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# Temporal and Spatial Dynamics of a Bipolar Pulsed Plasma at Audio Frequency

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### 1. Introduction

- Investigating techniques for plasma cleaning of electrodes in/near the convolute region on Z to reduce current loss by delaying/reducing plasma generation from surface contaminants that leads to gap closure.
- Our technique of using audio-frequency bipolar square waves of voltage/current for plasma cleaning is highly effective when compared to conventional method of rf discharge cleaning.
- What mechanisms contribute to this effectiveness?
  - What differences in plasma properties between square waves and rf play a role?
  - Why does audio frequency work, not dc?
- Preliminary modeling efforts attempt to address questions raised by experimental observations and study mechanisms contributing to the effectiveness of square waves.
- Scaled experiments investigate temporal-spatial plasma dynamics by optical techniques.

### 2. Observation with Plasma Test Bed

**Optical Emission Spectroscopy**

- Asymmetric parallel-plate assembly in a 700-liter cylindrical vacuum chamber.
- OES signals analyzed for plasmas generated by 10 kHz bipolar square wave vs. 13.56 MHz rf using 80/20% Ar/O<sub>2</sub>.
- Plasma generated by square wave at similar powers looks visibly "bluer".
  - Confirmed by OES signals showing stronger lines in 'blue' region. Most of the peaks identified as ion lines.
  - Bluer lines → higher-energy transitions → higher electron energy → higher ionization?
  - Higher ion density/flux to electrode surface?

### 4a. Dynamics of Square-Wave Plasma

**Plasma Induced Emission**

- ICCD camera to capture plasma formation during pulses.
- Streak-like images revealed pressure-dependent dynamics.
  - Collisionality dependence?
- PIE showed that "active" plasma occurs largely during the cathode phase.
  - Localized vs. diffused at high vs. low pressures.
- During the anode phase, plasma persists for short duration.
  - More energetic at higher pressure.

**Evolution of Argon Metastable**

- Probe plasma excitation state and track dynamics by measuring Ar 1s<sub>5</sub> metastable concentration.
  - Diode laser absorption: probe 811.5-nm Ar 1s<sub>5</sub>→2p<sub>9</sub> transition.
  - Planar LIF: excite Ar from 1s<sub>5</sub> to 3p<sub>2</sub> state, monitor 418.2-nm 3p<sub>2</sub>→1s<sub>3</sub> transition.
- Plasma region switches between powered /grounded electrodes.
- Drastically reduced metastable concentration end of anode phase, onset of metastable generation in anode-to-cathode transition.

### 3. Modeling and Simulation

- Scoping study to address questions raised by experimental observations.
  - PIC for coupled particle-field plasma simulation.
  - DSMC for particle kinetics/chemistry.
- Modeling expedients taken:
  - gas was neon (existing set of neon chemistry; vetted cross section).
  - 1D3V: 1-cm domain.
  - 500 kHz (reduced computational time) – quasi-steady state in <1 μs.
- Polarity switch in low-frequency square wave causes much more abrupt potential variation than sinusoids to support interesting transport phenomena; ions will not see electric field at high frequency.

**Polarity Reversal**

- Electron pulsing: generation of a "wave" of higher temperature electrons leading to more ionization.
- "Sheath capture" of low energy ions: a higher density bolus of ions that are accelerated to the wall when the polarity switches.
- Plasma state at beginning of polarity switch.
  - Deep vs. shallow (at 110 ns vs. 0 ns) sheath structure at left boundary.
  - A population of ions "captured" and will be accelerated into the wall.
  - Increased electron temperature at 228 ns.

### 4b. Waveform Tailoring?

- Argon metastable and plasma emission suggest asymmetry in plasma dynamics during anode/cathode phase leading to asymmetric plasma generation and energy deposition into the electrodes.
- Data suggest strong plasma generation during cathode phase.
  - Energy deposition into powered electrode straight-forward.
- Plasma generation during anode phase responsible for energy deposition into grounded electrode.
  - LIF data show significant electron density decay during phase.
  - Data suggest "useful" work (i.e. cleaning) possibly occurs only during short duration associated with initial current spike.

Would reducing duty cycle (i.e. time spent in anode phase) produce more efficient cleaning by more optimal use of time spent in anode phase?

- Preliminary study suggests stronger, more persistent plasma generation during shortened anode phase.
- Effect due to higher peak current resulting from reduced duty cycle? Or plasma potential remaining higher than electrode potential due to shortened time spent in anode phase → higher ion flux?