High voltage pulse generators for an atmospheric pressure plasma jet

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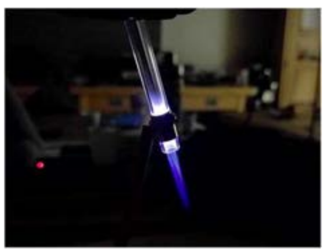
Abstract:

We present two circuit designs for supplying pulsed high-voltage to an atmospheric pressure plasma jet. Hard to break down contaminants, including per-fluoroalkyl substances (PFAS) can be destroyed effectively by atmospheric pressure plasma. For this application, producing energetic electrons is a primary goal. Short duration pulses, on the order of several nanoseconds, allow for a strongly non-equilibrium plasma, which in turn yields a higher efficiency energy transfer to electrons. Parameter goals include sub-nanosecond rise times, 10 kV peak voltage, and kHz repetition rates. In an effort to create a low-cost, high-repetition-rate pulse generator, we worked to combine Linear Transformer Driver (LTD) design with diode-based pulse compression. LTD setups allow for a modular design, making current and voltage easily customizable, while pulse compression gives the desired rise times and pulse duration.

What Is an Atmospheric Pressure Plasma Jet?

An APPJ generates plasma using high voltage electrodes. The electrode configuration we used was a ring and pin. This allowed for a strong electric field around the end of the pin. Additionally, with this configuration we can flow gas between the two electrodes. Plasma is formed when the electric field is strong enough to accelerate electrons to energies at which they can ionize neutral atoms by colliding with them. The gas, ions, and electrons that flow out of the jet can then be used to treat materials and efficiently break down harmful chemicals.

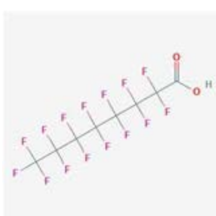


You can see the pin electrode on the inside of the glass and the ring electrode is the dark part on the outside of the glass.

The glass used is quartz glass. This is so that optical characteristics are not lost. Once we try to characterize ion temperature and electron temperature, we will need the light to pass through the quartz glass unaltered.

PFAS

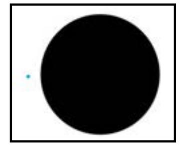
PFAS is a chemical that is used for its hydrophobic properties as well as its high resistance to degrading. It is hard to break down because of the carbon-fluorine bonds and therefore is widely used as a fire retardant. It is a highly toxic compound if ingested so it's a problem if it makes its way into the water supply. It has done just that in southern Colorado Springs and other areas around the world, but in low enough concentrations that filtration isn't effective. Therefore, the electrons in plasma provide an energy efficient and safe method of breaking down PFAS.



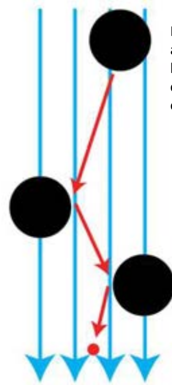
National Center for Biotechnology Information. "PubChem Compound Summary for CID 9554, Perfluorooctanoic acid" *PubChem*, https://pubchem.ncbi.nlm.nih.gov/compound/Perfluorooctanoic-acid. Accessed 11 September, 2020.

Momentum and E Field Strength

We want the electrons to obtain as much of the energy as possible because they will be breaking the bonds. Giving ions energy does not make the plasma more effective and lowers efficiency. Electrons have .1% of the mass of an ion. When the electric field exerts a force on the electrons and Ions, the electrons will have a much higher acceleration.



This figure compares the mass (represented by area) of an electron (blue) to a proton (black)



This Figure depicts the mean free path of an electron(red). Black dots are ions or neutrals and the blue arrows represent the electric field (arrowhead is +)

In order to form plasma, the electric field needs to be strong enough to accelerate an electron and give it enough energy to break free from a gas molecule before it bumps into another particle. That distance before it bumps into another particle is called the mean free path. Once we know the mean free path, we can find the electric field strength.

This first equation shows that the mean free path is equal to one over the density of the gas multiplied by the size of the gas particles. The mean free path is denoted by λ. N is the number of particles, V is volume, and r denotes the radius of a gas molecule. We use argon gas so a typical mean free path is 400nm.

$$\lambda = \frac{1}{\frac{N}{V}\pi r^2}$$

Using the equation for work, we can find the force needed to be exerted over the mean free path. The work done is equal to the change in energy. Electrons need 15 eV in order for plasma to form.

$$W = \Delta k$$

Using that value for work, we can solve for the force the electric field needs to exert. We find the force required to make plasma in argon is equal to 3.75 MV/m or 37.5kV/mm.

$$W = fd$$

Why high Voltage?

As shown above, an electric field exerts a force on charged particles. The ions also have a charge, but they weigh about 1800 times more than an electron meaning its acceleration is much smaller than an electron's. This can be taken advantage of by applying a stronger electric field, decreasing the amount of time it takes for an electron to travel the mean free path.

Why ns pulses?

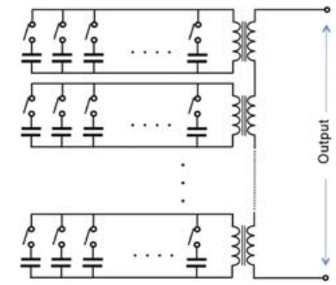
During our research we tried to make a circuit that generated pulses as fast as possible (ns range) and the reasoning behind this comes down to the collisions between electrons and heavier neutrals and ions. The shorter the time the charged particles are accelerated for, the less energy is wasted on accelerating the ions. The pulse duration should be as close as possible to the amount of time it takes the electrons to travel the mean free path because when the electrons collide with ions, they transfer their energy and the efficiency goes down.

Linear Transformer Driver (LTD)

This type of circuit design is highly modular meaning we can achieve the desired variation in parameters. The main benefit of this design is that the pulse of the circuit is inductively coupled to the output through a 1 to 1 transformer which makes it simple to add multiple pulses in series.

The figure shows the idea behind an LTD. Many capacitors arranged in parallel make a single module and each module can be stacked in series. The switches will all be triggered at the same time so the discharge of the capacitors will be added together.

With *n* capacitors, *m* modules, capacitor voltage rating of *V*, and capacitor current rating of *I*, the output pulse has current=*nI* and peak voltage=*mV*.

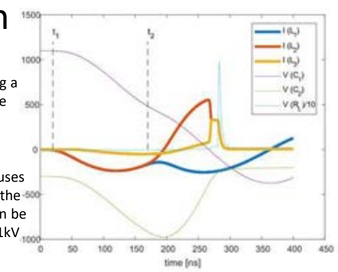


The figure illustrates the idea behind a linear transformer driver.
https://www.sciencedirect.com/science/article/pii/S2468080X17301012

Pulse Compression

Using a special type of diode called a Drift Step Recovery Diode (DSRD), we can get increased peak voltages and pulse compression. By driving a diode in parallel to the output pulse, we can see an improvement in our output pulse.

The graph depicts a simulation of a circuit that uses inductor(L) and capacitor(C) pairs coupled with the DSRD to form pulses. The increase in voltage can be seen as the peak voltage over the capacitor is -1kV and the peak output Voltage (RL) is 10kV.



Thanks to Amit Kesar for sharing his code to simulate the circuit in the paper given: https://ieeexplore.ieee.org/document/8293686

Future Work

We will continue to look at the pulse compression seen with the diode. This is not well understood and combining DSRD pulse compression with a linear transformer driver is a future goal. Additionally, we will continue to broaden the range of the LTD circuit's output voltage and pulse lengths.

Slide 1

A(L2 You could put a typical table of plasma parameters (T_e, T_i, T_gas), you could put an image illustrating the difference in mass between electrons and ions, or you could put a derivation of the velocity to which a particle is accelerated given a certain distance and electric field.

Adam (he/him) Light, 9/10/2020

A(L1 I would illustrate this with an annotated version of the Kesar simulation output, showing the inductive spike across the diode.

Adam (he/him) Light, 9/10/2020