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Compact Accelerating System for a Multichannel Electron Linear Accelerator.

**Aleksandr Evgen'evich Novozhilov*, Aleksandr Nikolaevich Filatov, and
Vladimir Kuz'mich Shilov.**

National Research Nuclear University "MEPhI" Kashirskoye shosse 31, Moscow, 115409, Russian Federation.

ABSTRACT

This article deals with the issue of increasing the intensity of electrons flow in a small accelerator for an efficient use in industry, medicine and many other fields of science and technology, where installation dimensions are of high importance. Since the increase in the intensity of the accelerated particle beams occurring only due to the improvement of acceleration and focusing techniques has a certain limit, one of the methods is suggested to improve the technical and economic characteristics of the accelerator due to transition from using a conventional accelerator system to a multi-channel system.

Keywords: electron linear accelerator, multichannel accelerator, accelerating cell, communication cell, phase shifter, attenuator, waveguide coupler, oscillation mode, wavelength.

**Corresponding author*

INTRODUCTION

Electron linear accelerators (ELA) are now widely used especially in medicine [1], in industry [2], and for other radiation purposes (food preservation, sterilization of toxic wastes, etc.). The main areas of the ELA technological application can be divided into the following aspects: processing of materials, synthesis and polymerization of composite materials, tomography and introscopy of engineering products [3].

Interest in using ELA for engineering purposes can be explained not only by their high efficiency, but also by the ease of inputting and outputting accelerated particles, which makes it possible to obtain a strictly directed beams of fast electrons and bremsstrahlung radiation; by the ease of adjusting dose rate and energy; by a high rate of bremsstrahlung dose even at relatively low energies of accelerated electrons.

One of the main requirements to advanced electronic accelerators is the deep restructuring of beam parameters. Therefore, the engineering solutions that provide a wide range of changes in the accelerator's output parameters are of special value. One of the currently growing areas of non-destructive testing equipment comprises systems for radiation inspection of containers configured to identify atomic number of the objects substance contained within the container [4] specially designed for customs and security agencies. The charged particle accelerators are usually used to solve this problem.

In recent decades, scientists in the field of accelerating technology pay much attention to the charged particle linear accelerators at low energies, mostly up to 10-20 MeV, wherein accelerator has become an indispensable tool for applied research in the fields of medicine, biotechnology, microelectronics and power engineering.

When creating a charged particle linear resonance accelerator, one must consider a number of factors that are common to almost all accelerators regardless of the mode, kind of accelerated particles and type of accelerating structure, as well as differences in the output energy and currents of accelerated beams.

In addition to the beam characteristics, which are determined by the accelerator application, a number of technical issues has to be solved: the choice of an operating wavelength, the efficiency of an accelerating structure, the type of focusing and the energy of injection, the geometric dimensions of an accelerating section, the electric strength of the structure and its manufacturability, the tolerances for both accuracy of manufacture and high frequency parameters, and the cost. These issues are interrelated and their final solution depends on the specific use of the accelerator [5].

It should be noted that using accelerators in industry and medicine increases demands for the beam current value and the type of accelerated particles. When creating and self-using an accelerator for small energies, a number of specific problems occurs, the main of which are the choice of an efficient accelerating structure, the simplicity of its manufacture, a relatively low cost, small volume, and low operating costs [6].

Increasing the intensity of accelerated particle beams only due to the improvement of acceleration and focusing techniques has a certain limit. One of the ways to improve the technical and economic characteristics of linear accelerators is the transition from using a conventional accelerator system to a multichannel system.

One of the most promising ways of solving this problem is to combine accelerating and focusing functions within one structure. Comparison of different types of accelerating structures shows that in the long-wavelength band and at injection voltages below 100, kV the multichannel accelerating structures are mostly preferred. These structures have a sufficiently high value of shunt impedance. They are adaptable to streamlined production methods and small since their cross dimensions do not depend on the operating wavelength. The construction design of such structures simplifies the implementation therein of the focusing kinds that are most effective within this range of energies [7].

Creating small powerful sources of charged particle beams is a relevant scientific and technical task. The work [8] examines the multichannel accelerating systems for ELA with a standing wave. It is shown that in the ELA, working in a standing wave mode and having an accelerating system arranged on the basis of biperiodic slow-wave system (BSS), the efficiency of acceleration significantly increases due to the higher oscillation modes.

METHODOLOGY

Among the BSS designs, the structure [9] that ensures achievement of a very high rate of acceleration is of particular interest. Structurally the system consists of two high frequency (HF) sections combined into a single transmitter unit, wherein the cavities of the first and second sections alternate with each other, and the accelerating cavities of one section are interconnected by lateral coupling cavities. The structure is supplied with the HF power through a waveguide coupler, the output ports of which are connected to the adjacent accelerating cavities that belong to different sections.

The waveguide coupler introduces a phase shift between the incident waves in the output ports, which is equal to $\frac{\pi}{2}$. Therefore, the electromagnetic fields in the adjacent accelerating cavities feature difference in phases as well $\frac{\pi}{2}$. In addition, the size of the system's geometrical period (the length of a single accelerating cavity) is halved as compared to a conventional BSS and makes $\frac{\lambda\beta_f}{4}$, where λ is the wavelength of the oscillator, β_f is the equivalent phase velocity. Consequently, the transit time coefficient value is increased and, besides, a significantly increase in the accelerating field value due to increased breakdown voltage is possible within such a system thanks to a simple cylindrical shape of the accelerating cavities. Thus, a possible pace of electron acceleration increases.

In the majority of existing ELA with a standing wave, the magnetron oscillators are applied at the low energy as a source of HF energy. According to the pilot experience, the most cost-effective and relatively simple circuit, which has minimal loss of HF energy and provides stabilization of the magnetron frequency, is a bridge supply circuit. In this case, the accelerating system is divided into two accelerating sections that have similar HF characteristics. This is true for the structure described in [9].

Figure 1 shows a multichannel accelerating system design based on the BSS, within which it was managed to organically combine the technical advantages of the systems discussed earlier. In addition to these advantages, this system has additional positive qualities, which in combination with the previously mentioned ones allow the higher increase in the efficiency of the accelerating process within the multichannel BSS with a standing wave.

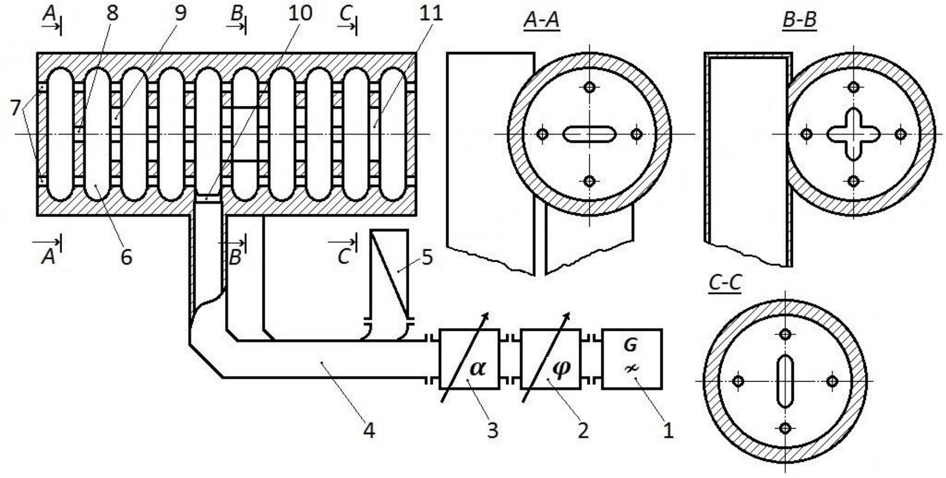

Fig. 1. 1 – high-frequency oscillator, 2 – phase shifter, 3 – attenuator, 4 – waveguide coupler, 5 – waveguide artificial load, 6 – accelerating cavity, 7 – drift apertures, 8 – horizontal coupling slot, 9 – cross shaped coupling apertures, 10 – high-frequency energy input windows, 11 – vertical coupling slot.

The ELA HF system with a new type of BSS comprises the HF oscillator (a magnetron), a phase shifter, an attenuator, and a waveguide coupler. The output ports of the coupler are connected to the two adjacent accelerating cavities via the HF energy input windows. Furthermore, the waveguide artificial load is attached to the second input port of the coupler. Communication between all accelerating cavities, except in the extreme and the adjacent thereto cavities, is carried out by means of cross shaped coupling apertures located in the center of the cavities' end surfaces. Communication between the extreme and the adjacent thereto cavities is carried out by means of coupling slots, the projection of which on one plane is orthogonal. Four drift apertures are located in the end surfaces of all accelerating cavities on a diameter of $\sim 0.6\lambda$. The structure is excited at E_{110} the form of oscillations (the structure diameter is $\sim 1.2\lambda$), while four electron beams are accelerated at the same time.

The system operates as follows. The HF energy passes from the oscillator through the phase shifter that allows choosing an optimal operating phase. Through the attenuator, the energy is further supplied to the first input port of the waveguide coupler. The purpose of the attenuator is to regulate the HF energy passing into the accelerating system, while the phase shift between the incident waves in the output ports of the coupler makes $\frac{\pi}{2}$. Through the input windows, the HF energy enters the adjacent accelerating cavities and due to the presence of apertures and coupling slots, it is distributed throughout the accelerating structure, that is, an electromagnetic field is excited in all accelerating cavities. Thus, it turns out that the structure contains only the accelerating cavities.

It should be noted that at first all the HF energy is reflected from the high-quality accelerating system and enters the artificial waveguide load. Then the intensity of the electromagnetic field in the accelerating system increases to its nominal values, wherein from each power supply the accelerating system is excited at $\frac{\pi}{2}$ in the form of oscillations with the help of windows and coupling slots. The structure of the HF field on E_{110} in the form of oscillations is such that for each specific input of HF energy different sets of accelerating cavities located one after another will be excited. Part of accelerating cavities for the given energy input will act as the coupling cavities, because the HF fields excited therein by this energy input are almost equal to zero. However, the presence of the second HF energy input leads to the fact that in these cavities the electromagnetic fields are excited, which are shifted in phase with respect to the fields in the adjacent cavities at $\frac{\pi}{2}$.

This occurs because the coupling slots between the extreme and the adjacent thereto accelerating cavities are acting selectively, which makes it possible to excite every extreme cavity only from one HF energy input. The coupling slots are oriented along the power lines of the azimuthal magnetic field component of one HF energy input. Wherein, for the azimuthal magnetic field component excited by the other input, it is oriented across the power lines, and in this case, the excitation of the accelerating cavity is not happening.

The cross shaped coupling apertures, which constitute a connection of the given coupling slots in one place, enable excitation of the adjacent accelerating cavities at both field orientations of the oscillation mode E_{110}, which are excited by different HF energy input windows. In fact, the communication between the accelerating cavities can be performed (instead of one cross shaped coupling aperture) through four coupling slots, which are located near the lateral wall of the cavity parallel to the slots of a cross shaped aperture. While the coupling slots between the extreme and the adjacent thereto cavities can be replaced with two slots parallel thereto and located near the lateral wall. At the same time, they will be located in zero field for the different orientation of the HF field structure of the oscillation mode E_{110}.

Four apertures in the end walls of cavities, which are intended for transmitting electron beams, are arranged at the locations of the two antinodes of the electric field in the given accelerating cavity and the two antinodes in the adjacent accelerating cavities. It should be noted that the lengths of the output ports of a waveguide coupler differ by a multipleΛ number of times, where Λ is the wavelength in a waveguide. This allows for the normal functioning of a HF system, while maintaining the desired phase difference between the electromagnetic fields in the adjacent accelerating cavities, which is equal to $\frac{\pi}{2}$.

DISCUSSION AND RESULTS

Since the waveguide coupler is formed with a connection on the narrow wall, it is structurally advantageous to connect one output port directly to the accelerating cavity through a HF energy input window within the striking face of a waveguide, to short circuit the second port, and to connect the accelerating cavity through the energy input window, which is disposed within a narrow lateral wall of the waveguide. At the same time, the HF energy input window center must be distanced from $\frac{\Lambda}{4}(2k+1)$ a place of short-circuiting, which will ensure proper communication with the accelerating cavities.

Depending on the total number of M accelerating cavities, the spatial arrangement of coupling slots and HF energy input windows are defined, which is determined by the given boundary conditions at the edges of a HF structure for its normal excitation. Thus, the major axes of symmetry of the energy input windows and the major axes of symmetry of the coupling slots, which are arranged from the side of a corresponding coupler's output port, are orthogonal in the event $M/_2$ of an even number, and parallel in the event $M/_2$ of an odd number.

Since in this case four beams of electrons are accelerated at once, it becomes possible to harness more current. At the same time, the design of an accelerating system is not very complicated as compared to the single-beam systems. Due to the lack of lateral coupling cavities, its transverse dimension is reduced, since the accelerating system consists of cavities of almost the same type and of simple cylindrical shape. Moreover, such design involves simplification of the preliminary HF tuning, which is reduced to fitting dimensions of cylindrically shaped accelerating cavities, the technical realization of which is fairly simply and highly accurate.

Implementing the transportation and focusing of beams within the structure without increasing the dimension of a transmitter unit becomes possible only with the help of a HF focusing [10]. Using in this case the recommendations on focusing with HF fields E_{010} within such a structure on a kind of oscillations will allow the achievement of an extremely small dimension of a transmitter unit while maintaining high efficiency of the acceleration process of such a BSS.

CONCLUSION

High efficiency of the accelerating system under study with the simplicity and low cost of its manufacture allows a successful use of linear accelerators in many industrial processes and medicine. Being in the off-state, the accelerators of this type are totally safe in terms of radiation, which makes it possible to perform their line maintenance. Installations may be operated without constructing special facilities with radiation protection because the local protection level of an accelerating structure is quite sufficient.

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