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Investigation into the Mechanisms of X-Ray Generation during the Interaction between Relativistic Electrons and a Medium by means of the Röntgen-1 Setup

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Abstract—The Röntgen-1 setup which is intended for use in investigating the spectral-angular characteristics of X-rays generated due to the interaction between a 7-MeV electron beam and substances, including different shaped surfaces, is described. The setup is distinguished by a low radiation background, enabling the determination of low-intensity radiation spectra. The results of measuring the characteristics of the polarized bremsstrahlung of relativistic electrons from media with different atomic structures are presented.

Keywords: parametric X-ray radiation, polycrystals, relativistic electrons, polarized bremsstrahlung

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INTRODUCTION

The mechanisms of interaction between charged particles with a substance and electromagnetic fields are commonly used in medicine, biology, solid-state physics and other areas. The development of new applications of charged-particle beams has always been an urgent problem. In this area, the main obstacle is the extremely small number of experimental facilities allowing the given studies to be performed. This is related to the fact that the operation of accelerators is complex and the utilization of expensive equipment is necessary. One of the aforementioned facilities is the Röntgen-1 setup developed at the Lebedev Physical Institute (LPI), Russian Academy of Sciences (RAS).

This setup was built on the basis of the S-25R Pakhra synchrotron located at the Accelerator Laboratory of the High-Energy Physics Department, at the LPI RAS [1] to investigate the properties of polarized bremsstrahlung (PB) [2] in media with a partially ordered atomic structure [3]. The electron source was a 7-MeV microtron included in the synchrotron injector [4]. PB is generated when atoms of a medium are polarized under the action of the Coulomb field of an accelerated particle moving through the medium. In the case of the ordered arrangement of atoms, the coherent component is dominant in PB, the characteristics of which are related to the parameters of the atomic structure [3]. Such a feature enables us to determine the atomic-structure parameters according to the measured spectrum of coherent PB [5, 6]. In crystals, coherent PB is better known as parametric X-radiation (PXR) [7, 8]. It is significant that, in the first works [3, 9], PXR in polycrystals was called PB.

During the study of PXR from media with a partially ordered atomic structure, the main problem was the low intensity of the recorded signal [3, 9]. In this context, Röntgen-1 was initially designed as a low-background setup making it possible to effectively record the useful-signal spectrum at a level of about several photons per minute if the spectrum contains intense quasi-monochromatic lines of characteristic X-ray radiation (CXR), which is also generated upon the interaction of an electron beam with a target.

Over the course of studies performed beginning in 2003, the Röntgen-1 setup has been updated several times. Hence, this setup is now universal in many respects, making it possible to carry out investigations both in a wide spectral range and in an arbitrary geometry of observation of the emission process.

In this work, the key features of the Röntgen-1 setup are described.

EXPERIMENTAL

The source of relativistic electrons was the injector microtron of the Pakhra synchrotron by which a 7-MeV

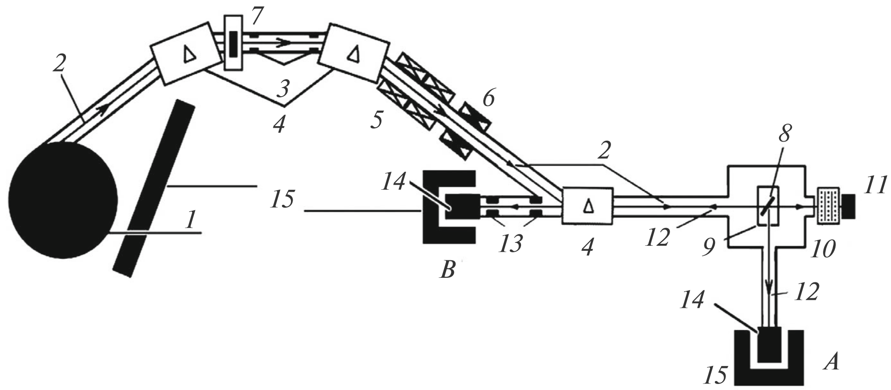

Fig. 1. Experimental setup: (*1*) microtron, (*2*) electron beam, (*3*) electron-beam collimators, (*4*) bending magnets, (*5*) quadrupole magnetic lenses, (*6*) corrector, (*7*) vacuum shutter, (*8*) target, (*9*) goniometer, (*10*) proportional chamber, (*11*) Faraday cylinder, (*12*) measurable radiation, (*13*) collimators, (*14*) detector, (*15*) lead radiation shielding, and *A* and *B* are the geometry types.

beam of accelerated electrons was formed. The microtron generates a time-structured electron beam with a pulse repetition frequency of 50 Hz (the pulse duration is up to 4 μs). The internal structure of each pulse is determined by "small" pulses (bunches) whose duration and periodicity are ~1 and 10 cm, respectively [4]. The Röntgen-1 setup is diagrammatically represented in Fig. 1. During its design, special attention was devoted to the radiation-background level in the proposed region of detector location.

In its use as a source of relativistic electrons, the microtron is intended mainly for the injection of electrons accelerated to 7 MeV into the synchrotron channel with the aim of further acceleration. The electron beam was primarily extracted from the injection channel with the help of a bending magnet which was installed in order to deflect the electron beam toward a single vacuum channel.

The X-ray generation yields calculated within the limits of electron-beam characteristics demonstrated the necessity of decreasing the beam current and its angular divergence. To solve this problem, two graphite cylindrical collimators, the aperture and length of each of them were, respectively, 3 and 50 mm, were installed at a distance of around 1.5 m from each other after the first bending magnet of the channel. These collimators decreased the beam intensity by three to four orders of magnitude but initiated an intense background, which was created predominantly by bremsstrahlung and CXR. As regards the electron-beam axis, the intense radiation background propagated within a cone whose apex angle was about 30°. Graphite was chosen as the material of the collimators to prevent charge accumulation in their volume. This is explained by the low bremsstrahlung yield and good conducting properties. (Bremsstrahlung propagates predominantly within a cone whose apex angle is on the order of γ^{-1} with respect to the trajectory of radiating electrons, and the yield is proportional to Z^2. In this case, γ is the Lorentz factor of a radiating electron and Z is the atomic number of the element of the target material.)

An intense radiation background was generated in the microtron as well and propagated mainly along the orbital planes. To decrease its influence on the system of recording of the signal under study, the channel incorporated a second bending magnet ensuring beam deflection at a specified angle, which was chosen so as to direct the beam with minimum background toward the experimental hall.

At an invariable intensity of the electron beam, the bending magnets substantially deformed it. As a result, the problem of beam-shape correction arose. With the aim of solving this problem, the beam focusing and correction system, which comprised two pairs of focusing quadrupole magnetic lenses and a corrector whereby the beam position was adjusted in the vertical direction of the channel cross section, was mounted behind the second bending magnet. At different stages of creating the setup, the beam shape was investigated using continuous-flow proportional chambers with operating surface sizes of 32 × 32 mm and the beam coordinate over the channel cross section was determined with an accuracy of ±1 mm. The intensities were found by means of a Faraday cylinder [4].

The distances between the setup's basic components, namely, magnet no. 1—magnet no. 2, magnet no. 2—magnet no. 3, magnet no. 3—target, and target—proportional chamber distances, are 0.24, 2, 0.8, and 0.6 m, respectively. The electron-beam collimators are spaced 1.5 m apart.

The experiment occurs as follows (Fig. 1). Microtron *1* generates an electron beam *2* with an energy of 7 MeV. The first of the bending magnets *4* (along the electron-beam direction) extracts the beam from the injection channel. Afterward, its formation is carried out by two carbon collimators *3*, each having an aperture of 3 mm. The interaction between the beam and the collimators excites an intense radiation background propagating mainly along the collimator axis. The second bending magnet *4*, directs the beam from the radiation background to the magnetooptical channel of beam formation involving two pairs of quadrupole magnetic lenses *5* and a corrector *6*. The third bending magnet *4* directs the electron beam into a vacuum chamber with a target *8* whose orientation is controlled by a goniometer *9*. Moreover, there is the possibility of extracting the target from the electron beam. The beam's spatial position and its intensity are diagnosed with the help of the proportional chamber *10* and a Faraday cylinder *11*. Radiation *12* caused by the interaction between the electron beam *2* and the target *8* is formed by the collimators *13* installed before the detector *14*. The microtron and the detector are covered by lead shielding *15* to reduce the radiation background level. The microtron and the target-containing chamber share common vacuum, which, if necessary, can be separated by means of a sliding shutter *7*.

The unmodified setup made it possible to perform measurements in the geometry of two basic types designated by *A* and *B*, the latter of which is unique and corresponds to the case where radiation is recorded in the direction opposite to that of propagation of the electron beam interacting with a target.

With the aim of investigating the spectral-angular characteristics of X-rays arising from the interaction between relativistic electrons and a substance, a universal vacuum chamber was designed to measure these characteristics in a wide range of observation angles. The chamber incorporates vacuum ports with mylar windows 100 μm thick whereby an electron beam is extracted to the proportional chamber and the Faraday cylinder.

The chamber enables us to observe the process of interaction between an electron beam and a target at angles of 1°–10°, 30°–150°, and 170°–180° with respect to the radiating-electron direction in the horizontal plane. The position and orientation of the target is controlled by means of a vacuum goniometer with four degrees of freedom: three rotational degrees of freedom in the orthogonal planes with an accuracy of 0.01° in the range of 0°–360° (a single-step mode in combination with the possibility of carrying out controlling actions at step fractions of 1/2, 1/4, and 1/8) and the target's linear translation in the horizontal plane perpendicular to the electron beam to within 12 μm in the range of 0–100 mm.

In the vicinity of the target, the measured electron-beam characteristics are the following: the beam's transverse size (width at half height if the beam-current density is approximated by the Gaussian distribution) is less than 3 mm and the angular divergence is less than 5 mrad.

To create high vacuum, an evacuation system based on a turbomolecular high-vacuum pump in conjunction with an oil-free forepump was mounted in the chamber, enabling the achievement of a pressure of about 10^{-6} Torr.

In the context of microtron characteristics, the minimum possible off-duty ratio was 5000 at a reset-pulse duration of 4 μs. The given circumstance signifies that the detector must quickly respond to any action and have a maximum load of no less than 10^4 event/s. Under the given conditions, one photon could conceivably be recorded for each reset pulse. Calculations of PXR yields from media with a partially ordered atomic structure and the results of preliminary experiments demonstrated that the arising radiation spectrum can be represented as a smooth "substrate" of bremsstrahlung and background with CXR and PXR peaks located on its surface. The PXR contribution is 0.1–1% of the total recorded signal.

A sufficiently low PXR yield made it preferable to measure detector signals with a count rate of no less than 10^5 event/s in the spectral range of research. The detector's energy resolution must be as high as possible to identify PXR spectral lines against the smooth substrate of the background. Additional loading of the detector was implemented on account of the intense radiation background of the microtron created by electromagnetic interference, X-rays, and charge components. The background load is determined predominantly by the volume of the detector component used to record radiation, in which the radiation energy is transformed into an electrical signal. Hence, the application of a detector with the small operating-component volume is preferable.

With allowance for the aforementioned requirements to detectors, it should be noted that an optimal variant is the use of semiconductor detectors with typical load indices of about 10^5 pulse/s, an energy resolution of 100–200 eV in the range of 1–10 keV, and an operating-component volume of ~1 mm^3. An additional advantage of the given type of detectors is that their photon recording efficiency is close to 100% in the range of 1–10 keV. Thus, XR-100CR and XR-100SDD semiconductor X-ray detectors were chosen as the basis of the spectrometry unit.

The main advantages of the employed detectors were a high recording speed and thermoelectric cooling of the detector crystal, which made it possible to perform measurements under conditions of an intense radiation background and a high off-duty ratio of the electron beam. Since there was no need for the supply of liquid nitrogen to cool the crystal, the detector was located in a small volume and screened by lead.

A disadvantage of the detectors can be regarded to be instrumental phantom signals (the contribution of the given effects is ~0.1%) which manifest themselves during measurements. These effects are especially appreciable in measuring intense peaks on a smooth substrate, e.g., CXR on a bremsstrahlung substrate. In this case, the measured spectrum involves phantom ESC peaks (escape peaks), the energy of which is equal to the difference between the determined peak energy and the silicon photoabsorption edge (the radiation-recording detector is made of a silicon crystal). The mechanism behind the formation of ESC peaks is explained by the inelastic scattering of radiation measured for the crystal.

The detector signals were processed with the help of spectrometric electronics comprising a primary dis-

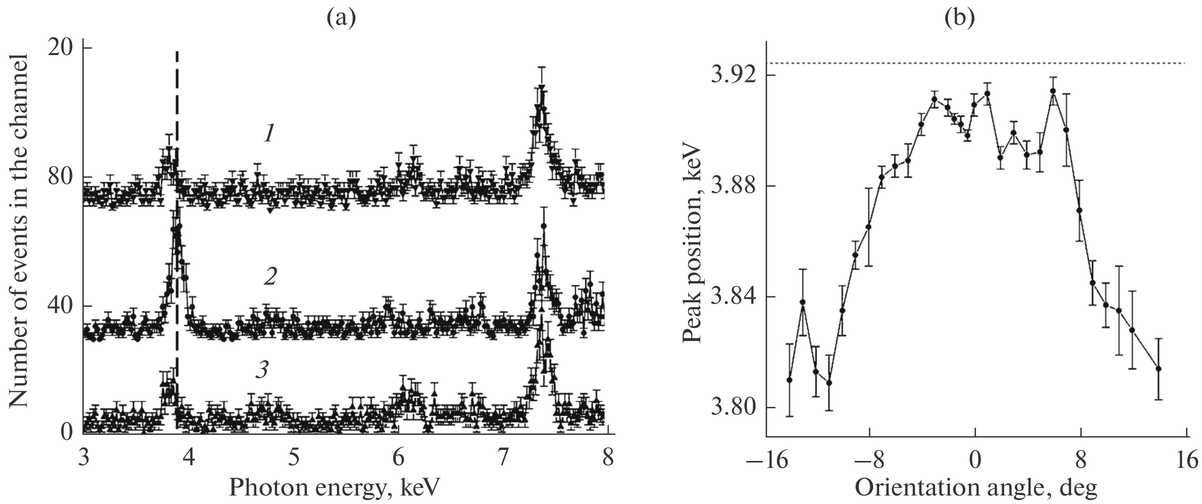

Fig. 2. (a) PXR spectra from a textured tungsten polycrystal at orientation angles of (*1*) −10°, (*2*) 0°, and (*3*) 10°, and (b) the dependence between the 200 PXR peak and the orientation angle.

criminator, a shaping amplifier, an ADC, and a multichannel pulse-amplitude analyzer. All key assigned parameters of the detectors were controlled using the statistical-data acquisition and processing program. As a result, it was possible to substantially vary the modes of detector operation under different measurement conditions. Of most value is the possibility of changing the pulse-formation time, enabling measurements at loads of up to 10^6 photon/s.

The detectors were additionally protected by lead to reduce the background. In all experiments, the measurable signal was strictly collimated to obtain an extra decrease in the background recorded from the internal surface of the spectrometry channel and the target-containing chamber.

To suppress the background formed on the internal surface of the target-containing chamber and the target holder, chamber parts were protected by acrylic resin and mylar in the signal-recording region. A shield-induced decrease in the background is explained by the elemental composition of shielding materials: C, O, and H inclusions. Firstly, bremsstrahlung is generated more slowly in these substances than in stainless steel from which the target-containing chamber is fabricated. Secondly, the CXR of mylar and acrylic resin atoms corresponds to energies of up to 1 keV and does not stimulate additional detector loading. At the same time, the CXR of chamber parts is in the range of 1–10 keV where the measurable signal is concentrated. The used shields made it possible to eliminate the background peaks of CXR in the measured spectra.

RESULTS AND DISCUSSION

As was mentioned above, the Röntgen-1 setup was developed to measure the spectral-angular characteristics of PXR from media with a partially ordered atomic structure. Its first application was the study of PXR from polycrystalline Al, Cu, and Ni foils [5]. In the context of the experiments, PXR spectral peaks were revealed at an observation angle of 90° and the absolute PXR yield was determined. A comparison between the measurement results and the theory [3] demonstrated good quantitative agreement. At the next stage, PXR was measured at an angle of 75°. As a result, it was found that the spectral peaks are shifted in accordance with theoretical predictions [11]. The obtained results indicate the possibility of identifying coherent PXR peaks in accordance with their position in the spectrum because the PXR peaks alter their positions with observation angle in contrast to CXR peaks whose position remains invariable.

In a finer experiment performed with the help of the Röntgen-1 setup, PXR from polycrystals and crystals in the backscattering geometry was determined. The most important outcomes consisted in the fact that, as was predicted in [13], an anomalous narrowing of the PXR spectral peaks [12] was recorded and PXR was observed in an anomalous diffraction region [14]. The performed measurements are distinguished by a low background and a high energy resolution. The measured spectra of PXR from a textured tungsten polycrystal are presented in Fig. 2. The target surface plane coincided with the (200) crystallographic plane. The target grain distribution over orientation angles was approximated by the Gaussian function. The width at half height (texture "value") was 5.44°. In the spectral region located to the left of the vertical line, X-ray diffraction is impossible, but virtual photon diffraction can be implemented. It is seen in Fig. 2 that, at target orientation angles of −10° and 10° with respect to the electron beam, the peaks are shifted toward the X-ray region where diffraction is forbidden. Therefore, the recorded peaks are characterized as PXR ones. At all orientation angles, PXR peaks man-

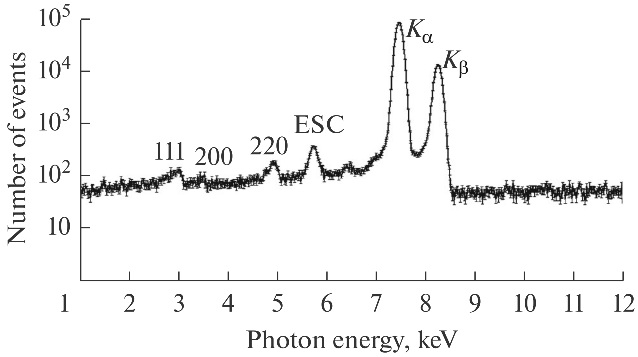

Fig. 3. Spectrum of PXR from a polycrystalline nickel foil with an average grain size of 300 nm [17, 18].

ifest themselves in the region lying below the Wulff–Bragg energy by 0.11 keV (3%).

In addition, it should be noted that the Röntgen-1 setup was employed to measure the characteristics of PXR from a silicon crystal in the asymmetric diffraction geometry [15]. The effect of an increased PXR yield was ascertained upon grazing interaction between relativistic electrons and crystals [16].

Such a high level of measurements enables us to qualitatively compare the theory and experiment. The results of comparison between the orientation dependences of the PXR yields from the textured tungsten polycrystal and pyroelectric graphite are presented in [14].

The Röntgen-1 setup was likewise used in attempts to measure PXR from polycrystals with submicron grain sizes. The measured spectrum of PXR from a polycrystalline nickel foil with an average grain size of 300 nm [17, 18] is depicted in Fig. 3.

The important features of the performed experiments are both the measured spectral width and the measured positions and amplitudes of the PXR peaks, which confirm the high functional characteristics of the Röntgen-1 setup.

CONCLUSIONS

The Röntgen-1 setup is a multifunctional low-background facility intended for the investigation of X-ray mechanisms implemented upon the interaction between relativistic electrons and a substance. The given feature makes it possible to study parametric X-ray radiation from substances with different degrees of atomic-structure ordering, starting from polycrystals with randomly oriented grains and finishing with crystals whose atomic structure is of high quality. In addition, the measurements of PXR from polycrystals with submicron grain sizes are carried out because the setup has a low level of background.

At present, the Röntgen-1 setup is modified to measure radiation spectra both in the vacuum UV and soft X-ray (100–1000 eV) ranges and in the hard X-ray (10–100 keV) region. This peculiarity enables us to perform the planned experiments on PXR investigations in nanostructured and amorphous media and, additionally, observe diffracted Vavilov–Cherenkov radiation in layered substances.

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