A 500 kW L-Band Klystron with Broad Bandwidth for Sub-harmonic Bunching in the CLIC Test Facility

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1. INTRODUCTION

The CERN requirement is for a microwave amplifier which will provide pulsed microwave power for a sub-harmonic bunching system in the CFT3 accelerator test facility. The microwave output is required to have a peak power level of greater than 500 kW over a 150 MHz bandwidth centred upon 1500 MHz.

The application has a combination of parameters which are difficult to fulfil with existing tube types. In particular the required frequency band is centred around 1.5GHz, which lies outside the radar bands where most of the tubes of this type are found in manufacturer's catalogues.

The requirement for a minimum bandwidth of 150 MHz would suggest a coupled cavity travelling wave tube (TWT) for this application. However, the peak power level of 500 KW is above that which can be easily obtained with such a TWT. TMD Technologies Ltd. has built a number of broadband klystrons, using a special Resonant Coupled Cavity Output (RCCO) system, which have given the required percentage bandwidths over a range of peak power levels from 50 kW to 2.5 MW. This experience suggests that such a klystron could provide the best solution for the requirement.

TMD manufactures a klystron (PT6006) which produces an output power of 100KW with a bandwidth of 100MHz at a slightly lower frequency in L–Band. It was thought that this tube could provide the basis for the required design as this type of broadband klystron amplifier produces wider bandwidths at higher power levels. The requirement of five times the peak power should enable a design with 10% bandwidth to be produced. The existing klystron has a pulsed cathode gun and solenoid beam focusing.

This paper reports work carried out in a CERN funded design study to find the best solution to satisfy the requirement.

2. SPECIFICATION REQUIREMENTS

The cardinal points of the specification were provided by CERN. They are as given below.

Peak Output Power	500KW minimum
Pulse Repetition frequency	10Hz
Duty Cycle	0.002 %
Centre Frequency	1500 MHz
Bandwidth	150 MHz minimum
Efficiency	20 % minimum (without collector depression)
Gain	> 30 dB

3. POSSIBLE DESIGN SOLUTIONS

In finding a solution to this design problem, several factors were taken into account.

i) The centre frequency lies outside the radar frequency bands so that it is unlikely that a tube exists which has broadband capability and does not require to be scaled in frequency.

ii) The quantity of tubes needed for the application is very small so that a costly development programme would not be justified.

iii) It is difficult to obtain a percentage bandwidth of 10% at the required power level of 500 kW.

3.1 The Travelling-wave Tube (TWT) Solution

One possible solution was to use a travelling-wave tube. Tubes exist which operate in L-band and have wide bandwidths at power levels of hundreds of kilowatts. However it was decided against using a TWT for a number of reasons.

i) There are very few designs which operate in L-band with high peak powers. The state-of-the-art appears to be between 200 and 300 kW for TWTs at the lower end of the microwave region.

ii) The slow-wave structure in a TWT is a complex component which makes the cost and risk of scaling it to a new centre frequency quite high.

iii) The length of a high power TWT in L-band would be much greater than for the alternative solution which is to use a klystron amplifier.

For these reasons the TWT solution was rejected.

3.2 The Klystron Solution

The klystron is normally seen as a narrow band amplifier with relatively high efficiency; wide bandwidths are not associated with a tube of this type. However a variant of the standard klystron was developed at TMD's predecessor, EMI Varian Ltd., which had wide bandwidth and high efficiency. This was achieved by developing a resonant coupled cavity output (RCCO) section to increase the bandwidth of the output cavity of the klystron. Because the bandwidth of the buncher section could be increased by stagger tuning [1], the output cavity was seen as the bandwidth-limiting element of the klystron design.

3.2.1 Previous Experience of Broad Band Klystron Design

The development of the RCCO output section, which was carried out in the 1970's, was in response to the need for a broadband, pulsed amplifier giving 1 MW output power in S-band. It was perceived that there was a gap in the output power range of tubes for radars which needed percentage bandwidths in the region of 5% to 10% and peak output powers around 1 MW. The performance envelope for coupled cavity TWTs appears to lie about the 300 KW level. Above 2 MW peak output power level, a number of slow-wave structures such as the Centipede structure, the Clover Leaf structure and the Long Slot structure gave useful broadband devices. A gap existed from 500 kW to 1 MW and the RCCO output was developed to fill this gap.

The S-band klystron, the PT1120, which resulted from the development programme, achieved 7% bandwidth between 1.0 MW and 1.2 MW. This tube used a two cavity extended interaction output section (the RCCO). Both modes of resonance of the output were used in an overlapping mode configuration to achieve the bandwidth [2]. This bandwidth was later extended to 10% by increasing the interaction impedance or R/Q of the output section. The efficiency achieved was 35 % at the 1 dB bandedges.

The technique was then used to design a klystron in L-band with 100 kW of peak output power and a bandwidth of 7% centred at 1.3 GHz. This tube the PT6006 is the basis for the design of the tube for CERN.

In passing, it is interesting to note that the RCCO output has also been used for other applications. There are three main uses for this technology:-

i) To achieve wide bandwidth with relatively high efficiency as described above. This can be best achieved by using both modes of resonance in an overlapping configuration.

ii) To reduce the output gap voltage in klystrons where extremely high powers are required, especially at high frequency. Several coupled output cavities are used in one mode and the RF energy is extracted from the beam progressively as the beam passes through the output [3]

iii) To achieve high efficiency with a narrower bandwidth. The effect of the extended interaction used in single mode is to increase the R/Q factor of the cavity enabling higher electronic efficiency. This mode of operation was the one which originally stimulated the development of the extended interaction output cavity [4]

At TMD tubes have been built using the overlapping mode technology over a range of frequencies and power levels including an X-band tube with 50 kW of peak output power and 5% bandwidth. All the devices have been stable in operation under a wide range of EHT voltages and beam currents. The tubes have also been operated into a range of output matching conditions, normally considered to be fault conditions in radar equipment without showing any instability. Provided that the pitch, or distance between the coupled cavity output gaps, is chosen correctly it has been found that the circuit is extremely stable.

Now that the bandwidth of the output cavity has been increased, it is found that the limitation in achieving a flat, broad bandwidth with a klystron is the design of the buncher which provides RF current on the beam to drive the output section. Due to the existence of zeros of the transfer characteristic of the buncher section, which can occur within the band of the stagger-tuned buncher, it is difficult to design a buncher which can drive the output bandwidth which is potentially available.

3.2.2 Relationship Between Bandwidth, Efficiency and Power Level

Modelling has established the relationship between the peak power level at which the RCCO operates and the efficiency obtained for different bandwidths.

In general the bandwidth available at a fixed efficiency level increases as the output power level is increased for a fixed perveance level; this is because of the decrease in beam impedance as the beam power is increased under these conditions. However it is possible to operate the output cavity to give wider bandwidths by sacrificing efficiency. The RCCO is coupled more heavily to the output system and the coupling between the cavities increased to give a flat bandpass. Figure 1 shows the results of modelling carried out as part of a study on the bandwidth of overlapping mode RCCOs.

The curves show the efficiency achievable from the RCCO at various combinations of bandwidth and peak output power. These curves are calculated for beams of 2.0 microperveance. The bandwidth shown is the 1 dB bandwidth.

The use of the curves suggests that an electronic efficiency of 29% can be achieved for the conditions of the CERN specification.

3.2.3 Feasibility of a Klystron Solution

From the considerations given above it was decided that the klystron solution would be the optimum one in this case. The major points in its favour are as follows:-

i) A klystron with the necessary extended interaction output section exists in L-band with a centre frequency (1.3 GHz) close to the required one (1.5 GHz).

ii) The scaling laws show that the 10% bandwidth of the CERN requirement can be achieved, as the bandwidth capability is increased with increasing output power level.

iii) The cost of scaling the klystron frequency band is small, which is an important consideration when so few tubes will be built.

iv) The klystron is quite a short device and has a relatively high electronic efficiency without needing a complex depressed collector.

For these reasons the decision was made to use the PT6006 as the basis of the design.

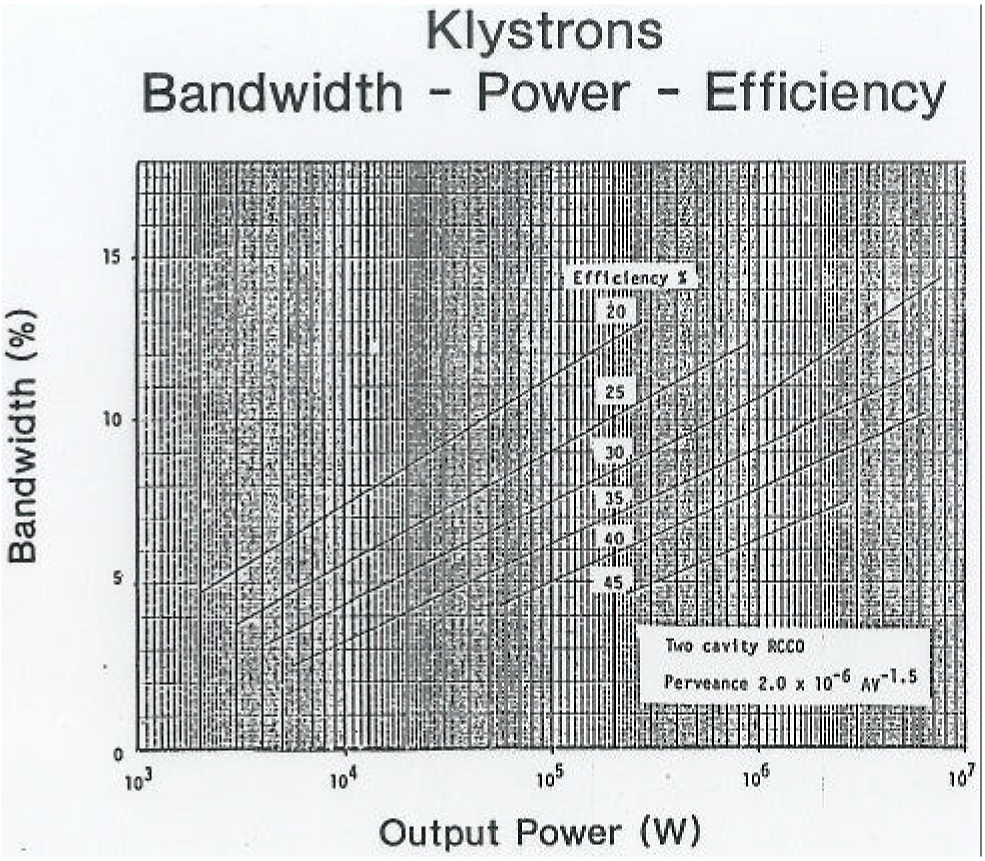

Figure 1 Efficiency achievable with variations of peak output power and bandwidth

4. DESIGN AND PREDICTED PERFORMANCE

4.1 The Existing Klystron

The existing klystron, the PT6006 has a two cavity overlapping mode RCCO and an eight cavity buncher. The tube in its solenoid is shown in Figure 2.

A typical output bandpass is shown in Figure 3; this performance is achieved with an EHT voltage of 33 kV and a peak beam current of 12.6 A. The performance of the original design has been reported in the literature [5].

The output power is delivered through a standard 3.125 inch coaxial connector via a coaxial window. The tube is designed to operate at a duty cycle of 5%, considerably higher than required by the CERN specification.

The beam is produced by a standard Pierce gun; modulation is by the use of a pulsed EHT supply.

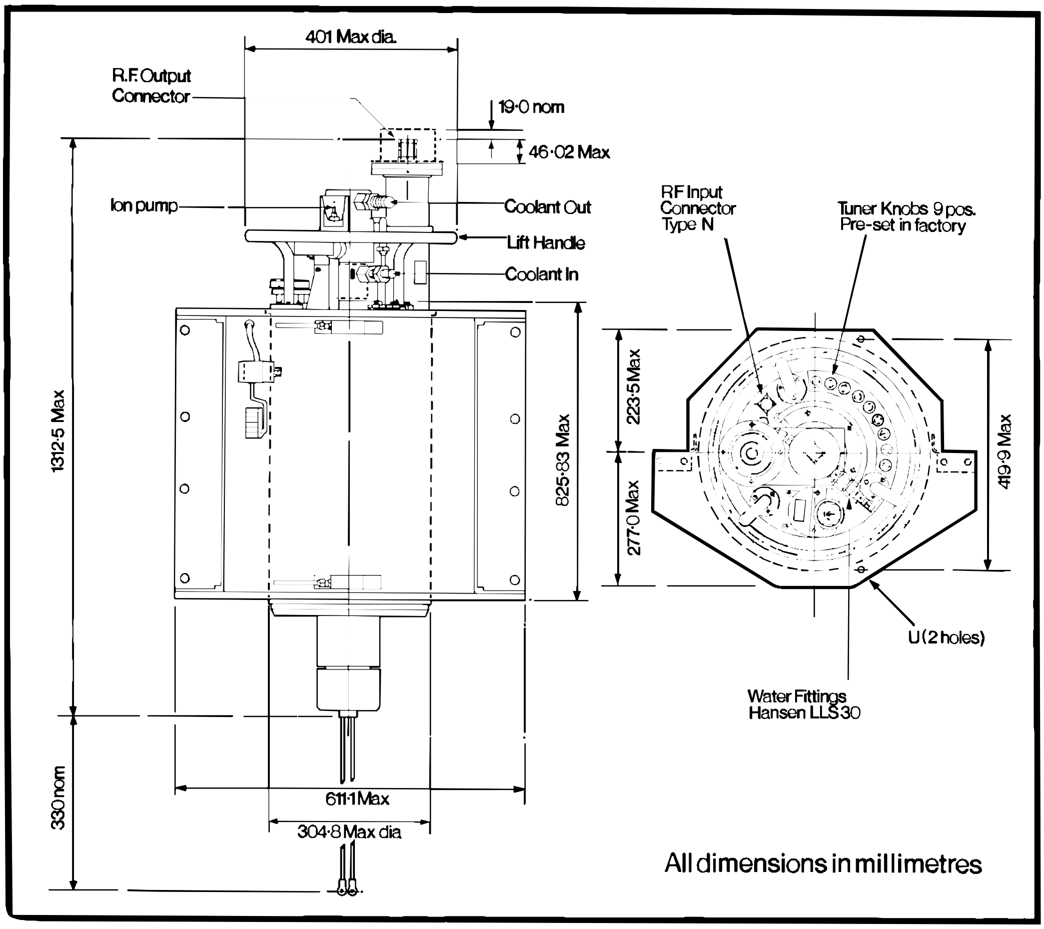

Figure 2 Dimensions of existing PT6006 klystron

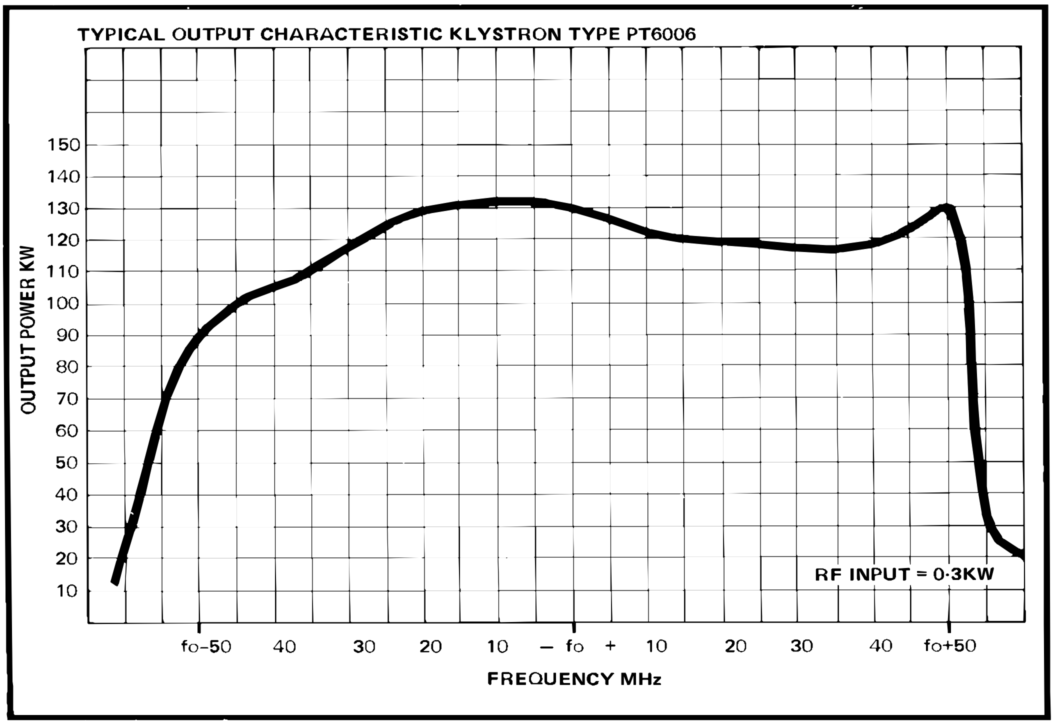

Figure 3 Typical bandpass of existing PT6006 klystron

4.2 RF Design

Experience shows that a beam perveance in the order of 2.0 uP is required for optimum bandwidth and efficiency. Preliminary calculations were carried out to establish the main operating parameters. The initial small signal modelling established the following parameters as the basis of the design.

EHT Voltage	69 KV
Peak beam current	36.6 A
Beam diameter	17.5 mm
Focusing Magnetic Field	0.07 T

The PT6006 has a minimum efficiency of 25% and, as described above, this type of tube has greater efficiency at higher power levels. Against this is the larger percentage bandwidth of 10%. The performance of the output cavity is not the only factor effecting the overall performance of the klystron. The design of the buncher must also be taken into account and it was found that it was necessary to use a higher operating EHT to obtain a flat bandpass with the required gain. It is expected that the tube will give in excess of the required 500 kW under these conditions.

The RF design breaks down into the design of the RCCO and the design of the buncher cavities.

4.2.1 Output Cavity (RCCO) Design

The design was carried out by constructing a lumped circuit model of the output cavity so that the required interaction impedance across the specified frequency band could be found. The values of the lumped components are calculated from the individual cavity frequencies, the degree of coupling between the cavities and the R/Q of the cavities.

The R/Q is a figure of merit which measures the interaction impedance of a cavity; the higher the value the better the gain/bandwidth product. To optimise this, the individual cavity geometries were modelled using Superfish, a finite element electromagnetic program. The geometry of the output section is also determined by the cavity gap spacing (pitch), the external loading and the thermal design required to handle a specified beam interception without damage. Considering the conflicting requirements, the maximum values of R/Q's obtained for the individual output cavities were about 130 Ohms and 120 Ohms respectively.

4.2.1 Buncher Design

The eight cavity buncher section of the PT6006 was scaled using the TMD small signal gain program. The cavity frequencies, the drift lengths between cavities and the cavity loading were adjusted to obtain the required performance with the estimated beam parameters.

Cavity dimensions and R/Q's were modelled using the Superfish finite element program. A typical plot showing a half section cavity is shown below in Figure 4.

It is particularly important to ensure that the zeros of the buncher transfer characteristic are kept out of the operating band. This was achieved by adjusting the inter-cavity spacings and cavity loading. The small signal program located the poles and zeros of the characteristic to ensure that the correct result was obtained.

4.3.2 Overall Tube Performance

The resulting 8 cavity buncher plus RCCO output section gave the small signal results shown below in Figure 6. This shows a small signal gain in the order of 45/50dB indicating a large signal gain of about 40dB over most of the 150MHz, falling off at the bottom end. The buncher section will be about 25% longer than the PT6006 because of the higher beam voltage. The gain was chosen to be within the range of a solid state driver amplifier.

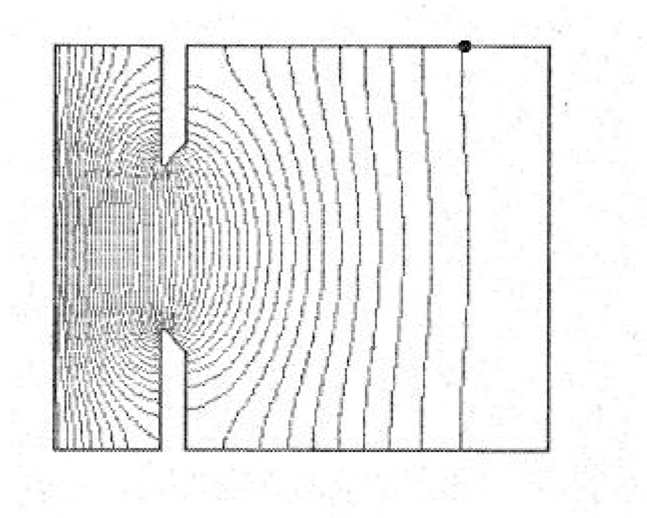

Figure 4 Superfish model of RF cavity showing electric fields

4.3 Predicted RF Performance

4.3.1 Performance of Output Cavity (RCCO)

Using both the simple lumped circuit model and the TMD small signal computer program, the design of the output cavity was scaled to the higher frequency with an increase in bandwidth. The response of the RCCO at different beam voltages are shown in Figure 5. These plots assume that the RF drive current from the buncher is constant across the band.

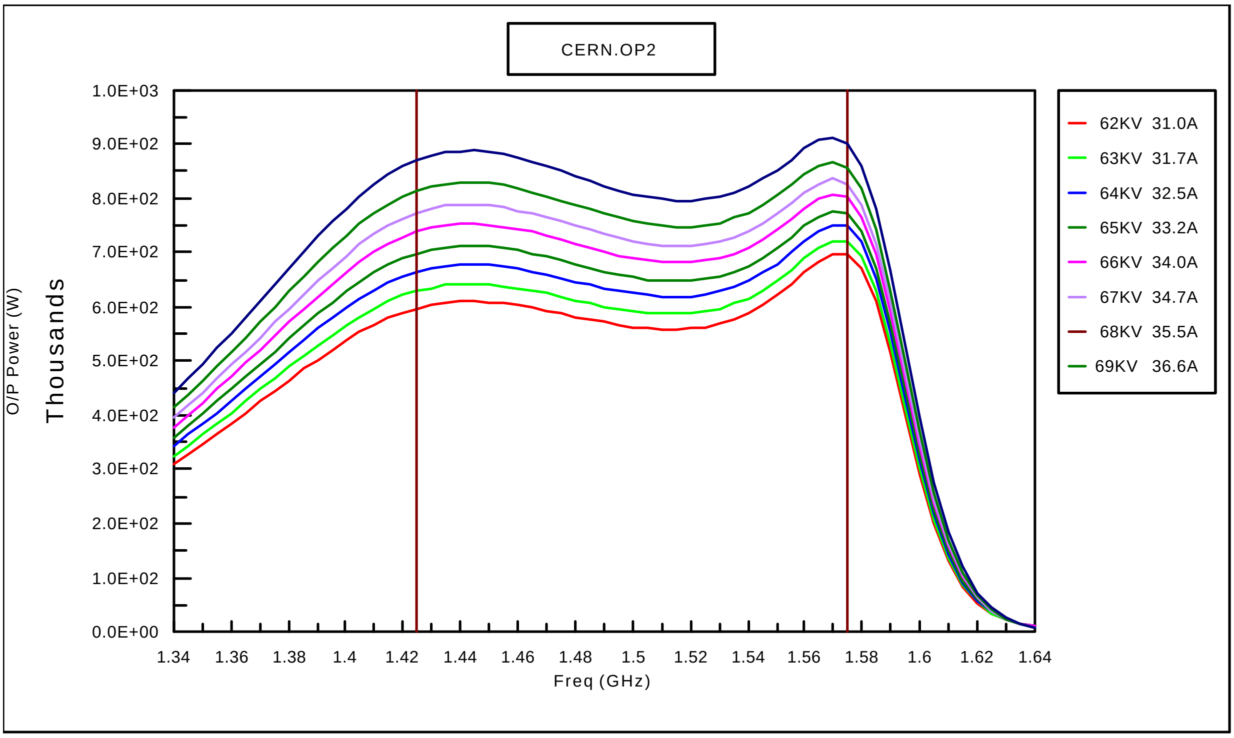

Figure 5 Variations of output power from RCCO with change of beam power

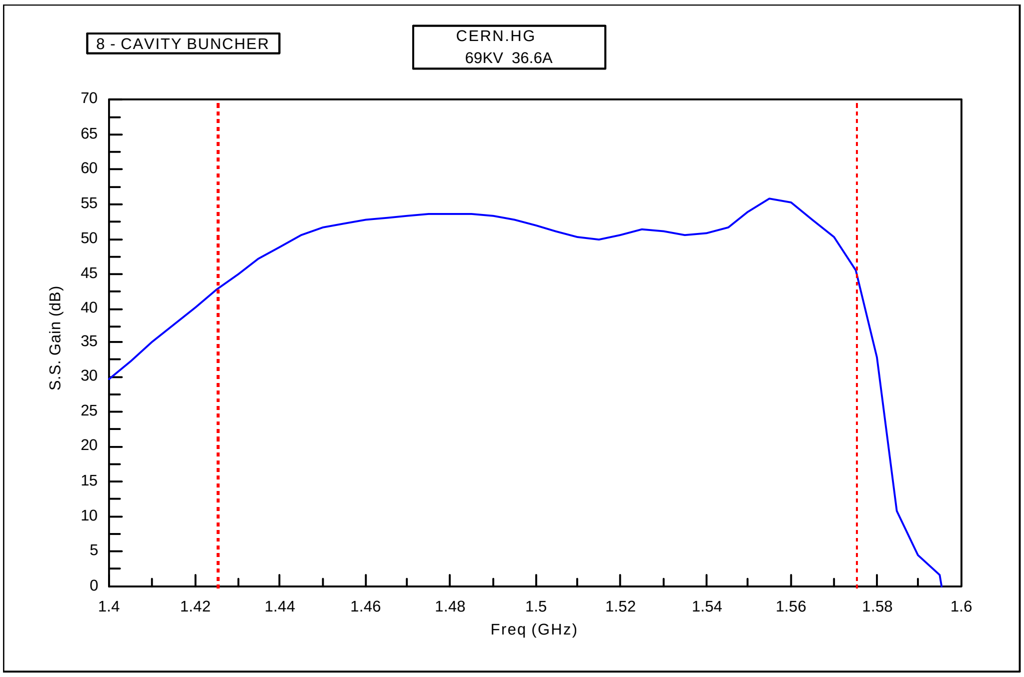

Figure 6 Small signal gain of complete klystron

The phase of the signal through the tube is shown plotted in Figure 7. In reality the signal phase is continuous.

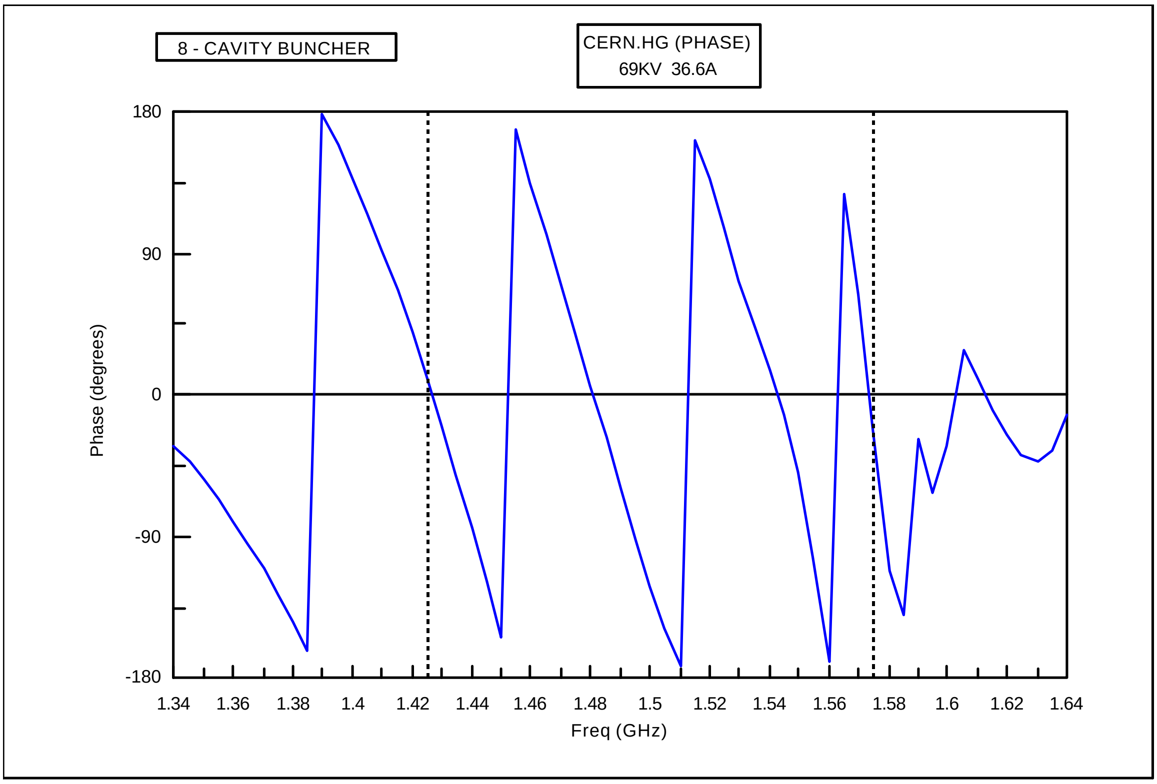

Figure 7 Phase variation of signal with change of frequency

4.4 Design of Other Klystron Components

With the exception of the RF window most of the components of the tube are simply scaled versions of those used on the PT6006 or similar tubes. The components are covered briefly below.

4.4.1 RF Window Design

The existing PT6006 klystron has a 3.125 inch broadband coaxial window which has a peak power capacity higher than that required. This window is connected to a coaxial output line via a standard RF connection designated as ANDREWS type 18200.

Small changes to the window dimensions will be required to ensure minimum VSWR at the higher CERN centre frequency. The window may also require pressurised air or some specialised gas like SF6 to avoid voltage breakdown on the non-vacuum side. On the vacuum side, the widow should adequately hold off the RF voltage even with a total short circuit on the output.The existing coaxial window connects via a pressurisable waveguide transition into waveguide WR860.

4.4.2 Electron Gun

The existing klystron uses a pulsed cathode gun. It was necessary to redesign the gun to provide the correct beam diameter and cathode current needed by the new tube design. It was considered advantageous to produce a gridded gun design for this application. The RF pulse produced by the gridded gun is much flatter and well controlled. The pulse length can also be adjusted with ease, which is not the case with pulsed cathode guns driven by line modulators.

Because of the low duty cycle, an intercepting grid was chosen. This will handle the heat produced by the interception current and is simpler and cheaper to manufacture.

It will be possible to run the gridded gun using a line modulator, if this is required, by tapping-off the grid voltage from the EHT voltage using a resistor chain.

From the parameters EHT voltage, cathode diameter, throw and the beam diameter, the electron-optical design of the gun was carried out. This was broken down into three stages, the electrostatic design, the magnetic design and then a check on the design was carried out using three dimensional finite element software.

The first two stages were carried out using TMD's in-house electron optics program. This is a finite difference code which is 2½ D (two dimensional with cylindrical symmetry). The results were checked using a 3D finite element code from Vector Fields. Figure 8 shows the resulting beam with magnetic field.

4.4.3 Collector

Because of the low duty cycle involved, the design of the collector is not critical. A proven design from another tube has been chosen and calculations carried out to check its suitability.

The collector has lead shielding which can provide X-ray protection against emissions from electrons with energies up to 80 keV.

An insulating ceramic, used to enable the monitoring of collector and body current separately, has been designed. This collector has the capability of being depressed to improve overall electrical efficiency. Up to 20 kV of depression can be applied.

4.4.4 Solenoid Design

The beam diameter, voltage and current define the required magnetic flux needed to focus the beam. The minimum magnetic flux to produce a smooth beam, the Brillouin field, is calculated to be 0.0713 T. In order to focus the beam when it is bunched by the klystron interaction, it is customary to work at a higher level of flux. In this case twice the Brillouin level has been chosen based upon experience with the PT6006 tube.

The cavity structure determines the length of the solenoid; in this case the 8-cavity buncher and output cavity have an overall length of 0.987 m. The cavity outer diameter, cavity tuner dimensions and the output window determine the internal diameter of the solenoid which in this case is 280 mm.

The overall weight of the solenoid is 287 kg. The calculated operating voltage is approximately 100 V and the current will be 18A.

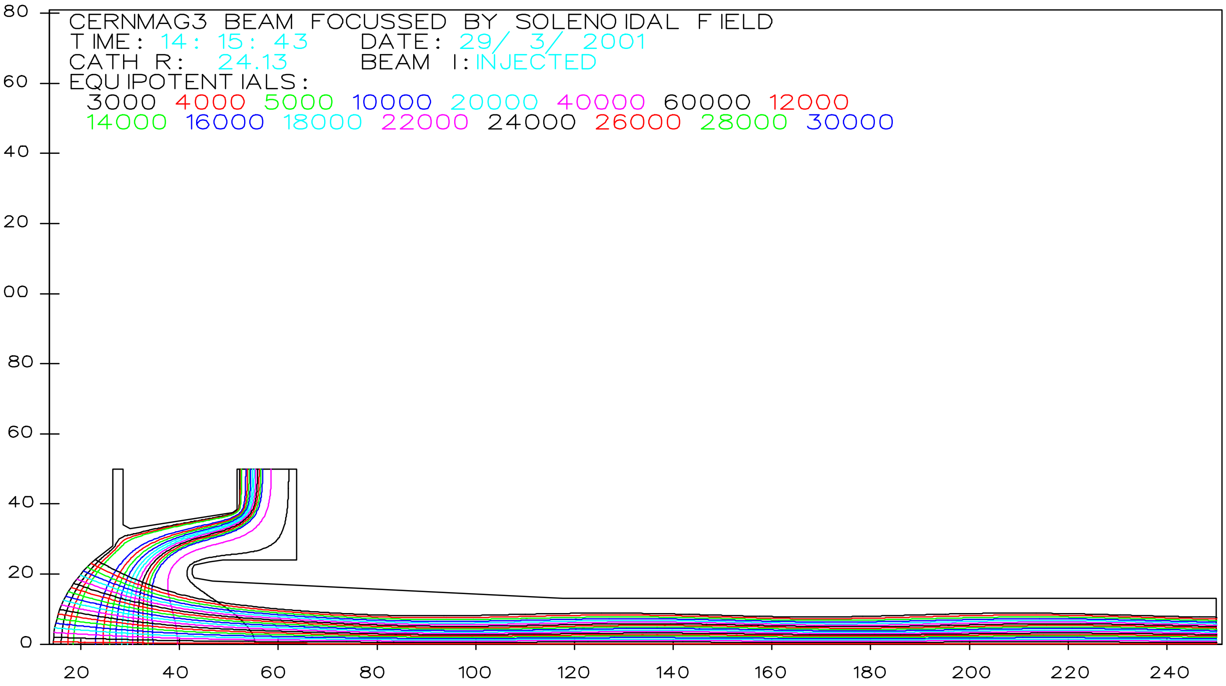

Figure 8 Electron trajectories in gridded gun with magnetic focusing field

4.4.5 General Mechanical Design

The mechanical design of the tube follows the construction of the PT6006. The cavity stack is made of welded stainless steel.

The cooling is provided by water jackets which cool the drift tubes directly. The drift tubes are copper, which is used because of its high thermal and electrical conductivity.

A cut-away drawing of the tube with overall dimensions is shown in Figure 9.

5. CONCLUSIONS

The main conclusions of this feasibility study were:-

i) The calculations show that the PT6006 klystron can be scaled to give the required output power over the correct bandwidth at the higher frequency required.

ii) The same number of buncher cavities will be needed as in the standard design but a longer body stack will be required because of the higher power operation. The latter means operating at a higher EHT voltage which increases the interaction length.

iii) The existing coaxial RF window used on the PT6006 will be adequate for use in the new design although it may need pressurised air or insulating gas to ensure arc-free operation.

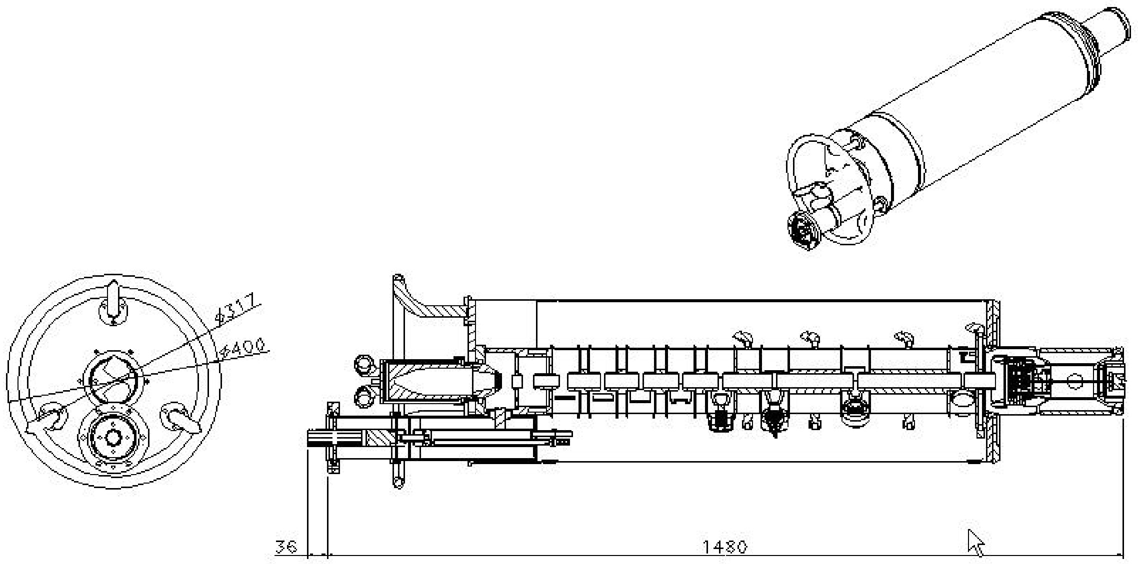

Figure 9 Drawing of complete tube with dimensions

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