RFQ ACCELERATION SECTION AND ITS OPTIMIZATION

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Abstract

The acceleration section is a crucial component of any radio-frequency quadru pole (RFQ). It is common a practice to design this section with a constant modulation factor equal to its value at the end of the gentle buncher. A new method of design is proposed in this paper. The algorithm is based on the fact that the transverse space-charge current limit (TCL) is approximately proportional to the instantaneous velocity of the accelerated particle and the longitudinal space-charge current limit (LCL) is nearly independent of the velocity in the acceleration section. The modulation factor is increased such that the TCL is slightly larger than the double of the design current. Simulation using this method shows that transmission efficiency and emittances are the same as the conventional design. The advantage gained is a 50-75 % increase in accelerating rate. The optimization of the length of this section is also discussed.

Introduction

The radio frequency quadrupole (RFQ) design recipes[1] include four longitudinal regions: the radial matching section, the shaper, the gentle buncher, and the acceleration section. In the radial matching section, the vane aperture is tapered out to adjust the focusing strength from almost zero to its full value in the first few cells. This allows the DC injected beam to match into time dependent focusing of the RFQ. In the shaper, the acceleration efficiency 'A' and the synchronous phase increase linearly to bunch the beam. In the gentle buncher, the modulation factor 'm' and synchronous phase are increased such that the longitudinal small oscillation frequency at zero current and the spatial length of the separatrix remain constant, and the beam is adiabaticlly bunched as it accelerates. In the acceleration section, modulation and the phase angle are conventionally kept constant.

If the ion species, initial and final energies are given, and the frequency, and the bravery factor are specified, to design an RFQ one first selects the synchronous phase at end of the gentle buncher. Generally energy at end of the gentle buncher is given as $W_{GB}(MeV) = W_i(MeV)[99.5/\phi_s(deg)]^2$; with this value of energy the modulation factor and average radius are determined such that the transverse and longitudinal space-charge current limits are equal. The common practice is that this value of the current limits is taken to be twice of the design current. After determining the synchronous phase, average radius and the modulation factor at end of the gentle buncher, one follows the recipe given above to design the rest of the RFQ. The transverse space-charge current limit (TCL) is approximately proportional to the instantaneous velocity of the accelerated particle and the longitudinal space-charge current limit (LCL) is nearly independent of the velocity. In the acceleration section, if the synchronous phase kept constant, then the LCL remain nearly constant and TCL increases as the particle's velocity increases. In the RFQ the minimum current limits are at end of the gentle buncher as shown in fig. 1. A new method to design acceleration section is proposed in this paper and the optimization of the length of this section is also discussed.

General Properties of the Acceleration Section

The lowest order potential function for an RFQ in cylindrical coordinates (r, ϕ, z) is

$$U = V/2\left[\chi(r/a)^2\cos 2\phi + AI_0(kr)\cos kz\right]\sin(\omega t + \alpha). \quad (1)$$

From this the following electric field components are derived:

$$E_r = \frac{\chi V}{a^2} r\cos 2\phi - \frac{kAV}{2} I_1(kr)\cos kz \quad (2)$$

$$E_\phi = \frac{\chi V}{a^2} r\sin 2\phi \quad (3)$$

$$E_z = \frac{kAV}{2} I_0(kr)\sin kz \quad (4)$$

each multiplied by $\sin(\omega t + \alpha)$. The second term of E_r is the normal RF defocusing field. The acceleration efficiency 'A' and the focusing efficiency 'χ' are given by

$$A = \frac{m^2 - 1}{m^2 I_0(ka) + I_0(mka)}, \qquad \chi = 1. - AI_0(ka). \quad (5)$$

Where V is the potential difference between adjacent pole tips, k $= 2\pi/\beta\lambda$, I_0 is the modified Bessel function, 'm' is the modulation factor and 'a' is the minimum aperture radius. The focusing strength B and the average bore radius r_0, which are constant throughout the RFQ, except for a short intial radial matching section, are given by

$$B = \frac{q\lambda^2\chi V}{mc^2 a^2} = \frac{q\lambda^2 V}{mc^2 r_0^2}, \qquad r_0^2 = \frac{a^2}{\chi}. \quad (6)$$

The transverse and longitudinal phase advance for zero current are given by

$$\sigma_{0t}^2 = \frac{B^2}{8\pi^2} - \frac{\sigma_{0l}}{2}, \qquad \sigma_{0l}^2 = \frac{\pi^2 eqAV\sin\phi_s}{mc^2\beta^2}. \quad (7)$$

The second term in σ_{0t} takes into account the rf defocusing parameter Δ_{RF}.

Both transverse and longitudinal space-charge current limits of the bunched beam are approximated by using a three-dimensional ellipsoidal model and are given by[2]

$$TCL = \frac{4\mu_t mc^2 \beta|\phi_s|\sigma_{0t}^2 a^2}{3Z_0 eq\psi[1-f(p)]\lambda^2}, \quad LCL = \frac{8\pi^2 \mu_l r^2 b E_0 T|\sin\phi_s|}{3Z_0 f(p)\beta\lambda}. \tag{8}$$

Where space-charge parameter, μ, is the ratio of space-charge force to the smoothed focusing force. The subscript 't' and 'l' corresponds to transverse and longitudinal direction respectively. In these derivations it is assumed that current limits occur when μ has a value of 0.84. Here, I, is the beam current in amperes averaged over a rf period assuming that all the rf buckets are filled, $Z_0 = 376\Omega$ is the free-space impedance, r and b are the transverse and longitudinal semi-axes of the ellipsoid, and the ellipsoid form factor f(p) is equal to r/3b. The beam bunch is represented by an ellipsoid, whose dimensions are averaged over a focusing period. The effective ellipsoid is therefore azimuthally symmetric about the beam axis. The bunch length, 2b, is estimated by assuming that the bunch is near LCL, λ is the wave length of the rf, and β, γ are the relativistic parameters. The quantities b, E_0, T, ψ are given by

$$T = \frac{\pi}{4}, b = \frac{\beta\lambda|\phi_s|}{2\pi}, E_0 = \frac{2AV}{\beta\lambda}, \psi = \frac{\left[1+\left(\frac{B}{\sqrt{2\pi}}\right)\right]}{\left[1-\left(\frac{B}{\sqrt{2\pi}}\right)\right]} \tag{9}$$

It should be noted that ψ does not depend on the beam current. TCL, LCL can be written as

$$TCL = \frac{4\mu_t mc^2 \beta|\phi_s|\sigma_{0t}^2 a^2}{3Z_0 eq\psi[1-f(p)]\lambda^2}, \quad LCL = \frac{\pi\mu_l a AV|\sin\phi_s|\phi_s^2}{Z_0\lambda\psi^{1/2}} \tag{10}$$

Note that if r_0 and ϕ_s are kept constant, then TCL is proportional to βa^2, LCL is proportional to 'a' and is independent of β.

This is the most simple set-up, which does not include higher modes. These equations show definite disadvantage of the RFQ. Since all the parameters are strongly dependent on each other, which leads to a larger inflexibility of a chosen layout.

New Design of the Acceleration Section

Conventionally the acceleration section is designed with a constant modulation factor $[m = (2r_0/a) - 1]$ equal to its value at end of the gentle buncher. Consequently the accelerating field strength ((4) and (5)) drops as the $1/\beta$ at higher energies, thus limiting the use of RFQs to energies up to 2 or 2.5 MeV/amu. In this section the transverse phase advance(σ_{0t}) increases and longitudinal phase advance(σ_{0l}) decreases because of $1/\beta$ dependance in σ_{0l}. The current through the RFQ is limited by the bottleneck at the gentle buncher. Therefore there is no need for an increased TCL in the acceleration section. In the present method to increase the accelerating field strength, the modulation factor can be increased in two ways: (1) Keeping the TCL constant and equal to its value at end of the gentle buncher until 'm' has reached a value of 3 and then keeping 'm' constant; (2) decreaseing the DTL linearly, if it is more then twice of the design currnt, until 'm' has reached a value of 3 and then keeping 'm' constant (see fig 2.) These methods give a higher value of the σ_{0l} and a slightly lower value of the σ_{0t} (see table 1) in the comparison with the conventional design practice. The advantage gained is a 50 - 75 % increase in the accelerating rate at the cost of the acceptance which is proportional to a^2. Thus RFQs can be designed for higher energies up to 4 or 5 MeV/amu. One cannot go to a higher values of the modulation factor 'm' because of the higher order multipoles which will provide coupling in transverse and longitudinal directions and might blow up the beam. RFQCOEF[3] calculation shows that high order multipoles are acceptable for the value of modulation factor given above.

PARMTEQ[1] simulation using this method (case 2) to design the acceleration section for 2.5 MeV proton RFQ with an injection energy of 0.03 MeV, shows that the transmission efficiency and emittances are almost the same as the conventional design shown in table 1. Figure 3. shows the PARMTEQ output.

Table 1: Simulation Results

	Conventional design	This design
Average radius(cm)	.3	.3
Modulation factor m	2	3
σ_{0t}(deg)	45	44
σ_{0l}(deg)	15	25
Acceptance(π cm mrad)	.38	.16
Bravery factor*	2.5	2.5
E_0 (MV/m)	2.14	3.74
Length(cm)	151	100
Current (mA)	50	50
Transmission	94%	94%
Emittances(90%)		
Input		
x-x'(π cm mrad)	0.0325	0.0325
y-y'(π cm mrad)	0.0346	0.0346
ϕ-w(π deg MeV)	DC	DC
Output		
x-x'(π cm mrad)	0.0504	0.0493
y-y'(π cm mrad)	0.0516	0.0513
ϕ-w(π deg MeV)	0.8294	0.8313

* bravery factor = max. surface field/Kilpatrick limit

Optimization

Because all the parameters are strongly dependent on each other, graphical approach is used to optimize the design of the acceleration section. Figure 4 shows the length of acceleration section (La) using different methods and current limits at the end of the gentle buncher (TCL and LCL are equal at end of the gentle buncher) as a function of the average radius for an RFQ with the following parameters: input energy=30 keV, output energy = 2.5 MeV, $\phi_s = -35° to -30°$, bravery factor=2.5 . Curve 1 gives the current limits vs average radius r_0. For a 50 mA RFQ, a r_0 of .225 cm is required which will give the current limits of 110 mA. Curve 2 gives the length of the acceleration section, using the conventional method to design this section, for this value of r_0, La is 114 cm (denoted by p1). Curve 3 gives length of acceleration section when the TCL is kept constant and equal to its value at end of the gentle buncher until 'm' has reached a value of 3 and then it is kept constant. Curve 4 gives the value of La when TCL is decreased linearly, if it is more then twice of the design currnt, until 'm' has reached a value of 3 and then 'm' is kept constant. On the curve 3, r_0 of .3 cm gives La=72 cm (denoted by p2). The transverse phase advances, σ_{0t}, at the end of the RFQ for p1 and p2 are 60° and 44° respectively. Generally RFQs are followed by drift-tube linacs (DTL). The transverse matching of the RFQ to DTL is easier if the phase advance per unit length is approximately the same in both structures. Because of beam stability considerations, the transverse phase advance in the DTL is typically 60°

or less. Thus p2 is a better choice of the average radius r_0. A conventional design gives, for this value of r_0 (0.3 cm), La=120 cm (denoted by p3). The accelerating field strength at p2 is 3.74 MV/m which is higher than at p1 and p3 (2.14 MV/m); this choice of p2 makes it easier to match the RFQ to the DTL in the longitudinal plane. The RFQ acceptance at the p1,p2 and p3 are 0.18, 0.15 and 0.38 π cm mrad respectively. The acceptance of 0.15 π cm mrad is acceptable for most of the proton and H^- ion sources.

Conclusions

This new method of designing acceleration section provides a higher accelerating field. Consequently RFQs can be designed for higher energies in the range of 4 to 5 MeV/amu. This method also provides a favorable condition to match RFQ to DTL in all planes, while giving the same transmission efficiencies and emittances. This work was supported by the U.S. Department of Energy under grant No. DE-FG05-87ER40374.

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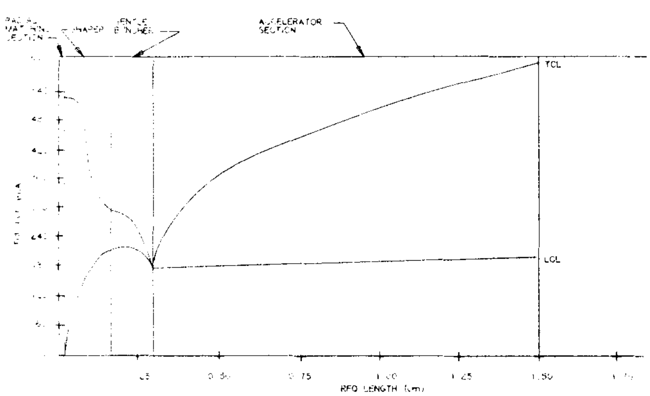

Figure 1. TCL and LCL vs RFQ lenght for the conventional design.

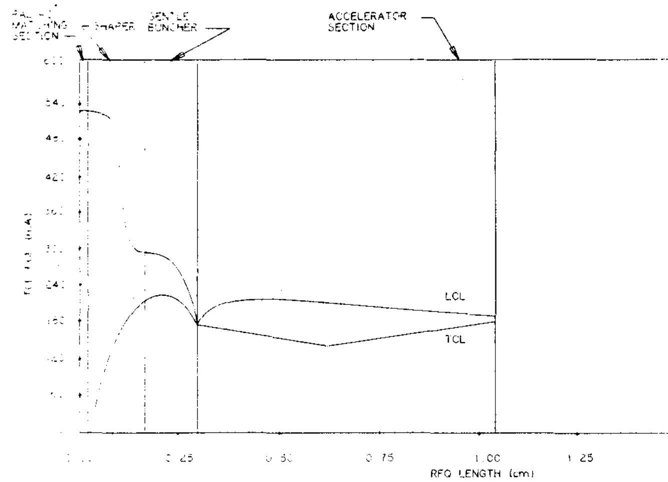

Figure 2. TCL and LCL vs RFQ length for this design (case 2).

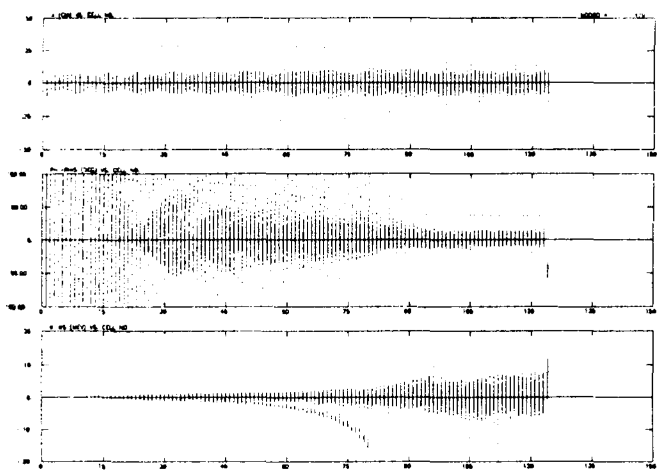

Figure 3. x, phase and energy pofile for this design (case 2).

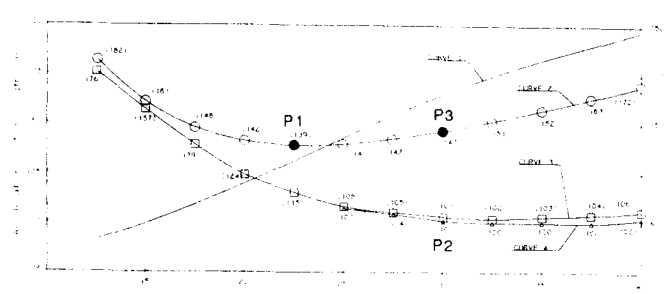

Figure 4. Acceleration section length and current limits (at the end of the gentle buncher) vs average radius. The quantities shown in parenthesis are RFQ length.