# AUXILIARY ACCELERATING SYSTEM FOR TRIUMF CYCLOTRON

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## Abstract

A 92 MHz auxiliary accelerating cavity has been designed and manufactured for installation in the TRIUMF cyclotron. Operating at the fourth harmonic of the rf with a peak voltage of 150 kV, it almost doubles the present energy gain per turn in the 400-500 MeV range, and reduces by ~50% the stripping loss of the $H^-$ beam. This significant improvement will allow a substantial increase in the extracted current above the present routine level of 150$\mu$A while maintaining the same levels of residual radioactivity. The system is completed and being commissioned. A description of the design and commissioning procedures is presented, and results of beam tests given.

## 1. Introduction

The possibility of either flat-topping the acceleration waveform or increasing the energy gain per turn in the TRIUMF cyclotron by modifications to the existing dees or the addition of new rf structures was considered even before the machine was commissioned. The first serious discussions about hardware followed J.R. Richardson's note[1] published in 1983.The scheme employing additional cavities operating at the fourth or fifth harmonic of the dee frequency was originally proposed as part of the $H^-$ extraction project[2,3], however, a resonant excitation of a coherent radial oscillation was eventually used to enhance the turn separation. The increased energy gain and consequent reduction in the number of turns made during acceleration also reduces the beam loss from electromagnetic stripping. The associated reduction in cyclotron activation was a sufficient reason to continue the project and install one cavity, schematically illustrated in Fig. 1.

The orbiting ion receives two impulses at the edges of the trapezoidal cavity on each passage. The accelerating voltage at 92.24 MHz (fourth harmonic of the main rf frequency) sinusoidally increases from zero to a maximum of 150 kV in the energy interval 330 to 520 MeV.

The physical dimensions and rf parameters of the cavity were calculated using simplified analytical formulae[4], and the code SUPERFISH. Measurements taken on a test cavity operated under vacuum up to ~50 kV confirmed that the frequency, Q-factor and impedance matching at the coupling loop were correct, and the design of the final system commenced.

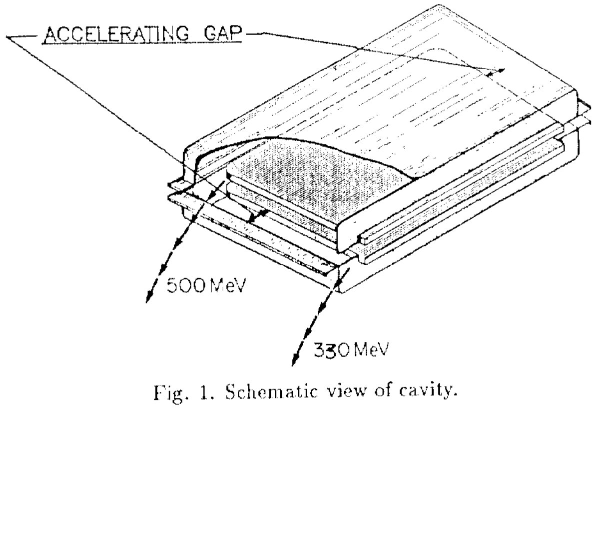


Fig. 1. Schematic view of cavity.

## 2. Cavity Description

The azimuthal length of the trapezoidal cavity is $\beta\lambda/2$, the radial extent $\sim\lambda/4$. In physical dimensions this corresponds to 1.2 × 0.8 m with a height of ~35 cm. The cavity consists of upper and lower halves symmetrical about the cyclotron midplane, mounted to the lid and floor of the vacuum tank and separated by 64 mm to provide a region free of all components (Fig. 2). The rf surfaces of the three main parts, viz. the ground arm, the hot arm and the root short, are OFHC copper 1.6 mm thick with all seams TIG welded. The cavity is formed by brazing these parts together. The cooling tube arrays are then soft soldered by a silver-tin alloy to the back sides of the parts in a carefully controlled sequence so that the previously fastened array is not disrupted.

The rf parts are supported by a robust aluminum frame. The cantilevered hot arm strongback is exceptionally stiff to minimize tip vibrations, permitting at the same time thermal expansion. The calculated stiffness was 360 N/mm, and the frequency of the lowest mode of natural vibrations 27 Hz. When the elasticity of the aluminum base plate is included, the stiffness drops to ~220 N/mm and the frequency to 20 Hz. Measurements indicate 19.63 Hz for the longitudinal mode, and 15.88 Hz for the torsional mode. Hot arm tip vibration amplitude with a water flow of 132 l/min. was measured 2.7 $\mu m$ p-p, not appreciably affected by changes in the flow rate.

The rf surfaces are subject to very high skin losses, reaching up to 8.5 W/cm$^2$ at the hot arm edges. The cooling tube arrangement was designed employing a computer code written for that purpose[5] to keep these surfaces plus the beam side panel at a temperature rise below 25°C at all points. The beam side panel is a separate, loosely restrained sheet on the underside of the strongback, which both shields the structure from stray rf fields, and isolates it thermally to minimize the frequency drift. Water flow to each cavity half is ~132 $l$/min., supplied through 5 cm dia. manifolds from coupling blocks on service modules. These parts provide the connection from each cavity half to the respective tank vacuum feedthrough. The coarse frequency adjustment was done on the assembly by shimming the ground arm – hot arm distance. For capacitive fine tuning an 8 × 30 cm water cooled, hinged gate is built into each ground arm tip, which is controlled through a zero-backlash linkage system from the service module.

## 3. Coupling Loop and Vacuum Feedthroughs

The coupling loop assembly is designed with a smooth 50 Ω transition to a 6 in. transmission line. All rf surfaces are water cooled with separate circuits; the loop is supplied from the ground arm circuit, the transmission line conductors from outside of the vacuum tank. Two new access ports were cut and welded into the cyclotron vacuum tank to accommodate

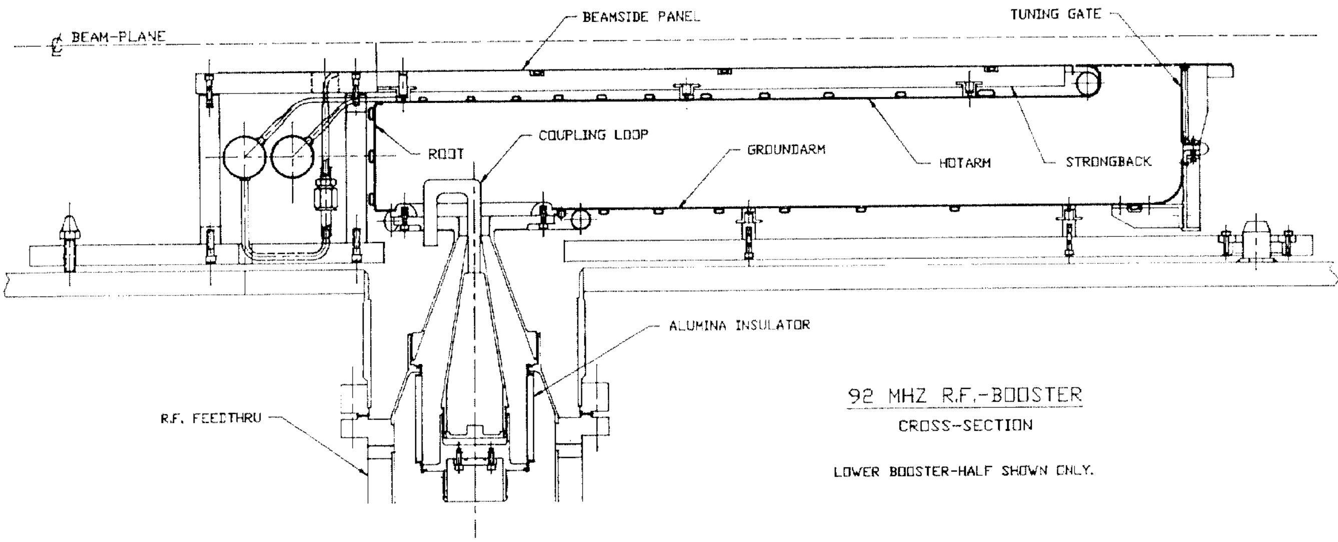


Fig. 2. Cross section of lower cavity half.

the cooling water lines, coaxial feedthroughs for rf signals from capacitive pick-up probes, thermocouples, and a mechanical linear bellows for movement of the tuning gate in each cavity half. A third port was cut for the coupling loop. The cutting method used was electrical discharge machining (EDM) where material is removed by spark erosion between the material and a contoured electrode in a stream of coolant fluid. It was necessary to make the apparatus portable and remotely operable to cut through the 23 mm stainless steel vacuum tank either in the floor or overhead. This remote overhead cutting process developed at Triumf was to our knowledge successfully applied for the first time. In parallel, equipment was designed and built to remotely weld the port tubes to the floor or lid, as well as to remotely install both cavity halves in the cyclotron. Finally, each half of the cavity takes ~20 min. to install with the only manual operation inside the tank being the connection of two BNC connectors. The coupling loop assembly is installed manually from beneath the tank.

## 4. Amplifier

The cavity skin loss plus additional power due to the beam loading, a safety factor for tube ageing, transmission and any other losses were calculated to be 120 kW. To meet the rf power requirements with a comfortable margin, the amplifier was designed for 160 kW using an EIMAC Y567B tetrode in a grounded grid, dc grounded screen configuration (Fig. 3). Stability and simplicity were prime considerations in the design.

The low input impedance at the cathode is brought out through the tube socket to a junction via a short section of a ~15 Ω coaxial line. From the tip of the grid-cathode structure to this point the electrical length is ~105°. At this point the filament leads and the negative cathode voltage are brought on and inside the center conductor of a coaxial $\lambda/4$ stub. A pi-network then matches the ~15 Ω to the 50 Ω required for the 3 in. input line. The driver is an FM-band 10 kW commercial transmitter that uses a 3CX10000A final triode.

The dc-grounded screen construction was chosen to achieve the best shielding between the input and output circuits. Further, the control grid is held at low impedance by a double layer of 0.13 mm thick copper-clad Kapton in the form of a radial transmission line. The space between the grids leads was filled with Emerson & Cumings MF-124 Eccosorb, and 286E lossy epoxy resin to increase the power absorption in this critical region. The rather complete electrical and mechanical isolation required separate air cooling in each of the two parts. In addition, the tube socket elements are directly water cooled to insure low seal temperatures in the tube.

At 92 MHz the effective length of the anode-screen grid coaxial structure is short enough that the output circuit could be constructed as a $\lambda/4$ coaxial resonator with sufficient cross-sectional area for variable loop coupling to match the required tube impedance to the 6 in. 50 Ω output line.

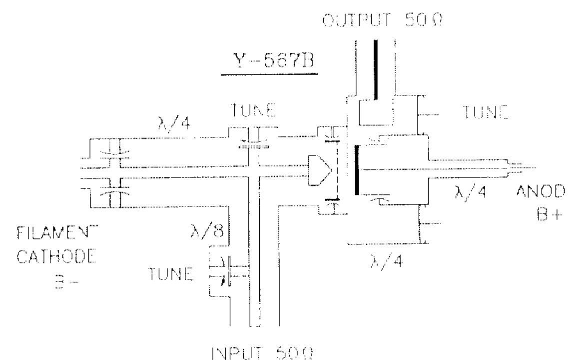


Fig. 3. Power amplifier schematic diagram.

## 5. System Commissioning

The requirement to install and commission the cavity inside an operational cyclotron routinely delivering 150 μA of protons dictated that the entire system had to be pre-commissioned outside of the radioactive environment of the machine. This was done in an auxiliary vacuum vessel dedicated for such tests, and the effort expended was well worth the time and expense. Signal level measurements on the power amplifier (input and output circuit matching) and the cavity (resonant frequency, shunt impedance, coupling loop matching) were thoroughly carried out using the HP network analyzer. The length of the transmission line was adjusted so that the amplifier works into a true parallel resonant circuit. During all adjustments a computer code NODE[6] was extensively utilized for on line modelling. This proved extremely useful, and resulted in substantial time saving.

During the first power test of the amplifier into a resistive load 50 kW was achieved in two hours, and the nominal 150 kW a few days later. In the actual installation the length of the transmission line is 64 m, ~20 times the wavelength at the operating frequency. As can be seen in Fig. 4, the intrinsic line resonances are then only ~1.2 MHz apart. In order to minimize possible problems with parasitics when first bringing the cavity to power, a line section only 6 m long was used. With the cavity under vacuum ~4 kW of cw power were delivered with 75% reflexion, and in 3 hours the multipactoring regions overcome. The cw method is preferable to pulsing since the cavity behaviour seems to be more stable in the end. The same operation was repeated with the full length transmission line. Parasitic oscillations in the power amplifier occurred but were easily eliminated by modestly lowering the screen grid voltage.

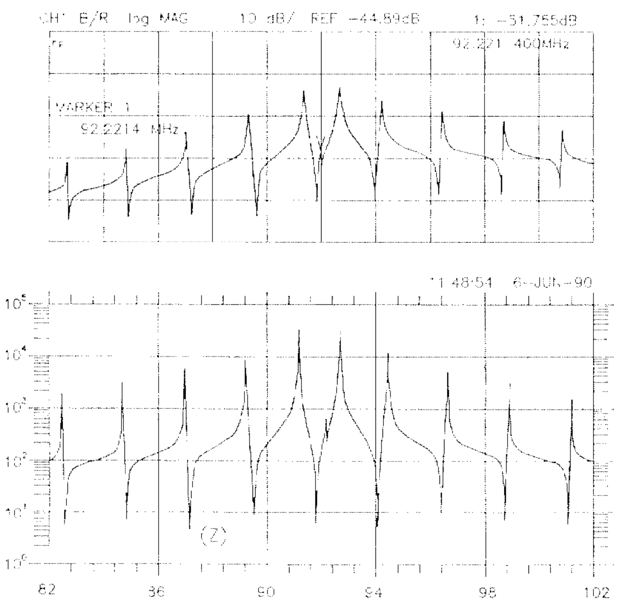


Fig. 4. Calculated (a) and measured (b) load impedance.

Following the cavity installation in the cyclotron the commissioning proceeded very smoothly and a voltage of 100 kV was achieved within several hours.

The voltage and phase stability required, ±0.5% and ±2.5° at 23 MHz respectively, are easily achievable with conventional rf control systems used at TRIUMF. The phase reference is the dee voltage (which is not phase regulated), the frequency is quadrupled and the signal used as a reference for driving the amplifier.

When the cavity is not energized the beam bunches passing through the cavity give rise to a voltage at the harmonics of the bunched beam frequency. Using MAFIA it was found that for a Gaussian-shaped pulse during operation at 100 $\mu$A cw in a phase interval 10° wide, the amplitude of the induced voltage is 16 kV for critical cavity coupling. As a consequence the flow of cooling water through the cavity is maintained at all times when beam is accelerated to avoid any possible damage due to overheating.

## 6. Beam Tests

The cavity structure now sets the limiting vertical aperture for the beam beyond 330 MeV. After adjustments to the scraper foil system protecting the cavity, 120 $\mu$A was successfully accelerated when the cavity was not energized. The amplitude of the beam induced voltage in the cavity was found to be 10 kV at 100 $\mu$A with the cavity in resonance. Detuning of the cavity by 200 kHz causes the voltage to drop to 3% of the above value. Subsequently the cavity was powered up to 90 kV and low current beam tests were conducted. Fig. 5 shows results from measurement of the beam time-of-flight through the machine vs. cavity voltage. The beam intensity was reduced by varying the duty factor of a 1 kHz macro-pulser located in the ion source. The time of flight is measured by using a start signal from the pulser and a stop signal produced by the first beam to reach a capacitive pickup probe in the extraction beam line. The measurements show that even at 90 kV reductions of ~20 $\mu$s or ~100 turns are possible. This is quite significant, since the number of turns made by the beam in the cavity region is ~400.

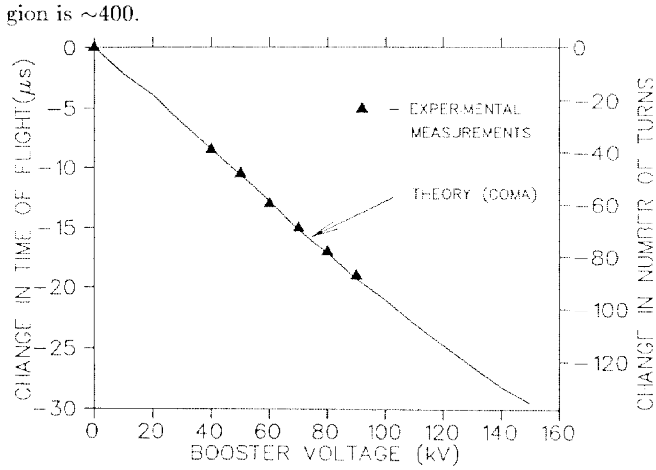


Fig. 5. Measured reduction in time of flight for the beam through the cyclotron as a function of the cavity voltage. A theoretical prediction using the matrix code COMA[7] is also shown for comparison. The reduction in number of turns is also shown. In the cavity region (350 to 500 MeV) the beam makes ~400 turns.

## References

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