PRELIMINARY DESIGN OF A HIGH-INTENSITY CONTINUOUS-WAVE DEUTERON RFQ

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Abstract

A high-intensity deuteron linear accelerator is currently being studied as a promising candidate to treat high-level radioactive waste through the nuclear transmutation process. This paper presents the study on a design of a 75.5 MHz, 400 mA, continuous-wave deuteron radio-frequency quadrupole (RFQ), which is proposed as the front-end of such a linear accelerator. The results of the beam dynamics simulation suggest that the designed RFQ can accelerate a 400-mA deuteron beam from 100 keV to 2.5 MeV with a transmission rate of 92 ~ 93.3%, depending on the assumed input transverse emittance.

INTRODUCTION

To reduce nuclear waste, we are proposing a linear accelerator (LINAC) system that delivers high-intensity deuteron (D) beams to the waste target. The reaction between D and the elements in the waste has been under investigation [1, 2]. The required beam intensity has been estimated to be 1000 mA [3], which is beyond the capability of existing accelerators. Thus, a continuous-wave (CW) 400 mA D^+ LINAC is being considered. Multiple LINACs can be built to meet the intensity requirement. Superconducting cavities are also being designed [4] for the high-energy part of such a LINAC. The low-energy part is also critical, for which we propose a radio-frequency quadrupole (RFQ) structure.

High intensity RFQs have become a popular low-energy solution since the 1980s [5]. Especially for the CW beam, RFQs can be used as a buncher as well as an accelerator. The most recent high-intensity D^+ RFQ is the RFQ of the IFMIF project (IFMIF-RFQ) [6], which is scheduled for beam commissioning this year [7]. Our RFQ is similar to the IFMIF-RFQ in many ways except that in our case, we are considering a higher-intensity, 400 mA beam. In this paper, we will present our conceptual beam dynamics design of the RFQ by leaving some of the challenging issues for future work.

In the next section, the RFQ parameters and estimation of the design parameters are presented. The simulation results are discussed after that, followed by a summary.

DESIGN PROCESS AND OPTIMIZATION

RFQ Parameters

The design specifications of this deuteron RFQ (RFQ-D) are listed in Table 1. The input beam energy is 100 keV. The frequency is chosen to be identical to the superconducting cavities [4], which can accept D^+ with a $\beta(= v/c$, where v is the particle velocity and c is the speed of light) as low as 0.05. Thus, the output energy is chosen to be 2.5 MeV. For the emittance, there is currently not enough information. In the study of the IFMIF-RFQ design, this value is chosen to be 0.25 π.mm.mrad. The commissioning results of the IFMIF ion source indicate that the actual emittance is 0.34 π.mm.mrad in the case of their 109 mA D^+ beam in CW mode [7]. Based on the simulation carried out in this study, the results with a normalized emittance of 0.25 ~ 1 π.mm.mrad will be compared.

Table 1: Design Specifications

Beam	D^+
Frequency [MHz]	75.5
Input current [mA]	400
Duty	100% (CW)
RMS input emittance (normalized) [π.mm.mrad]	0.25 ~ 1
Input total energy [MeV]	0.1
Output total energy [MeV]	2.5

Design Parameters Estimation

The maximum surface electric field is determined by the well-known Kilpatrick criterion [8] which can be written as,

$$f = 1.643E^2 e^{-8.5/E} \tag{1}$$

The maximum electric field allowed for the RFQ-D is 18.67 MV/m, if given the same $K_p = 1.82$ as the IFMIF-RFQ. Both RFQs are marked on Fig. 1, where RFQ-D is the RFQ in this paper.

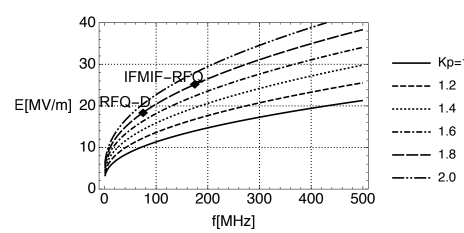

Figure 1: Maximum surface electric field in terms of frequency and Kilpatrick factor.

In the RFQ, the transverse motion is well-approximated by Mathieu's equation when the space charge is negligible,

$$\frac{d^2x}{d\eta^2} + (B\sin(2\pi\eta) + \Delta_{\rm rf})\, x = 0 \tag{2}$$

where B is the focusing factor, $\Delta_{\rm rf}$ is the RF defocussing factor, and $d\eta = dz/\pi$ is the longitudinal coordinate.

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The focusing factor B is,

$$B = \frac{q\lambda^2 V_0}{m_0 c^2 r_0^2} \tag{3}$$

where q is the particle charge, λ is the wavelength, V_0 is the vane voltage, m_0 is the particle mass, and r_0 is the average aperture.

The RF defocussing factor is,

$$\Delta_{\rm rf} = \frac{q\pi^2 V_0}{2m_0 c^2 \beta^2} A \sin\phi_s \tag{4}$$

where A is the acceleration efficiency, which can be expressed in terms of the modulation m, and k and a are the wave number and small aperture of a Bessel function, respectively.

$$A = \frac{m^2 - 1}{m^2 I_0(ka) - I_0(mka)} \tag{5}$$

The electric field on the pole tip is $E_s = V_0/r_0$ and the maximum electric field is $E_{max} = 1.36E_s$. With $K_p = 1.82$, E_s is 13.72 MV/m.

With Eq. 3, the average aperture r_0 and surface field E_s can be written in terms of B and V_0,

$$r_0^2 = \frac{q\lambda^2 V_0}{m_0 c^2 B} \tag{6}$$

$$E_s^2 = \frac{m_0 c^2 B V_0}{q\lambda^2} \tag{7}$$

Figure 2 shows the relationship of B, V_0, E_s and r_0 when f = 75.5 MHz, given by Eq. 6 and Fig. 2. For such a high-intensity, we can expect a large B to provide sufficient transverse focusing. In Fig. 2, when E_s is about 14 MV/m, B will be about 10, the vane voltage V_0 will be between 100 kV and 200 kV, and the average aperture r_0 will be 10 mm. A higher vane voltage is advantageous in reducing the total RFQ length. In our design, 150 kV is considered a practical maximum. By choosing B to be about 10 and with $\Delta_{\rm rf}$ being a typical negative value, the synchronous phase will be less than $\pi/2$ to avoid envelope instability [9].

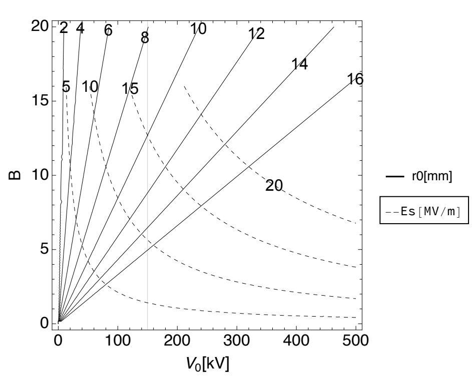

Figure 2: Relationship between focusing factor B, vane voltage V_0, surface field E_s and average aperture r_0 (Eqs. 6 and 7).

RESULTS AND DISCUSSION

A tool-set provided by Los Alamos National Laboratory (LANL) has commonly been used for the RFQ design [10, 11]. An RFQ designed with this tool set is divided into four sections: Radial Matching Section (RMS), Shaper (SH), Gentle Buncher (GB) and Accelerator Section (ACC).

Designs with different parameters are then optimized by scanning the ranges of the parameters estimated in the previous section. The transmission rate given by PARMTEQM is used to judge the goodness of a design. Figure 3 shows the cell parameters of the designed RFQ, where W_s is the energy of the synchronous particle, from 0.1 keV to 2.5 MeV. The synchronous phase is -62° at the GB end and gradually shifts to -45° at the RFQ end. If we increase the vane voltage in the ACC region, the synchronous phase will shift to a more typical value of -30°. However, 150 kV is already a large value, so the final synchronous phase is -45° and the total RFQ length is about 11 meters. While r_0 and V_0 are kept constant along the RFQ, B and A are slightly modified by PARI along the RFQ, around 10.6 and 0.29, respectively.

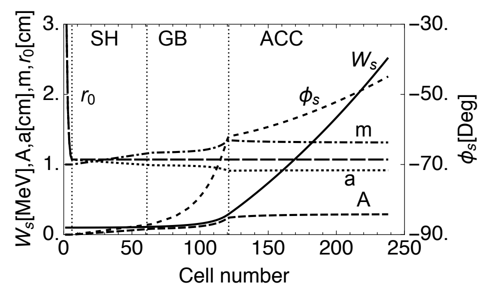

Figure 3: Cell parameters of RFQ-D.

The dependence on the input emittance is also investigated. Figure 4 shows the transverse RMS emittance evolution along the RFQ. Four cases of emittance have been assumed, as shown in this figure. The horizontal and vertical emittance values are equal at the input, and both directions are shown in the figure. The results suggest that a smaller input transverse emittance leads to a smaller output emittance. However, if we look at the emittance blowup in terms of the ratio, as presented in Table 2, under the same beam intensity, a higher input emittance will have a smaller emittance blowup. There is no need to suppress the transverse emittance to an extremely small level for such an RFQ.

Table 2: Emittance and Transmission Rate at RFQ End

ϵ_{in}	0.25	0.50	0.75	1.00
$\epsilon_x(/\epsilon_{x0})$	0.72(2.9)	0.82(1.6)	1.00(1.3)	0.11(1.1)
$\epsilon_y(/\epsilon_{y0})$	0.70(2.8)	0.84(1.7)	0.99(1.3)	0.11(1.1)
Trans.%	93.3	92.5	92.3	92.1

The transmission rate also depends on the input transverse emittance as shown in Fig. 5. Table 2 presents the values of the transmission rate at the RFQ end. Most of the beam loss occurs in the bunching process, where the energy is still low,

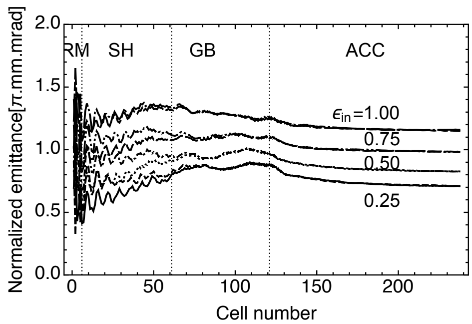

Figure 4: Transverse RMS emittance along the RFQ.

thus, the power loss to the RFQ chamber is low. The beam loss continues gradually in the ACC region.

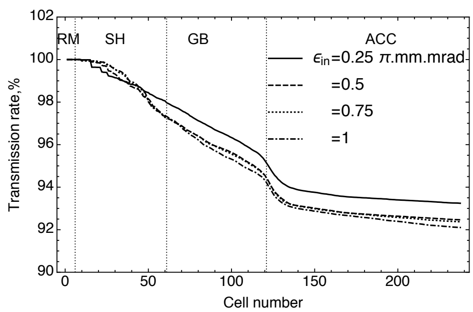

Figure 5: Transmission rate depending on the input transverse emittance.

SUMMARY

A CW high-intensity D^+ RFQ is designed for the purpose of nuclear transmutation. The beam dynamics design is carried out in a traditional manner while considering the convenience of fabrication. Both the average aperture and vane voltage are kept constant along the RFQ. PARMTEQM is used to perform the particle tracking simulation. The simulation results suggest that the designed RFQ is capable of accelerating the 400 mA D^+ beam to an energy of 2.5 MeV with a 92.0~93.3% transmission, depending on the input emittance of 0.25 ~1.00 π.mm.mrad. The cavity design is scheduled to estimate the power consumption and verify the construction feasibility of such a machine.

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