Monte Carlo simulation of bremsstrahlung spectra for low energy electron accelerators

I.I. Haysak, O.V. Takhtasiev
Department of Theoretical Physics,
Uzhgorod National University
Uzhgorod, Ukraine
ivan.haysak@uzhnu.edu.ua
J.Khushvaktov, A.A. Solnyshkin
Joint Institute for Nuclear Research
Dubna, Russia

A. Tanchak, R.R. Holomb, K. Katovsky
Department of Electrical Power Engeeniring
Brno University of Technology
Brno, Czech Republic
xtanch00@stud.feec.vutbr.cz

***Abstract* - Four Monte-Carlo codes where tested to simulate bremsstrahlung spectra for accelerated electron beams at the energy range 4-20 MeV. All four codes give the same shape of the spectrum, in which in addition to the bremsstrahlung part there are characteristic energy lines of the target atom and an annihilation line of 0.511 MeV caused by secondary processes of the photoelectric effect and of electron-positron pair production. The absolute values of the energy spectrum have close magnitudes but it requires a more thorough study.**

Keywords - bremsstrahlung; photoelectric effect; pair production process; tungsten

I. INTRODUCTION

The bremsstrahlung gamma beams are widely used in medicine, technology, astrophysics, accelerator-driven subcritical reactor research, photonuclear reaction study, and other fields. Such beams are produced by electron accelerators. Accelerated electrons fall on a brake target in which electrons emit a continuous spectrum as a result of deceleration. The shape of the spectrum is determined by the energy of the primary electrons, the material of the brake target, and its thickness. In practice, Schiff's analytical expression [1] is used to describe the energy spectrum of a "thin" target [2].

To avoid the approach of the "thin" target, we used four Monte-Carlo simulation codes, namely, a specialized EPHCA (Electron PHoton CAscade) code [3] developed at Tomsk Polytechnic University and universal codes MCNP6 [4], FLUKA [5] and GEANT4 [6].

Here we present our preliminary results of the bremsstrahlung spectra simulation, but the universal codes also can be used for simulation of (γ,n)-reactions, for simulation of efficiency of gammas and neutrons registration by a different type of detectors.

II. ELECTRON ACCELERATORS

In Uzhhorod National University there are two electron accelerators - microtron M-10 with electron energies up to 10 MeV and a betatron B-25, in which the internal beam of electrons is accelerated up to 25 MeV [7]. The induction electronic accelerator betatron, in comparison with the microtron, has a significant advantage in the possibility of a smooth change in the energy value of the electron accelerated beam. But the disadvantage of this comparison is a much less (up to three orders of magnitude) the intensity of the accelerated beam. However, this fact does not play a significant role in research on the effects of radiation on the needs of biology and medicine [8].

From the microtron, the accelerated beam is pulled outwards and hits the brake target. The brake target is a tungsten plate of 93x55x2 mm size.

In the betatron, the accelerated beam hits the inner brake target and only the gamma beam goes out. The brake target of betatron is also made of tungsten and has dimensions of 3x5x1.5 mm. The target is situated at an angle of 15 degrees to the beam direction.

The penetration depth of a monoenergetic electron beam in aluminum is well described by these phenomenological formulas [9]

$$R = 412 \cdot E^n; \quad 0.01 \le E \le 3\,MeV, \qquad (1)$$
$$R = 530 \cdot E - 106; \quad 3 \le E \le 20\,MeV,$$
$$n = 1.265 - 0.0954 \cdot Ln(E)\,.$$

where: R is the penetration depth in g/cm^2, E is the energy of electrons in MeV. Conversion to other materials is made by the formula:

$$R_x = R_{Al}\frac{(Z/A)_{Al}}{(Z/A)_x} \qquad (2)$$

TABLE I. SOME PARAMETERS OF THE BETATRON AND THE MICROTRON

	B-25	M-10
Beam energy, MeV	4-25	5-10
ΔE, keV	12	25
Intensity, 1/s	$6.2\cdot10^{10}$ (10 nA)	$1.2\cdot10^{14}$ (20 μA)
Burst time	5 μs	2.5 μs
Pulse frequency	50 Hz	400 Hz

Project No. LTAUSA18198
ADAR - Accelerator Driven Advanced Reactor
Centre for Research and Utilization of Renewable Energy
Ministry of education, youth and sport of the Czech Republic

978-1-7281-9479-0/20/$31.00 ©2020 IEEE

where Z/A is the charge to mass ratio of the corresponding element. Characteristic X-ray emission lines for tungsten are $K_{\alpha 2}$ = 58.0 keV, $K_{\alpha 1}$ = 59.3 keV, $K_{\beta 1}$=67.2 keV.

III. BREMSSTRAHLUNG SPECTRA

One of the tasks where the bremsstrahlung beam is used is to study photo-nuclear reactions. For the experiment the yield $Y(E_e)$ of the reaction under the action of a continuous bremsstrahlung beam with the energy distribution of $S(E_e, E_\gamma)$ formed by electrons with E_e energy need to be measured. The magnitude of the yield $Y(E_e)$ is related to the effective cross-section of the reaction $\sigma(E_e)$ by the equation

$$Y(E_e) = N_e n \int_0^{E_e} S(E_e, E_\gamma)\cdot \sigma(E_\gamma) dE_\gamma\ , \quad (3)$$

where N_e is the total electron flux, n is the target thickness in units of g/cm^2 [10]. So, the dimension of photon spectrum $S(E_e, E_\gamma)$ must be 1/(N_e·MeV). To find the cross-section $\sigma(E_e)$ we need to solve the integral equation (3). This equation is so called Volterra integral equation and it belongs to "invers problem" and 'ill-posed problem" because the solution procedure is unstable, namely, arbitrary small errors in the measurement data may lead to indefinitely large errors in the solution [11].

A. The bremsstrahlung spectra for microtron

Interfaces of the GEANT4 and FLUKA codes allow user to create equable bins of modeling gamma spectra only. But interfaces of the MCNP6 and EPHCA codes allow ones to create uneven energy bins too.

Fig. 1 shows the gamma-ray spectrum on the forward direction of 5 MeV electron beam of microtron M-10 created on a 2 mm thick tungsten target. The spectrum is generated by the FLUKA code. In the spectrum are present the characteristic X-ray lines of tungsten atoms in the energy region less than 0.1 MeV, also the annihilation line of 0.511MeV is evident and the actual bremsstrahlung part in the region 0.1 -5 MeV. Here the dimension of the gamma spectra S(E_γ) is number of photons per source electron.

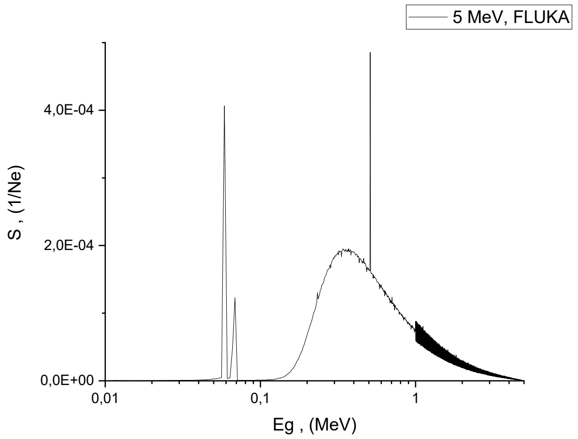

Fig. 1. Bremsstrahlung spectrum simulated by FLUKA code for electron beam 5 MeV on a 2 mm thick tungsten target.

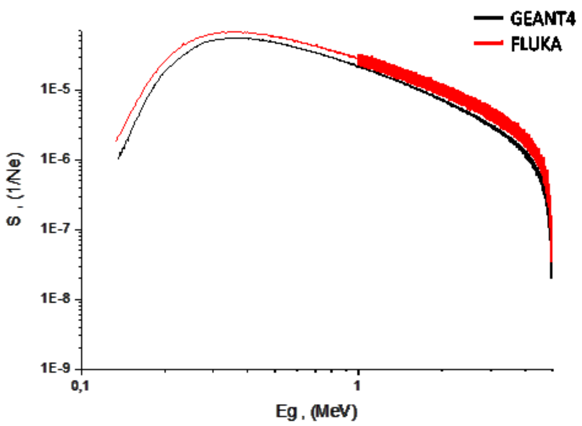

Fig. 2. Comparison of the bremsstrahlung spectra simulated by GEANT4 (black line) and FLUKA (red line) codes.

Fig. 2 shows comparison of the bremsstrahlung spectra simulated by GEANT4 (black line) and FLUKA (red line) codes for electron beam of 5 MeV. Here the dimension of the gamma spectra S(E_γ) is number of photons per source electron per 1 MeV. The shape of the spectra is similar, but the magnitude is different. (The annihilation peak was removed in figure for simplicity).

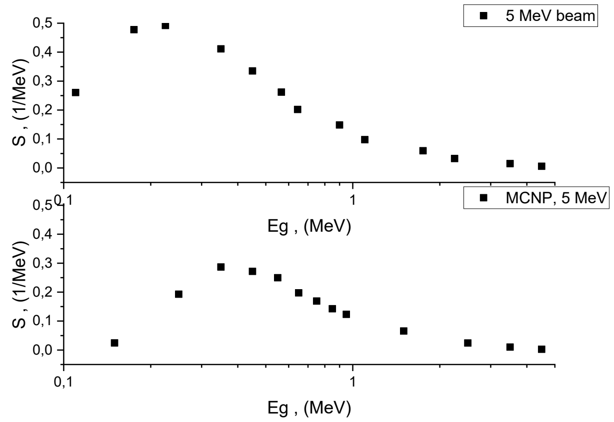

Fig. 3. Comparison of the bremsstrahlung spectra simulated by EPHCA and MCNP6 codes.

Figure 3 shows comparison of the bremsstrahlung spectra simulated by EPHCA and MCNP6 codes. Again, the shape of the spectra is similar, but the magnitude is different. There is no annihilation line in these spectra due to the broad energy bin in the histogram.

Figure 4 shows comparison of the bremsstrahlung spectra simulated by EPHCA code for electron beam of energies 4 MeV, 5 MeV, 8 MeV and 9 MeV. With increasing of electron energy, the intensity of the spectrum increases, the shape of the spectrum is almost unchanged and the maximum remains in the region near 0.2 MeV.

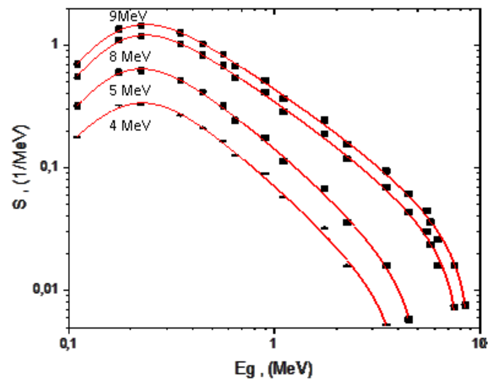

Fig. 4. Comparison of the bremsstrahlung spectra simulated by EPHCA code for electron beam of energies 4 MeV, 5 MeV, 8 MeV and 9 MeV.

The lines in Fig. 4 are approximants of the simulated spectra by a function that can be convenient for the numerical solution of the integral equation (4). The form of this function is chosen as follows

$$S(E_e, E_\gamma) = A\frac{(E_\gamma)^s(E_e-E_\gamma)}{1+b(E_\gamma-x_0)^2}\ , \tag{4}$$

where A, b, x_0 and s are fitting parameters for a fixed electron beam energy E_e. This approximated function can be used in a solution algorithm of the integral equation (3).

B. The bremsstrahlung spectra for betatron

Since the electron beam is output from the microtron, it is possible to change both the braking target material and its thickness. On the betatron, the braking target is located in the accelerator chamber and cannot be changed. Figure 5 shows the microtron and betatron bremsstrahlung spectra for the existent braking targets as indicated above (thickness 2 mm and 1.5 mm).

In Fig. 6 it is shown the simulated spectra for betatron electron energies 5 MeV, 10 MeV and 20 MeV. It can be seen that at the energy of 20 MeV the high-energy part of the brake spectrum is strongly increasing. The maximum of the brake spectrum with increasing energy of the electrons almost does not shift. However, the absolute values of spectra sharply increase with electron energy increase. For example, for electron beam energy 10 MeV and 20 MeV intensity of gamma increase near 7 times.

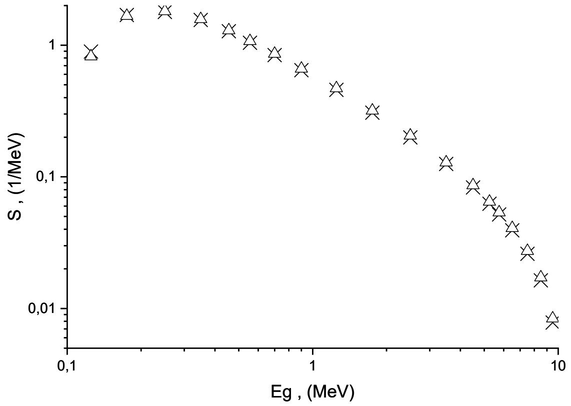

Fig. 5. Bremsstrahlung spectra of microtron (cross) and of betatron (triangles) for electron beam energy 5 MeV (EPHCA code).

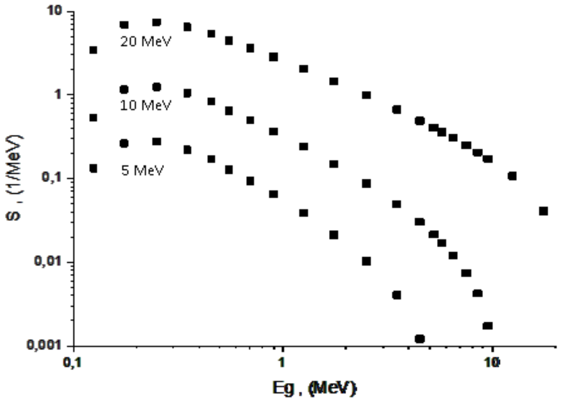

Fig. 6. Bremsstrahlung spectra of betatron at energies 5 MeV, 10 MeV and 20 MeV (EPHCA code).

IV. CONCLUSION

A widely used analytical expression for the bremsstrahlung spectrum [1,2] is obtained in the approximation of a thin target. This expression for low-energy gamma quanta behaves as $1/E_\gamma$, which is obviously incorrect. Figure 7 [2] shows bremsstrahlung spectra obtained with analytical formula of Schiff.

Our computer simulation shows that in interesting for us region of electron beam energies 5 -20 MeV the bremsstrahlung spectrum reaches a maximum near the energy of 0.2 MeV. This feature of the spectrum shape is present in the calculations of all four software codes we tested.

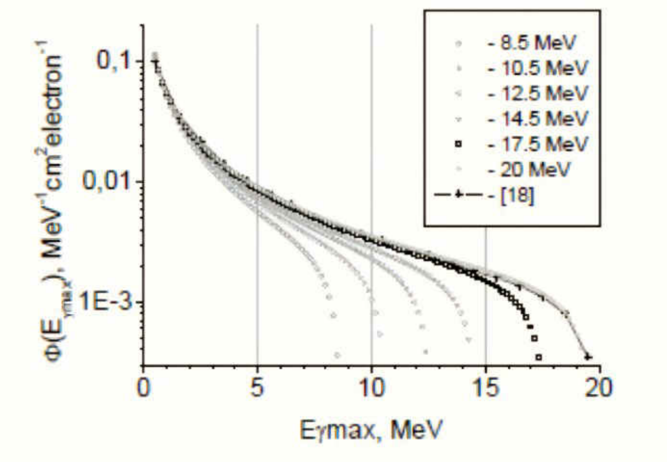

Fig. 7. Bremsstrahlung spectra from 1 mm tantalum target [2].

Our results of simulations with different codes give different values of the spectrum at maximum. This may be due to the difference in the physical models used. In most cases, we used the default parameters in our calculations.

We tried to find an analytical function (4) that approximates bremsstrahlung spectra for fixed electron beam energy in gamma energy interval 0.1 - E_e. Fitted parameters can be used for the numerical solution [12] of the integral equation (3) or for adsorbed dose calculation.

The braking radiation is strongly forward, and the radiation of the secondary processes of photo effect and annihilation are isotropic. Therefore, at large angles to the electron beam direction, photo-effect lines and annihilation will prevail. This can be used to monitoring the bremsstrahlung beam.

REFERENCES

[1] L.I. Schiff, Energy-angle distribution of thin target bremsstrahlung, Phys. Rev. 83(1951)252-253.

[2] Pylypchynets, I.V., Parlag, O.O., Oleynikov, E.V. Simulation the yields of actinide nuclei photofission products induced by bremsstrahlung of electron accelerators // Uzhhorod University Scientific Herald. Series Physics. Issue 42. -2017. p.169-177. (in Ukrainian)

[3] B.I. Bespalov Computer Laboratory CL/PCLab. Program Manual (Version 9.8). Tomsk: Tomsk Polytechnic University, 2016. 216p. (in Russian)

[4] C.J. Werner (editor), "MCNP Users Manual - Code Version 6.2", LA-UR-17-29981 (2017).

[5] Ferrari, A.; Sala, P.R., Ranft, J.; Siegen U. FLUKA: A Multi-Particle Transport Code. SLAC-R-773. (2015).

[6] J.Allison et al. Recent development in Geant4. Nucl. Inst. and Meth. in Phys. Res. A, http://dx.doi.org/10.1016/j.nima.2016.06.

[7] Ivan Haysak, Vasyl Martishichkin, Ruslan Plekan, Olexandr Takhtasiev, Karel Katovsky, Jan Varmuza, Robert Golomb Measuring and simulation of dose at irradiation by bremsstrahlung gamma beam // 2018 19th Conference Electric Power Engineering (EPE), p.508-511.

[8] N Tomasovicova, I Haysak, J Kovac, M Kubovcikova, V Zavisova, M Timko, A Okunev, A Zorkovská, P Kopcansky Radiation Stability of the BSA Modified Biocmpatible Magnetic Fluid // Acta Physica Polonica A, V.126,Issue 1, p.262-263. 2014.

[9] Physical quantities: Handbook / A. P. Babichev, N. A. Babushkina, A. M. Bratkovsky and others; Ed. I. S. Grigoriev, E. 3. Meilikhova. - Moscow: Energoatomizdat, 1991 - 1232 p. ISBN 5-283-04013-5 (in Russian)

[10] V.I.Zhaba, I.I.Haysak, A.M.Parlag, V.S.Bohinyuk, M.M.Lazorka Energy dependence of cross section of photonuclear reactions on indium isotopes // Problems of atomic science and technology. #3(115). 2018. p.155-158.

[11] S. Kabanikhin Definitions and Examples of Inverse and Ill-Posed Problems // J. of Inv. and Ill-Posed Probl. V.16, Iss.4, -2008. p317-357. DOI: 10.1515/JIIP.2008.019

[12] I.I.Haysak, K.O.Oganesyan On the Integral Technique for Studying Angular distributions // Communication of the Joint Institute for Nuclear Research, Dubna, 1978. 11p. DOI: 10.13140/RG.2.2.29210.75208