# ACCELERATION OF THE MULTICHARGED IONS WITH DIFFERENT A/Z RATIOS IN SINGLE RFQ CHANNEL WITHOUT MAGNETIC FIELD FOCUSING

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*Abstract*

There are considered acceleration of few types multicharged ions with different A/Z ratio in single accelerating RFQ channel without outer focusing magnetic field. RFQ may be independent accelerator or as part of injection system into DTL of high energy. There are considered compact RFQ with high operating frequency (for example frequencis of P-diapason). So magnetic focusing is absent mathematical methods of control theory are used for optimization of RFQ vane geometry to obtain exit beam parameters suitable for further acceleration. It is possible separate acceleration a few type of ions in single RFQ channel or simultaneous acceleration if (case of heavy ions) ion currents are very small.

## INTRODUCTION

The purpose of this paper is to study the possibility to use a radio-frequency quadrupole (RFQ) with high operating frequency for acceleration of somewhat ion types with different A/Z in single RFQ accelerating channel without outer focusing magnetic field. Forces if space charge are considered under modelling.

At present multicharged ions are used for different applications purposes such as implantation, medical radiation therapy, filter manufacturing and researches of nuclear structure. In this last case contemporary heavy ion injectors are complex systems which can include many different elements, for example [1]: an ECR source, an extracting system, magnetic and electrostatic lenses, an accelerating column, single and multi–harmonic bunchers, a RFQ, superconducting resonators. In the papers [2, 3] it has been shown that the use of RFQ after low-energy beam transport(LEBT) improves emittance, capture ratio and current value ot the ion beams.

Resonators for multicharged ion injector that could accelerate the ions in diapason from hydrogen to uranium and from carbon to uranium were considered in papers [4] and [5] respectively. Naturally, the operating frequencies of these resonators are low (85 and 5 MHz accordingly), and they need a strong additional focusing magnetic field to provide good particle dynamics.

Separate acceleration of two or more ions types in single accelerating channel of RFQ withouth magnetic field focusing is considered in this paper. RFQ may be independent accelerator or first part of accelerating tract.

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The successful acceleration of the different types of ions separately in single RFQ channel depends on the fulfillment of a few conditions.

1. Initially RFQ channel is designed to accelerate an ion beam with the greatest A/Z ratio. It is the main particle.
2. Velocities of the ions of different types injected into the RFQ channel must be equal to the RFQ input.
3. To obtain better conditions for the acceleration of other ions (not main) the matching section geometry needs to be optimized (see [6]) and there should be a possibility to change the intervane voltage depending on the ion type in the determined limits.

The examples of ion dynamics modelling in such RFQ and description of the used codes are given below. The initial data for modeling can be found in [2, 3, 7, 8]. In general case formation of the beam for injection into RFQ can require optimization of the LEBT parameters. Possible procedure of particle dynamics optimization is presented in [9].

## RFQ OPTIMIZATION AND BEAM DYNAMICS MODELING

Software package DAISI was used for RFQ designing. For dynamics modeling the DAISI uses the standart model with standing-wave approximation [10].

$$\frac{d^2 z}{d\tau^2} = Q_z, \quad \frac{dS_{11}^{x,y}}{d\tau} = S_{21}^{x,y},$$
$$\frac{dS_{21}^{x,y}}{d\tau} = Q_{x,y}S_{11}^{x,y} + S_{22}^{x,y}, \quad \frac{dS_{22}^{x,y}}{d\tau} = 2Q_{x,y}S_{12}^{x,y}.$$

Here $\tau = ct$; $Q_z, Q_x, Q_y$ is RF field and space charge forces; $S_{11}^{x,y}, S_{21}^{x,y}, S_{22}^{x,y}$ — elements of $G^{x,y} = \begin{pmatrix} S_{11}^{x,y} & S_{21}^{x,y} \\ S_{21}^{x,y} & S_{22}^{x,y} \end{pmatrix}$, which describe the dynamics of the initial transversal distribution ellipses $G_0^{x,y}$ in phase planes $(y, dy/dt)$ and $(x, dx/dt)$. In this mode longitudinal motion dont depend on transversal one. Space charge forces may be included on optimization stage. Calculations by code LIDOS are used on this stage also for find correction of results. Two of methods of numerical optimization dynamics are used in DAISI: particle swarm method(PSM) and gradient descend paradigm for evaluation of synchronous phase sequence and acceleration efficiency. In PSM multivariable function optimization may



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be represented following way: $F(\mathbf{x}) \to \min_{\mathbf{x}\in U}$. Here $F$ is the fitness function, $\mathbf{x}$ is the vector of the fitness function arguments, $U$ is the set of allowable $\mathbf{x}$ values (search-space).

Updating agents position at the each method iteration is:

$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + d\mathbf{x}_i(t).$$

The agents positions increments are updated using the following equation

$$d\mathbf{x}_i(t+1) = d\mathbf{x}_i(t) + \varphi_p r_p(\mathbf{p}_i(t) - \mathbf{x}_i(t)) + \\ + \varphi_g r_g(\mathbf{g}(t) - \mathbf{x}_i(t)).$$

Here $\varphi_g$ and $\varphi_p$ are the predefined weight parameters, $r_p \in [0,1]$ and $r_g \in [0,1]$ are random numbers.

Gradient's method completes PSM and permits to obtain local minimum of fitness function. The $i^{th}$ component $x_i^k$ of solution $\mathbf{x}^{k-1}$ on $k^{th}$ algorithm iteration are updated using the following equation

$$x_i^k = x_i^{k-1} + \alpha^k \frac{F(\mathbf{x}^{k-1} + \Delta x_i^{k-1}) - F(\mathbf{x}_i^{k-1})}{\Delta x_i^{k-1}} + \\ + \beta(\mathbf{x}^{k-1} - \mathbf{x}^{k-2}).$$

Here $\alpha^k$ is the step on the $k^{th}$ iteration, $\Delta x_i^{k-1}$ is the small argument increment, $\beta$ is the predefined constant.

The RFQ design approach realized in the DAISI code is based on the division of the regular part of the RFQ channel in four parts — two parts for the gentle buncher, forming section and accelerating section. On each part with label $k$, the modulations and the synchronous phases are approximated using the following approach.

$$\varphi_i = \varphi_k + \frac{\varphi_{k+1} - \varphi_k}{N_k^{p_k}}(i - \sum_{j=0}^{k} N_j)^{p_k},$$

$$m_i = m_k + \frac{m_{k+1} - m_k}{N_k^{q_k}}(i - \sum_{j=0}^{k} N_j)^{q_k}.$$

Here $i$ is the cell number, $\varphi_k$ and $m_k$ are synchronous phase and modulation at the beginning of the part with the label $k$, $q_k$ and $p_k$ are non-negative constants, $N_j$ is the number of cells that forms a part with the label $j$. In the first part we assume $m_0 = 1$ and $\varphi_0 = -\pi/2$. The matching section is located before the regular part of the RFQ channel. Therefore, we have to obtain a set of 18 parameters $N_k$, $q_k$, $p_k$, $\varphi_{k+1}$, $m_{k+1}$, $(k = \overline{0...3})$, which will determine the geometry of RFQ electrodes. In the work [11] we propose a procedure of obtaining these parameters based on the maximization of the capture ratio and minimization the beam emittance growth.

For the accurate estimation of the beam characteristics, the electrode parameters calculated by the DAISI were exported to the LIDOS RFQ Designer code [12]. Later, LIDOS was used for the final correction and selection of the channel parameters, considering the real shape of the electrodes, their possible sectioning for mechanical processing, electrodynamics settings, etc. Full 3D particle-in-cell simulations were performed by LIDOS considering the real shape of electrodes.

## EXAMPLES OF PREACCELERATION OF CARBON IONS WITH Z=4+ AND Z=6+

The preacceleration of $C_{12}^{4+}$ and $C_{12}^{6+}$ ions was considered in papers [7, 8] with respect to the German proposal for the HIT medical facility. Because the yield of $C_{12}^{6+}$ ions from ECR source is small, $C_{12}^{4+}$ ions were accelerated up to 7 MeV/u by a tandem of RFQ + IH-linac and necessary quantity of $C_{12}^{6+}$ ions was obtained by stripping of $C_{12}^{4+}$ ions on special foil. It is possible in the future to obtain quite enough quantity of $C_{12}^{6+}$ ions directly from ECR source and only then RFQ channel may be used for the acceleration of both $C_{12}^{4+}$ and $C_{12}^{6+}$ ion type.

The characteristics of the beam and the RFQ channel parameters are presented in Table 1. The initial data for modeling can be found in works [7, 8]. We suppose that $C_{12}^{4+}$ ion beam may be optimally matched to the RFQ channel with the help of LEBT and RFQ matching section, as discussed in [7]. In this case, the beam of $C_{12}^{6+}$ can be mismatched. To estimate a capture ratio of mismatched $C_{12}^{6+}$ beam, the neutral input ellipses in XdX and YdY axes were used. Dependences of the current capture ratio on the input current are presented in Fig. 1.

Table 1: Main Carbon RFQ Parameters

| | |
|---|---|
| Input ions energy, MeV | 0.096 |
| Output ions energy, MeV | 3.57 |
| Operating frequency, MHz | 216 |
| Kilpatrick factor Emax/Ekilp | 1.8 |
| Intervane voltage for $C_{12}^{4+}$ ions, kV | 70 |
| Intervane voltage for $C_{12}^{6+}$ ions, kV | 46.6 |
| Average channel aperture radius, mm | 3 |
| Maximal modulation | 1.3 |
| Input impulse current, mA | 0-10 |
| Input emittance, pi·cm·mrad (RMS, norm) | 0.03 |
| Initial momentum spread, % | ±2.5 |
| Accelerator length, m | 1.83 |
| Zero current 90% emittance growth ($C_{12}^{4+}$) | 2.1 |
| Bunch phase width (90%, 1 mA, $C_{12}^{4+}$), deg | 38 |
| Bunch momentum width (90%, 1 mA, $C_{12}^{4+}$), % | 2.3 |

## EXAMPLES OF PREACCELERATION OF HARD MULTICHARGED IONS KR, AR

The characteristics of the beam and the RFQ channel parameters are presented in Table 2. The initial data for modeling can be found in work [13]. The system of the axial beam injection described in this work produces the beam of $Kr_{86}^{13+}$ ions with 8 mm width and 35 mrad divergence. For matching this beam with the RFQ, the channel radius has



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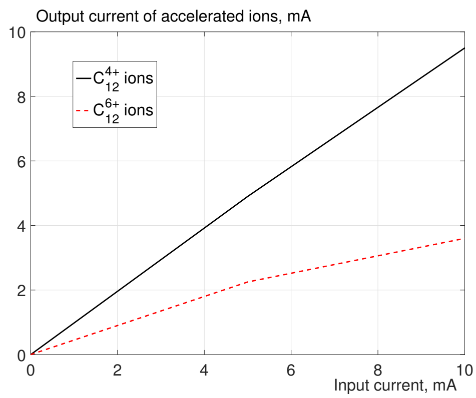


Figure 1: Dependence of the current of accelerated ions on the input impulse current

to be increased to 6.25 mm. The capture ratio in this case considerably decreases to 0.52 obtained using the DAISI. However using the above described optimization procedure (PSM, gradient descend optimization), the capture ration significantly improved (see Table 3).

Table 2: Main RFQ Parameters for Multicharged Ions Kr, Ar

| | |
|---|---|
| Input ions energy, keV/u | 3 |
| Output ions energy, keV/u | 350 |
| Operating frequency, MHz | 108 |
| Intervane voltage for Ar/Kr ions, kV | 90/68 |
| Average channel aperture radius, mm | 6.25 |
| Maximal modulation | 1.5 |
| Minimal channel radius, mm | 5.44 |
| Input impulse current, mA | <0.2 |
| Input emittance for Ar/Kr ions, pi·cm·mrad (RMS, normalized) | 0.04/ 0.03 |
| Initial momentum spread, % | ±2.5 |
| Accelerator length, m | 4.66 |

Table 3: Output parameters of Kr, Ar accelerated beams before and after optimization calculated using LIDOS and DAISI.

| | Capture ratio | Bunch phase width (90%), deg | Bunch momentum width (90%), % | emittance growth (90%) |
|---|---|---|---|---|
| before optimization | | | | |
| $Kr_{86}^{13+}$ | 0.52 | 22.2 | 1.28 | 2.4 |
| $Ar_{40}^{8+}$ | 0.5 | 21 | 1.34 | 1.8 |
| after optimization | | | | |
| $Kr_{86}^{13+}$ | 1.0 | 21.6 | 1.26 | 2.3 |
| $Ar_{40}^{8+}$ | 1.0 | 20.6 | 1.3 | 1.7 |

## CONCLUSION

Modeling results presented in this paper show it is possible separate acceleration a few type ions with different ratio A/Z in single RFQ channel with current 2-10 mA and withouth magnetic field focusing. Thank to application of numerical optimization methods vanes geometry of mathiching section and regular part of RFQ one obtained output beam parameters (capture, beam losses, emittance, phase width, energy spectrum) suitable for injection into DTL, booster or for transport to target.

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