Formation of electron beams with given spatial distributions by the scanner

V.G. Rudychev, V.T. Lazurik, Y.V. Rudychev

In work [1], in order to ensure the minimum dose inhomogeneity under polyethylene layer irradiation, we proposed double-sided irradiation by electron beams at different angles, the main beam and additional beam. Figure 1 shows a possible scheme of using (X, Y) - scanner for irradiating the surface of the polyethylene layer by the main electrons beam incident perpendicular to the surface of the irradiated object and additional beam incident at angle $\Theta \neq 0$ relative to the normal of the object surface. In [1], the influence of the energy spread of electron beam on dose distributions for double-sided irradiation under the main and additional beams was studied. However, the influence of the energy and angular spreads of the initial electron beam on the fluxes distribution from the main and additional electron beams on the irradiated objects surface has not been studied.

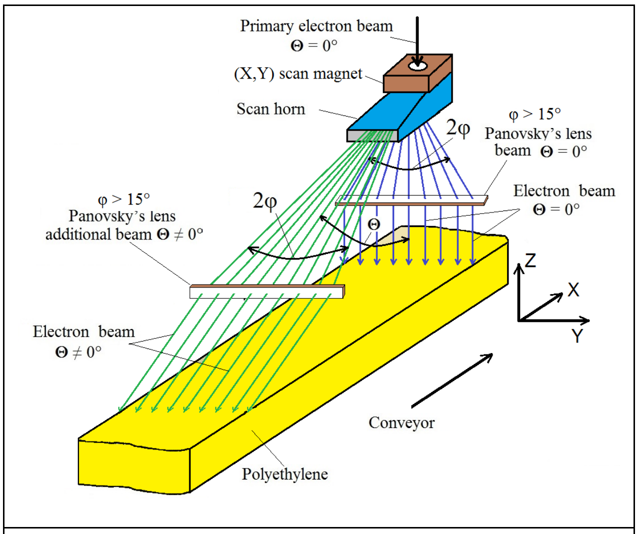

Fig.1. Possible scheme of using (X; Y) - scanner for irradiating the surface of the polyethylene layer by electron beam at different angles.

Let a scan magnet field area is rectangular parallelepiped in which a magnetic field is directed vertically, homogeneous and varying in time [2]. Width of a magnetic field area in initial beam direction is marked h and a distance between field area and an object is L (see fig.2). Let electrons of E_0 energy fly into a field area perpendicularly to intensity vector and to a field bound line and the intensity amplitude is H=H(t) .

As the electron velocity at few MeV energy is approximately c , than a field intensity does not change during the particles pass the field area. Therefore the electron arrived to magnetic field in time t moves along circumference that radius can be evaluated from the relation

$$\sqrt{E^2-(m_e c^2)^2} = R \cdot H(t) . \tag{1}$$

From a magnetic field area electron flies out at the angle α=arcsin(h/R) (see fig.2) to a drift space. A transverse electron displacement y(t) from its initial position is determined by

$$y(t) = R \cdot (1-\sqrt{1-h^2/R^2}) + \frac{h}{R} \cdot \frac{L}{\sqrt{1-h^2/R^2}} , \tag{2}$$

where $R=R(t)$ can be obtained from (1).

Introduce into consideration a dimensionless variable χ(t) = h/R(t) which is equal to sine of electron entrance angle, so that $-1< \chi < 1$. Let rewrite (2) in dimensionless values where u(t)=y(t)/h and η = l/h, so we can obtain

$$u(t) = \frac{1}{\chi(t)} \cdot (1 - \sqrt{1 - \chi^2(t)}) + \frac{\eta \cdot \chi(t)}{\sqrt{1 - \chi^2(t)}} . \tag{3}$$

A particle number corresponding to Δu length of irradiated object is proportional to Δt time and a particle density on the object can be determined up to a factor as

$$\rho(t) = \frac{\Delta t}{\Delta u} = \left(\frac{du}{dt}\right)^{-1} \tag{4}$$

Using (3) and (4) and setting a law for magnetic field change in time we can obtain a particle density distribution on the object.

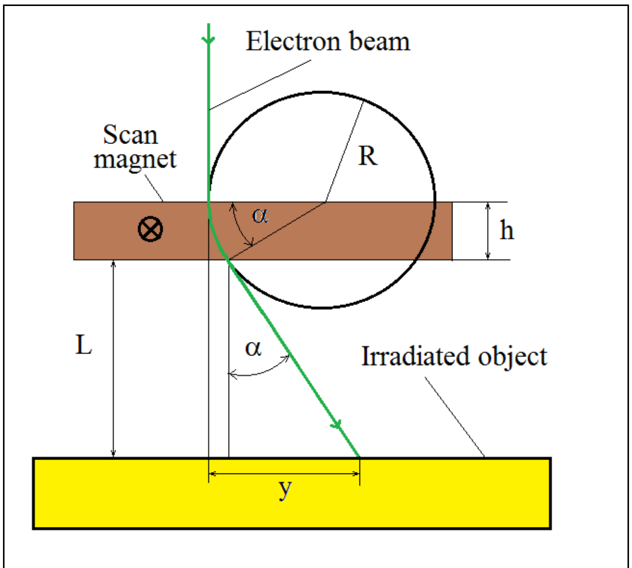

Fig.2. To inference of displacement equation into scanner field

Let solve an inverse problem and find the law for magnetic field change in time χ(t) needed for obtaining a given density distribution. We can rewrite an equation (4) in a form:

$$\frac{d\chi}{dt} = \frac{1}{\rho(t)} \cdot \left(\frac{du}{d\chi}\right)^{-1} \tag{5}$$

Taking into account (3) the differential equation for an arbitrary *ρ(t)* is nonlinear and has no solution in general case. As a rule, for the most applications the uniform beam distribution is needed, that is ρ(t) = const.

For ρ (t) = 1 and taking into account that | χ | < 1, after substituting (3) into (5) and expanding in a series in χ, we obtain an approximate value of χ (t) in the form

$$\chi(t) = A\cdot\tanh(B\cdot t) \tag{6}$$

In fig. 3a shows the dependences of the magnetic field varying in time for the following options: χ (t) - optimal (ρ (t) = 1), χ (t) = k t - sawtooth change, χ (t) - optimal + field jump at large angles of deflection. In fig. 3b shows varying in the particle density on the irradiated object with time for the following options: χ (t) - optimal, χ (t) = k t - sawtooth change, χ (t) - optimal + field jump. In fig. 4a, b shows the dependences of the magnetic field varying and the density of particles on the irradiated object, similar to Fig. 3, but instead of varying the magnetic field, the optimal + field jump, the optimal + stepwise varying in the magnetic field and the corresponding particle density are used.

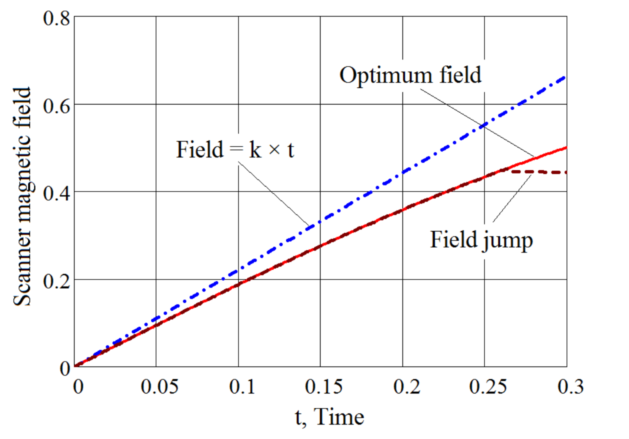

Fig.3a. the dependences of the magnetic field varying in time for the following options: χ (t) - optimal (ρ (t) = 1), χ (t) = k t - sawtooth change, χ (t) - optimal + field jump

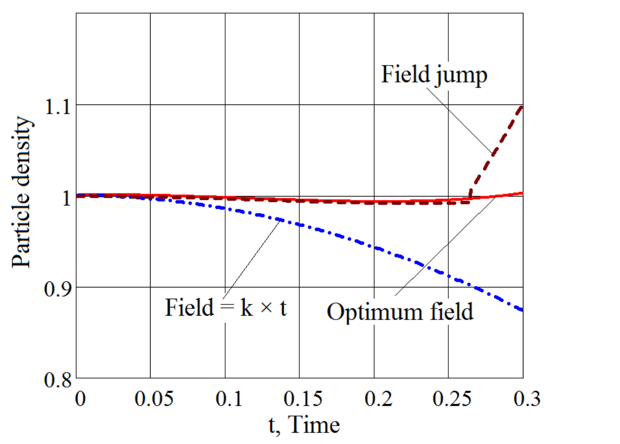

Fig. 3b varying in the particle density on the irradiated object with time for the following options: χ (t) - optimal, χ (t) = k t - sawtooth change, χ (t) - optimal + field jump.

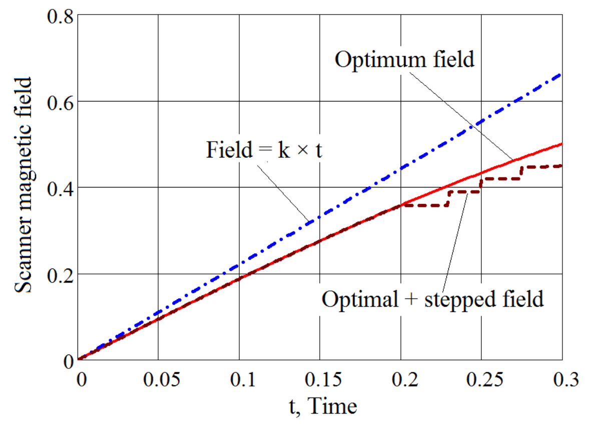

Fig.4a. the dependences of the magnetic field varying in time for the following options: χ (t) - optimal (ρ (t) = 1), χ (t) = k t - sawtooth change, χ (t) - optimal + stepped field.

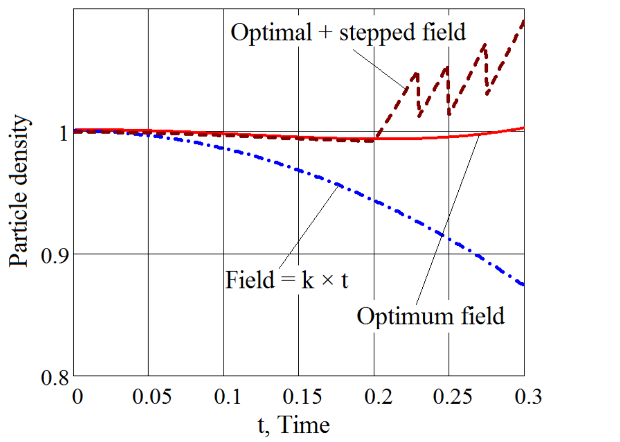

Fig. 4b varying in the particle density on the irradiated object with time for the following options: χ (t) - optimal, χ (t) = k t - sawtooth change, χ (t) - optimal + stepped field.

The influence of the energy spread in the electron beam on the particle density varying on the surface is analyzed. Assuming that the initial energy of the electrons is E_0, the deviation of the energy is δ, then the energy of the electrons is $E = E_0 \cdot (1+\delta)$. Then, taking into account relation (1), the relation for the magnetic field has a simple form:

$$\chi(t,\delta) = A\cdot\tanh(B\cdot t)\cdot(1-\delta) \qquad (7)$$

Using (7) and (5), the dependences on the particle density varying in time of the irradiated object were obtained, taking into account the deviations in energy δ, shown in Fig. 5.

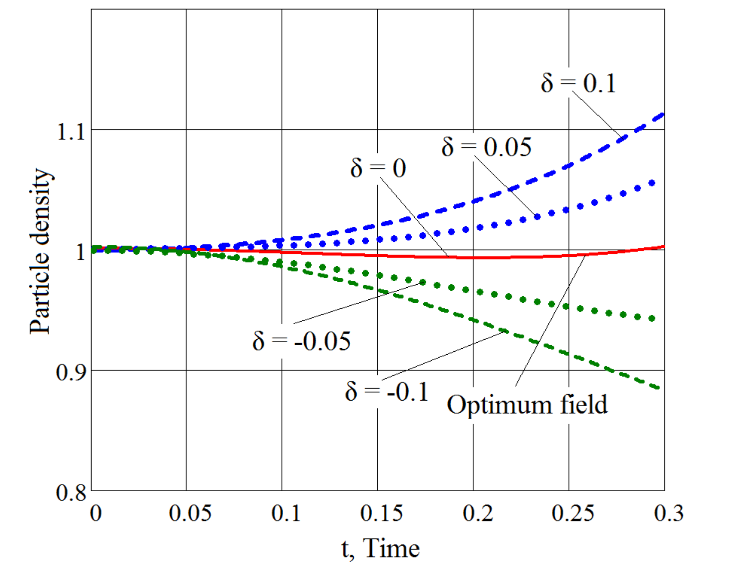

Fig.5. the dependences on the particle density varying in time of the irradiated object taking into account the deviations in energy δ.

The influence of the energy spread in the electron beam on the change in the electron beam incidence angles of the irradiated object is determined by the following relation:

$$\sin(\alpha_1) = \sin(\alpha) \cdot \sqrt{\frac{E^2 - (m_e c^2)^2}{E_1^2 - (m_e c^2)^2}}, \tag{8}$$

where, α is the incidence angle of the initial electron with energy E, α_1 is the incidence angle of electron with energy E_1. In [1], the calculations of dose distributions for electron energies in the range $0.9E_0 < E < 1.025E_0$ where $E_0 = 2, 6, 10$ MeV for angles Θ = 0° (main beam) and an additional beam Θ = 65° and ΔΘ = 1° (option scanner + Panovsky lenses). For angles α = 15°, 30°, 45° and 65 and energies $E_0 = 2, 6, 10$ MeV with energy range of $0.9E_0 < E < 1.025E_0$ using relation (8), the values of the angles α_1, given in Table 1, were obtained. Table 2 shows the relative deviations of the angle α_1 from α when the electron energy deviates from the nominal value.

Table 1. Values of angles α_1 for different deviations of the electron energy from the nominal values.

	2				6				10			
α, degree	15	30	45	65	15	30	45	65	15	30	45	65
ΔE_0	α_1, degree				α_1, degree				α_1, degree			
0.9	16.9	34.1	52.4		16.7	33.8	51.8		16.7	33.8	51.8	
0.925	16.3	32.9	50.3	80.3	16.3	32.7	49.9	78.6	16.3	32.7	49.9	78.5
0.95	15.9	31.9	48.3	73.3	15.8	31.8	48.1	72.6	15.8	31.8	48.1	72.6
0.975	15.4	30.9	46.6	68.6	15.4	30.9	46.5	68.4	15.4	30.9	46.5	68.4
1	15.0	30.0	45.0	65.0	15.0	30.0	45.0	65.0	15.0	30.0	45.0	65.0
1.025	14.6	29.1	43.5	62.0	14.6	29.2	43.6	62.1	14.6	29.2	43.6	62.1

Table2. Relative deviations of the angle α_1 from α when the electron energy deviates from the nominal value.

	2				6				10			
α	15	30	45	65	15	30	45	65	15	30	45	65
	$(\alpha_1-\alpha)\cdot 100/\alpha$, %				$(\alpha_1-\alpha)\cdot 100/\alpha$, %				$(\alpha_1-\alpha)\cdot 100/\alpha$, %			
0.9	12.4	13.6	16.4	>100	11.5	12.6	15.2	>100	11.5	12.5	15.1	>100
0.925	9.0	9.8	11.7	23.5	8.4	9.1	10.9	21.0	8.3	9.1	10.8	20.8
0.95	5.8	6.3	7.4	12.7	5.4	5.9	6.9	11.7	5.4	5.9	6.9	11.7
0.975	2.8	3.0	3.6	5.6	2.6	2.9	3.3	5.2	2.6	2.8	3.3	5.2
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.025	-2.7	-2.9	-3.3	-4.7	-2.5	-2.7	-3.1	-4.4	-2.5	-2.7	-3.1	-4.4

Conclusions

The types of time dependences of magnetic fields are determined, which provide the specified distributions of electron fluxes on the surfaces of irradiated objects and on converters of bremsstrahlung. The influence of the energy and angular spread in the electron beam on the change in the particle density on the surface is analyzed. The influence of these factors can be compensated for magnetic field varying. For (X, Y) - scanner that produces electron beams: the main (incident perpendicular to the object) and additional (incident at angles of 60°-75° relative to the normal of the object), a significant influence of the energy spread on the additional beam incidence angles is shown.

1. V.G. Rudychev, V.T. Lazurik, Y.V. Rudychev. Influence of the electron beams incidence angles on the depth-dose distribution of the irradiated object. Rad. Phys. Chem. 186, (2021), 109527, https://doi.org/10.1016/j.radphyschem.

2. S. Pismenesky, G. Popov, V. Rudychev. Reproduction of a given particle distribution by means of scanner, Rad. Phys. Chem. (2002) 63, Issue 3-6, 601-604