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Test results for an EEV (old Valvo) klystron made at CERN on the 4th and 5th November 1999

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1. Introduction.

The klystron YK1600/ Serial Number 010 has been repaired and reconditioned, with some difficulty, at the EEV plant at Chelmsford UK. This tube is the very first high power pulse klystron that EEV have had for repair from the Valvo(Philips) range of klystrons, so additional care was taken for the reception testing. The difficulties encountered during the repair period can be partially put down to inexperience with the klystron type by EEV, but mostly with the difficulty in putting into operation the old modulator from Valvo, Hamburg at the EEV plant. This also includes initial problems of calibration of test equipment at the EEV factory. CERN personnel helped where possible in this matter in order to speed up the testing and delivery of the repaired the klystron. Finally at the beginning of October 1999, after a 2 years repair period, the klystron was ready at the Chelmsford plant, and CERN staff participated in the acceptance testing. There was again some difficulty in accepting voltage and current measurements, although at the time it was believed that these were probably correct. A set of test results were obtained and written up in PS/LP Note 99-05 (Min). The conclusion drawn at that time was that the results looked promising but because of the calibration and RF drive problems a second acceptance test should be made at CERN using the standard LIL test modulator, with known calibration and performance data.
Some of the initial test data taken at the EEV plant in October 1999 is repeated below.

2. Tests of repaired Valvo klystron Serial No. 010 made at EEV plant.

a). Six different diode tests made with the focal current settings below and shown in the Table 1:

A: 166 Amps, B: 112 Amps, C: 86 Amps

Test number:	1	2	3	4	5	6
V klystron (meter) kV	260	240	220	200	180	160
I klystron (meter) A	319	285	240	220	189	158
V PFN (meter) kV	46	42	37.4	33.6	29.5	25.8
V klystron (tank divider) kV	281	259	238	219	197	176
I klystron (tank CT) A	315	283	249.6	223	192.8	163.2
Microperveance	2.11	2.14	2.15	2.17	2.2	2.21
Mismatch (load to PFN) %	3.2	4.2	5	5.5	6	7.9

Table 1. Diode tests of repaired klystron

b). 25 MW RF test at EEV plant

This was made with the following test parameters:

Focal currents. A = 180 A
B = 80
C = 110

Tank measurements 259 kV (voltage divider), 283 A (current transformer), μP= 2.15
Analogue meter measurements 240 kV (voltage meter), 285 A, (current meter), μP= 2.42

The measured parameters for this 25 MW test using a water load and peak power meter are shown below.

Peak Power Input (watts)	Peak Power Output Water load MW	Peak Powe meter MW
10	11.1	13.5
20	13.5	15.3
40	16.7	18.3
60	19.5	21
80	21.5	23.5
100	23.7	25
120	24.3	25.7
140	24.4	24.9
160	24.6	25.2
180	24.9	25.2
200	25.3	24.3
220	24.6	23.6
240	24.9	24.3
280	24.9	24.3

Table 2. 25 MW test data taken at EEV plant

This data has been plotted below in Figure 1. The visit note PS/LP Note 99-05 (Min) shows also other tests at up to what was thought to be 30 MW output power using the EEV equipment.

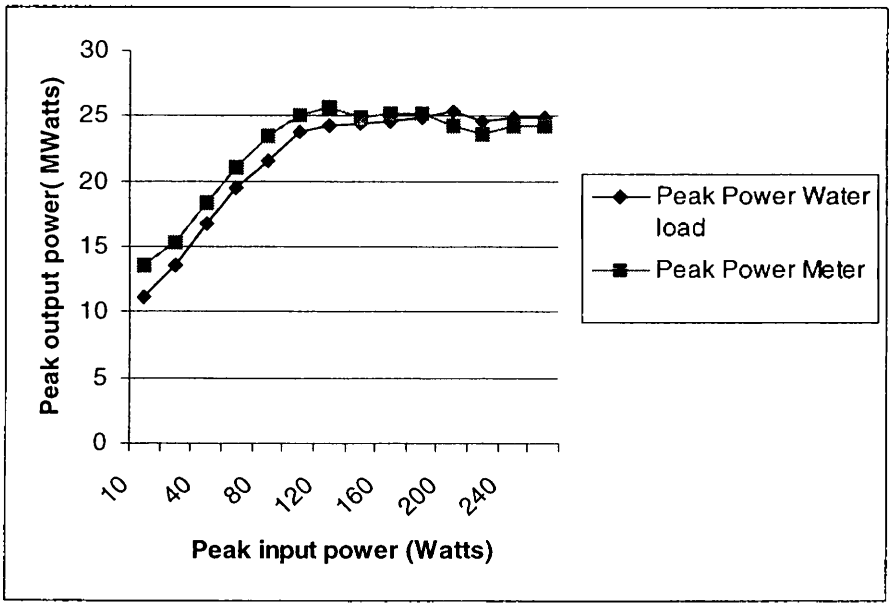

Figure 1. 25 MW test data taken at EEV plant

3. Klystron reception tests at CERN

These tests were for verifying the results previously obtained at the EEV plant, but using the LIL test modulator MDK35. The MDK35 was equipped with the same water load and temperature measuring probes that had been loaned to EEV for their tests and returned with the repaired klystron. The tube was received about 10 days before the testing started and was mounted in a spare Valvo klystron tank and equipped with a low power RF drive amplifier and all necessary measuring instruments before the EEV engineer arrived.

a) Heater curve data.

The initial testing was made in diode mode at various beam voltages. A set of values were obtained of heater voltage versus beam current to establish the normal operating point for heater voltage and what tolerance existed above and below this point. The heater curve at 238 kV is shown below in Figure 2.

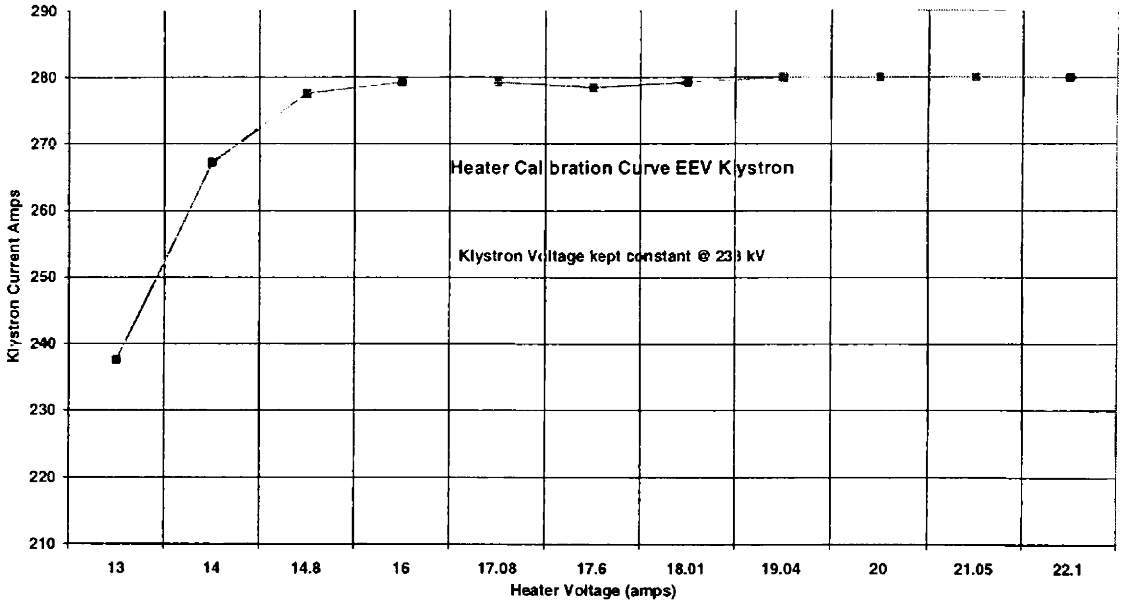

Figure 2. EEV klystron heater curve

The normal heater voltage for a Valvo (Philips) klystron in the past has always been 20 volts and a heater current of 20 amps. From the above we see that this position is fairly well back and a long way from the knee point on the curve. The operating point can safely be chosen from between 18 to 20 volts to be above the knee to ensure a reasonable performance over the cathode lifetime. The standard voltage of 20 volts was chosen. From the heater curve data a second curve can be obtained which shows what microperveance value has been obtained during the tube repair. The calculated perveance values taken from the above test data are plotted below in Figure 3. These show strongly that the actual klystron microperveance is 2.4, rather than the previous normal value of 1.9 to 2.0 for this tube type. This result has a significant impact on the overall performance of the repaired klystron, as will be seen.

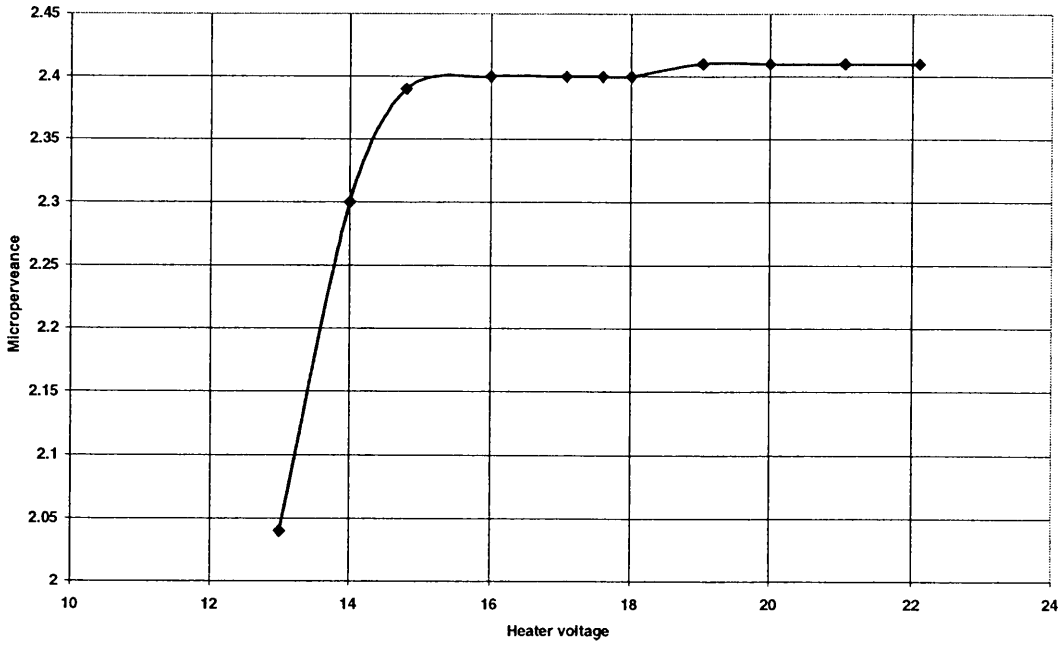

Figure 3. Microperveance curve for EEV klystron

b) RF power tests.

25 MW testing.

The first test was to remake the 25 MW power curve and to compare it with the one made at EEV, as shown in Figure 1. The heater voltage was set to the nominal value of 20 volts and the PFN was charged to 38 kV(indicated) and actually 38.5 kV measured, producing a klystron beam voltage of 248 kV. The voltages were measured with the high voltage divider in the tank and than checked by calculation using the standard impedance mismatch technique. The S-band frequency of 2998.55 MHz was used and an RF pulse of 4.5 μs width was applied at the 100 Hz repetition rate.

The input power to output power curve is shown in Figure 4 below. Each data point was made at saturation and the output power measured with both a peak power meter and the water load. The input power was measured with a peak power meter and cross-checked against the MilMega power source output meter. The peak klystron beam current was measured with a Pearson current transformer in the klystron tank.

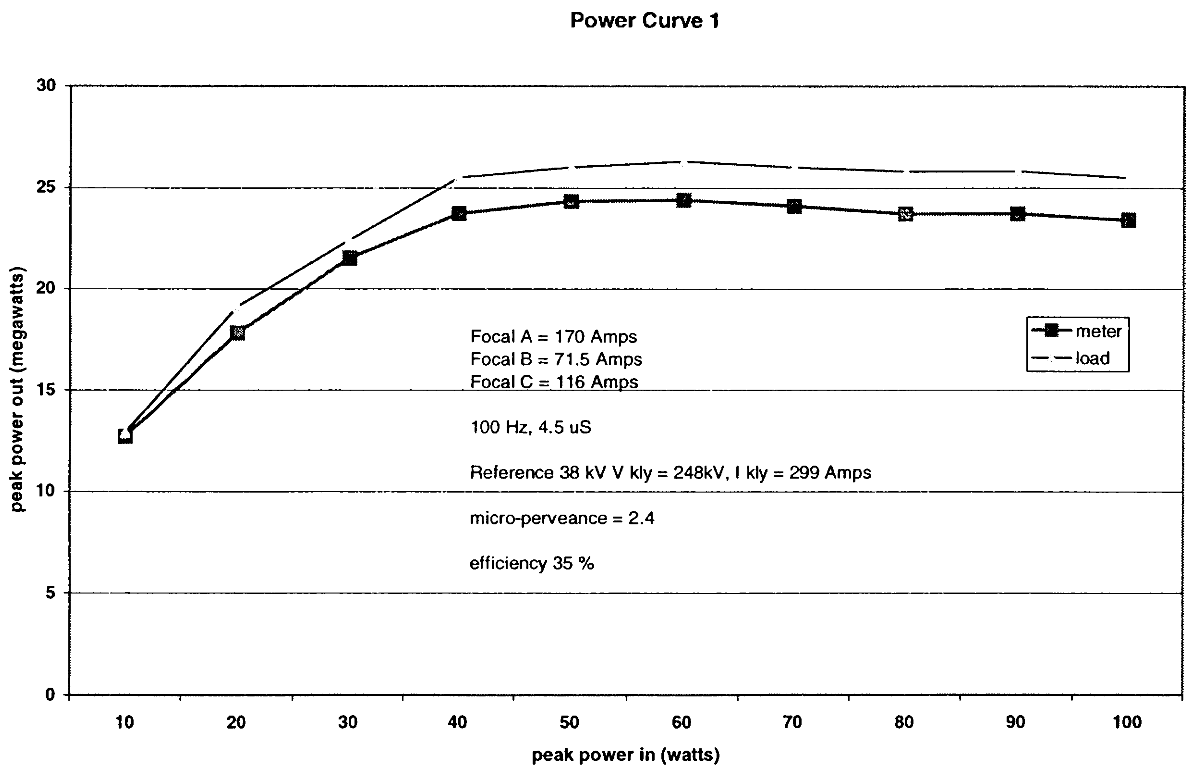

Figure 4. 25 MW peak output power curve

The curve shows a maximum klystron output power of 26.3 MW was measured in the water load with 60 watts input, and using the focal current and voltage settings mentioned above. The RF peak power meter measurement of klystron output power reads slightly lower (usually seen in these tests), and is 24.4 MW for the same input power point (a difference of about 7%).

The peak input high voltage beam power applied to the klystron is 74.15 MW, so that the maximum electron efficiency becomes about 35% for the water load measurement. The average power in the klystron at the pulse width and repetition rate used in the test is 11.8 kW. The power gain for the tube in this test is calculated for the water load measurement as 56 dB.

28 MW testing.

The PFN voltage was raised to 39.7 kV (indicated) and measured was 40.2 kV, producing a beam voltage of 260 kV and beam current of 315 amps in the klystron. The focal current settings of the previous test were maintained as shown. The peak RF output power measured in the water load was 28.3 MW, and the RF peak power meter reading was 26 MW (a difference of about 8%). The maximum output power occurs at a RF drive setting of 60 watts with the klystron working in saturation. The high voltage beam input power is about 82 MW, so that the maximum electron efficiency is calculated as 34.5% for the water load measurement. The klystron gain is found to be about 56.7 dB. The input to output power curves for the klystron is shown below in Figure 5.

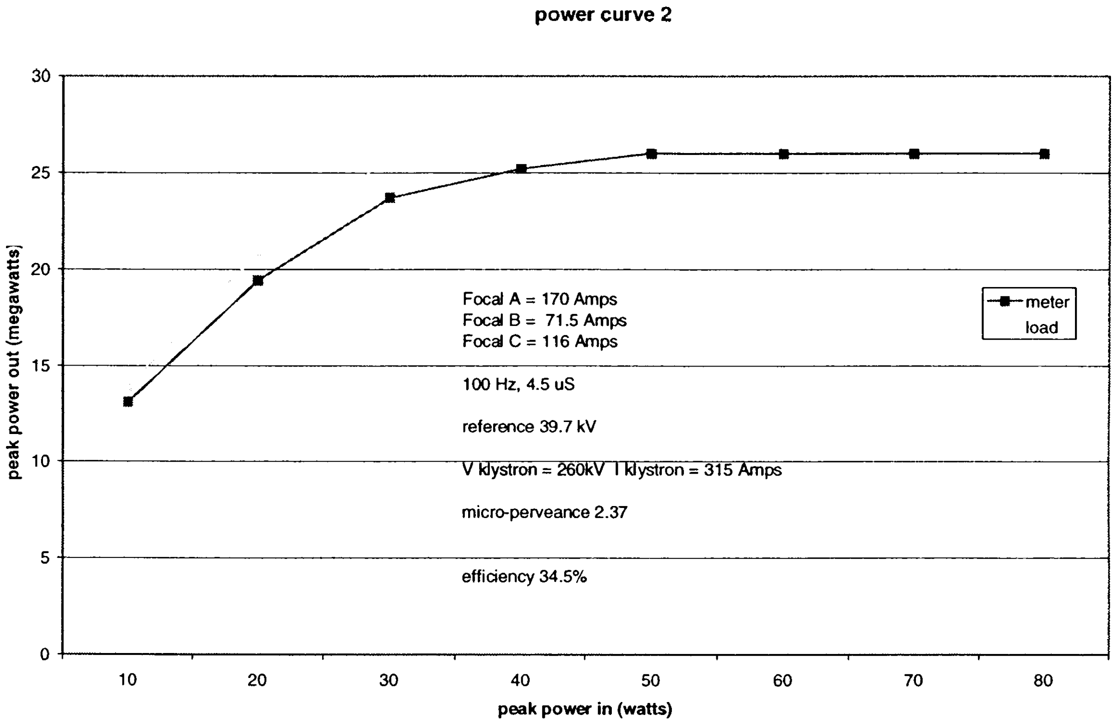

Figure 5. 28 MW peak output power curve

Lower heater voltage RF testing

In order to look at the klystron performance with a lower micro-perveance the heater voltage was reduced to a value of 13.64 volts. From Figure 3 we can see that the effective perveance has decreased to approximately 2.13 from the actual operating value of 2.4. This artificial reduction of micro-perveance (as if the tube was getting old) has pushed the heater curve operating point further to the left and is getting away from the space charge limited operating region of the gun. Increasing the beam voltage to too high a level in this situation could possibly cause sparking at the cathode surface. Therefore for this RF power test the voltage was limited to 240 kV and the current to 251 amps, although quick spot checks were made at higher voltage levels later on. The focal current settings have been left as in the previous tests because better settings were not found.

The peak beam input power is calculated as about 60.2 MW, and the peak RF power output measured with the water load was found to be approximately 20.1 MW. The electron efficiency at this level is found to be about 33.3%, and the RF gain is 54.6 dB with a peak RF drive input level of 70 watts. The input to output RF power curves for this test is given in Figure 6 below.

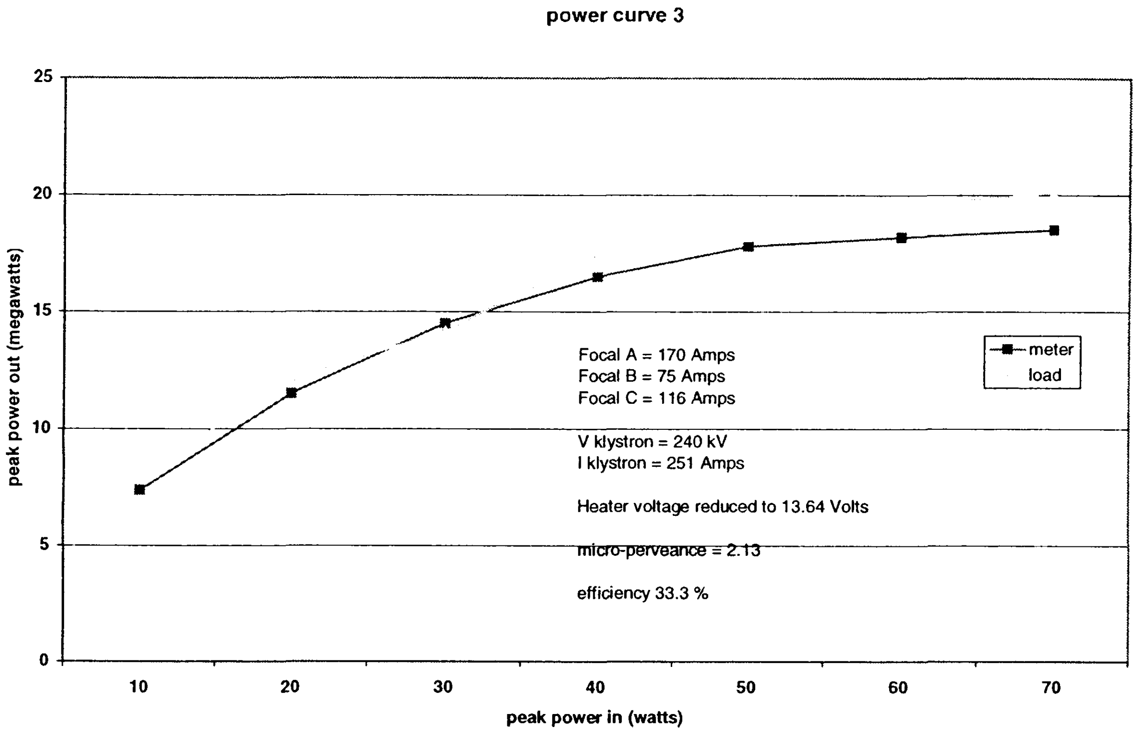

Figure 6. 20 MW peak output power curve (low heater test)

Some other spot tests were quickly made at this heater voltage setting to verify the perveance and efficiency of the klystron. These are shown below in Table 3.

Input power (watts)	Output power MW (meter)	Output power MW (load)	Vkly	Ikly	perveance	efficiency
60	22	24	252kV	265 Amps	2.09	35.90%
60	24.5	26.5	265kV	280 Amps	2.05	35.70%
55	25.2	27.6	270kV	289 Amps	2.06	35.30%

Table 3. Higher RF power tests

As can be seen at these higher voltages the peak output power does not increase above 27.6 MW and the perveance and efficiency have values essentially similar to what was found previously. The RF gain for the highest output power is found to be 57 dB.

4. Summary of results.

As was said in the introduction, this klystron is the first of its type to be repaired by EEV and we know that the learning curve for this technology is steep, so that the final performance results are not altogether unexpected. Nevertheless, a serious review of what has been achieved so far is necessary in order to decide how to proceed for the future.

a) Current calibration

The CERN test modulator voltage and current reference calibration is obtained by ensuring that the same methods and equipment are used for every klystron test. The klystron current and thyratron current are measured with built-in Pearson current transformers having sensitivities of 40 volts/A when unterminated or 20 volts/A with a 50 ohm termination, and with an accuracy of 2%.

b) Voltage calibration

The voltage is measured with an open capacitive divider (approx. ratio 30,000:1) installed in the klystron oil tank. The signal is used for viewing the shape and approximate value of the voltage pulse and its mismatch. Because of the difficulty of ensuring a constant or known oil quality (the changing tank temperature and oil quality affect permittivity, which changes the divider ratio) this signal is not used for absolute measurements. Instead a calculation method has been developed and used with success for many years, which has the merit of being simple to use and gives consistent results. It is based on the fact that a certain number of modulator parameters are well known and remain constant, and additionally that the lower PFN voltage is rather easy to measure with good accuracy. As well as these parameters, a measurement of the impedance mismatch between the klystron and PFN needs to be made. The capacitive divider signal provides this impedance ratio information to complete the calculation. This is explained below.

c) PFN mismatch and klystron voltage.

The klystron presents a dynamically varying diode type load to the pulse-forming network during the voltage pulse. Consequently, the impedance mismatch will be different for different values of applied peak voltage. As the voltage increases the klystrons dynamic resistance decreases as shown in [1] below and so does the mismatch m. The absolute value of the referred klystron impedance, that is to be matched to the PFN impedance, depends also upon the turns ratio (1:N) of the pulse transformer used. The test modulator has a high voltage pulse transformer with a 1:13 step-up ratio.

The klystron resistance is $R_k = \frac{V_k}{I_k}$ and $I_k = \rho . V^{\frac{3}{2}}$ where ρ is the klystron perveance. Then the klystron resistance is written as $R_k = \frac{1}{\rho . \sqrt{V_k}}$ ohms. [1]

A typical value (when new) for the perveance of the TH2100C or YK1600 35MW klystron used in the modulator is about $\rho = 2 \times 10^{-6}$ $A.V^{-1.5}$ with a range between 1.9 to 2.1 maximum.

The 35MW klystron will operate with a maximum pulse voltage of about 280kV, requiring that the PFN charging voltage is about 41kV. These voltages enable the maximum output power to be obtained with a new klystron of this type and with a positive 5-10% mismatch between the klystron load and PFN impedances. The adjustment of the PFN is made at the required operating voltage.

The choice of the step-up pulse transformer turns ratio N is closely linked to the amount of mismatch, the transformer efficiency, and the maximum PFN voltage desired. In order to optimize this part of the design, a mismatch expression is obtained. The mismatch equation using a step-up pulse transformer is written as:

$$Vkly = \frac{Vpfn \cdot N \cdot \eta}{(2 - m)} \quad [2]$$

The pulse transformer efficiency η ~ 98% and the percentage voltage mismatch measured at the klystron is $m = \frac{v}{Vkly}$ and is shown on the waveform in Figure 7.

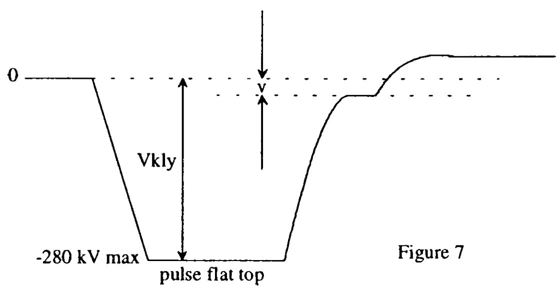

Figure 7

For the measurements made at 28 MW the PFN voltage was measured as 40.2 kV (but indicated as 39.7 kV on computer display) with an accuracy of ~3%. The pulse transformer has a step-up ratio of 1:13 and the impedance mismatch (m) measured was 3.3%. Then taking the transformer efficiency as 98% and using the equation [2], a peak voltage value of 260 kV is found that was applied to the klystron. This method has been used with very many different klystrons and modulators and found to give consistent results when compared to other methods used by klystron manufacturers and laboratories, and has the merit that each parameter can be separately controlled for accuracy.

d) RF measurements.

The RF measurement for acceptance testing of a klystron is a calorimetric method requiring a water load and accurate PT100 temperature probes. The peak power meter is normally used for easy reference to the operating level of the RF pulse, and is not used in the calibration of the klystron output power. The present test results show a 7 to 8% difference between the two methods (and is normally the case), with the peak power meter being lower. This is generally thought to be due to the fact that the water load measures power as heat deposited by the fundamental frequency and all other modes coming from the klystron. The peak power meter is made frequency selective by internal or external filters and therefore measures power at the fundamental frequency only. However, a peak power meter is used to obtain the peak value of the applied input power, and is cross- checked with an analogue readout from the drive amplifier. The same water load and PT100 probes were used both at EEV and at CERN for these tests.

e) Test results.

The results obtained are summarised below in Table 4. The performance data at 25 and 35 MW of an original Valvo YK1600 klystron (S No. 06 R1) repaired and reconditioned at Valvo Hamburg in 1995 are included for comparison to see where the EEV repaired tube falls short of the specification.

Parameter	EEV (25 MW)	EEV (28 MW)	VALVO (25 MW)	VALVO (35 MW)
Peak output MW	26.3	28.3	25	35.8
Peak input W	60	60	40	40
Gain in dB	56	56.7	57.9	59.5
Perveance	2.4	2.37	2.06	2.05
Klystron volts kV	248	260	233	268
Klystron current A	299	315	232	284
Peak beam power MW	74.15	82	54.1	76.1
Focal 1 A	170	170	158	158
Focal 2 A	71.5	71.5	112	125
Focal 3 A	116	116	95	112
Heater volts V	20	20	20	20
Heater current A	20.4	20.4	20.4	20.4
Efficiency %	35	34.5	46.2	47
Ion pump curr. μA	1.0	1.0	0.5	0.5
RF pulse width μs	4.5	4.5	4.5	4.5
RF freq. MHz	2998.5	2998.5	2998.5	2998.5
Rep. Rate Hz	100	100	100	100

Table 4. Klystron test results

The maximum values of certain parameters in the design specification for this tube are given below.

Peak klystron voltage = 280 kV, Peak klystron current = 300 A, Focal currents = 190 A
Peak beam power = 78 MW, Perveance = 2.1, Heater power = 600 W

It was not possible with the test equipment either at EEV or CERN to obtain the full 35 MW peak power from the repaired klystron. If sufficient voltage had been applied, and the efficiency and perveance is assumed to remain constant then the following values for voltage and current would have been needed.

$$Vb := \sqrt[5]{\left(\frac{P}{\eta \cdot 2.4\,10^{-6}}\right)^2} \qquad Vb = 2.805\,10^5 \qquad Ikly := \frac{P}{\eta \cdot Vb} \qquad Ikly = 356.52$$

The beam voltage would have to be increased to 280 kV, which is the maximum value in the specification, and the resulting beam current would have risen to about 356 A, which is far too high for the device to stand. The total beam power under these conditions would have been at the 100 MW level, and again outside specification.

From Table 4 we see that the effect of the high perveance causes the beam current to be much higher than was forseen in the original design specification (Ikly $\propto$ perveance). This causes the beam power in the tube to increase proportionately and quickly gets to the maximum allowable value. Additionally the high beam power for the modest output RF power level brings down the efficiency to a very low value of 35%. The normal value of efficiency for this type of klystron is about 45%, and the usual efficiency obtained with a new or repaired Valvo klystron at the maximum specified output power is 47%.

The perveance of a klystron gun depends on the cathode area and the distance from the cathode to anode. If the same sized cathode disk has been used in the repaired tube as was installed in the original klystron then increases in perveance can only come about from a change in the distance between cathode and anode during assembly of the gun. It has been estimated that the change of perveance from the nominal value of 2.0 to 2.4 could come about from a reduction of distance between cathode and anode of 5 mm or a 6.6% error in assembly. This can only be verified if the klystron was disassembled of course.

During the course of the testing at CERN it was noted that the ion pump current stayed at a level of $\geq 1\mu A$ when the tube was being pulsed continuously. When the modulator was stopped and then restarted the ion pump current increased to $\geq 10\mu A$ and slowly descended to the $\geq 1\mu A$ level again after a few seconds. This tube vacuum activity did not cause any breakdowns in the device when RF power was applied, but was not the usual performance expected from a fully conditioned microwave tube. For comparison, the repaired Valvo klystron has an ion pump current level of less than $0.5\mu A$ at all times.

5. Conclusions.

In conclusion, the repaired klystron showed that it could not produce the full 35 MW peak output power, and was limited at around 28 MW even though the tubes operating values were increased beyond the maximum specified levels. The perveance and efficiency values were found to be outside the nominal specified ranges usually found in this type of klystron. Also the set of focal current settings used were far away from the original values used with the klystron before repair, and were found to be very narrow in range adjustment to allow performance improvements to be made. The original focal currents were actually tried out, but the body interception current and delta temperature increased above the 5 degree C allowed for in the original specification and caused the modulator safety interlocks to operate. The repaired klystron therefore does not have the characteristic performance of the original YK1600 device, and for many of the operating parameters falls outside of the nominal tube specification.