ACCELERATION OF HEAVY IONS IN SPACE PERIODIC QUADRUPOLE RF FOCUSING STRUCTURE

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INTRODUCTION

Accelerators with space uniform quadrupole radio-frequency focusing (RFQ) are used for a long time already for acceleration not only protons, but also almost all spectrum of accelerated ions. In IHEP the first-ever such accelerator has been implemented, and then various accelerators with RFQ [1] have been produced some more. However, their wide application is limited only by low energy area as an initial part of the accelerator. The effective utilization of radio-frequency focusing on higher energy demands application of accelerating structure with space periodic focusing (RFQ DTL) [1], it has been carried out successfully in IHEP Protvino. Application RFQ DTL is practically realized for acceleration of protons up to 30 MeV [1]. Acceleration of heavy ions with the help RFQ DTL was never carried out, though at acceleration of heavy ions in the first sections of the linear accelerators energetically favorably use of resonators with a longitudinal magnetic field. Essential feature of space periodic focusing is dependence of focusing properties of the channel on a phase of a high-frequency field. Thus, the bunch of particles after preliminary acceleration in RFQ should be enough small in phase size, it is quite provided at acceleration of such easy ions as protons and deuterons. However at acceleration of heavy ions the phase size of the bunches changes essentially more slowly, than for protons, and its remains rather big at the reasonable sizes RFQ, used for a preliminary grouping and acceleration.

In the given report it is offered the suitable device, developed in IHEP Protvino, and parameters of section RFQ DTL. That device will consist of buncher and quadrupole lenses which allow to solve the given problem and, in general, to improve the matching of all six phase variables. Correctors of beam position in transverse plane are proposed in this matching device also.

Numerical calculations are carried out with the example of gold ions Au_{197}^{+32} at working frequency 74 MHz. Energy of transition from RFQ in RFQ DTL 0.4 MeV/u and final energy in RFQ DTL section 2 MeV/u. Calculation of section parameters for the accelerator has preliminary been carried out, determined it acceptance and separatrix. Then parameters and dynamics of a beam in the matching device have been designed. The operating mode of the described devices: $10\,\mu s$ - duration of current pulses and frequency pulses up to 10 Hz is supposed.

PARAMETERS OF RFQ DTL SECTION

The scheme of the acceleration period for RFQ DTL section is presented on fig. 1.

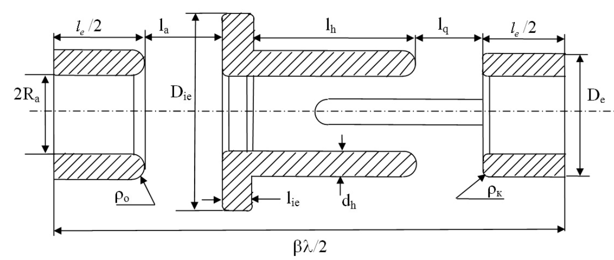

Figure 1: Acceleration period. $2R_a$ – diameter of an aperture, D_{ie} – external diameter of a space electrode, D_e – external diameter of an main electrode, d_h – diameter of a finger electrode, ρ_o – radius of a main electrode, ρ_k – radius of edges of electrodes, $\beta\lambda/2$ – length of the period of acceleration, $l_e/2$ – half of length of an main electrode, l_a – length of an axially-symmetrical gap, l_{ie} – length of an space electrode, l_h – length of a finger electrode, l_q – length of a gap between of a finger electrode and a next main electrode.

Parameters of the periods of acceleration should satisfy to a number of criteria, such as maintenance of electric strength of structure, maintenance of appropriate parameters of longitudinal and transverse movement and enough high rate of acceleration. At a choice of parameters of section RFQ DTL the special attention has been given transverse movement of particles. In this case the type of focusing FFDD has been chosen.

Acceleration and focusing of heavy ions is essentially concerned with acceptance of the channel. Dependence of focusing on phase RF field should be considered already at a preliminary stage. In this case by choice of lengths of quadrupole (focusing) electrodes l_h and lengths of axial (accelerating) gaps l_a it was possible to receive in all range of phases of acceleration such phase advance μ and the minimum value of frequency of transverse oscillation ν_{min} , which yield minimum changes μ and ν_{min} . These changes are not critical for the necessary interval phase of RF field (Fig. 2). This dependence was controlled on all length of the focusing RFQ DTL channel. It is necessary to note, that first and last period of the accelerating channel differs from the regular period (fig. 1).

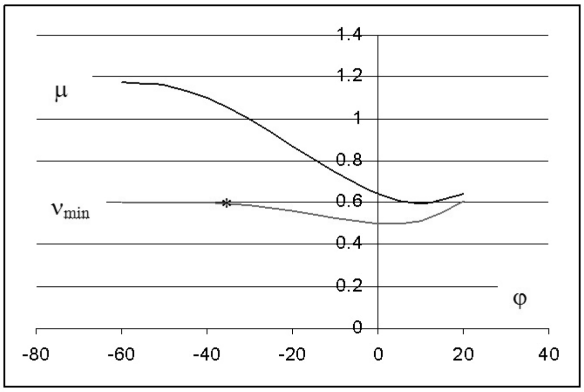

Figure 2: Phase advance μ and ν_{min} .

Under condition of preservation of transverse movement parameters presented on fig. 2 it is possible to generate geometry of the focusing channel for section RFQ DTL with the parameters presented in tab.1.

Table 1: Parameter list of RFQ DTL

Parameter	Value
Beam energy, in, KeV/u	407.113
Beam energy, out, MeV/u	2.012
Voltage across cell, kV	192÷247
Voltage across accelerating gap, kV	119÷174
Voltage across quadrupole gap, kV	73
Max. E-field on surface, kV/cm	280
Stable phase angle	-37°
Gap efficiency	0.65÷0.81
Relative frequency of longitudinal oscillation	0.07÷0.04
Trans. Phase advance	1.07÷0.901
Min. transverse frequency, ν_{min}	0.6
Norm. acceptance, mm ·mrad	2.3π

On the basis of this data the concrete geometry of section RFQ DTL has been evaluated and simulation of beam dynamics is carried out. Received separatrix and acceptance of the channel are presented on fig. 3 ÷ fig.5.

Section RFQ DTL is proposed on the basis of the sector resonator [1] with a longitudinal magnetic field. This resonator possesses good shunt impedance in a considered range of speeds of ions and experimental studies of the resonator were performed in IHEP. Essential feature of this resonator is possibility to realize variable factor of a division of voltage on length of the structure [1]. It is necessary for compensation of a decrease in acceleration rate.

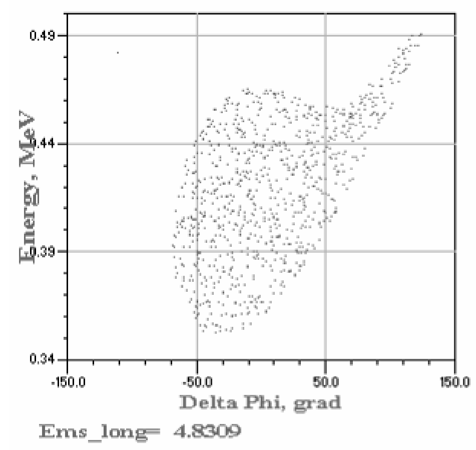

Figure 3: RFQ DTL separatrix.

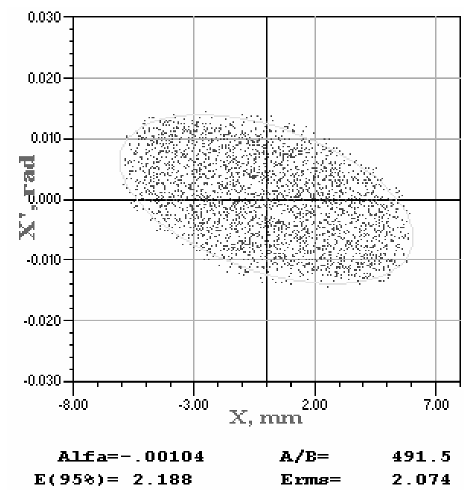

Figure 4: Acceptance x-plane.

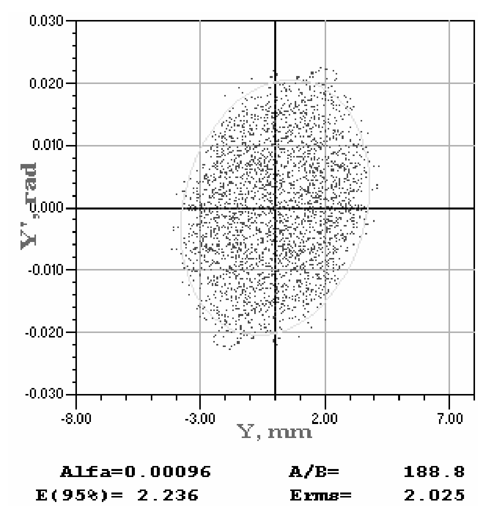

Figure 5: Acceptance y-plane.

MATCHING RFQ AND RFQ DTL

The received parameters of acceleration rate and acceptance in section RFQ DTL allow using it for acceleration of heavy ions and, particulars of ions Au_{197}^{+32} for which numerical calculation was produced. However, in this case the additional matching of a beam between sections RFQ and RFQ DTL on all phase variables (at acceleration of protons [1] these sections joined directly) is necessary. The example of calculation RFQ for heavy ions is considered in [2]. The scheme of matching device chosen in this report is shown on fig. 6.

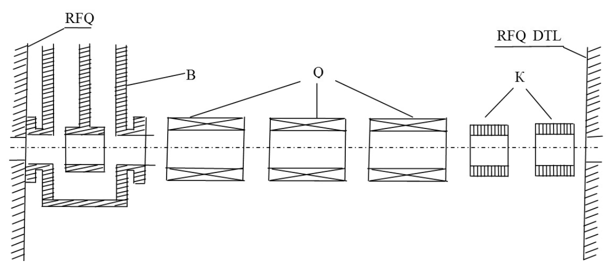

Figure 6: The scheme of matching device, B - buncher, Q - quadrupoles, K - correctors.

It is necessary to notice that for the beam matching it was applied not only the elements of the scheme represented here, but also parameters RFQ at last periods. Namely, due to a small increase of aperture radius at the output of RFQ, characteristics of a transverse movement in RFQ channel are smoothly changed and accordingly a phase portrait of a beam changes also. Such change of parameters of focusing RFQ channel already was applied in accelerator URAL 30M [1]. This part of RFQ electrodes is named by "bellmouth". Thus change of RFQ parameters and variations of magnetic field intensity in three quadrupoles Q of a matching device has allowed receiving four parameters of properties management of a beam for the matching of transverse movement for four phase coordinates.

Distance between RFQ and RFQ DTL (616 mm) is the result of the compromise between the requirement to increase this distance for placing of elements of the channel of the matching and necessity to reduce this distance to that size at which the minimum phase length of a bunch turns out. The named distance is limited by buncher in the given concrete conditions: at its further increase the phase length of a bunch increases. The distance between gaps of a buncher is equal $\beta\lambda/2$. Gradients in quadrupole lenses were estimated from matching conditions. The lengths of lenses in matching device were chosen as long as possible in order to decrease values of magnetic field gradients, but possible in the given conditions. Diameter of the aperture of lenses is chosen so that it greater than the maximum size of a beam.

The special computer program was designed for a finding of an optimum variant of the matching. It works with the help of following algorithm. In a bunch, moving in RFQ, the transverse section corresponding to a synchronous particle is selected. The rms ellipse in each of phase planes is transformed to a canonical form by turn on a angle α_i (i=1,2) and ratio of the half dimensions of ellipse is determined P_i. This procedure takes place at the RFQ DTL input. The same becomes for a corresponding acceptance ellipse of RFQ DTL. Then the functional minimum

$$F = \sum_i \left(\frac{\alpha_i - \alpha_i^0}{\alpha_i^0}\right)^2 + \left(\frac{P_i - P_i^0}{P_i^0}\right)^2$$

is solved by numerical method. The parameters designated by an index (0) concern acceptance figures. The gradients in lenses and parameters of change of transverse movement on RFQ output had been chose by the way, that was stated above. Final accurate definition of gradients in triplet lenses was provided by means of the program for numerical simulation of a beam dynamics in matching channel together with RFQ DTL. In this program all phases of a bunch, and also influence of a space charge of a bunch are considered.

The received parameters of the matching device are presented in tab.2

Table 2: Parameter list of matching device.

Parameter	Value
Length, mm	616
Aperture diameter, mm	30
Voltage, kV	202
Gap efficiency	0.89
Gradient in the first quadrupole, Tl/m	51.2
Gradient in the second quadrupole, Tl/m	60.7
Gradient in the third quadrupole, Tl/m	15.8

CONCLUSION

In the report possibility of application of structures with high-frequency quadrupole space periodic focusing for acceleration of heavy ions is shown. Developed matching device provides the beam matching in transverse phase space and reduces the longitudinal phase size of bunch for reliable capture of a beam in an acceleration mode.

REFERENCES

[1] O.K. Belyaev et al, RFQ Drift-Tube Proton Linacs in IHEP, Proceed. of LINAC 2004, Lubeck, Germany, p. 285–287.

[2] Yu.A.Budanov et al, Heavy Ion Injector for NICA/MPD Project, Proceed. Of LINAC 2008, Canada, p. 121-123.