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NEW BEAM-DYNAMICS DESIGN PROCEDURE FOR RFQs

A. Ueno and Y. Yamazaki
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

So far, two computer programs have typically been used for the beam-dynamics design of radio-frequency quadrupole (RFQ) linacs. One is RFQUIK developed for high-current proton linacs. The other is GENRFQ developed for low-current heavy-ion linacs. In order to optimize the design of RFQs, especially intermediate-beam current RFQs, a new guideline is proposed by keeping the longitudinal acceptance constant for the design current in the gentle buncher. The acceleration efficiency in the acceleration section is also improved by gradually increasing the modulation factor under the condition of a constant transverse acceptance. An RFQ linac designed with these guidelines was simulated by using the code PARMTEQ. A good transmission efficiency and a small longitudinal emittance for a relatively short cavity length were obtained with this design procedure.

Introduction

Various computer programs[1-4] have been developed for designing the beam-dynamics of radio-frequency quadrupole (RFQ) linacs. We attempted to use these programs in order to design the RFQ linac for the Japanese Hadron Project (JHP).[5] However, further improvements in the programs were necessary for the present purpose. The reasons for the improvements are presented by briefly describing the beam-dynamics designs of two typical programs, namely RFQUIK [1] and GENRFQ.[2] The former was developed at LANL (Los Alamos National Laboratory) for high-current proton RFQs and the latter was developed at INS (Institute for Nuclear Study, University of Tokyo) for low-current heavy-ion RFQs.

In the RFQUIK, an RFQ is divided into four longitudinal regions: a radial matching section, a shaper, a gentle buncher and an acceleration section. In the radial matching section, the bore aperture is tapered off in order to adjust the focusing strength from almost zero to its full value in the first several cells. This allows the injected DC beam to match into the time-dependent focusing of the RFQ. In the shaper, the modulation factor, m, and the synchronous phase, ϕ_s, increase linearly in order to shape the beam bunch. In the gentle buncher, m and ϕ_s are increased in order to keep constant the longitudinal infinitesimal oscillation frequency and the spatial length of the separatrix at zero current. The beam is gradually bunched as it is accelerated. In the acceleration section, m and ϕ_s are held fixed.

Two shortcomings of this design procedure come to mind. First, space-charge effects are not taken into account in the calculation of the bunch length. Second, it is hard to find any strong reasons for keeping both m and ϕ_s constant in the acceleration section. It is noted that the acceleration efficiency (accelerating energy per unit length) can be improved by making m and/or ϕ_s variable. The acceleration efficiency is important, particularly for a high-energy RFQ like the JHP linac, since the low acceleration efficiency results in a long RFQ which is, in general, difficult to fabricate. Thus, Raparia [3] proposed a new guideline for the acceleration section in which m is gradually increased so as to keep constant the transverse space-charge limited current defined by Wangler.[6] However, the nonlinearity of the longitudinal focusing force and the space-charge effects of other bunches are not considered in the calculation of the transverse and longitudinal space-charge limited currents defined by Wangler.

In the GENRFQ, the gentle buncher is further divided into two regions (the pre-buncher and the buncher), as is the acceleration section (the booster and the accelerator), in order to optimize the design more flexibly. In the pre-buncher and the buncher, m and ϕ_s are increased under the condition of constant longitudinal acceptance at zero current. The rf defocusing parameter, Δ_{rf}, is linearly changed in the pre-buncher and is kept constant in the buncher. In the booster and the accelerator, ϕ_s is held fixed. The modulation factor, m, is varied for keeping constant Δ_{rf} in the booster and the minimum bore radius, a, in the accelerator.

The space-charge effects are ignored in this design procedure, since the GENRFQ was developed for the design of low-current heavy-ion RFQs. Thus, the GENRFQ is not suitable for the design of RFQs with significant space-charge effects. The constraint of constant a and ϕ_s in the accelerator is not efficient for acceleration. However, the constraint of a constant longitudinal acceptance in the bunching procedure is a useful guiding principle.

In this paper, a new beam-dynamics design procedure is proposed in order to optimize the design of RFQs, especially for the intermediate-beam current RFQs. First, we estimate the longitudinal and transverse acceptances more realistically. Second, an attempt is made to improve the acceleration efficiency in the acceleration section by varying the modulation factor, m, while keeping a constant transverse acceptance. Third, the longitudinal acceptance is held fixed in order to determine the parameters in the gentle buncher, following the method of the GENRFQ. The new design procedure, thus developed, was programmed in the computer code package KEKRFQ. In the next section, methods to estimate the longitudinal and transverse acceptances in RFQs are described. Then, a new beam-dynamics design procedure is described. Finally, the acceleration efficiency and the beam qualities of the design are compared with those of the RFQUIK and GENRFQ on the basis of simulation results using the computer code PARMTEQ.[7]

Estimation of RFQ Acceptances

Estimations of the longitudinal and transverse acceptances are essential in order to optimize the RFQ design. The estimation method, in which the nonlinearity of the longitudinal focusing force and the space-charge effects are taken into account by numerical calculations, is described in this section.

The longitudinal acceptance, A_l, is estimated by solving the following differential equation system numerically with an assumption of the constant synchronous particle energy and by finding the area of a stable region:

$$\frac{d\Delta\phi}{dz} \cong -\frac{2\pi\Delta W}{\lambda m_0 c^2 \beta^3 \gamma^3}, \qquad (1\text{-a})$$

$$\frac{d\Delta W}{dz} = qAV\frac{\pi}{4}I_0(kr)\{\cos(\phi_s + \Delta\phi) - \cos\phi_s\} - qE_{SC}. \qquad (1\text{-b})$$

Here, $\Delta\phi$ and ΔW are the phase and energy differences between the reference particle and the synchronous particle, respectively; λ is the rf wavelength; m_0 is the rest mass; c is the velocity of light; β and γ are the relativistic parameters; q is the electric charge of the particle; A is the acceleration parameter; V is the intervane voltage; I_0 is the modified Bessel function; r is the distance from the beam axis, and $k=2\pi/\beta\lambda$. The electric field, E_{SC}, produced by the space charge in eq. (1-b) is given by

$$E_{SC} = \frac{\rho_{sc} f \beta \lambda}{2\pi\varepsilon_0}\Delta\phi + \frac{\lambda I}{c\beta^2\lambda^2}\sum_{i=1}^{n}\left(\frac{1}{(\phi_s + \Delta\phi - \phi_c + 2\pi i)\left|\phi_s + \Delta\phi - \phi_c + 2\pi i\right|} + \frac{1}{(\phi_s + \Delta\phi - \phi_c - 2\pi i)\left|\phi_s + \Delta\phi - \phi_c - 2\pi i\right|}\right), \qquad (2)$$

where ρ_{SC} is the charge density in the bunch and ε_0 is the permittivity of the vacuum. The space-charge effects from the other bunches, which we approximate by point electric charges, is represented in the second term of this equation.

The phase of the bunch centroid ϕ_c is approximated by

$$\phi_c = \phi_f - \sqrt{\frac{(\phi_f - \phi_i)(\phi_f - \phi_s)}{2}} \qquad (3)$$

by using the phases of the bunch head, ϕ_i, and the bunch tail, ϕ_f. Since none of the values of ϕ_i, ϕ_f or ϕ_c was known prior to the estimation of the longitudinal acceptance, an iteration procedure is necessary in determining these values.

It is noted that the field E_{SC} includes the effect of the other bunches which was neglected by Wangler. This effect is significant at the beginning of the bunching process, where the constraint of the constant longitudinal acceptance plays an important role. We also define the longitudinal space-charge limited current, I_l, as the minimum beam current which makes the longitudinal acceptance vanish. This value is more accurate than the value defined by Wangler, since the nonlinearity of the longitudinal focusing force and the space-charge effects of the other bunches are taken into account.

The transverse acceptance is estimated by

$$A_t = \frac{a^2\sqrt{\frac{B^2}{8\pi^2} + \Delta_{rf} + \Delta_{SC}}}{\beta\lambda\left(1 + \frac{B}{4\pi^2}\right)^2}\beta\gamma, \qquad (4)$$

which was derived by Wangler[6] using a smooth approximation; B is a focusing parameter. For the space-charge defocusing parameter Δ_{SC} we use the expression

$$\Delta_{SC} = -\frac{3Z_0 qI\lambda^3(1-f)}{8\pi m_0 c^2\gamma^3 r_b^2 b} \qquad (5)$$

assuming an ellipsoidal beam bunch with a uniform space-charge distribution. Here, Z_0 is the free-space impedance, I the beam current, r_b the radius of the beam and b the half-bunch length. The ellipsoid form factor, f, is a function of r_b and b. It can be seen that the bunch length is necessary in order to estimate the transverse acceptance. We use the bunch length calculated from the values of ϕ_i and ϕ_f, which were obtained in estimating the longitudinal acceptance.

New Design Procedure for RFQs

In the KEKRFQ, an RFQ is divided into four longitudinal regions in the same way as the RFQUIK. Each region is referred to by the same name as that in the RFQUIK. However, the guidelines for the gentle buncher and the acceleration section are different. We hold the average bore radius, a_0, fixed and use the guidelines to determine two independent variables of m and ϕ_s from which all of the cell parameters are derived.

In the gentle buncher, the longitudinal acceptance is kept constant and the rf defocusing parameter, Δ_{rf}, is determined as a function of β by

$$\Delta_{rf} = \Delta_{rfi} + (\Delta_{rfG} - \Delta_{rfi})\left(1 - \left|\frac{\beta - \beta_G}{\beta_G - \beta_i}\right|^n\right)^{1/n}, \qquad (6)$$

where Δ_{rfi} and β_i are the rf defocusing parameter and the relativistic parameter at the beginning of the gentle buncher, respectively, Δ_{rfG} and β_G are those at the end of the gentle buncher, and n is a free coefficient. Since eq. (6) varies Δ_{rf} gradually as the energy is increased, the transverse motion never suffers from an abrupt change of the focusing parameters.

The constraint of the constant longitudinal acceptance is imposed for the following reason. Since the injected DC beams almost fill out the longitudinal acceptance at the beginning of the gentle buncher, the longitudinal acceptance should always be smaller than or equal to those of the following cells in order to obtain a high transmission rate. On the other hand, at the first cell of the gentle buncher, where the beam energy is near the injection energy and the synchronous phase is slightly larger than -90 deg, the larger acceleration field ,that is, the larger Δ_{rf} implies the larger longitudinal acceptance. Therefore, the constraint of the constant longitudinal acceptance is a way to ensure a high transmission rate in the longitudinal motion, keeping a high acceleration efficiency.

In the acceleration section, the synchronous phase is fixed at a value of around -30 deg, following the other design procedures, since the acceleration efficiency can be improved slightly by varying ϕ_s. On the other hand, it is effective regarding acceleration efficiency to make the modulation factor, m, variable; m is increased as the beam is accelerated, while keeping the transverse acceptance constant. This is possible, since the defocusing parameters Δ_{rf} and Δ_{SC} in eq. (4) decrease for constant modulation factor as the energy is increased.

The beam-dynamics design based upon the above guidelines was made almost in the same way as the RFQUIK. The beam energy, W_G, and the cell parameters at the end of the gentle buncher, where both of the longitudinal and transverse acceptances have the minimum values, were determined first. For this purpose the code KEKRFQ1 was used in order to calculate the transverse acceptance and the longitudinal current limit for certain values of m, ϕ_s, a, W_G and the bravery factor. The bravery factor is the maximum surface electric field divided by the Kilpatrick limit. In the KEKRFQ1 the maximum field was assumed to be $1.38*V/a_0$. After the determination of the cell parameters at the end of the gentle buncher, the parameters of each cell were determined by the code KEKRFQ2 on the basis of the guidelines described above. The input data for the KEKRFQ2 were the cell parameters at the end of the gentle buncher, the shaper length L_{SH}, the synchronous phase of the end of the shaper ϕ_{SH}, and n of eq.(6). The cell parameters, thus obtained, were used in order to simulate the beam motion with the program PARMTEQ. The shaper length was adjusted in order to optimize the transmission and the longitudinal emittance of the simulation results.

Comparison of Designs

Three designs of the RFQ for the JHP, referred to as KEKRFQ-D, RFQUIK-D or GENRFQ-D, were made by using the programs KEKRFQ, RFQUIK and GENRFQ, respectively, and were compared on the basis of the simulation results with the PARMTEQ. The principal requirements for the RFQ are as follows: the resonant frequency is 432 MHz, the peak beam current is 20 mA, the 90% normalized transverse emittance is 1.0 π mm mrad, the injection energy is 50 keV and the final energy is 3 MeV. The GENRFQ-D was the first design for the JHP made by Tokuda.[8] In order to make a fair comparison, the same average bore radius (a_0=3.4 mm) was used for all of the designs. In the KEKRFQ-D, L_{SH}, ϕ_{SH}, and n of eq.(6) were chosen as 0.395 m, -88 deg and 3, respectively.

The cell parameters of the KEKRFQ-D, RFQUIK-D and GENRFQ-D are shown as functions of the longitudinal position in Figs. 1a), 1b) and 1c), respectively. As can be seen from these figures, the high acceleration efficiencies with relatively short cavities are obtained by rapid bunching in the cases of KEKRFQ-D and GENRFQ-D. The acceptances for the design current (20 mA) and the current limit of each design at the end of the gentle buncher estimated with the KEKRFQ1 are listed in Table I. These values almost determine the beam quality and limited current of the design based upon the KEKRFQ or RFQUIK, since both of the longitudinal and transverse acceptances have minimum values at the end of the gentle buncher in these design procedures. It can be seen from Table I that the longitudinal acceptances of the KEKRFQ-D and GENRFQ-D are smaller than that of the RFQUIK-D, but the limited currents do not decrease in proportion to the acceptances. Since the longitudinal acceptance restricts the longitudinal emittance of the accelerated beam, the smaller longitudinal emittance is expected for the KEKRFQ-D and GENRFQ-D than for the RFQUIK-D at the design current. The higher beam current can be accelerated with the KEKRFQ-D than GENRFQ-D, as can be seen from the limited currents in Table I. The estimated acceptances, the limited current and the half-bunch length of the KEKRFQ-

D are shown in Fig. 2 as functions of the longitudinal position.

In order to study the margin for the beam current, simulations were carried out for the following three different injected beams: (1) the design beam (the beam current I=20 mA and the 90% normalized transverse emittance ε_t=1.0 π mm mrad), (2) I=25 mA and $\varepsilon_t=1.0\times\sqrt{(25/20)}=1.12$ π mm mrad which mean the same brightness as the design beam, (3) I=50 mA and ε_t=1.0 π mm mrad. The results of the simulation are summarized in Table II. It is seen that with the KEKRFQ-D we obtained the smallest transverse and longitudinal emittances of the accelerated beam for all cases. With the RFQUIK-D though a slightly higher transmission can be obtained, the longitudinal emittance is about 50% larger than that of the KEKRFQ-D at the design current. The transmission of the KEKRFQ-D is about the same as that of the GENRFQ-D at the design beam current, but higher at the higher injected current (50 mA).

Conclusion

The new design procedure is proposed and compared with two typical ones. For the intermediate-beam current RFQ we obtain the smallest emittances, both longitudinally and transversely, keeping almost the same transmission as those of the others. It is expected that this procedure is useful in order to optimize lower or higher beam current RFQs, since the nonlinearity of the longitudinal focusing force and the space-charge effects of the other bunches are take into account.

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TABLE I
The acceptances and the limited current of each design at the end of the gentle buncher estimated with KEKRFQ1.

	KEKRFQ-D	RFQUIK-D	GENRFQ-D
Energy W_G (keV)	250	550	250
Longitudinal limited current I_l (mA)	34.8	46.5	29.7
Longitudinal acceptance (π deg MeV)	0.546	2.390	0.482
Normalized transverse acceptance (π mm mrad)	2.26	2.04	2.99

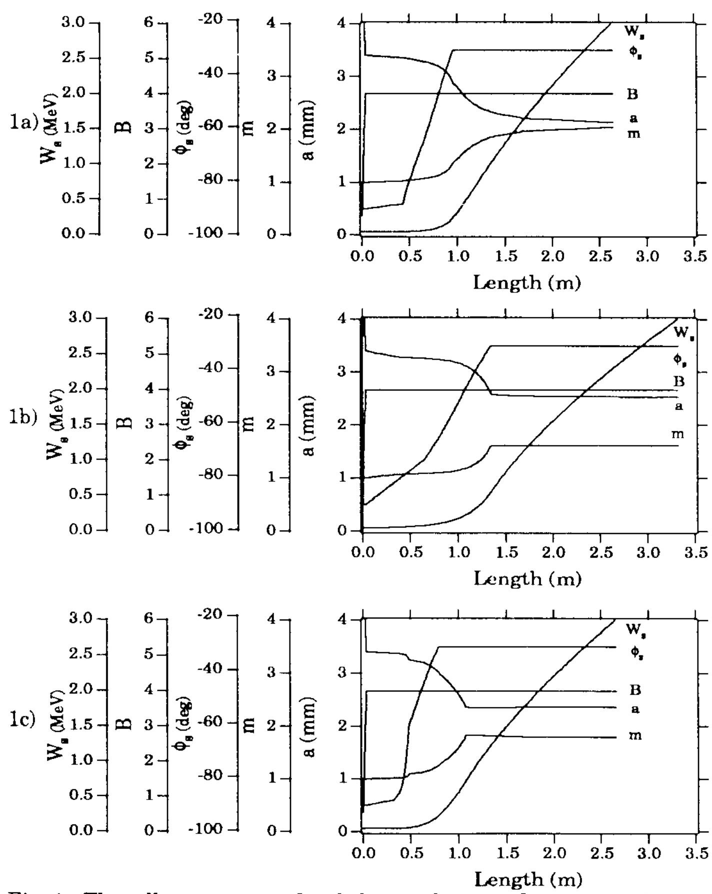

Fig. 1. The cell parameters of each design shown as functions of the longitudinal position: (a) KEKRFQ-D, (b) RFQUIK-D, (c) GENRFQ-D.

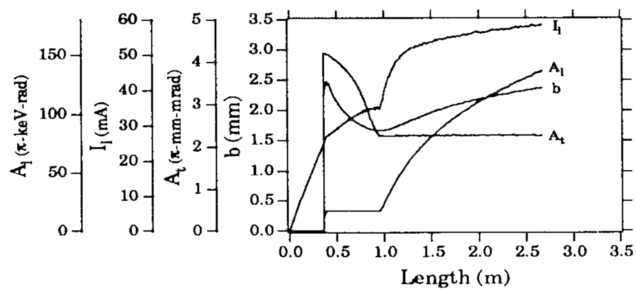

Fig. 2. The estimated acceptances, the limited current and the half-bunch length of KEKRFQ-D shown as the functions of the longitudinal position.

TABLE II
The principal parameters and the simulation results of each design (the number of injected particles is 5000).

	KEKRFQ-D	RFQUIK-D	GENRFQ-D
Kinetic energy (MeV)	0.05-3	0.05-3	0.05-3
Average bore radius a_0(mm)	3.4	3.4	3.4
Focusing parameter B	4.0	4.0	4.0
Inter-vane Voltage V(kV)	90.0	90.0	90.0
Cavity Length (m)	2.64	3.32	2.66
(1) Injected Beam: ε_t(90%)=1.0 π mm mrad, I=20 mA (DC)			
Transmission (%)	94.0	95.2	93.5
90% transverse emittance(π mm mrad)	1.10	1.18	1.15
90% longitudinal emittance(π deg MeV)	0.333	0.550	0.370
(2) Injected Beam: ε_t(90%)=$\sqrt{(25/20)}$π mm mrad, I=25 mA (DC)			
Transmission (%)	90.8	93.2	90.9
90% transverse emittance(π mm mrad)	1.19	1.25	1.29
90% longitudinal emittance(π deg MeV)	0.358	0.549	0.387
(3) Injected Beam: ε_t(90%)=1.0 π mm mrad, I=50 mA (DC)			
Transmission (%)	72.4	85.6	66.9
90% transverse emittance(π mm mrad)	1.06	1.16	1.25
90% longitudinal emittance(π deg MeV)	0.445	0.520	0.540