Beam Dynamics Design of an RFQ for the SSC Laboratory

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Abstract

The design of the Radio Frequency Quadrupole (RFQ) accelerator for the Superconducting Super Collider (SSC) is presented. The RFQ, which accepts the beam from the ion source through the low energy beam transport (LEBT) line, is designed to accelerate H^- beam from 35 keV to 2.5 MeV. Key design considerations and the final design parameters for the RFQ are presented. Results of simulation studies with and without misaligned input beam are also discussed.

I. INTRODUCTION

The Radio Frequency Quadrupole (RFQ) accelerator section of the SSC linac is designed to provide ~25 mA of accelerated H^- beam at 2.5 MeV with a beam bunch frequency of 427.617 MHz. The ion source[1] followed by a suitable LEBT section is expected to provide up to 70 mA of H^- beam at a normalized rms transverse emittance, ε_t, of 0.020 π cm mrad. In keeping with the design philosophy of operational flexibility and reliability as stated in Ref. 1, the RFQ should be able to provide output beam varying from 5 to 50 mA. The maximum peak surface field should not exceed ~36 MV/m (1.8 Kilpatrick). The low energy booster (LEB) ring filling requirement dictates the linac to operate at 10 Hz with a pulse length of ~37 μs, limiting the duty factor to less than ~0.05%. The transmission through the RFQ, should also be high, preferably around 90%. The RFQ beam dynamics design, described in the following sections, meets these goals.

BEAM DYNAMICS DESIGN

The fixed starting parameters of the RFQ are contained in Table I.

TABLE 1

Ions		H^-
Frequency	f	427.617 MHz
Injection Energy	w_i	0.035 MeV
Output Energy	w_f	2.500 MeV
Injection Current (nominal)	c_i	30 mA
Input Emittance	ε_i^t(n, rms)	0.02 π cm mrad
Maximum Peak Surface Field		~1.8 E_k (36 MV/m)

A schematic of the RFQ vane geometry is shown in Figure 1. In the radial matching section, the beam changes from a round time independent shape to a transverse time dependent quadrupole shape. Next the shaper section, accelerates the beam to 75 keV. The acceleration efficiency A and synchronous phase ϕ_s vary linearly with longitudinal position.

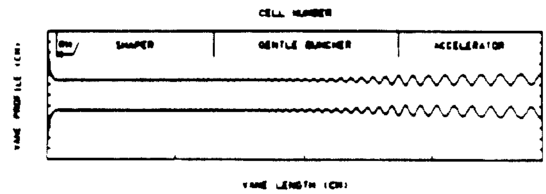

Figure 1. Schematic of the RFQ Geometry

The potential used in the design has eight terms. The first four terms of the radial electric field

$$E_r = \frac{-V}{r_0}\left[A_{01}\left(\frac{r}{r_0}\right)\cos 2\Theta + A_{03}\left(\frac{r}{r_0}\right)^5 \cos 6\Theta + \left[A_{10}\frac{kr_0}{2}I_0'(kr) + A_{12}\frac{kr_0}{2}I_4'(kr)\cos 4\Theta\right]\cos kz\right]$$

$$\text{where } k = \frac{2\pi}{\beta\lambda},$$

correspond to quadrupole, duodecapole, rf defocusing and the octupole field components respectively. Alternate focusing and defocusing is not provided by the 'rf defocusing' and 'octupole' terms because the voltage (cos ωt) and cos kz factors both change sign with the same periodicity. Therefore, the defocusing fields can be very important even though these fields are an order of magnitude weaker than the quadrupole fields which focus with alternately focusing and defocusing fields. Figure 2 shows the relative contribution of the different radial electric components (the quadrupole term is ~1 and is not shown) along the entire RFQ length.

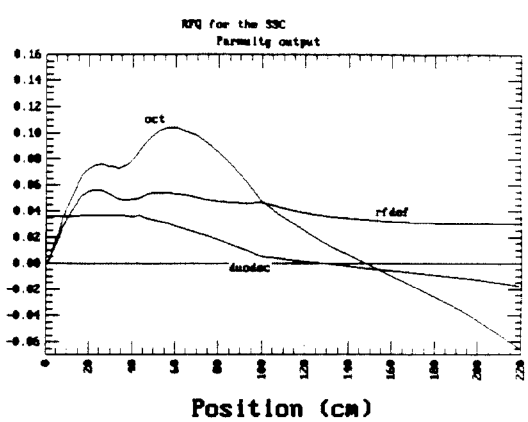

Figure 2. Higher order multipole components and the rf defocusing field along the length of the RFQ, evaluated at $r = r_0$.

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Table 2 lists the relevant design final parameters. The gentle buncher section follows the shaper. The accelerator and the exit fringe field sections follow the gentle buncher.

Table 2

Key Final Design Parameters

Injection energy	w_i	0.035 MeV
Energy at end of Shaper	w_s	0.075 MeV
Energy at end of GB (Gentle Buncher)	w_g	0.115 MeV
Final energy	w_f	2.500 MeV
Synchronous phase at end of GB	Φ_g	−55°
Final synchronous phase	Φ_f	−30°
Modulation at end of GB	m_g	1.23
Final modulation	m_f	1.93
Aperture radius, minimum	a_{min}	0.178 cm
Aperture radius, minimum (pt. of symmetry)	$r_{o,min}$	0.198 cm
Final aperture radius	a_f	0.240 cm
Final aperture radius (pt. of symmetry)	$r_{o,f}$	0.366 cm
Intervane Voltage	V	54.8 to 88.5 kV
Power (copper)		278 kW
Maximum peak surface field		36.24 MV/m = 1.81 E_k
RFQ Length		219.64 cm
Accelerating efficiency at end of GB	A_g	0.133

The variation of several of the parameters along the length of the RFQ is shown in Figure 3, as a function of position. Vane voltage and peak surface field along the length are plotted in Figure 4.

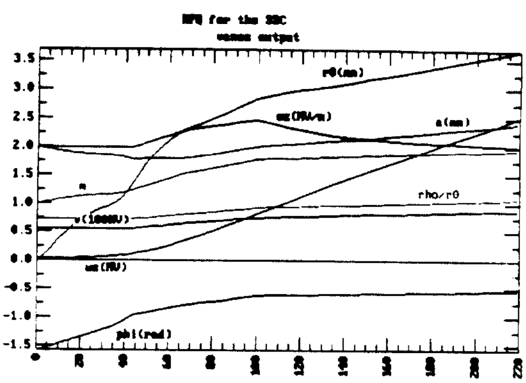

Figure 3. Variation of key design parameters along the length of the RFQ.

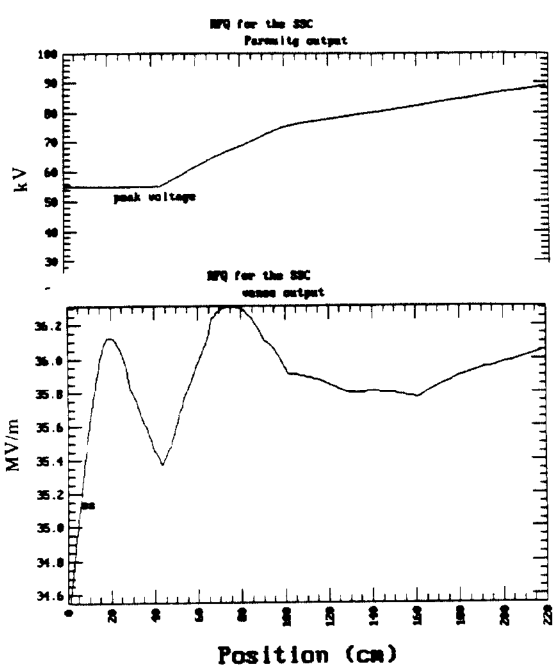

Figure 4. Vane voltage and the peak surface field along the length of the RFQ.

BEAM DYNAMICS SIMULATIONS

Particle simulation runs were made using several versions of PARMTEQ. One version [2] includes the eight term potential to incorporate the higher order multipoles discussed earlier. Another version [3] calculates 3D space charge and image charge effects. Figure 5 shows the transverse and longitudinal emittances and the transmission along the length of the RFQ. Figure 6 shows the profile plots for the standard 30 mA input run. We have also considered the case when 30 mA and 70 mA misaligned beams are injected 0.25 mm off-axis and 5 mrad off-angle in the x-plane. The beam profile plots for such a misaligned input beam of 30 mA are shown in Figure 7. In Table 3, transmission and emittance growths are presented for the case of an aligned and misaligned 30 mA and 70 mA input beam.

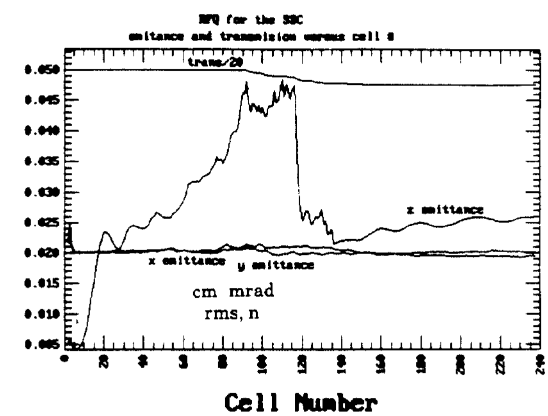

Figure 5. Transverse and longitudinal emittances, and the transmission along the length of the RFQ as a function of the cell number, for an input beam of 30 mA.

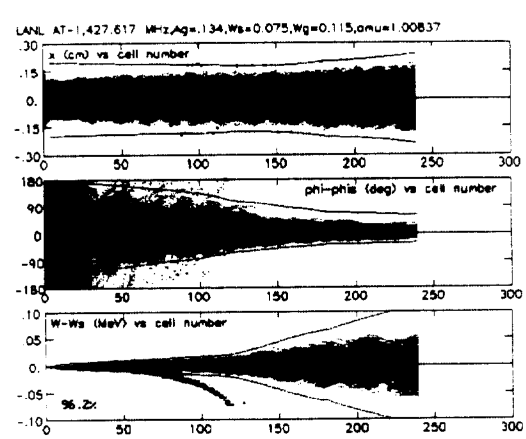

Figure 6. Profile plots for a matched beam of 30 mA. Multipole code.

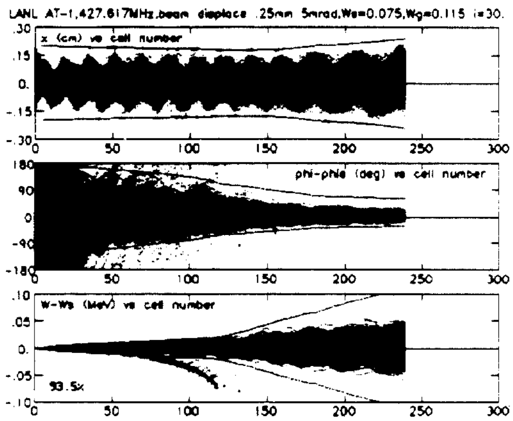

Figure 7. Profile plots for a misaligned (Δx = 0.25 mm, $\Delta x'$ = 5 mrad) input beam of 30 mA. Transmission is 93.5%

TABLE 3

Code	Input Beam Displacement mm mrad		Input Beam Current mA	Percent Transmission	ϵ_xn, rms mm mrad	ϵ_yn rms mm mrad	$\epsilon_l$rms MeV deg
2D Space Charge	0	0	70	63.9	208	.224	130
3D Space Charge	0	0	70	85.1	199	.208	098
3D & Image Charge	0	0	70	79.7	.206	.198	101
2D & Multipoles	0	0	70	62.8	.228	192	124
2D & Multipoles	0.26	5	70	80.0	.204	.212	.123
3D & Image Charge	0.25	5	70	73.6	.195	202	100
3D Space Charge	0.26	5	70	80.3	207	200	093
2D & Multipole	0	0	30	95.4	197	.203	127
2D & Multipole	0.25	5	30	93.5	.200	.197	125
3D & Image Charge	0.25	5	30	94.0	.205	198	.102
3D Space Charge	0.26	5	30	95.3	207	.191	100
2D & Multipole	0	0	5	98.2	.205	.199	.166

RF STRUCTURE

This RFQ design uses r_o = 0.198 cm (the aperture, at the symmetry point) at the low energy end. The beam dynamics design then increases r_o to 0.366 cm at the high energy end.

In order to maintain a constant vane tip to vane tip capacitance with a changing r_o the ratio of the vane transverse radius of curvature (ρ) to r_o must change. The ratio ρ/r_o varies from 0.75 at the low energy end of the RFQ to 1.06 at the high energy end. The ratio of ρ/r_o is determined with the program SUPERFISH.

The RFQ will be tuned using 32 slug tuners, 8 slug tuners in each quadrant. The slug tuners remove the effects of small misalignments of the vanes, tune the frequency of the cavity to the required frequency and in this RFQ will induce a voltage ramp in the accelerator section.

Dipole tuners that are placed on the endwalls will be used to adjust the frequency of dipole modes away from the quadrupole mode. These dipole tunes have virtually no effect on the quadrupole mode.

CONCLUSION

An RFQ for the SSC has been designed which exceeds the baseline 25 mA output current (30 mA input) and the upgrade 50 mA output current (70 mA input) requirements. The peak surface field, 1.81 E_k, (target value = 1.80 E_k) is conservative for the low duty factor of <0.05%. There is essentially no growth in the transverse emittances. Simulations with 2D and 3D space charge, multipoles and images charges predict high (~95%) transmission through the RFQ for an input beam of 30 mA. For 70 mA input beam the transmission value is also fairly high, i.e., 79%.

REFERENCES

1. J. Watson, et.al., contribution to this conference.
2. K. Crandall, private communication, AccSys Technology
3. F. W. Guy, private communication, SSC Laboratory