Progress in High Power Klystron Manufacturing at EEV

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INTRODUCTION

Prior to 1990 EEV was well known as a world supplier of communications klystrons and particularly those used in TV broadcast transmitters. A small number of high power pulsed klystrons was produced by the Company but it had not entered the field of super power klystrons for cw operation. In 1990 the opportunity to do so arose and since then a number of types has been designed and supplied to customers. A recent contract has been to supply 1.3 MW cw klystrons for use in the LEP ring at CERN.

As always happens with any new product, problems were encountered. To overcome these, it was essential to get a better understanding of the factors involved in the operation of klystrons at very high efficiency. This paper describes how this has been applied to the design and operation of a high efficiency klystron exhibiting stable performance.

SPECIFICATION

This paper mainly relates to the K3513C klystron shown in Figure 1 which was designed to meet;

a) 1.3 MW of CW power at 352.21 MHz.
b) an operating efficiency greater than 65%.
c) capable of operating into a 1.2:1 mismatch at any phase.
d) stable performance.
e) 40 dB gain.

Klystrons have been built and supplied which meet these requirements.

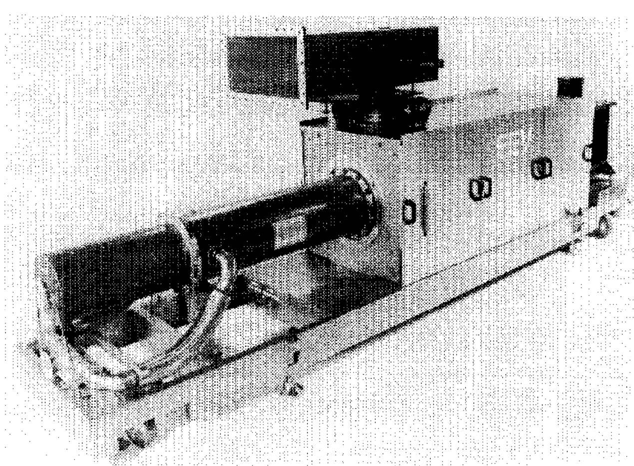


Figure 1. K3513C 1.3 MW Klystron

HIGH EFFICIENCY

The efficiency of a klystron is dependent upon two main factors;

1. the maximisation of the degree of bunching that can be achieved on the beam.

and

2. the effectiveness with which the energy contained in the bunches can be transferred to the load.

Although at first sight unrelated, these factors interrelate as the voltage in the output gap approaches saturation. Under these conditions a high retarding voltage will exist and will result in the creation of a significant number of slow electrons which ultimately sets the limit on the efficiency attainable and the onset of instability.

The number of slow electrons is influenced by the cavity tuning pattern and by the voltage across the output gap. This voltage depends on the impedance presented to the induced current flowing in the output circuit. The impedance is determined by the coupling between the cavity and the external load and this must be set to ensure that the gap voltage is the correct value for efficient deceleration but not so high as to cause acceleration of the electrons back up the drift tube tunnel.

CAVITY TUNING PATTERN

At EEV a network analyser is used to display a swept frequency response of the output signal. A typical response is shown in Figure 2 in which four peaks are visible. These peaks occur at the tuned frequencies of the input, second, fourth and fifth cavities.

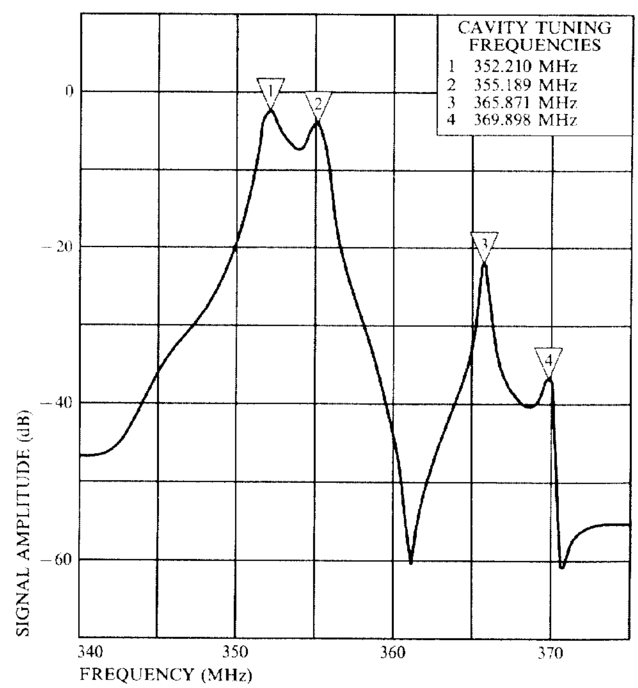


Figure 2. Swept Response to show Cavity Tuning Pattern

The input and second cavities determine the bandpass characteristic close to the drive frequency and initiate the bunching process which gathers the electrons into peaks and troughs of charge density.

The third cavity (peak not visible, in Figure 2) is a second harmonic cavity tuned to a frequency just under twice the drive frequency. Its function is to sweep electrons from the troughs into the peaks thus increasing the bunch definition as the beam enters the fourth cavity.

The fourth and fifth cavities are the main contributors to achieving high efficiency. As shown, they are tuned to frequencies well above the drive frequency. This ensures that they are inductive at the drive frequency and thus the voltage across the cavity gap lags the induced current by very nearly 90°. This results in a voltage which is negative ahead of the bunch, is zero as the main bunch passes through and is positive to following electrons. The effect of this is to concentrate more electrons in the bunch and importantly acts to minimise the electron velocity spread within the bunch. These are the conditions required to give high efficiency and stable performance.

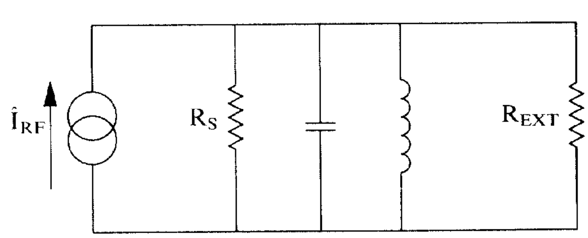
THE OUTPUT CIRCUIT

The function of the output circuit is to transfer to the load as much of the power, present as kinetic energy in the electron bunches, as possible.

As the bunches approach and cross the output gap they induce current to flow in the output cavity. The voltage generated by this current depends on the value of the circuit impedance which is mainly determined by the external load.

The fundamental energy exchange process is the conversion of the kinetic energy into electrical energy and this is achieved by slowing down electrons. At high efficiency, this process results inevitably in the formation of a significant number of slow electrons in the output gap. The electrons remaining in the output gap are reaccelerated by the fields thereby extracting energy from the cavity. This mechanism ultimately limits the achievable efficiency. A further limitation in practice is that slow electrons accelerated in the reverse direction can create a possible feedback loop which gives rise to oscillations and the creation of sidebands.

Any attempt to optimise the efficiency while maintaining stability must take account of how to achieve the desired voltage at the gap. A better understanding may result from consideration of the output circuit which for simplicity can be shown as



where R_S represents all the internal shunt resistance and R_{EXT} is the transformed value of the load resistance.

The power delivered to the load is given by.

$$P_L = \frac{\hat{I}_{RF}^2}{2} \cdot \frac{R_{EXT} \cdot R_S^2}{(R_{EXT} + R_S)^2}$$

As $R_{EXT} << R_S$ this reduces to

$$P_L = \frac{\hat{I}_{RF}^2}{2} \cdot R_{EXT}$$

Thus power into the load increases linearly with the value of R_{EXT} until the peak voltage across the gap approaches a limiting value roughly equal to the dc beam voltage. Beyond this point the circuit can no longer be considered as a constant current source but may be considered as a constant voltage source when the power into the load is given by

$$\frac{\hat{V}_{RF}^2}{2R_{EXT}}$$

Thus it reduces inversely with the value of R_{EXT}.

There is therefore a value of load resistance which will result in the coincidence of the maximum value of rf current and a gap voltage equal to the beam voltage. In theory this is calculable and the output loop coupling can be set to achieve it. In practice it is preferable to tune the klystron with the loop overcoupled and then to adjust the external impedance to achieve the specified efficiency while maintaining stability.

Operation with a teflon plate fixed in the waveguide was not considered a practical solution and so an alternative means of providing the equivalent impedance was sought.

A number of different options were tried leading to the choice of a capacitive post as the preferred solution. This approach offers flexibility and has the advantage that the post can be located within the coaxial line to waveguide transition.

PROCEDURE TO ADJUST THE IMPEDANCE

One of the specified requirements is that the klystron should operate into a mismatch of 1.2:1 at any phase. This is demonstrated by inserting a teflon plate into the waveguide and moving it through a half guide wavelength. It was recognised that this test also presented a convenient means of establishing how the output power of the klystron varies as a function of impedance and this was exploited as follows.

The klystron was manufactured with an overcoupled output when operated into a matched system. Output power and VSWR were measured as a function of plate position and the results were plotted as shown in Figure 3. At some position the output power is seen to exceed 1.3 MW and therefore the klystron will meet the specification when operated into a load of this impedance and phase.

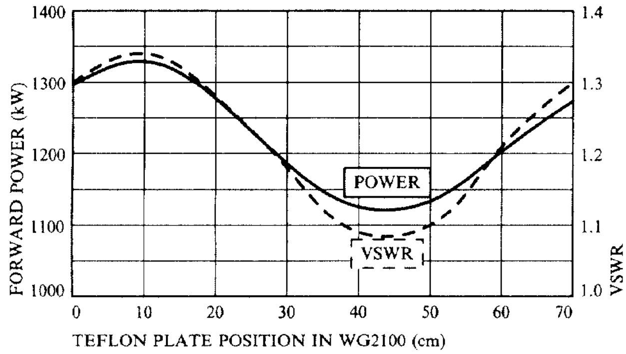


Figure 3. Variation of Output with Teflon Plate Position

Measurements were made of the VSWR as a function of longitudinal position, over a quarter of a wavelength within the transition, for posts of various heights. These are shown plotted in Figure 4.

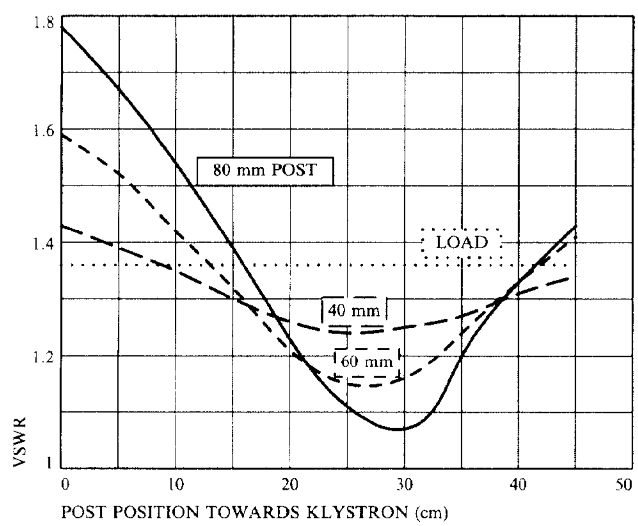


Figure 4. Variation of VSWR with Post Position (Measurements taken with a cold load)

The procedure followed is to establish the optimum position of the teflon plate to achieve stable, high efficiency, operation and then using the graph (Figure 4) to find the equivalent post; its height and position. This is then fixed at the indicated position in the transition.

An additional advantage of this approach is that by varying the height of the post it is possible to adjust the impedance to suit the specific characteristics of a customer's load. Furthermore a post can be fitted to optimise the performance of the klystron when operated at a different beam voltage or beam perveance.

STABILITY

Operation at high efficiency inevitably results in the production of a significant number of slow electrons in the output gap. A further consequence of the decelerated beam is to increase the charge density beyond the output gap and into the mouth of the collector. This creates a condition which results in some electrons being re-accelerated back up the drift tube tunnel giving rise to feedback and the onset of oscillation.

This oscillation can be expected to occur at the frequency showing the highest internal gain. It became apparent by looking carefully at the frequency response that the highest gain occurred at the frequency to which the second cavity was tuned. Various tuning patterns were tried with the objective of ensuring that the highest gain should be at the drive frequency. It was found that the second cavity has to be externally loaded and tuned to a frequency as high as possible consistent with achieving the specified systems gain and higher frequency bandwidth.

How far up in frequency the second cavity can be tuned is limited by where the input cavity is tuned. In order to maximise the gain at the drive frequency and to ensure that this is greater than the gain at the second cavity frequency, it is necessary to tune the input cavity to the drive frequency. This results in a skewed frequency response as shown in Figure 5.

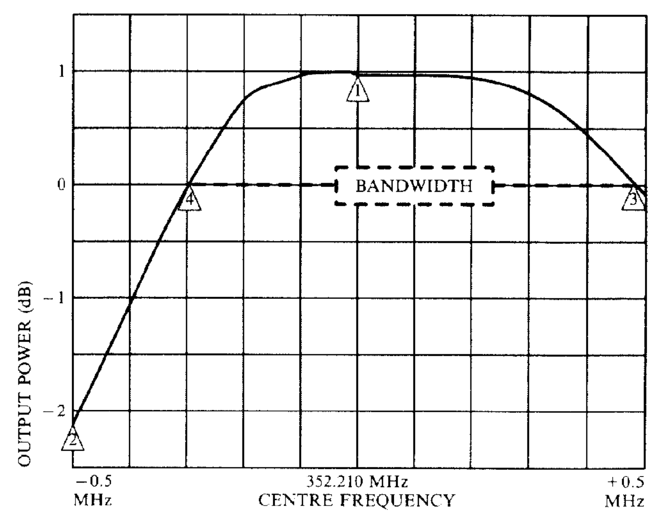


Figure 5. Bandwidth Response at 100 kV, 20 A

CONCLUSION

The frequency response shown (Figure 5) is the result of applying the principles discussed. This was plotted during the acceptance tests on a K3513C klystron. The associated test results were:

a) Output Power 1.33 MW
b) Efficiency 66.6%
c) Gain 40.3 dB
d) Stability - Stable at all phase angles when operated into a 1.2:1 mismatch.

ACKNOWLEDGEMENTS

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