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NEW KLYSTRON TECHNOLOGY

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Introduction

The characteristics of high power RF sources are subject to increasingly demanding requirements, and, precisely for this reason, much important progress is made in this field.

These klystrons are used mainly in two fields : radars and scientific instrumentation. Particle accelerators create the needs for higher and higher peak or CW power levels, and also high efficiencies, in order to optimize the costs of installation and utilization. Plasma heating tubes benefit from progress in these areas, but an additional requirement of tolerance of high output SWR is imposed because of the plasma which is a very instable, fluctuating load.

High Peak Power Pulsed Klystrons

A large number of linacs are powered by S-band klystrons (2.856 or 2.9985 GHz) with pulse durations on the order of a few microseconds. Peak output power levels which can be presently chosen in the various projects surpass 30-40 MW. Table 1 shows some examples.

The TH 2094 is a five cavity tube which delivers 37 MW peak or more with an RF pulse length of 5 μsec and average power of at least 20 kW at 3 GHz. Besides the gain of 53 dB (175 W driver), its most important characteristic is the efficiency of 48 %, whereas the operating voltage is quite modest, 275 kV, which means a perveance of 2 μperv. (figure 1). A special output cavity has been designed in order to get the optimum low coupling factor, Qex, between the cavity and the single output waveguide.

Indeed the TH 2094 has a single output arm and a single window which is very convenient for the simplicity of the whole RF generator system. The window is pressurized with 3 to 4 bars of SF6. At higher levels (50 MW and more), tests have shown that SF6 breakdown voltage can be reached, unless special precautions are taken : very dry SF6, frequent purges, additional components,... Therefore a second window type with vacuum on each side is under development : in this case, the problem to be solved is to protect the ceramic against discharges whose origins are not well known. This protection is obtained by very thin titanium coatings which are difficult to form and to process, and the windows must often be tested before use.

In order to avoid any arcing on the lips of the output cavity, where the alternative fields can reach 400 kV/cm, the beam transmission obtained by a suitable magnetic field must be perfect. And beyond 10^{-3} of duty factor, these lips can be damaged if their cooling is not taken into account in the design. The missing-pulses rate of the TH 2094 is much less than one in 10^7.

In C-band, we have a similar situation, but with lower power levels. Presently the TH 2067 delivers 5 to 7 MW of peak power in 10 μsec pulses, and may put out up to 8-10 kW of average power. Power-doubling tests are already planned. Beyond that, modifications will need to be considered, not of the technology, but of the construction parameters, in order to improve the efficiency as well as the output power levels. The C-band is attractive to reduce accelerator dimensions.

Very Large Pulsewidth Tubes

Some linacs, especially in FEL applications (but in others as well) require peak power levels of a few MW but with pulse durations of several hundreds of usec, mostly in L-band for the moment. This type of performance has been obtained with the TH 2095 : 6 MW peak/50 kW avg. at 1.3 GHz in 300 μsec pulses. This large pulsewidth, also useful at times for radar applications (500 μsec in S-band with the TH 2092) is generated by a pulse-forming network (PFN), but in a more flexible manner by a hard tube, or by a modulating anode with which the klystron, such as the TH 2095, should be equipped. This demands, among other things, a very high dc voltage (130 kV) on the cathode, and also electric dc field between the BFE and the anode on the order of 10-12 kV/mm during the entire pulse, in spite of the conception of forms having as large a radius of curvature as possible. The following necessities arise as a result : to obtain a very high vacuum in the electron gun ; to lower the cathode temperature as much as possible ; to avoid all barium evaporation ; to heat-treat and surface-treat the HV ceramic insulators ; and, above all, to protect the tube in case of arcing (current-limiting resistors in series with the HV, fast crowbar circuit breaker, etc...).

CW Tubes

CW klystrons are used for synchrotrons, storage rings, stretchers, and of course for the entire microtron family. The frequencies and power levels required vary greatly in the different cases, as illustrated by the TH 2075 and TH 2089 in Table II.

The TH 2075 was designed to operate at 2450 MHz with high efficiency (62-64 %) at 50 kW of output power (25 kV), and retains a rather high efficiency of 55 % even at a reduced output power level of 25 kW (20 kV). The perveance is 0.8 μperv. The collector is insulated and can operate with a simple vaporization cooling system. The tube lifetime exceeds 25,000 hours, and is often used for industrial heating in a very hostile environment.

The TH 2089 delivers 1.1 MW at 352 MHz (see figures 2 and 3), two characteristics which explain its size (approx. 4.5 m long). Unlike the TH 2075 it is of recent design, which made extensive use of sophisticated computer codes employing both time- and z-stepping. The extremely high efficiency of 68-70 % obtained with the production tubes is partially explained by the perveance of 0.75 μperv. A modulation anode allows to optimize the efficiency at different output power levels. The collector is not insulated, and can dissipate 1.6 MW dc. The tube operates in the horizontal position to fit easily into a tunnel.

These two tubes are the starting points of an entire family of CW klystrons, for example the TH 2105 (figure 4) now under development to furnish 1 MW at 508 MHz with a 65 % efficiency, and with collector cooling by vaporization or forced water. The TH 2105 operates in the vertical position, and like the 352 MHz tube, the coaxial window is connected by a door-knob to a WR 1500 waveguide. The adaptation of these two tubes to furnish peak power levels of 2.5-4 MW in pulses of a few msec at 352 and 508 MHz or neighboring frequencies is also foreseen after a complete change in the window technology.

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As for the TH 2075, it may also be designed to operate at 2856 or 3000 MHz and optimized for lower or higher power levels (10-20 kW, 75-80 kW).

Limits of the Power-Frequency Domain

The tubes given as examples above demonstrate that projects are demanding performances near the limits of the state-of-the-art (1). The state-of-the-art is described in the power versus frequency diagrams by curves whose features suggest several limiting phenomena which we have tried to analyse.

The peak RF voltage developed across the gap of the output cavity is slightly greater than the acceleration voltage. This implies fields two or three times that strong on the reentrant ends of the drift tubes, and 300 kV/cm in 10 µs pulses and 150 kV/cm CW can be considered as very high fields. Cathode loadings of 10 or 15 A/cm^2 peak and 2 or 3 A/cm^2 CW become classical. But for the gun design we must also take into account the area convergence C and the perveance K : the greater these two parameters are, the more difficult the gun design becomes. The following pair of classical values can be advanced : C = 40 ; K = 2 µperv and C = 80 ; K = 0.5 µperv. The heating of certain parts of the tube imposes a third limit : 500 to 1000 W/cm^2 are now acceptable in the collector with forced water, or with the Hypervapotron® which needs low water flow rates, and vaporization phenomena. But in the cavities and especially in the output cavity, the lips are heated by violently decelerated electrons and furthermore by strong RF surface currents. An acceptable temperature limit is around 250-300 °C unless special copper alloys are used, which would allow to increase these values by about 100 °C. Technological studies are now underway in this area.

The figures 5 and 6 give some examples of such calculated diagrams, where can be indicated both existing klystrons and also new klystrons in the design stages, such as the TH 2103. This tube, now under development, will deliver 500 kW CW at 3.7 GHz with two windows. The electron beam (58 kV x 20 A) allows an efficiency of more than 45 % and a gain of 43 dB with 5 fundamental cavities : these characteristics have been confirmed on the first preprototype tests at 50 msec pulse length. At the moment several problems relating to CW operation are being solved. The first is the cooling of the output cavity, which is complicated by the small dimensions characteristic of operation at 3.7 GHz. The geometry and electrical characteristics of the output cavity are still undergoing final adjustments. The second problem arises from the goal of being able to tolerate an all-phase SWR of the load as high as 2:1 or even 3:1.

The operation of the klystron will be stabilized by a feedback loop controling the driving or the anode voltage using signals taken from the output circuit, or possibly even in the tube itself. The electron gun will, in fact, be equipped with a modulation anode in order to better optimize the performance.

Conclusion

The performances of klystrons presently under development give a good indication of the increasingly severe demands of the users. Undoubtedly, this escalation will force the klystron manufacturers to find new solutions involving fundamental modifications, as mere technological refinement is reaching its limits.

(1) Microwave Journal, October 1983

TABLE I - Thomson-CSF Very High Peak Power Pulsed Klystrons

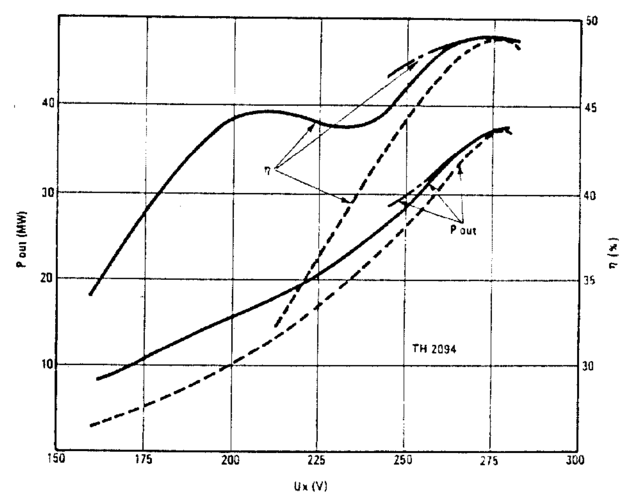
Klystron	Frequency (MHz)	Po peak (MW)	Po avg. (kW)	RF pulse duration (µsec)	Vo x Io (kV x A)	Efficiency (%)	Pdrive (W)	Nb. of RF windows (medium)
F 2042	2998.5	41	12.5	6.5	303 x 324	42	240	2 (S F6)
TV 2030	2998.5	35.5 38	15 20	4.5 5	300 x 296 300 x 327	40 39	180 550	1 (S F6) 1 (S F6)
TV 2002D	2998.5	32 30	10 20	6 6	274 x 315 266 x 280	37 40	240 240	1 (vacuum) 1 (vacuum)
TH 2094	2998.5 2998.5	37 37	20 20	5 5	275 x 280 275 x 280	48 48	180 180	1 (S F6) 1 (vacuum)*
TH 2067	5712	6	6	10	135 x 105	42	80	1 (S F6)

* Under development

TABLE II - Thomson-CSF CW and Long-Pulse High Power Klystrons

Klystron	Frequency (MHz)	Operating mode	Po peak	Po avg.	RF pulse duration	Vo x Io (kV) (A)	Efficiency (%)	Pdrive (W)	Output waveguide
TH 2089*	352	CW	1.1 MW	1.1 MW	CW	87.5 x 18.5	68	75	WR 2300
F 2055*	500	CW or pulsed	300 kW 500 kW	300 kW 250 kW	CW 100 ms	46 x 15.2 50 x 25	43 40	50	Coaxial
TH 2105**	508	CW	1 MW	1 MW	CW	85 x 18	65	80	WR 1500
TH 2086A	1300	Pulsed	1 MW	60 kW	1 sec	69 x 36	40	20	WR 650
TH 2095*	1300	Pulsed	6 MW	60 kW	300 µsec	130 x 96	48	200	WR 650
TH 2054 and TH 2075	2450	CW or pulsed	50 kW 80 kW	50 kW 40 kW	CW 100 ms	26 x 3.1 32 x 4.1	62 61	1 1.5	WR 340
TH 2103**	3700	CW	500 kW	500 kW	CW	58 x 20	46	5	WR 284

* With a modulating anode
** Under development



—— Magnetic field and drive power optimized at each voltage
- - - - Magnetic field and drive power optimized at 275 kV (Pd : 160 W)
— - — Magnetic field, drive and tuning optimized at each voltage

FIGURE 1 - RF OUTPUT POWER AND EFFICIENCY VERSUS CATHODE VOLTAGE (TH 2094)

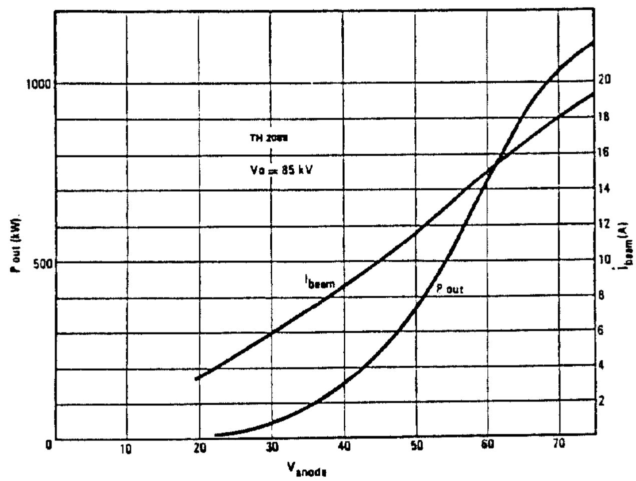


FIGURE 2 - BEAM CURRENT AND OUTPUT POWER VERSUS ANODE VOLTAGE (TH 2089)

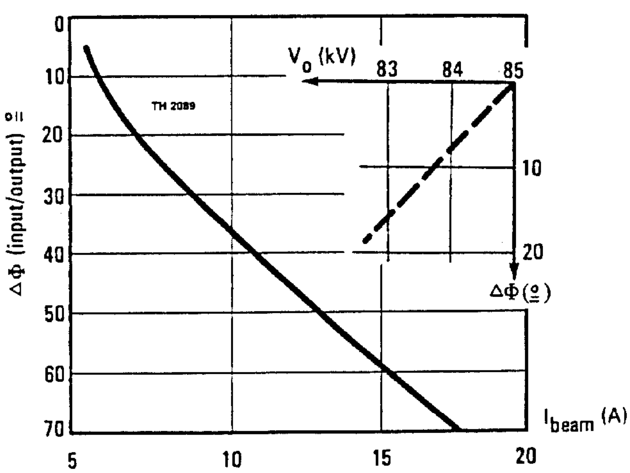
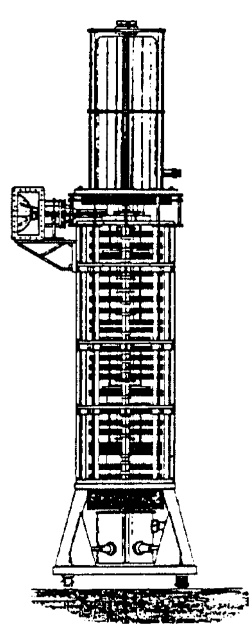


FIGURE 3 - PHASE VARIATIONS VERSUS I BEAM AND V_0 (TH 2089)

FIGURE 4 - TH 2105
KLYSTRON 1MW CW
508 MHz (85kv)



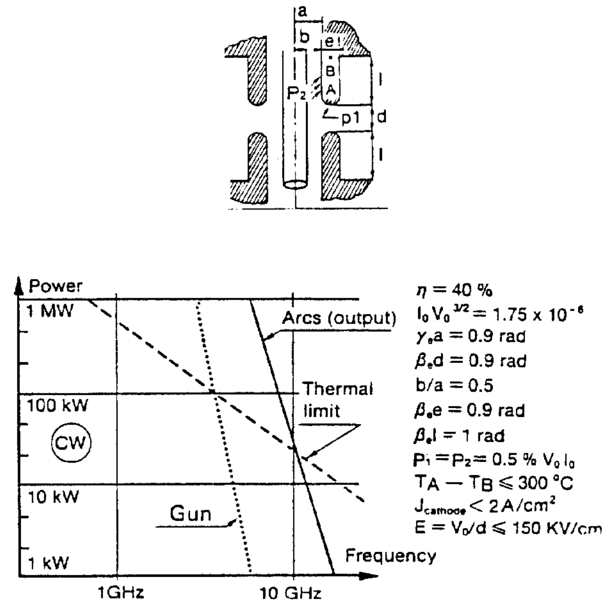


FIGURE 5 - POWER, FREQUENCY AND COMPUTED LIMIT DIAGRAM FOR KLYSTRON WITH A 40% EFFICIENCY AND 1.0 μ PERV. PERVEANCE

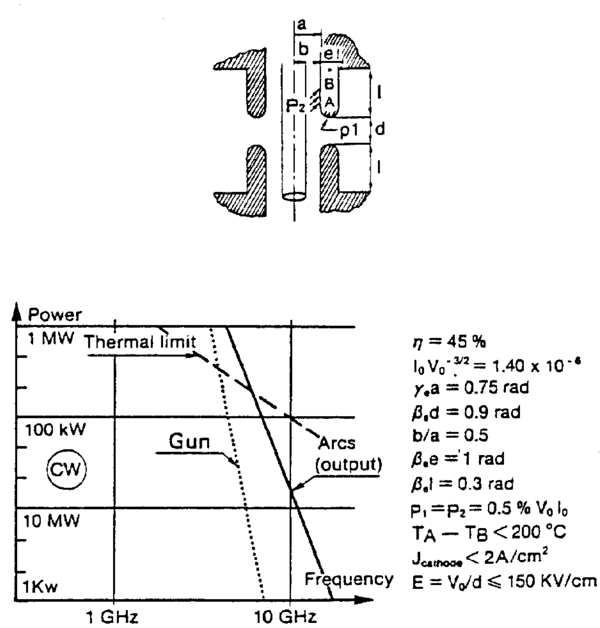


FIGURE 6 - POWER, FREQUENCY AND COMPUTED LIMIT DIAGRAM FOR KLYSTRON WITH A 45 % EFFICIENCY AND 1.40 μ PERV. PERVEANCE