RF Cavity and RFQ Design and Simulation

Vivek Sharma
Illinois Institute of Technology
vsharm12@iit.edu

Physics Division
Argonne National Laboratory
9700 S. Cass Ave
Argonne, IL, 60431
USA

Abstract

A low cost Medium Intensity Upgrade has been proposed for ATLAS facility to accelerate ion beams with intensities 10-15 higher than beams currently available. This encompasses upgrades and replacements in some of the existing equipment. This project mainly attempts to simulate and optimize the design of RF Cavities and RFQ for the proposed upgrade. For RF Cavities, we aimed at simulating super conducting RF cavities of different geometries with a fundamental frequency of 72.75 M Hz. The goal was optimization of various parameters such as Quality Factor, Accelerating Electric Field, Geometry Factor etc. For RFQ, our goal was to simulate and optimize a design that would accept beams of ionized U-238 at initial energy of 30 keV/u and deliver it appropriately bunched at a final energy of 300 keV/u. The limiting constraints are Vane Voltage and length of the unit.

CONTENTS

SIMULATION AND OPTIMIZATION OF RF CAVITIES

1. INTRODUCTION

Whereas the superconducting cavities have extremely low surface resistance and therefore are extremely efficient in power, they are bound by the physical limitation that the microwave magnetic field must stay below the critical field of the superconductor. This restricts our choice of RF Voltage.

Additionally, although superconductors (below their critical temperature) pose zero resistance to DC currents, same is not true for microwave cavities. The electrons not bound in Cooper Pairs undergo forced oscillations under time varying magnetic field and dissipate power. The result of even this small power dissipation is devastating for the superconductivity as temperature rises. Also, owing to low temperatures in the cavity, the amount of energy required to remove heat from the cavity and eject it to heat sinks at room temperatures is exorbitant.

This calls for a very careful study into the parameters and viability. We began our analysis with studying normal conducting (Copper) cavities. Our goal was to find an optimized geometry. The work mainly involved understanding the optimization parameters.

2. OPTIMIZATION PARAMETERS

Surface Resistance

The RF electric field causes basically no losses since its tangential component vanishes at the cavity wall while the azimuthal magnetic field penetrates into the wall with exponential attenuation and induces currents within the skin depth [1]. The skin depth is given by:

$$\delta = \sqrt{\frac{1}{\mu_0 \sigma \omega}}$$

where σ is the conductivity of metal.

The surface resistance is given by [2]:

$$R_{SURF} = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0 \omega}{\sigma}}$$

We should aim at minimizing the Surface Resistance.

Quality Factor and Geometry Factor

The Quality Factor is 2π times the number of cycles required to dissipate the stored energy. Alternatively, it is the resonant frequency to the full width at the half height of the resonance curve. It can be given by [2]:

$$Q_0 = \omega \frac{\mu_0/2 \int_V |H|^2 \, dV}{R_{SURF}/2 \int_S |H|^2 \, dS}$$

The value of the integrals can be evaluated by the software.

The Geometry Factor is related to the Quality Factor by the relation:

$$G = Q_0 R_{SURF}$$

It is purely based on the geometry or shape of the cavity and not on its material. Both Quality Factor and Geometry Factor are the factors that we aim at maximizing.

Accelerating Field, Peak Electric and Magnetic Fields and Transit Time Factor

The particle needs time L_C / v to travel across the cavity. During this time, the longitudinal Electric Field changes with time. The Accelerating Field is defined as the longitudinal field as seen by the particle:

$$E_{ACC} = \frac{2\pi}{\omega} \int_{-L_C/2v}^{L_C/2v} E_Z(t) dt$$

The Transit Time Factor gives us the fraction of Electric Field available to the particle for acceleration and is defined as:

$$\Gamma = \frac{E_{ACC}}{E_Z(0)}$$

Again, the Peak Electric and Magnetic Fields in the cavity must be maintained below the critical field of the superconductor. This calls for maximizing Accelerating Field and the Transit Time Factor while keeping Peak Fields low.

Increasing the ratio of Volume of the cavity to the Surface Area of the cavity improves the Quality Factor (Q_0) where as reducing the gap size L_C enhances the Transit Time Factor (Γ) [2].

Shunt Impedance and R/Q

To understand how the RF power coming from the klystron is transferred through the cavity to the particle beam it is convenient to represent the cavity by an equivalent parallel LCR circuit. The parallel Ohmic resistor is called the shunt impedance R_{SHUNT} although this quantity has only a real part [3].

$$R_{SHUNT} = \frac{(E_{ACC} L_C)^2}{P_{dissipated}}$$

The factor R/Q is the ratio of Shunt Impedance to the Quality Factor.

$$R/Q = \frac{R_{SHUNT}}{Q_0}$$

It is independent of the material and is dependent only on the shape of the cavity and is seen as a figure of merit.

3. DESCRIPTION OF GEOMETRIES PROPOSED

The main task was to get familiar with construction of various cavities on CST Microwave Studio. The target was to choose dimensions such that the fundamental frequency comes out to be close to 72.75 M Hz.

In all cases z axis is taken as longitudinal axis, x the horizontal axis and y the vertical axis.

All the cavities considered had a drift tube in the bottom middle and two half drift tubes on the bottom curved wall. All drift tubes have their axes along the z axis. All the cavities were constructed by taking three independent ellipses within the planes parallel to x-y planes – bottom, middle and top – and lofting them to produce the exterior.

Keeping the dimensions of drift tubes constant, the following cavities were considered:

Cavity 1:

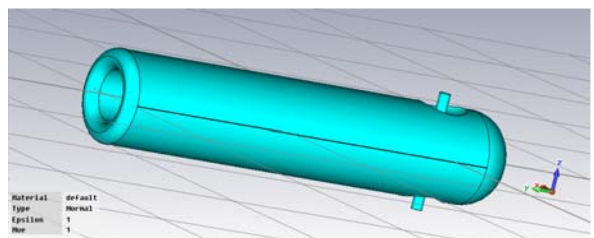

Fig. 1.1
Cavity 1: Cylindrical

Cavity 1 has all the three ellipses of same major and minor axis: 12.5 cm. This makes it essentially circular cylinder.

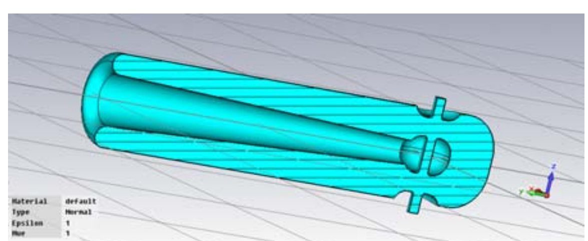

Fig. 1.2
Cross Section of Cavity 1 along y-z plane

While keeping the distance, between the two lower and middle circles (referred to as ellipses hereafter) constant, the distance of the upper ellipse from origin was adjusted till the JDM Solver gave an eigen mode solution close to frequency 72.75 M Hz.

The distance between the two lower ellipses is 40 cm with centers placed at (0,-20 cm, 0) and (0, 20 cm, 0) where as the top ellipse is centered at (0, 101 cm, 0).

The calculations performed by the Solver gave the following profile for Longitudinal Electric Field:

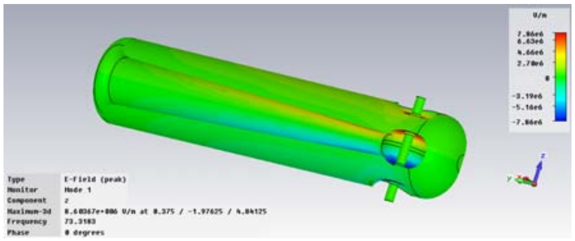

Fig. 1.3:
Electric Field Intensity in Cavity 1

Green shade represents zero, and Red represents positive and Blue represents negative field. The figure shows most of the cavity with green with only space close to drift tubes as blue at one end and red at other. Again, the drift tubes themselves are green, since they are supposed to electrically insulate the beam. This is purely as expected from a drift tube which must not provide any acceleration.

Since most of the accelerating field is concentrated in the bottom, we must expect energy density of Electric field to be maximum along the z axis (with the exception of drift tubes). That is indeed found to be the case in the following figure for energy density:

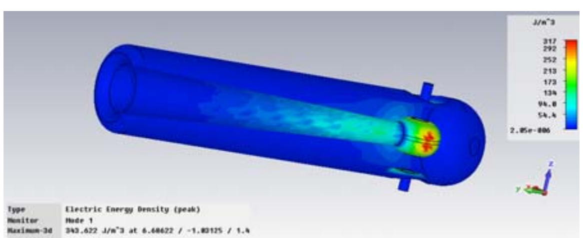

Fig 1.4:
Energy Stored in Electric Field in cavity 1

Most of the surface currents are induced by the time varying magnetic fields. Thus the figures with surface current density and magnetic field intensity must also be quite similar. The following figure shows stored magnetic field energy:

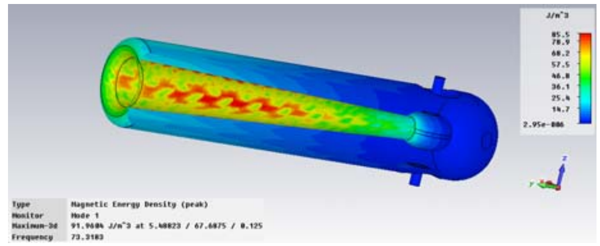

Fig. 1.5
Magnetic Energy Intensity in Cavity 1

This shows that inner hollow of the cavity has the greatest share of magnetic field energy. Similar is the case in the distribution of surface currents:

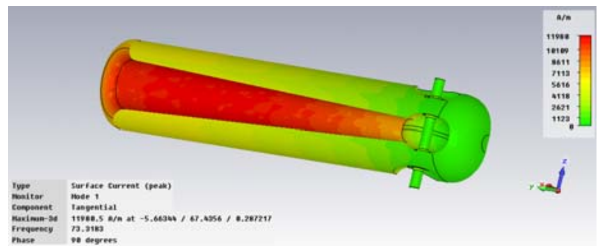

Fig 1.6:
Surface Currents in Cavity 1

Cavity 2:

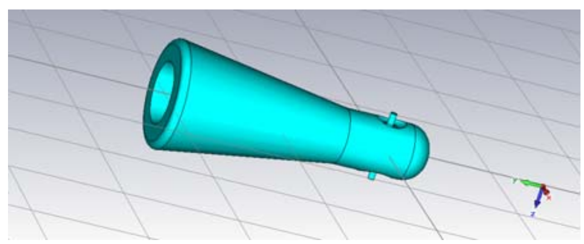

Fig. 1.7
Cavity 2: Circular Conical

Cavity 2 has the same geometry as the Cavity 1 with the sole difference that the radius of top circle (ellipse) is twice that of the other two. The top radius of the hollow is likewise twice that of Cavity 1.

The distance between the two lower ellipses is 40 cm with centers placed at (0,-20 cm, 0) and (0, 20 cm, 0) where as the top ellipse is centered at (0, 102.5 cm, 0).

A discussion similar to that in Cavity 1 leads us to surmise that an efficient cavity must have bulk of its electric field energy and longitudinal electric field along z axis. This is confirmed by the profiles showing Electric Field intensity along z and electric field energy density respectively.

Similarly, the analysis of tangential magnetic field and surface current density profile shows us quite similar results to those in Cavity 1.

Cavity 3:

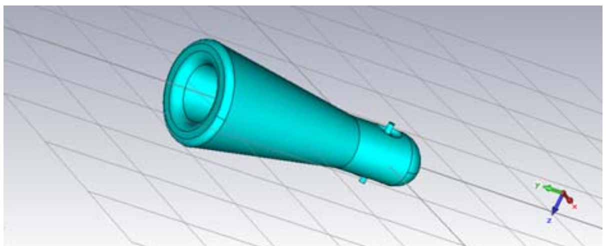

Fig. 1.8:
Cavity 3: Elliptical Conical

Cavity 4 differs from Cavity 3 by the fact that all vertical and longitudinal dimensions are kept same, whilst just increasing the horizontal dimensions by a factor of 1.2.

Additionally, the top ellipse is translated a little higher to 103 cm from origin while keeping other two lower ones at the same heights. Thus the distance between the two lower ellipses is 40 cm with centers placed at (0,-20 cm, 0) and (0, 20 cm, 0) where as the top ellipse is centered at (0, 103 cm, 0).

We again obtained quite similar results from magnetic and electric field intensities as seen in the profiles of Electric and Magnetic Fields in the previous cavities.

4. OPTIMIZATION PARAMETERS OBTAINED

The parameters were evaluated using CST Microwave Studio. It employs Jacobi Division Method to solve the Eigen modes.

It was found that the elliptical conical design of Cavity 3 was best suited geometry for the RF Cavity. It had the best Quality Factor, Geometry Factor and Shunt Impedence.

The results are summarized as follows:

Summary of Parameters

Cavity	f M Hz	E_{PEAK} MV/m	H_{PEAK} A/m	β	V_{GAIN} MV	TTF (Γ)	E_{ACC} MV/m	Q_0	P_{DISS} k W	R_{SURF} mΩ	R_{SHUNT} MΩ	G	R/Q Ω
1	73.318	9.4043	12659	.0766	0.4855	0.9243	2.4301	7753.0	59.417	2.2339	3.96920	17.32	511.95
2	72.773	8.5901	7446	.0766	0.4289	0.9225	2.1498	9452.8	48.371	2.2256	3.82203	21.038	404.32
3	73.653	7.8953	6985	.0769	0.4301	0.9219	2.1568	9997.3	46.289	2.2390	4.01983	22.384	402.08

Parameters Normalized for $E_{ACC} = 1$ MV/m

Cavity	H_{TOP} cm	f M Hz	E_{PEAK} Normalized	B_{PEAK} Normalized	β	U_{STORED} (Normalized)	G	R/Q Ω
1	101	73.318	3.869923	65.46137	.0766	0.169336941	17.32	511.95
2	102.5	72.773	3.995767	43.5246	.0766	0.216373407	21.038	404.32
3	103	73.653	3.660655	40.69738	.0769	0.214971185	22.384	402.08

Summary of Geometries

Cavity	***Remark***	***H_{TOP}***	***Top***		***Middle***		***Bottom***	
			R_X	***R_Z***	***R_X***	***R_Z***	***R_X***	***R_Z***
1	Circular Cylindrical	101	12.5	12.5	12.5	12.5	12.5	12.5
2	Circular Conical	102.5	25	25	12.5	12.5	12.5	12.5
3	Elliptical Conical	103	30	25	15	12.5	15	12.5

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Simulation and Design Optimization of Radio Frequency Quadrupole

1. INTRODUTION TO RFQ’s

Proposed in 1970 by Kapchinskiy and Teplyakov in USSR, the Radio Frequency Quadrupole was first used at Los Alamos National Laboratory in late 70s. The RFQ is a low velocity high current linear accelerator device. Magnetic quadrupoles cannot be used for focusing low energy beams because magnetic forces are velocity dependent and therefore not very effective at low velocities. This led to the idea of RFQs, wherein electric quadrupoles were used instead of magnetic quadrupoles to produce electric fields that would strongly focus the beam. A time varying alternating electric field focuses and defocuses the beam alternately in order to give a net focusing effect.

Besides focusing the beam, the RFQ can also bunch the beam and accelerate it. The RFQ, therefore is a homogeneous transport channel with additional acceleration. The acceleration is provided by the mechanical modulation of the electrodes, resulting in a linac structure which accelerates and focuses with the same RF fields.

The RFQ works on the basis of Adiabatic Bunching principle and Strong Focusing Principle. [1]

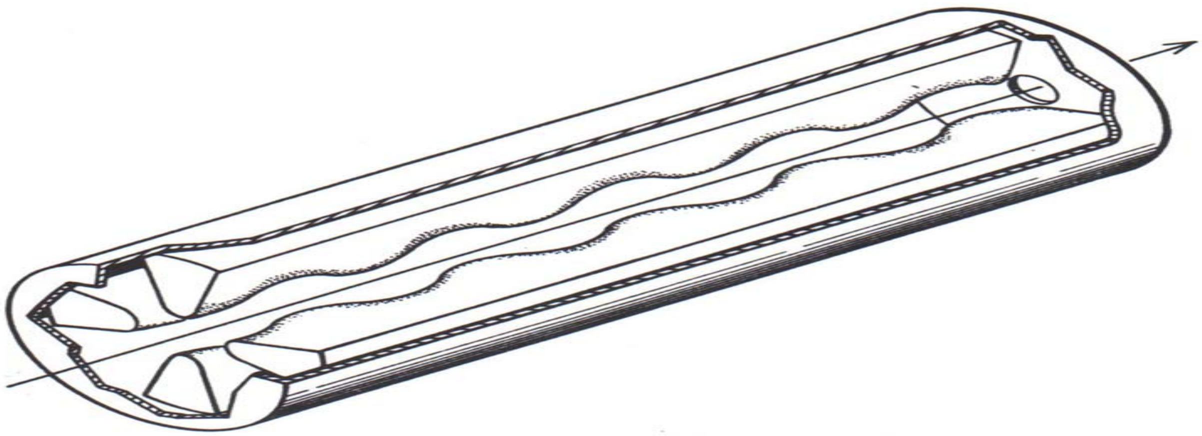

Fig 2.1
Radio Frequency Quadrupole

The design of an RFQ is usually characterized by Aperture, length of a single cell and Modulation. Aperture is the minimum distance of the electrodes from axis.

a - Aperture

ma - Maximum Distance of electrodes from Axis.

$L = \frac{\beta\lambda}{2}$ - Length of a unit cell

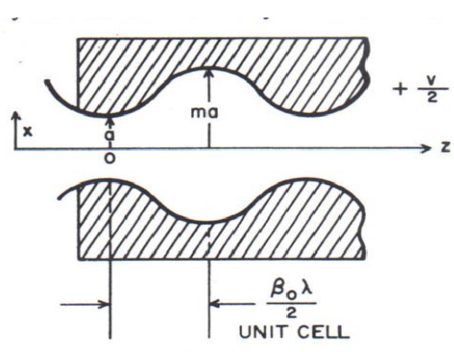

Fig 2.2: A Unit Cell

The Potential Amplitude at a given point is approximated from its Fourier Bessel series to the two term potential function [1]:

$$U(r,z,\theta)$$

$$= \frac{U_0}{2}\left[A_{01}\left(\frac{r}{r_0}\right)^2 \cos 2\theta + A_{10} I_0(kr)\sin(kz)\right]$$

where U_0 = Vane Volatge

$r_0 = a\left[1 - A_{10} I_0(ka)\right]^{-1/2}$

k = wave number

I_0 = 0^{th} order modified Bessel function

A_{01} and A_{10} are dimensionless constants

The operation of an RFQ is often characterized by Vane Voltage, Acceleration Efficiency, and Focusing Efficiency.

Accelerating Efficiency [1]:

$$T = \frac{\pi}{4} A_{01}$$

Focusing Efficiency [1]:

$$B = \left[1 - A_{10} I_0(ka)\right]\frac{qV}{mc^2}\frac{\lambda^2}{a^2}$$

RFQ channel can be arbitrarily divided into three parts: shaper (where beam is bunched and accelerated by small accelerating fields and synchronous phase near to –90.0), gentle buncher (where smooth transition to nominal accelerating field and nominal synchronous phase take place) and proper accelerator. [3] Additionally, RFQ's also have Radial Maching cell in the beginning and the end. The demarcation however is ambiguous throughout the literature.

The possible criteria of optimization for RFQ channel designing usually are: minimal length of RFQ channels and beam transmission no less than a given one. The control parameters are: Vane modulation, intervane voltage, synchronous phase and bore aperture in each cell. But such optimization method is possible in principle but it cannot be realized in practice. Time needed to solve the procedure will be astronomically large because control parameters are more than thousand. It must be added that time for one RFQ version simulation is measured by minutes. Modern computer techniques have no power to make such optimization. [4]

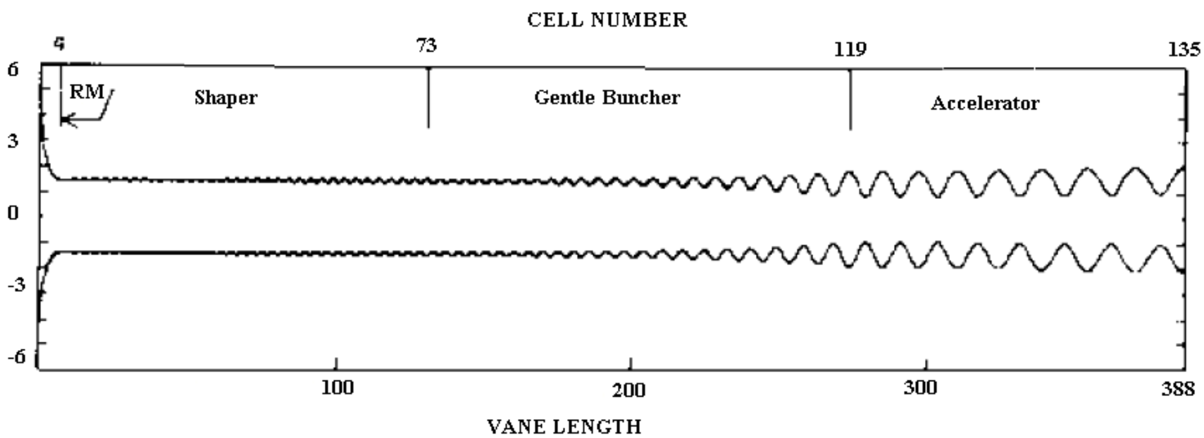

Fig. 2.3:
Various Sections in the RFQ

Therefore majority of work involving determining length and RFQ parameters variation is still done using trial and error. Various software tools have emerged in recent times that help us simulate RFQs. Of these, this paper pertains to PARMTEQ, DESRFQ and TRACK.

The RFQ under consideration is a part of assembly that incorporates a Low Energy Beam Transport (LEBT), a Multi Harmonic Buncher

(MHB) and the RFQ. The MHB is located about 3 m upstream of the RFQ and operates at a fundamental frequency of 12.125 MHz. the RFQ is proposed to operate at the 5th harmonic of the fundamental frequency, which is 60.625 MHz. We are further restricted to maintain the Vane voltage to around 90 kV. Also, the length of the RFQ is restricted between 3 m and 4 m while the aperture radius is to be kept around 6 mm.

2. PARMTEQ STUDY

PARMTEQ stands for **P**hase **a**nd **R**adial **M**otion in a **T**ransverse **E**lectric **Q**uadrupole. It is used with the software toolkit RFQ Codes distributed by Los Alamos National Lab. The kit is composed of the program Curli, RFQuick, Pari and Parmteqm.

The basic design parameters of the RFQ are given below:

Charge	34 e
Mass	238 u
Input Energy	30 keV/u = 7.14 MeV
Output Energy	300 keV/u = 71.4 MeV
Vane Voltage	~ 90 kV
Aperture Radius	~ 6 mm
Beam Current	0.5 mA
RF Frequency	60.625 MHz
Length	~ 3 cm – 4 cm

Curli takes the following parameters as its inputs: charge, mass, initial energy, vane voltage, apperture radius, synchronous phase and energy at gentle buncher. Since all but the last two are fixed, we can vary them so as to obtain the optimal design. Curli generates a table for vane modulations and respective maximum current values. It also generates the input file for RFQuick code to build upon.

RFQuick further uses the table generated by Curli to generate the input file for Pari and Parmteqm. RFQuick takes following parameters as inputs: charge, mass, vane voltage, beam current, transverse emittance, number of radial matching cells, input energy, energy at gentle buncher, shaper energy, output energy, synchronous phase at the end of gentle buncher, synchronous phase at the end of the RFQ accelerating efficiency and focusing parameter.

It must be noted that focusing parameters directly relates to the vane voltage. Thus, if one is altered, other too changes. However, we can exercise some control over the accelerating efficiency. A high focusing parameter ensures high transmission efficiency, but increases the length of the RFQ.

RFQuick generates the input file for Pari. Pari allows a very limited scope of changes – most of the changes made in Length, Output Energy and number of cells do not show any effect in the output file generated. Pari generates a table of modulations, synchronous phase, beta etc. for every cell. After Pari, Parmteqm can be run to analyze the graphs of transmission through the RFQ. [5]

Another point of observation is that the aperture radius entered in Curli is not maintained throughout in the simulation. Pari actually makes changes in order to optimize.

With this background of understanding, PARMTEQ was employed to generate the desired RFQ. It was found that the values of initial energy and energy at gentle buncher can be later altered. In order to optimize the RFQ, following inputs were fed in to Curli:

Charge	34 e
Mass	238 u
Input Energy	7.14 MeV
Energy at Gentle Buncher	78 MeV
Vane Voltage	95 kV
Aperture Radius	4.5 mm
Beam Current	0.5 mA
RF Frequency	60.625 MHz
Synchronous Phase	-54 degrees

The modulation table was set to produce values from 1.2 to 2.2 at intervals of 0.005.

The resulting output file generated input file for RFQuick. Here, the following adjustments were made:

Charge	34 e
Mass	238 u
Input Energy	7.14 MeV
Energy at Gentle Buncher	24 MeV
Vane Voltage	98 kV
Aperture Radius	4.5 mm
Beam Current	0.5 mA
RF Frequency	60.625 MHz
Emittance	π 0.025 cm-mrad
Accelerating Efficiency	0.7
Radial Matching Cells	0
Synchronous Phase at the End of RFQ	-30 degrees
Synchronous Phase at the End of GB	-54 degrees
Shaper Energy	~12.5 MeV

A little adjustment and trial gave an excellent capture of above 98% for lengths about 4.2 m.

Then Pari and Parmteqm were run to generate the following graphs:

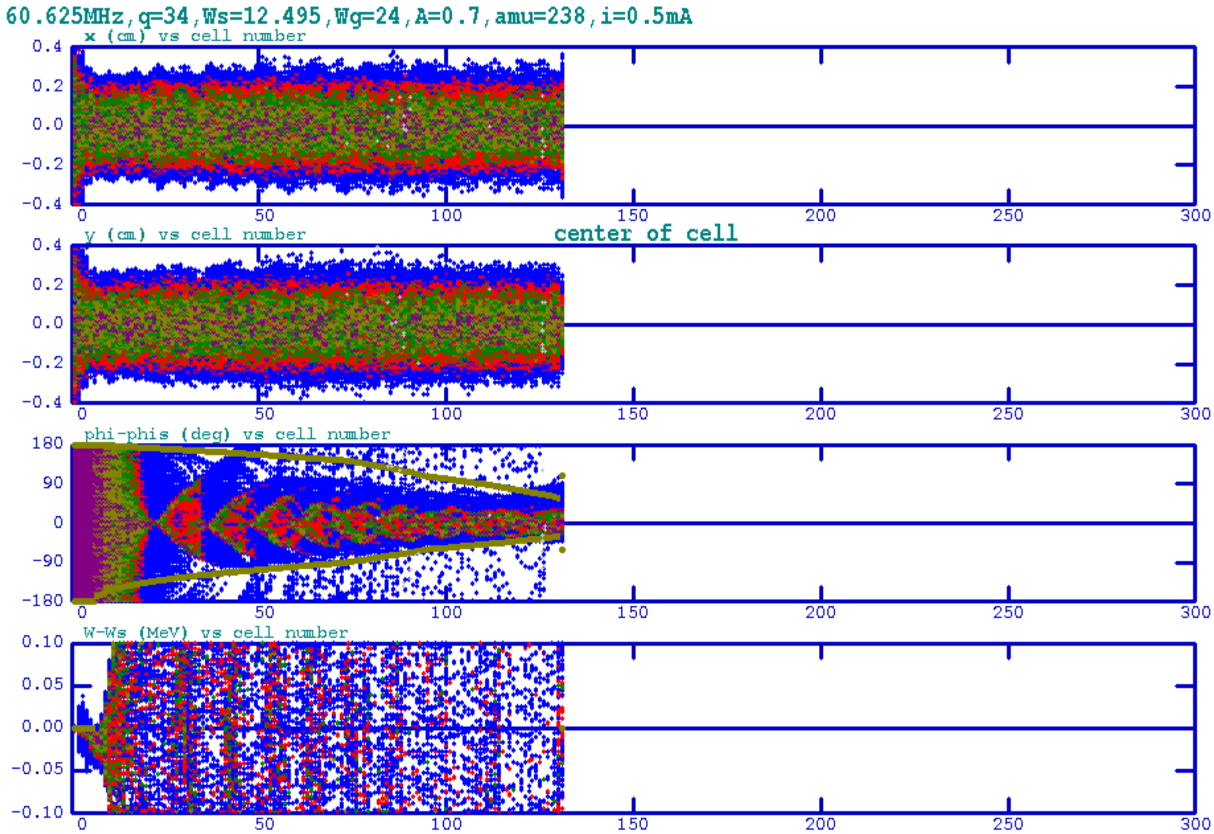

Fig. 2.4
Final results generated by PARMTEQ: x and y coordinates are maintained within confines. Particle phase progressively approaches -30 degrees. Most of the lost particles are lost in the last few cells.

It gave a transmission of 97.5%, a capture of 97.4% and a length of 3.98 m, just what we had wanted, but after jeopardizing the vane voltage constraint.

Also, as expected, the aperture radius that finally came out was quite different from what was specified in Curli. The final simulation gave average aperture radius of 6.246 mm.

Definitely, further optimization was needed. That brings us to the code DESRFQ.

3. DESRFQ AND TRACK

This code uses a Laplace equation solver, which takes into account the physical vane shape to generate the RFQ vane tip geometry in every cell and the RFQ parameters required for the final simulations with the TRACK. [6]

DESRFQ gives the user the flexibility to alter synchronous phase and modulation at any given cell and graphically see the result it makes on the seperatrix. Additionally, it can also be a very helpful diagnostic tool as it generates the pulse-spread vs. phase graph for every cell. Using this we can determine cell by cell where particles are lost out of the seperatrix.

The modulation table generated from PARMTEQ was used to produce input file for DESRFQ Gentle Buncher. After closely observing the population of particles in the seperatrix, it was observed that it was best to increase the synchronous phase in the cell where the phase width was minimum. Thus fewer particles were lost and a transmission of 97% was obtained at a vane voltage of 92 kV.

The results obtained in DESRFQ still are deceptive. Sometimes the numerical figures obtained may betray the graphs. For a better analysis, we require the code TRACK. The TRACK code tracks particles through the whole RFQ in 3D accounting for both the external and internal space charge fields. The 3D electric field in the regular bunching-accelerating section has been presented by an 8-term Fourier-Bessel expansion. [7]

Thus DESRFQ is used for fine tuning and TRACK is used to test the RFQ.

So far there has been no success in this regard. The best configurations shown by DESRFQ correspond to a poor transmission. The reason is that in order to maintain the length constraint as well as synchronous phase angle it is not possible to get enough energy gain. Thus, in order to receive the desired energy, the synchronous phase has to be brought closer to -30 degrees. This causes the seperatrix to shrink and we lose particles.

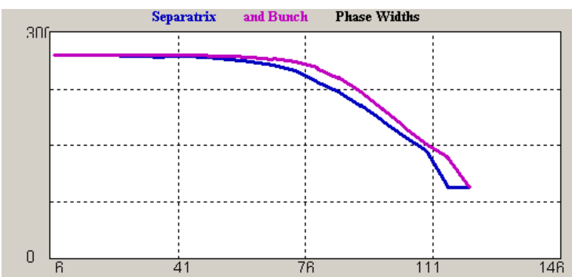

Fig 2.5
Example of a poor vane profile: The magenta colored graph of seperatrix is most of the time below the graph of the bunch in blue. Most of the beam is lost - 35% transmission.

Because of this shortcoming, this design was abandoned and further modifications were made. It was realized that it was more vital to keep the transmission high than to maintain the synchronous phase, which could be later corrected. As a result, the following profile was generated:

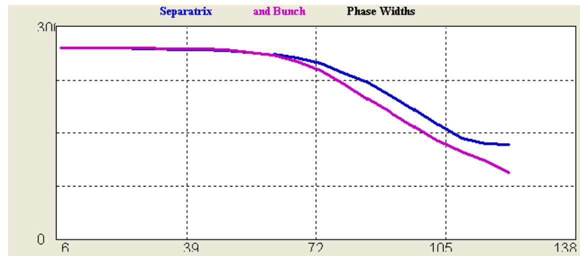

Fig. 2.6
Vane Profile of the final design: 90% beam transmitted, but synchronous phase has been compromised

This is further elucidated by the energy spread vs. phase angle plot of the beam in the final cell. The pulse spread throughout the phase angle gives an indication of whether the particles will be contained in the bunch or not. It was observed that as the beam progressed along the RFQ, the beam was initially kept within the confines of the seperatrix. The seperatrix progressively shrank and the beam phase spread also shrank. There was however a considerable loss of particles in the last few cells. This can be seen by the red dots outside the bounds of the seperatrix.

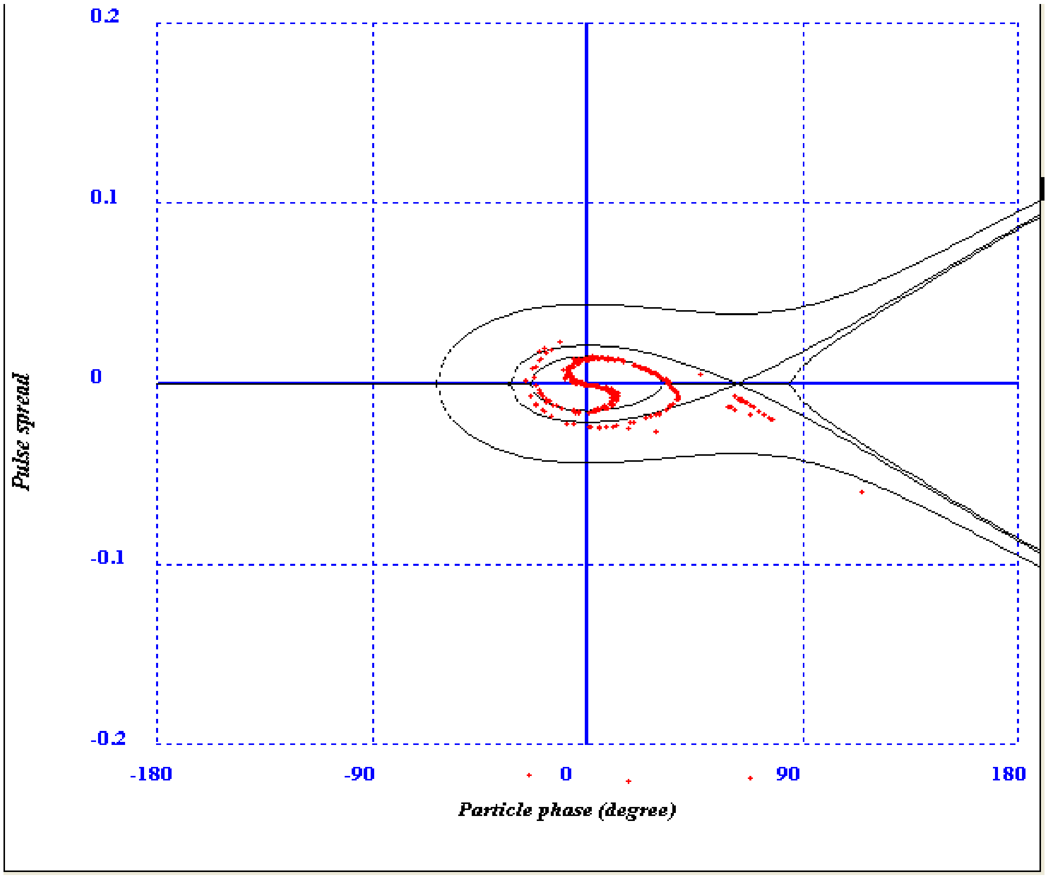

Fig 2.7
Energy (Pulse) Spread vs. Phase Angle plot: Although the majority of the beam is preserved a significant amount of particles still have escaped out of the seperatrix.

However, in order to test our RFQ more precisely, TRACK was employed. The input file generated by DESRFQ was used to run the code TRACK, additionally the Twiss Parameters were adjusted a little. It yielded the following results:

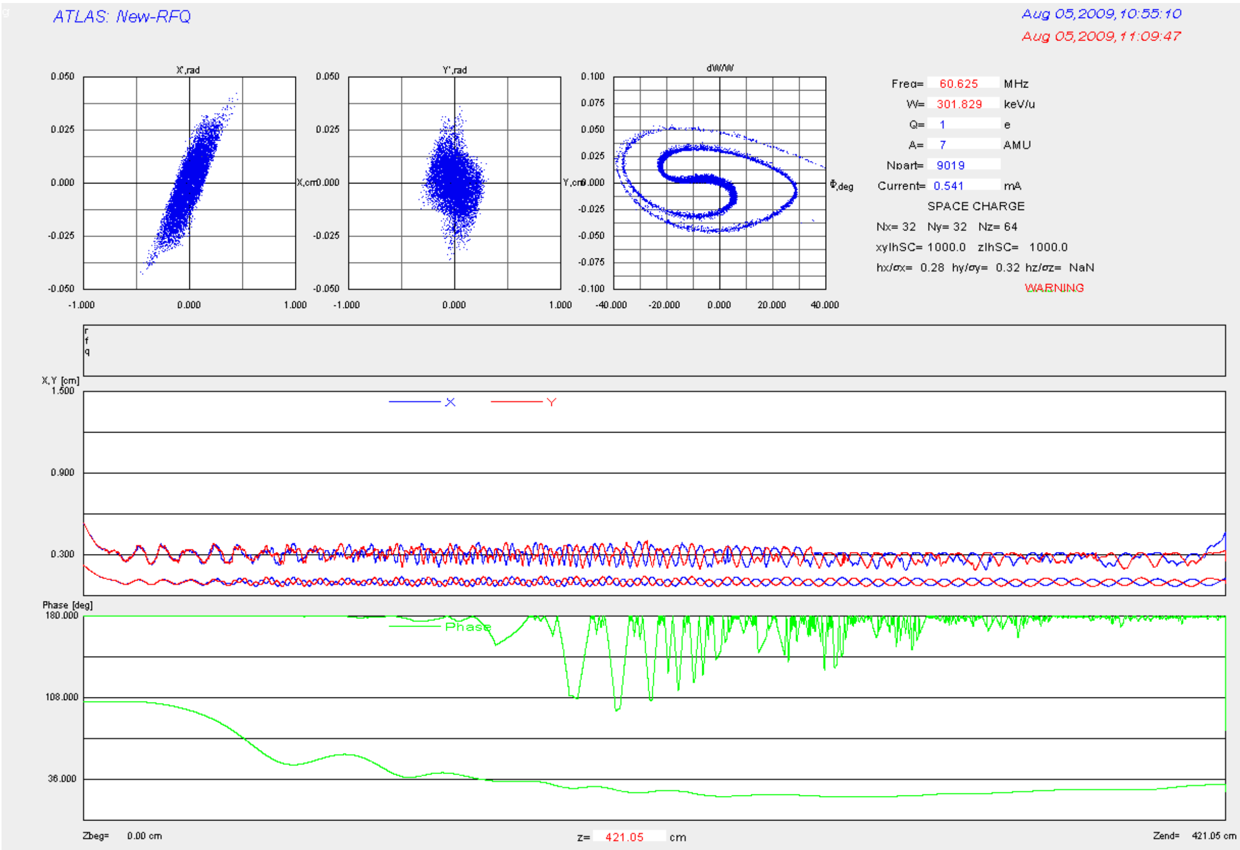

Fig. 2.8
TRACK output: Even after significantly exceeding the 400 cm limit for the length of RFQ, it was barely possible to get a transmission of 90%.

The beam obtained was well confined within the aperture radius and had suffered minor losses preserving 90.19% of the particles. The length of the final design came out to be 421 cm.

4. CONCLUSION

Optimization process appears to be far from complete. More rigorous and elaborate simulations and are needed. Additionally, at a later stage while dealing with TRACK, it was felt that time duration of this internship was too inadequate to reach an optimum RFQ. It is a project that demands better acumen than mine and more time.

However, the project its current state, will give a platform to build the optimum RFQ. The issues that need to be addressed are:

Average Aperture Radius: We started with a value of 4.5 mm. The current best value is 6.246 mm. We must aim for 6.0 mm.

Vane Voltage: We started with 98 V. The current best value corresponds to 92 MV. We should aim for a value smaller than 90 MV.

Length: We started with 6 m. The current best length is 4.21 m. We should try to constrain it between 3.0 m and 4.0 m.

Transmission: While PARMTEQ did successfully capture and transmit 97% of the beam, we could not see the same results for TRACK. A 90%

The primary goal should be to get the length to fall within the constraints with an improved transmission. The question of acceptable emittances is yet to be explored.

5. REFERENCES

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