45th International Symposium of the American Vacuum Society
Baltimore, Maryland
November 2-6, 1998.

MULTI-FREQUENCY OPERATION OF RIE AND ICP SOURCES*

Shahid Rauf and Mark J. Kushner
Department of Electrical & Computer Engineering
University of Illinois, Urbana-Champaign

*Work supported by AFOSR/DARPA, SRC and NSF.

AGENDA

- Introduction
- Computational Model
- Asymmetric Capacitively Coupled Discharge
    - Electrode Currents and Voltages
    - Effect of Frequency, Voltage Waveform and Source Interaction
- Inductively Coupled Plasma
    - Electrode Currents and Voltages
    - Effect of Frequency and Source Interaction
- Conclusions

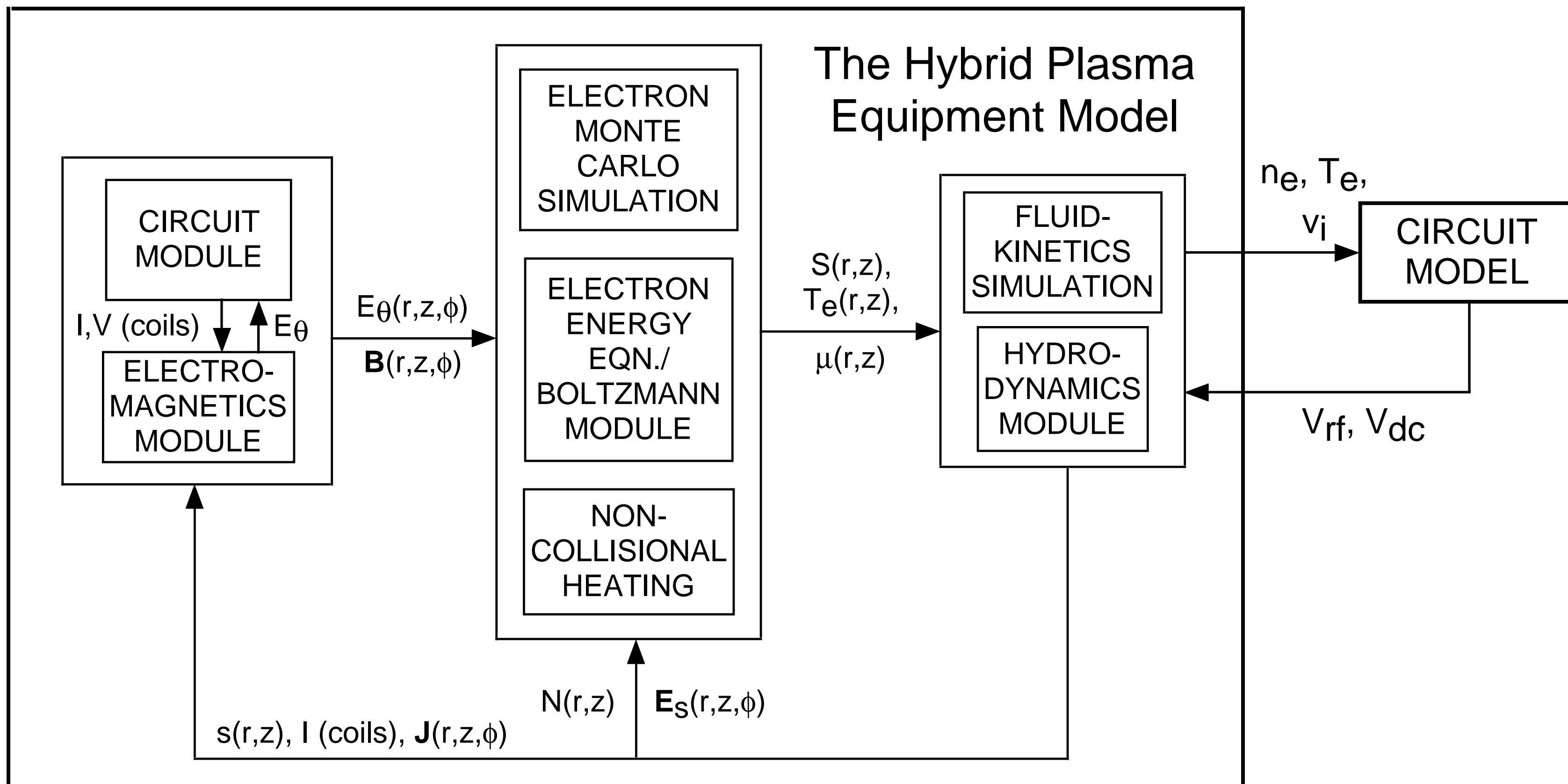
Optical & Discharge Physics
University of Illinois

INTRODUCTION

- Source frequency has a strong influence on plasma characteristics in radio frequency (rf) discharges.
- Multiple sources at different frequencies are often simultaneously used to separately optimize the magnitude and energy of ion fluxes to the substrate.
- The sources can, however, nonlinearly interact if the frequencies are sufficiently close, and resulting plasma and electrical characteristics can be different than due to individual sources.
- A plasma equipment model has been used to investigate the interaction of multiple frequency sources in both capacitively and inductively coupled discharges.
- In this talk, we discuss the effect of frequency on plasma and electrical characteristics, and describe the consequences of source interactions.

THE COMPUTATIONAL MODEL

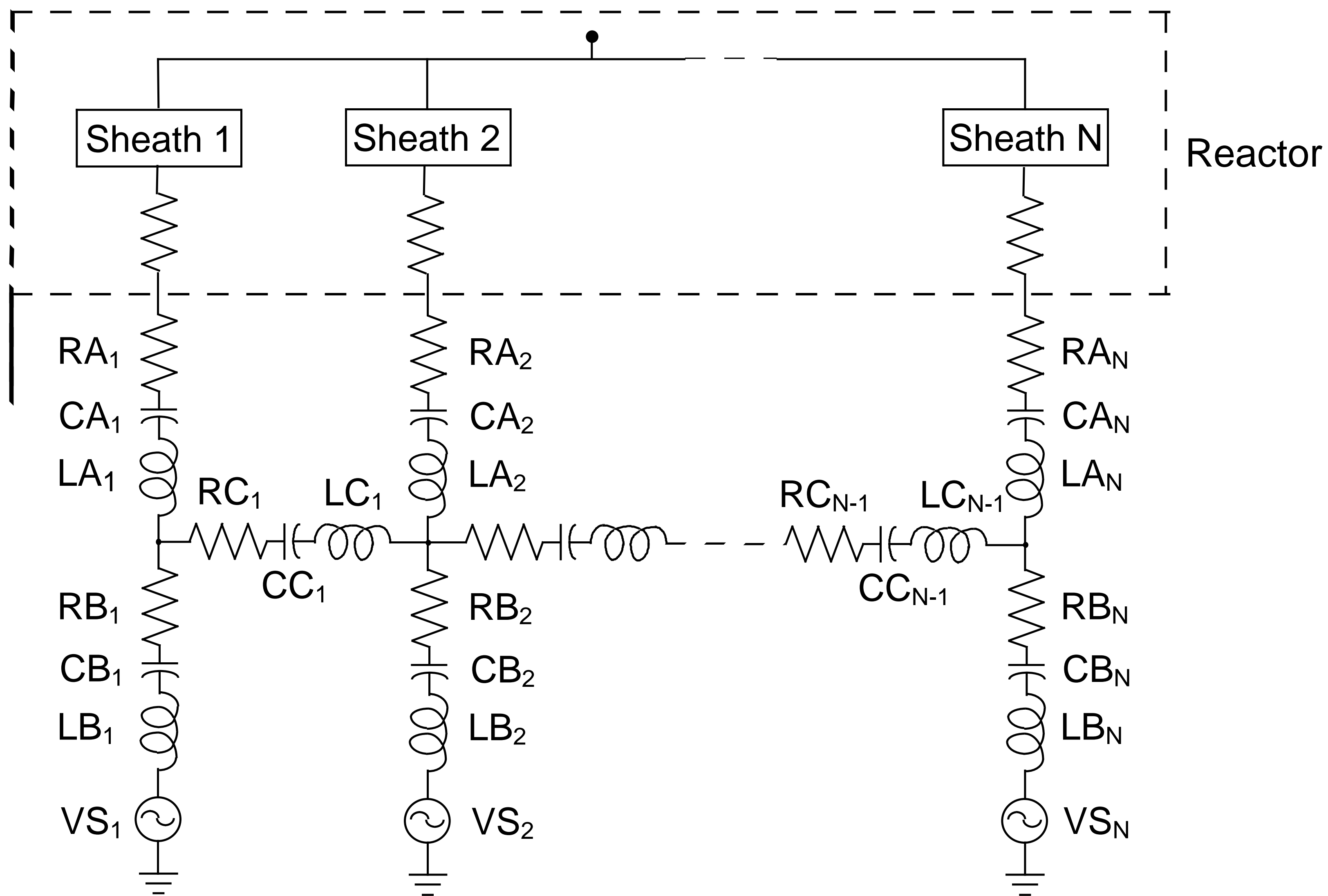
- Our computational platform consists of the coupled Hybrid Plasma Equipment Model (HPEM) and a circuit model.
- The circuit model uses intermediate results from the HPEM to compute voltages (dc, fundamental and harmonics) at electrodes.



Optical & Discharge Physics
University of Illinois

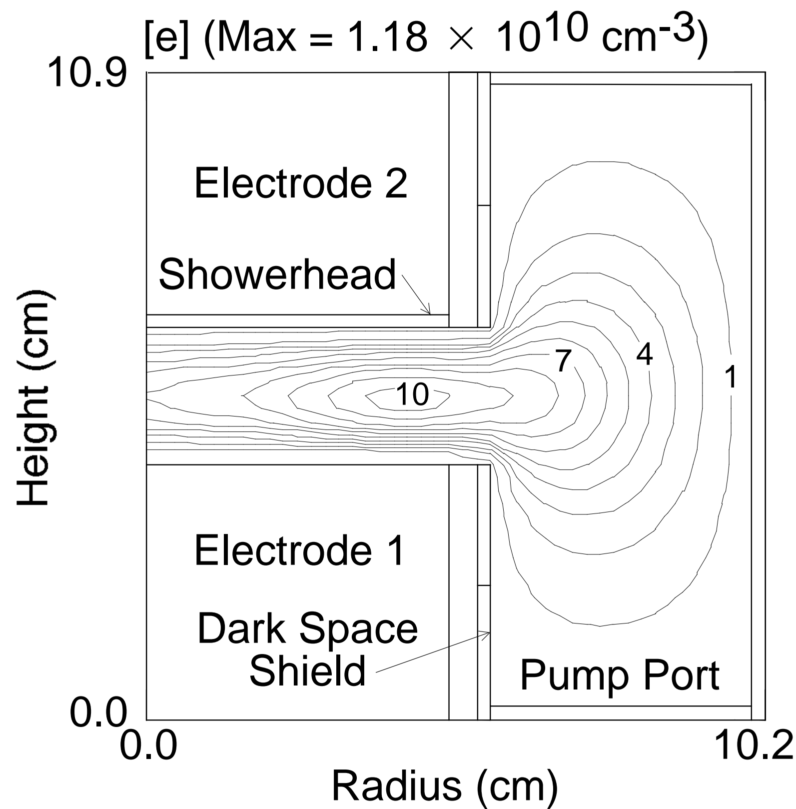
SHEATH-CIRCUIT MODEL

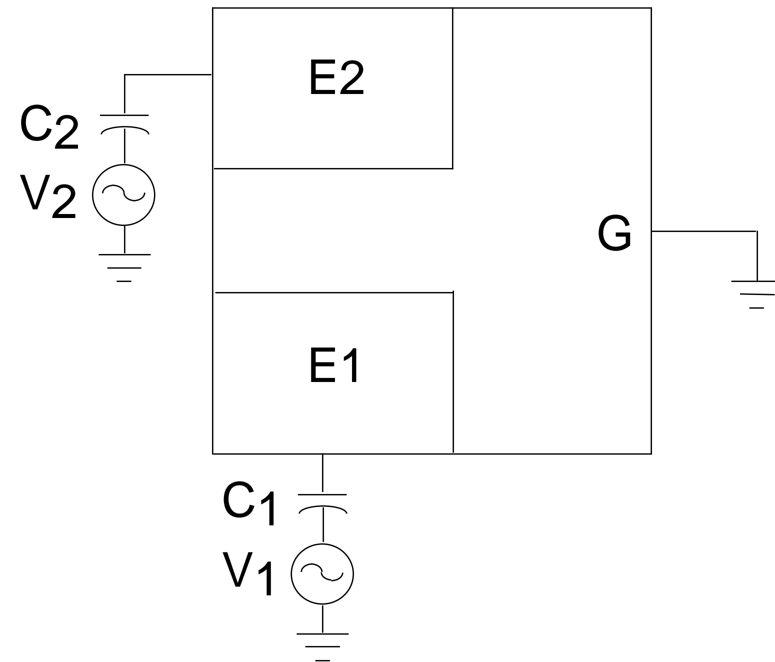
- The reactor and circuitry are replaced by the following equivalent circuit.



GEC REFERENCE CELL

- We first explore the effects of frequency and source interactions in the capacitively coupled GEC reference cell with Ar at 100 mTorr.
- Sources and blocking capacitors have been connected to both electrodes.



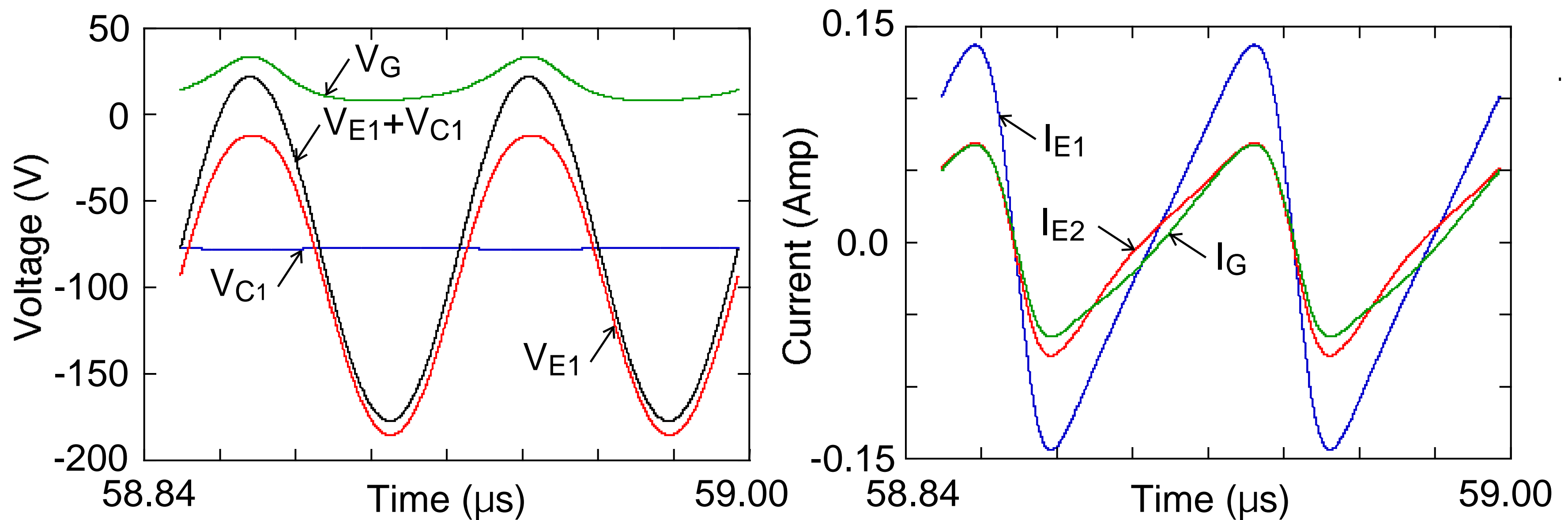


- Ar, 100 mTorr, V_1 = 100 V, V_2 = 0 V.

Optical & Discharge Physics
University of Illinois

SHEATH VOLTAGES AND CURRENTS

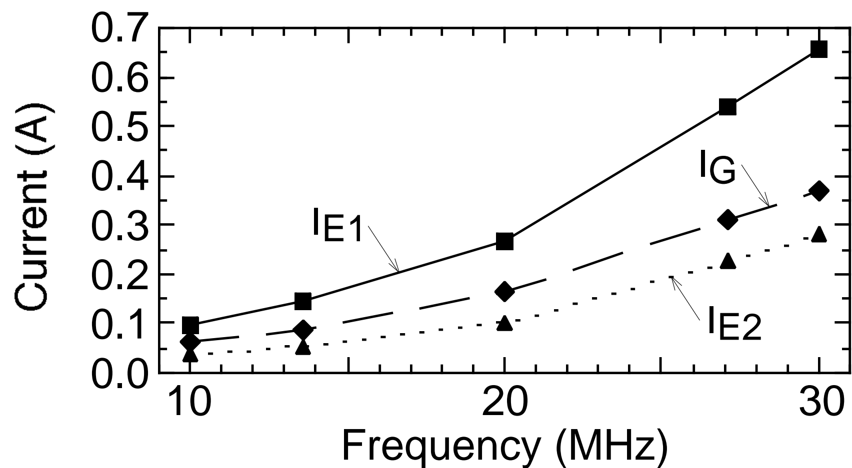
- A negative dc voltage appears across the capacitor C_1 (dc bias) to balance currents through the powered and grounded surfaces.
- The sheath currents are fairly nonlinear with large higher harmonics.

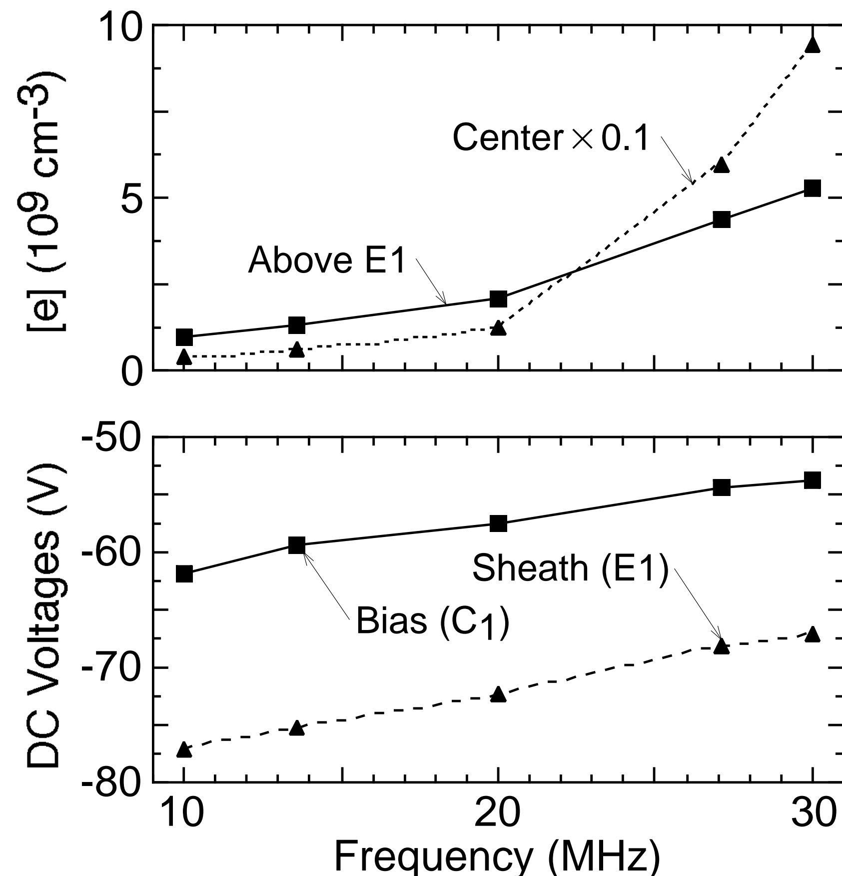


- Ar, 100 mTorr, V_1 = 100 V, V_2 = 0 V, 13.56 MHz.

EFFECT OF SOURCE FREQUENCY

- Total current through electrodes and walls increases with frequency because of enhancement of displacement current.
- Larger current leads to more electron heating and larger electron densities.
- Electron temperature decreases with frequency, resulting in better electron confinement between electrodes and smaller dc biases.





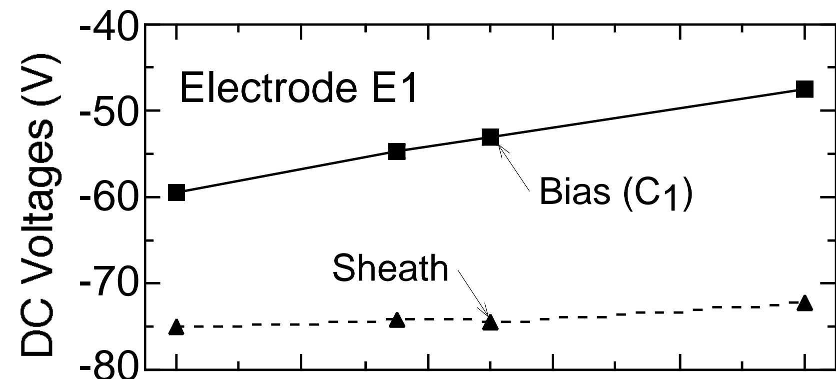
- Ar, 100 mTorr, V_1 = 100 V, V_2 = 0 V.

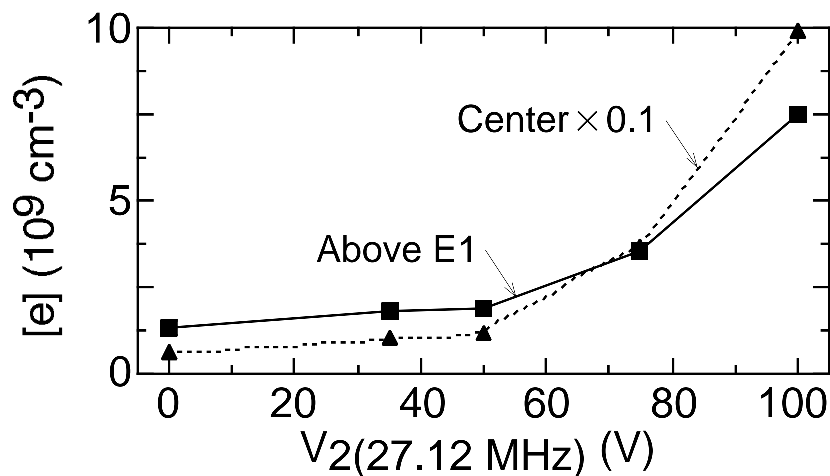
Optical & Discharge Physics
University of Illinois

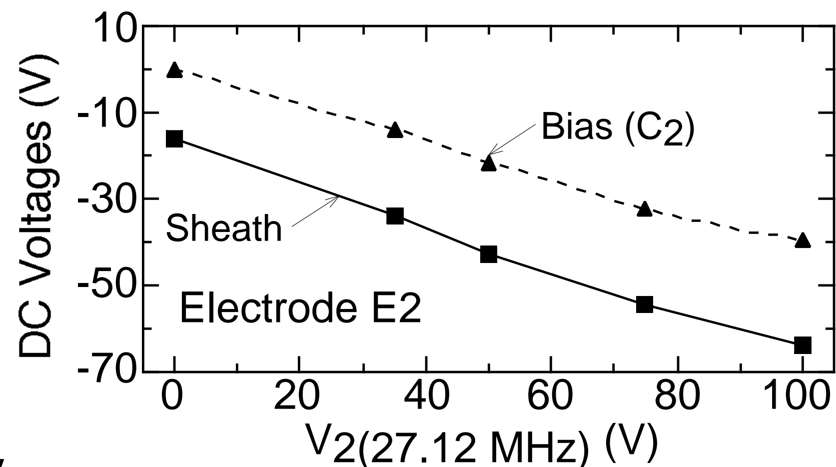
AVS98_P1_F7

INTERACTION OF MULTIPLE FREQUENCY SOURCES - I

- In these results, a 13.56 MHz source (V_1=100 V) is connected to E1 while a 27.12 MHz source is connected to E2.
- Electron density increases with V_2 (27.12 MHz) due to the enhancement of displacement currents.
- The dc bias magnitude on E1 decreases with increasing V_2 (27.12 MHz) due to source interactions.



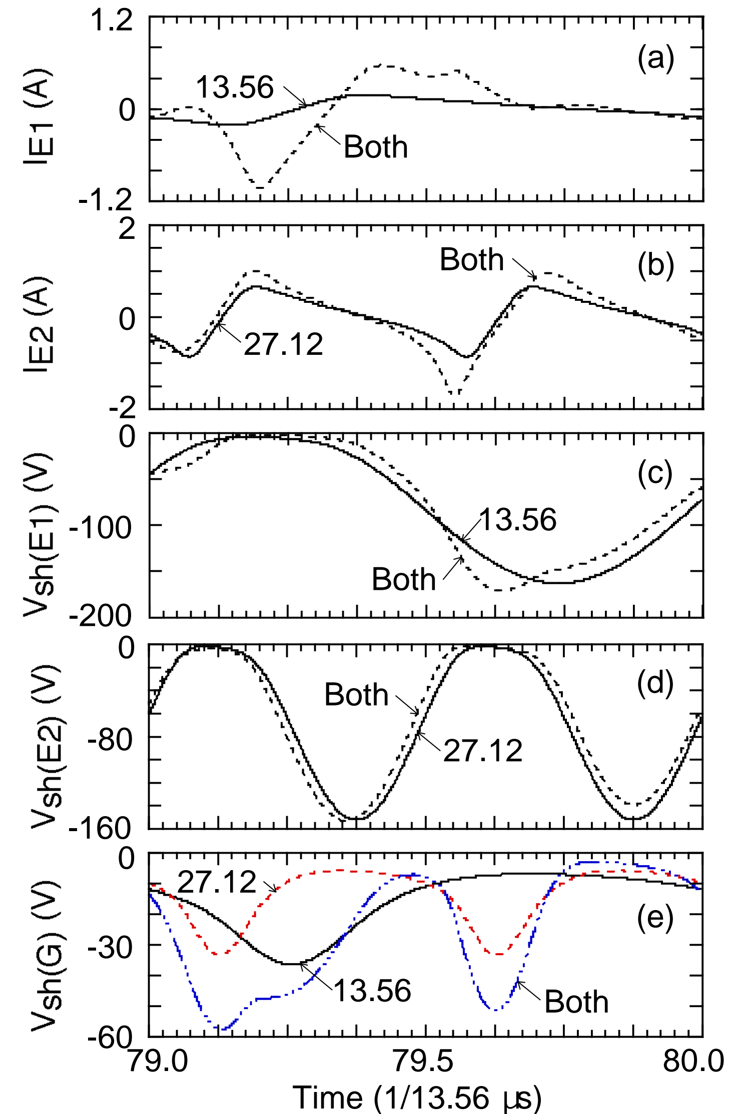




- Ar, 100 mTorr, V_1 (13.56 MHz) = 100 V.

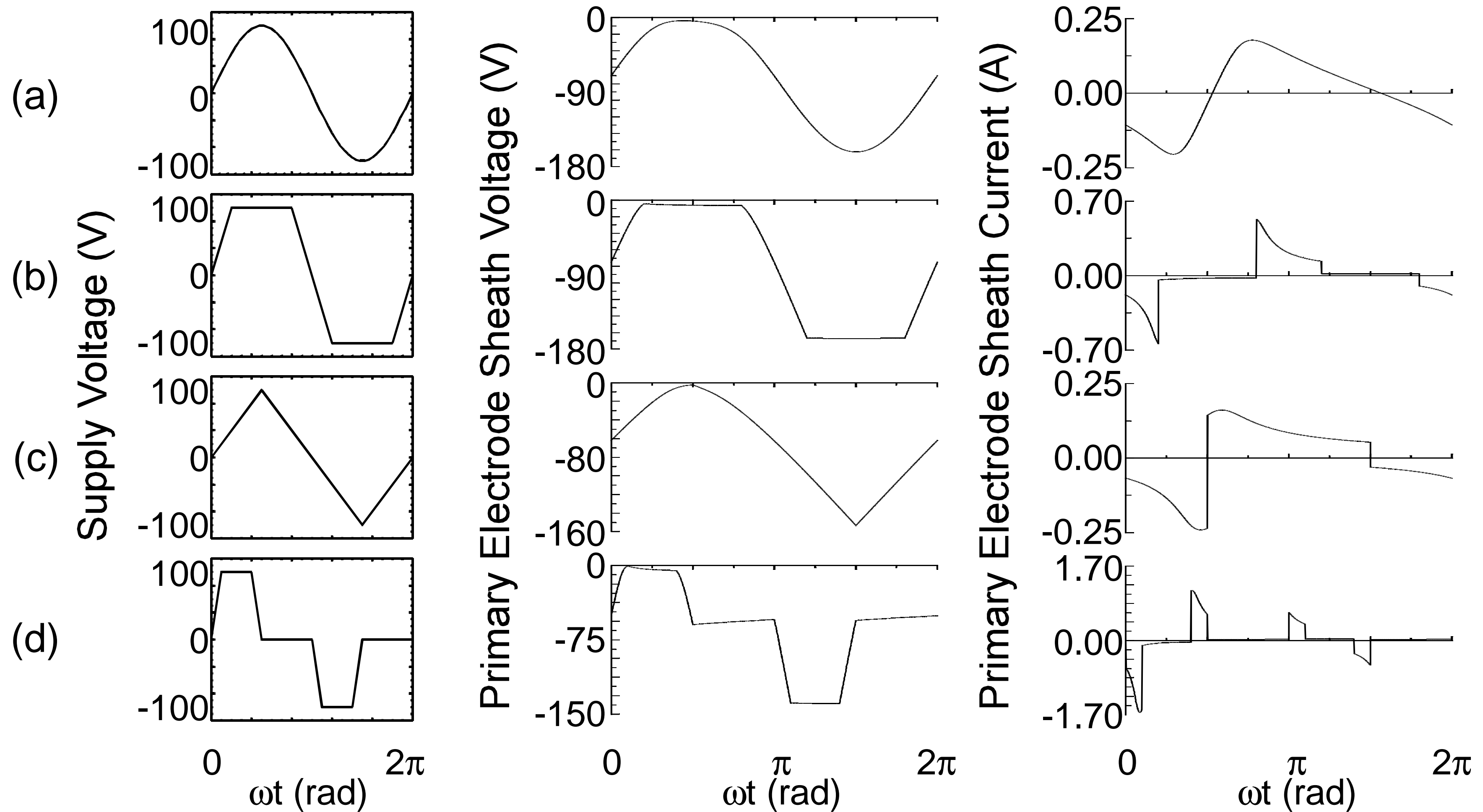
INTERACTION OF MULTIPLE FREQUENCY SOURCES - II

- In these results, we show the sheath voltages and currents for only the 13.56 MHz source, 27.12 MHz source and their combination.
- Sheath voltages at E1 and E2 are primarily governed by the sources connected to them.
- The sheath voltage at the grounded wall is, however, in the linear regime and the two sources interact increasing the sheath voltage drop.
- DC bias at E1, which is the difference between the dc sheath voltage at E1 and wall, therefore decreases in magnitude.



ARBITRARY VOLTAGE WAVEFORMS

- By varying the rf bias voltage waveform, one can control the dc bias, sheath voltage, plasma characteristics and the ion energy distribution at the substrate.

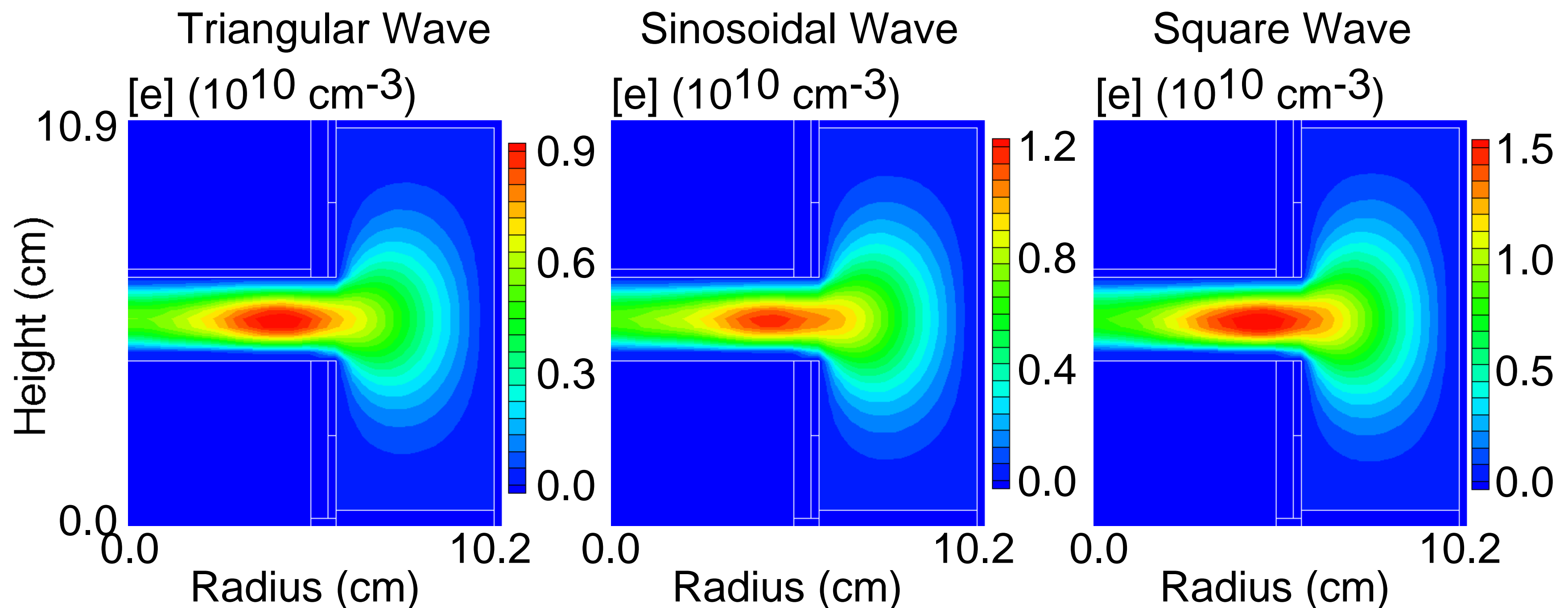


Optical & Discharge Physics
University of Illinois

AVS98_P1_F17

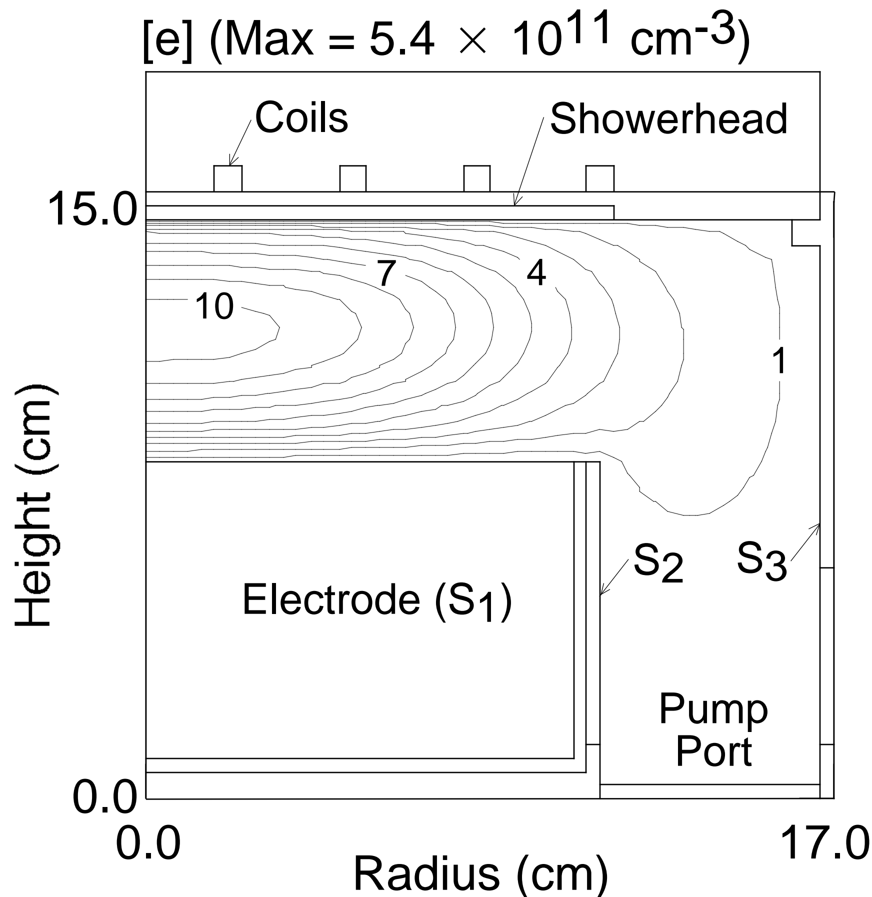
EFFECT OF WAVEFORM ON PLASMA PARAMETERS

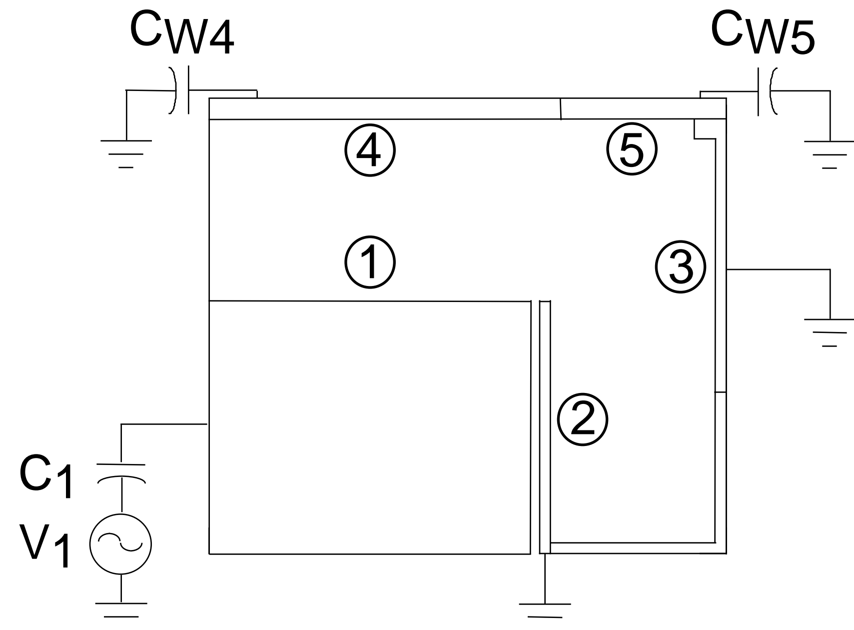
- Waveforms which have higher first harmonic lead to larger dc biases.
- Higher first harmonics also lead to enhanced power deposition in the plasma and higher electron densities.
- Since displacement current increases with frequency, waveforms with larger amplitudes at higher harmonics result in larger plasma densities.



INDUCTIVELY COUPLED PLASMA (ICP) SOURCE

- We next consider the effects of rf bias frequency and rf source interaction in an ICP reactor.
- For circuit simulation, the dielectric window is replaced by effective capacitors.

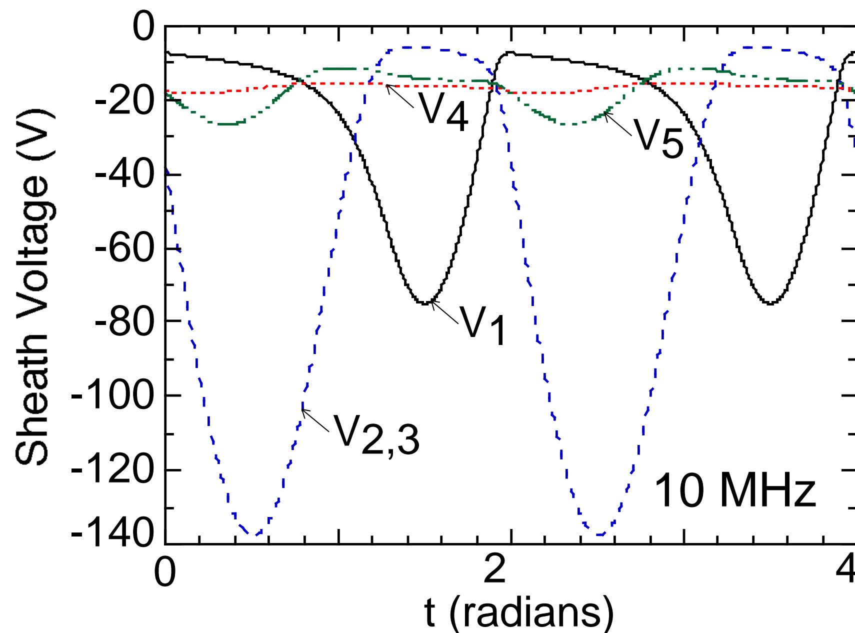


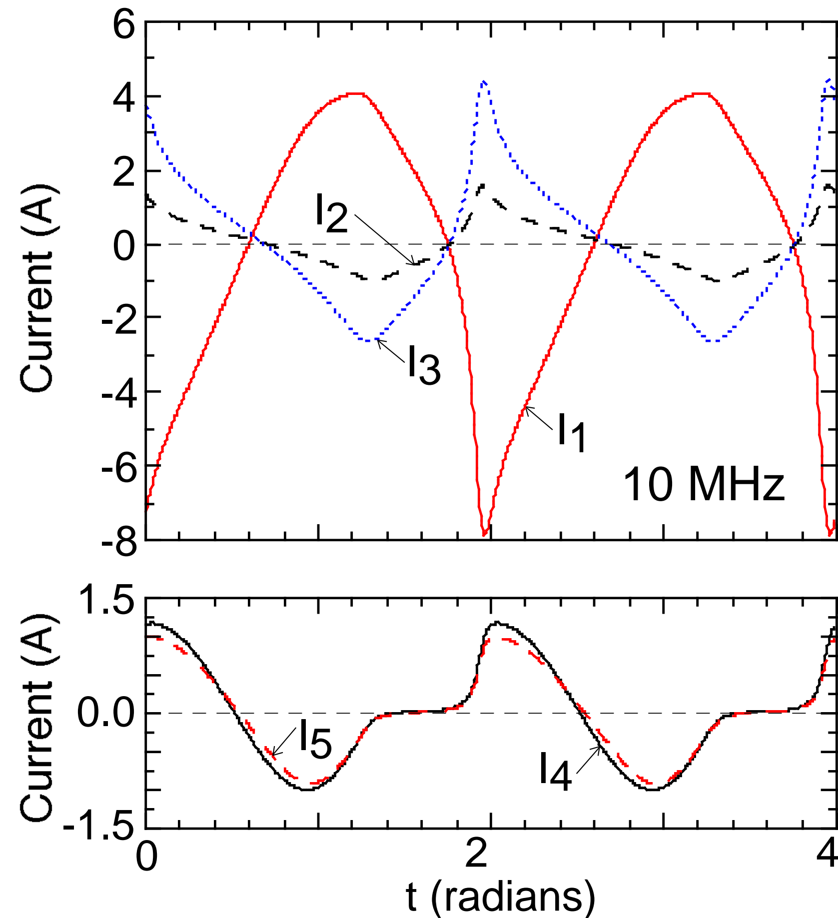


- Ar, 20 mTorr, 500 W, V_1 (13.56 MHz) = 100 V.

TYPICAL SHEATH VOLTAGES AND CURRENTS

- Most of the rf current flows out through the grounded surfaces.
- Sheath voltage is larger near the grounded walls at 10 MHz because of low plasma density (i.e., high impedance) adjacent to them.



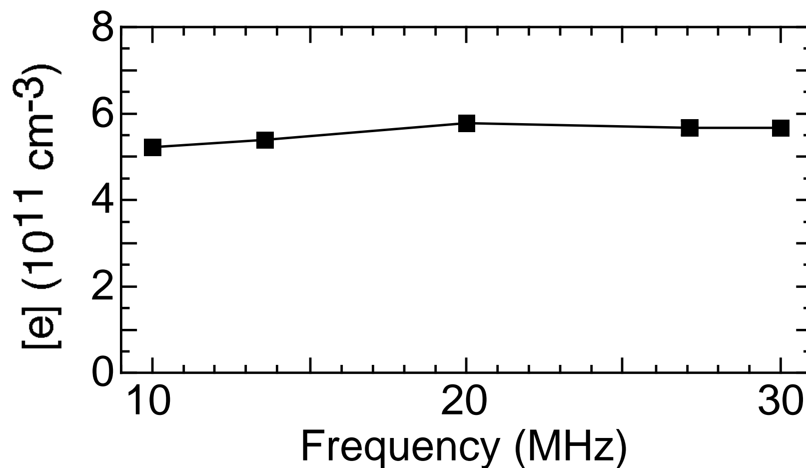


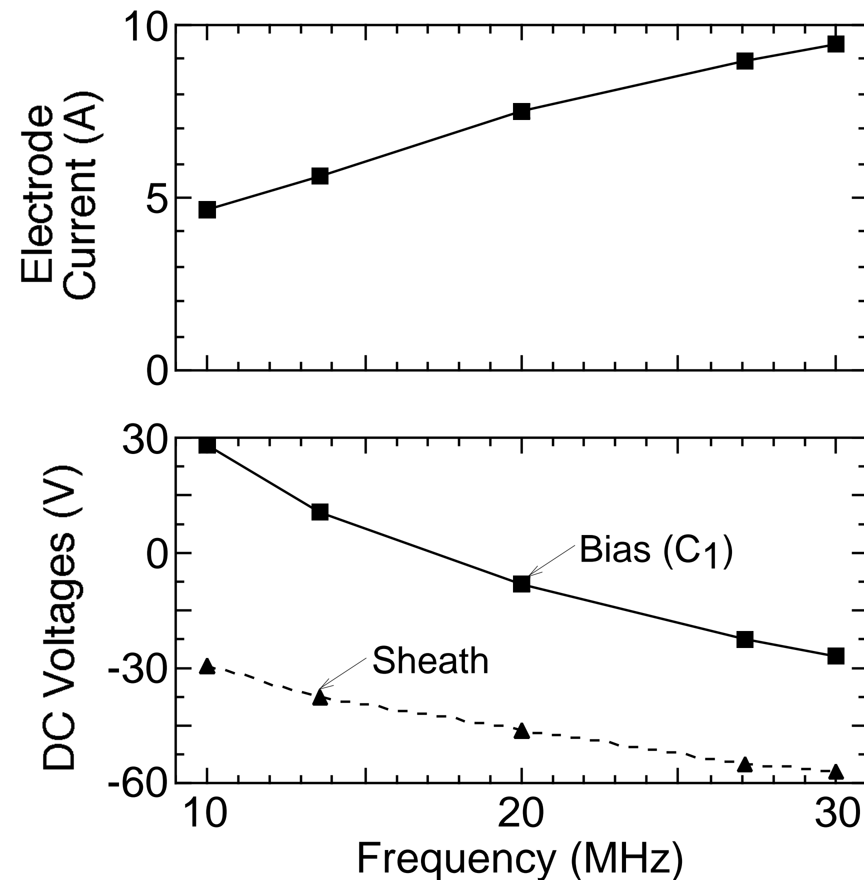
- Ar, 20 mTorr, 500 W, V_1 (10 MHz) = 100 V.

Optical & Discharge Physics
University of Illinois

EFFECT OF RF BIAS SOURCE FREQUENCY

- Since plasma is generated by the inductive source, rf bias frequency does not significantly affect the electron density.
- Displacement current through the sheaths increases with bias frequency, enhancing the total sheath current.



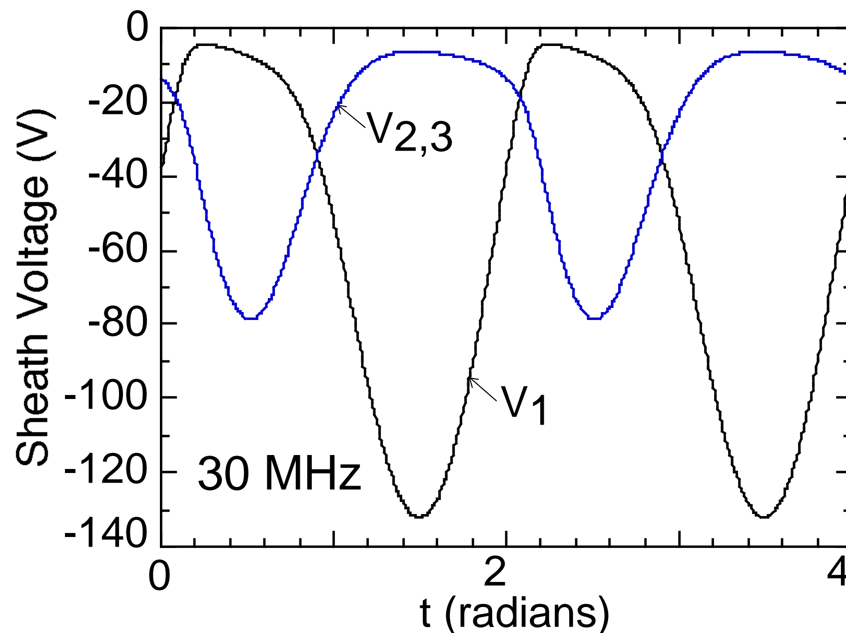


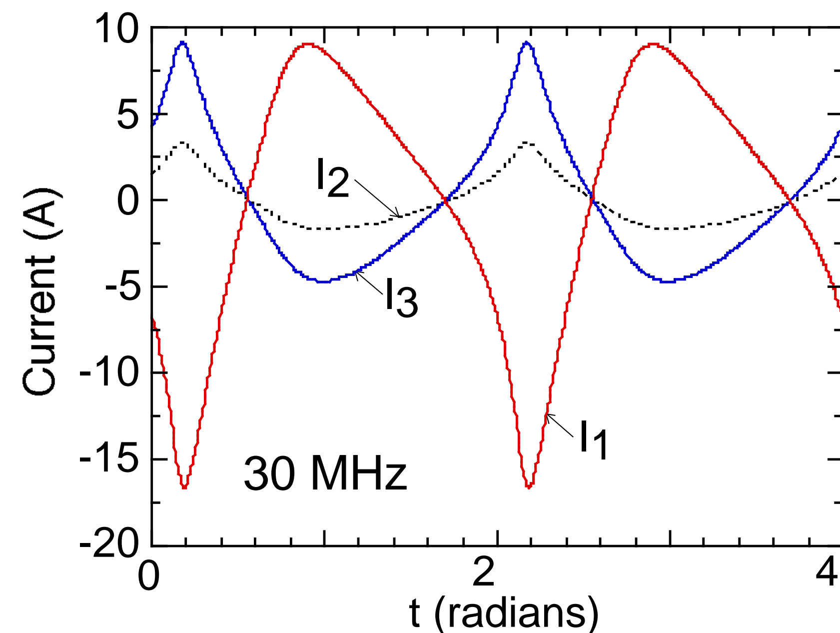
- Ar, 20 mTorr, 500 W, V_1 = 100 V.

Optical & Discharge Physics
University of Illinois

WHY DOES RF BIAS FREQUENCY STRONGLY EFFECT DC BIAS?

- Most of the current through the substrate is conduction while that at grounded surfaces is displacement.
- An increase in rf bias frequency, therefore, decreases the sheath impedance more strongly at grounded surfaces than at the substrate.
- The resulting disproportionate change in sheath voltage at different surfaces modifies the dc bias at the substrate.

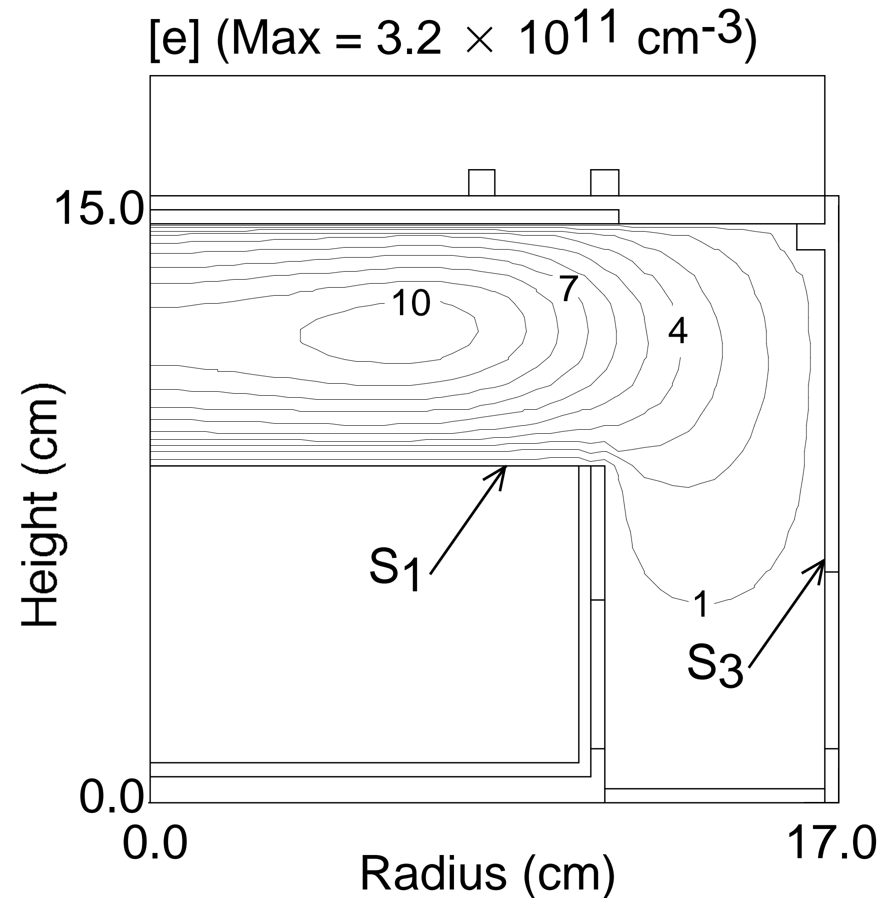




- Ar, 20 mTorr, 500 W, V_1 (30 MHz) = 100 V.

DEPENDENCE OF DC BIAS ON INDUCTIVE POWER DEPOSITION

- Dc bias was positive at low frequencies (in the previous results) because electron density is much larger near the powered electrode than the grounded surfaces.
- By powering only the outer two coils, electron density profile can be shifted towards the grounded wall (S_3).
- This changes the dc bias at the powered substrate (S_1) from 10.8 V to -21.9 V.

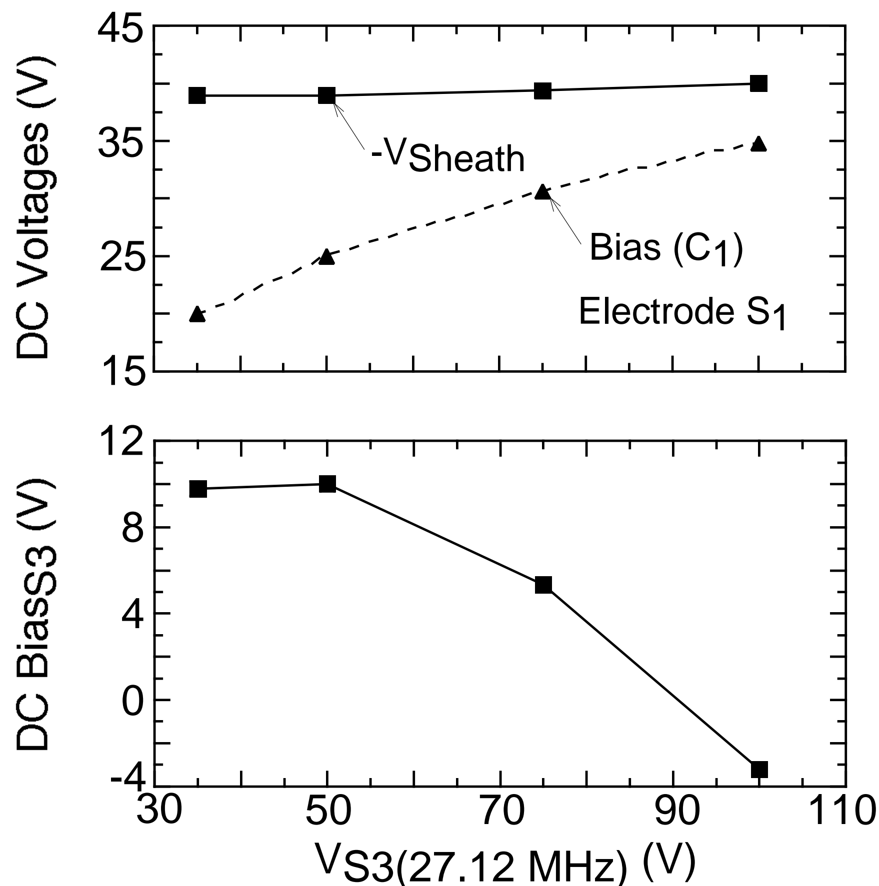


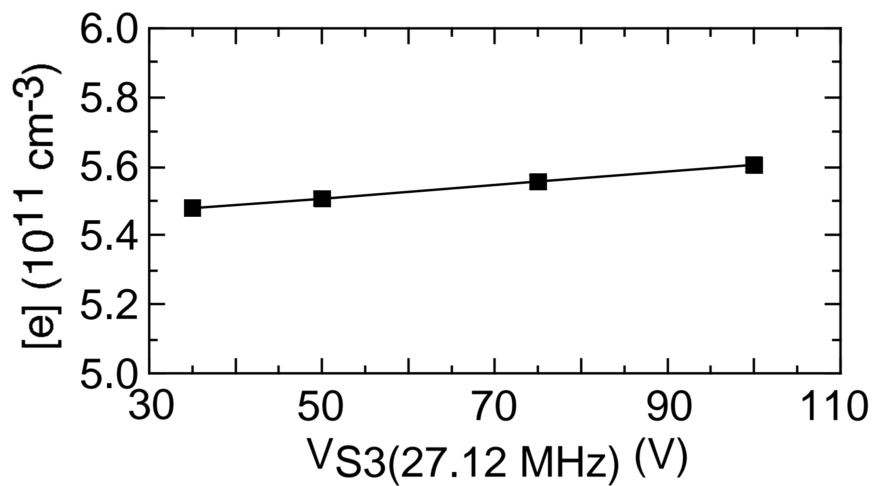
- Ar, 20 mTorr, 500 W, V_1 (13.56 MHz) = 100 V.

Optical & Discharge Physics
University of Illinois

RF SOURCE INTERACTION IN ICP REACTOR

- In these results, a 13.56 MHz source (V_1 = 100 V) is connected to S_1 while a 27.12 MHz source is connected to S_3.
- Sheath voltage at S_1 is mainly governed by the rf bias source.
- The two rf sources, however, interact at the grounded surface S_2 and change the sheath voltage there.
- Dc bias at S_1 is therefore modified.





- Ar, 20 mTorr, 500 W, V_1 (13.56 MHz) = 100 V.

CONCLUSIONS

- The effect of rf bias source frequency and source interactions have been discussed in both capacitively and inductively coupled sources.
- In the capacitively coupled GEC reference cell, frequency had a significant effect on currents and electron density, but not dc bias.
- On the other hand, rf bias source frequency appreciably modified the dc bias in the inductively coupled plasma reactor, but not plasma density.
- Multiple rf sources at different frequencies were found to interact with each other in both inductively and capacitively coupled reactors.
- This interaction was strong near surfaces where sources were not attached and very weak in sheaths connected to the sources.
- Due to this inhomogeneous and nonlinear response of different sheaths to multiple sources, the electrical characteristics of the discharge were significantly modified.