

DESIGN STUDY OF A MULTIPLE-BEAM RFQ VERSION OF A HIGH-CURRENT LINAC INJECTOR FOR A NEUTRON SOURCE

Valeri KAPIN, Makoto INOUE and Akira NODA
Accelerator Laboratory, Nuclear Science Research Facility,
Institute for Chemical Research, Kyoto University,
Gokanoshō, Uji, Kyoto 611

Abstract

The linac-based hybrid neutron source has been outlined in Ref. [1] as a future plan of the Research Reactor Institute of Kyoto University. An alternative concept of a high-current pre-injector for the hybrid system is proposed. It consists of a multiple-beam RFQ structures (MB-RFQ) and beamlets-combining systems.

Beam dynamics study for the initial 400-keV part of MB-RFQ has been performed using PARMTEQ code. The MB-RFQ parameters and the results of beam dynamics simulations are presented. The calculated beam transmission is 30% at injection of 50-keV, 20mA deuteron beam.

1 INTRODUCTION

An accelerator-driven nuclear fuel assembly [1] had been outlined as a future plan of the Research Reactor Institute of Kyoto University. The initial part of the accelerator has to accelerate 100-mA deuteron beam with a high-duty factor. Up to now, a practically achieved current for CW deuteron RFQ is about 50 mA [2]. To facilitate difficulties at an initial part of the linac, an alternative design with multiple-beam initial part is considered in the present work as one of possible candidates.

The proposed multiple-beam injector consists of a multiple-aperture ion source, multiple-beam RFQ structures (MB-RFQ) and beamlets-combining systems. In this injector, the beamlets arranged as a matrix-array has to be accelerated and combined into a single high-current beam.

A new principle for MB-RFQ had been suggested in Ref. [3]. In this structure, neighbouring beamlets are located closely each to other in order to accept highly packed beamlets from a multiple-beam ion source and to facilitate a further funneling system. To provide high packing of beamlets, discrete connections of adjacent RFQ electrodes are allowed. The beam dynamics in RFQ-channels is modified. Beams perform a “slalom” motion due to intrinsic transverse oscillations.

The modification of the beam dynamics degrades RFQ characteristics. It is important to evaluate an achievable

beam transmission and current for the modified RFQ. In this paper, the results of beam dynamics simulations for the RFQ channel with a “slalom”-beam are presented.

2 STUDY OF MB-RFQ BASED LINAC

1.1 An 8-MeV Multiple-beam injector

A basic concept of a high-current 8-MeV 108-MHz injector which accelerates and combines the initial 36 beamlets arranged as a 6x6 matrix array of beamlets into a single RF bucket is summarised as the following .

Ions of deuterons or hydrogen molecules extracted from a 50-keV ion source are accelerated to 400 keV by the first 6x6-matrix array MB-RFQ. Combining transversely groups of four neighbouring beamlets, a system of electrostatic (or permanent magnet) deflectors provides 9 united beamlets, which are accelerated by the second MB-RFQ to 1 MeV. Combining 9 beamlets longitudinally, a system of bending magnets and RF deflectors provides a resulting single beam, which is bunched and accelerated to 8 MeV by the third RFQ.

The key unit of the proposed injector is the initial 400-keV MB-RFQ. In this paper, a study of its potential abilities is reported.

2.2 400-keV MB-RFQ

The 400-keV MB-RFQ linac consists of two different RFQ structures. The first MB-RFQ is a conventional RFQ acceleration and focusing in a quarter-wave resonator with an increasing RFQ voltage. The second structure is MB-RFQ resonator for a “slalom”-beam. The Fig. 1 shows the cross-sections of a one channel and the voltage distributions on the electrodes of the RFQ resonators.

The first resonator performs a radial matching, bunching and pre-acceleration of beam from 50keV to 114 keV. All RFQ-electrodes are connected to the one bottom of the tank and have open ends at the right bottom. The length of the resonator, l is equal to about a quarter of the wavelength λ , i.e. $l=0.7$ m at the frequency $f_0=108$ MHz.

The “slalom”-beam RFQ accelerates a bunched beam at an almost constant synchronous phase up to 400 keV.

It is composed of two unit modules. In order to prevent close packing of beam channels in the multiple-beam structure, this resonator has a special voltage distribution patterns, which allows discrete connections of adjacent RFQ electrodes.

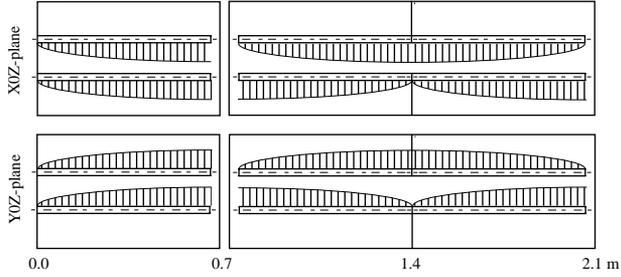


Figure 1: The cross-sections of two RFQ resonators and the voltage distributions on the electrodes.

At every cross-section of the resonator, its conductors have some definite voltages U_1, U_2, U_3, U_4 . A conventional RFQ field is provided by a special shaping of the pole tips. The surfaces of the pole tips are defined from the equation

$$U_i = U(r, \psi, z), \quad i = 1, \dots, 4, \quad (1)$$

where $U(r, \psi, z)$ is the lowest order electric-field potential function fields given by the equation [4,5]

$$U(r, \psi, z) = (V/2)[\kappa(r/a)^2 \cos 2\psi - AI_0(kr) \sin kz] \quad (2)$$

with

$$A = \frac{(m^2 - 1)}{m^2 I_0(ka) + I_0(mka)}, \quad \kappa = 1 - AI_0(ka), \quad k = \frac{2\pi}{\beta\lambda}$$

Figure 2 shows the pole tips at the ends and the middle of the second resonator. The length of the unit module of the resonator, l is about a quarter of the wavelength, λ . Apart from conventional modulation of RFQ electrodes with period length, $\lambda_{\text{RFQ}} = 2\beta\lambda$, the pole tips are modulated with the period length, $\lambda_{\text{RFQ}} = 2l$. The RFQ-channel has a zero optical transparency, and could not provide a conventional RFQ acceleration on z-axis.

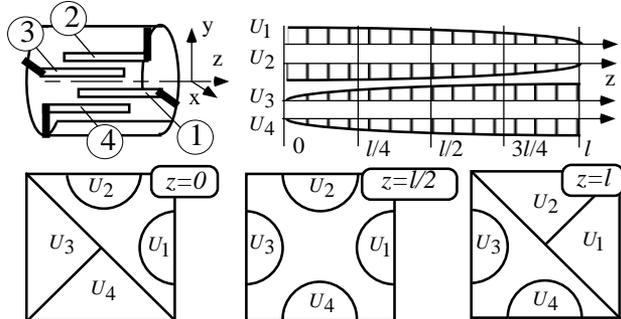


Figure 2: Unit module of a "slalom" beam RFQ resonator, voltage distributions on its conductors, and pole tips at different cross-sections of the resonator.

The beam motion is modified in this case. The beam with the velocity, $v = \beta c$ is injected with a shift from the RFQ axis and oscillates coherently around the quadrupole

axis with the frequency of betatron oscillations, Ω_R . When the wavelength of the betatron oscillations, $\Lambda_R = 2\pi\beta c/\Omega_R$ is matched to the period length of the pole tips modulation, i.e. $\Lambda_R = \lambda_{\text{RFQ}}/(2n+1)$, the beam bends round the pole tips performing a kind of "slalom" motion. Under this condition, the smooth frequency of betatron oscillation, μ_R is proportional to the relative velocity, β

$$\mu_R = 8\pi(n + 1/2)\beta \quad (3)$$

The last equation defines the increasing dependence of the radial focusing forces along the RFQ channel at a fixed number, n .

The design parameters of MB-RFQ calculated with RFQGEN of PARMTEQ code are presented in Fig. 3. The "slalom"-beam RFQ section was designed using the condition (3).

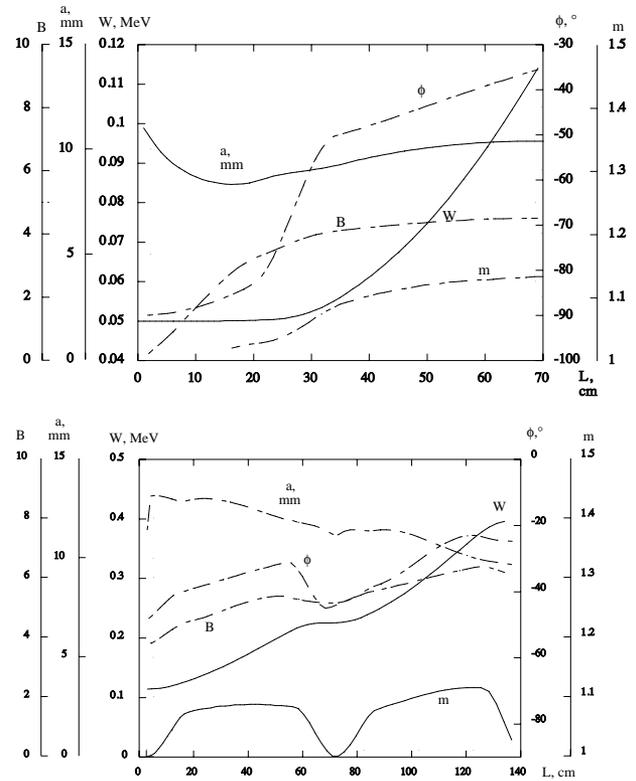


Figure 3: Parameters for the first (the top graph) and the second (the bottom graph) 108-MHz MB-RFQ channels.

2.2 Simulations Results of the RFQs

The beam dynamics simulation has been performed with PARMTEQ code. The pole tips of RFQ-electrodes have been obtained by a numerical solution of equation (2) and introduced into PARMTEQ code. Particles which hit the pole tips of modified RFQ electrodes in the second section has been marked as lost particles and excluded from beam dynamics simulations.

The first section has been designed to accept a continuous monochromatic beam with the transverse emittance $\varepsilon=25\pi$ cm mrad at 50 keV. The beam is bunched within a short length of structure ($l = \lambda/4$) with a fast increase of the synchronous phase (see Fig.3). For initial K-V beam ($\alpha_{x,y}=0.8$, $\beta_{x,y}=15.0$ cm/rad), the beam transmission is equal to 78% for a zero-current beam. It reduces to 68% and 62% at the beam current 15 mA and 30 mA, respectively. Figure 4 shows the example of the beam-structure and the electrode profiles in the X0Z-plane.

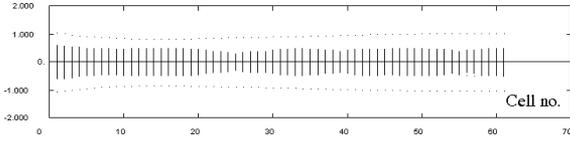


Figure 4: The X0Z cross-section of the RFQ-channel showing the beam structure and the electrode profiles of the first section.

The simulation of the “slalom”-beam RFQ has been made for beam with the energy spread ± 5 keV and the phase spread $\pm 50^\circ$ and the transverse emittance $\varepsilon=15\pi$ cm mrad. The initial and final phase spaces for injected K-V beam ($\alpha_x=-0.8$, $\beta_x=8.0$ cm/rad and $\alpha_y=0.8$, $\beta_y=8.0$ cm/rad) with a zero current are shown in Fig.5.

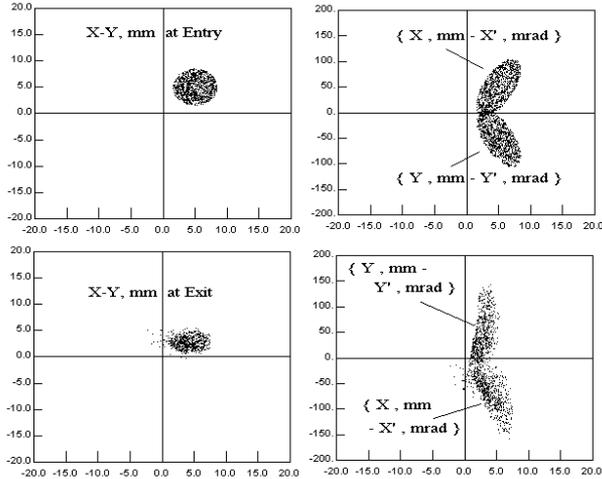


Figure 5: The phase spaces of the injected beam (the top graphs) and at the end of structure (the bottom graphs).

It was found that due to different initial phases of betatron oscillations in X and Y planes, the beam should be injected at some angle to the system axis. The X, X', Y, and Y' displacements of the injected beam are equal to 0.5cm, +0.05rad, 0.5cm, and -0.05, respectively.

The calculated beam transmission is equal to 66% for a zero-current beam. At the beam current 15 mA and 30 mA the beam transmissions become to 63% and 53%, respectively. Figure 6 shows the example of the beam motion and the electrode profiles in the X0Z-plane. Similar situation occurs for XOY-plane. Beam performs “slalom” motions, avoiding pole tips.

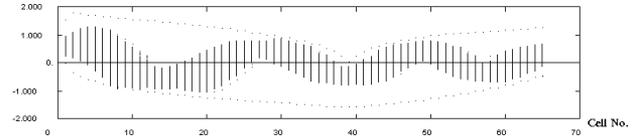


Figure 6: The X0Z cross-section of the RFQ-channel showing the beam structure and the electrode profiles.

Finally, common transmission of two structures has been calculated. The transmission of 42% for a zero-current beam reduces to 33% at the beam current of 20 mA, respectively. Fig. 7 shows the phase spaces of the output beam for the latter case.

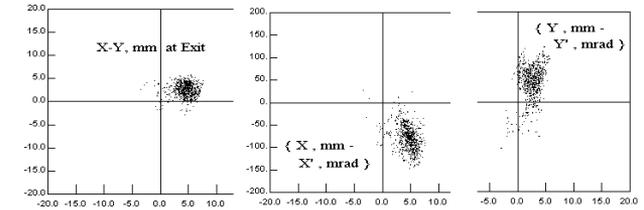


Figure 7: The phase spaces of the 400-keV beam at the injection current of 20 mA..

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