep-seated tumors are limited due to their low penetrating power. For irradiation of deep-seated tumours, the megavoltage photon beams from linear accelerators are widely used, where the Compton effect is maximal and the photoelectric effect is minimal.

Although the effect of PCT should be low, different studies shows the escalation of energy in the target volume due to the introduction of dose-enhancing agent (DEA) at megavolt photon beams [4-6]. Some authors suggest that the observed effect is caused by the wide energy spectrum of photon beams, which including the low-energy kilovolt energy range.

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Measurement of Wide-Aperture X-ray Beam Trasverse Profile Based on Multiangular Wire Scanning

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Nowadays radiation sources are widely used in different investigations and technological applications, such as radiation therapy, sterilization of medical equipment, welding, microstructuring processes etc. It is necessary to control beam parameters in exploitation of devices designed for this purposes. One of the main parameter is the particle flux density distribution in a transverse plane of the beam.

Previously we suggested a new method for particle flux density distribution in a transverse plane of the beam. The method is based on mathematical reconstruction of experimental data, which is observed multiple beam scanning by thin strip under different angles.

In this work these method is tested experimentally. In the experiment, an X-ray tube is used as a radiation source, while thin scintillation strip as a sensitive scanning detector. In this strip, light photons is generated due to interaction with X-ray beam. These photons is guided by optical fiber to the photomultiplier. Scintillation strip moves in the plane, which is perpendicular to the beam propagation. Thus, we experimentally observe a set of registered photons intensity on strip location and angle orientation with particular angle step. These dependences is further used to reconstruct particle flux density distribution in a transverse plane of the beam.

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Self-amplification of Radiation from an Electron Bunch Inside a Waveguide Filled with Periodic Medium

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We investigate the radiation from a bunch of relativistic electrons moving along the cylindrical waveguide axis, assuming that a part of the waveguide is filled with a layered material, the dielectric permittivity and magnetic permeability of which are arbitrary periodic functions. Analytical expression is provided for the spectral distribution of the radiation energy flux through the cross section of the waveguide at large distances from the layered medium. It is based on the corresponding exact solution of Maxwell equations for the case of a single electron moving along the waveguide axis. The results of numerical calculations are presented in the special case of layered medium consisting a finite number of dielectric plates separated by vacuum gaps. We show that under certain conditions on the problem parameters, the quasi-coherent Cherenkov radiation generated by the electron bunch inside the plates is self-amplified at certain waveguide modes. A visual explanation of this phenomenon is provided. We also present a simplified model that reproduces with satisfactory accuracy the main features of the self-amplification phenomenon. The possibility of using this phenomenon to develop powerful radiation sources in the terahertz frequency range is discussed.

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2D Focusing of Reflected Hard X-rays and Thermal Neutron Beams in the Presence of External Temperature Gradient

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It was experimentally shown that in the presence of temperature gradient in X-cut quartz crystal it was possible to obtain 2D bending of reflecting atomic planes (10-11) depending on the position and shape of heater, thereby ensure the possibility of 2D focusing of X-rays at reflection from these planes. It is noteworthy that the degree of bending depends on the thermal expansion coefficient in the given direction. Consequently, in case of appropriate choice of crystal, of its cut and the family of reflecting atomic planes, one can provide such a 2D bending, at which a point focus of reflected X-ray radiation is obtained. It is also shown that under these conditions the integrated intensity of reflected X-ray radiation increases by several orders of magnitude, and the angular width in mutually perpendicular directions is controllable.

Reflection of thermal neutrons beam from the quartz crystal in the Laue geometry under the external influences was investigated theoretically. The possibilities and estimation of the time-spatial control of thermal neutrons beam parameters (relative maximum intensity, angular and energy distributions of receiving beams, etc.) are analyzed.

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Investigation of the Interaction of Ion Beams with Deuterated Crystal Structures at the HELIS Facility

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The results of studies of the interaction of ion beams with deuterated crystal structures at the HELIS facility (LPI) are presented. In DD-reactions in deuterated crystal structures at deuteron energies 10-25 keV, significant enhancement effects are observed. For CVD-diamond and Pd targets, the orientation of the sample with respect to the deuteron beam was shown to affect the neutron yield.

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Piezoelectric Transformer for Generation of X-rays in Vacuum

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Today, third- and fourth-generation synchrotron radiation (SR) sources and X-ray free-electron lasers (FEL's) find many different applications in materials science, molecular biology and biochemistry, biomedical studies, crystallography, spectroscopy, studies of rapid processes and other areas of scientific and applied research. For these applications the crucial problem consists in reaching the diffraction limit for a given beam energy of 3-6 GeV: thereby, an object can be imaged with high contrast and sharpness once its size is comparable with the wavelength of the synchrotron or undulator radiation. It was assumed that transverse emittances below 100 pm rad are necessary for the fourth generation to achieve new horizons in the research using SR. Long years it was assumed than such values of the emittance can be reached only with FEL's driven by high-brightness electron linacs. Few years ago it was demonstrated that storage synchrotrons also enable for reducing the horizontal emittance and first beams with emittances near 100 pm rad were indeed generated by the MAX-IV (Sweden) [1] and Sirius (Brazil) [2] synchrotron light sources commissioned in 2016-2017. Several similar facilities are under the design and construction stages but today's leading trend consists in upgrading the existing SR sources to fourth generation [3-7].

It is proposed that SSRS-4 complex will includes both the 6 GeV storage synchrotron and a FEL(s) [8]. Such layout leads to the complex injection system based on full-energy linear accelerator which will uses both for top-up injection into storage ring and for generation of the high-brightness drive bunches for FEL.

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Adaptive X-ray Optical Elements Based on Longitudinal and Transverse Acoustic Waves in the KHz and MHz Frequency Ranges

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X-ray acoustic interactions allowing to implement the control of X-ray parameters are widely studied. Among the numerous researches, it is possible to highlight the ability of controlling the spatial and energy spectrum of X-ray radiation [1] and the effect of redistribution of intensity between transmitted and diffracted beam [2]. This paper describes the implementation of a combination of these two possibilities.

Fast control of X-ray parameters, including scanning diffraction conditions and controlling by times much shorter than possibilities of traditional approaches, is a very relevant scientific task. It will be shown that overcoming of limitation of traditional approach, such as complex goniometric systems, possible by using of non-mechanical adaptive X-ray optic elements, such as X-ray acoustic resonators of longitudinal oscillations or bimorph piezo-actuators. It allows fast and precise variation of X-ray diffraction parameters, varying the angular position of the X-ray beam and controlling its wavelength. Description of schemes and elements for fast tuning of beam parameters will be given.

The effects of the redistribution of intensities between the diffracted and transmitted X-ray beams under the conditions of excitation of resonant acoustic thickness oscillations in quartz crystals were investigated. It has been established that the effect of increasing the intensity of a diffracted beam almost linearly depends on the amplitude of ultrasound (the FWHM of the rocking curves does not change at the same time) and is observed for all the studied reflexes.

The time characteristics of the observed effects upon excitation and relaxation of ultrasonic oscillations were investigated for the first time: the process of increasing intensity takes about 250 microseconds, then its oscillation is observed for about 1 millisecond, and the process of complete relaxation takes about 1.5 milliseconds. Preliminary design of elements combining thickness and longitudinal oscillations are considered, several schemes of implementation are proposed. The effect of intensity redistribution in Potassium and Rubidium hydrogen phthalate crystals, which are emerging materials for creating a two-frequency element, was studied for the first time.

Prospects of implementation of such methods and elements at synchrotron radiation as well as laboratory sources will be discussed.

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Section 7

Crystal-assisted Processes

Recent Advances of Crystal Channeling in Accelerating Science

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Ideas of use the particle channeling in bent crystals for steer the beams have been checked up and advanced in many experiments. Recently, a curved single crystal was tested at the LHC for the task of the beam collimation [1]. This method is also widely used in U-70 accelerator of IHEP, where crystals are used in regular runs for beam extraction and forming [2]. However, until now, this method of beam formation has limitations in application, since the channeling process involves beam particles with low angular divergence, limited by the angle of Lindhardt (it is equal to 25 microradians for the energy of the Protvino accelerator U-70 for 70 GeV). Here we describe two crystal devices, the focusing crystals and multistrip crystals, which expand the boundaries of application of bent crystals at accelerators. The created focusing crystal [3] reveal the possibility of a new optics of the beams for extremely high energies. Modern accelerators go into the TeV Energy region, the LHC is already operating at 6.5 TeV. The FCC and SPPC with energies up to 100 TeV are planned. In this region of energies, the scattering of secondary particles from the targets is very narrow, a fraction of milliradian. We propose special crystal elements with a focusing edge for the formation of particle beams of such energies. These crystals can work as super-strong lenses with a focal length of about 1m, with an equivalent magnetic field of 1000 Tesla. The proposed ideas are supported by experimental studies on the U-70. Multistrip crystals [4] are also created, which can deflect beams of positively and negatively charged particles due to the phenomenon of reflection from curved atomic planes by more than 90% efficiency. These devices are promising for radiation-protection septum SM24 and collimation of the proton beam crystals in a magnetic block 86 accelerator U-70. Also, multilayer crystal structures can be used to protect the electrostatic septum of the SPS accelerator at CERN [5], for which the corresponding calculations will be carried out using the proposed algorithm.

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Measurements of Charge of Particles by a Semiconductor Detector

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Usually, magnetic field is used for identification of different accelerated particles. This method is sensitive to the relation Z/M, where Z and M are the charge and mass of the particles respectively. Here, we propose to apply measurements of ionization loss that depends mainly on Z for identification of particles. Recently, we observed carbon ions +6C and its fragments with Z=1,2,3,4,5 of energy 25 GeV/nucleon by Si surface-barrier detector of size 10*10 mm and thickness of the depleted layer 300 mkm at accelerator U-70 [1,2]. The measured spectrum of ionization loss, shown in figs. 8 in both papers [1,2], contains 6 corresponding Landau spectral peaks at different energies depending on the charge of particles. The measurements of ionization loss together with application of magnetic field can be used for identification of particles in a beam that contains different particles.

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Possible Method of Spatial Sizes Measurement of Relativistic Electrons Beam with Small Longitudinal Bunch Length

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Possibility of practical realization suggested earlier methodic of electron beam sizes determination for electron bunches with short length by measurement of two-dimensional angular distributions of relativistic electrons coherent emission in a crystal for two distances between a crystal, where the radiation is born, and a coordinate detector [1] is analyzed. As an emission source the diffracted transition radiation is used. The minimum measured beam size is about 10–15 microns for electrons with energy above several GeV. The technique is weakly sensitive to pulse heating of the target if it does not destroy the crystal, and can be used on intense beams of linear accelerators creating x-ray free-electron lasers [2]. Influences of secondary electrons and photons outlet from a coordinate detector and the method applicability for different longitudinal bunch length are discussed. The limits of the technique applicability and sensitivity are presented.

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Application of Semiconductor Detectors with Smoothly Tunable Thickness in Space Telescope of Relativistic Charged Particles

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Space telescopes of charged particles consist of stack of Si detectors and are intended for measurements of energy and direction of motion the particles. The detectors are as Si slabs supplied by permanent bias voltage [1]. We proposed [2] application of Si detectors with smoothly varying by the bias voltage thickness of the depleted zone in the telescope. The application of such detectors would allow optimize operation of the space telescope without any mechanical motions.

For instance, 1.6 mm thick beryllium slab is installed before the first detector of the telescope for absorption of low-energy particles [1]. The slab provides fixed energy threshold for incident particles. Instead of beryllium slab, we propose to install the first Si detector with depleted zone turned toward the telescope. Regulating bias voltage, one can simultaneously change the thickness of the depleted zone and the thickness of non-sensitive Si layer, where charge is not collected from. Thus, one can smoothly regulate the thickness of absorbing layer and register passed particles in depleted zone of the same first detector. This means that the energy threshold at observation of charged particles can be variated smoothly, that is impossible with the beryllium slab.

Si detectors with variable thicknesses were studied in our researches with electrons of energy < 1 MeV in KIPT [3] and 50 GeV protons at accelerator U-70 [4].

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Scintillation Signal Strong Enhancement in an Axially Oriented Lead Tungstate Crystal

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The interaction between a 120 GeV/c electron beam and a 4 mm thick lead tungstate scintillator was investigated at H4 beamline of SPS, in CERN North Area. The high Z target material was chosen in order to provide intense fields ($E \approx 10^{11}$ V/cm). In the beam rest frame, the internal electric fields are enhanced by a Lorentz factor. Thus, the effective field perceived by electrons exceeded Schwinger critical field limit ($E0 \approx 1.32 \times 10^{16}$ V/cm). In this condition, the electromagnetic shower process is supposed to be accelerated inside the medium. In this experiment, evidences of faster shower development were probed by measurements of the scintillation light produced by the crystal. A reflective coating was applied to the sample, a SiPM was coupled to the base of the sample to collect signal intensity. Measures were performed in condition of alignment with [001] axis and in condition on misalignment with major crystallographic axes and planes. A clear enhancement of scintillation light intensity was measured in case of axial alignment. This effect could prove of great interest for future electromagnetic calorimeters with improved features of signal intensity and maximum measurable energy, provided a flux of incoming particles with small angular spread (i.e. forward physics, astrophysics sources)

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Manufacturing of Silicon Crystals for Steering of Ultra-High Energy Particle Beams

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Physics of interaction between X-rays or gamma beams and crystals have been worldwide investigated at synchrotron where electrons with energy from tens of MeV to few GeV circulating in storage rings produces X-ray beams which are delivered to extracted lines.

Since the '70, physics of interaction between bent crystals and heavy particles (protons or ions) is investigated at various worldwide particle accelerators, driven by the possibility to use bent crystals as optical elements for steering or focusing charged particle beams. Recent developments in crystal manufacturing, joined with a deeper understanding of the physics behind crystals-particle beams interaction lead to a discovery of numerous interactional effects.

Nowadays technology readiness level is mature enough to allow the use of crystals even in the Large Hadron Collider (LHC) of CERN, where crystals are being experimented as primary collimators of the protons or ions circulating beam and are suggested as core elements of fixed-target experiments. Given the extremely high intensity and energy reached in modern accelerators or in future planned ones (such as FCC, ILC, CLIC and CEPC), implementation of bent crystals at such facilities demands to face with various technological challenges. In this contribution we describe manufacturing and characterization of crystals suitable for installation in the LHC as primary collimators of circulating beams. Successful development of such crystals is based on a merging of ultra-modern technologies used in microelectronics, X-ray science, ultra-precise optical and mechanical machining.

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Angular Anisotropy of Multiple Scattering in a Crystal

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The interaction between a 120 GeV/c electron beam and a 4 mm thick lead tungstate scintillator was investigated at H4 beamline of SPS, in CERN North Area. The high Z target material was chosen in order to provide intense fields ($E \approx 10^{11}$ V/cm). In the beam rest frame, the internal electric fields are enhanced by a Lorentz factor. Thus, the effective field perceived by electrons exceeded Schwinger critical field limit ($E0 \approx 1.32 \times 10^{16}$ V/cm). In this condition, the electromagnetic shower process is supposed to be accelerated inside the medium. In this experiment, evidences of faster shower development were probed by measurements of the scintillation light produced by the crystal. A reflective coating was applied to the sample, a SiPM was coupled to the base of the sample to collect signal intensity. Measures were performed in condition of alignment with [001] axis and in condition on misalignment with major crystallographic axes and planes. A clear enhancement of scintillation light intensity was measured in case of axial alignment. This effect could prove of great interest for future electromagnetic calorimeters with improved features of signal intensity and maximum measurable energy, provided a flux of incoming particles with small angular spread (i.e. forward physics, astrophysics sources)

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Section 4

Parametric X-ray Radiation

For Notes

Dynamical Effect of Asymmetry in the Parametric X-rays Radiation Generated by Relativistic Electrons in a Single-Crystal Target

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The dynamic theory of coherent X-rays of a relativistic electron crossing a single-crystal target in the Laue scattering geometry is discussed. In [1] Expressions describing the spectral-angular characteristics of radiation in the direction of Bragg scattering are obtained and investigated by the author of the present work. The radiation is considered as a result of coherent addition of the contributions of two radiation mechanisms parametric X-ray (PXR) and diffracted transitional (DTR). The calculations showed that in the case when the diffracting atomic planes in the target are located relative to the target surface at an angle of, a noticeable difference is observed in the results of the calculation of the spectral-angular density of the PXR within the dynamical theory and the kinematical one (reflection asymmetry effect). The analysis showed that the main cause of this effect is the absent in the kinematic theory of the dependence of the width of the PRI spectrum on the asymmetry angle. In [2], good agreement between the developed dynamic theory and experiment [3], which was carried out under conditions of asymmetric reflection of the Coulomb field of an electron on a single-crystal target, was shown.

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Diffraction of Real and Virtual Photons in Crystalline Powders

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The distance between crystallographic planes is of the same order as the X-ray wavelength. For this reason, crystals act as diffraction gratings for X-ray [1]. This interaction is referred as diffraction of real photons. On the other hand, Parametric X-ray Radiation (PXR) has been described as the diffraction of the charged particle Coulomb field in the crystal. This mechanism is referred as diffraction of pseudo, virtual or equivalent photons [2].

This experimental work presents the measurements of signals produced during the interaction of both 7 MeV electrons and X-rays with tungsten powders. The measurements correspond to the diffraction of virtual and real photons respectively. Tungsten powders were chosen because in the energy region between 2 and 7 keV the diffracted peaks from five crystallographic planes can be analysed without the influence of background peaks. The characteristics of both diffraction processes are analysed and compared. Parameters such diffraction peak yield, peak FWHM and peak to background ratio are discussed.

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