A METHOD FOR ANALYSIS AND OPTIMIZATION OF ELECTRON ACCELERATOR EXIT DEVICES UNDER BREMSSTRAHLUNG GENERATION MODE

V.I. Nikiforov, V.L. Uvarov
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: vinikiforov@kipt.kharkov.ua

The method of the analysis of a mixed e,X-radiation field along a path of the output target devices of the electron accelerator is proposed. The concept of stopping length of a path and representation of a real path as multicomponent layered target with infinite cross-section size lays at the heart of a method. A set of basic characteristics of the e,X-radiation is formulated. It is shown, that the description of target devices in terms of stopping length allows to reduce the basic characteristics of radiation to unified form in the range of initial electron energy 5…60 MeV at a value of the nuclear number of target material 6…73. As a result, three stages of the e,X-radiation formation differing by a ratio of its component intensity are established. Procedure of optimisation of a path in order to receive the specified values of basic characteristics is described.

PACS: 03.50.-z; 07.05.Tp; 07.85.Fv

1. INTRODUCTION

Modern radiation technologies make wide use of both electron radiation and bremsstrahlung (e.g., see refs. [1,2]). In every case the amount of "impurities" contained in the particle flux must be minimal.

The interaction of the electron beam with the elements of accelerator output devices represents the transformation of the primary "pure" electron beam into a mixed e,X-radiation. The ratio of its component intensities in the given transverse plane is specified by the initial electron energy E_0, the thickness and atomic number of the materials in the region of radiation formation.

Analytically, the conditions of electron radiation transformation into the bremsstrahlung are generally described in terms of the radiation length of converting material [3]. The formulae derived are rather complicated and, as a rule, are applicable to a limited range of electron energy, thickness and atomic number of converting media [4].

The present work offers a generalized approach to the description of the conditions of mixed e,X-radiation formation. Numerical results given in the paper have been obtained by the mathematical modeling method, using the transport code PENELOPE-2008 as the basis [5].

2. STOPPING THICKNESS UNIT AND STOPPING LENGTH OF THE OUTPUT

The stopping thickness of a layer of a certain material is defined as the ratio of the linear thickness of the layer (in cm) to the average range (in cm) of the electron of given energy in this material. The resulting in this way stopping thickness of the layer is dimensionless. The corresponding unit of measurement is referred to as the stopping thickness unit (stu).

The stopping length of the output path of the accelerator is equal to the sum of stopping thicknesses of all the output device elements, of all water, air gaps or the like. In this case, the average range of the electron in every medium is calculated at the same energy equal to the mean electron energy in the beam spectrum.

It is evident that the Z-coordinates of the device elements along the path can be measured in the stu, and the state of radiation along the path can be described by the functions of the stopping coordinate.

3. BASIC CHARACTERISTICS OF THE e,X-RADIATION

The basic characteristics of electron-photon radiation include the **energy coefficient of electron transmission** (Eel/Ebeam) and the **energy coefficient of electron-to-photon conversion** (Ega/Ebeam). Here Ebeam is the total of electron beam energy; Eel, Ega are, respectively, the total energies of forward flying electrons and photons, which cross the transverse plane that passes through the given Z-coordinate.

Of considerable practical use is the ratio of the mentioned coefficients (Ega/Eel) hereinafter called as the **secondary radiation energy factor**. The corresponding parameters relating to the positron component of radiation are calculated in the same way, but on account of their insignificance they are not shown here.

The behavior of absolute values of basic radiation characteristics in different substances versus their stopping thickness in the electron energy range between 5 and 60 MeV is shown in Figs.1 to 3.

If each of these characteristics is normalized to its highest value, then their behavior versus the stopping coordinate will be essentially unified (Fig.4). In other words, the behavior of normalized basic characteristics depends only slightly on the atomic number of the substance and the electron energy. These two important facts count in favor of the practical use of the stopping range concept for describing the state of mixed e,X-radiation in the substance.

4. GENERALIZED DESCRIPTION OF THE ACCELERATOR OUTPUT PATH

The accelerator output elements have finite sizes (height, width, thickness). From now forth we shall call the path described with due regard for real dimensions of its elements as the RAM (Real Approximation Mode)-path. To represent the base characteristics of radiation as continuous functions of stopping coordinates of the path, we shall also introduce the concept of LAM (Layer Approximation Mode)-path. Its fundamental difference from the RAM-path consists in that the transverse dimensions (height, width) of all the elements are assumed to be infinitely large. In the calculations performed, the transverse dimensions of all the elements were finite and put to be 20 meters. Thus, the LAM-path of the accelerator presents a layered multicomponent target, i.e., a set of different materials closely adjoining each other (titanium, aluminum, water, air, etc.). Owing to a great value of the height (width)-to-thickness ratio, all the particles escaping forwards (i.e., along the beam) from any layer come to the next layer.

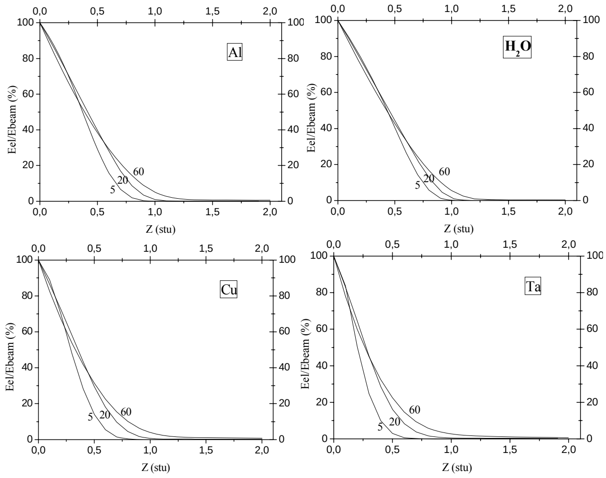

Fig.1. Electron transmission coefficient versus material thickness. Figures near the curves indicate the beam electron energy in MeV

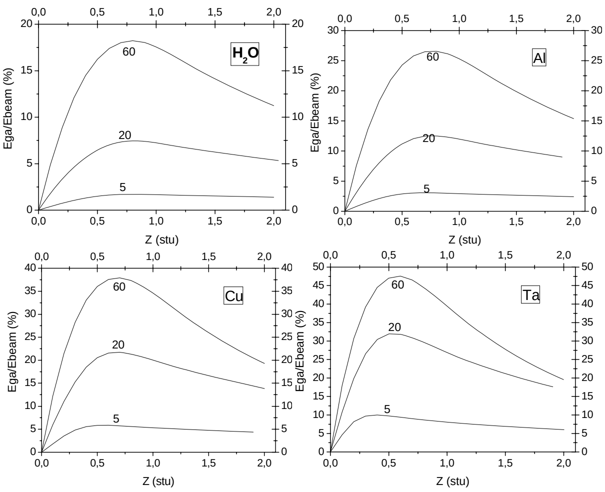

Fig.2. Conversion coefficient as a function of the material thickness

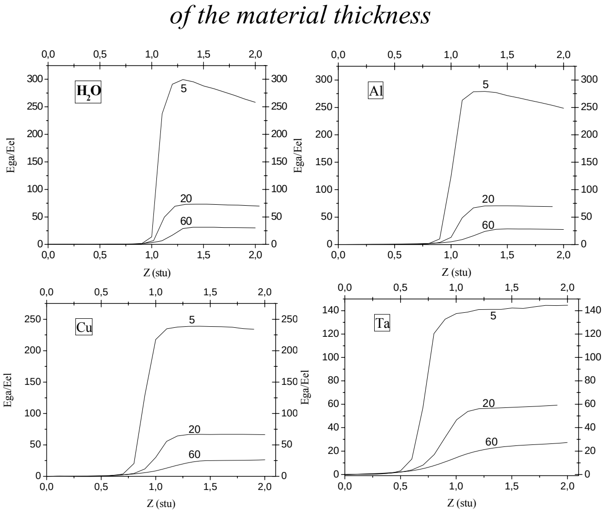

Fig.3. Secondary radiation factor versus material thickness

This provides the continuity of the base characteristics of radiation as functions of the stopping coordinate of the path.

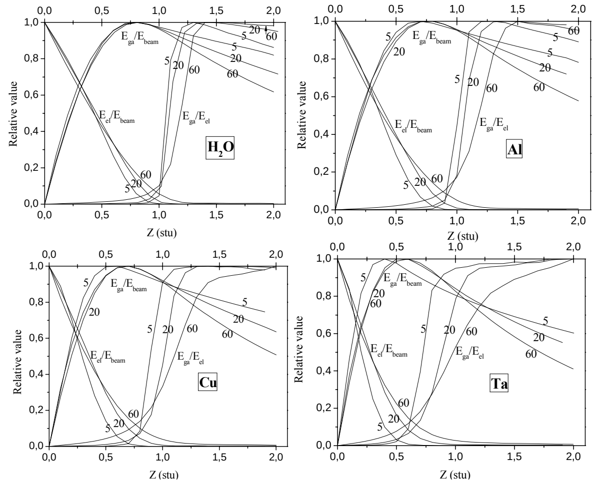

Fig. 4. Normalized coefficients of transmission, conversion and the secondary radiation factor as functions of material thickness

As an example, Fig.5 gives the calculation data on the coefficients of electron transmission/conversion and the factor of secondary radiation along the output devices of the NSC KIPT accelerator LU-10 operated in the mode of bremsstrahlung generation [6]. The data were obtained with the use of both RAM and LAM representations. The solid circles refer to the calculations of the base characteristics along the RAM-path of the accelerator, and the open circles refer to the LAM-path. The letters near the circles indicate the belonging of the abscissa of the calculation point to a definite output device of the path: e – scanner foil, c – converter, f – filter, o – irradiation object, v – monitor. Because of a small stopping thickness (0.0041 stu), the point referring to the scanner foil lies practically at the origin of the coordinates and appears only slightly in the plots.

The calculations confirm that in the LAM representation the base characteristics of the beam transformation path are the continuous functions of its stopping Z-coordinate, while the characteristics of the RAM description show natural jumps due to the finite transverse dimensions of its elements. The differences between the absolute values of RAM and LAM base characteristics concern only the ordinates. **The abscissas of the points remain the same**. This gives grounds for the use of the base characteristics of the LAM-path when choosing the optimum thickness of output device elements and the site of their location. Owing to their continuity, these characteristics can provide more definite evidence on the properties of radiation at different cross sections of the path.

5. OPTIMIZATION OF THE ACCELERATOR OUTPUT PATH

The path of the accelerator operating in the mode of bremsstrahlung generation comprises a converter and a filter as the basic devices, after which the irradiation object is placed. The task of output-device path optimization is thus reduced to optimization of the converter and the filter. Its purpose is to attain the maximum intensity of the photon flux on the surface of the irradiated object at a minimum content of the electron component in the radiation.

The converter. By definition, this device is intended to produce at its output the radiation with maximum electron-to-photon energy conversion. As a main photon-producing medium in it, the material having a high atomic number (tantalum, tungsten, gold, etc.) is generally used. In reality, apart from one or a few photon-producing plates, the converter unit also includes the casing with entrance/exit windows, and also, the cooling water gaps. The optimum design of the converter is the one, where the maximum conversion is attained on the last (along the beam path) surface of the photon-producing material.

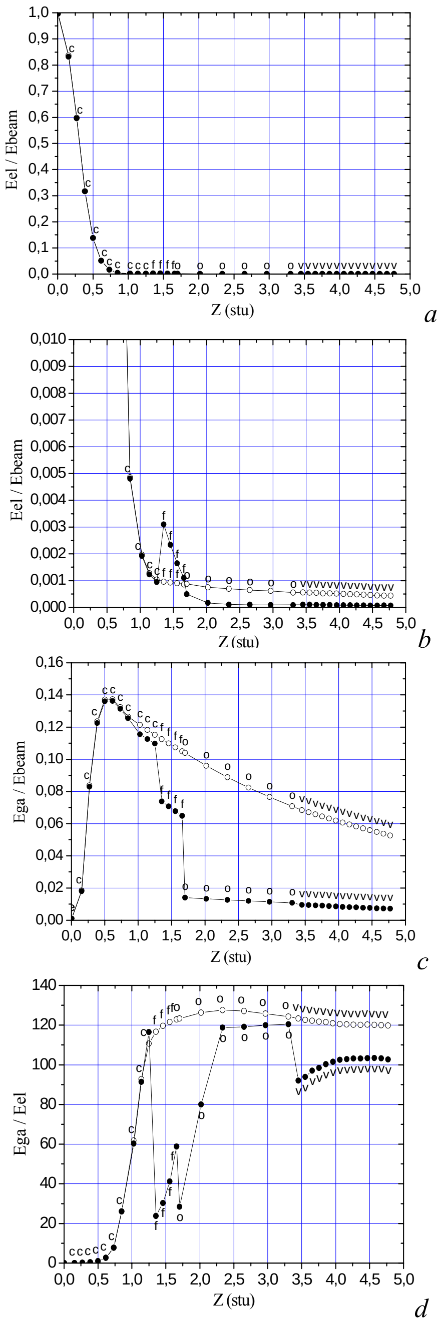

Fig.5. Electron transmission coefficient (a) and its enlarged fragment (b), energy conversion coefficient (c) and the secondary radiation factor (d) along the output-devices path. Solid circles refer to the RAM-path, open circles – LAM-path

The filter has to provide a full stop of beam electrons, exerting minimum influence on the photon flux obtained in the converter. In other words, the function of the filter is to provide the maximum photon-to-electron component energy ratio (secondary emission factor Ega/Eel). The material having a low atomic number (e.g., aluminum) is generally used as a filter.

Let $T_{\max}^{conv}$ is the abscissa of maximum electron-to-photon conversion (see Fig.5,c), while T^{factor} – the abscissa of cessation of the intensive growth of secondary radiation factor (see Fig.5,d).To determine the optimum stopping thicknesses of the converter, $t_{N\ conv}$, and the filter, $t_{N\ factor}$, we write the following optimization equations

$$\sum_{k=1}^{k=N_{conv}-1} t_k + t_{N_{conv}} = T_{\max}^{conv}\ , \tag{1}$$

$$T_{\max}^{conv} + \sum_{k=N_{conv}+1}^{k=N_{factor}-1} t_k + t_{N_{factor}} = T^{factor}. \tag{2}$$

In these equations, t_k is the total stopping thickness of the k-th medium (e.g., total thickness of all water layers).

The left sides of the equations are the sums of thicknesses of all the media passed through by the radiation, starting from the exit of beam electrons from the vacuum volume of the accelerator. In eq. (1), the summation up to the last (along the beam path) surface of the converter embraces N_{conv} media. In eq. (2) the summation up to the last surface of the filter embraces (N_{conv} +N_{factor}) media. The sought-for thicknesses of the photon-producing converter material, t_{Nconv}, and the filter material $t_{Nfactor}$ are presented as separate terms.

The general requirement for the path elements entering under the summation sign into eqs. (1) and (2) consists in minimization of their effect on the radiation. In other words, the presence of these path elements and their thicknesses are governed exclusively by the requirements on heat removal, strength, etc.

CONCLUSIONS

The behavior of normalized base characteristics of secondary radiation as functions of the output devices thickness with the material atomic numbers between 6 and 73 at primary electron energies ranging from 5 to 60 MeV has demonstrated that these characteristics:

1) depend only weakly on the atomic number of the substance and

2) have only a weak dependence on the electron energy.

These two important facts count in favor of the practical use of the concept of stopping length for the description of the state of e,X-radiation in substances.

The analysis of the behavior of normalized base characteristics of radiation also enables us to argue that in any substance, at any electron beam energies the e,X-radiation experiences three stages of development, and thus, we can indicate the boundaries of the corresponding regions. This is more pronounced with the secondary radiation factor, the behavior of which has a marked step-like character.

The primary radiation region. This is the zone of intense continuous stopping of primary electron beam. Here the maximum conversion coefficient is attained, which specifies the upper boundary of this region.

The transient radiation region. Here a complete stop of electron beam takes place. Therefore, the secondary radiation factor rises sharply here. The region extends from the abscissa of the maximum conversion coefficient to the point, at which a sharp rise in the secondary emission factor ceases.

The secondary radiation region. This is the region of steady-state dynamically equilibrium secondary radiation, where there are no primary electrons of the beam. The region is characterized by a high secondary radiation factor, i.e., by an essential excess of the photon component energy over the electron one. Since in the end the radiation is absorbed by the substance, then with an increasing depth each of the radiation components decreases so that their ratio is a slowly varying function of depth. The slowness of the factor is a consequence of photon domination and high photon penetrability.

The quantitative estimation of the transient radiation region is of crucial importance for optimization of the output devices of the accelerator operated in the mode of bremsstrahlung generation. The boundaries of the region are the initial data for the optimization equations and for determination of optimum thickness values of the converter photon-producing material and the filter. So the proposed here optimization of the path of the accelerator output devices includes three stages.

At the first stage, in the LAM approximation, the path is formed with model parameters of the converter, filter and other elements.

At the second stage, the mathematical model approach is used to calculate the absolute values of the conversion coefficient and the secondary radiation factor as stopping coordinate functions. Relying on the results obtained, the boundaries of the transition region are determined.

At the third stage, the optimization equations are solved and the parameters of the converter, filter, and other devices are determined.

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Статья поступила в редакцию 23.09.2011 г.

МЕТОД АНАЛИЗА И ОПТИМИЗАЦИИ ВЫХОДНЫХ УСТРОЙСТВ УСКОРИТЕЛЯ ЭЛЕКТРОНОВ В РЕЖИМЕ ГЕНЕРАЦИИ ТОРМОЗНОГО ИЗЛУЧЕНИЯ

В.И. Никифоров, В.Л. Уваров

Предложен метод анализа поля смешанного е,Х-излучения вдоль тракта выходных устройств ускорителя электронов. В основе метода лежит концепция тормозной длины тракта и представление реального тракта как слоистой многокомпонентной мишени с бесконечно большими поперечными размерами. Сформулирован набор базовых характеристик е,Х-излучения. Показано, что базовые характеристики излучения как функции тормозной длины можно привести к унифицированному виду в диапазоне энергии первичных электронов 5…60 МэВ при значении атомного номера материалов выходных устройств 6…73. В результате установлены три стадии формирования е,Х-излучения, отличающиеся соотношением интенсивности его компонент. Описана процедура оптимизации тракта для получения требуемых значений базовых характеристик.

МЕТОД АНАЛІЗУ ТА ОПТИМІЗАЦІЇ ВИХІДНИХ ПРИСТРОЇВ ПРИСКОРЮВАЧА ЕЛЕКТРОНІВ У РЕЖИМІ ГЕНЕРАЦІЇ ГАЛЬМІВНОГО ВИПРОМІНЮВАННЯ

В.І. Нікіфоров, В.Л. Уваров

Запропоновано метод аналізу поля мішаного е,Х-випромінювання уздовж тракту вихідних пристроїв прискорювача електронів. У основі методу лежить концепція гальмівної довжини тракту і представлення реального тракту як багатокомпонентної шаруватої мішені з нескінченно великими поперечними розмірами. Сформульовано набір базових характеристик е,Х-випромінювання. Показано, що опис вихідних пристроїв у термінах гальмівної довжини дозволяє привести базові характеристики випромінювання до уніфікованого вигляду в діапазоні енергії первинних електронів 5...60 МеВ при значенні атомного номера матеріалів вихідних пристроїв 6…73. В результаті встановлено три стадії формування е,Х-випромінювання, що розрізняються співвідношенням інтенсивності його компонент. Описана процедура оптимізації тракту для здобуття необхідних значень базових характеристик.