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ADVANCES IN HIGH-POWER RF AMPLIFIERS*

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Abstract

Several powerful accelerators and storage rings are being considered that will require tens or even hundreds of megawatts of continuous rf power. The economics of such large machines can be dictated by the cost and efficiency of the rf amplifiers. The overall design and performance of such narrow-band amplifiers, operating in the 50- to 1500-MHz region, are being theoretically studied as a function of frequency to determine the optimum rf amplifier output power, gain, efficiency, and dc power requirements. The state of the art for three types of amplifiers (gridded tubes, klystrons, and gyrocons) is considered and the development work necessary to improve each is discussed. The gyrocon is a new device, hence its various embodiments are discussed in detail. The Soviet designs are reviewed and the gyrocon's strengths and weaknesses are compared to other types of microwave amplifiers. The primary advantages of the gyrocon are the very large amount of power available from a single device and the excellent efficiency and stable operation. The klystron however, has much greater gain and is simpler mechanically. At very low frequencies, the small size of the gridded tube makes it the optimum choice for all but the most powerful systems.

Introduction

The state of the art for high power rf systems for accelerators and storage rings is discussed. For accelerators that enrich nuclear fuel,[1] or storage rings such as LEP,[2] the economics of the entire project depend greatly on the rf power costs, which are functions of the rf amplifier frequency and output power per amplifier. The rf frequency depends on the type of particles to be accelerated and the frequencies vary from a few megahertz for heavy ion machines to a few gigahertz for electron linacs. The general requirements for accelerator and storage ring applications are that the rf gain and dc-to-rf conversion efficiency be as high as possible and that the physical size and cost be minimized. The bandwidth requirements are tightly coupled to the control system and a 3-dB bandwidth of a few megahertz is often required for adequate time response. The phase and amplitude stability requirements are often severe, such as ±1% in amplitude and ±1 degree in phase as required at LAMPF.

Four families of vacuum tubes have been used to provide rf power for these large accelerators. Gridded tubes, triodes, and tetrodes are used extensively at and below 201 MHz. Klystrons are generally used at higher frequencies. Crossed-field amplifiers, such as the amplitron and the magnetron, are often used in small, commercial x-ray accelerators, but not in large machines. In a recent compendium[3] of the characteristics of 41 linear accelerators, 26 used klystrons and 16 used gridded tubes. The total is 42 because LAMPF uses both types of rf generators.

The VEPP-4 accelerator complex at Novosibirsk in the Soviet Union uses a new type of rf amplifier, called a gyrocon by its inventors.[4,5] Gyrocons are used to drive the electron linac and the VEPP-4 ring.

We discuss the present state of the art and the expected improvements in the gridded tube, klystron, and gyrocon technology. About 10 years ago, groups at LAMPF and at the Intense Neutron Generator (ING) in Chalk River, Canada, attempted to use crossed-field amplifiers to drive large linear accelerators. In both cases, the crossed-field amplifiers did not satisfactorily power an accelerator and klystrons were used instead. Because of the negative results, the reader who is interested in this history has to study carefully the progress reports of these projects to comprehend the difficuties of driving a large accelerator with crossed-field amplifiers. The worst problem at LAMPF was the tendency of the amplifier to oscillate when connected to the accelerator. Many changes were made to make the amplifier more stable but these changes also lowered the dc-to-rf conversion efficiency. The combination of a crossed-field amplifier and a standing wave accelerator, which presents a time-varying load to the generator during the filling transients, should definitely be avoided.

Triodes and Tetrodes

Triodes or tetrodes are used in many accelerator applications, especially for frequencies at or below 200 MHz. The large proton machines at Brookhaven National Laboratory, LAMPF, and Fermi National Accelerator Laboratory all use the 7835 superpower triode to drive Alvarez structures at 201 MHz. This triode can deliver 5 MW peak power and up to 450-kW average power at this frequency. Large tetrodes can deliver higher average powers at lower frequencies. The X2159 tetrode can produce 1.5 MW of cw power at 50 MHz and the X2170 can produce 0.5 MW at 100 MHz. For higher frequencies the average power available varies inversely with the frequency and the limiting physical factor is the heating of the screen grid. When the plate dissipation per unit area is the limiting factor, the output power varies inversely as the fourth power of the frequency. When the cathode current density is the limiting factor, an inverse square frequency dependence is found.

The triode amplifier generally has a low rf power gain of 10-13 dB; thus, the driver stage is large and powerful. The gain in a tetrode is usually between 20 and 30 dB, which simplifies the drive stage design. To drive a cyclotron, the output frequency must vary over a very large range. Gridded tubes are generally used for this application[6,7] with either a broadband circuit or mechanical tuning to provide the bandwidth. Although the plate efficiency of a gridded tube can be very high, the system efficiency, which includes the driver and filament power, is often between 50-70%. The efficiency can be even lower if a series modulator controls the output power.

There are three evolutionary trends in the gridded tube field. Newer materials are being used to obtain better performance. An example is the use of pyrolytic graphite as a grid material to improve the dissipation capability. A second trend is to have the plate current out of phase with the plate voltage to reduce the power wasted at the anode. This idea, originally proposed by Tyler,[8] in 1958, is now used[9] in the standard AM broadcast band to raise the dc-to-rf conversion efficiency of gridded tubes above 90%. In the Tyler circuit third harmonic power, either externally supplied or generated from the tube's own nonlinearities, is used to shape the plate voltage. The aim is to have a square voltage wave and an out-of-phase square current wave on the plate so that no net heat is delivered to the anode. Although

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the Tyler circuit can raise the plate efficiency to over 90%, one should note that the overall efficiency of the commercial transmitters[9] is only slightly over 65%. If higher power tetrodes could be developed, a closer agreement of plate and overall efficiencies would be possible.

The third trend is an extension of the resnatron concept,[10] which may be more practical now because of improvements in beam control technology. The linear beam tetrode[11,12] would combine the cathode and the control grid of a triode or a tetrode with a modulating anode and a collector similar to those used in klystrons (Fig. 1). The grid and anode can be designed to intercept little or no cathode current. The anode and the collector are at the same dc potential but have a large rf potential between them. If the collector potential is depressed by the rf voltage at the time the electrons arrive, the collector heat dissipation can be quite low. This tetrode is very similar to a klystron in which the bunching is accomplished by a grid, rather than by velocity modulation. It appears that these linear beam tetrodes can be built in modules that could be used in parallel within the vacuum envelope to deliver large amounts of rf power. The usual transit-time limitations still apply to the resnatron family but they are reduced by the higher electron velocities in these amplifiers. It also seems likely that the output capacitance of the linear beam tetrode will be lower than in a conventional tetrode, causing a significantly higher upper frequency limit. We speculate that this technology may raise the break-even point between klystron and tetrode rf systems into the 150- to 250-MHz range. An excellent review of the status of gridded tubes up to 1972 is presented in Ref. 13.

Klystrons

Klystrons power more large accelerators than any other tube type. In 1970, the first highly efficient klystron,[14] realized with second harmonic bunching methods and with optimized drift and cavity parameters, produced 75% dc-to-rf conversion efficiency. Other high performance klystrons,[15-17] with 57-67% conversion efficiencies, are used in accelerator applications. PETRA[16] uses klystrons rated at 600-kW cw output power at 500 MHz and PEP[17] uses klystrons rated at 500-kW cw at 353 MHz. The klystrons at these facilities deliver the highest average output power now being used for accelerators. These klystrons have efficiencies that vary between 60-67%. The highest power cw klystron that has been built for high frequency operation is an X-band tube, the X-3030, which produced[18] 530-kW power at 8 GHz, using an extended interaction output cavity and multiple output windows. The commonly accepted limit to the power that can be delivered by a single klystron is about 1-MW cw, although it is technically possible to generate more power, especially at lower frequencies. The relation

$$P_{out} = 612.5/f_{MHz} \tag{1}$$

was suggested[19] as a conservative guide for the output power (P_{out}) in megahertz that may be easily achieved at any frequency in megahertz. Based on the X-band performance cited above, the constant in Eq. (1) may be seven times larger. In our opinion, the constant in Eq. (1) may be doubled or tripled if a serious, several-year development plan were started to satisfy higher power requirements. In a recent review,[20] Kaisel suggests that the limit to cw power production lies between 2 and 8 MW at 1 GHz. This limit would require the constant in Eq. (1) to be an order of magnitude larger.

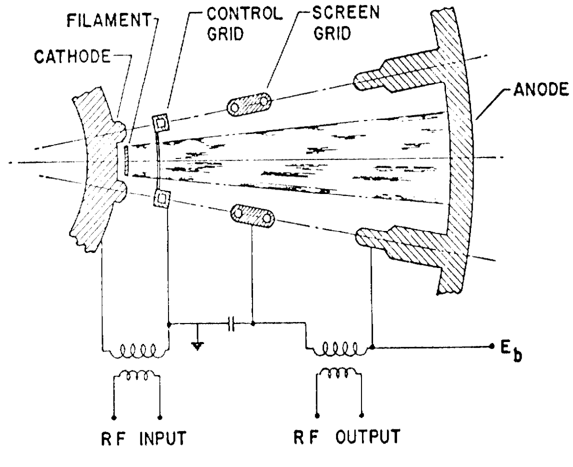

Fig. 1 The resnatron beam tetrode.

Klystron performance at the lower microwave frequencies is limited by several physical processes including peak electric fields, power dissipation in the output cavity, heat dissipation in the output window, or current density at the cathode. The first two problems are reduced by using a multicavity output section in the klystron, which is called an extended interaction output cavity. Multiple output windows reduce window heating problems. Some amplifiers share vacuum systems with the accelerators they drive. Thus, no output windows are required. Current density limitations in the beam or at the cathode are fundamental, but they have not been approached by the current technology below 3 GHz.

The klystron velocity-modulation principle continues to operate at very low frequencies, although the cavities and the rf drift lengths become very large. The low frequency at which klystrons become inferior to gridded tubes is a matter of opinion. We feel that gridded tubes are the optimum choice at or below 100 MHz, while klystrons should be used above 200 MHz. Between 100 to 200 MHz, the optimum amplifier type depends primarily on the size of the rf system and gridded tubes are probably the best choice except for the largest systems. Perhaps the resnatron type of tetrode will dominate this frequency range. The lowest frequency klystron now under commercial development is a 216-MHz unit rated at 3-MW peak power, 500-kW average power.

The limits to the dc-to-rf conversion efficiency in the klystron also are unknown. Experimental progress has been very slow; the first 65% efficient klystron was reported[21] in 1964, and 75% efficiency was achieved[14] in 1970, and has not been repeated since then. Many calculations on the optimum dc-to-rf con- version efficiency of the klystron have been made. There is considerable disagreement on the value of this maximum efficiency, but our evaluation, based primarily on the calculations of Mihran[22] and Hechtel,[23] is shown in Fig. 2. The optimum perveance, (the klystron's current divided by the 15th power of the beam voltage), is about 0.5 and the optimum efficiency for a solid beam klystron should be about 80%. Several improvements such as hollow beams, multiple-gap output cavities, depressed collectors, and symmetrical extraction of the energy from the output circuit will probably be required to raise the efficiency to 85-90%.

There are several recent developments in pulsed high power klystron technology. The maximum peak power from a single klystron is the 55 MW obtained[24] at 2856 MHz with an optimized Stanford Linear Accelerator Center klystron operating at 300 kV. This amount of peak power should be easier to obtain at lower frequencies. Fast modulators have been developed for television transmitters with 150-ns rise and fall times at the television repetition rate of 15 kHz. Even faster rise time and repetition rates are now possible and the accelerator community will undoubtedly benefit from this technology.

Gyrocons

The gyrocon is a new type of electron tube (Fig. 3), which operates by deflection modulation. The electron beam starts at an electron gun, is transversely deflected by the magnetic field within an input cavity, and deflected again by a static magnetic bender field. The beam then traverses a waveguide ring that resonates at the input cavity frequency. The azimuthal bunching may be considerably better than the temporal or spatial bunching that occurs in other rf amplifiers. The late G. I. Budker and his group at Novosibirsk have substantially improved this rather old idea and developed two gyrocons that can drive accelerators. The first Soviet gyrocon demonstrated[5] electronic efficiencies of over 90% and it now produces 40-MW pulses of 430-MHz rf power at a 1-Hz repetition rate with a 20-μs pulse length. The overall efficiency is 75%, although this pulsed gyrocon could produce 85% efficiency if more parameters were empirically optimized. This gyrocon is used regularly to drive the electron linac at the VEPP-3 accelerator complex.

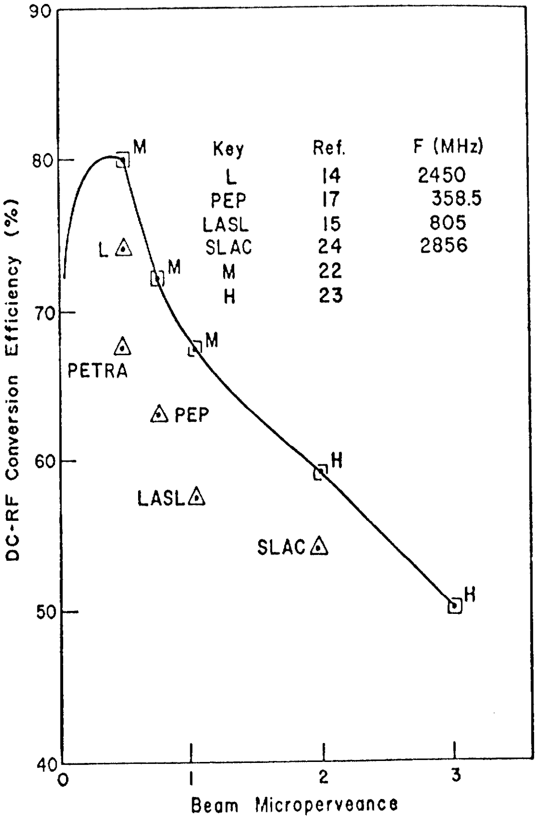

Fig. 2. Calculated and experimental klystron efficiency vs perveance.

The second gyrocon at Novosibirsk was designed to produce 5-MW cw rf power at 180 MHz to drive the VEPP-4 ring. Because the frequency is quite low, the gyrocon is 4.5-m tall and has a 1.4-m diameter. This gyrocon has operated reliably at 250 kW although it has operated for short periods of time at 1-MW beam power. The major problems arise from the large physical size of the gyrocon, parasitic oscillations, and the complex interlock system that protects the device. The designers hope to see conversion efficiencies between 75-85%. It is not clear what the best experimental data are.

An effort to analyze and build a gyrocon of the type shown in Fig. 3 is underway at the Los Alamos Scientific Laboratory (LASL). A computer model to follow electrons through the various gyrocon regions has been made and applied to many examples to determine how the dc-to-rf conversion efficiency and gain vary with beam voltage, current, and frequency. The computer code[25] includes the effects of space charge and relativity. Our earlier works[26,27] on the gyrocon provide additional historical background but they are limited to one-dimensional analysis of the problem. The one-dimensional case is interesting because the electronic efficiency can approach 100% when space charge and finite beam size are neglected.

The LASL gyrocon is being designed to produce 650 kW at 450 MHz. The calculated conversion efficiency is over 85%. Electronic and overall efficiencies for several gyrocons are listed in Table I, grouped by the power in the dc beam. The beam voltage and current, the electric field in the input and output resonators, and the rf gain are also tabulated. The frequency was held at 450 MHz and an initial beam radius of 1 cm was assumed. The initial beam was assumed to have zero emittance. This gyrocon is called radial style, because the electrons interact primarily with the radial electric field in the output resonator. We performed some frequency response calculations for this type of gyrocon and the results are summarized in

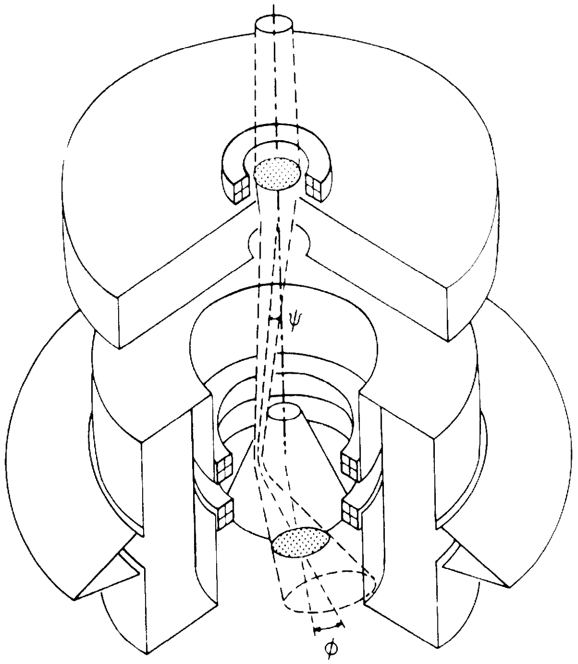

Fig. 3. The gyrocon.

TABLE I

450-MHz GYROCON PERFORMANCE SUMMARY
WITH A 1-cm INITIAL BEAM RADIUS

V_o (kV)	I_o (A)	E_{od} (MV/m)	E_{oo} (MV/m)	Electronic Efficiency	Overall Efficiency	P_{out} (kW)	rf Gain
			100-kW Beam Power				
50	2.0	1.05	1.10	0.8872	0.7187	78.1	8.9
100	1.0	1.05	1.80	0.9026	0.5852	61.9	10.6
200	0.5	0.90	1.30	0.4803	0.2389	24.9	5.9
500	0.2	1.10	0.50	0.0989	0.0506	5.4	0.9
1000	0.1	2.10	0.30	0.0312	0.0126	1.5	0.1
			300-kW Beam Power				
50	6.0	1.30	1.15	0.8582	0.7522	245.9	8.9
100	3.0	1.30	2.15	0.9615	0.8149	254.9	19.8
200	1.5	1.00	3.50	0.9626	0.7332	226.0	27.5
500	0.6	1.65	4.10	0.7384	0.3993	125.1	9.4
1000	0.3	1.00	1.80	0.1945	0.1277	38.8	9.4
			1000-kW Beam Power				
100	10.0	1.80	2.05	0.9135	0.8329	868.0	20.6
200	5.0	0.70	3.40	0.9559	0.8848	894.4	83.0
500	2.0	1.80	5.85	0.9381	0.7378	749.3	48.3
1000	1.0	2.40	2.80	0.3017	0.1490	152.6	6.5
			3000-kW Beam Power				
100	30.0	3.60	2.05	0.8514	0.8058	2508.7	22.2
200	15.0	1.80	3.00	0.9269	0.8830	2703.3	43.8
500	6.0	1.40	5.40	0.9096	0.8283	2499.9	137.1
1000	3.0	2.40	7.30	0.7459	0.4197	1269.4	51.6
			10000-kW Beam Power				
200	50.0	1.50	4.00	0.8231	0.7548	8064.8	11.8
500	20.0	2.00	5.90	0.9426	0.8975	9067.3	88.9
1000	10.0	2.90	10.20	0.9549	0.8700	8756.1	136.5
2000	5.0	4.80	17.80	0.8647	0.6112	6181.6	53.9

TABLE II

EFFECT OF FREQUENCY ON GYROCON PERFORMANCE
(V_o = 86 kV, I_o = 9 A, r_o = 1 cm)

f (MHz)	E_{od} (MV/m)	E_{oo} (MV/m)	Electronic Efficiency	Overall Efficiency	P_{out} (kW)	RF Gain
100	2.90	2.90	0.7204	0.4933	514.8	1.9
200	2.00	1.00	0.9017	0.8037	662.5	13.2
450	2.00	1.80	0.9184	0.8502	682.6	22.4
600	2.10	2.60	0.9155	0.8257	662.9	22.9
900	1.90	2.80	0.8174	0.7399	587.8	28.8
1200	2.40	3.10	0.6342	0.5215	438.0	6.7
1500	6.00	3.25	0.4666	0.4130	331.6	11.5

Table II. The initial beam once again has a 1-cm radius and the current and the voltage are 9 A and 86 kV, respectively. The gyrocon can have a higher efficiency than a klystron at frequencies below 1 GHz. There is no theoretical low frequency limit but the author suggests that the 4.5-m long, 181-MHz gyrocon may be considered very close to the limit set by sheer size.

The bender solenoid of the gyrocon must be eliminated to give good efficiency above 1 GHz. It may be possible to make a planar gyrocon (Fig. 4) in which the electrons travel radially from an rf driven cathode, across a dc accelerating gap, and into an output resonator. The most complicated part of the planar gyrocon is the rf driven gun but several possibilities to solve this problem have been suggested. One possibility is that an rf traveling wave on the cathode circuit produce a multipactor discharge, as in the multipactor electron gun.[28] A second possibility is to have an rf excited crossed-field gun, as is used in some amplitrons.[29] A third possibility is to use a traveling wave version of an ordinary grid-cathode arrangement similar to that in an ordinary triode. Lebacqz[30] discusses this arrangement, called a triotron at this Particle Accelerator Conference. If we assume that one of these guns operates and produces a rotating cathode, it is quite simple to compute rather high dc-to-rf conversion efficiencies. As an example, at 2450 MHz, a planar gyrocon analysis code predicted a dc-to-rf conversion efficiency of 86% provided that the cathode emitting area is less than 1 radian in azimuthal and 3 cm in axial extent. The electron gun is the key to the planar gyrocon, and until a good gun is demonstrated or a good electron gun code is made for the rf-driven cathode, we can do little more than speculate on the utility of these devices above 1 GHz.

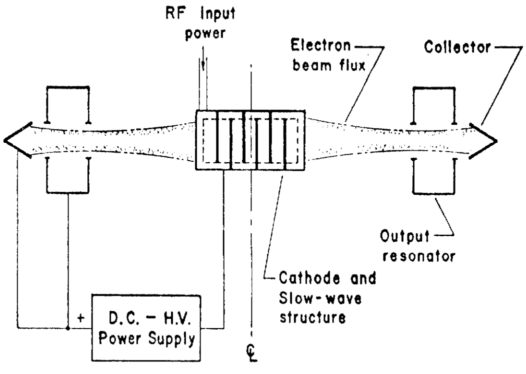

Fig. 4. The planar gyrocon.

The theory of a spherical gyrocon, a benderless gyrocon, is being developed at LASL. The electron beam is deflected directly into a spherical resonant output cavity, as shown in Fig. 5. Spherical coordinates describe the rf fields in the output waveguide and the primary interaction is again with the radial component of the electric field. Another concept, shown in Fig. 5, is the use of one or more beam-driven deflection cavities to provide the large deflection angle required for the spherical case with a relatively small rf drive. The supplemental cavities are

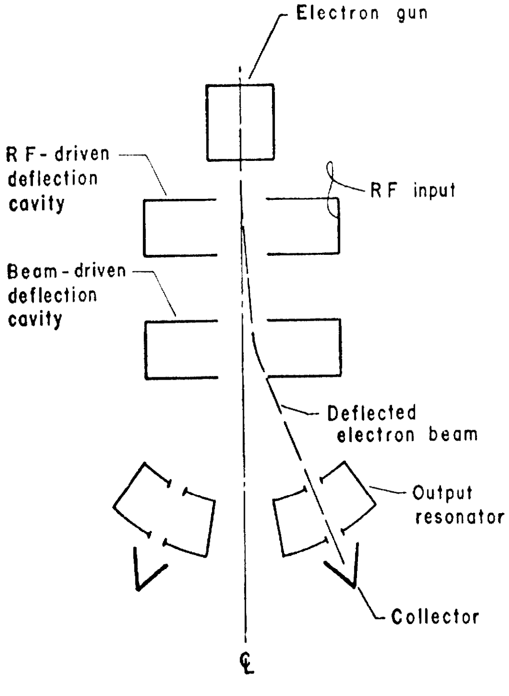

Fig. 5. The spherical gyrocon.

tuned to provide additional beam deflection, just as the intermediate cavities in a klystron provide additional bunching to a partially bunched beam. The supplemental cavities may be used with the Soviet type of gyrocon to raise the rf gain.

Conclusion

Although progress in high power rf amplifiers has been fairly slow in the past decade, the technology is now advancing at a more rapid rate. There have been no revolutionary breakthroughs but the frequency, power output, and efficiency frontiers are advancing. Several older ideas, such as the resnatron and deflection modulated amplifiers, are being investigated again with the better understanding of particle dynamics now available. The technology mentioned above should be significantly advanced by the work that is now beginning.

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