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TRIUMF RF SYSTEM

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Introduction

The specifications of the TRIUMF RF system have been covered in previous literature.[1-4] This paper describes the design concepts of the TRIUMF resonator structure and traces its development from models to final installation in the vacuum chamber. The 1.8 MW transmitter and transmission line are described briefly. Problems encountered in testing and commissioning the RF system are discussed, and the paper concludes with a summary of RF system performance over the first two months of cyclotron operation. Details of the RF controls are given in a separate paper presented to this conference.[5]

The Resonator

Design

The resonant accelerating electrodes, or dees, form the heart of the RF system. The basic design concept of the dees arose from three main considerations: their physical size, unparalleled in any other cyclotron; the early decision to eliminate all insulators inside the vacuum chamber; and the axial injection of the ion beam. The addition of third harmonic to the accelerating voltage was also envisaged. The dees are evolved from a section of coaxial transmission line, as shown in Fig. 1. A resonator structure of this size, with an accelerating gap over 53 ft long, would obviously have to be constructed in segments, and naturally models were used in arriving at the final design.

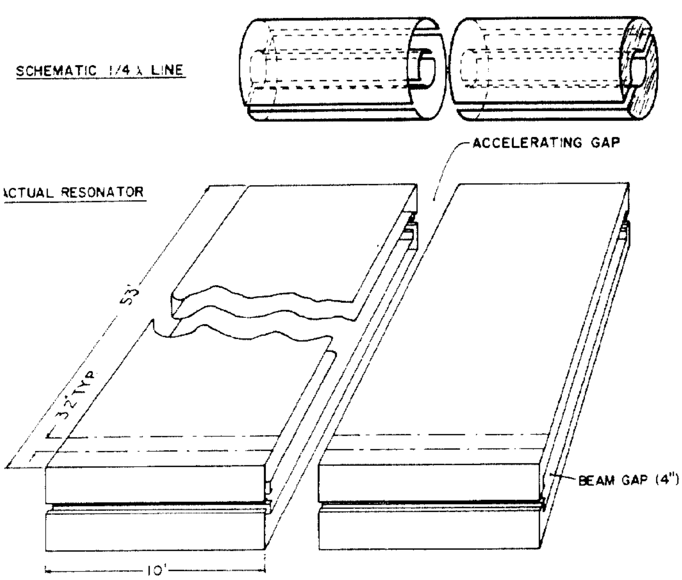

Fig. 1. The TRIUMF resonator is derived from a simple quarter-wave stub.

Results of measurements on the first half-scale copper-sheathed models confirmed the following fundamental assumptions:

a) The upper and lower row of resonator segments are tightly coupled by the RF magnetic flux when flux guides are used.

b) The coupling capacity between the high-voltage hot arm tips, dee-to-dee, is sufficiently high so that only one coupling loop need be used.

c) The geometry at the centre of the dees, tailored in order to accommodate the electrostatic inflector, still allows high quality factors (Q) at both the fundamental and third harmonic frequencies to be achieved with very good voltage profile along the accelerating gap.

d) Two possible ways of tuning the natural frequency of the resonator can be employed: deflecting the segment tips at the high-voltage end, and varying the cavity volume with pockets at the short-circuit end.

Prototype Measurements

The next step in the development of the TRIUMF resonator system involved the central region cyclotron,[6] where full-size resonator segments, fed via the transmission line/coupling loop assembly, were tested under vacuum at the full design voltage of 100 kV. The most significant result of these tests was the verification of all theoretical assumptions and computer programs[7] used for the design of the CRC resonators and later for the main cyclotron. All the basic components were tested, and all the problems of the entire RF system were studied, measured, and understood, including impedance matching, resonator tuning, voltage holding, vacuum performance, and multipactoring (since the dees are grounded no dc bias can be applied). Stability measurements called for an improved mechanical design of the hot arm, and the importance of perfect electrical contacts between the resonator segments at the root was recognized. The tuning elements were tested and improved. The coupling loop assembly and vacuum feedthrough, which contains the only RF insulator exposed to vacuum, were redesigned for water cooling.

Manufacture and Preparation of the Resonator Segments

With all the changes implemented in the design, the contracts for fabricating the resonator segments and the cooling manifolds were awarded to local manufacturers in early 1972, and in the fall of the same year the last tests on the RF system outside the vacuum chamber were started, using only one dee. As a result of these tests only two improvements were necessary. The centre resonator segments had to be shortened by approximately 3% to achieve the maximum Q at the third harmonic frequency. The low mechanical stability of the hot arms caused variations in the resonant frequency of the dee of ± 1.2 kHz, which is prohibitively high for a system with a Q of 6000. As expected, the main stimulus causing the segments to oscillate at their mechanical resonant frequency of 4.7 Hz, mechanical Q = 50, was found to be pressure fluctuations of up to ± 0.5 lbf/in.^{2} in the resonator cooling system. This effect was later suppressed by installing a smoothing tank in the closed system, and reduced further by applying Coulomb dampers[8] at the tips of the resonator hot arms. The remaining vibrations of the resonator segments are of the order of ± 0.001 in., resulting in power fluctuations of about 4%.

Upon completion of the tests each of the 80 segments went through the following procedure:

a) A leak test on the cooling lines

b) Ultrasonic cleaning in a 10% Oakite #33 solution for 10 min

c) Spray rinsing by cold water and hand brushing

d) Spray rinsing by water at 170°F

e) Drying in air at 140°F for 1 h

f) Outgassing at 230°F in a vacuum of $<10^{-4}$ Torr for 6 h

g) Cooling to room temperature at 10^{-5} Torr

h) Final leak testing

i) Sealing into plastic and storing

Resonator Installation in the Vacuum Chamber

The installation of the dees was certainly not a simple task. Each resonator segment is approx 16 ft long, 32 in. wide, 6-1/2 in. high, and weighs 600 lb. Although the hot arm is relatively rigid, its current-carrying 'skin' is only 0.1 in. thick and flexibly attached to the heavy supporting frame. The ground arm is not self supporting, and the whole unit is very fragile and vulnerable. All the components (24 tons of segments and 4 tons of cooling manifolds) had to be lifted and moved into the vacuum chamber through a vertical opening of only 46 in., with many obstructions at the periphery. Special installation equipment was developed and built, and the installation crews were trained in simulated conditions outside the vacuum tank, observing at the same time the strict requirements of high vacuum cleanliness.

During the actual installation three teams of 13 people worked a total of 14 shifts a week for seven weeks, compared with the 42 days scheduled.

A view of the installed resonator array appears in Fig. 2.

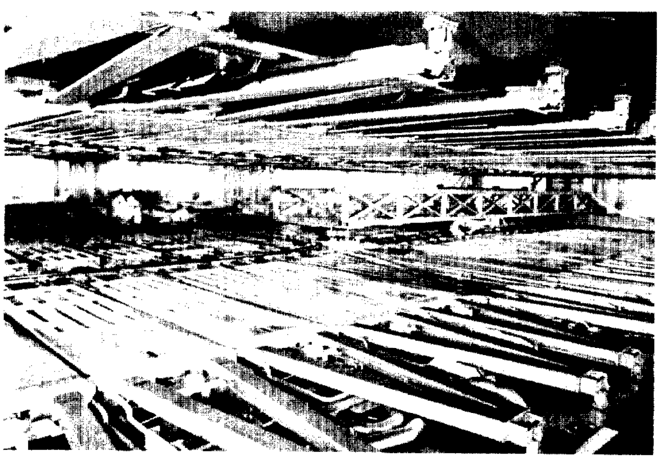

Fig. 2. The resonator structure after installation in the vacuum chamber. The service bridge rests on the centre post and may be rotated to any position around the chamber.

In spite of all the precautions that could be reasonably enforced in an operation of this character and scale (the vacuum chamber was totally enclosed in plastic curtains and pressurized with filtered air; the workers wore white protective clothing with only their faces uncovered), the contamination of the vacuum chamber was much higher than desired. The following cleaning proved useful, but the quantity of organic matter in the tank is still disturbing.

Besides cooling, each segment has a pair of pneumatic lines for actuating the tuning elements located in the shorting bar at the rear. All seals and manifolds were helium tested for leaks, first by pumping on the lines and finally by pressurizing them with helium when the vacuum chamber was evacuated.

The dees were aligned in two steps. Prior to resonator installation the crucial mounting points for all segments were aligned vertically to better than ±0.01 in. The geometry of the accelerator gap was then established within ±0.03 in. or better in the horizontal plane by direct measurements. Since the vacuum chamber deflects significantly under the vacuum load, the vertical alignment had to be done in the following steps: The positions of the hot arm tips (which form the accelerating gap) were optically surveyed, the lid was raised and shims placed. In most cases two iterations were sufficient to achieve a tolerance of ±0.03 in. The upper and lower centre segments are rigidly connected by a latching mechanism to ensure mechanical stability. Special care was given to the central region defining the geometry of the injection gap.

Preliminary Tests

Initial measurements on the resonator-transmission line assembly were carried out in air. At low power levels the standing-wave portion of the transmission line was easily tuned for optimum set-up, and the frequency, quality factor and the tuning range of the system were found to be within expected tolerances.

The complete RF system and controls were then employed to power the dees only to 10 kV in order to avoid any damage by sparking. The main purpose of this operation was to test the system as a whole without the limitations imposed by multipactoring, and to verify that the cooling circuits of the dees, transmission lines and coupling loop, as well as the temperature monitoring on all 80 segments, were working.

During the first measurements in rough vacuum an RF power level of less than 1 W was necessary to keep well below the first multipactoring level. At that stage the dees were adjusted not only to resonate at the nominal frequency but at exactly three times the fundamental, and the respective quality factors were measured. This provision allows the simultaneous injection of the third harmonic frequency without any further modifications inside the vacuum chamber.

The high-power tests on the RF system proved that the control system was working to expectations, and no difficulties were experienced in overcoming the multipactoring regions.

Conditioning of the Dees

Conditioning is the term applied to the process by which the resonators are outgassed; the microstructure of the faces exposed to RF is cleaned in an electric discharge under intensive pumping. The voltage holding of the electrodes under conditioning reaches its design value, often expressed in conjunction with sparking rates.

The results of measurements on the 10-times smaller CRC have shown that the main gasload during the conditioning of the dees consists of water and hydrogen. The latter comes from two sources: from the stainless steel surfaces, abundant in the CRC and TRIUMF, and from water molecules dissociated in the electrical discharge. In TRIUMF the pumping speed for water is very high because cryogenic pumping at 80°K and 20°K is employed. The hydrogen load is handled by an auxiliary pumping system of turbomolecular and titanium-sublimation pumps, representing a pumping speed of approx 10,000 ℓ/sec at 10^{-7} Torr, and approx 1600 ℓ/sec above $\approx 5 \times 10^{-6}$ Torr.

This feature of the vacuum system turned out to put severe limitations on the speed of progress during the conditioning of the dees. It was therefore decided to increase the pumping speed for hydrogen by installing four LN_2 baffled diffusion pumps, originally used on the CRC, thus providing adequate pumping speed over the full pressure range experienced during conditioning. This improvement, and the repair of one serious leak in the resonator cooling system, allowed the conditioning to proceed much as expected.

RF Power Source and Transmission Line

The high-power components of the RF system are shown in Fig. 3. This is a fixed-frequency system, so no tuning of the transmission line or transmitter is required during operation. These devices have sufficient bandwidth to accommodate the full range of resonator frequencies, 22.9 to 23.1 MHz, which occur under various conditions of start-up and high-temperature bakeout of the vacuum chamber. The frequency range during cyclotron operation is 23.05 MHz ± 3 kHz.

The Transmitter

Designed and manufactured by Continental Electronics Mfg. Co. of Dallas, Texas, the transmitter has a maximum tested power output of 1.8 MW, which is developed by four power amplifiers, each utilizing two Eimac 4 CW 250000A water-cooled tetrodes. The power amplifiers are driven by a 100 kW intermediate power amplifier (IPA) stage through a power divider and phasing network of passive components. A series of three hybrid combiners brings together the four power amplifier outputs at a single port where the transmission line is connected. Any combination of two, three or four power amplifiers may be used, thus increasing the system reliability. As each power amplifier can deliver 850 kW, two will provide enough power to run the cyclotron, although normally all four are in operation. The dc power supply, rated at 2.6 MW, limits the RF power output to 1.8 MW in this configuration. 1.2 MW is required to excite the resonator up to 100 kV, with a maximum of 1.65 MW needed under conditions of full beam load when third harmonic is added. The transmitter output may be fed to a 50 Ω resistive soda-water load for testing up to full power. An electronic crowbar across the dc power supply is fired in the event of a power amplifier tube arc-over. The crowbar may also be triggered by the facility's hardwired safety system since this is the fastest means of disabling the cyclotron.

Not shown in Fig. 3 are the transmitter's input stages. A 1500 W stage drives the IPA grid, and is in turn driven by a 20 W untuned transistor amplifier. RF input drive signal level for the transmitter is 10 mW.

Transmission Line

A coaxial transmission line 100 ft in length is used to convey the RF power from the transmitter in the shielded RF room to the cyclotron. The first 60 ft is 9 in. o.d., 50 Ω line, operated under matched conditions, i.e. with virtually zero standing wave. This section is connected to 40 ft of 11 in. line operated with high standing-wave (VSWR ≈ 6). The standing-wave section extends to the vacuum feedthrough where the coupling loop is located. In order to vary its effective electrical length there are three tuning capacitors mounted on the line: at the junction with the matched line, at about 8 ft further along, and at the coupling loop. The standing-wave line therefore provides a convenient means of setting up correct matching between the coupling loop and the source. A further advantage of operating part of the line with high VSWR is that the system is rendered less susceptible to severe mismatch caused by a resonator spark or by gross detuning between the driving and resonator frequencies. If such a mismatch occurs, the standing-wave line reduces the reflected power on the flat line and thus protects the transmitter. Under normal conditions the power dissipated by the whole line is less than 1% of the forward power. To assist in setting up the three tuning capacitors, 40 voltage probes are installed on the standing-wave line so that its voltage distribution may be monitored.[5] Part of the standing-wave line is shown in Fig. 4.

Vacuum Feedthrough and Coupling Loop

The RF power is passed into the vacuum chamber using a coaxial feedthrough. The insulator is a ceramic cylinder as used in high-voltage vacuum capacitors, a great improvement both mechanically and electrically over the disc seal used in the CRC. Both inner and

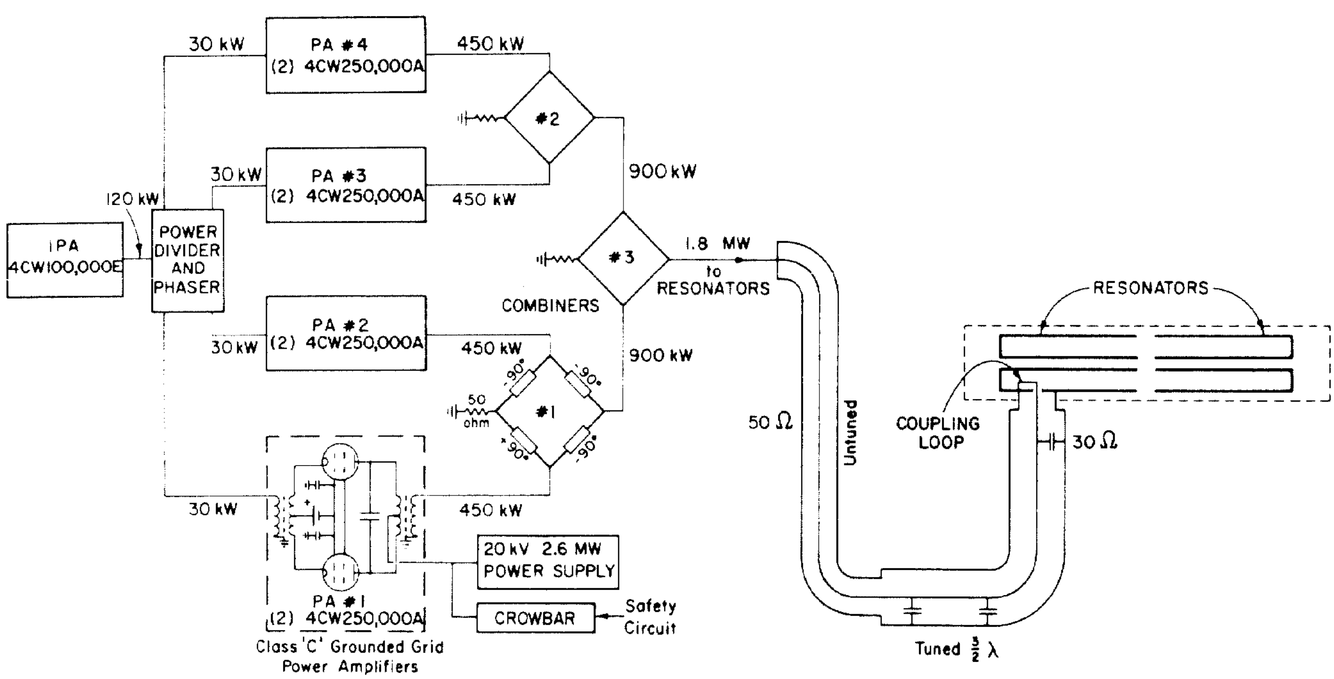

Fig. 3. Block diagram of the RF system high-power components.

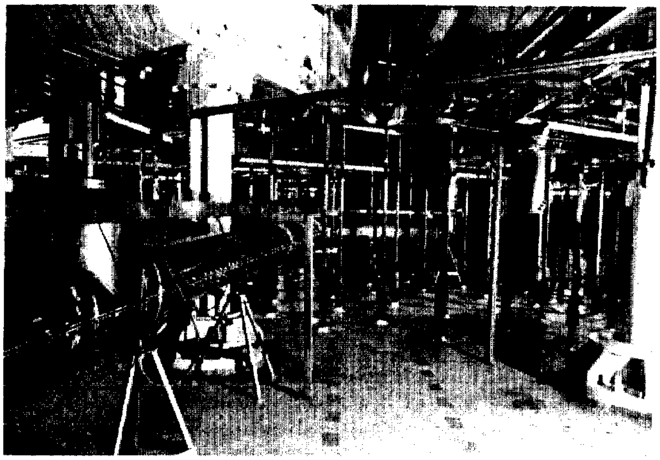

Fig. 4. The transmission line installed under the cyclotron. A capacitor station is shown on the left.

outer conductors of the feedthrough are water cooled, as is the coupling loop itself. Fig. 5 shows that in order to avoid excessive power dissipation in the loop and feedthrough, the system must be operated at the resonator frequency, as defined by minimum loop current, or more sensitively by the loop current leading the resonator current by 90 deg in phase. As was first learned with the CRC, satisfactory tuning up of the transmission line for efficient power transfer to the resonators with freedom from parasitic resonances and minimum stresses on the RF hardware cannot be achieved unless the resonator is driven at its natural frequency as defined above.

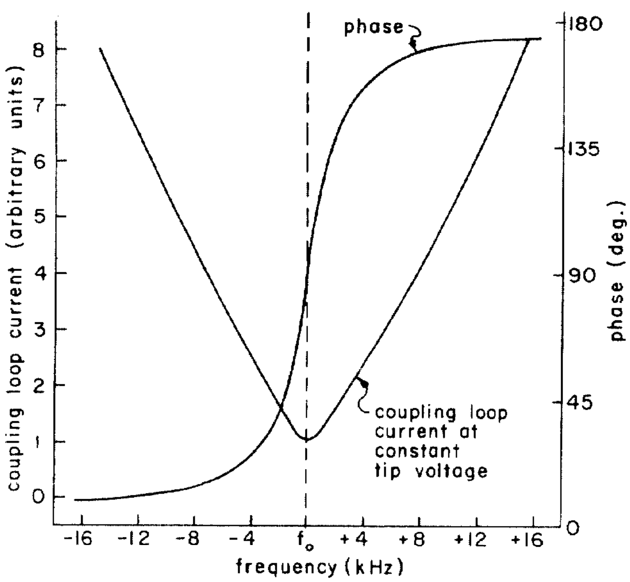

Fig. 5. Coupling loop current and phase between resonator and coupling loop currents, as a function of driving frequency, measured during tests.

RF System Performance

The present operation of the TRIUMF cyclotron does not require the fine RF stabilities set out in the following table. The exact value of the dee voltage has as yet not been determined; this will be done by further beam measurements. The resonator tuning range was found to be ±4.6 kHz, and no problems were encountered in activating the automatic tuning control. Ten of the 144 tuning foils have shown signs of overheating, so their life expectancy is questionable. Apart from this all the hardware in the RF system has performed most satisfactorily during 1000 h of operation for resonator tests and conditioning and beam commissioning, as well as about 700 h of cyclotron operation. At no time have parasitic oscillations appeared in the resonator and transmission line. In the event of a spark the dee voltage is automatically restored in less than 2 sec. The sparking rate has improved in the two months immediately preceding this conference from 2 sparks an hour to 1 in 2-3 h on average over a 15-1/2 h operating day. On one day no sparks occurred. This improvement has been caused mainly by adopting a standard reconditioning procedure following venting of the vacuum chamber, during which the dees are held at 150°F for 12-16 h with only the diffusion pumps operating in order to remove as much contamination as possible from the tank.

Dee voltage	100 kV peak
Energy gain per turn	400 keV
Voltage stability	±2.5 parts in 10^5
RF frequency (nominal)	23.05 MHz 5th harmonic of ion rotation frequency
Frequency stability	±7.5 parts in 10^8
Resonator tuning range	±4 kHz
Q	≥6000
Power dissipated at 100 kV	1.2 MW
Maximum anticipated beam load	300 kW
Dee width	640 in.

Further Developments

It is envisaged that in about one year's time the simultaneous injection of third harmonic power will be implemented in order to improve cyclotron performance. Since the dees have been built and adjusted to accept both frequencies, as verified at low power, further work to achieve flat-topping is confined to equipment outside the vacuum chamber, and can be done without interrupting cyclotron operation.

Acknowledgement

The work described in this paper was carried out under the guidance and with the active participation of Dr. K.L. Erdman, Department of Physics, University of British Columbia.

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