Channeling and radiation of electrons and positrons in diamond hetero-crystals

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We analyze numerically the radiation and channeling properties of ultrarelativistic electrons and positrons propagating through a periodically bent diamond crystal grown on a straight single-crystal diamond substrate. Such systems can be called hetero-crystals and they are one of the experimentally realized samples for the implementation of crystalline undulators. We state that in such systems the channeling and radiation properties of projectiles are sensitive to the projectile particles energy and the beam propagation direction, i.e. on whether the beam of particles enters the crystal from the side of substrate or from the side of periodically bent crystal. The predictions made are important for design and practical realization of new crystalline undulators.

I. INTRODUCTION

It was predicted by Lindhard1 that charged particles can penetrate anomalously large distances in a crystal moving along a crystallographic direction. This effect is called channeling. The channeled particles emit radiation (channeling radiation, ChR2) which by orders of magnitude exceeds the background bremsstrahlung radiation.

In recent years, study of the channeling phenomenon has attracted much attention. A significant number of theoretical3–16 and experimental17–26 studies have been carried out in order to determine the channeling parameters and radiation spectra which arise in different systems.

It was predicted in Refs.27,28 that additional radiation appears in periodically bent crystals (PBC). The radiation is emitted when the beam of ultra-relativistic particles undergoes planar channeling in PBC, such systems are called in literature29 crystalline undulators (CU). The periodic bending of the atomic planes gives rise to strong, undulator-type CU radiation (CUR) in the photon energy range 0.1 – 10 MeV. Light sources with this photon energy can be used in various new experimental and technological applications16,30–33.

In recent years, several experiments have been performed aiming at detecting CUR. One of the most studied system is a strained Si1−xGex superlattices. Periodically bent planes can be obtained by variation of the Ge concentration x. Such crystals has been grown by the method of molecular beam epitaxy at Aarhus University. This PBC can be manufactured with undulator wavelength \( \lambda_u \) much longer than channeling oscillations wavelength of the particles, these are often called LALP undulators (large-amplitude-long-period undulators). Such crystal, 4-period undulator with \( \lambda_u = 9.9 \mu m \), was examined experimentally at MaInzer Microtron (MAMI), a broad excess yield around the theoretically expected photon energy of 0.132 MeV has been observed.34 Another type of PB structures is SASP (small-amplitude-short-period)9,14. Where regular jitter-type modulations of the projectile motion with the period shorter than the period of the channeling oscillations produces radia-
FIG. 1. (a) Sketch of the crystal geometry. The diamond single crystal is cut with its surface perpendicular to the [100] direction. In order to achieve the planar channeling regime between (110) planes, the crystal is tilted under 45°. The crystal consists of two main parts: the single-crystal substrate with a thickness of 141 µm and the 4 periods of PBC with total thickness 20 µm. Top figure illustrates case of positron channeling in PB-S crystal and bottom figure case of electron channeling in S-PB crystal. (b) shows the 2D projection of *exemplary* trajectory of positron channeled through the whole PB-S crystal (see explanation in the text). (c) shows the 2D projection of *exemplary* trajectory of electron propagated in S-PB crystal. Note: several channeling and dechanneling segments, dechanneled electron leaves the borders of the figure between 130 and 150 µm. Gradient shading shows the boron concentration which results in PB of crystalline planes.

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thickness of the crystal in the projection onto the direction of beam propagation is $L_{cr} = 161 \, \mu m$, see Figure 1(a). Where 20 $\mu m$ is the thickness of the PBC and 141 $\mu m$ is the thickness of the straight substrate. The cosine bending profile $a \cos(2\pi z/\lambda_u)$ of the PB part was assumed with coordinate $z$ measured along the beam direction. The bending amplitude $a$ was considered equal to 2.5 Å, the bending period $\lambda_u$ was fixed at 5 $\mu m$. The lattice temperature was set to 300K. This results in bulk atoms oscillations with mean amplitude 0.04 Å.

The beam parameters were chosen to be in line with experimental conditions for electrons at MAMI, similar experimental conditions are achievable for positrons at DAΦNE acceleration facility. Thus, we simulated the planar channeling of $\varepsilon = 270$ and 855 MeV of electrons and positrons in oriented diamond hetero-crystals. The projectiles were assumed to have zero transverse velocity at the entrance of the crystal, hence the beam of particles has zero divergence.

Particles which propagate in a straight crystal can experience quasi-periodic oscillations in the potential of atomic plane or axis. Such oscillations are called channeling oscillations. A particle, which is channeling in the PBC, are involved in two types of quasi-periodic motions: the channeling oscillations and oscillations due to periodic bending of the channel. Spectral distribution of the radiation emitted in that case consists of a set of harmonics, for each value of the emission angle $\theta$ the spectral distribution consists of a set of narrow and equally spaced peaks. For each particle trajectory spectral distribution of electromagnetic radiation was calculated within the opening angle $\theta_0 = 0.24$ mrad, which corresponds to one of the detector apertures used at MAMI. The total radiation spectra were considered as averaging over all ($N = 6000$) simulated trajectories.

Numerical modeling of the channeling processes in the crystalline environment was performed using MBN EXPLORER computational software. By means of its channeling module it is possible to simulate motion of ultra-relativistic particles in different environments, including the crystalline ones. This computational package was benchmarked previously for variety of ultra-relativistic projectiles and different crystalline environments. The method of all-atom relativistic molecular dynamics is described in great details in Refs. Using this software in combination with advanced computational facilities it is possible to calculate significant number of projectiles trajectories to analyse. The software also allows one to calculate the radiation distributions $dE/\hbar d\omega$ for each projectile trajectory using the quasi-classical formalism due to Baier and Katkov. All this allows one to numerically analyze the channeling, radiation and related phenomena of ultra-relativistic particles in various media, while the accuracy of the predictions made can be compared with that in the experiments.

II. RESULTS AND DISCUSSION FOR POSITRONS

Let us now analyze the case of positron channeling in hetero-crystals. In the planar channeling regime, a charged projectile moves along a crystallographic planes experiencing a collective electrostatic field of the lattice atoms. For positrons, the atomic field is repulsive, so that the particle channels in between two adjacent crystalline planes. In this case, nearly harmonic channeling oscillations give rise to narrow photon emission lines.

Figure 2 presents the spectra calculated for the 270 and 855 MeV projectiles. The spectra consist of two main parts: the CUR (peak at lower energies) and ChR (peak at higher energies). The CUR radiation emits from the PB segment while the ChR can be generated in the PB and straight segments of the crystal.

Figure 2 (a) shows the results for 270 MeV positrons. The spectra are dominated by peak of ChR (strong peak at $\hbar \omega \approx 0.7$ MeV), CUR reveals itself as a small bump (note the insert in Figure 2 (a)) in low energetic part of the spectra ($\hbar \omega \approx 0.13$ MeV). It is easy to notice that for $\varepsilon = 270$ MeV electrons the spectral densities of
FIG. 2. Radiation emission spectra produced by ε = 270 and 855 MeV positrons in $L_{cr} = 161 \mu m$ diamond hetero-crystals. The collection angle was set to $\theta_0 = 0.24$ mrad. (a) Spectra by 270 MeV positrons propagated in PB-S and S-PB crystals. (the inset shows the $\times 6$ magnified CUR peak) (b) same as (a) but for 855 MeV positrons. Shading indicates the statistical error due to the finite number of simulated trajectories. For the sake of comparison we quote the intensities of the background incoherent bremsstrahlung estimated within the Bethe-Heitler approximation: $2.9 \times 10^{-6}$ and $2.5 \times 10^{-5}$ for $\varepsilon = 270$ and 855 MeV, respectively.

CUR and ChR for PB-S and S-PB crystals are deviate within margin of statistical error.

For 855 MeV positrons spectra are shown in Figure 2(b). The spectra consist of two main peaks: the peak of CUR around $h\omega \approx 1.1$ MeV and the peak of ChR around $h\omega \approx 3.6$ MeV. One can notice small bumps around $h\omega \approx 2.2$ MeV and $h\omega \approx 7.2$ MeV which is second harmonics of CUR and ChR respectively. As well as for $\varepsilon = 270$ MeV positrons intensities of CUR are the for two types of crystal, but spectral densities of ChR in S-PB is $\approx 2$ times large than this in PB-S. In case of 855 MeV positrons the difference in the intensities between CUR and ChR should be even less pronounced in the experiments, where usually, not the spectral density $dE/h\omega$ is measured, but the number of photons $(1/h\omega)dE/h\omega$ with certain energy.

In order to analyze difference in the radiation spectra, let us plot the trajectories of positrons. Figure 3 presents the exemplary trajectories of 855 MeV positrons. Figure 3(a) shows parts of the trajectories of positrons which channels in PB-S crystals. In that case positrons firstly enter through the PB crystal and than penetrate through the interface to the SC. For $\varepsilon = 855$ MeV positrons the amplitude of channeling oscillations is strongly suppressed, since the potential barrier is reduced due to centrifugal force. This also results in strong suppression of ChR for high energetic particles in PB diamond crystals. Because of that, the positrons which are propagating in the PBC experience strong dechanneling in the parts of the crystal
with large curvature of its planes where the centrifugal force acting on the channeled positron is maximal. However, the opposite process, re-channeling, can occur in the segments of the crystal with small curvature. Re-channeling results in effective increase in total channeling length of the particles. Positrons, which are captured to the channel in PB segment then penetrate to the straight segment without dechanneling. Propagating through the interface they retain the amplitude of their channeling oscillations.

In opposite situation when the positrons propagate in S-PB crystal (Figure 3 (b)) they first come through the straight segment and then penetrate to the PB segment. However, positrons can channel in the straight segment with transverse energies higher than in the PB segment. This results in higher amplitude of channeling oscillations in straight segment. As a result strong dechanneling occurs on the interface between the straight and PB segments of the crystal (Note: the dechanneling in the region between 140 and 145 µm in Figure 3 (b)).

To illustrate the channeling properties of positrons, we plot (Figure 4) the dependence of primary fraction and fraction of channeled particles with account of re-channeling as a functions of penetration distance $z$. These dependencies can be used to analyse the intensities of CUR and ChR in PB-S and S-PB crystals. Since, the intensity of radiation due to periodic motion is proportional to the number of particles participating in quasi periodic motion and square of the amplitude of corresponding oscillation.

For $\varepsilon = 270$ MeV positrons the dependencies of primary fraction, Figure 4 (a), and fraction with account of re-channeling Figure 4 (b) are almost identical for both types of crystal. The acceptance in case of S-PB crystal is higher than for PB-S crystal, due to the centrifugal. Since, the amplitude of the periodic bending $a$ is equal for both types of crystal and the number of particle involved in the channeling motion in PB parts of the crystals are approximately same the intensity of CUR should be the same (see Figure 2). Same is true for the intensity of ChR. The centrifugal force is small and as result, change in channeling amplitudes is also small. Thus the number of channeled particles in PB-S and S-PB crystals are comparable.

For $\varepsilon = 855$ MeV the situation is different, due to the increase of the centrifugal force in
the PB parts of the crystals the number of particles involved into the channeling motion drops as well as alternates the amplitude of channeling oscillations. The primary fraction of positrons in PB-S crystal decrease steadily drops every time particles propagate through the segments of the crystal with high curvature (note the step-like dependence in first 20 µm in Figure 4 (c)). However, in the straight segment of the crystal this dependence remains constant, since the centrifugal force caused by the crystal bending is absent in the straight segment of the crystal. Account for re-channeling gives rise to oscillations of the number of channeled particles in PB segment and the rise of number of channeling particles in straight segment.

For \( \varepsilon = 855 \) MeV positrons propagating behavior of the dependencies is different. In the case of S-PB crystal the value of acceptance is higher and no significant re-channeling occurs in the straight part of the crystal. However, the drastic drop in number of primary particles appears at the interface. This happens due to appearance of the centrifugal force in the PB part of the crystal. The number of channeling particles with account of re-channeling become approximately equal to the number of particles in the channeling regime in case of PB-S crystal (see Figure 4 (d)).

As a result of such behavior of channelled positrons, the intensity of CUR are approximately same. But, the intensity of ChR for the PB-S crystal should be about 2 times smaller than for the S-PB crystal (see Figure 2 (b)).

To conclude, two main effects are observed for positrons in two types of crystals: 1. For the two cases considered ChR intensities are same within margin of errors for \( \varepsilon = 270 \) MeV and differs at least two times for \( \varepsilon = 855 \) MeV positrons. 2. CUR intensities are the same for both types of crystals. They can be explained by the presence of the centrifugal force in the PB segments of the crystal.

### III. RESULTS AND DISCUSSION FOR ELECTRONS

Let us now return to the analysis of electron channeling in hetero-crystals. Electrons, in contrast to positrons, move around crystalline chains. This results in increase of the number of hard collisions with bulk constituents and thus the dechanneling/re-channeling rates.

The anharmonicity of the interaction potential between ultra-relativistic electrons and lattice atoms results in significant broadening of the peaks. The examples of the spectra are shown in Figure 5.

In Figure 5(a) the results for \( \varepsilon = 270 \) MeV electrons are presented. For the given electron energy the intensities of ChR for the two geometries coincide within the margin of statistical error. For PB-S crystal the small bump corresponding to the CUR arises in the radiation spectra around \( \hbar \omega \approx 0.13 \) MeV. In the case of S-PB crystal this peak is nearly absent.

As a result of such behavior of channeled positrons, the intensity of CUR are approximately same. But, the intensity of ChR for the PB-S crystal should be about 2 times smaller than for the S-PB crystal (see Figure 2 (b)).

To conclude, two main effects are observed for positrons in two types of crystals: 1. For the two cases considered ChR intensities are same within margin of errors for \( \varepsilon = 270 \) MeV and differs at least two times for \( \varepsilon = 855 \) MeV positrons. 2. CUR intensities are the same for both types of crystals. They can be explained by the presence of the centrifugal force in the PB segments of the crystal.

For \( \varepsilon = 855 \) MeV electrons the intensities of ChR differ approximately \( \approx 1.5 \) times. The CUR radiation for 855 MeV electrons in the PB-

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**FIG. 5.** Same as Figure 2 but in case of electrons.
S crystal reveals itself as a peak at the photon energy $\hbar \omega \approx 0.7$. This peak is much more pronounced $\varepsilon = 855$ MeV electrons than for 270 MeV and nearly absent for S-PB crystal.

In order to understand these behaviors, one can plot the dependencies of fraction of accepted electrons (Figures 6 (a), (c)) and fraction of electrons with account of re-channeling (Figures 6 (b), (d)) upon the penetration distance. As for positrons, the value of $N_p/N$ at $(z = 0)$ corresponds to the acceptance value. For PB-S the acceptance is determined by the PB part of the crystal. Thus it is reduced by the presence of the centrifugal force. For the S-PB crystal the acceptance is the same as in the straight crystal.

Compared to positrons, electrons have significantly shorter dechanneling lengths, this leads to the fact that the number of primary fraction of channeled electrons practically dies out for crystal thicknesses greater than 50 µm, both for PB-S and for S-PB crystals. At both 270 and 855 MeV CUR emission requires a particle to pass at least one full channel period CU. If channeling length becomes shorter than half of CU period photon emission by electrons becomes similar to synchrotron radiation. Taking into account the dynamics of dechanneling/re-channeling of electrons in PBC, the main contribution to CUR is produced by particles accepted into the channeling regime. This explains why CUR radiation arises in spectra mostly in the case of PB-S crystal. Also, it explains why CUR peak is more pronounced for 855 MeV electrons than for 270 MeV ones.

ChR intensity is proportional to the number of particles involved in channeling the motion. The difference in number of channeled electrons with energy 270 MeV in the two cases (Figure 6 (b)) manifests itself only at the first 20 µm of the crystals. Beyond this region the difference is negligible. This results in a small difference in the ChR intensities for 270 MeV of electrons in two cases consider which falls within the margin of error. For $\varepsilon = 855$ MeV the difference in the number of channeled electrons significant, leading to a greater difference in spectral ChR intensities in Figure 6 (b).

To conclude this section let us state: 1. For the two cases considered ChR intensities are the same within margin of errors for $\varepsilon = 270$ MeV and become different for the $\varepsilon = 855$ MeV electrons. 2. CUR vanishes in the case of S-PB crystals and is present for PB-S crystals. Such behavior, as for positrons, can be explained by the centrifugal force acting on the electrons in the PB segments of the crystals. The manifestation of CUR is also determined by relatively short dechanneling length of electrons with respect to positrons.

IV. CONCLUSIONS

In summary, the channeling and radiation phenomena for 270 and 855 MeV positrons and electrons in oriented diamond hetero-crystals were simulated by means of all-atom relativistic molecular dynamics. We predict the radiation spectra for the two orientations (PB-S and S-PB) of crystals with respect to the beam. In the case of positrons the peaks of CUR are clearly distinguishable from the background and have comparable intensity with respect to the ChR peaks. However, in the case of electrons, the CUR peaks observation over the broad peak of ChR becomes a challenging task, especially at low energies. This prediction opens a possibility for the experimental detection of CUR in the PB structures grown on a substrate.

One possible way to analyse experimental data for such systems is to measure the radiation spectra for particles propagating in PB-S and S-PB crystals and analyse their ratio. An example of such analysis is shown in Figure 7. In this case not only the enhancement of radiation in the CUR desired region, but also the difference in channeling radiation intensities can be a fingerprint of the PB segment inside the crystal.

Finally, the analysis performed demonstrates that usage of PBC with a straight substrate does not provide advantages for the CUR production. However, in the cases when a high-quality PB crystals can only be produced as segments of hetero-crystals practical realization
of CUs based on such crystal with high quality positron beams is a feasible task. Electron beams can be used for probing the quality of PB segments of hetero-crystals.

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1J. Lindhard, Kongel. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 34 (1965).
2M. A. Kumakhov, Phys. Rev. A 57, 17 (1976).
3T. N. Wistisen and A. Di Piazza, Phys. Rev. D 99, 116010 (2019).
4A. V. Pavlov, A. V. Korol, V. K. Ivanov, and A. V. Solov’yov, J. Phys. B 52, 11LT01 (2019).
5A. V. Pavlov, A. V. Korol, V. K. Ivanov, and A. V. Solov’yov, Eur. Phys. J. D 74, 21 (2020).
6K. B. Agapev, V. K. Ivanov, A. V. Korol, and A. V. Solovyov, St. Petersburg State Polytechnical University Journal. Physics and Mathematics 11 (2), 129 (2018).
7H. Shen, Q. Zhao, F. S. Zhang, G. B. Sushko, A. V. Korol, and A. V. Solovyov, Nucl. Instrum. Meth. B 424, 26 (2018).
8A. V. Korol, V. G. Bezchastnov, and A. V. Solov’yov, Eur. Phys. J. D 71, 174 (2017).
9A. V. Korol, V. G. Bezchastnov, G. B. Sushko, and A. V. Solov’yov, Nucl. Instrum. Meth. B 387, 41 (2016).
10G. B. Sushko, A. V. Korol, and A. V. Solovyov, Nucl. Instrum. Meth. B 355, 39 (2015).
11R. G. Polozkov, V. K. Ivanov, G. B. Sushko, A. V. Korol, and A. V. Solov’yov, Eur. Phys. J. D 68, 268 (2014).
12G. B. Sushko, V. G. Bezchastnov, A. V. Korol, W. Greiner, A. V. Solov’yov, R. G. Polozkov, and V. K. Ivanov, J. Phys.: Conf. Ser. 438, 012019 (2013).
13G. B. Sushko, A. V. Korol, W. Greiner, and A. V. Solov’yov, J. Phys.: Conf. Ser. 438, 012018 (2013).
14A. Kostyuk, Phys. Rev. Lett. 110, 115503 (2013).
15A. V. Pavlov, V. K. Ivanov, A. V. Korol, and A. V. Solovyov, Petersburg Polytechnical State University Journal. Physics and Mathematics 12, 104 (2019).
16A. V. Korol and A. V. Solov’yov, arXiv:1910.13359 (2019).
17H. Backe, W. Lauth, and T. N. Tran Thi, Journal of Instrumentation 13, C04022 (2018).
18T. N. Wistisen, U. I. Uggerhøj, J. L. Hansen, W. Lauth, and P. Klag, Eur. Phys. J. D 71, 124 (2017).
19T. N. Wistisen, U. I. Uggerhøj, U. Wiemands, T. W. Markiewicz, R. J. Noble, B. C. Benson, T. Smith,
FIG. 7. Difference between radiation intensities for two propagation direction for 855 MeV (a) positrons and (b) electrons. The data is taken from Figure 2 (b) and Figure 5 (b) respectively. $I_{S-PB}$ stands for the spectral densities of radiation $dE/d\omega$ for particles propagating in S-PB crystal, $I_{PB-S}$ same but for PB-S crystal.

E. Bagli, L. Bandiera, G. Germogli, et al., Phys. Rev. Acc. Beams 19, 071001 (2016).

20U. I. Uggerhøj and T. N. Wistisen, Nucl. Instrum Meth. B 355, 35 (2015).

21U. Wienands, T. W. Markiewicz, J. Nelson, R. J. Noble, J. L. Turner, U. I. Uggerhøj, T. N. Wistisen, E. Bagli, L. Bandiera, G. Germogli, et al., Phys. Rev. Lett. 114, 074801 (2015).

22L. Bandiera, E. Bagli, G. Germogli, V. Guidi, A. Mazzolari, H. Backe, W. Lauth, A. Berra, D. Lietti, M. Prest, et al., Phys. Rev. Lett. 115, 025504 (2015).

23H. Backe and W. Lauth, Nucl. Instrum. Meth. B 355, 24 (2015).

24A. Mazzolari, E. Bagli, L. Bandiera, V. Guidi, H. Backe, W. Lauth, V. Tikhomirov, A. Berra, D. Lietti, M. Prest, et al., Phys. Rev. Lett. 112, 135503 (2014).

25E. Bagli, L. Bandiera, V. Bellucci, A. Berra, R. Cammatti, D. De Salvador, G. Germogli, V. Guidi, L. Lanzoni, D. Lietti, et al., Eur. Phys. J. C 74, 3114 (2014).

26T. N. Wistisen, K. K. Andersen, S. Yilmaz, R. Mikkelsen, J. L. Hansen, U. I. Uggerhøj, W. Lauth, and H. Backe, Phys. Rev. Lett. 112, 254801 (2014).

27A. V. Korol, A. V. Solov’yov, and W. Greiner, J. Phys. G 24, L45 (1998).

28A. V. Korol, A. V. Solov’yov, and W. Greiner, International Journal of Modern Physics E 8, 49 (1999).

29A. V. Korol, A. V. Solov’yov, and W. Greiner, Channeling and Radiation in Periodically Bent Crystals, 2nd ed. (Springer Verlag, Berlin Heidelberg, 2014).

30K. W. D. Ledingham, R. P. Singhall, P. McKenna, and I. Spencer, Europhysics News 33, 120 (2002).

31K. W. D. Ledingham, P. McKenna, and R. P. Singhal, Science 300, 1107 (2003).

32R. Hajima, T. Hayakawa, N. Kikuzawa, and E. Mineharu, Journal of Nuclear Science and Technology 45, 441 (2008).

33B. Weon, J. H. Je, Y. Hwu, and G. Margaritondo, Physical review letters 100, 217403 (2008).

34H. Backe, D. Krambrich, W. Lauth, K. K. Andersen, J. L. Hansen, and U. I. Uggerhøj, in J. Phys. Conf. Ser., Vol. 438 (IOP Publishing, 2013) p. 012017.

35U. Wienands, S. Gessner, M. Hogan, T. Markiewicz, T. Smith, J. Sheppard, U. Uggerhøj, J. Hansen, T. Wistisen, E. Bagli, et al., Nucl. Instrum Meth. B 402, 11 (2017).

36D. Boshoff, M. Copeland, F. Haffejee, Q. Kilbourn, C. Mercer, A. Osatov, C. Williamson, P. Shiroyiha, M. Motsoai, C. A. Henning, S. H. Connell, T. Brooks, J. Härtwig, T. N. Tran Thi, N. Palmer, and U. Uggerhøj, in 4th Int. Conf. “Dynamics of Systems on the Nanoscale” (Bad Ems, Germany, Oct. 3-7 2016) Book of Abstracts (2016) p. 38.

37B. G. de la Mata, A. Sanz-Hervás, M. Dowsett, M. Schwitter, and D. Twitchen, Diamond and related materials 16, 809 (2007).

38T. N. Tran Thi, J. Morse, D. Caliste, B. Fernandez, D. Eon, J. Hårtwig, C. Barbay, C. Mer-Calfati, N. Tranchant, J. Arnault, et al., Journal of Applied Crystallography 50, 561 (2017).

39H. Backe and W. Lauth, in 4th Int. Conf. “Dynamics of Systems on the Nanoscale” (Bad Ems, Germany, Oct. 3-7 2016) Book of Abstracts (2016) p. 58.

40H. Backe, D. Krambrich, W. Lauth, B. Suogono, S. B. Dabagov, G. Mazzitelli, L. Quintieri, H. Lundsgaard, J. I. Uggerhøj, B. Azadegan, et al., Nuovo Cimento C 34, 175 (2011).

41I. A. Solov’yov, A. V. Yakubovich, P. V. Nikolaev, I. Volkovets, and A. V. Solov’yov, J. Comput. Chem. 33, 2412 (2012).

42G. B. Sushko, V. G. Bezchastnov, I. A. Solov’yov, A. V. Korol, W. Greiner, and A. V. Solov’yov, J. of Comp. Phys. 252, 404 (2013).

43H. Backe, Journal of Instrumentation 13, C02046 (2018).

44V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, Electromagnetic processes at high energies in oriented single crystals (World Scientific, Singapore, 1998).