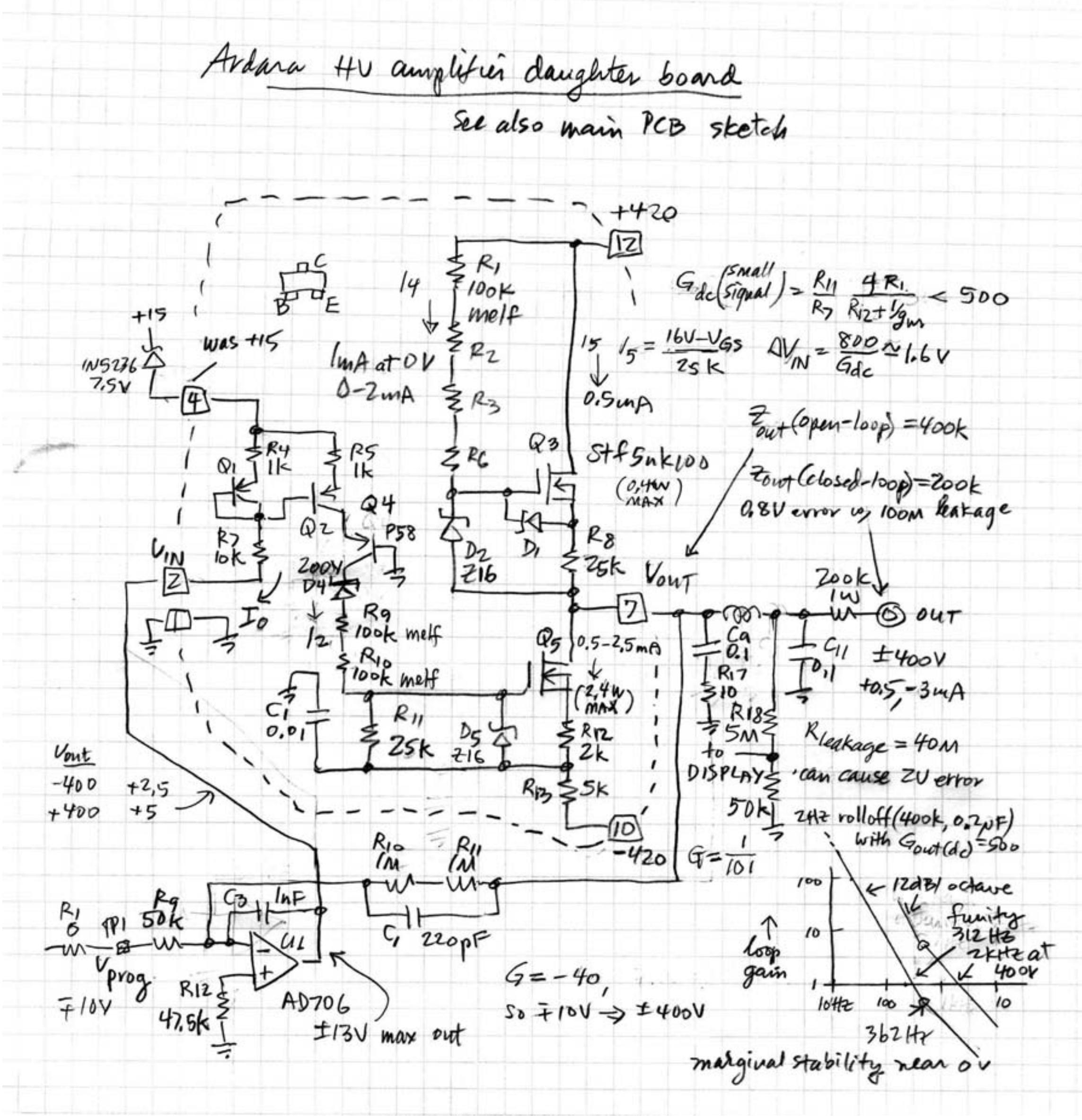
Ardara eight-channel ±400V electrode supply. **By Winfield Hill**

We have reverse-engineered and analyzed the Ardara ±400V eight-channel electrode voltage source. This instrument contains a large main circuit board and eight amplifier daughter boards. The schematic of one daughter board is shown below, along with some of the off-board wiring (simplified), for context.

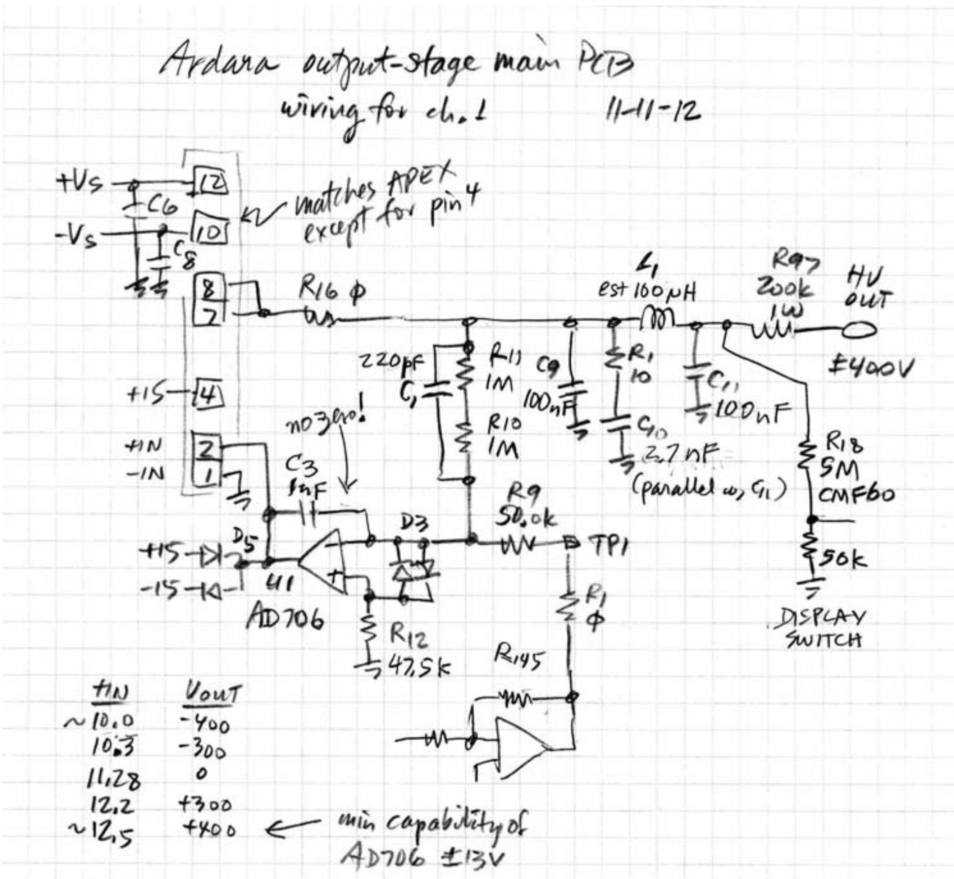


Analyzing the circuit we see Q4 in a level-shifting stage with a gain of -R11 / R7 = -2.5, followed by Q5 in a common-source MOSFET output stage. This stage has a 400k resistor drain pullup load resistance and a gain of about 4 R1 / R12 = -200 (there's a $1/g_m$ term with only a small effect). So the overall daughter-board low-frequency gain is about +500. At high positive output voltages the resistor pullup current is quite low, 0.05 mA at +400V. To improve on this situation, MOSFET Q3 has been added, wired as a fixed 0.5 mA current source. Note that unlike a source follower we might see at this location, MOSFET Q3 does not serve to lower the amplifier's output impedance, which remains 400k open loop at DC.

Zout drops as capacitors to ground C9 and C11 load down the output, starting at 2Hz. However open-loop Zout is still above 10k at 60Hz. The loop gain is quite low and does not dramatically lower the output impedance.

In addition there's a 200k resistor, R97 on the motherboard, that's outside the feedback loop. This increases Zout to over 200k. This means in use you'd want to be sure not to have significant cable or wiring leakage. For example, a modest 100 Meg leakage would cause 0.8V error at a full-scale output. Lower leakage resistances would be unacceptable. You'll also want to insure there's no nearby pickup interference source.

From the wiring diagram and pin layout we can see that the motherboard was originally designed for an APEX PA97 amplifier module. This module required a compensation capacitor between pins 4 and 6. The daughter boards replacing the PA97 don't have any compensation components, and pin 4 has been reassigned to +15V and used to power a current mirror in the level-shifting stage. In our Ardara box a set of eight looping wire jumpers under the motherboard connects +15V to pin 4 of each daughter board.



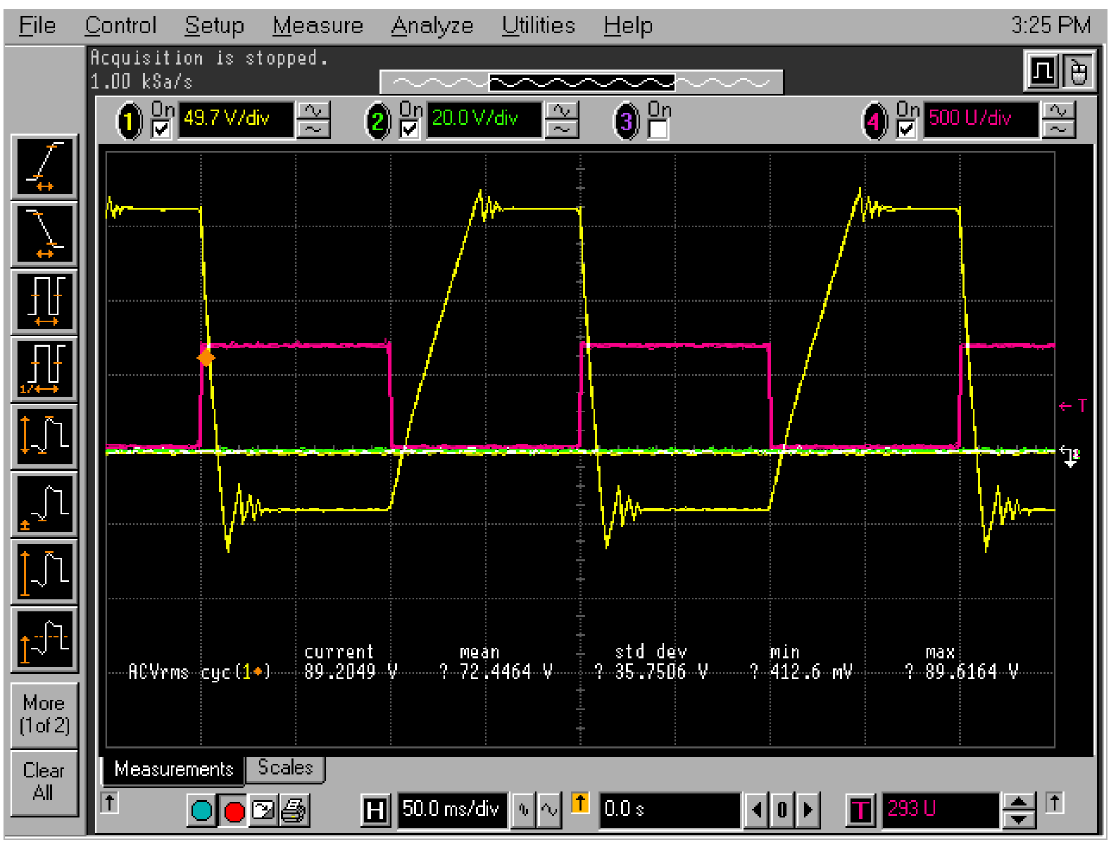
As shown on the schematic above, pin 4 is connected to +15V. Unfortunately current mirror Q1 and Q2 drops only a small voltage from the +15 supply rail, especially when the HV amplifier's output is near positive full scale. This means the op-amp's output may need to go above its maximum rated output voltage to successfully drive the daughter board to full scale. Also, the daughter board's gain of +500 means that only a small signal of about 1.6Vpp from the control-loop op-amp is needed to drive the output stage through its range of 800Vpp. As originally wired, this means the AD706 op-amp is always operating near or above its maximum output voltage.

Fortunately there's a simple fix to allow the op-amp to operate in the middle sweet-spot of its range. We added a single 1N5236 7.5-volt zener diode under the motherboard, in series with the above-mentioned looping "roach-wire" jumpers feeding pin 4 for the eight boards. We unsoldered the wire at the end that's connected to +15, and added the zener in series (the zener is shown in place in the first drawing). This sets all the daughter-board pin 4 connections to +7.5V. The eight control op-amps are now working in their happy regions.

Feedback amplifiers need to be compensated, generally to have a -6dB/octave open-loop gain slope with its corresponding -90 degrees of phase shift. Here this is implemented with what's called "brute-force" compensation, with big capacitors on the output. C9 and C11 add 200nF of capacitance to load the 400k output pullup resistor, this creates a rolloff pole at 2Hz.

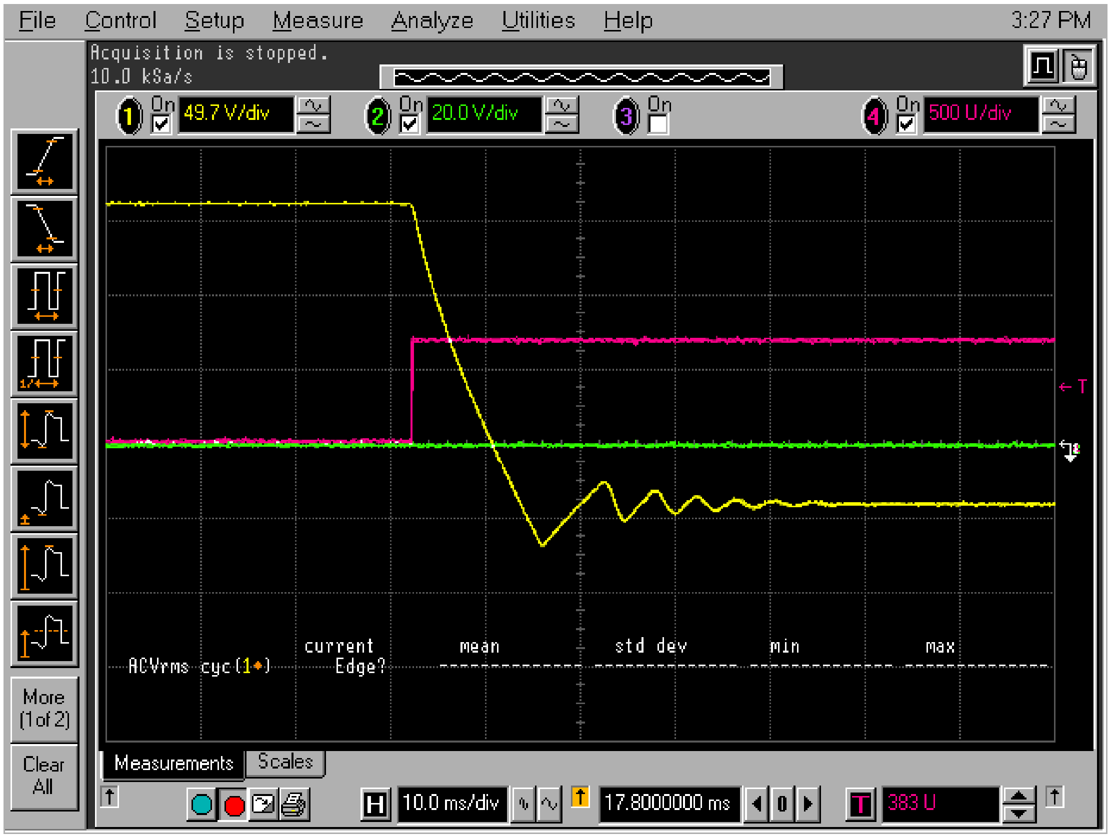
These large capacitors also give the amplifier a very slow slew rate and a slow step response. We can calculate S = I / C = 500uA / 200nF = 0.0025 V/us. That's for near positive full scale, where the 400k pullup resistor current contribution is low. This is so slow that it's better expressed in milliseconds, 2.5V/ms. This would mean it takes 40ms to go 1/8 scale or 100 volts. At lower output voltages, such as near zero volts, the 400k pullup resistor contributes some current, speeding up the amplifier's response.

An oscilloscope screen shot shows the amplifier taking over 50ms to slew +200 volts and settle from an overshoot.



The amplifier's maximum pulldown current, through Q5, is higher than the maximum pullup current, so negative-going slewing is faster.

In the next scope trace we see that after slewing -220 volts, the amplifier experiences more than 50 volts of overshoot. In the end it takes about 40ms to slew and settle.



In use one would be well advised to wait about 0.1 seconds after a change before using the voltage.

By comparison, the Rowland Institute's AMP-62 / AoE Chapter 4x ±500V high-voltage amplifier is over 1000 times faster, taking 200us to go 1kV (5V/us) when driving 30 feet of coax (or 700us with 100 feet of coax). It has a low Zout, a symmetrical response, and no overshoot.

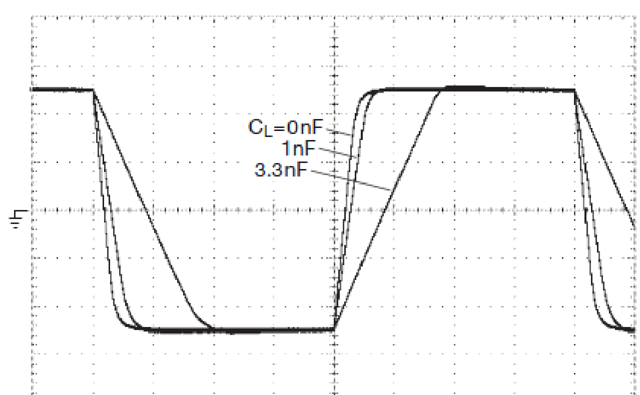


Figure 4x.49: *Full-swing (1 kVpp) response of the amplifier of Figure 4x.42. The circuit's output current limit of* ± 5 mA *limits the slew rate of into 3.3* nF: $dV/dt = I/C = 1.5\,\mathrm{V}/\mu\mathrm{s}$. *Horizontal: 400* μs/div.; *Vertical: 200* V/div.