Beam Dynamics of the TRIUMF ISAC RFQ

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Abstract

We describe the beam dynamics design and report the anticipated performance, including a sensitivity analysis with respect to beam injection errors or vane displacements, of the proposed TRIUMF ISAC Radio frequency Quadrupole (RFQ) accelerator. The 35MHz RFQ is intended for the acceleration of ions with a charge-to-mass ratio greater than 1/30 from 2 keV/u to 150 keV/u. Novel features of the design include the use of an external quasi-sawtooth buncher, the use of only 'booster' and 'accelerator' sections, and a single constant phase angle of $-25°$. The vane design has large modulations and a constant transverse radius of curvature, and has been corrected to give the two term potential function coefficients. An important design objective is achieving small emittances.

1 INTRODUCTION

The ISAC project conceptual design was presented in [7] and more recently in [8]. ISAC consists of a an ISOL and two c.w. linear accelerators: a 35 MHz RFQ and a 105 MHz drift tube linac. The RFQ design can be separated into two parts: RF-electrical and beam-dynamic.

1.1 RF-theoretical design

RF/mechanical engineering aspects of the design, including results of power tests on a prototype, are reported in [9], while RF-theoretical considerations are given in [10, 11, 12, 15, 16], and RF cold model studies reported in [17, 18].

An important part of the electrical design is to produce symmetrical vane voltages such that the orthogonal mid-planes between the electrodes are at ground potential; and so the split coaxial type resonator[1], which leads to inherent asymmetry, was avoided. Instead, the Frankfurt 4-rod split-ring type resonator[5] was adopted. Unlike the Frankfurt design, which compromises voltage symmetry in favour of higher shunt resistance, the TRIUMF design has the inductively loading stems placed in close-pairs rather than equidistant; and this eliminates the unwanted even-type transmission line mode in favour of the desired odd-mode. Detailed 3D design work with the MAFIA code and extensive measurements on cold models resulted in a design that has a specific shunt resistance of ≈ 400 kOhm.m.

2 BEAM DYNAMICS DESIGN

The history and progress of the beam dynamics design may be followed in [7, 13, 19], etc.. The present accelerator design has an external multi-harmonic buncher (composed of an RF gap and 5.3 m drift space) followed by an 8.0 m long RFQ which contains 7.6 m long modulated vanes and ancilliary space for vacuum flanges and RF tank end walls. The ISOL transmits a reference beam of 100% emittance $= 0.1\pi$ mm.mrad (normalized), and based on tracking with the 2-term-potential the RFQ acceptance is almost 0.5π mm.mrad.

2.1 Choice of parameters

Let V be inter-vane voltage and r_0 be characteristic radius from beam axis to pole tip. For a constant Kilpatrick factor, and average electric field $\hat{E} = V/r_0$, it is found that the focusing strength B, the transverse acceptance A (in x-x' space), and the kinetic energy gain per cell ΔT are respectively given by

$$B = q\hat{E}\lambda^2/(m_0c^2r_0) \quad , \quad A = q\hat{E}r_0\lambda/(m_0c^2 \times 8.88) \; , \quad (1)$$

$$\Delta T = q\hat{E}r_0 \cos\phi_s \times 0.7854(1-a^2/r_0^2)/[1+(\pi a/\beta\lambda)^2] \; . \quad (2)$$

From these equations, it is clear that increasing B by reducing bore radius will lengthen the RFQ and reduce the acceptance. For this reason, we have taken B rather lower than is conventional. Contrarily, too small a value of B results in inadequate transverse focusing. A compromise was reached with $B = 3.5$. Increasing B by using long wavelength λ leads to prohibitively large RF-electrical structures.

Because a pre-bunched beam is injected into the RFQ and because space-charge effects are negligible, the RFQ vane profiles are shortened to comprise only 'booster' and 'accelerator' sections. Though a Yamada-type recipe is used for the vane profiles, the shaper and gentle buncher portions of the RFQ are omitted leading to substantial shortening. Further, the synchronous phase is large and constant, which maximises the acceleration. Two candidate reference designs were studied in detail, and the main parameters are presented below.

#	L (m)	kV	r_0	B	$\Delta_{\rm rf}$	$\hat{m}$	$\breve{a}$
(1)	6.25	85.4	.8645	3.0	-.0400	2.637	.4476
(2)	7.60	73.2	.7410	3.5	-.0408	2.599	.3846

Both designs have a gap-dependent Kilpatrick factor of $\hat{E}/E_{\rm Kilp} = 1.15$. Design (1), though very attractive, has the transverse and longitudinal tunes cross. To avoid the possibility of a 2nd order synchro-betatron parametric resonance[3], the focusing strength was raised from $B = 3.0$ to $B = 3.5$ resulting in design (2). Larger B also reduces the sensitivity w.r.t. transverse injection errors. To compensate the lower intervane voltage of design (2) the RF-defocusing parameter was raised so as to shorten the 'booster' section, and the minimum bore radius, $\breve{a}$, was reduced from 0.45 to 0.38 cm to shorten the 'accelerator' section. The chosen RFQ reference is design (2). In the booster section the modulation index, m, is rapidly ramped from 1.124 to 2.6 The beam radius is typically 2.5 mm.

J. Staples, of LBL, advised to consider the scenario of inadequate vane voltage and its impact on the longitudinal acceptance; and after study (see figure 1) it was concluded to move the synchronous phase angle further from the crest of the RF waveform; from -20 (design 1) to -25 degrees (design 2).

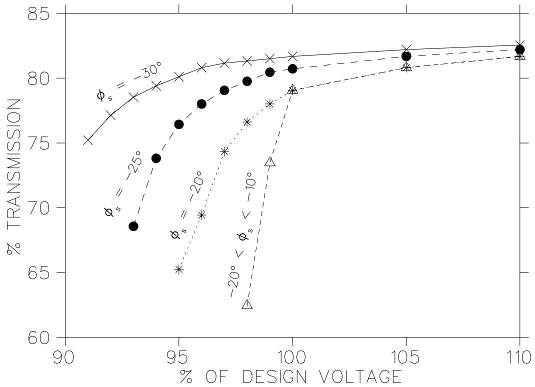

Figure 1: Transmission versus voltage fraction

2.2 External buncher

The use of an external, independent buncher had been considered academically for some time [13, 14, 20] but the request from experimentalists to do 'time of flight' work and discriminate against background made this essential. Pulse spacings of 86 nsec. are obtained by placing a quasi-sawtooth waveform klystron-type buncher operating at the 3rd sub-harmonic 5.3 m upstream of the RFQ. The buncher is excited with 11.667 MHz fundamental and its first three harmonics. The choice to bunch rather than chop the beam maximizes the beam transmission by phase-concentration into the RFQ's acceptance. This approach also shortens the RFQ (by eliminating the internal bunching sections) and improves longitudinal emittance at the RFQ exit.

The buncher-to-RFQ separation is a compromise: close proximity makes bunching less sensitive to energy spread and/or offset of the incident beam but increases the required voltages. Kinetic energy errors arise from imperfect regulation of the ion-source voltage and from the inherent energy spread produced within ion source itself; and are anticipated to be several eV. With a separation of 5.3 m, the system can accomodate beams with a Gaussian distributed random energy variation of $1\sigma = 10$ eV without any significant degradation in performance.

The proposed buncher hardware consisists of two parallel plates, with apertures of radius 0.7 cm, separated by 0.8 cm and enclosed in a grounded box. The dimensions are large compared to $\beta\lambda$ so that the acceleration is confined to the region between the plates. The peak inter-plate voltage will be less than 400 V for each of the Fourier components. A broad-band solid-state amplifier in conjunction with a ferrite core step-up transformer will be used to drive the plates in push-pull mode.

The beam dynamics of the buncher have been modelled numerically[25] by integrating 5000 particles through calculated 3D fields. Because the buncher dimensions are much less than λ, the static field approximation was used to determine the spatial dependence of the fields using the RELAX3D[6] code. The subsequent buncher-to-RFQ beam line was assumed to be composed of a periodic section of quadrupole doublets. The transverse emittance growth due to the buncher is less than 1%.

Figure 2 shows the longitudinal distribution of the bunched beam at the RFQ entrance extends over three periods of the 35 MHz RF. Calculations with PARMTEQ[2] indicate that approximately 80% of this beam can be successfully transported to

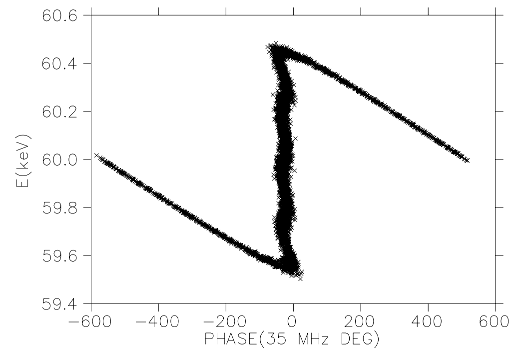

Figure 2: Longitudinal phase space

the exit of the RFQ. About 20% of the particles are lost longitudinally, because the tails of the bunched beam fall outside of the RFQ's acceptance and will be eliminated with a chopper.

2.3 Radial matching section

The designs of Yamada and Crandall for the vane profiles in the radial matching section (RMS) have been improved[24] and used as a basis for 3D particle tracking through the fringe fields in the region between the tank wall and the RFQ periodic focusing channel. The fields were computed with RELAX3D and input to the tracking program TRACK[27]. A detailed study[26] was deemed necessary, because of the very low rigidity of 2keV/u ions and consequent sensitivity to disturbances. The RMS profile was optimised (by stretching from 8 to 10 cells) to reduce the required beam convergence at the RFQ input.

3 VANE PROFILES AND FIELD CORRECTION

If one uses the ideal pole-tip geometry of the two-term potential function, then constant focusing parameter, B, leads to a constant characteristic radius r_0. However, we have adopted vanes with constant transverse radius of curvature (i.e. semi-circular pole tips), in which case constant B implies a varying r_0. The simpler geometry gives rise to high order multipoles, but the choice of low tunes, makes the beam dynamics inherently insensitive to them. This electrode geometry is inexpensive to manufacture, but has the disadvantage that the local bore radius, a, and modulation index, m, of each cell must be adjusted to obtain the same electric fields as for the ideal geometry. A method to do this and its implementation is described in [12, 13]. The algorithm leaves the cell length, l, invariant, and recently advantage was taken of this property to improve the accuracy by replacing

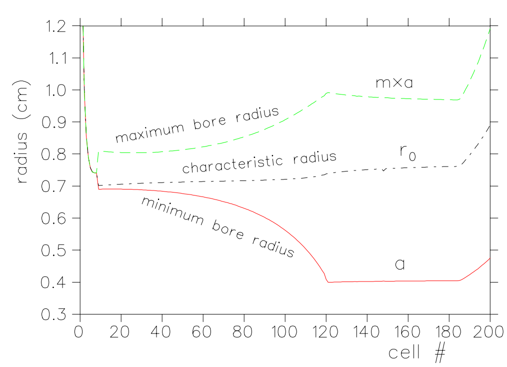

Figure 3: Vane profiles a, $m \times a$ and r_0 variation.

3D interpolation from an array of coefficients indexed by m, a, l with a set of 2D interpolations, one for each cell. The vane profiles are sketched in figure 3.

4 SENSITIVITY ANALYSIS

The goal of the most recent RFQ beam dynamics simulations was to perform a sensitivity analysis of the RFQ performance (transmission and emittance) with respect to injection errors of the beam and displacement errors of the vanes.

4.1 Beam injection errors

To facilitate automation, interactive shells for the RFQ simulation programs were devised using the LISP-like scripting and GUI builder language 'tcl/tk' with 'expect'. The PARMTEQ program was modified so that the description of a field-corrected RFQ could be read from file. Particle tracking with the 8-term potential shows[23] substantial halo formation and emittance growth even for the on-axis beam: 1% of particles constitute 40% of the occupied phase-space area.

Based upon tracking an ensemble of 4400 particles with various initial injection errors it is concluded that beam position, angle, phase and energy offsets, respectively, $\Delta r \leq 0.5$ mm, $\Delta r' \leq 0.02$ rad, $\Delta\phi \leq 5°$, $\Delta T \leq 0.5$ keV will cause less than 10% growth of the 95% emittance contours; and often much less. Growth of the 99% contours is usually much less than 25%. Within the stated injection error tolerances, the transmission through the RFQ is always 91.5% except for the case of $\Delta = -0.5$ keV where it drops to 90%.

4.2 Vane position errors

The vane displacement study is being performed with the package 'RFQCOEF'[4] in conjunction with PARMTEQ. Extensive modifications and improvements have been made to these codes at TRIUMF, particulalry to the algorithms for the effect on the meshing of displacing the vanes. The mesh generator now accepts the RFQ description after field correction, and this entails using a different r_0 for each cell. When vanes are moved, the 8-term potential is supplemented with dipole and sextupole components to give a 10-term potential; normalization discrepancies between RFQCOEF and PARMTEQ of the 10-term coefficients have been corrected.

Let us number the vanes counter-clockwise. Based upon the mechanical support and connections we consider two types of vane displacement: (i) where vanes 1&3 and/or 2&4 move as pairs with radial errors (likely vibrational modes); and (ii) where all vanes twist (likely thermal deformation). We have considered both constant and ramped vane position errors.

For combinations of vane movements of norm less than .2 mm, there is no detectable change in the transmission, and the growth of the 95% emittance contours is typically less than 5%. For movements of less than .5 mm, the emittance growth is less than 40%. But for larger displacements the emittance grows very quickly and the transmission drops dramatically; e.g. with a 0.1-0.9 mm rampthe transmission falls to 77% and the 95% emittance increases more than 5-fold. Analytic estimates of the dipole coefficients and emittance growth are given in[28].

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