REDUCING RFQ LONGITUDINAL EMITTANCE*

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Abstract

A new method has been developed that reduces the output emittance of zero-current heavy-ion RFQ accelerators by as much as a factor of four. A discrete buncher incorporated in the RFQ replaces the traditional adiabatic buncher and a transition section matches the zero-longitudinal-field drift section into a constant longitudinal gradient accelerating section. Besides a significantly lowered longitudinal emittance, the transverse emittance is slightly lowered, and a lower vane voltage is required for the same length accelerator compared to one generated by traditional methods.

Introduction

RFQs serve well as the first accelerator in a chain of linear accelerators, providing the initial bunching and acceleration of the beam. Nearly 100% of the beam can be adiabatically captured, using schemes proposed initially by Kapchinskii and Teplyakov [1] and developed at LANL [2] for beams with significant space charge forces, or by Yamada [3] for beams with insignificant space charge forces. Ueno has developed a design code for intermediate values of space charge and has compared his method to the other two in detail [4]. These methods, using adiabatic bunching of the beam, result in nearly 100% longitudinal capture but a rather large longitudinal phase space area.

A new design technique for zero space-charge RFQs is presented here which reduces the longitudinal emittance by a factor of three to five over the Yamada prescription. Two highly successful RFQs have been built at LBL using the Yamada prescription, the q/A = 1/7 Bevatron injector RFQ [5] and the q/A = 3/16 oxygen injector RFQ used at CERN [6], both operating at 200 MHz.

The new design technique gives comparable capture and transmission through the RFQ, and the vane voltage is slightly less than with the Yamada design technique. For capture and acceleration of rare or radioactive heavy-ion beams, the resulting low longitudinal emittance simplifies the design of the following accelerators and provides a sharper bunch structure that can be used in TOF experiments and a smaller energy spread for nuclear level structure experiments.

Non-Adiabatic Bunching

This new design technique uses a discrete buncher followed by a drift, a transition section and an acceleration section. An overall optimization of the parameters of all four sections is required to minimize the longitudinal phase space area while maintaining high transverse and longitudinal capture. The resultant design, at least for the case presented, has a slightly lower vane voltage and length than an RFQ designed to the same set of specifications using the Yamada design technique.

The buncher section is incorporated in the RFQ itself immediately following the radial input matching section. Placing the buncher in the LEBT is less desirable, as it requires the beam to be focused to a small waist to minimize transverse r.f. defocusing related to the phase of the buncher gap voltage. In addition, complication of the LEBT design is avoided by including the buncher in the RFQ itself. Harmonic bunchers, which cannot be placed in the RFQ, do not seem to be required, as good results are obtained with a single fundamental-frequency buncher.

The transition section between the buncher/drift and the acceleration section involves rather non-linear longitudinal behavior and is not amenable to a linear analytic approach. Accordingly, several approaches to this vital transition section were investigated using macroparticle techniques and the method described here was selected as giving the best results.

The basic parameter choices for the accelerator are the operating frequency and peak surface field, the input and output energy and the strength of the focusing parameter B. It has been found that the acceleration section is optimized in length and acceptance by choosing the average accelerating rate E_{acc} to be a constant fraction of the peak surface field $E_{surface}$. This establishes the separatrix height at the beginning of the acceleration section, from which the transition section parameters and the buncher voltage strength and drift length are determined.

Implementation of the Discrete Bunching Process

The RFQ sections that implement the discrete bunching process and subsequent accelerating are described below. The design process is still somewhat complex, but a code is being written which will simplify this process.

The Radial Matcher. The radial matcher section is conventional and matches the d.c. input beam from the LEBT to the time-varying transverse envelope inside the RFQ. The cubic longitudinal dependence of the focusing parameter B is given by $B(\eta) = B_0\eta^2(3-2\eta)$, where $\eta = z/L_{RM}$, and the focusing strength B is constant throughout the rest of the RFQ.

The Buncher Section. The buncher is implemented in the RFQ by distributing it over several cells, with a longitudinal field strength that ramps from zero to a maximum and then back down to zero. The ramping minimizes abrupt transitions from an unmodulated cell to a cell with a large modulation index, resulting in a more accurate field integral. In this case, the buncher is spread over five cells with relative strengths

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1/13, 3/13, 5/13, 3/13 and 1/13 of the strength of an equivalent single-cell buncher.

The energy spread introduced by the buncher is about 25% of the constant separatrix height in the transition section.

The Drift Section. The drift section is unmodulated and allows the bunch to form. The length of this section allows bunch to approximately coalesce.

The Transition Section. In the transition section, the separatrix height is suddenly increased to a constant value of about 90% of the first cell of the acceleration section and the stable phase is ramped linearly from -90° to the final value, usually -30°. The length of the transition section is chosen so the small-amplitude phase oscillation advances by about 90°. As the stable phase moves toward its final value, the beam is slightly accelerated.

The Acceleration Section. The acceleration is continued at a constant stable phase and a constant ratio $E_{acc}/E_{surface}$ until the final energy is reached.

Throughout the accelerator, except for the input radial matcher, the vane voltage, average radius r_0 and focusing parameter B are constant, so that the local cut-off frequency everywhere in the cavity is constant. Figure 1 shows the values of m, a and A in the five sections of a sample design.

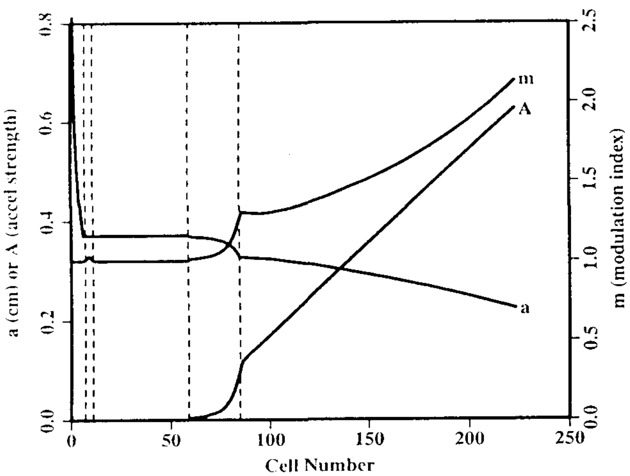

Figure 1. a, m and A vs. cell number.

Design Equations

The acceleration section is defined by $E_{acc}/E_{surface}$ = constant with 0.04 as a representative value. The values of a, A, χ and m are calculated self-consistently throughout the acceleration section with the usual equations [2], from the input to the final energy with constant ϕ_s and focusing parameter B. The height of the separatrix at the entrance of the accelerating section is

$$(\Delta W_{sepx})^2 = 2A\,\xi VeW_i(\phi_s\cos\phi_s - \sin\phi_s)$$

where ξ is the charge-to-mass ratio of the ion. The constant separatrix height in the transition section ΔW_{trans} is given by $\Delta W_{trans} = c_1 \Delta W_{sepx}$, where $c_1 \approx 0.9$. The stable phase ϕ_s in the transition section is ramped by an equal increment per cell from -90° to the final stable phase, usually -30°. The length of the transition section is chosen to advance the small-amplitude longitudinal tune $\sigma_{l\ tot}$ by $c_2 \times 90°$, where $c_2 \approx 1.0$. The phase advance per cell is given by $\sigma_l = k_l \beta\lambda$, where

$$k_l^2 = -\frac{\xi\pi^2 eAV}{mc^2\beta^4\lambda^2}\sin\phi_s$$

The peak energy ΔW_b imparted by the buncher is $\Delta W_b = c_3 \Delta W_{sepx}$, where $c_3 \approx 0.25$. The length of the drift following the buncher is given by

$$L_b = c_4 \frac{\Delta\phi}{\pi}\beta\lambda \frac{W_{preaccel}}{W_{buncher}}$$

where $\Delta\phi = \pi/2 - \phi_s$, $W_{preaccel}/W_{buncher}$ is the ratio of initial beam energy to additional energy spread due to the buncher and $c_4 \approx 0.5$.

The values of the four constants c_1 to c_4 are given only approximately: they are adjusted for best results by testing the performance of the resulting RFQ design with PARMTEQ.

A Sample Design

This technique has been used to calculate the parameters for a prototype split-coaxial RFQ accelerator for the front-end of a radioactive beam accelerator complex. This test accelerator is designed for 70 MHz as r.f. amplifiers for this frequency are already at hand. The full-scale accelerator design frequency is 25 MHz. The prototype accelerator parameters are:

frequency	70	MHz
q/A	1/20	
input energy	2.5	keV/n
output energy	100	keV/n

The Yamada technique was also used to design an accelerator with the same specifications. The results of the two design techniques with an input beam peak emittance (waterbag distribution) of 5.7π cm-mrad are compared in the following table.

	This	Yamada	
Transmission	85.3	88.0	%
rms Long. emitt	0.030	0.11	MeV-degree/π
	1.2	4.4	keV-nsec/π
Length	300.12	299.77	cm
Number of cells	223	211	
Vane Voltage	56.2	60.4	kV
Focus Parameter B	4.0	3.72	

Figure 2 shows the rms longitudinal output emittance for this and the Yamada design techniques and figure 3 shows the corresponding transmission as a function of the peak transverse input emittance with a waterbag distribution. The Yamada design has a slightly larger transmission for larger values of transverse input beam emittance, but the longitudinal output emittance is significantly larger.

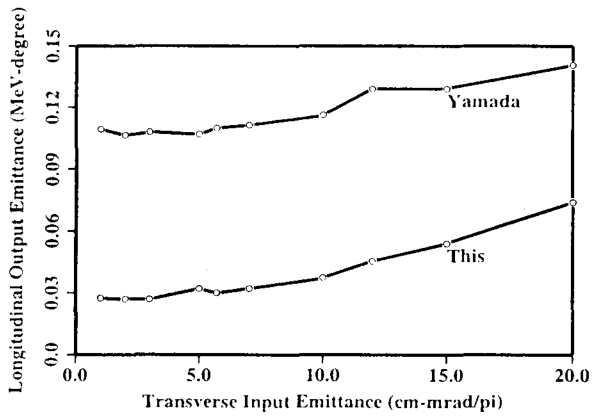

Figure 2. $\varepsilon_{l,\mathrm{Output}}$ vs. $\varepsilon_{t,\mathrm{Input}}$

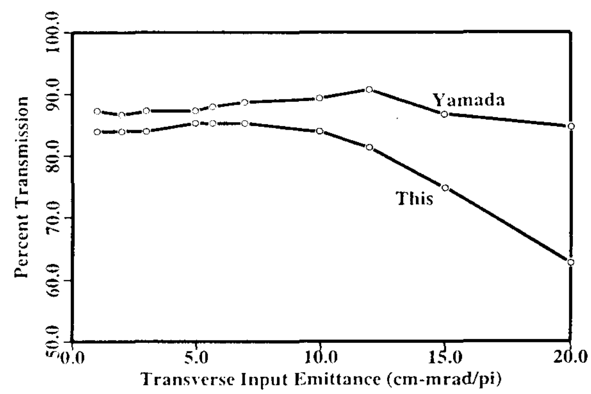

Figure 3. Transmission vs $\varepsilon_{t,\mathrm{Input}}$

Error Sensitivity

A buncher-drift will be more sensitive to preinjector energy error than will an adiabatic buncher scheme. This, and several other error analyses were carried out in the discrete buncher design. The characteristics of the discrete buncher design are surprisingly independent of the input energy or vane voltage. Input energy variation or spread of ±0.4% or more are acceptable, as shown in Figure 4.

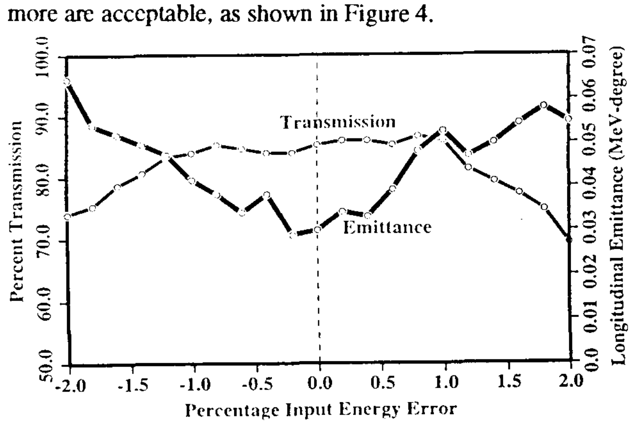

Figure 4. Sensitivity to Input Beam Energy Error

The sensitivity of the design to vane voltage error is also minimal. Figure 5 shows that a vane voltage error by as much as ± 3% does not significantly affect the transmission or longitudinal output emittance.

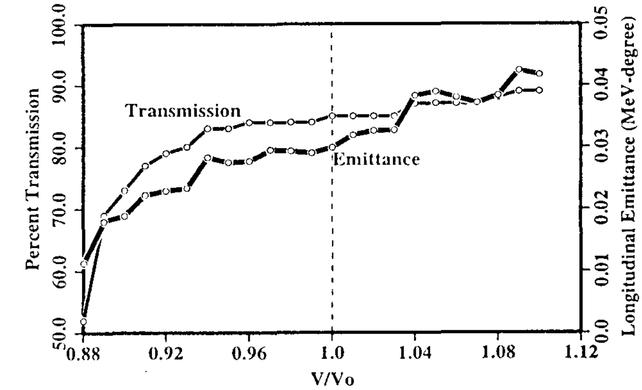

Figure 5. Sensitivity to Vane Voltage Variation

Summary

A new design technique reduces the longitudinal output emittance of zero-current heavy-ion RFQs to levels significantly lower than previous methods. The transmission fall-off is more significant for large values of transverse input emittance, but the output parameter sensitivity to variations in input beam energy or vane voltage is quite small.

A simplified design procedure is being developed for the discrete-buncher formulation and will be reported on in a subsequent paper.

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