THE INTERACTION BETWEEN THE THIRD HARMONIC RESONANCE AND PARASITIC MODES INSIDE THE TRIUMF CAVITY

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Abstract

The TRIUMF resonator system has been designed for possible "flat-top" operation. This mode of operation implies simultaneous excitation of the fundamental and the third harmonic resonances in the same rf cavity. A precise 1:10 scale all-metal model of the TRIUMF cyclotron has been used to study the feasibility of achieving flat-topped operation. The third harmonic voltage has been shown to vary considerably along the resonator tip due to the higher capacitive loading in the central region. In addition, higher-order parasitic modes of the "fundamental" group have been observed to interfere with the TEM third harmonic resonance, denoted by TEM_{030}, resulting in voltage variations along the dee gap of as much as 10 dB. The observations, a theoretical treatment of the interference and possible solutions are discussed.

Introduction

The resonator for the rf system of TRIUMF consists of two quarter wave flattened coaxial stubs ($\lambda/4 = 325$ cm) facing the dee gap as in a conventional two-dee cyclotron. Each of the flattened stubs is made up of 40 individual segments joined edge to edge to form the coaxial resonator. The segments are joined electrically at the dee gap and at the root (shorting plane). The gap between the dee, or coax centre conductor, and the ground liner is a uniform 10 cm from tip to root. This form suggests the possibility of exciting the third harmonic mode to produce a flat-topped rf waveform. A flat-topped rf waveform would considerably improve beam quality and phase acceptance of the cyclotron[1]. The feasibility of combining the fundamental and third harmonic components in the **same** resonant cavity was explored first in high power test facility consisting of two TRIUMF resonator segments[2]. A series of a high power tests with the third harmonic pulsed have also been carried out on the main rf system. A flat-topped rf waveform with the third harmonic pulsed at a 2% duty cycle pulsed mode is shown in Figure 1.

Third harmonic power is fed into the TRIUMF resonator through a coupling loop. The loop is matched to a 50 Ω transmission line with three tuning stubs. During the course of a flat-topped test it was observed that matching the coupling loop had become extremely difficult. It was also observed that the quality factor for the third harmonic was severely reduced. Signal level measurements on the resonator revealed the these effects were due to excitation of parasitic modes whose resonant frequencies were close to that of the third harmonic. By tuning the resonator to shift the frequencies of these modes away from the third harmonic it was possible to restore the expected value for the Q and to match the coupling loop. This effect has been observed and investigated on a precise 1:10 scale model of the TRIUMF resonator.

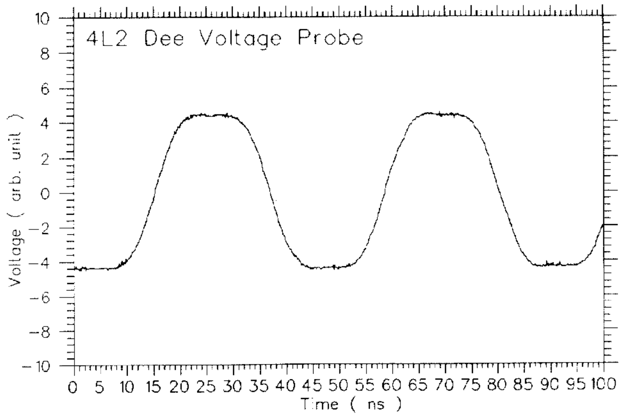

Figure 1: Flat-topped waveform in the cyclotron during pulsed operation.

Theory

When a cavity is driven by an external source, for example a coupling loop with current density **J** and frequency ω, the resultant electric field **E** inside the cavity will be a superposition of the profiles of the different resonant modes, each weighted by the difference between the square of its frequency ω_n^2 and ω^2.

$$\mathbf{E} = \sum_n \frac{j\mathbf{E}_n}{\omega^2 - \omega_n^2}\left(\omega \iiint_V \mathbf{J} \cdot \mathbf{E}_n^\star d^3x\right). \tag{1}$$

Here $\mathbf{E}_n$ is the normalized electric field due to the n^{th} mode and V is the volume inside the cavity. For a real cavity with ohmic loss, the ω_n's are complex and **E** is always finite, even at resonance. The input impedance of the cavity similarly depends on the volume integral and is given by

$$Z = -\sum_n \frac{j\omega}{\omega^2 - \omega_n^2}\left(\iiint_V \mathbf{J} \cdot \mathbf{E}_n^\star d^3x\right)^2. \tag{2}$$

The above equations show that the excited voltage and the input impedance depend on $\omega^2 - \omega_n^2$, and on the amount of overlap between the profile of the modal electric field $\mathbf{E}_n$ and the profile of the exciting current density **J**, as well as on its magnitude.

When ω_n's are spaced far apart, the resultant voltage profile and input impedance will depend only on the single n^{th} mode which is closest to ω. However, if the cavity is being excited at a frequency where the ω_n's are closely spaced, the voltage profile will be the superposition of these modes. Similarly, the input impedance will be very different from that of a single mode response. In the TRIUMF rf cavity, this is possible between the third harmonic TEM_{030} mode and one of the higher order transverse modes TE_{i10}, where $i \geq 6$. Considering only these two modes, one can derive the overall dee gap voltage from Equation 1 as:

$$V = V_{030}(1 - ax) + V_{i10}\cos\left(\frac{xi\pi}{20} + \phi\right), \tag{3}$$

where V_{030} represents the voltage due to the TEM_{030} mode, a its reduction factor along the dee gap due to the centre region capacity loading, x the distance from the centre, V_{i10} the voltage due to the TE_{i10} mode and ϕ is the relative phase between the two modes. When V_{i10} is comparable in magnitude to V_{030}, the dee gap voltage

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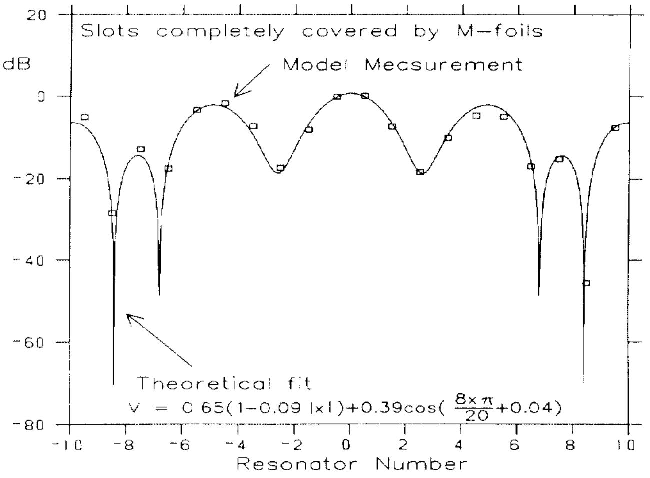

Figure 2: Interference between TEM_{030} and TE_{810} mode.

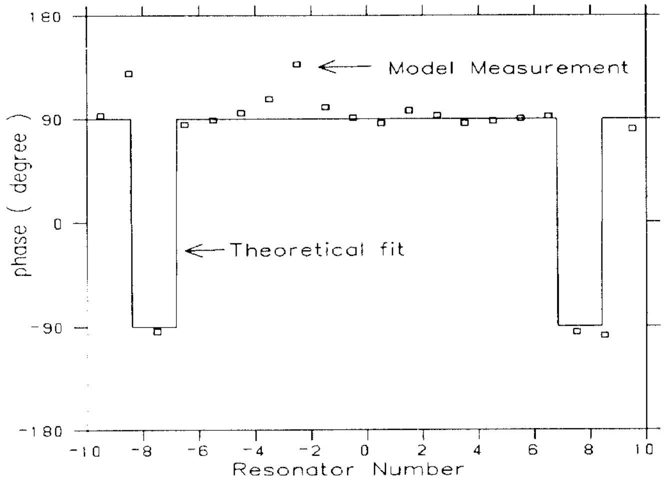

Figure 3: Resultant phase of the TEM_{030} , TE_{810} interference

will show a correspondingly large modulation. In order to reduce the non-uniformity, it is necessary to tune the cavity such that a is small, and $\omega^2 - \omega_{i10}^2$ is large.

An important property of the TE_{im0} modes is that the induced currents flow parallel to the dee gap. This implies that the currents flow from one resonator segment to the next through the electrical connections at the dee gap and the root. Any alteration of these connections can have significant effect on the resonant frequencies of these modes. A far greater effect can be obtained by shorting the gaps between the resonator segments at selected positions with M-shaped contact foils. This provides a means for tuning these frequencies. The frequency shift is maximum when the M-foils are located in regions of high current density. The spatial distribution of the current, which depends on the order of the mode, is a maximum at the root, where the M-foils are most effective. The fundamental TEM mode has no transverse current and is not sensitive to the placement of the M-foils. Due to higher capacitive loading of the central region the TEM_{030} has some transverse current and is slightly affected by M-foils.

Model Measurements

An investigation of the interference of parasitic modes on the third harmonic has been carried out on a 1:10 model of the TRIUMF resonator. Figure 2 shows the resultant dee gap voltage profile of an interference between the TEM_{030} and TE_{810} modes. In this particular case all the slots are covered by M-foils, which allow the TE_{810} mode to resonate at a frequency close to the TEM_{030} mode. The measured result was fitted to Equation 3, and the fitted parameters show that the voltage of the TEM_{030} mode decreases by approximately 10 dB from the centre to the outer most segment, due to the detuning effect of the centre post. Furthermore, the amplitude of the TE_{810} mode is roughly half of the third harmonic mode at the centre. Figure 3 shows the measured phase distribution and the calculated one. At the outer radii, where the transverse mode has a higher amplitude and opposite phase with respect to the TEM_{030} mode, the resulting voltage reverses its polarity, which is not acceptable for uniform flattopping along the dee gap. By removing specific M-foils from the central segments, we observed a reduction in the resonant frequencies of the fundamental transverse modes due to an increase in inductance. The frequency of the TE_{810} mode is shifted down and therefore is not excited. However, now the $TE_{10,1,0}$ mode has almost the same resonant frequency as the TEM_{030} mode, and the measured voltage profile shown in Figure 4 is the result of the interference between these two modes. This is again an inappropriate profile for beam acceleration. In general, as the transverse mode number gets larger, their frequencies are spaced closer and it becomes much more likely that some of these transverse mode have frequencies close to the third harmonic mode.

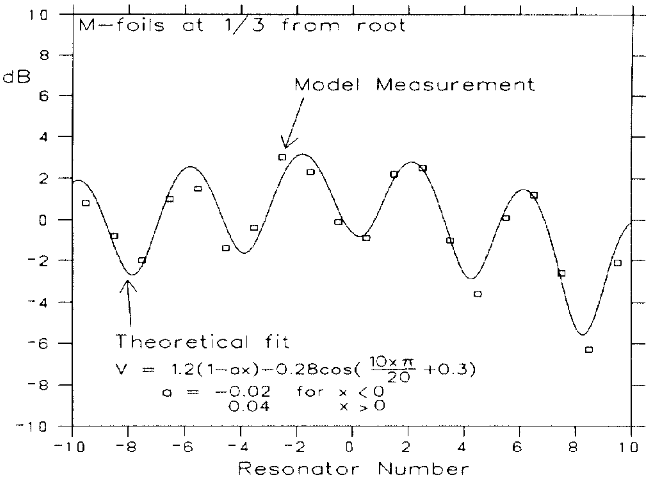

Figure 4: Interference between TEM_{030} and $TE_{10,1,0}$ mode.

The presence of these transverse modes causes waste of RF power and detuning of the input circuit. Since the resonant frequencies of the transverse modes shift upward as more M-foils are installed, the transverse modes that can potentially interfere with the third harmonic will have lower mode numbers and larger frequency separations. Therefore it is desirable to install as many M-foils as possible. Figure 5 shows an improvement in dee gap voltage obtained when the M-foils are installed only in the root region between every resonator segments.

The results acquired during the third harmonic studies on the 1:10 model strongly suggest the importance of the installation of M-foils within the TRIUMF cyclotron. However, because of existing operational requirements and of radiation dose exposure to personnel in the cyclotron, it would be too lengthy and therefore impractical to experiment with M-foils and other RF modifications in the cyclotron itself. A more comprehensive examination of the effects of M-foils must be carried out in a better model. To overcome the limitations of the 1:10 model for measurements at the higher frequencies, a larger 1:3 scale model has been designed. Because of more accurate modelling of the dee tip contacts, centre region geometry and other details, it is believed that the larger model will allow the accurate

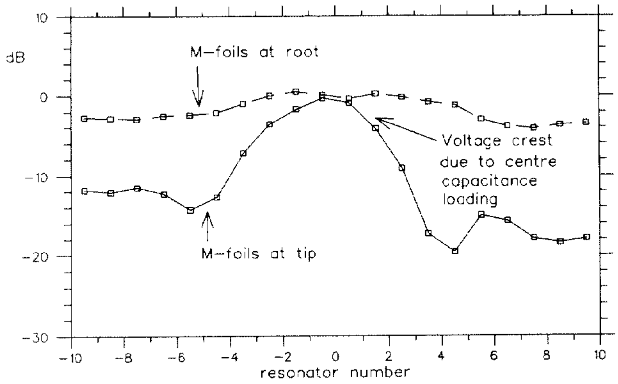

Figure 5: Improvement in dee gap voltage by locating the M-foils in roots.

determination of the optimum location and form of the M-foils for the cyclotron.

Summary

Due to the abundance of fundamental transverse modes around the third harmonic TEM_{030} frequency, there is always the possibility of interference between the third harmonic TEM_{030} mode and these transverse modes. The result is distorted voltage profile generally inappropriate for beam acceleration. Since the M-foils play a very important role in determining the resonant frequencies of all the modes in the cavity, they have a significant effect on the voltage profile. Therefore the installation of the M-foils can either bring a large distortion of the voltage profile, or on the contrary, when installed in some strategic positions they can improve the overall voltage distribution along the dee gap.

References

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