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R. F. Note 107

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K800 RF AMPLIFIER TUBE UPGRADE

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1. INTRODUCTION

The K800 RF System came up almost trouble free, it ran smooth for hours and days at dee voltages anywhere from 10 to 130KV. We had no immediate need to push it higher than this and have no reason to believe it would not perform well above these levels. We did note a problem with the cyclotron cavity Q above 20 MHz, but have had no need to pursue it yet. The RF performed well and has allowed the cyclotron to be developed through the extraction of 3 beams to date.

During this initial running stage we began to have failures of the large power tube in the final stage of the RF Amplifier. The tube used is a RCA 4648 tetrode. The failure was a grid to filament short. By sending the first failed tube back to Burles Industries (the tube manufacturer), we found the failure was due to a broken filament.

Since the price of the RCA tube is rising quickly, it is not as available as other suitable tubes, it appears to be more fragile than other tubes we have experience with, and it has unfavorable intrinsic electrical characteristics such as unstable operation and GHZ parasitic modes, we have decided to retrofit to a more suitable tube for our application. This note shall describe our problems and work through our solution.

2. RCA 4648 OPERATING EXPERIENCE AND EVALUATION

The RCA 4648 tetrode has a geometry, which is unique for this sort of tube. Appendix D contains some engineering sketches of the fundamental design. These sketches are not absolutely complete or correct in detail, but are correct in function and component placement. The tube design is “inside out” with respect to normal tube design such that the anode is the innermost structure and the cathode the outermost structure. It is also unique in its grid and filament structures. The filaments are long individual flat rods which are spring loaded and poke through the control grid assembly. The control and screen grids are rectangular constructs placed 15 degrees apart in a circular arrangement. There exists a place in the tube where the filaments can see the screen structure directly without the control grid in between. When the filament is operated at 1600 Amperes, the screen draws 400mA due to the direct path available from filament to screen electrode. The failure occurred at this location and appeared to be a rapid burn through. This burn through probably was caused by a spark from the anode to screen. This spark caused the screen to charge to a high potential which then caused a spark to a filament rod and during the last failure, which blew apart. We also now know that the crowbar was not functional at that time.

The inspected tube also reveals some non-destructive, non-symmetric damage was occurring to the filament. The filament rods have multiple superficial pits at 2 broad locations spaced 120 degrees apart. The anode at these locations have large cloudy spots most likely due to the material discharged from the cathode from the pitting phenomena. The overall geometry is circularly symmetric, so there is no reason for circular functionality of any phenomena. The overall geometry is circularly symmetric, so there is no reason for circular functionality of any phenomena at our frequencies. We did have a 90 to 130 Gauss magnetic filed from the Cyclotron imposed however, and I claim a magnetic effect is what caused the problem whatever it was. One likely scenario for these pits is due to sparks from the anode which were guided by the magnetic field to one of these two broad locations depending on the spark location and initial conditions. These would be arcs the missed the screen and grid completely and went on through to the cathode. The small size of the pits on the very hot and pliable cathode most likely means the crowbar was functioning properly. The tubes have since been double shielded from the magnetic field, and I hope this aspect of the problem will disappear. It should be noted that the failure occurred in one of the general locations where the pitting was occurring, however, no pitting occurred in the immediate location of the failure. The pits are occurring in the location of the screen and grid rectangular constructs, whereas the failure occurred where the solid screen electrode can see the filament rod directly. There were no pits on any of the filament rods in the location of the failure.

To remove the undetected crowbar condition or failure, we have added remote current coils at each transmitter capable of firing the crowbar and an automated crowbar test sequence to the RF PLC based interlock system. The test sequence will automatically test the crowbar circuit every 24 hours and interlock the anode power supply if it does not pass. We have electrodes to try to eliminate the destructive nature of a spark if the crowbar has failed. We hope this will eliminate this problem, or at least compensate for it. Hopefully the measures described will get us up and operating in a more reliable manner in the near future. Next, the RCA 4648 tetrode will be compared to more conventional designs.

A standard design for a high power tetrode has the anode on the outside and filament on the inside. The filament is a “chicken wire” looking cylindrical one-piece structure. Just outside this cylinder is the control grid cylinder consisting of horizontal circular hoops held together by vertical wires. Outside the control grid cylinder is the screen grid cylinder constructed the control grid, with its wires perfectly aligned with the control grid wires. Finally, surrounding the screen grid is the solid cylindrical anode. No place on this structure can the screen grid directly sees the filament without the control grid being in between. Because the filament is very hot when activated, it is rather weak, whereas the grid and screen wires are designed to be quite robust. Should the anode spark to the screen in this structure, the screen will charge up and most likely spark to the grid, not to the filament. A spark occurring from anode to filament is much less probable than on the 4648, because of the reduced filament surface which has a line of sight view of the anode.

An inspection of the sketches of the 4648 tetrode quite clearly show the filaments to be wide flat planer bars. In the 4648 design a much larger percentage of the filament has a line of sight view of the anode than in conventional tubes. Since the filament is much more delicate than the other grids in a operating tube, this feature of the 4648 design is undesirable. The fact that a spark can jump directly from the screen to the filament in the 4648 tubes is a most undesirable feature. This latter feature also causes a dc current to flow under zero drive bias conditions which is undesirable. The cathode structure in the 4648 tubes is mechanically resonant at 120 Hz. This means the filament cannot be ac excited without damaging or destroying the tube. The tube can therefore be destroyed by a diode failure in the filament power supply, also undesirable. The RCA 4648 has a very high gain which allows it to be broadband driven under certain types of operating conditions. This feature causes it to be unstable if driven by anything other than a very low impedance driver.

The stability of any system higher than order 1 is a function of gain and phase shift. As the gain is increased in higher order systems, the margin of stability is simultaneously reduced, our system uses a tuned tube based driver. We have plenty of drive capability for any conventional tetrode suitable for this application. Because these new Superconducting Cyclotrons are tightly toleranced, we experience more sparking than in other types of cyclotrons. As a consequence, we must break through mulipactoring and ramp back up a great deal more often than in other cyclotron designs. When the cavities are in the first 10mS of turn on, the load seen by the anode changes dramatically. These are the times an anode to screen spark are most likely. Since we go through this much more often than other cyclotrons, we certainly want to use a more robust tube. This type of cyclotron also has multiple cavities which are coupled to one another in the center by the dee-to-dee capacities. The cavities are normally operated at 120 degrees phase shifts from one another. This operation is not a minimum energy configuration; in other words, this operation is not a natural mode. Due to this operation, the cavities must be phase locked or regulated in order to maintain this phase relationship. For this reason, it is desirable to have double anode isolation in the rf amplifier so that we may operate the rf system without phase loops active at all times. If we were to broadband drive the final amplifier, we would see kilohertz phase oscillations without the phase loops activated. This would require the phase loops to be locked in even during debugging or tuning periods. This would make the setup of the machine more difficult and time consuming in my opinion.

The above paragraph explains why I don't want or need a tube which is broadband driven. We need a tube in our final stages which has moderate gain for stability reasons, is robust, has a stable price, and is widely used and readily available. The remainder of this note deals with the identification and analysis of various tubes which are much more suited to our operation than the RCA 4648.

3. TUBE SELECTION CRITERIA

This section will describe the general criteria used to select an appropriate tube for this application.

Absolute Requirements

A. The tube must have moderate gain and be stable
B. The tube must not have any intrinsic parasitic modes
C. The tube must be a robust design
D. The tube must have a relatively stable price
E. The tube must be capable of dissipating greater than or equal to 250kW.
F. The tube must operate up to 30MHz.
G. The tube must be widely used and readily available

Preferred Characteristics

A. The tube may easily be adapted to our amplifiers
B. The tube vendor supplies sockets and screen bypass capacitors
C. More than one manufacturer can supply the tube

4. COST AND AVAILABILITY OF SUITABLE TUBES

Tube	**$ Vendor**	**$ Distributor**	**Delay Vendor**	**Delay Distributor**
4CW250,000	$31,250.00	$31,220.00	30 DAYS	2 DAYS
TH555A	$30,870.00		60 DAYS	
4CM300,000	$35,125.00		150 DAYS	160 DAYS

No screen bypass condenser available.
Tube does not easily fit into existing amplifier design

The 4CW250,000 and 4CM300,000 are produced by EIMAC a division of Varian Corp. The TH555 is produced by Thomson.

The manufacturers have assured me that none of these tubes are unstable or have any intrinsic parasitic modes. The vendor which is doing the most R&D in the field is Thomson. The 4CM300,000 is actually a basic copy of the TH555; the advanced technology licensed to EIMAC by Thomson.

5. COST AND AVAILABILITY OF TUBE SOCKETS, ETC.

4CW250,000		
Filament Connectors	SK-1710	$1,590.00
Grid Connector	SK-1712	$990.00
Anode Water Connector	SK-1720	$3,045.00

No screen bypass condenser available.
Tube does not easily fit into existing amplifier design.

TH555A		
Tube Socket	TH 16110	$5,510.00
Tubing	TH 17317	$540.00
Tube Coupling	TH 17399	$636.00
	TOTAL	$6,686.00

This socket contains an integrated screen bypass capacitor.
Tube easily fits into existing amplifier.

4CM300,000		
Tube Socket	SK-2450	$5,710.00
	TOTAL	$5,710.00

The socket contains an integrated screen bypass capacitor.
The tube does not easily fit into our amplifier cavity.

6. USE AND USER COMMENTS ABOUT THE TUBES CONSIDERED

4CW250,000

I spoke to Continental Electronics (Dallas, Texas 214-381-7161) and Triump (Vancouver 414-222-1047) about their experience with the 4CW250,000. Both places were very pleased with the tube behavior. They said it was very stable, rugged, no intrinsic parasites, and long lived. Their appears to be 100 to 140 of these in service at any time in the world, which means it has a large market and is readily available. This tube is probably the fastest and easiest to get your hands on.

TH555

I spoke with Continental Electronics about this tube and other tubes like it from THOMSON. They said they were very pleased with the tube behavior. They said it was very stable, rugged, and had no intrinsic parasites. I have no knowledge of its lifetime. It is used extensively in Europe in critical transmitters such a Voice of America, and Radio Free Europe along with many other standard stations. Thomson guarantees to have them available at all times for 1 to 2 day delivery in emergency situations. No other manufacturer would make this claim. There appears to be about 50 or more at use in the world. This tube uses technology developed by Thomson and licensed to Phillips, EIMAC, and Siemaens for their tubes. This technology consists of special molded graphite grids and special cooling techniques for the anode circuit. These techniques have lots of desirable characteristics for our operation and it appears for many others considering how many people are copying them.

4CM300,000

This tube is similar to the TH555, and therefore has all of the same sorts of electrical and cooling characteristics. It does not have widespread use yet, and is not readily available as a consequence.

7. MECHANICAL AND ELECTRICAL DESIGN CONSIDERATIONS

It would greatly speed up the process, use less shop time, and be more cost effective if we use a tube which has readily available sockets and will fit in our transmitter with a minimum of modifications. The Thomson tube fits all of these desires. Furthermore, the Thomson tube has almost the identical output capacitance and similar input capacitance, which means the transmitter would not need different of additional electrical components. Therefore the Thomson tube is the most desirable tube based on electrical and mechanical requirements.

8. TUBE SELECTION

The TH555 best meets all of the selection criteria. I believe the TH555 is the best tube for our initial try at retrofitting. I have no reason to believe that it will not work as well or better than any of the other tubes considered at this time.

9. RESULTS OF ANALYSIS OF TUBES CONSIDERED

This section contains an operating point for the RCA 4648, 4CW250,000 and the TH555. I don't have constant current curves for the 4CM300,000 yet. The operating points given are preliminary calculations by me for each tube. This information along with the tube electrode intercapacitances is necessary for determining the necessary amplifier changes.

RCA 4648	
Tube Operating Conditions	
DC Grid Bias	-119.0 KV
DC Screen Bias	1000.0 V
DC Plate Bias	20.0 KV
Peak Grid Drive	155.5 V
Peak Anode Swing	17.0 KV
Anode Bias Current	0.1 A
Tube Response	
DC Grid Current	1.08 A
DC Screen Current	0.94 A
DC Plate Current	17.89 A
DC Grid Dissipation	128.00 W
DC Screen Dissipation	942.00 W
DC Plate Dissipation	107.44 KW
Real Load	578Ω
Output Power	250.0 KW
Plate Efficiency	70.00%
Tube Characteristics	
Voltage Gain	109
Input Capacitance	1200 pF
Output Capacitance	85 pF
Feedback Capacitance	1 pF
Driver Coupling	0.13 V/V
Effective Driver Capacitance	156 pF

4CW250,000	
Tube Operating Conditions	
DC Grid Bias	-355.0 V
DC Screen Bias	1200.0 V
DC Plate Bias	20.0 KV
Peak Grid Drive	417.5 V
Peak Anode Swing	17.0 KV
Anode Bias Current	0.2 A
Tube Response	
DC Grid Current	0.18 A
DC Screen Current	0.98 A
DC Plate Current	17.19 A
DC Grid Dissipation	63.12 W
DC Screen Dissipation	1173.31 W
DC Plate Dissipation	93.67 KW
Real Load	578Ω
Output Power	250.0 KW
Plate Efficiency	73.00 %
Tube Characteristics	
Voltage Gain	41
Input Capacitance	765 pF
Output Capacitance	124 pF
Feedback Capacitance	6 pF
Driver Coupling	0.35 V/V
Effective Driver Capacitance	262 pF

TH555	
Tube Operating Conditions	
DC Grid Bias	-390.0 V
DC Screen Bias	1000.0 V
DC Plate Bias	20.0 KV
Peak Grid Drive	443.3 V
Peak Anode Swing	17.0 KV
Anode Bias Current	0.6 A
Tube Response	
DC Grid Current	0.24 A
DC Screen Current	0.16 A

DC Plate Current	16.91 A
DC Grid Dissipation	92.24 W
DC Screen Dissipation	164.22 W
DC Plate Dissipation	88.06 KW
Real Load	578Ω
Output Power	250.0 KW
Plate Efficiency	74.00 %
Tube Characteristics	
Voltage Gain	38
Input Capacitance	645 pF
Output Capacitance	65 pF
Feedback Capacitance	4 pF
Driver Coupling	0.37 V/V
Effective Driver Capacitance	377 pF

The responses listed are not optimized for each tube, but rather were set to be similar to the RCA 4648 operating point so that we could get a comparison. In all cases the gain is lower than the 4648 and the efficiency is higher. Also note that the TH555 uses less grid and screen currents than the others which is a plus.

10. LONG TERM PROJECT GOALS

In the short term our goal is to quickly get the one amplifier and associated equipment running with the selected tube in order to evaluate its performance. This involves small modifications to an amplifier, and modifications to our spare filament power supply. Should we be pleased with the results, there are longer term goals I would want to accomplish.

The long term goals are:

1. Try to get EIMAC involved as an alternate manufacturer.
2. Redesign the final cavity and driver coupling.

Item 1 would help a US manufacturer gain a larger market and would yield an alternate manufacturing for us in emergency situations.

Item 2 would allow me to further improve the magnetic shielding necessary, further decrease any harmonic distortion in the cavity, and finally set the losses in the cavity so that the tube anode always sees at least a known minimum load. I would also add some electronic circuit that would clamp the final anode voltage to the maximum allowed value. This would further reduce the wild anode swing that results during cavity turn on conditions and tend to reduce crowbar conditions.

11. PROPOSED PROJECT SEQUENCE

The following list of tasks assumes that each step is accomplished without any insurmountable problems.

1. Identify and order 1 tube and socket, etc.
2. Identify and order filament power supply parts
3. Do the necessary mechanical design
4. Detail the needed mechanical parts
5. Procure or build the necessary mechanical parts
6. Design and build clamping circuit
7. Install and test clamping circuit
8. Hi-Pot test the tube on arrival
9. Get all parts together and modify one transmitter and spare filament supply.
10. Test the driver with the final tube off
11. Test the final tube under DC bias conditions for parasites
12. Test the entire amplifier into a dummy load at various frequencies
13. Test the amplifier driving the cyclotron at various frequencies
14. Put the amplifier in to operation for long term evaluation
15. Begin procurement of more parts for the other amplifiers
16. Electrical design of new final resonator and driver coupling
17. Procure parts for other amplifiers
18. Mechanical design of new final resonators and grid coupling
19. Detail new parts
20. Build and procure new parts for one amplifier
21. Modify one amplifier with new parts and test
22. Procure parts for other amplifiers
23. Modify other amplifiers
24. Test other amplifiers and close project

12. TOTAL PROJECT ESTIMATE AND CONCLUSION

Assuming we use the THOMSON TH555, then the major component cost break down is as follows:

Cost Breakdown	
-	
Tubes and auxillary equipment	$150,224.00
Filament Supply Upgrade	$12,000.00
Mechanical Parts	$30,000.00
Electrical Parts	$6,000.00

The above estimate includes 1 spare tube and spare parts for it. To try one transmitter it would cost about $43,000.00.

If everything worked out and we were pleased with the amplifiers for an operational period of one year, then we could consider selling the RCA 4648 tetrodes. This may get us back up to half of this expenditure if we could find a buyer.

APPENDIX A
(4CW250,000)

APPENDIX B
(4CM300,000)

APPENDIX C
(TH 555)

APPENDIX D
(RCA 4648)