https://doi.org/10.46813/2026-165-113

MODERNIZATION OF THE HELIUM ION LINEAR ACCELERATOR STRUCTURE. COMPUTER SIMULATION

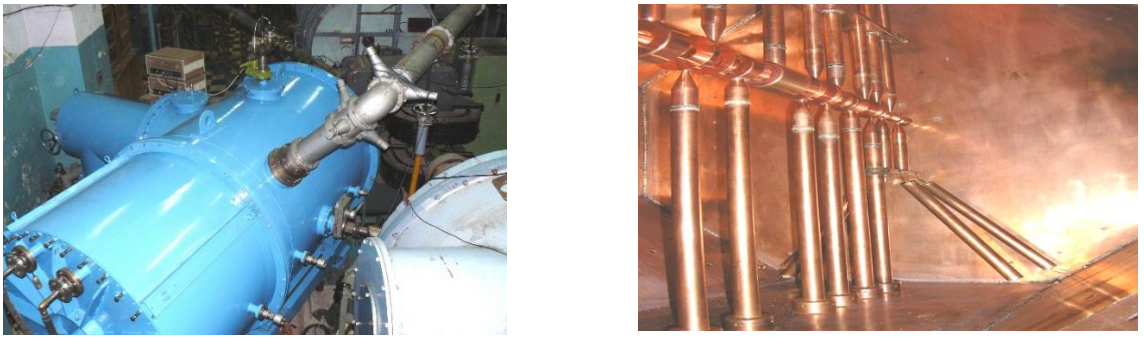
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The paper describes the alternating-phase focusing for the helium ion linear accelerator operating at the NSC KIPT. The essence of the modernization is that permanent magnet quadrupoles are built into certain drift tubes. This modification creates an additional focusing effect without changing the design configuration of the structure itself. The main parameters of the focusing channel are presented. By numerical simulation of beam dynamics in the linear accelerator, taking into account the additional focusing, it is shown that the root-mean-square transverse beam dimensions at the accelerator output can be reduced by a factor of 4 in this case.

PACS: 29.17.+w, 29.27 Bd

INTRODUCTION

The helium ion linear accelerator based on modified alternating-phase focusing (APF) [1–3] with an output energy of 4 MeV (Fig. 1) is used at NSC KIPT for both fundamental and applied research [4–12]. The advantage of the accelerator is its relative simplicity of construction, operational reliability, and ease of maintenance. A common problem with accelerators of this type is the growth of geometric dimensions and beam divergence during acceleration. This phenomenon subsequently leads to a decrease in the density of accelerated particles at the accelerator output [13]. In this work, to solve this problem, it is proposed to use focusing based on permanent magnet quadrupoles [14]. These quadrupoles are placed inside the existing drift tubes in the final part of the accelerator, as well as in the space between the vacuum jacket and the accelerating structure. Since the lengths of the drift tubes do not change, adjustment of the RF field amplitude will not be required or will be minimized.



a *b*

Fig. 1. Helium ion linear accelerator: a – general view; b – accelerating structure

EXPERIMENTAL SETUP AND METHOD OF INVESTIGATION

An important task in creating low-energy ion linear accelerators is the development of accelerating structures. These structures must allow accelerating charged particles starting from low injection energies (~ 100 keV) and possess a maximum particle capture coefficient into the acceleration mode. Among the currently known methods for bunching and pre-acceleration of ions, systems with radio-frequency quadrupole focusing (RFQ) are mainly used. These systems are well studied and widely used both in the injection complexes of large accelerators intended for fundamental research and for applied problems. They possess several undeniable advantages. These include low beam injection energy, a high current transmission coefficient, and a high limiting current of the accelerated beam. At the same time, the system is not without a number of drawbacks. The most significant of these disadvantages are a relatively low acceleration rate and a decrease in acceleration efficiency with increasing energy. Having extensive experience and technical capabilities for manufacturing accelerating structures, NSC KIPT developed and commissioned a helium ion linear accelerator based on APF in the energy range of 0.12…4 MeV.

As mentioned above, the APF structure allows accelerating particles starting from low injection energies and features a high acceleration rate. However, it is inferior to the RFQ in terms of the beam capture coefficient into the acceleration mode. To increase the particle capture angle into the acceleration mode in the accelerator, a rising field is used in the accelerating gaps along the initial part of the accelerator. The idea of using an increasing field is as follows. In APF, the longitudinal and transverse beam stability is provided by the axisymmetric field of accelerating gaps. However, the focusing properties of this field decrease as the particle velocity increases. The simplest way to solve this problem in the bunching part of the accelerator is to

increase the field strength in the accelerating gaps proportionally to the increase in particle velocity [15, 16].

The entire accelerating-focusing channel consists of individual focusing periods. Each period contains a certain number of gaps with negative and positive synchronous phases. The values of the synchronous phases in the accelerating gaps are chosen based on specific criteria. For a given distribution of the accelerating field in the gaps, simultaneous longitudinal and transverse beam stability must be ensured at the maximum acceleration rate [15]. The design of the accelerating-focusing channel was performed using the LINACV2 program [16]. This program was subsequently updated with a graphical user interface and named APFRFQ [17, 18]. The program allows calculating the channels of ion linear accelerators with RF focusing. It takes into account the real geometry of the channel and the impact of space charge forces. The accelerating channel is implemented on the basis of an IH structure in which the drift tubes are mounted on individual stems. Such structures have been thoroughly investigated and are widely utilized at NSC KIPT to accelerate multiply charged ions.

RESULTS

Initially, the accelerator was designed for an input current of 30 mA (injection energy 120 keV) and an output current of 11.5 mA with an energy of 4 MeV [16]. As a result of the fabrication and tuning of the structure, the amplitudes of the RF fields in the accelerating gaps deviated from the designed values (Fig. 2). In addition, the beam current at the accelerator input obtained in the experiment was lower than the calculated value and amounted to 10 mA. In this regard, a repeated numerical simulation of the particle dynamics in the accelerating-focusing channel was conducted for the experimental data.

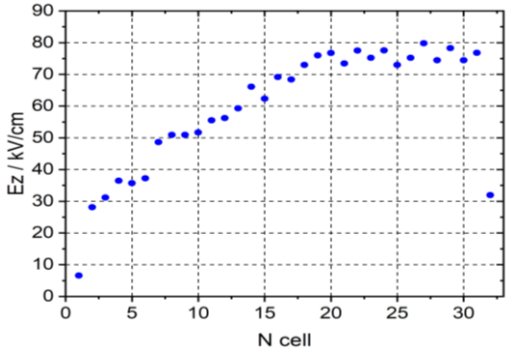


Fig. 2. Experimentally measured field amplitudes in the accelerating gaps

The calculation utilized the macroparticle PP (particle-particle) method, with an initial number of particles equal to 10,000. The input distribution of particles was selected as follows. In the longitudinal direction, a uniform distribution of particles in phase and a random distribution in energy (118…122 keV) were used. In the four-dimensional transverse hyperspace, a chaotic filling of a four-dimensional ellipsoid in the space of transverse coordinates and velocities was applied [13]. Fig. 3 shows the dependence of the particles captured into the acceleration mode on the number of the accelerating period. Fig. 4 presents the projections of the beam phase volume onto the planes xx', yy', xy, $\Delta\varphi\Delta E$ at the accelerator input. Fig. 5 shows the projections of the beam phase volume onto the planes xx', yy', xy, $\Delta\varphi\Delta E$ at the accelerator output. Here $\Delta\varphi$ and ΔE are the differences in phase and energy between a non-synchronous and a synchronous particle. These values for the input and output of the accelerator were obtained through numerical simulation.

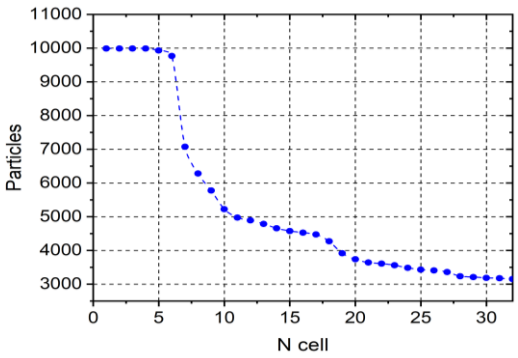


Fig. 3. Dependence of particles captured into the acceleration mode on the number of the accelerating period

As seen from Figs. 4, 5, the geometric dimensions of the beam increase sharply at the accelerator output.

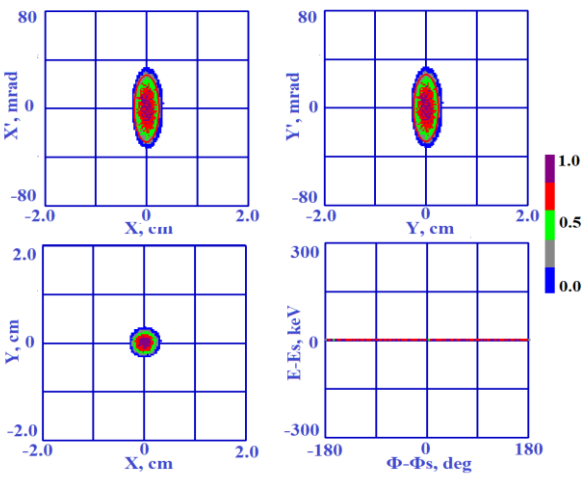


Fig. 4. Projections of the beam phase volume at the accelerator input of the accelerating channel

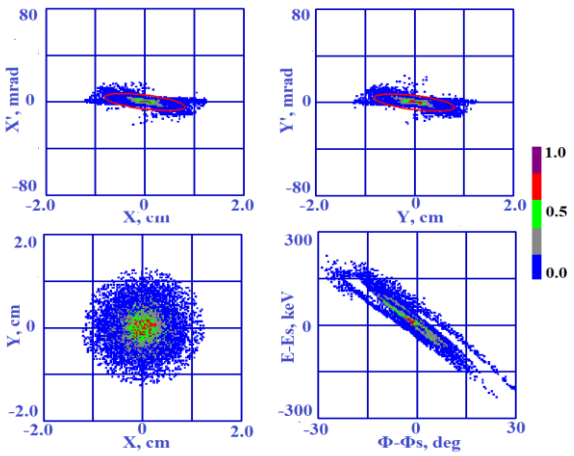


Fig. 5. Projections of the beam phase volume at the output of the accelerating channel

To eliminate this drawback, it is proposed to use an additional focusing section in the final part of the accelerator. This modification will allow obtaining a focused beam at the accelerator output. The main parameters of the focusing channel are shown in Fig. 6:

– I – section of the accelerating structure with the last two drift tubes;

– II – section between the accelerating structure and the vacuum jacket;

– III – section after the vacuum jacket – 140 mm;

– G – center of the accelerating gap before the last drift tube;

– Q – quadrupole lenses (length): 1 – 70 mm; 3 – 30 mm; 5 – 100 mm; 7 – 110 mm;

– distance between lenses: 2 – 78.64 mm; 4 – 10 mm; 6 – 40.34 mm;

– magnetic field gradient values in the lenses: 1 – -25 T/m; 3 – 10.8 T/m; 5 – 40 T/m; 7 – -41 T/m.

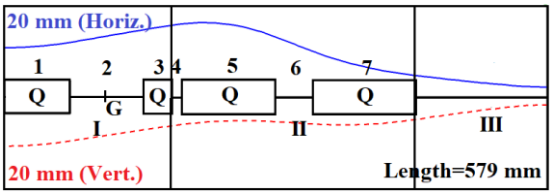


Fig. 6. Structure of the focusing section and evolution of the beam envelopes

The beam envelopes in the focusing section, calculated using the TRACE 3-D [19], are presented in Fig. 6. The blue curve (solid) represents the horizontal beam envelope, and the red curve (dashed) represents the vertical envelope. The input parameters for the TRACE 3-D are the data obtained from the numerical simulation of particle dynamics starting from the accelerator input up to the beginning of the additional focusing section (before the penultimate drift tube): beam energy – 3.9 MeV, emittance $\varepsilon_{n,x}(rms)$ =0.543 mm·mrad, $\varepsilon_{n,y}(rms)$ =0.539 mm·mrad, beam current 3.17 mA.

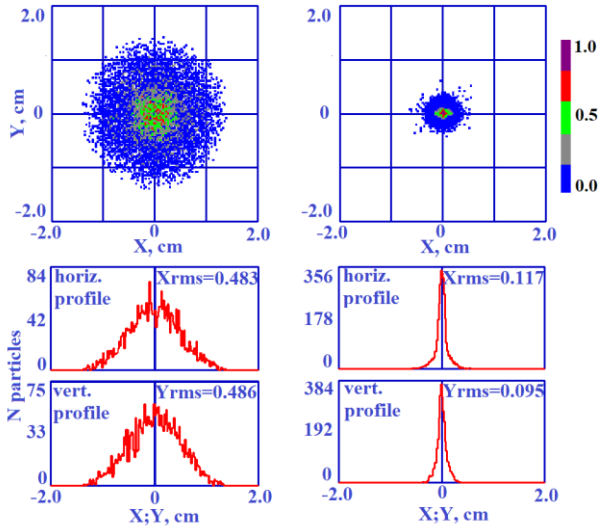


Fig. 7. Beam profile before entering the focusing section (left) and of the focused beam (right)

The TRACE 3-D uses a matrix calculation method. For a more detailed consideration of the beam dynamics, the macroparticle method was used (Figs. 7, 8).

Figs. 7, 8 show the beam profile at the entrance to the focusing section and the main parameters of the focused beam obtained with macroparticle method. It can be seen that the transverse dimensions of the beam at the accelerator output are reduced by 4 times.

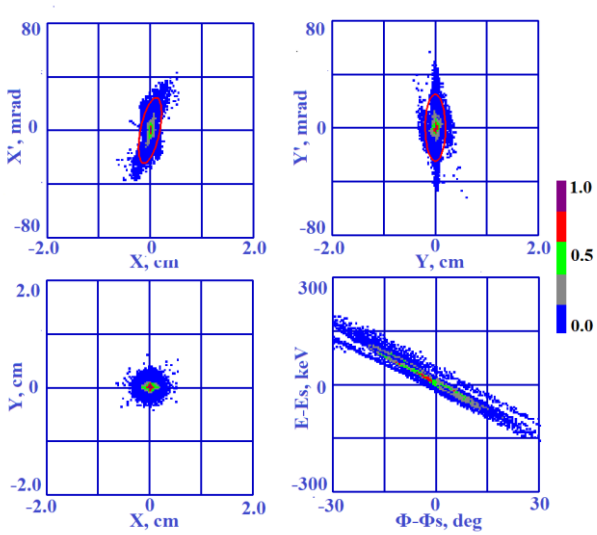


Fig. 8. Projections of the beam phase volume for the focused beam

A comparison of the calculation results obtained by the two methods is presented in the Table.

Calculation method	Unfocused beam	Focused beam
Matrix method radius, mm	11	1.9
Macroparticle method X(rms), mm	4.83	1.17
Y(rms), mm	4.86	0.95

CONCLUSIONS

The presented results demonstrate that the problem of beam current density drop can be successfully solved. This drop occurs at the output of a helium ion linear accelerator and is corrected using an additional focusing section. The section consists of permanent magnet quadrupole lenses located inside the structure of the accelerator itself. Since the initial design configuration of the structure remains unchanged, frequency tuning after modernization will not be required. This approach eliminates the need for additional focusing elements outside the accelerator. Consequently, it optimizes the overall dimensions of the entire installation. Since this problem is common to APF accelerators without preliminary bunching sections (such as an RFQ), the proposed method can be applied in all these similar cases.

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Article received 20.07.2026

МОДЕРНІЗАЦІЯ СТРУКТУРИ ЛІНІЙНОГО ПРИСКОРЮВАЧА ІОНІВ ГЕЛІЮ. ЧИСЛОВЕ МОДЕЛЮВАННЯ

В.І. Бутенко, О.В. Мануйленко, К.В. Павлій, С.С. Тішкін, Б.В. Зайцев

Наведено опис змінно-фазового фокусування для лінійного прискорювача іонів гелію, що працює в ННЦ ХФТІ. Суть модернізації полягає у тому, що всередину певних трубок дрейфу вбудовуються твердотільні квадруполі, які створюють додатковий фокусуючий ефект, не змінюючи при цьому розрахункову конструкцію самої структури. Наведено основні параметри фокусуючого каналу. Методом числового моделювання динаміки пучка в лінійному прискорювачі з урахуванням додаткового фокусування показано, що середньоквадратичні поперечні розміри пучка на виході прискорювача у цьому випадку можна зменшити в 4 рази.