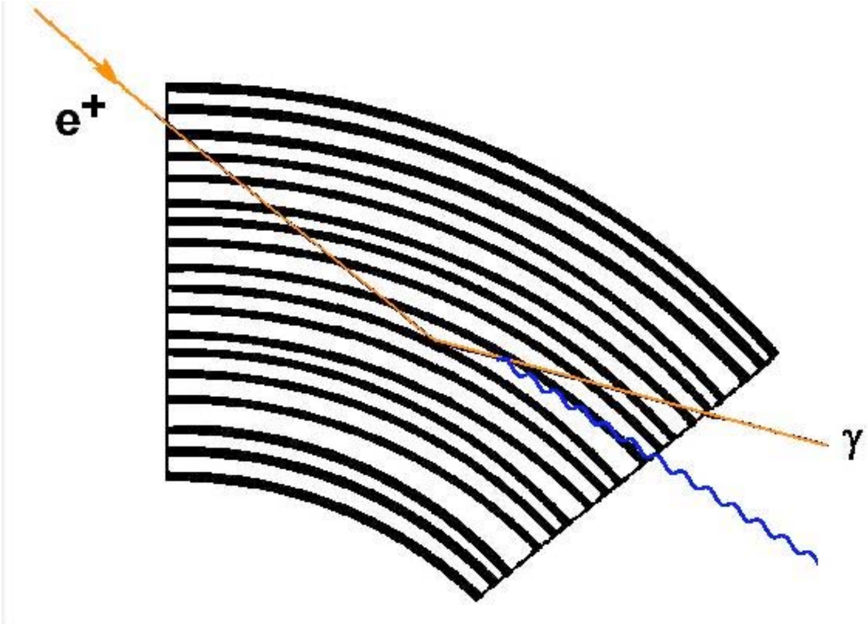
PHOTON EMISSION AND PHOTOPRODUCTION PROCESSES IN BENT SINGLE CRYSTALS

V. A. MAISHEEV*

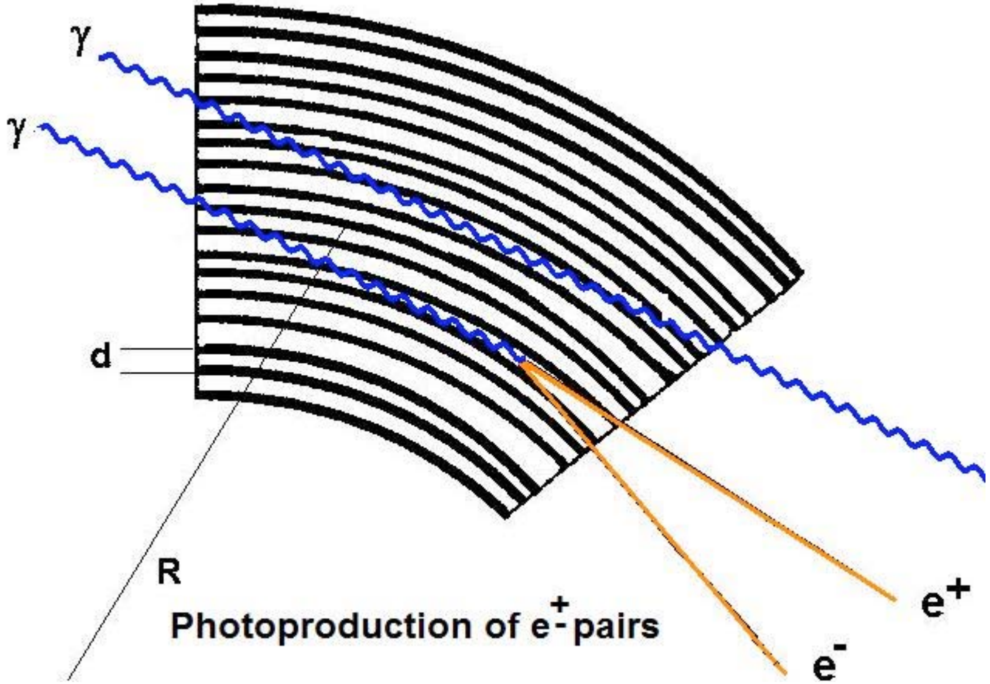
Institute for High Energy Physics,
Protvino, 142281, Russia
* *E-mail: maisheev@ihep.ru*
http://mail.ihep.ru/~maisheev

Process of photon emission by high energy electron or positron moving in a bent single crystal was considered. The spectrum of energy losses of particles and polarization of emitted photons were calculated. Corrections due to multi photon emission were obtained.

Photoproduction process of electron-positron pairs in a bent single crystal was also studied. Dependence of the total cross section at different bending radii was calculated for different initial polarization states of high energy photons.



Photon emission



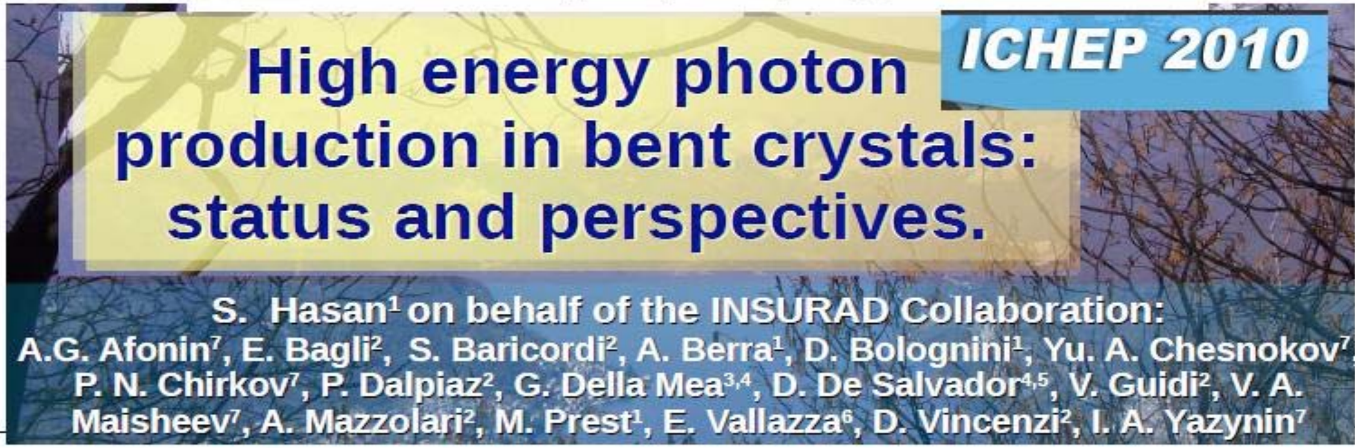
Photoproduction of e± pairs

Photon emission of volume reflected positrons (electrons) in planar fields of bent single crystals

First experimental observation:

IHEP 10 GeV positrons A.G. Afonin et. al. JETP Letters, 88, 488, 2008
CERN 180 GeV positrons and electrons W. Scandale et. al. Phys. Rev. A 79, 012903, 2009.

Recent experiment (2009, September)
CERN 120 GeV positrons Si single crystal, (110) plane, thickness 2 mm, R=11 and 4.7 m



The 1st calculations of the process

Yu. A. Chesnokov, V.I. Kotov, V.A. Maisheev and I.A. Yazynin, JINST, 3, P02005, 2008.

were based on quasiclassical theory developed by V.N. Baier with coauthors:

V.N. Baier, V.M. Katkov and V.M. Strakhovenko, Electromagnetic processes at high energies in oriented single crystals.

There are many difficulties in usage of the method for our problem, which strongly restrict the field of applicability.

In this report the simple method of calculation of photon emission spectra will be considered.
The results of calculations will be compared with experiment (CERN, 120 GeV).

The type of radiation process depends on the character of particle motion. For quasiperiodic motion the type may be characterized with the help of ρ-parameter

$$\rho = 2\,\gamma^2 < (v(t) - v\,)^2 > /c^2$$

where

γ is the Lorentz factor of a particle

v(t) and v are the transversal velocity and its mean value

c is the velocity of light

<...> is averaging over time

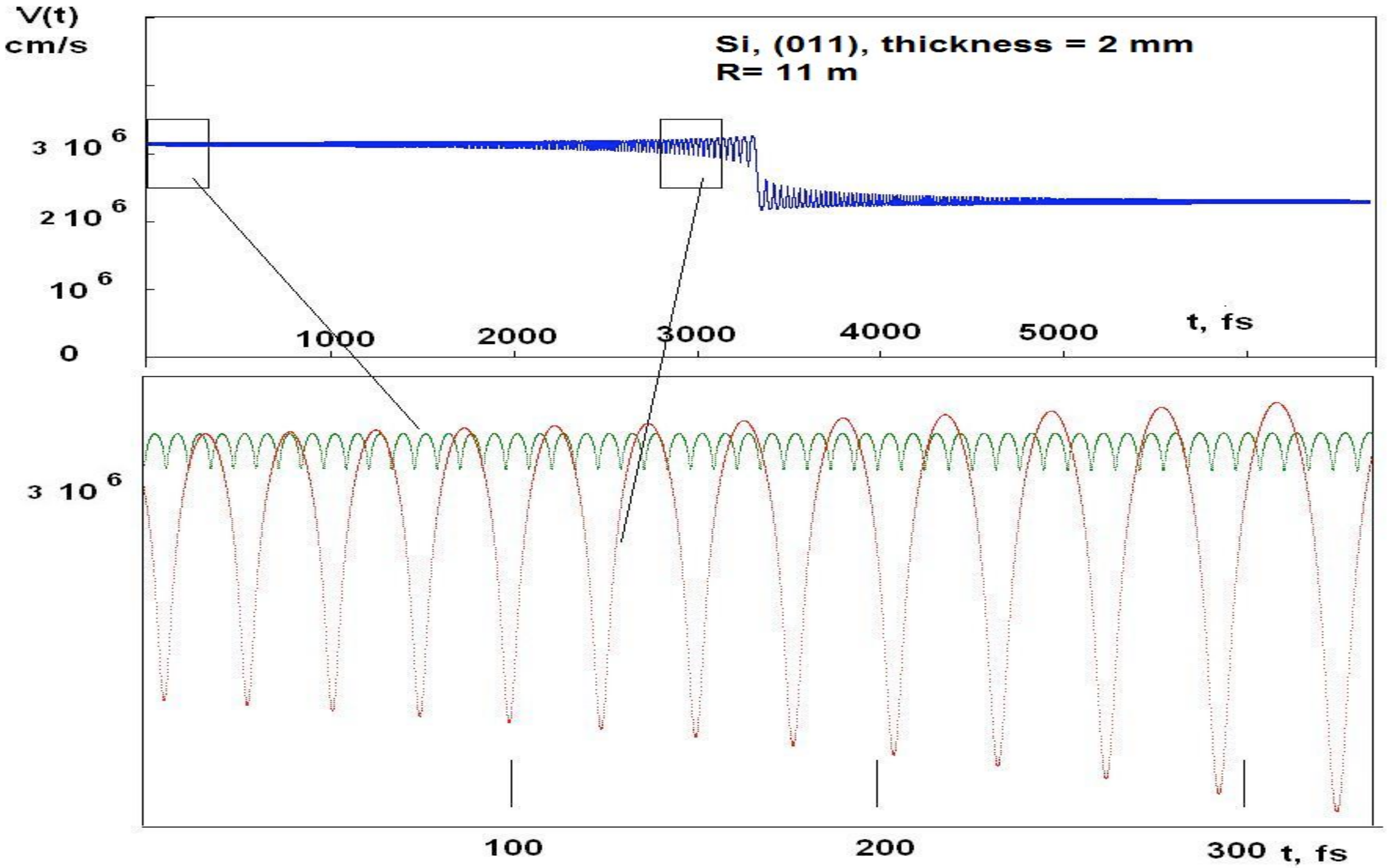
The case when $\rho \ll 1$ corresponds to dipole radiation (interferention character)

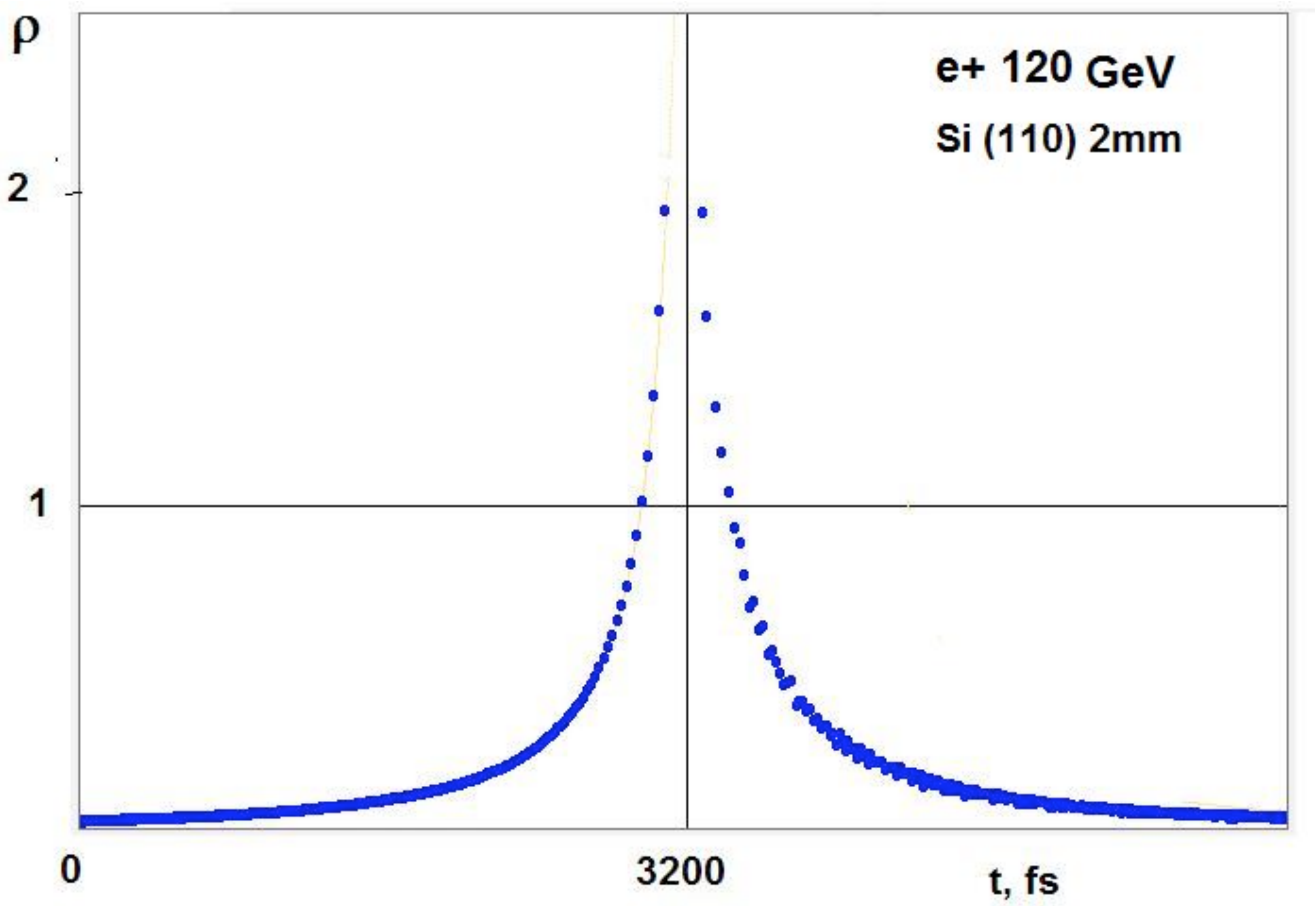
$\rho \gg 1$ synchrotron like radiation

$\rho \sim 1$ is the intermediate case

Motion of charged particles in bent single crystals was considered in the paper (in particularly)

V.A. Maisheev Phys. Rev. ST Accel. Beams, 13, 084701, (2007).


V(t)
cm/s
Si, (011), thickness = 2 mm
R= 11 m
3 10 6
2 10 6
10 6
0
1000
2000
3000
4000
5000
t, fs
3 10 6
100
200
300 t, fs


ρ
e+ 120 GeV
Si (110) 2mm
2
1
0
3200
t, fs

For conditions of CERN experiment
(120 GeV positrons, Si (110) 2 mm)
the type of radiation is approximately dipole type.

Based on results of paper

V.A. Arytunov, N.A. Kyadryashov, V.M. Samsonov and M.N. Strkhanov Nuclear Physics, B363, 283 (1991)

and as result of our consideration we take for calculations of radiation energy losses of positrons or electrons the following simple relation:

$$\frac{d\mathcal{E}}{dE_q}(E_q) = R\int_{\theta_1}^{\theta_c} \frac{dI}{dE_q}(\tilde{\theta})d\tilde{\theta} + R\int_{\theta_c}^{\theta_2} \frac{dI}{dE_q}(\tilde{\theta})d\tilde{\theta}$$

$E_q = E_0 - E_1$, E_0, E_1 are the positron energies before and after photon emission.

R is the bending radius.

$\tilde{\theta}(t) = \int_{t-\Delta t/2}^{t+\Delta t/2} \theta(t)dt/(\Delta t)$ is the averaged over period the angle reala-tive to plane.

I is the intensity of radiation which defined by the planar angle $\tilde{\theta}$.

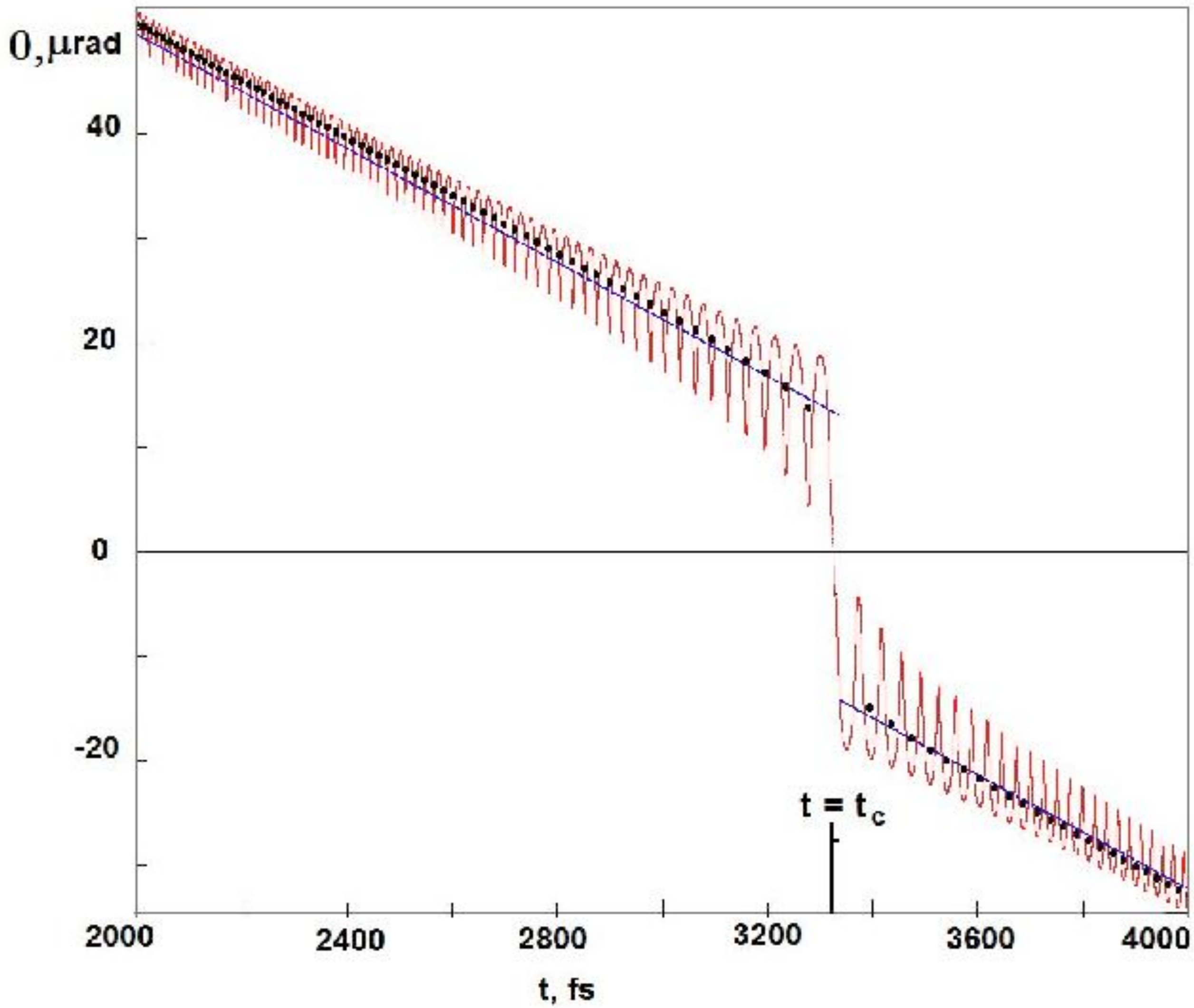
We take function $dI/dE_q(\tilde{\theta}))$ from theory of the coherent bremsstrahlung in straight single crystals

see for example M.A. Ter-Mikaelian, High Energy Electromagnetic Processes in Condensed Media, (Wiley, New York, 1972).

This equation is valid at condition

$$\frac{\pi L^2}{dR} \gg 1$$

where d and L are the interplanar distance and thickness.


θ, μrad
40
20
0
-20
t = t
c
2000
2400
2800
3200
3600
4000
t, fs

Relations for mean angle $\tilde{\theta}(t)$ relative to plane

$$\tilde{\theta}(t) = \frac{\tilde{v}_0}{c} - \frac{ct}{R} \qquad 0 \le t \le t_c$$

$$\tilde{\theta}(t) = \frac{2ct_c}{R} - \frac{\tilde{v}_0}{c} - \frac{ct}{R} \qquad t > t_c$$

$\tilde{v}_0 \approx c\theta_0$

θ_0 is the entrance angle of particle.

$$\tilde{\theta}_{min} = \frac{\tilde{v}_0}{c} - \frac{ct_c}{R} \qquad |\theta_{min}| \approx |\alpha|/2$$

where α is the mean value of angle of volume reflection.

It is valid at $R > R_0 = E_0 d / U$

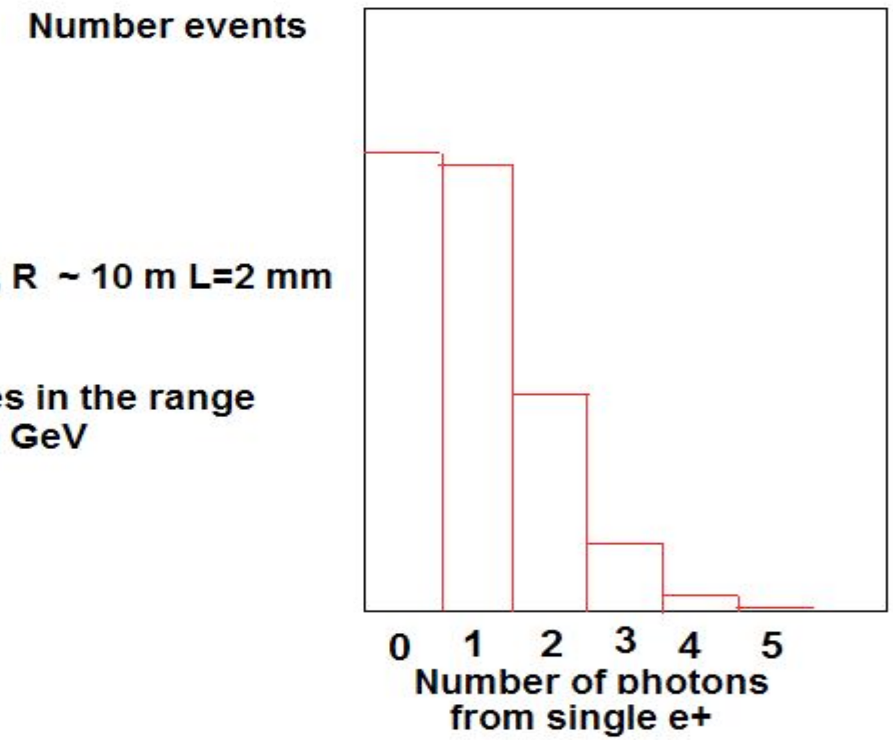
$R_0 \sim$ 1 m for 120 GeV

E_0 is the particle energy

d is the interlanar distance

U is the potential barrier

The calculations with the help of suggested relations show the valuable difference with experimental data.
Analysis shows that for crystals about 1-2 mm of thickness the probability of second photon emission is large enough.
This conclusion was confirmed by Monte Carlo calculations.



E = 120 GeV, R ~ 10 m L=2 mm
Si (110)

Photon energies in the range
1.2 GeV till 120 GeV

The analytical approach was used for multiple photon emission.
We start from equation

$$\frac{dN_e}{N_e} = -n\sigma_\gamma(\epsilon, E_0, z)dz$$

where $N_e(z)$ is the flux of positrons which emitted one photon on a thickness from z=0 up to z, and $\sigma_\gamma(\epsilon, E_0, z)$ is the cross section of coherent bremsstrahlung on coordinate $z = ct$ of a crystal which takes into account radiation of photons in energy range from ϵ till E_0. The value $n\sigma_\gamma(\epsilon, E_0, z)dz$ is the probability for positron to emit the photon on the thickness dz with energy range from ϵ till E_0 and it coupled with the intensity on the same coordinate (see Eq. (9)) by relation $d\sigma_\gamma/dE_\gamma = \frac{1}{E_\gamma}dI/dE_\gamma$.

The distribution of photon radiation over coordinate one can describe by the following expression:

$$\frac{d^2N_e}{dzdE_+}(\epsilon, E_+, z) = \exp(-n\int_0^z \sigma_\gamma(\epsilon, E_0, z)dz)n\sigma_\gamma(\epsilon, E_0, z)\rho(\epsilon, E_0, E_+, z)$$

where the function

$$\rho(\epsilon, E_0, E_+, z) = \frac{1}{n\sigma_\gamma(\epsilon, E_0, z)}\frac{d\sigma_\gamma(\epsilon, E_0, E_+, z)}{dE_+}$$

represents the normalized distribution over the energy of a secondary positron E_+ ($E_\gamma = E_0 - E_+$).

The final result is (for emission of two photons or less)

$$\frac{dN_{1e}}{dE_+}(\epsilon, E_+, z_0) = \int_0^{z_0} \frac{d^2 N_e}{dz dE_+}(\epsilon, E_+, z) \exp(-n \int_z^{z_0} \sigma_\gamma(\epsilon, E_+, z) dz) dz$$

$$\frac{dN_{2e}}{dE'}(\epsilon, E', z_0) = \int_0^{z_0} \int_{E'+\epsilon}^{E_0-\epsilon} \frac{d^2 N_e}{dz dE_+}(\epsilon, E_+, z)\{1 - \exp(-n \int_z^{z_0} \sigma_\gamma(\epsilon, E_+, z) dz)\}\rho(\epsilon, E_+, E', z) dE_+ dz$$

where E' is the energy of electron which has energy E_+ before photon emission and the function $\rho(\epsilon, E_+, E', z)$ is similar as in Eq.(12). Here N_1 is the number of electrons emitted one photon with the energy $> \epsilon$ and N_2 is the number of electrons emitted two photons with the energies $> \epsilon$. Now we can write for the relation for radiation energy losses:

$$\frac{d\mathcal{E}}{dE'}(\epsilon, E', z_0) = (E_0 - E')(\frac{dN_{1e}}{dE'}(\epsilon, E', z_0) + \frac{dN_{2e}}{dE'}(\epsilon, E', z_0))$$

For small thickness (when $n \int_z^{z_0} \sigma_\gamma(\epsilon, E', z) dz) \ll 1$)

$$\frac{d\mathcal{E}}{dE'}(\epsilon, E', z_0) = (E_0 - E') \int_0^{z_0} \frac{d\sigma_\gamma}{dE'}(\epsilon, E_0, E', z) dz$$

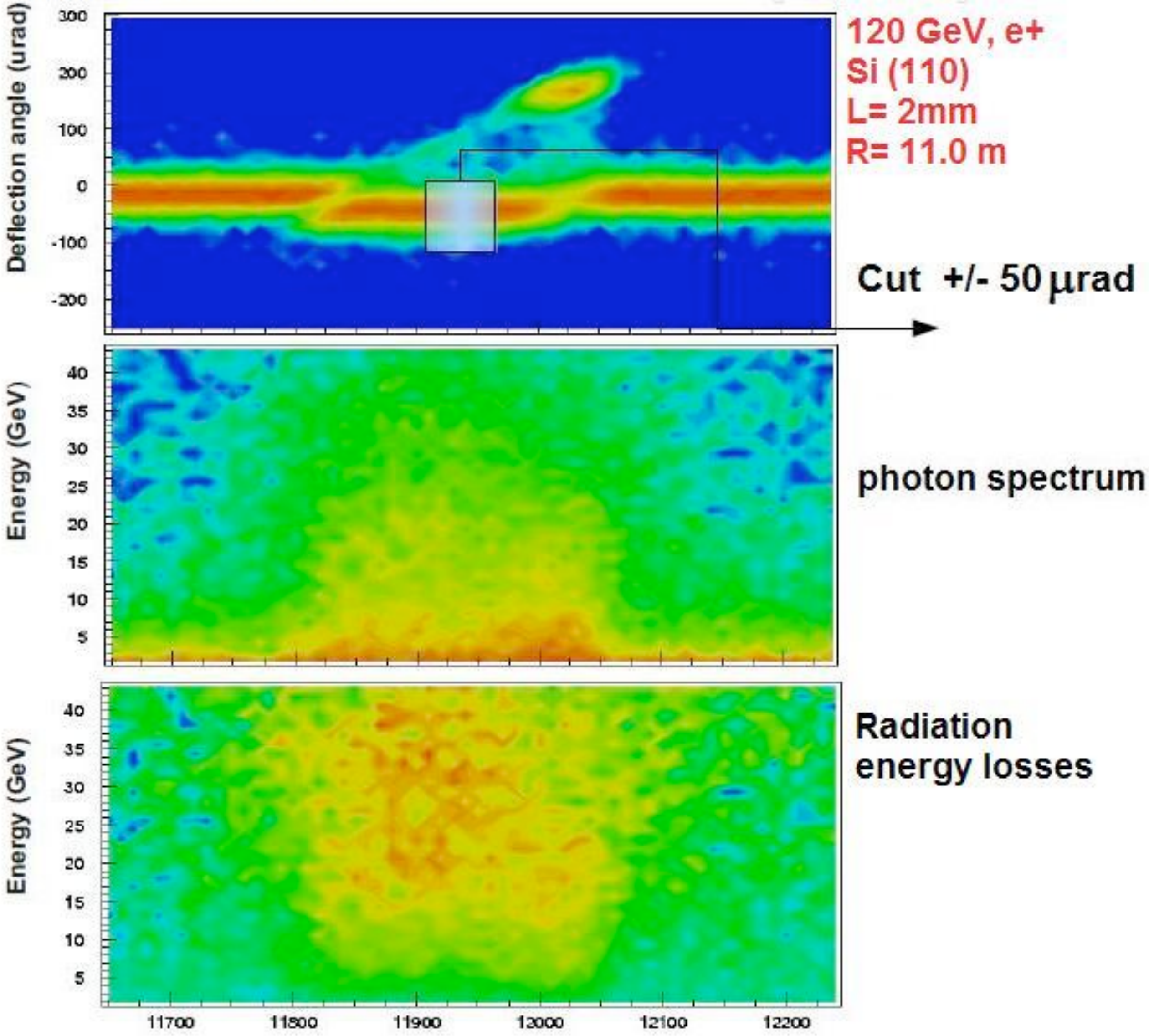
This consideration allow one to takes into account:

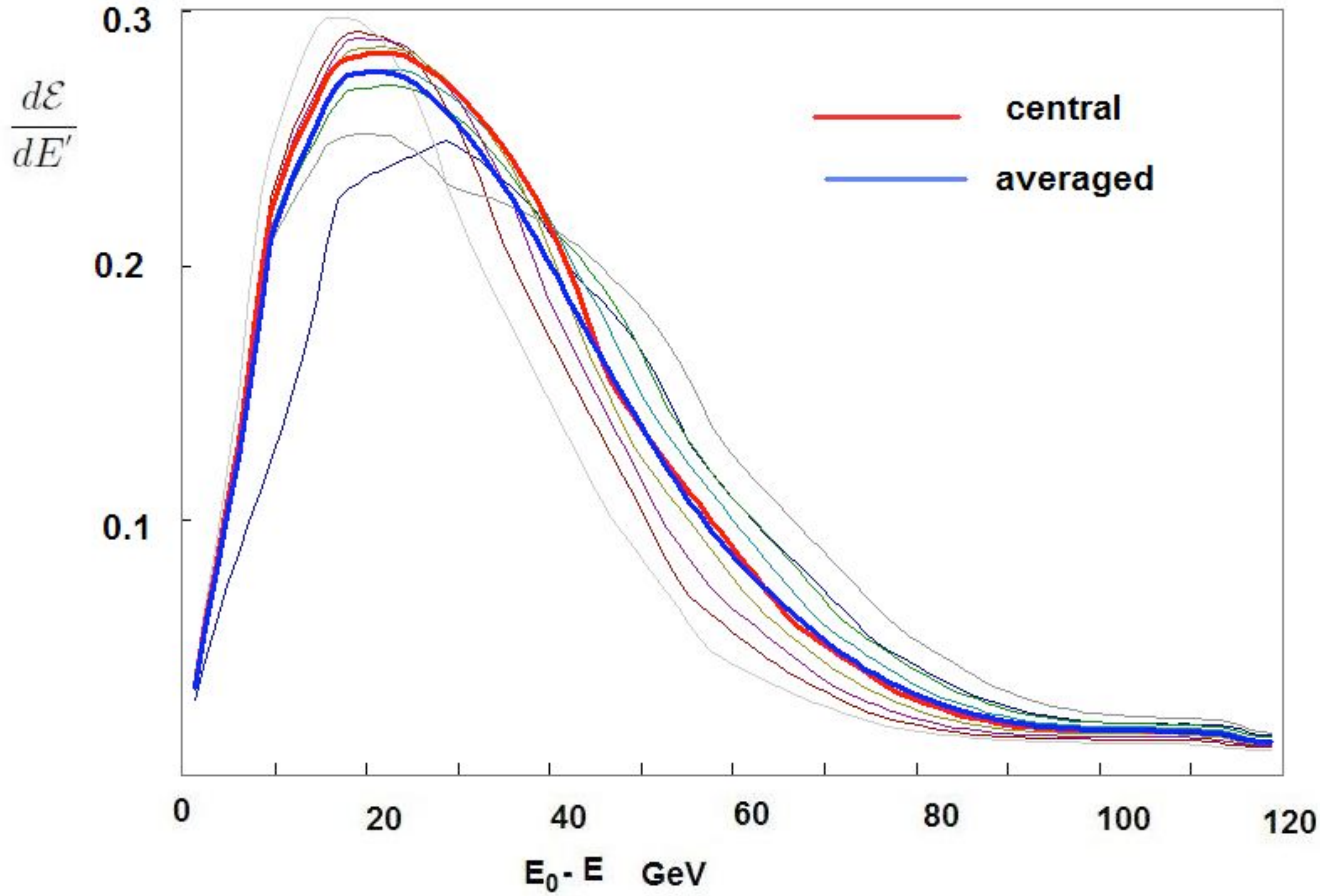
1) nonlinear (exponential decrease) character of the process as a function of thickness;

2) multiplicity of photon emission by one positron.

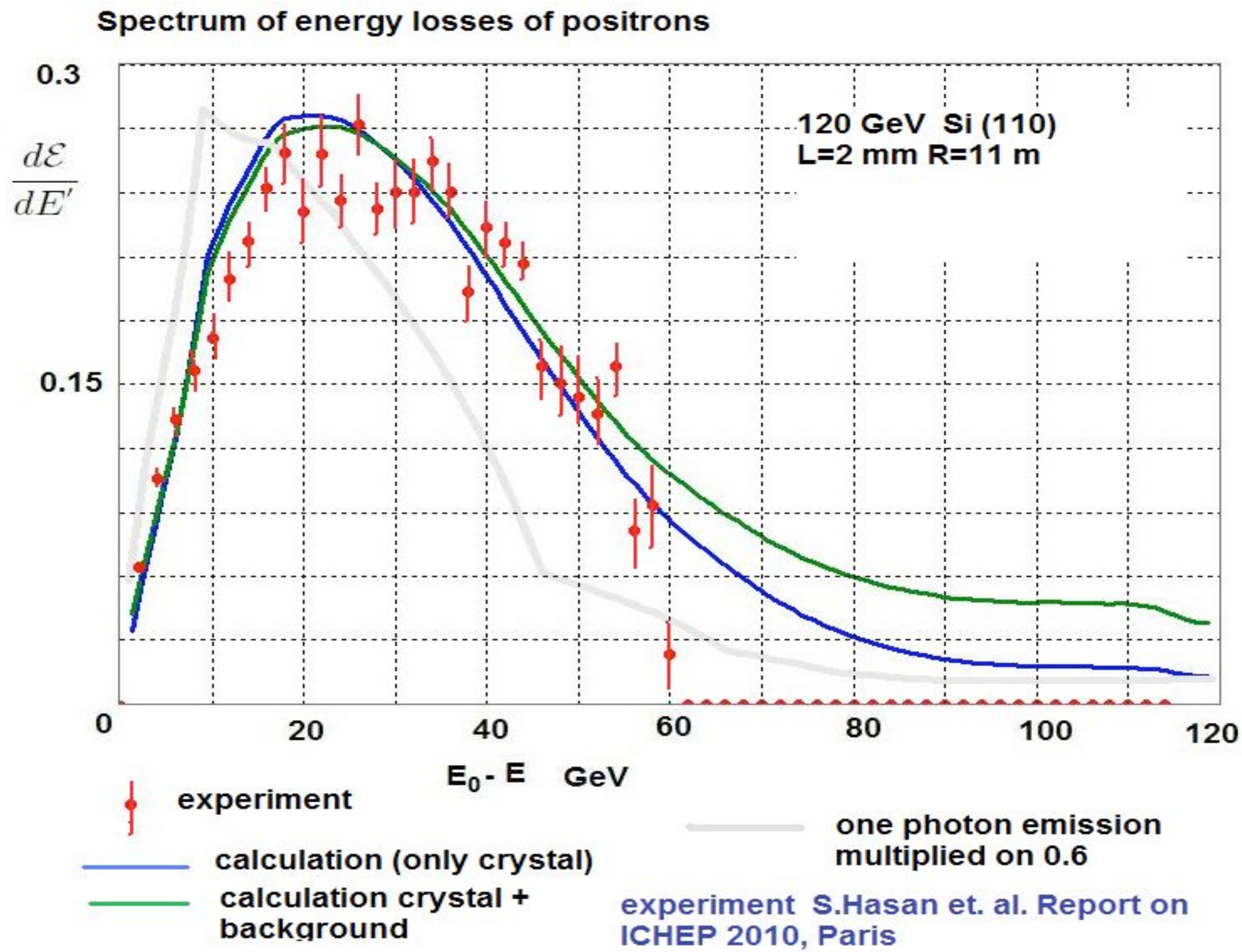
Comparison calculations with the experiment (CERN, Sept. 2009)

S. Hasan *et al.*, http://indico.cern.ch/materialDisplay.py?contribId=843&sessionId=58&materialId=slides&confId=73513.

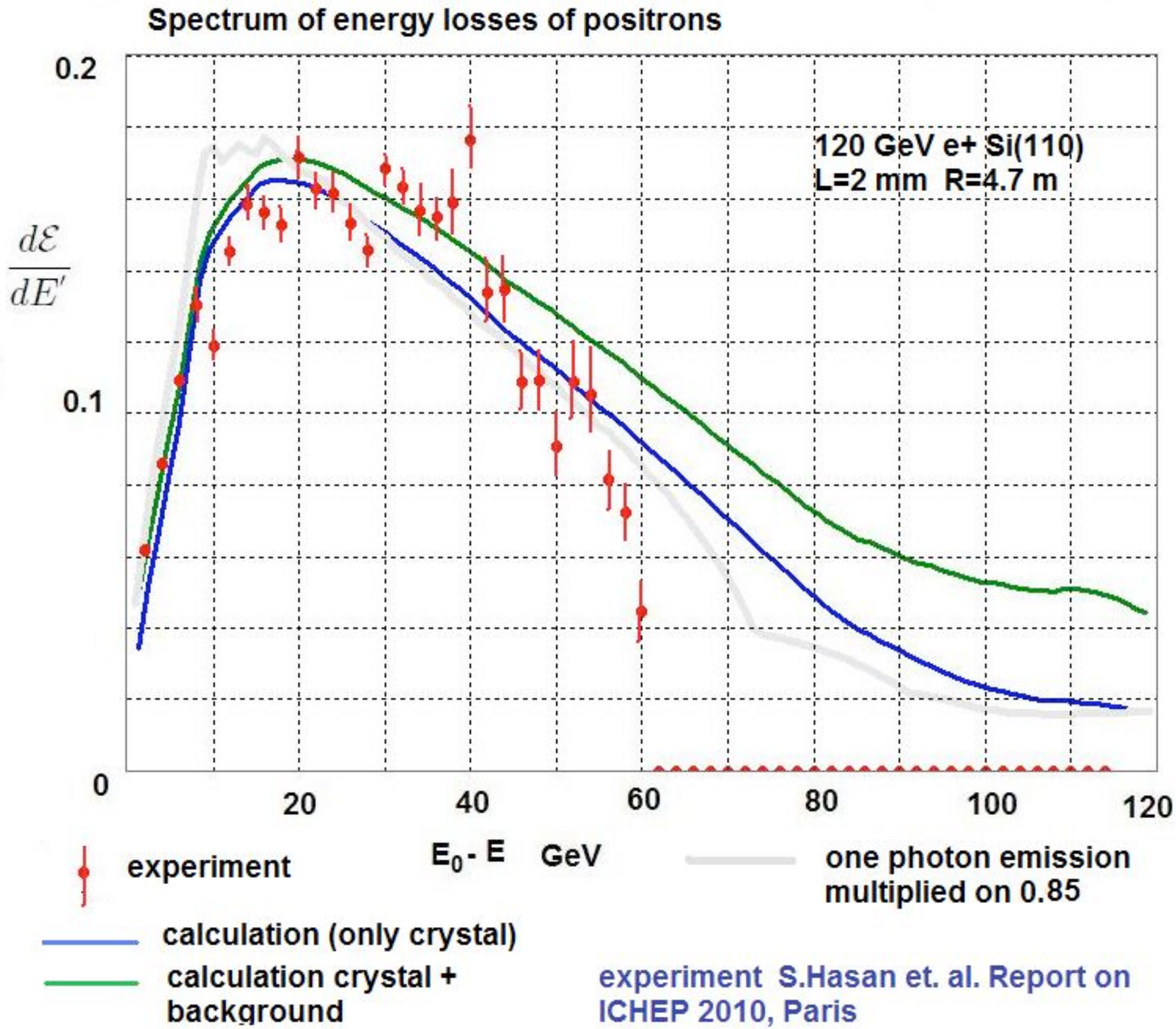




Conclusion Averaged and central curves are close in between



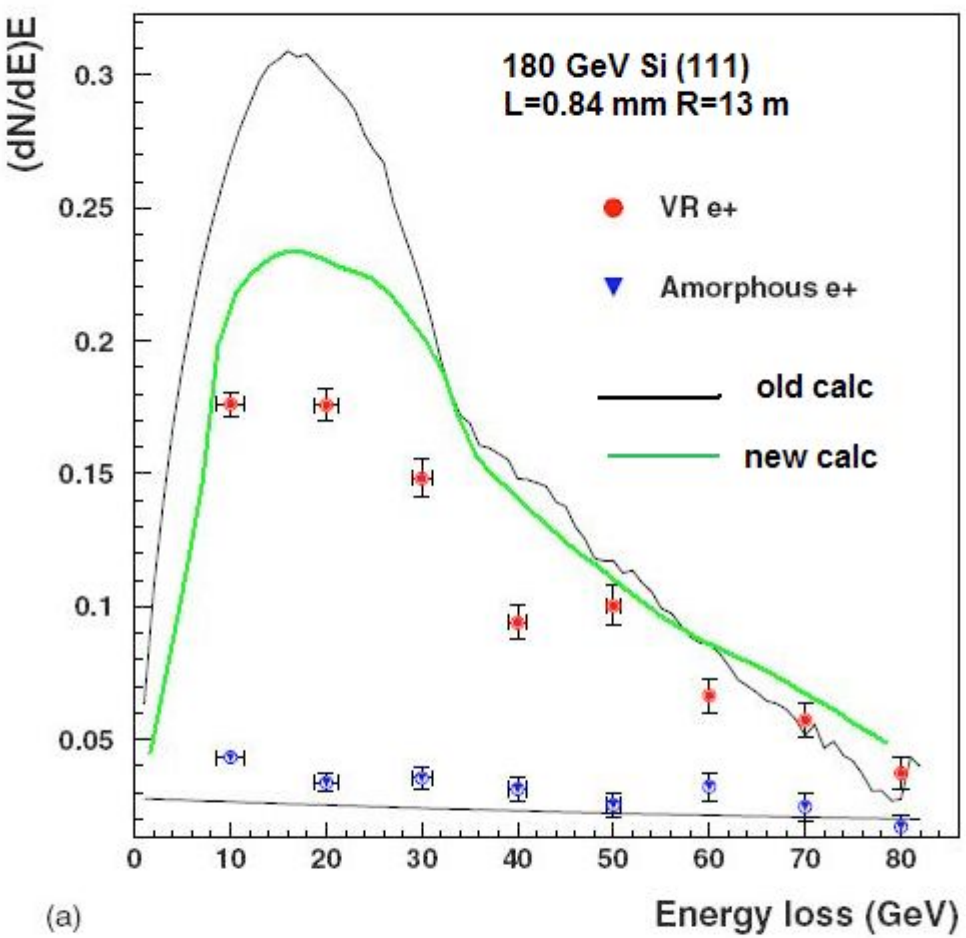
Spectrum of energy losses of positrons
0.3
$\frac{d\mathcal{E}}{dE'}$
0.15
0
20
40
60
80
100
120
120 GeV Si (110)
L=2 mm R=11 m
E_0 - E GeV
experiment
calculation (only crystal)
calculation crystal + background
one photon emission multiplied on 0.6
experiment S.Hasan et. al. Report on ICHEP 2010, Paris



Spectrum of energy losses of positrons
0.2
0.1
0
$\frac{d\mathcal{E}}{dE'}$
120 GeV e+ Si(110)
L=2 mm R=4.7 m
20
40
60
80
100
120
E_0 - E GeV
experiment
one photon emission
multiplied on 0.85
calculation (only crystal)
calculation crystal +
background
experiment S.Hasan et. al. Report on
ICHEP 2010, Paris

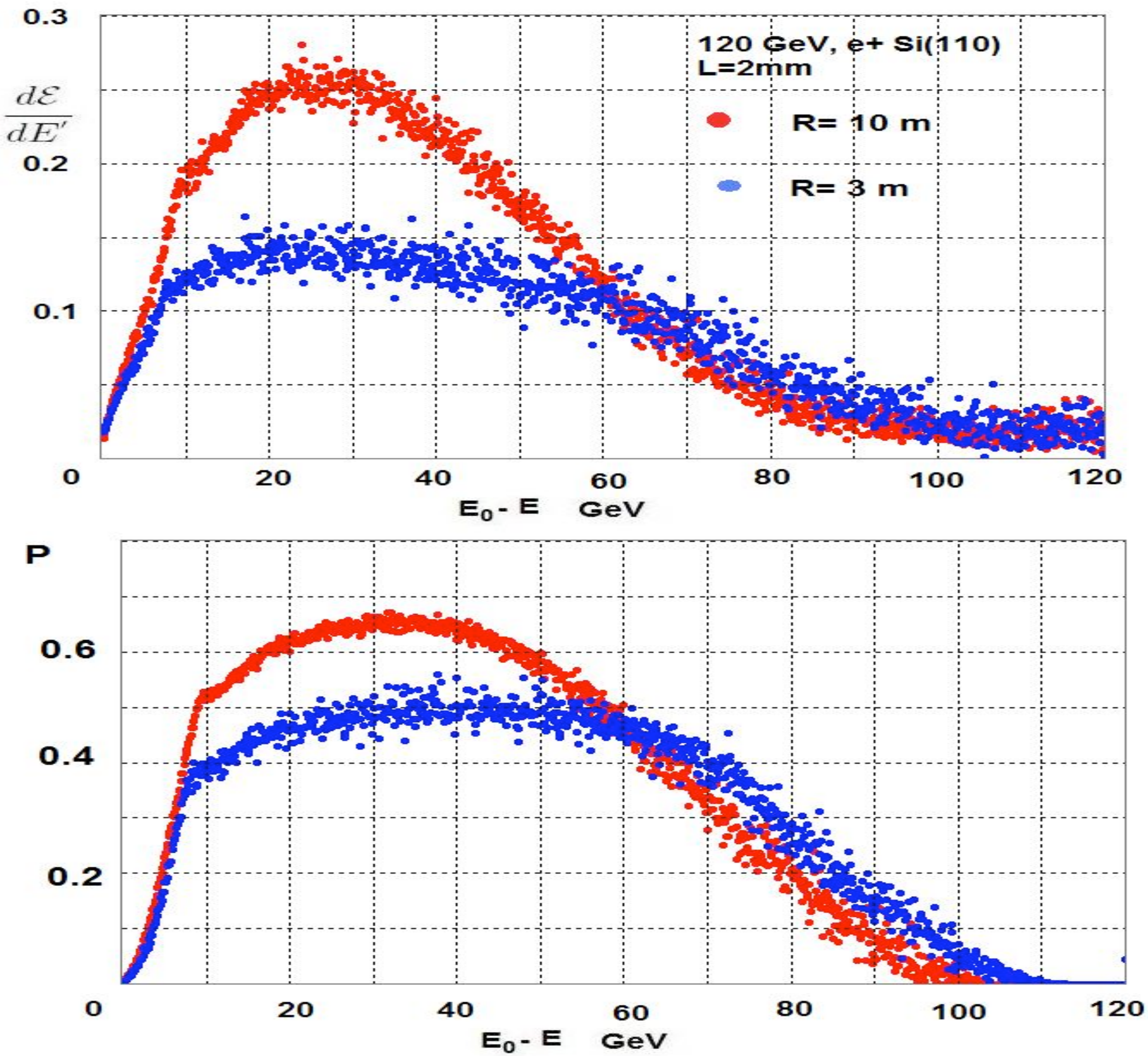
Recalculation of CERN experiment for e+ and 180 GeV
(W. Scandale et. al. Phys. Rev. A 79, 012903 (2009).)

taking into account multiplicity of photon emission



(a)

Linear polarization of photons
(Monte Carlo calculations)



Photoproduction of e+- pairs in bent single crystals

(Yu. A. Chesnokov, V.A. Maisheev, D. Bolognini, S. Hasan, M. Prest, E.Vallazza

Phys. Rev. ST Accel. Beams 13, 070706, (2010) ; ArXiv: 1006.3391

Consideration is similar as at bremsstrahlung in bent single crystals.

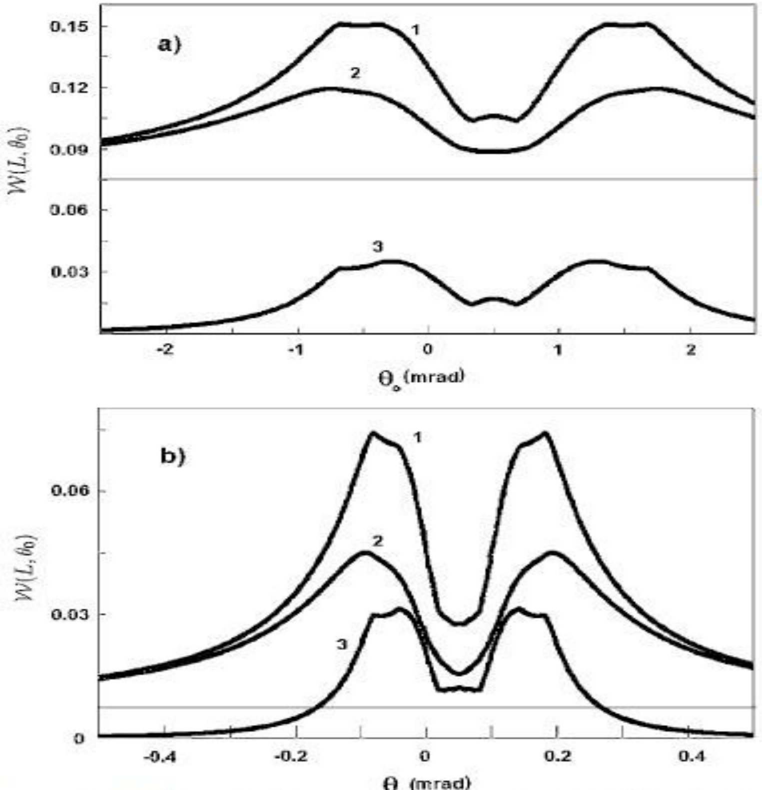
Si (110)

R=10 m

L= 1 cm

E_γ= 120 GeV

Amorph. contrib



L=0.1 cm

E_γ= 1000 GeV

Amorph. contrib

The probabilities of pair production in the (110) bent planes of a silicon single crystals as a function of the entrance angle θ_0. Curves 1 and 2 are the $\mathcal{W}_{\|}$ and $\mathcal{W}_{\perp}$-probabilities and curve 3 is their difference. The thin straight line is the probability in a nonoriented single crystal. The bending radius is 10 m. The photon energies and the thickness of the crystal are 120 GeV and 1 cm (a) and 1000 GeV and 0.1 cm (b).

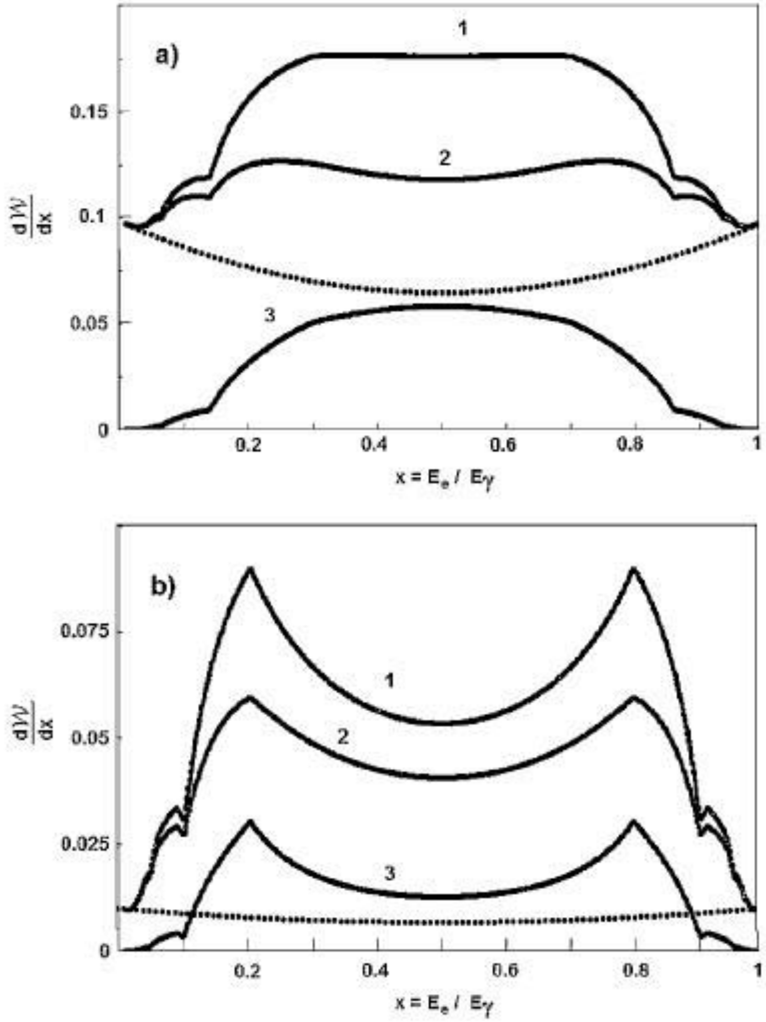
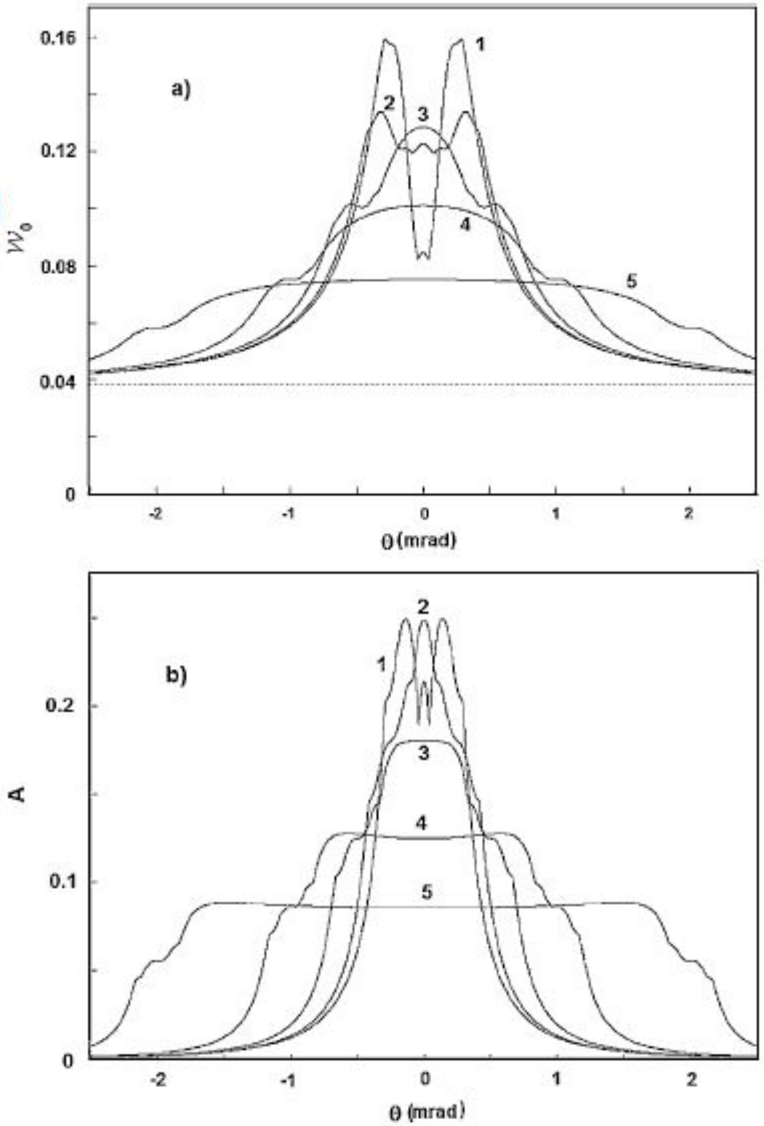


FIG. 3. Spectral distributions of the electrons (positrons) produced in a single bent silicon crystal at the conditions of Fig. 2, for the two cases (a) and (b). The entrance angle is $\theta_0 = +1.5$ mrad (a) and $+0.2$ mrad (b). The numbers near the curves indicate the probabilities as in Fig. 2. The black point curves are the ones for nonoriented single crystals.

Probability for unpolarized photons

R, m

1 - 20
2 - 10
3 - 5
4 - 2.5
5 - 1.25



Asymmetry

$$\frac{\sigma_{||} - \sigma_{\perp}}{\sigma_{||} + \sigma_{\perp}}$$

Photon energy = 500 GeV

The probability $\mathcal{W}_0$ (a) and asymmetry A (b) for a 0.5 cm single silicon crystal at different bending radii as functions of the orientation angle θ. Curves 1–5 correspond to $R = 20, 10, 5, 2.5$, and 1.25 m ($\theta = 0$ for a symmetric orientation of the single crystal). The point curves correspond to a nonoriented crystal. The photon energy is equal to 500 GeV.

Conclusions

1) The simple method of simulations of radiation energy losses of positrons (electrons) in bent single crystals of a planar orientation was proposed. The method is valid for energies particles about 150 GeV or less and crystal thickness about several millimeters or less.

2)The results of simulations and corresponding experimental data are in a good agreement in between.

3) The method may be expandend on axial case of orientations.

4) The process of photoproduction of electron-positron pairs in bent single crystals was considered.

5) The polarization dependences for the both processes were presented.

Thank you for the attention.