IMPROVED RELIABILITY OF THE TRIUMF RESONATOR SYSTEM THROUGH INSTALLATION OF NEW RESONATOR PANELS

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Summary

The rf resonator of the TRIUMF cyclotron is being upgraded with newly designed resonator segments. In addition to having higher dynamic stability and an adjustable ground-arm geometry, these segments also contain modified water-cooling circuits and thermally isolated strongbacks. The heat from resistive rf losses inside the resonator cavity as well as that from leakage into the beam cavity is removed efficiently, eliminating mechanical distortions and instability caused by differential thermal expansion. Improvements in the water circulation pattern have reduced flow-induced vibrations. Nine new resonator segments were installed in locations at which the power dissipation was observed to be substantial. The location of maximum power dissipation is controlled by adjusting the tip capacity of individual segments, which alters the leakage pattern in the beam cavity to maintain the peak dissipation on these particular water-cooled segments. Remote ground arm tip control was installed to accomplish this without interrupting beam operation.

Introduction

The resonant cavity of the 500 MeV TRIUMF cyclotron has been described previously.[1,2] Briefly, because of the relatively low magnetic field required to prevent stripping of the H^- ions, the cyclotron allows a large magnet gap for the rf cavity. Further, by using harmonic acceleration the two-dee system can be reduced in size to fit entirely inside the magnetic field.

The dee structure evolves directly from a uniform $\lambda/4$ coaxial resonator as shown in Fig. 1. One simply compresses the coaxial line flat to fit in the magnet gap and combines two such units for the complete resonator. The fifth harmonic (23.06 MHz) of the particle revolution frequency has a $\lambda/4$ of 3.25 m while the overall width required for the resonator is 16.25 m. Normal operation is currently at 86 kV, which takes a total excitation of 1.2 MW rf power. No insulators are used for support. The 43.0 cm vacuum tank height allows 10.2 cm for the beam and 10.2 cm for each rf gap, with the remaining 12.6 cm available for the mechanical structure of the top and bottom parts of the resonator.

Practical handling of the dee requires that it be assembled in parts, or segments. By breaking the top and bottom structure of a dee into 20 segments each and making the breaks parallel to rf current flow lines (perpendicular to the dee gap), one gets segments that are 0.81 m wide and, after allowing for tip capacity, 3.10 m long, as shown in Fig. 2. To support and position a top, or bottom, segment a heavy V-shaped 316 stainless steel levelling arm is rigidly connected to the main mechanical support strongback structure and attached to the vacuum chamber. The Aℓ alloy strongback, which is on the beam side, supports the copper rf panel (hot arm) and pivots on the root. The liner or ground arm, which completes the rf circuit, is attached to the surface of the vacuum vessel.

The photograph of Fig. 3 was taken inside the vacuum vessel with the upper half of the magnet and the top

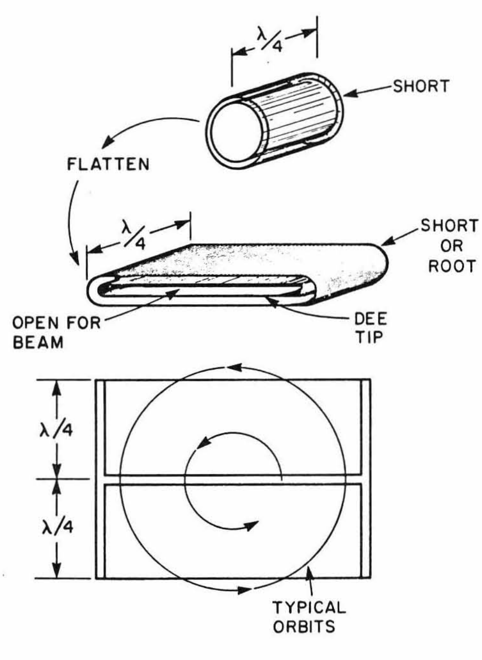


Fig. 1. Evolution of coaxial line into 2-dee resonator.

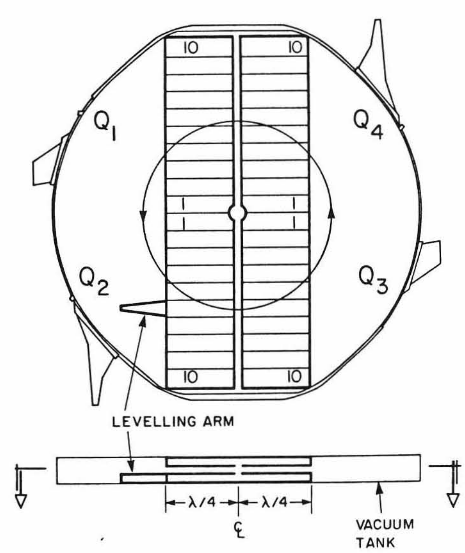


Fig. 2. Fitting of resonator in vacuum tank with support levelling arm for cantilevered strongback. Note segments are numbered 1-10, centre outward, in each of 4 quadrants.

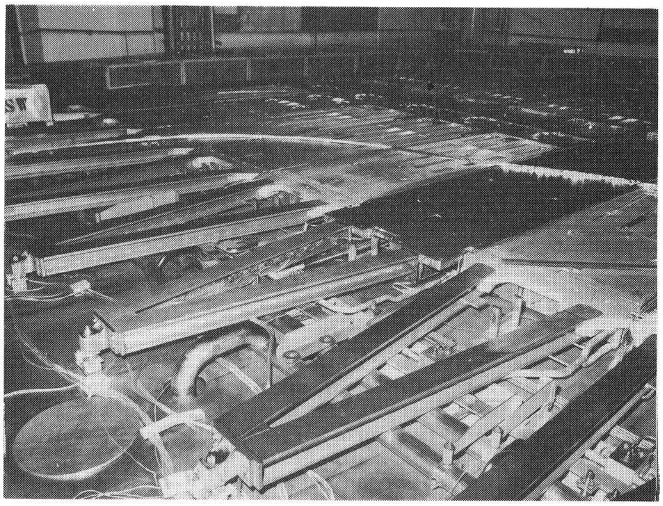


Fig. 3. View of lower segments in quadrant 3 with tank lid raised. The first segment with the newly designed beam-side panel is in position 5.

lid of the vacuum tank raised about 1.2 m. Several segments are visible with their strongbacks and V-shaped levelling arms. The dee gap can just be seen between opposing sets of strongbacks. One segment corresponding to the new design is shown in place.

Rationale for an Improved System

Three aspects of the original resonator performance required improvement and suggested a resonator improvement program based mainly on the design of a new segment.

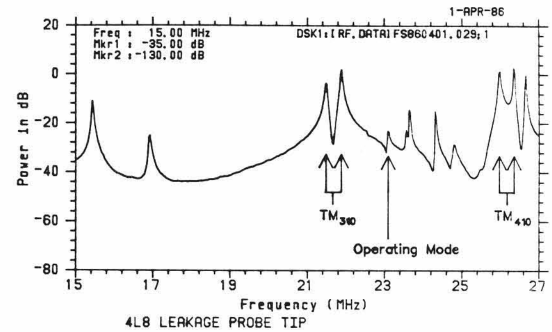
Firstly, parasitic modes[3] were excited within the dees, generating multipactoring heat that caused distortion of the segments, which in turn increased the leakage leading to a runaway condition that could result in melting or permanent deformation of components. Secondly, pneumatically driven mechanical tuners[2] which were provided in each segment failed to perform satisfactorily at the beginning of operations. Thirdly, to achieve greater beam stability in keeping with plans that call for beam intensity upgrade to 500 μA, extraction of 100 μA H^- beams,[4] and third harmonic flat-topping,[5] tip vibration amplitude had to be minimized.

Vibration

The source of the driving power to excite the tip vibration was traced to turbulence in the cooling water of the dee panel. In an earlier paper[6] it was shown that by elimination of the rollbond panels with their complex flow patterns and by replacement with flattened tubing soldered to the rf panel in a simple geometric pattern, the vibration levels could be reduced by a factor of 10 to 50. In addition, but to a lesser extent, the levels were brought down by increasing the stiffness of the strongbacks to 143 lb/in., measured at the tips, up from 55 lb/in. in the original design. With these two improvements an overall level of less than 5 μm - the value required - could be obtained in isolated segments.

Tuning of the Resonator

Mechanical fatigue of the tuning foils and bellows in the original root tuners[2] led to their replacement by a separate system that used the water pressure in the rollbond cooling channels of the rf panels to control the resonator frequency. The range of 4 kHz obtained was quite sufficient for operation of the resonator after a brief warm-up cycle. In the new design with rigid cooling tubes soldered to the panels, this frequency variation with pressure is being eliminated. A new system with motorized dee tip adjustment gives wider range of control and, in addition, provides other necessary functions: leakage control and third-harmonic tuning.



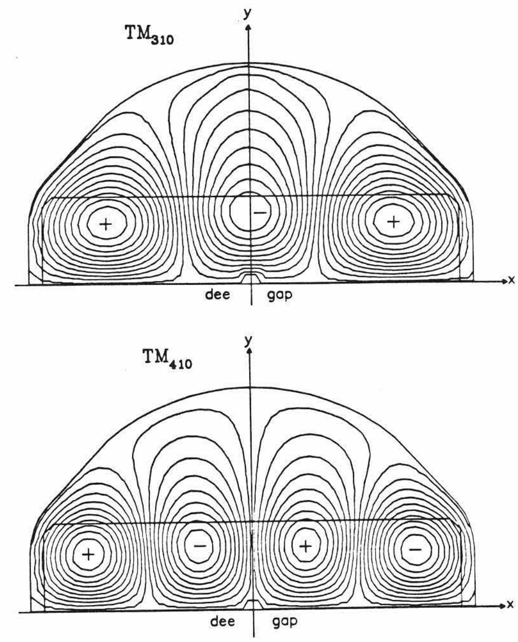


Fig. 4. TM_{310} and TM_{410} parasitic modes excited in beam gap.

Parasitic Modes in the Resonator

The beam gap inside a dee is a rectangular waveguide that is 10.2 cm high by 16.25 m wide. It runs with uniform cross section from the dee tip back 3.1 m to the root at which point it opens up into the full vacuum tank with its radius of nearly 9 m and 43 cm height. This section of waveguide, with an aluminum surface plus the tank with a stainless steel surface, forms a cavity that has two resonant modes near the 23.06 MHz operating frequency.[7] In Fig. 4 the patterns of the H-fields of these two modes, TM_{310} and TM_{410}, are shown. From the patterns it can be seen that the current flow would extend over the dee tips and into the resonator. And in the upper part of the figure it can be seen that the natural frequencies of these modes span the operating TEM mode of the resonator. Each mode is characterized by two peaks corresponding to the push-push and push-pull component. A cross mode of the main rf cavity can be observed on the right of the TEM peaks, but does not produce leakage effects. Other leakage modes are sufficiently far from resonance that their effects are negligible.

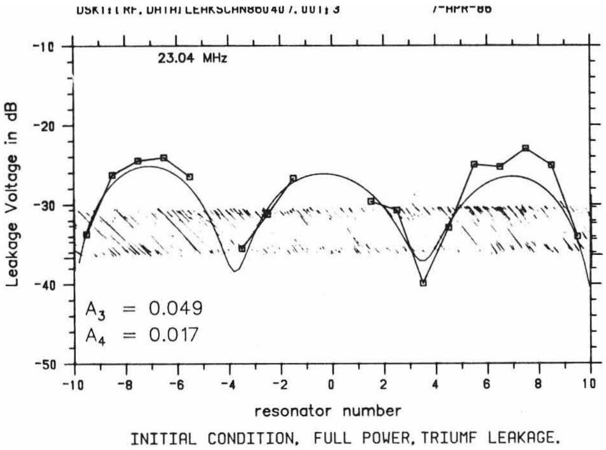


Fig. 5. Leakage voltage measured (squares) and calculated. The hash-marked band shows the range of voltages for which multipactoring can occur.

Imbedded in the strongbacks are electrostatic probes to pick up the vertical electric field of these modes in the beam gap. The results of such a measurment are shown in Fig. 5. The data show the combined TM_{310} and TM_{410} vertical voltage both as measured (squares) and as determined from the analysis described in a companion paper.[7] Note that the symmetrical TM_{310} mode is in this case, which is typical, nearly three times the magnitude of the asymmetrical TM_{410} mode. Further note that the current maxima induced by these modes would be greatest in segments 3, 4, 5 and 10, which are the locations of maximum heating observed in normal operation.

However, from the leakage voltages measured, the power loss generated by the corresponding surface currents could not exceed 100 W per segment while measurements from a water-cooled strongback[6] have shown that the power loss can be as large as 1200 W. The major source of heating is multipactoring. In the beam gap of 10.2 cm with ~23 MHz rf and the vertical magnetic field of the cyclotron, first-order multipactoring can occur for a voltage across the beam gap between 300 and 600 V.[7] The hash-marked band of Fig. 5 shows values where such a condition would exist. In this situation, note that in the right quadrant segment 4 would not be heated since its voltage is below multipactoring while segments 3 and 5 would, since they fall within the band. In segments 1, 2 and 6, 7, 8, 9 the voltage is above the multipactoring band, hence, they would not be band heated. The temperature chart of Fig. 6 shows an example of such a situation.

In the TRIUMF cyclotron, with just the number 8 segments remotely adjustable it is possible to lower the leakage pattern by as much as 10 db. However, as may be expected from the data of Fig. 5, segments such as 7, 8, 9 tend to get hot.[7] Further reduction such that all segments could have leakage voltages below that leading to multipactoring appears quite feasible with the addition of more remotely adjustable drives for the tips in regions corresponding to strongest coupling of the leakage to the dee voltage.

New Resonator Segment Design

As mentioned previously, the prototype segment design described in Ref. 6 met all of the goals for vibration and stiffness. Further, the suspension for the new rf panel worked well in its 6-month trial period; there were no problems with the new rf panel design and no problems were encountered with remote handling during insertion into or extraction from the machine. However, because of excessive temperature gradients in the cooled strongback, the goals of tip stability under rf load were not met. For the final segment, the only new tasks were the addition of a water-cooled panel on the beam side and the inclusion of a new ground arm with special hinged tips. The beam-side panel is made of copper for high thermal conductivity and is shaped to shield electrically the strongback from all rf currents, when combined with the rf panel. No water cooling is required on the strongback, since the heat source and thermal gradients are now negligible.

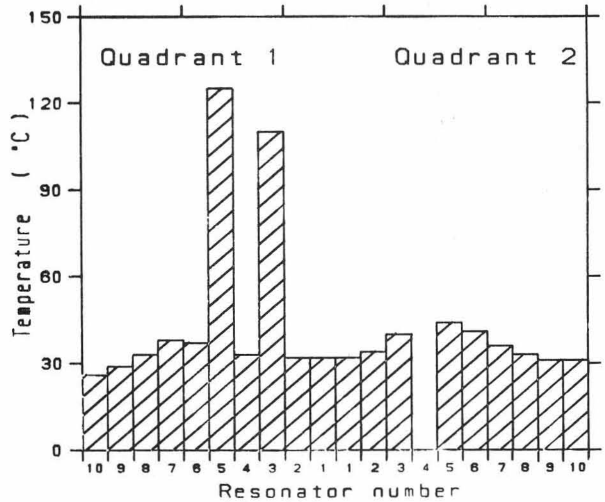


Fig. 6. Temperatures of strongbacks in normal operation. In quadrant 1 only segments 3 and 5 have leakage voltages suitable for multipactoring, in this case.

The arrangement of the components of the hot arm are shown in Fig. 7. The rf panel and its suspension

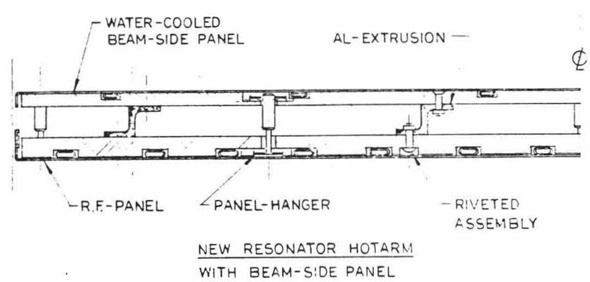


Fig. 7. Cross section of newly designed strongback.

are described in Ref. 6. The strongback cross section differs from the earlier version only in the space allowance for the beam side panel and in the simpler Z-shaped separators that could be used since water cooling was not necessary. Naturally, the overall thickness of this panel is of extreme importance since any increase takes space either from the rf system or from the beam gap. In addition the weight of the panel should be the minimum possible to reduce the loading on the cantilevered strongback. A 0.8 mm thickness of copper was found to be sufficient with the three water-cooling loops to remove the heat and limit the temperature rise in the panel. Thermal isolation was achieved by supporting the panel from the strongback on small cup-shaped indentations in the panel that were about 1 cm in diameter and spaced about 30 cm apart on average. A screw through each indentation, which holds the panel in place on the strongback, prevents vertical motion of the panel but allows relative horizontal motion of the panel with respect to the strongback.

First, to measure the effectiveness of the thermal isolation, a test panel was constructed using a radiant heat source to simulate leakage equivalent to 2000 W. The hottest spot in the beam side panel was 9°C above the water cooling temperature. And the maximum differential temperature in the strongback, top-to-bottom, was <0.5°C - a value small enough to produce no signicant tip deflection. The first complete segment constructed with this new design is shown in Fig. 8. When this unit was first tested in a special rf teststand at 100 kV tip rf voltage with 2000 W radiant power to simulate the leakage, a telescope was used to observe the tip motion throughout the operation. No motion was observed in the complete cold-hot-cold cycle exceeding the 0.25 mm resolution of the telescope. Further, measurement of vibration showed no detectable increase from the added water cooling in the beam-side panel.

This new segment design will serve for all segments except the special ones, numbers 1 and 10. In the centre region, space for injection upsets the uniformity of the resonator by additional tip capacity and a shorter segment length. Also, the flux guide at 10 is a perturbation. However, these perturbations affect only third harmonic operation for flat-topping with 12 dB variation of the voltage along the dee gap.[3] The impedance modifications required for segments 1 and 10 for uniform third harmonic dee gap voltage are being determined in model studies.[3]

The original ground arm, constructed with roll bond tubing exactly like the rf panel of the hot arm, could not be adjusted reliably under the conditions required for third-harmonic tuning.[3,5] The newly designed unit uses the same copper panel and cooling that works well for the rf hot arm but with a rigid stainless steel framework for support and attachment to the vacuum tank. In addition, a hinge is located in the panel at a specified distance from the tip to meet the requirements of the third-harmonic tuning[5] with precise reproducible motion.

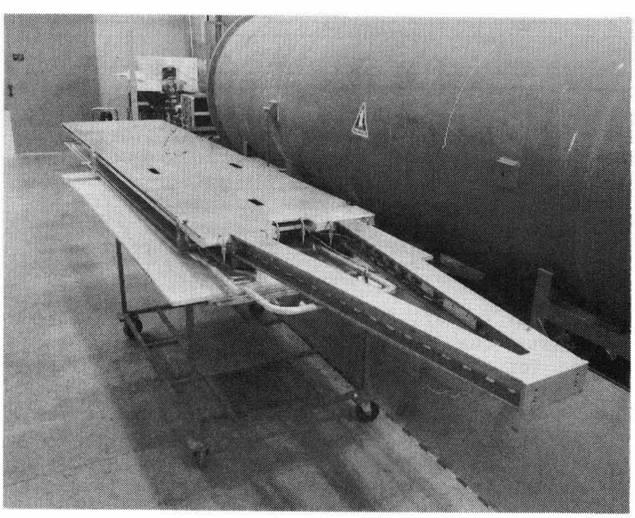


Fig. 8. Complete segment of new design with beam-side panel.

Operational Experience with New Segments

The first segment was installed in quadrant 3, lower position 5 (3L5) in October 1985. It can be seen in Fig. 3. Prior to replacement, this segment was usually the hottest place in the machine with temperatures about 135°C. Now with the beam-side panel a typical operating temperature is 30°C - within 2° of the water cooling temperature. Even though the new segment is joined at the tip to adjacent segments 4 and 6, which are of the old type and subject to some leakage heating, the tip motion is now less than 0.75 mm compared to more than 2.5 mm before. Further, by its location at the centre of a quadrant, its increased stiffness acts most effectively to reduce the vibration level in that quadrant (observed ~10 μm) a factor of 3 times lower than with the original segment, even with the tip attachment to the old type #4 and $6 segments.

In February 1986 four additional segments of this new design were added in the upper 4 positions. Now in October the corresponding lower 4 positions are being filled with units of the new design to give full symmetry with one new segment in the centre part of each group of 10.

Another effect observed is that with the 5 new stiffer segments tested to date the frequency change and the time to reach operating temperature have been cut by a factor of at least two - significantly improving operating time.

Conclusion

The nature of the phenomena that have imposed limitations on the rf system of TRIUMF would appear to be well understood, and solutions have been demonstrated. It is clear from these results that the future plans call for added remote tip drives to control leakage and tuning, replacement of the number 1 segments to remove dee voltage nonuniformity for the third harmonic, and replacement of the other segments subjected to multipactoring heating in particular, numbers 3, 5 and 10.

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