CONTROL OF RF LEAKAGE IN THE TRIUMF CYCLOTRON

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

Summary

The TRIUMF vacuum chamber and beam gap form a cavity with resonant rf modes close to the operating frequency. The resultant leakage into this beam cavity poses significant problems to beam diagnostic equipment and can damage non-cooled components in this volume. Model studies, machine measurements and theoretical calculations have been carried out in order to understand and control the leakage. The amount of this rf leakage is shown to depend critically on the alignment at the dee gap. Two dominant leakage modes have been identified and their excitation mechanisms have been studied. The total leakage field depends critically on the amplitudes and phases of these parasitic modes. Through suitable superposition of these modes, the leakage can be reduced and its pattern modified by the realignment of the top and bottom ground arm tips. Reductions in the leakage by 10 to 15 dB have been achieved on the model and on the machine. The major cause of heating of the resonator strongbacks has been found to be due not to the leakage currents themselves, but to multipactoring effects in the beam cavity driven by leakage electric fields.

Introduction

The rf resonator of the TRIUMF cyclotron has previously been described and is shown schematically in Fig. 1 of Ref. 1. Since the beam circulates within the beam cavity, which has parasitic modes close to the operating frequency, rf leakage into this beam cavity poses significant problems to beam diagnostics as well as to the structural integrity of the cyclotron. We have reported previously[1,2] that a reduction of 15 dB in leakage rf power in the beam cavity in a 1:10 scale model of the cavity and the vacuum tank was obtained by shifting the natural frequencies of the parasitic modes that are present in the beam cavity. These changes are achieved by changing the structure of the hot arm

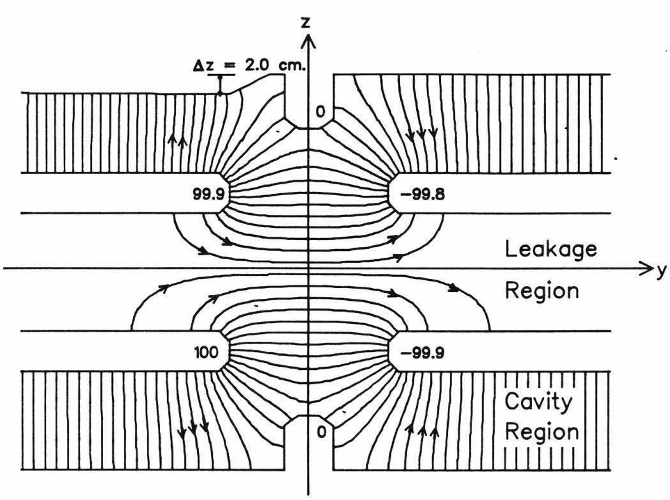

Fig. 1. A cross section of the TRIUMF resonant cavity at the dee gap region.

strongback in regions of high circulating surface rf current. To achieve the same result in the cyclotron would however require similar but very expensive and time-consuming changes in the hot arm structure.

In the search for other methods of reducing the leakage, 1:10 model studies and machine measurements have shown that, at the operating frequency of 23 MHz, the rf energy in the resonator is coupled into the beam cavity through the dee gap, and the amplitude of the leakage depends on the difference between the top and bottom dee tip voltages. This difference is due to the sagging of the resonator strongbacks and to the misalignments in individual strongbacks. By purposely misaligning certain resonator segments we can introduce further asymmetry in the dee gap voltage profile. This additional asymmetry can creat an extra leakage field which can be used to cancel the original field due to sagging.

Theory

Let the beam cavity be represented by a volume V, enclosed by the surface S. Assume that the surfaces on S are lossless and the boundary conditions on S are well defined. Under these conditions the electromagnetic fields inside V can be expressed in terms of the natural frequencies of the cavity

$$\vec{E} = \sum_i A_i \tilde{E}_i \ ,$$
$$\vec{H} = \sum_i B_i \tilde{H}_i \ , \qquad (1)$$

where $\tilde{E}_i$ and $\tilde{H}_i$ are the two sets of orthonormal eigenvectors corresponding to the i^{th} eigenfrequency.

Now assume that the cavity is being excited by a current density $\vec{J}(\vec{r})$. Using Maxwell's equations and the orthonormal properties of the eigenvectors to solve for A_i and B_i:

$$\vec{E} = \sum_i \frac{j\omega\tilde{E}_i}{\omega^2-\omega_i^2} \iiint \vec{J}\cdot\tilde{E}_i \, dV \ ,$$
$$\vec{H} = \sum_i \frac{j\omega\tilde{H}_i}{\omega^2-\omega_i^2} \iiint \vec{J}\cdot\tilde{E}_i \, dV \ . \qquad (2)$$

For capacitative coupling,

$$\vec{J} = j\omega\varepsilon \vec{E}_d, \qquad (3)$$

where $\vec{E}_d$ is the electric field across the coupling capacitor, which in the case of TRIUMF is located at the dee gap as shown in Fig. 1. For the particular case of the TRIUMF beam cavity, the operating frequency of the rf system is 23 MHz, whereas the modes that are relevant in Eq. (2) are the TM_{310} and the TM_{410} modes at frequencies of 22 MHz and 24MHz, respectively:

$$\omega = 23 \times 10^6 \times 2\pi \ s^{-1} \ ,$$
$$\omega_3 = 22 \times 10^6 \times 2\pi \ s^{-1} \ ,$$
$$\omega_4 = 24 \times 10^6 \times 2\pi \ s^{-1} \ . \qquad (4)$$

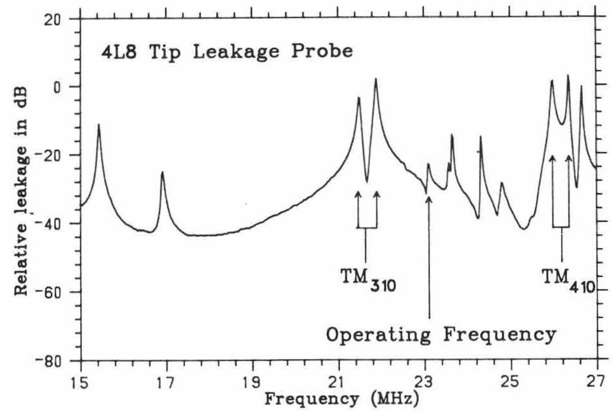

Fig. 2(a). Frequency scan of the machine measured by a voltage probe located on the hot arm.

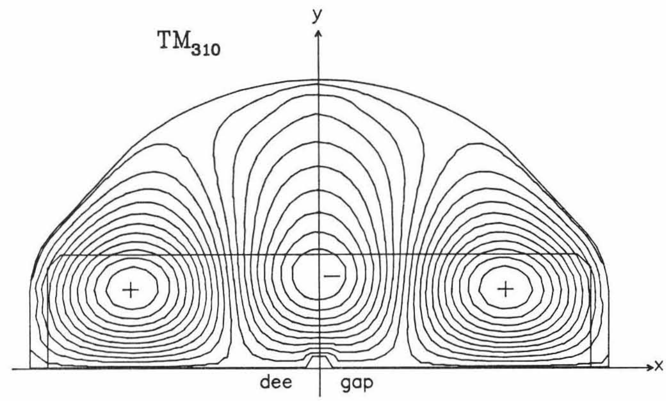

Fig. 2(b). Voltage contour of the TM_{310} mode from SUPERFISH.

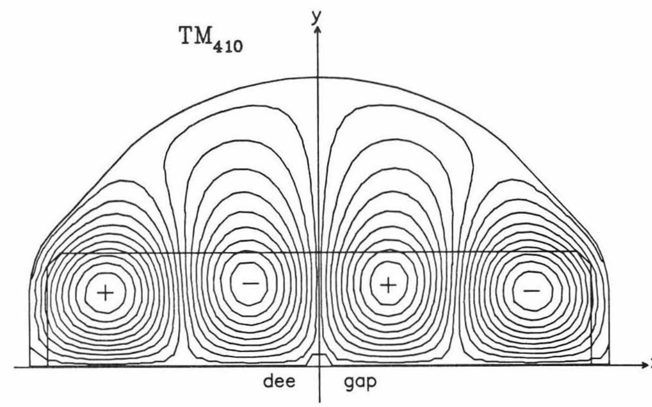

Fig. 2(c). Voltage contour of the TM_{410} mode from SUPERFISH.

Figure 2 shows the frequency response of the beam cavity, indicating the locations of the TM_{310} and the TM_{410} modes. Only the z-component of the electric field is non-zero in the two parasitic modes. Equipotential lines of these modes as calculated by SUPERFISH[3] are shown in the figure. Note that the TM_{310} mode is symmetric while the TM_{410} mode is antisymmetric about x=0. Expressing the electromagnetic field in the beam cavity as a linear combination of these two spatial modes when the cavity is excited at 23 MHz, one gets

$$\vec{E}(x,y) = \sum_{i=3,4} \left[\iiint \vec{E}_d(x',y',z') \cdot \tilde{E}_i(x',y') dx'dy'dz' \right] \times \left[- \frac{\omega^2 \tilde{E}_i(x,y)\varepsilon}{\omega^2 - \omega_i^2} \right] . \quad (5)$$

In order to calculate the response of the cavity to misalignment in the dee gap, we assume that the only sources for the beam cavity is the upper and lower electric fields at the dee gap (y = 0). It should be noted that the coupling between the upper/lower resonator to the beam cavity is quite strong, of the order of -3 dB. However, these fields are opposite in direction, and therefore the net field is due to the difference in voltage between the top half and the bottom half of the resonant cavity (Fig. 1). Let the upper dee gap voltage be V_u, the lower dee gap voltage be V_ℓ and the vertical distance between the two gap be h, then Eq. (5) reduces to

$$\vec{E}(x,y) = - \frac{\omega^2 \tilde{E}_i(x,y)\varepsilon}{(\omega^2 - \omega_i^2)h} \int_{y=0} \left[V_u(x') - V_\ell(x') \right] \left| \tilde{E}_i(x',y') \right| dx' \quad (6)$$

The coupling now appears much weaker due to the cancellation between the upper and the lower resonators. The leakage is suppressed when the integral at the right hand side of Eq. (6) is zero, when the contribution from every point in the source results in overall destructive interference. This occurs when all the resonator segments are perfectly aligned. In this case, $V_u = V_\ell$ independent of x. Practically, the local misalignments in the resonator segments and the global misalignment due to sagging causes a difference between V_u and V_ℓ.

To understand the dependence of the dee gap voltage on the alignment, we shall consider each segment as an individual resonator, which are inductively coupled together to form a dee. The tip loading capacitance in a particular segment is increased if its misalignment reduces the distance between the hot arm and the ground arm at the dee gap tip. As a result the operating frequency is higher than the natural frequency of the misaligned segment, causing it to behave like a shunt capacitance. Since the segments are coupled together through transverse series inductance, the presence of this shunt capacitance will raise the tip-to-ground voltage of the misaligned segment with respect to the rest of the segments. The reverse is true for any resonator segment that has the hot arm tip displaced away from the ground arm. For uniform sagging $V_\ell > V_u$ due to sagging of the hot arm, and the integral for i=3 is non-zero while it is zero for i=4. Since the coupling from the upper/lower resonator into the beam gap is quite strong, a small misalignment will produce a measurable amount of leakage. As a result 2-d SUPERFISH calculations showed that the leakage field is of the order of -40 dB with respect to the dee gap electric field when the resonator tips are sagged by 5%, although the difference between the upper and lower resonator voltages is small.

However, given a certain misalignment, one can manipulate both V_u and V_ℓ by purposely adjusting the distance between the hot arm and the ground arm in order to reduce the value of the integral. Since the contribution to the integral of the two side-lobes of the TM_{310} mode is larger than the contribution from the centre lobe, which has the opposite phase, the integral is non-zero for this mode. If one can reduce the dee gap voltage difference simultaneously at both the side lobes, then the TM_{310} mode can be reduced without affecting the TM_{410} mode.

Measurements

The above strategy was tried on the model and on the machine. The initial alignment on the model hot arm was set to correspond to a 5% sag, which is the amount

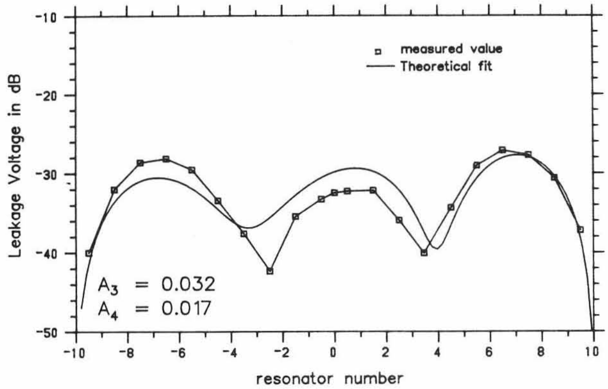

Fig. 3. Leakage voltage measured behind the root in the tenth scale model. All the hot arms have 5% sag to simulate the misalignment in the machine.

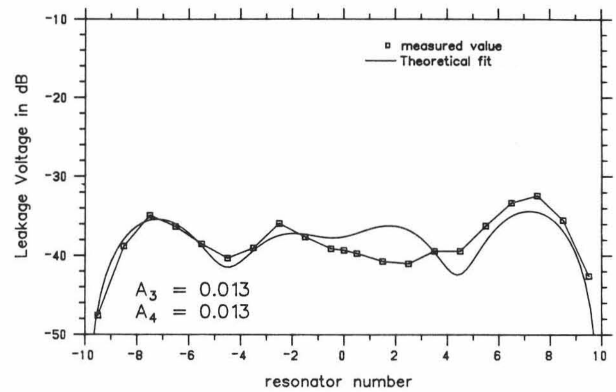

Fig. 5. Leakage voltage measured from the tenth scale model after the hot arms have been adjusted to cancel out the TM_{310} mode.

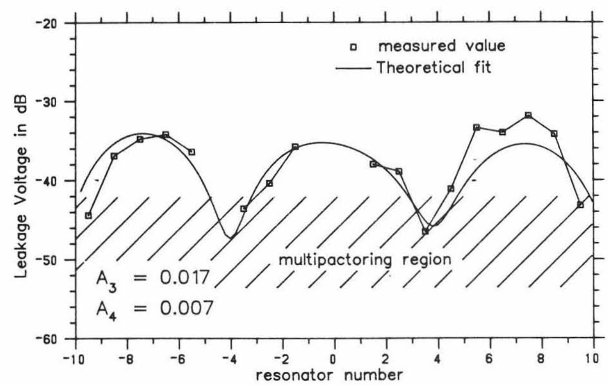

Fig. 4. Leakage voltage in the machine under normal operating conditions. These are measured by a series of voltage probes located in the hot arm.

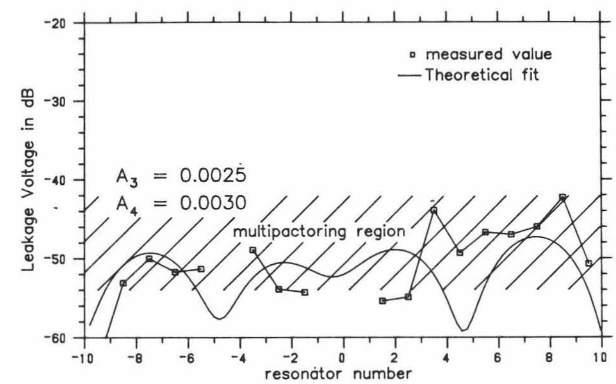

Fig. 6. Leakage voltage in the machine after the ground arms have been adjusted to minimize the leakage.

we feel that best represents the amount of hot arm sag in the machine. The voltage at the lower dee gap is thus higher than the voltage at the upper dee gap. The leakage voltage measured behind the root for the model is shown in Fig. 3, together with a theoretical fit based on Eq. (1). The coefficients A_3 and A_4 are obtained using the function minimization routine MINUIT.[4] The measured leakage voltages are expressed in dB, referenced to the dee gap voltage at the centre. Similar results for the machine are shown in Fig. 4. This result is measured using pick-up probes located at the mid-point of the strongback. Note that the leakage is not symmetric with respect to the centre, due to the combination of the TM_{310} mode and the TM_{410} mode. Comparison of the coefficients A_3 = 0.026 and A_4 = 0.013 with Eq. (5) also indicates that since the voltage source at the dee gap is uniform due to the uniform sagging, the symmetric TM_{310} mode is strongly excited. The amplitude of the antisymmetric TM_{410} mode is much weaker but still non-zero because of residual asymmetry in the geometry and misalignment of the cavity. Another important observation is that both of these modes have voltage maxima at around resonator segments 7 and 8, which is about 2.4 m from the centre. For the TM_{310} mode these two maxima are in phase while the centre maximum is 180° out of phase. For TM_{410} mode these two maxima are 180° out of phase with respect to each other. Equation (6) shows that the amplitude of the leakage is most sensitive to misalignment at these locations. When the distance between the hot arm and the ground arm at resonator segments 7 and 8 on both sides of the centre for the upper dees is reduced, it has the effect of reducing the driving term at the two outer maxima for the TM_{310} mode, while maintaining the same strength for the centre maximum, which is, however, 180° out of phase. By reducing the hot arm to ground arm distance for segments 7 and 8 on the upper dee by the same amount on each side of the dee, the driving term at the two outer maxima for the TM_{310} mode is reduced, while maintaining the same strength for the centre maximum. As a consequence the integral in Eq. (6) is reduced. This change has little effect on the TM_{410} mode since the two maxima in which the adjustments occur are 180° out of phase. If one adjusts the resonator segments at the two sides antisymmetrically, then the residual amplitude present in the TM_{410} mode can also be tuned out. The result of these changes is shown in Fig. 5 for the model. For the machine the strongbacks are not readily accessible for adjustment and adjustments were made at the ground arm. The result is shown in Fig. 6. Note that in both cases the significant reduction in the strength of the TM_{310} mode as well as on the overall amplitude of the leakage field. For the machine a factor of 6 reduction in voltage (-16.7 dB) was obtained for the TM_{310} mode while the TM_{410} component was reduced by a factor of 2.

Multipactoring

Theoretical calculations show that Joule heating due to circulating rf leakage currents is only of the order of several watts per segment, while the heat load on one of the strongbacks in TRIUMF has been measured by the temperatures of the cooling water to be as high as 1 kW.

As described in the theory section, since the net coupling between the beam cavity and the rf resonator is very weak, multipactoring can occur in the beam cavity without electrically loading down the rf resonator. When multipactoring occurs in the beam gap, however, the resultant electron bombardment produces a much higher thermal load on the strongback, which can exceed by many orders of magnitude the ohmic heating by rf circulating current as confirmed by measurements of the strongback temperatures.

Calculations showed that first order multipactoring in the beam gap occurs when the leakage voltage is between 170 to 680 V.[5,6] Under ordinary operating conditions at a dee voltage of 86 KV, multipactoring occurs when the leakage voltage in the beam gap is between -42 to -54 dB of the dee voltage. As can be seen in Fig. 4, most of the resonator segments have leakage voltages above the multipactoring range. Only a few segments in the voltage minima region (segments 3, 4, 5, 9 and 10) have leakage voltages within the multipactoring range and high strongback temperatures are observed in these segments. Those that are water-cooled are able to remove the imposed heat load with no adverse effect. For the strongbacks that are not cooled by external means intense multipactoring can cause the strongback structure to overheat. In order to prevent this from happening thermocouples are installed in most strongbacks to monitor their temperatures, and automatic rf shutdown is initiated when the temperatures indicated by the thermocouples are above a pre-set trip point.

When the rf leakage is reduced in the machine by adjusting the alignments of the ground arms, the overall leakage level is reduced by 10 dB as described before. However, after several hours of operation under this reduced leakage condition we observed substantial temperature rise in most of the strongbacks. For the safety of the machine the ground arms were returned to the alignment with the higher leakage voltage but lower strongback temperature. Due to the reduced voltages unfortunately a large portion of the cavity now has leakage voltages which are within the multipactoring range according to Fig. 6, resulting in substantial heating of a number of strongbacks. Under these conditions, in order to improve the reliability of the cyclotron, rather than adjusting the resonator alignments for minimum leakage, the preferred strategy is to achieve a tune such that the region of multipactoring occurs at region in which the heat can be removed effectively, i.e. the water-cooled resonator segments. At the present time these water-cooled segments are located in segment number 4 in all the quadrants. The curved shapes of the TM_{310} mode show that the regions of multipactoring can be moved to these points when the TM_{410} mode is suppressed. Since the strength of this mode is already quite weak, which is excited only by the residual asymmetry in the dee gap, it can be easily nulled out. Efforts are being made to apply this strategy to the cyclotron.

Conclusion

We have presented a very simple and effective way of suppressing the rf leakage into the beam gap by tuning the resonator alignment to achieve destructive interference. Power reduction of the order of 10 dB was observed in the model as well as in the machine. Unfortunately this also puts a larger region of the strongback to within the multipactoring ranges, and substantial heating was observed in this region. However, the resonator segments can be tuned in such a way that multipactoring only occurs at specific locations, in which the heat generated can be removed by cooling water. Eventually, when enough segments are installed in the cyclotron to handle this load the cavity will be tuned for mininum leakage, thereby reducing rf pickup and noise on beam pickup probes.

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