SIMULATION OF RF STRUCTURE OF TRIUMF CYCLOTRON WITH HFSS

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Abstract

Fundamental accelerating mode and rf leakage of the TRIUMF 500 MeV cyclotron rf structure into the beam gap has been studied with the help of a 3D structure simulator software, HFSS (High Frequency Structure Simulator, Ansoft Corporation). The center post, flux guides, the quasi-circular vacuum chamber and the rf structure have been incorporated into the simulation. median plane. This leads to a large number of tetrahedrons in HFSS whereby Eigen modes and field solutions obtained are not very accurate. A simpler model was chosen to solve for the electric and magnetic fields of both the accelerating mode (push-pull) and non-accelerating mode (push-push). The rf parameters have been computed and are in close agreement with the parameters measured on the cyclotron. Vertical asymmetry at the dee gap, caused mainly by resonator misalignment, leads to rf leakage fields into the beam gap tank volume outside the resonators. HFSS simulations of this misalignment have been carried out.

INTRODUCTION

The TRIUMF cyclotron [1] has been operating since 1975 and is now routinely producing 250 μA protons at 500 MeV. In the meantime the rf system has gone through many improvements for more reliable operation of the cyclotron [2]. A 3D HFSS Eigensolver from Ansoft Corporation has been used to simulate the cyclotron rf cavity for the accelerating mode and also to investigate some of the problems associated with parasitic modes and rf leakage [3, 4]. Figure 1 is a representation of the top and side view of the cyclotron. The two dee resonating cavity is completely contained within the 16 m diameter, 43 cm high quasi circular vacuum tank. In the vacuum tank 10.2 cm is allowed for the beam, each rf gap occupies 10.2 cm and the remaining space is kept for the top and bottom parts of the resonator. The dee structure evolves directly from a uniform λ/4 coaxial resonator. The structure is made of eighty segments, 10 upper and 10 lower segments in each quadrant. Thus, each segment is 0.81 m wide and 3.1 m long. The operating frequency of the cyclotron is 23.06 MHz and the rf gap voltage is typically 90 kV. The frequency adjustment of the resonator is done by moving the ground arm tips. Vertical asymmetries of the rf structure excites parasitic modes.

SIMULATION OF CYCLOTRON

The actual dimensions of the cyclotron have been used to generate the model of the cyclotron. First a very accurate

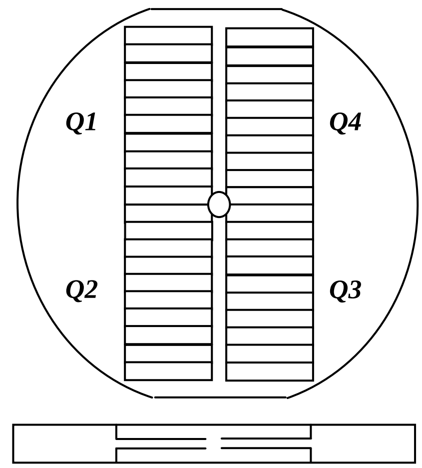

Figure 1: Top and side view of the main resonator

3D model was created with HFSS Modeler including the center region [5]. This model was used as a reference for the simplified model for rf simulations preserving the main cavity structure. The center region was simplified in the model so that the structure is symmetric in the median plane. For the simulation three models were created: a full model for eigen modes identification, a second full model with distorted tuning plate to explore asymmetry of fields in the rf structure and a half model (below medium plane) for more precise calculation of cyclotron rf parameters. Perfect conductor walls for all the three cases were used to reduce computation time. A PC with Intel Pentium IV 3.0 GHz processor and 2 Gb RAM was used to run HFSS. Solution time for the models with mesh of 120,000 to 190,000 tetrahedrons was about 3-5 hours with convergence of 2 %. A mesh of 200,000 tetrahedrons was used for the half structure to get more precise calculated parameters of the cyclotron for the operating mode. Most of these tetrahedrons were concentrated in the gap region by using a virtual object technique.

Eigenmodes

The full structure model was used for eigenmodes identification. Five simulations were run to detect the modes in the range of 10 to 35 MHz. 17 modes are listed in Table 1. Among them we can see the accelerating operational push-pull mode (mode 5 in the Table) with a frequency of 23.047 MHz and the closest TEM210 push-pull mode (mode 4) at 22.627 MHz and push-push mode at 23.238 MHz (mode 6).

Table 1: Solved modes for full cyclotron model.

Mode	F, MHz	Mode	F, MHz
1	13.368	10	28.251
2	15.626	11	28.416
3	20.105	12	28.866
4	22.627	13	29.460
5	23.047	14	29.614
6	23.238	15	31.019
7	24.739	16	31.163
8	24.955	17	34.584
9	26.355		

The polarization of the electric fields for the operational and the nearest lower mode are the same in the horizontal plane. Figure 2 shows the vector plot of E field for the operating mode in the median plane. E vector plots for the modes nearest to the operating mode is shown in figure 3.

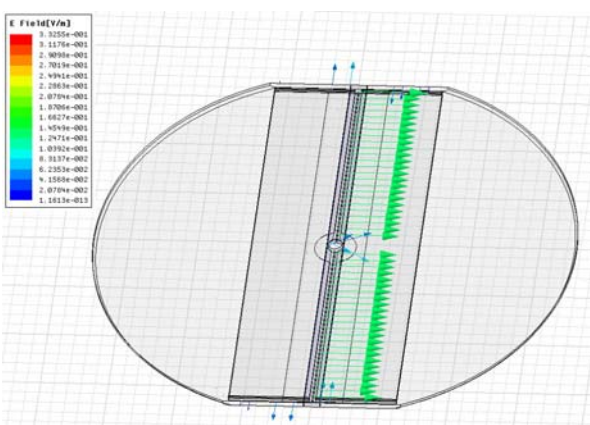

Figure 2: E vector plot for the operating mode in medium plane (mode 5 in Table 1).

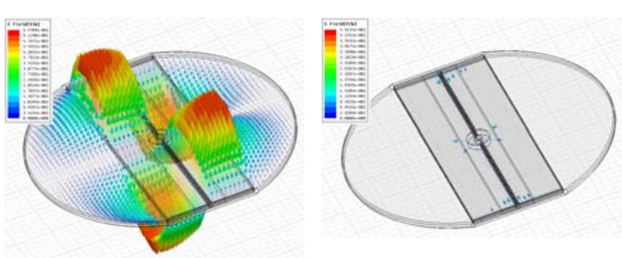

Figure 3: E vector plots for the modes (mode 4 and mode 6 in Table 1) in medium plane nearest to the operational mode.

Table 2: Operational and the nearest push-push mode parameters obtained from half model of the cyclotron

mode		f	Q
1	operational	23.106	5815
2	push-push	23.292	5938

Push-push and push-pull mode

Push-push and push-pull (accelerating) modes are rather close to each other. In push-push mode the opposite plates across the gap have the same polarity and gives rise to a higher frequency than the push-pull mode. By inspecting the voltage across the gap it is easy to identify the modes Figure 4 shows the voltage across the gap for both the modes. The vertical lines denote the dee gap. The longitudinal component of electric field for the push-pull mode changes polarity as it crosses the gap.

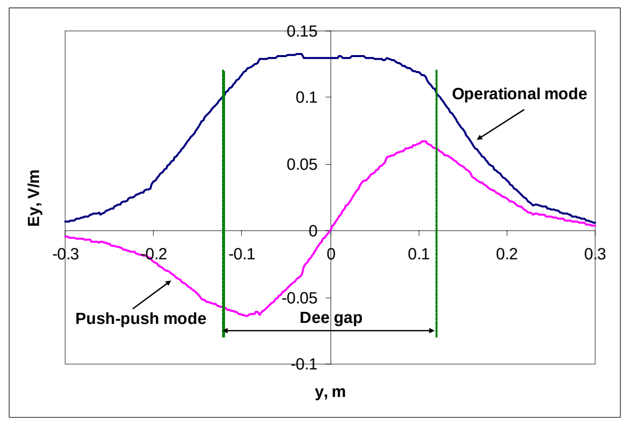

Figure 4: Longitudinal component of electric field across Dee gap for push-push and push-pull modes.

Asymmetries

The beam gap inside a dee is a rectangular wave-guide, 10.2 cm high, 16.25 m wide. This wave-guide is uniform in cross-section for 3.1 m and opens to 43 cm high at the root and extends to nearly 9 m. The wave-guide modes are thus inherent in the cyclotron volume. It was discovered that small vertical electrical asymmetries in the cavity will excite TM310 and TM410 parasitic modes in the beam volume [3]. To reduce parasitic amplitudes, hot arm to ground arm distances are adjusted at the tip of the segments. This is done with the help of temperature sensors and voltage probes that have been installed. RF leakage into the beam gap and other normally field free regions, causes damage to the probes and cables. In HFSS modeling, one of the four ground arms has been misaligned and corresponding rf field leakage inside the rf cavity has been simulated. This can be seen in figure 5. To simulate asymmetry a full structure model of the rf cavity was used.

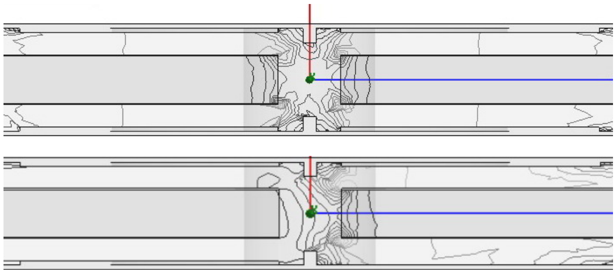

Figure 5: E field isoplot for operational mode in vertical plane across the dee gap for ideal and distorted rf structure of the cyclotron (the distortion or asymmetry is introduced in the ground plane with one tuning plate).

Computed rf parameters

Rf parameters of the TRIUMF Cyclotron for the operating mode were calculated in the HFSS Postprocessor from the half cyclotron model. Power dissipation in the solution was calculated assuming the wall material is copper with a conductivity σ=5.8*10^7 1/(Ωm). The results are shown in Table 3. Calculated quality factor is about 5800 which is very close to the measured Q=5500. Accelerating shunt impedance was calculated from the accelerating voltage, which is an integral of longitudinal electric field component across the dee gap (Fig. 4). The shunt impedance R_{sh} uses the following equation.

$$R_{sh} = V_{av}^2/P \qquad (1)$$

Where V_{av} is the average gap voltage and P is the power dissipation in the full structure cavity.

It can be seen from Table 3 that the calculated rf parameters for the operating mode are in good agreement with the measured values.

Table 3: Calculated and measured rf parameters of the cyclotron.

Parameter	HFSS	measured
Resonant frequency	23.106 MHz	23.060
Quality factor	5814	5500
R_{shunt}	38.6 kΩ	36.0 kΩ
Power for dee gap voltage 180 kV	840 kW	900 kW
Sensitivity to all ground arm tips displacement	83 kHz/mm	-

The sensitivity to all ground arm tips displacement was calculated by using the Slater theorem.

$$\Delta f = f_o \frac{\Delta U_E - \Delta U_H}{2U} \qquad (2)$$

where Δf is the frequency shift, f_o is the resonant frequency, U is the stored energy in the structure, ΔU_E and ΔU_M are electric and magnetic energy changes respectively. The volume of the structure is changed by deforming the tuning ground arm plates and the frequency change is obtained from the change in the stored electric and magnetic energies in the deformed volume. Full tuning plates excursion is 15 mm and it produces ~1.3% frequency change which is ~83 kHz/mm for all 4 tuning plates. The sensitivity of the hot arm tip movement is about twice that of the ground arm tip movement. The frequency of the rf cavity of the cyclotron is determined by the hot arm tip adjustment and the ground arm tip adjustment.

SUMMARY

A better and clearer understanding of the cyclotron's rf structure was possible by using HFSS 3D simulation techniques. The half structure model of the cyclotron was used where the vertical symmetry could be utilized and the accuracy of the solution was important. To study asymmetry a full structure model was required. Electric and magnetic field distribution of various modes and estimation of power requirement to achieve required gap voltage could be done with the model described in this paper. Close agreement between measured and computed rf parameters demonstrates the usefulness of the simulation. This model simulation technique can be further used to study the center region of the accelerator. Rf leakage can be investigated in depth and parasitic modes and mode suppression can be the scope of future work.

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