Proceedings of the 1984 Linear Accelerator Conference, Seeheim, Germany

A High-Efficiency 37 MW / 3 GHz / 5 μs Multicavity Klystron

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Introduction

The RF energy for particle accelerators is usually supplied by either CW klystrons (synchrotrons, synchrocyclotrons, storage rings, etc.) or by pulsed klystrons ($e^{\pm}$ and proton linear accelerators, FEL, etc.).

In the last few years, there has been a marked improvement in the characteristics (power, efficiency, and pulselength) offered by CW and very long pulse klystrons, as shown in Table I.

Pulsed klystrons can be divided into 2 categories :
1) wideband klystrons used in long range radar systems, which boast a relative instantaneous bandwidth of up to 10 % and peak power on the order of 20 MW (Table II); and 2) klystrons for particle accelerators (Table III), which have enjoyed the benefits of R and D work on the former tube types, especially concerning the windows and elimination of spurious oscillations.

Calculations

Great advances have recently been made possible by computer-aided design techniques, especially in the non-linear regions near the output cavity.

The initial approximation is to consider the beam as made up of rigid discs ; the equations of motion are then solved stepwise ("Z-stepping") using the field values and space charge in the cavities for each Z-value throughout the length of the tube (one dimensional model). One of the first such models was that of Wang (1958). The EIGER computer program (Thomson-CSF) was based on this model, but with some improvements : the space-charge fields and cavity fields are known more precisely, and the currents are calculated by iteration using the characteristics of each cavity (R/Q, frequency, gap length ...).

The validity of these programs has been demonstrated, for example, on the TH 2054, a 2.45-GHz, 50-kW CW klystron (perveance 0.8 μperv), for which the computed and measured efficiencies are, respectively 66 and 62 % ; and recently on the TH 2094, a 37-MW peak, S-band, short pulse klystron with efficiencies (computed and measured) of 50 and 48 %.

Nevertheless, it seemed rather difficult to employ such Z-stepping, rigid-disc programs to fairly correctly compute structures and beams with tube efficiencies of 70 % and to take into account some non-linear phenomena. A first step towards greater precision is to shift to a time-stepping program, while remaining undimensional. These programs, applied to the last drift tube and the output cavity, allow, for instance, to obtain an indication of the klystron response to a varying load ; however they are more expensive to use than the Z-stepping type, which may explain why they are little used.

A second step towards greater precision in predicting tube behavior is the r-z ballistic computation of the beam in the presence of RF fields, deduced from an earlier program, without ommiting the effects of the beam-confining magnetic field. The kinetic efficiency is also computed. It is seen that the ripple is perturbed after passage through the final cavities, and that the braking field in the output cavity has a convergent effect before the demodulated beam breaks up and produces strong current interception on the output lips.

Certain reflected electrons are in fact electrons that oscillate once or more in the output cavity and then continue toward the collector. These so-called "oscillating electrons" provide the first sign of a coming drop-off in efficiency and an increase in the electron interception on the drift-tube lips.

A more compact form of the RF field has a beneficial influence on the efficiency. An analogous effect can be obtained by locally reducing the magnetic field, but the compromise between the reflection of electrons and the interception of electrons on the output drift-tube lips is then difficult to compute - and difficult to achieve, of course, technologically speaking.

Perveance

Because of the rising cost of energy, and also the high investment cost of power supplies and high voltage modulators, the last ten years has seen an increasing interest in obtaining the maximum tube efficiencies. Some relevant design considerations include the position and geometry of the respective cavities, their resonant frequencies (and harmonics), and the radius of the electron beam.

However the efficiency also seems to have a general dependence on the beam perveance : in minimizing the perveance, the maximum efficiency limit obtainable in a "perfectly-designed" tube is increased. The explanation of this effect lies in the reduction of space charge forces (in the case of reduced perveance) which allow for better electron bunching performance and thus more pronounced current modulation. The experimental results obtained on recent tubes that were especially designed to yield high efficiencies (TH 2089 ; TH 2054 ; TH 2094) confirm the theoretical calculations.
With a perveance of 0.5 μperv, we cannot presently hope for a real efficiency (as opposed to interaction efficiency) better than 70 - 75 % ; in addition to known limiting factors such as cavity losses, interception, and potential wells, we need also consider the imperfect braking of the electron bunches in the gap of the output cavity.

Windows

Windows are one of the most critical elements in high power RF systems, and are also one of the most difficult to design, develop, fabricate and use. A frequent choice is the "pill-box" type window with a thin disc ($e \ll \lambda g$). The thicker, half-wave windows are sturdier and generally are less lossy, but their use demands much more careful attention ; in addition their technological realization is more delicate, as is that of rectangular windows.

Heating gives rise to physical constraints : compression in the center and traction at the edges. In some cases this force reaches 6 kg/mm^2, which is considerable compared to the maximum "breaking-point" force of 21 kg/mm^2.

In addition, when the electric field values are very high (TV 2030, TV 2002, TH 2094) there can be dangerous discharge phenomena in the window region (field emission, multipactor effect, ...) which are to be avoided by machining, mechanical and thermal surface treatments, and by appropriate "start-up" procedures to gradually approach the maximum operating power levels. This is how a single window can be used to transmit 40-50 MW at 3 GHz with a 4-5 μs pulsewidth (TH 2094). The window design differs slightly for use under vacuum or in a SF6 atmosphere.

TH 2094

The **TH 2094** is a high power, pulsed klystron, especially designed for linear accelerators. This five cavity tube delivers a peak output power of 37 MW or more, with a RF pulse length of 5 µs and an average power of at least 20 kW at 3 GHz. Its most important characteristics are a very high gain of 53 dB (drive power less than 200 W) and a very high measured efficiency of 48 %, with a perveance of about 2 µperv, and a modest operating voltage of 275 kV.

Another important feature is its single output window, which eliminates the problem of a recombiner. The window is (in the case of the TH 2094) pressurized with 3 bars of SF6. The tube is derived from the TV 2030 and TV 2002, and features : an impregnated cathode and a built-in ion pump to ensure a long operating life ; a simplified collector technology ; and water cooling of the collector, body, and window.

The electromagnet consists of three main coils and a countercoil around the gun, supplied in series with the coil no. 2.

The Figure 1 gives the transfer curve where the small signal gain is 58-60 dB and the saturation gain 53 dB.

The Figure 2 shows the output peak power and the efficiency versus the high voltage (48 % at 275 kV) in different cases, and the Figure 3 gives the constant drive instantaneous bandwidth at saturation (10 MHz for ΔP/P = 0.2 dB).

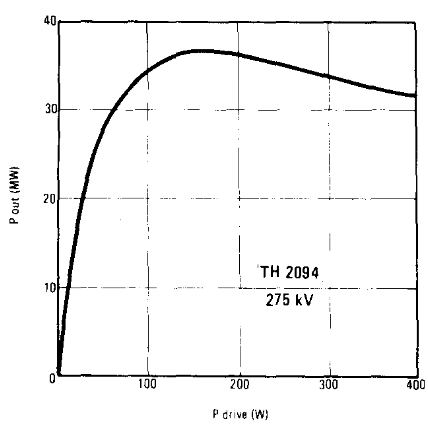

Figure 1 - RF output power versus RF drive power at 275 kV and 2998.5 MHz

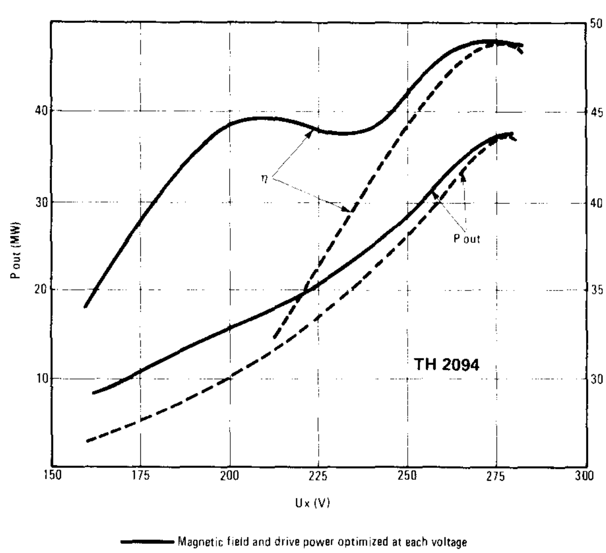

Figure 2 - RF output power and efficiency versus cathode voltage

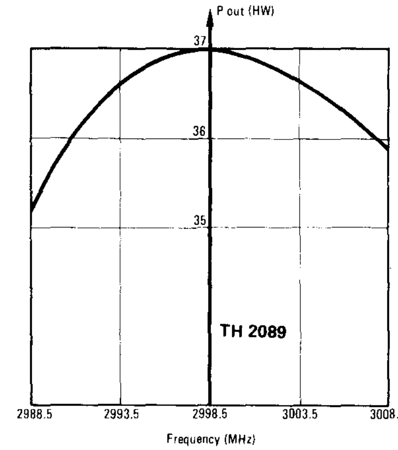

Figure 3 - RF output power versus frequency
(Uk = 275 kV - Pd = 150 W at each frequency)

TH 2089

At the other end of the frequency spectrum (352 MHz), the TH 2089 continuous-wave superklystron delivers 1.1 MW (CW) with one of the highest operating efficiencies ever obtained : **68 %**. This high efficiency is obtainable with a suitable combination of low perveance (0.72 µperv) and optimum geometry (beam diameter, cavity dimensions and positions). In addition, four of the (tunable) cavities are adjusted to resonate at (or near) the fundamental frequency Fo for a four stage gain of 42-43 dB, whereas the remaining cavity is adjusted to the 2nd harmonic 2Fo. The TH 2089 is a very large klystron because of its high power and low frequency : 5 m long and 2500 kg. It has therefore been designed to be used in a horizontal position, supported by a rigid I-beam chassis. The electromagnetic beam-confinement coils are incorporated, as is the high voltage oil tank. A coaxial output window and transition allow output coupling to a WR2300 waveguide. The collector is capable of dissipating 1.6 MW using the patented Hypervapotron® cooling principle. The output power level may be controlled by the RF driver signal or the modulating anode, which is energetically advantageous.

The test facility at Thomson-CSF used for this superklystron includes a power supply of 18 A at 115 kV or 21 A at 100 kV. The high voltage may be increased some 25 kV in order to allow the development and testing of klystrons delivering up to 2-2.25 MW (CW) and up to 300-600 kW (avg.) for the pulsed klystrons.

Figures 4, 5, and 6 show some characteristics of the TH 2089.

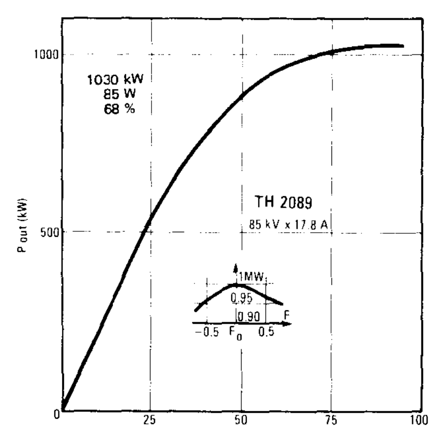

Figure 4 - Output power versus drive power and bandwidth

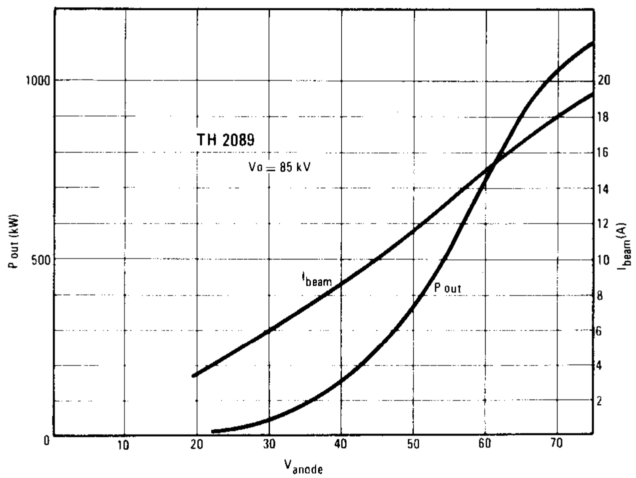

Figure 5 - Beam current and output power versus anode voltage

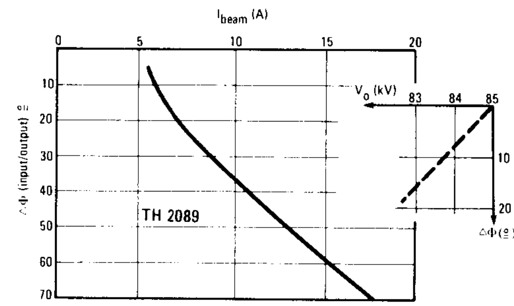

Figure 6 - Phase variations versus I_{beam} and V_o

TABLE I - Thomson-CSF CW and long-pulse high power klystrons

Klystron	Frequency (MHz)	Operating mode	P_o peak	P_o avg.	RF pulse duration	V_o x I_o (kV) (A)	Efficiency (%)	P_{drive} (W)	Output waveguide
TH 2089*	352	CW	1.1 MW	1.1 MW	CW	87.5 x 18.5	68	75	WR 2300
TH 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	-	Coaxial
TH 2086A	1300	Pulsed	1 MW	60 kW	1 sec	69 x 36	40	-	WR 650
TH 2095*	1300	Pulsed	6 MW	60 kW	300 μs	130 x 96	48	200	WR 650
TH 2054	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

*Has a modulating anode

TABLE II - Thomson-CSF large-bandwidth high power klystrons

Klystron	Frequency	P_o peak (MW)	P_o avg. (kW)	Bandwidth (< - 1 dB) (MHz)	RF pulse duration (μs)	V_o x I_o (kV x A)	P_{drive} (W)
TV 2030	S-band	20.0 10.0	20 20	100 100	4 4	230 x 238 170 x 160	750 750
TV 2018	S-band	5.5 3.5	10 10	100 100	5 5	130 x 100 108 x 74	400 400
TV 2091*	S-band	20.0 10.0	20 20	300 300	4 4	232 x 241 175 x 165	750 750
TV 2092*	Low S-band	7.5	180	250	500	160 x 122	400
TV 2053	C-band	5.4	10	300	10	133 x 105	800
TH 2068**	L-band	4.0	10	50	8	115 x 80	40

*Several mock-ups and prototype ; no series production
**Tunable, with a system of remote controls and counters

TABLE III - Thomson-CSF very high peak power pulsed klystrons

Klystron	Frequency (MHz)	P_o peak (MW)	P_o ave (kW)	RF pulse duration (μs)	V_o x I_o (kV x A)	Efficiency (%)	P_{drive} (W)	No. of RF 1 (vacuum)
F 2042	2998.5	41	12.5	6.5	303 x 324	42	240	2 (SF_6)
TV 2030	2998.5	35.5 38	15 20	4.5 5	300 x 296 300 x 327	40 39	180 550	1 (SF_6) 1 (SF_6)
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	37	20	5	275 x 280	48	180	1 (SF_6)