PROGRAM FOR HIGH-INTENSITY RFQ DESIGN WITH MATCHED AND EQUIPARTITIONED DESIGN STRATEGY

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Abstract

The deuteron driver accelerator of the Beijing Isotope Separation On-Line (BISOL) facility will accelerate and deliver a 20 mA deuteron beam to the targets with an energy of 40 MeV. As the injector of the driver linac, an RFQ is required to bunch and accelerate the 20 mA deuteron beam to 3 MeV with very high beam quality. In order to fulfil these requirements and reduce time spent on optimization, an RFQ design program named RFQEP has been developed to generate the input file for the PARMTEQM code. In this program, the 'matched and equipartitioned' design strategy is adopted to prevent halo formation and to avoid structure resonances in high intensity RFQs. The detailed design aspects are studied in this paper and simulation results are given for an RFQ designed by this code, which shows the accuracy and the merits of the new program.

INTRODUCTION

The Beijing isotope separation online (BISOL) facility will be used to study new physics and technologies at the limit of nuclear stability [1]. This important facility will use two separate drivers, a high current deuteron RF linear accelerator, and the China Advanced Research Reactor (CARR). The deuteron driver linac will accelerate the cw deuteron beam up to 40 MeV via a 3 MeV RFQ and 40 MeV superconducting RF linac. The cw deuteron RFQ is one of the most critical parts of the driver linac. It should be able to accelerate the 20 mA deuteron beam up to 3 MeV with high transmission efficiency and good beam quality.

In the conventional RFQ design strategy first proposed by LANL [2], the overall RFQ is divided into four sections: radial matching section (RM), shaper (SH), gentle buncher (GB) and accelerating section (ACC). However, structure resonances and envelope resonances at 90° phase advance may occur for this design strategy. In addition, the beam is not brought to and held in an equipartitioned (EP) state along the structure, so the space charge forces may couple the longitudinal and transverse motions, with consequent halo formation and emittance growth [3]. Therefore, an equipartioned design strategy was proposed [4], and has since been successfully implemented in a number of RFQ designs [5]. In order to fulfil these requirements and reduce time spent on optimization, an RFQ design program named RFQEP has been developed to generate the input file for the PARMTEQM code. Through this program, a RFQ dynamics design for a matched and equipartitioned beam can be produced automatically.

EP DESIGN STRATEGY

In the EP design strategy, the beam reaches EP state at the end of the SH section and may be held in equilibrium through the GB and ACC sections. For a matched beam, the rate of change of divergence is zero in the envelope equations, hence according to smooth approximation theory we get matching equations:

$$\varepsilon_{tn} = \frac{a^2\sigma_t\gamma}{\lambda}, \tag{1}$$

$$\varepsilon_{ln} = \frac{(\gamma b)^2\sigma_l\gamma}{\lambda}, \tag{2}$$

where ε is the normalized rms emittance, a and b are transverse and longitudinal rms beam radii, respectively (assuming an ellipsoidal distribution after the SH section), σ is the phase advance with beam current, t denotes the transverse and l the longitudinal plane, γ is the relativistic factor, and λ is the wavelength. The phase advances with space charge for the external focusing forces are of the form:

$$\sigma_t^2 = \sigma_{0t}^2 - \frac{I\lambda^3K(1-f)}{a^2b\gamma^3}, \tag{3}$$

$$\sigma_l^2 = \sigma_{0l}^2 - \frac{2I\lambda^3Kf}{a^2b\gamma^3}, \tag{4}$$

where the constant $K = \frac{3}{8\pi}\frac{Z_0 q 10^{-6}}{m_0c^2}$ is written with impedance of the vacuum $Z_0 = 376.73\,\Omega$, q and m_0 are the charge and the rest mass of particle respectively, I is the beam current, f is the geometry factor, and σ_0 is the zero current phase advance, which can be defined as

$$\sigma_{0t}^2 = \frac{B^2}{8\pi} + \Delta_{rf}, \tag{5}$$

$$\sigma_{0l}^2 = -2\Delta_{rf}. \tag{6}$$

The focusing factor B is

$$B = \frac{q\lambda^2V}{m_0c^2r_0^2}. \tag{7}$$

The RF defocusing factor Δ_{rf} is

$$\Delta_{rf} = \frac{\pi^2 qVA\sin\phi_s}{2m_0c^2\beta^2}, \tag{8}$$

where r_0, ϕ_s, A and β are the average aperture, synchronous phase, acceleration parameter and relative velocity, respectively.

When the EP state is satisfied, there is no free energy within the beam. This means that the beam has equal transverse and longitudinal temperatures. Consequently, the EP condition can be derived as follows:

$$\frac{\gamma b}{a} = \frac{\varepsilon_{ln}}{\varepsilon_{tn}} = \frac{\sigma_t}{\sigma_l}. \tag{9}$$

This also implies:

$$\frac{\varepsilon_{ln}\sigma_l}{\varepsilon_{tn}\sigma_t} = 1. \tag{10}$$

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RFQEP PROGRAM

In the RFQEP program, the four-step philosophy is adopted. The crucial program elements are the descriptions of the four independent dynamics functions: aperture $a(z)$, vane modulation $m(z)$, synchronous phase $\phi_s(z)$ and inter-vane voltage $V(z)$. These functions can be obtained from secondary variables such as the equipartitioned condition or constant average aperture, or determined by certain rules, as functions of cell number, velocity or position. Various different rules can be adopted for every parameter in the different sections, in order to improve overall beam transmission. At the same time, the matched method is used to obtain the optimal input beam parameters, which can reduce the emittance growth induced by mismatch [6]. The rules of the dynamics parameters in the different sections will be described next.

The SH section (~ 80 cells) aims to bring the beam to the EP state. Here V is kept constant, and m, a are changed linearly. ϕ_s is kept at -90° at first and then grows linearly to the end of SH. The values for the phase $\phi_{s,eos}$ and aperture a_{eos} at the end of the shaper are given as inputs to the program. For the EP condition, the modulation at the end of the shaper m_{eos} can be calculated according to equations (3), (4) and (9). The emittance values ε_{tn} and ε_{ln} are given to the program.

The GB and ACC sections aim to bunch and accelerate the beam at the EP state. The phase ramp can be determined by the K-T rule [7]. This means that the ratio between the accelerating bucket length and the beam longitudinal length will be kept constant. The bucket length is varied with beam velocity as:

$$H = H_{eos} \cdot \left(1 + f_1 \left(\frac{\beta-\beta_f}{\beta_{eos}-\beta_f}\right)^{f_2}\right), \tag{11}$$

where β_{eos} and β_f are beam velocities at the end of the SH section and end of the RFQ respectively, f_1 and f_2 are independent parameters to adjust the bucket length, and H_{eos} is the bucket length at the end of SH, which can be calculated according to the longitudinal beam length. After this, the synchronous phase ϕ_s will be determined by:

$$\psi = \frac{H}{\beta}, \tag{12}$$

$$\tan\phi_s = \frac{\sin\psi - \psi}{1-\cos\psi}. \tag{13}$$

The aperture a is the critical parameter for RFQ dynamics, which has great influence on RFQ length and transmission efficiency. In the RFQEP program, the aperture is set to increase with the beam energy after the shaper because beam loss should be strictly controlled at higher energies. The aperture is varied with beam velocity as:

$$a = a_{eos} \cdot \left(1 + f_3 \left(\frac{\beta-\beta_f}{\beta_{eos}-\beta_f}\right)^{f_4}\right), \tag{14}$$

where f_3 and f_4 are parameters to adjust the rate of change of the aperture. In the BISOL RFQ case, the aperture is minimal at the end of SH section in order to cut off most of the lost particles with low energy.

The inter-vane voltage can be kept constant along the RFQ. However, the radial focusing forces will decrease as the aperture increases, resulting in beam loss at higher energies. Fixing the inter-vane voltage also means that the EP state can't be held in the ACC section. Hence, the program uses a varied voltage along the RFQ. There are two different rules in the GB section and ACC section.

1) The voltage is varied by keeping the peak surface field less than a certain value (such as $1.7E_k$) in order to avoid sparking:

$$V = Kp_{\text{limit}} \cdot E_k \cdot r_0/\kappa, \tag{15}$$

where E_k is the Kilpatrick field at the operation frequency, r_0 is average aperture of one RFQ cell, and κ is the field enhancement factor, which depends on ρ_t/r_0, modulation (m) and L/r_0, where ρ_t and L are the transverse radius of curvature and cell length, respectively. κ is usually in the range of 1.2~1.4.

2) The voltage is varied along z as following.

$$V = V_{eos}(1 + f_5(z - z_{\text{SH}})/z_{\text{RFQ}}), \tag{16}$$

where V_{eos} is the inter-vane voltage at the end of the SH, z_{SH} and z_{RFQ} are length of the SH section and the whole RFQ, respectively. At the same time, the maximum voltage shouldn't be too high, in order to save rf power.

Finally, the vane modulation can be calculated according to the EP condition using the calculated values of a, ϕ_s and V.

DYNAMICS SIMULATION

The BISOL deuteron driver linac RFQ has been designed using the RFQEP program. First of all, some basic parameters are determined. The inter-vane voltage has great influence on the RFQ length and RF power consumption. Consequently, the maximum inter-vane voltage is set to 120 kV, as higher voltages will require too much RF power. In order to decrease the sparking risk, the maximum Kilpatrick factor is set to 1.7, to ensure high availability and reliability. The minimal aperture a_{eos} is set to 3.4 mm after considering the RFQ length and transmission efficiency. Next, some independent parameters are adjusted to realize high transmission efficiency and short RFQ length. The main dynamics parameters generated by RFQEP are shown in Fig. 1. The deuteron beam can be accelerated to 3 MeV with a transmission of 99.8% with a length of 5.2 m. The maximum peak surface electric field is 22.4 MV/m, which corresponds to $1.65E_k$. The final values of the main RFQ parameters and simulation results based on PARMTEQM are summarized in Table 1. The emittance growth is less than 7%.

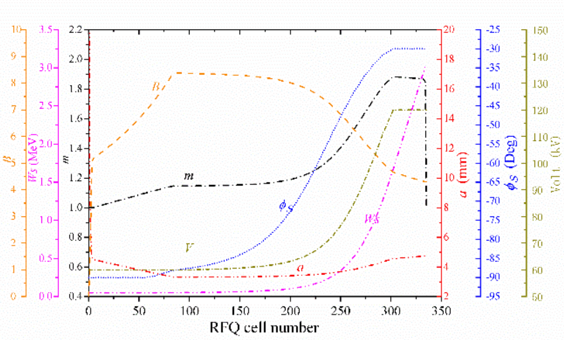

Figure 1: Variation of the main RFQ parameters with cell number, where W_s is the kinetic energy of the synchronous particle.

Table 1: Main RFQ Parameters

Parameter	Value	Unit
Particle	D	
Frequency	162.5	MHz
Input energy	50	keV
Output energy	3	MeV
Vane length	5.2	m
Beam current	20	mA
Inter-vane voltage	60~120	kV
Max. peak surface electric field	22.4	MV/m
Kilpatrick coefficient	1.65	
Min. average aperture	3.36	mm
Max. modulation factor	1.85	
Max. synchronous phase	-30	deg
Input trans. nor. rms emittance	0.20	mm·mrad
Output trans. nor. rms emittance	0.22	mm·mrad
Output long. rms emittance	0.40	MeV· deg
Transmission efficiency	99.8	%

The EP parameters are presented in Fig. 2, including the ratio of the transverse beam radius to the longitudinal beam radius, the ratio of longitudinal phase advance to transverse phase advance, the ratio of longitudinal normalized emittance to transverse emittance. The plot shows that the beam reaches EP condition at the end of SH section (about cell 80) with ratio 1.68, and then is kept at EP condition through the GB section and ACC section. The EP ratio $\varepsilon_{ln}\sigma_l/\varepsilon_{tn}\sigma_t$ is also kept close to one in the EP condition.

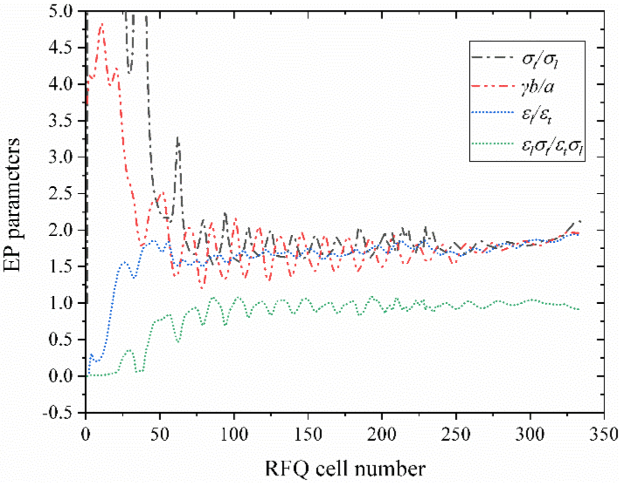

Figure 2: EP parameters against cell number.

Figure 3 shows the phase advance ratio and tune footprint in the Hofmann chart with an emittance ratio of 1.65. The status of equipartitioning and resonance crossing can be checked. It is seen that EP condition is held in the GB and ACC section. Some points quickly pass through the resonance regions such that no significant emittance growth occurs.

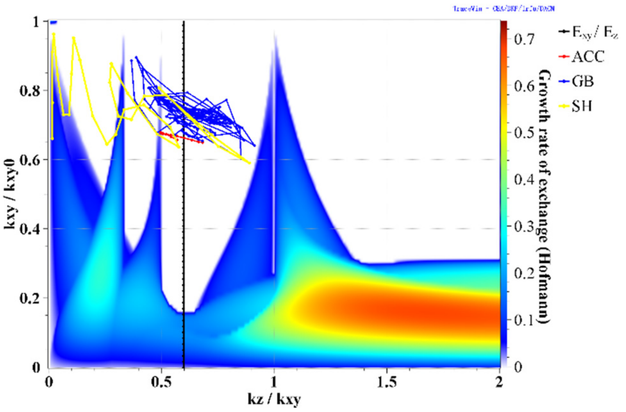

Figure 3: Phase advance ratio and tune footprint in the Hofmann chart of the RFQ.

CONCLUSION

The RFQEP program has been developed using a matched and equipartitioned strategy for the automatic design of RFQ dynamics. In the program, different variation rules can be adopted to determine the four independent dynamics parameters: aperture a, vane modulation m, synchronous phase ϕ_s and inter-vane voltage V. The deuteron RFQ for the BISOL driver linac has been designed using the RFQEP program. The simulation results show that the beam maintains EP condition throughout the GB and ACC section, which verifies that a good RFQ design can be produced by RFQEP.

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