# FRONT END DESIGN OF THE RIA DRIVER LINAC*

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*Abstract*

This paper describes the front end design for the RIA driver linac which is able to select, separate and accelerate in the RFQ the required ion species of one- or two-charge states. The front end consists of an ECR ion source located on a 100 kV platform, LEBT, RFQ and MEBT. The first section of the LEBT is an achromatic bending system for charge-to-mass analysis and selection. For the heaviest ions with masses above 180, the transport system is able to deliver to the entrance of the first buncher a two-charge-state beam with similar Twiss parameters for both charge states. In order to match two-charge-state ions with different mass to charge ratios, the straight section of the LEBT upstream of the RFQ will be placed on a high-voltage platform. A voltage ~30 kV is required in order to match velocities of ions with mass to charge ratio less than the design value and to maintain the possibility accelerating two charge states simultaneously. Several beam matching schemes in the transitions LEBT-RFQ and RFQ-MEBT have been studied.

## INTRODUCTION

The RIA driver linac will deliver a wide range of ions to secondary beam targets. The linac is designed for simultaneous acceleration of ions with different charge states to obtain the required beam power, up to 400 kW, even with limited intensity of highly charged heavy ions available from present ECR ion sources. The dynamics of multiple-charge-state beams have to be designed to prevent emittance growth in all sections of the linac. It is especially important to form high quality two-charge-state beam in the front end of the linac. To achieve this goal the front end has been designed taking into account higher order terms of focusing and accelerating fields and space charge of multi-component heavy-ion beams extracted from the ECR. Finally, the design has been analyzed and corrected with the help of beam dynamics simulation codes in realistic 3D fields.

## LEBT DESIGN

The LEBT performs two main tasks: 1) an achromatic bending system for charge-to-mass analysis selects one or two charge state heavy ion beams; 2) a straight section forms longitudinal emittance and matches the beam to the following RFQ. The design of the straight section which comprises a multi-harmonic buncher (MHB), velocity equalizing resonator and focusing elements has been reported in ref [1]. The schematic layout of the LEBT is shown in Fig. 1. According to ref. [1] the lowest possible longitudinal emittance of a two charge state beam accelerated through an RFQ can be obtained using an external MHB. A resonator installed immediately upstream of the RFQ entrance equalizes the average velocity of ions with different charge states.

### *Achromatic bending system*

This section consists of two $60^0$ bending magnets, two electrostatic quadruple lenses, four sextupoles and a solenoid. A high dispersion area is formed by the first magnet where the required one- or two-charge state beam can be defined and transported to the RFQ. The baseline design of the RIA driver linac calls for 100 kW uranium beam that requires ~2 pμA in charge states 28 and 29. The estimated total beam current extracted from the ECR will be ~2 mA. The space charge of this multi-component ion beam effects the uranium beam parameters. To compensate the linear component of the space charge forces a solenoid magnet between the ECR and bending magnet is used. It has been found that changing solenoid position and field level provides required beam matching to the location of the horizontal slits.

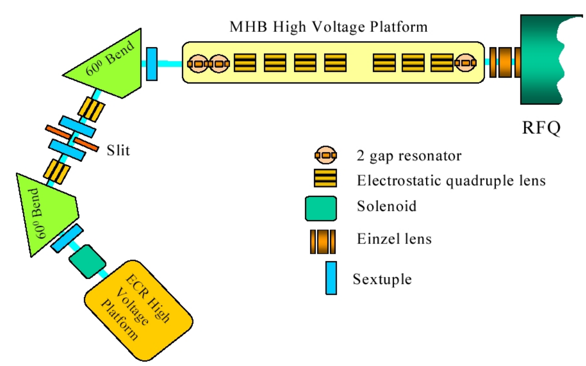


Figure1: Schematic layout of RIA driver LEBT

### *Straight section*

The straight section of the LEBT includes a MHB, a velocity equalizer (VE), electrostatic quadruples and Einzel lens. All elements of this section except the Einzel lens are placed on a high voltage platform. The MHB consists of two quarter wave resonators. The first resonator provides the required voltage at the fundamental operating frequency, 28.75 MHz, and the third harmonic. The second resonator is operated at the second harmonic.

The distance between MHB and VE is determined by the need to separate the two charge states into adjacent RF buckets of the RFQ and is defined by the following expression:

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$$L = \lambda \sqrt{\frac{2e \cdot V_0}{Am_0 c^2}} \frac{\sqrt{q_0 (q_0 - 1)}}{\sqrt{q_0} - \sqrt{q \ \ -1}},$$

where $e$ is the elementary charge, $V_0$ is the accelerating voltage, $A$ is the mass number, $m_0$ is the nucleon rest mass, $q_0$ is the highest charge state of ions, $c$ is the speed of light. The distance depends on the charge-to-mass ratio and is equal to 1.507 m for the heaviest ions $U^{29+}$ and $U^{28+}$ at $V_0$=100 kV.

The LEBT can be tuned to accept any two-charge-state ions with masses A≥180 by satisfying two conditions: 1) provide the design velocity at the RFQ entrance for the average charge state; 2) provide the same time difference between the two charge states over the distance $L$, between the MHB and VE. The first condition is fulfilled if the voltage of the ECR ion source is

$$V_{01} = 2\beta_{av}^2 \frac{Am_0 c^2}{e \cdot \left(\sqrt{q_0} + \sqrt{q_0 - 1}\right)^2}.$$

The second condition can be satisfied if the MHB and VE are biased by the voltage $\Delta V = V_{01} - V_{02}$, where

$$V_{02} = \left(\frac{L}{\lambda}\right)^2 \frac{Am_0 c^2}{2 \cdot e} \left(\frac{1}{\sqrt{q_0}} - \frac{1}{\sqrt{q_0 - 1}}\right)^2.$$

This value varies as a function of the charge to mass ratio of ions. This dependence is shown in Figure 2 which plots the voltage ΔV as a function of the charge state $q_0$ for three different mass number.

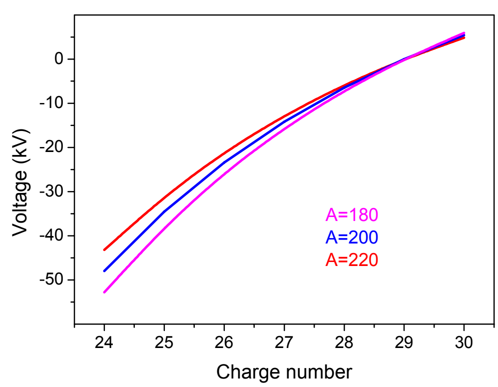


Figure 2: LEBT bias voltage as a function of charge state.

The electrostatic quadruples are used for beam focusing in this section of the LEBT and form a round beam waist in the VE. Matching of the low-velocity beam to the RFQ acceptance is a challenging task due to the large difference in the focusing strength of the LEBT and RFQ. The distance between the VE and RFQ should as short as possible in order to have effective bunching of two-charge-state beams. To minimize this space a relatively short Einzel lens is used for the matching of the axially symmetric beam to the RFQ acceptance which is defined by the RFQ radial matcher.

# MODIFICATIONS OF THE RFQ DESIGN

The detailed description of the RIA RFQ is given in [2]. The main goal of the beam dynamics design of the RFQ was to match the parameters of the RFQ with the longitudinal emittance formed by the MHB, eliminate halo particles from the acceleration process and keep the transverse emittance of a two-charge-state beam unchanged. The basic RFQ parameters are given in Table 1. To address the beam matching in the transitions LEBT-RFQ and RFQ-MEBT the entrance and exit radial matchers have been carefully analysed and modified designs of these sections of the RFQ have been proposed.

Table 1: The main RFQ parameters.

| | |
|---|---|
| Average radius $R_0$ | 0.6 cm |
| Vane-to-vane voltage $U_0$ | 68.5 kV |
| Output beam energy | 199 keV/u |
| Synchronous phase $\varphi_s$ | $-25^0$ |
| Normalized trans. acceptance | >1.8 π·mm·mrad |
| Vane length | 392 cm |

## *Entrance radial matcher*

The external buncher forms a very short bunch length ~40° at the entrance of the RFQ. For such a short bunch there is no need for a standard radial matcher which provides dynamic matching over 360° and requires convergent beam to be matched. As was pointed out in ref. [3], by providing an appropriate RFQ vane profile it is possible to form matched conditions of the beam waists in both planes at the RFQ entrance. For this modified matcher there is no need to have any focusing elements between VE and RFQ because the matched parameters can be easily provided by quadrupoles placed upstream of the VE. The parameters of the conventional and modified matchers are given in Table 2.

Table 2: Parameters of the conventional and modified radial matcher.

| | Conventional | Modified |
|---|---|---|
| Length | 170 mm | 300 mm |
| Mismatch factor | 1.15 | 1.107 |
| Emittance growth in the upstream LEBT | 14% | - |
| Twiss parameters α<br>β (cm/mrad) | 1.3737<br>0.088 | -0.048<br>0.093 |

The quoted length of the conventional matcher includes Einzel lens. In spite of the fact that the modified matcher is longer, it does not increase the total length of the RFQ because electrodes behind the horn are modulated so the number of accelerating cells is the same as in the initial design. The modified matcher mitigates emittance growth in the LEBT.

### *Exit radial matcher*

We have found that solenoid focusing in the MEBT produces a minimal mismatch of two-charge state beams compared with any other type of focusing. There is a need to match beam between the RFQ and this axially symmetric transport channel. One solution is using electromagnetic or electrostatic triplet quadruple lenses immediately after the RFQ. A short transition cell at the end of the RFQ vanes is used in this case to obtain the beam waists in both transverse planes. The second option is using a 4-cell RFQ radial matcher which can form an axially symmetric beam as was proposed in ref. [4]. As was found both solutions provide required beam matching to the MEBT based on solenoid focusing.

## BEAM DYNAMICS SIMULATIONS

The first order design of the LEBT has been carried out using TRACE-2D and -3D codes [5]. Higher order optimization has been done using the code GIOS [6]. The RFQ has been designed using code DESRFQ [7]. Further optimization of the LEBT has been based on simulations of multi-component heavy-ion beam dynamics using multiparticle codes TRACK [8] and DYNAMION [9].

TRACK has been especially developed for the RIA driver design and allows us to perform end-to-end simulations beginning from the ECR ion source. The main feature of the code is the use of a realistic preliminary calculated 3D representation of external accelerating and focusing fields. DYNAMION has been primarily used for the beam dynamics simulations in the RFQ.

Beam simulations starts with a multi-component heavy-ion beam exiting the ECR. To produce 60 eμA total uranium two-charge-state beam at the RFQ entrance the ECR extracts >2 mA multi-component heavy-ion beam. In our design and simulation we have assumed the same Twiss parameters for all ion species exiting the ECR. Most ion species are eliminated by the first bending magnet. Figure 3 shows phase space plots at the location of the slits shown in Fig.1. It presents the design uranium ions and nearest unwanted ions $O^{2+}$ simulated for a total input total current 2 mA. The simulations show the system separates charge states reliably over full range of total input beam current and provides at MHB similar Twiss parameters of transverse emittances for both charge states.

The Fig. 4 shows simulated beam envelopes in a modified and conventional radial matcher. The envelope for the last case is shown for Einzel lens and RFQ matcher. The simulations confirm that the modified matcher provides perfect matching not only for short bunches, but also in case of unbunched beam.

The results for both exit matchers are presented in Table 2. It shows that the both options solve the task of matching the RFQ output beam with a solenoid channel but the option with a short transit cell seems more practical because it simplifies the RFQ design and allows more flexible control of beam parameters.

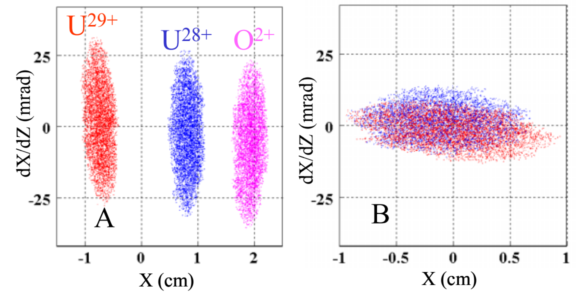


Figure 3: Transverse phase space plots in bending section. (A) at slit position shown in Fig.1. (B) – at MHB entrance.

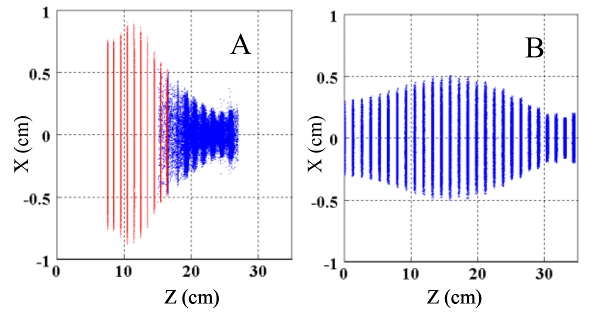


Figure 4: Envelopes in conventional (A) and modified (B) RFQ entrance radial matcher.

Table 2: Beam parameters of the beam at RFQ exit for both charge state

| Twiss parameters | 4-cell matcher | | Short transition cell | |
|---|---|---|---|---|
| | X | Y | X | Y |
| α | -0.446 | -0.37 | 0.04 | 0.05 |
| β (cm/mrad) | 0.029 | 0.030 | 0.019 | 0.010 |

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