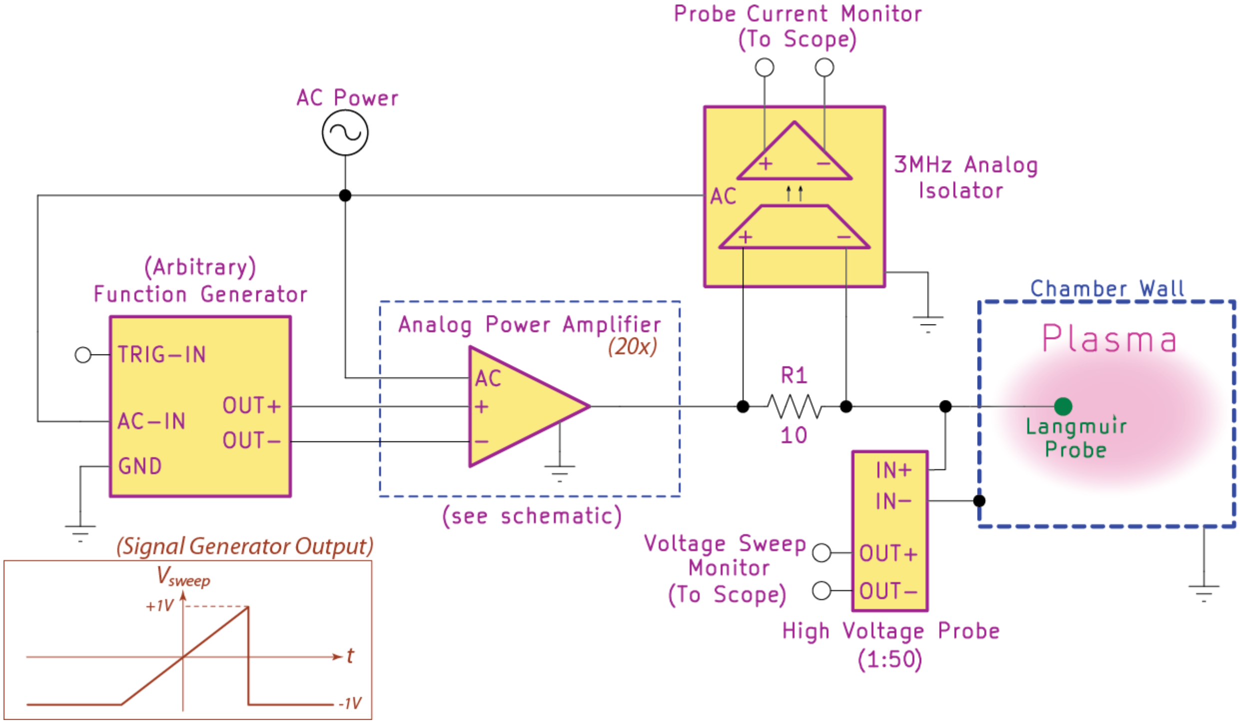
# Appendix III Electrical Schematics

## Langmuir Probe Sweep Circuit



Langmuir probe system block diagram: including waveform generator, amplifier, current sense resistor, isolation amplifier, and probe. The analog power amplifier circuit employs at least one isolation power amplifier across a current monitoring resistor ($R_1$). The value of the resistor should give a full-scale signal level in the range 0.5-5V. The sweep voltage waveform originates in a signal generator programmed to output one (or several) ramp voltage pulses starting with the input trigger. In this case the trigger comes from a Stanford pulse generator that in turn is triggered at the beginning of the plasma pulse.

## Linear power amplifier for sweeping probes

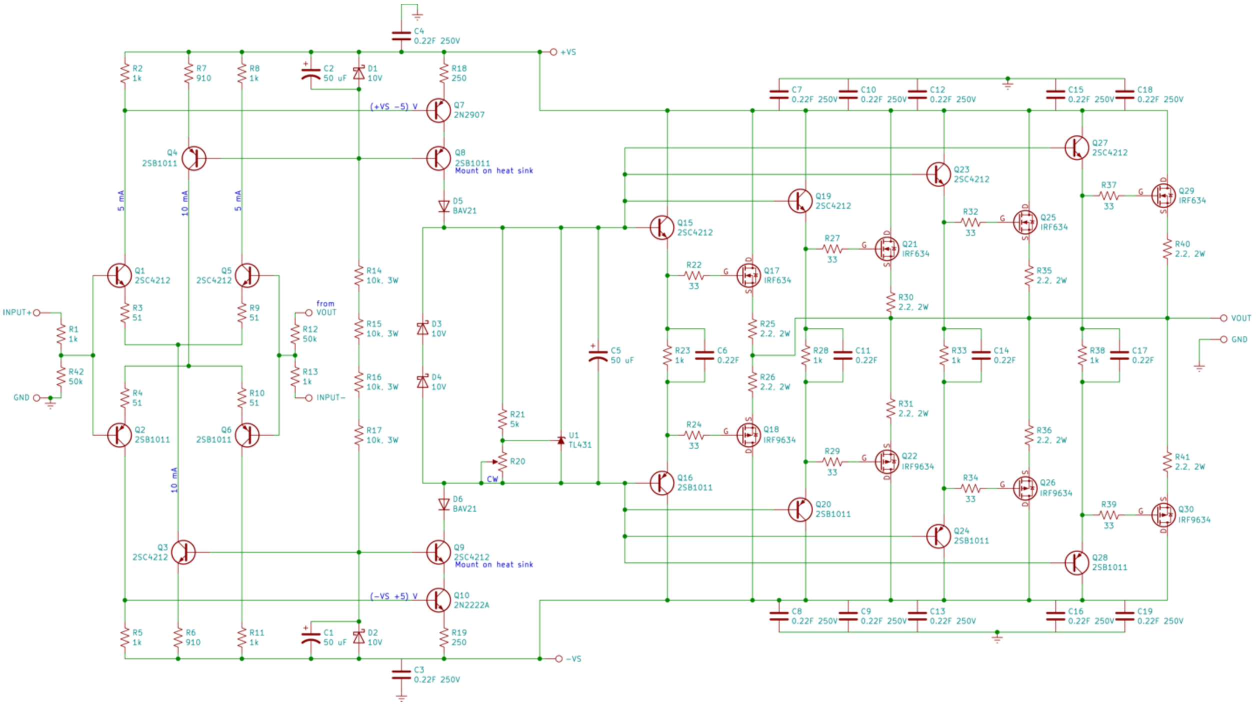


Figure A3.1 An analog power amplifier suitable for low duty cycle operation drives Langmuir probes in this plasma lab and more broadly in LAPD. The schematic is shown in Figure A3.1. This is a fairly standard differential amplifier circuit constructed from discrete components. We abandoned single package amplifiers-on-a-chip due to the regularity of burning them out and the expense of replacing them. This analog amplifier is robust enough that it survives abuse typically with only a blown fuse. In the occasions that a transistor also burns out, they are easy to replace. Other than that it has no overcurrent protection.

Bipolar transistors used in the circuit should be 200V or higher, rated 10 Watts or more. Since there is a limited selection of power PNP transistors, we chose this part number first, looking for as high a cutoff frequency ($f_T$) as possible. Safe operating current at 200V must also allow operation at up to 20 mA. Then Q2,Q4,Q6,Q8,Q16,Q18,Q20,Q22 are this type of PNP power transistor, mounted on the heatsink. The NPN transistors (Q1,Q3,Q5,Q9,Q15,Q17,Q19,Q21, also mounted on the heatsink) should then be chosen have a roughly similar cutoff frequency. If a complementary PNP/NPN pair is available that is even better. For ease of mounting we also selected "full-pack" transistor packages. The power MOSFETS in the circuit are both P-channel and N-channel enhancement mode devices and must also be rated for 200V or more; these are chosen for low input capacitance, but since they are driven by emitter followers their specific characteristics are not too important. We used part numbers IXTH24P20 (U3,U5,U7,U9), and

SPW52N50C3 (U2,U4,U6,U8). Resistors are 1/4W unless indicated. The transistors used in the original design, 2SC4212 and 2SB1011 are no longer manufactured. Suitable replacements may be MJE15034/MJE15035.

A frequency compensation capacitor (not shown on the schematic) is typically beneficial across R13, depending on the load. This is in the range 3-10 pF but must be 200V. In practice we construct this from a short piece of coax, starting at 10 cm then trimming it to a length that optimizes the response. Larger load capacitance (for instance a long coax) require more compensation capacitance.

R21 is adjusted to set the quiescent current in the output transistors. Higher current minimizes distortion in the output waveform, with about 0.05-0.1A being good provided the heatsinks on the output transistors are sufficient to dissipate the associated amount of quiescent power (< 10-20 W)

The power supply is a simple center-tapped full-wave rectifier circuit, using a transformer with a 120V center-tapped secondary. The transformer is similar to Triad Magnetics F8-120. The output of the transformer/rectifier circuit is smoothed by 560 µF filter capacitors. When more power is desired, up to 3 of these transformer/rectifier/capacitor circuits have been connected in parallel.

Care should be taken when assembling this circuit, as it requires working with potentially lethal voltages. After assembly, the circuit is initially tested using two current-limited adjustable power supplies capable of supplying up to 50 V at 0.1 A or more, connected in a center-tapped DC configuration. These are used in lieu of directly plugging the circuit into the wall for the smoke test. The quiescent current pot R21 is adjusted in this test setup. Once the circuit is working we remove these DC supplies and plug it in.

## IGBT driver

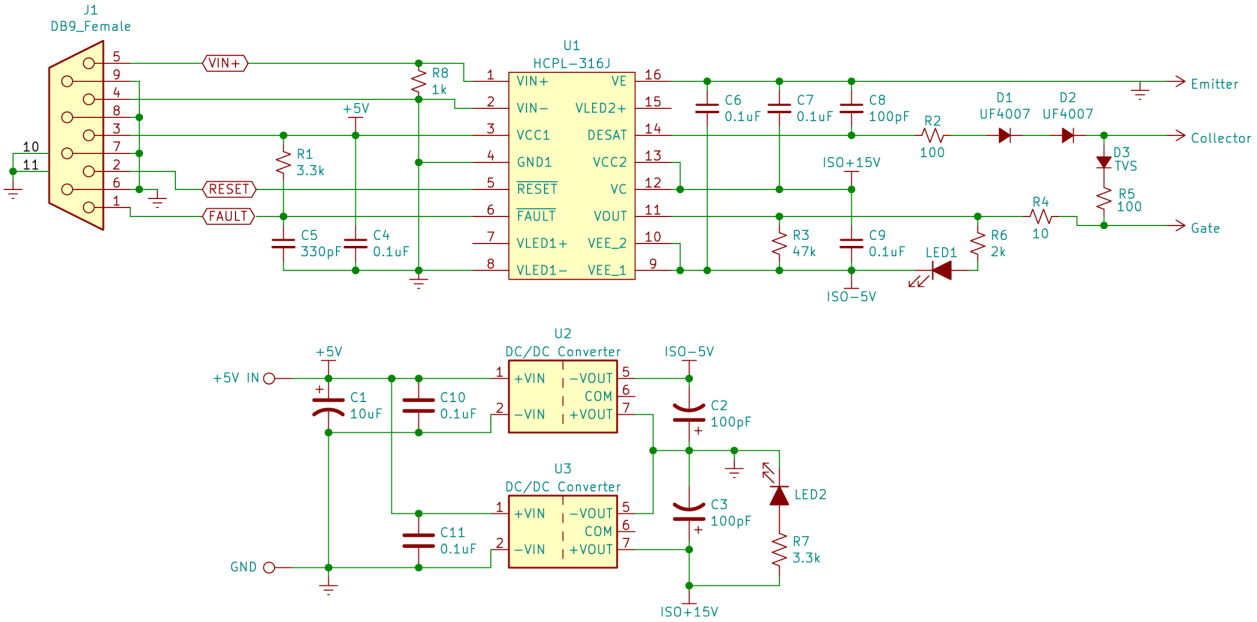


**Figure 3.A.2 IGBT driver Circuit**

Much of the high-current switching needed in the lab is accomplished by IGBTs with a generic gate driver circuit shown in figure 3.A2. This circuit controls the IGBT in the capacitor bank circuit of Figure A3.3, but is also useful for applying pulses to e.g. a paddle in the plasma. It is built around the HCPL-316J isolated driver circuit. This chip has "desaturation" detection – that is it can detect when the output transistor is being asked to supply so much current that it can no longer remain fully turned on, for instance in short-circuit or arc conditions. The IC generates a fault signal in this case, which is available but ignored in practice in our lab. The chip must be reset after a fault. We have found that simply connecting the On-command input signal (VIN+ in the figure) to the Reset input provides sufficient protection for much of the abuse it typically faces. 15V is sufficient to fully turn on most IGBTs; this is provided by a DC-DC convertor. To insure that the IGBT remains in the off state at other times, a negative bias voltage of -5V is provided by a second DC-DC convertor. When the IGBT turns off, all but the simplest loads have enough inductance to result in a voltage transient across the transistor. This drive circuit relies on an active voltage clamp circuit (D3+R5) to turn on the IGBT enough to absorb this inductive energy. The turn-on voltage of the TVS diode must be greater than the DC supply voltage that the IGBT is switching, and at the same time at least 100V less than the maximum rated collector to emitter voltage. Absorbing the power circuit inductive energy like this operates the IGBT well outside of its DC safe operating area during the transient, but at the low pulse frequencies we typically use (< 20 Hz) we have not found this to be a problem.  The alternative is a diode clamping circuit and local bypass capacitor, which achieves similar protection at the cost of a number of extra components.

### Capacitor Bank and Pulser

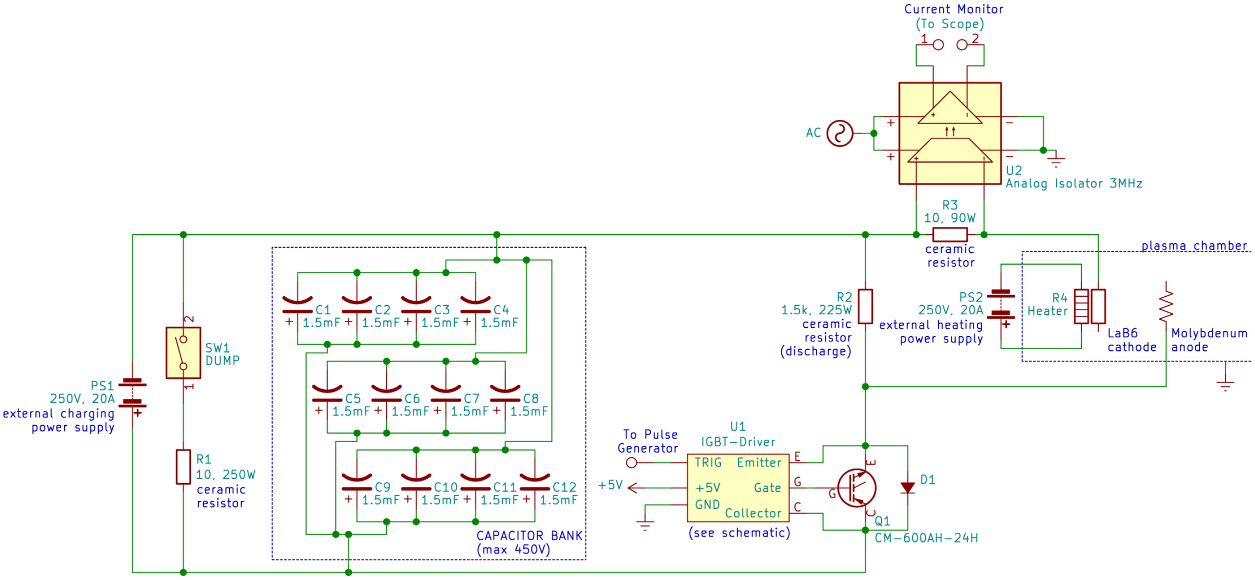
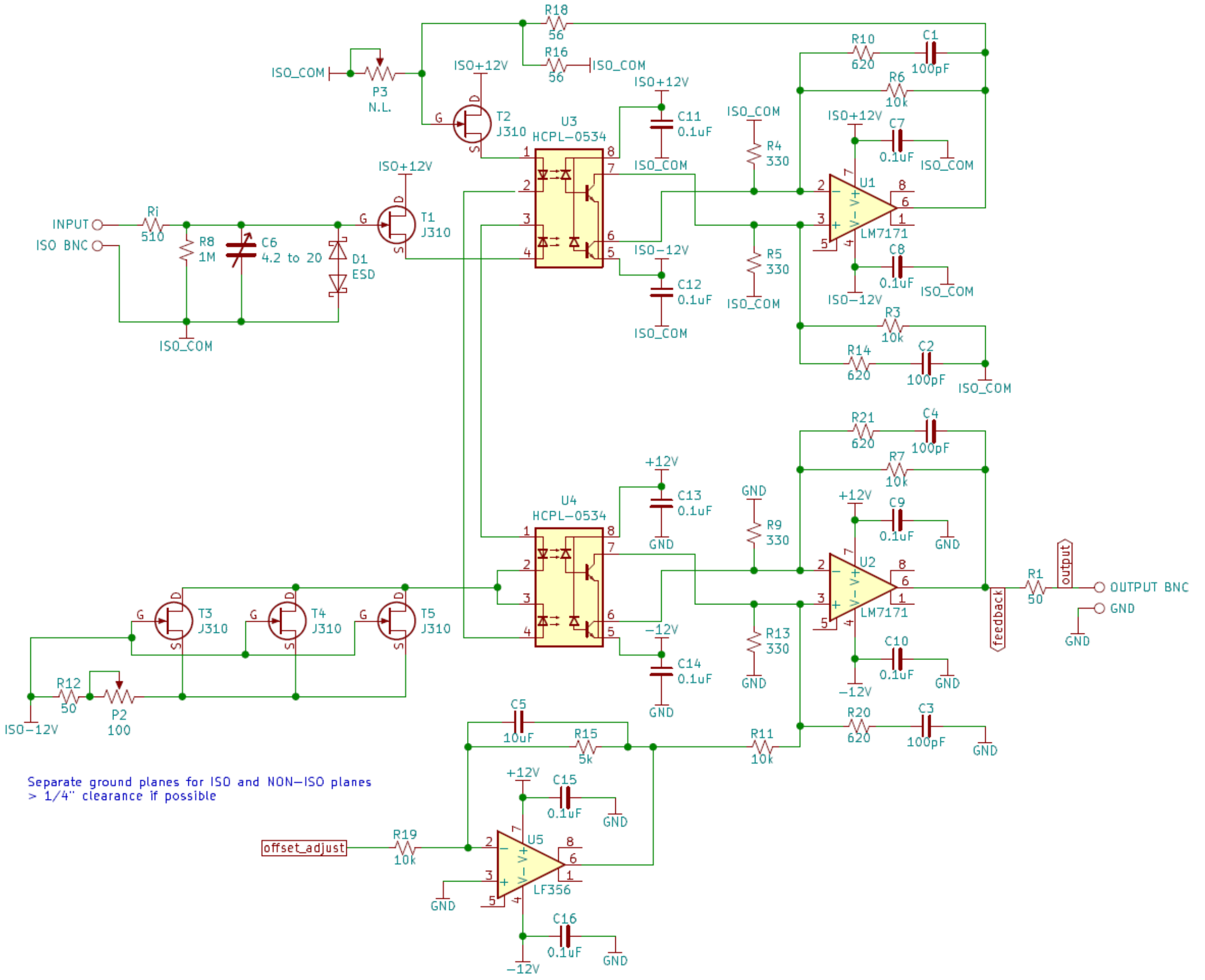


**Figure 3.A3 Capacitor Bank and Pulser**

The capacitor bank and pulser circuit that drives the plasma is shown in Figure 3.A3. A number of 450V electrolytic capacitors are connected in parallel, and charged by an external current limited power supply. In many cases we use a CM600 type IGBT (from eBay) as indicated in the schematic, although any sufficiently high current and voltage IGBT would work. For the plasma arc smaller 40-50 A IGBTs are fine. We have found that simply turning the IGBT on and off does not result in a good square pulse – the rising edge is fine, but once the plasma shuts down stray capacitance keeps the voltage high since there is nothing to pull the output voltage rapidly down to zero. R2 is added to drain charge from the wiring and IGBT output capacitance. The plasma is run at between 1 and 20 Hz, with typical pulse lengths of 1-10 ms. Discharge current is typically less than 10A. R3 is a high power resistor and limits the current in the case of arcs or other shorts. R3 serves double duty as the current monitor: an isolation amplifier with a voltage attenuation at the input of 100× is used to monitor the voltage across this resistor. The input to the gate drive is a timing pulse from a Stanford pulse generator, not shown in the figure.

### 3 MHz Isolation Amplifier



### Figure 3.A4. MHz Isolation Amplifier

We often need an isolation amplifier with a gain near unity and a frequency response up to 1 MHz; one of these is used as the current monitor in the Langmuir probe sweep circuit shown in Figure 3.A4. This circuit, shown in Figure 3.A4, relies on the individual elements of a dual opto-isolator being nearly identical. A feedback circuit is constructed around the first opto-isolator, then the second is operated to generate a nearly exact replication of the output waveform of the first circuit. The output of U1 is connected with negative feedback that linearizes the response of the circuit to accurately track the input voltage×2. In so far as the circuits can be made identical, the output of U2 then matches this voltage. In practice, there is some offset and gain variation; a trimpot provides an offset voltage adjustment available from the front panel, but we have found the gain is sufficiently close to 2 that we do not have an adjustment for that. The entire circuit is operated in a differential configuration to improve a) common mode rejection, and b) linearity. In addition, the HCPL-0534 isolator has an internal electrostatic shield to help with isolation. The measured bandwidth is about 3 MHz. One useful feature of this circuit is that the input mimics that of a typical oscilloscope, and as such 10× (e.g.) scope probes are useful for larger signals. The unit is sensitive to over-voltage on the input; for unknown reasons this lab's occupants frequently manage to put more than 5V in. Fortunately about 90% of the time the input resistor "Ri" is the only thing that is destroyed. An isolated power supply using a split-bobbin transformer and 7812/7912 voltage regulator chips provides the ISO side positive and negative rails. Note the gain of 2 is because the output impedance is 50 ohms, so connecting it to a 50 ohm scope input results in a net gain of 1.