TRIUMF RF SYSTEM - INITIAL OPERATING PROBLEMS AND THEIR SOLUTIONS

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Abstract

The TRIUMF RF system was commissioned in December 1974, with the cyclotron coming into operation later the same month. Details of the RF system have been published in previous papers and will only be summarized in this paper which discusses the performance of the RF system over the first eight months of operation. Some problems of resonator frequency drift were encountered as a function of temperature and changes in the cyclotron geometry. RF leakage within the beam gap led to serious sparking and RF pick-up on the beam diagnostic probes. The solution of these and other problems affecting the RF system, and therefore cyclotron availability, are discussed.

Introduction

The design concept and salient features of the TRIUMF RF system have been described before; a complete bibliography is given at the end of this paper.[1-11] A brief description is given here to introduce the discussion of operational problems encountered since cyclotron commissioning.

The major components of the RF system are shown in Fig. 1. The amplifier system has a maximum tested power output of 1.8 MW which is developed by four power amplifiers. A power divider and phasing network is used to adjust the drive power phase and amplitude, and a system of three hybrid combiners is used to bring together the output power of the four amplifiers at a single port. A coaxial transmission line 100 ft in length is used to transmit the RF power from the amplifier system to the cyclotron. The first 60 ft is a 9 in. o.d. matched 50 Ω line and the remaining 40 ft is an 11 in. o.d. 50 Ω line operating with a VSWR of 5 to 6. The standing-wave section of line provides a convenient means of setting up correct matching between the coupling loop and the source. The vacuum feedthrough for the coupling loop is a cylindrical ceramic insulator as used in high voltage vacuum capacitors. The resonators themselves, or dees, are derived from a tuned 1/4 λ line, and with an accelerating gap 53 ft long they are unparalleled in any other cyclotron.

A control system has been developed to allow relatively simple operation of the RF system; problems of multipactoring, resonator frequency changes, RF voltage breakdown and RF voltage disturbances are automatically handled through the use of fixed program logic circuits and feedback control loops.[3,9]

RF System Operational Record

It should be clearly stated at the outset that, despite the problems which have been encountered since the cyclotron came into operation in December 1974, the basic design concepts of the RF system have been vindicated. The somewhat controversial features, viz.:

1) combining the outputs of four power amplifiers,

2) feeding the power to the cyclotron through a 100 ft long transmission line, part of which operates with a high VSWR,

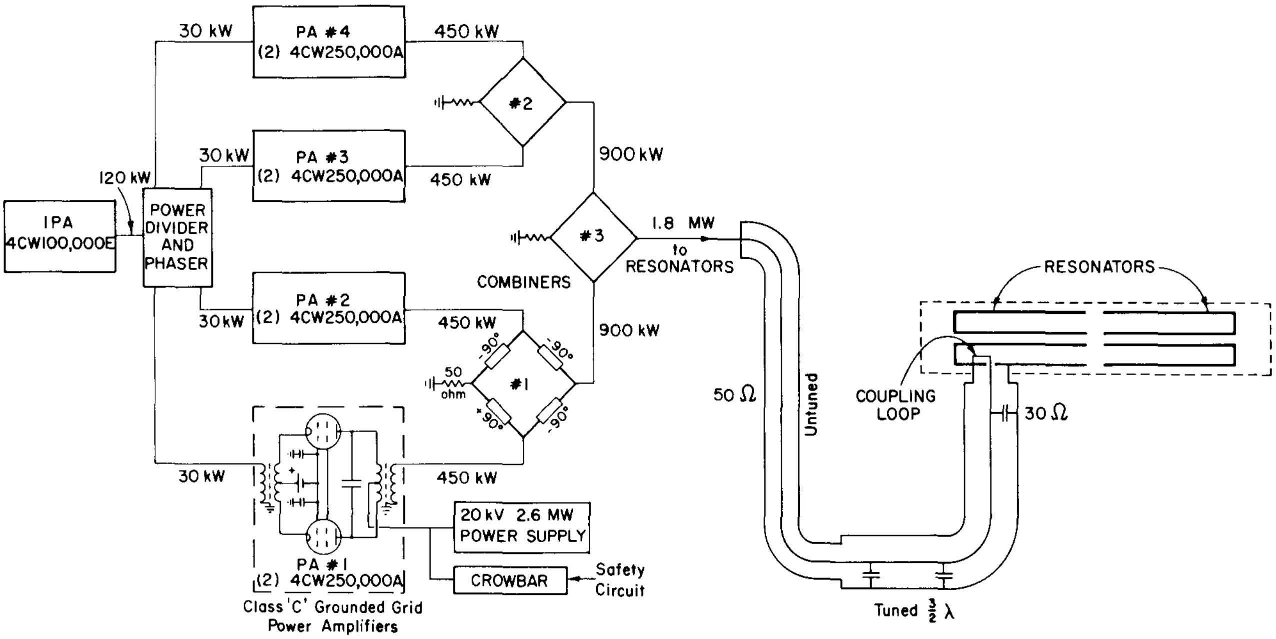

Fig. 1. Block diagram of TRIUMF RF system high-power components.

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3) injecting the power into the push-pull dee system with a single coupling loop in one dee, and relying on capacitive coupling between the two dees to excite the undriven side,
4) segmenting the dee structure,

have all proven themselves.

The difficulties have arisen from the implementation of some of these concepts as well as other hardware problems which might be expected to occur in high-power RF equipment.

Further stresses have been placed on the RF amplifier through the vacuum tank bakeout procedure, in which RF power is used to raise the temperature of the resonator and tank cooling water to 150°F. At the elevated temperature the vacuum pressure is relatively high, leading to severe resonator sparking, while the operating frequency is lower than optimum because of the resonator frequency dependence on temperature. These effects have given rise to RF amplifier failures, but improvements to the system described below allow the bakeout to be performed routinely with reduced stress on the system.

Between December 1974 and August 1975 the RF system has caused 20% of cyclotron down-time.

RF Amplifier Failures

The majority of the amplifier failures were confined to the input circuits of the PA's. Two major modifications were made to remedy this.

1) Adding water cooling to the power amplifier cathode drive d.c. blocking capacitors
2) Improvements to the tube sockets

Some down-time was caused by failure of surge-limiting resistors in the main 20 kV 130 A d.c. power supply. The failures appeared to arise from mechanical fatigue of the nichrome wire resistance element. Subsequent electrolytic dissociation of the cooling water developed sufficient pressure to rupture the PVC water jacket. These resistors will eventually be replaced with commercial air-cooled units.

Two power amplifier cathode current metering shunts have failed in service, causing destructively high voltages to reach the meters and crowbar driver circuits. The cause of this failure has not been determined, but it is suspected that an intermittent filament supply short-circuit to ground has occurred, allowing the filament current of 700 A to flow through the 35 A shunt.

The crowbar has operated over 500 times since powering of the dees began in the fall of 1974, and as a result the crowbar tube has been replaced twice. The purpose of the crowbar is to provide a fast short-circuit on the d.c. power supply should a power amplifier tube arc over internally. The cathode current of each tube is monitored by means of a 0.1 Ω resistor; if the voltage developed across this resistor exceeds 9 V, corresponding to 90 A flowing in the tube, the crowbar is fired, thus removing the plate voltage in 5 µsec and protecting the tube from damage. Recent investigation of the current sensing revealed that, when the tube current rises steeply during pulsing through multipactoring,[9,10] the voltage developed across the sensing resistor exhibits large leading and trailing edge spikes caused by self-inductance of the resistor. It therefore seems likely that many of the crowbar operations were spuriously triggered by this spike. The crowbar circuit has since been modified to prevent false triggering.

Resonator Malfunctions

Problems with the resonant dee structure in the vacuum tank fall into three broad groups:

1) Frequency shifts introduced by ambient temperature changes, dimensional changes in the support structure, reversal of the vault cooling fan, and heating of tie-rods by magnet trim-coil feeders
2) RF leakage into the beam gap and other normally field-free regions causing beam probe malfunction and damage; intolerable resonator frequency shifts caused by moving the beam probes
3) Failure of resonator hardware, viz. burnt-out contacts, interlock wiring and tuning foils; leaking tuning bellows

Frequency Changes

The TRIUMF RF system operates at a fixed frequency of 23.05 MHz, with a required stability of ±7.5 parts in 10^8. The resonator Q is about 5000, giving a bandwidth of 4 kHz. A dynamic tuning system of pneumatically-actuated plungers has a total range of 8 kHz and keeps the resonator tuned to the driving frequency. Any disturbances to the resonator causing its resonant frequency to shift beyond the range of the tuning system must be avoided, but may be compensated to a degree by changing the cooling water temperature or pressure. The following table gives the measured frequency dependence on a number of resonator parameters:

hot arm length	-50 kHz/0.25 in.
hot arm tip to ground arm spacing	250 kHz/0.25 in.
ground arm tip deflection	100 kHz/0.25 in.
cooling water average pressure	-1.4 kHz/lb/in.^{2}
cooling water temperature	-1 kHz/F°

Changes in resonator frequency may be readily observed by operating the RF system in the self-excited mode.[9]

In order to understand the reasons for the changes in resonator frequency which have occurred, it is necessary to consider the overall construction of the cyclotron, particularly the means of supporting the vacuum tank to which the resonators are fastened. Fig. 2 shows a vertical cross-section of the machine. The vacuum tank is supported by a total of 664 tie-rods about 32 in. apart. The bottom tie-rods are fastened to steel-work embedded in the concrete slab vault floor, while those on top are suspended from the support structure which lifts the top half of the magnet and the vacuum tank lid. The distance between the tank lid and bottom is fixed in the centre by the rigid centre post, and at

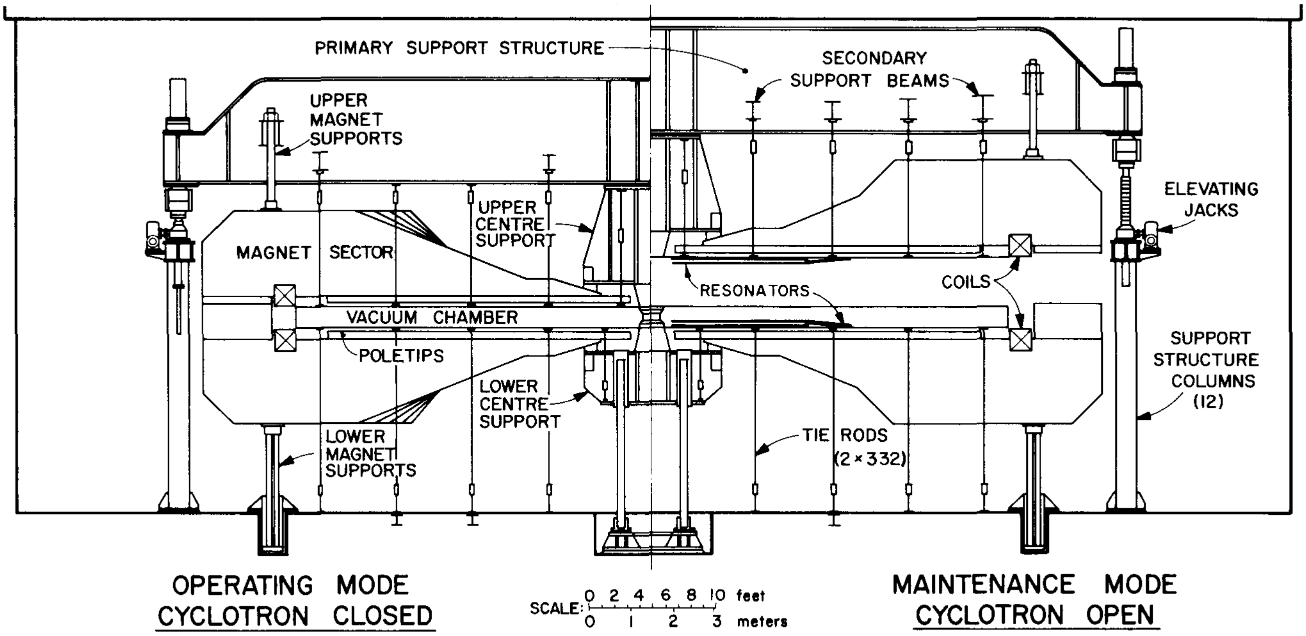

Fig. 2. Cross-sectional view of the cyclotron.

the periphery by the tank wall. Everywhere else the contour of the lid or bottom is affected by the tie-rod length. The lid is further dependent upon the cyclotron support structure. The tie-rods which have the greatest effect on resonator frequency are fastened to the tank at each levelling arm tip and at the root-to-root contacts between segments. The hot arm is cantilevered, pivoting about the root, with the levelling arm used to adjust the hot arm tip position. The effect on the position of a given hot arm tip caused by a change in tie-rod length depends on the particular resonator segment's position with respect to the tank wall and centre post. However, the overall effect is that the resonator frequency decreases with a temperature increase in the cyclotron vault. Fig. 3 shows the resonator cooling water temperature required to maintain a fixed operating frequency of 23.05 MHz from January to April 1975; the same figure also gives the Vancouver air temperature readings over the same period. The discontinuity and increased slope following the March shutdown are attributed to repairs made to the cyclotron support structure following damage by a liquid nitrogen spill, and to reversal of the vault ventilation fan which now brings warmer building air into the vault.

Towards the end of April the cooling water had been reduced to the minimum attainable, so it became impossible to operate the RF system at the correct frequency. During a cyclotron shutdown in May the resonator segments were realigned and adjusted to give 23.05 MHz with the cooling water at 80°F. Since then the correct frequency has always been attainable with small adjustments to either the water temperature or pressure. A pressure adjustment has the advantage of almost immediate response, without the 2 min delay and initial reverse effect which occurs on a temperature change.

The problem of magnet trim-coil feeders heating the tie-rods and thereby affecting the frequency was solved simply by thermally isolating the feeders from the tie-rods.

RF Leakage

RF leakage into the beam gap is the one major RF problem which has yet to be solved with respect to operation of the cyclotron. Although this leakage represents only a small fraction, ∿0.01%, of the power fed into the resonator, and does not appear to degrade RF system performance, significant voltages are built up to cause serious RF pick-up on the beam probes and damage to the probe tracks and cabling.

During the May shutdown an attempt was made to define the leakage in terms of a measurable parameter, to determine its major sources, and to suppress it as much as possible. The leakage was defined in

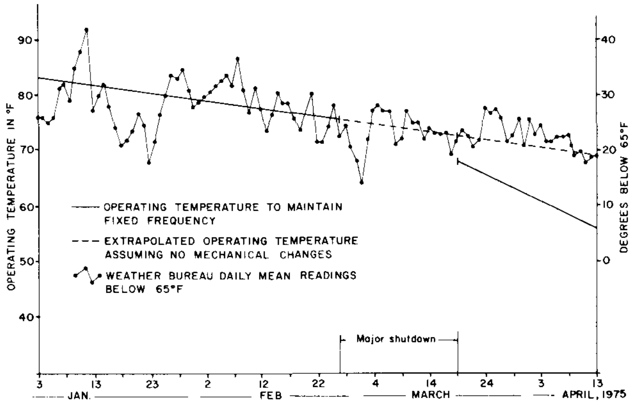

Fig. 3. Resonator operating temperature and air temperature as a function of time.

terms of the voltage developed between the upper and lower levelling arms, since the beam probes were most affected here. Several RF voltage probes were inserted in this region near the centre of the cyclotron, and numerous changes were made to the existing RF shielding and RF grounding inside the tank in an effort to suppress the leakage. Most of the results were negative or inconclusive. The greatest reduction in upper to lower levelling arm voltage was obtained by removing all copper shielding from the gaps between resonator segments, and by providing a reliable RF connection between the vacuum tank lid and side-wall where previously the seal had prevented a good contact around the periphery. Unfortunately the shielding between segments had to be reinstalled in order to prevent localized RF leakage, especially where the probe tracks cross the gap between segments.

Before the May shutdown a frequency drop of ≈10 kHz was observed when the beam probes were moved. After the shutdown the effect was an increase of ≈3 kHz, indicating that the leakage field has been altered by the changes described above.

Further tests are planned for a cyclotron shutdown in August. Thirty-two RF flux-sensitive probes will be permanently installed in the vacuum tank, in the region around the levelling arms and back to the cryo-panels. From these probes it is hoped to obtain directional information about the leakage field, and a second program of leakage suppression will follow.

Resonator Hardware Failure

1) Burning root-to-root contacts in the central region. This appears to be a design problem of the contacts in a position where initially large currents were not expected to flow; the principal resonator current flows longitudinally, root to tip. Tests during development showed that better voltage uniformity along the accelerating gap could be obtained by tying the segment roots together. Normally the finger-stock contacts installed proved more than adequate. However, in the central region it was necessary to shorten the segments at the root by 4 in. in order to improve the third-harmonic Q. The discontinuity thus introduced causes enough lateral current to flow to burn out the contacts if they are not installed properly. The contacts are at present being redesigned.

2) RF overheating of some of the copper-plated stainless steel tuning foils has occurred. Soon after cyclotron operation began, 7 of the 144 foils appeared to be seriously damaged. Subsequent inspection has revealed no further foil failures; it is suspected that the damaged foils were all made from a badly-plated sheet, and hopefully no more will fail.

3) After several months of operation small leaks occurred in two of the 144 pneumatic tuning bellows. As a temporary cure the leaking bellows were pumped out externally, and later were sealed off and opened into the vacuum tank.

4) The centre four resonator segments are latched together, upper to lower, during operation. A set of microswitches indicates the latched or unlatched states to inhibit RF power or the elevating jacks appropriately. At first, solid sheath coaxial cable was used to connect the microswitches to the tank feedthrough, but this overheated, ruptured and short-circuited with stray RF pick-up. Next, radiation crosslinked polyalkene coated wire sleeved in braid was used, with success this time, except when one set of wiring was installed over a gap between resonator segments and was again exposed to a high RF field, causing severe heating and outgassing. Improved installation has removed the latching interlock wiring problem.

Conclusion

Since the resonator realignment and tank lid contact installation in May the RF system has operated reliably apart from some of the amplifier failures reviewed above, with the correct frequency easily obtained. Restricting the use of the low-energy probes has temporarily avoided the RF leakage problem. Continuous operation over five 24-hour days has greatly improved system availability by avoiding the daily start-up and stabilization delays. The planned program of RF leakage surveys and suppression experiments is hoped to remove the one remaining problem with the RF system.

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