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R.F. Note #117

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CCP K500 Transmitter: Final Stem Modification

Introduction

The Coupled Cyclotron Project (CCP) is underway here at the NSCL. Within the next two years, the K500 cyclotron will be significantly renovated, including the entire RF system. This RF note focuses upon the new RF transmitters associated with this upgrade.

Since years of design have gone into the development and improvement of the existing K1200 RF transmitters, we are highly confident that we can use this same design for the RF drive system of the CCP K500. Furthermore, since the mechanical design of the CCP K500 vault layout required some retrofitting of the RF drive transmitters, the electronics group saw this as a chance to improve upon the existing design in particular regards to the higher order resonances of the final anode stem circuit. The additional mechanical design required for these electrical improvements was smoothly incorporated into the work which had to be done for the retrofitting.

On Higher Order Resonances

Single frequency RF amplifiers are usually designed for a mode of operation other than Class A. By a class A amplifier it is meant that the amplifying device is continuously on; or in other words it conducts current for 360 degrees of the input signal's cycle. For a single frequency amplifier, it is very inefficient to have the amplifier conducting for the entire cycle. A more efficient way of amplification is achieved by attaching a resonant circuit (called a tank circuit) at the output stage. With the amplifying device biased at a point where it will only conduct during a small portion of the input signal's cycle, the output current will then be a periodic pulse with a fundamental frequency equal to the input signal's frequency. Since the output tank circuit is resonant at this same frequency, the signal seen at the output will in fact be a sinusoidal signal.

However, if the tank circuit is resonant at any other frequency that is a harmonic of the periodic current pulse, the output signal will contain an amount of this harmonic component along with the fundamental. This is termed harmonic distortion. For narrow band loads, one problem caused by harmonic distortion is this:

> The equivalent load resistance that the tank circuit presents to the output at the higher order resonances is usually greater than the equivalent resistance at the fundamental resonance. This implies that although the harmonic components of the current pulse may be smaller in magnitude than the fundamental, the voltage swing of the harmonic at the output may be greater than the voltage swing of the fundamental. In the case of a grounded cathode, tetrode tube amplifier, the maximum output voltage swing is limited by a value called E_{min}. This value is the minimum potential difference that can exist between the anode and the screen before the screen starts looking like the anode. When this occurs, the current (in

a positive sense) begins to flow into the screen instead of into the anode, thereby limiting the output. For maximum fundamental output power, the tube amplifier is designed for a maximum voltage swing at the fundamental. It is therefore crucial that the harmonic voltage swing be minimized such that it does not cause a premature value of E_{min} to occur. Additionally, the unwanted harmonics tend to lead to other problems.

From the above discussion it is clearly obvious that the best way to minimize the effects of harmonic distortion is to eliminate the harmonics altogether; corresponding to forcing the inevitable higher order resonances in the tank circuit away from the harmonics of the anode current pulse. This may be possible to do if the amplifier was designed to operate at only one fixed frequency. In the case of the CCP K500, however, the amplifier is designed to be tuned over a large band of frequencies ranging from 11 MHz to 27 MHz. Practically, it is virtually impossible to make sure that the frequencies of the tank circuit's HOR's do not cross with a harmonic component at some operating frequency. Therefore, it is crucial that the tank circuit's HOR's are analyzed to determine whether they can cause a large harmonic distortion which can lead to a premature value of E_{min} to occur. If they can, then a method to either shift the HOR's to occur elsewhere has to be employed, or a method to reduce the equivalent resistance at the HOR's has to be pursued.

Analysis of the K1200 Final Stem Circuit

Previously, RF Notes 107-109 discussed the upgrade of the K1200 RF Transmitter from using an RCA 4648 tetrode to the Thompson TH555 tetrode. During this upgrade, an analysis of the driver circuit in regards to harmonic distortion and harmonic oscillation was performed. This analysis was concerned with the output circuit presented to the initial amplifying stage consisting of the 4CW2000 tubes and not the output circuit presented to the TH555. This note discusses an analysis of the TH555's output tank circuit.

The first step in any analysis is to determine a model from the physical realm. In this case, the particular physical device we are interested in modeling is the output tank circuit on the anode of the TH555. A view of the amplifier box can be found in Figure 1 with the transmission line equivalent model for the final stage shown in Figure 2.

The transmission line equivalent model was formulated in a similar manner as the dee stem model described in RF Note 116. Therefore, the exact details of the model's extraction from the physical realm will not be fully discussed. However, the important aspects of the model's development will be explained.

First of all, due to the presence of an AC blocking inductor connected between the anode and the DC bias supply, this connection is excluded from the model. Also, due to the

small value of the feedback neutralizing value between the anode and the grid, the model excludes the feedback network. However, the anode to screen capacitance is included in the model along with the equivalent transmission lines representing the screen connection to the screen bypass capacitor. The model therefore includes the following physical building blocks:

1.) The DC blocking capacitor between the anode and the output circuitry
2.) The entire anode tuning stem circuit
3.) The output coupling capacitor
4.) The harmonic suppresser circuit (C_damp and R_damp of figure 2)
5.) The load presented to the output by the dee resonator
6.) The capacitance between the anode and screen along with the equivalent transmission lines representing the screen connection to the screen bypass capacitor.
7.) The equivalent anode current source representing the voltage controlled current source equivalent of the amplifier tube

The Tuning Stem

The tuning stem was divided into appropriate uniform transmission lines and discontinuity capacitances. The characteristics of each transmission line were determined using an electrostatic analysis of the cross sections in a similar manner to the modeling of the dee stems in RF Note 116.

The Output Coupling Capacitor

The output coupling capacitor is a variable capacitor which provides a voltage drop to match the 50 Ohm output line impedance to the anode impedance required for a desired output power level. Since Phoenix, our power supply, can provide a total of 1.2MW and the TH555 tubes are run at approximately 75% efficiency, the maximum available power per station is 300 kW. To determine the output capacitance values required at each frequency for this 300 kW power dissipation with an anode voltage swing of 17 kV peak, a simple hand calculation was performed. The analysis included the series RC harmonic damper connected in parallel with the 50 Ohm load representing the tuned dee resonator. The exact expression for this capacitance value becomes quite complex with the inclusion of the harmonic damper. However, a simplified analysis was done by representing the damper's series combination of resistance and capacitance by an effective resistance which represented an equivalent power dissipation. The actual value of capacitance was determined by adjusting the initial hand analysis value within the circuit model until the simulation resulted in the desired 300 kW total power dissipation with a 17 kV peak voltage swing on the anode.

A list of the output coupling capacitance values for each frequency are given below along with the associated total output power, power delivered to the dee resonator, and the dee voltage attainable at these power levels.

Freq. (MHz)	Calaculated C_{Out} (pF)	Actual C_{Out} (pF)	P_{Total} (kW)	P_{Dee} (kW)	V_{Dee} (kV peak)
11	92.60	75.00	192.1	190.6	258.4
13	78.50	75.00	257.5	255.2	279.5
15	68.10	71.48	300.1	296.9	282.3
17	60.10	63.75	300.3	296.3	262.1
19	53.90	57.75	300.5	295.7	246.2
21	48.80	52.90	299.9	294.2	226.2
23	44.60	49.10	301.0	294.3	214.1
25	41.10	45.75	299.1	291.5	197.9
27	38.10	43.15	300.2	291.5	186.5

Note that the total output power is limited at frequencies between 11 MHz and roughly 13.5 MHz due to the maximum attainable output coupling capacitance value of only 75 pF.

The Load Resistance

The load resistance represented by the dee resonator was set to the 50 Ohm matched resistance at the fundamental frequency. This load value was used in determining the stem's short position as a function of frequency. In order to investigate the HOR's, the load resistance represented by the dee resonator was set to an open circuit. This is valid since the resonator nominally looks like a very high impedance at any other frequency other than the fundamental frequency for which it is tuned. This may not be entirely valid if the dee resonator itself actually has a higher order resonance which would closely cross with one of the tank circuit's HOR. This is virtually impossible due to the high quality factor of both the tuning stem and the dee resonator. However, it cannot be completely ignored. In fact, it was seen that a HOR of the dee resonator was in close proximity to a HOR of the final stem at a fundamental frequency of 18 MHz. But as said, these resonances would have to nearly line up in order for energy to propagate into the dee due to the high Q of each circuit. This will be investigated if we see such evidence when the RF system is tested.

The Anode to Screen Capacitance

The capacitance between the anode and screen was initially modeled with a single capacitor whose value is given in the data sheets for the TH555 tube. However, initial simulations showed that the results did not match the current operating data. In fact at 27 MHz, the model predicted the stem length to be 2.5 inches longer than the current operating data. Since the physical data is the real model, the analysis model needed to be tuned to match the physical condition. A more detailed model of the anode to screen capacitance was then developed. This model accounted for a total capacitance value as given in the data books with a capacitively terminated transmission line between the screen and the anode instead of with a single capacitor. This model is represented as

TR_SA and C_AS in figure 2. The transmission line is actually represented by two 3-terminal lines to give an appropriate 4-terminal line within the circuit analysis program.

Unfortunately, the more detailed model had little effect in correlating the simulation results with the physical data. The physical picture was then examined more carefully and it was discovered that there probably existed some stray capacitance between the anode and the screen bypass capacitor as well as some capacitance between the anode and ground due to the spark gaps. To compensate for these effects and to correlate the simulations with the physical data, a single capacitor was added between the anode and screen bypass capacitor. Its value was adjusted to exactly match the simulation with the physical data at 11 MHz. With this correction, it was seen that the model now over predicted the stem length by only 0.5 inches at 27 MHz.

With the simulation model having been fine tuned, the HOR analysis was pursued. As discussed previously, the load resistance representing the dee resonator was set to an open circuit for this analysis. The results of the HOR frequencies as a function of the fundamental operating frequency are plotted along with the harmonics of the fundamental frequency in figure 3. A more informative plot which also includes information on how the fundamental and HOR frequencies vary with stem length is shown in figure 4.

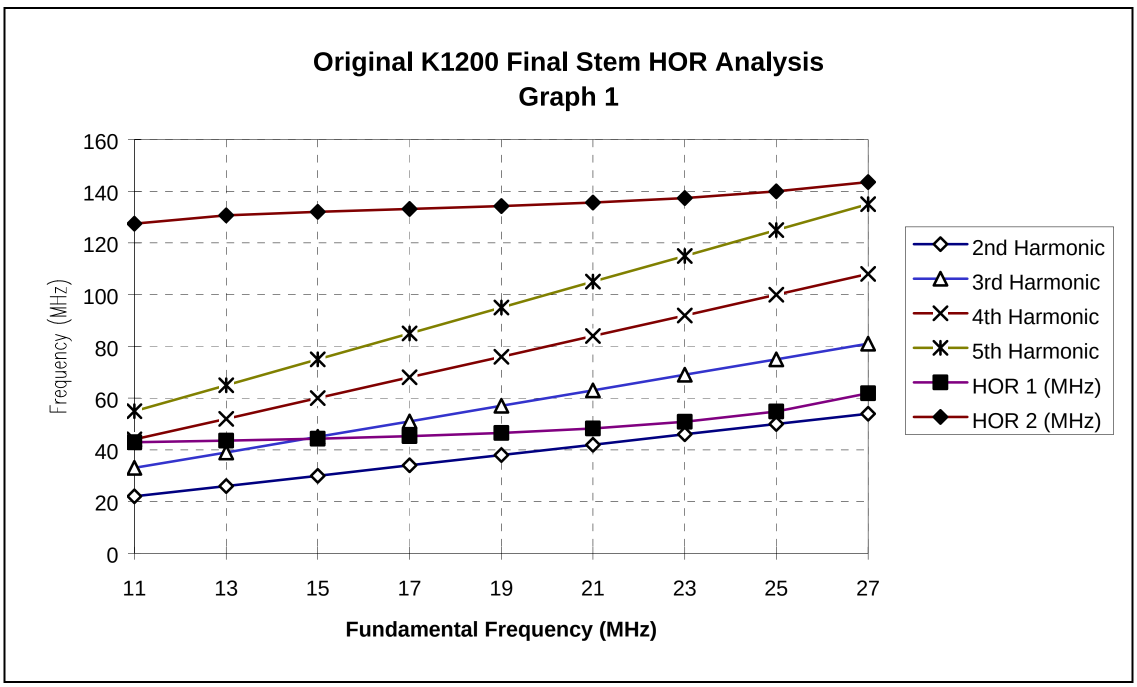

Figure 3

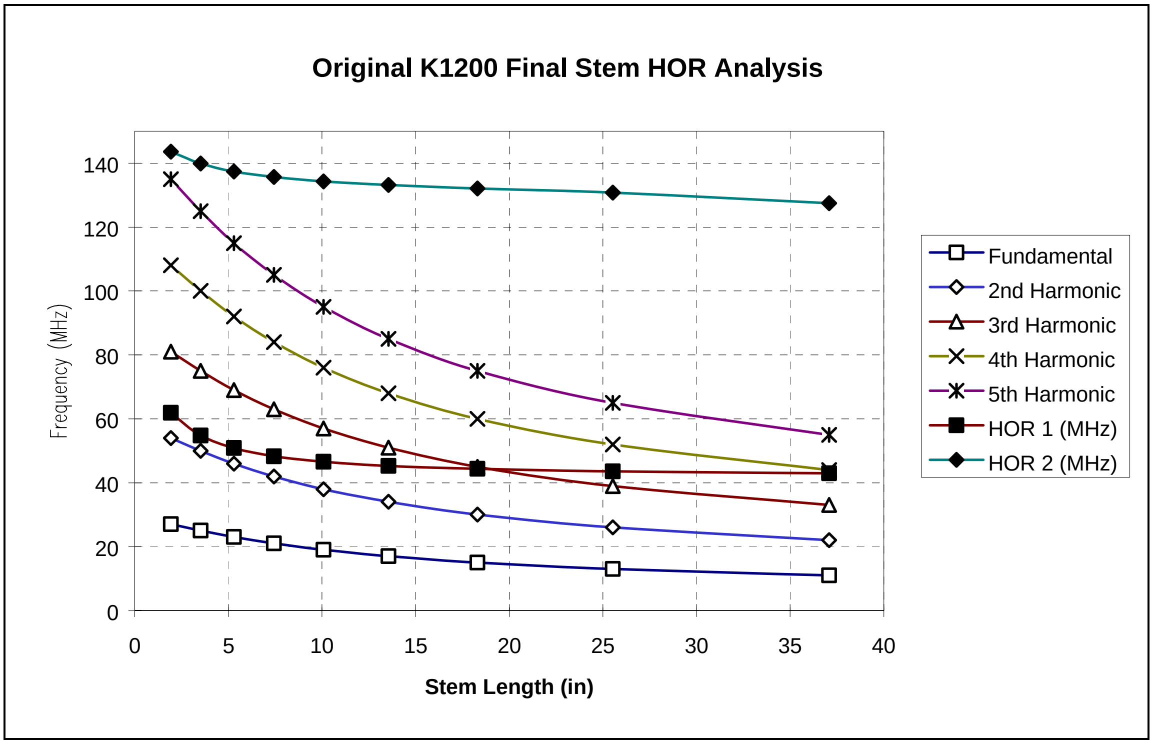

Figure 4

From these graphs, it is seen that the HOR frequencies do not tune in a similar manner to the fundamental frequency; causing the cross over points with the operating frequency harmonics. It is clearly evident that the first HOR crosses with the third harmonic at a fundamental frequency of 15 MHz and with the fourth harmonic at a fundamental frequency of 11 MHz. Also the simulation shows the first HOR to come near to the second harmonic at frequencies between 23 MHz and 25 MHz. This was actually observed in RF Note 109 which mentioned that a strong second harmonic content was actually seen in the output at a tuned fundamental frequency of 23 MHz. With this evidence, confidence in the model was affirmed.

Modification to the K1200 Final Stem

As stated previously, the electronics department took advantage of the mechanical design effort being put into the CCP transmitters and decided to add some modifications of its own to improve upon the HOR's. The most intuitive improvement which could be made to the final stem upon inspection was to present a smoother taper to the anode along the stem. As seen in figure 1, from the anode the stem steps *out*, then *in*, then *out* again, and then back *in*. The final step *in* cannot be avoided since it is the crucial tuning adjustment segment. It was decided that an improvement upon the HOR may occur if the *out-in-out* section was changed to a represent a smoother taper consisting of an *out-out-out* segment. The middle section's inner radius was therefore increased to an average of the inner radii of its adjacent segments. The modification is shown in figure 5.

The original K1200 final stem circuit model was then altered to represent this modification. Again, the output coupling capacitance values were fine tuned within the circuit simulation model. Then the stem position versus fundamental frequency was determined, followed by an analysis of the HOR at each fundamental frequency. The output coupling capacitance values are given below. The HOR results are shown in figures 6 and 7 in a similar fashion to the results of the original K1200 final stem.

Freq. (MHz)	Calculated C_{Out} (pF)	Actual C_{Out} (pF)	P_{Total} (kW)	P_{Dee} (kW)	V_{Dee} (kV peak)
11	92.60	75.00	192.2	190.7	258.4
13	78.50	75.00	257.3	255.0	279.4
15	68.10	71.48	300.4	297.0	282.3
17	60.10	63.75	300.2	296.1	262.1
19	53.90	57.75	300.3	295.4	246.1
21	48.80	52.95	300.2	294.4	226.3
23	44.60	49.00	299.8	293.0	213.6
25	41.10	45.75	299.3	291.5	197.9
27	38.10	43.15	300.3	291.4	186.5

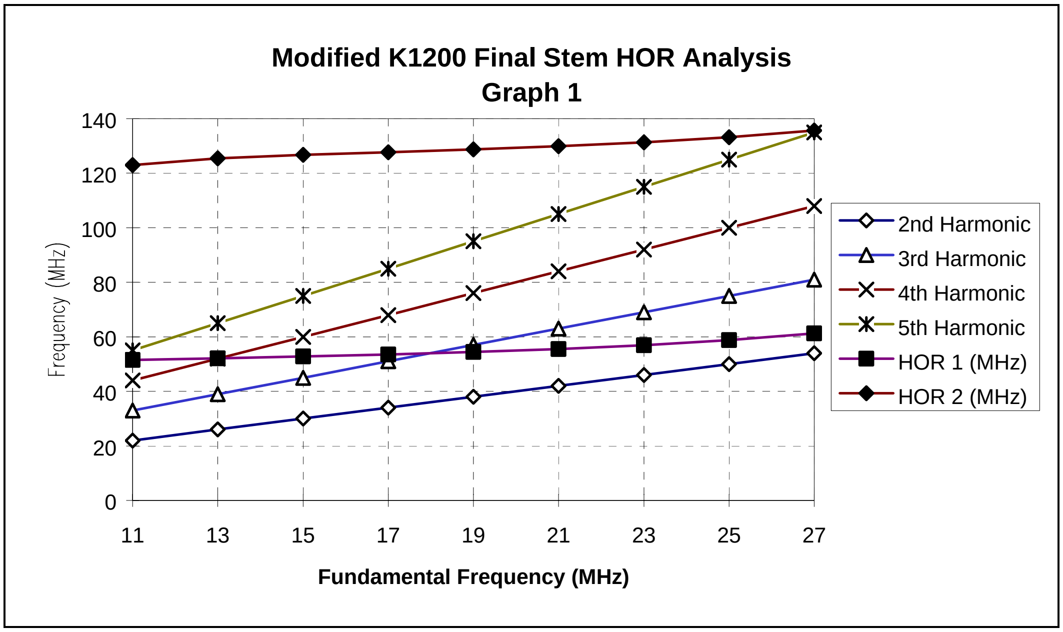

Figure 6

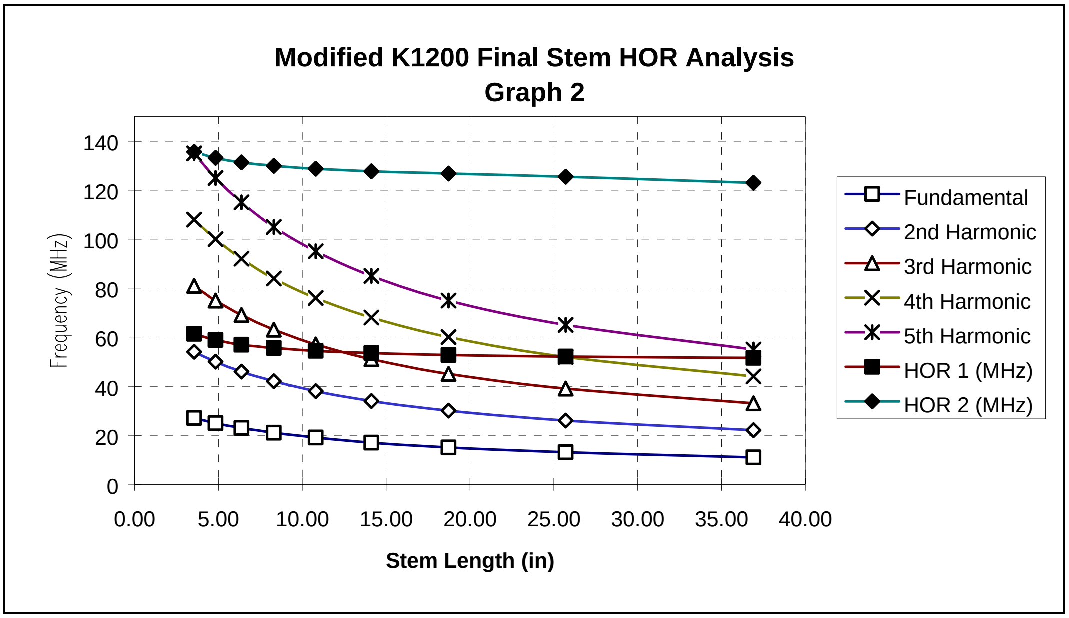

Figure 7

Upon comparison between the modified and original stems, it is evident that the first HOR was effectively pushed up while the second HOR was pulled in. Most importantly, the first HOR was moved away from the second harmonic at a fundamental frequency between 23 MHz and 25 MHz. The original cross over of the first HOR with the third harmonic at a fundamental frequency of 15 MHz, now occurs at 18 MHz. Also, the original cross over of the first HOR with the fourth harmonic at a fundamental frequency of 11 MHz, now occurs at 13 MHz. One noticeable added cross over of the second HOR with the fifth harmonic was added at a fundamental frequency of 27 MHz. This is of little concern since the fifth harmonic of the current pulse, along with its effective gain, is of small magnitude as will be seen shortly when the current pulse is analyzed.

The major advantage of the modification was in pushing the first HOR away from the second harmonic at fundamental frequencies between 23 MHz and 25 MHz which, as mentioned earlier, was actually physically evident as seen in RF Note 109. The modification will therefore be made to the K1200 and incorporated into the CCP K500 transmitters.

Further Modifications: The CCP K500 Final Stem

Due to mechanical restraints in the vault area for the CCP K500, specifically the ceiling height, the entire transmitter box had to be effectively recessed into the floor by about four inches. This caused a relocation of some step discontinuities as well as an additional transmission line segment due to the recession of the largest inner conductor into the panels. This mechanical modification is shown in figure 8 along with the newly

discussed electrical modification. Besides these modifications there is an additional modification which was made to eliminate an unneeded historical element.

Upon comparison of figures 1 and 8, this additional modification can be observed. In figure 1, the driver box containing the 4CW2000's sits upon a smaller boxed area at the location of the screen bypass capacitor. This smaller boxed area then steps out to become the outer conductor for the anode stem. Historically, this smaller boxed area was initially larger and housed the RCA 4648 tetrode. Due to the conversion from the RCA 4648 tetrode to the TH555, this discontinuity is unnecessary. Figure 8 shows the additional modification which will be incorporated into the CCP K500 transmitter to eliminate this discontinuity.

Although the additional modifications included to transition from the modified K1200 transmitter to the CCP K500 transmitter were expected to have little effect in the overall response of the circuit, an analysis had to be performed to predict its behavior. The circuit model for the modified K1200 final stem was then altered to represent the CCP K500 final stem. Again, the output coupling capacitance values were found along with the short position versus operating frequency with a 50 Ohm load. This was followed by the HOR analysis. A table of the output coupling capacitance values is shown below while the HOR results are shown in figures 9 and 10 in a similar format to the previous analyses.

Freq. (MHz)	Calculated C_{Out} (pF)	Actual C_{Out} (pF)	P_{Total} (kW)	P_{Dee} (kW)	V_{Dee} (kV peak)
11	92.60	75.00	192.2	190.7	194.2
13	78.50	75.00	257.3	255.0	213.9
15	68.10	71.48	300.4	297.0	218.9
17	60.10	63.75	300.2	296.1	208.0
19	53.90	57.75	300.3	295.4	197.7
21	48.80	52.95	300.2	294.4	188.3
23	44.60	49.00	299.8	293.0	179.8
25	41.10	45.75	299.3	291.5	171.9
27	38.10	43.15	300.3	291.4	165.2

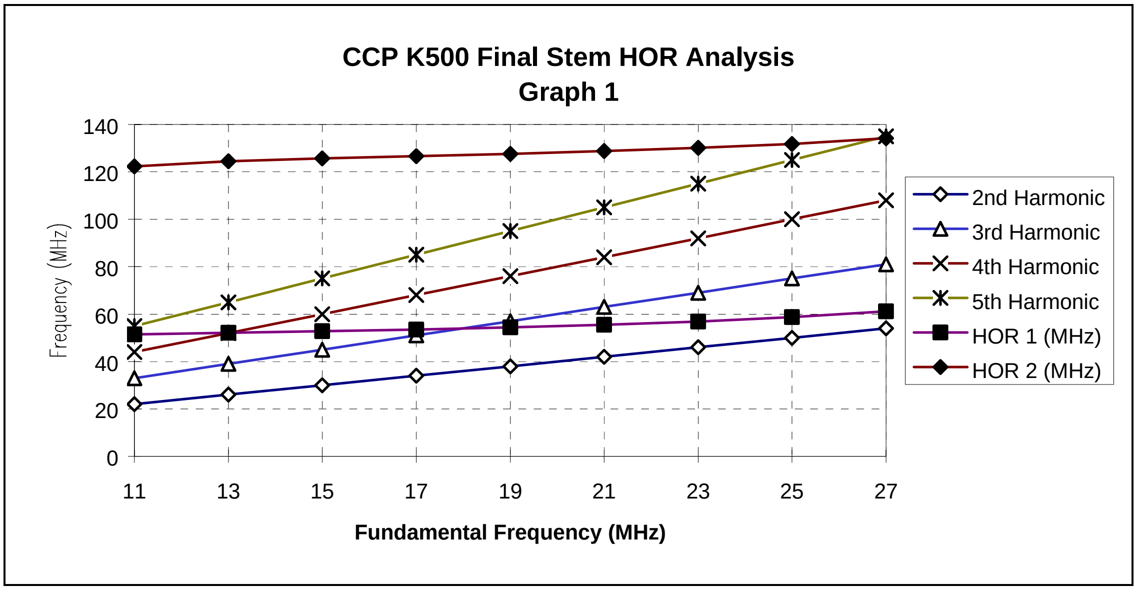

Figure 9

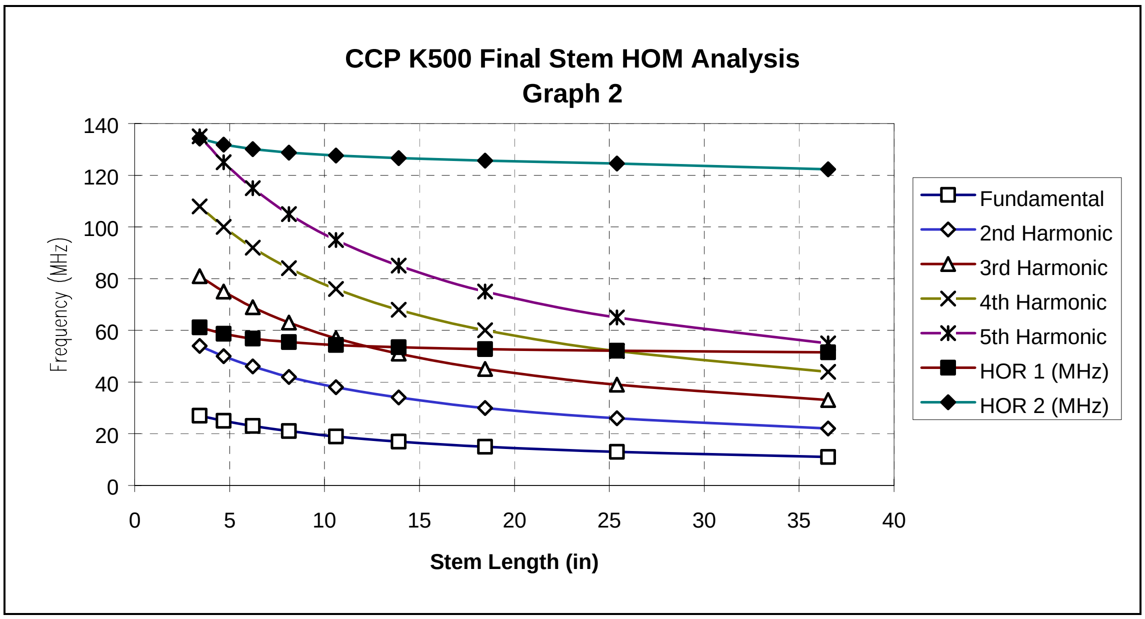

Figure 10

Upon comparison of the results for the modified K1200 final stem and the CCP K500 final stem, there is little difference between the two in terms of HOR frequencies. There are also only slight differences in the effective gain of the harmonics which will be seen shortly when the current pulse is analyzed. The most profound difference between the CCP K500 and the K1200 is seen by observing the value of the dee voltage that is achieved under the same power levels. This is due to characteristic differences between the K500 and the K1200, specifically in regards to the equivalent shunt resistance at the dee tip.

The Anode Current Pulse

To determine a more detailed analysis of how improvements in the HOR's do indeed improve upon the harmonic content at the output and reduce the chances of premature screen currents, the gain of the harmonics needs to be determined by analyzing the anode current pulse. The waveform of this current pulse can be derived from an analysis of the tube's characteristic curves. Such an analysis can be performed using a program provided by Precision Power Products called WinTube. The program's output gives the resultant anode current pulse for our operating conditions of 300 kW output power with a 17 kV peak voltage swing on the anode. These results are shown in figure 11.

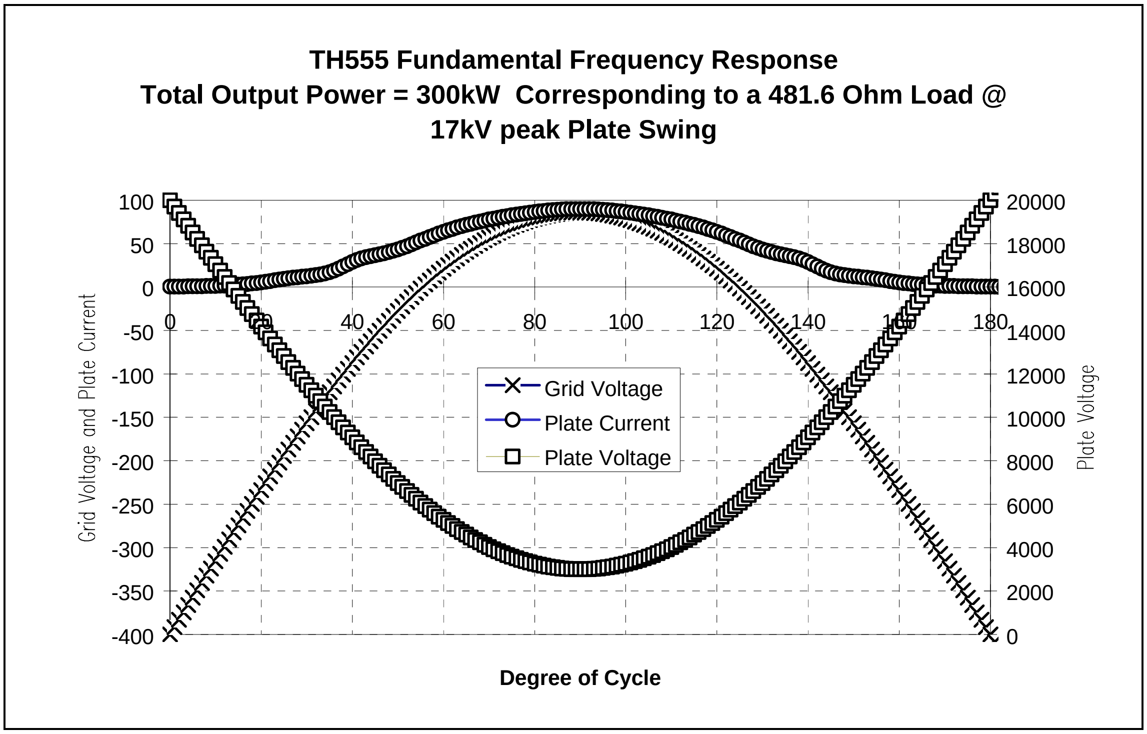

Figure 11

Only the first 180 degrees of the cycle are shown since the plate current is flat for the other half of the cycle. Also, please take note of the equivalent terminology of 'anode' and 'plate'.

This current pulse is periodic at the frequency of the drive signal and can therefore be decomposed into its Fourier series components. WinTube provides the magnitude of the first five of these components as normalized to the magnitude of the fundamental component. The results are given below:

Linear Harmonic Analysis of the Plate Current

Component	Normalized Magnitude (dB)
Fundamental	0.00
Second Harmonic	-10.62
Third Harmonic	-12.26
Fourth Harmonic	-15.66
Fifth Harmonic	-43.10

As was seen in the HOR analysis, some of these components will be present at the output at points where the HOR frequency crosses with a harmonic frequency. Since the equivalent resistance seen at the anode is different at the HOR's than at the fundamental, the voltage gain of each will also be different. In particular, it was seen that the equivalent resistance seen at the anode is 481.6 Ohms at the fundamental while it is 1 kOhm at the first HOR and roughly only 100 Ohms at the second HOR. Therefore, the effective voltage gain at the first HOR will be twice that of the fundamental. This is of little concern since it is seen that the second harmonic of the current pulse is 10.62 dB below the fundamental, which is equivalent to 30%, well below the greater than 50% value which would cause the harmonic voltage swing to be greater than the fundamental voltage swing, which in turn would cause premature screen currents. The value of 50% is obtained due to the equivalent resistance of the harmonic being approximately twice that of the fundamental.

Below are tables giving the ratio of the harmonic anode-to-screen voltage to that of the fundamental for each harmonic component at the operating frequencies where the HOR's are excited. A value greater than 1 would represent the condition of premature screen currents.

Original K1200 Final Stem
Harmonic Content in the Output

Fundamental (MHz)	Harmonic Component in Output	$V_{Harmonic} / V_{Fundamental}$
11	4th Harmonic	0.27
15	3rd Harmonic	0.62
23	2nd Harmonic	0.76

Modified K1200 Final Stem
Harmonic Content in the Output

Fundamental (MHz)	Harmonic Component in Output	$V_{Harmonic} / V_{Fundamental}$
13	4th Harmonic - HOR1	0.32
18	3rd Harmonic - HOR1	0.57
27	5th Harmonic - HOR2	0.002

CCP K500 Final Stem
Harmonic Content in the Output

Fundamental (MHz)	Harmonic Component in Output	$V_{Harmonic} / V_{Fundamental}$
13	4th Harmonic - HOR1	0.32
18	3rd Harmonic - HOR1	0.57
27	5th Harmonic - HOR2	0.002

Conclusion

The modifications described in this note will be incorporated into both the K1200 and CCP K500 as discussed. The major improvement upon the transmitters was in effectively pushing the first HOR away from the second harmonic at frequencies between 23 MHz and 25 MHz. Another slight improvement which is easy to overlook is that the short position became longer at 27 MHz and slightly shorter at 11 MHz, thus improving the transmitter tuning range. The following graph represents this data.