Supplemental Information
Development and Characterization of an Inexpensive Electrostatic Lifter

AUTHOR INFORMATION (place here)

The layout of the electronic components is provided given in **FIG S1** and the circuit diagram is provided in **FIG S2**. For instructional purposes, we discuss the layout of the printed circuit board and device with reference to a “multiplier” module (Region A), a “driver” module (Region B), and connections to the housing. The purpose of the multiplier is to generate a high-voltage, low-current DC power supply from a low-voltage, low-current AC input. The driver module provides the AC input.

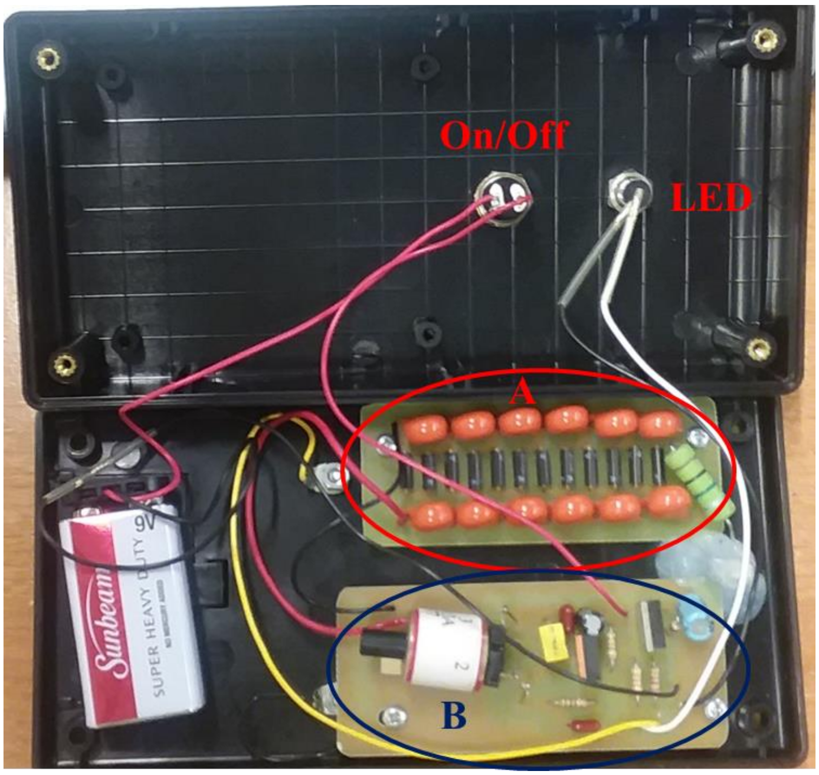

Figure S1 - *The internal layout of the electrostatic device can be accessed upon removal of four screws. A = Cockroft Walton multiplier; B = driver circuit for the multiplier.*

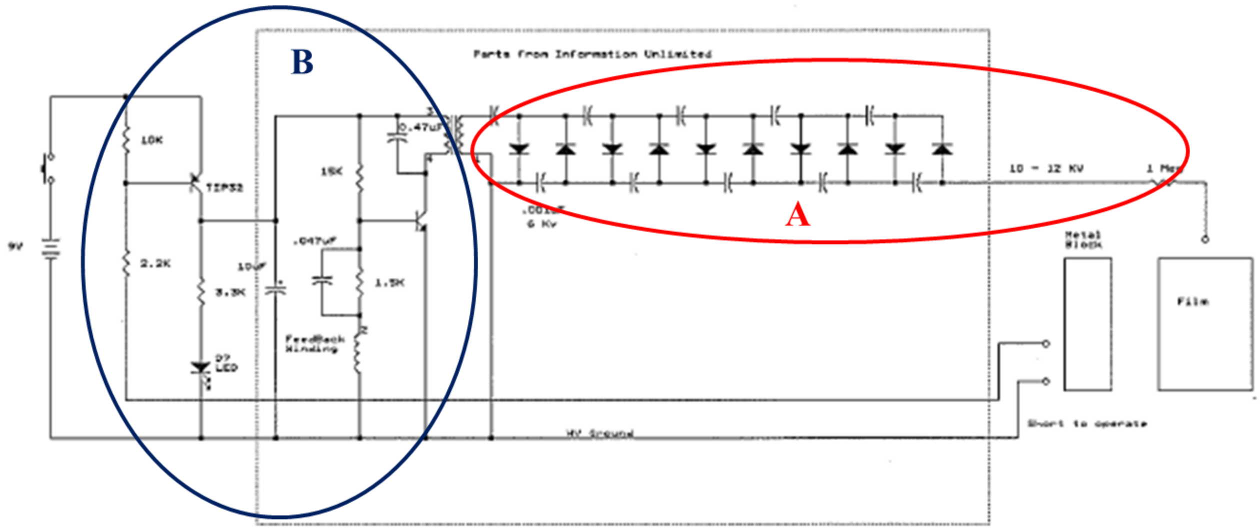

Figure S2 - *The circuit diagram for the electrostatic lifter. A = Cockroft Walton multiplier; B = driver circuit for the multiplier*.

Multiplier Module (Region A)
This particular circuit, the diode rectifier circuit, was first constructed by Heinrich Greinacher in 1919 and produces an output voltage greater than that of the applied input voltage without the use of a transformer. Such circuits are commonly used in devices where it is necessary to have a very high DC voltage generated from a relatively low AC supply (such as microwave ovens, high-voltage test equipment, and electrostatic based instruments). The circuit is also referred to as a Cockroft-Walton generator as John Douglas Cockcroft and Ernest Thomas Sinton Walton used the circuit to power a particle accelerator to perform the first artificial nuclear disintegration in history, for which they received the 1951 Nobel Prize in Physics.

The multiplier module consists of a variable number of stages placed in series; the output of each stage serves as the input for the subsequent stage. The output of each stage doubles its input voltage. Each stage is comprised of a clamper (the diode-capacitor pair, D1 and C1) and a half-wave rectifier (the diode-capacitor pair, D2 and C2), as shown in **FIG S3**.

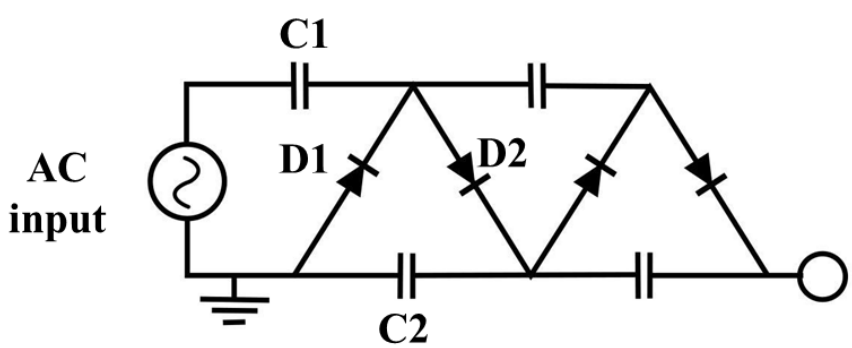

Figure S3 - *A two-stage Cockroft-Walton multiplier showing the diode-capacitor pairs of the first-stage.*

The following generalized discussion of the multiplier uses a 1 kHz, 2 $V_{p\text{-}p}$ AC signal (**FIG S3)** as an example input. During the **positive half-cycle** of the AC input (**FIG S4**), diode D1 is forward-biased which charges capacitor C1 to the peak value of the input voltage (in this example, V_p = 1 V = peak value of the input voltage); whereas, diode D2 is reversed-biased blocking capacitor C2 from charging. During the **negative half-cycle** of the sinusoidal input waveform, diode D1 is reversed-biased blocking capacitor C1 from discharging. At the same time, diode D2 is forward-biased and charges capacitor, C2. Because there is a voltage across capacitor C1 already equal to the peak input voltage (V_p), capacitor C2 charges to twice the peak voltage value of the input signal, ie. $V_{p+} + V_{p-}$, so on the positive half-cycle, D1 charges C1 to V_p and on the negative half-cycle D2 adds the AC peak voltage to V_p on C1 and transfers it all to C2.

The voltage across capacitor, C2 can be calculated as: $V_{out} = 2V_p$, (minus of course the voltage drops across the diodes). Note that this doubled output voltage is not instantaneous and is frequency dependent. As capacitor C2 only charges up during one half cycle of the input waveform, the resulting output voltage discharged into the load has a ripple frequency equal to the supply frequency. The multiplier output shown in **FIG S4** illustrates an ideal DC output rather than the true ripple voltage.

FIG S5 illustrates the oscilloscope readings of the various input and output voltages for a single-stage multiplier that were built on a digital breadboard. The circuit uses two 0.001 µF capacitors and two 1N270 diodes. The input voltage is a 76 kHz 2 $V_{p\text{-}p}$ sine wave (V_p = 1 V).

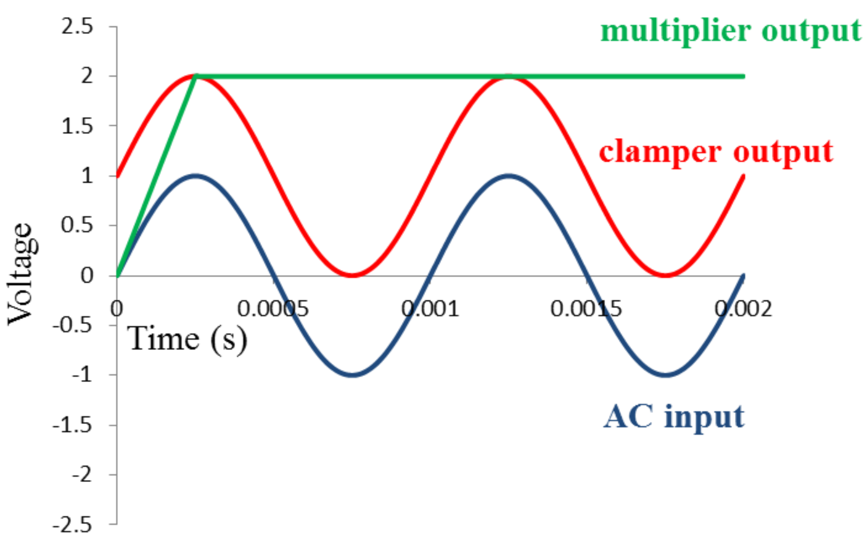

Figure S4 - *The output of the clamper (D1-C1 pair) and V_{out} of the single-stage multiplier unit for a 2 $V_{p\text{-}p}$ AC input. The figure represents ideal outputs. In reality, the output is highly distorted with a significantly lower V_{out} at such a low-frequency input. A 1 kHz AC input is shown strictly for clarity of presentation.*

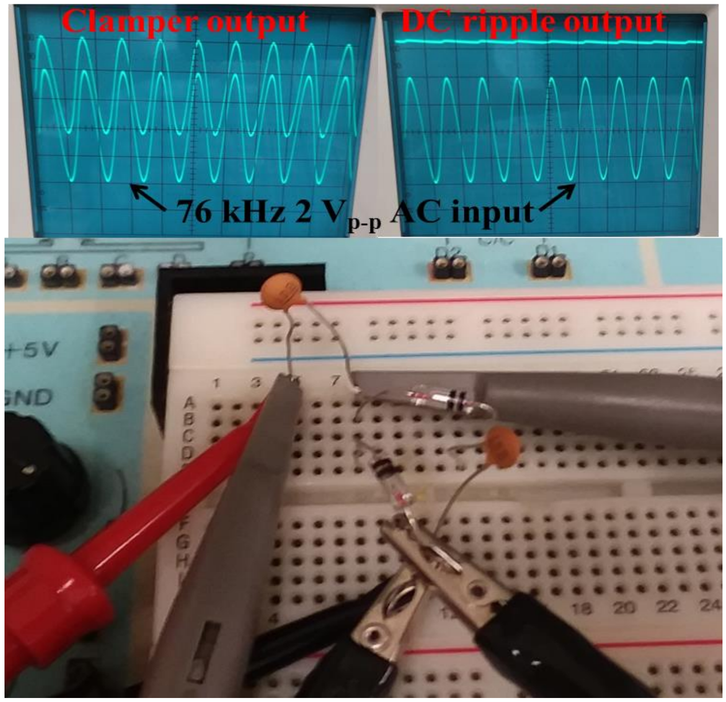

Figure S5 - *The output of the clamper is compared to the AC input (**upper left**) and the final output of the multiplier (DC ripple) is compared to the AC input (**upper right**). We obtained an output voltage of about 1.5 V DC instead of 2 V DC due to voltage drops across the diodes*.

The total output voltage of the multiplier can be calculated using the equation:

$$\mathbf{V_{out} = 2 \ x \ V_p \ x \ (\# \ of \ stages)}$$

The electrostatic lifter in this study uses a pre-assembled multiplier unit purchased from Information Unlimited. The multiplier has five stages and V_p (from the transformer) is 1.2 kV. Ideally, the output of our multiplier is 12 kV but in reality is less because of voltage drops across the diodes, the ripple voltage, and leakage currents, among other non-ideal effects.

Driver Module (Region B)

The driver module consists of the AC transformer and its input supply. The AC transformer was purchased from Information Unlimited (Part #: 28K077). The transformer supply circuit is similar to the representative circuit provided in the component's specification sheet (available online: https://www.amazing1.com/content/download/28K077-28K074-28K089.pdf). For our circuit, the transformer output is a 76 kHz 2.4 kV_{p-p} sine wave (V_p = 1.2 kV), which then serves as the input to the multiplier module.

Housing Connections

The case, or housing, was purchased from Hammond Manufacturing (Part #: 1599EBKBAT) and includes a 9 V battery door. The dimensions (170 mm L x 85 mm W x 34 mm depth) are important as there should be sufficient room for the circuit components but also sufficient distance between the output leads to prevent arcing. Five holes are drilled into the housing to accommodate the momentary on switch, the LED, and the three output contacts. We used a benchtop drill press but a handheld drill works equally well. The size of each hole depends on the dimensions of each of the above components and the machine screws/nuts used as the contacts. In **FIG S1**, the contact (machine screw and nut) connected to the 1 MΩ resistor on the output of the multiplier is covered in silicone to prevent arcing between the contact and nearby board components. The 9 V battery is affixed to the top of the case using double-sided foam tape.

Overall Cost

Table 1 provides a list of components purchased to assemble the instrument. The total cost was approximately $50. Alternatively, an all-in-one unit (driver + multiplier) can be purchased for approximately $55.00 (e.g., Information Unlimited Model #CH-10: https://www.amazing1.com/hv-dc-power-supplies.html). The housing, LED indicator, momentary-on switch, additional wires, and screws are still required but construction of the device is much simpler. The cost then increases to about $75.00 to construct the device.

TABLE 1 - *Cost breakdown to construct the electrostatic lifter. If a particular model number is not provided then almost any models/type of that component is appropriate.*

Component (qty)	Manufacturer/Retailer	Model #	Cost ($)
Transformer			
2kV 10ma 20-100 kHz Transformer (1)	Information Unlimited	28K077	9.95
Transistors			
TIP32 (1)	Mouser	TIP32	1.25
TIP41C (1)	Mouser	TIP41C	0.60
Multiplier			
Multiplier (1)	Information Unlimited	MULTI50	19.95
Indicator/Switch			
Indicator LED (1)	Allied Electronics	70127672	0.40
Momentary-On Switch(1)	Allied Electronics	70244920	1.60
Resistors			
1.5k 5% (1)	Mouser		0.10
2.2k 5% (1)	Mouser		0.04
3.3k 5% (1)	Mouser		0.02
10k 5% (1)	Mouser		0.70
15k 5% (1)	Mouser		0.12

Capacitors			
0.047 μF 250V (1)	Mouser		0.40
0.47 μF 63 V (1)	Mouser		0.25
10 μF, 25V (1)	Mouser		0.90
10 μF, 35V (1)	Mouser		0.20
Miscellaneous			
Housing (1)	Hammond Mfg	1599EBKBAT	9.95
9 V battery snap (1)			1.00
9 V battery			
Wires, nuts and screws			-
		Total	**~$ 50.00**