

HIGH-VOLTAGE AMPLIFIER WITH DC ADAPTIVE CAPABILITY FOR PIEZOELECTRIC ACOUSTIC TRANSMITTER/ACTUATOR

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The piezoelectric element of an acoustic transducer requires a high voltage drive signal. This paper describes the development of a compact high-voltage amplifier (HVA) capable of driving piezoelectric elements and providing the additional capability of a DC response. This opens the possibility to control the DC displacement of an active array of transducers, which would not be possible using a step-up transformer due to the lack of a DC response. This HVA is particularly suited for low frequency operation, where the elimination of the transformer will provide the greatest benefit due to its large size, cost and weight at these frequencies. The HVA is very compact allowing large-scale integration, and therefore can be utilized for driving large arrays of transducers. Such an array could facilitate an active correction system driven by the DC signal from the amplifier. Considering the target application for large multi-element transducer arrays, design goals have been to minimize the size and cost. The features and benefits of the HVA will be presented.

INTRODUCTION

Acoustic transducers fabricated from piezoelectric materials (PZT) must be driven by high voltages. An array of transducers requires a multitude of high voltage driving sources. The method of generating the high voltage drive signal by utilizing a step up-transformer cannot accommodate a large number of transducers efficiently. Specifically, it cannot be used while maintaining an acceptable volume, weight or cost, especially for mobile applications. This prompted the necessity to develop a small footprint, high-voltage amplifier (HVA) that can generate the required high voltage drive signals and be produced at low cost. However, PZT devices represent a highly capacitive load when driven below resonance; as a result

large, potentially damaging currents may develop during dynamic operation or switching. Therefore, they have to be limited to a safe level. The developed HVA which meets these requirements will be described in this paper.

1. DESIGN GOALS

The proposed system is based on a low-power, high-voltage, compact amplifier that allows a very high level of integration and will be ideally suited for driving many transducers, especially large transducer arrays. By using off-the-shelf components, a low component cost was possible. In addition, the added capability of a DC response spanning ± 400 V is available, something which would not be possible with step-up transformer for high voltage generation. This additional capability provides the means for operating a transducer that may require a DC drive, such as positioning of a PZT actuator. The development of the HVA was performed with the following specific features:

- Number of channels up to 4000
- Low component cost per channel
- Small circuit footprint, to fit 96 HVA channels on one 6U Eurocard [1]
- 3 dB bandwidth > 1.8 kHz @ 15nF load (extending to DC)
- Output voltage span of ± 400 V
- Input signal voltage span of ± 5 V to be driven by 32-channel, 14 bit Digital to Analog Converters.
- Voltage gain of 80 V/V (38 dB)
- Output current limiting capability incorporated in hardware

The HVA design initially progressed from SPICE simulation experimentation, leading to experimental evaluation of the prototypes. Simulation results have proven to provide an accurate prediction of circuit performance and behavior thanks to the usage of the manufacturer supplied SPICE transistor models. The amplifier circuit is based on small, discrete, high-voltage MOSFET transistors. To achieve the output voltage range of +400 to -400 V the circuit requires the N and P-channel MOSFETs with hard to find $|V_{DS}|$ rating over 800 V. A number of candidate MOSFET transistors were eventually chosen, and were used in simulations.

Through multiple iterations involving simulation and hardware tests, an optimized HVA circuit has evolved. Hardware prototyping has provided the opportunity to investigate those characteristics of the circuit which were not possible to predict using simulation since the real components parameters spread and the tolerances of transistors were not available. Specifically the variability of bandwidth, gain as well as output offsets was determined using several prototypes. The construction of a 32-channel prototype shown in Fig.1 allowed the collection of this data from a sample population of 16 HVAs as well as to verify design choices of high voltage routing on a circuit board.



Fig.1. 32-Ch amplifier test board.

The board is supplied from a single 24 V DC power source and incorporates all circuits to produce the high voltage supplies and bias voltages. Total power consumption of the 32-channel board is 22 W when each channel is drawing 550 μ A from the \pm 400 V rails. The total power consumption includes losses from DC/DC voltage conversion and support circuitry. The board uses only surface-mount (SMT) components in order to maximize layout density. The HVA inputs are driven via a computer interface from an off-board Digital to Analog Converters (DACs) through a ribbon cable.

The simplified schematic is shown in Fig.2 without showing proprietary circuits for current limiting and short circuit protection.

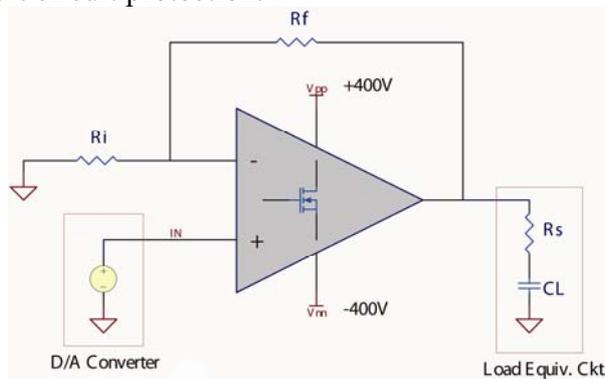


Fig.2. Simplified schematic of HVA.

2. SUMMARY OF TEST RESULTS

The gain of the HVA is established such that the full output span (\pm 400 V) can be reached with a standard \pm 5 V input signal delivered from a digital-to-analog (DAC) converter; the gain is set by two external resistors R_i and R_f at 80 V/V or 38 dB. Components with high tolerances were used to ensure the consistency of gain in the production run. The DC gain was measured on the 16 hardware prototypes. The statistical results shown in Tab.1 demonstrate a small variance in gain.

Tab.1. DC gain statistical results of measurement

DC Gain	Mean (μ)	80.29	-
	Std. Dev. (σ)	0.220	-
	σ / μ	0.27	%

Bandwidth of the HVA is dependent on the load capacitance. A bandwidth as high as 1.8 kHz can be reached at the nominal gain of 38 dB (80) and capacitive load of 15 nF. An important result is the repeatability of the frequency response (the cut-off frequency, f_C). This information was not attainable through the use of simulation since the available active device models did not contain tolerance data. The statistical experimental results shown in Tab.2 demonstrate a small variation of the bandwidth. The corresponding plot of frequency response is shown in Fig.3 demonstrates the high accuracy of the simulation relative to the actual measured result.

Tab.2. Bandwidth statistical results of measurement, $C_L = 15$ nF

Bandwidth	Mean (μ)	1779.38	Hz
	Std. Dev. (σ)	28.16	Hz
	σ / μ	1.58	%

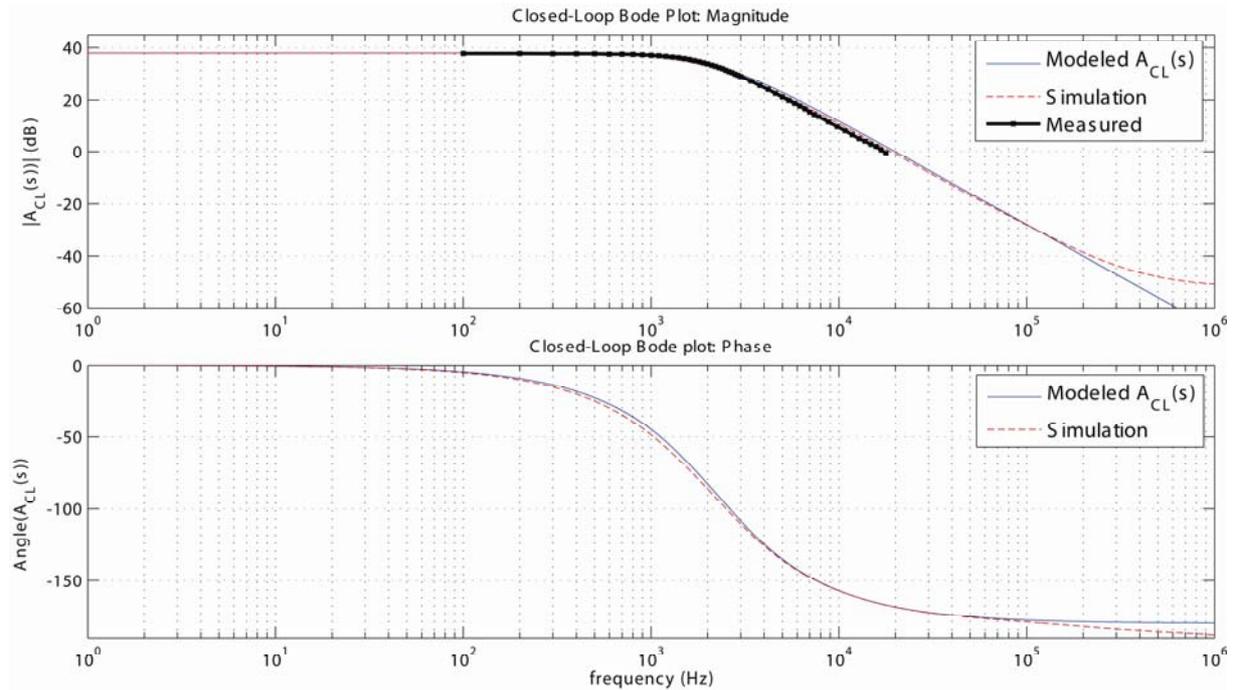


Fig.3. Bode plot of the closed-loop response for $A_0 = 38$ dB, $C_L = 15$ nF.

3. CURRENT LIMITING

The equivalent circuit for piezoelectric load consists of a series LCR resonant branch to represent the mechanical vibrating system in parallel with the static capacitance of the transducer as shown in Fig.4a. A small resistance R_s represents the cabling and contact resistance. This electrical model is valid for operation at frequencies near the resonant

frequency, typically occurring at 100 kHz or greater dependent upon the transducer. We expect to operate at frequencies much below resonance and therefore the electrical equivalent model is simplified as shown in Fig.4b since the inertia (L) and losses (R) are negligible at these low frequencies.

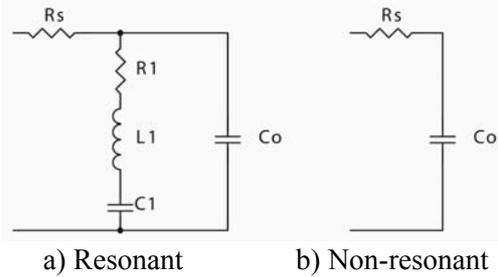


Fig.4. PZT transducer equivalent electrical model.

This represents a dominantly capacitive load that can result in large charge/discharge currents, which must be limited to prevent amplifier damage and excessive strain on the PZT material. This has been accomplished by proprietary circuit incorporated in the hardware. For testing of the design, the loads were represented by a bank of the equivalent non-resonant loads of Fig. 4b that were driven by a bank of 16 amplifiers through a 15m cable as shown in Fig.5.

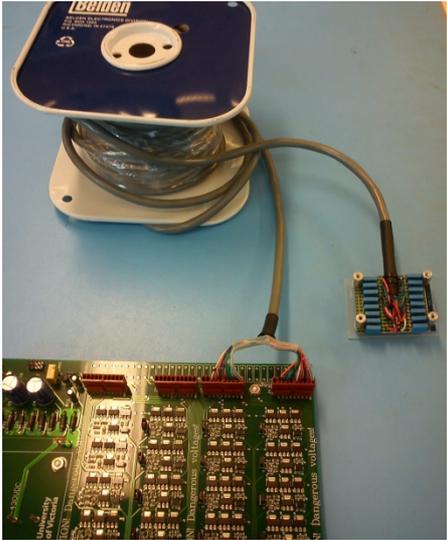


Fig.5. Amplifier board connected to a load bank.

The maximum output current is controlled by a bias voltage common to all HVAs. Considering the high voltages across the output transistor (up to 800 V), the maximum output current is limited by the maximum power dissipation 2.1 W in the output stage. The maximum load current is therefore $2.1 \text{ W} / 800 \text{ V}$ or 2.625 mA. Since HVA is a class-A linear amplifier, quiescent power dissipation will increase with this current limit correspondingly. Quiescent power dissipation is equal to 800 mW for every milliamp of output current capacity (at $\pm 400 \text{ V}$ rail potential). Typical operating range will be between 1 to 2 mA leading to 0.8 to 1.6 W of transistor power dissipation.

4. ACOUSTIC GENERATION

As a consequence of the current protection limits I_{max} , consideration must be taken when driving an acoustic transmitter since reaching this limit during operation will cause non-linear distortion. The available operating regime that avoids such distortion depends on the following parameters; static load capacitance (C_0), operating frequency and peak output amplitude (A). The highest frequency of operation without distortion due to current limiting is given by Eq. 1, and the corresponding plot of maximum output amplitude versus frequency is shown in Fig.6. This provides a region of operation based on the parameters frequency, I_{max} , C_0 , and A .

$$f_{max} \leq \frac{I_{max}}{2\pi C_0 A} \quad (1)$$

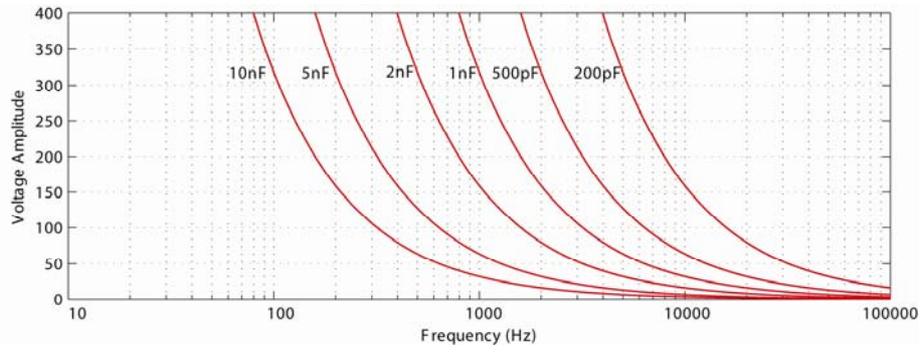


Fig.6. Maximum output amplitude versus frequency at ± 2 mA max, for various C_0 .

5. APPLICATION: PZT ACTUATOR

Considering the DC capability of the ± 400 V output span and current limiting, the HVA can also be used for driving piezoelectric actuators such as multi-layer stack actuators. The DC response of the HVA is shown in Fig.7. Multi-layer actuators require hundreds of volts drive to achieve their maximum stroke, given by Eq. 2, which is typically between 5 and 200 μm dependent on the actuator construction. For this application, the limited output current of the HVA is less restrictive since this will only limit the actuator expansion rate, as given in Eq. 3.

$$\Delta L = d_{33} N V \quad (\text{m}) \quad [2] \quad (2)$$

$$\frac{dL}{dt_{MAX}} = d_{33} N \frac{dV}{dt} = \frac{d_{33} N I_{max}}{C_0} \quad (\text{m/s}) \quad (3)$$

where d_{33} is the piezo expansion coefficient (m/V)
 N is the number of layers comprising the actuator
 $dV/dt = I_{max} / C_0$ in a capacitive load (V/s)

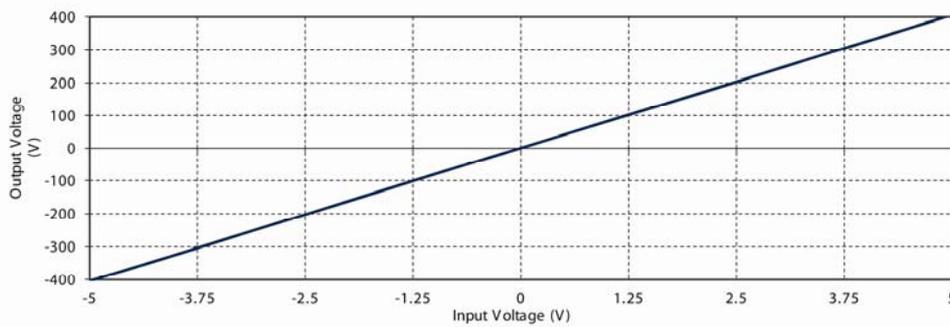


Fig. 7. DC response of HVA.

The static load capacitance (C_0) of these actuators can vary greatly depending on the geometry of its construction and can be significantly larger than that of an acoustic transducer. The bandwidth of the HVA is dependent on the load capacitance; the bandwidth that can be achieved for various actuator capacitances is shown in Fig. 8.

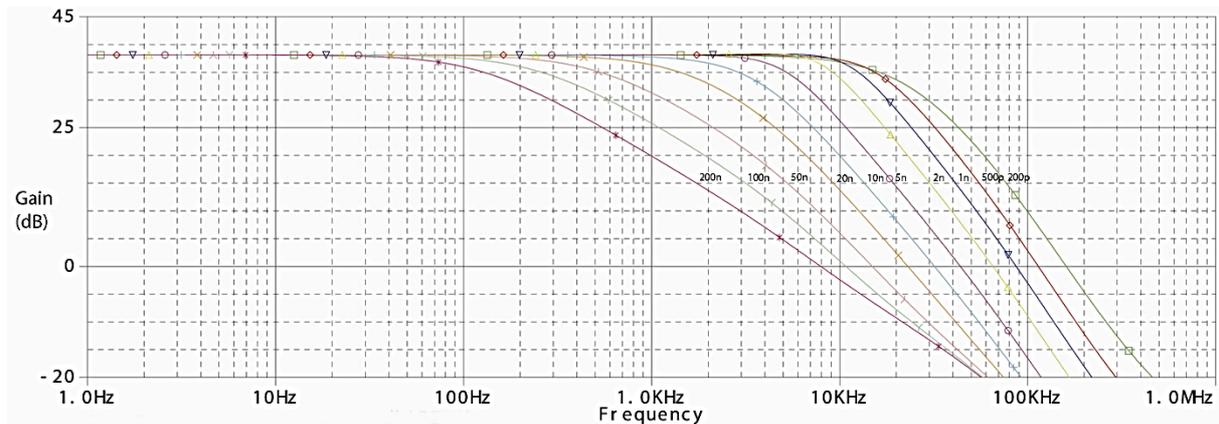


Fig. 8. Frequency response of HVA for various capacitive loads.

This will determine the maximum available bandwidth for a positioning controller which utilizes the HVA to drive the linear actuators. Commercially available drive amplifiers are not suitable for large arrays such as those constituting an array for which each element can be individually positioned by an actuator. These applications require compact drive electronics for the very reason of the large size of the array. Such large adaptive positioning arrays containing hundreds or now even thousands of PZT positioning elements are commonly used in astronomy; these are called the deformable mirror (DM) [3]. The DM is used in telescopes and employs adaptive control to cancel the distortions of light caused by the time varying refractive index of the earth's atmosphere. A similar acoustic scenario could exist whereby positions of individual transducer elements of an acoustic array are actively controlled. In both situations, there is the requirement for compact, low-cost and low-power drive electronics which are capable of a DC response. The functionality of an adaptive acoustic array could provide a time-varying characteristic of the transmission or reception function of the array such as beam steering, focusing, tracing, phase correction etc. If used with a reference source, either reflecting or independent, adaptive phase correction across the array could be performed after reconstructing the constant phase wavefront of the received reference wave. This could be used as a means of medium sensing or for the purpose of

eliminating medium effects on the received signal. Cancellation of vibration noise from the vessel is another possible application.

Considering the multi-use functionality of the HVA, it would therefore be quite possible to achieve these goals while utilizing this one common electronics system for the paired acoustic transducer and positioning actuator thus requiring two channels per paired element. This would provide a cost and complexity benefit compared to two separate electronics systems. Alternatively, one can envision the utilization of just one PZT element that will produce stroke (linear actuation) as well as generate acoustic pressure waves, as shown in Fig.9.

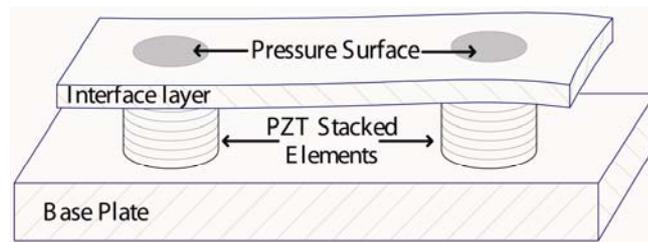


Fig.9. Two element section of an adaptive array.

In either case, the electronics will consist of a crate containing up to 12 amplifier cards per crate, shown in Fig.10. Each amplifier card will contain 96 copies of the amplifier and all necessary support circuitry and power supplies. This will facilitate expansion of the electronics system to an arbitrary size.

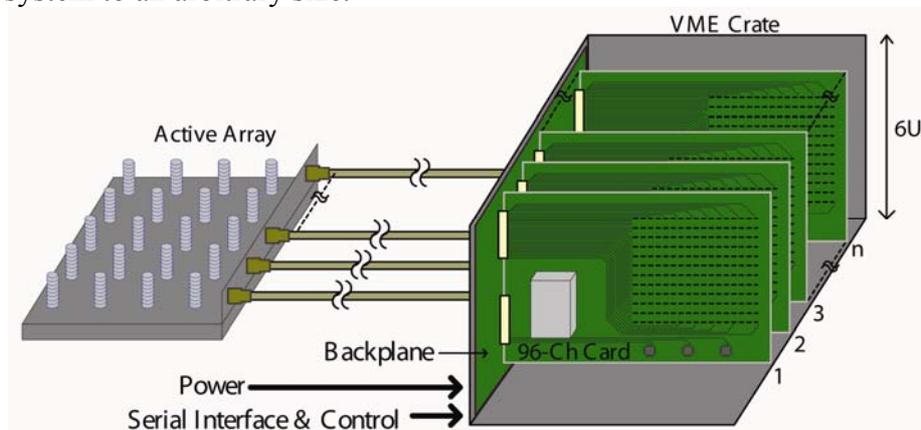


Fig.10. Acoustic / electronic system diagram.

6. RELIABILITY

Considering the large scale of the electronics system built and the multitude of components, the total component failure rate must ensure an acceptable mean time between failures (MTBF). The reliability analysis of all active components of the HVA was performed and the results are summarized in Table 3. The total reliability of the amplifier was found to be 14.431 FIT at 60% confidence level (CL), where one FIT is equivalent to one failure per billion hours of operation.

Tab.3. Reliability of the amplifier at 55°C.

Component (count)	FIT 60% CL	FIT 90% CL
<i>A (n = 3)</i>	0.107	0.269
<i>B (n = 1)</i>	12.9	32.405
<i>C (n = 1)</i>	1.22	3.065
<i>D (n = 1)</i>	1.2	2.308
TOTAL = $\sum \text{FIT} \cdot n$	14.431	35.899

A board containing 96 amplifiers will have a failure rate of 14.431×96 channels = 1385 FIT at 60% CL. This represents a MTBF = 82.4 years. This reliability data only accounts for the circuitry comprising the amplifiers and does not (as yet) include contributions of the support circuitry, however that is expected to have a small contribution to the overall reliability. An electronics system containing N boards will have a MTBF of 82.4/N years; this is considered a satisfactory level of reliability for most practical cases where N is in range of 10-30.

7. FUTURE PLANS

Currently the 32-channel HVA prototype board has been constructed and fully tested. This prototype validated fully the custom HVA designed for driving piezoelectric loads of large arrays. In particular the following characteristics of the HVA have been confirmed:

- Output voltage span of +/- 400 V
- Input sensitivity of +/- 5V (DC gain 80 or 38dB)
- 3dB bandwidth of DC to 1.8 kHz when driving 15 nF capacitive loads
- Current hard-limiting protection
- HVA immunity to output short circuits between channels and to ground
- Small printed circuit footprint to construct a 96-channel module on a 6U Eurocard
- Circuit stability in densely packed configuration and absence of cross-talk
- Absence of dielectric breakdown
- Good reliability
- Component cost per channel <\$10 including the cost of D/A components (the cost of board fabrication and stuffing not factored in yet)

The next step is to build the board containing 96-channels. In reaching this milestone, experimenting with the 32-channel board was an important step towards this since any oversights in the high voltage multi-channel layout of this board will reveal themselves during testing and can be corrected in the 96-channel design. Work is currently underway on the development of a 96 channel amplifier board; a preliminary layout is shown in Fig.11. This board will be the building block of acoustic/positioning systems requiring many hundreds of channels.

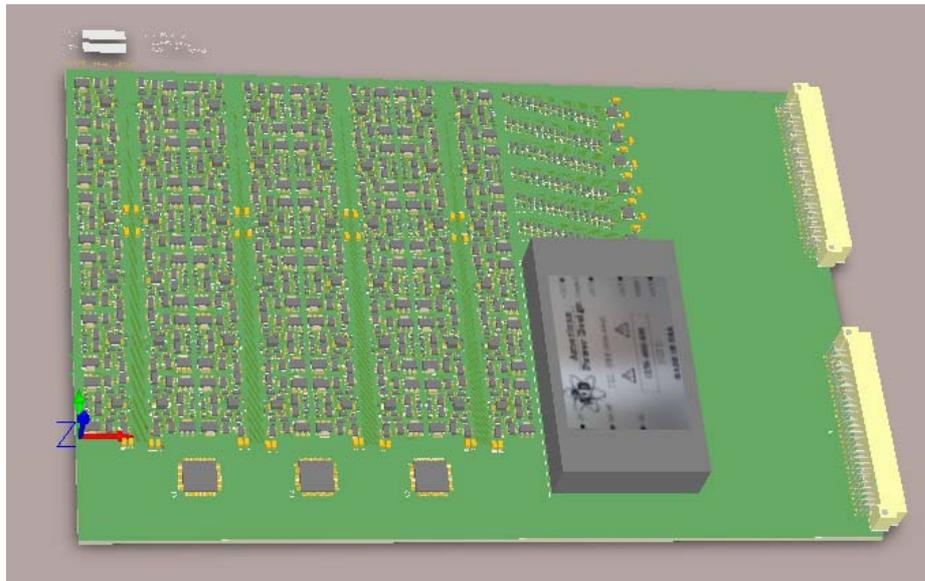


Fig.11. 96-channel HVA board.

Among the improvements incorporated into this new design will be a reduction in the per-channel layout area and a transition to a 4-layer PCB from 2-layers to achieve higher density. This decision was made since routing of high voltage traces occupies a very large area. The effective laid-out channel density has been optimized to $3.7 \text{ cm}^2/\text{channel}$, versus $6.9 \text{ cm}^2/\text{channel}$ for the 32 channel layout. New circuit improvements and optimizations will also be incorporated; among these is an improvement for the offset voltage uniformity and reducing the temperature dependence which had been found to be unacceptably large. This involves incorporating an operational amplifier (op-amp) into the input stage. This modification requires only a small amount of board space and additional power but has been found to provide significant performance benefits including a small boost in bandwidth. Three on-board 32-channel digital-to-analog circuits with high speed serial interface will also be incorporated into this new board for driving the HVAs. This work will be performed over the spring and summer of 2012 with a goal of having a fully functional 96-channel HVA board ready for testing in the summer of 2012.

REFERENCES

- [1] IEEE, Std 1101.1-1998, IEEE Standard for Mechanical Core Specifications for Microcomputers Using IEC 60603-2 Connectors, 1998.
- [2] PI, Basic Designs of Piezoelectric Positioning Drives/Systems (Online), GmbH & Co. KG., 2011, cited 3/18/2012. Available at: www.physikinstrumente.com/en/products/prdetail.php?sortnr=400800.00
- [3] R. E. Aldrich, Deformable Mirror Wavefront Correctors in "Adaptive Optics Engineering Handbook". Marcel Dekker Inc., 2000.