

Session 1-2  
Chairman : G. Caryotakis (SLAC)

## *Klystron Technology*

## REVIEW OF SESSION 1.2 KLYSTRON TECHNOLOGY

G. Caryotakis (Chairman)  
SLAC

These were 4 completely different papers with essentially nothing in common except that all devices were designed or built to power accelerators.

To summarize:

1. The CPI paper (Ed. Eisen)

CPI is developing klystrons for SNS at 805 MHz. Ed discussed the experimental performance of the high power tube (2.5 MW peak, 250 kW average) and the predicted performance of a lower power tube (550 kW peak, 8% duty cycle) for superconducting cavities. These are pretty straightforward klystrons, with good efficiency. The design (single beam, ordinary cavities) is optimised for the frequency and power.

2. The TMD Technologies paper (Graham Phillips)

This is a paper tube, so far, but a design that will probably be successful. The problem is getting a very wide bandwidth (10%) at a relatively low power (500 kW) at L-band. At 100 kW and a microperveance of about 2, and 30% efficiency the beam impedance is about 2500 ohms. If one assumes a required gap impedance of perhaps 3000 ohms and an R/Q of 120 in a single cavity, then the Qext would be about 25, which would only produce a half-power band width of 4%. The fact that an overlapping mode (0- $\pi$ ), 2-gap output cavity was used and the 10% bandwidth obtained, is quite impressive.

3. The THALES paper (Armel Beunas)

This is the first MBK built and delivered to a customer in the Western world. It is assumed that the reasons for the 7 beams are both lower the voltage and increased cooling surfaces, in addition to higher efficiency at lower perveance, (which is the main reason). The tube appears quite uncomplicated despite the seven cathodes and drift tubes. If a single beam tube had been attempted, instead of an MBK, and if a comparable efficiency was desired, then a klystron with  $\mu K = 1$  and an efficiency of 50% would have a beam voltage of 210 kV, instead of 117 kV. The tube would have also been much longer.

4. The SLAC paper (George Caryotakis)

This is perhaps the first fully simulated sheet beam klystron. It uses 2 sheet beams ( with a 10:1 aspect ratio) to produce 150 MW peak, and 50 kW average power, at 11.4 GHz. Simulations performed so far suggest that the beam and circuit will be stable, the efficiency is high, and parts count very low, hence a low cost source for the NLC which requires over a 1000 klystrons at half that power.

We believe that a “DSBK” klystron at 30 GHz (for CLIC) could be designed to produce 50 MW at good efficiency (> 50%).

# A SHEET-BEAM KLYSTRON PAPER DESIGN

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## **Abstract**

What may be the first detailed cold test and computer simulation analysis of a Double Sheet Beam Klystron (DSBK) was performed at SLAC. The device was conceptually designed mechanically, and evaluated electrically for beam formation, gain, stability and efficiency. It is believed that the DSBK can be built at a relatively low cost for a future NLC collider and can produce at least 150 MW at 11.4 GHz with PPM focusing. Voltage and current are 450 kV and 640 A, respectively.

The Sheet Beam Klystron (SBK) is a device that has been considered as a microwave source for at least 60 years, but has never been fully designed or constructed. It was first proposed by Kovalenko in Russia in 1938 and revisited repeatedly over the years in the USSR, France and the US. The fact that no serious attempt was ever made to build and test an SBK can probably be attributed to the existence of alternatives and to perceived electrical and mechanical difficulties.

The principal electrical difficulties have been the large drift tube and overmoded cavities that the SBK requires. Also, designers have been concerned with the possibility that the sheet beam might be unstable suffering from diocotron break-up, or be difficult to contain laterally at the edges. Mechanical issues centered mostly at the gun, and the thermal design of a large cathode/heater package. Certainly, the construction of sheet-beam guns is beyond the capabilities of most universities and national laboratories. Industry, for the most part, has not taken on the SBK design problem, simply because other klystron types could serve existing requirements, or could be easily developed.

The chief virtue of the SBK is that its large lateral dimensions permit high power to be attained with low current densities in the cathode, and low power concentration in the cavities. This is the same advantage that multiple beam klystrons have over single-beam klystrons. The difference is that an SBK can be made with a fraction of the parts an MBK requires, or for that matter, that are normally used in an ordinary klystron.

At SLAC, the logistics of the Next Linear Collider (NLC) initially required several thousand 75-MW X-band klystrons for the 500 GeV versions of the machine. Gradually, as these tubes were built, put to use, and accumulated hours, confidence in their performance led to increases in the pulse length and the ratio of pulse compression. Today, the baseline NLC klystron has a pulse length of approximately 3 microseconds and the number of PPM-focused klystrons is approximately 1600. Obviously, this is still a large number of fairly complicated tubes. A klystron with twice the output would be very desirable, especially if a 1-TeV NLC were to be considered. However, 150 MW peak and a 50 kW average power at 11.4 GHz is uncomfortably high with a single beam and an output circuit with a one-centimeter bore. This is what motivated us to look very seriously into the SBK.

Through a process of parameter trade-offs, the design that has emerged employs two beams, each with an aspect ratio of 10:1 and perveance of  $1.1 \times 10^{-6}$  (0.11 micropervs per square). These are conservative numbers, and they are, in part, dictated by the necessity to use periodic focusing and to place magnets and polepieces at some distance from the beams in order to simplify the mechanical design and allow water-cooling in the space between the circuit and the magnet stack.

As a matter of fact, mechanical considerations formed the basis for the overall design of this DSBK (Double Sheet Beam Klystron). Referring to Figs. 1 and 2, it can be seen that the cavities, drift tunnels and collectors are fabricated on numerically controlled machines out of four (4) slabs of copper. The two klystrons making up the DSBK share the same vacuum plenum at the double gun, but are otherwise separate mechanically and electrically. The two halves of each klystron are separated by a fraction of a millimeter so that cavities and drift tubes can be pumped from vacuum manifolds running along the entire length of the rf sections and the collectors. This is possible because the TM modes in the cavities do not have rf currents crossing the surface where the two halves are separated. (The guns are shown gridded because the picture was drawn for a different version of the DSBK).

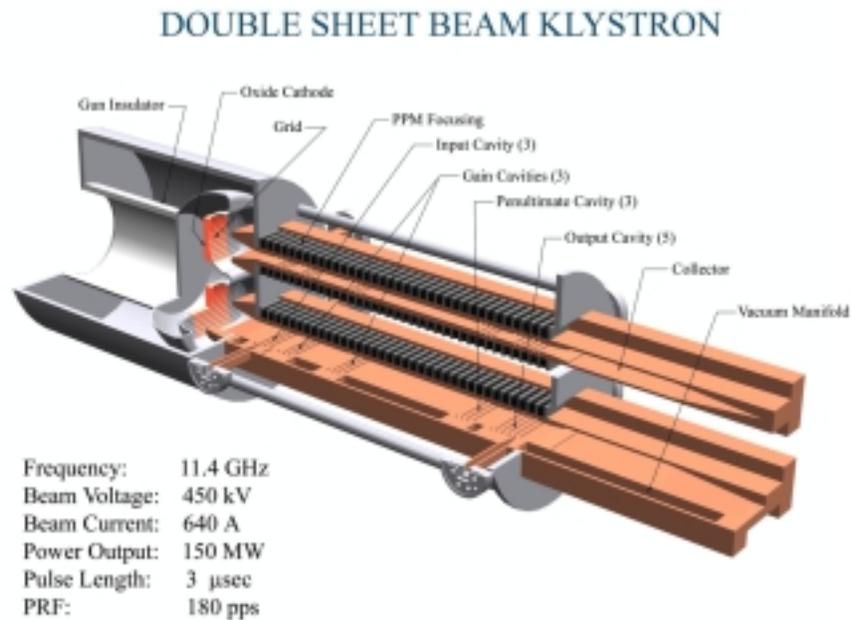


Fig. 1

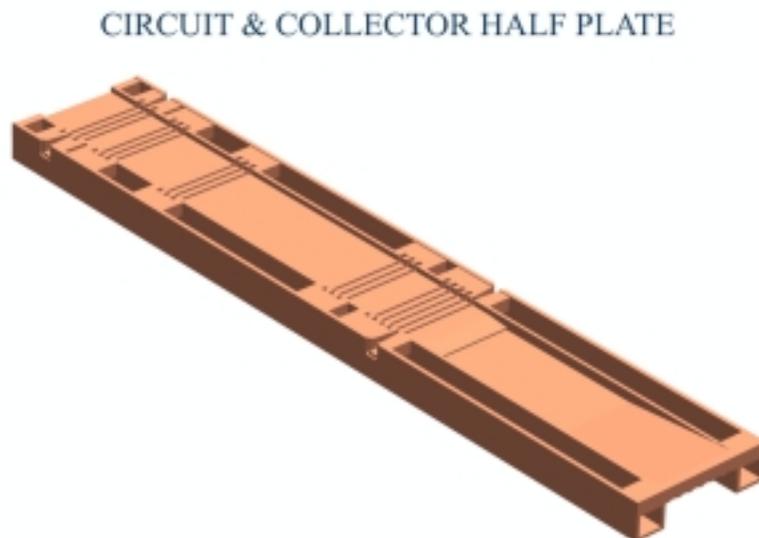


Fig. 2

These are twin 5-cavity klystrons, with all cavities of the extended type operating in the „- mode. The paper design consisted of a number of simulations and some cold testing. We wished to verify the following go, no-go conditions:

1. A gun can be designed with the necessary convergence and a low cathode current density.
2. The beam is well behaved and does not spread excessively laterally.
3. Cavities with sufficiently good R/Q and coupling coefficient can be designed, and provide a reasonably uniform field across the beam.
4. The klystron has good gain and efficiency.
5. The cavities are free of monotron oscillations for TM modes.

These were the conditions that had to be satisfied before prototype construction is attempted. Results are shown in the figures that follow.

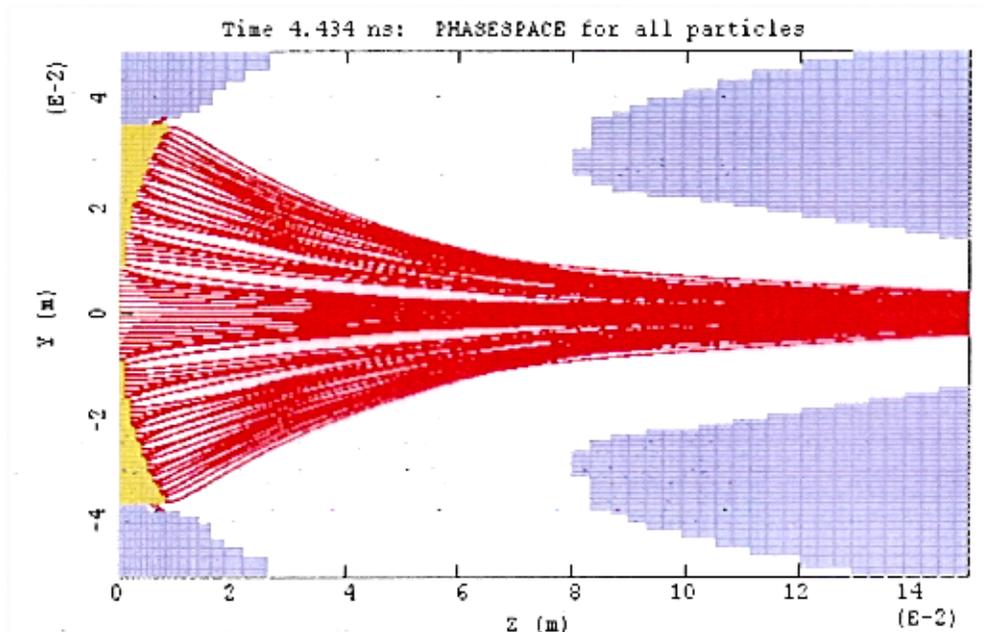


Fig. 3

1. Figure 3 shows a MAGIC 3D simulation of a gun which provides a beam 8-mm thick, 8-cm wide, with a beam current density of  $50 \text{ A/cm}^2$ , and an area convergence of 10, i.e. a cathode current density of  $5 \text{ A/cm}^2$ . The cathode surface is elliptical for good optics.
2. Lateral gun electrodes have not been designed as yet, but Fig. 4 shows that a beam artificially injected in the drift tunnel and immersed in a 3000 magnetic field is not spreading in a 10-cm distance and remains evenly distributed along its width. PPM simulations have not been performed as of yet, but PPM focusing is not expected to be a problem.
3. The cavities for the DSBK were at first designed as single cutoff waveguides. This is the method proposed at SLAC more than 15 years ago for providing a flat electric field across the width of the beam. A cold test model was constructed to test this scheme, as well as the isolation between cavities separated by varying lengths of a  $1.2 \times 9 \text{ cm}$  drift tunnel (Fig.5) Cavity isolation was found to be more than 50 db in 5 cm of drift tube. However, GdfidL and MAGIC calculations showed that the coupling coefficient and R/Q were too low for a single cavity of the cutoff waveguide type. Figure 6 shows that the coupling coefficient for a transit angle of about 1 radian was only 0.09. Using triplet cutoff waveguides coupled capacitively

through the drift tube and operating in the  $\pi$  mode corrected this. The coupling coefficient increased to 0.36 with an R/Q of 52 ohms. The light spots in the middle of the top view of the beam (Fig. 4) are a printer artifact.

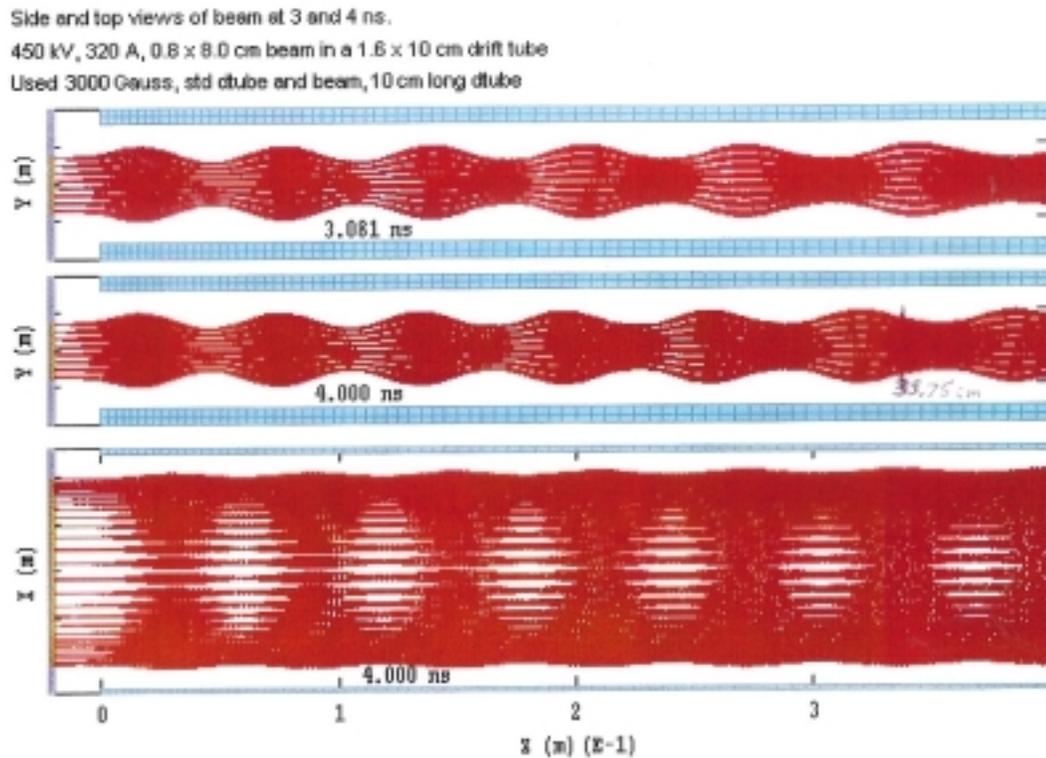


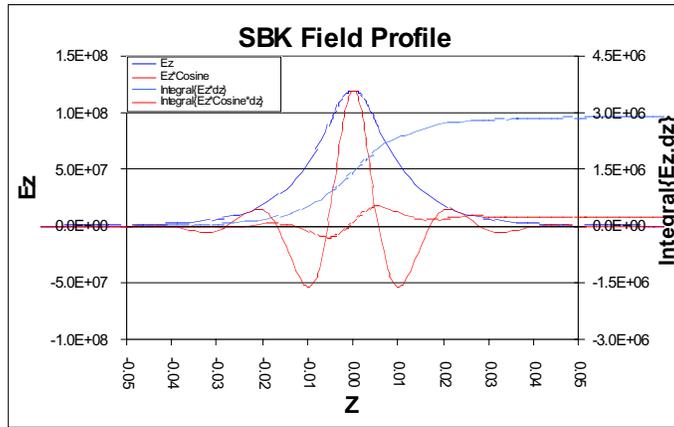
Fig. 4

4. With two of these cavities and an artificial beam, a MAGIC calculation produced a gain of about 18 db between two triplets spaced about 30 cm apart. Figure 7 shows the ratio of the rf current induced in the second cavity to the artificial rf current in the beam exciting the first cavity. We have inferred from these simulations the reduced plasma wavelength and beam loading parameters necessary to calculate small-signal gain. Using these in a standard gain vs. frequency calculation, we predict a 68+ db gain for the 5-cavity tube (Fig. 8 is on a separate page). Finally, a large-signal 3D-MAGIC simulation (Fig. 9) was run in which a beam modulated with an  $I_1/I_0$  of 1 drives a triplet. The figure shows normal debunching, and Figure 10 indicates that this is evenly distributed across the width of the beam. A simulation for a higher value of  $I_1/I_0$  will follow.



Fig. 5

Single Cavity  $M = 0.088$



Triple Cavity  $M = 0.36$

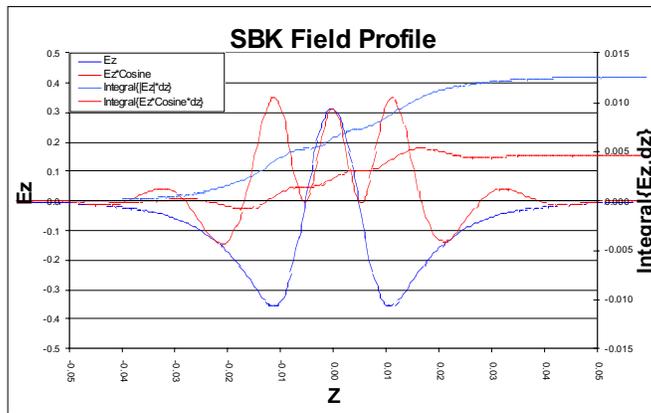


Fig. 6

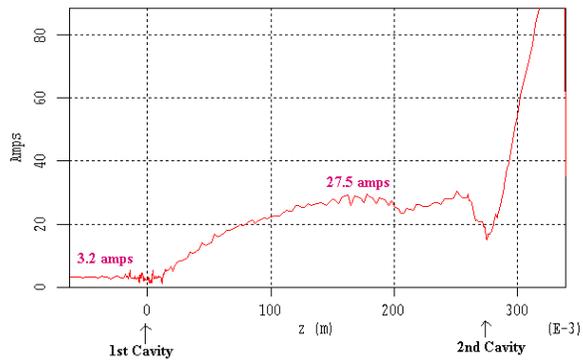


Fig. 7. RF current vs. Z.

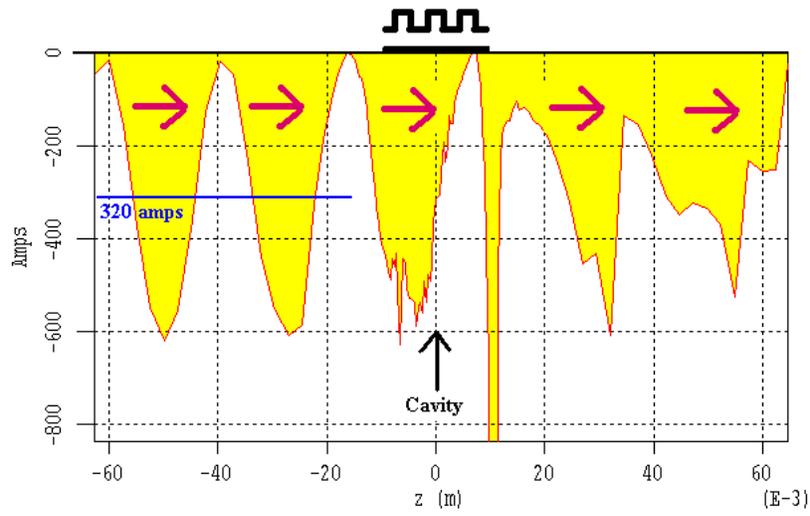


Fig. 9

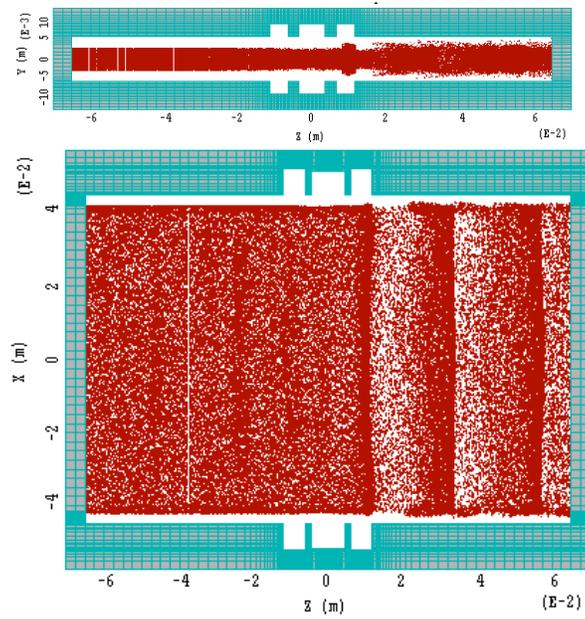


Fig. 10

# One-half of an 11.4 GHz 150-MW DSBK (Coupling coefficient from GdfidL, beam loading, reduced plasma frequency from MAGIC)

----- Data Inputs -----GPSDRV02.MCD

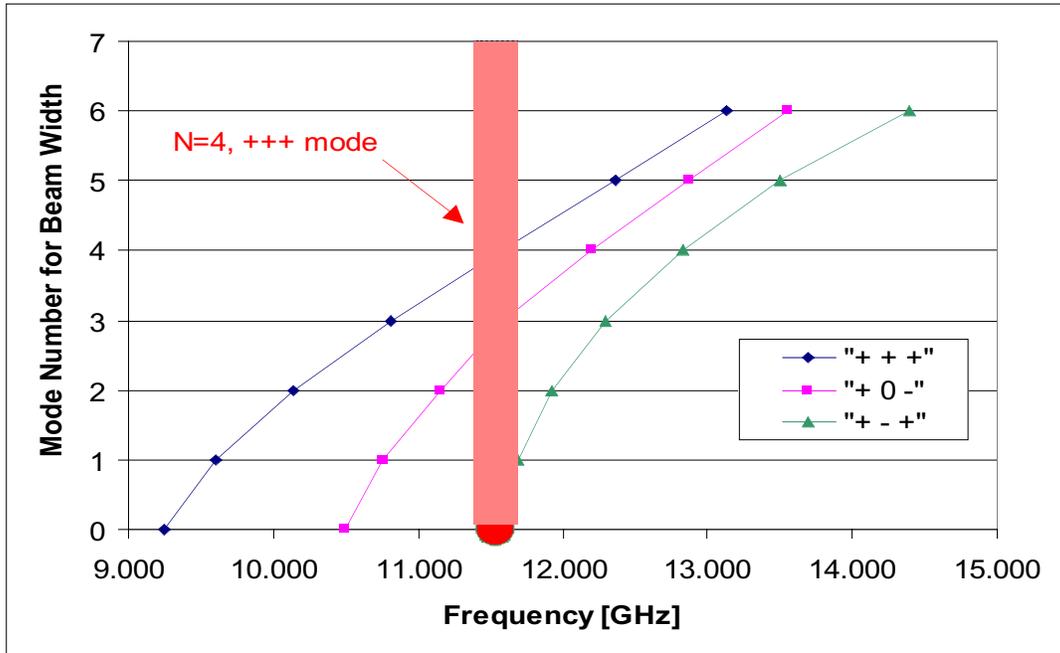
<p><math>V_0 \equiv 450000</math> <b>Beam Voltage (V)</b></p> <p><math>I_0 \equiv 320</math> <b>Beam Current (A)</b></p> <p><math>f_0 \equiv 11.42</math> <b>Center Frequency (GHz)</b></p> <p><math>a \equiv 0.006</math> <b>Drift tunnel half-height (meters)</b></p> <p><math>b \equiv 0.004</math> <b>Beam half-thickness (meters)</b></p> <p><math>w \equiv 0.08</math> <b>Beam width (meters)</b></p> <p><math>\gamma \cdot a = 0.902</math>    <math>\gamma \cdot b = 0.601</math></p> <p><b>Beam resistance</b>    <math>R_0 = 1.406 \times 10^3</math> <b>ohms</b></p> <p><b>Brillouin field</b>    <math>B_{br} = 368.297</math> <b>Gauss</b></p> <p><b>Plasma Frequency (rad/s)</b>    <math>\omega_p = 2.425 \times 10^9</math></p> <p><math>2 \cdot \gamma \cdot b = 1.202</math></p> <p><math>S := \frac{a}{b}</math>    <math>S = 1.5</math></p> <p><math>R \equiv 0.62</math></p> <p><math>\frac{2 \cdot \pi \cdot f_0 \cdot 10^9}{\omega_q} = 47.723</math></p> <p><math>\lambda_q = 1.061</math> <b>meters</b>    <math>\lambda_p = 0.658</math> <b>meters</b></p> <p><b>Power output @ 50% total efficiency:</b> <math>0.5 \cdot V_0 \cdot I_0 \cdot 10^{-9} = 0.072</math></p>	<p><b>Gun Microperveance (uA/V<sup>1.5</sup>)</b> <math>K = 1.06</math></p> <p><b>Beam current dens.</b>    <math>J_0 = 50</math> <b>A/cm<sup>2</sup></b></p> <p><b>Electron Prop. Constant (rad/m)</b>    <math>\beta_e = 282.604</math></p> <p><b>Radial propagation constant (rad/m)</b> <math>\gamma = 150.271</math></p> <p><b>Bunching wave number (rad/m)</b>    <math>\beta_q = 5.922</math></p> <p><b>Gap transit angle</b>    <math>2 \cdot \beta_e \cdot d_1 = 3.109</math></p> <p><b>No of cavities:</b>    <math>N \equiv 5</math></p> <p style="text-align: center;"><b>GAIN (DB) vs FREQUENCY</b></p> <p><b>Gain</b>    <math>PP_{max} = 68.369</math> <b>Db</b></p>
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Cavity Rs/Q	External Q and Qo		Cavity Frequency (GHz)	Gap-Gap L (m)
$RQ_1 \equiv 52.5$	$Qe_1 \equiv 805$	$Qo_1 \equiv 6550$	$f_1 \equiv 11.42$	$l_1 \equiv 0.0$
$RQ_2 \equiv 52.5$	$Qe_2 \equiv 1000$	$Qo_2 \equiv 6550$	$f_2 \equiv 11.4$	$l_2 \equiv 0.1$
$RQ_3 \equiv 52.5$	$Qe_3 \equiv 1000$	$Qo_3 \equiv 6550$	$f_3 \equiv 11.43$	$l_3 \equiv 0.1$
$RQ_4 \equiv 52.5$	$Qe_4 \equiv \infty$	$Qo_4 \equiv 6550$	$f_4 \equiv 11.45$	$l_4 \equiv 0.1$
$RQ_5 \equiv 52.5$	$Qe_5 \equiv 400$	$Qo_5 \equiv 6550$	$f_5 \equiv 11.42$	$l_5 \equiv 0.1$

----- Data Output -----

Beam loaded Q	Gap Distance (m)	Coupling Coefficient (induced current)	Drift Length (degrees)
$Qb_1 \equiv 918$	$Zg_1 = 0$	$M_1 = 0.357$	$\beta_{q1} = 0$
$Qb_2 \equiv 918$	$Zg_2 = 0.1$	$M_2 = 0.357$	$\beta_{q2} = 33.929$
$Qb_3 \equiv 918$	$Zg_3 = 0.2$	$M_3 = 0.357$	$\beta_{q3} = 33.929$
$Qb_4 \equiv 918$	$Zg_4 = 0.3$	$M_4 = 0.357$	$\beta_{q4} = 33.929$
$Qb_5 \equiv 918$	$Zg_5 = 0.4$	$M_5 = 0.357$	$\beta_{q5} = 33.929$

Fig. 8

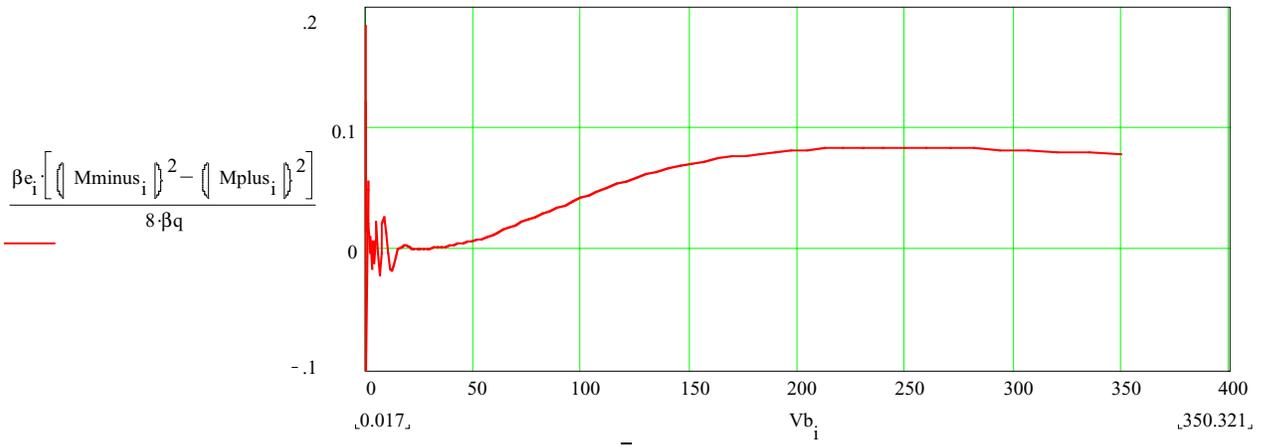


N	"+ + +"	"+ 0 -"	"+ - +"
0	9.245	10.502	<b>11.542</b>
1	9.598	10.762	11.689
2	10.143	11.152	11.930
3	10.817	11.575	12.292
4	<b>11.588</b>	12.193	12.827
5	12.358	12.876	13.497
6	13.129	13.558	14.394

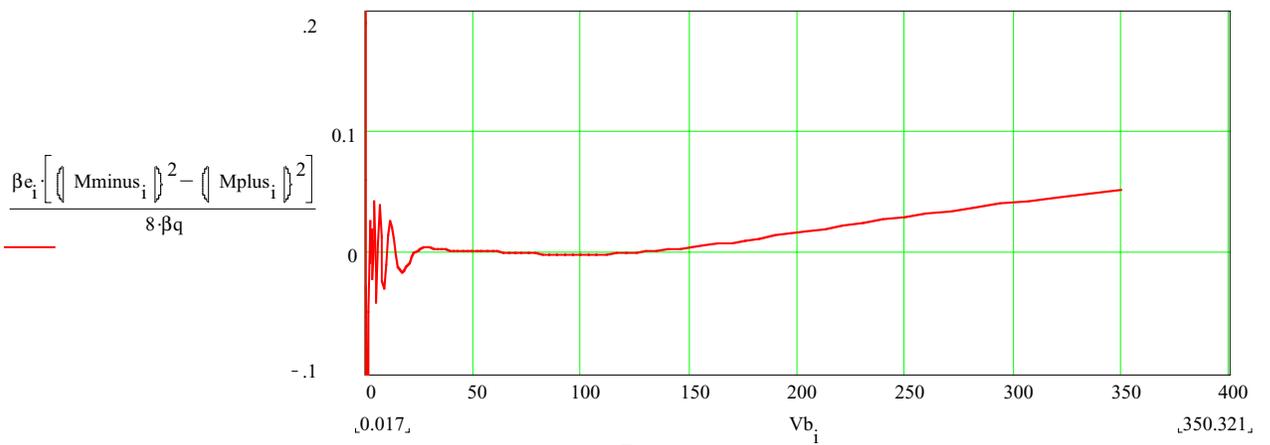
Fig. 11

- To test for stability in unloaded triplet cavities, a mode search was conducted using MAGIC (Fig. 11), and several of the TM modes were tested for negative beam loading, using GdfidL and the  $M_{\text{minus}}^2 - M_{\text{plus}}^2$  criterion, the difference between the squares of the coupling coefficients for the fast and the slow space charge waves. (See Fig. 12). The slight differences in the frequencies between Fig. 12 and mode search and the stability tests in Fig. 12, are due to the fact that the structure used in Fig. 12, was tuned at 11.426 GHz, instead of 11.542 GHz.

**Beam Coupling**  
*pi-mode 11.4226*



+0- mode  $N=0$  and 2, 10.5203 and 11.2096



+++ mode  $N=4$ , 11.5735

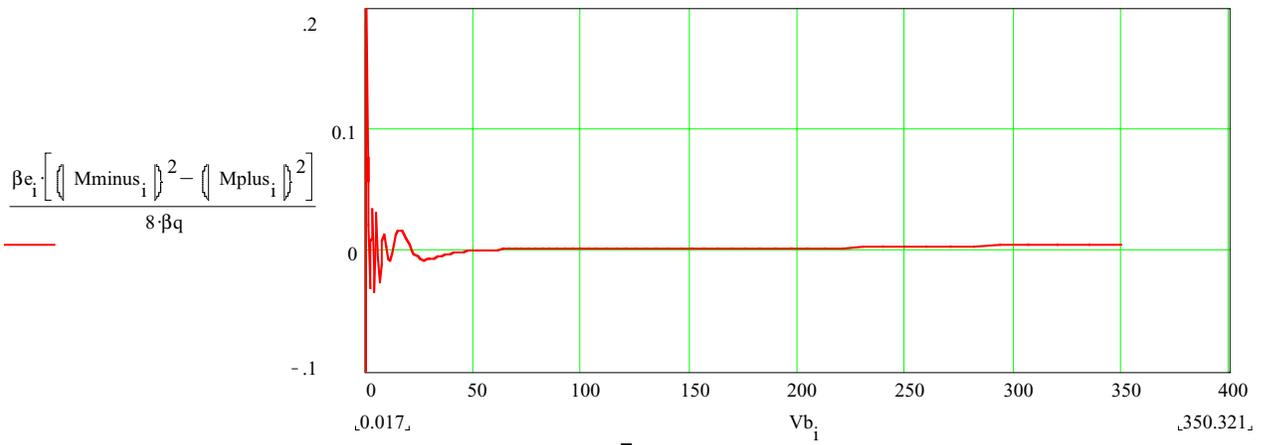


Fig. 12 Stability test examples

## **CONCLUSIONS**

Although additional simulations will be necessary, it is clear the device has an excellent chance to work and should be built. This may take place in 2002.

## APPENDIX 1 — LATE BREAKING RESULTS FROM MRC

Some recent results arrived from MRC which were too late to incorporate into the body of the paper, but too important to leave out. The first transmission from Dave Smithe of MRC, who was asked to drive a triplet cavity with a fully pre-bunched beam, is reproduced here without comment except to note that this is the first effort to run the simulation for full power. No attempts have been made to tune or otherwise adjust for maximum power.

### A.1.1 OUTPUT POWER

Geometry: Resistive load filling each of the end cells.

Beam voltage = 450 kV, Beam current = 320 amps,  $I_1/I_0 = 1.8$ .

Output Power: 62.0 MWatts,

Wall Losses: 5.5 MWatts

A top view of the cavity geometry is shown in Fig. A.1.1.1. There is resistive load in each of the end cells.

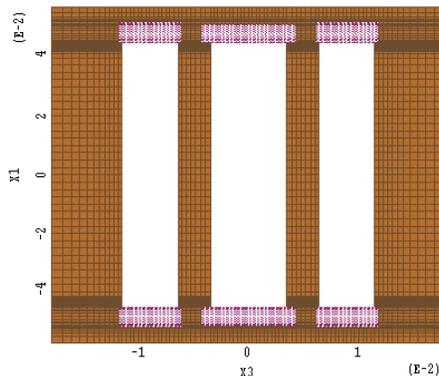


Fig. A.1.1.1

A pre-bunched beam is injected into the cavity, and it is rung up to saturation. Many runs were done to optimize the output power by varying the amount of resistance (cavity Q), and hot-test frequency-shift (+0.01%). The following figure (A.1.1.2) shows the time-history of cavity saturation. The first plot shows the sum of power to the end-cell load plus wall-losses, and the second plot shows just wall-losses.

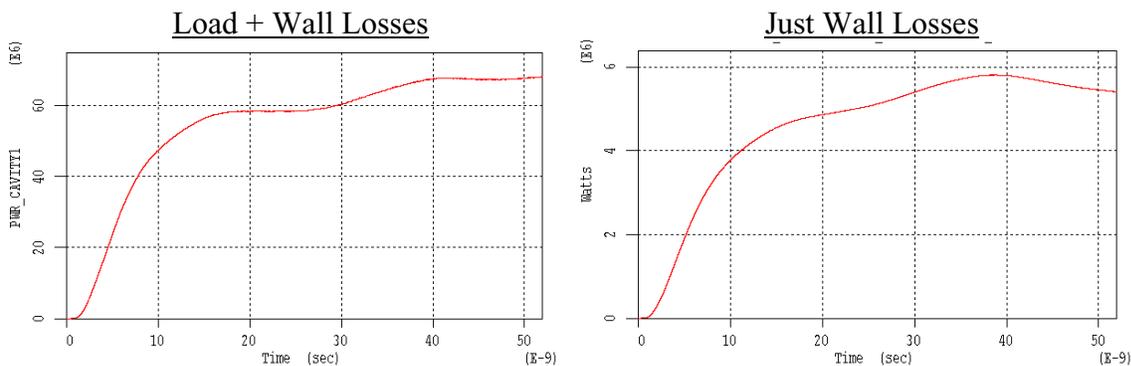


Fig. A.1.1.2

A view of the particles and current is shown below (Fig. A.1.1.3). The shape of the pre-bunched current is a sine wave, truncated below some value, and re-scaled to give the correct DC current. The particles are injected at a single energy of 450 kV.

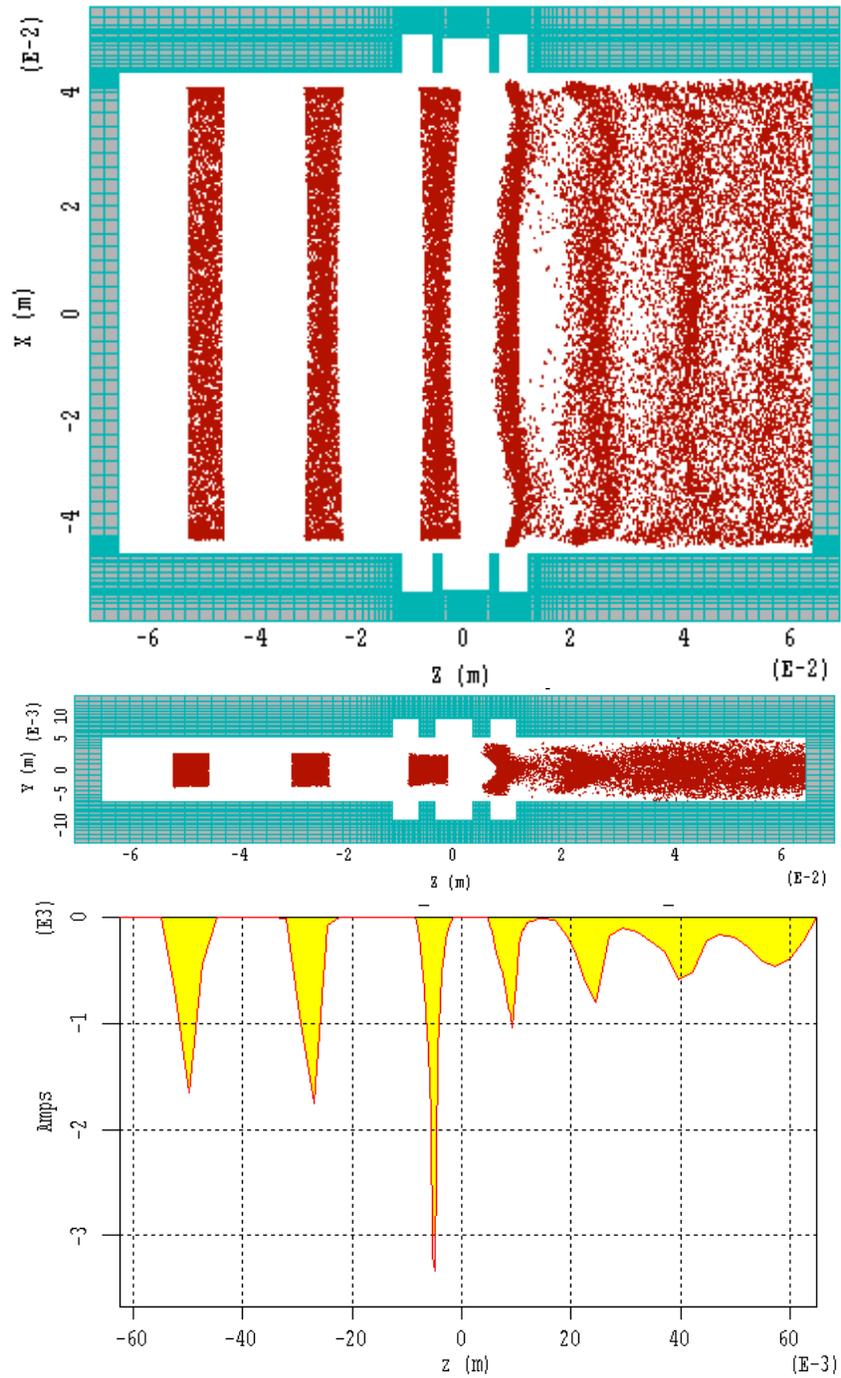


Fig. A.1.1.3

Shown below are views of particle-energy, average-energy-per-particle, and RF-current, down the length of the drift tube (Fig. A.1.1.4). Note that few, if any, particles are turned-around. About 47% of the original beam energy is lost, 43% to the output load, and 4% to copper wall losses. The RF current at the exit is about  $\frac{1}{3}$  of the original pre-bunched RF current.

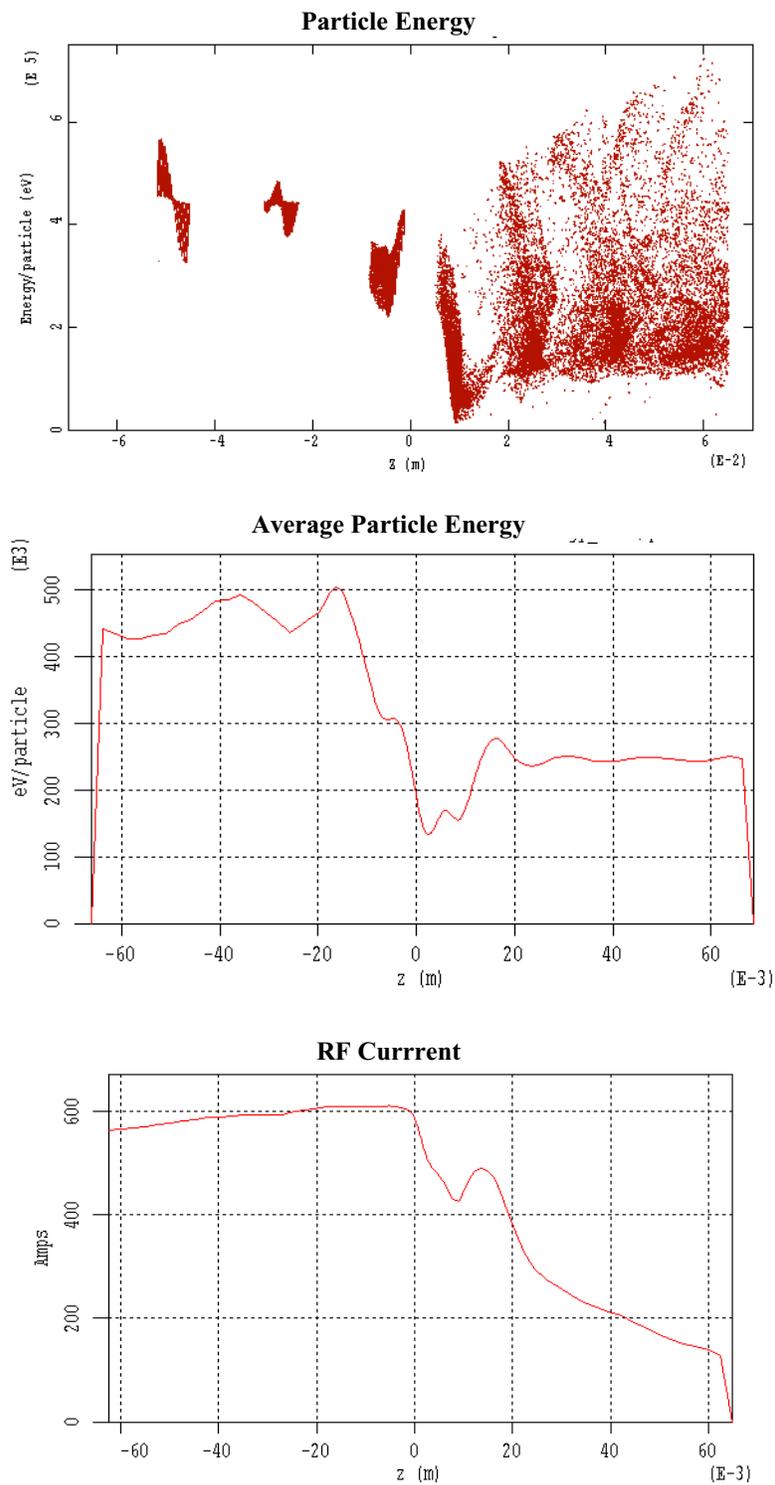


Fig. A.1.1.4

### A.1.2 TEST OF CAVITY STABILITY

This is a final transmission from MRC (Fig. A.1.2.1). The objective here was to completely unbalance the beam to see whether modes might be excited in the cavity that would lead to oscillations. It can be seen from the treatment below that this did not happen.

Geometry: Unloaded, copper cavity.

Used \_ of beam, e.g., missing right and lower halves, with no RF signal, other than the initial transient. The offset beam and the initial transient provide the seed for any unstable modes. The beam current density is the same as for the previous 450 kV, 320 amp runs.

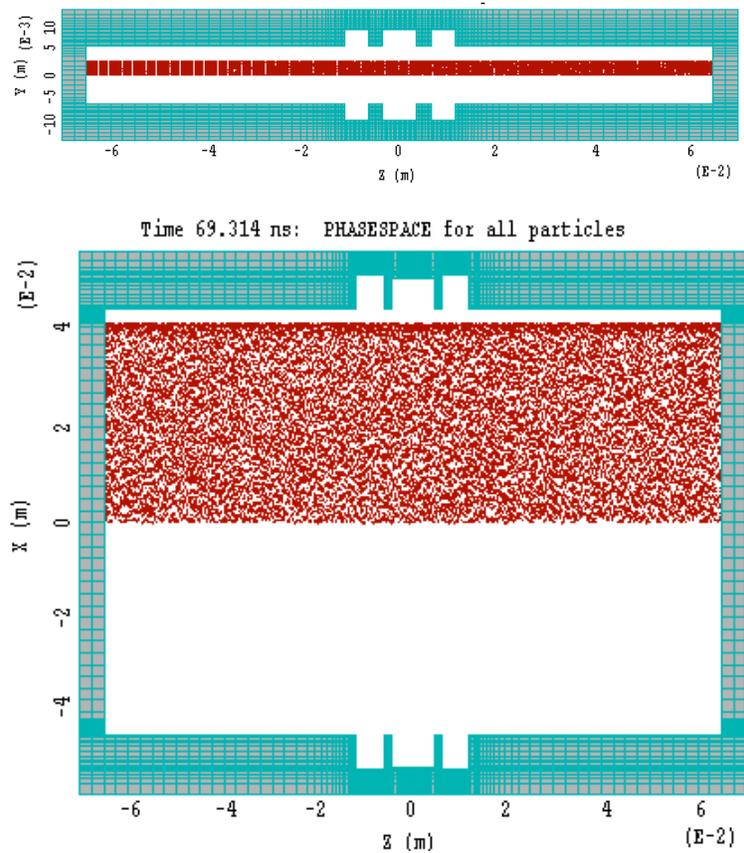


Fig. A.1.2.1

From previous simulations, it is already known that the system is stable at the operating mode, as the operating mode has been seen to saturate in a conventional manner during small-signal analysis.

The simulation was run for 80 nanoseconds. Any linear instability would exhibit an *exponential* increase in the electromagnetic energy ( $U_{em} = \epsilon|\mathbf{E}|^2 + \mu|\mathbf{H}|^2$ ) stored within the cavity, as the instability mode grew in amplitude. *No such increase was observed.* The offset beam, in both X and Y directions, should couple strongly to virtually all conceivable modes, thus there is little chance that an instability exists, but is undetected, since the instability seed is quite strong.

Wall losses of copper have been included. Thus it is still possible that a perfectly conducting cavity might experience an instability, but that the copper wall-loss loaded system is stable.

Instead of an exponential rise in EM energy, a very slow, approximately *linear*, growth in electromagnetic energy was observed (Fig. A.1.2.2). This is typical of all unfiltered relativistic particle-in-cell simulations and is associated with growth of short-wavelength (grid-size) particle noise in a simulation. There is no identifiable cavity mode structure associated with particle noise (Fig. A.1.2.3).

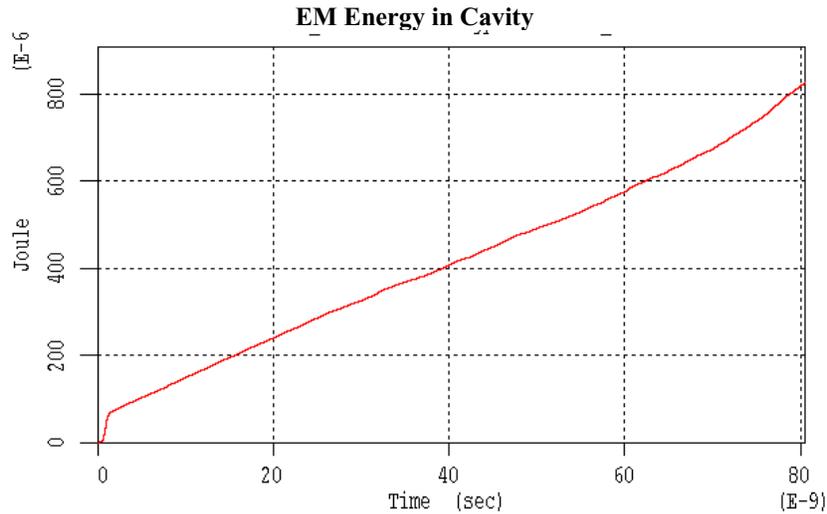


Fig. A.1.2.2

There is also no evidence of a coherent RF signal on the particle positions or energy after 80 nanoseconds.

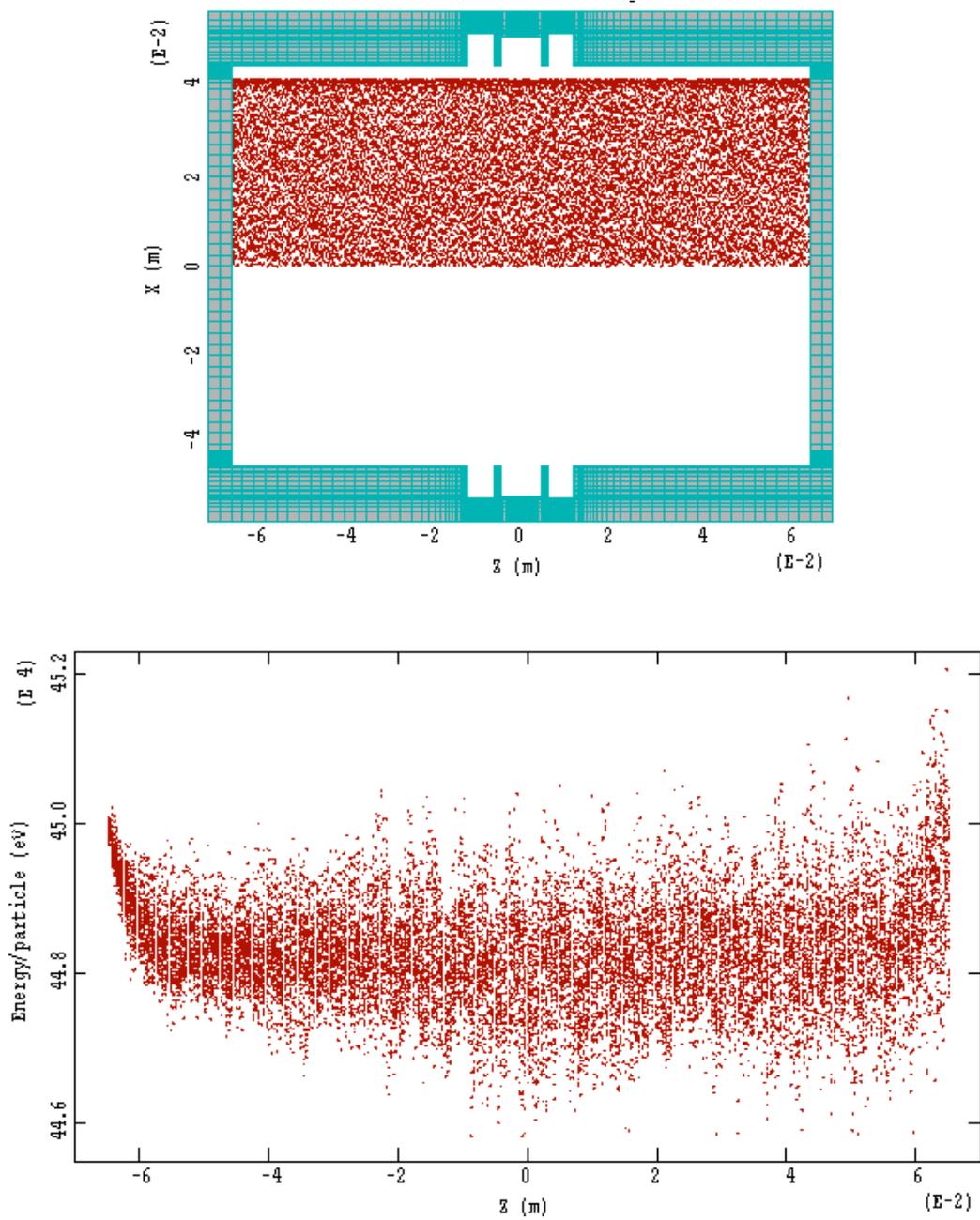


Fig. A.1.2.3

This result is for a single cavity. Instability associated with power propagation between two or more triple-cavities separated by rectangular drift tube has not been investigated here.

## **ACKNOWLEDGEMENTS**

Thanks are due to Daryl Sprehn, who developed the gun optics, Mike Neubauer for the GdifdL simulations, David Smithe of MRC who performed the MAGIC simulations, and Randy Fowkes for the cold test work.

# A HIGH POWER LONG PULSE HIGH EFFICIENCY MULTI BEAM KLYSTRON

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## **Abstract**

THALES ELECTRON DEVICES has developed and built a new high power - long pulse - high efficiency - multi beam klystron (MBK), the TH1801. This MBK uses 7 low perveance beams in parallel and is in operation at the TESLA TEST FACILITY at DESY, where it was tested at full pulse duration of 1.5ms. It reached 10MW at 117kV and 131A with an efficiency of 65%. This paper reports on the tube and the test results obtained on the TH1801 multi beam klystrons built up to now.

## **1. INTRODUCTION**

In the field of long pulse high power tubes, new challenges have to be taken up to go further in the increase of peak power, efficiency and reliability. This boost of performance is requested to minimize the investment and the operation costs of the entire RF system of a particle accelerator.

The peak power delivered by a long pulse single beam klystron is limited by the high voltage its gun can withstand. For instance, the regular L-band TH2104C klystron delivers 5MW peak at 2ms pulse duration. It operates at a voltage of 128kV and a current of 88A. The efficiency is 44%, in agreement with a beam perveance close to the maximum practical value of  $2 \cdot 10^{-6} \text{A/V}^{1.5}$ . To increase the current and then the power, a solution is to use several low perveance beams in parallel within the same vacuum envelope[1,2]. The advantage of this solution is the lower voltage required and the higher efficiency compared to the single beam klystron.

This multi beam concept, which is not a new one, has been applied on the tube THALES ELECTRON DEVICES has developed for the TESLA TEST FACILITY (TTF), the 10MW 1300MHz 1.5ms high efficiency multi beam klystron TH1801 (see photograph in figure 1).

About 1200 5MW TH2104C would be required to power the TESLA linear collider. Thanks to the multi beam klystron, the number of RF source is two times smaller, without increasing the high voltage and with an efficiency yield of about 20 points.

## **2. DESIGN ASPECTS**

### **2.1 Main design parameters**

The main design parameters are discussed in the following paragraphs and are summarized in table 1. This MBK uses 7 low perveance parallel beams which propagate in 7 drift tubes and which interact with the electric field of the common cavities they travel through.

The effective perveance of the MBK is  $3.510^{-6} \text{A/V}^{1.5}$  at the design voltage of 110 kV, with each single beam perveance being  $0.5 \cdot 10^{-6} \text{A/V}^{1.5}$ , that is to say 18.2A per beam. This low single beam perveance, with low space charge forces enables strong beam bunching and consequently high efficiency.

According to the empirical relation  $\eta=0.78-0.16K(\mu\text{perv})$  (1), an efficiency of 70% is achievable with a perveance  $K=0.5 \cdot 10^{-6} \text{A/V}^{1.5}$ .

Table 1  
Design parameters of the TH1801

Operating frequency	1300	MHz
Output peak power	10	MW
Output average power	150	kW
RF pulse duration	1.5	ms
Frequency repetition	10	Hz
Number of beams Nb	7	
Cathode voltage, max.	115	kV
Total beam current	130	A
Total perveance	3.5	$10^{-6} \text{A.V}^{-1.5}$
Efficiency (VSWR=1.2:1 optimized phase)	70	%
Gain (saturated), min	47	dB
Bandwidth (-1dB)	3	MHz
Number of cavities	6	
RF input	N type	
RF output	2xWR650	
Cathode loading, max.	5.5	A/cm <sup>2</sup>
Beam area convergence	9:1	
Electric field at 120 kV	7	kV/mm
Focussing field	1350	Gauss
Collector dissipation	full beam	
Tube height	2.5	M
Position	vertical	
Electromagnet power. goal	4	kW



Fig. 1 The TH1801 multi beam klystron

## 2.2 Interaction section

The interaction structure has been optimized to maximize the degree of bunching and to ensure stable operation on a mismatch of 1.2:1 at any phase. This klystron is a 6 cavities design with four intermediate cavities inductively tuned, all operating on fundamental mode  $\text{TM}_{010}$ . The simulations were carried out on one of the seven beams with an harmonic disk 1D code, and assuming that the R/Q factor is Nb (number of beams) times the R/Q factor related to a single beam. As a high efficiency operation leads to the creation of slow electrons, and in order to inhibit possible oscillations, particular attention was paid to avoid reflected electrons in the output gap and at the entrance of the collector. Related to the load, the output cavity has been slightly over coupled, so that the klystron can operate with a good stability on a mismatched load, under optimum phase condition. In addition to the large overall perveance, this results in an unusual low value of external Qx, about 10.

## 2.3 Beams generation

The tube is equipped with a multi cathode diode gun for beams generation. The electron gun mainly consists of 7 cathodes and a beam forming electrode which surrounds each cathodes (see photograph in figure 2). The cathodes are M type dispenser cathodes with a maximum loading of 5.5A/cm<sup>2</sup> at 18A and a temperature in the range 1010°Cb to 1045°Cb. This gives an expected lifetime of around 36000 hours. The cathodes are powered in parallel.

The design of the gun and the solenoid were carried out with OPTIQUE3D and ANSYS codes. The simulation results, which take into account a 3D magnetic field pattern, are shown in figure 3. The gun produces quite laminar and low scalloping beams with a compression ratio of 9. The electric field is maximum on the radius of the focusing electrode and is kept below 7 kV/mm at a voltage of 120 kV. This value is consistent with long pulse operation.

The beams are focused in a magnetic field more than twice the Brillouin field, which involves magnetic flux through the cathodes. The design reduces, in a large extent, the asymmetry of the magnetic field around each beam axes. Except in the compression area, the axial magnetic field is kept constant in order to limit the defocussing radial components which would lead to beam interception.



Fig. 2 The multi cathode gun

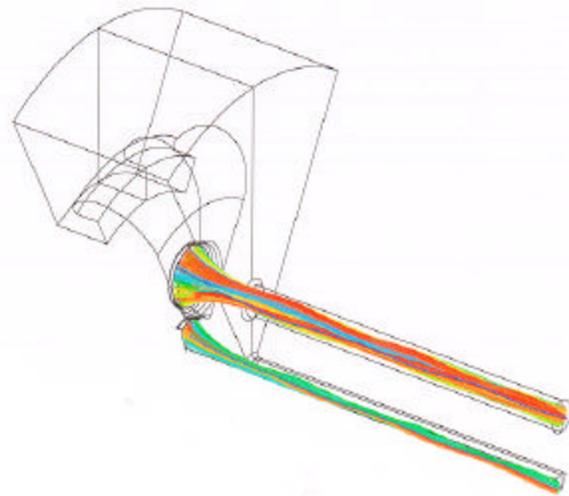


Fig. 3 Electron trajectories

## 2.4 RF cavities

A cross section of the cavity is represented in figure 4. The cavities are toroidal and operate in the fundamental mode  $TM_{010}$ . The beams are packed in the center of the cavity. Due to the field shape, the center beam experiences a larger voltage across the gap than the outer beams, and the field over the cross section of the outer beam lines is not symmetrical with respect to their axis. In this design the R/Q factor of the center gap is 40% higher than the one of the off axis gaps. The cavities were designed with HELMOT3D to investigate the higher order mode pattern. A study was carried out to identify and to damp the modes which could give rise to parasitic oscillations. Except for the input and output ones, the cavities are mechanically tunable, at least on the first tubes.

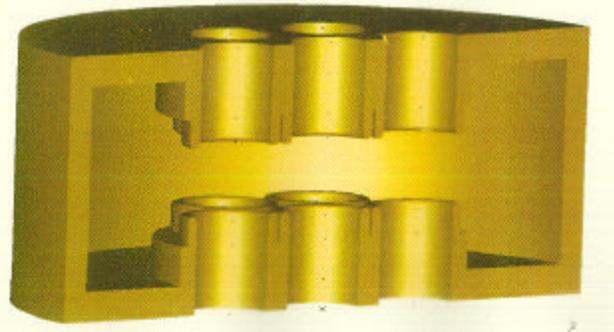


Fig. 4 Cross section of a cavity

## 2.5 Output circuit and collector

The RF power is fed from the cavity to two output WR650 waveguides via irises and pill box type windows used on regular L-Band klystrons.

After the RF extraction, the spent beams are absorbed in a common grounded collector. A 3D analysis of the electron beams spread allowed to limit the potential drop at the entrance of the collector in order to avoid reflected electrons. A particular attention was paid to the cooling circuit of the drift tube section comprised between the output gap and the collector.

## 3. TEST RESULTS

Four MBK have been produced until now. The first one suffered from high beam interception, oscillations and gun arcing. The two next tubes (MBK1 and MBK2) have completed the factory acceptance tests at THALES, where they were tested to full peak and full average RF power in 0.5ms pulse duration and at 30Hz frequency repetition. The pulse duration was set at the maximum that the PFN modulator can provide. The MBK 1 was installed in May 2000 in one of the HV modulators at the TESLA TEST FACILITY at DESY and then conditioned and tested to full RF power at full pulse width of 1.5ms, but lower repetition rate of 5Hz. It is now in use for the operation of TTF. The MBK 2 will be tested at full pulse duration in one of the new HV modulators now being installed at DESY. The MBK 3 is currently under housing at factory. The results of the MBK 1 and 2 are summarized in the following table.

Table 2  
Measurement results on tubes 1 and 2

parameter	unit	tube 1			tube 2	
		TED		TTF	TED	
cathodes voltage	kV	117	-	117	116	-
beams current	A	132	-	131	136	-
perveance	$\mu\text{perv}$	3.3	-	3.27	3.44	-
RF pulse width	ms	0.5	-	1.5	0.5	-
repetition frequency	Hz	30	-	5	30	-
VSWR		<1.1	1.2( opt. $\phi$ )	1.1	<1.1	1.2( opt. $\phi$ )
output peak power	MW	10	10.6	10	10	10.5
output average power	kW	150	159	75	154	161
efficiency	%	64.5	68.5	65	63.4	66.6
gain	dB	48	48.5	48	48.7	48.9
body power	kW	2	2.7	1.8	3.9	3.8
heater power	W	345		360	321	
solenoid power	kW	5.7		5.7	6.25	

Figure 5 shows output power of the first MBK as a function of the input power for several beam voltages, pulse duration and operation conditions. The curves are smooth, without any discontinuities, that means without multipactor or parasitic oscillations. The RF output power was determined from calorimetric data taken from RF loads. The measurements at 0.5ms performed at THALES and at 1.5ms performed at DESY respectively are in good agreement for the same voltage. The measurements were done using water loads at THALES and cooled ferrite loads at DESY, under matched load conditions with a VSWR smaller than 1.1. These measurements are indicated as mode A. The tube 1 delivers 10MW peak and 150kW average with an efficiency close to 65% and with a voltage of 117kV. The perveance of 3.27 is slightly lower than the design value. Additional measurements on a load with a VSWR of 1.2 at optimum phase conditions were performed at THALES, indicated as mode B. Under these conditions, the efficiency increases to 68.5%. During this test the tube demonstrated good stability.

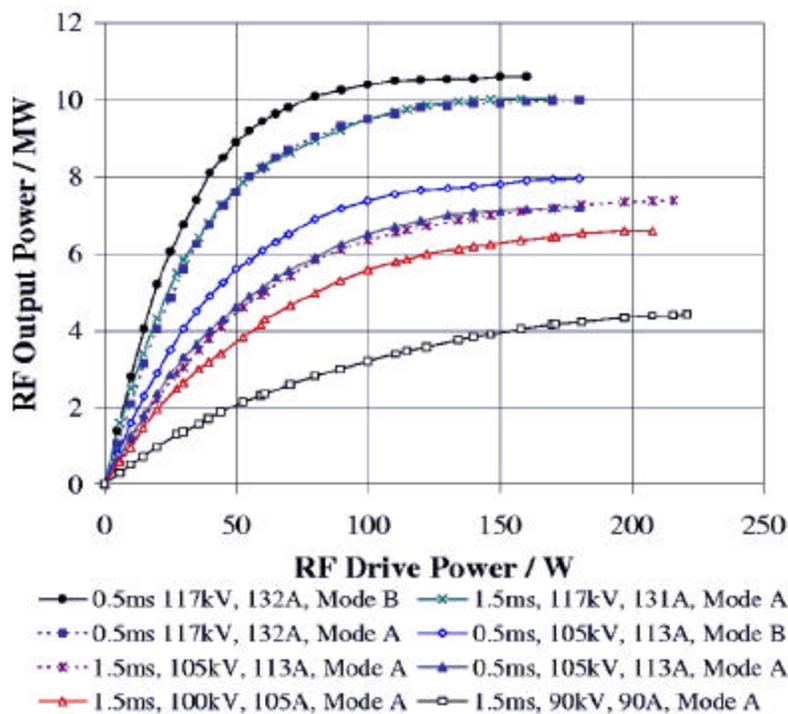


Fig5: RF output power as function of RF drive power of the MBK 1

The body losses include the RF losses in the windows and the cavities and the beam power intercepted on the drift tubes. The value measured on the THALES modulator at 150kW average power is less than 1% of the total beam power. The losses on the drift tubes located just after the output gap represent about 50% of the body power. This result confirms the design of the electron optics including the electromagnet. The greater body power measured on the DESY modulator is due to the longer high voltage rise time during which the beams are not correctly focussed. Figure 6 shows the waveforms recorded during the test at DESY.

At DESY, the MBK1 was operated at 5Hz repetition rate to full power. The -1dB bandwidth is more than 10MHz and the high gain of 48dB allows the use of semiconductor drive amplifiers. At 10Hz, measurements were restricted to 105kV or 7MW output power, because of main power limitations. At this power level, the efficiency is 60.5%.

The second tube also delivers the required RF power. The test results at 0.5ms pulse duration are shown in figure 7. The maximum efficiency of 63% for mode A, and 66% for mode B at 116kV is slightly lower than for the first tube. The reason is a 4 MHz detuning of the output cavity which occurred during the bakeout together with a too low Qx. The MBK 3 does not present this fault. The perveance of  $3.44 \cdot 10^{-6} \text{ A/V}^{1.5}$  is close to the design value. However, the body losses are two times larger than for the first tube. It could be due to a too large magnetic radial component of the solenoid.

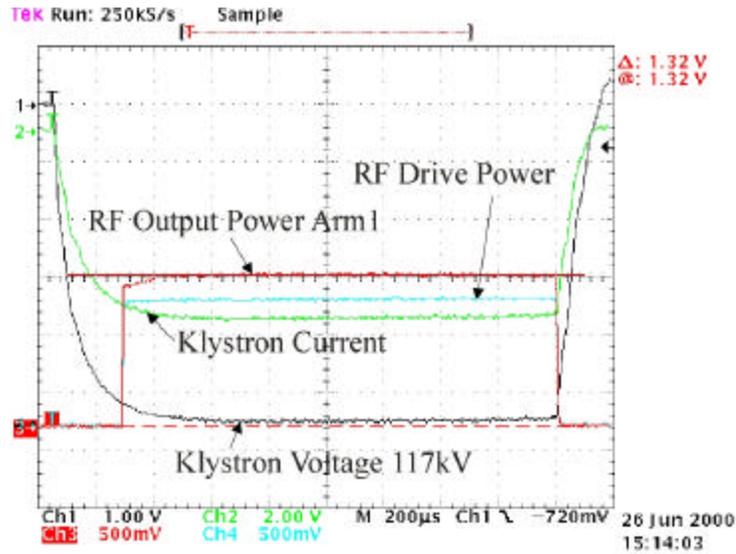


Fig 6: Waveforms at 10MW output recorded on MBK1

The MBK 1 is now used for TTF operation where it operates at low power, typically 3 to 4 MW, since only 16 superconducting are connected.

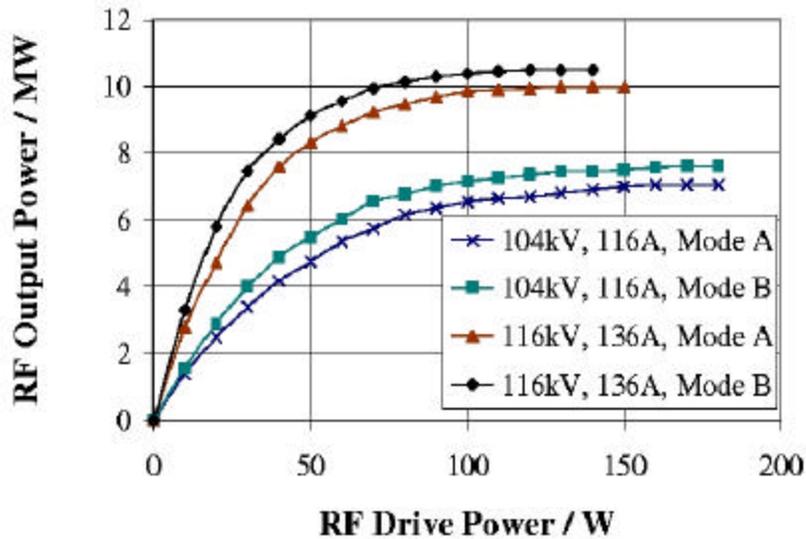


Fig.7 : RF output power as function of RF drive power of the MBK 2 at 0.5 ms pulse duration

#### **4. CONCLUSION**

THALES electron devices has successfully developed and built a long pulse high efficiency multi beam klystron. The two first tubes are close to the design goals.

For the TESLA linear collider, additional modifications are required in order to meet the infrastructure requirements of the tunnel installation, for instance the horizontal mounting position

#### **ACKNOWLEDGEMENTS**

The authors wish to thank Dr. A. Gamp of DESY for his support and for his collaboration. Thanks also go to the RF team of DESY for the work during the installation and tests of the first MBK.

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- [2] C.Bearzatto, A.Beunas, G.Faillon, "Long pulse and large bandwidth multi beam klystron", High Energy Density Microwaves, R.M. Phillips, AIP, NY, Pajaro Dunes California U.S.A Oct. 1998

# Pulsed Klystrons for Next Generation Neutron Sources

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## Abstract

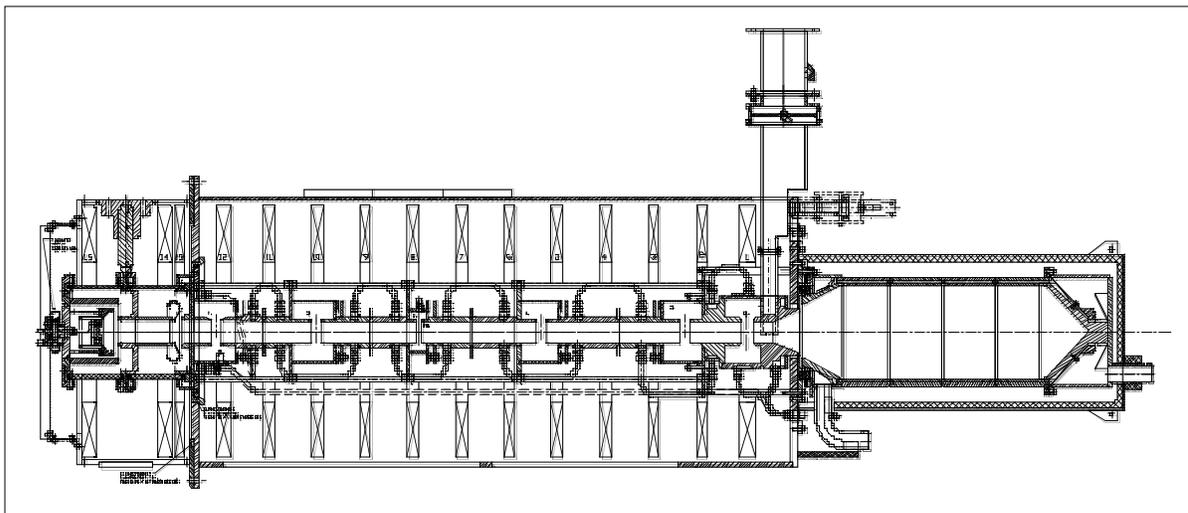
The U.S. Department of Energy (DOE) Office of Science has funded the construction of a new accelerator-based neutron source, the Spallation Neutron Source (SNS), which is expected to provide the most intense pulsed, neutron beams in the world for scientific research and industrial development. Communications and Power Industries, Inc. Microwave Power Products Division (CPI-MPP) has been engaged in the development of suitable high power, pulsed klystron amplifiers for use in energizing this new accelerator system. Actual performance data for the VKP-8290A klystron will be presented, as well as, simulated performance for the VKP-8291A klystron, currently under development. Some technical development and manufacturing issues will also be presented.

## 1. INTRODUCTION

The VKP-8290A and the VKP-8291A klystrons are two new microwave amplifiers developed by CPI for driving the Spallation Neutron Source. This new accelerator system is being built by the U.S. Department of Energy and is expected to provide the most intense pulsed, neutron beams in the world for scientific research and industrial development.

## 2. VKP-8290A — 805 MHz, 2.5-Mw, 10% Duty Klystron

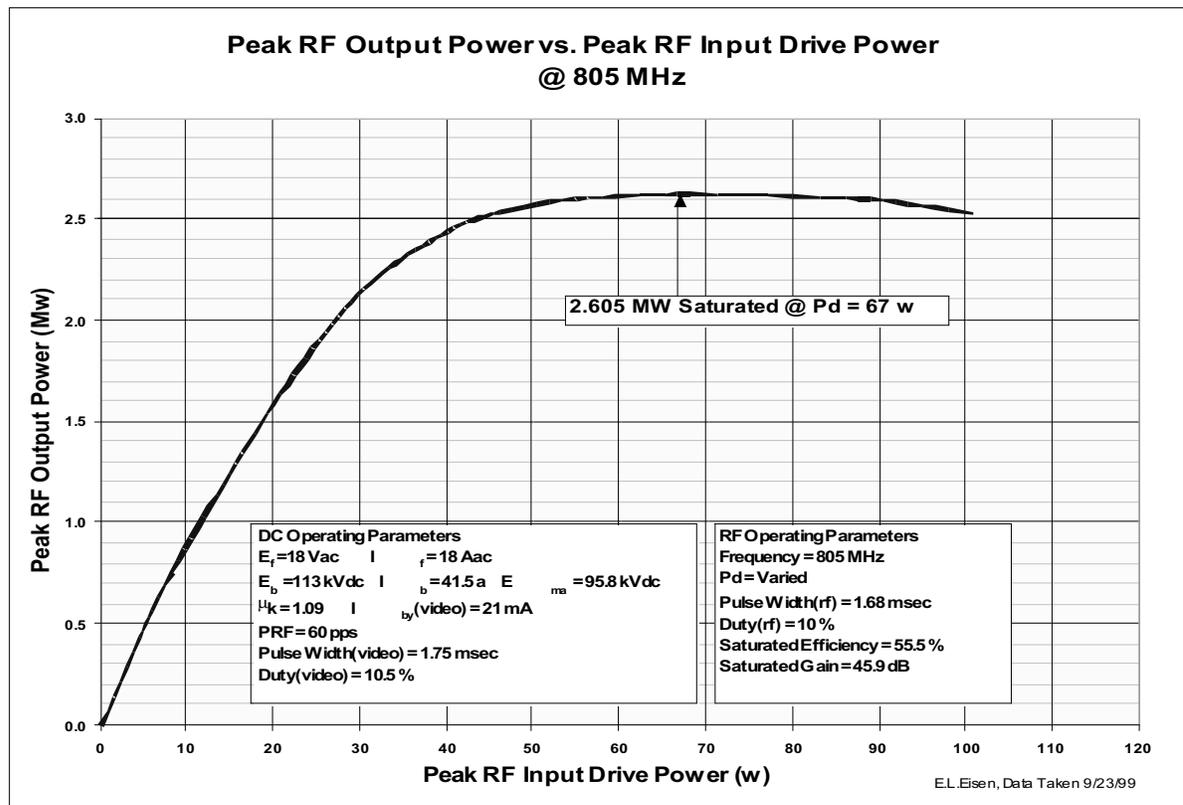
CPI delivered a working prototype of the VKP-8290A to Los Alamos National Laboratory in September 1999. The prototype is being used for test and integration of other system components under development. A layout of the prototype is shown in Figure 1 and RF performance data is shown in the Figures 2 through 4.



**Figure 1 - VKP-8290A Layout Drawing**

Operating Parameter	Min.	Nom.	Max.	Units
RF Frequency	-	805	-	MHz
Peak Output Power	2.50	-	-	Mw
Average Output Power	250.0	-	-	kW
RF Duty Factor	10	-	-	%
Pulse Repetition Rate	60	-	-	Hz
DC to RF Efficiency	55	-	-	%
Beam Voltage		118.0	120.0	kVdc
Peak Beam Current	-	39	55	a
Pulse Modulating Anode Voltage	24.00	89	96	kVdc
Micro-perveance	-	0.962	-	A/V <sup>3/2</sup>
RF Power Gain	45	-	-	dB
Instantaneous Bandwidth (-1dB @ Sat. Power)	+/- 0.7	-	-	MHz
Instantaneous Bandwidth (-1dB @ 80% Sat. Power)	+/- 0.4	-	-	MHz
Average Collector Power (1 Hour with no RF)	-	460.2	660	kW
Filament Voltage	-	20	30	Vac
Filament Current	-	20	30	Aac

**Table 1** – VKP-8290A Primary Performance Specifications



**Figure 2** — VKP-8290A Peak RF Output Power versus Peak RF Input Drive Power

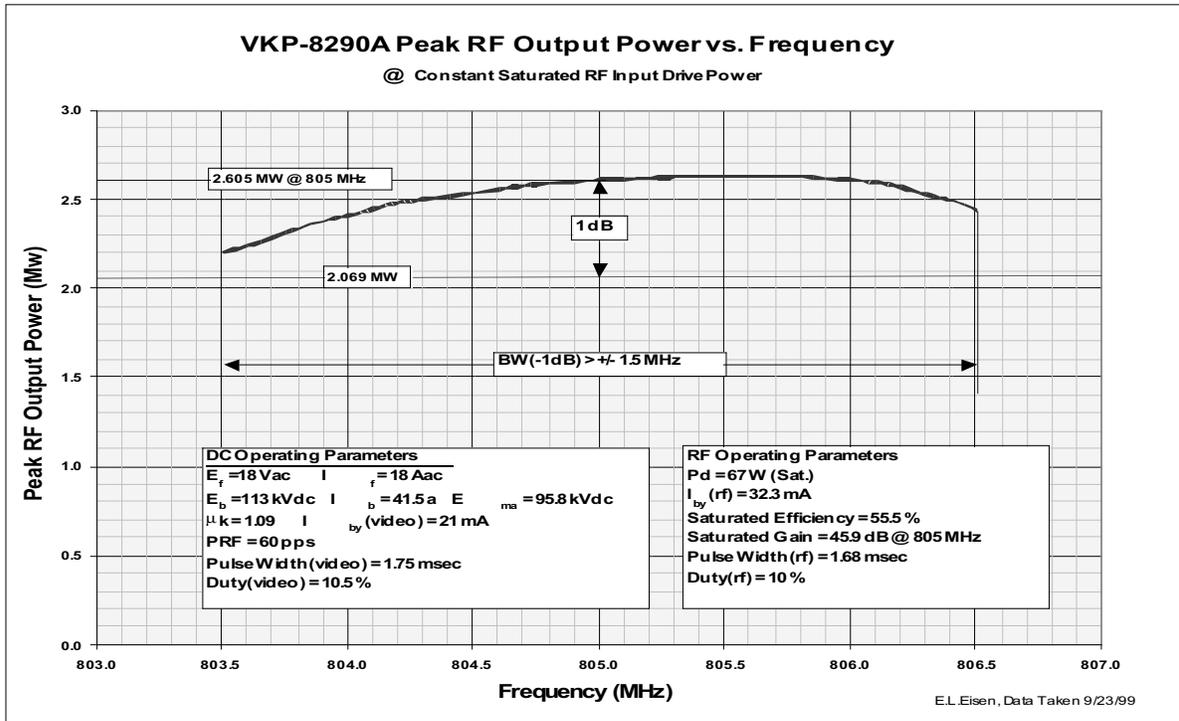


Figure 3 - VKP-8290A Peak RF Output Power versus Frequency

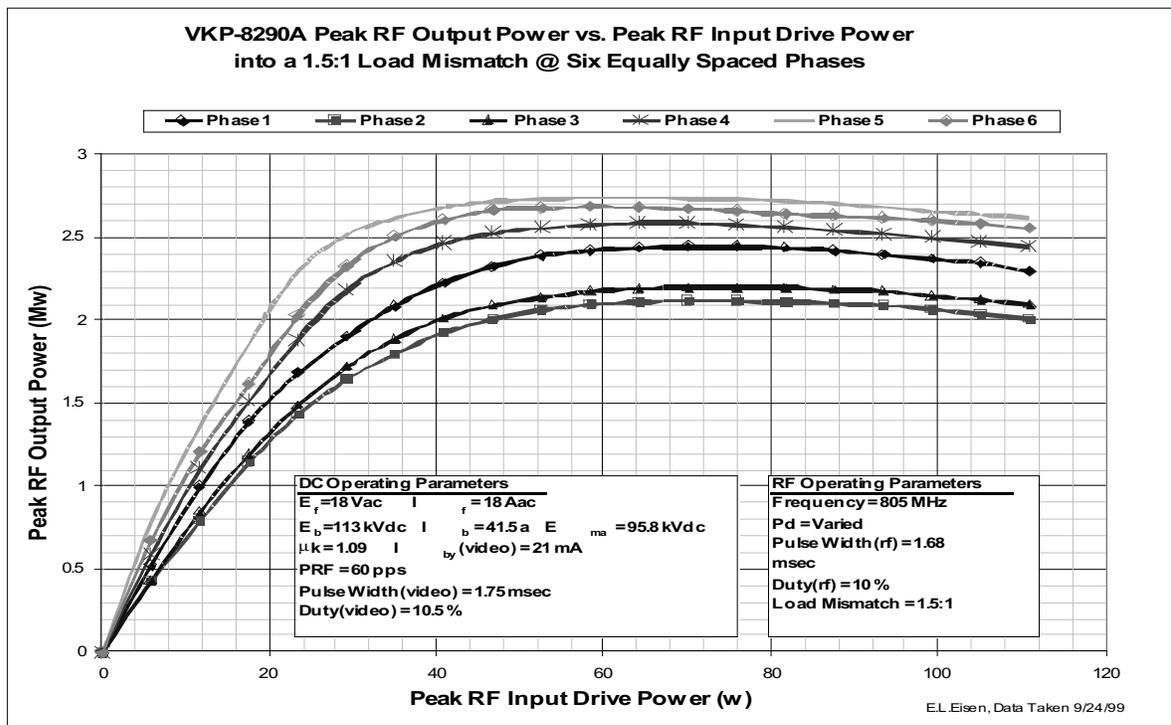


Figure 4 - VKP-8290A Peak RF Output Power versus Peak RF Input Drive Power as a Function of Load Mismatch Phase

The VKP-8290A klystron and solenoid met or exceeded all specification requirements for:

- beam voltage, beam current, and modulating anode voltage
- filament voltage and current
- peak and average output power
- efficiency, gain, and bandwidth
- collector operation with no RF applied
- 24 hour heat run
- operation into 1.5:1 load mismatch
- coolant flows and pressure drops
- RF and x-ray radiation limits
- phase transfer characteristics
- mechanical outline

### 3. VKP-8291A — 805 MHz, 550-kw, 9% Duty Klystron

CPI is currently developing the VKP-8291A under contract from Los Alamos National Laboratory. Changes in SNS system design philosophy resulting in the use of super conducting RF cavities considerably reduced the peak output power requirement for the klystrons driving the cavities. Though more klystrons will be needed to achieve the desired system power levels, the new lower power requirement for each individual device will allow a much more reliable klystron implementation.

CPI is using Design for Assembly / Design for Manufacture (DFA/DFM) techniques to greatly reduce the fabrication complexity and increased the reliability of our klystron designs. CPI also uses the latest available computer design simulation codes to reduce the time it takes to develop new products and to ensure proper product performance. All these tools were used to great advantage in the development of the VKP-8290A and the design experience is being carried forward in the development of the VKP-8291A. CPI will also leverage the best aspects of several current production klystrons resulting in a klystron design that will be efficient, reliable, and easy to manufacture.

The VKP-8291A klystron, electron gun, and RF vacuum window and waveguide are shown in Figures 5 through 8. The predicted performance is shown in Figures 9 through 19.

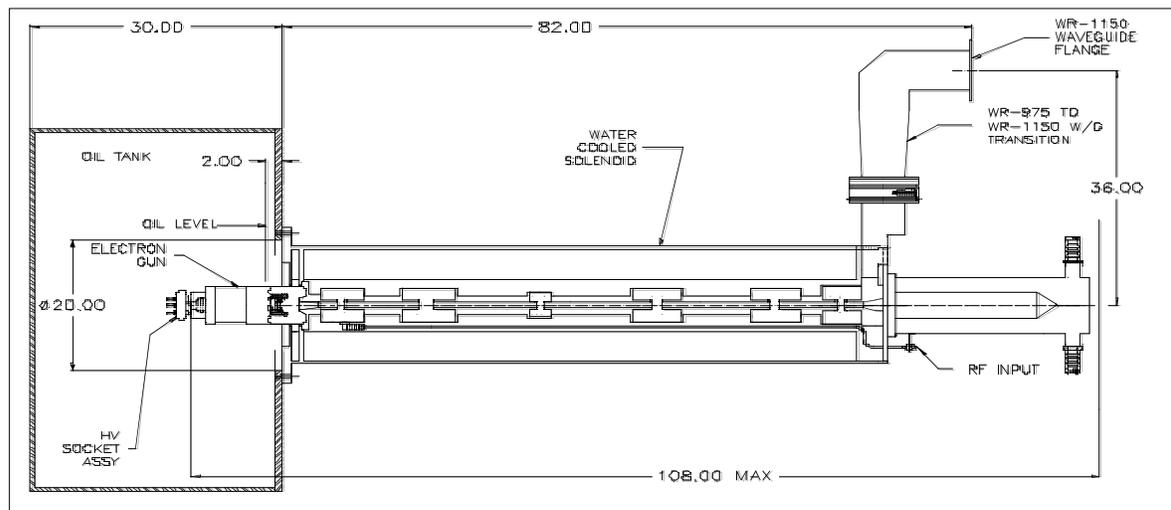
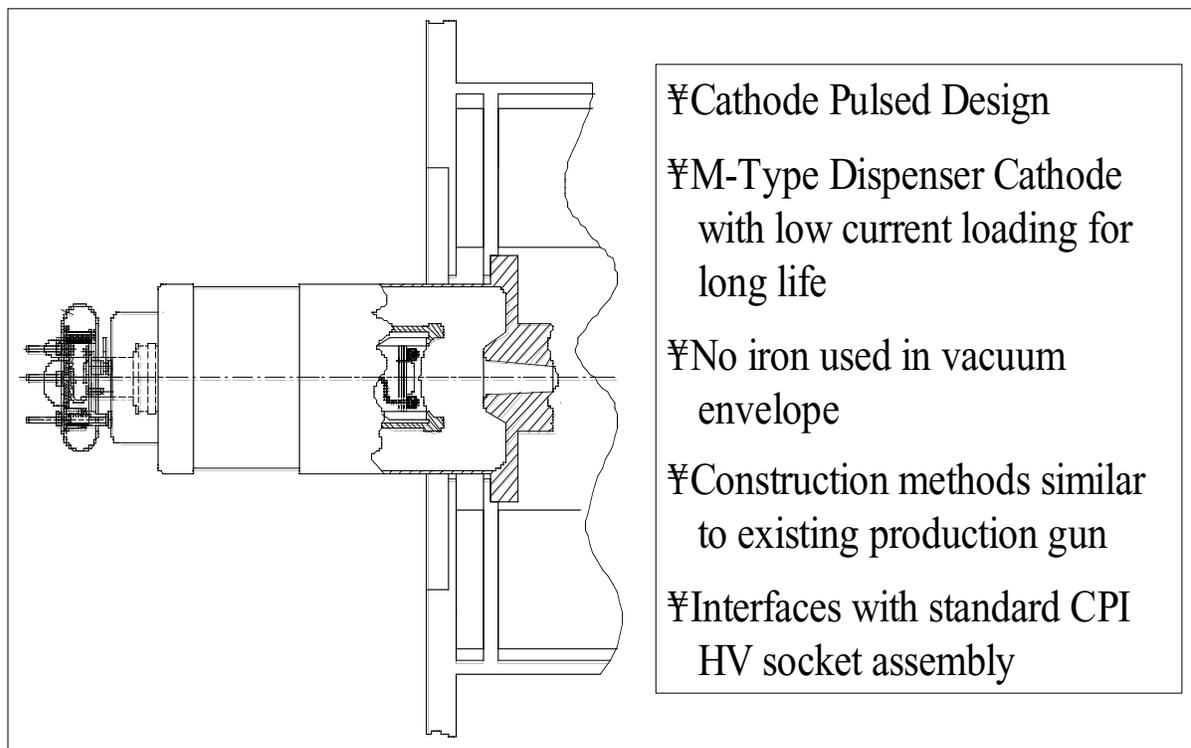


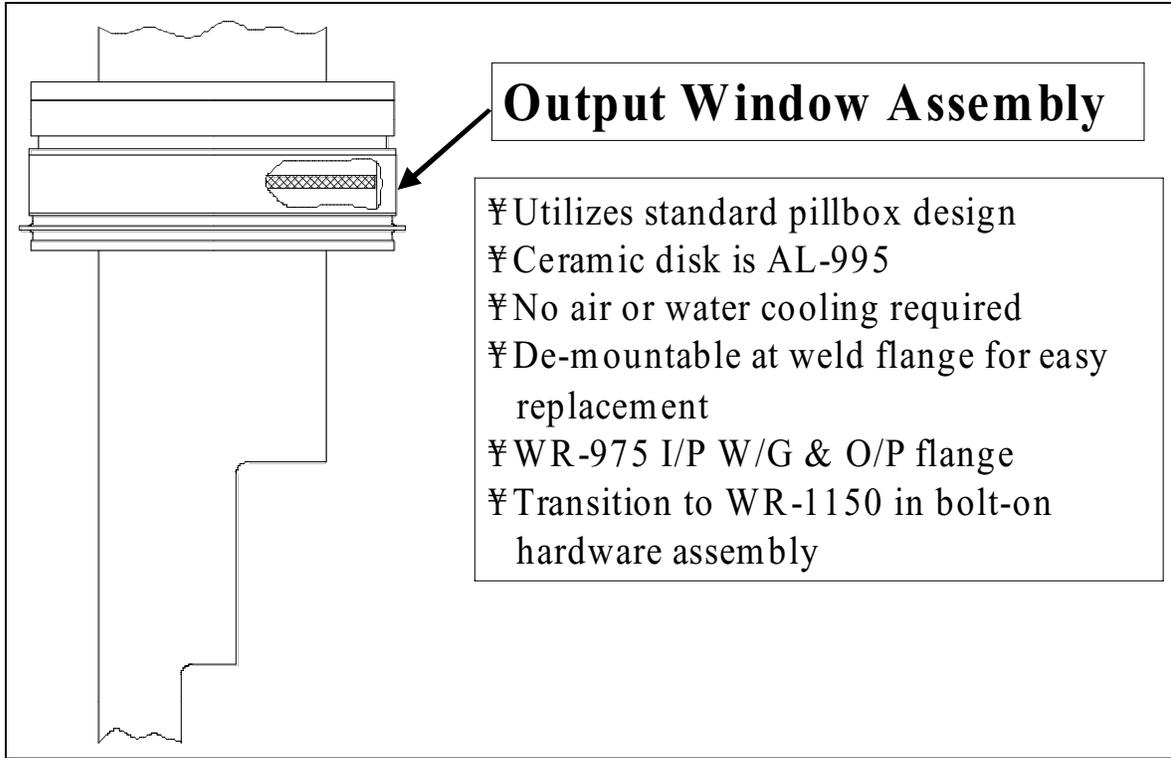
Figure 5 – VKP-8291A Klystron Layout Drawing

Operating Parameter	Min.	Nom.	Max.	Units
RF Frequency	-	805	-	MHz
Peak Output Power	550	-	-	kw
Average Output Power	49.5	-	-	kW
RF Duty Factor	9	-	-	%
Pulse Repetition Rate	60	-	-	Hz
DC to RF Efficiency	65	-	-	%
Beam Voltage	73.5	75.0	76.5	kVdc
Peak Beam Current	-	11.3	11.5	a
Micro-perveance	-	0.550	-	A/V <sup>3/2</sup>
RF Power Gain	50	-	-	dB
Instantaneous Bandwidth (-1dB @ Sat. Power)	+/- 1.3	-	-	MHz
Instantaneous Bandwidth (-1dB @ 80% Sat. Power)	+/- 1.0	-	-	MHz
Average Collector Power (1 Hour with no RF)	-	81	85	kW
Filament Voltage	-	-	25	Vac
Filament Current	-	-	25	Aac
Main Focus Magnet Power	-	-	2	kW
Auxiliary Focus Magnet Power	-	-	550	W

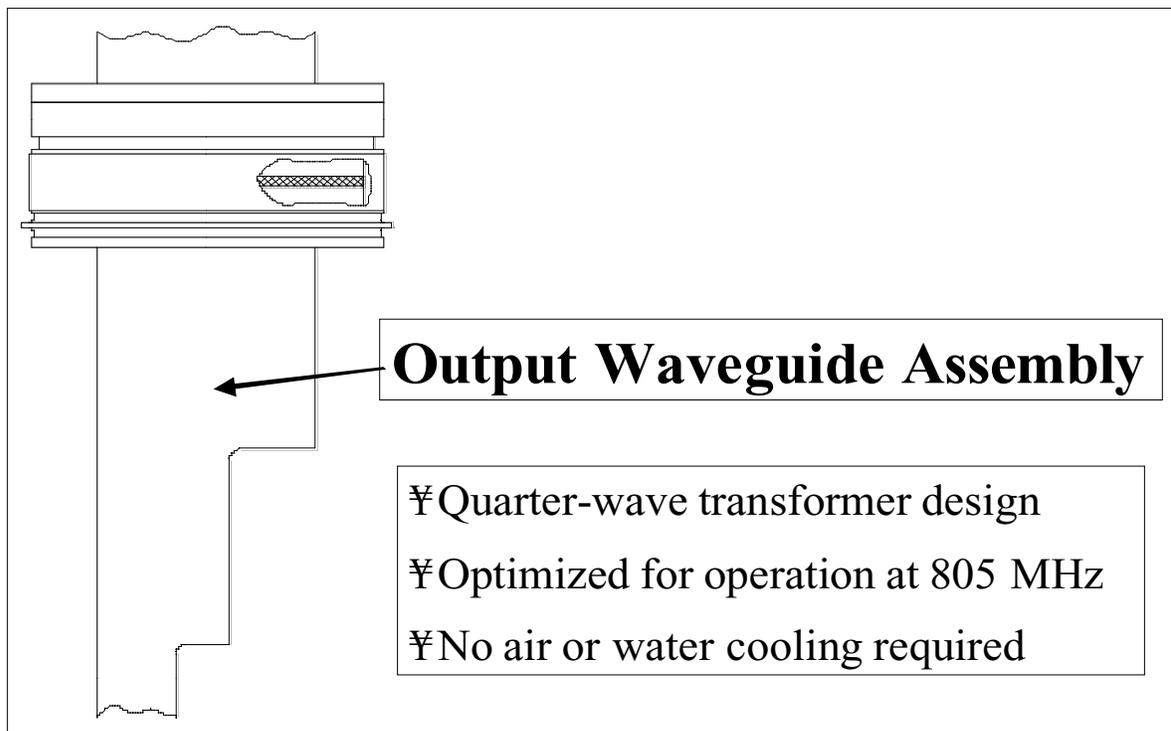
**Table 2** – VKP-8291A Primary Performance Specifications



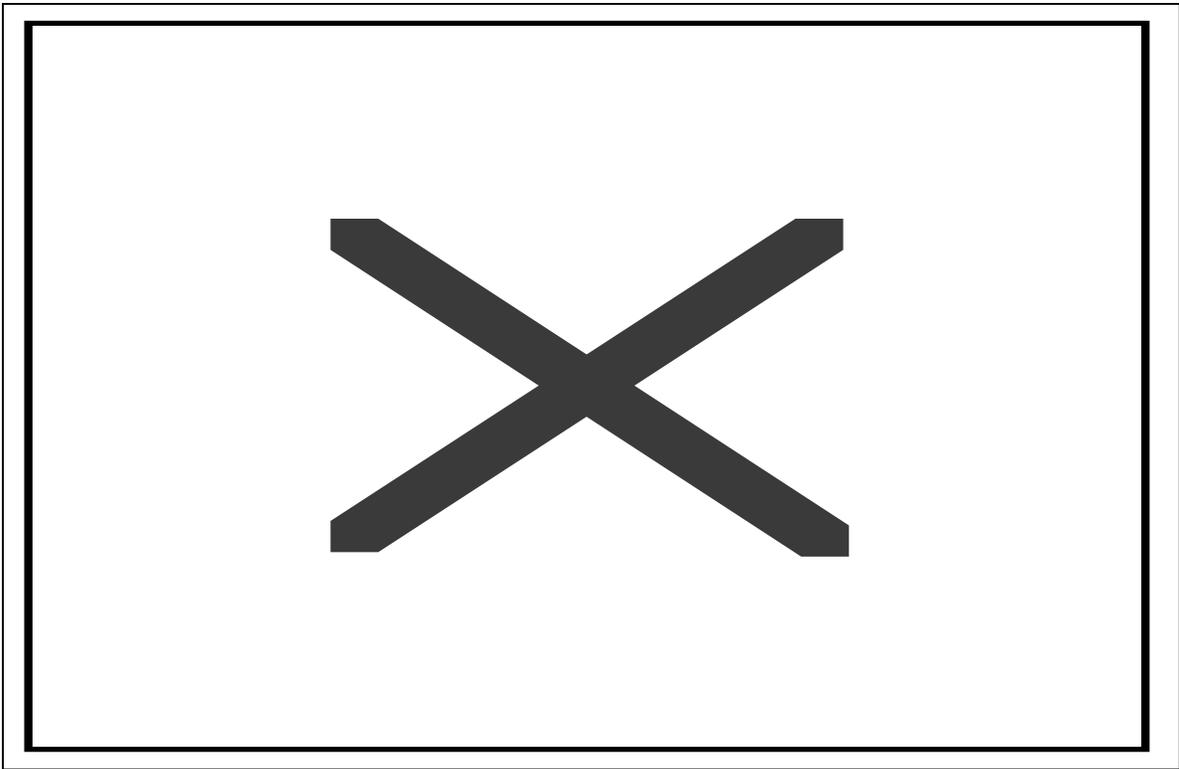
**Figure 6** – VKP-8291A Klystron - Electron Gun Design



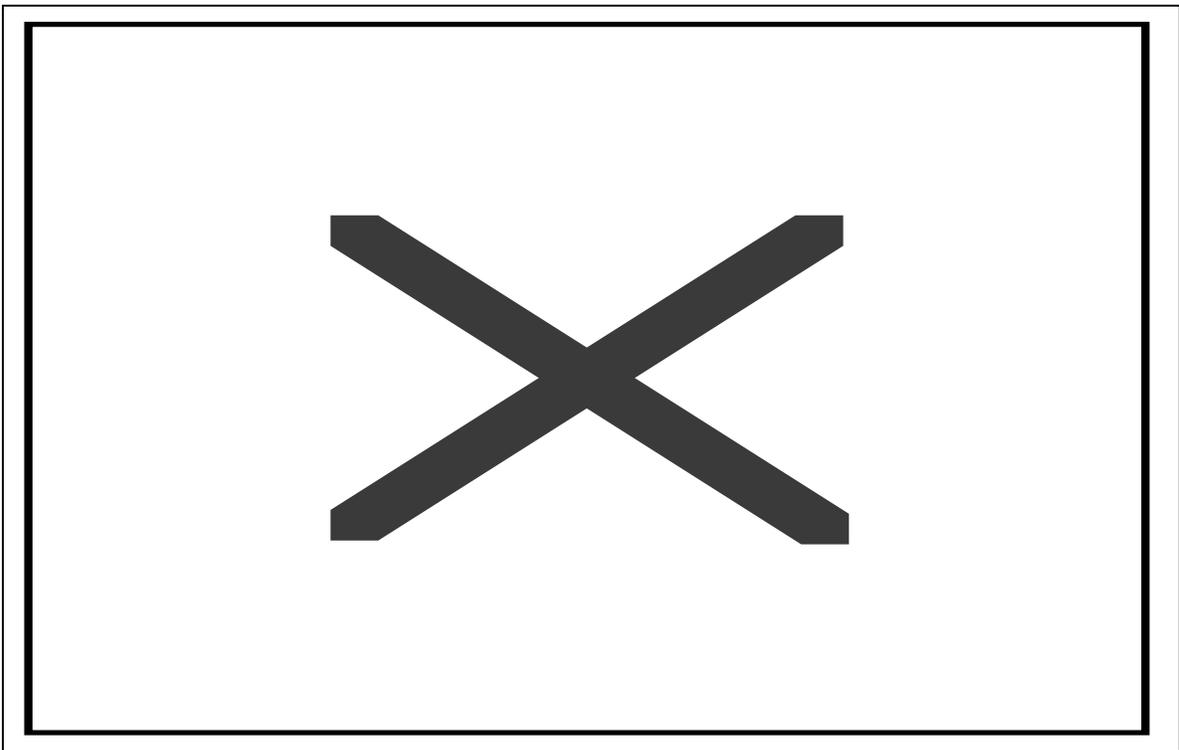
**Figure 7** – VKP-8291A Klystron – RF Vacuum Window Design



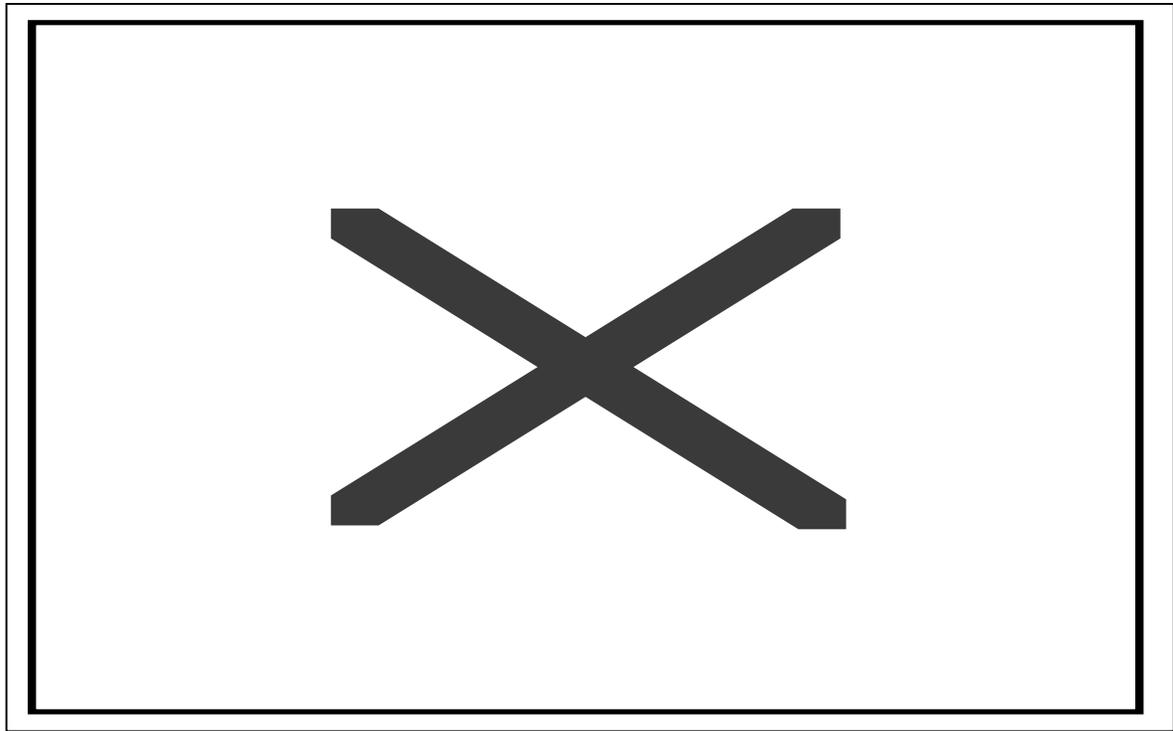
**Figure 8** – VKP-8291A Klystron – RF Waveguide Design



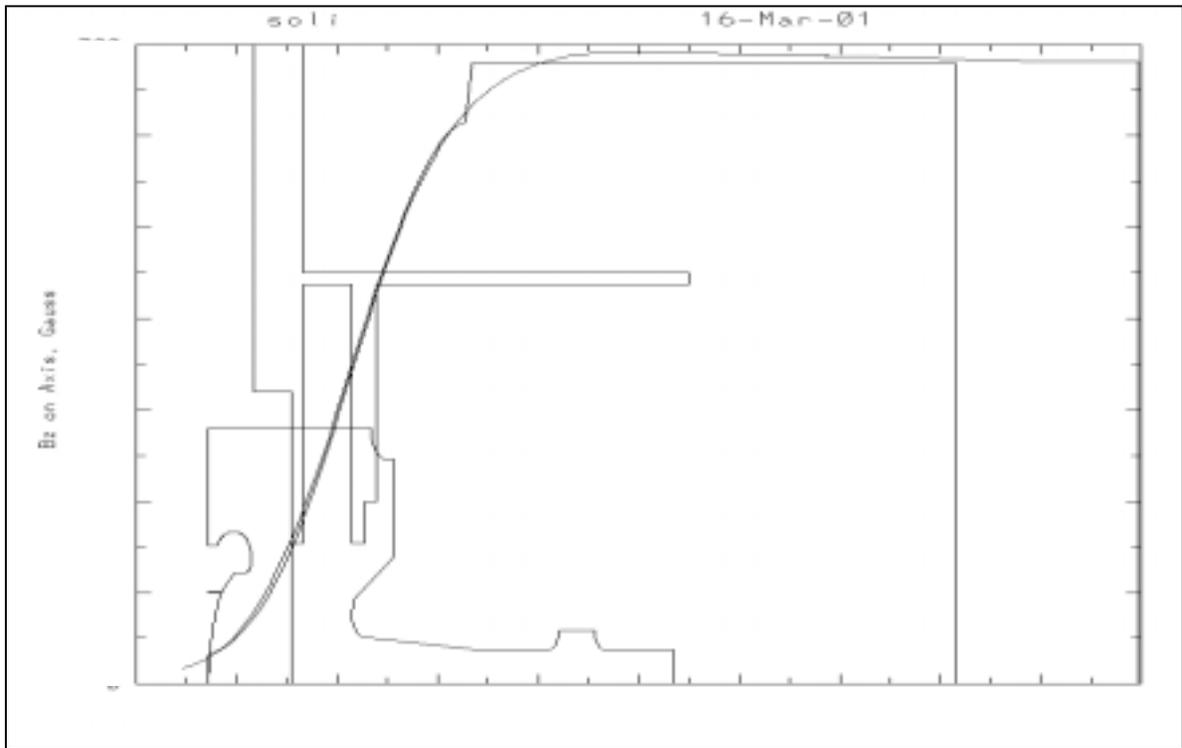
**Figure 9** – VKP-8291A Klystron - Electron Gun Electrostatic Performance Simulation



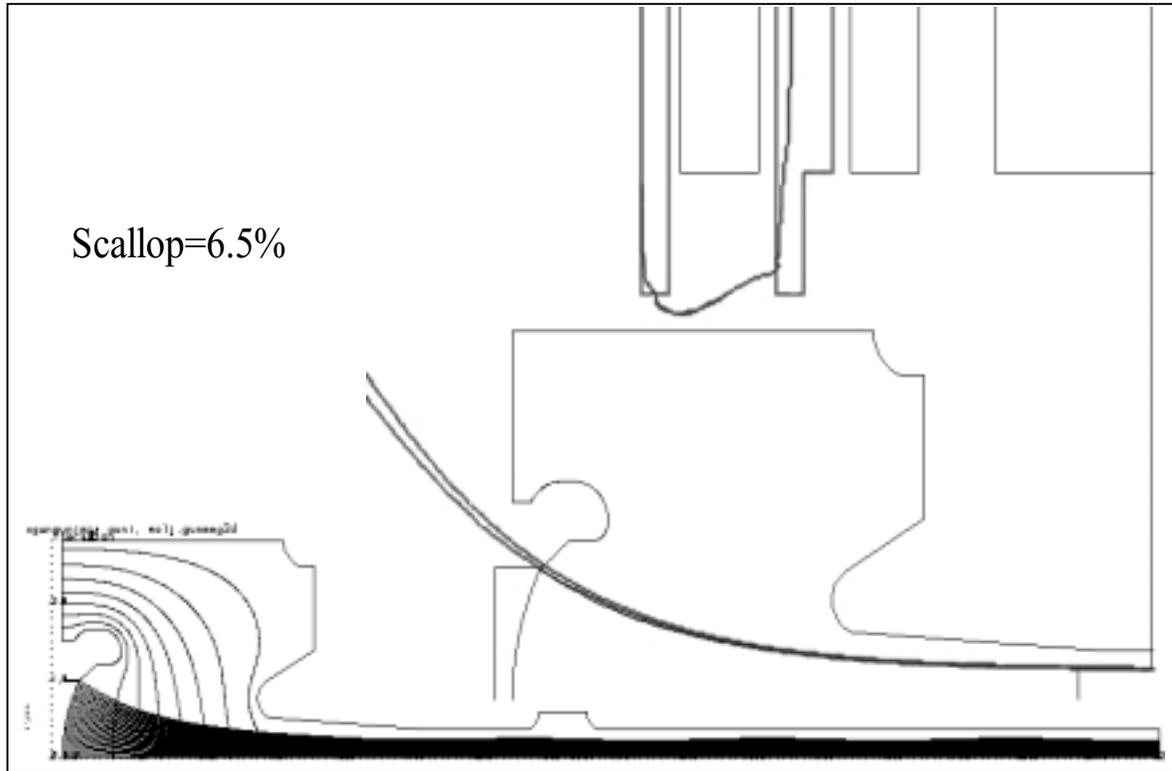
**Figure 10** – VKP-8291A Klystron - Electron Gun Magnetic Goal Field Performance Simulation



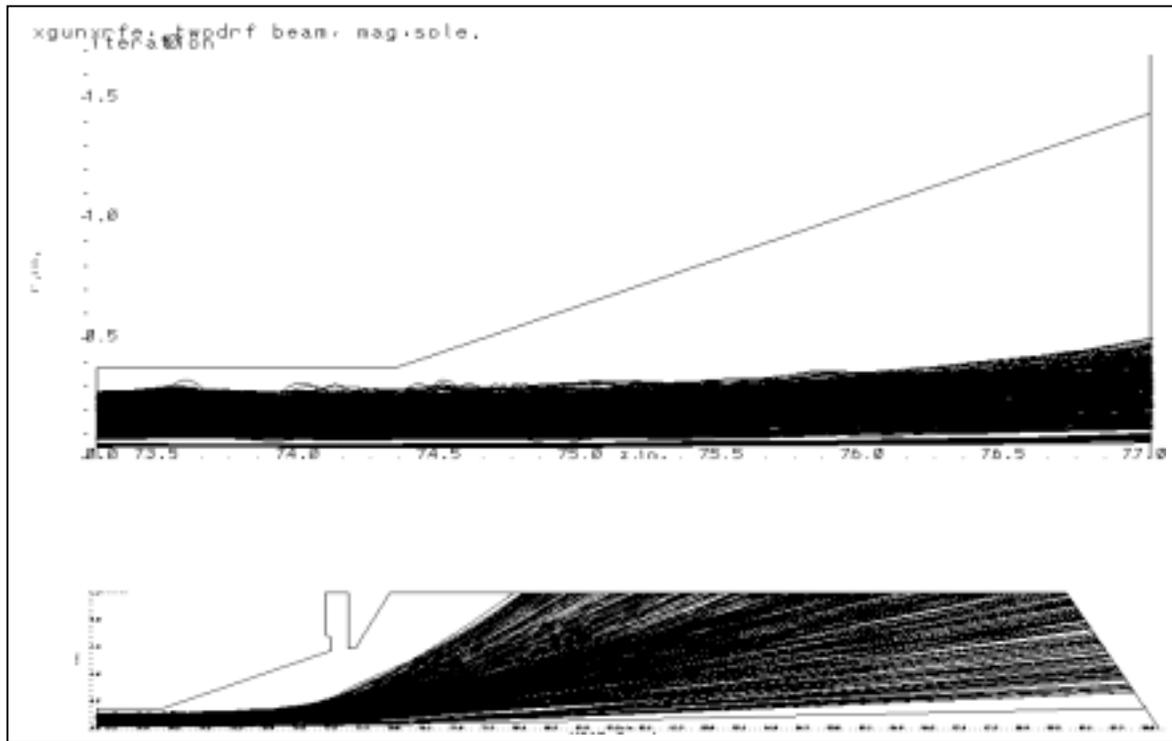
**Figure 11** – VKP-8291A Klystron – Solenoid Magnetic Field Profile



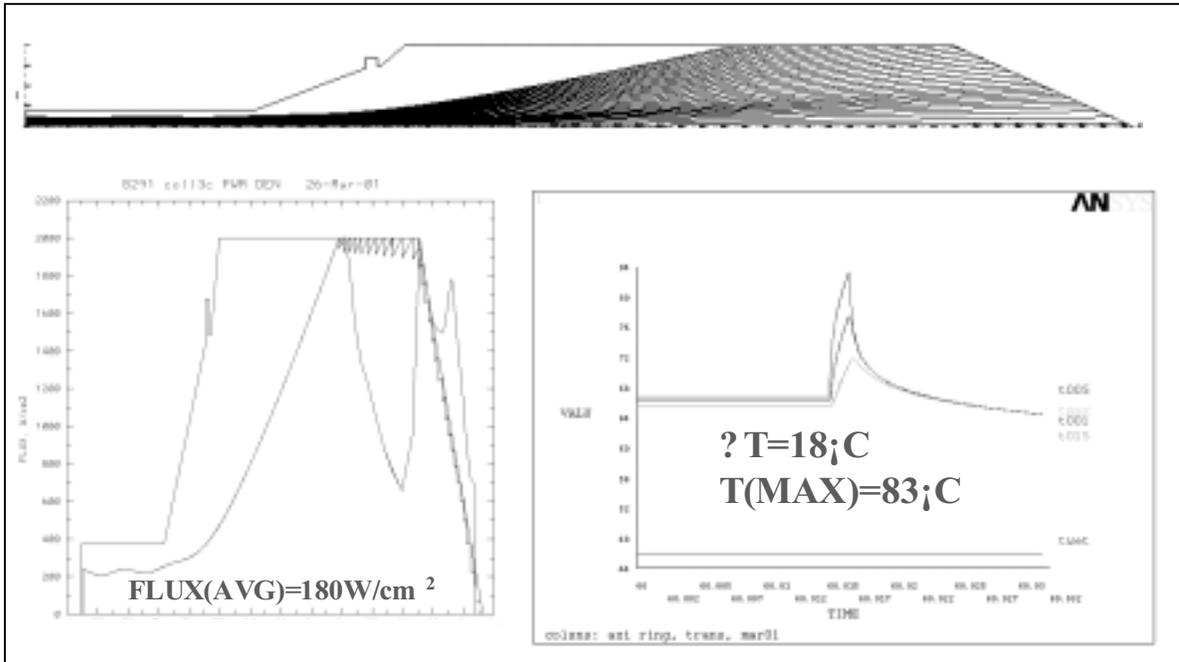
**Figure 12** – VKP-8291A Klystron – Solenoid Magnetic Field Profile in Cathode Region



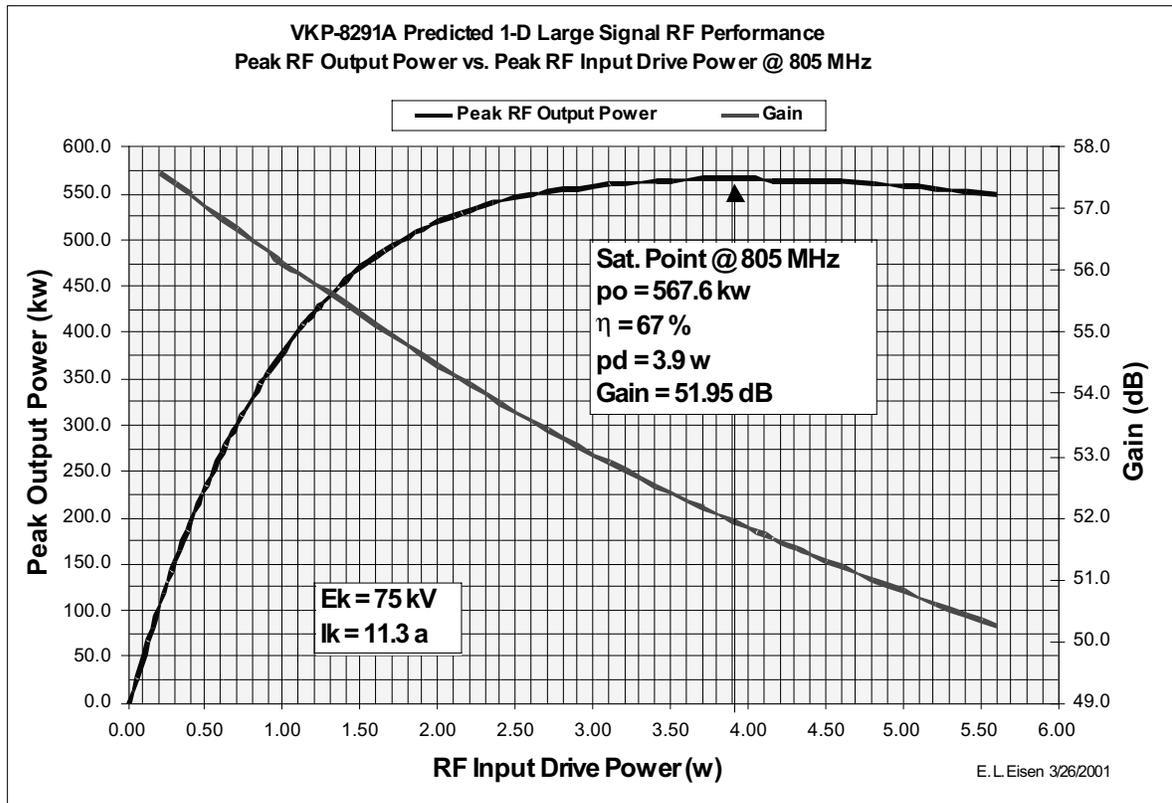
**Figure 13** – VKP-8291A Klystron – 2-D Magnetic Field Beam Simulation



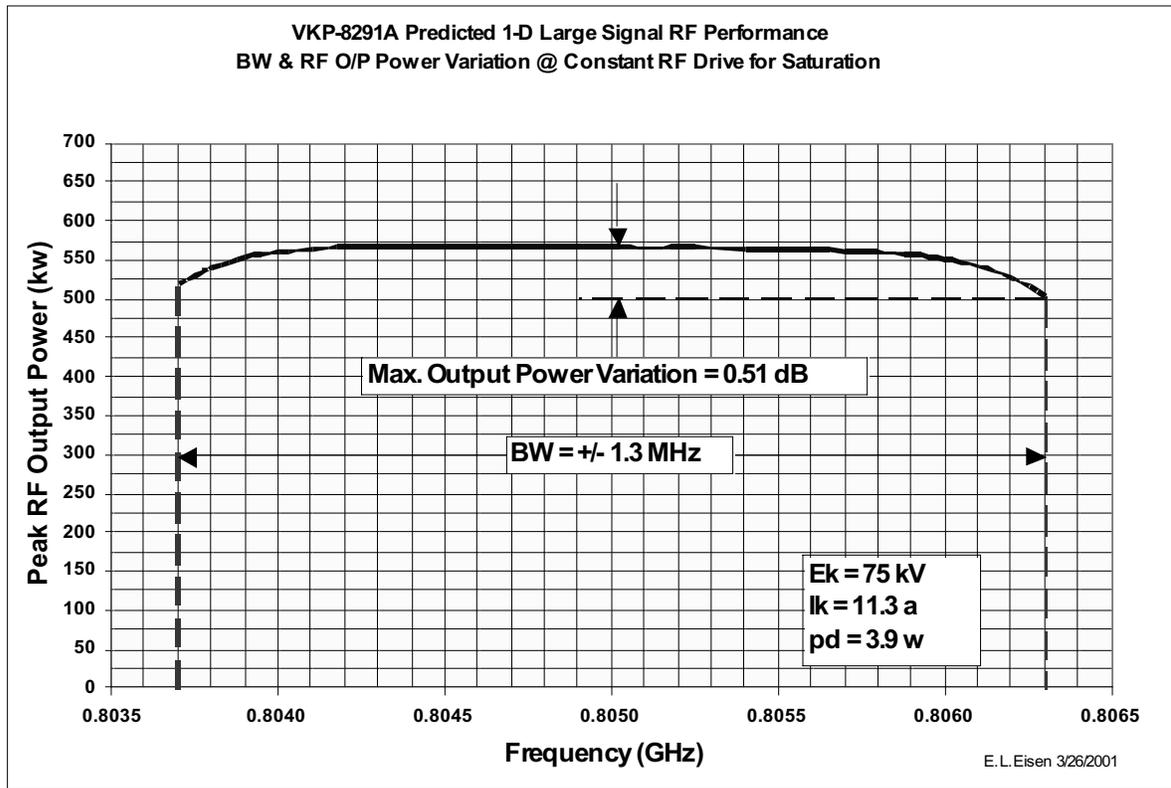
**Figure 14** – VKP-8291A Klystron – 2-D RF Beam Simulation in Collector Region



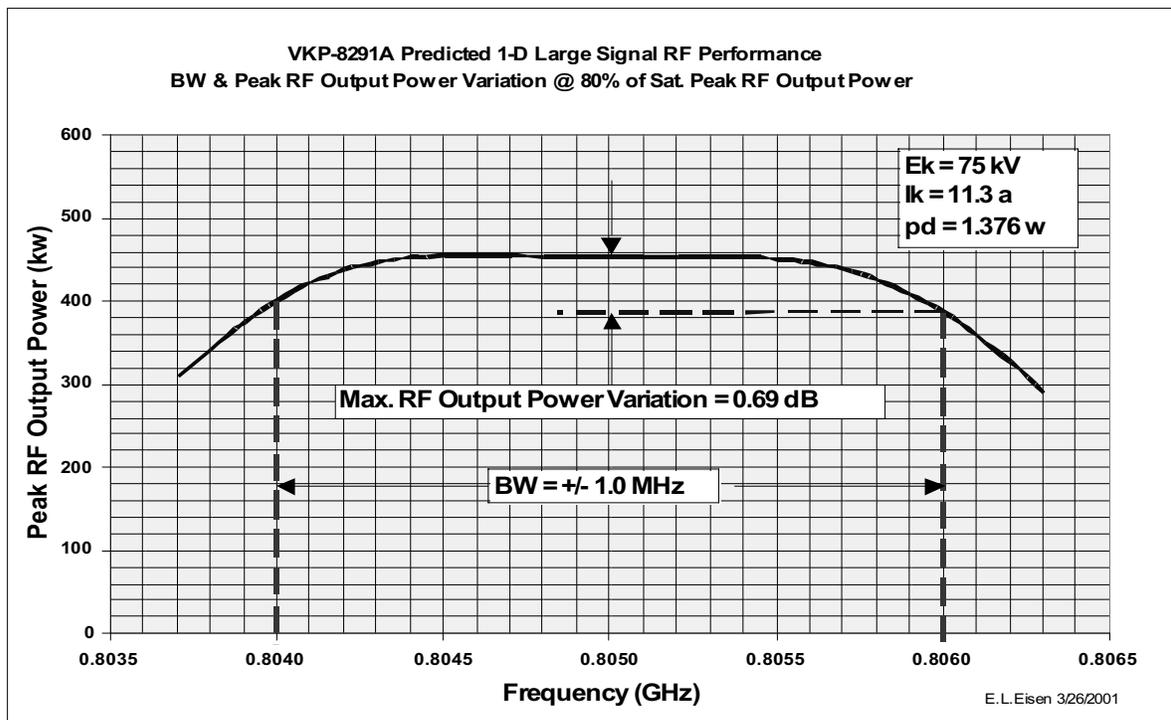
**Figure 15** – VKP-8291A Klystron – Beam Simulation in Collector Region – Pulse Heating Simulation



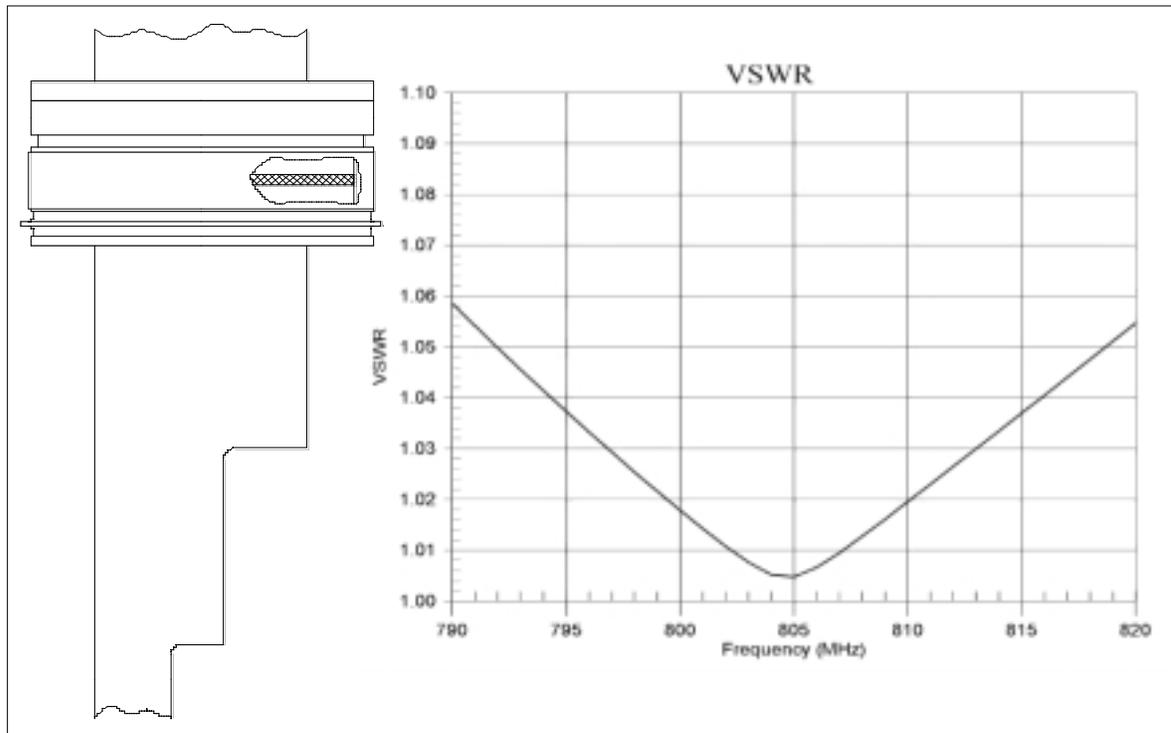
**Figure 16** – VKP-8291A Peak RF Output Power versus Peak RF Input Drive Power Simulation



**Figure 17** – VKP-8291A Peak RF Output Power versus Frequency — Saturated Output Power Bandwidth Simulation



**Figure 18** – VKP-8291A Peak RF Output Power versus Frequency — Reduced Output Power Bandwidth Simulation



**Figure 19** – VKP-8291A RF Vacuum Window and Waveguide Assembly — VSWR versus Frequency Simulation

#### 4. CONCLUSIONS / SUMMARY

##### Design Techniques

- CPI makes extensive use of sophisticated computer simulation programs and DFA/DFM techniques to simulate all aspects of klystron performance and develop reliable products that meet customer requirements
- This allows CPI to develop successful new products within shorter time frames, necessary to meet our customer's schedules

##### Current Klystron Development Status

- Baseline design of the electron beam, focusing fields, collector, and RF circuits have been completed on time
- The predicted DC & RF performance meets or exceeds customer requirements
- The mechanical layout meets customer's physical constraints
- Further computer simulations will be performed to fine tune klystron performance

# **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 micropervance. 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.

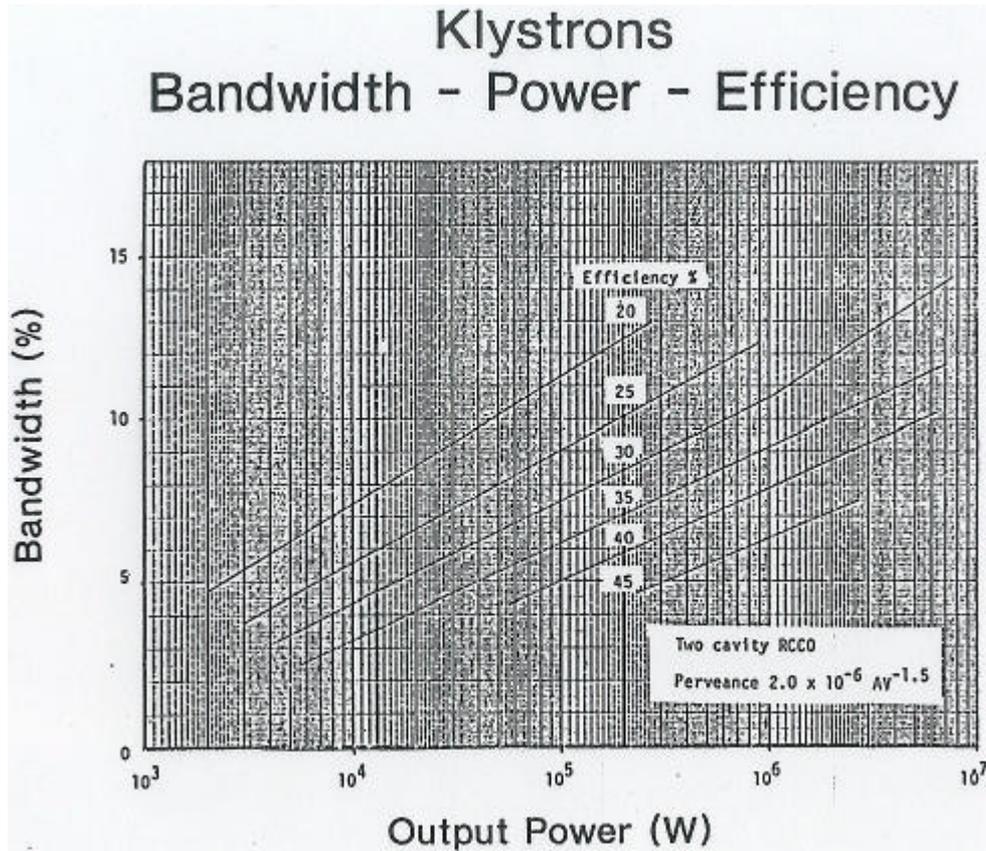


Figure 1 Efficiency achievable with variations of peak output power and bandwidth

#### 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.

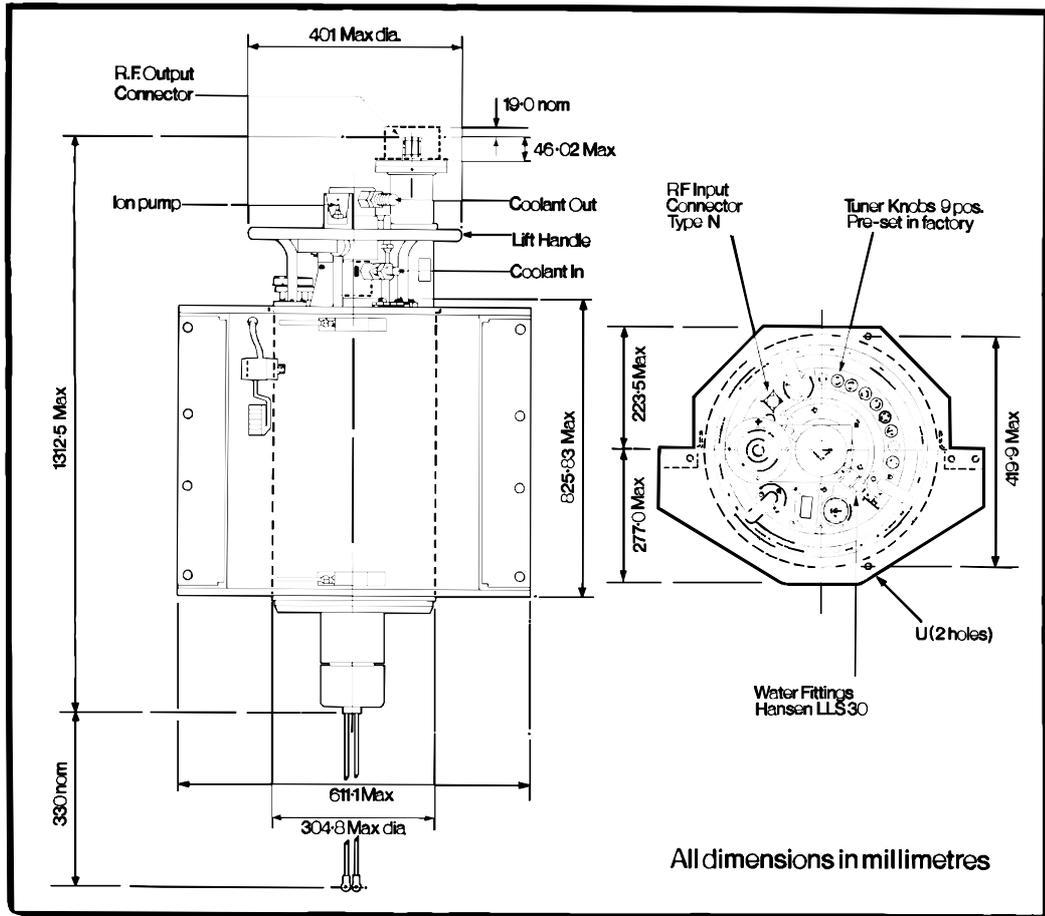


Figure 2 Dimensions of existing PT6006 klystron

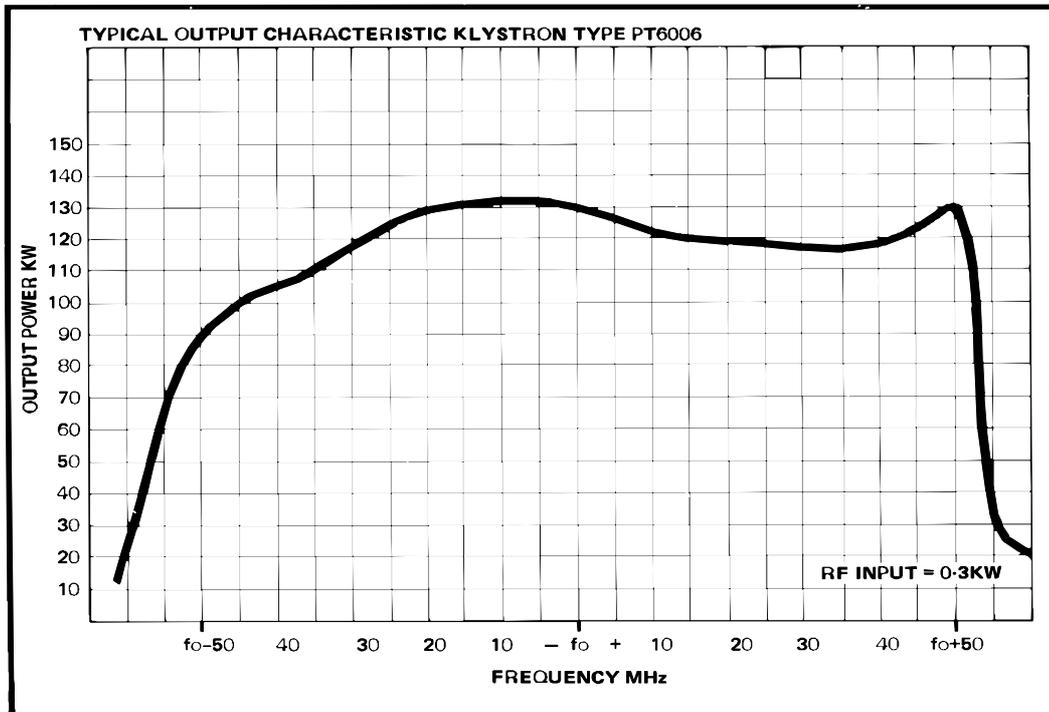


Figure 3 Typical bandpass of existing PT6006 klystron

## 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.

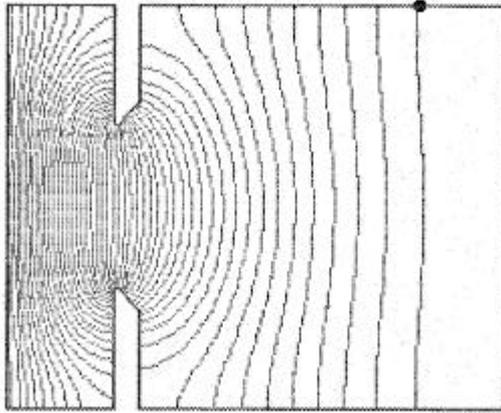


Figure 4 Superfish model of RF cavity showing electric fields

### 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.

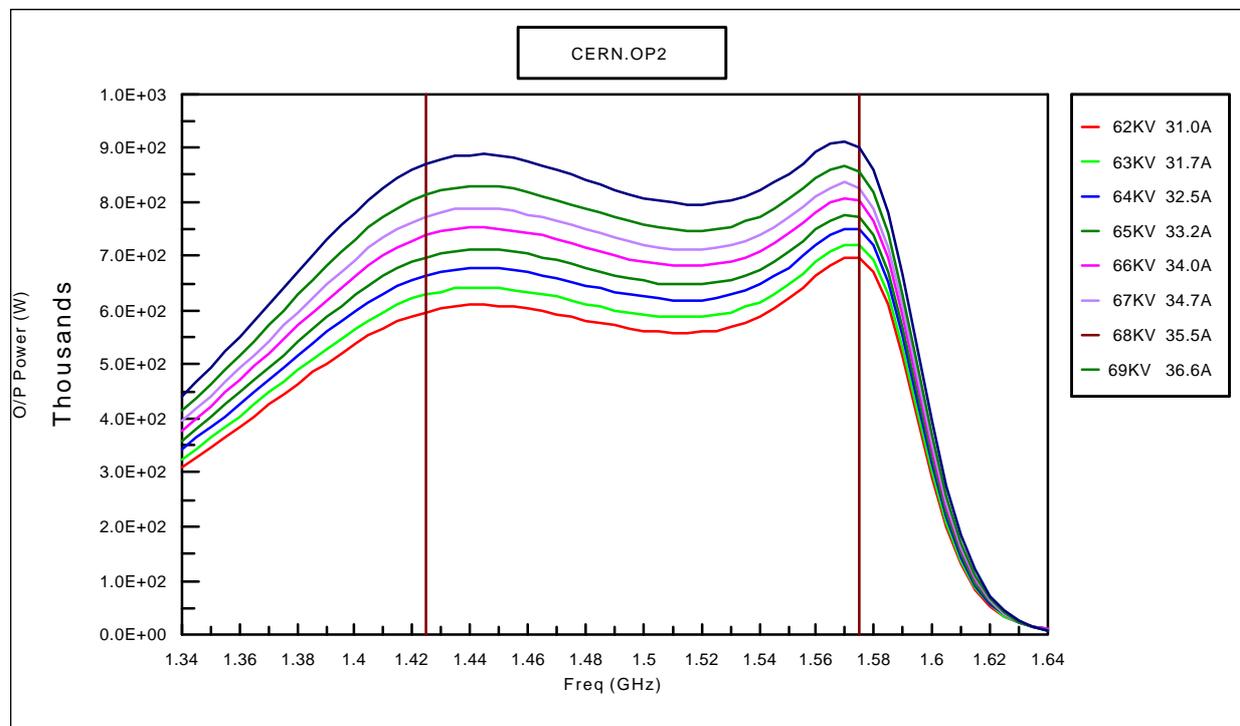


Figure 5 Variations of output power from RCCO with change of beam power

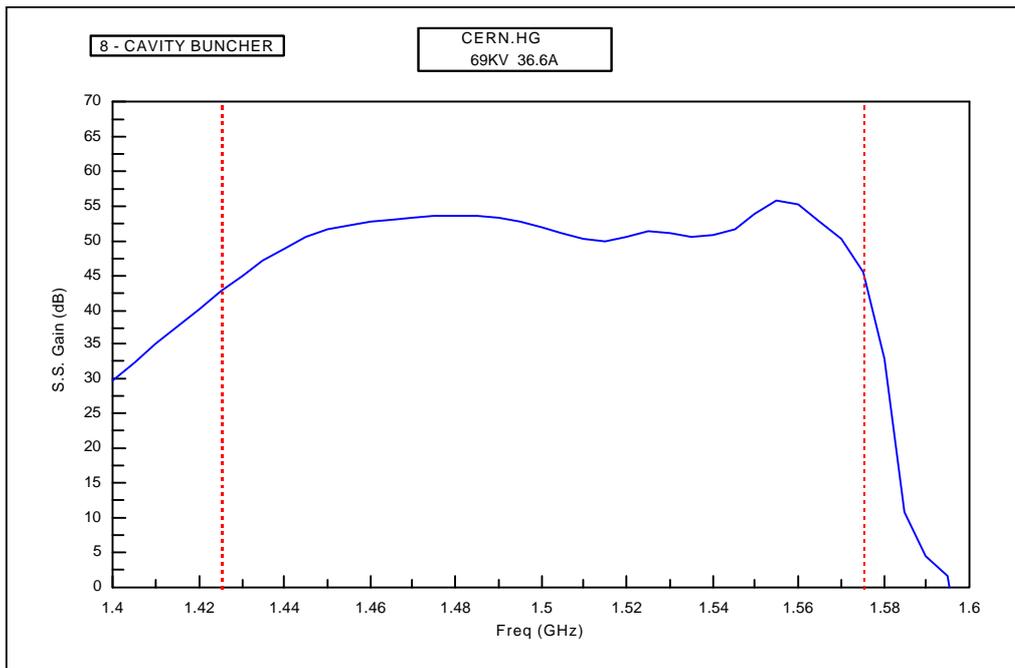


Figure 6 Small signal gain of complete klystron

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

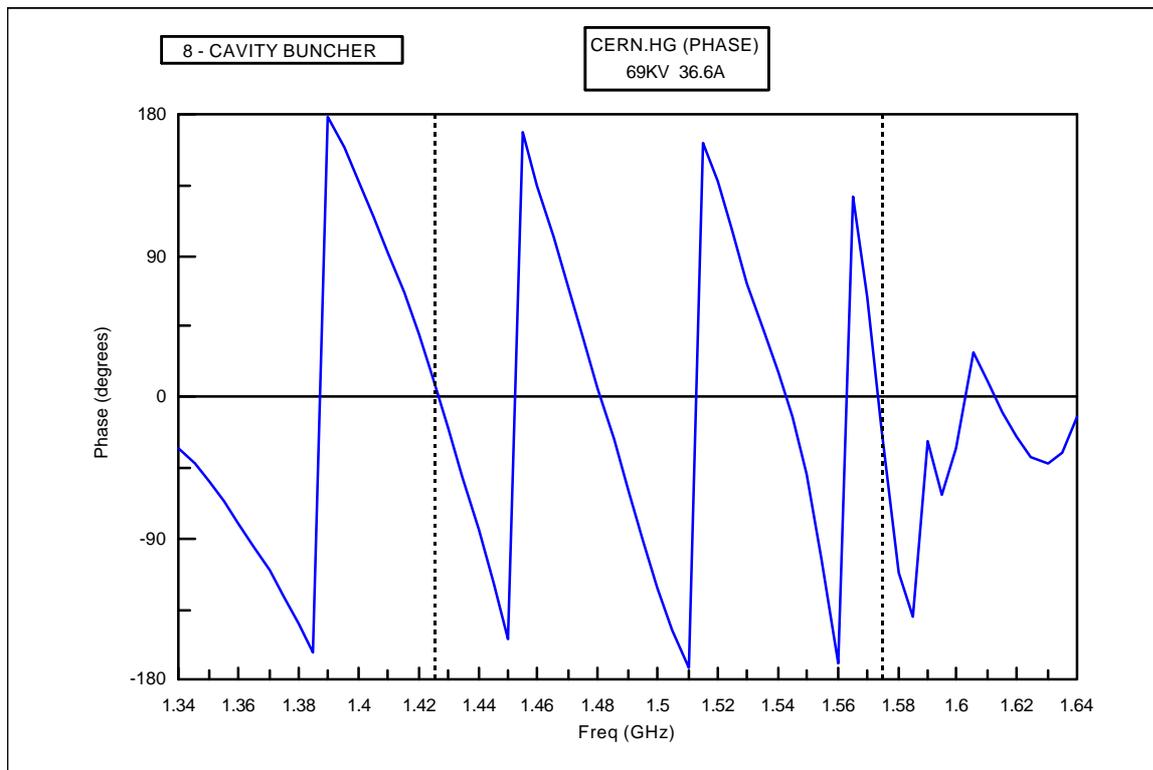


Figure 7 Phase variation of signal with change of frequency

## 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 SF<sub>6</sub> to avoid voltage breakdown on the non-vacuum side. On the vacuum side, the window 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.

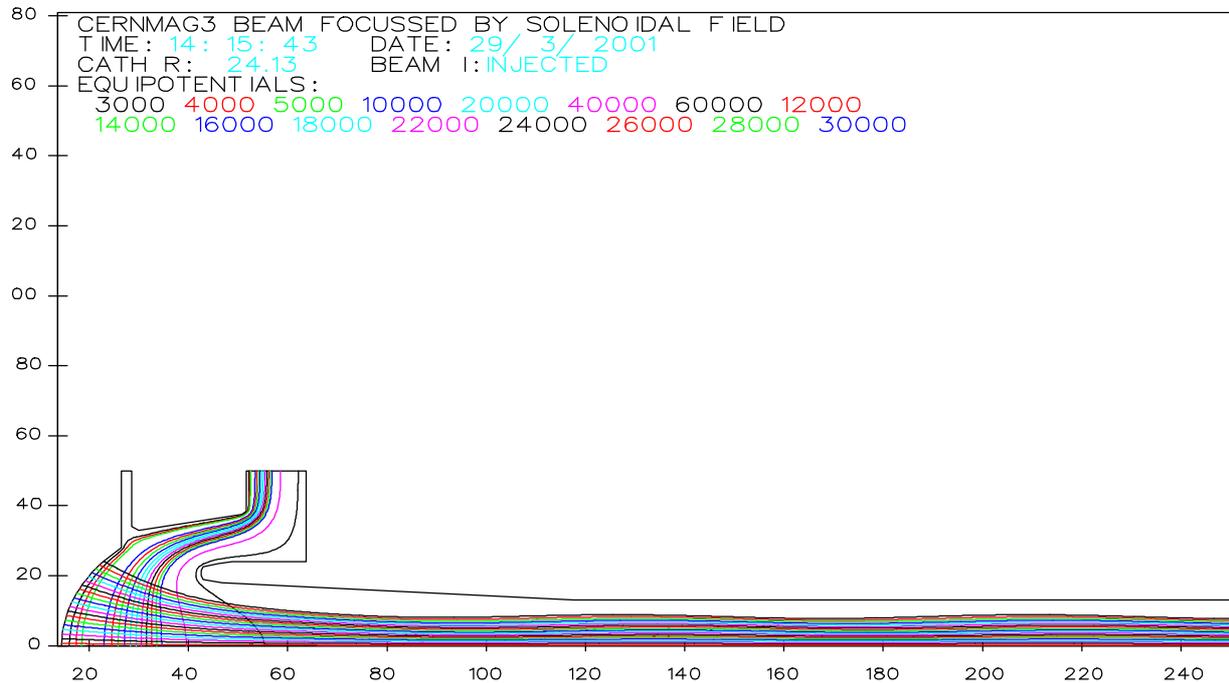


Figure 8 Electron trajectories in gridded gun with magnetic focusing field

#### 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.

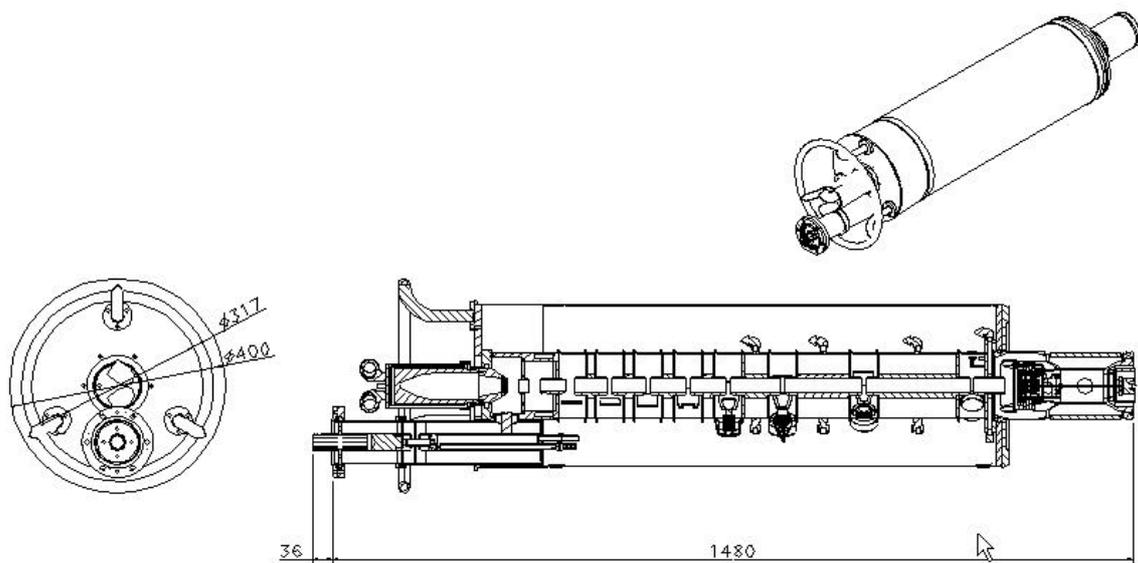


Figure 9 Drawing of complete tube with dimensions

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