Radiation Field Forming for Industrial Electron Accelerators Using Rare-Earth Magnetic Materials

A N Ermakov, V V Khankin, N V Shvedunov, V I Shvedunov and D S Yurov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 1(2), Leninskie gory, Moscow 119234, Russian Federation
Laboratory of Electron Accelerators MSU Ltd, 1/77, Leninskie gory, Moscow 119992, Russian Federation
E-mail: d_yurov88@mail.ru

Abstract. The article describes the radiation field forming system for industrial electron accelerators, which would have uniform distribution of linear charge density at the surface of an item being irradiated perpendicular to the direction of its motion. Its main element is nonlinear quadrupole lens made with the use of rare-earth magnetic materials. The proposed system has a number of advantages over traditional beam scanning systems that use electromagnets, including easier product irradiation planning, lower instantaneous local dose rate, smaller size, lower cost. Provided are the calculation results for a 10 MeV industrial electron accelerator, as well as measurement results for current distribution in the prototype build based on calculations.

1. Introduction
When treating materials and products with a beam of accelerated electrons at the conveyor lines, to ensure uniform distribution of the transmitted dose, electromagnets are traditionally used, which scan the beam in the direction perpendicular to the conveyor line. For pulsed linear accelerators with pulse frequency of tens to hundreds hertz and scan rate of under ten to tens hertz such an approach has a number of deficiencies. In particular, parameters such as electron beam spot size at the item being irradiated, scan width, pulse frequency, scan rate, conveyor speed, and pulse current become interdependent, which complicates irradiation planning to ensure given dose and its uniform distribution throughout the output volume. Besides, both for pulsed and continuous beams instant dose rate transmitted locally to the item being irradiated is much higher than mean dose rate during the scanning period. In some cases it requires decreasing the beam current and consequently increasing the treatment time.

The purpose of this work is to develop a nonlinear magneto-optical system on the basis of rare-earth permanent magnets, which would ensure uniform dose distribution across the entire width of the conveyor line (along the $x$ axis), to correct the above deficiencies. At that, for irradiated items moving along the $\xi$ axis, the requirement for dose uniformity is as follows:

$$Q(x) = \int q(x, \xi) \, d\xi = \text{const},$$

where $Q(x)$ is a linear charge density, $q(x, \xi)$ is a surface charge density.
2. Principle of Radiation Field Forming

With the exception of special cases, charge distribution across beam cross-section at the accelerator output is close to being Gaussian; therefore a linear optical system fails to ensure uniform charge density at the object. The task of forming uniform charge distribution of an accelerated beam in rectangular area was addressed in publications [1-7]. The approach in the above publications is based on using nonlinear optical systems with octupole lenses. Such systems are quite versatile, and their parameters can vary widely, however, they have significant length, which is not acceptable for industrial accelerators.

We propose a new principle of forming radiation field with constant linear charge density at the object based on using nonlinear quadrupole lens, which defocuses the beam in the scanning direction with focal length increasing as distance from the axis increases, and focuses the beam in the perpendicular direction. The principle of forming uniform linear beam charge distribution out of initially non-uniform distribution is illustrated in Figure 1.

![Figure 1. Principle of forming uniform radiation field using nonlinear lens.](image)

Let's assume that a parallel beam with some kind of particles distribution along the transverse coordinate falls on a thin nonlinear diverging lens. Figure 1 shows part of the beam that lies in the upper half-plane and contains \( N/2 \) particles. Particles distribution is presented as a bar chart with a step size \( h \), the number of particles at step \( i \) is \( n_i \), \( i = 1, 2, \ldots K/2 \), at that \( N/2 = h \sum_{i=1}^{K/2} n_i \). At the exit window of the scan horn we need to get uniform distribution of particles with density of \( n_{\text{out}} = N/S \), where \( S \) is the scan width. The condition for ensuring uniform distribution of particles is as follows: \( hn_i = n_{\text{out}} l_i \), therefore \( l_i = hn_i/n_{\text{out}} \). If the angle of particles to the lens axis at step \( i \) of the bar chart is \( x_i' \), the formula for optical power of the lens portion, which would ensure required particles distribution, is:

\[
P_i = \frac{\sum_{m=1}^{K/2} n_m}{n_{\text{out}}} l_i - \frac{1}{L} + \frac{\tan x_i'}{ih},
\]

where \( L \) is the distance between the lens and the object being irradiated.

The optical power of quadrupole lens is determined as:

\[
P_q = eGd \frac{\xi}{p},
\]

where \( e \) is the electron charge, \( G \) is the lens gradient, \( d \) is its effective length, \( c \) is the speed of light, \( p \) is the beam particles momentum. Using formulas (2) and (3) one can determine dependence of the \( y \)–component of magnetic induction in the median plane along the \( x \)-axis that is required to ensure uniform distribution of particles at the exit window:
Lens field nonlinearity should be formed within the beam. As a rule, the beam diameter at the linac output does not exceed several millimeters. Development of the required nonlinearity at such a small distance results in unacceptably small size of the lens aperture or high magnetic induction. Therefore, in order to increase the beam size in the scan plane at the nonlinear lens input, we use an optical arrangement shown in Figure 2, which includes an additional conventional quadrupole lens defocusing the beam in the scan plane.

\[
B_{y i} = -\frac{p}{edc} \tan x'_i + \frac{ph}{decl} \left( \frac{1}{n_{out}} \sum_{m=1}^{i} n_m - i \right)
\]  

(4)

Figure 2. Optical arrangement for radiation field forming system. \(Q_L\) is a linear and \(Q_{NL}\) is a nonlinear quadrupole lens.

To ensure necessary field nonlinearity we used magnet in which the field is formed by rare-earth magnetic material. One of the possible magnet configurations is shown in Figure 3. Magnetic field is generated by two pairs of rectangular blocks made of rare-earth magnetic material magnetized as shown in the Figure. Magnetic screen is placed at some distance from the blocks. The required field distribution is achieved through selection of residual magnetization of the blocks, their parameters \((a, b, c, d)\) and distances between the blocks \((h\) and \(H)\).

Figure 3. Option with nonlinear quadrupole lens. 1, 2 – Blocks made of rare-earth magnetic material, 3 – magnetic screen.

3. Numerical Simulation of the Radiation Field Forming System
Numerical simulation was done in 2D approximation using PANDIRA [8] code for calculating magnetic field and RTMTRACE [9] for calculating beam dynamics. The simulation was performed
for 10 MeV electrons, at that calculations were done for both Gaussian distribution of particles in the beam cross-section, and for distribution obtained using PARMELA [10] code for the accelerator described in publication [11].

Preliminary estimates were performed for Gaussian beam with 2 mm root mean square radius and 1.1 millirad root mean square divergence, which is close to an actual beam at the accelerator output.

The power of quadrupole lens $Q_L$ (Figure 2) was selected in order to get a crossover in the $y$-plane at the nonlinear lens input $Q_{NL}$, which minimizes its impact on the beam in the plane.

Magnetic field distribution in median plane along the $x$-axis was calculated using formula (4) for a 100 mm long nonlinear lens and Gaussian beam at the accelerator output. Magnets configuration ensuring such distribution was found using PANDIRA. Then magnetic field and corresponding magnets configuration were modified to ensure necessary particle distribution at the exit window of the scan horn with actual beam at the accelerator output calculated using PARMELA. The resulting distribution of particles at the system output is shown in Figure 4(b).

![Figure 4](image)

**Figure 4.** a) Phase portrait of the beam at the accelerator output with 10 MeV calculated using PARMELA, b) beam portrait at the exit window of the scan horn.

### 4. Experimental Study of Radiation Field Forming System

The nonlinear lens built consistent with calculated dimensions was placed in front of a 10 MeV accelerator horn. Figure 5(a) compares this lens with a regular scanning magnet; and Figure 5(b) compares the field measured in the median plane in the central cross-section of the magnet with calculated field.
Current distribution at the scan horn exit window was measured using relocatable 20 mm diameter copper cylinder. Uniformity of distribution was adjusted by changing the focal length of quadrupole lens placed in front of a nonlinear lens. Figure 6 shows measured current distribution after tune-up of the optical system. Scan width (about 50 cm) was determined by the size of the scan horn entrance aperture. Non-uniformity of current distribution was ±5%.

Figure 6. Measured copper cylinder current as a function of the coordinate along scan horn exit window.

5. Conclusions
As a result of this work, we have created a new type of radiation field forming system for industrial linear accelerators, which has a number of advantages over conventional beam scanning system that uses dipole magnet with variable field. The main advantages of such system are significantly easier product irradiation planning, and lower instant local dose rate. Besides, this system is much smaller, simpler and cheaper to build, and it does not require a power source.

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