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REDUCING RFQ OUTPUT EMITTANCE BY EXTERNAL BUNCHING*

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RFQ accelerators normally incorporate adiabatic bunchers in the accelerator proper. This produces high accelerator acceptance but less-than-optimum longitudinal emittance as a result of severe filamentation of the longitudinal phase space. The use of discrete bunchers both internal and external to the RFQ, along with new approaches in accelerator-only (no adiabatic buncher) RFQ beam dynamics designs produces significantly lower longitudinal output emittance with high acceptance.

KEY WORDS: RFQ, emittance, bunching

1 ADIABATIC BUNCHING WITHIN THE RFQ

RFQ accelerators have offered the designer considerable flexibility in beam dynamics design. This unique accelerator type incorporates strong focusing as the primary mechanism, with longitudinal accelerating fields introduced as a perturbation of the structure. This freedom to vary $E_z(z)$ arbitrarily has resulted in several design approaches, all of which incorporate some sort of adiabatic bunching within the RFQ itself.

Several advantages follow: discrete bunchers are eliminated from the LEBT. Adiabatic bunching allows nearly 100% of the beam to be accepted into the r.f. bucket. Adiabatic bunching copes well with space charge forces, which help control the bunching process itself to control the rate of bunch formation.

However, the quasi-adiabatic bunching process is highly nonlinear, resulting in a filamented longitudinal phase space with a relatively large area. The phase space resulting from a more precisely adiabatic bunching process would require an unrealistically long RFQ to accommodate the several phase oscillations needed.

In high-mass, low-current RFQs, a different beam dynamics prescription may be used.[1] Space charge is no longer significant, and the bunching process can be carried on more rapidly, with some attention given to preventing too rapid a bunch collapse. The separatrix area is kept approximately constant in the buncher sections, and grows in the accelerator section so the phase oscillations become more linear. The rapid bunching results in a shorter accelerator but still with a relatively high longitudinal emittance.

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The RFQ buncher sections usually dominate the length of the accelerator. Usually significantly less than half the length of an RFQ is devoted to accelerating the beam at full longitudinal gradient. In addition, the introduction of an unbunched beam to the RFQ entrance requires an adiabatic transverse matching section that transforms the time-independent envelope to a time-varying envelope matching the strong r.f. quadrupole focusing inside the RFQ structure.

2 DISCRETE BUNCHERS

Discrete bunchers may be applied to RFQs as they have been to other linear accelerators such as d.c. preinjector — DTL combinations. Fundamental frequency bunchers may be incorporated in the LEBT or the RFQ itself: harmonic bunchers will be restricted to the LEBT. Several types of buncher configurations are described in a comprehensive treatise by Blasche and Friehmelt.[2] We will consider three of these below.

3 SCR NON-ZERO AXIAL POTENTIAL

Problem One structure type appropriate for very low velocity, high mass ions is the split coaxial resonator (SCR), a heavily loaded cavity that operates efficiently in the 25–50 MHz region.[3] The SCR uses RFQ-like vanes, allowing the same flexibility in tailoring $E_z(z)$ as in conventional RFQs. However, the potential on the axis of the SCR rises from zero to $V/2$ in the space between the endwall and the vanes, where V is the intervane potential. The beam entering the accelerator must climb this time-varying potential hill without being accelerated or bunched. One scheme is to treat the entrance gap as a long accelerating gap with a negligible transit time factor for particles of all phases. One potential function in the entrance gap region is $V(z) = 3a^2 - 2a^3$, where $a = z/L_{\mathrm{matcher}}$ and L_{matcher} is approximately $20\beta\lambda$ long. This is accomplished by arranging the grounded vanes to have constant displacement from the axis, and the hot vanes to have a long and gentle departure from the axis as they approach the entrance endwall.

4 RFQ ACCELERATOR BEAM DYNAMICS CHOICES

Four design algorithms for the design of a low-β accelerator-only RFQ have been investigated. No adiabatic bunching was used, although a radial matcher was employed in all cases to allow a round beam to be introduced into the RFQ.

The four algorithms differ by requiring two different parameters to be kept constant from cell to cell. For a given set of initial conditions, (frequency, input and output velocity, surface field, q/A and stable phase), the specification of two more parameters fixes all the cell parameters. The four design algorithms are:

(1) Constant $E_{\mathrm{acc}}/E_{\mathrm{surface}}$ and B in each cell. This results in the lowest required intervane voltage and power dissipation, and allows a moderate growth of the height (energy) of the bucket toward the high-energy end.

(2) Constant Δ_{gap} and B in each cell. This requires a higher intervane voltage than (1), but has a higher transverse acceptance. The separatrix height grows more slowly, and slightly higher values of m are found at the exit. The accelerator is slightly longer than in (1).

(3) Conventional accelerating section, the same as the usual prescription used in GENRFQ for the acceleration section, with B, A_{init} and A_{final} specified. At reasonable values of the focusing parameter B the accelerator is substantially longer than in (1), and the separatrix height grows more than is necessary, throwing away needed acceleration rate. This algorithm works well when started at a higher energy, but not at very low β_{init}.

(4) Constant $E_{acc}/E_{surface}$ and m in each cell. Very heavy tilts of V, a and B occur along the structure. This is not seen as a practical design algorithm and will not be investigated further.

Algorithms 1–3 were tested, optimizing the selected parameters until the best design for that algorithm was found. The best design was defined as an accelerator with the modulation parameter m not significantly more than 2 so the vanetip geometry could be easily implemented; a length less than 3 meters; the lowest longitudinal emittance and the highest particle transmission. The common parameters for all cases were:

Freq	70	MHz
T_{in}	2.5	keV/n
T_{out}	100	keV/n
$E_{surface}$	22	MV/m
ϕ_s	−30	degrees
Input $\Delta\phi$	±30	degrees
Input ΔT	±4	%

The additional parameters for each specific case were:

Case (1): $E_{acc}/E_{surface} = 0.04, \quad B = 4$

Case (2): $\Delta_{gap} = -0.065, \quad B = 2.5$

Case (3): $B = 3.5, \quad A_i = 0.1, \quad A_f = 0.6$

The results of PARMTEQ simulations of these best accelerators in each class gave the following results:

Case	V_v (kV)	Length (cm)	m_{max}	Transm %	ε_l (MeV-°)
1	56.2	258	2.12	100	0.104
2	89.9	276	2.24	84	0.084
3	64.2	271	2.06	35	poor

Case (1), with constant $E_{acc}/E_{surface}$ and B is the clear winner. It is the shortest, uses the lowest vane voltage, and has the highest transmission, and the output emittance is satisfactory. We will use this accelerator to test various buncher configurations upon.

5 CHOICE OF BUNCHER CONFIGURATION

Kick bunchers can be placed in the LEBT or in the RFQ itself. As $E_z(z)$ can be arbitrarily varied in the RFQ, $h = 1$ bunchers can be realized, interposed by drifts in the structure itself. As the r.f. defocusing forces are significant at the low injection velocity, the strong focusing inherent in the RFQ which keep the beam size down may be preferable to bunchers in an external LEBT.

Four buncher configurations were considered:

(A) Single fundamental buncher. This is the easiest, and serves as a basis of comparison for more elaborate configurations.

(B) Single fundamental buncher in or near the RFQ, with a second harmonic buncher upstream in the LEBT.

(C) A fundamental and a second harmonic buncher at the same location in the LEBT.

(D) A sequence of three fundamental bunchers. These may be located in the LEBT or the RFQ itself.

Figures 1 through 4 show the longitudinal phase space for each of these buncher configurations, optimized to place as much of the beam as possible to within a $\pm 50\%$ phase spread, which matches accurately the actual phase acceptance of the test RFQ. A new beam generator was written for PARMTEQ which includes up to 10 spaced bunchers operating at arbitrary voltages and harmonics. The RFQ case (1), the constant $E_{acc}/E_{surface}$ and B case, was used to test each of these buncher combinations.

6 RESULTS OF SIMULATION RUNS

In addition to the four buncher configurations described above, two other classes of tests were added which include: (2) accelerating-only RFQ with an ideally bunched beam and (3) a conventional RFQ with adiabatic buncher. The parameters of each run are:

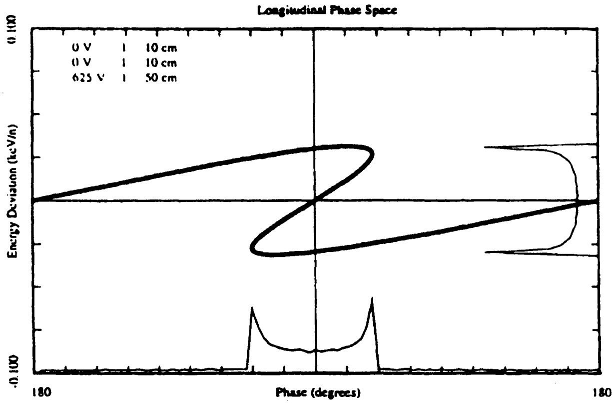

FIGURE 1: Single Fundamental Buncher

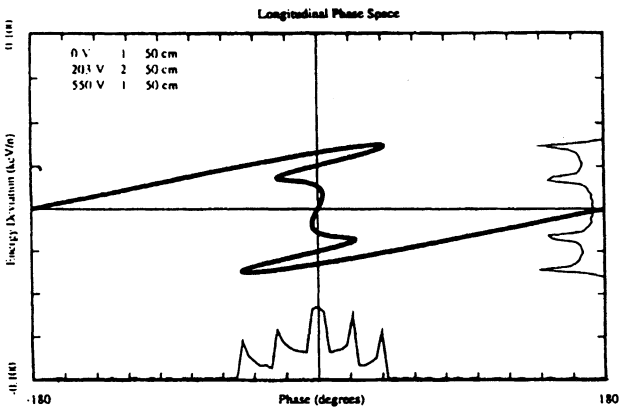

FIGURE 2: h=2 followed by h=1 Buncher

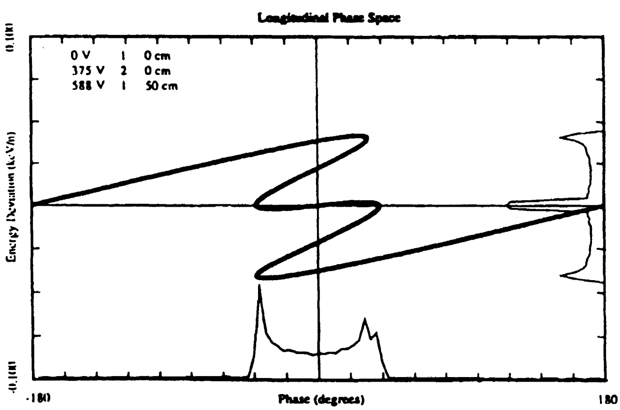

FIGURE 3: Coincident h=1 and h=2 Bunchers

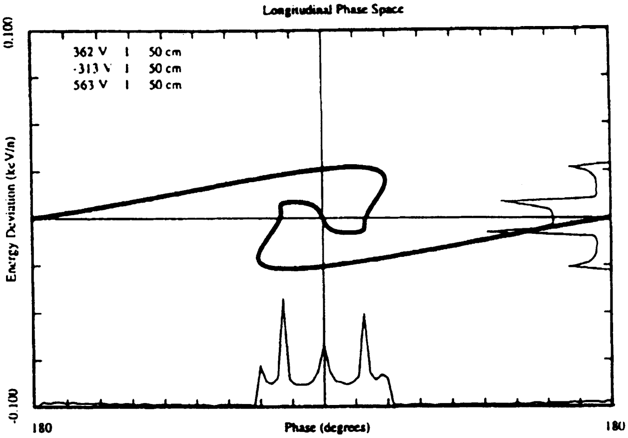

FIGURE 4: Three consecutive h=1 Bunchers

(1) Beams produced with above-described bunchers, corresponding to cases (A) through (D).

(2) Ideal bunched beam into accelerating RFQ. The two subcases are (A): $\Delta\phi = \pm 30°$ and $\Delta T = \pm 4\%$. (B): zero initial phase space with $\Delta\phi = \Delta T = 0$. These give the lower limit of longitudinal emittance possible with perfect bunching.

(3) Conventional RFQ with adiabatic buncher with two values of surface field: (A) 18 and (B) 22 MV/m, corresponding to 1.8 and 2.2 Kilpatrick. This machine was designed using the design scheme of Yamada.[1] Machines (3A) and (3B) have length of 320 and 210 cm, and intervane voltages of 50 and 75 kV, respectively. (The accelerate-only RFQ in classes (1) and (2) is 258 cm long with a 56 kV intervane voltage.)

In all cases, the initial normalized beam transverse emittance is 0.01π cm-mrad, at the 100% contour of a waterbag distribution, matched into the RFQ transverse phase space.

In each case, the buncher voltages and drift distances to the RFQ were adjusted to give the best match of the longitudinal axis ratio, that is, the best fit of the bucket shape. The most significant differences were in the beam survival fraction and the longitudinal output emittance. In all cases, the transverse emittance of the input beam was not increased appreciably.

The following table summarizes the survival and the contour that contains 95% of the longitudinal output emittance for all the methods of longitudinal beam preparation, and for two traditional RFQs with adiabatic bunching incorporated in the structure.

Case	% Survival	e_l (MeV-deg)
1A	74	0.289
1B	89	0.202
1C	85	0.230
1D	85	0.180
2A	100	0.104
2B	100	0.025
3A	85	0.466
3B	87	0.447

As can be seen, for the accelerator-only RFQ, all but the simple $h = 1$ buncher (1A) gives acceptable acceptance. The idealized case (2B) with no initial energy or phase spread indicates the lower limit of longitudinal output emittance, 0.025 MeV-degree. The two cases illustrating a conventional RFQ design with integrated adiabatic bunching, (3A) and (3B) show a longitudinal emittance more than twice that of the RFQ with external bunching.

Figures 5 and 6 show the input and output phase space for a representative accelerate-only RFQ, case (1B). Figures 7 and 8 show the output phase space for cases (3A) and (3B), the conventional RFQ, for comparison. The graph scales are ±30° and ±0.05 MeV, or ±2.5 keV/n.

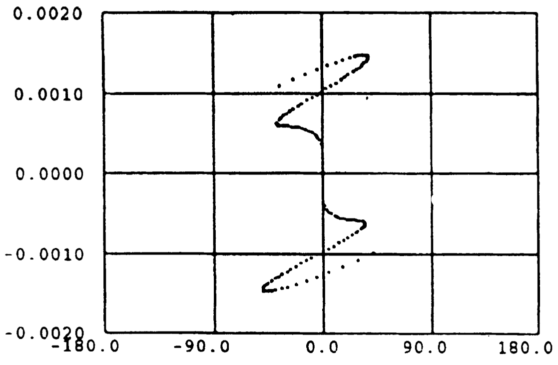

FIGURE 5: Case (1B) Input Phase Space

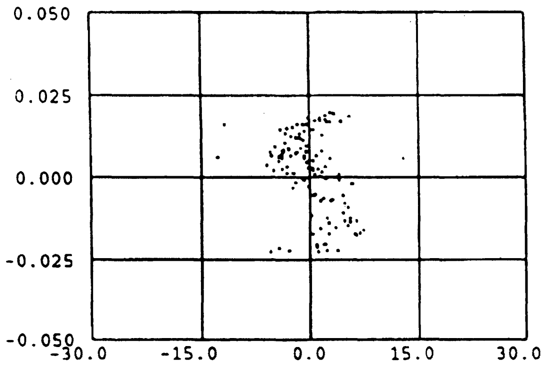

FIGURE 6: Case (1B) Output Phase Space

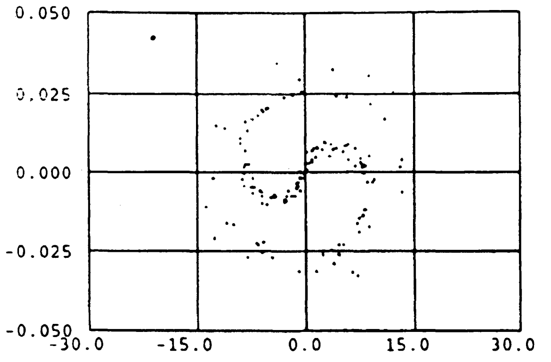

FIGURE 7: Case (3A) Output Phase Space

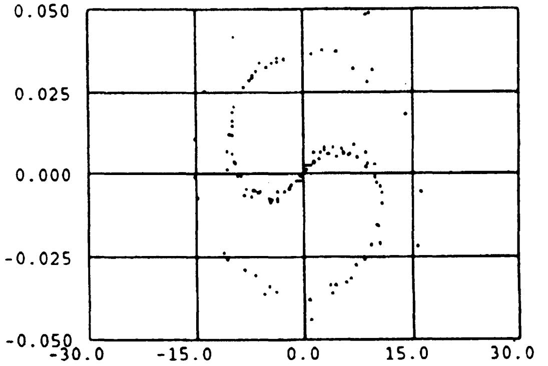

FIGURE 8: Case (3B) Output Phase Space

7 DISCUSSION

The longitudinal output emittance of an RFQ can be improved by replacing the adiabatic buncher with external discrete bunchers. The transmission of the RFQ is equal to that of a conventional RFQ with adiabatic bunching, and the RFQ length is reduced.

However, this does not come for free. The stability requirement of the preinjector voltage increases by about an order of magnitude, and the r.f. defocusing of the beam in the discrete buncher may be significant and may require either gridded cavities or small beam size in the bunchers.

The preinjector voltage stability required is

$$\frac{\Delta V}{V} = \frac{\Delta \phi}{\pi} \frac{\beta \lambda}{h L_{\text{drift}}} .$$

For a $\pm 5^\circ$ tolerance and a buncher-RFQ spacing of 25 wavelengths, the preinjector voltage regulation is about $\pm 0.1\%\ h$, where h is the harmonic number.

The r.f. defocusing in the buncher cavity causes an angular deflection $\Delta\theta$ given to a particle a distance r from the axis of

$$\Delta\theta = \frac{\pi}{2} \frac{V_{\text{cav}}}{V_{\text{preinj}}} \frac{r}{\beta\lambda} \cos\phi$$

or, for the case of a $q/A = 1/20$ beam with a 50 kV preaccelerator potential and a 1 kV peak buncher voltage, $\Delta\theta = 30r$ mrad, r in cm, which is significant for a 4π cm-mrad beam focused to a 0.5 cm spot radius in the buncher. Grids may be required.

If the beam is tightly bunched as it enters the SCR RFQ structure, the effect of the residual bunching while entering the non-zero axial field zone will become less important, and the longitudinal matcher section may be simplified. In addition, the conventional radial matcher may not be necessary.

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