Introduction

The resonator of the TRIUMF cyclotron, which is totally enclosed in the vacuum chamber, has been previously described and is shown schematically in Fig. 1 of Reference 1. The RF cavity is filled electrically through the dee gap to the remaining volume of the tank, here defined as the beam cavity. When the top and bottom halves of the RF cavity are not aligned symmetrically, a voltage difference will appear across the beam cavity in the region near the dee gap. This voltage then acts as an RF source, radiating energy into the rest of the beam cavity. The amount of RF power leaking into this cavity from the dee gap depends on the geometry of the vacuum tank, as well as on the other components inside the tank. A sufficiently high RF field inside the cavity can cause undesirable heating of the structures and diagnostic equipment. The heating of the structures and beam diagnostic equipment depends on the voltage distribution along the dee gap, as well as on the frequencies and the field patterns of the parasitic modes. These parameters are quite sensitive to the geometries and imperfections of the centre post, the flux guides on the cantilevered hot arms. Adjustments of these geometries have achieved a significant reduction in the RF leakage in the model.

The Frequencies of the Parasitic Modes

It was reported1 that the TM310 modes of the beam cavity can be shifted upward in frequency and away from the operating frequency by covering the slots between the resonator segments with proper RF contacts. When 6 of these slots were covered with metal in the 1:10 model the natural frequency of the TM310 mode was increased from 215 MHz to 257 MHz, and a reduction of 15 dB in leakage was achieved. However, when the same experiment was performed in the TRIUMF cyclotron, the frequency shift was less than 2 MHz and the TM310 frequency was only .06 MHz from the operating frequency, causing the leakage to increase instead. The result of this behaviour is attributed to the high circuital inductance in the walls of beam cavity. In the cyclotron each segment of the hot arm is composed of an aluminum strongback on the beam cavity side, supporting a copper panel on the RF cavity side. The aluminum strongbacks provide the surface for the circulating current of the beam cavity parasitic modes. However, since proper RF contacts between cyclotron segments could be obtained only through adjacent RF panels, the circulating current must cross the slots between the resonator segments via these panels, which are attached to the strongbacks only through a few mechanical anchorage points. Further restriction to the current path occurs because of the weight relieving holes in the strongback surface, forcing the current to detour and follow a conductive path. These effects result in a much larger circuital inductance than anticipated in the model.

After all the segments in the model were replaced with the correct modelling of the strongback and RF panels, the leakage field pattern was found to be a linear combination of the patterns of the TM310 mode and the TM310 modes, since the natural frequencies of these two modes are closest to the frequency of excitation. Fig. 1(a) shows this pattern measured behind the resonator root structure with a misalignment of 250 ¡­m on the hot arm tips. Because of the influence of the TM110 mode on the predominant TM310 mode, the...
leakage pattern is lopsided. In the left hand side the two modes are out of phase, resulting in a lower leakage of -35 dB, whereas in the right hand side they are in phase, resulting in a higher leakage of -32 dB.

In the upgraded model, with all intersegment slots covered in the same way as in the cyclotron the frequencies of the TM_{310} modes were moved from 210 and 214 MHz to 242 and 248 MHz. The operating frequency (227 MHz) is now between the frequencies of the TM_{310}, TM_{210} and the TM_{110} modes. The even TM_{210} modes are strongly attenuated, as described in the next section, and the resultant leakage field is mostly a combination of the pattern of TM_{310} and the TM_{110} modes as shown in Fig. 1(b). Since the RF cavity operates in the push-pull mode for beam acceleration, the leakage parasitic modes are also push-pull across the dee gap. The central maximum is due to both the two modes, while the two side lobes are primarily due to the TM_{210} mode alone. With the above TM_{310} mode shifted from the operating frequency, a reduction in leakage of 8 dB was observed at the two side lobes. Further improvement can be expected for a better aligned cavity.

The Mechanisms of Coupling

Two dimensional SUPERFISH calculations were used to calculate the behavior of a 2-d RF cavity and a 2-d beam cavity coupled at the dee gap. The calculated leakage amplitude for various amounts of tip misalignment as a function of the length of the beam cavity is shown in Fig. 2. The results showed that the leakage increases with misalignment. The maximum leakage for a given misalignment occurs when the length of the beam cavity is slightly less than 3/4 the wavelength of the excitation source. Since the driving point impedance $Z$ of a short circuited transmission line of length $L$ with attenuation constant $a$ and phase constant $k$ is given by

$$Z_L = Z_0 \frac{\sinh 2aL + j\sin 2kL}{\cosh 2aL + j\cos 2kL}$$

where $Z_0$ is the characteristic impedance of the line. The impedance into the beam cavity when the leakage is maximum is composed of a high resistive component and a small inductive component. As the maximum power transfer occurs when the source impedance is equal to the complex conjugate of the load impedance, this implies that the source impedance consists of a high resistive component and a negligible capacitive component that is to be expected since the coupling between the two cavities is primarily due to the difference between top and bottom electric field. In order to reduce the amount of leakage the driving point impedance of the beam cavity should be reduced. The impedance is minimum when the length of the beam cavity is equal to one half the wavelength of the excitation, and Eq. 1 reduces to

$$Z_L = Z_0 e^{-\alpha L} \quad \text{for } L = \frac{\lambda}{2}$$

which means that the driving point impedance, and hence the leakage, can be reduced by choosing the length of the beam cavity to be multiples of one half the wavelength of the excitation; and by using materials of higher electrical conductivity in the beam cavity.

In the three dimensional case, the impedance of the beam cavity varies along the dee gap, and in addition it also depends on the different modes that are present in the beam cavity. Furthermore, the frequencies and Q of these modes are modified by the intersegmental segment slots. These modes are usually of a higher order than the operating mode of the RF cavity, due to the larger volume and the additional inductance presented by the intersegment slots and the strongback-RF panel structure of the beam cavity. This results in the large variation of the beam cavity impedance along the dee gap.

This three dimensional problem can be studied using the quasi-3-dimensional code RP3D. The code treats the 4 hot-arms of the TRUMP RF structure as the 4 values of a RF cavity, and calculates the voltage behaviour along the vane segments (dee gaps) in function of the geometry of the cavity. In RP3D, which is not a true three-dimensional code, regions in the cavity are simulated using distributed inductances and capacitances. When applied to the TRUMP cavity, important features such as flux guides, centre post, the varying length as well as the non-zero boundary condition of the beam cavity can be taken into account by varying the local values of inductances and capacitances. The extra inductance due to the beam side panel structure is simulated by increasing the series inductances along the dee gap. However, since the code is not designed to handle coupled cavities which have completely different characteristics as it is the case with the RF cavity and the beam cavity, in particular the series inductances along the dee gap, the results obtained should only be treated qualitatively.

Since the beam cavity resonates at a different frequency than the operating frequency of the cyclotron, its response is composed of linear combinations of several of its normal modes. The amplitudes of each of these modes depend on the natural frequency of the mode, the frequency of excitation, the source impedance, the impedance of the beam cavity and the voltage profile of the exciting source. An important observation is that since the RF voltage developed at the dee gap is symmetric about the centre post, modes of even azimuthal numbers such as the TM_{210} and the TM_{410} modes which are anti-symmetrical about the centre post are only weakly excited. Imperfections in the RF structure prevent the RF dee gap voltage from being completely symmetrical and since the higher modes are more sensitive to these imperfections due to the shorter wavelength, the TM_{410} mode is more strongly excited than the TM_{210} mode. The most dominant mode is the TM_{110} mode, since it is only 1.3 MHz away from the operating frequency. The electric field of this particular mode has a positive lobe at the centre, and has two negative lobes at both sides as shown in Fig. 3(a). Since the voltages along the dee gap are of constant phase, it can be seen that whereas the excitation source is in phase with the TM_{110} mode in the outer segments (1-4), it is out of phase in the central ones (1-4). However, since the side lobes
have a larger total area than the centre lobe this destructive interference effect is only partially effective.

It should be pointed out that there is an important difference between the above TM310 mode and a normal TM3,10 mode found in a cylindrical cavity, namely that the boundary conditions of a normal cavity mode is well defined by the metal wall, in which the transverse electric field is zero. In the beam cavity, the boundary is not well defined at the dee gap and the flux guides. In general, the electric fields are not zero in these regions but have a small residual value. This is shown in Fig. 3(b) where the electric field in the beam cavity of a quadrant of the TRIUMF cyclotron is mapped. As this residual boundary electric field depends on the profile of the voltage along the dee gap and is instrumental in the coupling of energy from the RF cavity to the beam cavity, it is expected that the effective power coupled can be changed by changing the profile of the voltage.

Reduction of RF leakage by dee gap voltage profile

RFQ3D calculations showed that the voltage profile along the dee gap can be altered by changing the values of capacitances and inductances at the flux guides. A lower inductance and/or capacitance at the flux guides produces a dee gap voltage profile with lower voltages toward the outside resonator segments. The calculations further showed that the power coupled into the beam cavity is reduced when the non-uniformity of the dee gap voltage is increased, due to the destructive interference in the excitation of the TM3,10 mode. The reduction in leakage is of the order of a few dB. Further increases in non-uniformity will cause the leakage to increase again.

The 1:10 model was used to study this effect quantitatively. The flux guide inductance and capacitance were changed by placing movable metal straps between the grounded side and the hot side of the flux guides. The dee gap voltage profile was changed from an almost uniform voltage when the straps were absent to about 10 dB lower at the ends by locating the straps 23 cm from the root structure. Since the leakage pattern changes when the intersegment slots are covered is a combination of the TM3,10 and the TM3,10 modes, the influence of the voltage profile on these two modes can be studied by measuring the leakage at different locations. The results are plotted in Fig. 4. The figure shows that the non-uniformity in the dee gap voltage has almost no effect on the TM3,10 mode since the coupling between the two cavities for this mode occurs mainly at the centre, and is not being affected by variation in the electric field at the ends. The behavior of the TM3,10 mode is in agreement with that predicted by RFQ3D. The leakage is very sensitive to the voltage profile near the point of minimum coupling, and a 3.5 dB reduction in the leakage is observed when the dee gap voltage has a non-uniformity of 2 dB.

Fig. 4. Model measurement showing reduction in leakage due to TM3,10 mode and TM3,10 mode as functions of two dee gap voltage non-uniformity.

Conclusion

We have described three methods in which the leakage in the beam cavity can be reduced. The first and the most effective one is the reduction of the strength of the source through better alignment of the RF cavity. An improvement of 9 dB in the model when an artificial misalignment of 250 μm (2.5 mm in the cyclotron) is removed. The second most effective method is to reduce the coupling between the beam cavity and the RF cavity by reducing the driving point impedance of the beam cavity. This can be achieved in two ways. The impedance of the cavity can be reduced by using materials of higher conductivities, and by relocating the frequencies of the beam cavity parasitic modes away from the operating frequency. An improvement of 8 dB was obtained in the model. The third method involves shaping the dee gap voltage profile to provide destructive interference for leakage suppression. An improvement of 3.5 dB is obtained in the model.

References