THIRD HARMONIC FLATTOPPING IN THE TRIUMF RF CAVITY

T. Enegren, D. Dohan, K. Fong, V. Pacak and R. Worsham
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Summary

The TRIUMF resonant cavity is being modified to allow the simultaneous excitation of both the first and third harmonic resonances for RF waveform flattopping. For beam operation, the value of the fundamental frequency must be adjustable while maintaining a precise 1 to 3 ratio of the fundamental to the third TEM mode frequencies. Three tuning methods have been considered and will be described. The preferred method incorporates specially designed ground panels with a 10 cm dee-to-ground spacing at the root and a hinged section providing an adjustable spacing at the high voltage end. Movement of the hinged section perturbs the cavity and hence the frequency of the first and third TEM modes. The amount of the frequency perturbation is different for each mode depending on the location of the hinge point. Two sets of ground arms with different hinge locations are required to provide the necessary two degrees of freedom. The advantages of this method over previous methods will be discussed.

Introduction

Three methods have been considered for tuning the TRIUMF RF resonant cavity to make it possible to simultaneously excite the fundamental and third harmonic frequencies. Such a flattopped accelerating voltage would increase the acceptance of the beam, allow separated turn extraction and permit higher beam intensities. The TRIUMF resonant cavity consists of 80 individual resonant segments or resonators that form two quarter wave coaxial stubs that face the dee gap as in a conventional two dee cyclotron. The gap between the dee, or coax inner conductor, and the outer shield, or ground panel, is a uniform 10 cm from tip to root. Due to the dee-to-dee capacitance, the resonant frequency of the third TEM mode is not exactly three times that of the fundamental. For flattopped operation the fundamental and third TEM modes of the resonant cavity must be harmonically related, that is their frequency ratio must be precisely 3 to 1. A tuning method with two degrees of freedom is required to obtain and maintain this frequency ratio.

During cyclotron operation the fundamental TEM mode frequency is adjusted over a small frequency range while the third TEM mode is close to the desired value requiring only a slight perturbation in the cavity volume to obtain the correct frequency ratio. The effect of small volume changes on the resonant frequencies of the cavity modes can be qualitatively understood by considering the amount of electric or magnetic energy that has either been added or removed by the volume change. Since the fundamental and third TEM modes have different electric and magnetic field distributions it is possible to select the position of the perturbation such that the two TEM modes are altered in either the same direction or the opposite direction.

At present the fundamental mode is tuned by deflecting the ground panel in a small region near the dee gap. The electric fields for both the fundamental and third TEM modes are at maximum value in this region while the corresponding magnetic fields are at a minimum and therefore deflecting the ground panel removes mostly electric energy and the resonant frequency of both TEM modes is decreased (i.e. the two TEM modes are altered in the same direction). Since independent control of the two TEM modes requires two degrees of freedom a second tuning device is required which will either alter the two TEM mode frequencies in the opposite direction or alter only one of the mode frequencies. To provide the second degree of freedom for frequency tuning three additional types of cavity perturbations have been proposed for TRIUMF:

(1) Short circuited tuning stubs coupled near the root of the TRIUMF resonator cavity

(2) Deflecting the ground panel at a location 1/3 of the distance from the root to the dee gap

(3) Deflecting the ground panel near the dee gap about well-defined hinge points

Short Circuited Tuning Stubs

If the TRIUMF resonant cavity is considered as a simple coaxial transmission line resonator foreshortened by the dee-to-dee tip capacitance, then the third TEM mode frequency will be slightly higher than three times the fundamental frequency.[1] To lower the third TEM mode frequency without affecting the fundamental a proposal has been made to add one or more short circuited coaxial line tuning stubs to the TRIUMF resonant cavity[2] as shown in Fig. 1. The stub is located near the root of the cavity in a region of relative high magnetic and low electric field. The center conductor of the stub is connected to the inner conductor of the resonator. The distance to the short circuit of the stub is slightly less than one half wavelength long at the third harmonic frequency. The effect of the stub is to slightly increase the total magnetic energy for the third TEM mode and hence lower its resonant frequency.

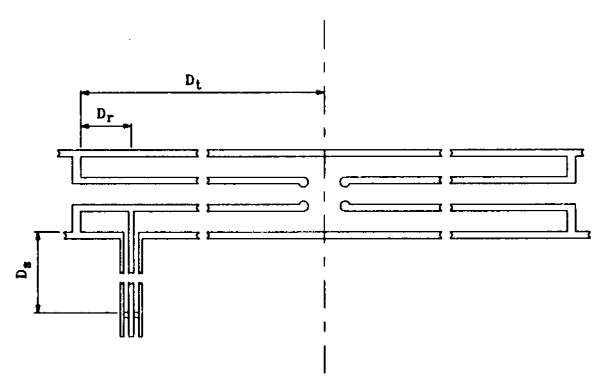

Fig. 1. Third TEM mode frequency tuning of 1:10 model using short-circuited tuning stub. D_t = 0.3025 m, D_r = 0.028 m.

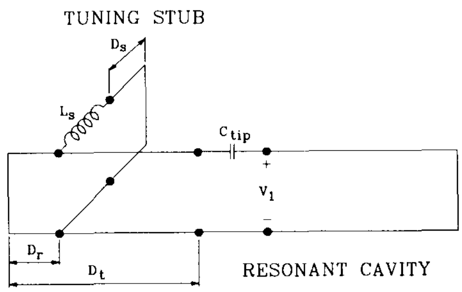

Fig. 2. Transmission line representation of third TEM mode frequency tuning using short-circuited stub tuning. C_{tip} = 346.6 pf.

The effectiveness of this method and its effect on the dee voltage profile were investigated on the tenth scale model of the TRIUMF resonant cavity and vacuum tank regions.[3] For purposes of analysis both the cavity and tuning stub are modelled by separate transmission line networks that are coupled as shown in Fig. 2. The resonant frequency is tuned by adjusting the position of the short circuit on the stub. The agreement between predicted and measured tuning characteristics as a function of stub length is shown in Fig. 3.

The predicted tuning characteristics and stub power losses for a single tuner coupled to the TRIUMF resonant cavity are shown in Fig. 4. For the stub power loss calculations it is assumed that the dee voltage V_1, Fig. 2, is held constant at 11 kV. The power losses are small until the stub approaches its self-resonant frequency at which point the losses increase dramatically.

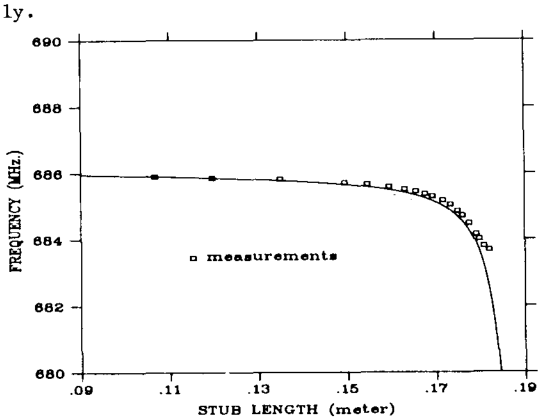

Fig. 3. Calculated and measured tuning characteristics for 1:10 model as a function of stub length.

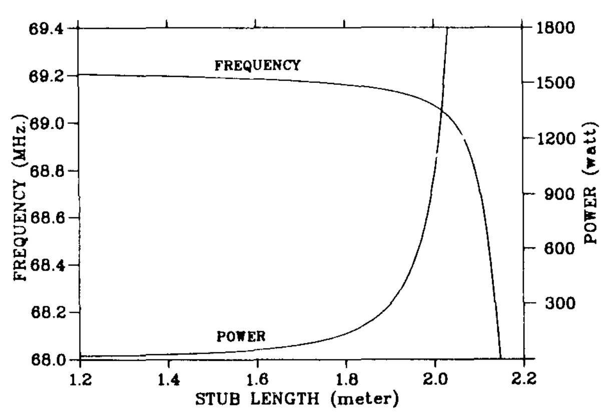

Fig. 4. Predicted tuning characteristics and stub power losses for a single short-circuited tuning stub coupled to the TRIUMF resonant cavity. Dimensions of stub are those of standard 6 in. diameter, 50 Ω, coaxial transmission line.

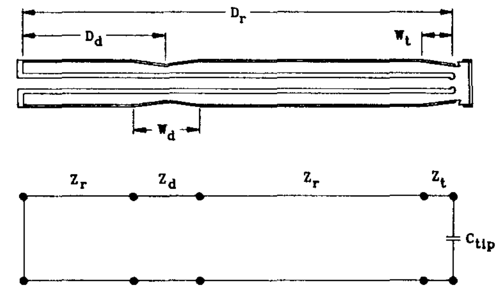

Fig. 5. Cross section of RF test facility resonant cavity and corresponding transmission line representation. D_r = 3.025 m, d_d = 1.0 m, W_d = 0.7 m, W_t = 0.4 m, Z_r = 17.29 Ω, C_{tip} = 37.15 pf.

Measurements on the model indicated that the tuning stub had an appreciable effect on the third harmonic dee voltage profile especially when the stub approaches self resonance. To avoid this problem and to maintain the tuning range it would be necessary to use more than one tuning stub. One advantage of this tuning method is that it has little effect on the resonant frequency or the dee voltage profile of the fundamental mode. The major disadvantages are that its implementation at TRIUMF would require considerable effort in modifying the present resonator design and constructing additional ports in the TRIUMF vacuum tank.

Deflections of the Ground Panels

Two proposals have been investigated that involve the perturbation of the ground panels of the TRIUMF resonant cavity. Since the magnitude of the proposed perturbation was quite small the investigations were carried out on the TRIUMF RF test facility.[4,5] The RF test facility consists of two TRIUMF resonator segments positioned one above the other, fluxguides and a shorting plane at the dee to form a coaxial λ/4 resonant cavity. The electrical characteristics are equivalent to those of TRIUMF. A cross section of the test facility resonant cavity showing the nature of the ground panel deflections and its transmission line representation is shown in Fig. 5. For the analysis it was assumed that the deflected section of the ground panels could be represented by a linear stepwise variation in the transmission line characteristic impedance (Fig. 6). This permitted transmission line theory to be used in calculating the resonant frequencies. A plot of frequency as a function of number of steps is shown in Fig. 7. Eighty steps to represent the ground panel deflections at the tip or at the 1/3 point is sufficient to provide acceptable convergence for the fundamental and third TEM mode frequencies.

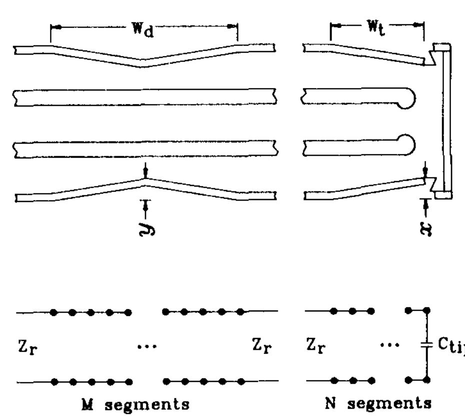

Fig. 6. Representation of deflected ground panels. Maximum x = 15.2 mm, maximum y = 2.54 mm.

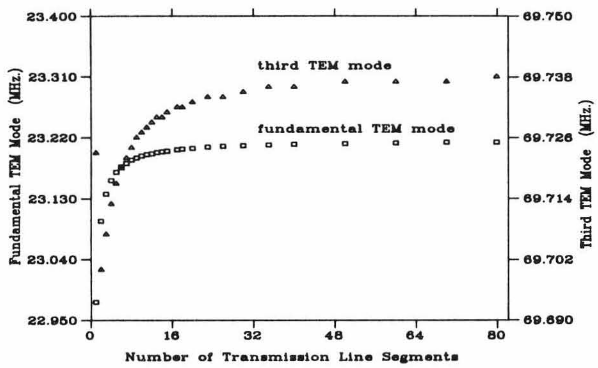

Fig. 7. Frequency convergence as a function of the number of transmission line subdivisions of deflected ground arm sections.

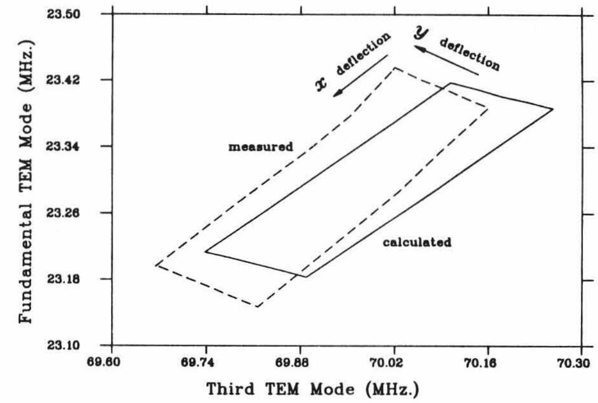

Fig. 8. Calculated and measured tuning characteristics of the RF test facility resonant cavity.

The first ground panel tuning method consists of perturbing the ground panels at a position which is 1/3 of the distance from the root to the tip. This is a region of high electric and low magnetic fields for the third TEM mode. For the fundamental TEM mode the magnetic field is greater than the electric field and therefore inward deflections of the ground panel in this region will lower the third and increase the fundamental TEM mode frequencies. The calculated and measured tuning characteristics for the first tuning scheme are shown in Fig. 8. The discrepancies between predicted and measured characteristics were attributed to the slight distortions in the flux guide sections of the cavity which could not be easily incorporated into the model.

The second ground panel tuning method involves modifying the existing ground panel tip tuning so that the panel deflects about a well-defined hinge point. Since the field distribution for the fundamental and third TEM modes are different, deflection of the ground panel perturbs the resonant frequencies of the two TEM modes differently depending on the location of the hinge point. This allows the two degrees of freedom that are required for independent frequency control to be obtained by selecting two distinct sets of hinge point locations. A plot of the third TEM mode frequency sensitivity with ground panel deflection as a function of hinge point location is shown in Fig. 9. If the hinge point is located approximately 1.1 m from the dee gap its resonant frequency is insensitive to deflections of the ground panel. This is due to the spatial variation of the electric and magnetic fields for the third TEM mode. The electric field decreases from its maximum value at the tip and is relatively low at this hinge point location. The magnetic field has opposite variation and as the ground panel is deflected equal amounts of electric and magnetic energies are removed and there is no change in the third TEM mode frequency. For the new resonator design this point has been chosen as the location of one set of hinge points as it provides partial decoupling of the fundamental and third TEM mode tuning. An optimum choice for the second hinge point location would be where the third TEM mode frequency is maximally sensitive to ground panel deflections as shown in Fig. 9 to be approximately 0.5 m from the dee gap.

Both ground panel tuning methods have been tested at high power and at full operating voltage on the RF test facility. The first ground panel tuning method was used in the successful demonstration of third harmonic flattopping at high power under vacuum.[5] Measured tuning characteristics of a ground panel whose hinge point was designed for minimum third mode frequency sensitivity are shown in Fig. 10. A factor that was taken into consideration in the design of the hinge mechanism was the high value of fundamental mode current flowing at this point which is 1/2 of its maximum value. Power tests indicated that the hinge section of the ground panel operated at only slightly higher than normal operating temperatures.

Conclusions

All three methods provided the required tuning range however the following conclusions are made:

Coupling of short-circuited tuning stubs to the TRIUMF cavity is not practical because of the consider-

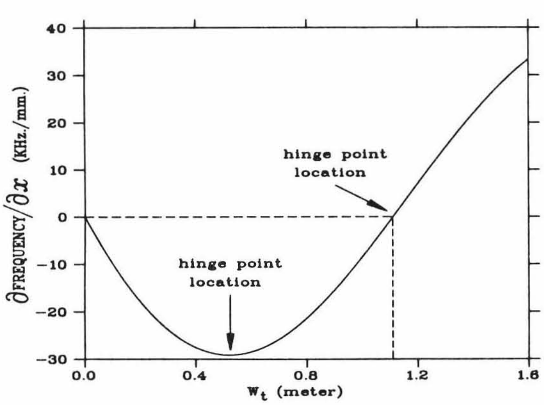

Fig. 9. Sensitivity of third TEM mode frequency with tip deflection as a function of hinge point location.

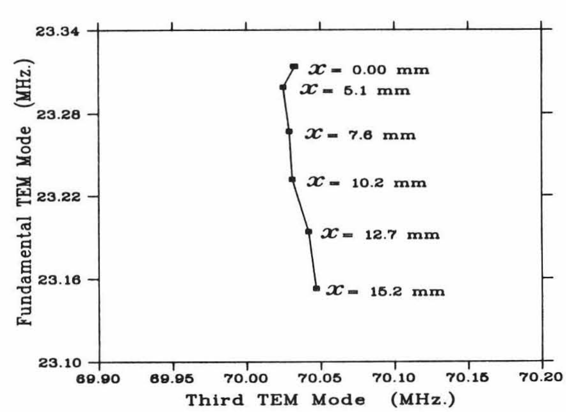

Fig. 10. Measured tuning characteristics of RF test facility resonant cavity with ground panel hinge location near the region of minimum sensitivity.

able effort required in modifying the existing resonator design and the TRIUMF vacuum tank.

Deflecting the ground panels at a position 1/3 of the distance from the root is not practical because this position is not easily accessible in the TRIUMF resonant cavity and the mechanical devices required to deflect the ground panels, given the limited space constraint, would be complex and expensive.

Deflecting the tips of the ground panels at different hinge points does not require the addition of mechanical devices or modifications to the vacuum tank but only requires that the ground panels deflect in a predictable and consistent manner. This tuning method has been chosen for TRIUMF and the new resonators have incorporated the necessary design changes.

References

1. A. Prochazka, "The Design of the RF System for the TRIUMF Cyclotron", Ph.D. Thesis, March 1972.
2. P. Lanz, private communication.
3. R. Poirier, D. Dohan, G. Dutto, T.A. Enegren, K. Fong and V. Pacak, "Determination of RF Leakage Field in the Vacuum Tank of TRIUMF Cyclotron", IEEE Trans. Nucl. Sci. NS-30, No. 4, 3514 (1983).
4. R.E. Worsham, T. Enegren, D. Dohan, L. Durieu and R. Poirier, "System for Flattopping the RF Waveform at TRIUMF", Proceedings of the 10th International Conference on Cyclotrons and their Applications, East Lansing, 1984, p. 82.
5. T. Enegren, L. Durieu, D. Michelson and R.E. Worsham, "Development of Flattopped Voltage for TRIUMF", IEEE Trans. Nucl. Sci. NS-32, No.5, 2936 (1985).