Seminar in Plasma Aided Manufacturing
University of Wisconsin, Madison, Wisconsin
September 18, 1998.

DYNAMICS OF NONLINEAR PLASMA-CIRCUIT INTERACTION*

SHAHID RAUF
Department of Electrical & Computer Engineering
University of Illinois, Urbana-Champaign

*Work done in collaboration with Mark J. Kushner and supported by AFOSR/DARPA, SRC and NSF.

AGENDA

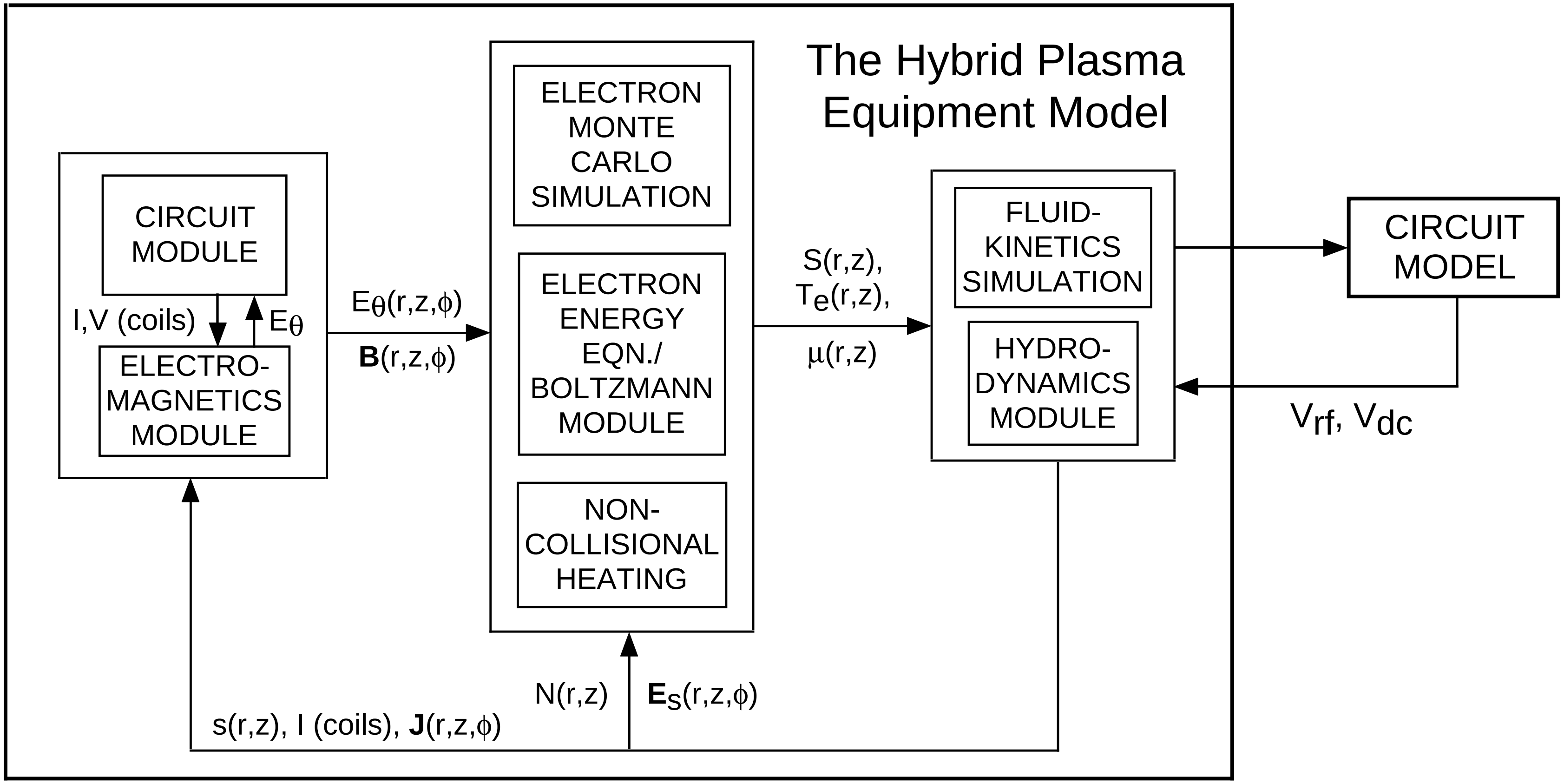
- Introduction
- Computational Model
- Capacitively Coupled Discharge
    - Electrode Currents and Voltages
    - Effect of Gas Pressure, Applied Voltage and Frequency
    - Source Interaction
- Inductively Coupled Plasma
    - Electrode Currents and Voltages
    - Effect of Frequency and Source Interaction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

INTRODUCTION

- External circuitry significantly effects the plasma characteristics and the performance of rf plasma processing reactors.
- A plasma equipment simulation, consisting of a coupled plasma reactor model and a circuit model, has been developed to investigate the interaction of plasmas and circuits.
- In this talk, we describe the model and use it to study relevant issues in asymmetric capacitive discharges and inductively coupled plasmas (ICP).
- Electrode currents generally have significant amplitude at higher harmonics due to the nonlinear nature of the sheaths.
- Nonlinear sheaths also lead to rf source interaction which can produce results that are significantly different than due to the sum of individual sources.
- Electrical and plasma characteristics sensitively depend on source frequency and voltage waveform, which can be used as actuators to control plasma processes.

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

THE HYBRID PLASMA EQUIPMENT MODEL

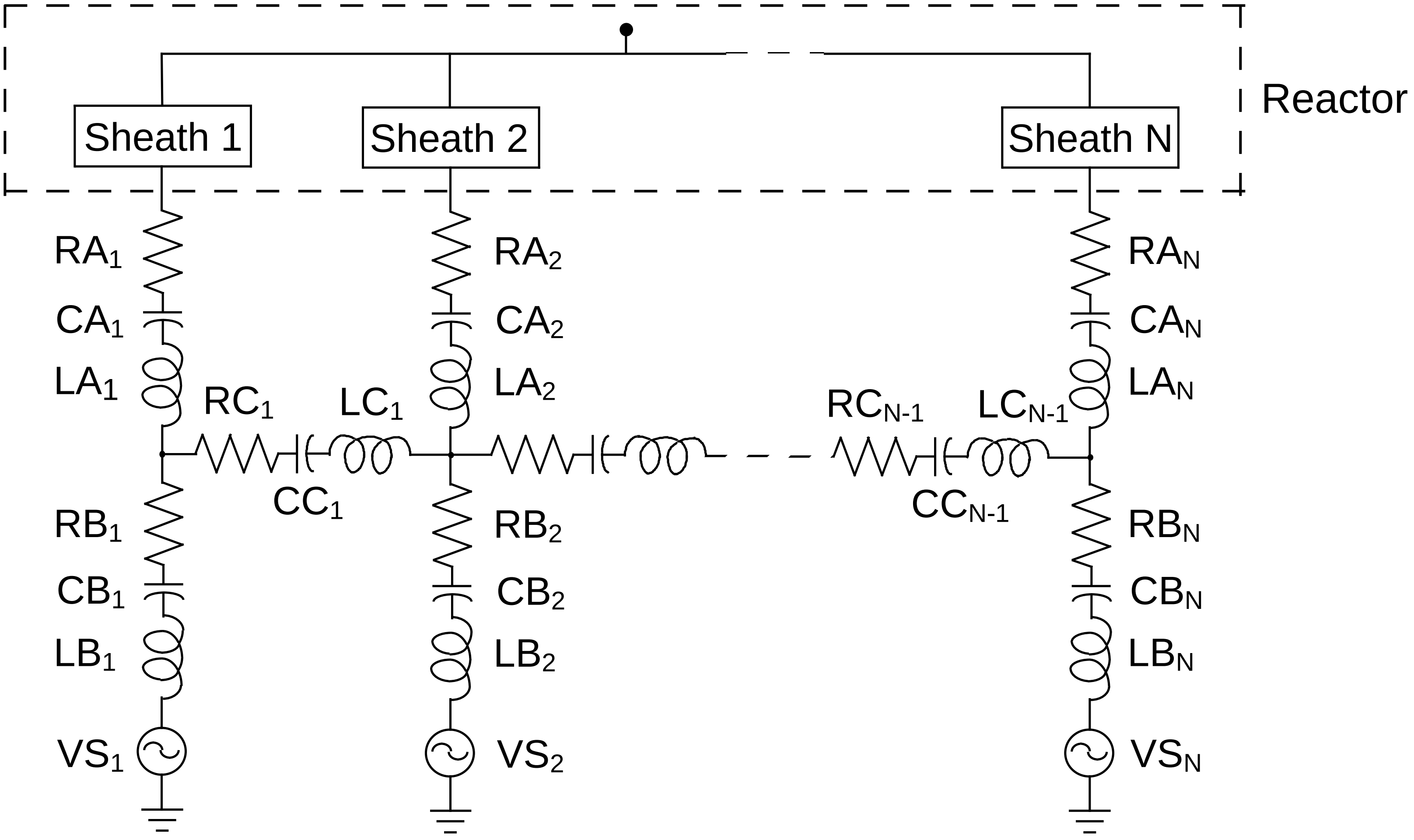
- The Hybrid Plasma Equipment Model (HPEM) is our general plasma equipment simulation and it consists of three coupled modules.
- In the first module, inductive electromagnetic fields are computed and coil circuitry is simulated.
- The second module computes electron transport coefficients and sources for electron impact reactions using either (1) a Monte Carlo simulation or (2) by solving electron energy equation in conjunction with the Boltzmann equation.
- The third module computes particle densities, fluxes and temperatures, and also the electrostatic fields.
- The three modules are coupled and they are iterated until quasi-steady state conditions are obtained.
- The HPEM is linked to an extensive chemical and physical database.
- In the past, the HPEM has been usd to model capacitive discharges, ICPs, dc plasma devices and many other plasma based systems.

SIMULTANEOUS PLASMA-CIRCUIT SIMULATION

- At the end of each HPEM iteration, the reactor is replaced with an equivalent circuit consisting of sheaths at all important reactor surfaces and effective resistors to represent the bulk plasma.
- Each sheath is treated as a nonlinear circuit element whose V-I characteristics are governed by the Riley’s sheath model.
- The nonlinear sheath elements are connected to the external circuitry as shown on the next transparency.
- The circuit is general enough that most external components and stray elements can be approximated.
- This nonlinear circuit is solved using an implicit time integration scheme until all voltages and currents reach steady-state.
- The resulting voltages (dc, fundamental and harmonics) at the electrodes are used as boundary conditions for the next HPEM iteration.

SHEATH-CIRCUIT MODEL

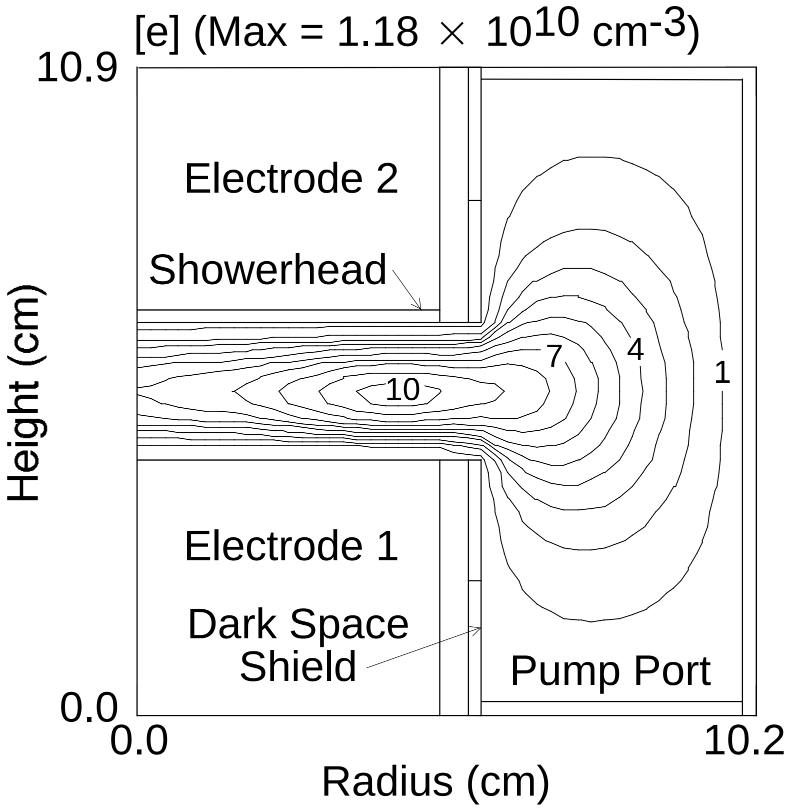
- The reactor and circuitry are replaced by the following equivalent circuit.

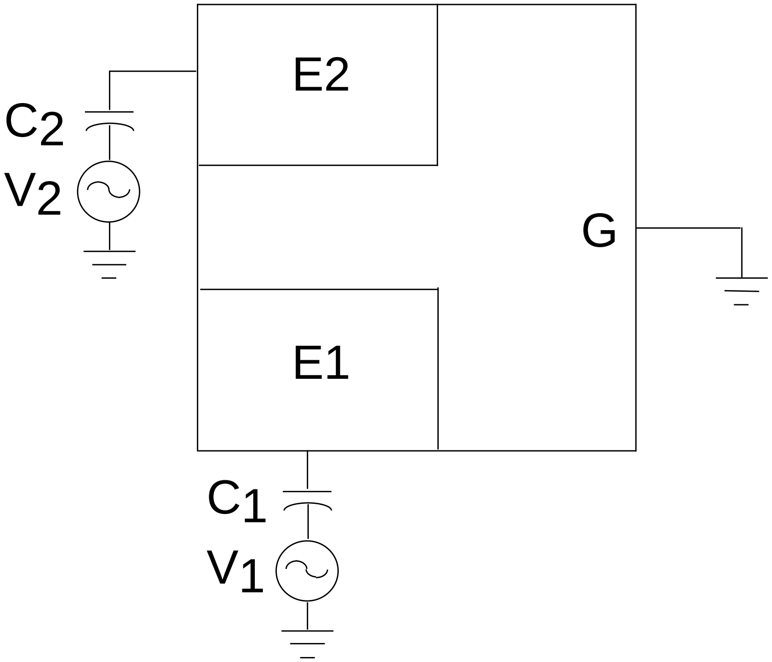


Optical & Discharge Physics
University of Illinois

THE GEC REFERENCE CELL

- We first explore plasma-circuit interaction in the capacitively coupled GEC reference cell.
- Sources and blocking capacitors have been connected to both electrodes.

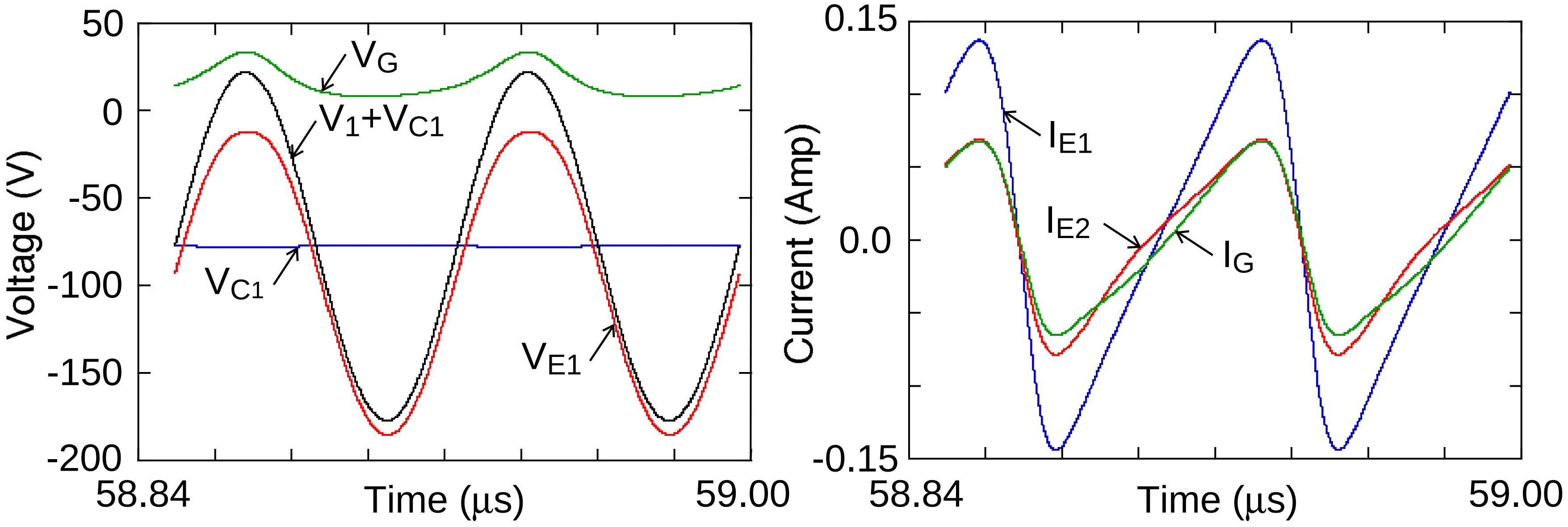




- Ar, 100 mTorr, V_1 = 100 V, V_2 = 0 V.

SHEATH VOLTAGES AND CURRENTS

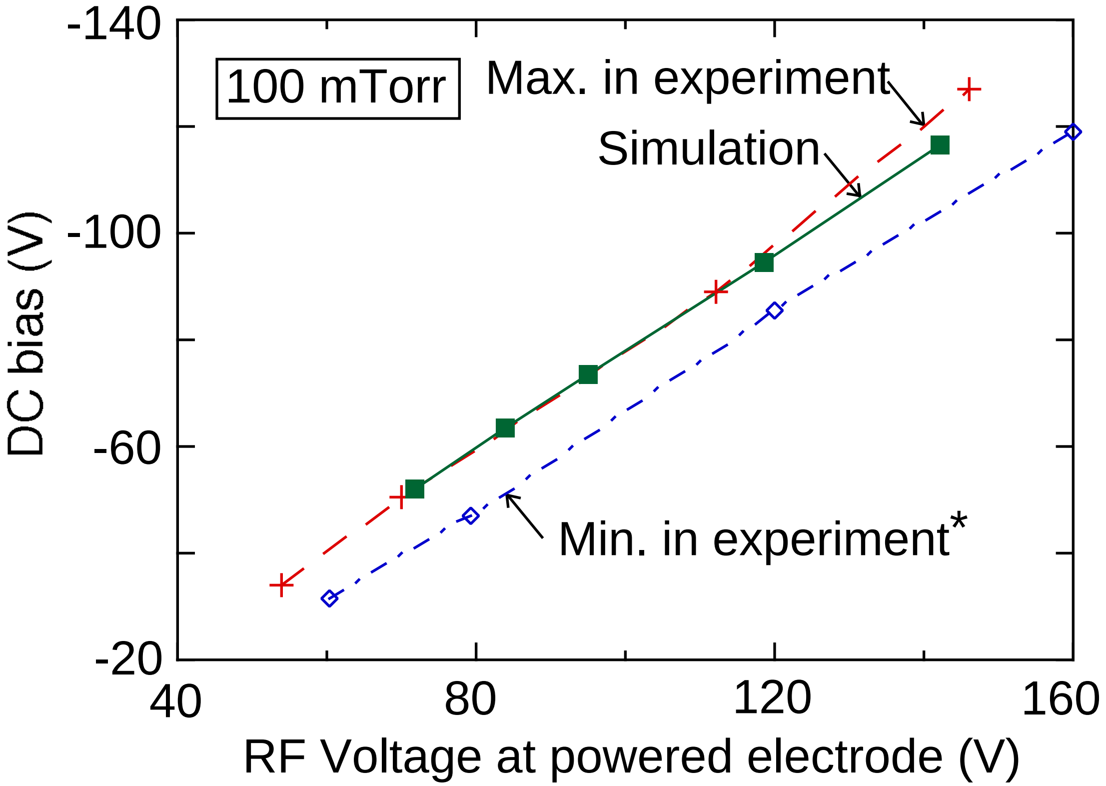
- A negative dc voltage appears across the capacitor C_1 (dc bias) to balance currents through the powered and grounded surfaces.
- The sheath currents are fairly nonlinear with large higher harmonics.



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

EFFECT OF APPLIED VOLTAGE

- At 100 mTorr in Ar, the sheath-circuit model correctly predicts the dc bias for applied voltages between 75-150 V.
- As applied voltage is increased, the dc bias amplitude increases to balance the disproportionate increase in the two electrodes’ electron current.

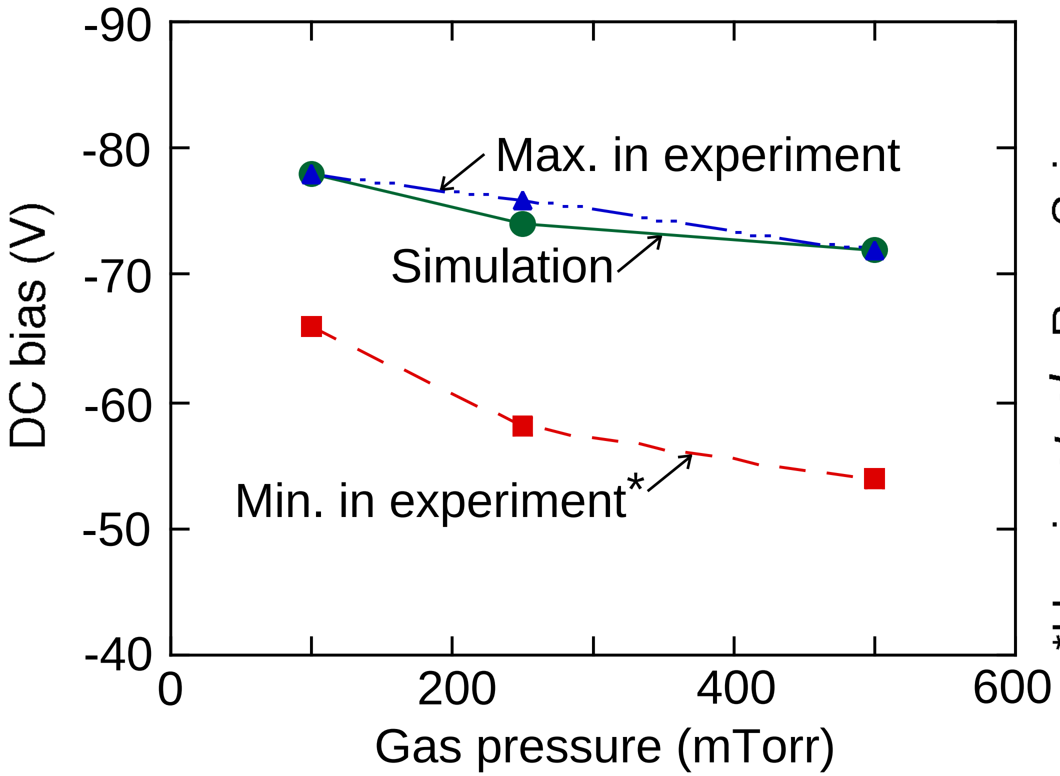


*Hargis *et al.*, Rev. Sci. Instrum. **65**, 140 (1994).

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

EFFECT OF GAS PRESSURE

- The sheath-circuit model is able to correctly predict the dc bias for higher pressures as well.
- As pressure increases, the plasma gets better confined between the electrodes, the discharge becomes more symmetric and the dc bias amplitude decreases.

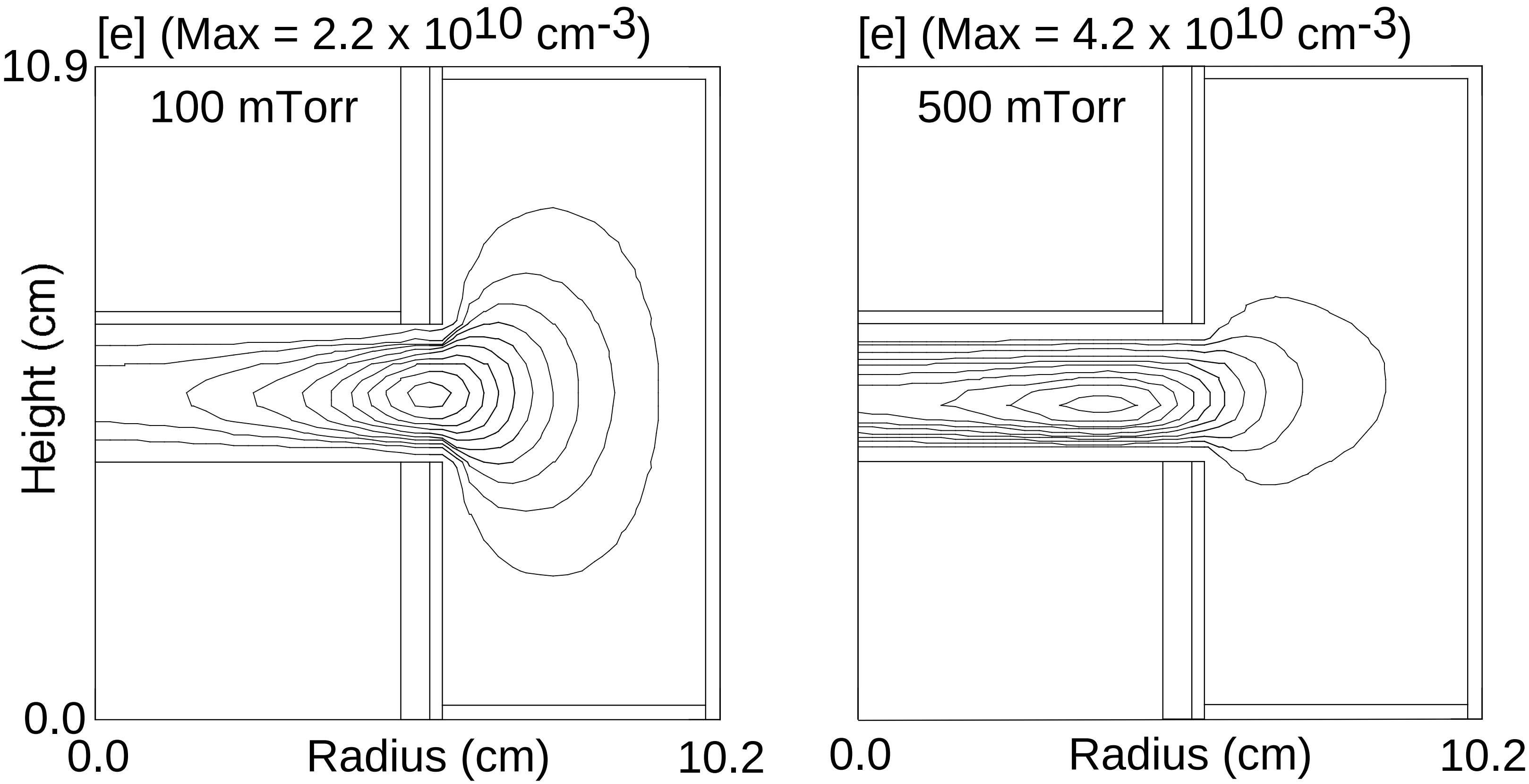


*Hargis *et al.*, Rev. Sci. Instrum. **65**, 140 (1994).

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

EFFECT OF GAS PRESSURE ON PLASMA DENSITY

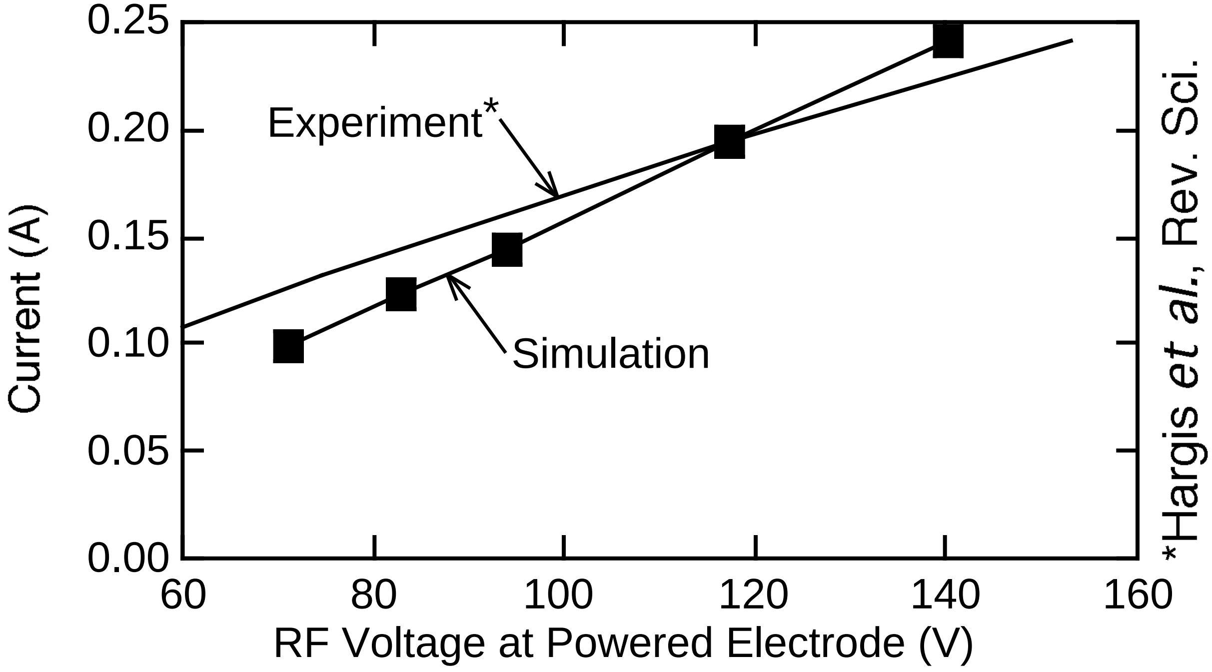
- As pressure increases, the plasma gets better confined in the inter-electrode region.



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

EFFECT OF APPLIED VOLTAGE ON ELECTRODE CURRENT

- As the applied voltage is increased, more stochastic and ohmic heating takes place.
- The resulting electron density and electrode currents are therefore larger.

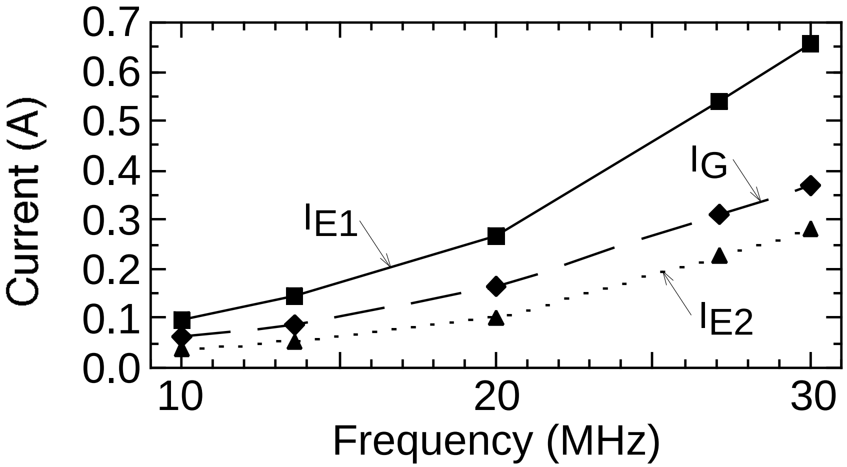


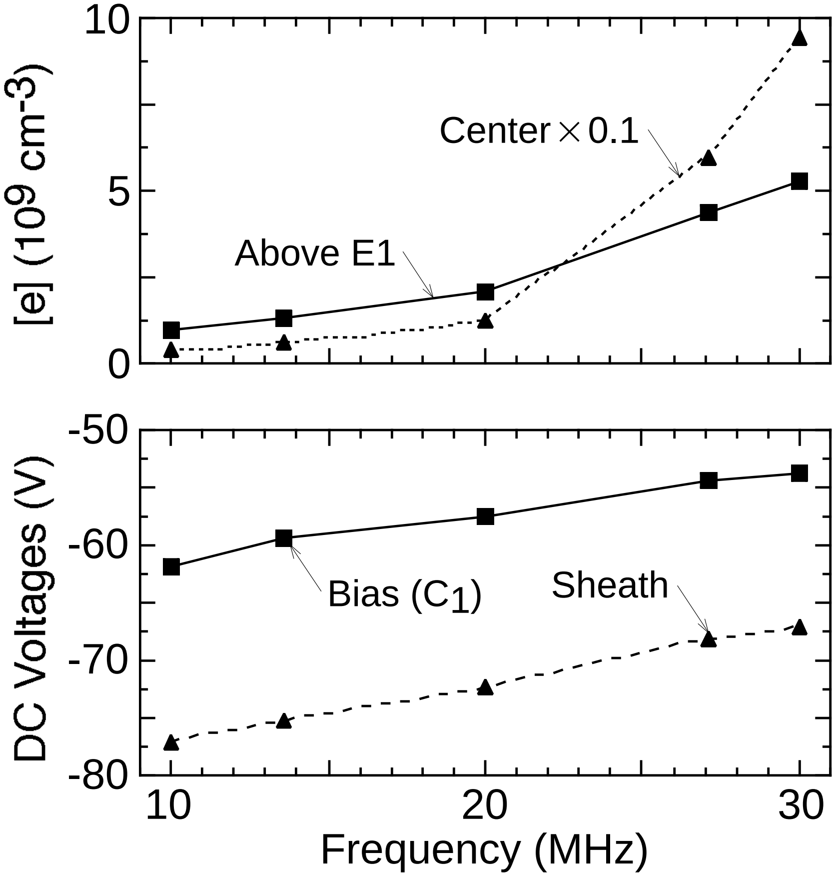
*Hargis *et al.*, Rev. Sci. Instrum. **65**, 140 (1994).

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

EFFECT OF SOURCE FREQUENCY IN Ar

- 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.





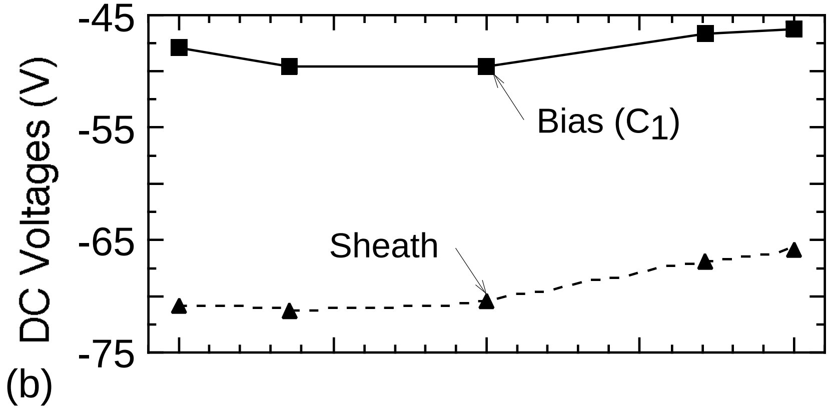
- Ar, 100 mTorr, V_1 = 100 V, V_2 = 0 V.

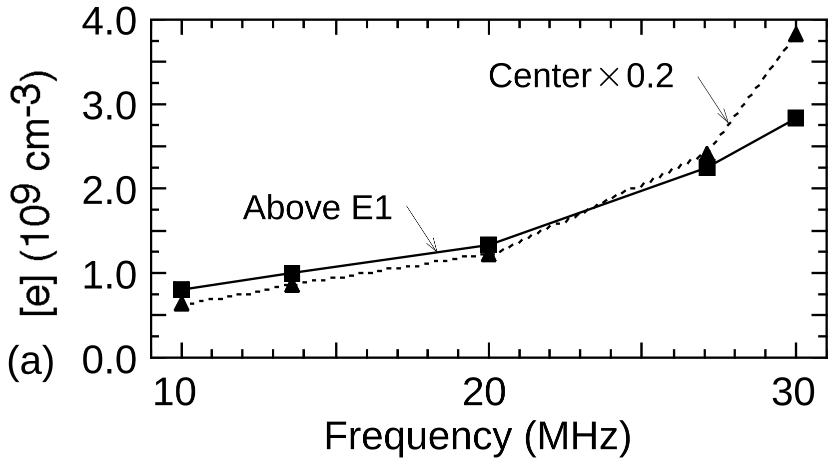
Optical & Discharge Physics
University of Illinois

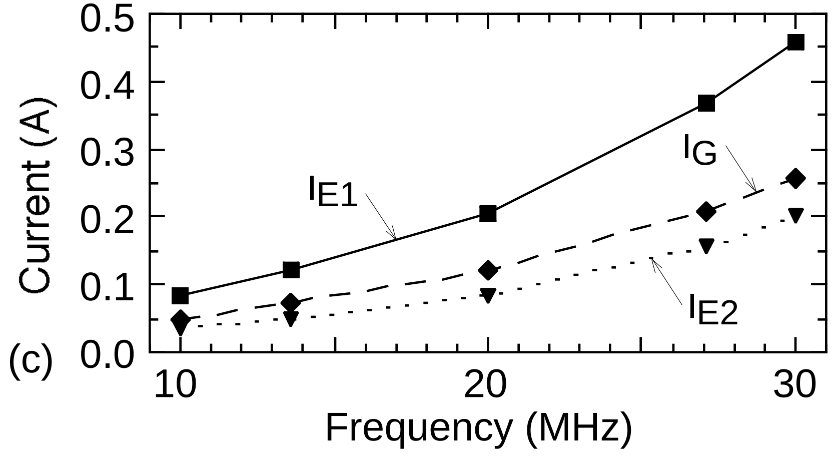
EFFECT OF SOURCE FREQUENCY IN Ar/CF_4

- Electron density and electrode currents depend on frequency in the same manner in Ar/CF_4 as in Ar.

- The dc voltages however vary non-monotonically with frequency in Ar/CF_4 because the electron temperature dependence on frequency is different.



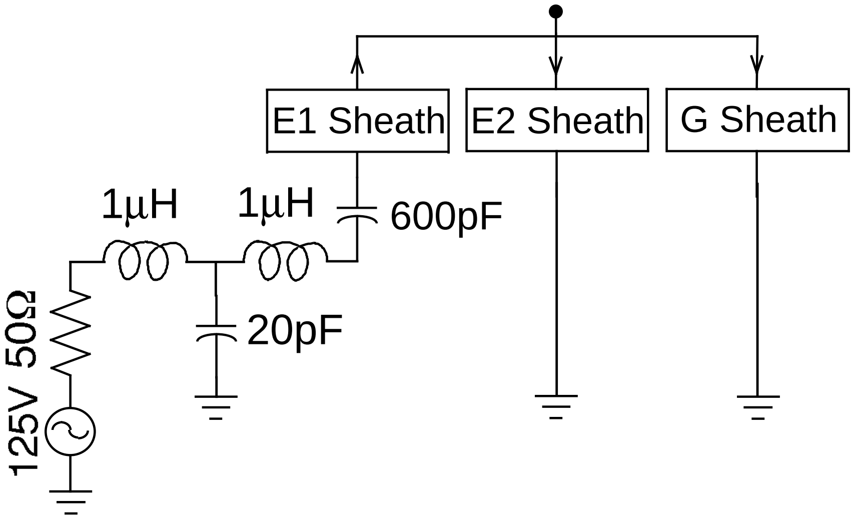




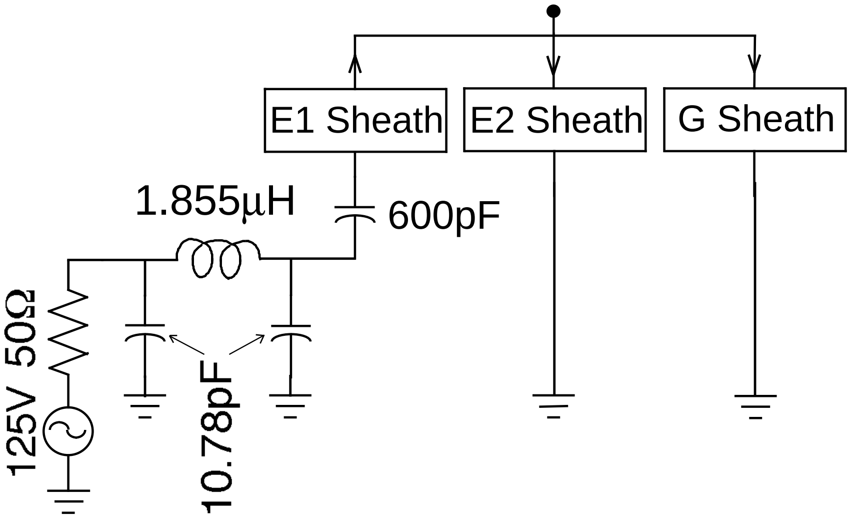
- Ar/CF_4 = 80/20, 100 mTorr, V_1 = 100 V, V_2 = 0 V.

EFFECT OF MATCHING NETWORK - I

- Since plasmas are nonlinear, seemingly similar external circuitry may lead to different plasma characteristics.
- In the circuits below, the two matching networks are exact (T-Π) transform of each other at the fundamental frequency.



With T Matching Network

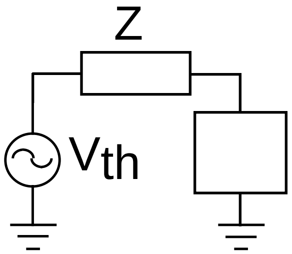


With Π Matching Network

EFFECT OF MATCHING NETWORK - II

- The two circuits look different to the plasma at other frequencies:

Thevinin Equiv.
Circuit at
2nd Harmonic:



	V_{th} (V)	Z (Ohm)
T Network:	$276.19\angle -22.11^\circ$	244.11 + i467.8
Π Network:	$284.73\angle -17.28^\circ$	259.43 + i663.56

- Since dc bias develops due to the nonlinear nature of the plasma, it is different with the two matching networks.

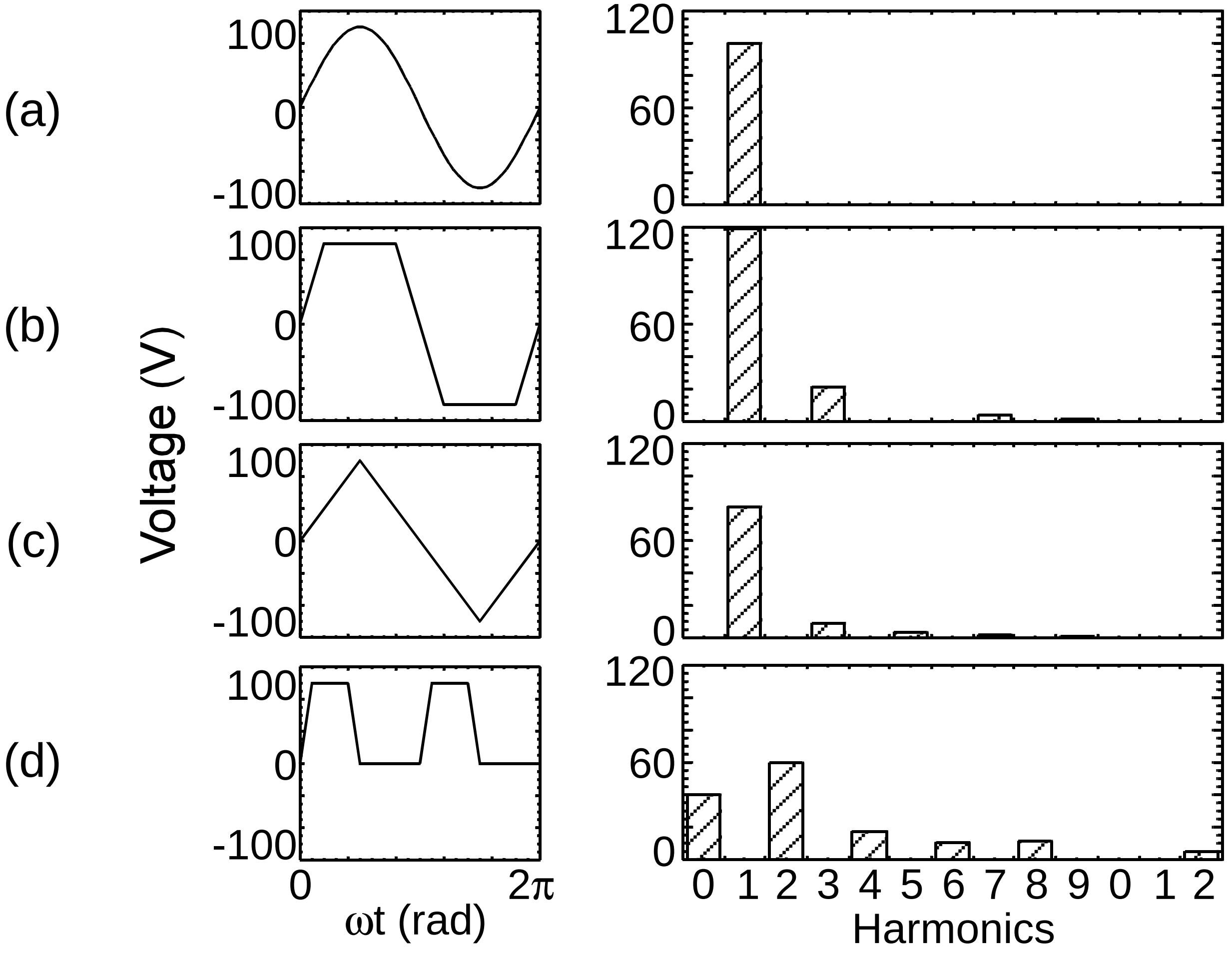
	Fundamental (V)	DC Bias (V)
T Network:	177.3	-123.49
Π Network:	179.5	-114.91

- The resultant plasma characteristics are consequently different as well.

	Peak [e] (cm^{-3})	Peak [Ar^*] (cm^{-3})
T Network:	3.76×10^{10}	1.61×10^{12}
Π Network:	3.58×10^{10}	1.51×10^{12}

ARBIRARY 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.



DC Bias

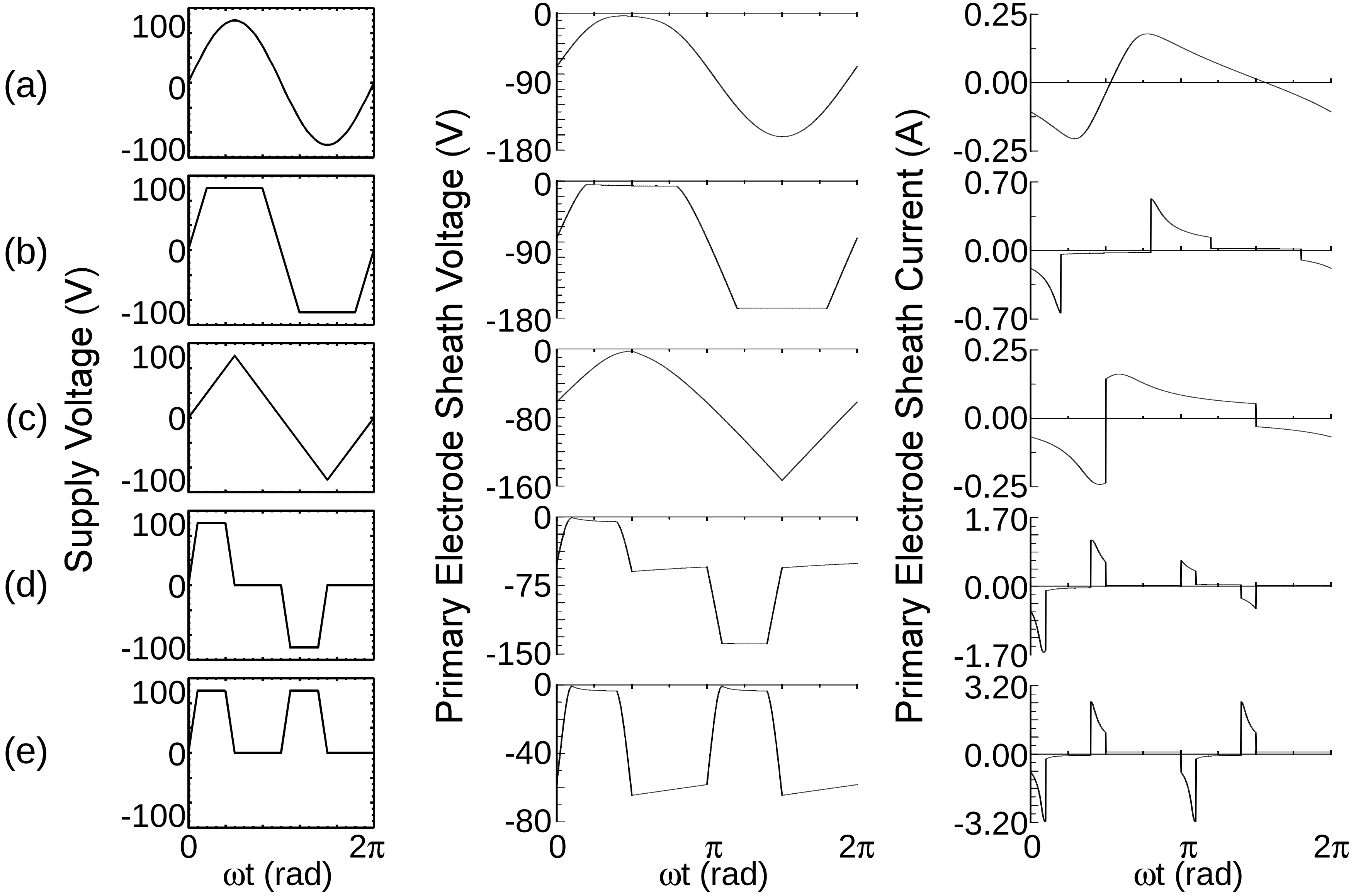
(a) -59.26 V

(b) -65.28 V

(c) -49.29 V

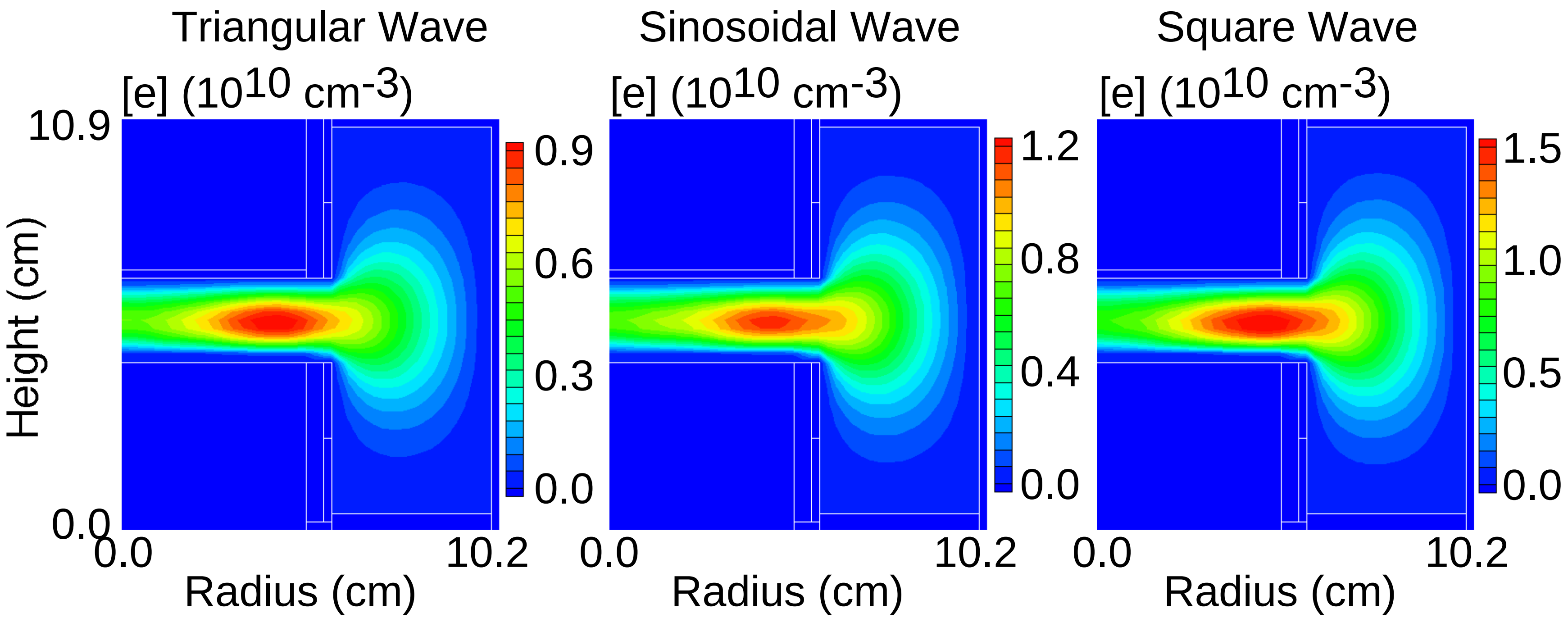
(d) -63.64 V

PRIMARY ELECTRODE SHEATH CURRENTS AND VOLTAGES



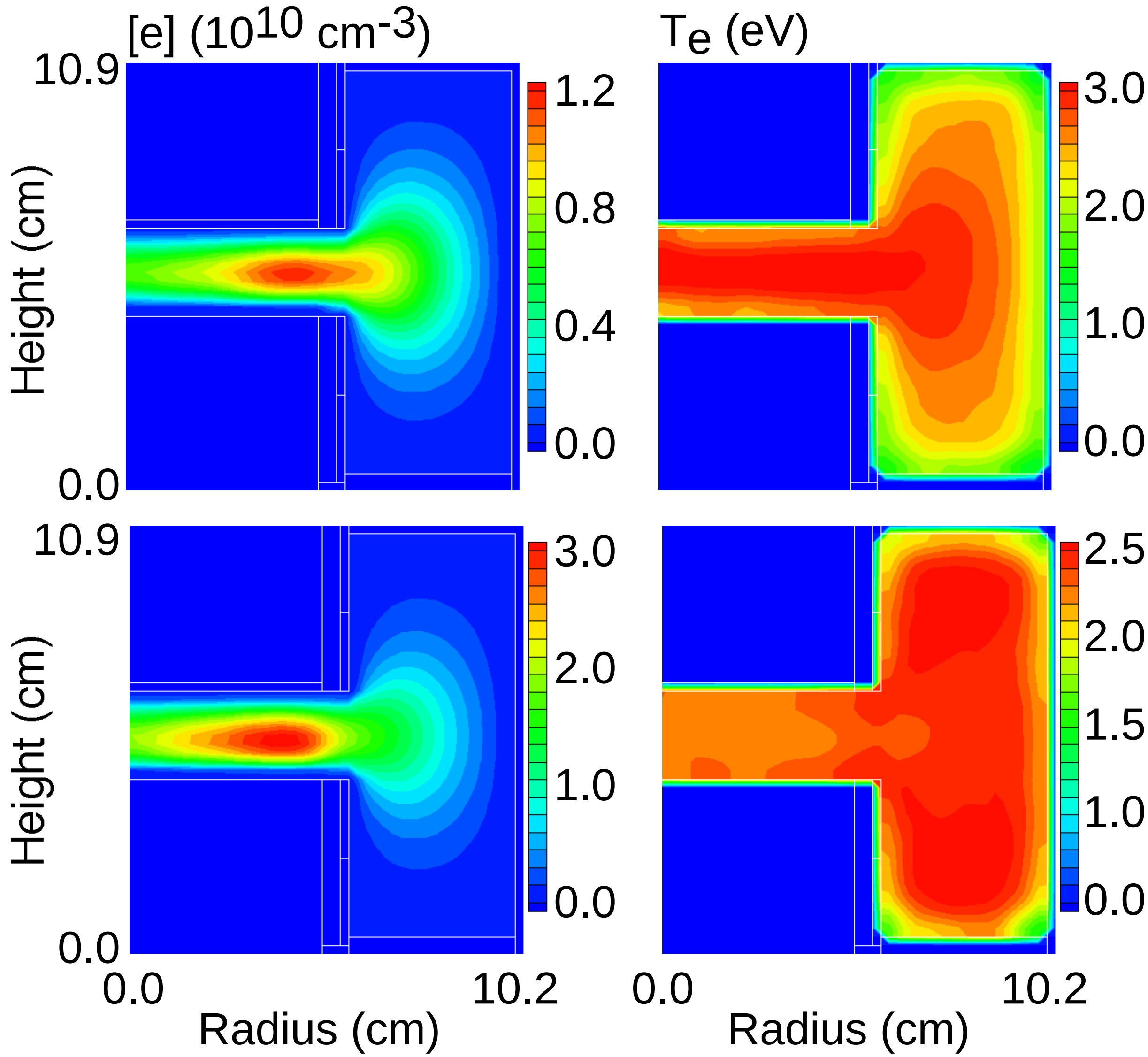
EFFECT OF WAVEFORM ON PLASMA PARAMETERS

- 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.



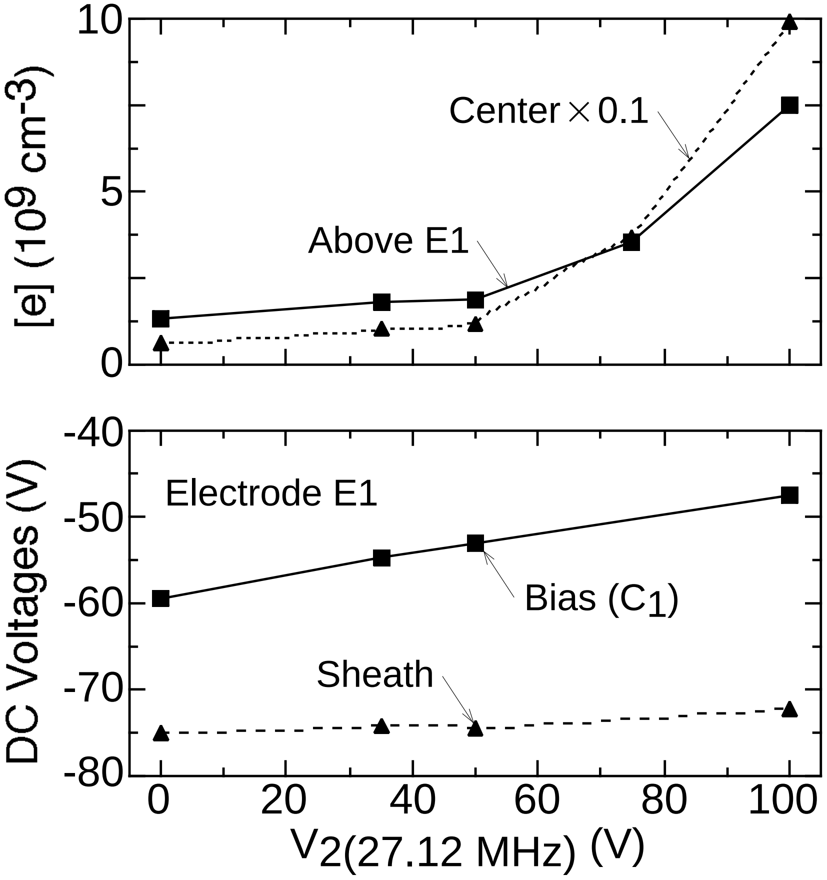
EFFECT OF HIGHER HARMONICS

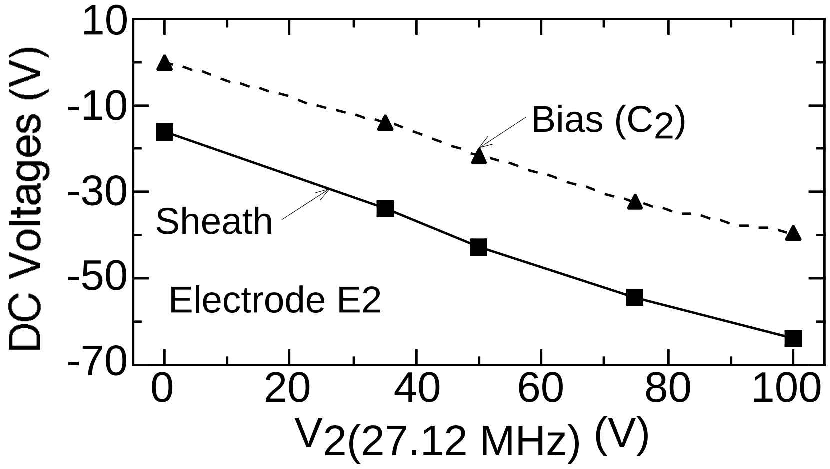
- Electron density is larger and $\boldsymbol{T_e}$ is smaller for waveforms with larger higher harmonics.



CONSEQUENCES OF SOURCE INTERACTION - 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.

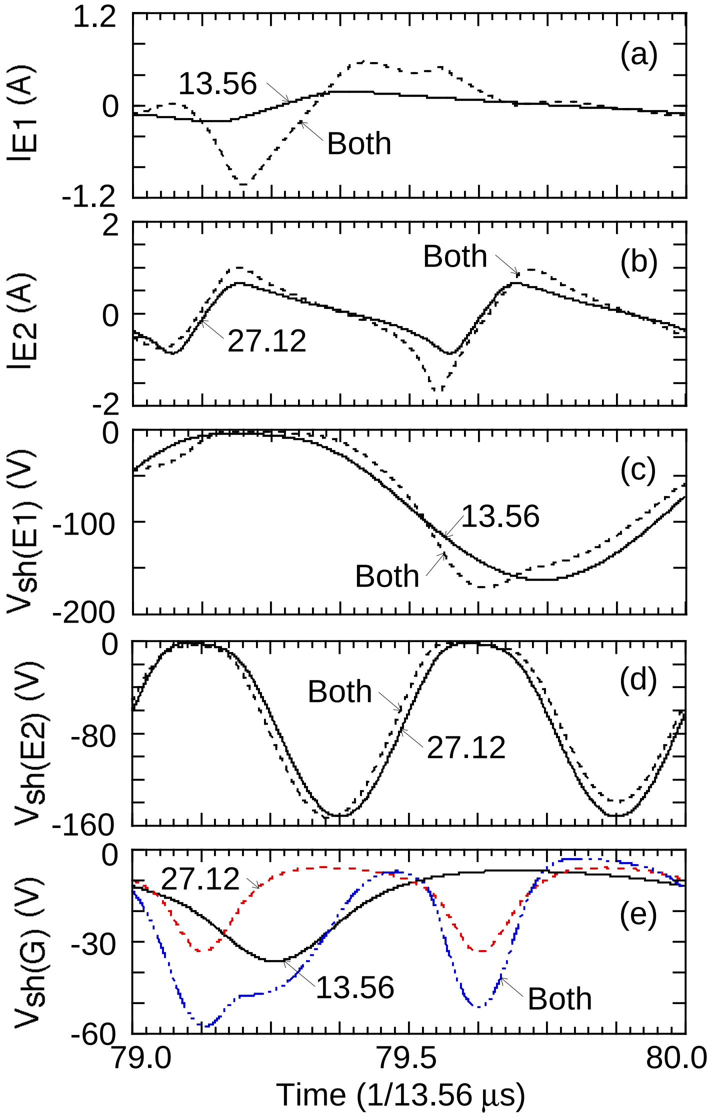




- Ar, 100 mTorr, V_1 (13.56 MHz) = 100 V.

CONSEQUENCES OF SOURCE INTERACTION - II

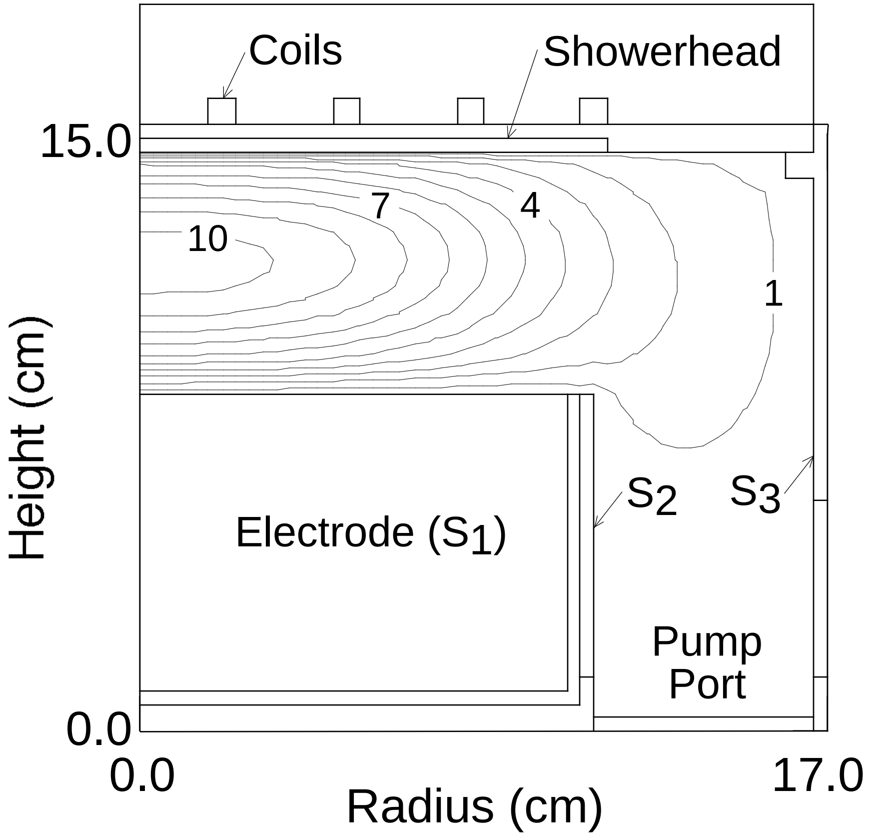
- In these results, we show the sheath voltages and currents for only the 13.56 MHz source, 27.12 MHz source and their combination.
- Sheath voltages at E1 and E2 are primarily governed by the sources connected to them.
- The sheath voltage at the grounded wall is, however, in the linear regime and the 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.

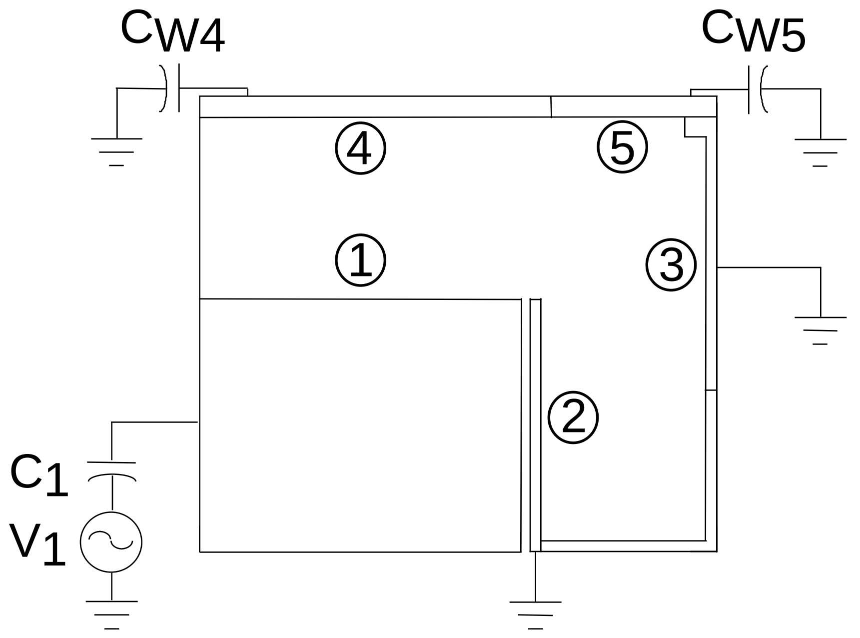


INDUCTIVELY COUPLED PLASMA (ICP) SOURCE

- 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.

[e] (Max = 5.4×10^{11} cm^{-3})





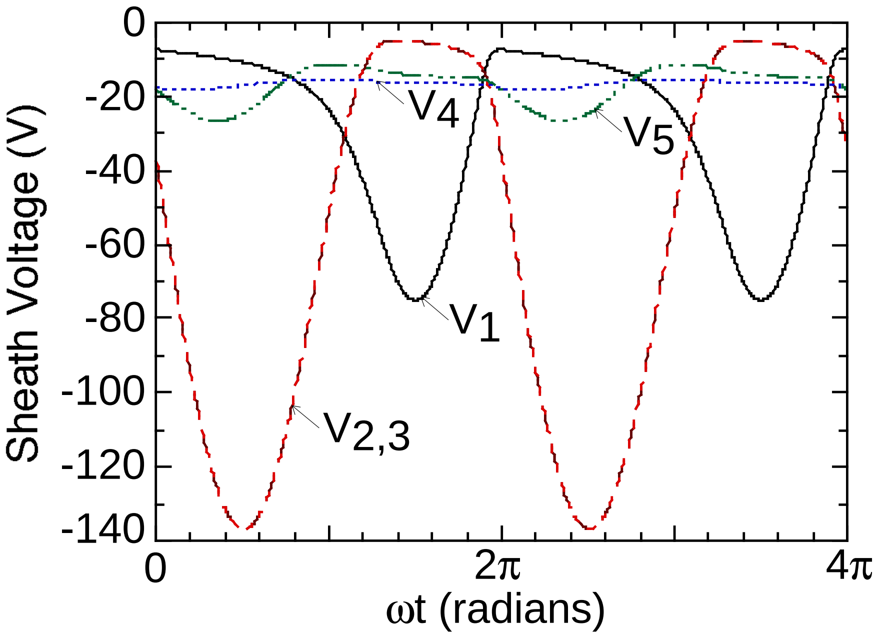
- Ar, 20 mTorr, 500 W, V_1 (13.56 MHz) = 100 V.

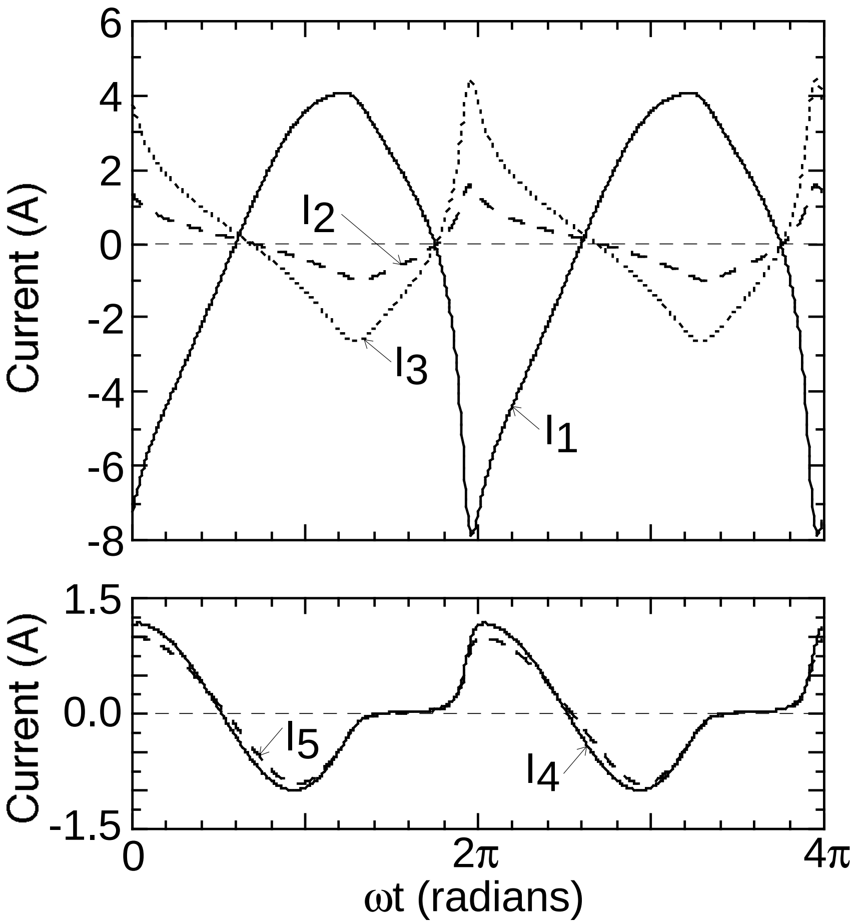
Optical & Discharge Physics
University of Illinois

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.





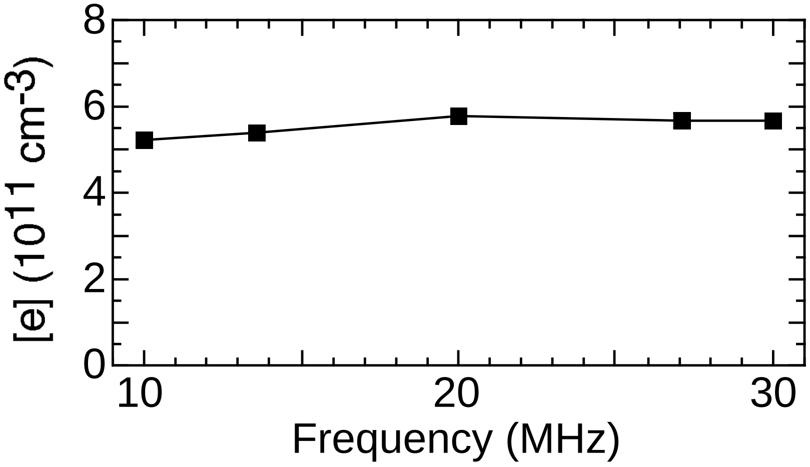
- Ar, 20 mTorr, 500 W, V_1 (10 MHz) = 100 V.

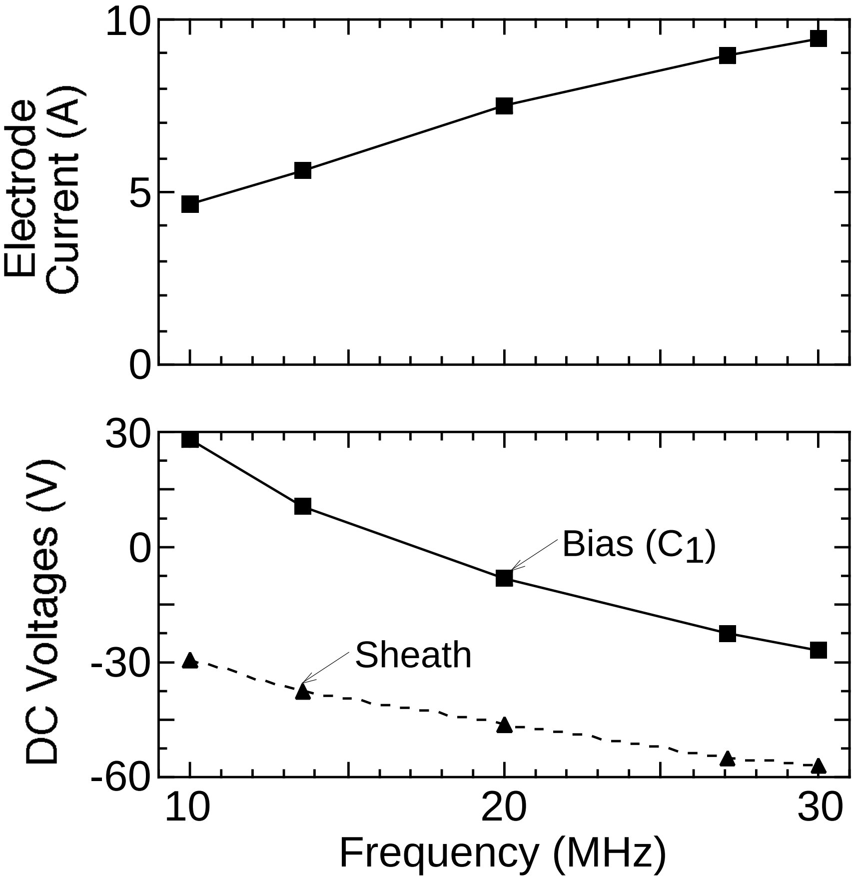
Optical & Discharge Physics
University of Illinois

WISC98_F25

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.

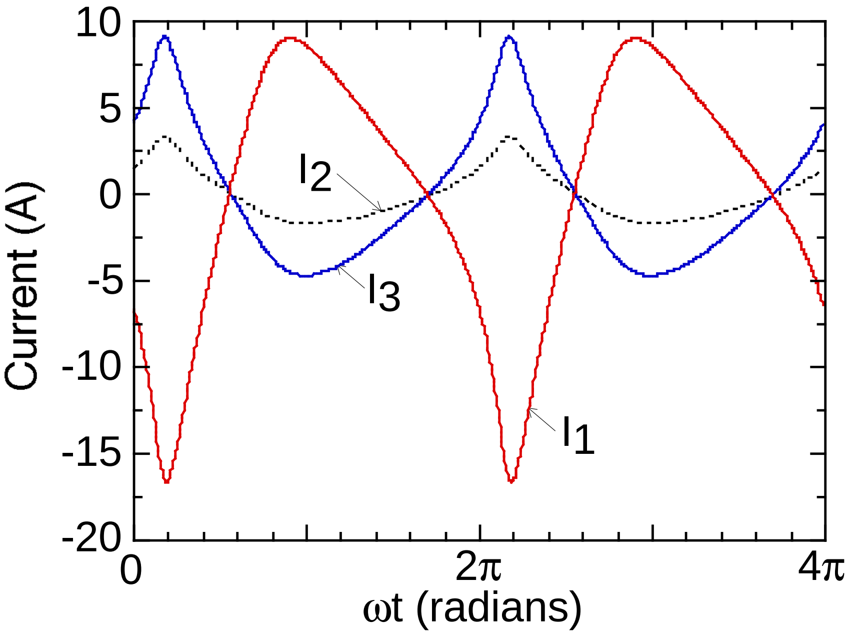


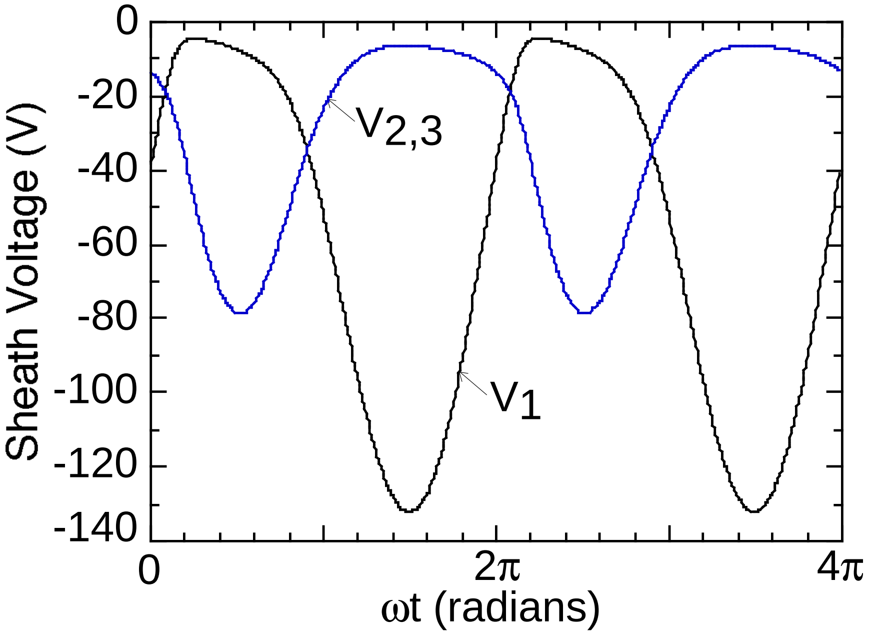


- Ar, 20 mTorr, 500 W, V_1 = 100 V.

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 disproportional change in sheath voltage at different surfaces modifies the dc bias at the substrate.

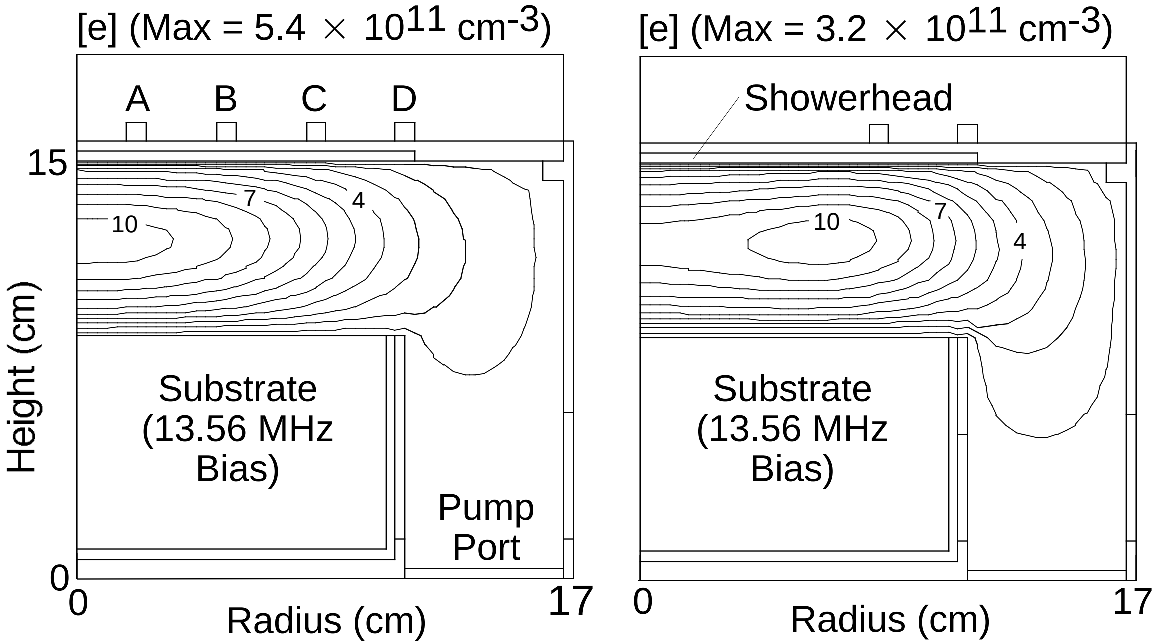




- Ar, 20 mTorr, 500 W, V_1 (30 MHz) = 100 V.

DEPENDANCE OF DC BIAS ON COIL DESIGN

- The dc bias is a global characteristic of rf discharges, which develops to balance rf current through the reactor surfaces.
- To the degree that the location of the coils governs the uniformity of the plasma, the location of the coils also governs proportions of current to surfaces.
- Since the rf impedance of the window is large, a shift in the plasma to larger radii allows more current to be collected by the walls, and makes the dc bias more negative.


[e] (Max = 5.4×10^{11} cm^{-3})

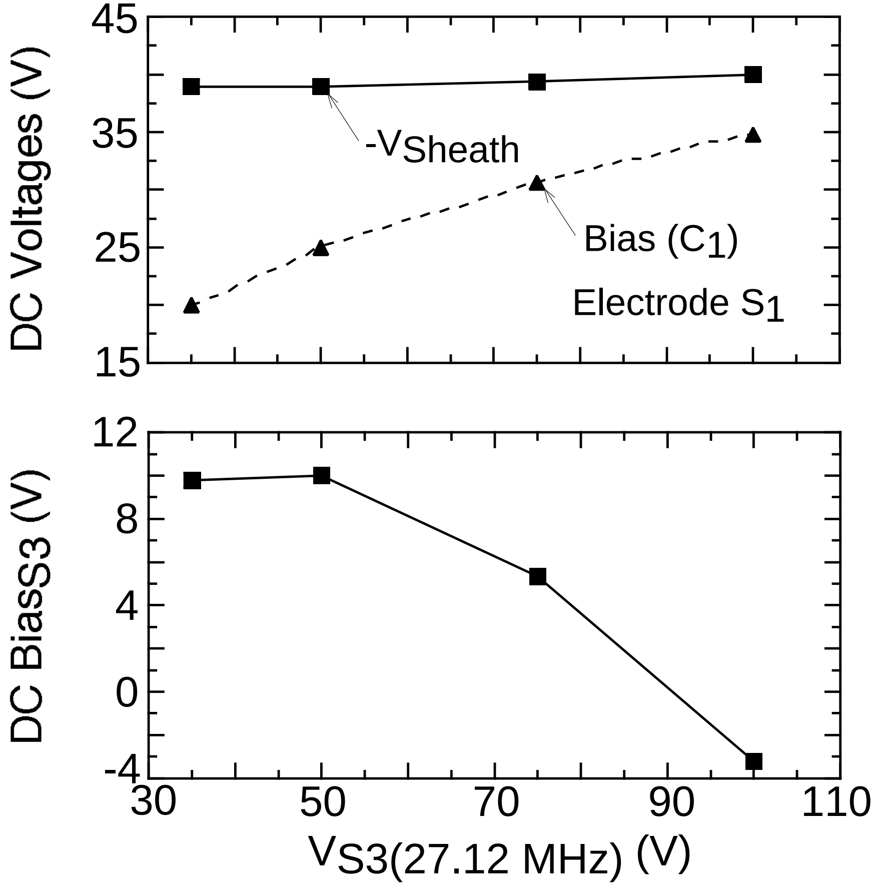
[e] (Max = 3.2×10^{11} cm^{-3})

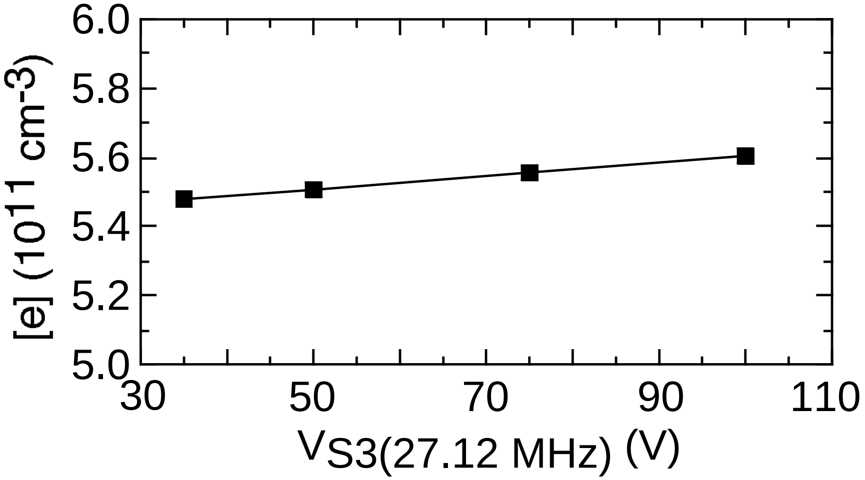
Coils	dc Bias (V)
A & B	52.8
B & C	31.7
All Four	10.8
C & D	-21.9

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

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

- To investigate plasma-circuit interaction, a coupled plasma equipment and circuit model has been developed.
- In this talk, results from the model were used to investigate the consequences of applied voltage and operating conditions on plasma and electrical characteristics of asymmetric capacitive discharges and ICPs.
- Electrode currents were generally found to have significant amplitude at higher harmonics due to the nonlinear nature of the sheaths.
- Nonlinear sheaths also led to rf source interaction, which produced results that were significantly different than due to the sum of individual sources.
- Electrical and plasma characteristics sensitively depend on source frequency and voltage waveform, which can be used as actuators to control plasma processes.
- Inductive power deposition profile governs the distribution of current through different surfaces in ICPs, and influences the electrical characteristics of the discharge.

COPY OF SLIDES AND PAPER REPRINTS

- Transparencies for this talk can be downloaded from:

  http://uigelz.ece.uiuc.edu/GM_webpages/Shahid/Papers/wisc98.pdf

- Reprints and manuscripts of some relevant papers are also available:

  S. Rauf and M. J. Kushner, J. Appl. Phys. **83**, 5087 (1998).
  (http://uigelz.ece.uiuc.edu/GM_webpages/Shahid/Papers/paper12.pdf)

  S. Rauf and M. J. Kushner, submitted to IEEE Trans. Plasma Sci.
  (http://uigelz.ece.uiuc.edu/GM_webpages/Shahid/Papers/paper15.pdf)