CONSIDERATIONS REGARDING THE EFFICIENCY OF HIGH POWER RF SOURCES FOR PARTICLE ACCELERATORS

G. CLERC, C. BEARZATTO, M. BRES, G.FAILLON and Ph. GUIDEE
THOMSON TUBES ELECTRONIQUES
Bât. CHAVEZ - B.P.121
78148 Vélizy cedex /FRANCE

1- INTRODUCTION

Recent advances in accelerator technology are now making possible the operation of high duty factor or CW facilities. Emphasis is therefore frequently put on accelerators designed not only on purely technical factors, but also on coqt criteria. From this point of view, the efficiency of high power RF sources feeding the electromagnetic power to the accelerating structures becomes an important issue in the design of a modern accelerator.

It is thus important to consider the efficiency of high power RF sources in a very objective manner and to examine advantages and drawbacks for each possible RF generator. The objective of this paper is to give a broad survey of this issue and to clarify this performance and its consequences.

2 - GRIDDED TUBES

Like all RF sources, triodes and tetrodes used in accelerators convert dc power provided by the HV anode power supply into RF power. The efficiency depends largely on the class of operation and also the quality of the amplified RF signal.

The theoretical efficiency of a gridded tube is given by :

$$\rho = \frac{\theta - \sin\theta \cos\theta}{\sin\theta - \theta \cos\theta} \times \frac{1}{2} \times \frac{Vp}{Vpo}$$

where θ is the passing angle of the anode current, Vp is the peak RF voltage and Vpo the dc anode voltage.

When a sinusoidal signal is applied between the cathode and the grid, three classes of operation are defined :

A- class : variation of the anode current is sinusoidal; the maximum theoretical efficiency exceeds 50%. At low level the efficiency drops to zero; all the power is dissipated on the anode.

B- class : the anode current flows for only a half period; the maximum theoretical efficiency reaches 79% and is only slightly degraded with a diminution of the output power.

C- class : the anode current flows less than half a period; with a 60° passing angle, the maximum theoretical efficiency is 89,5%.

Beyond these usual classes of operation, it is possible to increase the efficiency by working in D- class with a square wave obtained by adding the 3rd harmonic to the fundamental signal.

Because of the relatively low gain of the tetrodes and non negligible consumption of ancillary power supplies, there is a significant difference between the conversion efficiency discussed above and the overall efficiency, which takes into account dc power, RF drive power and heater power applied to the tube. Also operational efficiencies are less than maximum values because of the residual anode to cathode voltage which must be of the same order of magnitude as the screen to cathode voltage.

The loss in efficiency is around 5%. This effect is minimized by operating with a high load impedance as seen by the tube, i.e. with very high voltage and a low anode current.

Class-A operation doesnot generate harmonics; other classes of operation generate harmonics, whatever the quality of the tube linearity.

Finally the gain changes inversely to efficiency and increases from C-class. In scientific applications, it is frequent to operate in B-class to take advantage of a good efficiency while keeping a large enough gain. Table I shows the results obtained with TH 526 tetrode operated at TORE-SUPRA for Ion Cyclotron Resonance Heating (ICRH) experiments.

PARAMETER				
RF FREQUENCY	80	120	200	MHz
ANODE VOLTAGE	24	18	24,2	kV
SCREEN GRID VOLTAGE	1750	1750	1600	V
CONTROL GRID BIAS VOLTAGE	-350	-350	-290	V
ANODE DIRECT CURRENT	115	120	126	A
SCREEN GRID DIRECT CURRENT	5	5	2,7	A
CONTROL GRID DIRECT CURRENT	4	4	2,5	A
ANODE DISSIPATION	760	660	680	kW
PEAK OUTPUT POWER	2	1,5	2	MW
PEAK DRIVE POWER	70	60	50	kW
PULSE DURATION	> 30	> 30	2.10^{-}[illegible]	S
EFFICIENCY	72%	69%	66%	

TABLE I - EXAMPLES OF OPERATION FOR TH 526 TETRODE

3 - KLYSTRONS

In a conventional klystron, the efficiency $\acute{\eta}$ is usually defined as the ratio of the RF output power Po to the beam power (cathode voltage x cathode current), without taking into account the heater consumption and the focusing power (if any). Due to the high gain of the klystron - at least 35 to 45 dB - the RF drive power has no incidence on the efficiency. This efficiency $\acute{\eta}$ is called interaction efficiency, and corresponds to the conversion in the output circuit of the kinetic energy of the bunched electron beam into RF energy.

The main factor affecting efficiency is the perveance :

$K = I_{beam} \times V_{beam}^{-3/2}$

directly related to beam space charge forces. Fig.1 shows how efficiency increases with perveance and there is no doubt that 80% efficiencies could be obtained.

The physical explanation of this relationship is the following :

- As also perveance increases, the electron density in the bunches also increases, and repulsive forces between electrons make this bunching less and less sharp and efficient. Since the bunching is deteriorated, a increasing number of electrons comes out of the optimum phase for interaction with the electromagnetic fields in the cavities,

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especially in the output cavity. Some of them are completely out of phase and pick up energy form the RF instead of providing it.

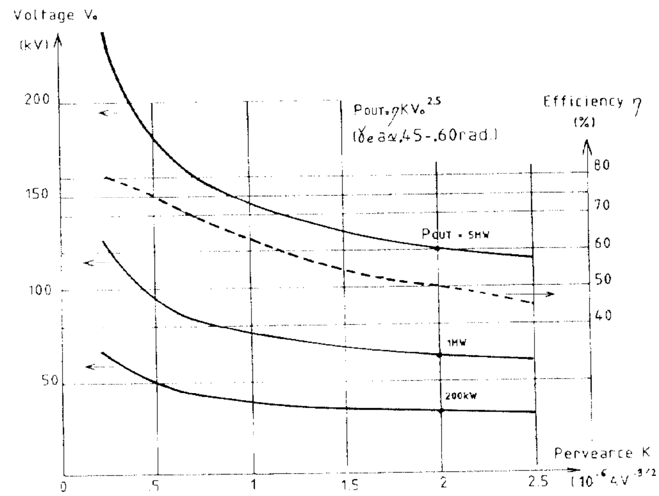

FIG. 1 : RELATIONSHIPS BETWEEN EFFICIENCY, CATHODE VOLTAGE AND PERVEANCE (KLYSTRONS)

- Another reason is related to the beam dynamics. As soon as the beam enters the first drift tube, the electrons encounter electrostatic repulsion from other ones already traveling in the tube. This ΔV depression becomes significant as the perveance increases and is deeper on the axis than on the edge.

Because the beam velocity and therefore the output power are related to $V_{beam} - \Delta V$, and not to V_{beam}, efficiency decreases as the perveance increases.

Beam diameter variations, laminarity and radial density variations play also an important role and explain why the magnetic focusing field must be carefully adjusted along the beam path from the cathode to the collector. The diameters of the drift tubes and beam are also important design parameters, because of their incidence on the space charge forces and the coupling between the beam and cavities.

The design of the interaction structure of a klystron must provide bunches as sharp as possible at the entrance of the output cavity. This is why many codes (1 and 2 1/2 codes, Z and time stepping, PIC...) have been developed to improve the design of the RF structure and subsequently the efficiency. As a consequence of the use of such codes, some high efficiency klystrons include a second harmonic cavity in the RF structure, but the effectiveness of such a device is not commonly accepted.

4 -EFFECT OF VSWR ON KLYSTRON EFFICIENCY

The interaction efficiency we are talking about is the optimum efficiency obtained when the RF power is delivered to a matched load (VSWR = 1 : 1) Around saturation , a klystron can be considered as a generator of current and maximum efficiency is obtained when the internal impedance is equal to the load impedance. When the load is mismatched, the efficiency decreases according to the RIEKE diagram. Further more, over a large phase range of the mismatched load, the impedance seen by the bunched beam is such that the RF voltage induced across the output cavity gap is too large, greater than the accelerating beam voltage ($V_o - \Delta V$). Therefore some electrons are reflected towards the cathode, causing beam interception and dangerous breakdowns. As a consequence, a high efficiency klystron does not accept a load with large variations of VSWR and phase. This point is often minimized or omitted, and a difficult trade-off is always necessary between efficiency and the range of possible load variations. This fact is particularly important in RF heating of plasmas, which are very unstable loads.

5 - DEPRESSED COLLECTORS

Depressed collectors are often seen as a solution to increase efficiency. Their design includes several electrodes whose voltages are gradually distributed between the ground and cathode potentials. Electrons coming from the output cavity - with a velocity dispersion $\Delta\vartheta/\vartheta$ related to the magnitude of their interaction in this cavity - are slowed down in the collector and ideally arrive on the electrodes with a small velocity. For a given design, the collector efficiency depends on the velocity dispersion.

Depressed collectors are really attractive if some conditions are met :

1) The interaction efficiency is low; the advantage of depressed collectors is high because of the increasing margin between the interaction efficiency and the overall efficiency. It is the case for traveling wave tubes, especially under operating conditions where energy is expensive, as in space (table II).

P/N	FREQUENCY	RF POWER	BEAM VOLTAGE	INTERACTION EFFICIENCY	OVERALL EFFICIENCY		
					2 STAGES	3 STAGES	4 STAGES
TH 3626	Ku-Band	20 W	3,9 kV	18 %	45 %	50 %	-
TH 3754	Ku-Band	110-130 W	5,6 kV	25 %	-	59 %	62 %
TH 3781	Ku-Band	55 W	4,7 kV	24 %	-	57 %	60 %

TABLE II - EFFICIENCY OF TWTs FOR SPACE APPLICATIONS WITH DEPRESSED COLLECTORS

2) The tube is not used at saturation, i.e. for telecommunications and some TV systems.

3) Voltages and powers are moderate, so depressed collectors do not involve too much technological complexity or too many operational difficulties for the product.

The interest of depressed collectors is limited to certain well defined cases, and they do not appear to be valid at high power levels.

6 - INDUCTIVE OUTPUT TUBE

This tube combines features of two types of tubes :

- gridded tubes for the grid excitation
- klystrons for the gun optics and the internal use of resonant cavities.

When a klystron works in A-class and therefore has theoretical efficiencies limitations, an IOT may be biased in B-class or C-class. Efficiency is as high as 60% were reported at nominal power levels of some tens of kW in UHF-range (TV broadcasting). These efficiencies do not drop below 35 to 40% at low RF levels (fig.2).

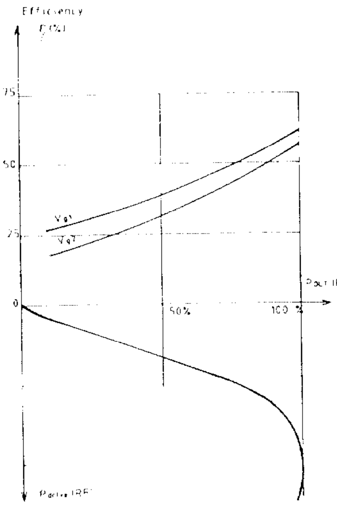

FIG. 2 : TYPICAL EFFICIENCY OF AN IOT (10 TO 100 % RF POWER / 2 GRID BIAS VOLTAGES)

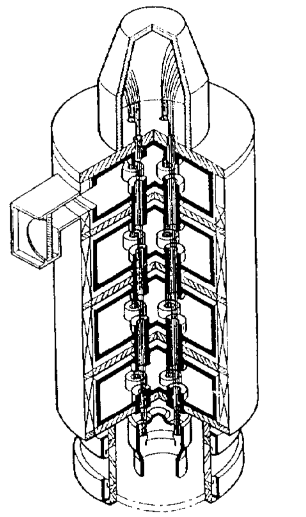

FIG. 3 : INTERNAL VIEW OF A MBK STRUCTURE

Apart from this advantage, and other ones such as small size and low weight, this device suffers some drawbacks :

- Beam voltage is significally higher than the corresponding klystron voltage.
- The gridded gun is complicated and has to handle higher electric fields between electrodes; so risks of breakdown and failures are increased.
- With a value around 18 to 20 dB, the gain is within 2 to 3 orders of magnitude below the gain of a klystron; so the driver becomes an item which cannot be neglected in terms of size and power systems.
- Because of high beam voltage, X-ray shielding is a more important issue than for klystrons.
- The design of the tube induces a limitation at high frequency; a klystron does not have so stringent limits.

In conclusion the IOT seems to have a field of operation limited to UHF frequencies at a power level of a few tens of kW CW or average, where an interesting efficiency may be obtained.

Finally, the most common way to obtain high efficiencies remains to design the microwave source with a low perveance. To get the same amount of power, it is necessary to increase the beam voltage (fig.1). High efficiency devices, such as magnicons, gyrocons or IOTs, are always tubes characterized by low beam perveance, operating with beam voltages significantly higher than klystron voltage; as a consequence of the use of high voltages, power supplies, modulators and HV links become bulky, quite expensive and less reliable.

7 - MULTIBEAM KLYSTRON (MBK)

The MBK concept originates from the search for a trade-off between the following features :

- As high an efficiency as possible.
- As low beam voltages as possible.
- Use of proven technology and intrinsic advantages - gain, frequency range,... - of the klystron.

Basically the MBK is a microwave tube in which several electron beams in parallel propagate across a common RF interaction structure (cavities) in a single vacuum envelope. For a given output power, this arrangement gives a high current and low voltage tube. Since the length of the RF structure is approximately proportional to the square root of the voltage, a significant reduction of size can also be obtained.

Because the perveance of each individual beam can be small, the interaction efficiency is high (fig.1). Table III shows comparative data of klystron and MBK; 39 kV is enough to obtain 1 MW of output power with the 0.78 μperv perveance of each beam.

	KLYSTRON	MBK	MBK	MBK
FREQUENCY	352 MHz	425 MHz	850 MHz	1700 MHz
OUTPUT POWER (CW)	1300 kW	1000 kW	1000 kW	850 kW
CATHODE VOLTAGE	100 kV	39 kV	38.5 kV	40 kV
NUMBER OF BEAMS x CURRENT	1 x 20A	7 x 5,7A	7 x 6,5A	6 x 6,4A
EFFICIENCY	65%	65%	58%	56%
GAIN/DRIVE POWER	42 dB/ 80 W	45 dB/ 30 W	45 dB/ 30 W	42 dB/ 50 W
GUN LENGTH	75 cm/OIL	35 cm/AIR	35 cm/AIR	35 cm/AIR
OVERALL LENGTH	4,75 m	2,9 m	2,20 m	1,85 m
OVERALL DIAMETER (WITH MAGNET)	90 cm	58 cm	36 cm	34 cm
OVERALL WEIGHT (WITH MAGNET)	2150 Kg	650 kg	580 kg	450 kg
WATT/GRAMM RATIO	0,60 W/g	1,54 W/g	1,72 W/g	1,78 W/g

TABLE III - COMPARATIVE DATA OF HIGH POWER KLYSTRON AND MBK (TENTATIVE)

TTE has carried out R&D on MBKs and manufactured a development model to verify the theory and prove the feasibility of such a concept. Experimental results are consistent with computations and show that this device could be suitable for high power, high efficiency RF sources to be used in scientific applications. Indeed it simplifies technology equipment with lower voltages and a higher power to weight ratio. Further developmental work will investigate the domain of operation of such a device.

8 - CONCLUSION

Efficiency is a key feature of modern RF sources because of its technical and economical implications. High power RF sources include many high efficiency electron tubes, but they generally require high voltages, with all the drawbacks involved. MBK are not yet a well explored solution to combine high efficiency and high voltage. However, they could provide a cost effective and reliable answer to RF transmitters and modulators for scientific applications.