Stabilizing a Power Amplifier Feeding a High Q Resonant Load

A. K. Mitra, R. L. Poirier, J. J. Lu and R. Hohbach, TRIUMF, Vancouver, Canada

A grounded grid power amplifier for the booster cavity of the TRIUMF cyclotron, operating at 92 MHz is found to be very stable when operating into a 50 Ω load. However, when connected to a high Q cavity via a long transmission line it can become very unstable. Even though a phase shifter (trombone) enables one to adjust the resonant frequency of the cavity to be centered between two transmission line resonances, the amplifier tends to oscillate near the operating frequency due to insufficient isolation between input and output circuits. An expensive but easy solution to such a problem is to decouple the amplifier from the cavity and transmission line by employing a circulator. However, the solution that is presented in this paper uses external feedback from anode to cathode to neutralize the internal feedback inherently present in the tube. The neutralization is adjusted such that the isolation over the amplifier's bandwidth is increased by at least 15 dB. This along with input and output resistive damping has further stabilized the amplifier, which now operates routinely with no parasitic oscillation. Results of computer simulation of the amplifier response are reported.

I. INTRODUCTION

The 92 MHz, 150 kW power amplifier employs a grounded grid EIMAC 4CW150000E tetrode and is driven at the cathode by a 10 kW broad band FM transmitter. The output circuit consists of a λ/4 cavity (Q of 10000) inductively coupled via a 65 m long transmission line. A variable length section (trombone) is interposed between the output loop of the amplifier and the transmission line to position the operating resonant frequency between the transmission line resonances. The anode loop is set to transform 1 kΩ to the anode circuit such that output power of 50 kW can be obtained with rf voltage swing of 10 kV peak. The tube operates in class AB. Figure 1 shows the schematic of the system.

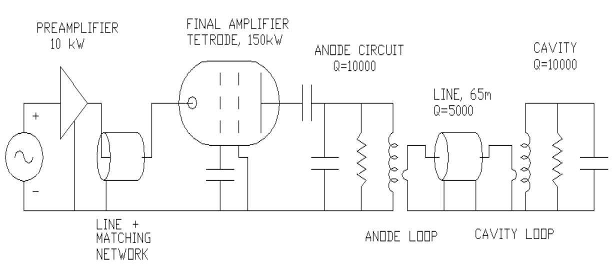

Figure 1: The booster rf system.

The amplifier produces an accelerating voltage at the cavity gap in excess of 120 kV. The amplifier is found to be very stable when tested into a 50 Ω load at full power. However, when the amplifier is connected to the booster cavity by a 65 m long rigid transmission line, it tends to oscillate with the slightest detuning in the input and output circuits. This led to the investigation of oscillations in the amplifier to find solutions to stabilize the unit for full power operation into the booster cavity[1].

II. THEORY

A. Stability margin.

A measure of stability margin can be expressed as a ratio of the magnitude of the reverse attenuation (S_{12}) to the magnitude of the forward amplification (S_{21}).

Forward amplification ($|S_{21}|$) $A_f = gm*R_a$

Reverse attenuation ($|S_{12}|$) $A_r = |X|/R_i$

where gm is the transconductance of the tube, R_i=1/gm, X is the reactance of the anode to grid capacitance C_{ag} and R_a is the effective anode impedance.

The stability margin $M = A_r/A_f = |X| / R_a$.

B. Transmission line modes.

The input impedance of a short circuited length of lossless transmission line exhibits minima at frequencies where the length of line is nλ/2. For l = 65m and n = 1 that frequency is 2.3 MHz and therefore the transmission line series resonances (minima) will be 2.3 MHz apart and the parallel resonances (maxima) will also be 2.3 MHz apart. The electrical length of the line in figure 1 was adjusted by a trombone to place the cavity resonance f_o at the transmission line minima making the difference from f_o to the first transmission line parallel resonance 1.15 MHz. A microcap simulation [2] of the input impedance at the input of the transmission line is shown in figure 2.

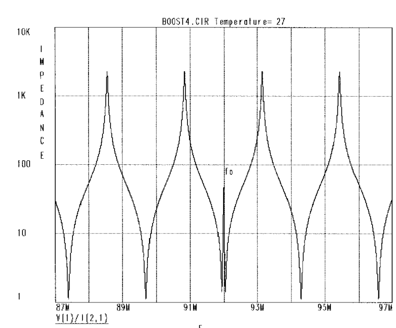

Figure 2: Simulated input impedance for a 20 λ length of transmission line connected to the booster cavity.

If we now look at the simulated impedance at the anode in figure 3, the two line resonances which were closest to f_o in figure 2 are shifted even closer to f_o, and are now characterized by the parameters of the anode circuit and load cavity rather than the transmission line. They are designated as side resonances (f_{s1} & f_{s2}) in figure 3, where the difference from f_o to the side resonance is only 0.65 MHz. Further simulations indicate that the resonances will get even closer if the coupling between the output loop and the anode circuit is decreased.

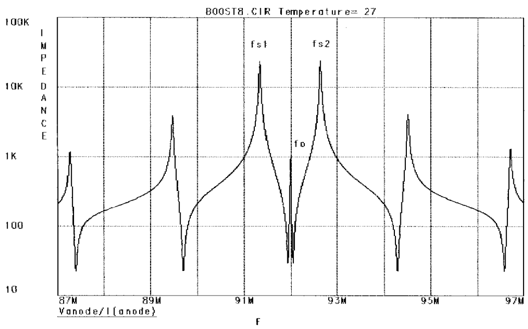

Figure 3: Simulated impedance at the anode coupled to a 20 λ long transmission line and booster cavity.

C. Neutralization

The purpose of neutralization is to make the input and output circuits independent of each other with respect to reactive currents. A completely neutralized amplifier requires that the inter electrode capacitances between the input and the output circuits be canceled. In the grounded grid amplifier, the control grid is at rf ground and serves as a shield to capacitive currents from the output to the input circuit. If the grid, screen and cathode lead inductances are insignificantly small, then neutralization can be achieved by employing a neutralizing capacitor approximately equal to the plate-grid capacitance of the tube, and a λ/2 transmission line which brings a voltage opposite in phase from the output circuit to the cathode circuit.

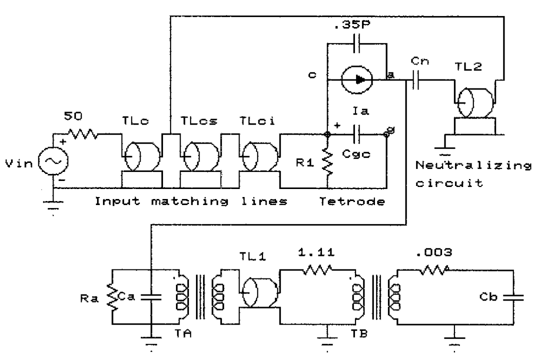

Figure 4: Micro-cap circuit model of the tetrode amplifier with neutralization.

The results of the analysis of the circuit modeled in figure 4 is shown in figure 5. It shows that the voltage gain at the side resonance is reduced by 11.0 dB and 15.7 dB whereas the gain at the operating frequency is reduced by 0.85 dB (although not evident from the graph) when a 0.7 pf neutralizing capacitor is used in conjunction with a λ/2 line. With neutralization the side resonances shift by 164 kHz and 118 kHz respectively.

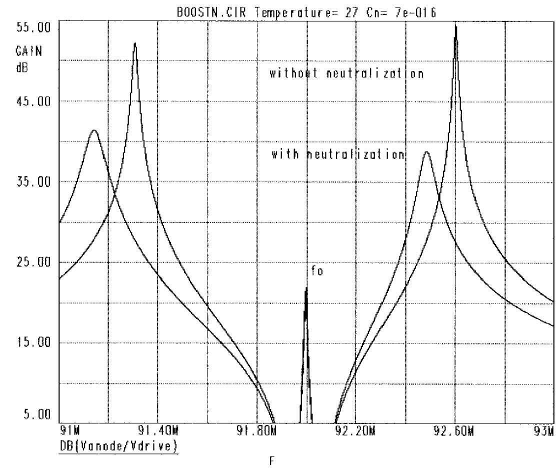

Figure 5: Voltage gain with and without neutralization.

III. MEASUREMENTS AND IMPROVEMENTS

Tests have been carried out at different power levels and operating conditions. The stability margin with and without neutralization was measured at signal level with a 50 Ω load connected to the amplifier (no transmission line) and all voltages applied to the tube. The same signal level measurements were carried out with the cold tube and the resonant load connected via a 65m of transmission line. The above tests helped to identify the parasitic modes , their impedances and proper value of the neutralizing capacitance to provide the largest stability margin. The signal level measurements also showed that a resistance in series with the neutralizing capacitor and the λ/2 line will increase the stability margin further (this has not been tried at full power).

The following improvements could be implemented without any major modifications to the power amplifier.

A. Additional Anode Loading

Fig 6 shows the effect of a 10% power damping (reduction of Q) in the anode circuit. This is achieved by capacitively coupling a 50 Ω load to the anode cavity. A 2.3 dB improvement in isolation is achieved at the fundamental frequency and 8.3 dB and 11.2 dB improvements at the more dangerous side resonances. The computed values are 1 dB for the fundamental and 12 dB for the side frequencies. Since this wastes 10% of the output power it puts an additional demand on the drive power to produce the same voltage at the cavity gap.

B. Neutralization

Neutralization was accomplished via a neutralization capacitor and a $\lambda/2$ line to bring a voltage opposite in phase from the output circuit to the input circuit. Although the voltage gain was not measured, figure 7 shows an improvement in isolation of 15 dB at f_o and 15 dB and 26 dB improvements for the respective side frequencies .

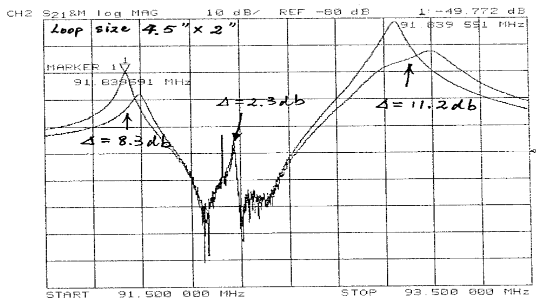

Figure 6: Resonance at the anode with and without loading of the anode circuit.

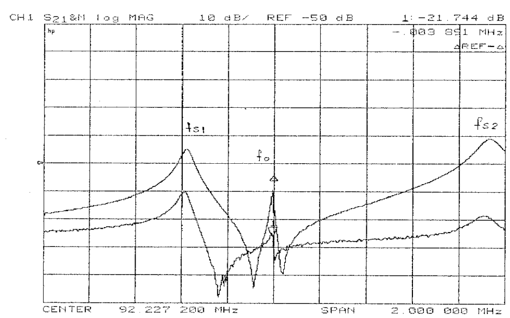

Figure 7: Resonance at the anode with and without neutralization.

C. Additional Input Loading

. Although there was no quantitative measurement made of the effect of input loading, an improvement in stability was observed by connecting a 50 Ω load (via a capacitor for dc blocking) to the input cathode circuit where the impedance is approximately 10 Ω. This should give an improvement in stability margin of 2 dB at the fundamental frequency but at the expense of a further increase drive requirement of 2 dB.

Summing up the results of the above three improvements, the stability margin should improve by at least 19.3 dB at f_o, 23.3 dB at the lower side frequency and 37.2 dB at the higher side frequency . The realistic test of course is the response at high power. One cannot make S_{21} measurements at high power without the risk of damaging the network analyzer. A spectrum analyzer was used to record a spectrum at the anode at an output power of 38 kW (figure 8). The upper plot shows more than 40 dB rejection of sideband signals. The lower plot shows the spectrum when the amplifier is intentionally detuned to produce all the sidebands and resonances. Before the improvements were implemented it would have been impossible to adjust any tuning without the amplifier becoming unstable.

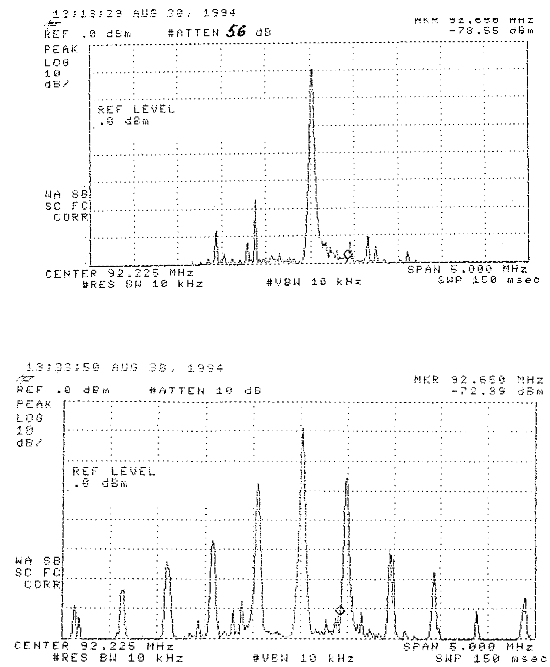

Figure 8: Spectrum of the output wave form at the anode.

IV. CONCLUSION

Although neutralization was not required when the amplifier was connected to a resistive load, it became necessary when connected to the resonant load via a long line in order to reduce the high impedance which were created at the side frequencies f_s near the operating frequency. These impedances were further reduced by anode damping and the overall stability further improved by damping the input circuit. To achieve this, only 10 % of the output rf power and 20 % of the input rf power is wasted in the terminating loads. This has enabled the amplifier to operate reliably on a regular basis without any parasitic oscillations.

V. REFERENCES

[1] R. Hohbach, "Investigation on Stabilizing the 92 MHz, 150 kW Booster Amplifier", TRIUMF Design Note TRI-DN- 95-03-07, Sept. 94.
[2] Micro-Cap IV, Electronic Circuit Analysis Program , Spectrum Software 1992.