Emission Spectroscopy of Atmospheric-Pressure Ball Plasmoids: Higher Energy Reveals Rich Chemistry

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Introduction

- **Ball lightning** is an unexplained natural phenomenon
  - **Sphere of light** dances through the sky during thunderstorms
  - **Several centimeters** in diameter
  - **Lives for ~10 seconds** (longer in some cases!)
  - Only **one peer-reviewed measurement** to date [1]

Figure 1. Artist's depiction of ball lightning entering a room in a home ca. 1901. Image obtained from the Wikimedia Commons.

- Plasmas at ambient conditions should recombine within a few milliseconds [2,3]:
  - Collisions are frequent at high pressure…
  - No external power source…

What is stabilizing ball lightning?

- **Ball plasmoids**: laboratory analogue of ball lightning; used to probe possible stabilization mechanisms

Circuitry

- **Capacitive discharge** over **grounded electrolyte** [4,5]
- DC power supply charges a capacitor bank; **1.958 mF max**
- Plasmoids are generated at between **5000 V and 8000 V**
- Discharge energy is on the order of **tens of kiloJoules**
- High current: tens of Amps; highest **126 Amps**
- Electrode submerged in electrolyte; cathode protrudes 1-2 mm

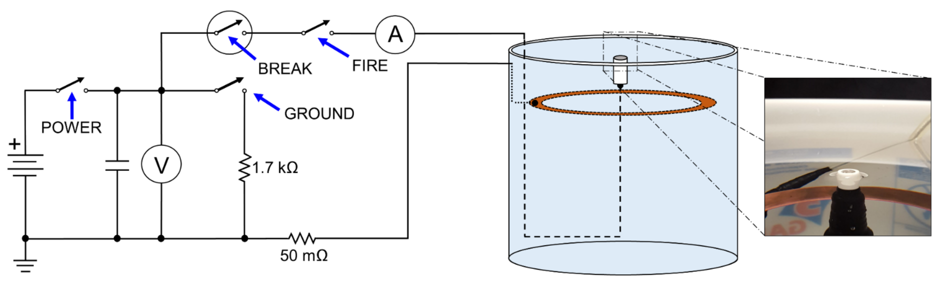
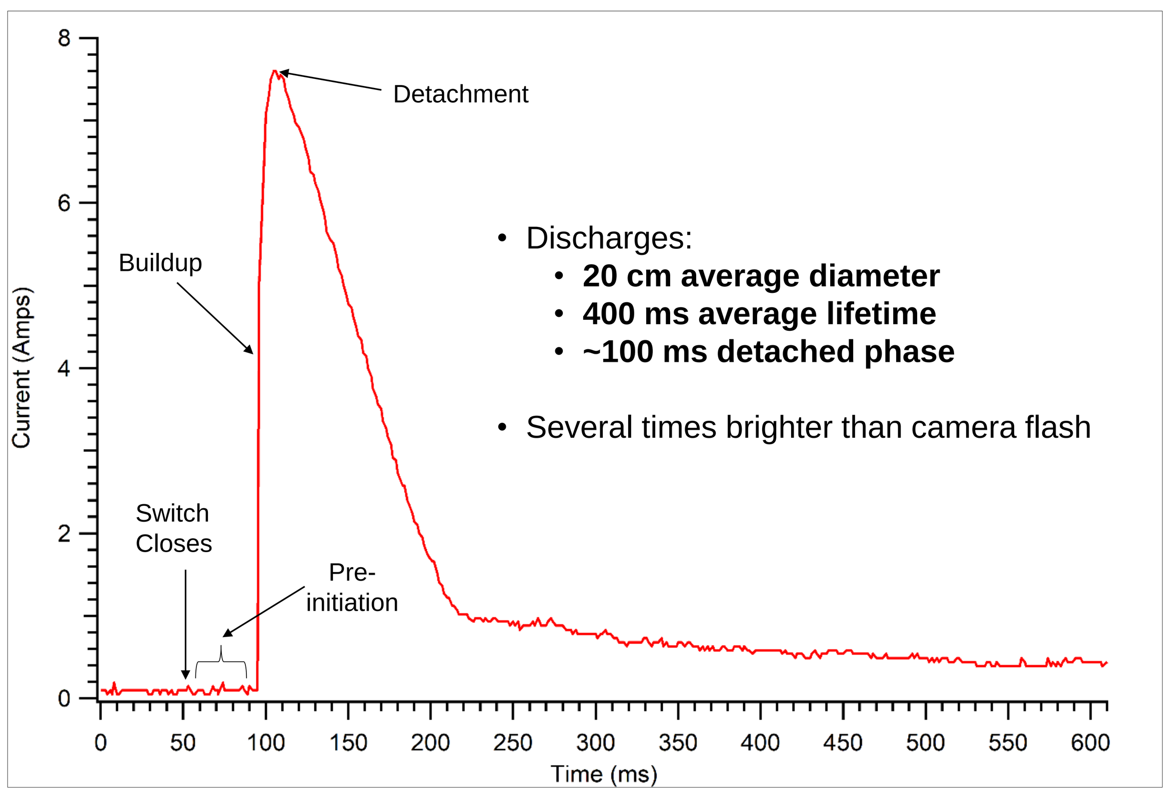


Figure 2. Schematic of discharge circuit. A and V are a Hall effect sensor and voltage divider.

- Arduino controls **timing**; records **current**, **voltage**, other signals
- External instruments isolated from discharge circuit

Figure 3. Photos of switching box and electrode setup.

Ball Plasmoids



- Discharges:
  - **20 cm average diameter**
  - **400 ms average lifetime**
  - **~100 ms detached phase**
- Several times brighter than camera flash

Figure 4. A current trace of a 7000 V ball plasmoid discharge. Phases of the discharge are labeled.

Three phases of plasmoid formation [6]:

1. Pre-initiation
   a) Current begins to flow
   b) Builds to cathode spot threshold
2. Buildup
   a) Plasma forms at cathode
   b) Streamers extend over electrolyte
   c) Current increases rapidly
3. Detachment
   a) Current reaches maximum
   b) Ball lasts with no external power

Link to video:

https://youtu.be/QI_8ewdnflw

Figure 5. A series of images obtained from plasmoid discharge shown in Figure 4 at 7000 V. Images recorded with a Phantom V5.2 high-speed camera at 1000 fps (990 µs exposure time) at a resolution of 1152 x 896 pixels (images are cropped to remove dark space). Scale bar included is 10 cm.

Previous Work

- Mass Spectrometry:
  - Formation of ions around metallic center (from cathode)
  - Water clusters
  - Deuterium substitution: electrolyte composition matters
- FTIR Emission Spectroscopy:
  - Emission from excited water and hydroxyl radical
  - Rotational temperatures agree with previous data

A Metastable Furnace?

- Nitrogen is the **major component of air**… is it involved in ball plasmoid chemistry/physics somehow?
- Nitrogen **metastable** electronic states have **long radiative lifetimes** [7]
- **Associative ionization** and **energy pooling reactions** of nitrogen are known [8]: is this a source of secondary electrons?

R1. N_2 (A, 6.22 eV) + N_2 (a', 8.57 eV) → N_2^+ (X, 15.58 eV) + N_2 (X) + e^- -0.79 eV (1)

R2. N_2 (a', 8.57 eV) + N_2 (a', 8.57 eV) → N_2^+ (X, 15.58 eV) + N_2 (X) + e^- +1.56 eV (2)

Nitrogen $B^3\Pi_g \rightarrow A^3\Sigma_u^+$ is accessible in the optical; signals would indicate population of A state

Emission Spectroscopy

Will we see signals from nitrogen B-A?

Instruments:

- Ocean Optics S2000: 200-500 nm, 0.5 nm resolution
- Ocean Optics Jaz: 250-800 nm, 0.7 nm resolution
  - measurements made with optical fiber
- Wavelength and intensity calibration with external sources
- Internal trigger: continuously fire when signal is >2% higher than dark current

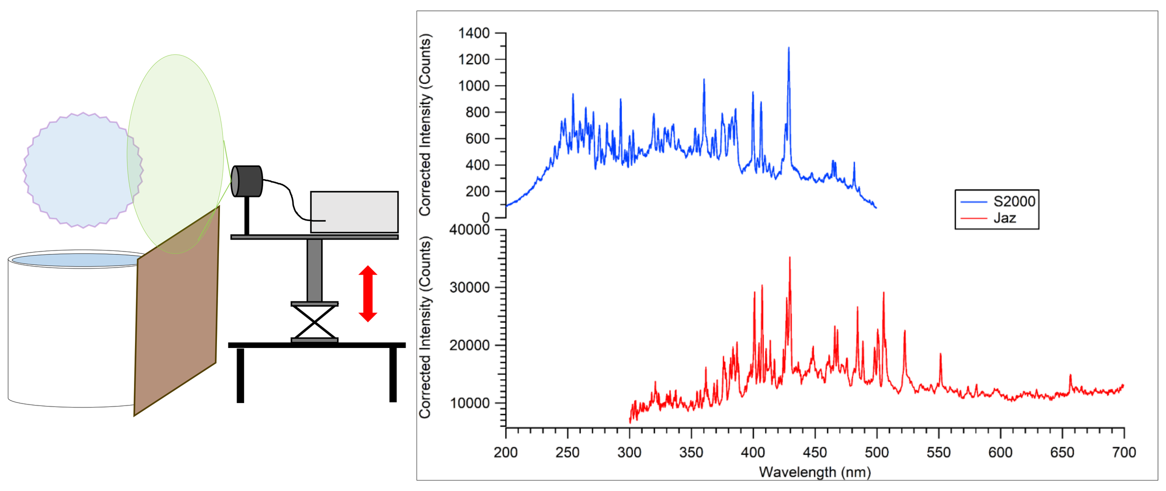


Figure 6. "Whole plasmoid" OES experiment. Left: optical setup; Right: example emission spectra. Spectra were recorded with different instruments under the same discharge parameters: tungsten electrode, 7000 V.

"Whole Plasmoid" Experiment:

- Spectrometer's field of view encompasses entire discharge
- Screen blocks emitted light from hot cathode
- Emission lines from W I, H_α, O I, OH, AlO
- Continuum emission: Triatomics? Thermal / Bremsstrahlung radiation?

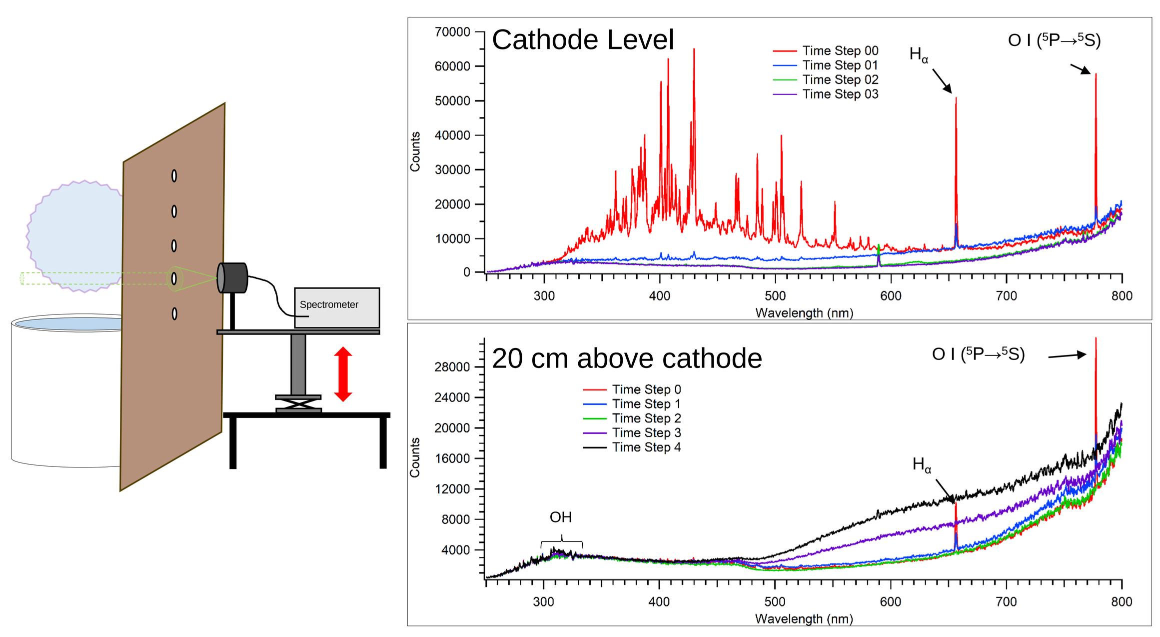


Figure 7. "Height resolved" OES experiment. Left: optical setup; Right: example emission spectra– top: cathode level, bottom: 20 cm above cathode. Spectra were obtained with the same instrument under identical discharge conditions; tungsten electrode, 7000 V.

"Height Resolved" Experiment:

- Five (5) holes cut into tall screen
- Holes oriented vertically along axis of discharge at 0, +10, +20, +30, +40 cm
- Spectra recorded as plasmoid passes hole
- 0 cm: very rich, many atomic signals
- 20 cm and above: H_α and O I ($^5P \rightarrow {}^5S$) and continuum signals persist

Varied Parameters

Discharges with different electrodes generate vastly different spectra:

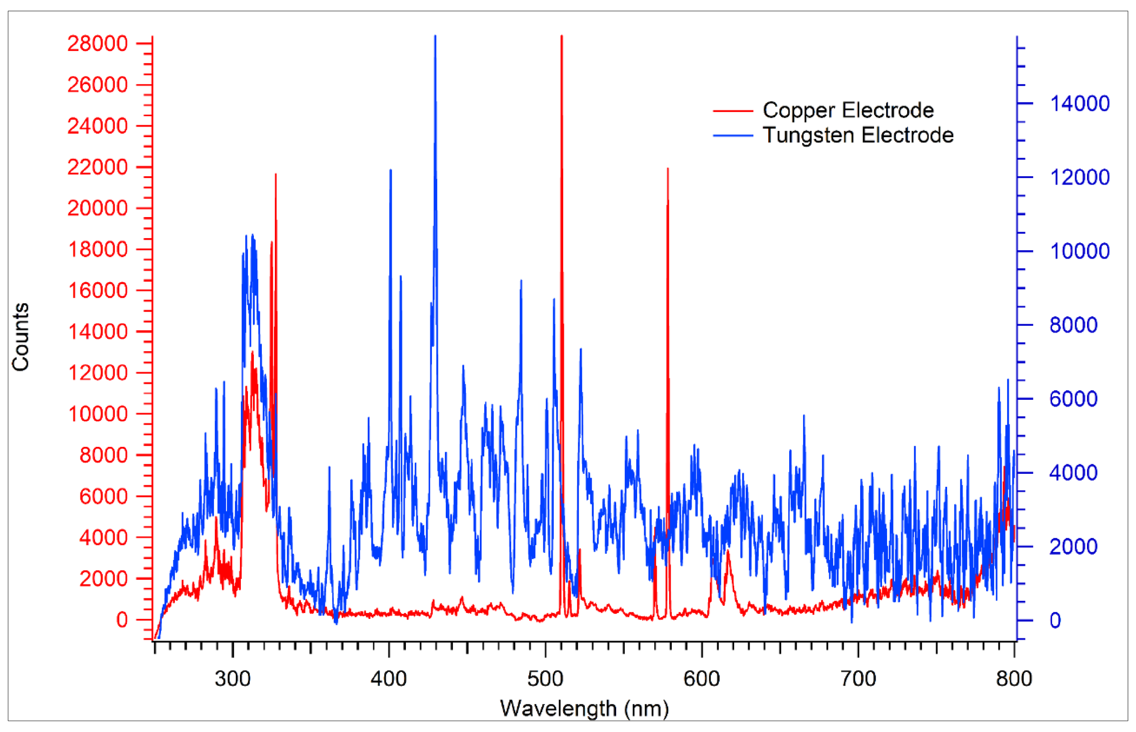


Figure 8. Spectrum obtained from a tungsten electrode (blue) overlayed with a spectrum obtained from a copper electrode (red). Spectra were recorded with the Ocean Optics Jaz instrument from 7000 V discharges under identical conditions.

Increasing discharge potential increases overall spectral intensity (continuum) and S/N of atomic/molecular signals:

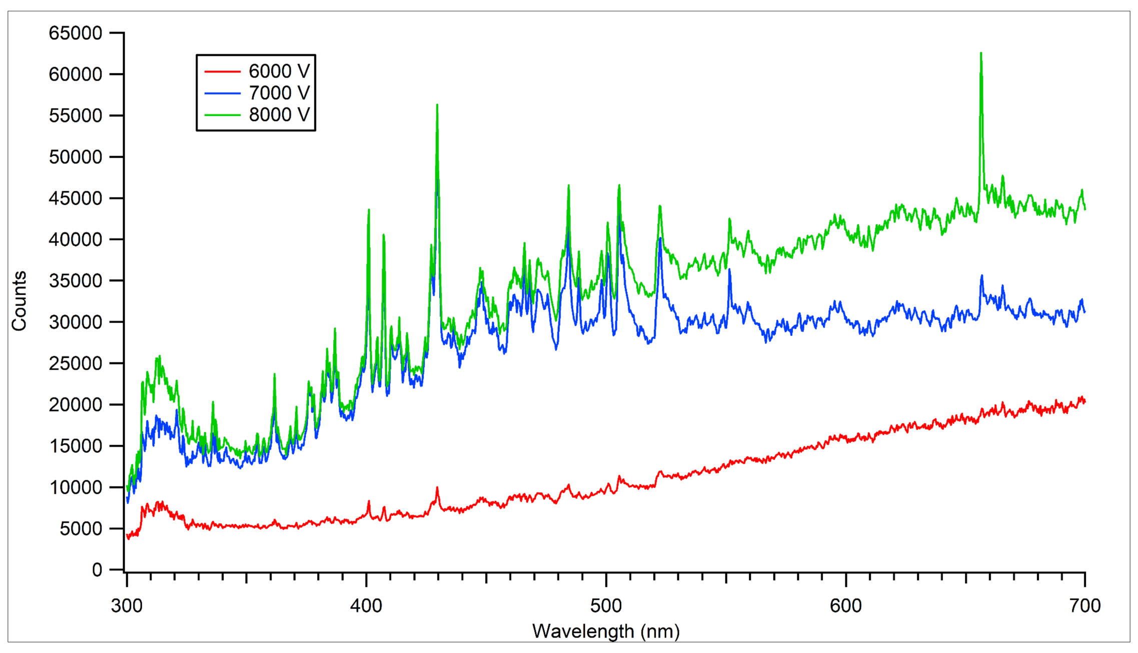
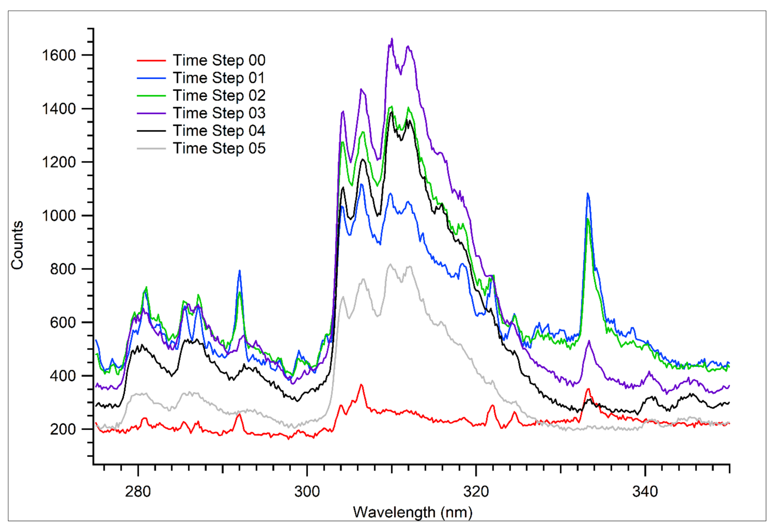


Figure 9. Spectra obtained from ball plasmoid discharges at three different voltages. Discharges were performed under identical conditions (other than voltage).

Quantitative Results

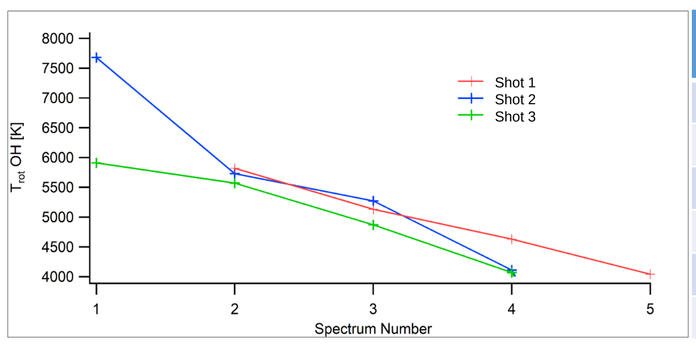
OH Emission Region: Simulate and fit with PGOPHER



#	T_{rot} OH [K]
0	No emission
1	4540 ± 490
2	3680 ± 360
3	3700 ± 350
4	3670 ± 350
5	3790 ± 370

Figure 10. Emission signals from OH radical used for extracting rotational temperatures. The temperatures are reported in the table (right). Names of traces follow the pattern "date_discharge_spectrum."

OH rotational temperature starts high, decreases over time



#	T_{rot} [K] Shot 1	T_{rot} [K] Shot 2	T_{rot} [K] Shot 3
0	No emission	No emission	No emission
1	No emission	7680 ± 900	5910 ±740
2	5820 ± 730	5730 ± 720	5570 ± 700
3	5130 ± 650	5270 ± 670	4870 ± 620
4	4630 ± 590	4110 ± 520	4070 ± 500
5	4040 ± 510	No emission	No emission

Figure 11. Plots of OH rotational temperature vs. spectrum number (time) for three successive ball plasmoid discharges. Temperatures are tabulated on the right.

Underlying continuum is not entirely a blackbody; likely cause is emission from triatomic species combined with some thermal / Bremsstrahlung radiation

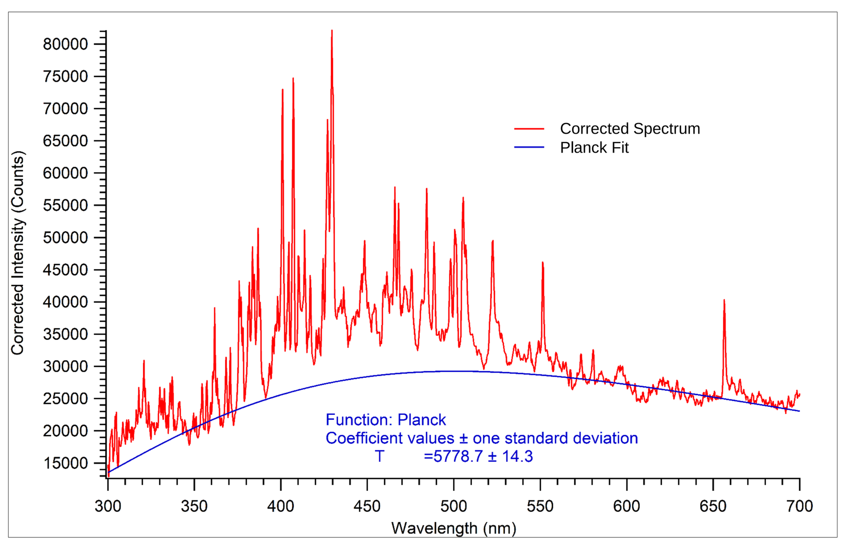


Figure 12. Example of a Planck function fit to an emission spectrum.

Summary

- Identified signals from W I, H_α, O I, OH, AlO
  - Some signals persist late into the discharge
  - Are atomic oxygen and hydrogen critical to plasmoid stabilization?
- First time-resolved measurements of OH rotational temperature in ball plasmoids
  - High temperature early in discharge, decreases over time
  - OH temperature agrees with previous measurements [9]
- First continuum analysis of ball plasmoid emission spectra

Microwave Interferometry

- X-band interferometer operating at **~9.2 GHz**
- Measure **phase shift** and **attenuation** of beam induced by plasmoid
- Calculate **electron column density** as a function of time [10]
- Deduce primary electron **recombination mechanism**?

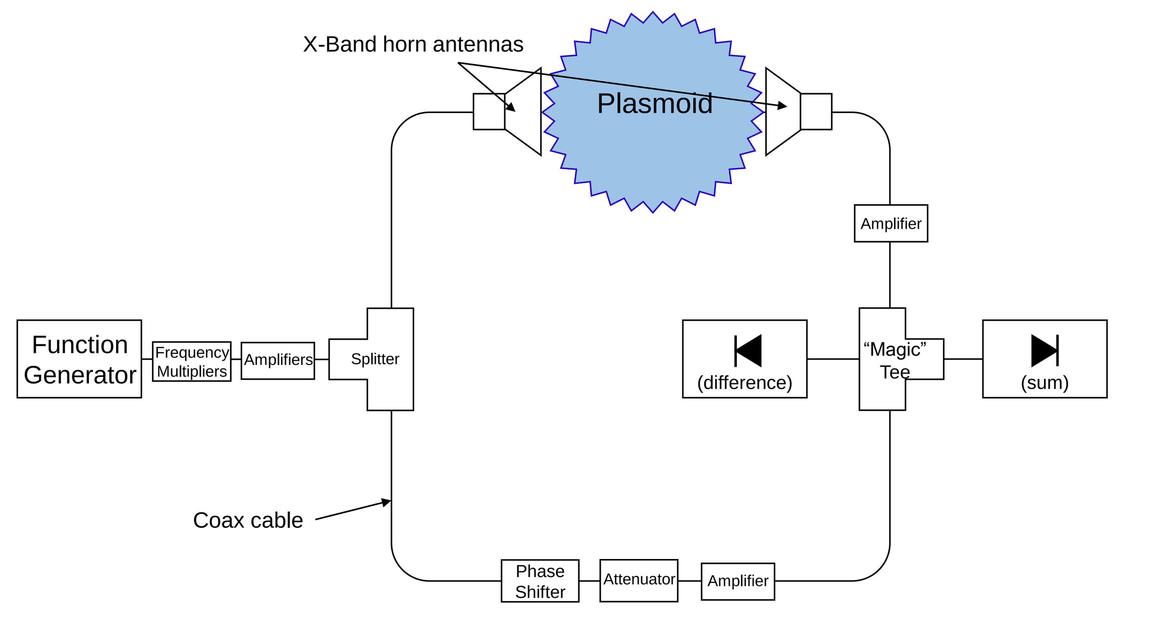


Figure 13. Proposed design of full-bridge X band microwave interferometer for electron density measurements.

References

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