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Xenon Plasma Toroid Theory

Introduction:

The novel xenon plasma toroid phenomenon is a beautiful example of inductively coupled plasma (ICP). ICP's are used in analytical chemistry in high efficiency atomic emission spectroscopy instruments that identify the elements present in a sample. But my desktop device pictured in Figure 1, is simply an inspirational illustration of electromagnetic laws! The device consists of two parts:

- A custom, borosilicate glass globe filled with 15 torr of xenon gas
- A 50W, class E oscillator (15.5 MHz in my case) (Figure 2)

The circuit, called a class e oscillator, generates a high frequency, high voltage oscillating electromagnetic field that ionizes the xenon into plasma, shapes the plasma into a toroid (donut), and sustains the plasma.

The device operates on several electromagnetic concepts, which I've linked to their respective Wiki pages and other learning resources:

- Inductively coupled plasma
    - Understanding Electrical Discharges - See The Pattern
- LC circuits
- Capacitive coupling
- Faraday's Law of Induction
- Eddy Currents
- Q factor
    - Resonant Magnetic Antennas Pt.3 : Losses and Q-Factor Optimisation

Figure 1: Xenon plasma toroid

If you're interested in making the circuit, check out Steve Ward's paper about an HFSSTC to understand how it works, and teslaundmehr's HFSSTC construction video of a lower power circuit. I built my first prototype by just building teslaundmehr's circuit.

HFSSTC - The Classy Self Oscillator ◦Steve Ward, Feb 2021

DIY Plasma flame Tesla Coil - Step by Step (ft.Plasma Channel)

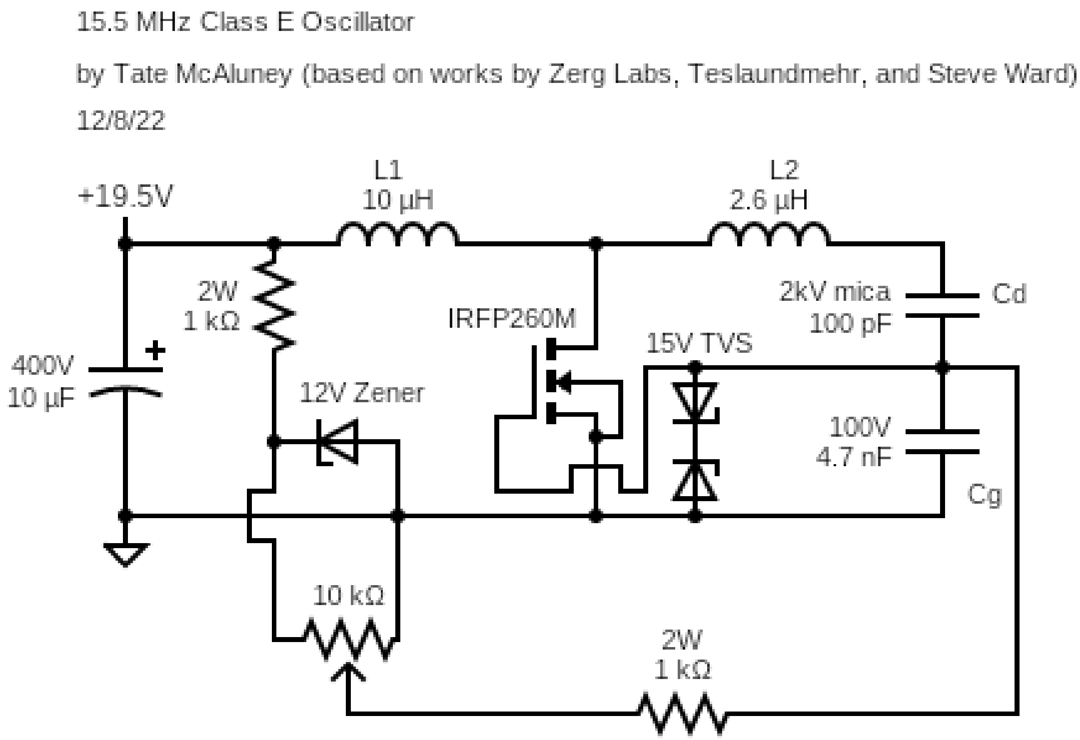

Figure 2: Class E oscillator

In-Depth Class E Circuit Theory:

1. Notice how this circuit has an inductor L2 and capacitors Cd + Cg in series, forming an LC circuit that will resonate.
2. At turn on, the tank capacitor (Cd +Cg) is charged by the input current through L1 and the potentiometer is turned to increase the voltage at the mosfet gate, until the gate voltage is equal to the mosfet's threshold voltage. At that point, the mosfet drain-source junction conducts, discharging the tank capacitors through the plasma drive coil, L2, with current flowing in the negative direction now.
3. Now that there is a negative resonant current, the gate voltage is pulled low by the capacitive voltage divider formed by Cd and Cg until the gate voltage drops beneath the threshold voltage and the mosfet stops conducting.
4. Now that mosfet isn't conducting, it acts like a capacitor and the voltage of it's output capacitance (Coss) will start to increase as it is charged by the input current and resonant current.
5. The resonant current through L2 eventually goes positive again, and once it's magnitude is greater than that of the input current, Coss is discharged through L2, while the gate voltage is also being pulled up by the positive resonant current flowing through the feedback network. Ideally, the gate voltage reaches the threshold voltage when voltage of Coss is 0V, so the energy in Coss is not shorted through the body diode upon mosfet turn-on.
6. The resonant current eventually goes negative again flowing back through the L2, and we're back to the beginning of a cycle. This cycle occurs 15.5 million times per second. And every time the mosfet switches on and off, there is the possibility for switching imperfection, which means heating of the mosfet. If the mosfet gets too hot, like 200˚C, the mosfet will short circuit and die. This is why we need to ensure the voltage of the mosfet's output capacitance is zero at mosfet turn on.

Theory of Device Operation

A) The class-e oscillator uses the plasma drive coil (2.6 uH) as part of a series-resonant LC circuit. To power on the device, the 10k potentiometer is turned to increase gate bias of the FET. Once sufficient bias is present, the circuit begins oscillating, as the FET gate is fed a phase-shifted signal from the LC circuit to achieve Zero Voltage Switched (ZVS) oscillation. The coil is operated significantly below self-resonance where additional in-line low-ESR series capacitors are used to determine the Q-factor and resonance frequency. Q-factors of about 100 provide sufficient voltage and current for successful operation. This means the output voltage is 100x the input voltage in the plasma drive coil.

B) The coil, simultaneously, has sufficient impedance such that it can maintain and sometimes even induce e-field based plasma ionization due to its relatively high voltage drop and capacitive coupling with the environment. The plasma seems to be a thermal arc discharge shaped by the magnetic field.

C) Though the RF driver circuit operates at its own LC resonance, there is no particular “magic” frequency required to induce a torus within this particular gas media. A range of 15-to 30 MHz is convenient at this scale and with readily available components.

D) A high-frequency current in the drive coil induces a sympathetic eddy-current within the plasma medium in accordance with Faraday’s law of induction. In other words, the plasma torus acts as a secondary winding of a transformer, but within the plasma media. This load is coupled to the drive and draws its power from the plasma drive coil, which acts as the primary.

E) The reason for the toroid shape is that xenon can easily produce filamentary discharges (discussed below) at relatively low pressure while the induced eddy current is circular in nature. Once this loop forms, the gas-like plasma ring exhibits thermal characteristics related to the convection of warmer, less dense gas rising while cooler, more dense gas, sinks.The plasma torus, though not stationary due to thermal effects, is effectively a “nucleation” region where the additional energy of the external magnetic field sustains ionization.

Why 15 torr Xenon?

- This is a sufficiently low pressure allowing for longer mean free path than atmospheric pressure, facilitating ionization with a low power oscillator, but a high enough pressure to form filamentary discharges.
- Xenon’s high atomic weight, 131.293 g/mol[1], means the gas particles diffuse slowly. Furthermore, plasma experimenter, Carl Willis says, about one of his plasma sculptures with xenon in it: “xenon contributes a sharp filamentary characteristic because of low diffusivity” (Carl Willis).
- Xenon’s relatively low ionization energy, 12.130 eV/atom, also allows the low power, high voltage circuit to ionize xenon while other noble gases struggle to be “struck” into a toroid.[2]

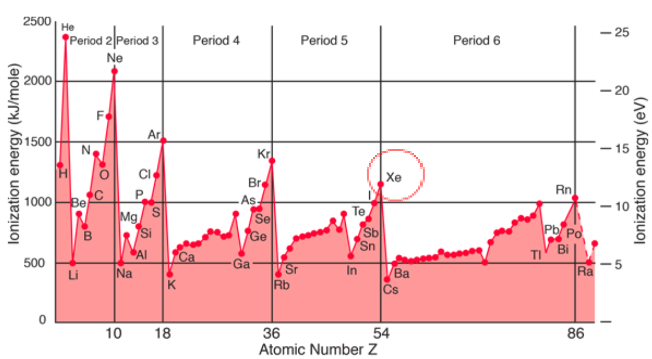

Figure 3: Ionization energy of elements, xenon emphasized

Observations:

1. An increase in current in the inductor means a stronger magnetic field around the coil, increasing eddy currents in the plasma toroid that heat the toroid, making it rise from the bottom of the globe due to convection currents (like the arc in a jacobs ladder).
2. If the input power is too low, the toroid will rotate ~90* to be perpendicular with the inductor or be destroyed by someone touching the globe.
3. If the input power is too high, the vessel will begin squeaking, and get pushed away from the drive coil until it is too far to be sustained by the eddy currents, and dissolves back to filaments.
4. If the input power is just right, the toroid is parallel to the plane of the coil and is stable, not bothered by someone touching the globe.
5. If a permanent magnet is brought near the globe, the toroid twists counter clockwise or clockwise, depending on the polarity of the magnet, but the toroid will always find a way to be attracted to the magnet, interestingly.
6. The drive coil and Cd capacitor will deliver RF burns to you if you touch them
7. The toroid can be struck by static electricity generated by rotating the globe while it is in contact with the coil or a miniscule high voltage source like the click of a nearby piezoeletric element.
8. Without a heatsink, the MOSFET will quickly overheat and die.
9. Upon interruption of the circuit with a wireless transceiver feeding PWM signals through a 1k resistor and into the mosfet gate, the toroid can be made to flicker and the interruption frequency is directly related to the minor diameter of plasma toroid.

Going forward:

- Possible other gas mixes that could "go full toroid":
    - Xenon + (iodine, bromine, or chlorine)
    - Xenon + (oxygen or nitrogen)
    - Krypton
    - Krypton + oxygen or nitrogen
    - Xenon or krypton + mercury
- Consider how thermal conductivity of xenon plays a role in toroid formation and stabilization.
    - Xenon thermal conductivity: 0.00569 (gas) W/mK (2)
    - Air thermal conductivity (@300K): 0.02623 $(gas)\ W/mK$
- Analyze system with EM software like Ansys Maxwell to model Eddy Currents
- Analyze toroid striking phenomenon with high speed videography

(Some) References

1. Prohaska, Thomas, Irrgeher, Johanna, Benefield, Jacqueline, Böhlke, John K., Chesson, Lesley A., Coplen, Tyler B., Ding, Tiping, Dunn, Philip J. H., Gröning, Manfred, Holden, Norman E., Meijer, Harro A. J., Moossen, Heiko, Possolo, Antonio, Takahashi, Yoshio, Vogl, Jochen, Walczyk, Thomas, Wang, Jun, Wieser, Michael E., Yoneda, Shigekazu, Zhu, Xiang-Kun and Meija, Juris. "Standard atomic weights of the elements 2021 (IUPAC Technical Report)" *Pure and Applied Chemistry*, vol. 94, no. 5, 2022, pp. 573-600. https://doi.org/10.1515/pac-2019-0603
2. HyperPhysics. Xenon. http://hyperphysics.phy-astr.gsu.edu/hbase/pertab/xe.html#c1 (accessed Nov 6, 2022).