GRID-CONTROLLED POWER TUBES IN PARTICLE-ACCELERATOR APPLICATIONS

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Summary

Typical illustrative examples are cited for the use of grid-controlled power tubes in the various classes of particle accelerators, e.g., cyclotrons, synchrocyclotrons, proton synchrotrons, electron synchrotrons, and linear accelerators, A state-of-the-art review of triode and tetrode power-tube technology is presented, together with some apparent trends in the design and development of new tubes. The use of triodes and tetrodes with integral cavity-resonators enhances the feasibility of their use at increasingly higher frequencies and/or power levels. In addition to their use as radio-frequency generators in particle accelerators, grid-controlled power tubes are also applicable as pulse modulators and amplitude regulators. The unique advantages of gridded power tubes for particle accelerators are discussed.

Introduction

Developments in particle accelerators have been inexorably contingent upon developments in grid-controlled power tubes from the first model of the cyclotron to the giant synchrotrons of today. Since the outlook is bright for continuing progress in the development of grid-controlled power tubes, particle-accelerator scientists can anticipate continuing contributions to the success of new generations in machine design.

Experience with grid-controlled tubes at very-high and ultra-high frequencies has demonstrated that electron transit-time effects can be obviated by appropriate tube and circuit design. Further progress in the development of grid-controlled tubes is being demonstrated by the continuing development of devices in which the electron-control systems and circuit elements are integrated within a common vacuum envelope. Compact high-gain "totem-pole" amplifiers are being developed as driving stages for super-power triodes and tetrodes. The development of high-speed fault-protection systems has been of keystone importance in the operation of power tubes at increasingly higher power levels.[1]

Shielded-Grid Triodes

The shielded-grid triode, shown in Fig. 1, has been employed in particle-accelerator service for more than a decade, dating from the beginnings of the Livermore LINACS (e.g., A-48). The original prototype sample of a shielded-grid triode has provided the rf power to the Berkeley Bevatron[2] for the past eleven years and has operated for more than 44,000 hours.

Shielded-grid triodes, described earlier in the literature[3], are capable of producing continuous power (cw) up to 700 kilowatts and pulsed peak power up to 2 megawatts. The single-ended version of the shielded-grid triode has an upper frequency capability of about 100 megacycles; the use of a double-ended envelope configuration on the tube permits operation at frequencies somewhat above 200 megacycles. At the lower frequencies, where input-circuit losses are negligible, the shielded-grid triode can provide 30 db of power gain.

In the 6949 triode shown in Fig. 1, 24 individual shielded-grid triode units are arranged cylindrically and, together with the anode as the outside cylinder, are housed in a ceramic envelope. The radial-compression ceramic vacuum seals used in the tube represent a significant development in vacuum-tube envelope design. An unusually strong aluminum-oxide ceramic cylinder is the insulating envelope. The mechanical compressive force necessary to achieve radial compression is obtained from hoop tension in the strong copper-plated metal band into which the ceramic insulator is forced. The resulting radial compressive force is localized in a narrow region so that the stress is sufficient to cause plastic flow of the metal and effect a vacuum-tight seal. Radio-frequency displacement currents flow through the seals without encountering intermediate high-resistance oxides or other semiconductor layers found in brazed types of ceramic-to-metal vacuum seals. Dielectric losses in the aluminum-oxide insulators are very low, even at ultra-high frequencies.

The Berkeley 88 inch Cyclotron[4] and the Livermore 90 inch Cyclotron have been operating with shielded-grid triodes for a number of years. More recently, the tube has been providing rf power for the Oak Ridge Isochronous Cyclotron[5]. The Berkeley and Yale HILAC[6] (Heavy Ion Linear Accelerator) machines are powered at 70 megacycles by five shielded-grid triodes operating at pulse durations of 2.5 milliseconds. Four shielded-grid triodes have operated for more than 20,000 hours in HILAC machines and one tube has operated for nearly 30,000 hours. Pulsed rf power for the Los Alamos PHERMEX[7] electron accelerator has been supplied at 50 megacycles by six shielded-grid triodes. The PHERMEX machine has been in operation for two years without a failure in the power-amplifier tubes.

Super-Power UHF Triodes

The 2054 super-power triode shown in Fig. 2 is believed to be the most powerful triode in the world. It is capable of producing at least 10 megawatts of pulse power and can operate at frequencies up to 600 megacycles. It has generated 450 kilowatts of continuous power at 450 megacycles, and is probably capable of considerably higher power at uhf - possibly in excess of 1000 kilowatts. At lower frequencies, technical projections indicate that this tube should be capable of producing about 2300 kilowatts of continuous power output. When operated as a grounded-grid (cathode-driven) uhf amplifier[8], this triode has a power gain of 13 db and a plate-conversion efficiency of 50 per cent.

As shown in Fig. 2, the tube has a double ended-configuration[3], i.e., the vacuum envelope is designed so that the tube is positioned at the middle of a half-wave circuit when it is operating in the fundamental-order circuit mode. The anode electrode at the center of the tube is water-cooled by a flow of 150 gallons per minute. Ceramic bushings on either side of the anode insulate it from the grid-flange terminals at each end of the tube (two grid-terminal connections are necessary for double-ended circuitry). The ceramic-to-metal vacuum-seals are of the radial-compression type described previously.

This giant triode contains a total of 96 individual units combined in a common vacuum envelope. Fig. 3 shows the grid-cathode mount assembly with its plurality of individual triodes arrayed on a 6.6-inch-diameter cylinder; the active-region length of each triode is 4 inches. Cathode construction is of the individual directly-heated filamentary type. Two different types of emitters are optional, depending on the specific service in which a particular tube type is to be employed. Thoriated-tungsten filament strands are utilized in tube types intended for services requiring high average power or long-pulse, high-duty-factor operation. When equipped with thoriated-tungsten filaments the tube requires a heating power of about 30 kilowatts (4.2 volts at 7200 amperes). If a particular tube type is intended for operation at high peak pulse power and more modest average power, the tube is equipped with filament strands containing a matrix-oxide emitter; the filament heating power is then only 2.7 kilowatts (1.5 volts at 1800 amperes).

Fig. 4 shows a cross-sectional sketch of triode units for use in uhf tubes. Integral wire-support fins extend from the control-grid cylinder on both sides of the directly-heated filament strand. Active 0.0033-inch-diameter tungsten wires are wound laterally in grooves across the fins in a circumferential direction on the outside diameter of the grid cylinder at a pitch of 72 turns per inch; the wires are then covered with copper by a firm rolling operation. This construction provides a short thermal-conduction path for the flow of grid heat to the fluid-cooled, copper grid-cylinder, and effectively overcomes the problems of excessive grid temperature sometimes encountered in triodes of classical design. The possibilities of primary grid emission are thus minimized. Grid-wire-to-filament-strand spacing is 0.015 inch. Thorough fluid cooling and individual pantographic suspension of the filament strands provide a thermally stable structure. Grid-anode spacing is 0.29 inch. Intense-cooling techniques are applied to the copper anode structure for the purpose of providing high anode-dissipation capability.

The first application of the uhf super-power triode in particle accelerators has been in operation for several years at Argonne National Laboratories. A single triode provides all of the rf power necessary for the operation of a 50-Mev LINAC Injector[9] to the Argonne Zero-Gradient Synchrotron (ZGS). The Argonne radio-frequency system shown in Fig. 5 was built by Continental Electronics. The cylindrical vessel in the foreground of Fig. 5 contains the super-power triode and associated radio-frequency circuitry, together with coupling circuits to a rectangular waveguide which conducts the power to the LINAC tank visible in the background of the photograph. This equipment operates at a frequency of 200 megacycles with 500-microsecond pulses, and has been tested at peak power output in excess of 5 megawatts. The initial sample of the super-power triode has operated in the Argonne system for more than 5500 hours over a period of four years. Circuitry to operate a super-power triode is currently being procured by Brookhaven National Laboratories for use in conjunction with the LINAC Injector to the Alternating-Gradient Synchrotron (AGS).

A single super-power uhf triode is also employed to supply radio-frequency power to the Cambridge Electron Accelerator (CEA)[10] at Harvard-MIT. The major portion of the radio-frequency equipment, shown in Fig. 6, was built by the RCA Equipment Division. The rf driver amplifier, employing a tetrode, is shown in the right side of the photograph.

The super-power triode is housed in the cylindrical cavity-resonator on the left atop a rectangular waveguide which conducts the rf power to the accelerator system. This equipment operates as a linear amplifier at 476 megacycles and produces 8-millisecond saw tooth shaped pulses with peak power in excess of 400 kilowatts and average power in the order of 100 kilowatts. The two-stage rf amplifier operates from a common 14-kilovolt dc power supply and provides a power gain of about 28db. The original sample super-power triode has operated in the CEA equipment for nearly 10,000 hours over a period of four years. Two-stage tetrode-triode equipment has also been supplied to the Daresbury-Liverpool Electron Accelerator currently under construction in Great Britain.

Gridded Tubes with Integral RF Cavities...Coaxitrons

Grid-controlled tubes have been operated almost exclusively in conjunction with external rf resonators. This practice has permitted a universality of application in utilizing a particular tube type over a range of frequencies, but it has also placed gridded tubes at a disadvantage in the following respects:

(a) An rf resonator must be designed and built for a specific application before a particular tube is useful.

(b) The use of external rf resonators has needlessly restricted the upper-frequency capabilities of gridded tubes as a consequence of circuit losses, spurious modes, parasitic circuits, voltage-insulation problems, possible difficulties with circuit contacts, and the like.

(c) Circuits external to the vacuum envelope require pressurization at the highest power levels in order to obviate environmental problems with dust, humidity, and voltage breakdown.

It has been apparent for a number of years that these disadvantages could be overcome by the design of grid-controlled tubes in which the electronics systems and rf-cavity resonators would be contained in a common vacuum-vessel, as is the practice in virtually all microwave-type power generators. Pioneering continuously-pumped triodes and tetrodes of this generic type have been used at 200 megacycles as super-power rf generators for the University of Minnesota[11] and Harwell[12] LINACS. More recently, RCA has been engaged in the development of sealed-off triodes and tetrodes with vacuum-contained circuitry, a class a devices designated as Coaxitrons[13] to differentiate them from classical tubes.

Super-Power Triode Coaxitron for 425-Mc Service

Fig. 7 is a photograph of the first RCA Super-Power Coaxitron, nominally capable of producing 5 megawatts of peak power without tuning over a frequency range of 10 per cent centered at 425 megacycles. The device has been tested to peak power of 9 megawatts with a plate potential of 32 kilovolts. Power gain is in the range of 13 to 15 db, and plate-conversion efficiency of 54 per cent has been measured. RF driving power is applied through a coaxial line to the base of the tube. Output power is delivered through a large coaxial ceramic window atop the tube. The ceramic window is inserted transversely into a waveguide to conduct output power to the load. Cooling water and plate potential are applied to appendages on the under-side of the tube. This particular Coaxitron employs 96 individual triode units in an arrangement similar to that shown in Figs. 3 and 4.

Super-Power Triode Coaxitron for 805-Mc Service

Fig. 8 is a photograph of a Super-Power Triode Coaxitron designed for service at 805 megacycles. This tube, a frequency-scaled version of the Coaxitron described above, is intended to produce 1.25 megwatts of peak power (75 kilowatts of average power) in pulsed service with 2000-microsecond pulses. Fig. 9 shows the Coaxitron installed in test-evaluation equipment; driving power is supplied by a coaxial line at the base of the tube, and output power is delivered by a waveguide connected atop the tube.

The 805 megacycle Coaxitron employs 48 unit triodes, generically similar to those shown in Figs. 3 and 4. Thoriated-tungsten filamentary cathode strands are heated with 8.75 kilowatts of power. Power gain of the tube is 12 db, and a plate-conversion efficiency of 42 per cent has been measured at a pulsed plate voltage of 35 kilovolts. Peak power output up to 1.4 megawatts has been produced. A Coaxitron of this type should be capable of producing about 300 kilowatts of continuous power (CW) at a plate voltage of 20 kilovolts. It is believed that a variant design of the tube will be capable of producing 2.5 megawatts of peak power at 1 percent duty-factor while producing pulses of 250-microsecond duration. Prototype samples of the 805 megacycle Coaxitron have been delivered to Los Alamos Scientific Laboratory for evaluation in connection with proposed LINAC applications. Additional samples are currently being built for Brookhaven National Laboratory.

Advantages of Coaxitrons

In addition to the well-known time-proven advantages of grid-controlled tubes, it is evident that the Coaxitron concept offers the following advantages:

(a) The capability and advantages of gridded electronics have been extended by the Coaxitron concept in terms of both power and frequency.

(b) Circuit efficiency is improved considerably at the higher frequencies, and circuits can be designed for optimum performance with fewer restrictions.

(c) Location of the rf-cavity circuits within the vacuum envelope of the Coaxitron provides superior voltage hold-off capabilities. Vacuum insulation eliminates the need for circuit pressurization, pressure vessels, and cavity-circuit maintenance. When separate insulators are used for the rf fields and the dc-supply voltages, Coaxitrons can be designed to operate at considerably higher voltages before difficulties are encountered with voltage-gradient problems.

(d) The Coaxitron eliminates tuning and loading adjustments and eliminates potentially troublesome sliding contacts in the resonant circuits. These advantages reduce set-up time, down time for tube changes, and operator-skill requirements. Factory-tuned, tamper-proof circuits in themselves will eliminate a factor which has been a major contributory cause to field-failures in grid-controlled tubes.

(e) For a given power capability, the compact integral-circuit Coaxitron package simplifies handling, installation, storage, and shipment.

(f) Because Coaxitrons can be designed to operate in fundamental-order circuit modes, there is a very significant reduction in the number of parasitic or spurious circuit modes which can cause tube and circuit malfunction. The use of fundamental-order circuit modes minimizes electrical stored energy in the circuits and thereby optimizes broad-band amplifier performance.

It is apparent that these advantages will permit Coaxitrons to establish new standards of reliability, life, and over-all performance as generators of rf power.

Grid-Controlled Tubes for Driver-Amplifier Stages

Contemporary super-power vhf and uhf triode stages operate with power gains in the range of 12 to 17 db, with gain being frequency-dependent as a consequence of increased circuit losses at the higher frequencies. Thus, from the standpoint of power gain, the grounded-grid triode super-power amplifier is at a disadvantage in comparison with velocity-modulated devices, e.g., multi-cavity klystrons and traveling-wave tubes. The following paragraphs describe high-gain tetrodes and related techniques which provide enhanced gain performance in driver-amplifier stages.

High-Gain UHF Tetrode

Many years of experience with beam power tubes like the types 6L6 and 807 have proved that the aligned-wire geometry of the tetrode electron gun is capable of providing high power gain when tubes are operated as grounded-cathode (grid-driven) amplifiers. The extension of this gun design for use at higher voltages, higher current densities, and ultra-high frequencies was accomplished more than a decade ago in a high-gain tetrode capable of producting 25 kilowatts of power for uhf television[14]. Since that time, variants of the tube have been designed for a variety of radar pulse transmitters and increasingly higher continuous-power (cw) capability. One of these tetrodes has operated for more than 40,000 hours in a uhf TV transmitter.

A typical high-gain uhf tetrode is shown in Fig. 10. Forty individual tetrode electron-gun units have been arrayed circumferentially in a common envelope. Directly-heated, pantographically-suspended filamentary cathodes are employed. Depending on the type of service intended, the tube is equipped with either thoriated-tungsten or matrix-oxide cathodes. Filament, control-grid, and screen-grid support structures are water-cooled to enhance thermal and mechanical stability of the structure. The anode, atop the tube in Fig. 10, is intensively water-cooled and has demonstrated a capability of dissipating more than 100 kilowatts of continuous power.

When the classical tetrode electron gun was adapted for uhf use, careful design consideration was given to the provision of very-low-inductance leads and the isolation of input-circuit from output-circuit displacement currents. Internal screen-grid bypass capacitors are used, and the mechanical configuration of the tube is such that it can only be operated in the high-gain grounded-cathode (grid-driven) mode of amplifier service. Coaxial circuit connections are provided on top of the tube. Filament terminals, screen-grid terminal, and a coaxial control-grid terminal are placed on the underside of the tube. Brazed ceramic-to-metal seals are used.

At low frequencies, the tube shown in Fig. 10 has produced 125 kilowatts of continuous power (cw) at a plate-conversion efficiency of 80 per cent and a power gain of 33 db, requiring a driving power of only 55 watts. Thus, transistorized amplifiers can drive the tube at lower frequencies. At 439 megacycles the high-gain tetrode has produced 56 kilowatts of continuous power with a plate-conversion efficiency of 58 per cent at a power gain of 19 db, and it is believed to be capable of significantly higher power. Variant designs are capable of producing 2 megawatts of short-pulse power, e.g., at 425 megacycles with a plate-conversion efficiency of 54 per cent and a power gain of 20 db. The uhf tetrodes can be used for applications at frequencies up to 950 megacycles. A typical circuit in which a uhf tetrode drives a super-power triode at 476 megacycles is shown at the right-hand side of Fig. 6.

"Totem-Pole" Amplifier Circuits

Driver-amplifier stages employing grid-controlled tubes have frequently occupied inordinate space and have been unduly complicated in both mechanical and electrical details. During the past year, RCA engineers have been engaged in the development of so-called "totem-pole" amplifier circuits which are very compact and simple in construction, yet provide spectacular improvements in electrical performance.[15]

Fig. 11 is a photograph of a "totem-pole" amplifier. It comprises a six-stage cascade of triodes and tetrodes capable of producing a peak power output of 5 kilowatts at 1300 megacycles with a minimum gain of 50 db across an untuned bandwidth (to 1-db points) of 10 per cent. The "totem-pole" amplifier is only 24 inches long. The amplifier obviously derives its name from the manner in which the individual stages are stacked. Coaxial resonators are arranged so that there is commonality between the output resonator of one stage and the input resonator of the following stage; this arrangement eliminates the need for coupling cables and kindred complexities. The amplifier could be shortened physically in applications requiring less bandwidth. The rf phase stability of the "totem-pole" amplifier is outstanding. A phase-shift of only 4.9 degrees was measured at 1365 megacycles when all supply voltages were varied by 10 per cent and rf drive power was simultaneously varied by 1 db. It is now quite practical to design a "totem-pole" amplifier for use in conjunction with the high-gain uhf tetrode shown in Fig. 10, thereby providing very compact driver stages with excellent rf phase stability.

Gridded Tubes as Hard-Tube Modulators & Regulators

Triodes and tetrodes have been used for more than two decades as hard-tube modulators in pulsing radar transmitters[16]. As the need for more precise control of particle accelerators has developed, machine engineers have begun to employ triodes and tetrodes as pulse modulators and regulators of supply voltages to rf generators. Thus, a triode hard-tube modulator and regulator system is used to supply plate pulses to the rf-generator tube (shown in Fig. 2) used in the Argonne National Labs Injector[9] to the Zero-Gradient-Synchrotron (ZGS). More recently, Rheaume[17] has reported on a hard-tube modulator and regulator system being procured for the rf system employed in the LINAC injector to the Brookhaven National Labs Alternating-Gradient-Synchrotron (AGS). The advantages of hard-tube modulator systems for particle-accelerator service include the following:

(a) Rapid means for regulation in the face of variations in system parameters,

(b) Good response against transients,

(c) Flexibility in varying pulse duration and repetition rates,

(d) Excellent "first-line defense" in fault-protection of rf power amplifiers,

(e) Favorable pulse-rise and pulse-fall times,

(f) Low internal noise,

(g) Long-life service capability, even when switching high average power in long-pulse applications,

(h) Capability of operating into widely varying loads with modest pulse distortion,

(i) Capability of producing higher pulse voltages without the use of pulse transformers.

Fig. 12 shows a super-power hard-tube

modulator capable of producing 21 megawatts of peak power (1200 kilowatts of average power). Pulses of 2000-microsecond duration are produced at 35 kilovolts and currents up to 600 amperes. This particular modulator employs a parallel pair of shielded triodes (shown in Fig. 1). Tube drop is in the order of 3 kilovolts.

Advantages of Grid-Controlled Tubes for Particle-Accelerator Applications

In summary, the use of grid-controlled tubes provides the following advantages in particle-accelerator applications:

(a) Excellent rf phase stability.

(b) Stable operation with load mismatch. Grid-controlled tubes can operate without isolators under conditions of severe load mismatch. One of the most severe variable-load situations is encountered in connection with LINACS operating in the "standing-wave" mode. In this case, the load presented to the rf power amplifier by the LINAC tank swings from nearly zero at the beginning of the pulse to an approximate match as the tank gradient is established. Another load transient appears when the beam is injected into the LINAC. The use of hard-tube modulators facilitates rapid corrective control of the rf generator output in the face of load variations.

(c) Freedom from the requirements of focusing magnets.

(d) Reduction of insulation requirements in equipment and cables as a result of low operating voltages. The need for oil tanks and pot-heads is obviated. Even when grid-controlled tubes are high-level pulsed, the voltages required are usually sufficiently low to permit pulsing without the use of pulse transformers.

(e) Freedom from x-rays.

(f) Compactness. The compactness of grid-controlled tubes simplifies handling, installation, storage, and shipment. Compactness can be an important advantage in certain particle-accelerator installations in which low ceilings are used for reasons of economy in tunnel construction.

(g) Linearity. Grid-controlled tubes operate simply and efficiently as linear amplifiers.

(h) Life. Grid-controlled tubes have established an excellent record of life and reliability over the gamut of applications required in particle-accelerator service.

(i) Low harmonic-frequency output. Grid-controlled tubes can operate with comparatively low harmonic-frequency output.

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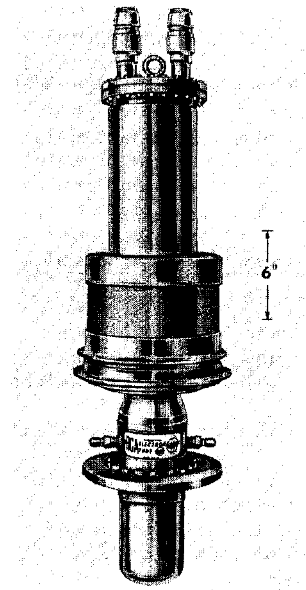

Fig. 1. Super-Power Shielded-Grid Triode.

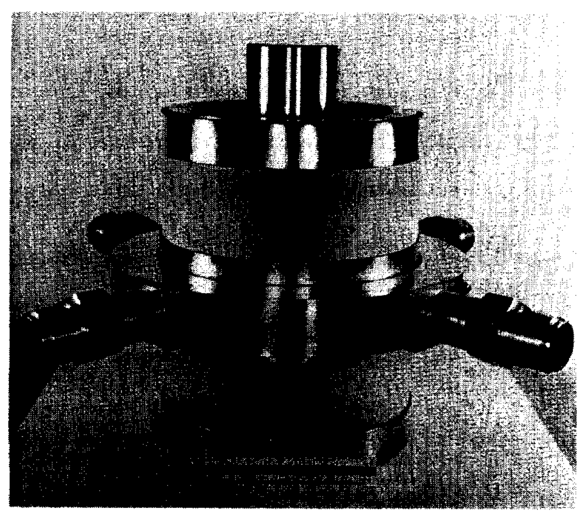

Fig. 2. Super-Power UHF Triode.

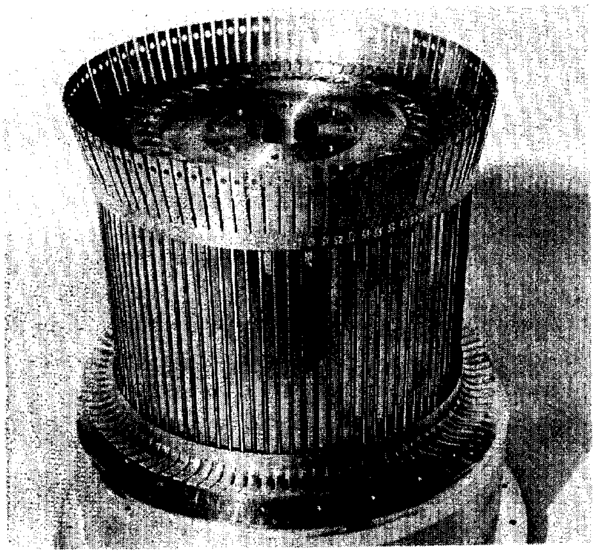

Fig. 3. Grid-Cathode Assembly for Super-Power UHF Triode.

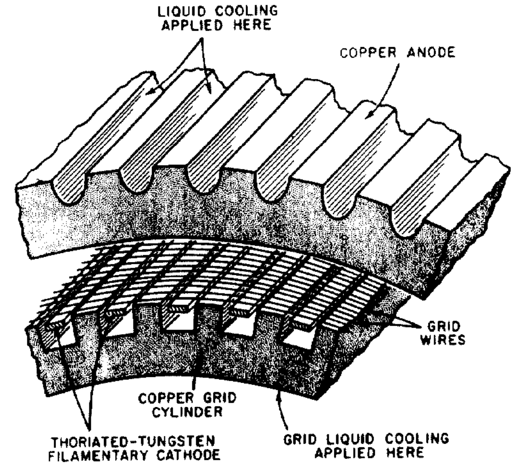

Fig. 4. Cross-section of Triode Units for Super Power Tubes.

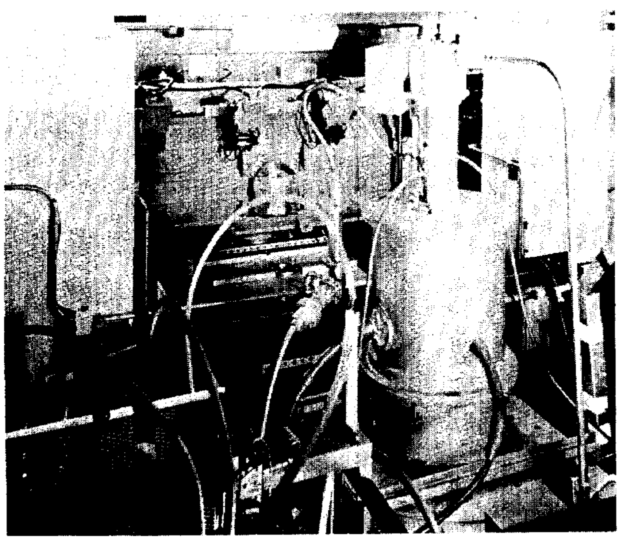

Fig. 5. Power-Amplifier Stage for Argonne National Labs. LINAC.

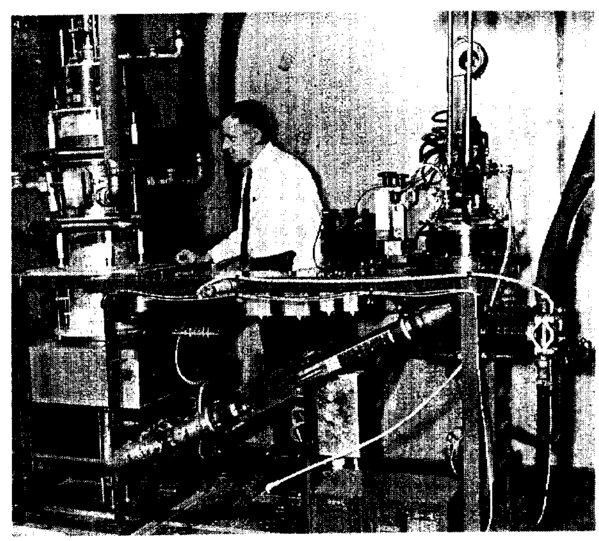

Fig. 6. The High-Power RF Generator for the Cambridge Electron Accelerator.

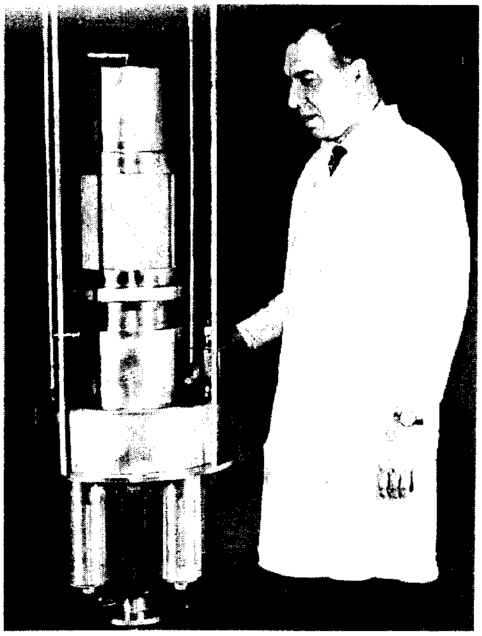

Fig. 7. A 5-Megawatt UHF Triode Coaxitron.

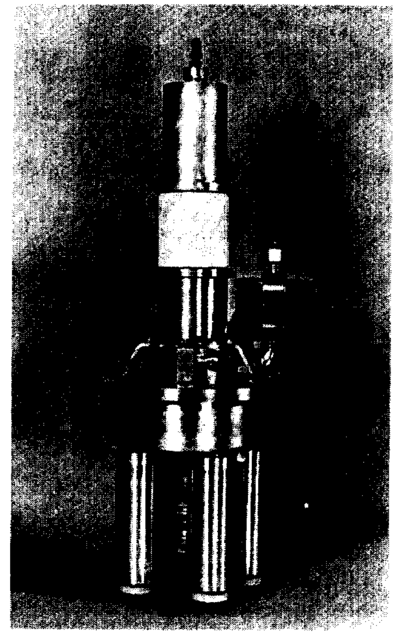

Fig. 8. An 805-Megacycle Triode Coaxitron for Particle-Accelerator Service.

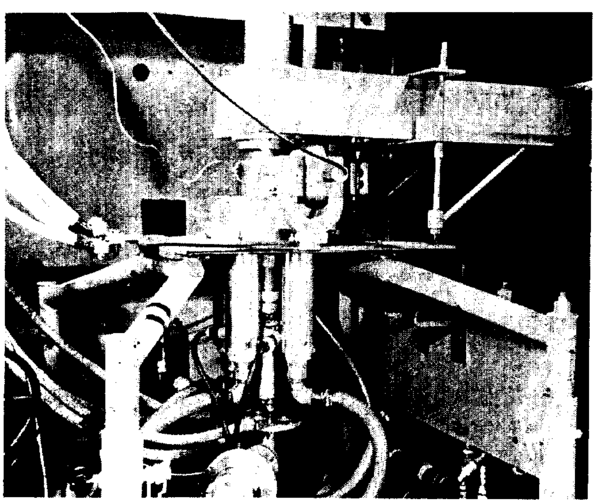

Fig. 9. An 805-Megacycle Triode Coaxitron in Test Cubicle.

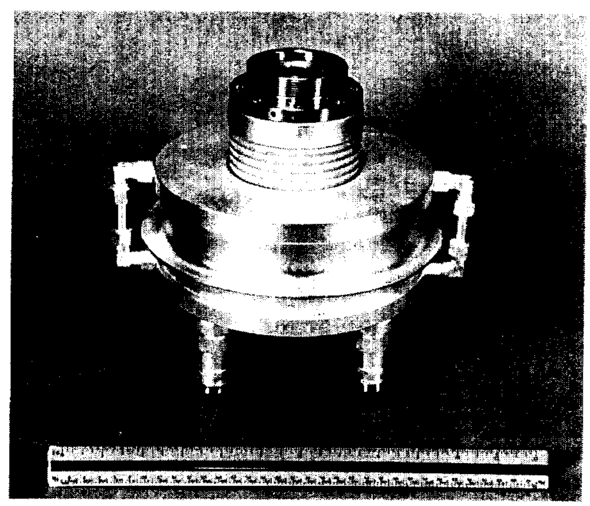

Fig. 10. High-Gain UHF Tetrode.

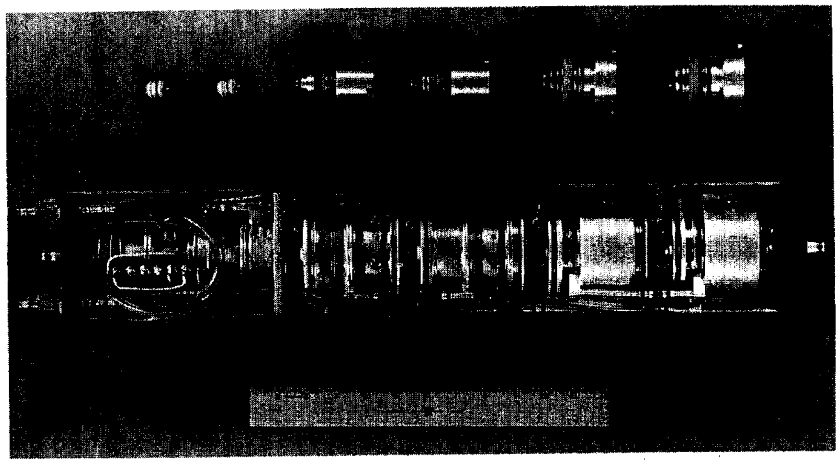

Fig. 11. A New High-Gain "Totem-Pole" Amplifier Utilizing Triodes and Tetrodes.

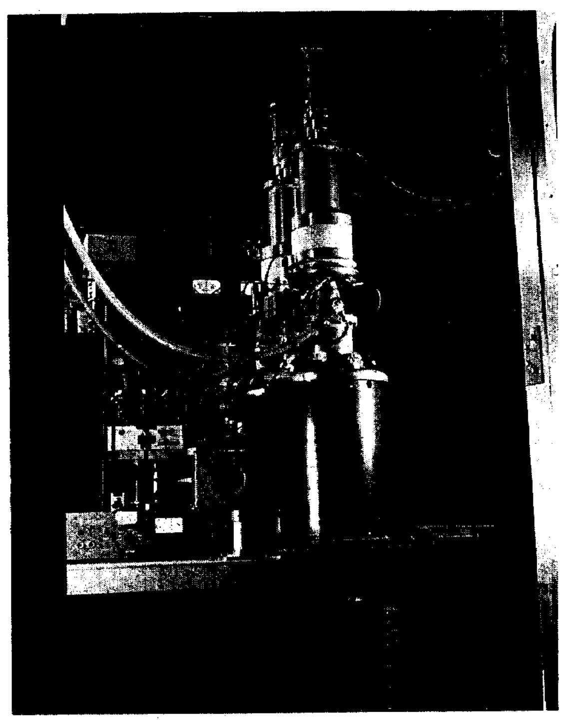

Fig. 12. A Typcial Super-Power Hard-Tube Modulator Employing Triodes.