# Triode Vacuum Tube Laboratory Development

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I present a detailed description of laboratory experiments and apparatus designed to aid students in research and understanding of Dual Triode Vacuum Tubes. Students will utilize the new laboratory setups in a new UIUC Physics Course 398 EMI, The Physics of Electronic Musical Instruments.

## WHY STUDY VACUUM TUBES

In the past, the vacuum tube was a common household item. Early televisions, radios, and calculators utilized vacuum tubes. However, the invention of the transistor practically eliminated the use of vacuum tubes in almost all applications. Despite the advantages of solid-state technology such as size, reliability and cost, the vacuum tube is still used today in high-end audio applications. Tube amplifiers produce a wonderfully warm tone that has not yet been successfully emulated through digital technology. This is one of the several reasons of why it is important to study vacuum tubes. It is obvious that a better understanding of vacuum tubes is required to achieve the same sound with digital signal processing. The accepted standard data and parameters for vacuum tubes were recorded almost a half-century ago, before the invention of a calculator. Therefore, using today's computers to study the characteristics of tubes will yield a better understanding, and possibly more accurate parameters then those that have been widely accepted for years. Through this approach students will also learn how to use computer software and hardware for data acquisition. Due to the dominance of transistors over tubes in society, vacuum tube technology is not always included in today's physicist/engineer's curriculum. Studying tube guitar amplifiers provides a more exciting way for students to learn tube theory than the standard textbook approach.

### P398EMI: The Physics of Electronic Musical Instruments

The vacuum tube is not the only interesting aspect of electric musical instruments. Physical phenomena involving electric guitar pickups, loudspeakers, transformers, effects boxes, guitar body resonances, and more are all worthy of academic study. This long list of interesting topics to investigate motivated Professor Steve Errede to create a new physics course on the physics of electronic musical instruments. The course will be taught for the first time this Fall 2000 semester at the University of Illinois at Urbana-Champaign. Due to the fact that this will be the first offering of the course, and that there are few courses on Electronic Musical Instruments being taught worldwide, much work and time is being spent deciding on issues such as the how to structure the course, and how much time is devoted to each topic. As a participant in NSF Research for Undergraduates program I worked on preparing laboratory experiments and apparatus for the course this fall. This included the following:

1. Designing and building hardware
2. Configuring standard laboratory equipment
3. Writing graphical software for data acquisition and analysis.
4. Writing student lab manuals with background information, detailed instructions and sample results.

## VACUUM TUBE OPERATION

The first vacuum tube device was the vacuum tube diode. It contained two active elements, the cathode and the anode/plate (Fig 1).

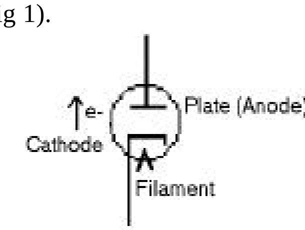


FIG 1. Vacuum Tube Diode

The vacuum tube operates through thermionic emission. The filament, also known as the heater, heats the cathode until the electrons acquire enough energy and boil off the surface of the cathode, forming a space charge. The cathode is typically made out of tungsten. When the plate is held at a high positive potential with respect to the cathode, current will flow from the cathode to the plate. Many consider that the discovery of this effect sparked the birth of modern electronics. The vacuum diode presented a method of rectification. The vacuum diode's ability to block negative voltages, and conduct only in the presence of positive voltage provided a way to rectify alternating voltages.

Although the vacuum diode was a major scientific breakthrough, a third active element was required to be able to amplify a signal. In the vacuum tube diode, there was no way of controlling the amount of current flow in the tube. It was either conducting, or not conducting. In 1907 Lee Deforest added the grid to the vacuum tube diode, creating a vacuum tube with three active elements, the triode (Fig 2).

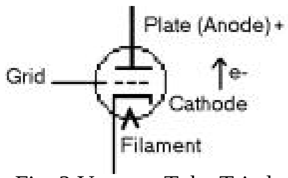

Fig. 2 Vacuum Tube Triode

It was found that if the grid was held negative with respect to the cathode, it would limit the electron flow from the cathode to the plate. The grid acts as a valve that reduces current as it becomes more negative. A sufficient negative grid voltage will put the triode in its cutoff condition, where no current will flow. Maximum current will flow when the grid is at 0 volts.

If a resistance is placed between the plate and the high voltage supply, a varying anode current will produce a proportional varying voltage drop across the resistance. Just a small change in grid voltage will produce a large variation at the plate. The triode effectively amplifies the grid voltage. The amount of gain (amplification) is then determined by the change in plate voltage for a given change in grid voltage.

The triode will amplify an AC signal on the grid without any change in frequency. However, phase shift will occur. In fact, knowing the phase shift between the input and output of a triode is important in understanding the triode's response to different input frequencies.

## VACUUM TUBE TRIODE EXPERIMENTS

Most tube guitar amplifiers rely on vacuum tube triodes for pre-amplification, and driving certain sections such as a spring reverb, tone controls, or tremolo. In some classic guitar amplifiers, one can find as many as five dual triode vacuum tubes in use. Understandably, the properties and response of the vacuum tube triode have a great effect on the tone of an amplifier. We wanted to provide the students with an opportunity to research different types, brands and eras of triodes. We wanted to create a convenient way to investigate triodes and display the data graphically.

Our goal was to have two different experiments for studying the triodes. Our first experiment, named TRIOPAR, (short for Triode Parameters) would be used for studying the tube parameters with static dc input. The students will be able to graph the results and compare to previously published values. The second experiment, named TRIOAMP (short for Triode Amplifier), would be used for studying the tube characteristics when acting as a voltage amplifier, with ac input. Before presenting the details of each setup, it is worthwhile to present the setup information that is common to both TRIOPAR and TRIOAMP experiments.

## GENERAL SETUP FOR TRIOPAR AND TRIOAMP

At the heart of both the TRIOPAR and TRIOAMP setups are modules that house the triode vacuum tube and circuitry (Fig 3). Each module is made out of an aluminum "bud"- type box.

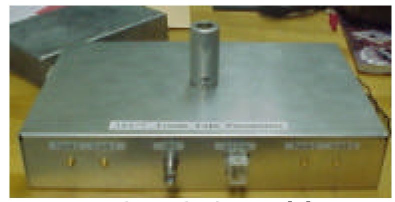
Fig. 3 TRIOPAR Module

It was debated whether a clear plastic box should be used instead of aluminum because of the benefit of being able to view the circuit "through a window". However, we decided to use the aluminum box because of its ability to shield the circuit and prevent noise. Since the modules are to be used in an undergraduate laboratory, safety was a main priority when designing the modules. For this reason, the high voltage plate supply uses SHV connectors. The filament/heater supply uses 3-pin Molex connectors. For all other connections, gold SMB connectors are used. The SMB connectors are much more resistant to corrosion and will provide the module a longer lab life then typical BNC or Phono connectors. Shielded SMB cable is used for all connections. The triode sits in a 9-pin tube socket mounted on the top of the module. The tube shield is used during all experiments to prevent noise.

A National Instruments PC+ Card is used for data acquisition and control. The PC+ Card contains 8 Analog-to-Digital Converters (ADC), and 2 Digital-to-Analog Converters (DAC). There also 24 standard TTL in and out lines available. We use the PC+ Card for controlling a Bertan 815 variable power supply. The Bertan has a maximum 500 V, 200 mA output. The voltage output is controlled by a 0-5 V signal from a DAC on the PC+ card.

Dell computers with Pentium processors are used for each setup. We use the C programming language in LabWindows/CVI 5.0 to control the PC+ card for data acquisition and analysis.

### *TrioPar*: Triode Parameters Experiment and Setup

Two main graphs have traditionally been included as part of a triode's data sheet published by the manufacture. The first is a graph of Plate Current vs. Grid Voltage. This graph is obtained when the plate voltage is set to a constant high voltage (50 -300 V), and the plate current is measured for different grid voltages ( –5 V - 0V). A family of these grid curves is obtained by repeating the test for different plate potentials (0- 300 V).

The second graph is of Plate Current vs. Plate Voltage. This graph is obtained when the grid voltage is set to a constant (-.5 - -3.0 V), and the plate current is measured for different plate voltages (0 – 300 V). A family of these plate curves is obtained by repeating the test for different grid potentials (-.5 - -3.0V).

The goal of the TRIOPAR Lab experiment is to obtain the Grid and Plate Family Graphs and to compare these to published values, and then possibly to utilize in new amplifier designs. From the two graphs, one can decide whether the tube is appropriate for the design, and decide what range of operation should be used.

Traditionally, the current flowing through the tube (plate current) is obtained by measuring the voltage drop across a resistor tied to the plate. However, the cathode current is equal to plate current. This voltage drop across a cathode resistance is equivalent to the plate voltage. Because it is safer to measure the voltage at the cathode, in this experiment, we place no resistance between the plate and the +HV supply. Instead, a 1 Ohm resistor is placed in series with the cathode (Fig. 5). Throughout the experiment an ADC reads the voltage across the 1 ohm resistor. Since V= IR, the voltage reading in mV corresponds to the cathode current in mA.

For the TRIOPAR setup, DAC 0 controls the Bertan which supplies the plate voltage. DAC 1 on the PC+ card controls both grid voltages, and ADC's 2 and 3 digitize the voltage across both cathode resistors for obtaining cathode 1 and 2 currents. A block diagram can be seen in figure 6.

## Grid Voltage vs. Cathode Current: Obtaining The Grid Family of Curves

We first set the plate voltage at 50 V. The grid voltage is set at –5 volts. We step the grid voltage from –5.0 V to –0.5 V in 0.01 V increments. At each point, the ADC's take 1000 samples of the voltage across the 1 Ohm cathode resistor. When this is completed, we increase the voltage by 50 V, and run the test again. This happens a total of six times (50, 100, 150, 200, 250, and 300 V plate potentials).

We included some protective code that prevents the max plate power dissipation from being exceeded. At each data point, we calculate the plate power dissipation ( Plate Voltage x Cathode Current). If the power dissipation rating is exceeded the software ends that plate voltage run. For this reason, each curve in the grid family will end at different grid voltages. This can be seen in sample graph of the Grid Voltage vs. Cathode Current for a Groove Tubes 12AT7 Dual Triode (Fig 7). The data was obtained using the new TRIOPAR experiment. The graph was created in Microsoft Excel, using the dat file generated by the TRIOPAR software.

## Plate Voltage vs. Cathode Current: Obtaining The Plate Family of Curves

We first set the grid voltage at –3.0 V. The plate voltage is set at 0 volts. We step the plate voltage from 0 to 300 V in 0.75 V increments. At each point, the ADC's take 1000 samples of the voltage across the 1 Ohm cathode resistor. When this is completed, we increase the grid voltage by 0.5 V, and run the test again. This happens a total of six times (-3.0, -2.5, -2.0, -1.5, -1.0, -0.5 V grid potentials).

In testing the TRIOPAR experiment, we ran plate family curves on a Groove Tubes 12AT7 dual triode (Fig. 8) and a vintage Telefunken 12AT7 from Germany (Fig. 9, 10).

## *TRIOAMP*: Triode Voltage Amplifier Experiment and Setup

In the TRIOPAR experiment, students will study the properties of dual triode tubes with DC input signals. In creating the TRIOAMP experiment, we provide an opportunity for students to study dual triode operation as a voltage amplifier with AC input. The TRIOAMP module houses a common triode voltage amplifier circuit (Fig 11).

In the TRIOPAR experiment, the cathode was tied directly to ground. That was acceptable with a DC negative voltage on the grid. However in the Triode Voltage Amplifier circuit there are both positive and negative input voltages on the grid. If the cathode was tied to ground in this circuit, only negative grid voltages would be amplified. To amplify the full cycle, the idle anode current must be reduced. Therefore a resistance is placed on the cathode. This reduces the idle current and creates a small voltage between the cathode and the grid. This grid bias allows the full input cycle to be amplified. It should be noted that phase inversion does occur. The load resistor is tied between the HV supply and the anode. An increase in plate current increases the voltage drop across the load resistor, forcing the anode voltage to decrease.

A block diagram of the TRIOAMP experiment can be seen in figure 12. The plate high voltage is supplied by the Bertan 815 power supply, which is controlled by the PC+ Card. The computer uses GPIB communication to control a Wavetek Function generator. The Wavetek places a 10 mV sine wave on the grid.

We read both plate voltages with two Stanford SR830 Lock-In Amplifiers. The lock-ins allow us to study the signal in the frequency domain, even with a lot of noise surrounding the signal. The lock-in requires a reference signal from the function generator synchronized with the triode grid input. The SR830 is a dual-phase lock in, so it has outputs proportional to the cosine and sine of the phase difference between the output signal and the input. These outputs are obtained by taking the low-pass filtered product of the input signal multiplied by internal reference oscillators that are both in-phase and out-of-phase. Output 1 (X) is $V_{sig}\cos\theta$, representing the in-phase component of the voltage. Output 2 (Y) is $V_{sig}\sin\theta$, representing the out-of-phase component of the voltage. When the output is completely in-phase with the input ($\theta = 0$), Output 1(X) will be the amplitude of the signal, however Output 2(Y) will be zero. We use 4 ADC's to digitize the X and Y outputs of both lock-ins.

In software we can compute the magnitude of the signal. The magnitude is equal to Sqrt(X^2 + Y^2). We can also compute the phase shift between the input and output by tan^-1(Y/X).

The TRIOAMP experiment starts with a 10 mV peak-to-peak 10 Hz sine wave on both grids of the dual triode. We then sweep the audio frequency range, from 10 Hz to 20 KHz with a step size of 20 Hz. We take 1000 samples per point of the 4 lock-in outputs. We also record the cathode voltage at every point during the run. When resonant frequencies of the triode are reached, there are usually large phase shifts. At these large jumps, the lock-ins need extra time to stabilize. Therefore, we included code in the software that delays stepping up to the next frequency allowing the lock-in to stabilize and provide an accurate measurement.

After building the experiment, we ran the TRIOAMP experiment for several tubes and found a mysterious 40% drop off of plate voltage vs. frequency (Fig 13). At first we couldn't figure out was causing the drop off. We investigated hypotheses that the responses of the function generator and lock-ins were not flat, but found that wasn't the problem. After much thought it was finally discovered what was causing the problem. We were using a 6-ft SMB cable to connect the lock-ins to the TRIOAMP module. What we originally didn't account for was the 30 pF capacitance per foot of the SMB cable and the high output impedance of the TRIOAMP circuit. The 200 pF SMB cable combined with the high output impedance had the effect of a low-pass filter between the module and the lock-in. The circuit was unable to drive the capacitance in the frequency range we were studying. To fix the problem we inserted a Texas Instruments TL072 Op-Amp in the module (Fig. 14).

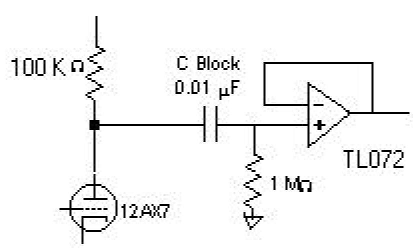


Fig 14. Addition of TL072 Op-Amp

The Op-Amp is non-inverting, and unity gain. The TL072 has an extremely high input impedance (10 ^10 ohms), but a fairly low output impedance (< 1Kohm). The addition of the TL072 to the circuit corrected the 40% drop off in plate voltage vs. frequency (Fig 13).

The output stays about 180 degrees out of phase for almost the whole frequency range (Fig 16). As frequency increases, the phase shift decreases a small amount from 180 (fig 15 and 16). The 180 degree phase shift between input and output is expected because the phase inversion does occur in the triode voltage amplifier circuit. The Cathode Voltage vs. Frequency graph is interesting in that shows the charge building up and discharging throughout the test (Fig 17).

Due to time constraints, we do not yet have a great amount of data or analysis from the new TRIOAMP experiment. Less time was spent on analysis for this project to allow time for working on other projects to have ready for the course this upcoming semester.

## CONCLUSION

We are quite pleased with the results of the experiments, and are looking forward to the new opportunities that TRIOAMP and TRIOPAR will give students for using and learning about vacuum tubes. We also think that having students build and set up additional vacuum tube triode modules would be an excellent learning opportunity.

## ACKNOWLEDGEMENTS


I'd like to thank Steve Errede for encouragement and the opportunity, Jack Boparai and Harold Scott for help in constructing the modules, the P398 REU team: Dustin Lindley and Nishant Parulekar, Julie Sonnenberg and Matthew Wenger for organizing the UIUC REU, and the NSF for funding.


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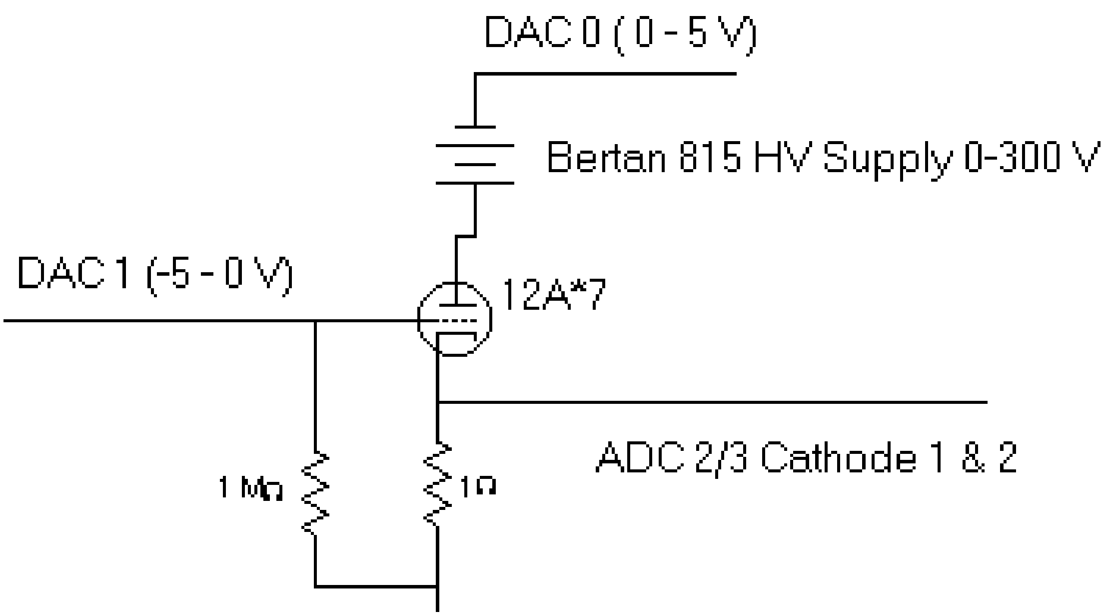
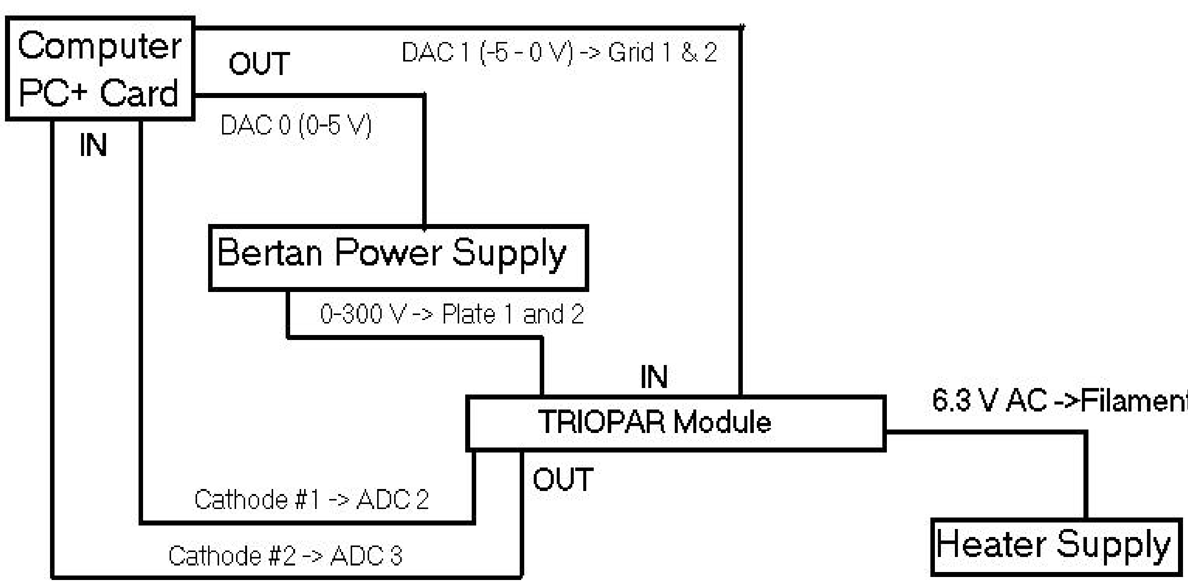
Fig 5: TRIOPAR Circuit

Fig. 6 TRIOPAR BLOCK DIAGRAM



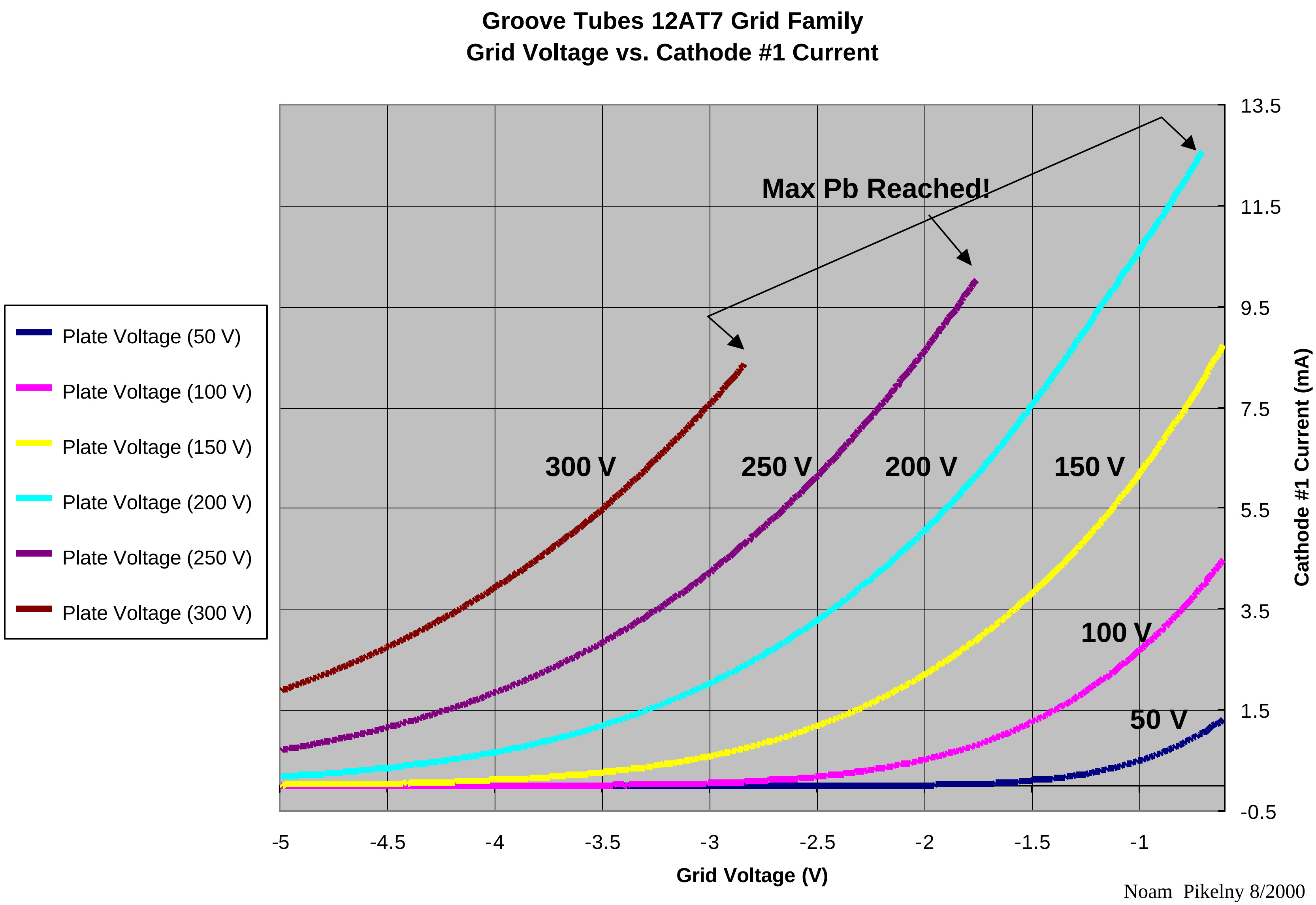



Fig. 7 GT12AT7 Grid Family

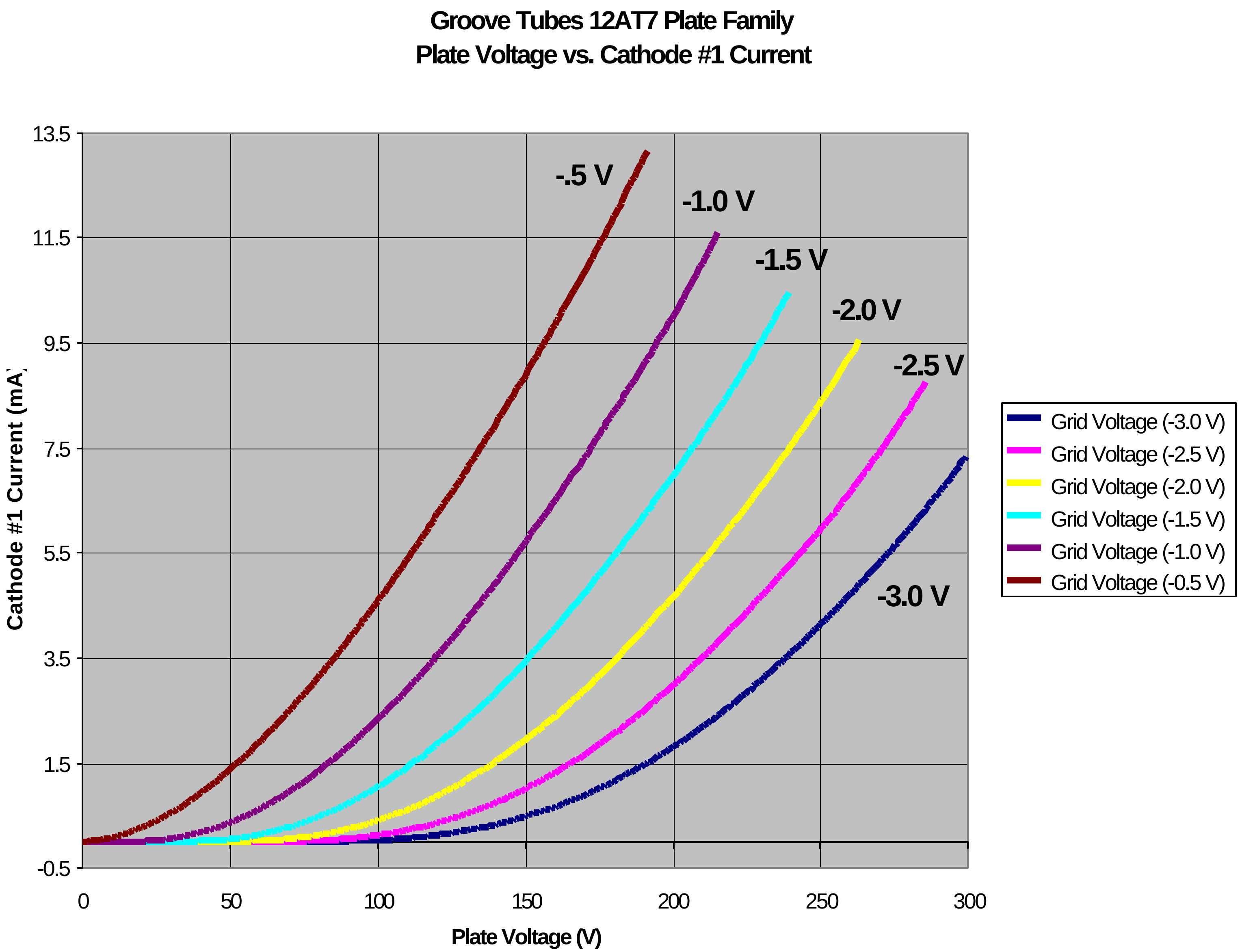



Fig. 8 GT12AT7 Plate Family

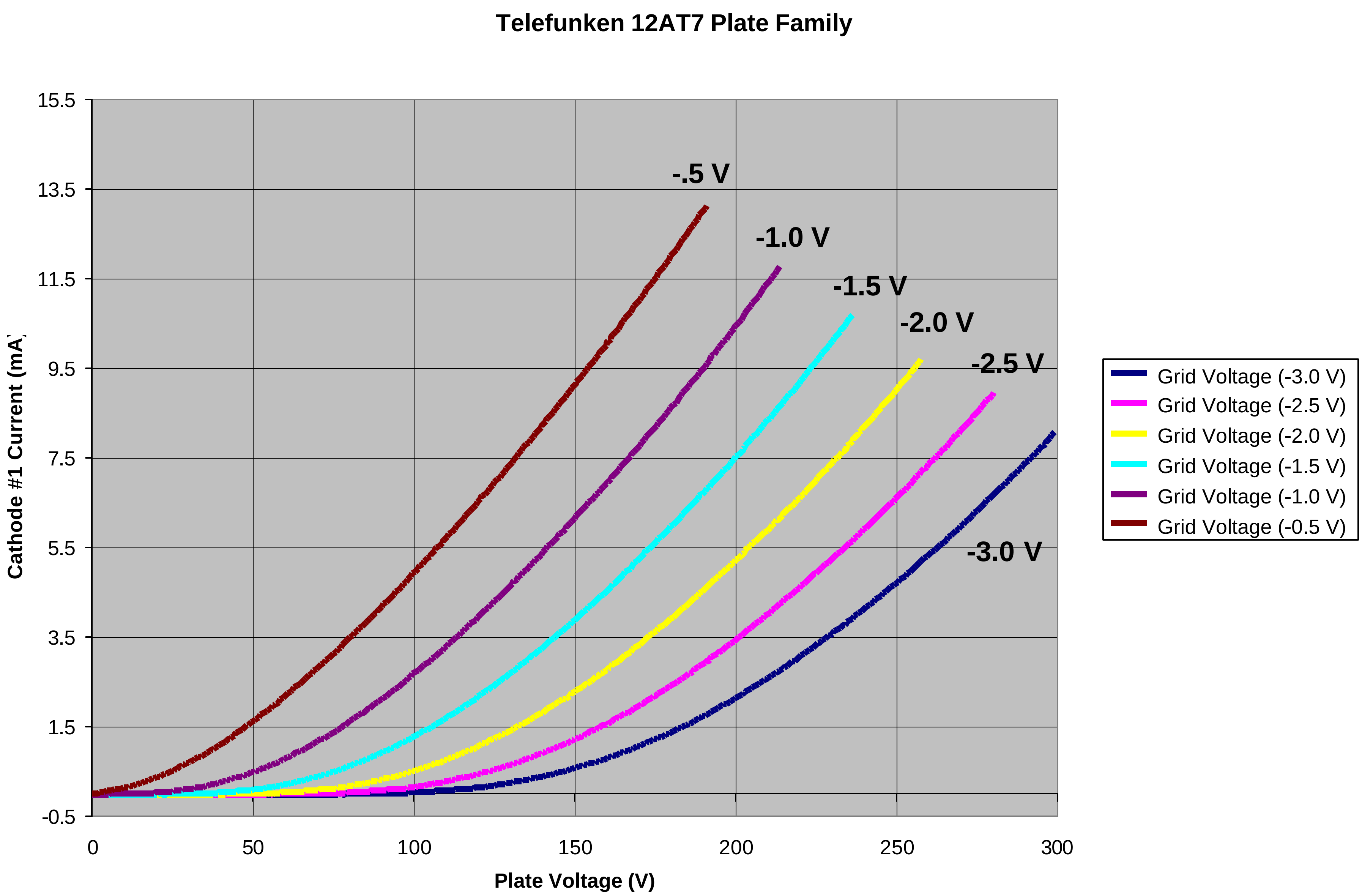



Fig. 9 Telefunken 12AT7 Plate Family

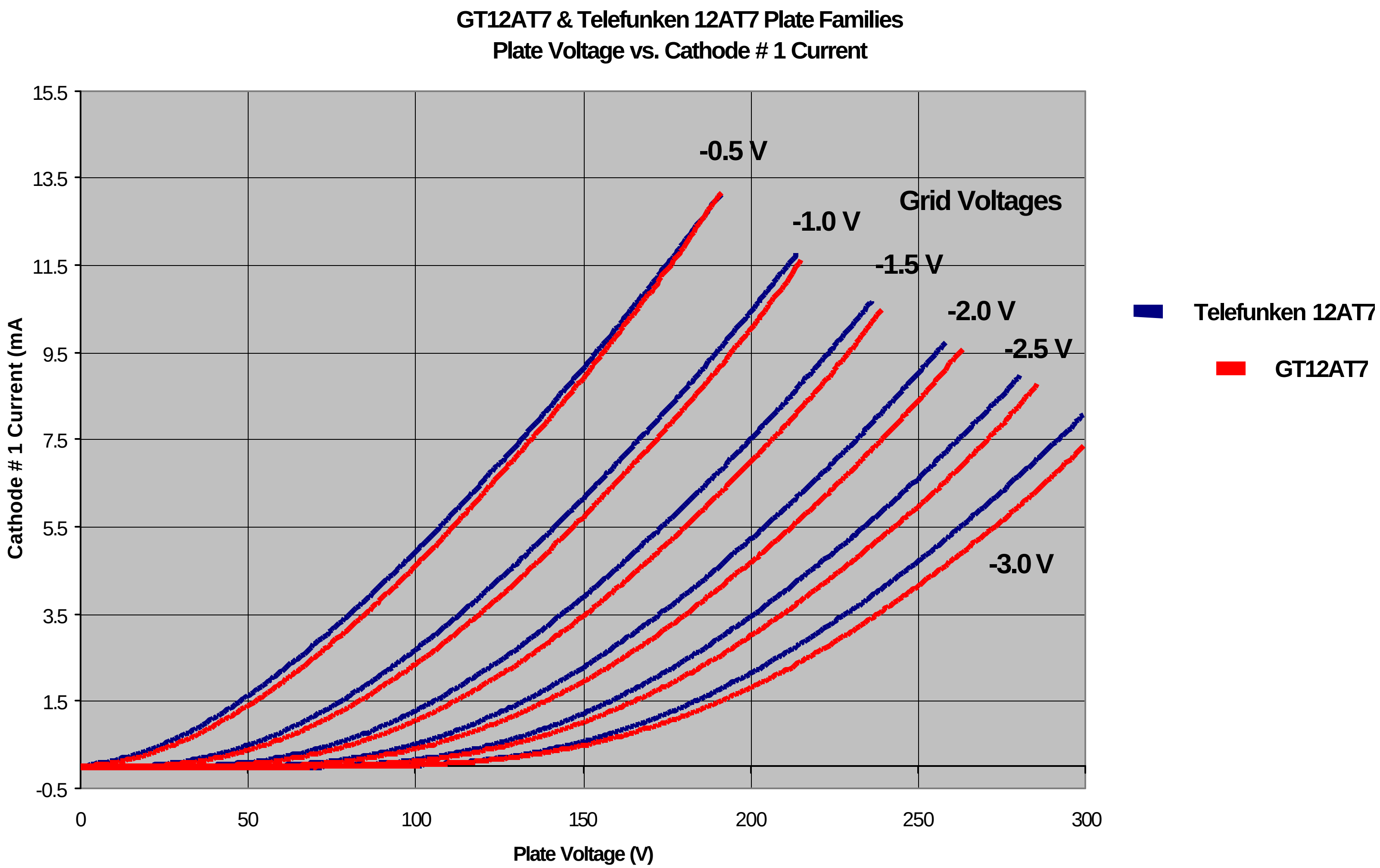



Fig. 10 GT and Telefunken 12AT7 Plate Families

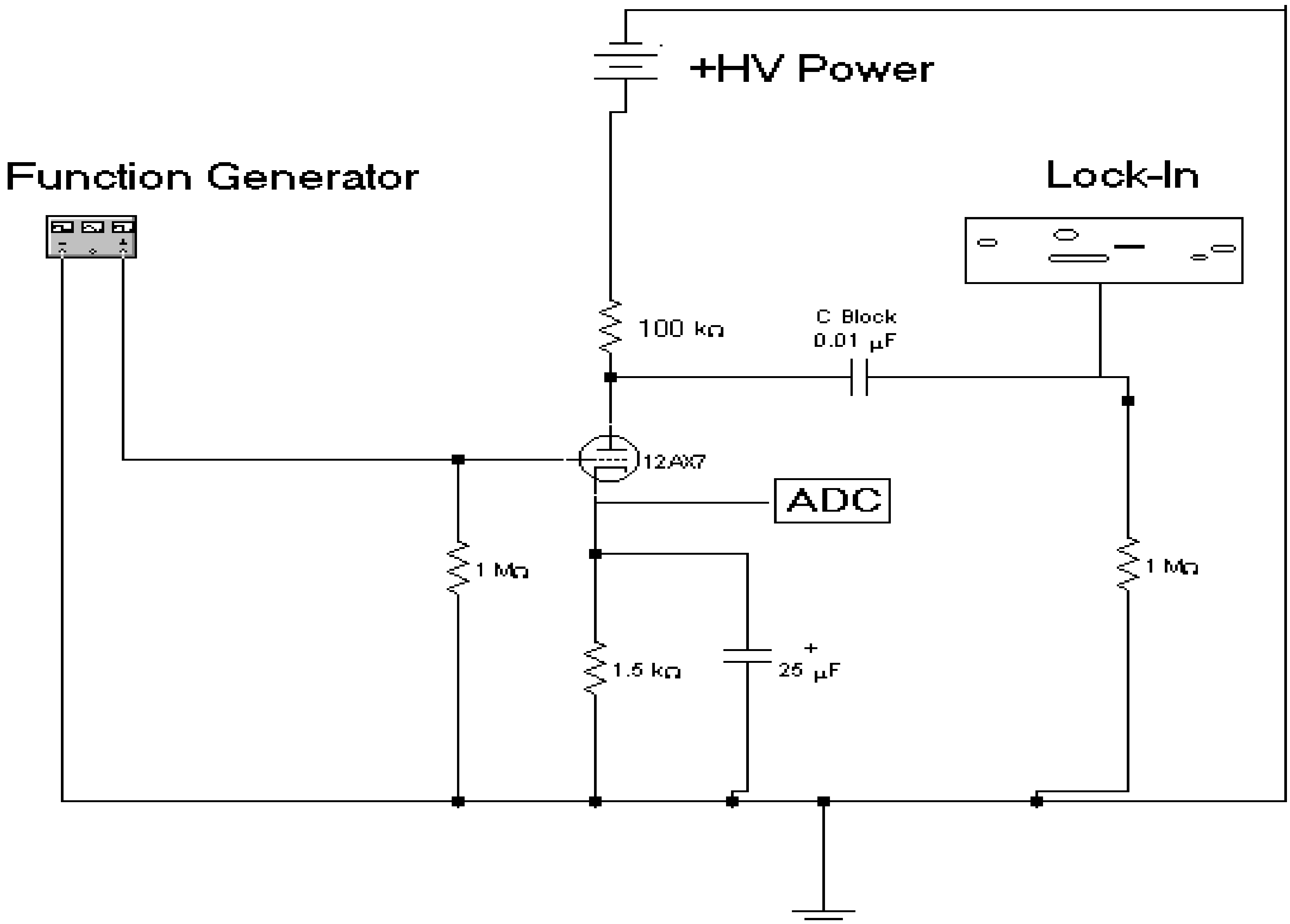



FIG. 11 TRIOAMP Circuit

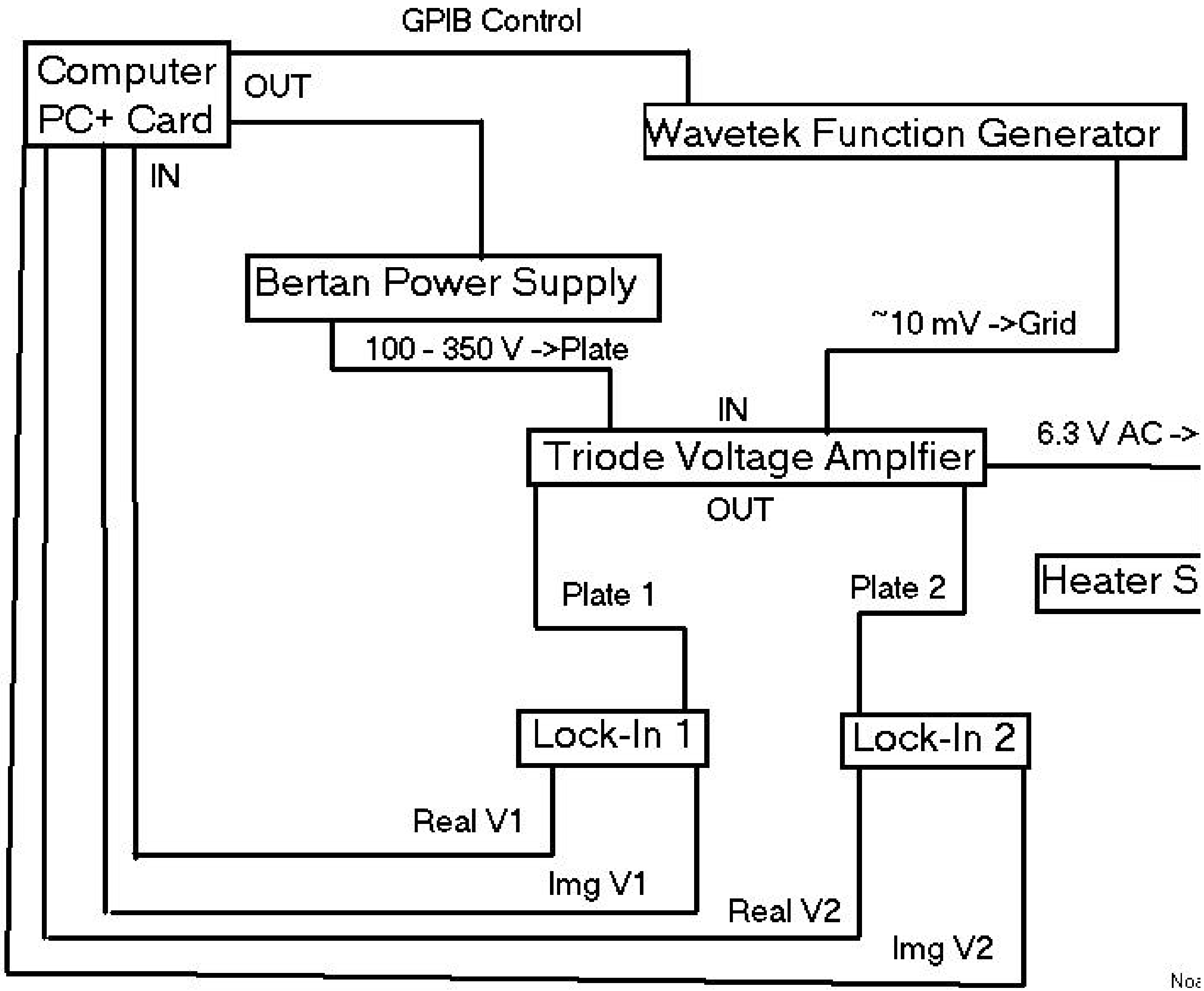



Fig. 12 TRIOAMP Block Diagram

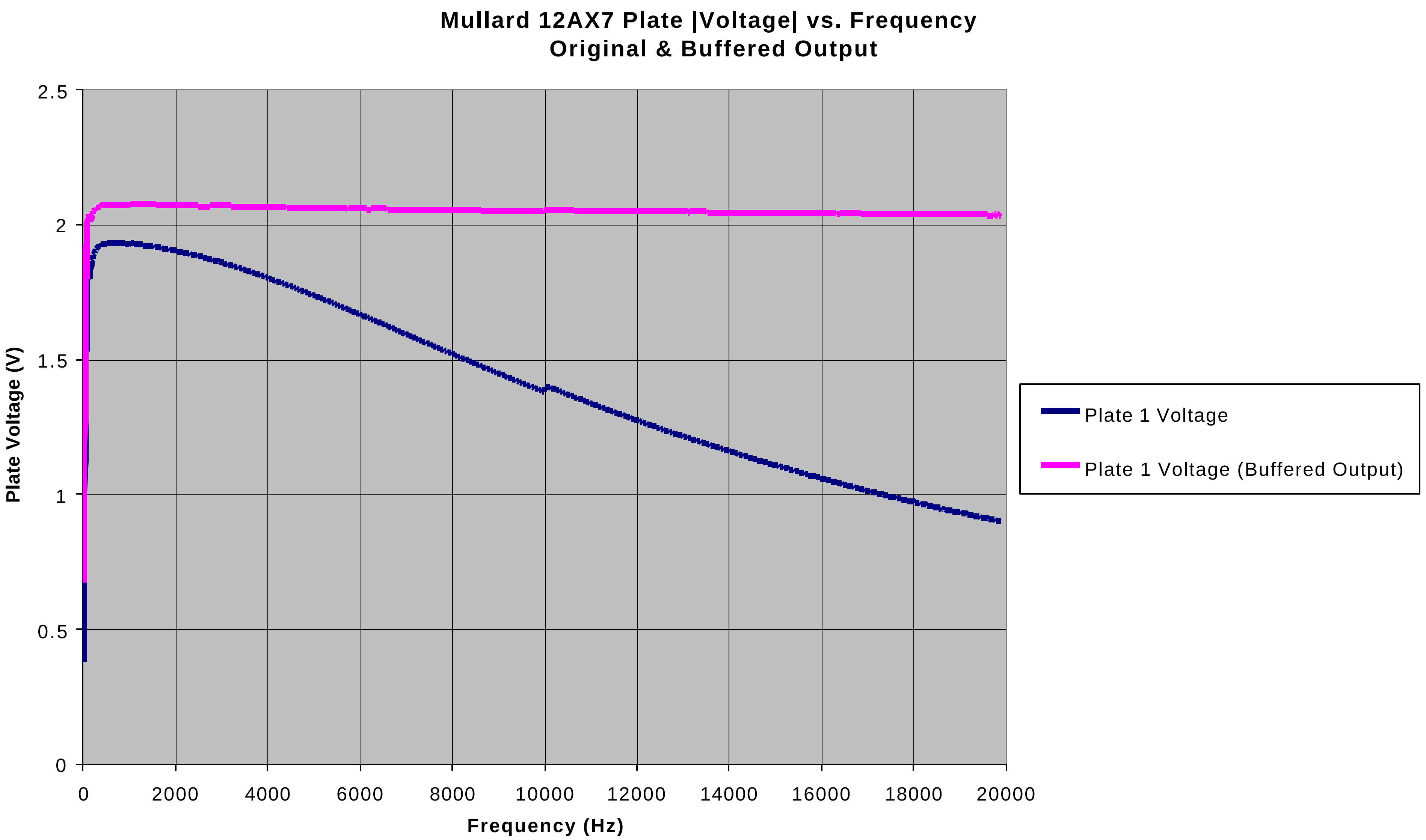



Fig. 13 Mullard 12AX7 Plate Voltage vs. Frequency

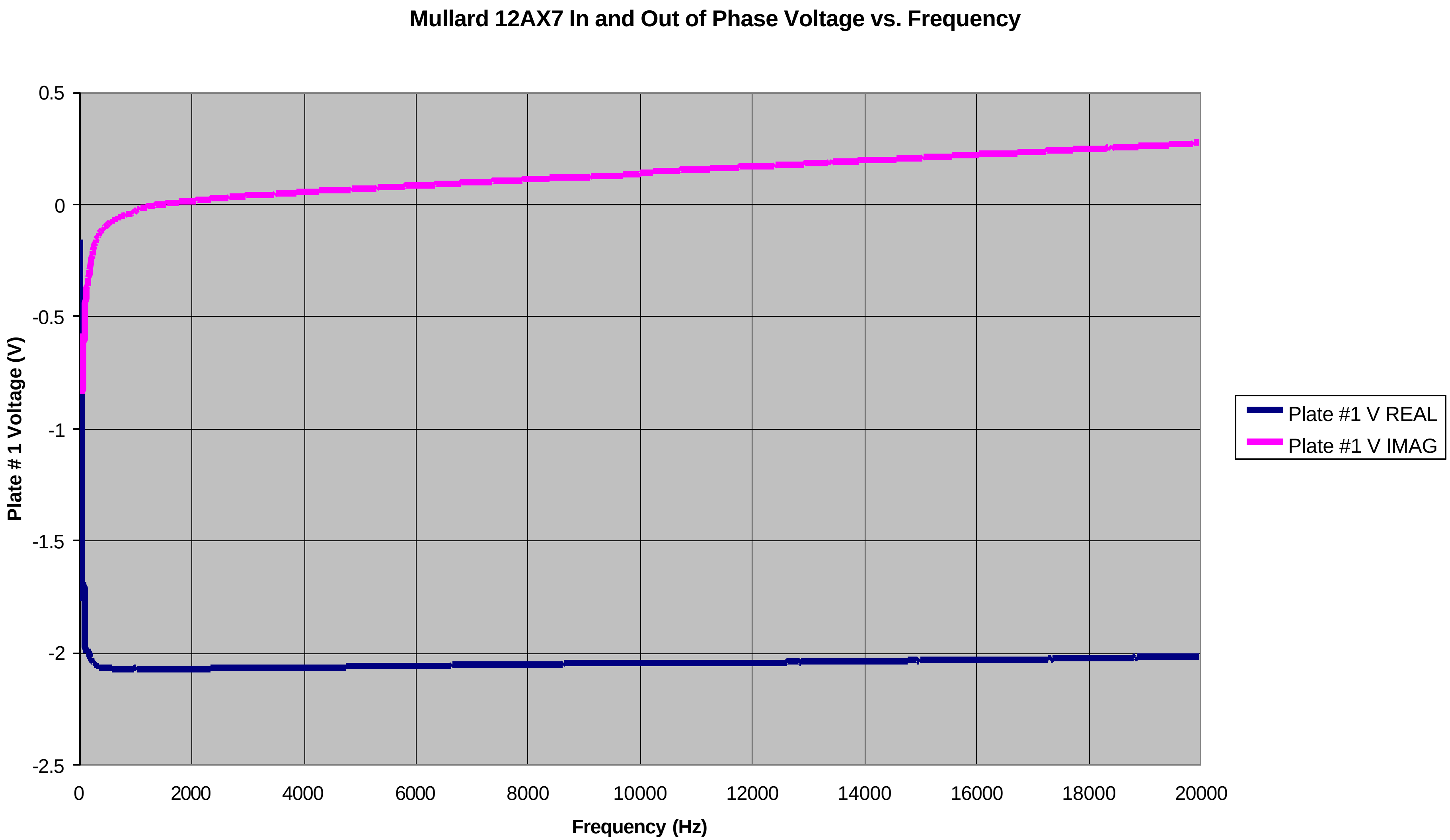



Fig. 15 Mullard 12AX7 In-Phase and Out-Of-Phase Voltage vs. Frequency

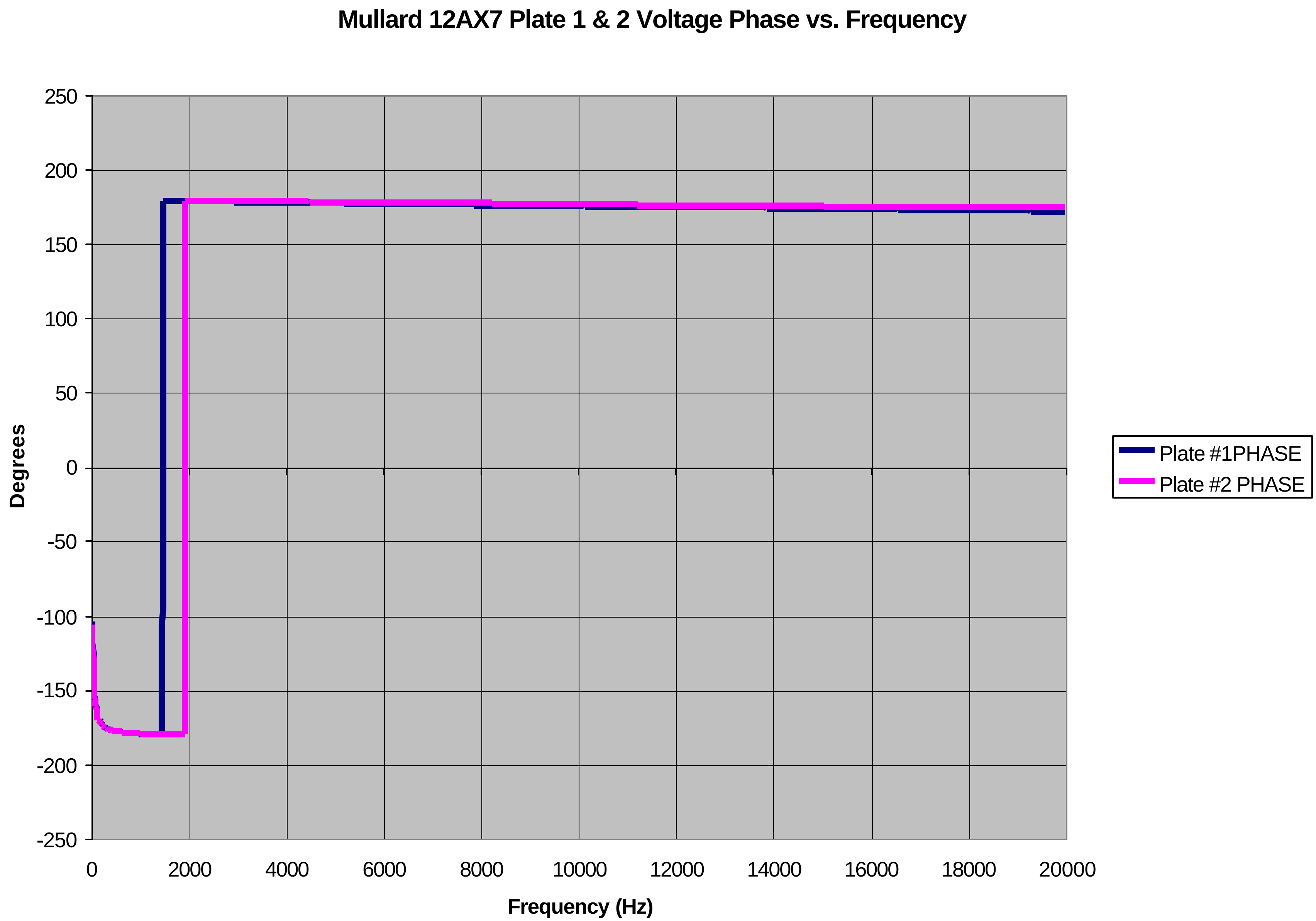



Fig. 16 Mullard 12AX7 Phase Shift vs. Frequency

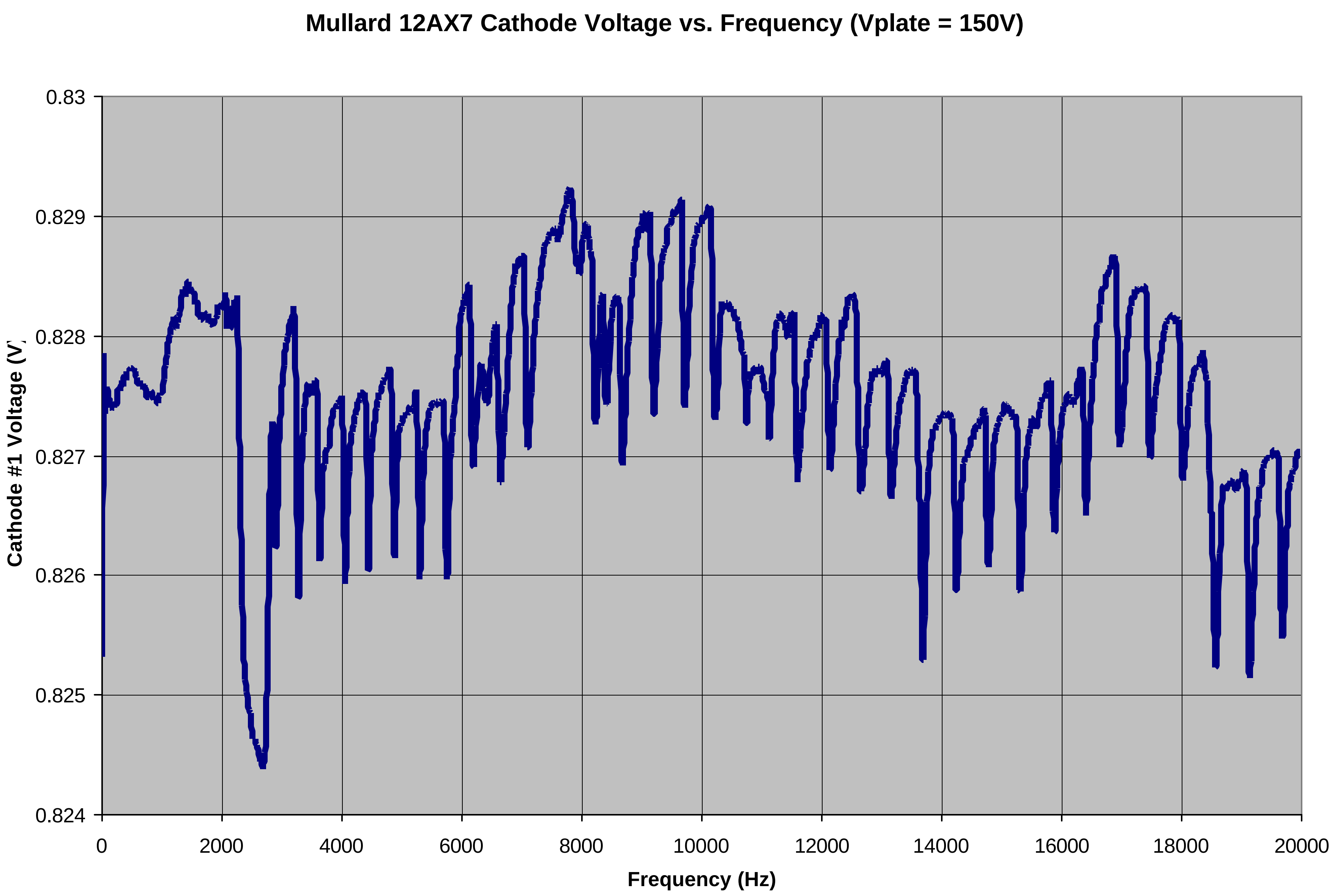



Fig. 17 Mullard 12AX7 Cathode Voltage vs. Frequency