SIMULATION STUDIES FOR OPTIMIZATION OF 60 MHZ ROD TYPE RADIO FREQUENCY QUADRUPOLE ACCELERATOR DESIGN AT IPR

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Abstract

A 60 MHz Rod type “Radio Frequency Quadrupole Accelerator” has been designed for material studies through Ion Irradiation at Institute for Plasma Research, Gandhinagar. The accelerated ion beam produced by RFQ and the subsequent reaction of the beam with different targets is used to study (a) Radiation enhanced segregation (b) Irradiated micro-structure (c) Radiation hardening (d) Irradiation assisted stress corrosion cracking in materials. For Ion-Irradiation, ion beam generated by an Electron Cyclotron Resonance (ECR) ion (H+) source coupled to (copper) Rod type Radio Frequency Quadrupole (RFQ) Accelerator through a Low Energy Beam Transport (LEBT) system will be accelerated to 1 MeV at 60 MHz @ 5 mA. Usually, high current RFQ are vane type RFQ’s that are designed at higher frequencies of few hundred of MHz due to their advantage of reduced RFQ length for particular energy gain and higher shunt impedance and quality factor. But their machining is very difficult as well as they have disadvantage of presence of detrimental dipole modes. At IPR, it has been decided to use the indigenously developed RF source (35-65 MHz frequency @ 1 MW power) and design a Rod Type RFQ @ 60 MHz RF frequency to obtain the required energy gain. Design considerations involve special emphasis on reduction of beam instabilities by keeping zero-current phase advance <90 degree in longitudinal as well as transverse direction, reduction of space charge effects by avoiding resonance condition along with other considerations. Detailed beam dynamic design of 60 MHz Rod Type RFQ for hydrogen beam is carried out and a 4.2 meter long RFQ comprising of 97 cells is designed after optimizing various parameters. A resonating frequency of 60.6 MHz has been achieved with 12 posts. Complete design and analysis will be discussed in the paper.

1. INTRODUCTION

Recently, Ion Irradiation has been preferred for characterization of fusion research material properties due to its inherited advantages of 1) absence of high residual radioactivity 2) well defined energy, dose rate and temperature values 3) its potential for well controlled experiments along with the fact that it rarely requires more than several tens of hours to reach damage levels of 1-100 dpa range [1]. Radio Frequency Quadrupole, first described in 1970 by I. M. Kapchinskiy and V. A. Tepliakov, is chosen as front end accelerator in almost every accelerator these days due to its ability to accelerate, bunch and focus the beam simultaneously. The accelerated ion beam produced by RFQ and the subsequent reaction of the beam with different targets is used to study material properties and damages.

At IPR, a project has been taken up to characterize Fusion Grade material properties using Radio Frequency Quadrupole accelerator. To serve the purpose, a 4.2 meter long rod type RFQ has been designed at 60 MHz @ 5 mA beam current for hydrogen ions with a transmission efficiency of ≈ 97%. The ions will be accelerated to 1 MeV energy and would create a damage of 1.7512e-04 (DPA/sec) over a range of 5-6 μm on tungsten target. Being capable of producing high particle flux, this accelerator can also be useful for studying the change in analog properties or the damage in Integrated Circuit (IC) microelectronic devices. It will provide a close simulation to natural space radiation environment and can help in the some test methods e.g., ionizing radiation (also called total dose) test and dose rate induced latch-up tests along with mitigation of the electronic component’s failure on the subassembly and assembly level.

The set-up mainly consists of an ECR (H+/D+) ion source coupled to (copper) Radio Frequency Quadrupole (RFQ) accelerator through a Low energy beam transport system (LEBT) to produce 1 MeV, 5mA hydrogen ion beams. Accelerated beam is then directed to the target using appropriate beam line components and required diagnostics to study material properties.

2. DESIGN OF RFQ

The RFQ consists of typically 4 electrodes with alternating RF voltage, V, impressed on them in a specialized mode where electric field has dominant characteristic of that of a quadrupole. A beam of ions travelling down the axis of an RFQ, with a cross section similar to that shown in Fig. 1. [2], sees alternating focusing and defocusing electric quadrupole fields that are spatially continuous along the axis of the RFQ. The inherent property of RFQ
i.e.; focusing, bunching and acceleration simultaneously in a single structure, is accomplished by these alternating focusing and defocusing fields along with the modulated pole tips.

FIG. 1. Two vertical vanes with same voltage $+v/2$

2.1. Design considerations

Careful consideration was given to the beam dynamics, mechanical, thermal and RF aspects of RFQ design. Different designs as well as methods were looked at and evaluated for treating vane average radius ($R_0$) and the vane voltage ($V$). The frequency, output energy, and current were preselected for the RFQ design. The frequency was fixed at 60 MHz for the RFQ in order to utilize available RF source @ 35-65 MHz at IPR. Higher frequency was chosen to limit the RFQ vane length from the mechanical point of view. The normalized transverse beam emittance has been taken as $0.2 \pi$ mm mrad on the basis of the designed ECR ion source.

In order to design RFQ with optimized parameters with minimum loss within a viable length (machining point of view), special consideration has been put on space charge induced effects and beam instabilities. Beam instabilities have been avoided by designing the lattice for zero-current phase advance $\sigma_0 < 90^\circ$ [3] in longitudinal as well as transverse direction, as inferred by beam envelope perturbation analysis. Space charge instability has been suppressed by avoiding the resonance condition between total transverse tune ($\sigma_T$) and longitudinal tune ($\sigma_L$) i.e., $\sigma_L/\sigma_T \neq n$, $1/n : n$ is an integer, and so space charge growth has been kept minimum. It has been observed that [4] with strong tune suppression though ($\sigma/\sigma_0 \leq 0.4$, $\sigma$ being the phase advance per focusing period) emittance exchange occurs at all tune ratios, stable region in Hoffmann stability reduces, so operating tune suppression has been maintained such that $\sigma/\sigma_0 > 0.4$.

2.2. Optimization procedure

First of all vane voltage, focusing factor ($B$) and characteristic radius ($R_c$) have been optimized. The vane voltage is chosen on the basis of Kilpatrick limit. Focussing factor $B$ is fixed at $\approx 9$ and maximum modulation $m$ $\approx 3$. The RFQ has been simulated using RFQGEN [5], written by Lloyd Young, a suite containing many codes that can generate a design for RFQ vane profile as well as can perform Beam tracking simulations. Above considerations have resulted into vane voltage of 95 kV and characteristic radius of 1.56 cm.

Gentle buncher parameters have been optimized for fixed aperture. Input phase acceptance has been kept constant along the gentle buncher section to satisfy the process of adiabatic bunching. Then to optimize the shaper section, modulation $m$ and synchronous phase $\phi_s$ have been varied to match the entry of gentle buncher section. In the accelerating section, vane modulation has been kept fixed and hence energy gain per cell also remains the same. Collectively final energy output of 1 MeV has been obtained. Number of iterations have been carried out to optimize beam energy, synchronous phase, aperture, modulation with cell number and focusing factor. Finally transmission of 97.4% has been achieved for 97 cells @ 5 mA beam current. Simulations results are shown in Fig. 2.
2.3. RFQ parameters

The input beam energy for the design is chosen to be 50 KeV corresponding to extraction potential of 50 KV for the ECR ion source.

Total number of RFQ cells achieved for all optimized parameters is 97 and total length of the RFQ is 4.2 m. Table 1 summarizes the optimized parameters of RFQ.

<table>
<thead>
<tr>
<th>TABLE 1. RFQ PARAMETERS</th>
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<tbody>
<tr>
<td>Ion Species</td>
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<tr>
<td>Beam Current</td>
</tr>
<tr>
<td>I/O energy</td>
</tr>
<tr>
<td>Vane Voltage</td>
</tr>
<tr>
<td>Characteristic Radius ($r_0$)</td>
</tr>
<tr>
<td>Modulation</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Q Value</td>
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<tr>
<td>No of posts</td>
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3. RESONANT CAVITY DESIGN

The RFQ is designed as a four-rod cavity structure consisting of vanes, stems and base plate. Diagonally opposite pair of the electrodes called vanes are aligned at 45° and are supported on the alternating posts known as stems. Each stem holds two equipotential rods called vanes. The rods act as capacitors and stems act as inductors. Two adjacent opposite stems holding the four rods make one RF cell. The resonator is formed by distributed
capacitance of the vanes and inductance of the posts. This way RFQ structure consists of a coupled transmission line which can theoretically be treated as lumped circuit elements. Vane and stem assembly arranged on base plate and enclosed in a rectangular cavity forms the resonant structure of RFQ. The outer cavity serves as a vacuum enclosure only and does not influence the resonance frequency of the RFQ.

3D model of cavity is prepared in Solid Works with modulated vanes from the 3D data set generated by beam dynamics simulations. Front view of RFQ is schematically shown in Fig. 3. To keep the model and results close to the real values, analysis (RF, mechanical, structural and thermal) is carried out on modulated vane structure and is then imported in CST MWS in Eigen mode solver for electromagnetic simulation study and for actual resonant frequency estimation. The resonant structure has been optimized to achieve 60.6 MHz frequency in the cavity by optimizing the distributed capacitance and inductance. Results are shown in Fig. 4.

4. RFQ ASSEMBLY

The RFQ is divided into two major parts: High Vacuum Chamber and Inner Assembly consisting of a) Vanes b) Vane Posts c) Base Plate.

![FIG. 3. Front View of RFQ](image1)

![FIG. 4. Resonant Frequency simulation](image2)

4.1. Inner assembly

The inner assembly of the RFQ is composed of 12 vane posts and twenty four vanes (Fig.5). The vane of RFQ is 39 mm thick and 4160 mm long. The base plate will be made in two segments of equal length.

In all vanes and vane posts cooling paths have been provided to limit the thermal load. Adequate cooling has been ensured by providing water entry from lower side of the vane posts, transfer through the vanes before coming out

![FIG. 5. Inner assembly of vanes, stems and base plate](image3)
from the adjacent vane post as shown in Fig. 6.

**FIG. 6. Cooling Layout**

4.2. Outer assembly

RFQ vanes, stems and base plates are enclosed in two Aluminium T-6061 Chambers as shown in fig.7. Both the chambers will be assembled together to make one single cavity. There are two base plates, made of solid copper, which will hold 12 vane posts. These vane posts will hold twenty four vanes. The inner dimensions (500 x 450x4160 mm) of the rectangular chambers (Fig.3.) were determined by simulation on CST Microwave Studio program.

**FIG. 7. Conceptual RFQ assembly with vacuum vessel**

It is essential that the deformations due to vacuum should be kept minimal so that the resonant frequency and RF characteristics of RFQ are maintained. Buckling load due to atmospheric pressure and vacuum was simulated and parameters are optimized further to achieve satisfactory limits in terms of deformation and stresses.

5. THERMAL ANALYSIS

Thermal analysis of the assembly (Fig. 8.) was carried using 3-D model with “ANSYS” Simulation software. Distribution of the total power among different RFQ component is obtained through simulation on the CST Microwave Studio software. The average linear power density is determined with a peak heat flux on hot spot locations and cooling design is carried to minimize temperature rise in the RFQ cavity and to control the de-tuning to less than 30-50 kHz. The distribution of heat is found as follows, Vanes 34%, Vane Posts 51%, Base Plate 13%,
vacuum chamber 2%. The load on each component has been assumed to be uniformly applied. Mesh size was taken as 5 mm, inlet water temperature as 20°C.

The thermal loads include heat flux from the RF on the cavity walls, stems, vanes and base plate, convective heat transfer on the cooling passage surfaces and the symmetry boundary conditions. This power dissipation causes large temperature gradient in the RFQ structure along with distortion in the vane, leading to the de-tuning of the structure.

Maximum temperature rise has been found on vane end portion which remain unsupported for a longer length than the other vanes. Along with these locations, interfaces between vane and stem also attain higher temperatures and are required to be cooled.

Temperature rise is restricted by cooling the vanes and vane posts through cooling channels of 8 mm diameter. In total twenty parallel cooling loops have been optimized with a pressure gradient below 0.5 bar through each channel. All water inlets are kept through the bottom of stems so that they are accessible for repairs in case of leakage and vacuum inside the chamber remains intact. The results for steady state operation are shown in fig. 8 and for pulsed operation maximum temperature of only 1°C has been shown in fig.9.

![FIG. 8. Temperature rise in case of steady-state operation of RFQ after cooling](image1)

6. CONCLUSION

The design of a 4.2 m long Rod Type RFQ to accelerate 5 mA proton beam to 1 MeV energy with the transmission efficiency of 97.4% has been presented in this paper. Design of the RF part has been optimized to achieve the operating frequency with a mechanical viable geometry and a reasonable Q value. Thermal optimization has been achieved with 20 cooling channels with a maximum temperature variation of 1°C for pulsed operation. Structural analysis and further optimization to reduce heat load in steady state operation will be carried out in future.
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