RHIC/RF-32

RHIC Project

BROOKHAVEN NATIONAL LABORATORY

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MODIFYING THE CERN SWC CAVITIES AND AMPLIFIERS FOR USE IN RHIC

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Introduction

The storage rf system in RHIC will use ten cavities operating at 197.05 MHz to keep the beam bunched. These cavities were purchased from CERN where they were used to accelerate leptons for injection into LEP [1]. As the amplifier-cavity system is configured at CERN there are two problems which make its use on RHIC questionable. There is an impedance pole about 2-3 MHz below the cavity resonance which is a possible source of oscillation with a feedback loop closed. At CERN the cavities were not operated with a feedback loop although the designers at CERN do mention that care was taken to isolate the output from the input [2]. The second concern is the amplifier was delivering about 50% anode efficiency. In the class of operation we are using an efficiency of 65%-75% is expected.

Several experiments were conducted to understand the operation of the amplifier-cavity system. From these experiments two modifications to the CERN design have been made which solve these two problems. This note describes the experiments and modifications, and compares the operating parameters before and after the modifications.

Impedance Pole

Figure 1 shows two network analyzer traces of the impedance pole. The top trace is the signal from the forward power coupler in the drive line and the bottom trace is the signal from a pickup loop in the cavity. In the cavity, the power received at the pole frequency is only 25 dB lower than at cavity resonance. With rf feedback this resonance can be the same or larger than the cavity resonance. Since this pole is within the driver amplifier bandwidth, oscillation is a distinct possibility.

To see if the problem was in the amplifier, it was separated from the drive-loop transmission line and copper tape was used to short the inner and outer conductors at the amplifier base. A network analyzer and broad-band amplifier were used to drive the amplifier and the signal was picked up on a diagnostic probe at the base of the amplifier. The result, fig. 2, shows that the amplifier transforms an electrical short to impedance poles which are exactly symmetric about 197 MHz indicating that the amplifier is correctly tuned for RHIC.

On a Smith chart, a loop in a cavity presents an impedance which is a circle symmetric about the real axis whose ends on either side of resonance are at zero ohms. As the measurement plane moves along the transmission line away from the loop this impedance circle rotates clockwise around the center of the chart with a complete rotation occurring every half wavelength. The measured impedance of the drive loop at the end of the transmission line is shown in fig. 3. The transmission line is about 3/8 λ giving an off-resonance

impedance which is capacitive. By adding a phase offset of 92° (equivalent to 19.4 cm of transmission line at 197 MHz) the transformed impedance completes one rotation of the chart and presents an electrical short off resonance.

Reference 2 describes the amplifer as being approximately a $\lambda/4$, 3Ω transmission line in series with a $\lambda/4$, 18.5Ω line. PSPICE was used to calculate the impedance of a short circuit transformed through a 3/8 λ section of 16Ω line in series with the two lines of the amplifier. The result, shown in fig. 4, gives an impedance pole at 197 MHz. As the 16Ω line is lengthened this pole moves to lower frequencies, fig. 5. When the line is $\lambda/2$ long the upper and lower poles are symmetric around 197 MHz. This shows that the impedance pole is near cavity resonance because the drive line is too short.

The 16Ω drive-loop tranmission line was lengthened by adding a 17.1cm insert. This insert initially was made 19.4 cm but measurements made before the pieces were welded indicated this was too long. The amplifier was placed back on a cavity with the longer drive line and network analyzer measurements were made. Figure 6 is a 50 MHz sweep showing that the impedance poles are 12 MHz below and 18 MHz above resonance. The initial length of 19.4 cm would have placed them exactly symmetric about the resonance. Figure 7 is a 20 MHz sweep of the cavity field showing the resonance as the only feature.

Amplifier efficiency

A storage cavity has a shunt impedance of about 8.5 MΩ and requires about 60 kW of rf power to produce 1 MV in the gap . The tetrode amplifier that drives the cavity is operated in class AB with a screen voltage of 900 V and anode voltage of 10 kV. To deliver 60 kW without drawing excessive screen current requires an anode impedance of about 625 Ω. Reference 2 states that the amplifier uses two $\lambda/4$ transformers to transform a loop impedance of 16Ω into 600Ω, and the cavities were delivered with the drive loops adjusted for 16Ω. Also we were given engineering drawings for building a $\lambda/4$ transformer to connect to a 50Ω load to operate the amplifier into 16Ω.

The amplifier is operated with very small quiescent current so it should be about as efficient as Class B operation. In Class B the maximum efficiency is [3],

$$\text{Anode efficiency} = \pi/4\ (1 - E_{min}/E_b) \qquad (1)$$

where E_b is the anode bias voltage and E_{min} is the smallest anode voltage achieved during an rf cycle. For the operating parameters of the amplifier eq. 1 gives an efficiency of 71%. Column 1 of the table gives the operating parameters reported by CERN in ref. 2 and column 2 gives the operating parameters we measured on the 16Ω test stand. We measured 16% lower rf power with 6% more dc power being supplied to the tube.

Because of the compact design and the high operating frequency it is difficult to measure the anode impedance directly. The results of an effort to do this are reported in ref. 4. It was decided to estimate the impedance from the operating parameters of the tube.

The electron current in a tube varies with grid voltage approximately as,

$$I(t) \approx (V_{g0} + V_{g1} \cos \omega t)^{1.5} \tag{2}$$

where V_{g0} is the grid bias voltage and V_{g1} is the drive amplitude. This expression can be used to calculate the Fourier components of the current [5]. The dc and rf fundamental components are,

$$\begin{aligned} I_0 &= \tfrac{1}{T}\int_0^T I(t)dt = I_P f_0 \\ I_1 &= \tfrac{2}{T}\int_0^T I(t)\cos(\omega t)dt = I_P f_1 \end{aligned} \tag{3}$$

where I_p is the peak current during the rf cycle. Figure 8 plots form factors, f_0 and f_1, together with a curve of quiescent current divided by anode current, I_{00}/I_0. From a measurement of this ratio the conduction angle of the tube can be determined. The rf current is the anode current times the ratio f_1/f_0 and this ratio is estimated from the graph. The tube power and anode current were measured and the impedance calculated from $P=I_{rf}^2R/2$.

Equation 2 is a good approximation for small anode rf voltages. A series of measurements were made of power as both the frequency and the amplifier tuning position were varied. The tube socket can be raised and lowered for tuning and it was not known whether this tuning changed only the frequency or both the frequency and transformed impedance. Figure 9 shows the family of curves generated. For all of these measurements the anode current was 3.1A and the quiescent current was 0.6A giving a ratio of f_1/f_0 equal to 1.52. All of the tuning curves peak at about 6.1 kW showing the tuning changes only the frequency of the impedance transformation. A power of 6.1 kW with an rf current of 4.71A gives an impedance of about 550Ω. The same analysis on other data sets have given values in the range of 515Ω-550Ω. From these measurements we conclude that the amplifier transforms 16Ω to about 525Ω. The low efficiency is a result of low anode impedance.

The rf test stand consists of a 50Ω water-cooled load connected to a λ/4 transformer of impedance Z_t. This presents an impedance to the amplifier equal to $(Z_t)^2/50$. The impedance of a coaxial line increases as the diameter of the center conductor decreases so we were able to increase the impedance presented to the amplifier in 1Ω steps by machining down the inner conductor of the λ/4 transformer. These results are shown in fig. 10. The measured efficiency peaked at 20Ω however the screen current started to get very high. We conclude the optimum impedance to present to the amplifier is 19Ω.

Conclusion

The loop was rotated to give 19Ω coupling and the drive-line extension was installed. The cavity was then conditioned to a peak gap voltage of 1.0MV at which point the measurements in the third column of the table were made. These two modifications have increased the amplifier efficiency from about 50% to about 70% and have moved the impedance pole 12 MHz away from the cavity resonance.

Acknowledgement

The author benefited from several useful discussions with Ralph Sanders and Mike Brennan.

Reference

1. P. E. Faugeras, H. Beger, H.P. Kindermann, V. Rodel, G. Rogner, and A. Warman, "The New RF System for Lepton Acceleration in the CERN SPS," Proc. 1987 IEEE PAC Conference, p. 1719.
2. W. Herdrich and H. P. Kindermann, "RF Power Amplifier for the CERN SPS Operating as LEP Injector," Proc. 1985 IEEE PAC Conference, p.2794.
3. F. E. Terman, "Radio Engineers' Handbook," (McGraw-Hill, New York, 1943), p. 393.
4. S. Kwiatkowski, "Optimization of the Anode Network for the 60kW, 197 MHz RHIC Storage Ring Cavity rf Amplifier," RF Tech Note.
5. W. Pirkl, private communication.

Comparison of amplifier parameters reported by CERN [2], those measured at BNL on 16Ω load, and those measured on cavity after modifications.

	CERN	16Ω load	Final
Anode voltage	10 kV	10 kV	9.8 kV
Anode quiescent current	0.5 A	0.5 A	0.5 A
Anode current	9.4A	9.95 A	7.77 A
Screen grid voltage	900 V	900 V	900 V
Screen grid current	320 mA	405 mA	150 mA
Control grid voltage	-200 V	-200 V	-200 V
RF output power	62 kW	53 kW	57 kW
RF drive power	1.8 kW	1.75 kW	1.44 kW
Gain	15.4 dB	14.8 dB	16.0 dB
Anode efficiency	64%	54%	73%

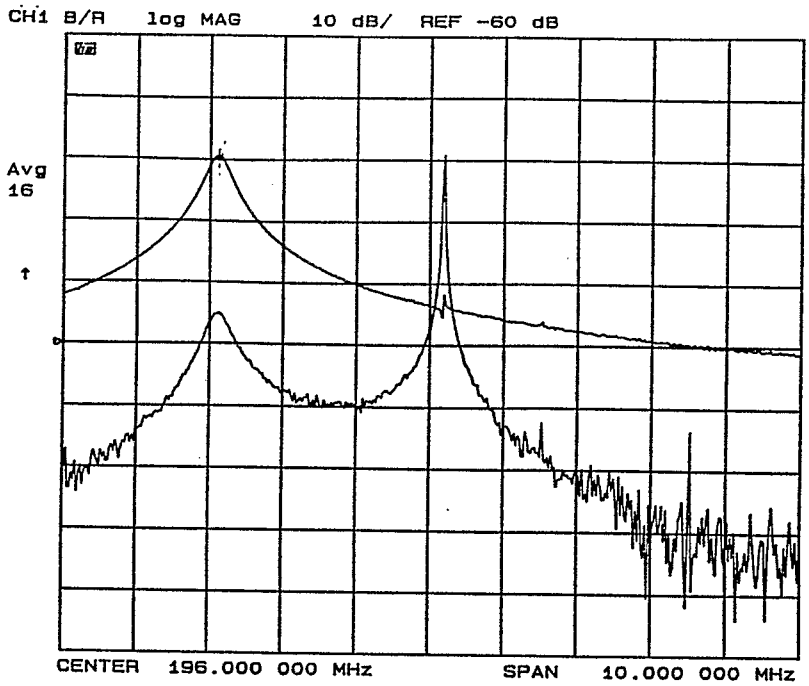

Figure 1. Network analyzer traces showing the impedance pole and cavity resonance. Top trace is the signal from the forward-power coupler in the drive line, and bottom trace is the signal from a pickup loop inside the cavity.

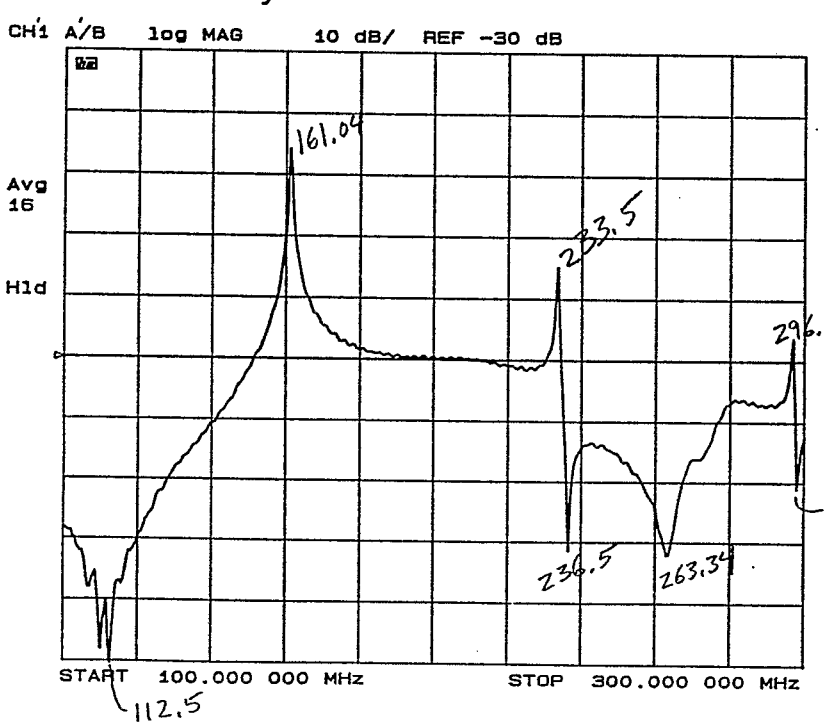

Figure 2. Anode impedance as a function of frequency with an electrical short across the ouput of the amplifier.

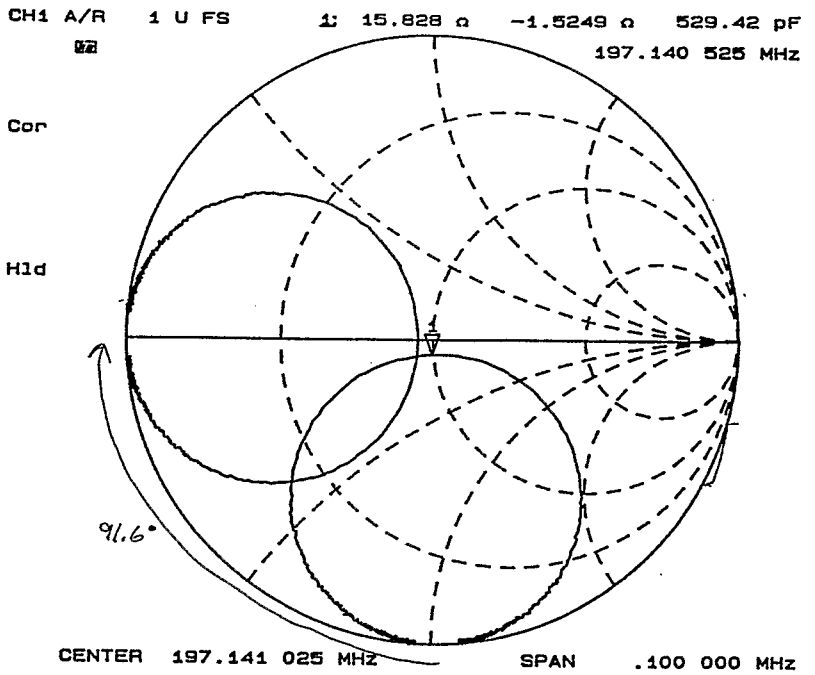

Figure 3. Impedance of drive loop from end of original transmission line. The bottom circle is the impedance and the left circle is the impedance phase shifted by 92°.

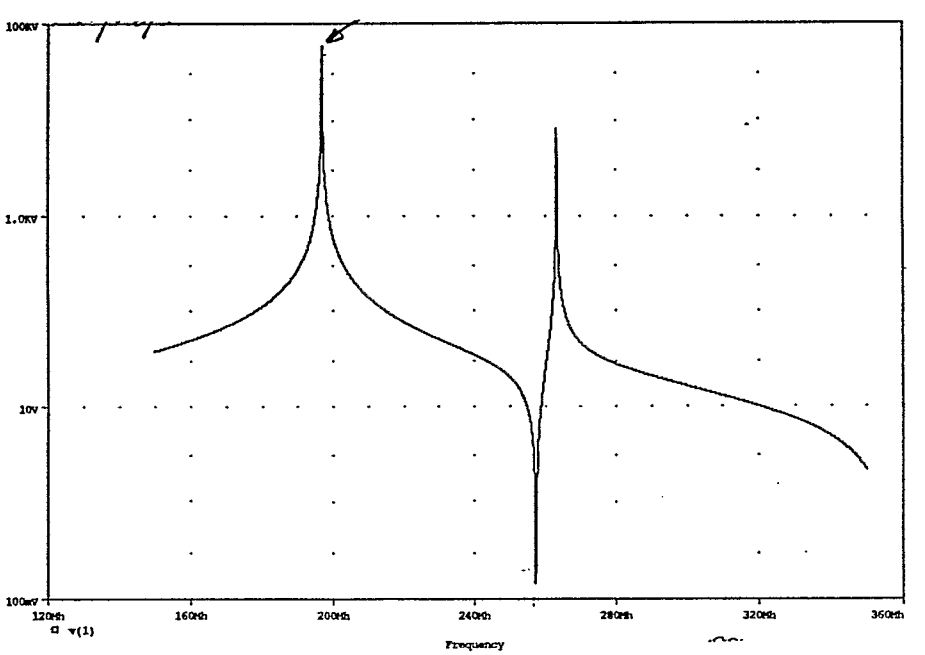

Figure 4. PSPICE calculation of impedance presented by a short circuit transformed through 3/8 λ of 16Ω transmission line, 1/4 λ of 3Ω line, and 1/4 λ of 18.5Ω line in series. Impedance pole is 197 MHz.

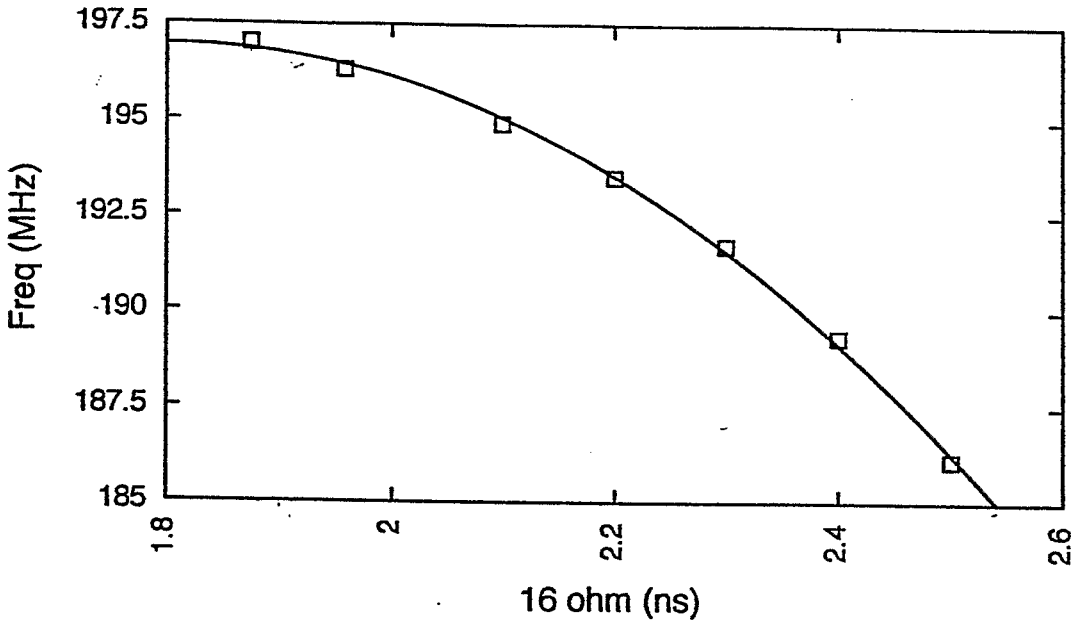

Figure 5. Calculated frequency of lower impedance pole plotted as a function of 16Ω line length. At 197 MHz λ/2 = 2.54 ns.

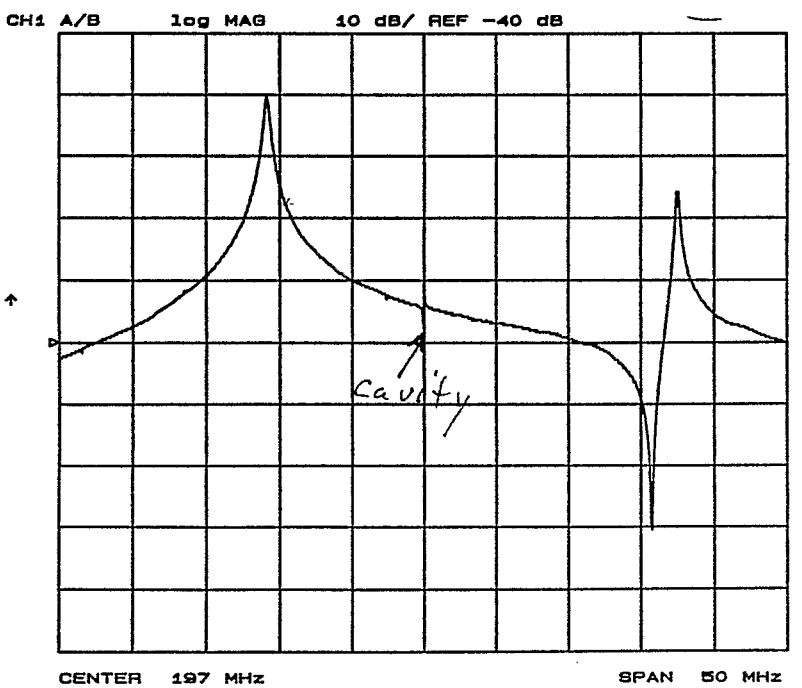

Figure 6. Forward coupler signal with drive-line extension installed. Cavity resonance is in center of plot.

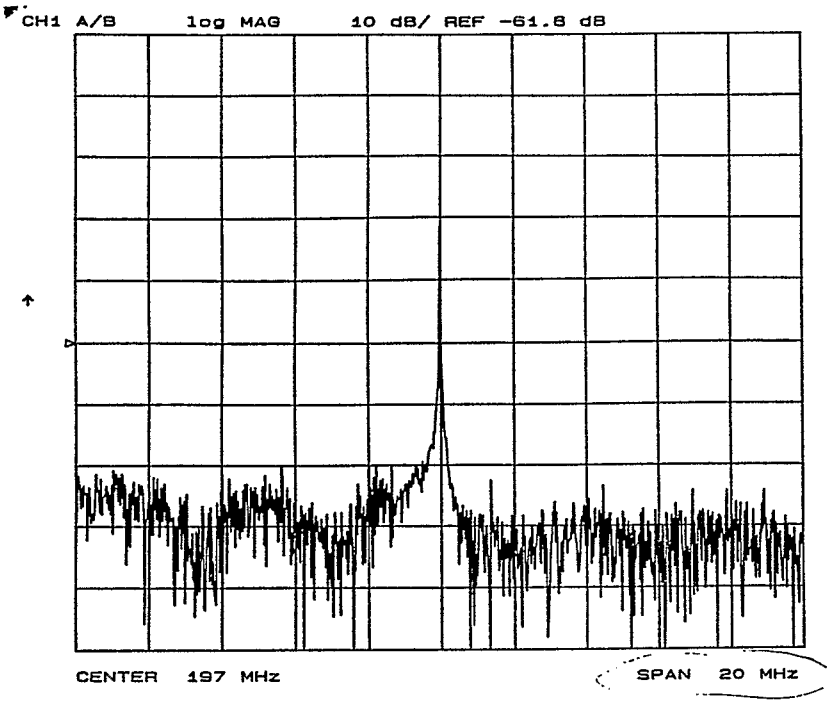

Figure 7. Cavity pickup loop signal with drive line extension installed. Cavity resonance is only feature in 20 MHz span.

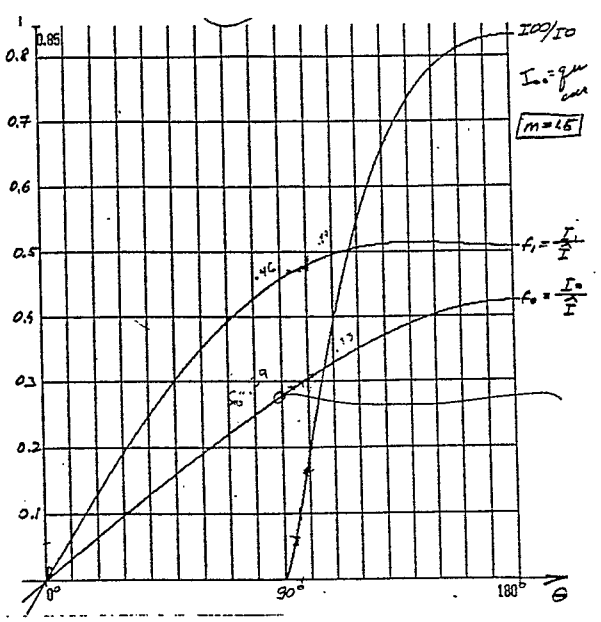

Figure 8. Tube current form factors calculated by W. Pirkl. Bottom axis is conduction angle of tube. All measurements are made with θ of 95°-100°.

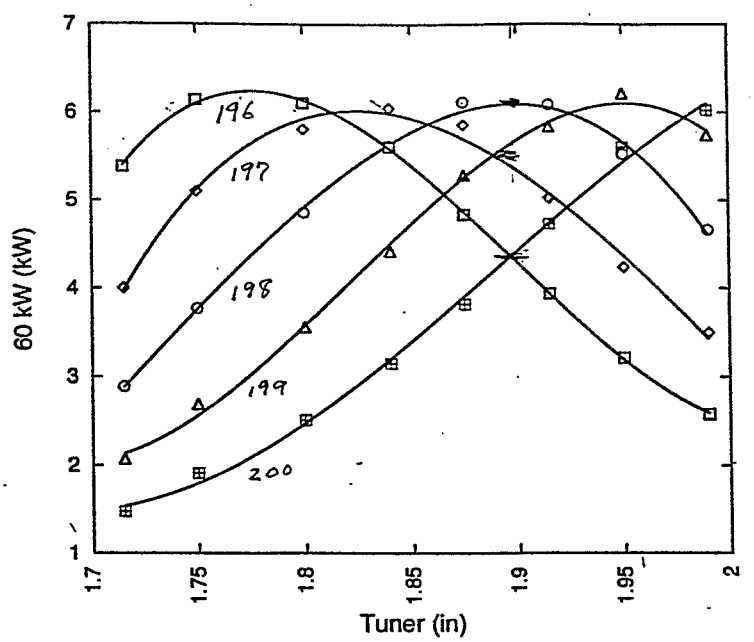

Figure 9. Measured power as a function of tuner position for five frequencies. Tuner changes frequency of maximum anode impedance but not magnitude.

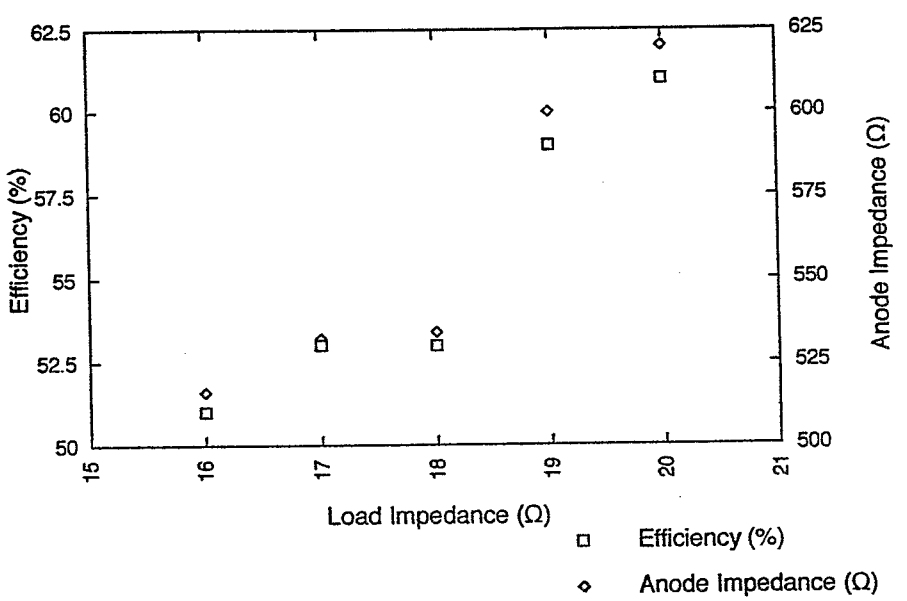

Figure 10. Measured tube efficiency and anode impedance as a function of load impedance presented to amplifier.