DETERMINATION OF THE RF LEAKAGE FIELD IN THE VACUUM TANK OF THE TRIUMF CYCLOTRON

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Summary

In the TRIUMF cyclotron the dees are partially defined by the two halves of the quasi-circular vacuum chamber, which completely contains the 1 MW resonating cavity. A stray electric field or "RF leakage" exists inside the dees and has occasionally caused problems to probes or other tank equipment. In order to understand the nature of this field a precise 1:10 scale metal model of the entire tank and resonator system has been built and is being investigated. Various resonances have been identified: the push-pull mode at 226 MHz and the push-push mode at 233 MHz; cross modes along the dee gap resonate at 243 MHz and 253 MHz. In the quasicircular tank region outside of the main resonating cavity the TM_{310} and TM_{410} modes are mainly responsible for the configuration of the leakage field since they are closer to the operating frequency. The measurements are in reasonable agreement with the results of numerical relaxation calculation and with measurements in the cyclotron tank.

Introduction

Due to the large size of the TRIUMF cyclotron the resonating cavity is unique and is completely contained within the 16 m diameter, 50 cm high quasi-circular vacuum tank (see layout in Fig. 1). Typically 1 MW of RF power at the fundamental frequency (23 MHz) is injected into the quarter wave length structure, with a Q value of ~ 5000 , producing 80 to 100 kV along the dee gap with a stability of $\sim 2 \cdot 10^{-4}$ in voltage and $\sim 10^{-7}$ in frequency.^{1 2} Beam currents of more than 100 μA are normally accelerated to 500 MeV with overall cyclotron reliability levels greater than 80%.³

However, eight years of operating experience have pointed out that the system is extremely sensitive to resonator alignment, largely because of the RF leakage field which can be excited in the tank volume outside the resonating cavity by vertical asymmetries at the dee gap.⁴ Tight monitoring and alignment procedures are now implemented in order to minimize damage, distortion or sagging of the resonators and malfunctioning of diagnostic equipment. At the same time an improved, more stable mechanical resonator structure is being developed and means of reducing the coupling of the RF field into the beam volume are being investigated with a 1:10 scale model and through numerical relaxation calculations.

Fig. 1. Sketch of model showing measurement points.

The Model Measurements and Computer Calculations

An aluminum model of the entire tank-resonator system (Fig. 1) was built in scale 1:10 with an accuracy of ~ 0.3 mm similar to the accuracy of ~ 3 mm realized in the cyclotron tank. The RF energy is coupled into the resonator through a loop positioned near the root of resonator 3 lower quadrant III. Holes are drilled in the model to allow the introduction of a special high impedance, 5 mm diameter probe for voltage measurement. A network analyzer was used to excite the resonator and to measure the frequency response.

Initially the resonators were approximated by solid sheets of aluminum. A 0.4 mm deflection was introduced to simulate some sagging of the resonators. The frequency response measured inside the resonant cavity is shown in Fig. 2. The operating frequency at 226 MHz corresponds to the push-pull TM_{100} mode of the resonator. The push-push TM_{100} mode is at 233 MHz and the two other peaks at 243 MHz and 253 MHz correspond to the push-pull and the push-push TM_{110} cross modes, respectively.

The frequency response measured in the tank volume behind the resonator is shown in Fig. 3(a), curve 1. Measurements of the field configurations throughout the 3rd and 4th quadrant permitted identification of the various modes indicated in the figure. For each mode the push-push and push-pull components can be identified. At the operating frequency the leakage is influenced mostly by the combination of the neighbouring TM_{210} and TM_{310} modes and the distribution measured along the holes of row A in Fig. 1. is shown in Fig. 3(b), curve 1. The amount of RF leakage as a function of the amount of misalignment of the resonators is shown in Fig. 4. A comparison with the result of a 2-dimensional SUPERFISH⁵ calculation is also given in the figure.

Introducing a series of slots to simulate the gaps between the 80 individual resonators inside the cyclotron modified the frequency response of the leakage in the tank and its distribution at the operating frequency as shown in Fig. 3(a) and (b), curve 2. The slots cause an inhomogeneous increase in the distributed

Fig. 2. Frequency response at the dee gap using solid panels.

Fig. 3. (a) Frequency response of RF leakage in tank behind resonator #8 with a 4% displacement from the aligned position. (b) Fundamental leakage in tank behind resonators along row A (see Fig. 1). (1) solid panels, (2) slotted panels, (3) same as (2) but slots shorted between resonators 3/4, 4/5, 5/6, 9/10.

Fig. 4. Effect of misalignment on leakage. The results of a calculation with program SUPERFISH are given for comparison.

inductance of the tank. This lowers the frequencies of the TM₃₁₀ modes so that they now lie slightly below the operating frequency, affecting the configuration of the leakage at the operating frequency. Using a crude wire probe it was found that the voltage in the beam region between the resonators was approximately 10 db higher than that in the tank behind the resonators and exhibited the expected TM₃₁₀ mode behaviour.

The 2-dimensional SUPERFISH can be used to calculate the field in a pillbox type vacuum tank configuration. In order to take into account the higher distributed capacitance in the narrow gap between the resonators a higher dielectric constant was assumed for this region. The agreement between the numerical result and the measurement is shown in Fig. 5(a) and (b) for the TM₃₁₀ mode. Similar agreement was found for the other modes and the correspondence between the calculated and the measured frequencies was satisfactory.

Reduction of RF leakage

Several methods to reduce the RF leakage in the beam gap have been investigated. The obvious way is improving the vertical symmetry of the resonator panels. This has been done operationally on the present resonators by improving the optical alignment procedure and by aligning the resonators under RF loading. Installation of the new resonators will allow a significant improvement in this direction. In addition, techniques aiming at the absorption of leakage power either with lossy material or with coupling into a dummy load are being investigated on the model. So far these techniques have not been found to be very effective in the reduction of the RF leakage (the most effective place to put absorbing material is in the beam gap where the fields are strongest). However, the amount of material that can be put into the beam gap in the cyclotron is severely constrained by beam clearance requirements.

An interesting possibility consisting in shifting the frequency of the TM₃₁₀ mode away from the operating frequency was found from the model study. Initially capacitive loading of the tank was attempted. This has been found to lower the resonant frequency of the TM₃₁₀

Fig. 5. Spatial distribution of the TM_{310} mode in quadrants III and IV. (a) SUPERFISH calculations, (b) model measurements, (c) cyclotron measurements.

mode. But this was undesirable since it also shifted down the resonant frequency of the TM_{410} and other higher order modes and increased their influence on the leakage field. It was found more effective instead to raise the resonant frequency of the TM_{310} mode. This is actually what causes the leakage with the solid panel configuration (Fig. 3(a), curve 2) to be 15 db less than the leakage with the slotted panel configuration (Fig. 3(c), curve 2). Intermediate solutions can be realized by shorting out slots between particular segments where the TM_{310} mode produces relatively large surface currents. A frequency response obtained by shorting the slots between resonators 3 and 4, 4 and 5, 5 and 6, and 9 and 10 is shown in Fig. 3(a), curve 3. The corresponding leakage distribution along row A is given in Fig. 3(b), curve 3. With this solution the leakage is reduced by a factor of 2. The non-symmetrical shape of the curve is due to the fact that the leakage is influenced by both the TM_{210} and TM_{310} and their phase relationship.

Measurements on the Cyclotron

In order to gain more confidence in the model measurements, RF leakage and frequency response were measured on the cyclotron RF system using 49 capacitive pick-up probes. A typical distribution of the measured TM_{310} mode is given in Fig. 5(c). Figure 6 shows a frequency response of one of these probes. Comparing this with Fig. 3(a), curve 2 the main discrepancies are

Fig. 6. Frequency response of a leakage probe in the cyclotron.

in the resonant frequency of the TM_{410} mode. The resonant frequency of the mode is higher than predicted by the model. One factor that accounts for this is that in the cyclotron RF system the slots between resonators 1 and 1, 1 and 2, and 2 and 3 are shorted. Model measurements show that this would increase the frequency of the TM_{410} mode.

The maximum RF leakage values in the beam gap and tank were found to be 27 db and 37 db, respectively. These numbers are in reasonable agreement with model results of 22 db and 32 db achieved with 0.4 mm deflection. This would seem to indicate

- (1) that the ratio of the field in the region between the resonators and the region behind the resonators is about the same in the cyclotron and the model, and
- (2) that the leakage in the cyclotron corresponds to an average misalignment effect of 5 mm.

Having verified the agreement between the measurements in the model and the cyclotron it is hoped that the improvements observed in the model can be realized in the cyclotron. From Fig. 3 we can see that by shorting out the slots between the segments one can achieve an improvement of 6 db. From Fig. 4 it appears that by improving the alignment by a factor of two in average, one can achieve an improvement of another 6 db. The cyclotron leakage level could therefore be reduced from the 30 db range to the 40 db range.

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