DESIGN OF A LINEAR ACCELERATOR WITH A MAGNETIC MIRROR ON THE BEAM ENERGY OF 45 MeV

A.N. Ermakov, B.S. Ishkhanov, A.N. Kamanin, V.V. Khankin, L.Yu. Ovchinnikova#,
N.I. Pakhomov, I.V. Shvedunov, N.V. Shvedunov, V.I. Shvedunov, I.Yu. Vladimirov, D.S. Yurov,
Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninskie Gory 1, 119992 Moscow, Russia
A.I. Karev, V.G. Raevsky, P.N. Lebedev Physical Institute, RAS, Leninsky prospect 53, 117924 Moscow, Russia

Abstract

The results of calculation and optimization of pulsed linear accelerator with magnetic mirror on the beam energy, adjustable in the range of 20 - 45 MeV, designed for explosives detection and other applications are presented. The accelerator consists of an electron gun with an off-axis placed cathode with a beam hole on axis; of about 1.6 m long section of standing wave bi-periodic accelerating structure, operating at 2856 MHz, which is optimized to achieve the capture coefficient of more than 50% and of the energy spectrum width of about 2%; of a movable dispersion free magnetic mirror made with rare earth permanent magnet material. Accelerator provides acceleration of the beam with a pulse current of 100 mA to an energy of 45 MeV with RF power consumption less than 10 MW.

INTRODUCTION

Electron accelerators with energies of the accelerated beam in the range of 20-30 MeV to 100 MeV can be used for medical isotope production, activation analysis, radiation therapy, as the injector for the storage rings, used for basic research in nuclear physics.

One of the promising and new applications of electron accelerators in this energy range is the detection of explosives by photonuclear reactions [1-3]. For the practical implementation of this technique a compact, easy to operate accelerator generating pulses of accelerated beam with an energy of about 45 - 50 MeV, with a charge per pulse of about 1 μC with a repetition rate of 50 -100 Hz is required. Sufficiently high charge per pulse is necessary to provide high sensitivity of the detection method.

Previously, as such an accelerator - pulsed race-track microtrons (RTMs) with energy of 70 MeV [4] and 55 MeV [5] were considered. Advantages of the RTM as compared with linac for the energy range above 20-30 MeV are compactness and low cost. However, operating experience with these RTMs showed that practically attainable accelerated pulse current is limited to about 10 mA, besides there is serious problem associated with the high level of beam losses during acceleration, resulting in high level of induced activity in the elements of the accelerator.

lub.ovch@yandex.ru

As a compromise, in this paper we consider a single-section standing wave linac with a magnetic mirror. A linac with magnetic mirror – linotron - was proposed in [6]. The practical implementation of the accelerator based on this principle with maximum beam energy of 25 MeV – reflexotron - was described in [7].

Here we present a design of the electron linear accelerator with a magnetic mirror for maximum beam energy of 45 MeV.

ACCELERATOR SCHEME

A schematic view of the accelerator is shown in Fig. 1, its main parameters are listed in Table 1. Electron beam from an electron gun (1) is injected into an accelerating structure (2) and is accelerated up to energy 22.5 MeV. Than the beam is reflected back by a magnetic mirror (6) and accelerated once more to the final energy 45 MeV. To provide beam passage through the accelerating structure with minimal losses steering coils (3) and a quadrupole lens (5) are used. An accelerating field in the accelerating structure of a required level is produced by an RF system (8), which is fed by a high voltage modulator (9). A cooling system (10) is used to remove heat from the RF system, the modulator, the accelerating structure, the magnetic mirror. The steering coils and quadrupole lens are fed by current sources (11). Parts of accelerator are also: a gun power supply (7), vacuum system (12), mirror position control (13). Beam current at different points is measured by beam current monitors (4). Accelerator operation is controlled by a control system (14).

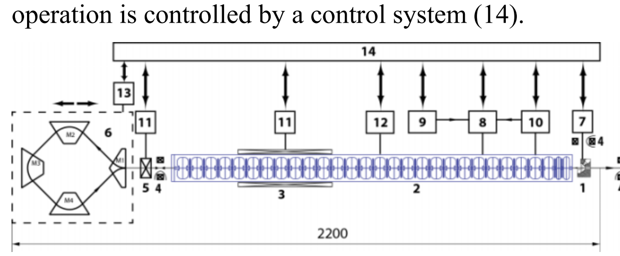


Figure 1: Accelerator scheme.

Table 1: Accelerator parameters

Parameter	Value
Max. beam energy	45 MeV
Max. pulse current	100 mA
Pulse duration	10 μs
Max. repetition rate	100 Hz
Operating frequency	2856 MHz
Max. pulsed RF power	10 MW

ISBN 978-3-95450-170-0

The main features of the accelerator are the next. Since the accelerated beam with energy of 45 MeV comes from the accelerating structure in the direction of the electron gun, for its unhindered passage we use gun with an off-axis placed cathode and the transit hole on the axis. The gun is similar to that described in [8], but is optimized to produce a beam with a current of ~200 mA at a voltage of 25 kV.

To accelerate the beam we use bi-periodic on-axis coupled standing wave accelerating structure operating at 2856 MHz with the beam hole diameter of 10 mm. The parameters of the first three accelerating cells have been optimized to obtain high values of the capture coefficient, a narrow energy spectrum and beam focusing with a crossover, located near the exit of the structure.

To reduce the cost and to simplify the accelerator configuration and operation it is essential to have a linear accelerator, consisting of only one section and powered by a single klystron. RF power required to produce the accelerating field and to accelerate the beam should not exceed ~ 10 MW in order to be able to use commercially available RF equipment, including the klystron, circulator, vacuum RF window and other waveguide elements. In this context, the choice of the number of accelerating cells of the regular part of the structure required to achieve 22.5 MeV, is determined by compromise between the length of the accelerating structure, the complexity of its manufacturing and tuning on the one hand, and amount of the RF power on the other.

As a result of analysis the number of the accelerating cells of a regular part was chosen to be 26, so the total number of accelerating cells is 29, the electrical length of the accelerating structure is 1460 mm, and the pulsed RF power required to create an accelerating field is 4.6 MW. Pulsed power of the accelerated beam is 4.5 MW. So, taking into account the loss of RF power in the waveguide and beam current loss, the output RF power of the klystron should be about 10 MW.

Narrow energy spectrum and the small size of the beam after the first passage through accelerating structure reduce requirements to the parameters of the magnetic mirror from viewpoint of aberrations and thereby simplify the magnets design. We have selected a magnetic mirror consisting of four dipoles. Bending radii, the distance between the magnets and the pole face rotation angles have been optimized in the first order to reach zero-dispersion and negative unite transfer matrix in horizontal and vertical planes. The magnets are designed using a rare earth permanent magnet material as the source of field. Use of permanent magnets with fixed and stable field will simplify tuning of the accelerator.

The parameters of the quadrupole lens installed between the accelerating structure and the magnetic mirror, through which the beam passes in the forward and backward direction, are optimized so as to focus the beam in vertical and horizontal planes.

BEAM DYNAMICS

Beam dynamics simulation was performed using the PARMELA [9] with electromagnetic fields, calculated by SUPERFISH [10], and the parameters of the mirror magnets, found with TRANSPORT [11].

Optimal distribution of the electric field on the axis of the accelerating structure is shown in Fig. 2. Amplitudes of the field and the length of the first three accelerating cells are selected from the conditions of beam bunching, focusing and pre-acceleration.

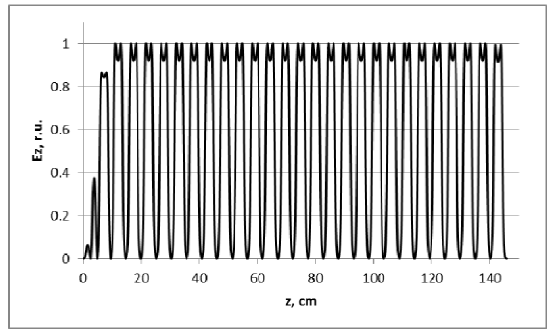


Figure 2: Optimal electric field distribution on accelerating structure axis.

Parameters of the magnetic mirror are shown in Table 2 in accordance with the notation of Fig. 3.

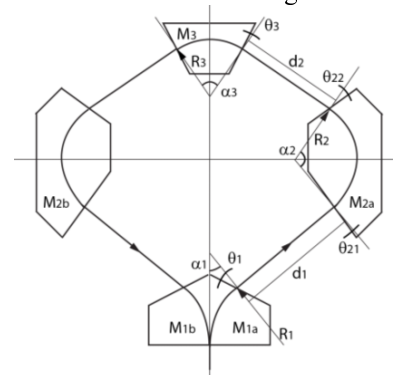


Figure 3: Notations for magnetic mirror.

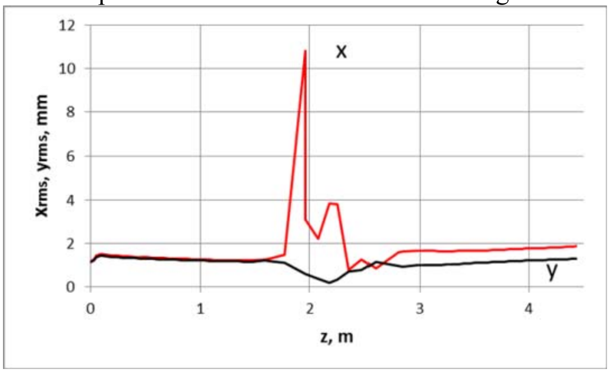
Table 2: Mirror magnets parameters

Parameter	M_{1a}	M_{1b}	M_{2a}	M_{2b}	M_3
R, mm	76.6	76.6	63.6	63.6	58.7
Magnetic field B, T	1.0	1.0	1.2	1.2	1.3
α, deg.	50.3	50.3	105.9	105.9	68.9
Entrance θ, deg.	0	23.0	-3.5	19.5	6.9
Exit θ, deg.	23.0	0	19.5	-3.54	6.9

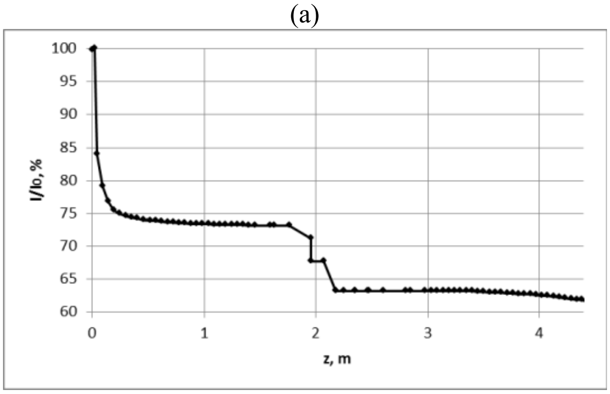
The behavior of the rms beam envelope along accelerator is shown in Fig. 4 (a). Fig. 4 (b) shows the relative loss of beam current during acceleration. The number of particles reaching the structure output after the first acceleration is about 74%. The magnetic mirror is positioned in the range 1570 - 2250 mm, by passing mirror additionally ~10% of low-energy particles are lost. Accelerator output reaches ~62% of the particles. The rms beam size in horizontal and vertical planes at output are respectively 1.9 mm and 1.2 mm.

ISBN 978-3-95450-170-0

Calculated spectra of the beam after first acceleration and at output of the accelerator are shown in Fig. 5.

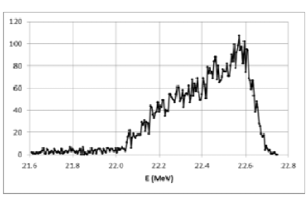


(a)

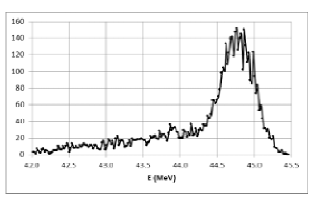


(b)

Figure 4: (a) Rms beam envelope in x- and y-planes and (b) beam current decrease along the accelerator.



(a)



(b)

Figure 5: Beam energy spectra (a) after magnetic mirror and (b) at accelerator output.

RF SYSTEM

Stable values of beam energy and current of the accelerator with the magnetic mirror can be achieved, first of all, due to the high stability of the accelerating field. Instability of the field can be caused by fluctuations in the output power of the klystron, and the change in the resonance frequency of the accelerating structure due to thermal processes, which include resonance frequency shift produced by structure heating by RF power and coolant temperature variation. A simplified block diagram of an RF power system of a linear accelerator, which provides stable accelerating field, is shown in Fig. 6.

The RF system includes a highly stable fast frequency adjustment synthesizer (1), ferrite isolators (2), p-i-n attenuator (3), a pulsed RF amplifier (4) and a klystron (5), the modulator (6), directional couplers (7, 14), a circulator (8) with a matched loads (9), the accelerating structure (10) with an antenna (11), a phase shifter (12), a phase detector (13), an RF detector (15), the frequency and amplitude controller (16).

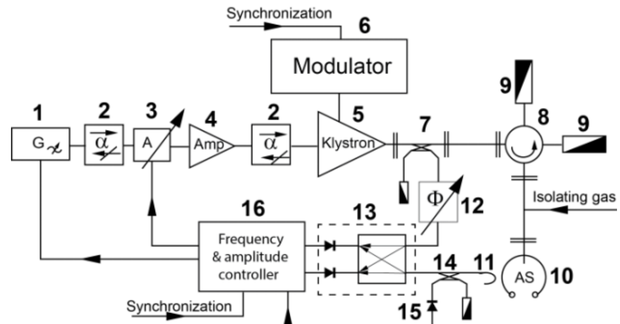


Figure 6: Simplified scheme of RF system.

The stability of the output power of the klystron from pulse to pulse is provided by a high voltage pulse amplitude stability, which for solid state modulator is ~0.1% [12]. Stabilization of the accelerating field is provided by two feedback loops: a fast loop for synthesizer frequency adjustment and a slow loop for adjustment of output klystron power. Adjusting the synthesizer frequency is performed by the controller of the resonance frequency and amplitude for each pulse of the accelerator basing on the signal of the phase detector, the sign and the amplitude of which is determined by the deviation of the frequency of synthesizer from the accelerating structure frequency. Slow adjustment of the accelerating field amplitude is achieved by means of p-i-n attenuator, installed at the input of pulsed RF amplifier.

CONCLUSION

We have designed compact 45 MeV linac with the magnetic mirror capable to produce 100 mA pulsed beam current with a single 10 MW klystron.

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ISBN 978-3-95450-170-0