RF-SOURCES FOR PROTON LINACS

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Introduction

In existing proton linacs, the choice of the RF frequency used at the beginning of the accelerator is the result of a difficult compromise between the injection energy (that is, the dimensions of the electrostatic injector), and the diameter of the accelerating structure (chosen in such a way as to allow the first quadrupole lens to be contained in the first drift tube). With few exceptions, the RF frequency used is 200 MHz. At this frequency, triodes can supply a few MW of peak power, but only with a duty cycle of a few percent or less. Klystrons would be able to improve this situation, but at this frequency the problem of klystron dimensions is encountered.

Recent developments of RFQ technology allow to overcome some of these difficulties by forming a bridge between the injector (which thus can operate at a few tens of kV) and the beginning of the accelerator (which then use an RF frequency at least twice as high). Klystrons are now perfectly adapted for operation in this frequency range (350-500 MHz) thanks to recent progress motivated by new demands (PEP, LEP, TRISTAN, etc.).

The first jump in frequency by a factor of three brings us to about 1.3 GHz, for which very high-performance klystrons have been developed for electron accelerators. Another jump by a factor of two brings us to 2.6 GHz, for which high-power, long-pulse klystrons have also been developed for certain military applications. Klystrons can thus cover the entire frequency range necessary for multi-GeV proton accelerators. This article discusses the present-day possibilities and describes improvements which can be anticipated in the near future.

Conventional Klystrons

Roughly speaking, below 200 MHz tetrodes are used as RF generators, whereas klystrons are used above (Table I). The state-of-the-art is shown in Figure 1 on a power/frequency plot for CW and pulsed klystrons.

Television bands IV and V extend from 470 to 860 MHz. Very large TV transmitters of several tens or even hundreds of kW output power, use klystrons putting out 10 to 50 kW per klystron. However TV klystrons are not perfectly adapted for high peak power operation at a fixed frequency, because the cavities incorporate a sophisticated internal or external tuning system. In the last few years, certain techniques have been explored in an effort to improve these tubes. One seemingly attractive possibility is the incorporation of a video modulation grid, however the increase in efficiency thus obtained is at the expense of increased transmitter complexity and decreased reliability.

In the frequency range of 300-600 MHz, klystrons have been generally developed for electron synchrotron or storage rings. 4 to 5 MW CW klystrons are feasible (fig. 1), but so far no concrete demand has arisen for unit power levels exceeding 1 to 1.2 MW. The TH 2089 (352 MHz) and TH 2105 (508 MHz) are two examples of such klystrons.

Figure 2 shows the calculated and measured efficiencies of a number of klystrons as a function of the beam perveance. The good agreement of the two curves results from increasingly accurate calculation codes, but also from a better technical mastery, of certain important parameters, including the shape and size of the cathode, insulating ceramics, output windows, output waveguide, and collector (water-cooled or vapor-coled).

A trade-off between better efficiency (higher at lower perveance) and cathode voltage (lower at higher perveance) results in the choice of typical perveance values between 0.6 and 0.8 μperv.

Extremely high DC voltages are to be avoided for numerous reasons, including: the cost and bulk of power supplies and cables, which vary exponentially with the voltage ; internal and external breakdowns, aggravated by inevitable resonances in the external circuits ; increasing difficulties in protecting the tube and all electronics in the surrounding environment (radiation, ground loops, electromagnetic disturbances, etc.).

Figure 3 shows some characteristics of the TH 2089 and TH 2105. The high voltage was chosen on the order of 80-90 kV. The large size of these tubes is partly due to the relatively low frequency, but also due to the chosen operating voltages. In the "non-underground" version, the vertical or horizontal TH 2089 measures 4.75 m and weights 2 tons, including the lead shielding, and the TH 2105 measures 4 m for 1.8 tons. Both tubes can dissipate the entire beam power (1.8 MW CW) on the collector without danger.

Numerous other versions of this tube are possible, for example anode pulsing with a cathode voltage of 112 kV DC would allow to almost double the output power to 2 MW peak with a 30-40 % duty cycle ; the F 2055 (see table) operates in this manner. By pulsing both the anode and the cathode, even higher peak power could be obtained, depending on the pulse duration.

Figure 4 shows the variation of the peak output power with pulse duration for a 1.3 GHz klystron. The main limitation comes from breakdown voltages in the electron gun, between the beam-focusing electrode and the anode, and along the ceramic insulator. In the case of an insulated anode, the situation is further complicated by doubling the insulation and the fact that one of the ceramics must withstand the entire DC voltage. Also, any resonances in the supply circuits and cables can reduce the high voltage capability of the electron gun even further.

The problems of RF breakdowns in the output gap and the window are easier to avoid, especially in view of the relatively low frequencies. This would not be the case in other bands : X, C, or even S-band.

MB-Klystron

Low-frequency klystrons can be rather bulky, especially if they have to deliver high power levels and high efficiency, resulting from the very principle of the velocity modulation. In spite of this inconvenience, klystrons are sometimes preferred to grid tubes for their well-known qualities : high-power capability (peak and average), ruggedness, lifetime, high gain, etc.

For a given frequency, the length of a klystron is determined by the HV. Thus in order to reduce klystron size, one possibility would be the use of a high-perveance beam, especially a hollow beam. Past efforts along these lines have been disappointing ; in particular, the efficiency obtained was less than that predicted by theoretical considerations. Two reasons are advanced for this discrepancy. Firstly, it is difficult to obtain a perfectly hollow beam over a long distance, as such a configuration is metastable around the beam axis. Secondly, it is practically impossible to avoid beam scallops arising from confinement magnetic field imperfections. This effect defeats the purpose of using a hollow beam, which must be as close to the drift-tube edge as possible in order to obtain the maximum benefit. Thus we are led to consider the principle of the multiple-beam (MB) klystron. As far as we know, the idea was first proposed by J.BERNIER[1], who also built a prototype[2]. Another prototype was built by BOYD & al.[3].

In a MB klystron[4], N beams emitted from N separate cathodes travel through N drift tubes arranged equidistant on a circle in between the klystron cavities (fig. 5). As in the case of a hollow beam, the space-charge effect is reduced by division of the beam into N identical beams, however each beam is treated here as in a standard single-beam klystron, for the beam confinement as well as for the coupling with the electromagnetic field. In other words, the MB klystron can be modeled as N klystrons in a parallel configuration.

The relation follows :

$$V = (P_{TOT} / \eta \; p \; N)^{2/5}$$

where :
V : beam voltage, same for all N beams
P_{TOT} : output power of MB-klystron
η : efficiency of a single beam
p : perveance of a single beam
N : number of beams.

Using this formula, we can see that for a given output power, a MB-klystron with six beams requires only about half the HV of a single-beam klystron ($6^{2/5} \simeq 2$) and thus would be shorter by a factor of $\sqrt{2}$. Of course these advantages can only be obtained at the expense of greater complexity of the electron gun and the beam-confinement electromagnets which must generate a homogeneous field in the neighborhood of each beam.

In order to imagine what would happen if one of the beams disappears, or if they don't all have the same current, we use the lumped circuit (fig. 6) as a model of a cavity. We deduce the RF current I_i induced into each drift tube :

$$I_i = (1 + \ell/NL) \; [(1 + jQ) \; N^{-1} \sum_{n=1}^{N} j_n - j_i],$$

where ℓ and L represent the equivalent inductances of each drift tube and cavity, respectively ; j_n is the beam current going through the n^{th} drift tube ; and $Q = L\omega/r$. We observe that if one of the beams disappears, the remaining beams see the same field, diminished by 1/N in relative value, with a general phase shift of 1/Q with respect to the initial field. We have the same situation as in a single-beam klystron which suffers a drop in beam current of 1/N. In the case where the beam currents are not exactly the same, it can be shown that each beam sees a field phase-shifted by $(\Delta j/jo)/Q$ with respect to the average phase, where $\Delta j/jo$ is the intensity fluctuation with respect to the average value jo. Thus the variations are seen to be quite small.

For the RF cavities, the mode TM_{01} can be chosen which will result in an accelerating field which varies along the diameter as shown in Figure 7 (solid curve) : there are two maxima located in the interaction spaces, and a minimum of the same sign in between. The mode TM_{02} could also be chosen[5], resulting in the variation depicted by the dotted curve with a minimum of opposite sign. The TM_{01} mode is preferred for low-frequency MB-klystrons whereas the TM_{02} is preferred for high-frequency MB-klystrons.

Typical characteristics of a one MW, 6-beam klystron operating at 425 MHz could be a beam voltage of 42 kV for 6 beams of 5.7 A (overall length ≃ 2.5 m). The same concept can also be applied to a lasertron.

Conclusion

We have shown that the range of frequency and power needed for multi-GeV proton linacs can be covered by feasible if not existing klystrons. The concept of MB-klystrons or MB-lasertrons could allow major pro-gress in the near future towards increasing power and frequency.

References

1. French Patent no. 992.853 - September 15, 1944.

2. R. WARNECKE and P. GUENARD ; "Les tubes électroniques à commande par modulation de vitesse", Ed. Gauthier-Villars, Paris, 1951, pp. 728-729.

3. M.R. BOYD, et al., Trans. IRE, E.D-9, no. 3, May 1962.

4. French Patents 8603949 & 8603950, April 20, 1986.

5. French Patent pending.

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

Klystron	Frequency (MHz)	Operating mode	Output power		RF pulse duration (msec)	Vo x Io	Efficiency (%)	Power drive (W)	Output waveguide
			peak	average		(kV) (A)			
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	46 x 15.2 50 x 25	43 40	-	Coaxial
TH 2105	508	CW	1 MW	1 MW	CW	90 x 18.5	62	100	WR 1000
TH 2086A	1300	Pulsed	1 MW	60 kW	1000	69 x 36	40	-	WR 650
TH 2095	1300	Pulsed	6 MW	60 kW	0.3	130 x 96	40	200	WR 650
TH 2104	1300	Pulsed	10 MW 15 MW	100 kW 50 kW	0.2 0.1	160 x 135 200 x 175	45	-	WR 650
TH 2054	2450	CW or pulsed	50 kW 80 kW	50 kW 40 kW	CW 100	26 x 3.1 32 x 4.1	62 61	1 1.5	WR 340
TH 2103	3700	CW or pulsed	500 kW	500 kW	CW	58 x 18	47	5	WR 284

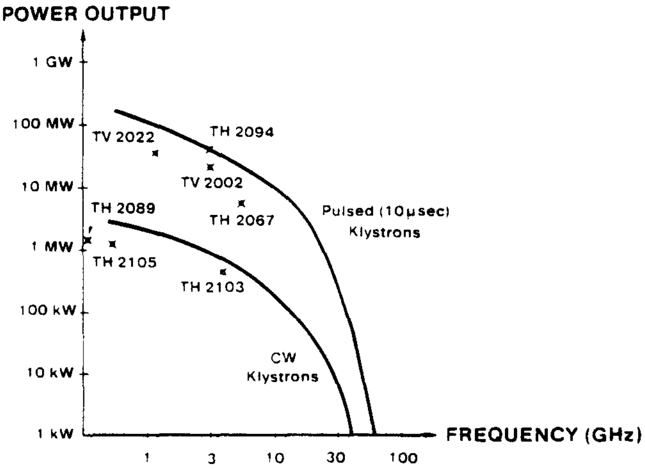


Figure 1 - Technology limits for pulsed and cw klystrons

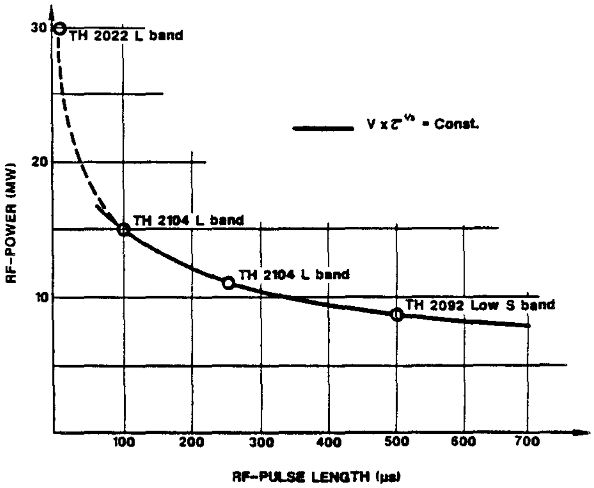


Figure 4 - Peak power vs pulse length

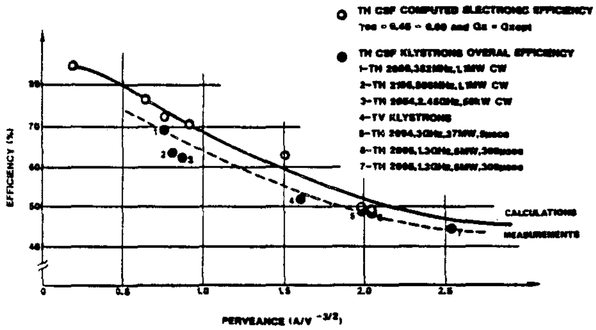
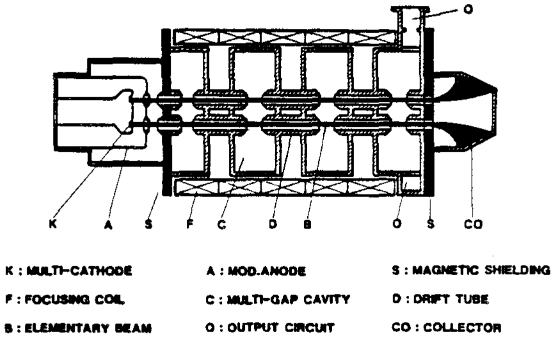


Figure 2 - Influence of perveance on klystron efficiency



K : MULTI-CATHODE
A : MOD.ANODE
S : MAGNETIC SHIELDING
F : FOCUSING COIL
C : MULTI-GAP CAVITY
D : DRIFT TUBE
B : ELEMENTARY BEAM
O : OUTPUT CIRCUIT
CO : COLLECTOR

Figure 5 - Schematic layout of a multi-beam klystron

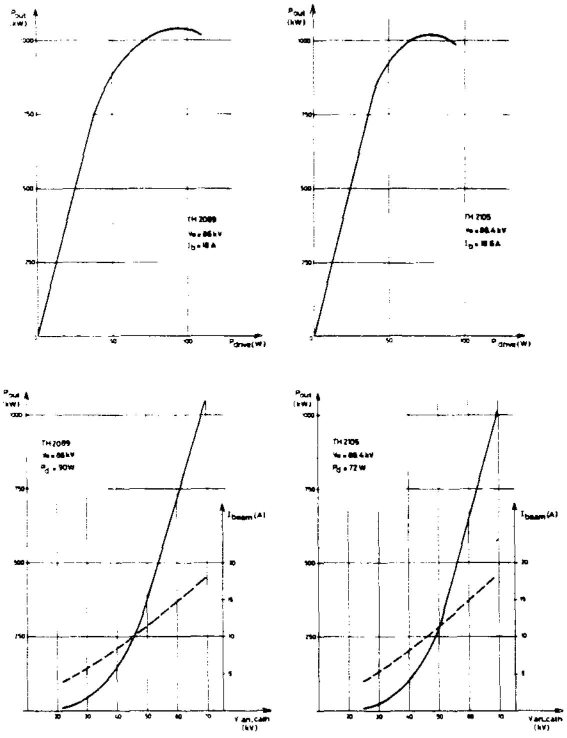


Figure 3 - TH 2089 and TH 2105 electrical caracteristics

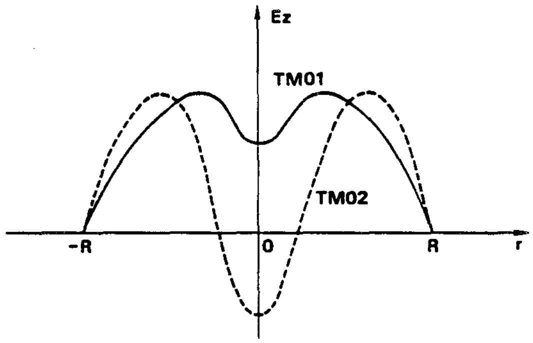


Figure 6 - Field distribution

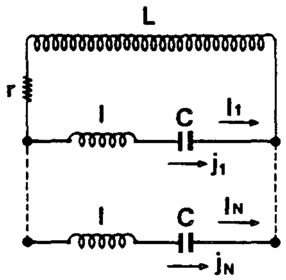


Figure 7 - Lumped circuit model