REDUCING LONGITUDINAL EMITTANCE GROWTH IN RFQ ACCELERATORS

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Abstract

Bunching and capture of a monochromatic beam into an rf bucket inevitably lead to substantial emittance growth through the mechanisms of filamentation and non-adiabatic variation of parameters. We describe a three step strategy for minimizing this growth, based on a clear understanding of the non-linear beam dynamics, and apply to acceleration of heavy ions with $Z/A = 1/60$ (and initial kinetic energy 60 keV/u) in a radio frequency quadrupole (RFQ) operating at 25 MHz. We also describe a scheme, to further reduce the emittance, based upon the use of an external RFQ-type prebuncher before the main accelerator. The external unit permits the bunching voltage to be reduced, to inject into a moving bucket, and to reduce the structure length.

1 Introduction

One design aim is to minimize the length of the RFQ linac and maximize the acceleration; this leads to the requirement to increase inter-vane voltage (if it does not compromise cw operation) and to increase the vane modulation parameter m. However, both these trends conflict with another aim of the ISAC RFQ design which is to minimize the longitudinal emittance (ε_z) of the heavy ion beam. In designing the post accelerator for the proposed radioactive beam facility[1] at TRIUMF, it is beneficial to both the linac design and also to the experimenters to maintain small ε_z throughout the acceleration process. There are two basic issues that impact on this problem: (a) the beam will filament to fill (eventually) any given longitudinal acceptance, so the emittance will be given by the rf bucket area; (b) for practicable vane machining and alignment tolerances, the longitudinal focusing in an RFQ is often too strong – leading to a large rf bucket.

This paper discusses two strategies for RFQ design: (i) all emittance manipulations are performed within a single RFQ; (ii) the functions of bunching and acceleration are separated between two independent RFQ units each run with a different vane voltage. Strategy (i) follows from the design of Staples[1][2] and is discussed in sections 2-3, while strategy (ii) has been developed independently at TRIUMF and is described in section 4.

2 Single RFQ Linac

We have modelled injection and capture of a coasting mono-energetic ion beam by an RFQ using the code PARMTEQ[3] with 4000 simulation particles. The RFQ model was generated with the preprocessor GENRFQ[4]. The ensemble was analyzed with the code OUTPROC.

2.1 Emittance growth and control

The effect on the beam of a sinusoidal energy modulation is for it to filament into an S-shaped curve in longitudinal phase space. During this process, the 100% emittance rises from zero to that of the circumscribing ellipse. Now, to guarantee a high capture efficiency, one must allow the filamentation to continue for 1/4 of a synchrotron oscillation. In this case, the ellipse area is approximately equal to that of the rf bucket. Consequently, to keep the emittance small we have to reduce the bucket height, which in turn depends on the vane modulation parameter $m \geq 1$. In principle we may make m as small as we like. In practice, very small values will be indistinguishable from machining and alignment errors, and an RFQ design that uses such values will perform stochastic acceleration. For a physical structure with transverse dimensions of order 1 cm, a modulation index of $m = 1.01$ implies dimensional accuracy down to 100 μm. These observations lead to the conclusion that one method to obtain low emittance is to make an RFQ with a super low gradient shaper section. Such a section can be approximated by alternating periods of finite ($m \geq 1.01$, say) and zero longitudinal electric field ($m \equiv 1$).

2.2 High capture efficiency

As pointed out by Batskikh[5] and Koscielniak[6], the secret to high capture efficiency in a system with non-adiabatic variation of bucket height and synchronous phase, is to allow the beam to filament for 1/4 of a small amplitude synchrotron oscillation [see Fig. 1]; and then to ramp the non adiabatic parameters. The capture efficiency is high, because the beam is sharply bunched with particles concentrated about the initial synchronous phase $\phi_s = -90°$.

2.3 Staples RFQ linac design

The Staples design employs a prebunching section with $m \geq 1.009$; even with such a small value, the longitudinal focusing is sufficiently strong that the bucket is very large compared with the beam emittance from the ion source. The emittance might, for example, be reduced by a factor three if the modulation index could be reduced to $m = 1.001$. One way to achieve this in a deterministic manner, is to take a period of twenty cells comprising 2 cells with $m = 1.01$ and 18 cells with $m = 1.00$. The beam dynamics is found to be not too different between the true $m = 1.001$ and effective $m = 1.001$ structures. Of course, what we have invented is the RFQ equivalent of a buncher cavity followed by a drift. The Staples RFQ design does not allow a full 1/4 synchrotron oscillation before ramping ϕ_s, and so can immediately be improved by simply increasing the length of the shaper section. Further steps to reduce ε_z are to reduce the rapidity of increase of m by reducing the peak rf transverse defocusing parameter $|\Delta_b| \leq 0.04$ and to lessen the vane voltage somewhat; this limits bucket height and suppresses emittance growth. These ideas were combined to give the following alternative RFQ design.

3 Strawman RFQ reference design

3.1 3-step strategy

Step-(1). Give adequate length for 1/4 synchrotron oscillation; for the ISAC design, this requires about 85 cells and accounts for some of the increase in length when compared with the Staples design.

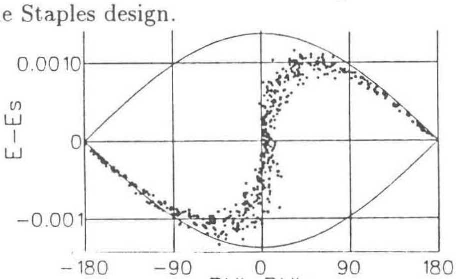

Figure 1: Longitudinal phase plane after 1/4 oscillation.

Step-(2). The phase profile $\phi_s(z)$ has to be thought about carefully. Initially, ϕ_s can be moved quickly because the phase space at the bucket ends is sparsely populated.

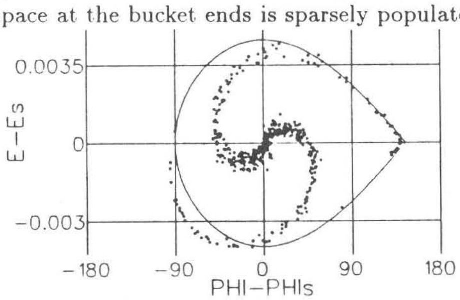

Figure 2: Phase plane after fast ϕ_s variation.

Step-(3). Later, however, when the bucket length collapses to encompass the core of particles, ϕ_s must be moved more slowly so that an adiabaticity condition holds for the bunch. If ϕ_s is moved too quickly, then the bucket will move through the bunch, resulting in large losses.

3.2 RFQ description

We shall adopt the terminology of Yamada[7] and Crandall[3] to name the sections of our strawman RFQ design. The transverse focusing parameter $B = 3.0$ is held constant[1] over the entire RFQ length of 904 cm. The first stage is a *radial matcher* of 8 cells. The next stage is a *shaper* of 85 cells in which $\phi_s = -90°$ and average $m = 1.001$ are held constant to get the S-shaped emittance. The third stage is a *prebuncher* in which the synchronous phase is quickly varied from $\phi_s = -90°$ to $\phi_s = -55°$ over 118 cells, and modulation index changes from $m = 1.006$ to $m = 1.07$. The fourth stage is a *buncher* in which the synchronous phase is slowly varied from $\phi_s = -55°$ to $\phi_s = -30°$ over 88 cells, and modulation index changes from $m = 1.07$ to $m = 1.183$. The fifth stage is a *booster* in which the modulation index increases (over 86 cells) to its limiting value of $m = 2.5$, while $\phi_s = -30°$ is held constant. The final stage is an *accelerator* of 66 cells in which $m = 2.5$ is held almost constant. The $m(z)$ and $\phi_s(z)$ profiles were generated with the code GENRFQ. The performance of this design is described in section 5.

[1]Except in the radial matching section.

4 RFQ with External Prebuncher

Initially, the use of an external RFQ prebuncher was motivated by the following considerations: (i) smaller emittance, by use of reduced vane voltage; (ii) better bunching action, by the use of bi-harmonic rf; (iii) realistically large m values to ease machining. Simple mindedly[2], in order to reduce ε_z by a factor 4 requires to reduce the energy modulation by at least a factor 2, that is from ±1 keV to ±0.5 keV.

4.1 Prebuncher designs

Bunching is only effective when the impressed energy modulation is substantially larger than the intrinsic energy spread of the beam. However, the off-axis longitudinal electric fields in the radial matcher leads to some longitudinal emittance growth even when $m \equiv 1$. In fact, for ISAC, passage through a single radial matcher is enough to degrade the beam to a local energy full width of 0.3 keV (and the effect is somewhat invariant w.r.t. length of the matcher). Initially we had intended using two RFQ prebunchers excited (in anti-phase) at 1st and 2nd harmonic of the rf. However, such bi-harmonic operation necessitates 5 matchers (so as to avoid betatron mismatch) and their study was quickly abandoned in favour of a single prebuncher running at the fundamental.

Two designs of prebuncher were tried: (i) small vane modulation followed by a long RFQ transverse focusing channel [length 146 cm]; (ii) large modulation followed by a short channel [length 52.3 cm]; both start with an 8 cell radial matcher. Design (i) leads to a smaller energy modulation (±0.5 keV), but inefficient bunching with many particles remaining in the arms of the S-shape; and this leads to emittance growth. Design (ii) starts with a larger energy modulation (±0.8 keV), but the tendency toward increased emittance is offset by the greater phase concentration of particles. For the ISAC parameters, design (ii) was found to be the more effective. The external prebuncher vane voltage was reduced to 15 kV; below this value the bore radius diminishes to the extent that there is inadequate physical aperture to transport the intended transverse emittances.

4.2 Main RFQ

The external prebuncher and main RFQ both have focusing parameter $B = 3.0$. There is a very short drift between their two respective vacuum tanks. The bore radius of the

[2]From experience with the strawman design.

main RFQ is much greater than that of the external prebuncher because of the very different vane voltage (67 kV). Therefore there is little problem with transverse particle loss despite the slight betatron mismatch due to the drift space. The main RFQ is independently phased with respect to the external prebuncher.

It was realized that the design of the main RFQ could be revised: eliminate the radial matcher section and reduce the length of the prebuncher section by injecting directly into the centre of a moving bucket. This has several benefits: (a) bucket height is reduced, (b) acceleration starts immediately, (c) part of the fast ϕ_s variation can be omitted, (d) the overall structure is shorter.

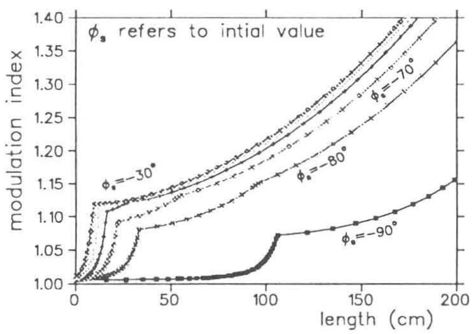

Figure 3: $m(z)$ variation for several initial ϕ_s values.

A variety of schemes were tried with injection angles between −85° and −30°. There is a rapid decrease in the RFQ length between −90° and −80°, but thereafter gains diminish [see Fig.3]. The schemes with smaller initial phase angles (i.e. −60° to −30°) suffer from two strong drawbacks: (i) the buckets are very short (down to 90°) and up to 30% of particles are lost immediately; and (ii) as m rapidly increases the bucket height grows in an extremely non-adiabatic manner, leading to the formation of halos and more losses. The final compromise design was a short prebuncher followed by injection into the main RFQ at an angle of $\phi_s = -85°$. Performance is summarized below.

5 Conclusion

Some aspects of the Staples, the strawman, and proposed reference design are tabulated below. The emittances are quoted in (MeV.deg). Figures 4–6 show the variations of $\phi_s(z)$ and $m(z)$ and the corresponding longitudinal phase plane at exit from each of the three RFQ designs discussed.

design	trans mission	r.m.s. emitt	100% emitt	vane volt (kV)	length (cm)
Staples	89%	0.104	1.134	76	754
strawman	96%	0.056	0.978	67	904
prop. ref.	93%	0.053	0.699	15+67	804

The most significant improvement in the newer RFQ designs comes in the r.m.s. emittance. The greater transmission efficiency of the TRIUMF designs should come as no surprise, it is always easier to transport a lower emittance beam. In all cases the emittances indicate a well established core of particles surrounded by a wide halo [see Figs.4–6]; this is unavoidable but could be removed by subsequent momentum collimation.

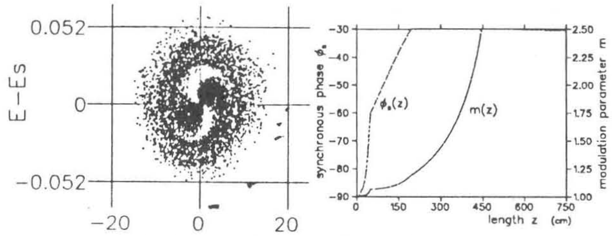

Figure 4: Staples RFQ design.

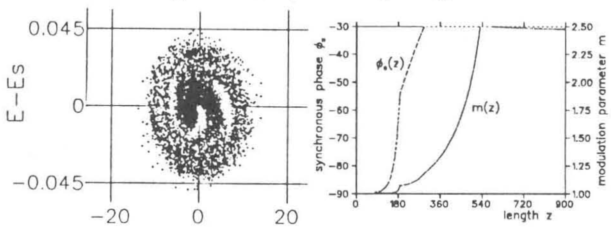

Figure 5: Strawman RFQ design.

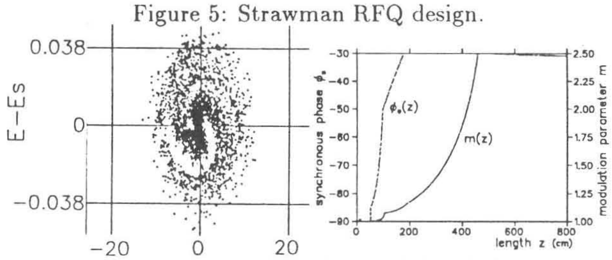

Figure 6: Proposed reference RFQ design.

5.1 Future work

It is intended to try and further reduce the RFQ length by allowing ϕ_s to rise to −10° before a transition to −30° which matches into the following linac. Further, it is intended to re-optimize the designs for $Z/A = 1/30$. Note, the peak value $\hat{m} = 2.5$ in these designs is somewhat high; considerations of tooling and higher order terms in the potential function may suggest to lower $\hat{m} \approx 2$ and increase the overall length of the structures.

References

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[2] We are indebted to Dr. John Staples, LBL, for deriving this set of RFQ parameters.

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