TRIUMF RF AMPLIFIER AND RESONATOR SYSTEM

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ABSTRACT

The TRIUMF RF system consists of a 23.1 MHz fixed frequency driven amplifier with a power capability of 1800 kW. Power is transmitted to the resonator system through a 50Ω water-cooled line and is coupled to the system by a single coupling loop in one side of the push-pull resonator system. The resonators are constructed of copper-surfaced roll-bond aluminum plates with integral cooling tubes. DC plate power for the four push-pull 4CW250000A tetrode amplifiers is produced in a single unit rated at 20 kV, 130 A with crowbar protection for the tubes.

RF POWER SOURCE

The basic RF system requirement for the TRIUMF cyclotron is 1650 kW of RF power at 23.1 MHz. A peak voltage of 100 kV is required at the resonator tip with voltage amplitude stability of ±2.5 parts in 10^5. The frequency stability required is ±7.5 parts in 10^8.

The 1650 kW of RF power includes approximately 30 kW for the future addition of 11% third harmonic voltage for flat-topping.

The frequency stability of the power amplifier is obtained by using a stable frequency synthesizer source (Rhode & Schwarz ND 30M).

For safe reliable cyclotron operation we chose to make the DC plate dissipation equal to or greater than the expected RF output power. The largest tetrode having good service data available at design time was the Eimac 4CW250000A. Seven of these tubes would more than meet the power criteria, but for simplicity in design and versatility in operation (as will be shown later) eight 4CW250000A tetrodes are being used.

An amplitude stability of ±2.5 parts in 10^5 corresponds to an amplitude disturbance of -92 dB referenced to average power output. The 4CW250000A produces current modulation noise of from -70 dB to -82 dB. In contrast to this a somewhat smaller tube (the 4CW100000E) using a mesh filament is approximately 10 dB better. This tube was initially considered because of its noise characteristics, but to meet the power criteria for safe, reliable cyclotron operation at least 16 of these tubes would have to be used. To meet the amplitude stability using the 4CW250000A a feedback circuit modulating the screen and the input drive level will be used to give the extra 10 to 20 dB of noise reduction. The high level of voltage stability will not be required during initial cyclotron operation.

AMPLIFIER STAGES

A block diagram of the RF source is shown in Fig. 1. Each of the four PA's uses a pair of 4CW250000A tubes in push-pull grounded grid configuration. Push-pull grounded grid has several advantages over the same tubes in a push-pull or parallel grounded cathode configuration, lower gain and reduced feedback capacity being the most important for stable RF operation. Other beneficial effects are reduced bias voltage and less screen dissipation for a given power output.

The IPA stage uses the low noise 4CW100000E tetrode in the grounded cathode configuration. The drive power for the IPA, which is obtained from a 5CX1500A pentode is sufficient to saturate the grid of the 4CW100000E. This saturation reduces the noise feedthrough from the previous stages and since the 4CW100000E is inherently a low noise level tube, the amount of noise appearing in the PA from the previous stages is very small. The power levels at the various amplifier stages are indicated in the figure.

POWER SPLITTER

The power splitter is nothing more than a combination of pi networks (Fig. 2), which provide the proper impedance and phase relationships between the various amplifiers under driving conditions.

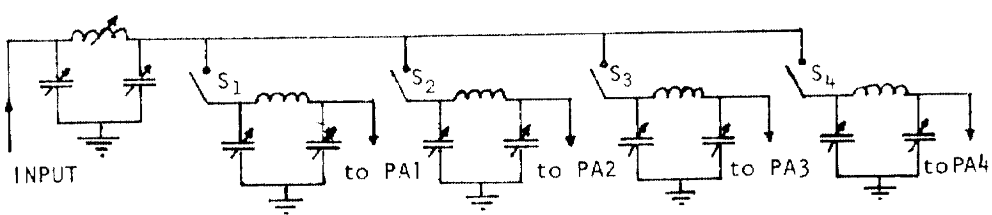
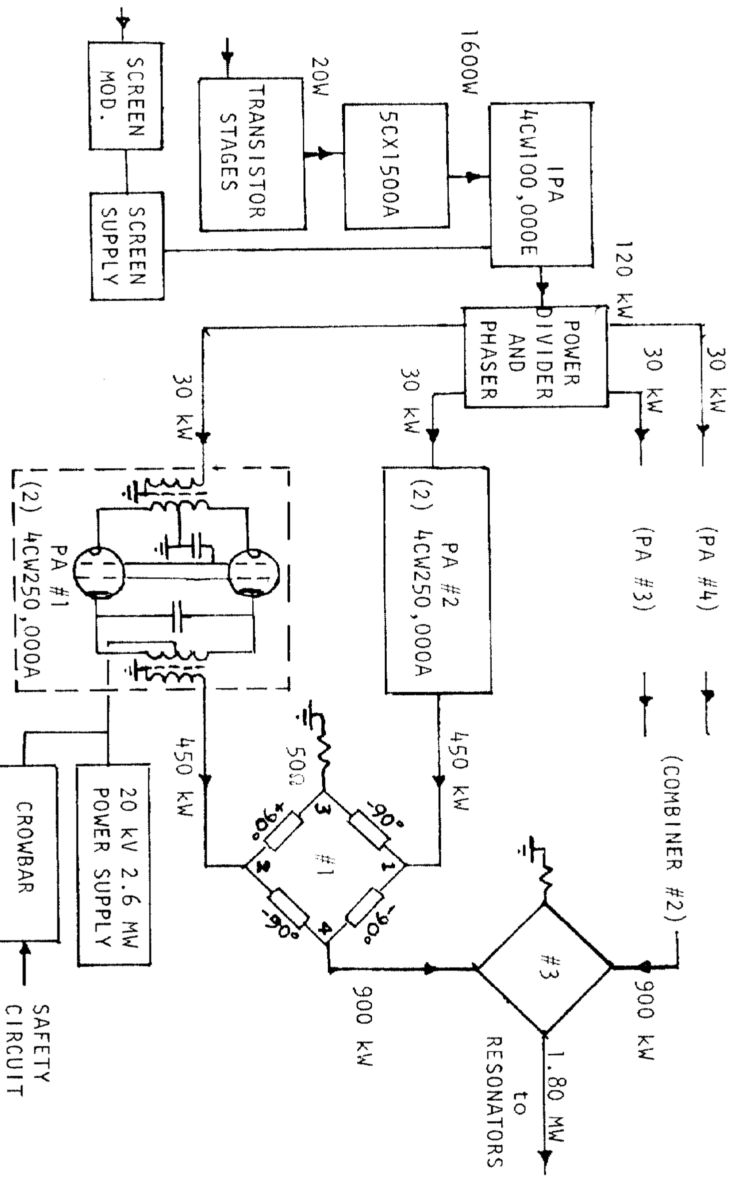


Fig. 2. RF amplifier power splitter



Class 'C' Grounded Grid Power Amplifiers

Fig. 1. 23.1 MHz RF amplifier

The impedance ratio for the four PA pi networks is 200Ω to 50Ω. The IPA pi network has three design ratios. 50Ω to 200Ω for two-amplifier operation, 50Ω to 70Ω for three-amplifier operation, and 50Ω to 50Ω for four-amplifier operation. Each pi network has a 90 deg phase shift.

PA AMPLIFIER

The PA amplifier circuit is a conventional push-pull ground grid stage, but has a rather interesting input circuit which uses a toroid coupling transformer to feed the low impedance presented by the grid cathode structure. The impedance presented by each tube is approximately 15Ω. Fig. 3 shows a schematic of the input circuit.

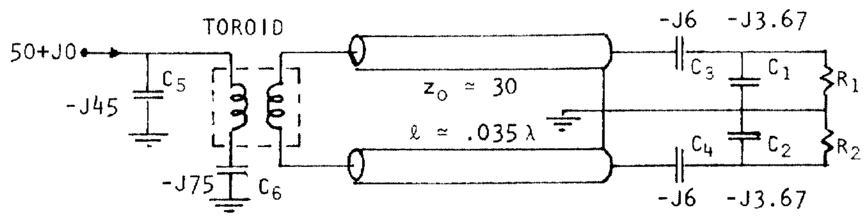


Fig. 3. Driver input circuit

C1 and C2 are necessary to establish a Q of about 3 in order to maintain reasonable wave shape of the driving voltage. R1 and R2 represent the tube-driving impedance. C3 and C4 are DC blocking capacitors but are also utilized to achieve the proper load conditions at the end of the transmission line. The short transmission line sections between the tubes and the toroid are used because of the physical space limitations in mounting the toroid between the two tubes. C5 and C6 form a pi network with the primary of the toroid making it extremely versatile in impedance-matching applications.

ANODE POWER SUPPLY

The anode power supply for the four PA amplifiers is rated at 20 kV 130 A. The secondary of the transformer is in two sections, one connected Δ and the other connected Y to give a 12-phase ripple configuration. An electronic crowbar on the output protects the tubes in case of an arc-over in the tubes and is also hardwired into the safety system. The filter system is designed to have a time constant of 50 μsec so that it can supply anode voltage for the period of time required to pulse through multipactoring.

COMBINERS

The outputs of the four power amplifiers are combined through a system of hybrid combiners as was shown in Fig. 1.

Referring to Combiner #1 in Fig. 1, the power from PA1 and PA2 will combine at port #4 but will cancel at port #3, so that under normal operating conditions the power absorbed by the waster load is ideally zero. However, if one of the amplifiers is turned off, then the power from the amplifier that is operating will split between the waster load and the output load. The waster load therefore is rated to absorb at least one-half of the output power from one amplifier, which for Combiner #3 is 450 kW when operating with four amplifiers. The physical layout and construction of the combiners is such that the system can easily be retuned to operate with two, three or four amplifiers for the various anticipated load conditions during the stages of machine start-up.

TRANSMISSION LINE

A 50Ω transmission line is used to transfer the RF power from the amplifiers to the resonators. The line is divided into an initial section which is operated in a low standing wave mode and a final high standing wave mode section that makes the transition between the power from the final combiner and the resonator coupling loop. The total length of the line is approx 100 ft and it is water cooled.

The initial line is a 9 in. coaxial, commercial line. It is switchable on the floor level below the transmitter and can be directly connected to a 50Ω soda water dummy load (Brown Boveri) which is capable of absorbing 2 MW of cw power.

The resonant section of the line begins inside the cyclotron vault. It has a diameter of 11 in. and is fabricated out of aluminum; the centre conductor consists of unitrace pipe. It has an electrical length of 1.5 wave lengths and is tuned by three Jennings vacuum capacitors, one at each end and one in the middle. The capacitors are used to adjust the length of the line and set the standing wave ratio to match the accelerator resonator input to the 50Ω flat line. Spark gaps at "nodes" on this line protect the system from spark-over transients in the cyclotron.

RESONATORS

Resonator Design Features

Mechanical. The resonator structure is 55 ft long, 21 ft wide and consists of 80 individual resonator segments and 4 end flux guides. Each segment is 193 in. long, 32 in. wide and 6.5 in. high, and weighs approx 600 lb. Fig. 4 illustrates the major segment components. With the exception of the stiff levelling arm and the mounting hardware, the segment is almost entirely made of aluminum.

RF Surface. The hot and ground arm utilize a copper-aluminum 'roll-bond' material with the copper as the conductive surface. Components such as the shorting plane and the arm tips feature electroplated copper surfaces.

The roll-bond panels used in the construction of the segment arms are 128 in. long and 34.5 in. wide, and are formed from two aluminum and one copper sheet. After rolling, the sheets are fused and provide a 0.115 in. thick panel, as shown in Figs. 5 and 6. A separating media between the two aluminum sheets provides for subsequent inflation of cooling passages.

With roll-bond considerable freedom exists in selecting a cooling pattern shape; this facilitated the matching of the cooling line pattern to the thermal energy flux in the copper surfaces. With a heat loss of about 12 kW per segment, temperature gradients in the roll-bond do not exceed 5°F.

Ground Arm and Hot Arm. A ground arm, of either an upper or a lower segment, attaches at five distinct points to the vacuum chamber, and this permitted the construction of a shallow but relatively rigid ground arm with a minimum of structural reinforcing. The flexible ground arm tip is provided with an actuator for RF frequency trimming.

The hot arm, and its levelling extension, is an integral structure with a thermal expansion compensating 3 point support system. Controlled vertical push-pull at the levelling arm end provides for fine hot arm tip adjustments. A large aluminum extrusion, as shown in Fig. 7, provides support for the floating roll-bond panel. In order to minimize tip deflections due to small temperature transients, thermal expansion compensating supports are employed between panel and structure. Pre-curving of the structure during manufacture compensates for an inherent natural sag of about 0.50 in. at the arm tip.

Shorting Plane. The shorting plane provides the electrical connection between ground and hot arm, while featuring two tuning pockets for adjusting root inductance. The structural connection between ground and hot arm is provided by the root structure which also accommodates the remotely-controlled pneumatic actuators for the tuning pockets.

Cooling Coupling. All water cooling lines from the various segment components are ganged before joining to the single disconnect. The coupling also accommodates the two pneumatic lines, so that on segment installation four high-vacuum service connections are made. Metallic C-rings were chosen for seals because of radiation environments and because of differential thermal expansion problems inherent with an aluminum-stainless steel coupling half combination.

Segment Installation

The segments are pre-assembled and tested in air before installation in the vacuum chamber. Mounting hardware and fasteners are of the horizontal slide-in type. This method is fully compatible with remote handling operations, and is a necessary consideration, as the cyclotron and the segments will become radioactive after a short period of cyclotron operation. An electro-mechanical manipulator, fitted with an impact torque wrench, will be employed to torque the four mounting bolts after segment installation.

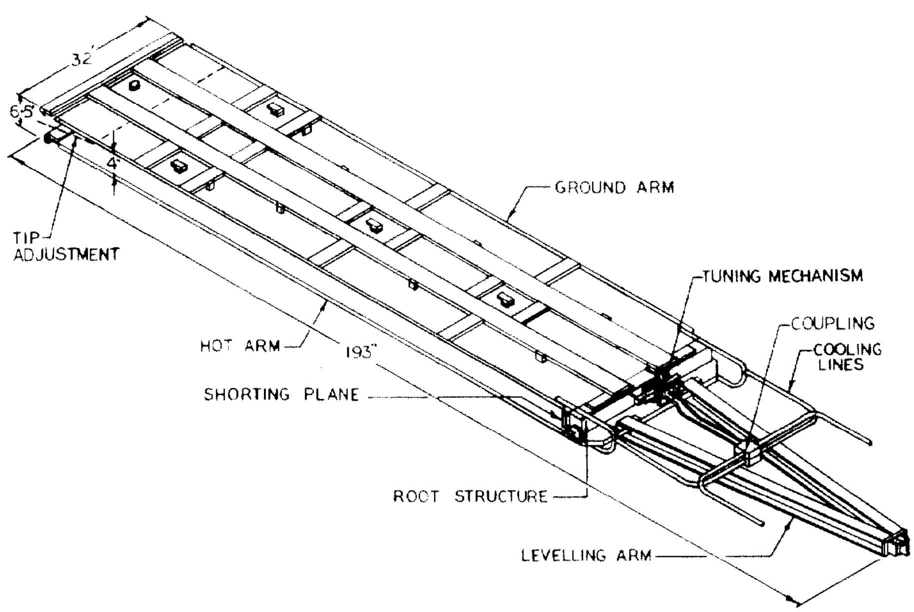


Fig. 4. An isometric view of an upper resonator segment.

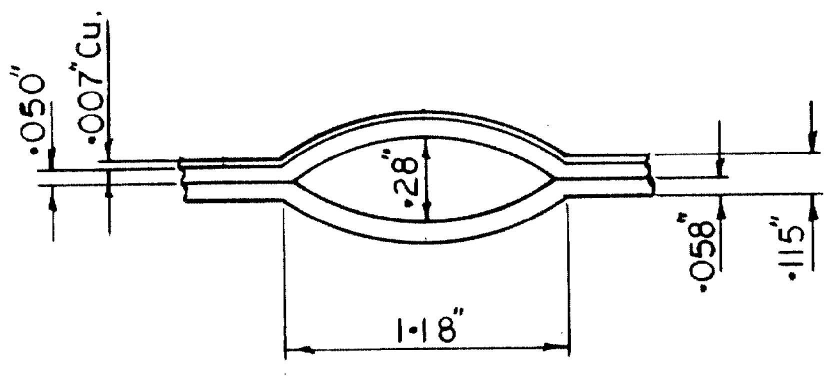


Fig. 5. Roll-bond panel cross-section at coolant channel.

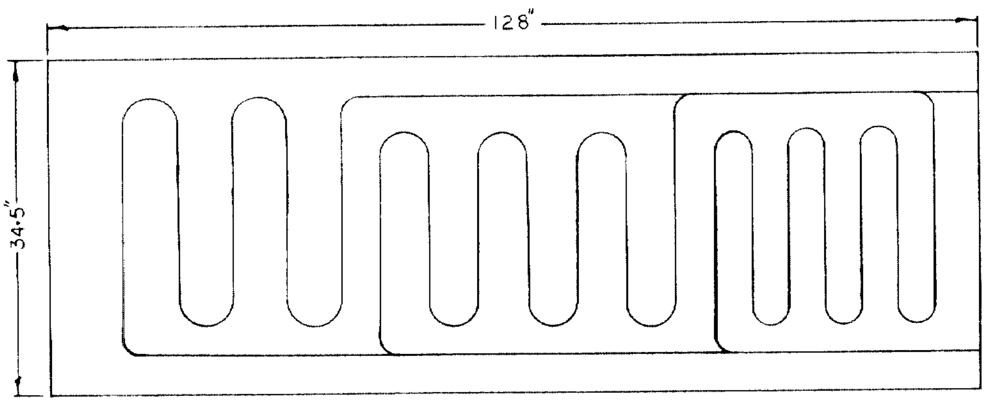


Fig. 6. Cooling channel pattern in roll-bond panel.

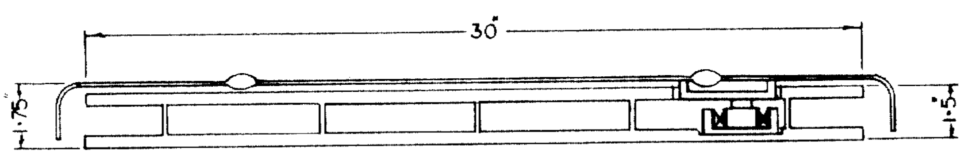


Fig. 7. Cross-section of hot arm structure.