COMPACT RARE-EARTH PERMANENT MAGNET MATERIAL SYSTEM FOR INDUSTRIAL ELECTRON ACCELERATORS IRRADIATION FIELD FORMATION

D. S. Yurov, A. N. Ermakov, V. V. Khankin, N. V. Shvedunov, V. I. Shvedunov, Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
also at Laboratory of Electron Accelerators MSU Ltd., Moscow, Russia

Abstract

A compact system for industrial electron accelerators irradiation field formation is described. This system permits to get uniform distribution of electron beam current along the direction perpendicular to product movement with the width 50 – 100 cm. Its main element is a non-linear quadrupole lens, based on rare-earth permanent magnet material. This system can be used instead of an electromagnet of the conventional beam scanning systems, making much more comfortable conditions for products irradiation. Operation principles, results of calculations and test results of the system for CW 1 MeV and pulse 10 MeV electron linear accelerators are described.

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.

To correct the above deficiencies we developed a non-linear 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):

$$Q(x) = \int q(x, \xi)\, d\xi = const, \qquad (1)$$

where ξ is the axis irradiated items moving along, $Q(x)$ is a linear charge density, $q(x, \xi)$ is a surface charge density.

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 problem of forming uniform charge distribution of an accelerated beam in rectangular area was solved for proton beams using optical systems, based on quadrupole and octupole lenses [1-7]. Such systems have significant length of about 10 m, which is not acceptable for industrial accelerators.

Such approach can be noticeably modified and simplified for industrial electron accelerators. Usually it is enough to ensure uniform dose distribution only in direction perpendicular to the irradiated items movement. It permits to obtain formulas for calculating the desired nonlinear magnetic field.

The main element of our system is a 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 arbitrary non-uniform distribution is illustrated in Fig. 1.

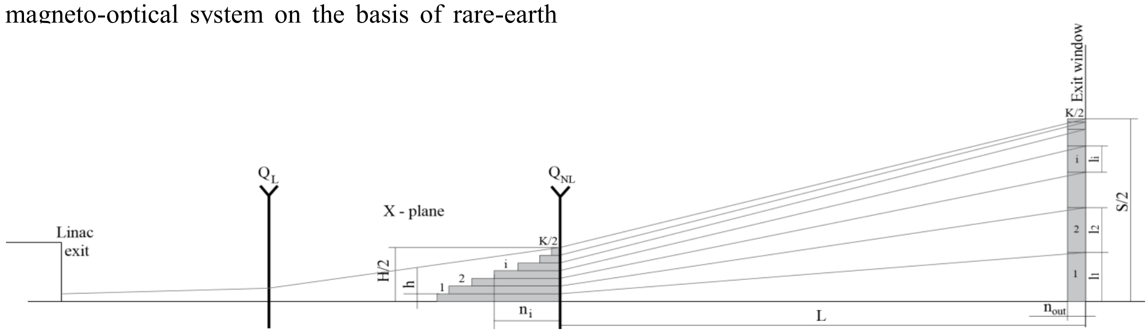

Figure 1: Principle of forming uniform radiation field using nonlinear lens. Q_L is a linear and Q_{NL} is a nonlinear quadrupole lens.

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Let's assume that a beam with some kind of particles distribution along the transverse coordinate falls on a thin nonlinear defocusing 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 histogram with a step size h, the density of particles at step i is n_i, $i = 1,2,\dots K/2$. At the exit window of the scan horn we need to get uniform distribution of particles with density of $n_{out} = N/S$, where S is the scan width. The condition for ensuring uniform distribution of particles is as follows: $hn_i = n_{out}l_i$. 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:

$$P_i = \frac{\sum_{m=1}^{i} n_m}{iLn_{out}} - \frac{1}{L} + \frac{\tan x_i'}{ih} = eGd\frac{c}{p}, \qquad (2)$$

where L is the distance between the lens and the object being irradiated, 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.

The 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 is as follows:

$$B_{yi} = -\frac{p}{edc}\tan x_i' + \frac{ph}{decL}\left(\frac{1}{n_{out}}\sum_{m=1}^{i} n_m - i\right) \qquad (3)$$

Equations (2), (3) are derived for a thin lens. Finite length of a nonlinear lens can significantly influence the result.

In order to increase the beam size in the scan plane at the nonlinear lens input and decrease the requirements for magnetic field gradient of a nonlinear lens, we use additional conventional quadrupole lens, defocusing the beam in the scan plane (Q_L in Fig. 1).

To ensure necessary field nonlinearity we used magnet in which the field is formed by two pairs of rectangular blocks made of rare-earth magnetic material magnetized as shown in the Fig. 2. Magnetic screen is placed at some distance from the blocks.

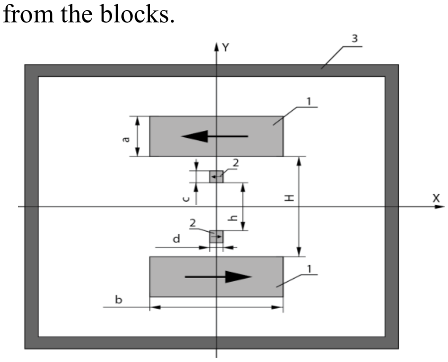


Figure 2: Possible design of nonlinear quadrupole lens. 1, 2 – Blocks made of rare-earth magnetic material, 3 – magnetic screen.

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).

NUMERICAL SIMULATIONS

Numerical simulations were done in 2D approximation using PANDIRA [8] code for calculating magnetic field and RTMTRACE [9] for calculating beam dynamics. The simulations were performed for 10 MeV electrons obtained using PARMELA [10] code for the accelerator described in [11] and for 1 MeV continuous-wave accelerator beam [12].

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

Magnetic field distributions in median plane along the x-axis were calculated using Eq. (3) for thin nonlinear lens and Gaussian beams at the accelerators outputs. Magnets configurations ensuring such distributions were found using PANDIRA. Then magnetic fields and corresponding magnets configurations were modified to ensure necessary particle distributions at the exit windows of the scan horns with actual beams at the accelerators outputs calculated using PARMELA, taking into account finite lengths of the nonlinear lens.

The resulting distribution of particles at the 10 MeV accelerator scan horn exit window is shown in Fig. 3.

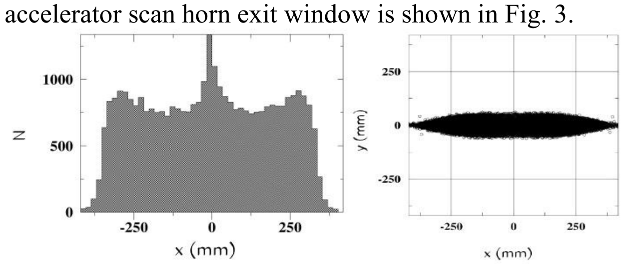


Figure 3: Beam portrait at the scan horn exit window.

Similar results were obtained for 1 MeV machine. Additional calculations simulated electron beam scattering at the exit window titanium foil were made for 1 MeV accelerator using GEANT4 [13].

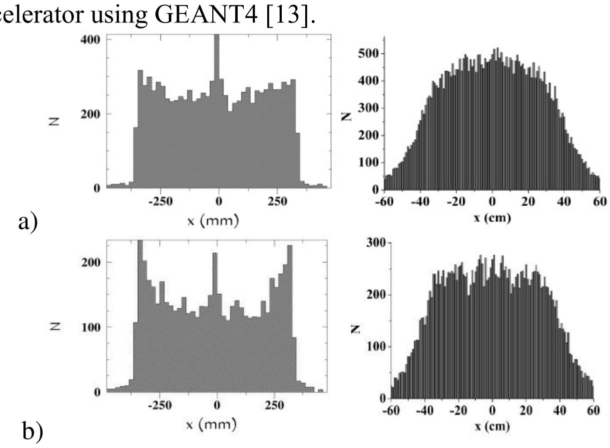


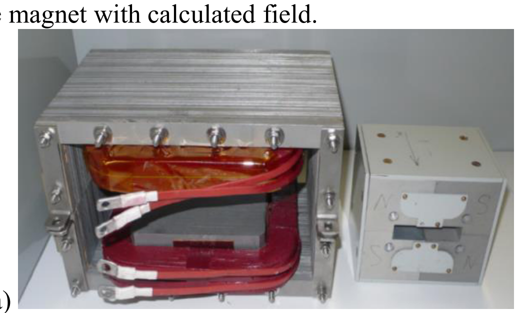
Figure 4: Particle distributions before output foil (left pictures) and at 10 cm after the foil (right pictures) for different nonlinear lens magnetic fields: a) with close to uniform particle density before the foil, b) with increased particle density near the edges.

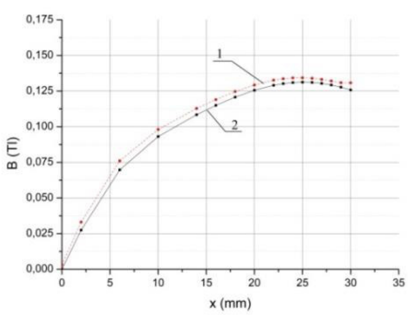
Figure 4 presents calculation results for various nonlinear lens magnetic fields before the foil and at distance 10 cm after the foil. Significant electrons scattering at the foil and 10 cm of air leads to reduced particle density at the edges after the foil. For uniform charge density it is essential to form distribution with increased density on the edges before the foil (Fig. 4b).

EXPERIMENTAL STUDY OF RADIATION FIELD FORMING SYSTEM

The nonlinear for 10 MeV accelerator lens built consistent with calculated dimensions was placed in front of the accelerator horn. Figure 5(a) compares this lens with a regular scanning magnet; and Fig. 5(b) compares the field measured in the median plane in the central cross-section of the magnet with calculated field.

a)





b)

Figure 5: a) Comparison of the magnet (on the right) with a scanning magnet (on the left), b) comparison of calculated (Curve 2) and measured (Curve 1) field distribution.

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 optical power of linear quadrupole lens placed in front of a nonlinear lens. Figure 6 shows measured current distribution after tuning of the optical system (Curve 2) compared with current distribution for electromagnet (Curve 1) shown in Fig. 5a.

Scan width (about 50 cm) was determined by the size of the scan horn entrance aperture. Non-uniformity of current distribution with designed radiation field forming system was ±6%.

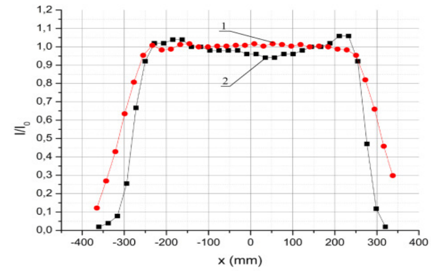


Figure 6: Measured copper cylinder current as a function of the coordinate along scan horn exit window for designed optical system (Curve 2) and for conventional electromagnet (Curve 1).

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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