TRANSPORT AND MATCHING OF THE INJECTING BEAM

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The properties of multi-element axially symmetric electrostatic lenses as a possible matching device of linear accelerator injector are considered. The electrostatic lenses are more effective at small (up to 150 keV) injection energy which used for small sized linear accelerators of ions. The criteria for choosing the most suitable lens parameters are discussed. The results of five-electrode lens study are presented. The investigation was carried out by a numerical method. Preliminary modeling was carried out applying original programs developed at NSC KIPT in which numerical code based on the integral equations method for calculating the distribution of the field strength between the electrodes of a lens was used. For a detailed numerical study of the five-electrode electrostatic lens, was used a package of three-dimensional computer simulation of charged particle optics – IBSimu.

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INTRODUCTION

An important direction in the development of accelerator technology is the creation of applied purpose charged particles accelerators. At small dimensions, their design should be reliable, ease of operation, ensure the efficient use of power energy, as well as the radiation purity throughout all accelerating path. Linear resonance ion accelerators, in which the stability of the beam dynamics is ensured by the use of high-frequency focusing (RFQ, MAPF, APF) are met these requirements. Radiation purity is ensured by minimizing beam losses both during capture to acceleration and during acceleration. This imposes stringent requirements on the parameters of the beam at the entrance to the accelerating path (phase volume, radius and angle of inclination of the envelope).

To transport the beam and matching its characteristics in accordance with the parameters required for effective beam capture in the acceleration, matching ion-optical systems are placed between the injector and the accelerator. The matching devices transform an ion beam with a high intensity diverging in the transverse plane into a convergent one, which is necessary for optimal matching with the acceleration path. In transporting and matching devices, both magnetic and electrostatic lenses are used. Both types of lenses have a one's own niche application, because along with the advantages they have inherent disadvantages. Magnetic lenses provide transportation and matching the characteristics of beam with minimal increase in emittance in comparison with electric lenses, but require significant expenditure of energy for feeding and removing heat generated in lenses, and in some cases also using superconductivity.

Electric lenses are more economical, easy to create and they are stable in operation. The gas neutralization of the beam charge does not occur in them and therefore they have no limitations on the pulse duration. However, this also makes it necessary to use stronger focusing fields, and hence is associated with higher aberrations and problems of electric strength. Therefore, the calculation and creation of matching devices based on the use of electrical lenses requires careful engineering of their design and modeling of the processes taking place in these devices.

The development of the transporting and matching device was carried out in two stages. In the first, preliminary stage, the optimal number of focusing gaps in the device, which is necessary for transportation and matching of the beam with a beam current of 150 mA and energy in the range of 75...150 kV was determined. For this, original programs developed at the NSC KIPT were used. The programs calculate the distribution of the field strength in the gaps between the lens electrodes taking into account the potential of the lens electrodes and the magnitude of the space charge of the transported beam, and also simulate the beam motion in the calculated electric fields.

In the second stage, the five-electrode electrostatic lens chosen at the first stage was studied in detail and optimized. In these studies, a freely distributed package of three-dimensional computer simulation of charged particle optics taking into account space charge forces – "Ion Beam Simulator" (IBSimu) was used [1].

The IBSimu package, in which libraries C^{++} are used, allows to solve many problems related with modeling of ion optics. [2, 3]. The choice of the package was due to both availability and a number of technical advantages over others. Steady and time-dependent processes are modeled in cylindrical coordinates, two-dimensional geometry or in full 3D. The accuracy of the calculation was improved by analytically determining the intersection of the simulation grid with the electrode boundary.

The package has a wide range of modeling results processing, the ability to output various graphs, as well as an easy-to-use interactive post-processing tool for outputting parameters of electric fields and particle trajectories.

The particle trajectories was determined using the adaptive Runge-Kutta method. In the first iteration, the electric field was calculated only taking into account the geometry and potentials of the electrodes forming the focusing field. Then the particles motion in the calculated electric field was simulated. At the second iteration, the electric potential (and subsequently the electric field) was recalculated again taking into account all the electrodes and the injected (simulated) particles. The potential and the field were recalculated as well as the trajectories of the particles, until convergence was achieved – that was, until the difference in these parameters in the neighboring iterations was became close to zero.

The advantage of the IBSIMU package is the possibility of injection an ion beam into the investigated device not only with beam parameters determined by random number generator but also with parameters that were determined in the modeling of ion extraction from an ion source.

The chosen pact was adapted to the conditions of modeling our problems.

1. SELECTING LENS PARAMETERS

When choosing the parameters of the transporting and matching device, modeling of ion dynamics in an electrostatic lens was carried out using a phase portrait beam, which is shown in Fig. 1. The distribution of particles in the phase space, shown in Fig. 1, is typical for proton injectors with beam energy in the range of 50...150 keV and a current of more than 0.1 A. As can be seen from Fig. 1 the beam diverges in the transverse direction. To match the characteristics of the beam with the accelerating path, the divergent beam must be converted into converging beam with a crossover with a given envelope radius.

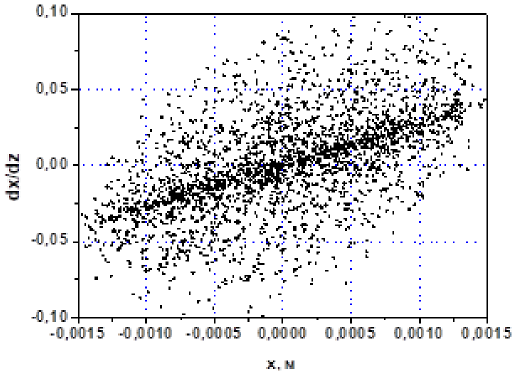

Fig. 1. Phase portrait of the beam at the injector output

When choosing a transporting and matching device in order to determine the limiting value of the beam current being focused, modeling of the beam dynamics in devices with different number of focusing gaps forming the lens was carried out.

To check the focusing capabilities of the simplest three-electrode lens, a device consisting of two outer electrodes of 5 cm in length was used. Between the outer electrodes was located an electrode 1.5 cm long, separated from them by gaps of 7 mm in length. The aperture diameter of the lens electrodes was 18 mm. Two outer electrodes had a ground potential, the central electrode was fed by focusing potential. With this lens design and the indicated potential distribution, in the first gap of the lens the electric field is appeared, which is braking the beam and its energy decreases, but at the lens output, after passing through the second gap, the beam energy will again be equal to the injection energy.

Fig. 2 shows a phase portrait of a beam with a current of 20 mA after passing through a three-electrode lens, which had a potential at the average electrode of +42 kV. Comparing Figs. 1 and 2, it can be concluded that the three-electrode lens sufficiently well focusses the proton beam at this current, and there is no loss of particles. The beam at the entrance to the accelerating path becomes convergent, and the diameter of the main part of the beam is approximately 3 mm.

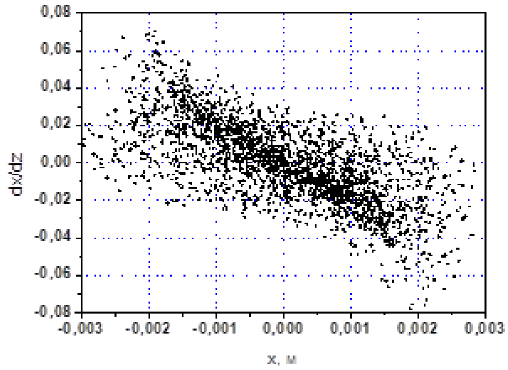

Fig. 2. Phase portrait of a beam with a current of 20 mA, which passed through a three-electrode lens

As the beam current increases, the focusing deteriorates because of the stronger defocusing effect of the space charge. An increase in the potential on the middle electrode leads to an increase in the density of the space charge and compensates for the defocusing effect, but at the same time the emittance of the beam increases.

The emittance at the entrance to the lens was 1.12 mm·mrad, at a current of 20 mA after the lens it is 1.13 mm·mrad, and at a current of 60 mA – 1.52 mm·mrad. Changing the polarity of the voltage on the middle electrode provides focusing even at a current of 60 mA or more, but the value of the focusing potential increases significantly and can exceed the electrical strength of the gap.

Fig. 3 shows the phase portrait of a beam with a current of 60 mA, passed through the same lens with the indicated potential distribution. As can be seen, not only the emittance growth occurs, but also the optical power of the lens is not enough to make the beam converging in the transverse direction.

When the polarity of the voltage is changed, the value of the potential on the middle electrode, at which the beam with a current of 60 mA is focusing, is 210 kV, which leads to an electric field strength exceeding the breakdown value. Therefore, to focus more intense beams, one must use lenses with a large number of focusing gaps.

In Fig. 4 shows the phase portrait of a beam transmitted through a five-electrode lens with four focusing gaps.

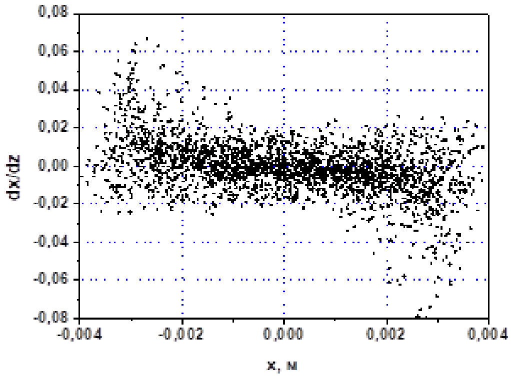

Fig. 3. Phase portrait of a beam with a current of 60 mA, passed through a three-electrode lens

As can be seen from Fig. 4, the beam at the output of the lens is convergent in the transverse direction. The beam's emittance increased slightly, and is equal to 1.4 mm·mrad, the beam diameter does not exceed

4 mm. To focus the beam, a voltage of ±40 kV was required. Consequently, it is possible to focus a more intense beam. This is confirmed by the one shown in Fig. 5 phase portrait of a beam with a current of 100 mA, passed through the same lens.

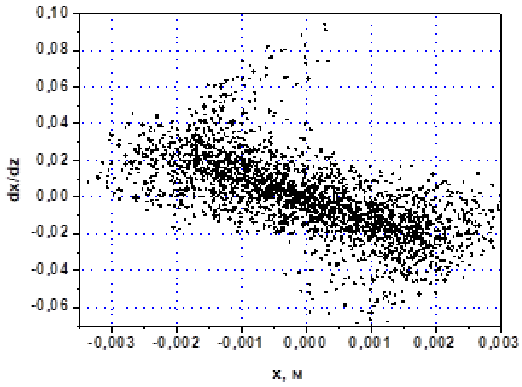

Fig. 4. Phase portrait of the beam with current of 60 mA, passed through a five-electrode lens

An increase in the number of focusing gaps can significantly reduce the potential needed for focusing the beam. The seven-electrode lens, constructed from electrodes and focusing gaps an analogous five-electrode lens, focuses the beam with a current of 0.1...1.15 A at an electrode potential not exceeding ± 80 kV, instead of -210 kV, in the case of using a three-electrode lens.

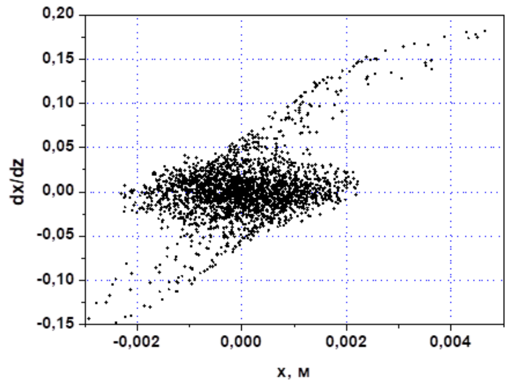

Fig. 5. The phase portrait of the beam with current of 100 mA, passed through a five-electrode lens

2. TRANSPORT AND MATCHING OF A PROTON BEAM IN MULD-3

To ensure the stability of the beam dynamics in the accelerating structure of MLUD-3, the principle of modified alternate phase focusing (MAPF) is used. In order to increase the of beam capture coefficient in such a structure, the first or several initial acceleration periods are selected as phasing periods and, as a consequence, they do not provide sufficient rigidity of beam focusing in the radial direction. The beam at the entrance to the MAPF structure must be convergent in the transverse plane and have a minimum radius. The beam at the entrance to the MPPE structure must be convergent in the transverse plane and have a minimum radius. To obtain a beam with the specified characteristics between the injector and the accelerating structure, it is necessary to install a focusing device. As shown in the previous section, at proton beam currents ≤ 0.1 A, it is necessary to use a lens with not less than five electrodes (four focusing gaps).

When creating a deuterons accelerator for matching of the injected beam with the accelerating structure, a transport and reconciliation device was developed – a five-electrode electric lens. A device for deuterons with an energy of 135 keV, which necessary for beam capture into accelerating structure, and with a current of about 0.15 A, provides the required beam parameters. The device was simulated using the programs developed in KIPT.

The geometry of the electrodes of the lens is shown in Fig. 6, and Table shows its longitudinal dimensions. The outer diameter of the electrodes is 42 mm, the inner diameter is 16 mm. The edges of the electrodes are rounded to increase the breakdown voltage. The lens electrodes have reversal of sign of potential distribution; their potential ±U is in the range (0≤U≤75 kV). The first and last electrodes of the lens are under zero potential, that is, the potential of "earth". Odd lens gaps accelerate the beam, and even ones retard. The energy of the ions changes with the passage of the lens, but at the output it is equal to the energy with which the ions were injected into the lens. The relation and polarity of the potentials on the lens electrodes is chosen so that the beam energy at focusing is never lower than the one it received in the injector. Due to this, the influence of the space charge forces is weakened, and the radial motion of the beam particles becomes more stable.

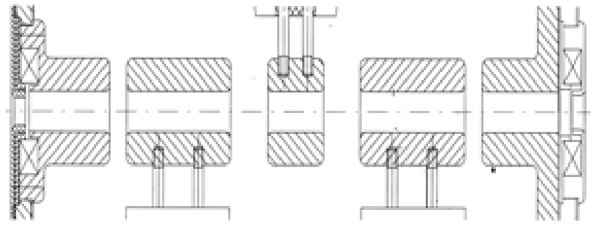

Fig. 6. Electrostatic lens of the transport and matching device

In the input electrode of the lens there is a magnetic induction sensor for measuring the position and current of the injected beam.

Longitudinal dimensions of the lens

№	Length, mm	
	Electrode	Gap
1	50.0	8.6
2	52.2	18.5
3	27.8	18.5
4	52.4	8.6
5	40.0	-

Numerical studies of the lens properties have shown that the necessary characteristics of the deuteron beam are achieved at potentials of electrodes 2 and 4 equal to -72 kV, and the third +48 kV. In the study used a beam with a phase portrait, shown in Fig. 1 obtained with the help of a random number generator.

To check the operation of the IBSIMU program, as well as the reliability of the lens characteristics obtained earlier, the dynamics of deuterons in the developed device was studied using the IBSIMU program. Unlike previous studies, a beam was injected into the lens with the characteristics obtained by simulating the extraction and beam formation in the ion injector of the accelerator. For modeling, 45.000 particulates were used.

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The result of modeling the beam propagation in the focusing lens was shown in Fig. 7. The figure shows the longitudinal section of the five-electrode lens (the electrodes are shown in blue) and the trajectory of the deuteron beam (red color) with energy of 135 kV. The equipotentials of electric field was drawn in green. The study was carried out with potentials at the electrodes determined earlier. Fig. 7 shows, that the beam losses on the electrodes of the lens are not observed.

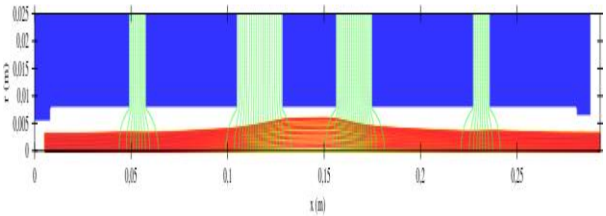
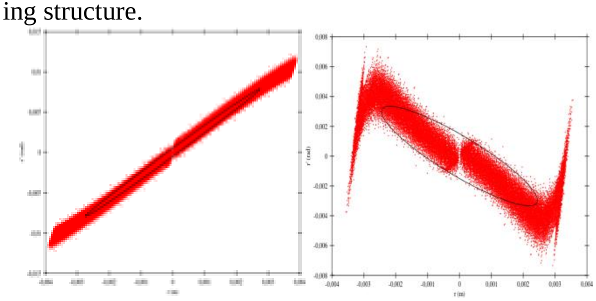


Fig. 7. Trajectories of the deuteron beam in the lens

The cross section of the beam at the exit from the lens, in the first gap of the accelerator, somewhat decreased compared to the cross section at the entrance to the lens and became equal to 6 mm. As can be seen from Fig. 8,a,b, where projections of phase portraits are presented, the beam diverging at the entrance to the lens (a) becomes at the exit from the lens convergent (b). During the passage of the lens, the emittance of the beam increased insignificantly from 2.2 mm·mrad at the entrance to the lens to 2.8 mm·mrad at the exit.

The accelerator MLUD-3 is also used in the proton beam accelerating mode. Therefore, the possibility of transporting a proton beam by the developed device and matching its characteristics with the accelerating system was investigated. Simulation of the proton beam dynamics in the device was carried out at an injection energy of 75 kV and the proton current of 0.15 A.

The simulation results shown in Figs. 9 and 10, were obtained with a potential on electrodes 2 and 4 equal to -48 kV, and on third electrode +52 kV. They indicate the possibility of using the developed device for mentioned purpose. The beam at the exit from the lens is convergent (see Fig. 10,b) and has a diameter of less than 5 mm in the plane of the entrance to the accelerating structure.



a *b*

Fig. 8. The beam's emittance at the entrance to the focusing lens (a), and at the exit from it (b)

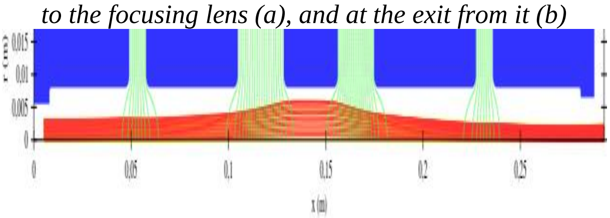
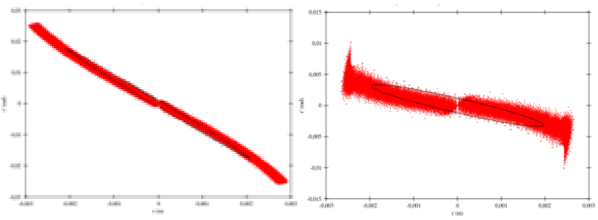


Fig. 9. The trajectories of the proton beam in the lens



a *b*

Fig. 10. The beam's emittance at the entrance to the focusing lens (a), and at the exit from it (b)

As can be seen from Fig. 9, the beam loss on the lens electrodes is not observed. Studies have shown that by varying the potentials on the lens electrodes, it is possible to control the angular convergence and diameter of the proton beam, and hence the position of the crossover of the beam along the longitudinal axis.

The focusing lens (see Fig. 6) was created using elements of the bancher design of the MLUD-3 accelerator. In the frame of the bancher on the insulators, potential lens electrodes was placed. The input and output electrodes of the lens, which was under zero potential, was fixed directly on the input and output bottoms of the device. The device was mounted on the input bottom of the accelerating structure resonator with the aid of alignment devices that ensure the positioning of the resonator and the lens. A detailed description of the device construction is given in [5].

CONCLUSIONS

The conducted studies show that to match the characteristics of the beam leaving the injector to the input parameters of the accelerating path in the transport devices, one can use electrostatic lenses. At proton beam currents up to 60 mA with energy of 50 keV, three-electrode (two gap) lenses can be used for focusing. With increasing beam intensity in the range of 60...150 mA, it is necessary to use five-electrode lenses, and at higher current, use a lens with a large number of focusing gaps.

The transport and matching device developed to agreement injected deuterons beam with energy of 135 keV and a current of 0.15 A with an accelerating structure can be successfully used for a proton beam with energy of 75 keV and with the same current, selecting the potentials on the lens electrodes.

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ЛИНИЯ ТРАНСПОРТИРОВКИ И СОГЛАСОВАНИЯ ИНЖЕКТИРУЕМОГО ПУЧКА

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Рассмотрены свойства многоэлементных аксиально-симметричных электростатических линз как возможного согласующего устройства инжектора линейного ускорителя ионов. Такие линзы наиболее эффективны в области малых (до 150 кэВ) энергий инжекции, используемых в малогабаритных ускорителях ионов. Обсуждаются критерии выбора наиболее подходящих параметров линз. Представлены результаты исследования пятиэлементной линзы. Исследование проводилось численным методом. Предварительное моделирование выполнено с использованием оригинальных программ, разработанных в ННЦ ХФТИ, в которых для расчёта распределения напряжённости поля между электродами линзы использован численный код на основе метода интегральных уравнений. Детальное исследование пятиэлектродной электростатической линзы было выполнено с использованием возможностей пакета трехмерного компьютерного моделирования оптики заряженных частиц – IBSimu.

ЛІНІЯ ТРАНСПОРТУВАННЯ ТА УЗГОДЖЕННЯ ПУЧКА, ЩО ІНЖЕКТУЄТЬСЯ

А.Г. Бєліков, Л.О. Бондаренко, С.О. Вдовін, Є.В. Гусєв, О.В. Мануйленко, М.Г. Шуліка

Розглянуті властивості багатоелектродних оксіально-симетричних електростатичних лінз в якості пристрою інжектора лінійного прискорювача іонів, що транспортує та узгоджує. Такі лінзи найбільш ефективні в області малих (до 150 кеВ) енергій інжекції, які використовуються у малогабаритних прискорювачах іонів. Обговорюються критерії вибору параметрів лінз. Представлені результати дослідження п’ятиелементної лінзи. Дослідження проводилося чисельним методом. Попереднє моделювання виконано з використанням оригінальних програм, розроблених у ННЦ ХФТІ, в яких для розрахунку розподілу напруженості поля між електродами лінзи використаний чисельний код на основі методу інтегральних рівнянь. Детальне дослідження п'ятиелектродної електростатичної лінзи було виконано з використанням пакету тривимірного комп'ютерного моделювання оптики заряджених частинок – IBSimu.