High Voltage $\mathcal{E}$-field Voltage Supply for Gen II

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I am trying to find a replacement for the APEX PA98a chip that is in the electric field power supply that we used in ACME Gen I. We like this chip for its nice noise and offset characteristics, but we'd like to replace this chip because:

- It operates at a max of ±250V in a bipolar mode, but we would like to be reach voltages up to ±400 V in Gen II (this is mostly due to the increased field plate separation - we require higher voltage by about a factor of 2× compared to Gen I to reach the same electric field)
- It tends to break after several months of use and the failure mode is slowly acquiring a large drifting offset that is usually not initially noticed.
- This chip runs very hot. Running a chip hot can mean large temperature fluctuations that can lead to drifting offsets, and may also contribute to the short lifetime of the chip

In this document, I lay out the specifications that we require for this voltage supply and compare power op-amps as a possible solution to this problem. In this document, unless otherwise specified, I will assume that we can obtain a power supply that provides ±500V, and I will discuss that other specs that would be required by experiment contraints.

Charging Time

We would still like the $\mathcal{E}$- field switch to be the fastest or second fastest switch in the experiment, and we would still like the experiment to be operated around 2Hz. In order to keep the duty cycle high, we require that the $\mathcal{E}$-field switch time δt is short compared to the repetition rate of the experiment, so $\delta t \ll 500$ms. We also require that the switch time allow for many exponential decay times such that the electric field arrives to the setpoint $\mathcal{E}-$field to within about 10 mV (we care about electric fields down to the level of observed imperfections on the few mV/cm level). With a total voltage of 1000V across the field plates, this requires that we wait $\delta t \geq 11.5\tau$ exponential decay times. Lets say that we want to switch the electric field such that the duty cycle is greater than 80% so that $\delta t \leq 100$ ms. This places the constraint that the decay time is $\tau \leq 8$ ms. We must also verify that the decay time is in fact exponential with a single time constant - often we will se longer time scales dominating at late times after the switch. For now, we will assume that all decay times are exponential since we do not have a good model for the non-exponential decay times. The switch time will necessarily be longer than $\delta t \geq 1$ ms because the $\mathcal{E}-$field power supply is programmed and triggered by the computer which has a finite programming time on that order.

Timescale from Capacitor Charging

As was previously measured with the field plate test pieces, the Gen II field plates have a resistance of about $R \approx 2500\,\Omega$/square. Given the field plate size was spec'd to be 17×9", and given that we plan to operate with a field plate separation of 4.5cm, then the capacitance of the field plate is about $C \approx 20$ pF. We use long (~25ft.) BNC cables to provide the voltage that have negligible resistance, but have capacitance of about 50-100 pF/m, which corresponds to $C \approx 350 - 700$ pFwhich dwarfs the capacitance of the field plates. So given the capacitance of the BNC cables and the resistance across the corners of the field plates, the total charging time is expected to be less than $\tau < 5\mu s$. Hence the cable and field plate charging will not significantly limit the switch time.

Requirement from Supply Slew Rate

If we are limited by slew rate, then we require minimum of $1000V/8\text{ms} = .125\text{V}/\mu s$ of slew rate - since these op-amps generally have speeds of greater than $1\text{V}/\mu s$, this will probably not be the limiting factor. However we should keep in mind that this sort of supply time constant could be non-exponential, so it might be nice to have slew rate that is at least an order of magnitude larger than our estimated requirement.

Requirement from Supply Current

If the power supply has a maximum output current, then in principle we could be limited by the current output of the power supply. The minimum current that we require is $I_{\text{min}} \approx CV/\tau \approx .1$ mA. We may want to require that the current be at least an order of magnitude greater than this to ensure that we are not limited by the current, $I_{\text{min}} > 1$ mA.

Voltage Offset

Initial Offset

In ACME Gen I, we observed $\mathcal{E}^{\text{nr}} \approx 5-10$ V/cm that we suspect was due to fixed charges or patch potentials on the electric field plates. A voltage offset can contribute to an $\mathcal{E}^{\text{nr}}$, and a comparable $\mathcal{E}^{\text{nr}}$ could come about due to an offset voltage of around $V_{\text{off}} \approx 25-50$ mV. Finding an HV supply that can provide $V_{\text{off}} < 50$ mV is possible at ±500V, but they typically do not get much better than that by an order of magnitude. It is reasonable to settle for a supply that will result in a comparable $\mathcal{E}^{\text{nr}}$ due to patches on the electric field plates and due to the field plate supply.

Additional Offset Contributions

We must also consider the variation in the offset with temperature, and these op-amp chips tend to get pretty hot. In the worst case scenario, we could imagine a chip heating up by maybe $10°C$. In order to keep the offset voltage below 50 mV, we would require a variation in the offset voltage with time to be less than 5 mV/°C. We must consider the variation in the offset with voltage - operating at up to ±500 V, we would require the offset variation to be less than .1 mV/V. It turns out to be hard to find an op amp with specs better than this, especially at higher voltages - i suppose at higher voltages we just have to live with higher offset voltages. We must also consider the variation in the offset with time. We might consider it reasonable to cancel out the offset on a day to day basis, and we wouldn't want the offset to drift by more than 1 mV over the course of a day. This then sets the requirement that the drift with time is less than roughly 50 mV/khr.

Input Voltage

The DACs that control the ±10 V input voltage into the amplifier have a 16 bit (BabyDAC) or 20 bit (BiasDAC) precision. With this precision, over the full range of ±500 V we expect the smallest unit by which we can control the voltage to be $500\text{ V}/2^{16} \approx 8$ mV and $500\text{V}/2^{20} \approx .5$ mV. We are currently using a BabyDAC, but we do have some BiasDACs in the lab that could get us down to 1 mV precision.

We have been focussed on the specs of the HV amplifiers, but have so far ignored the input voltage specs. Generally the DAC specs are comparable to or better than these HV chips. Asking Jim, he specifies the BabyDAC offset voltage to better than 5ppm/$°C$ for offset voltage. Any initial voltage offset can be trimmed out. This would correspond to about 2mV/$°C$, which is comparable to that from the amplifiers, but the temperature swings will be much smaller because these boards don't get hot.

Power Supply Comparison

In table , I compare three possible power op-amps that could be used in the Gen II ACME $\mathcal{E}$ field voltage supply, and compare them to the requirements that I estimated above for such a power supply.

	Requirements	PA-98a	PA-89a	Kepco-BOP-HV-500
Bipolar	yes	yes	yes	yes
Voltage	$\sim \pm$500V	±225V	±600V	±500V
Current	$>$ 1 mA	200 mA	100 mA	3.8A
Power	$>$ 1.5W	30 W	40 W	
Input Voltage	±10 V	±25V	±25V	±10V
Temp Range	$15 - 40°C$	-40 to $+85$ $°C$	-55 to $125°C$	
Assume Gain:		20×	60×	
Max Gain		111×	120×	50×
Offset (Initial)	$<$ 50 mV	$<$ 10 mV	$<$ 30 mV	<2.5 mV
Offset (vs. T)	$<$ 5 mV/$°C$	$<$ .6 mV/$°C$	$<$ 1.8$°C$	$<$ 50 mV/$°C$
Offset (vs. V)	$<$ .1 mV/V	$<$ .2 mV/V	$\sim$ .42 mV/V	
Offset (vs. t)	$<$ 50 mV/khr	$<$ 1.5 mV/khr	$<$ 4.5 mV/khr	100 mV/8hr
Slew Rate	$>$ 1 V/μs	$>$ 700 V/µs	$>$ 12 V/μs	18V/μs
Noise	$<$ 10 mV RMS	.02 mV RMS	.24 mV RMS	$<$ 10 mV
Controlled By		BabyDAC$\pm 10V$	BabyDAC $\pm 10V$	GPIB

Table 1: Comparison of 3 power op-amps that were considered for the ACME Gen. II $\mathcal{E}$-field supply.

1. **APEX PA98a** - this is the chip that was used in Gen I power supply. We would like to reach higher voltages than this chip can achieve while maintaining similar offset and noise specs. Ideally we would like a chip that runs a little cooler and is less flaky than this one.

2. **APEX PA89a** - this is another APEX chip that is similar to the PA98a in most ways except it can reach higher voltage and is much slower, but nevertheless meets our slew rate requirements. We should go with this chip if there aren't any hidden downsides that are uncovered.

3. **Kepco BOP-HV-500 -** this kepco was recommended by Jim as a possible commercial alternative to using an op-amp. It provides the necessary voltage (though provides a dangerously large amount of current), though the offset specs are not nearly as good as the other chips that are considered, and the temperature dependence of this supply does not meet our threshold (though to be fair, if this supply stays cool, it would be good enough).