Radiation of photons at reflection of electrons and positrons in bent single crystals

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Radiation of charged particles at Volume Reflection represents the radiation of over barrier particles moving near a reflection point in short bent single crystals. At the first time this radiation was considered in the paper

Yu.Chesnokov, V.I. Kotov, V.A. Maisheev and I.Yazynin JINST 2, 02005 (2008).

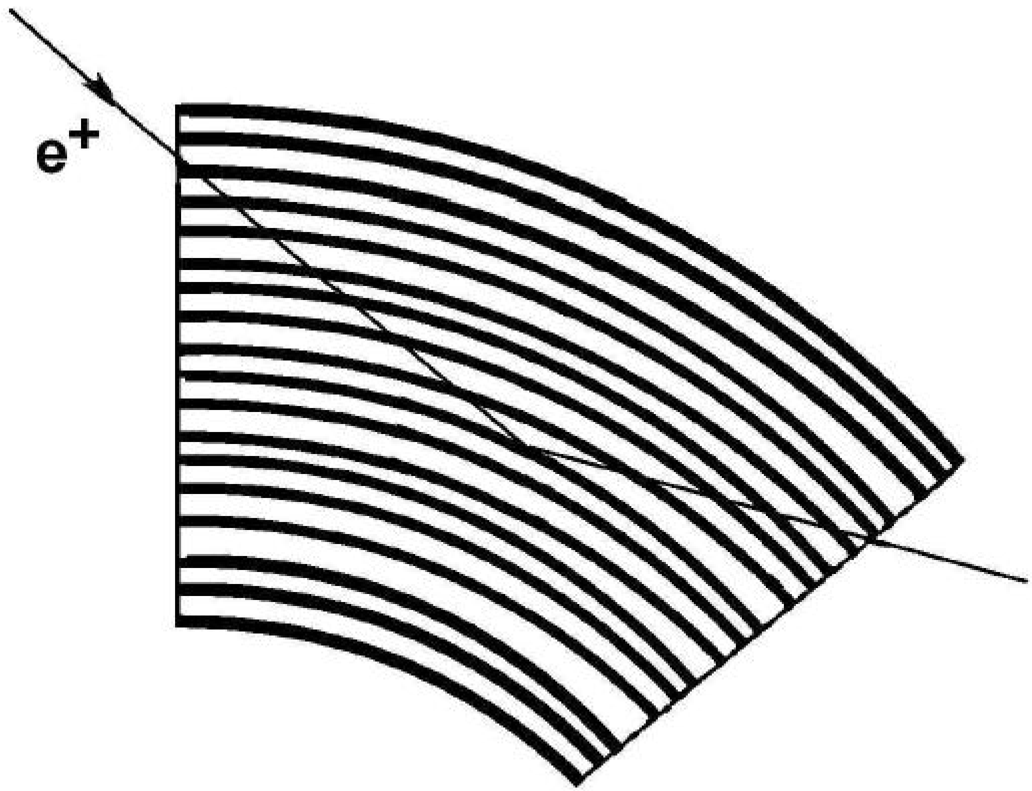
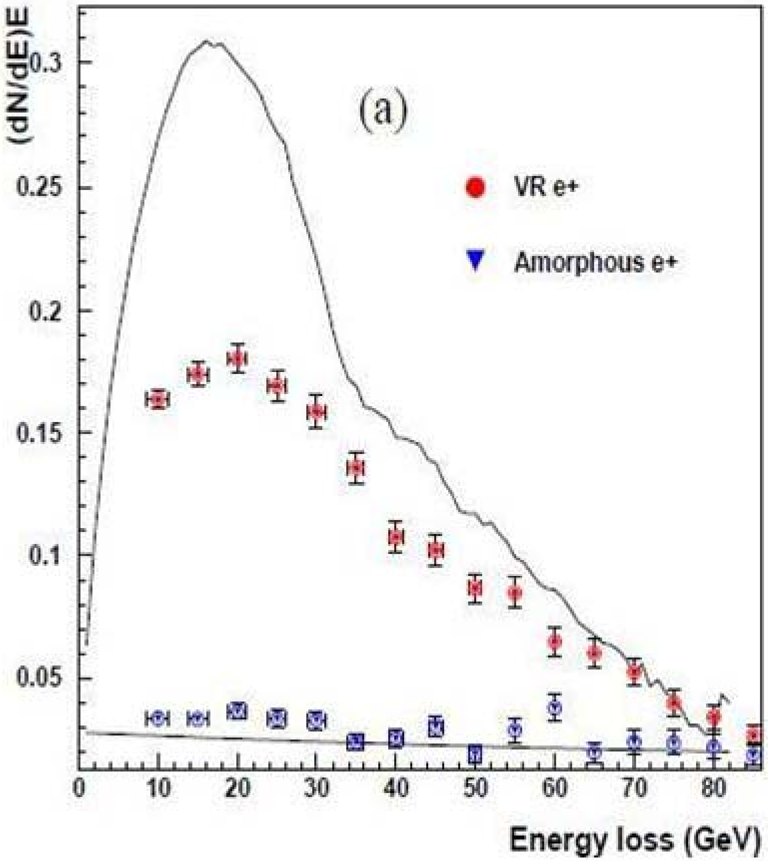


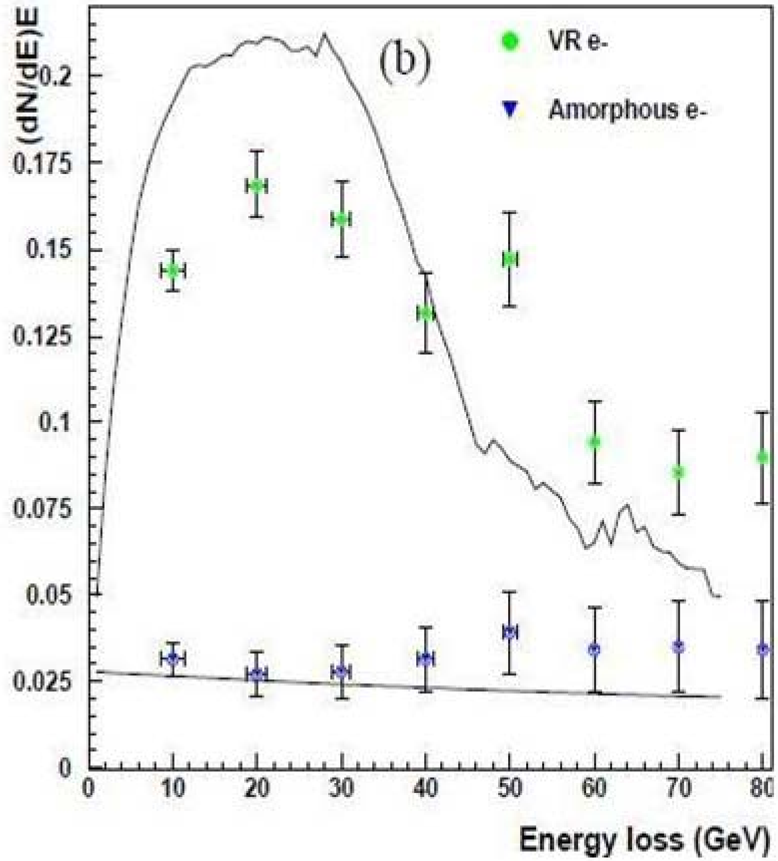
Figure 1: Scheme of the volume reflection process in bent single crystal

Recent experimental observations of the process in IHEP and CERN confirm the main predictions of theoretical consideration.

e+ 10 Gev - Afonin A.G. et. al. JETP Letters 88, 488, 2008.

e+, e- 180 GeV - Scandale W. et.al. Phys. Rev A 79, 012903, 2009





The first calculations of the radiation process were based on the quasiclassicall method

further reference BKS - method

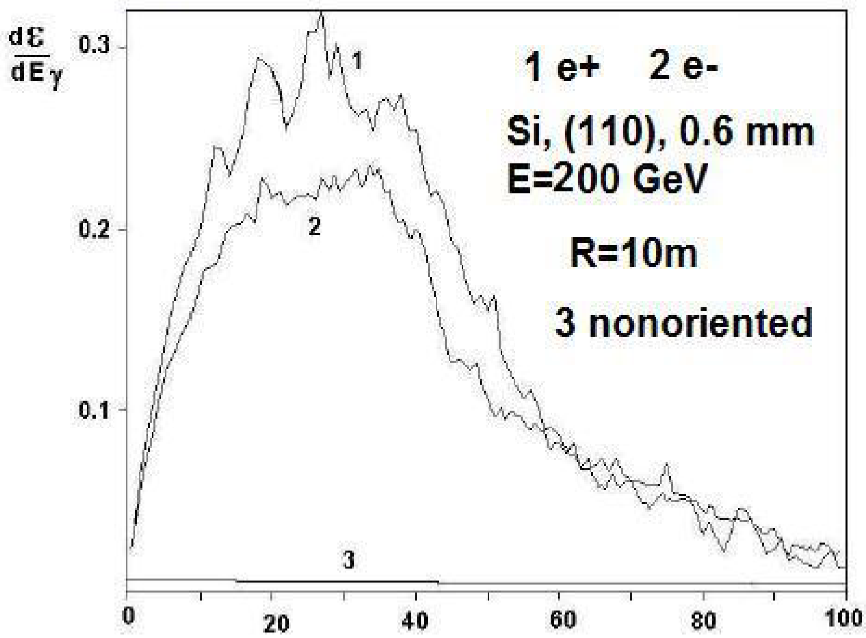
see:

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

$$\frac{d\mathscr{E}}{dE_\gamma} = \frac{i\alpha m^2 c^4}{2\pi\varepsilon^2}\omega\int_D \frac{dtd\tau}{\tau-0}\left\{1+\frac{\varepsilon^2+\varepsilon'^2}{4c^2\varepsilon\varepsilon'}\gamma^2[\Delta\mathbf{v}(t-\tau/2)-\Delta\mathbf{v}(t+\tau/2)]^2\right\}\exp -iA_1, \quad (3.1)$$

$$A_1 = \frac{\omega\varepsilon\tau}{2\varepsilon'}\left[\frac{1}{\gamma^2}+\frac{1}{\tau}\int_{-\tau/2}^{\tau/2} ds(\Delta\mathbf{v}(t+s)/c)^2-\left(\frac{1}{\tau}\int_{-\tau/2}^{\tau/2} ds\Delta\mathbf{v}(t+s)/c\right)^2\right], \quad (3.2)$$

where $\Delta\mathbf{v}(t,\mathbf{v}_0) = \mathbf{v}(t_1) - \mathbf{v}_0$ is the velocity variation as a function of time t_1, m and γ are the mass and Lorentz factor of particle, E_γ, ω are the energy and frequency of photon, ε is the particle energy, $\varepsilon \ = \varepsilon - E_\gamma$. The time variables t_1 and t_2 (t_2 is time variable as t_1) connected with variables t and τ by equations: $t_1 = t - \tau/2$ and $t_2 = t + \tau/2$. **D** is the domain of definition of integrand function.



Calculated radiation energy losses of positrons and electrons in bent single crystal.

The method allows one take into account the different peculiarities of the process, but it requires a lot of time for calculation due to strongly oscillating integrand function.

The comparison between experimental and computed radiation energy loss spectra shows the following:
1) There is good agreement between measured and calculated energy ranges of emitted photons;
2) The experimental values of energy losses is smaller in 1.7 and 1.2 times than calculated for positrons and electrons, correspondingly

In particular, the observed disagreement one can explain by multiple scattering of moving particles in the body of single crystal. Due to difficulties in the discription we cannot take into account this process in our calculations.

My report is devoted to recent progress in understanding of the radition at volume reflection for relatively small energies of electron and positrons.
Our approach is more simple and allow to take into account the problem of multiplay scattering, multiplicity of photon radiation and some others.

Our new consideration stands on the theory of the coherent bremsstrahlung in the straight single crystals.

In straight crystals
for planar case we can write the following equation for intensity of radiation:

$$I(x,\varphi) = I_c(x,\varphi) + I_a, \tag{1}$$

where I_c and I_a are the coherent and incoherent (like amorphous) contributions. $x = E_\gamma/E$ is the relative radiated photon energy (E is the electron energy and φ is the angle of direction of particle motion relative to the plane. In straight thin single crystals this angle is conserved at particle motion. Thus, one can say that process depends only on one parameter (φ-angle).

At large enough bending radii on a short part of particle trajectory (about 10 oscillations) the conditions for coherent bremsstrahlung are satisfied, because the variations of amplitude and oscillations periods is not changed practically.

In bent single crystals we modify this equation by the following way. We take into account that the angle φ changed at motion particles in bent single crystal. Now we can take into account this factor:

$$\mathcal{E}(x) = 2R \int_0^{\varphi_e} I(x, \varphi) d\varphi \qquad CB1 \tag{2}$$

where $\mathcal{E} = E_\gamma dN_\gamma / dE_\gamma$ is differential radiation energy losses per one electron passing through crystal. We consider the symmetric passage of electrons (enter and entrance angles are equal in between). This relation is valid for large enough bending radii R of single crystals.

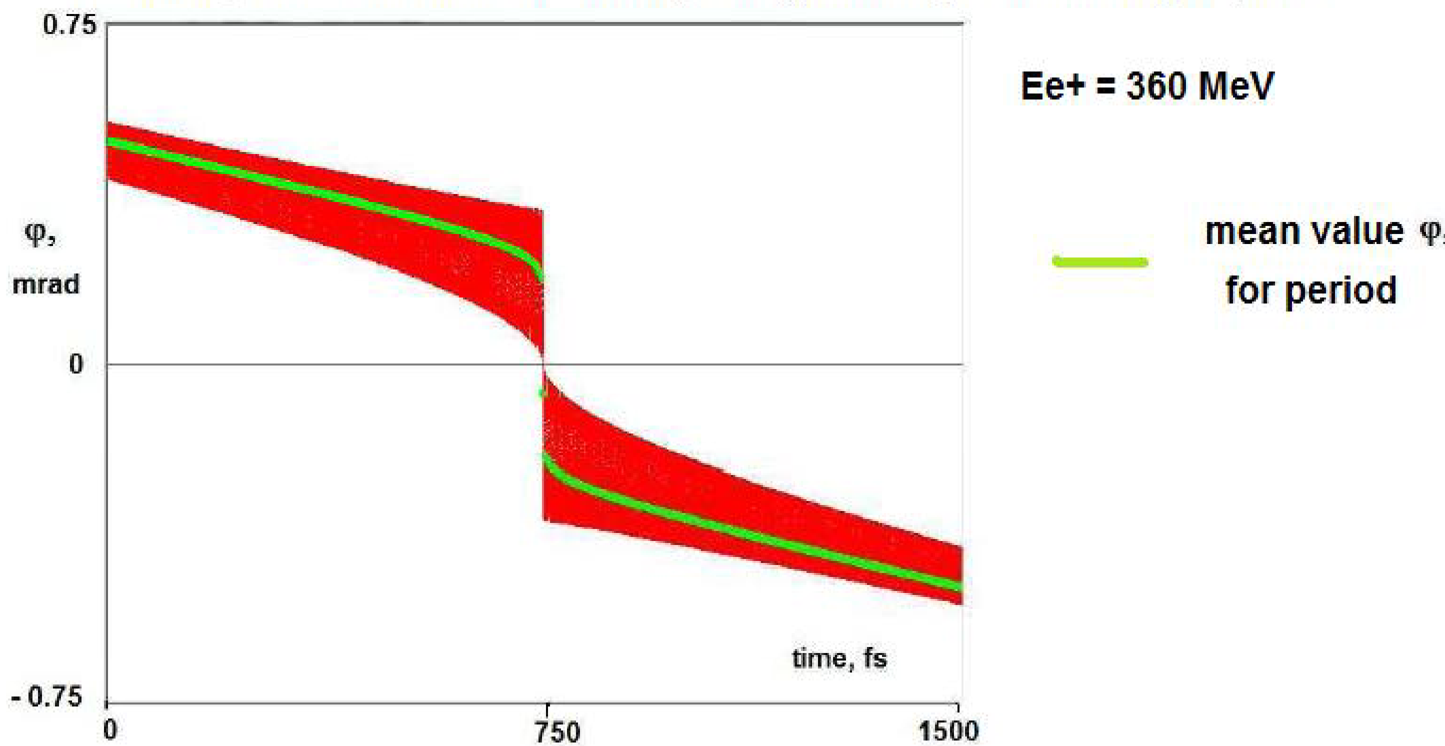


Figure 3: Angle φ as a function of time

We can also calculate the variation of φ-angle as a function of time (see Fig.3) Here the points represents the mean values of the transversal velocity. One can see that these points lie along a straight line and in the reflection point we see a break. From here we can find the φ_{min} and φ_{max} and hence to calculate the energy losses of particle. Then instead Eq.(2) we should use

$$\mathcal{E}(x) = 2R \int_{\varphi_{min}}^{\varphi_{max}} I_c(x,\varphi) d\varphi + I_a d \qquad CB2 \ (3)$$

d thickness

This is final equation for calculation of radiation energy losses for case of small electron and positron energies.

This equation is valid for energies while characteristic parameter < 1.
For silicon crystals max energy is about some tens of GeV.
This equation is also not take into account the process of multiplay scattering, however with the help of this equation it is possible in Monte Carlo program.

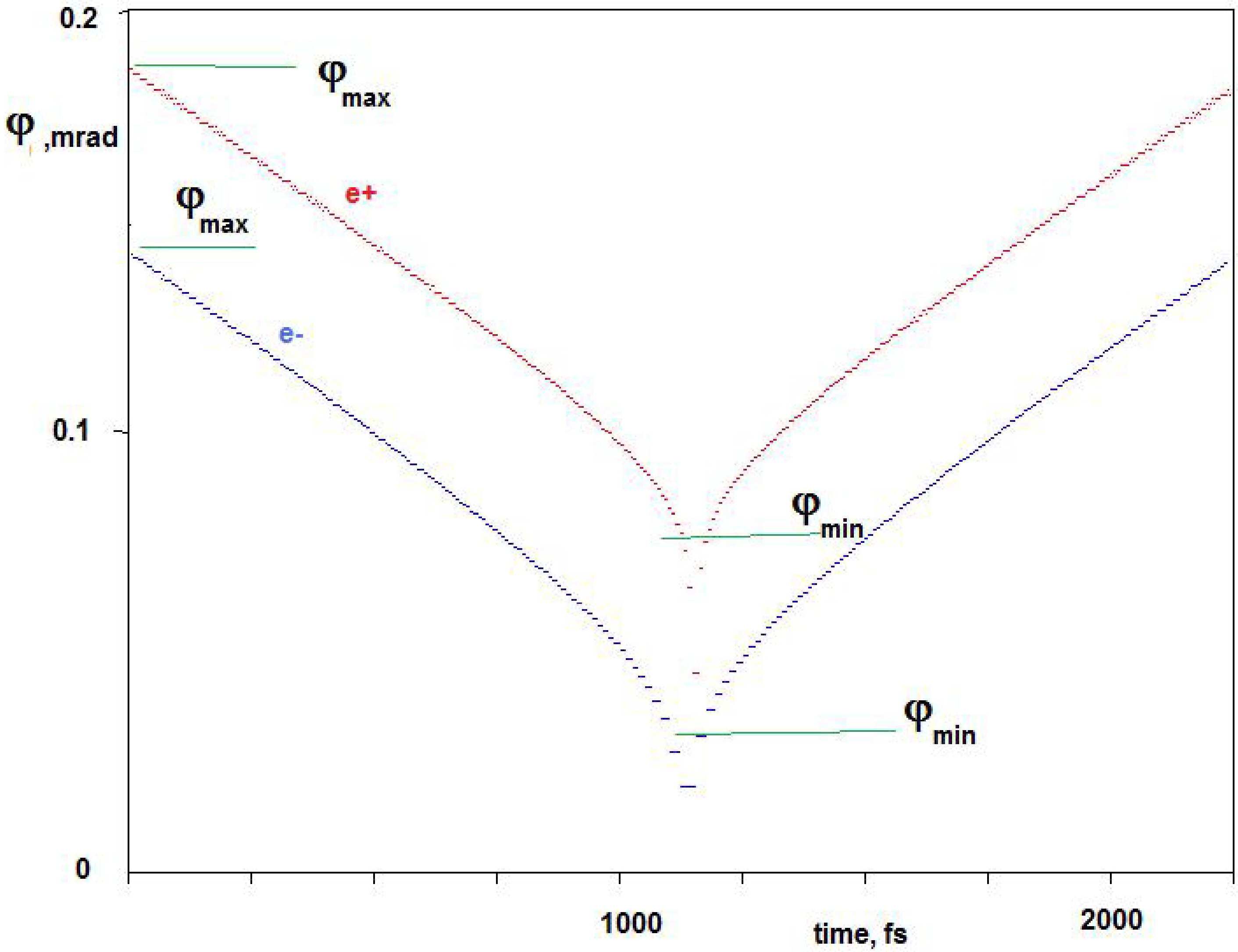
We hope that our expirience in calculation at small energies will very useful for undestanding of problem in the general case.

Besides, our solution is actual for many electron accelerators in range from tens MeV tiil 10 GeV.

In the talk D. Lietti on Channeling 2008 (Erice) workshop the experiment at energy of 3 GeV positrons was discussed.

Another parameters: Si single crystal, thickness about 0.7 mm, bending radius 3.75 m.
The working plane is (110).

Determination of φ_{min} and φ_{max} angles



$$\varphi = \frac{d}{cT}$$

d is the interplanar distance,
T is the period of one oscillation
c is velocity of light

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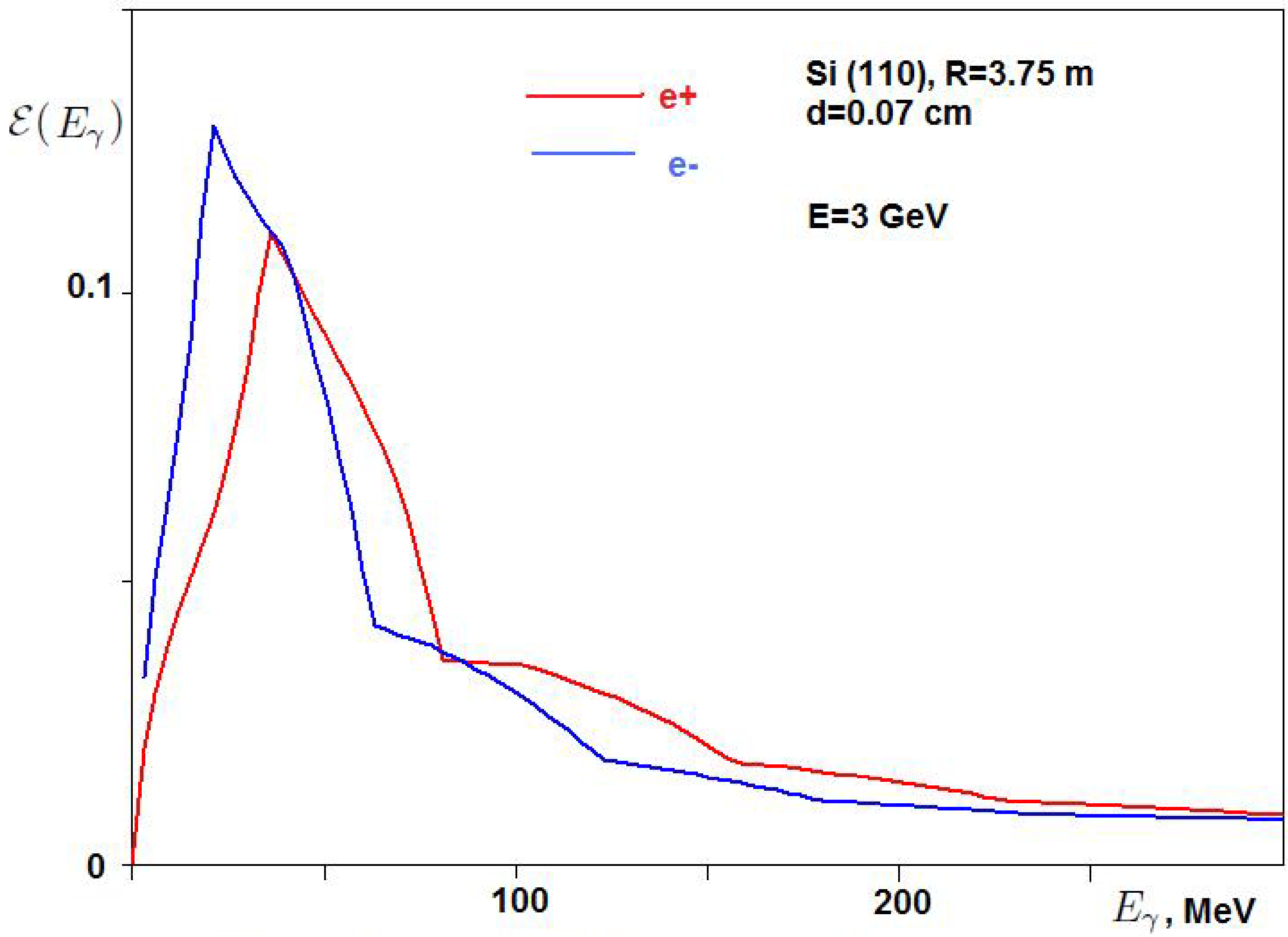


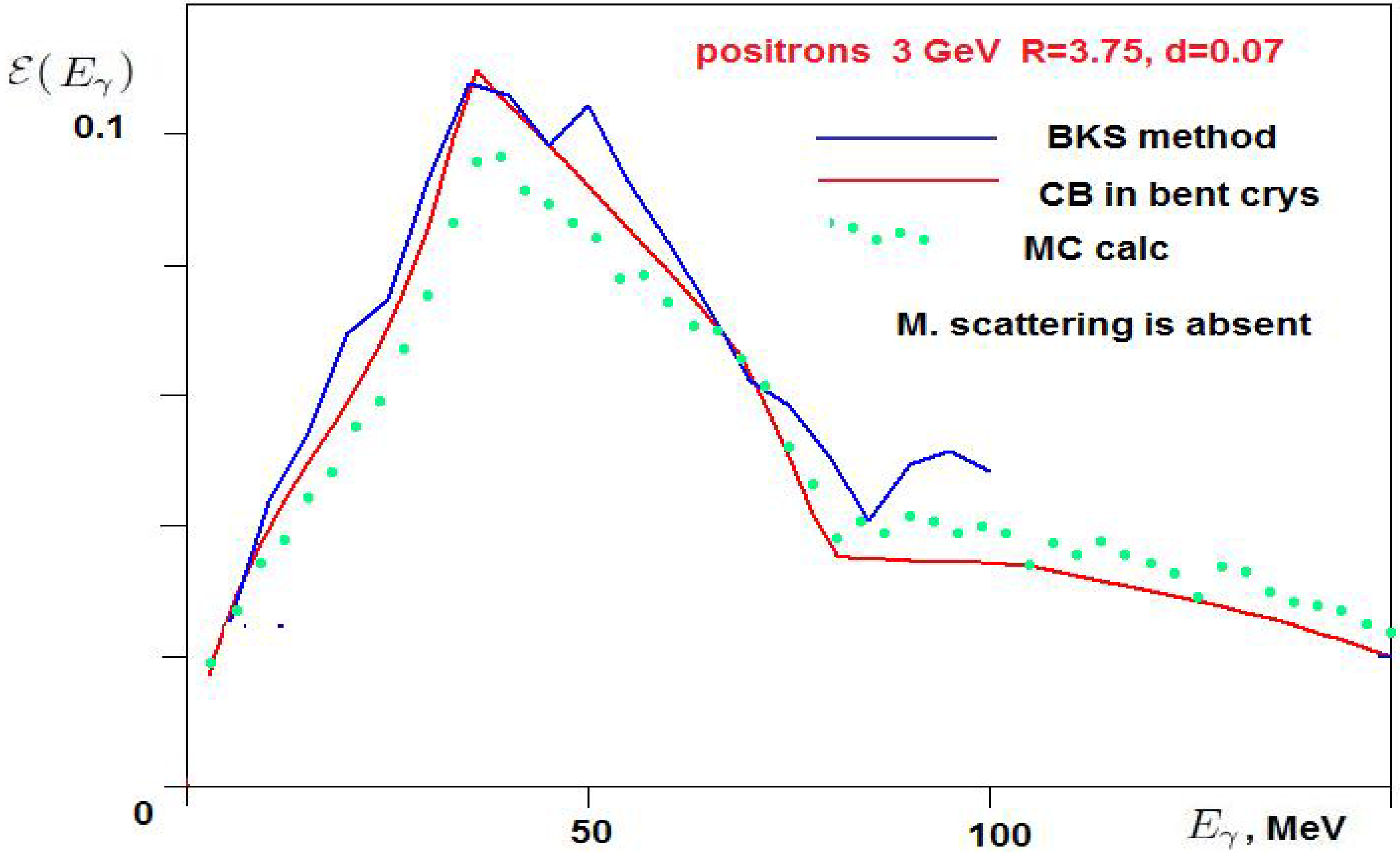
Energy losses of 3 GeV positrons and electrons.

Influence of multiplay scattering on the radiation process.

For silicon single crystal the rms angle of multiplay scattering in the 1 mm of thickness is equal to

about 1.5 mrad for 1 GeV
0.5 mrad for 3 GeV
0,15 mrad for 10 GeV
0.015 mrad for 100 GeV

For many practical cases value the bending angle (1 mm) single crystal is less then 1-2 mrad.
From here follows that the process of multiplay scattering can distort strongly the calculated spectra.

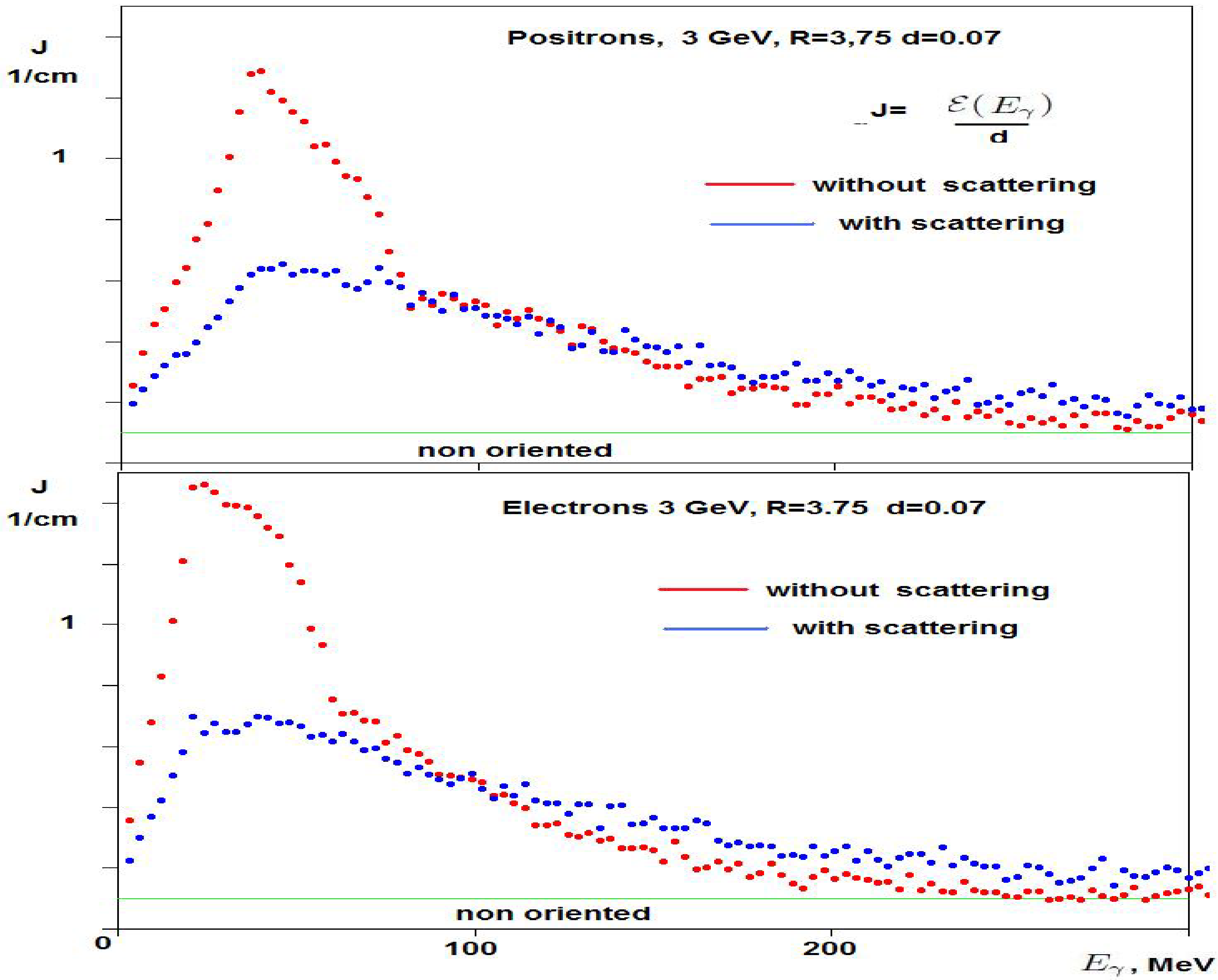


Thus Monte Carlo calculations stands on the description of coherent bremsstrahlung process in bent single crystals. Taking into account the importance of correctness of this description we made additional test. We compare results obtained by two methods

1) CB in bent crystals;

2)calculations by BKS- method

At small enough energies of particle the both methods should be give the same result. Of course, we don't consider the multiplay scattering in the both cases.



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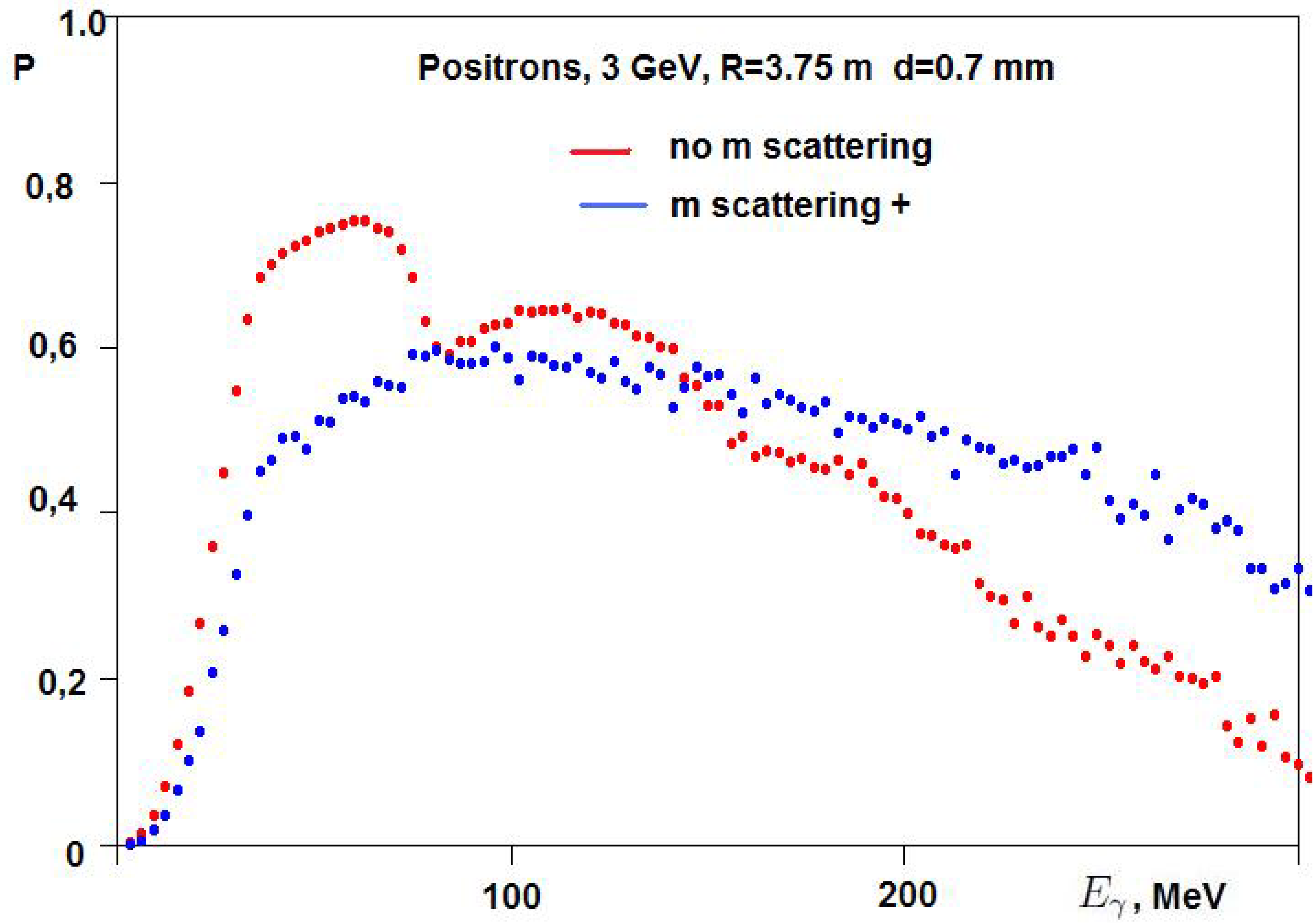
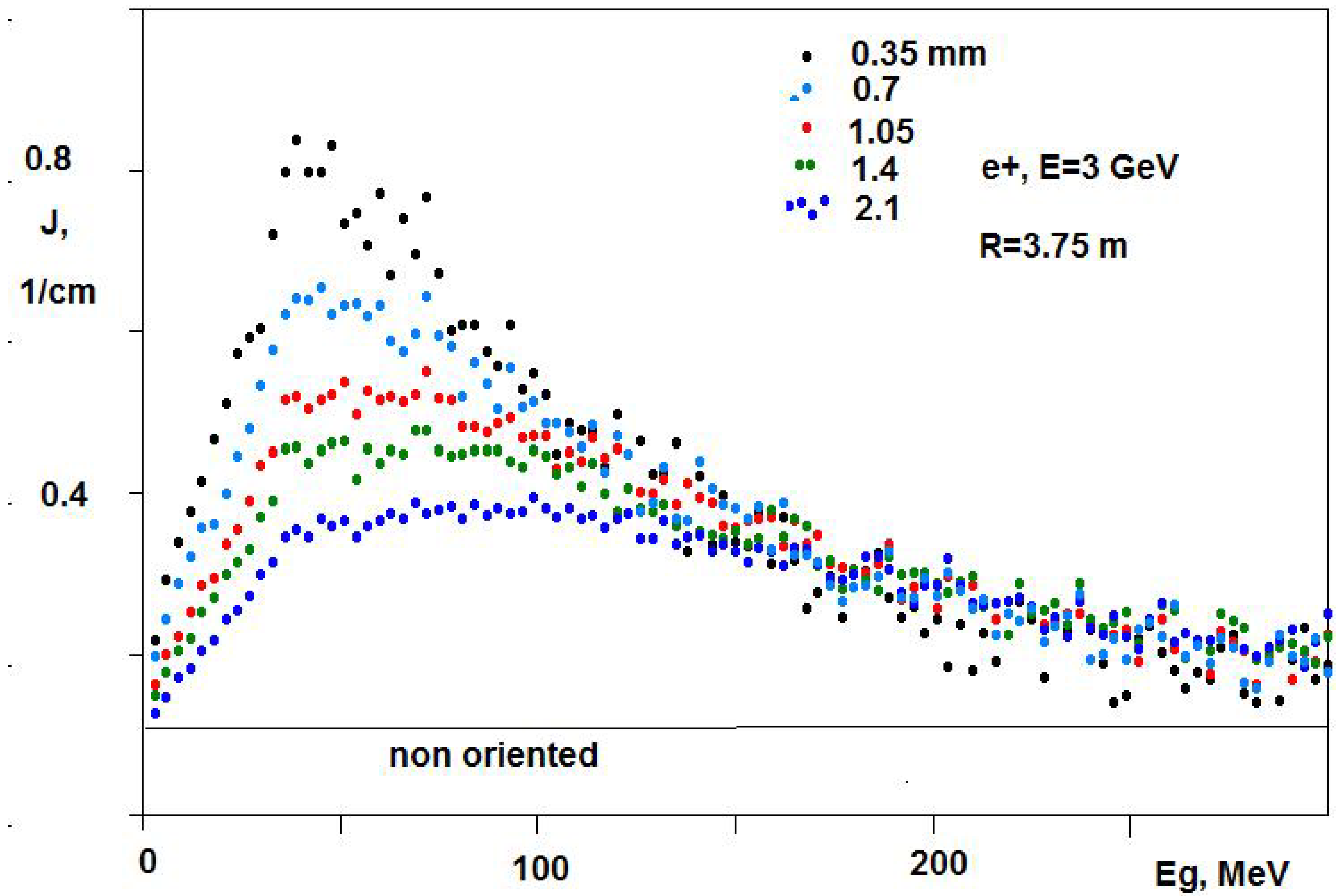
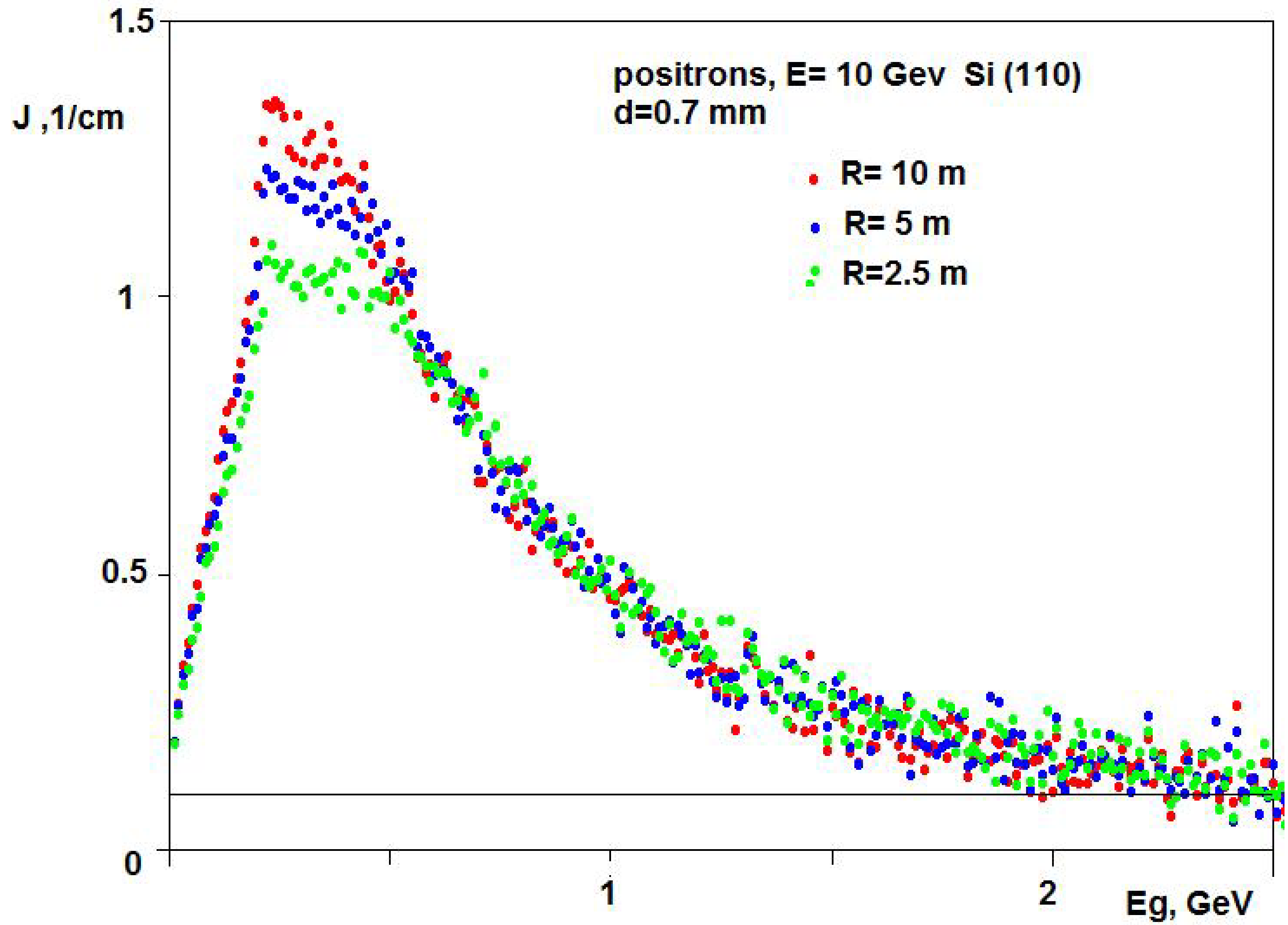


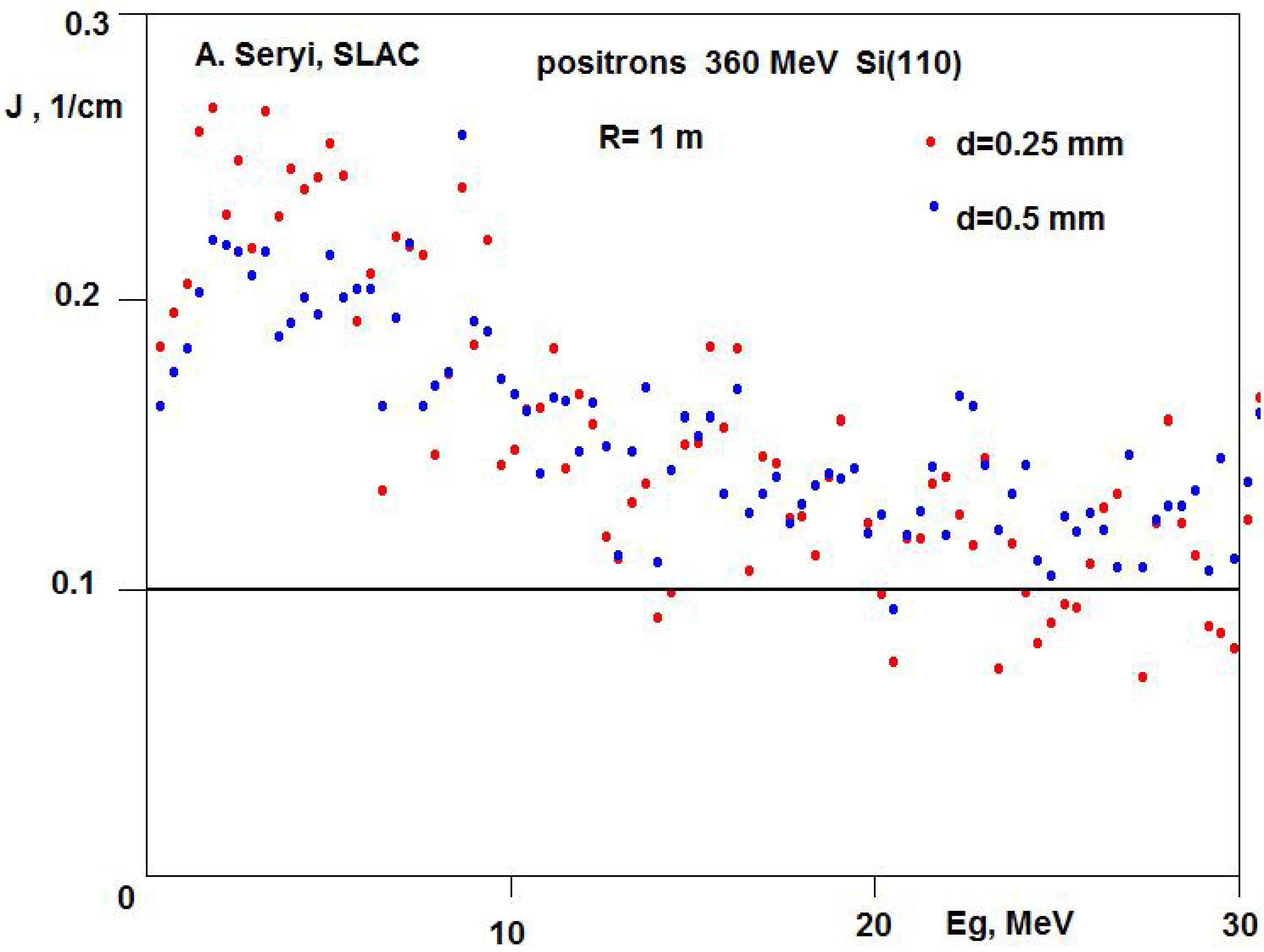
Linear polarization of emitted photons

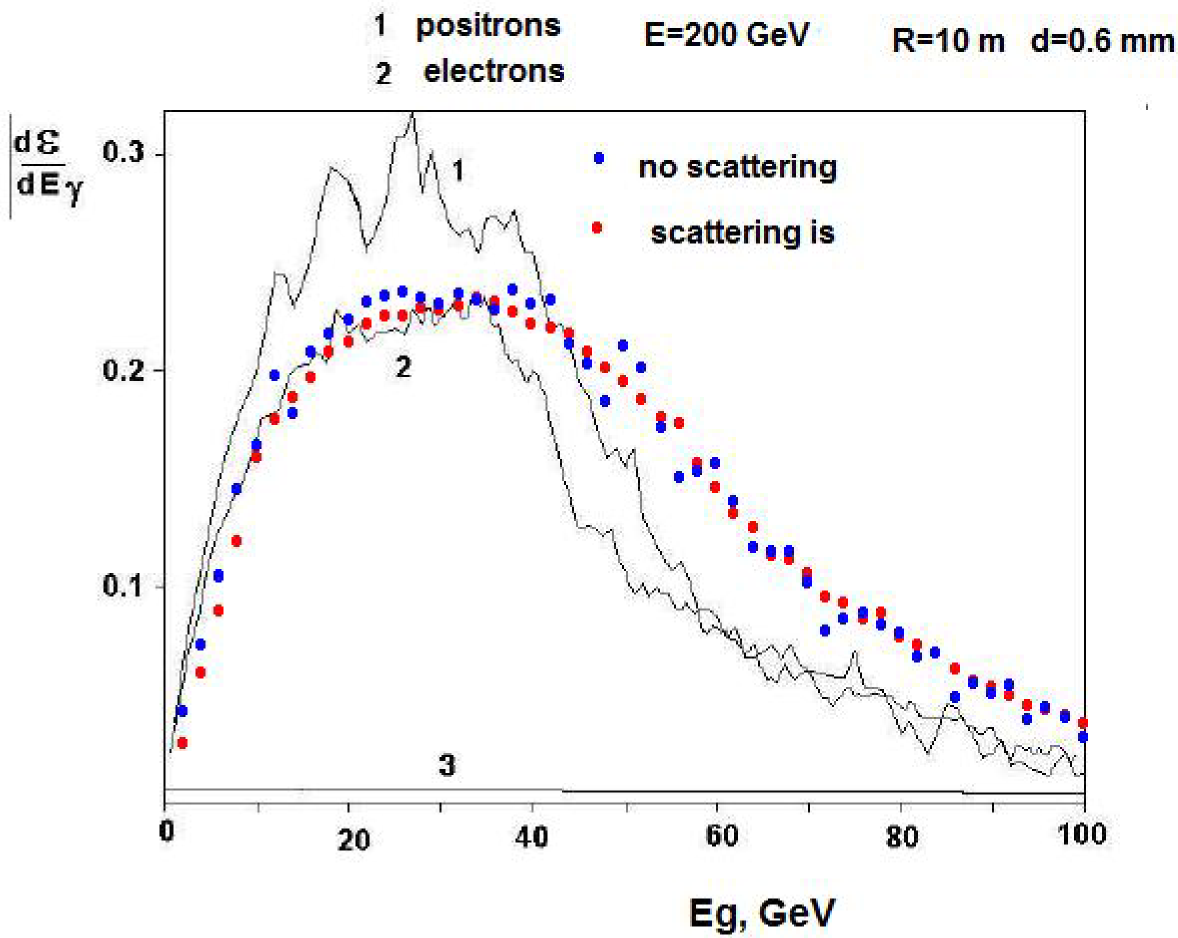


The mean energy losses per 1 cm about 0.35 MeV / cm



positrons, E= 10 Gev Si (110)
d=0.7 mm
R= 10 m
R= 5 m
R=2.5 m
J ,1/cm
1.5
1
0.5
0
1
2
Eg, GeV


0.3
A. Seryi, SLAC
positrons 360 MeV Si(110)
J , 1/cm
R= 1 m
d=0.25 mm
d=0.5 mm
0.2
0.1
0
10
20
Eg, MeV
30



One can make an estimation of range of emitted photons with help of the relations:[15]

$$\omega = \frac{2\gamma^2 \omega_0}{1 + \rho/2}$$

$$E_{\gamma,max} = \frac{\hbar\omega E_0}{E_0 + \hbar\omega}$$

where $\omega_0 = 2\pi/T$ and T is the period of one oscillation.

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- Besides, one can expect strong radiation intensity at axial orientation of the crystal.
- It is known that in straight single crystals the particles with the energies in hundred
- GeV lose most part of their initial energy. But these process takes place in a small
- range of initial angles. We suppose that in bent single crystals these process will
- take place in significantly more wide range of the initial angles of particle.

- We also think that the usage of the multy crystal systems may be very
- effectively for obtaining of large radiation losses of particles as well in the
- planar orientation as in axial one.
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Conclusions

- 1) The method of calculation of the radiation energy losses of electrons
- and positrons in bent single crystal was proposed;
- 2) This method allow one to calculate the radiation process for
- energies of particles < 50-100 GeV
- 3) The method takes into account the multiple scattering of particles
- In the body of the single crystal.
- 4) The method is in agreement with BKS method (if multiple scattering
- Is absent)
- 5)Calculations of the radiation at the volume reflection shows the
- high enough level of energy losses at relatively small particle energies.
- 6) The emitted at volume reflection radiation photons have enough high
- degree of the linear polarization (till 60-70 %).
- 7)We predict the high radiation energy losses of particles in the axial case
- In a wide angle range.

- Thank you for attention