REQUIREMENTS FOR A NEW RESONATOR STRUCTURE AT TRIUMF

D. Dohan, G. Dutto, K. Fong, R. Laxdal, V. Pacak, R. Poirier, R. Worsham and M. Zach
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Summary

The resonator cavity at TRIUMF is unique of its type with its large size (6 × 16 × 0.5 m^3) and its total containment within the magnetic field. Nine years of successful operation with RF fundamental at beam currents up to 150 μA have proven the validity of the concept. However, for greater reliability and third harmonic flat-topping a new resonator structure is being designed to incorporate improvements for reduced RF leakage into the beam gap, better alignment, and reduced dee vibration amplitudes. For separated turns at extraction, tolerances of ±80 ppm in voltage and ± 0.12° of third harmonic degrees in the phase jitter between fundamental and third harmonic have to be maintained. This imposes stringent requirements on the mechanical stability of the 3 m long cantilevered resonator panels and on the feedback systems for RF controls. New design criteria in terms of reduced leakage and mechanical stability have been derived from beam orbit calculations, RF cavity computer simulations, and 1:10 scale RF model measurements. The new requirements and the criteria will be discussed in relationship to the data from the present resonator system as measured through a system of voltage probes, RF leakage probes, induction coils and accelerometers.

Introduction

In the TRIUMF cyclotron each dee can be divided mechanically into two upper and two lower octants, each of which is composed of 10 separate resonator segments for the ease of handling.[1] The cavity is contained totally within the magnetic field, and the dee can be viewed as a grossly flattened λ/4 coaxial cavity. The inner conductors (hot arms) of this structure are supported by cantilevered arms (strongbacks) three meters long. Mechanical vibration with rms amplitude of ≈50 μm at the tips of the cantilevered arms have not deterred successfull operation at the RF fundamental frequency of 23 MHz. Careful alignment of the 80 individual resonator segments have reduced the RF leakage to reasonable levels which do not interfere with beam operation with currents of up to 150 μA.[2]

However, planned improvements for the cyclotron such as third harmonic flat-topping will put more stringent requirements on the resonator structure, both in terms of stable RF accelerating voltage and phase. The additional power of the third harmonic frequency, and its shorter wavelength, also call for greater leakage suppression.

Separated Turn Operation

A task force has been set up to study, design and commission an alternative extraction system that would allow extraction of H^- and/or pulsed beams.[3] At the extraction energy of 450 MeV the turn spacing is only 1.5 mm. Because of the finite beam emittance, the energy dispersion and energy drift of a turn must be kept to only a small fraction of the energy gain per turn (300 keV) in order to maintain turn separation. A total energy uncertainty of 150 keV puts extremely tight constraints on the voltage and phase stability of the RF accelerating field. To achieve the energy dispersion desired, the flat-topping of the RF acelerating field by addition of the third harmonic (69 MHz) is imperative.

To limit the energy drift, beam dynamic calculations[4] show that the fundamental RF voltage must be stabilized to ±80 ppm and the third harmonic voltage to ±660 ppm. To limit the energy dispersion the variation in the relative phase between the fundamental and the third harmonic should be less than ±0.12° in third harmonic degrees. However, there are no tight restrictions on the variation in these parameters with radius, and only the average values of these parameters from injection to extraction should be within the above tolerances.

Voltage and Phase stability

Mechanical vibrations of the cantilevered hot arms are excited by cooling water in the resonator panels. This vibration changes the geometry of the resonant cavity and causes subsequent variations in the accelerating RF voltage and phase. Induction coils and accelerometers installed on the tips of the hot arms showed that the mechanical vibration of the strongback is concentrated in vibrational modes from 2 to 18 Hz, above which there is very little vibration. As shown in Fig. 1, the most dominant mode is the 5 Hz fundamental cantilever mode. This mode accounts for 80% of the total tip displacement due to vibration. The third harmonic cantilever mode at 16 Hz accounts for most of the remaining vibrations. The vibration amplitudes (integrated from 2 to 18 Hz) for the resonator segments increase with radius, reaching a maximum of 50 μm rms at a radius of 5-6 m. The vibration then falls off slightly at the outer segments. Furthermore, measurements show that the individual segments within an octant vibrate coherently, but the vibrations between octants are incoherent.

The RF fields are measured by 133 capacitative pick-up probes in the cyclotron, 60 of which are located in the RF gap. These probes are located 10 cm from the tips of the hot arms in order to monitor the dee gap voltage. Since these probes measure the electric field that is at their surfaces, their signals are different from the accelerating voltage as seen by the beam for two reasons: electrical fore-shortening due to the dee-to-dee capacitance, and the vibration of the cantilevered structure which changes the distances between the probes and the hot arms. The remaining probes are leakage probes located at various positions in the beam gap to monitor the magnitude of the RF leakage.

Signals from two of the resonator probes are used for the RF control system. Consequently the

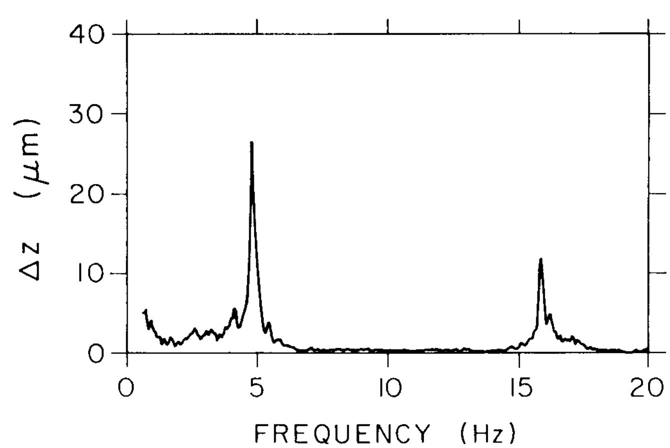

Fig. 1. Frequency spectrum of the mechanical vibration at the tip of a hot arm (lower quadrant 2, segment 6) as measured by an accelerometer.

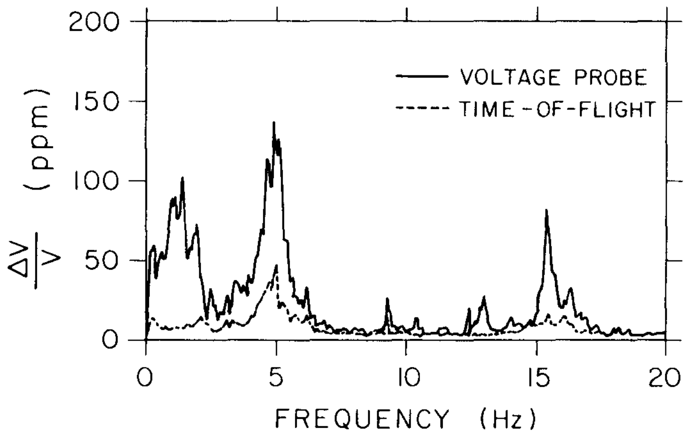

Fig. 2. Comparison of the voltage variation measured from a resonator probe (lower quadrant 2, segment 5) with an integrated variation of 700 ppm, and the voltage variation inferred from beam time-of-flight, which has an integrated variation of 200 ppm.

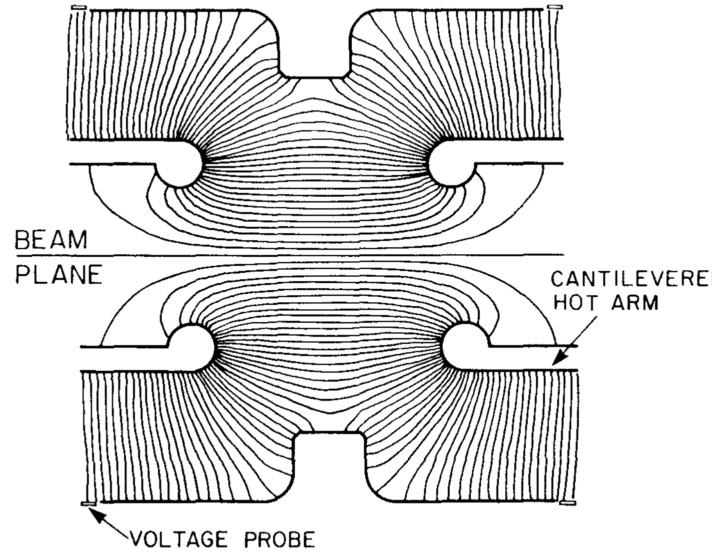

Fig. 3. Cross section of dee gap with electric field lines generated by SUPERFISH.

characteristics of the mechanical vibration will show up in the RF accelerating voltage and hence the beam stability. This is due to the fact that the signal is proportional to the intensity of the electric field at the probe surface rather than to the dee voltage at that point. The voltage standard deviation (Fig. 2) as measured by the resonator probes is of the order of 700 ppm, although a very high feedback loop gain is used in the control system. The average accelerating voltage inferred from the beam time-of-flight measurments (Fig. 2) gives a standard deviation of the order of 200 ppm, which is significantly less than that measured by the voltage probes. Although the eight octants are vibrating incoherently, the electromagnetic coupling between them results in some degree of compensation of the voltage variation between the opposing dees. This reduces the variation in the accelerating voltage and hence the beam time-of-flight.

Relative phase measurements taken between segments at both the fundamental and third harmonic frequencies show that the phase jitters are within the new design tolerance. The measurements show that the standard deviation of the phase jitter between any two resonator segments was of the order of 0.001° for the fundamental frequency and 0.03° for the third harmonic frequency.

Comparison of the voltage and phase stability required and that presently achieved indicates that the relative phase stability can easily be satisfied. When the phase between the fundamental and the third harmonic is locked at one point in the resonator, the phases will be locked everywhere due to the small phase jitter between the segments. However, the voltage stability will require an improvement by a factor of three in order to achieve separated turns at extraction energy. This can be achieved by removing the erroneous signal injected into the feedback loop. This requires that the mechanical vibrations should either be reduced or their effects compensated.

Computer simulation of the RF resonant cavity was used to calculate the maximum allowable amplitude of mechanical vibration in order to satisfy the beam dynamic requirements when distance compensation was not used. A plot of the electric field lines in the dee gap as calculated by SUPERFISH[5] is shown in Fig. 3, in which the four cantilevered arms are perfectly aligned. For the vibration calculations, these arms were misaligned by various amounts in both directions, and the effect on the electric field near the voltage probes and in the beam gap was observed. Since it is not possible to simulate the misalignment of an individual resonator segment and the magnetic flux linkage between the upper and the lower resonator in a 2-d program, the results obtained must be extrapolated to include the above three-dimensional effects. From measurements on the dees, it can be safely assumed that there is perfect flux coupling between the upper and lower resonators. Hence the entire cavity can be simulated by using only the lower part of the cavity. Furthermore, it was assumed that the voltage in the dee is uniform along the cantilevered tips, which is the case for a TEM wave, and that the effect of misalignments is linear. This means that the effects observed by deflecting the entire dee can be interpolated linearly for individual octant or segment deflections.

Under the above assumptions, and using the requirement of SUPERFISH that the accelerating voltage is constant, the following results are obtained from the simulations:

(1). Decreasing the gap of one entire dee by 25 μm (250 ppm) by bending the cantilevered arm will cause the electric field at the voltage probe on the deflected dee to increase by 1400 ppm, and the voltage on the undeflected dee to decrease by 1100 ppm at the fundamental frequency. These effects are reduced by a factor of 10 at the third harmonic frequency.

(2). When deflections occur on both dees, the overall variation is equal to the algebric sum of (1) above.

(3). The natural frequency of the entire cavity is changed by +20 ppm at the fundamental frequency and by -0.26 ppm at the third harmonic frequency by a 25 μm inward deflection of one dee.

Using the above results, then in order to achieve a standard voltage deviation of less than ±80 ppm with feedback regulation by averaging the voltages of two voltage probes in the opposing dees with no distance compensation, the amplitude of the mechanical vibration of the resonator structure must be kept below 5 μm.

RF leakage

RF leakage into the beam gap can adversely affect the cyclotron operation by heating the uncooled components in the vacuum tank and causing RF damage to beam diagnostic equipment. For introduction of third harmonic frequency into the resonant cavity, the RF leakage into the beam gap must be reduced below the present level. For this purpose a 1:10 scale model of the cyclotron and the resonant cavity was constructed and is being used to study the mechanism of RF leakage.[6] It is found that the amount of leakage depends on the asymmetry of the dees. Model measurements and computer calculations showed that asymmetry between the upper and the lower resonators will cause a significant increase in the RF leakage. Hot arm vibrations have little effect on the RF leakage into the beam gap due to their small amplitude. Sagging of the cantilevered arms is an important contribution to the asymmetry. Joule heating of the structural members by the increased RF leakage field can further aggravate the sagging, causing progressive deterioration of performance. Furthermore, static misalignment of the resonator segments, which causes local non-uniformity in the dee gap voltage also contributes to the leakage.

Due to the frequency proximity of a parasitic mode (TM_{310} at 21.5 MHz) in the beam gap, the leakage power is quite high, and it has caused a considerable amount of RF heating of the structures. The leakage can be lowered by as much as 10 dB when the frequency of this parasitic mode is shifted away from the operating frequency. This can be achieved by electrically shorting out the slots between the resonator segments, changing the geometry of the arm components, and their connections.

New Resonator Structure

The above criteria will be incorporated into the design of the new dees. In particular, provisions will be made for segment-to-segment electrical contact and all components exposed to stray RF fields will be water-cooled. Increased mechanical stiffness to maintain resonator alignment is imperative. This increase in stiffness of the new resonator will reduce its response to the excitation by water turbulence. The existing resonator has transverse cooling lines on the resonator panel. An order of magnitude reduction in the vibration amplitude was measured on a prototype resonator segment which has longitudinal cooling lines on the resonator panel. As a result of vibration measurements a more detailed study is being carried out with regard to water flow patterns and mechanical attachments for the resonator panel to the cantilever support structure. However, even after the expected reduction in vibration amplitude is achieved, the required voltage stability will not be met. Further improvements to the voltage controls system using input signals proportional to the true dee gap voltage are planned.

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