https://doi.org/10.46813/2025-157-089

VARIANT OF A HIGH-CURRENT LINEAR PROTON ACCELERATOR IN THE MIDDLE ENERGY RANGE WITH COMBINED RF FOCUSING BASED ON SHORT RESONATORS

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A variant of a high-current linear accelerator of medium-energy protons with combined RF focusing is considered. The results of numerical modeling of beam dynamics in the accelerating-focusing beamline in the energy range 3...70 MeV are presented. It is shown that the maximum current of charged particles accelerated without losses in the accelerating path is 160 mA at an acceleration rate of 5 MeV/m. A scheme for implementing this type of beamline based on short RF resonators is proposed.

PACS: 29.17.+w, 29.27 Bd

INTRODUCTION

Currently, accelerators of charged particles in the medium energy range (3...100 MeV) are used not only as part of large research complexes but also have independent applications in industry, energy, and medicine.

This energy range is the most problematic, with no established opinion about how to focus charged particles and their implementation.

Structures with drift tubes and focusing elements in the form of electromagnetic quadrupole lenses or solenoids are mainly used here. However, electromagnetic lenses and solenoids themselves are complex technical devices that require separate power and cooling. In addition, the length of external focusing devices turns out to be greater than the length of the accelerating period of the system, which creates significant difficulties in their placement.

At the same time, the use of powerful linear accelerators to solve problems of safe nuclear energy requires high reliability in their operation; they must operate for a long time without stopping for maintenance or due to emergency failures. Such reliability can be ensured by extremely simplifying the design of accelerating systems. The fundamental solution, in this case, is to abandon particle focusing through the use of external focus-ing devices and switch to focusing by the accelerating field itself.

Such installations must meet the following requirements: accelerated beam current (for protons) – 100 mA or more, acceleration rate 3...5 MeV/m, beam transmission coefficient 98...100%, have small dimensions and cost. Alternating phase focusing (APF) [1-4], although it has design simplicity, cannot provide the required beam parameters without the use of additional sources of external focusing fields.

The solution to this problem is to use combined HF focusing (CRFF) [5-7]. The paper considers a variant of a high-current linear proton accelerator of the middle energy range with CRFF based on short resonators.

METHODS

Currently, two methods of focusing by the accelerating field are used in practice: RF quadrupole and alternating-phase.

Systems with spatially uniform quadrupole focusing [8], called Radio-Frequency Quadrupole (RFQ) in the literature, are widely used in the initial part of accelerators. Instead of traditional drift tubes, a quadrupole system consisting of four electrodes that are uniform along the accelerator axis, each pair of which has the same high-frequency potential, is used in accelerators with RFQ. A particle moving along the axis of such a structure experiences the effect of rigid focusing. This structure makes it possible to focus all particles of the beam regardless of the speed and phase of the particle. The accelerating component is created due to longitudinal modulation of the electrodes. Accelerators with RFQ currently have no competitors in the low energy region (0.1...3 MeV). They do not require a high-voltage injector and provide almost 100% capture, acceleration and focusing of charged particle beams with a high limiting current. This type of focusing is also applicable in the main part of the accelerator. However, due to the low acceleration rate, it is not used for medium and high energies. The fact is that it is difficult to create an effective component of the accelerating field in a system consisting of four extended quadrupoles.

Therefore, a transition is being made to other principles of ensuring the stability of particles in the region of higher energies. But, despite its structural simplicity and good compatibility with superconducting structures, focusing by an RF field in high-current linear accelerators has not become widespread. The use of APF in this range solves the problem of increasing the acceleration rate, but is not suitable for accelerating intense beams. The reason is the nature of this type of focusing. Only an axially symmetric RF field is used to initiate the stable motion of charged particles in the APF. It is possible to ensure the radial stability of the particles only by weakening the longitudinal stability and vice versa in this case. Therefore, in terms of the current value of accelerated particles, APF is inferior to classical focusing methods that use the principle of autophasing and external focusing devices. In addition, the strong coupling between longitudinal and transverse motion leads to an increase in beam emittance even at low currents of particles being accelerated [9].

To eliminate these issues, the CRFF method could be used, in which the accelerating-focusing period of the APF is supplemented with quadrupole RF focusing to increase the transverse focusing rigidity. These two types of focusing were compared using the example of a linear helium ion accelerator with an output energy of 4 MeV [10]. It is shown that the calculated parameters of the accelerated beam obtained using CRFF have significant advantages over the accelerator with APF using the method of mathematical modeling. The structure of the accelerating-focusing period of the CRFF and the choice of the type of accelerating structure depend on the type of particles being accelerated, the energy range, and the operating frequency of the RF field. The implementation of the considered focusing method in the middle energy range using a “long” CH structure [11] in Fig. 1 is shown. The term “long” indicates a structure containing more than one accelerating-focusing period.

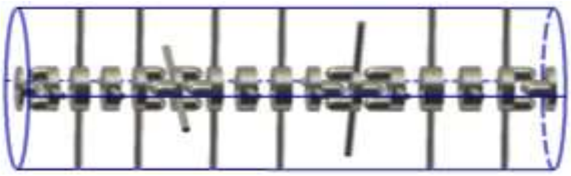

Fig. 1. CH structure with CRFF

The drift tubes are attached by two rods to opposite sides of the resonator shell, with the rods of each subsequent tube rotated 90° relative to the previous ones, in a CH resonator. Structurally, the accelerating path with CRFF is a combination of gaps with quadrupole field symmetry, between which a certain number of axisymmetric gaps are located. The quadrupole field component is formed by the insertion of additional electrodes into the accelerating gap, which is attached to the ends of the drift tubes. This leads to a decrease in the electrical strength of the quadrupole section, so there is a need to reduce the potential difference in the quadrupole sections relative to the axisymmetric gaps. For a CH structure, such adjustment can be made by azimuthal rotation of the rods on which the central drift tube of the quadrupole focusing section is attached.

Currently, short, independently phased H resonators, between which, to ensure longitudinal stability of the beam, focusing elements are located: solenoids or quadrupole magnetic lenses, are increasingly being used when developing linear accelerators in the mid-energy range. The use of short resonators with CRFF [7] does not require the use of external focusing devices at all, which significantly simplifies the design of a linear accelerator [12].

The variant of the main part of the high-current linear accelerator of protons (3...70 MeV) with CRFF based on short resonators is under discussion.

RESULTS

The particle accelerator development includes the next steps: choosing a method for focusing beams of charged particles, determining the main parameters and geometry of the accelerating beamline, providing the necessary current of charged particles, and determining the optimal accelerating structure for its practical implementation. For the chosen CRFF method, depending on the problems being solved, two types of accelerating-focusing beamlines can be distinguished [5, 7]: for the formation and acceleration of a bunch of charged particles upon injection into the accelerating structure of a continuous beam and the acceleration of formed bunches of charged particles. In the first case, the accelerating-focusing period OFDOO should be used (where O is an axisymmetric accelerating period, F is an accelerating period containing a quadrupole section focusing in the direction of one of the coordinates of the transverse plane, D is a defocusing quadrupole section in this direction). In the second case (the option under consideration), the most optimal period structure is FOOODDOOOF. The number of axisymmetric gaps in a half-cycle is usually 3-5. The more such gaps will be included the higher the acceleration rate and the lower the current value of the accelerated particles will take place, and vice versa.

Two options for accelerating-focusing periods: 10 gap one for the energy range of 3...10 MeV and 12 gap one for the energy range of 10...70 MeV in Fig. 2 presented. The beam input parameters are given in Table 1.

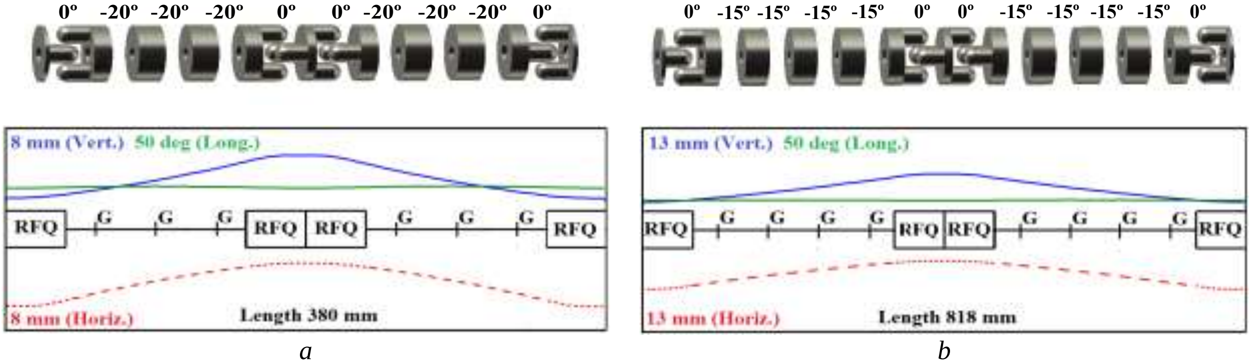

Fig. 2. Phase distribution of synchronous particles in accelerating gaps, vertical and horizontal beam envelope, beam phase length for 10-gap accelerating-focusing period of CRFF (a) and 12-gap accelerating-focusing period of CRFF (b)

Table 1

Beam input parameters

Parameter	Value
Energy, MeV	3
Operating frequency, MHz	325
Beam current, mA	100
Transverse emittance, mm·mrad	
$\varepsilon_{n,x}(90\%)$; $\varepsilon_{n,x}(rms)$	1.037; 0.243
$\varepsilon_{n,y}(90\%)$; $\varepsilon_{n,y}(rms)$	1.030; 0.238
Longitudinal emittance, degree keV	
$\varepsilon_{z}(90\%)$; $\varepsilon_{z}(rms)$	851.7; 192.1

The envelopes and phase extension of the bunch for each of these two periods, calculated using the Trace-3D program, are also shown [13]. The program allows one to determine the evolution of beam envelopes during the focusing period, taking into account space charge forces. It is assumed that the accelerator beamline consists of focusing periods consistent with each other. Since the influence of the space charge forces of the beam is maximum in the initial part of the accelerating beamline, to determine the nature of the beam motion it is enough to consider the first focusing periods. A bunch of particles is represented as a triaxial ellipsoid, the effect of gaps is considered in the approximation of a thin lens. The following designations are used: RFQ is the quadrupole section, G is the center of the axisymmetric gap, continuous curve is the beam envelope in the horizontal direction (red), dotted curve is the beam envelope in the vertical direction (blue), line in the upper half of the figure (green) is phase extension of the bunch. The current value, taking into account the possible error, was chosen higher than the calculated one: for a 10-gap period is 150 mA, and for a 12-gap period is 200 mA. The average gradient of the transverse RF field in a gap with quadrupole symmetry for the 10th gap period is 160 kV/cm^2, and for the 12th gap period is 100 kV/cm^2. The maximum electric field strength in the gap is 160 kV/cm.

The final calculation of the accelerating-focusing beam line taking into account the real geometry of the electrodes. The beam dynamics modeling taking into account Coulomb forces was carried out in the development environment for linear accelerators with RF focusing of APFRFQ [5, 14]. The value of the maximum field strength on the electrode surfaces in a gap with quadrupole field symmetry is 2Kp (where Kp is the Kilpatrick criterion [15]). For a frequency of 325 MHz this value is equaled to 357 kV/cm. To take into account space charge forces, the large particle PP (particle-particle) method was used. The number of particles used in the numerical simulation of particle dynamics is 10.000.

The calculated output characteristics of the beam are given in Table 2. The maximum pulse current of particles passing through the accelerating beamline without losses is 160 mA. The projections of the beam phase volume in the plane: xx', yy', xy, $\Delta\varphi\Delta W$ (where $\Delta\varphi$, ΔW is the difference in phases and energies of asynchronous and synchronous particles) at the input and output of the accelerating beamline for a beam current of 100 mA in Fig. 3 are presented.

Table 2

Beam output parameters

Parameter	Value
Energy, MeV	70
Beam current, mA	100
Transverse emittance, mm mrad	
$\varepsilon_{n,x}(90\%)$; $\varepsilon_{n,x}(rms)$	1.490; 0.348
$\varepsilon_{n,y}(90\%)$; $\varepsilon_{n,y}(rms)$	1.527; 0.353
Longitudinal emittance, degree keV	
$\varepsilon_{z}(90\%)$; $\varepsilon_{z}(rms)$	860.2; 197.2
Total length, m	13.35
Beam transmission, %	100

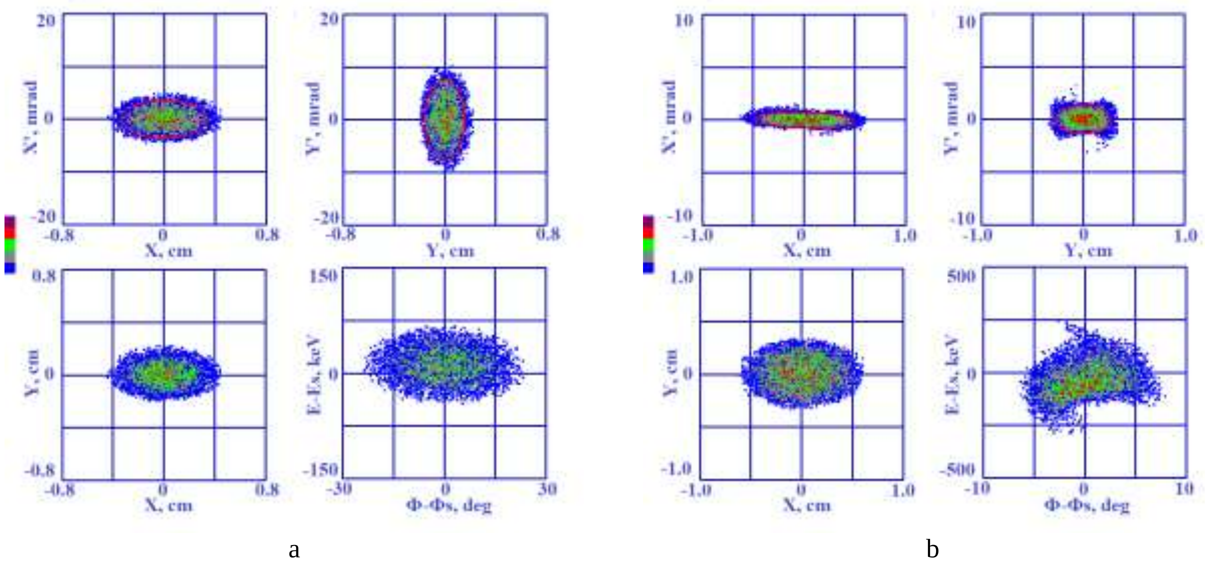

Fig. 3. Projections of the beam phase volume at the input (a) and output (b) of the accelerating beamline (beam current is 100 mA)

As a result, four variants of implementation of this accelerating beamline for different energy ranges are presented below.

Energy range of 3…10 MeV

The structure of the accelerating-focusing period is presented in Fig. 2,a (top picture). The number of such periods is 3. The length is 157 cm. The section consists of 6 resonators. The resonator view in Fig. 4 is shown.

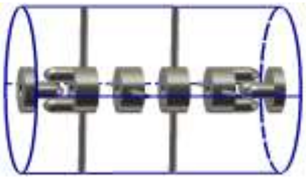

Fig. 4. 5-gap CH structure with CRFF

Energy range of 10…32.76 MeV

The structure of the accelerating-focusing period (hereinafter) is presented in Fig. 2,b (top picture). The number of periods is 3. The length is 456 cm. The section comprises five 6-gap resonators (Fig. 5) and one 5-gap one. To match the next section of the accelerating path, the last gap with quadrupole symmetry is missing in this resonator. The first gap of the next resonator plays the main role.

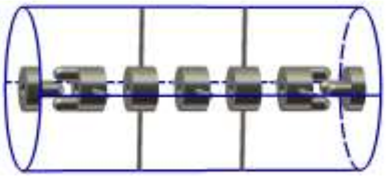

Fig. 5. 6-gap CH structure with CRFF

Energy range of 32.76…49.20 MeV

In this range, it is proposed to use two types of resonators: 2-gap ones with quadrupole field symmetry and 4-gap axisymmetric ones (Fig. 6). Using autonomous power supply in the first case, an RF quadrupole element with adjustable transverse focusing rigidity will obtain separately. In the second case, a structure in which the acceleration and phase stability of the beam are carried out. The section contains 2 accelerating-focusing periods, which begin and end in the middle of 2 gap resonators. Between them, there are 4 axial symmetric resonators and 3 with quadrupole field symmetry. The length of the plot is 325 cm.

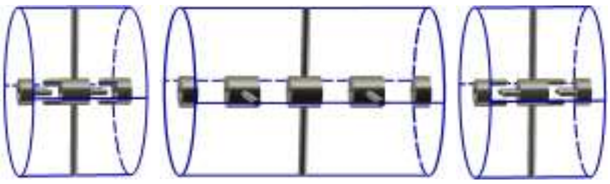

Fig. 6. Implementation of CRFF based on 2- and 4-gap resonators: focusing area of FFOOOODD

Energy range of 49.20…70.00 MeV

The section contains 2 accelerating-focusing periods and is implemented on the basis of 2-gap resonators: 8 of which with axisymmetric accelerating gaps and 4 with quadrupole ones (Fig. 7). The length is 397 cm. This choice of implementation of the final section was made for the following reasons. Since the resonators are self-powered, it is possible to independently change the amplitude and phase of the RF field in them, which will allow smooth regulation of the output beam energy.

The overall acceleration rate in the considered accelerating beamline is 5 MeV/m.

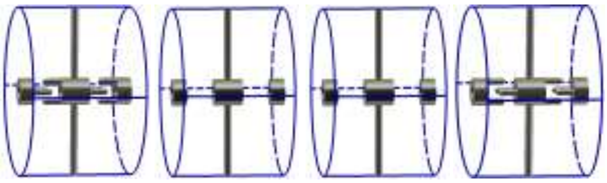

Fig. 7. Implementation of CRFF based on 2-gap resonators: focusing area of FFOOOODD

CONCLUSIONS

The results of the above studies show that the problems that arose during the development of a high-current accelerating-focusing beamline accelerator in the middle energy range can be successfully solved on the basis of combined RF focusing. Its implementation based on short resonators makes it possible to significantly simplify the manufacture and operation of the entire accelerator. Note that this development is general and may be used in one form or another in projects where it is necessary to use high-current beams with low losses and a high acceleration rate. The absence of external focusing devices and the design simplicity of the accelerating beamline make it attractive to use this type of focusing in structures with superconductivity.

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Article received 14.04.2025

ВАРІАНТ СИЛЬНОСТРУМОВОГО ЛІНІЙНОГО ПРИСКОРЮВАЧА ПРОТОНІВ СЕРЕДНЬОГО ДІАПАЗОНУ ЕНЕРГІЙ З КОМБІНОВАНИМ ВЧ-ФОКУСУВАННЯМ НА ОСНОВІ КОРОТКИХ РЕЗОНАТОРІВ

С.С. Тішкін, С.Г. Карпусь

Розглянуто варіант сильнострумового лінійного прискорювача протонів середнього діапазону енергій з комбінованим ВЧ-фокусуванням. Представлено результати чисельного моделювання динаміки пучка в прискорювально-фокусуючому каналі в діапазоні енергій 3...70 МеВ. Показано, що максимальний струм заряджених частинок, що прискорюються без втрат у прискорювальному тракті, становить 160 мА при темпі прискорення 5 МеВ/м. Запропоновано схему реалізації цього типу каналу на основі коротких СН-резонаторів.