Plasma Discharges in Atmospheric Pressure Oxygen for Boundary Layer Separation Control

By

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KINEMA

OUTLINE :

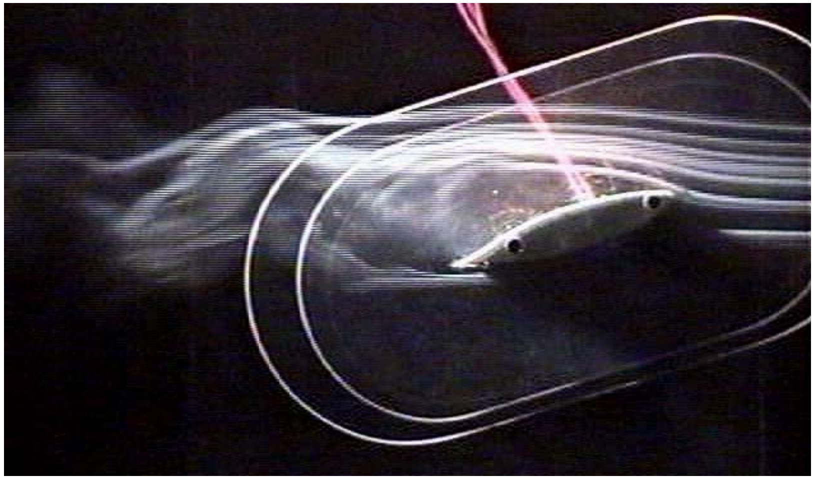
- Introduction
- Numerical Theory
- Computational Geometry and Flow Conditions

- Results
  - Plasma Discharge
  - Force Production
  - Oxygen and Nitrogen Differences
  - Experiments

- Summary

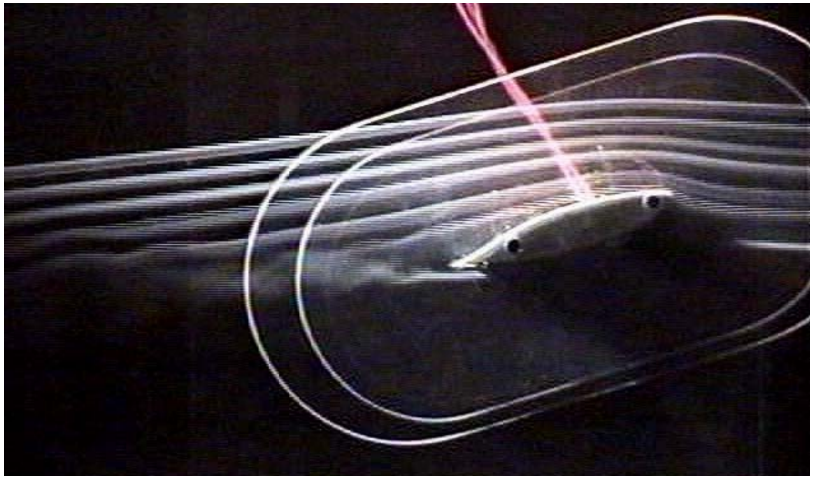
INTRODUCTION:
Plasma Actuator Can Control Boundary Layer Separation

plasma actuator OFF



separated flow

plasma actuator ON

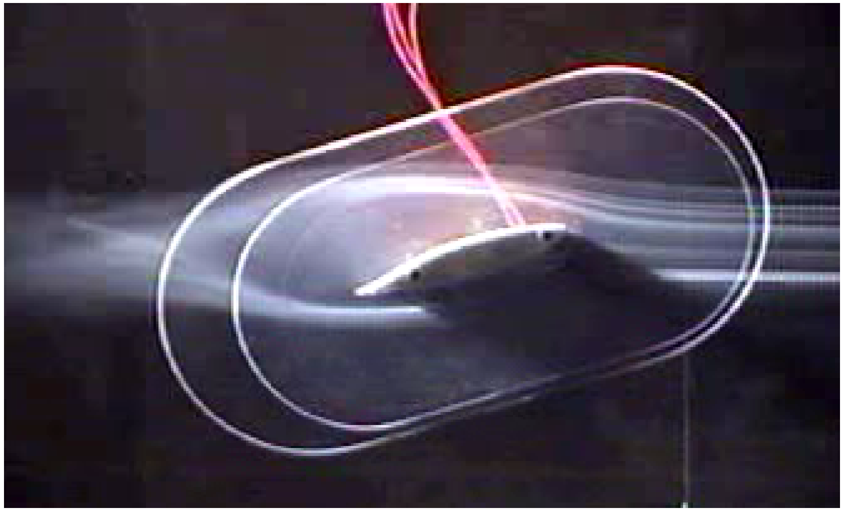


attached flow

**Pictures from T. Corke, E. Jumper, M. Post, D. Orlov at Notre Dame

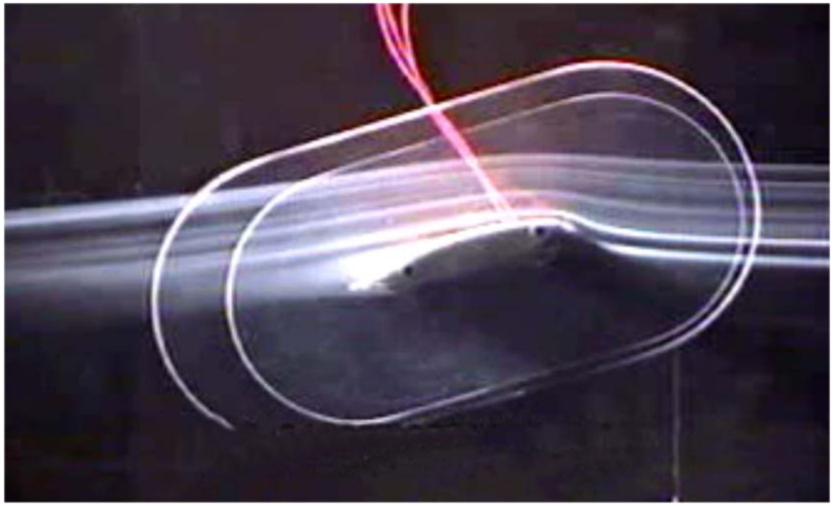
INTRODUCTION:
Plasma Actuator Can Control Boundary Layer Separation

plasma actuator OFF



separated flow

plasma actuator ON



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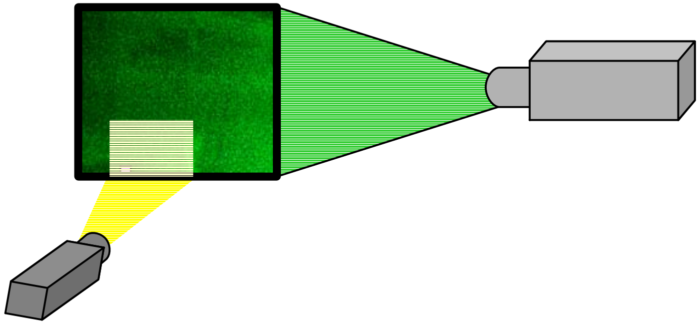
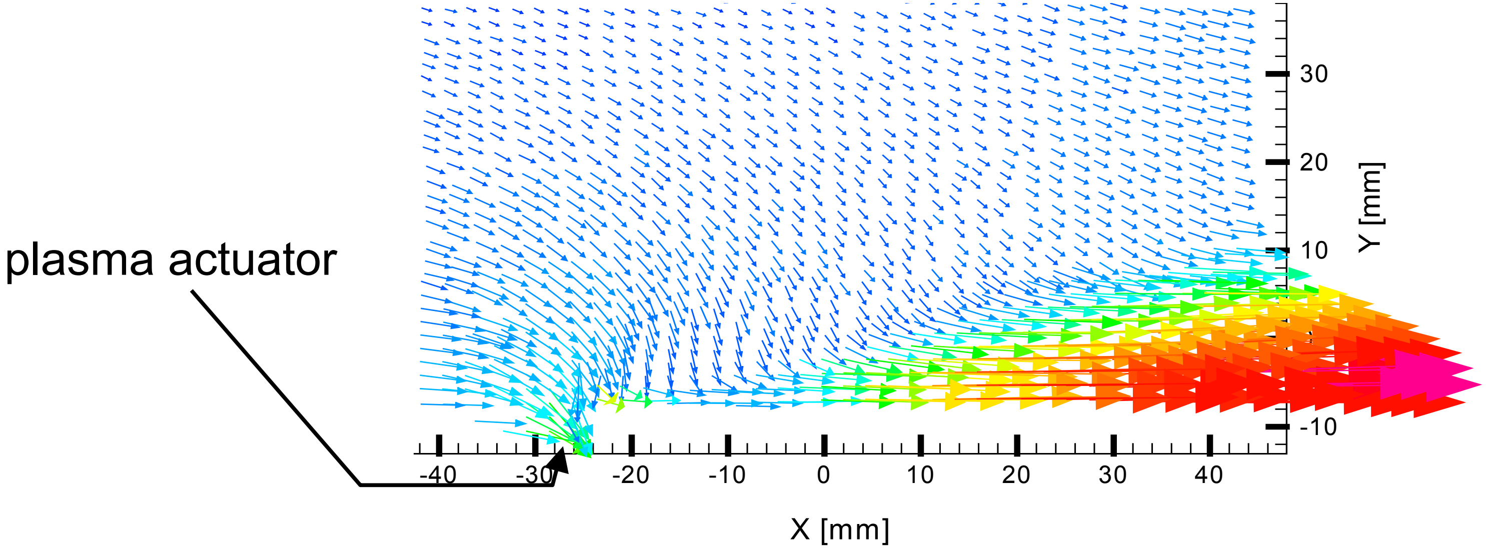
INTRODUCTION:

Plasma Actuator Adds Momentum to the Boundary Layer



PIV Measurements of Induced Velocity Field



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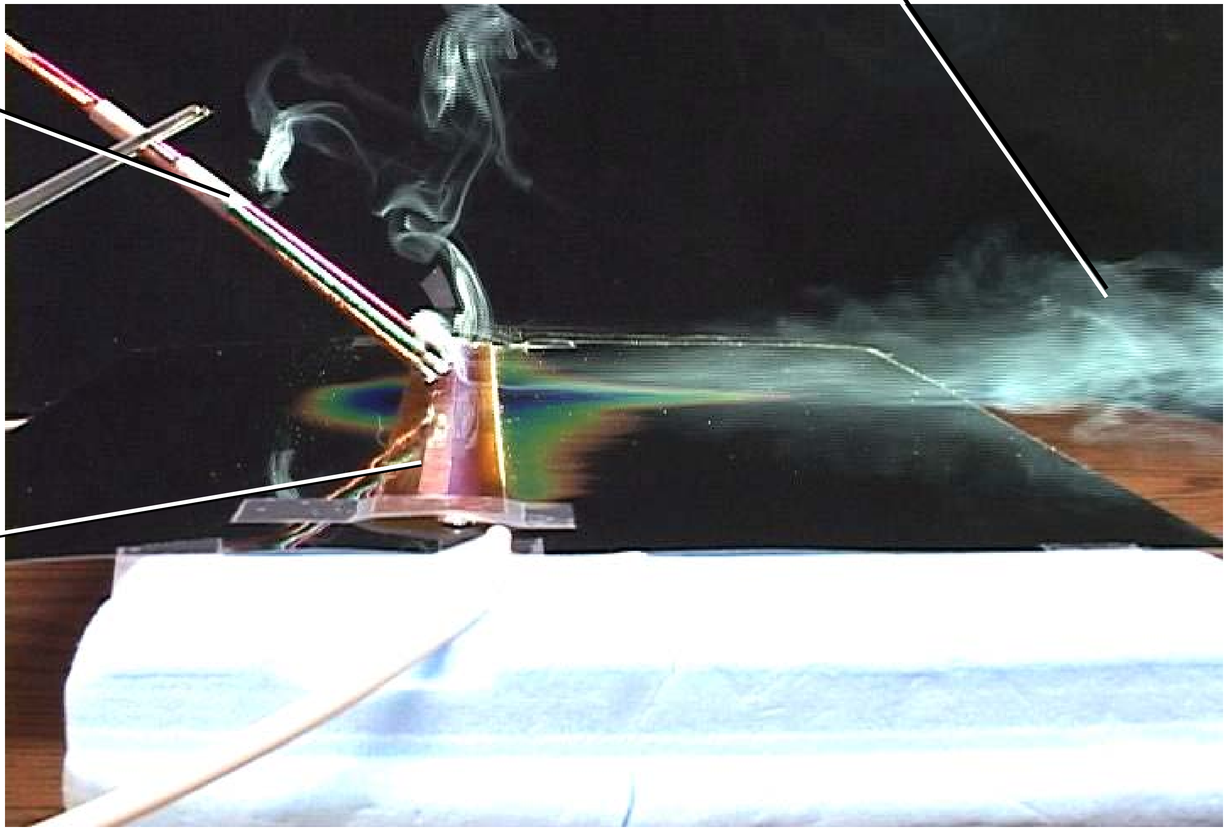
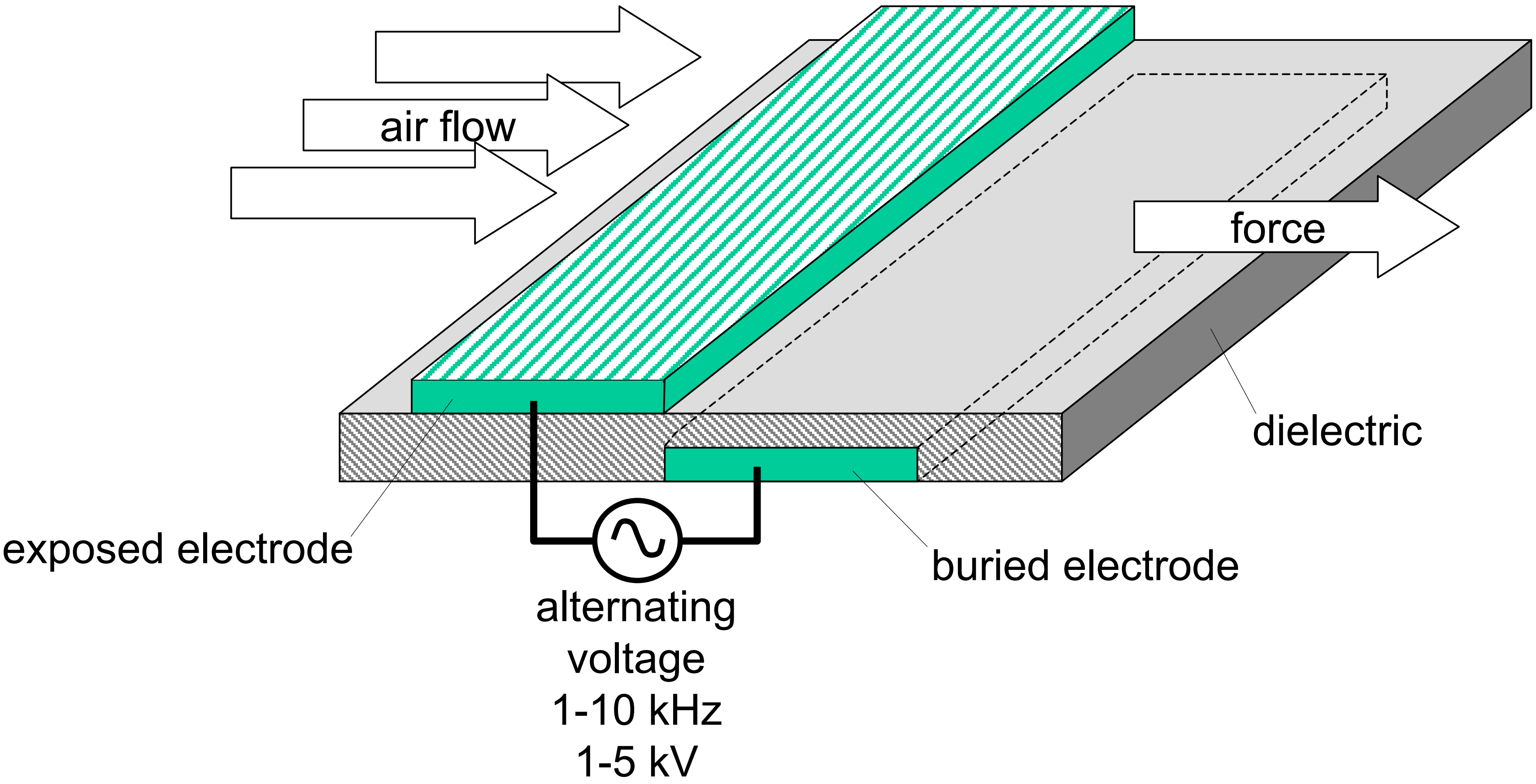
INTRODUCTION:
Plasma Actuator Adds Momentum to the Boundary Layer

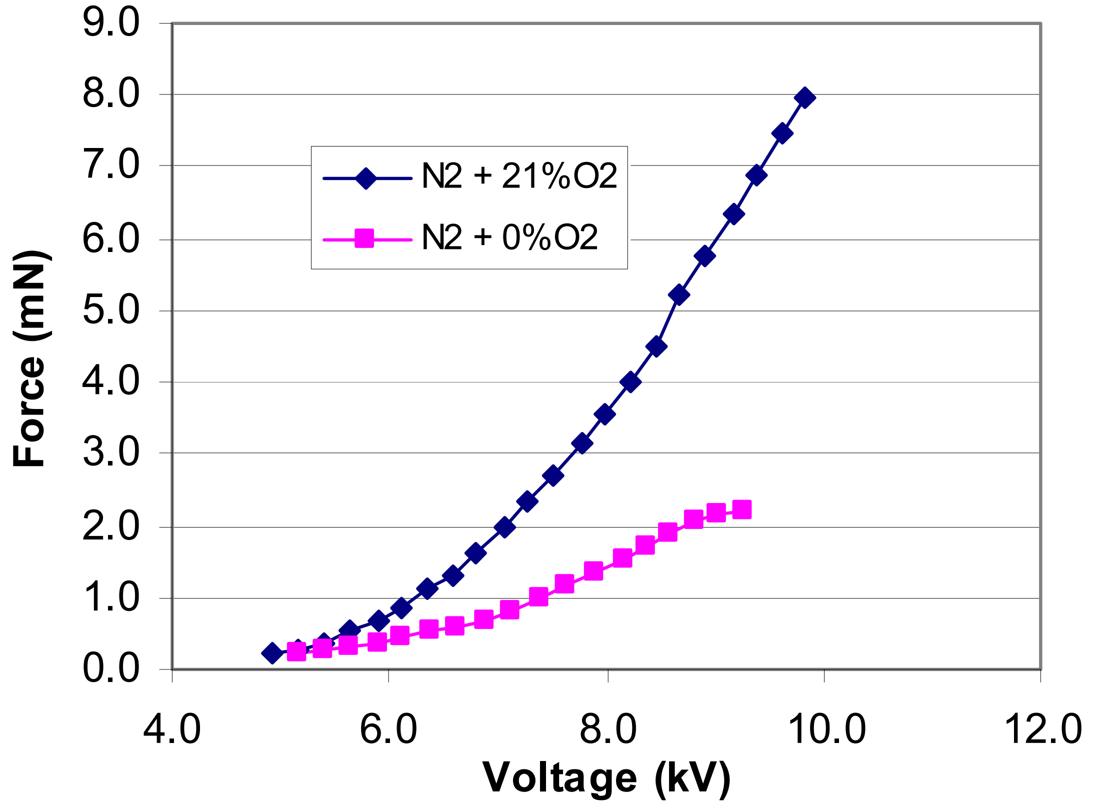


**from L. Enloe, et al. (2004)

INTRODUCTION:
Plasma Actuator Components



INTRODUCTION:
Differences in Oxygen and Nitrogen Behavior



- The presence of oxygen leads to higher force levels and faster increase.
- The role of negative ions is unknown.

**from L. Enloe, et al. (2005)

NUMERICAL METHOD:

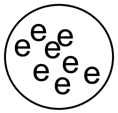
Modeling an Electron Avalanche

PIC-DSMC

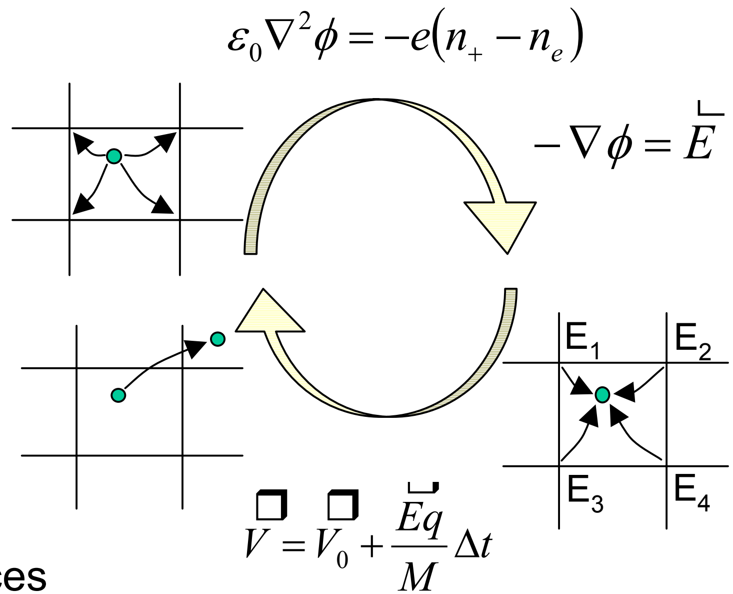
NUMERICAL METHOD:
Particle-In-Cell with Direct-Simulation-Monte-Carlo

Particle – In – Cell:

- Computational particles represent 1000's of real particles



- Both electrons and ions are treated as particles
- Charge density is weighted onto grid
- Poisson's equation solution → electric potential
- Gradient of electric potential → electric field
- Forces weighted from the grid to the particles
- Particle velocities are updated from with the current forces
- Particle position is updated with new velocities



NUMERICAL METHOD:
Particle-In-Cell with Direct-Simulation-Monte-Carlo

Direct-Simulation-Monte-Carlo:

- Treats collisions with the neutrals
- Each particle evaluated for the statistical probability of a chemical reaction occuring
- Probability calculated using collision cross-sections and particle velocity
- Random number generator is used to decide whether reaction takes place
- New ions and electrons are generated
- Chemical composition change in each cell is recorded
- Momentum transfer to the neutrals is recorded
- Neutral species motion is not tracked due to time scale

NUMERICAL METHOD:
Nitrogen Chemical Reaction Set

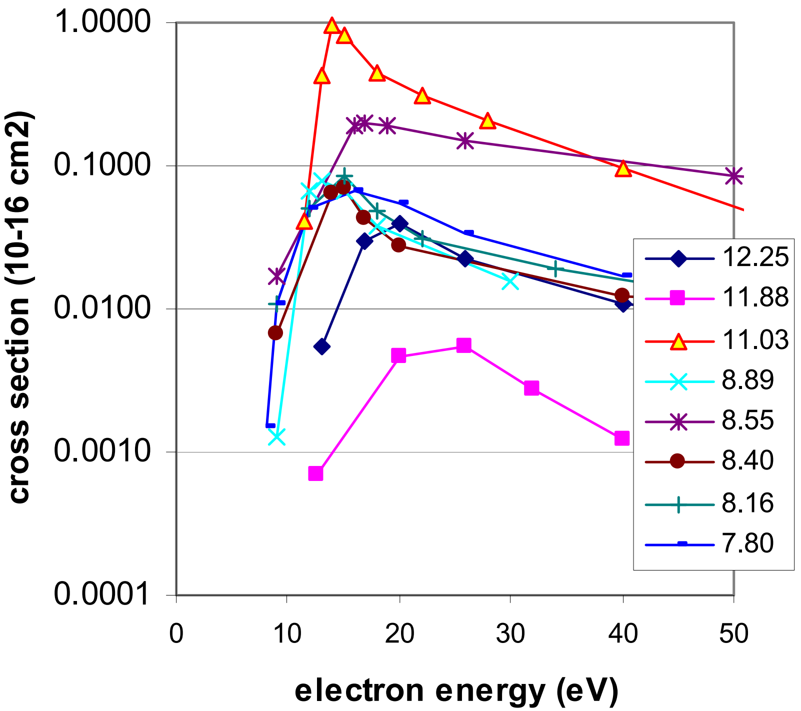
e	+	N_2	→	N_2	+	e	momentum transfer
e	+	$2N_2$	→	N_4^+	+	2e	ionization ($N_2 + N_2^+ \rightarrow N_4^+$)
e	+	N_2	→	N_2^*	+	e	meta-stable excitation
e	+	N_2	→	2N	+	e	dissociation
e	+	N_4^+	→	$2N_2$			dissociative recombination (glow)
N_4^+	+	N_2	→	N_4^+	+	N_2	momentum transfer
N_4^+	+	Cu_{surf}	→	$2N_2$	+	0.03e	secondary electron emission

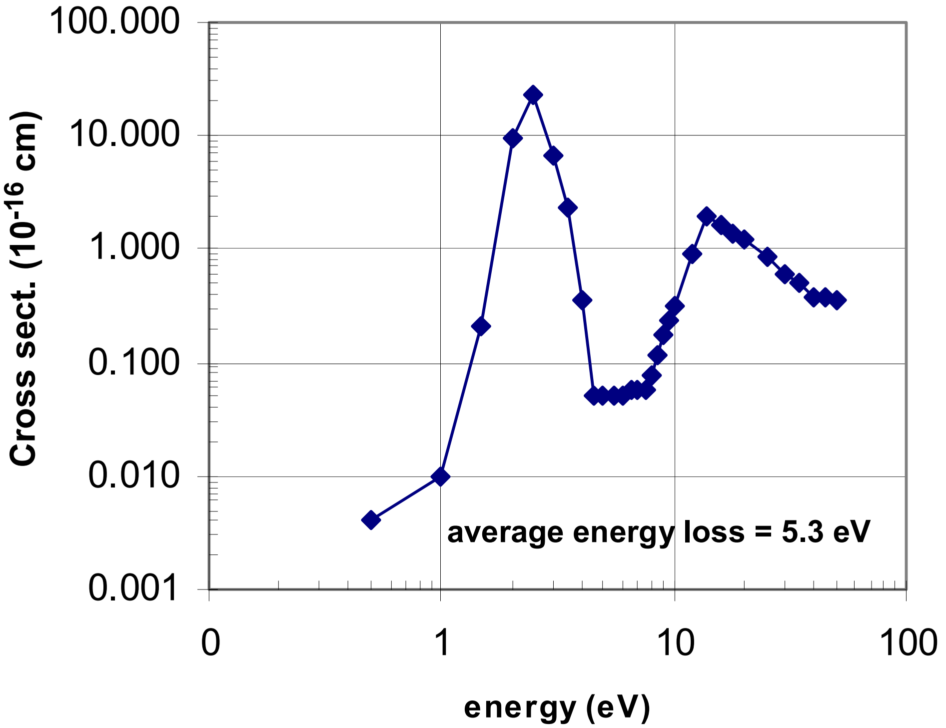
NUMERICAL METHOD:
Oxygen Chemical Reaction Set

e	+	O_2	→	O_2	+	e	momentum transfer
e	+	$2O_2$	→	O_4^+	+	2e	ionization ($O_2 + O_2^+ \rightarrow O_4^+$)
e	+	O_2	→	O-	+	O	dissociative attachment
e	+	O_2	→	O_2^*	+	e	meta-stable excitation
e	+	O_2	→	2O	+	e	dissociation
e	+	O_4^+	→	$2O_2$			dissociative recombination (glow)
O_4^+	+	O_2	→	O_4^+	+	O_2	momentum transfer
O-	+	O_2	→	O-	+	O_2	momentum transfer
O_4^+	+	Cu_{surf}	→	$2O_2$	+	0.03e	secondary electron emission

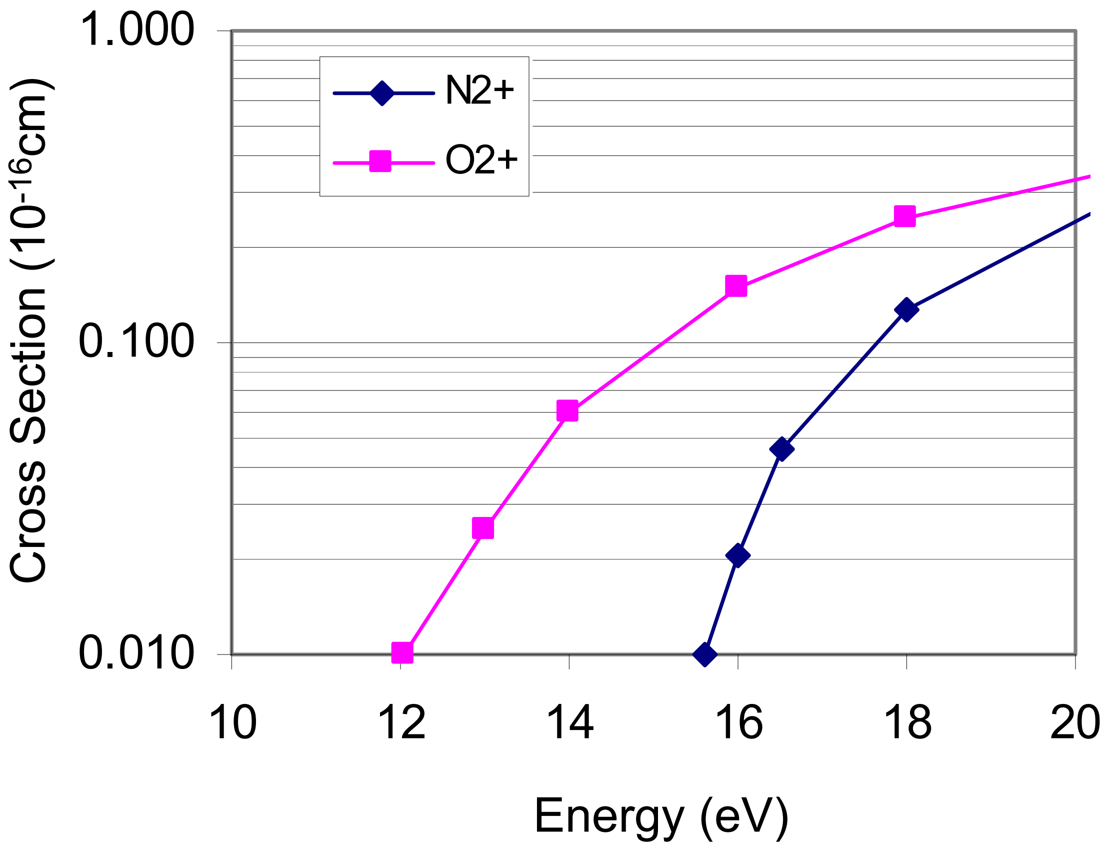
NUMERICAL METHOD:
Collision Cross Section – Nitrogen Excitation

$$e + N_2 \rightarrow N_2^* + e$$





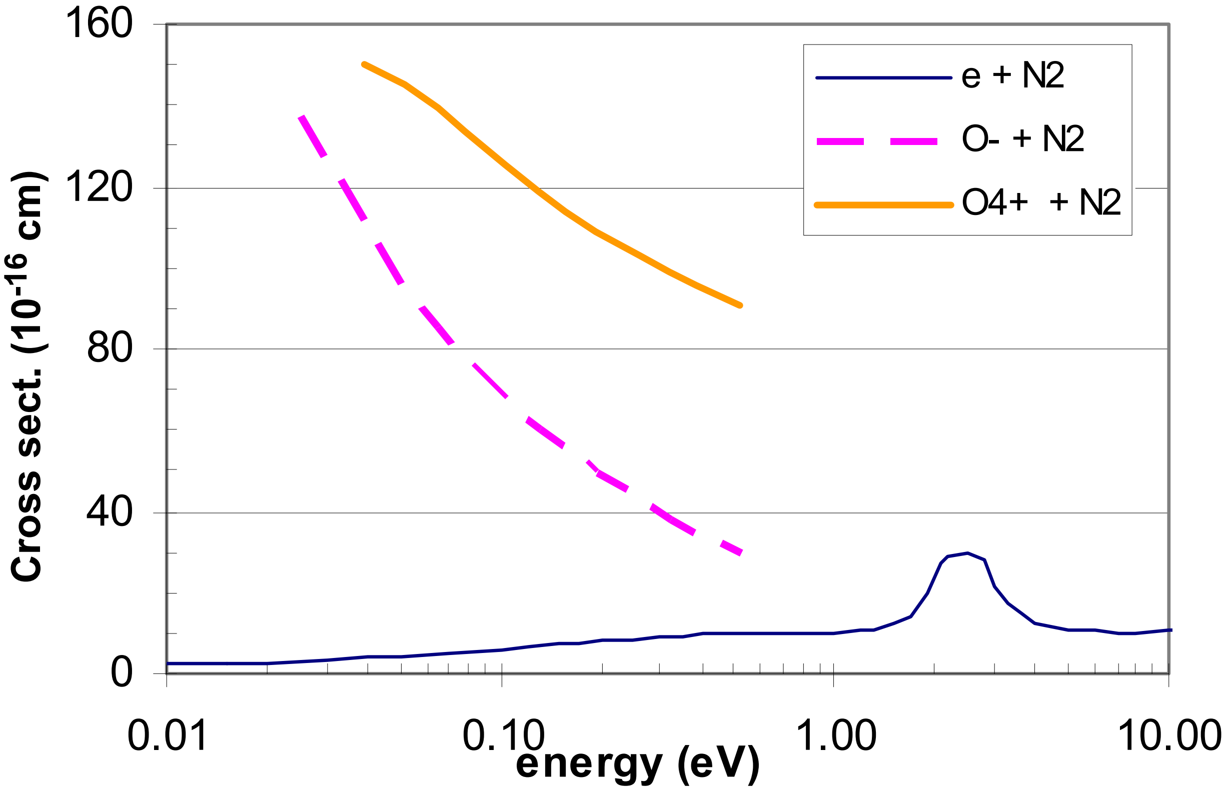
NUMERICAL METHOD:
Collision Cross Section – Ionization



$e + N_2 \rightarrow e + N_2^+$

$e + O_2 \rightarrow e + O_2^+$

NUMERICAL METHOD:
Collision Cross Section – Momentum Transfer in Oxygen

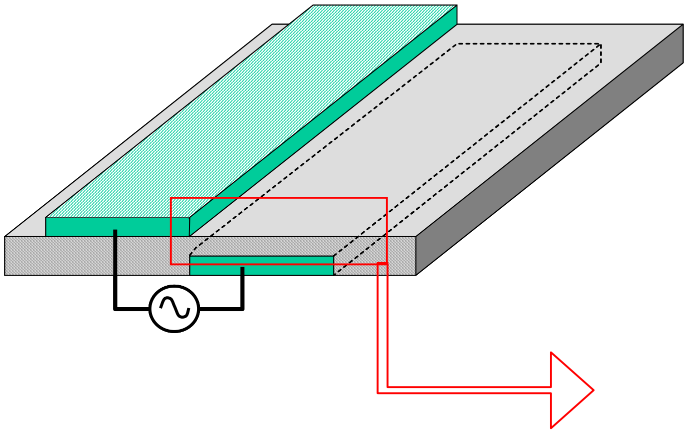


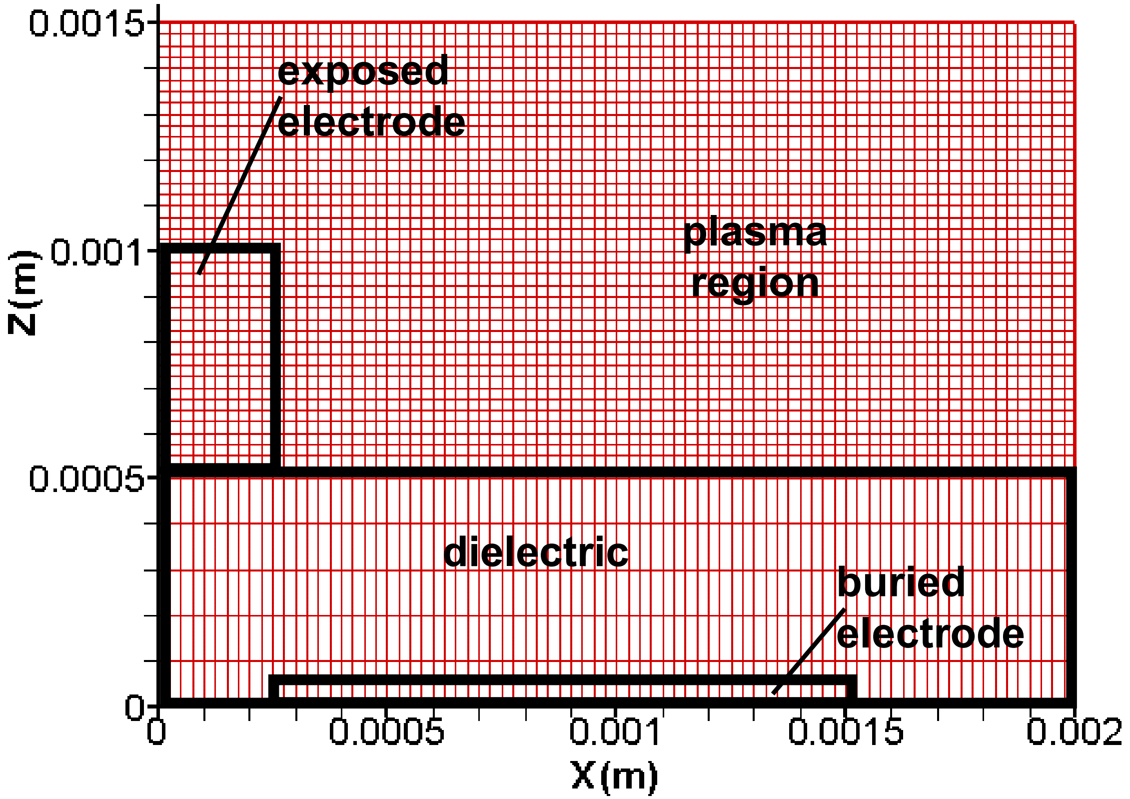
$e + N_2 \rightarrow e + N_2$

$O^- + N_2 \rightarrow O^- + N_2$

$O_4^+ + N_2 \rightarrow O_4^+ + N_2$

NUMERICAL METHOD:
Computational Geometry

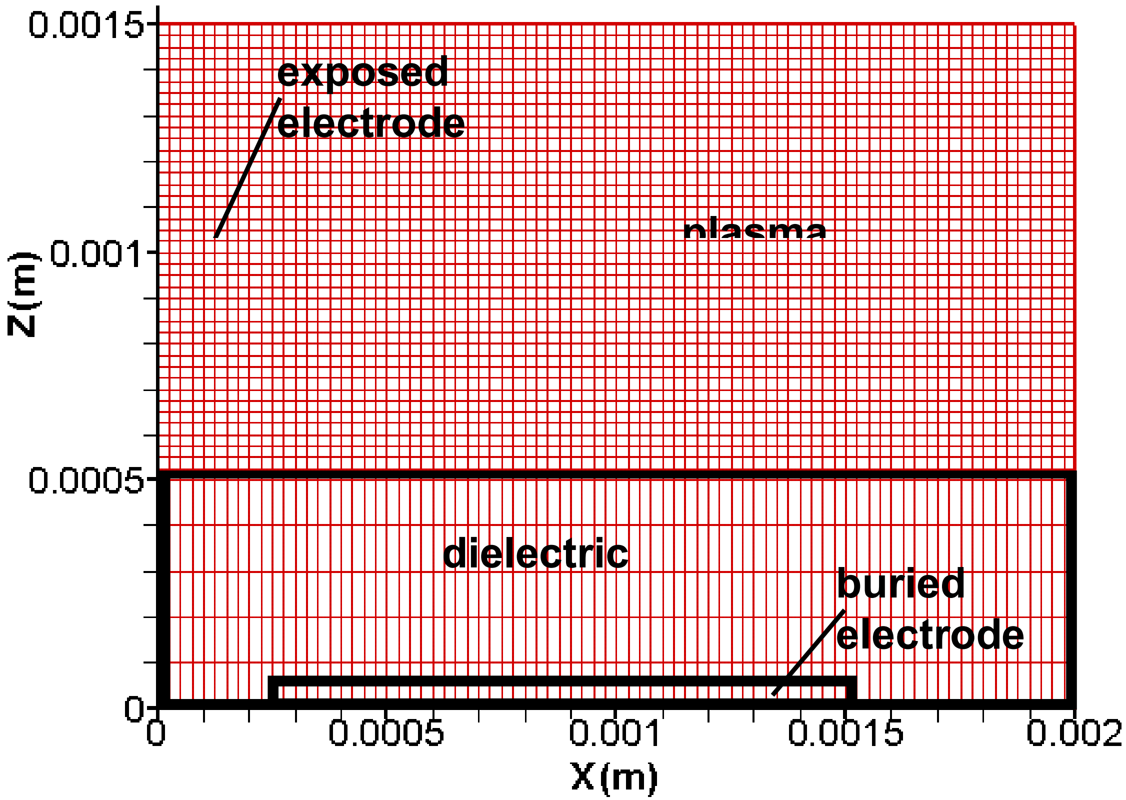




Computational Grid:
1.5 x 2.0 x 0.1 mm
165 x 320 x 1 cells

Each cell:
$6x10^{-6}$ m square x 0.1 mm wide

NUMERICAL METHOD:
Boundary Conditions



Exposed Electrode
-5500 to 5500 V

Buried Electrode
0 V

Boundaries
$\nabla \phi = 0$

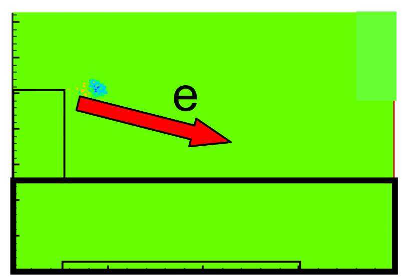
Particles on Dielectric
motion → halted

Particles on Boundary
deleted

Particles on Exposed Electrode
neutralized, deleted

COMPUTATIONAL RESULTS:

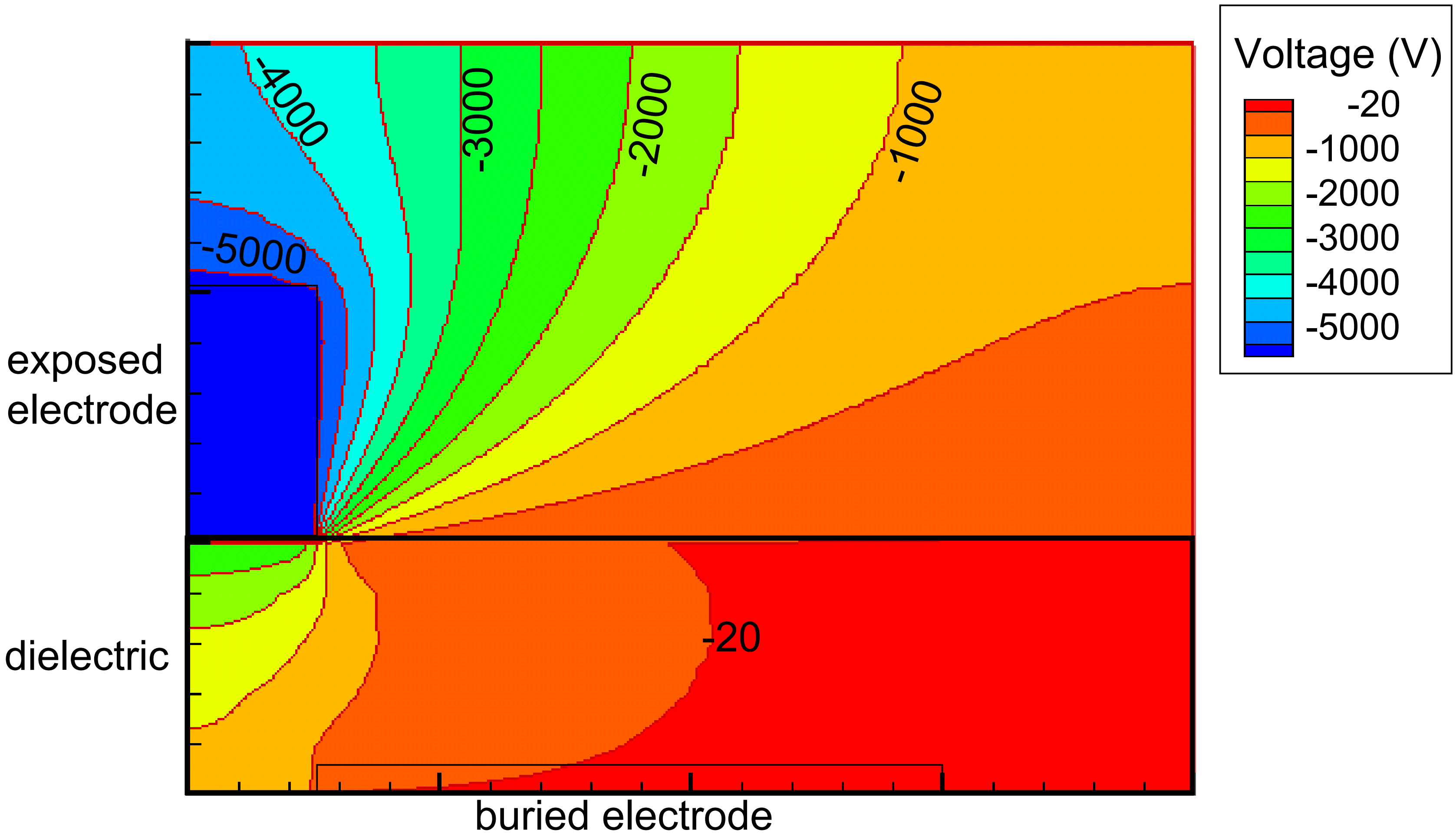
Forward Discharge



- exposed electrode negative
- electrons move away from exposed electrode

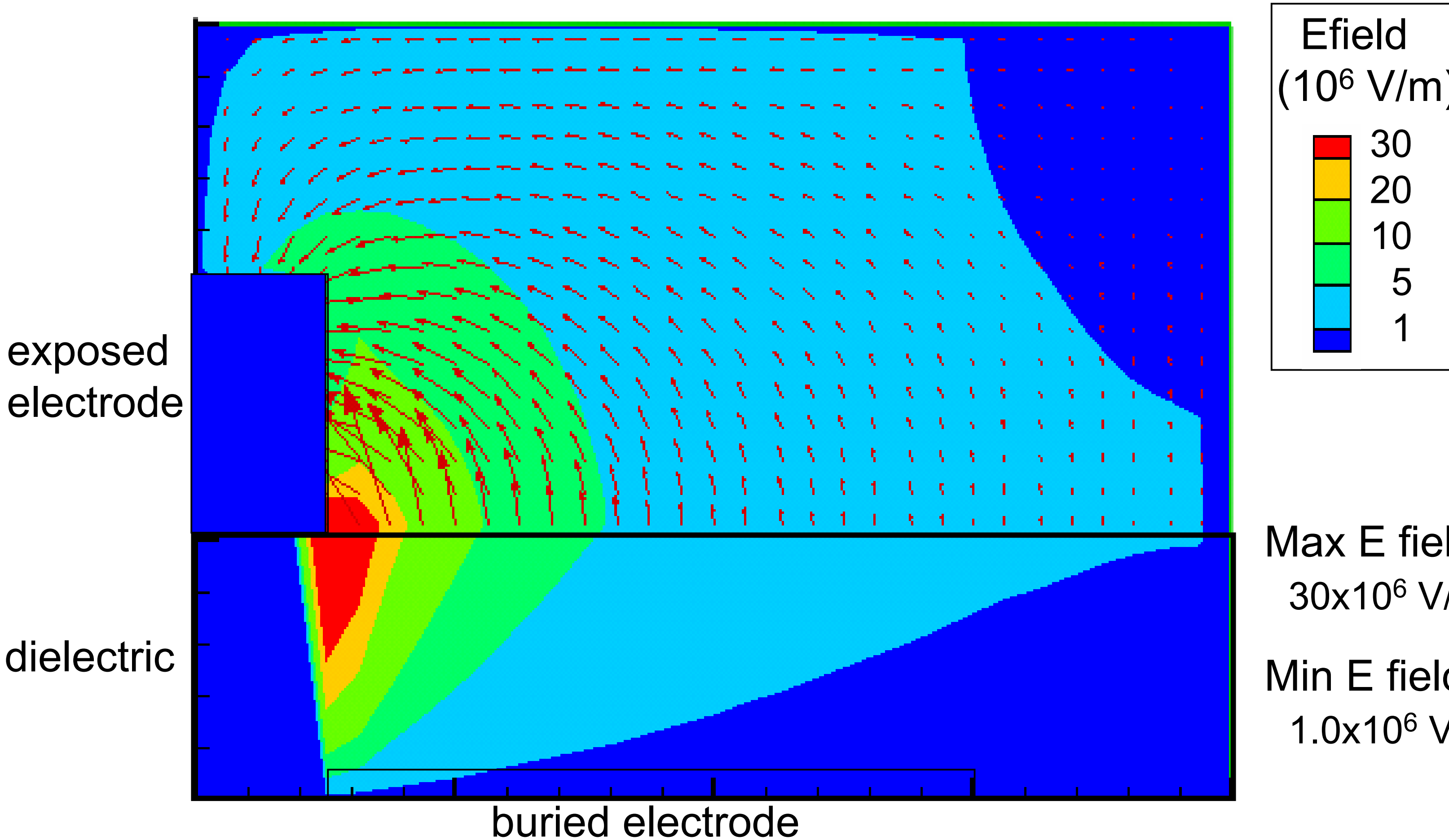
COMPUTATIONAL RESULTS: FORWARD DISCHARGE

Potential Distribution



COMPUTATIONAL RESULTS: FORWARD DISCHARGE

Electric Field Magnitude and Vectors

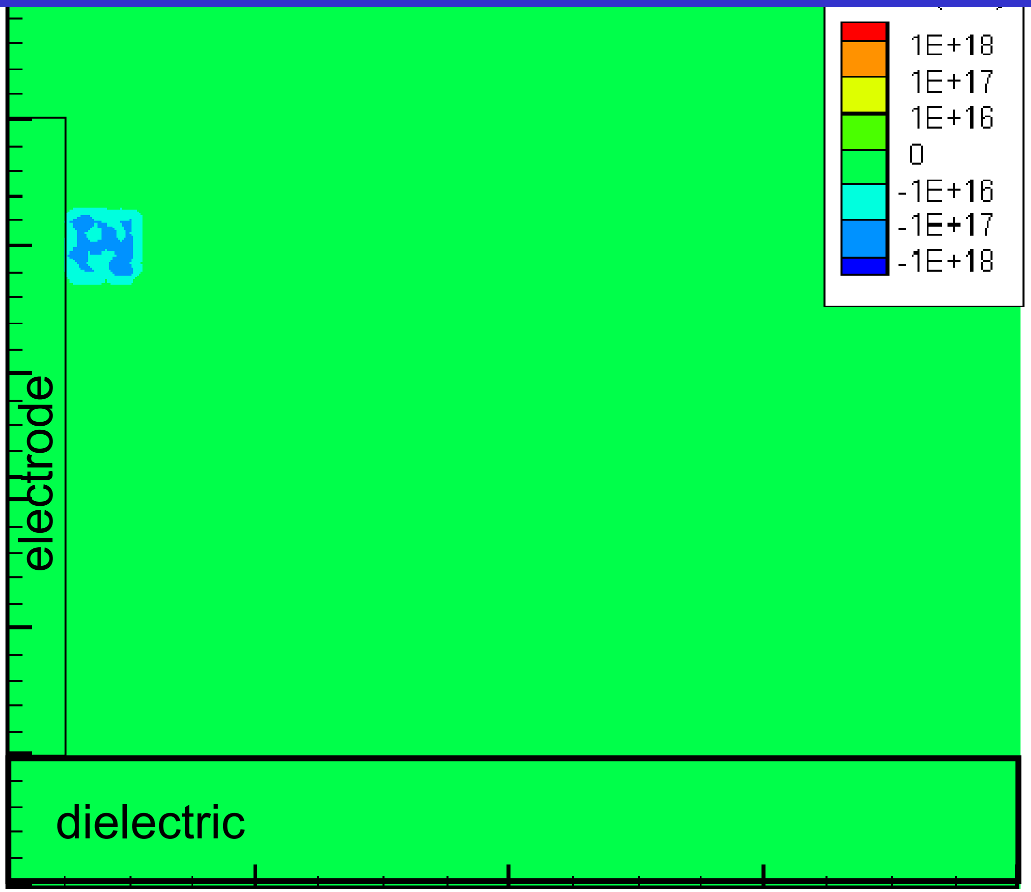


Max E field:
30×10^6 V/m

Min E field:
1.0×10^6 V/m

COMPUTATIONAL RESULTS: FORWARD DISCHARGE

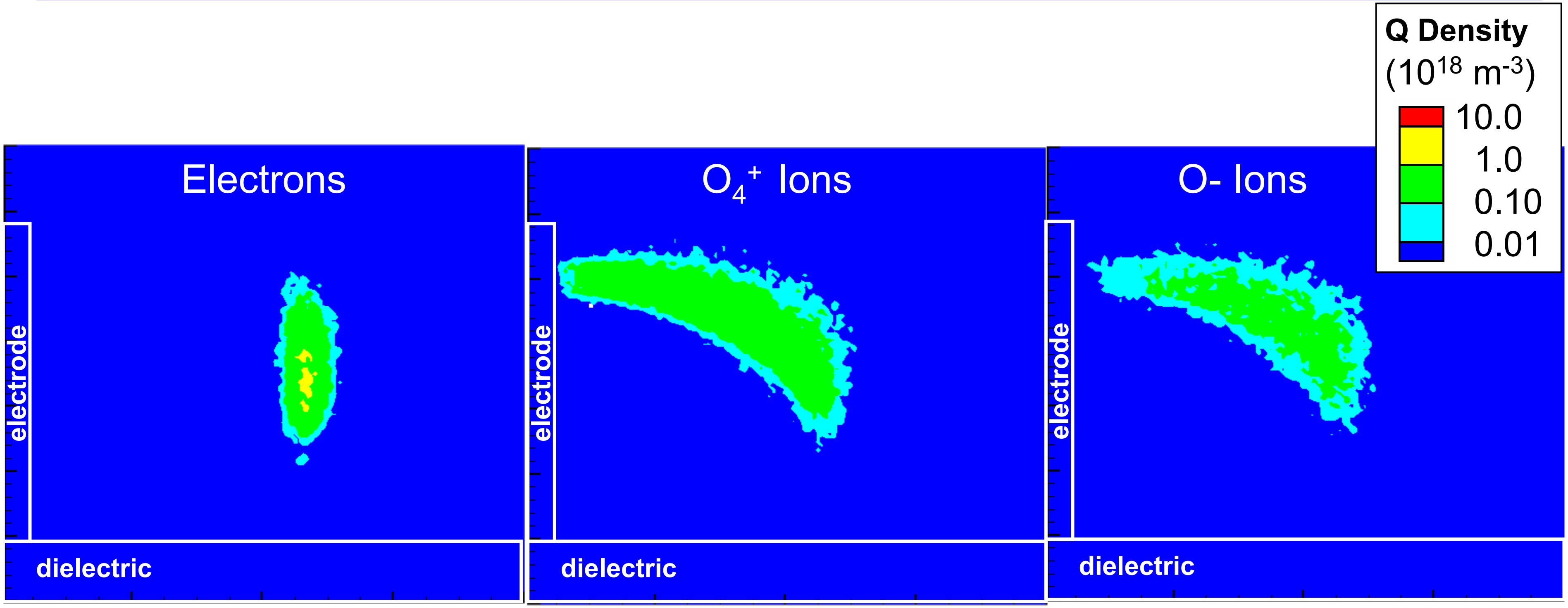
Electron Avalanche – Charge Density – 1-2 nsec



frames are 0.1 nsec apart

COMPUTATIONAL RESULTS: FORWARD DISCHARGE

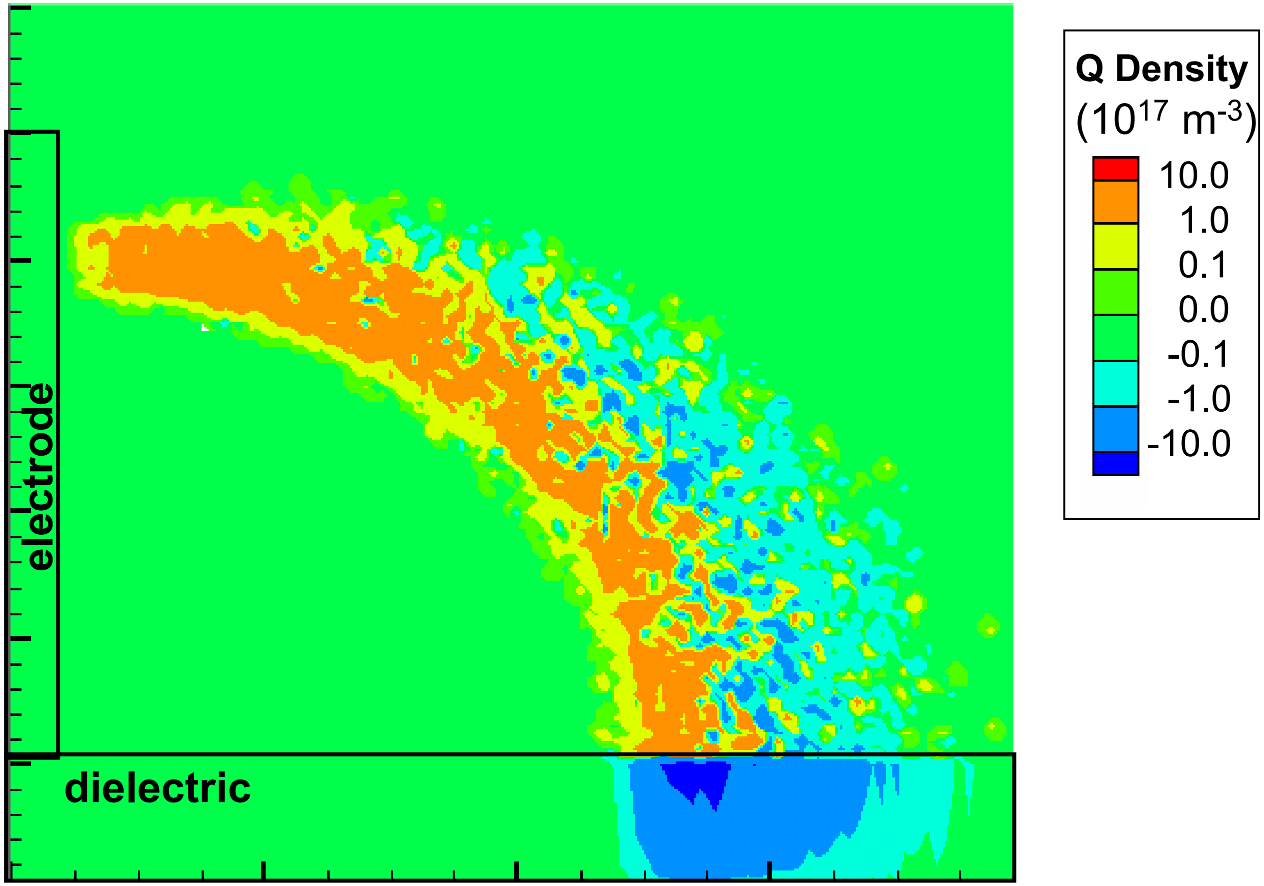
Charge Density at time = 1.1 nsec



- Electrons are concentrated at the head
- Tail is dominated by positive and negative ions
- Negative ions are 30-40% of positive ions
- Average Ion density is about 10^{17} m^{-3}

COMPUTATIONAL RESULTS: FORWARD DISCHARGE

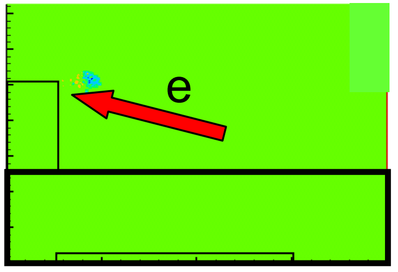
Charge Density at time = 60 nsec



- Positive -Negative ion column decays in 3 μsec
- Millions of electrons are left on the dielectric

COMPUTATIONAL RESULTS:

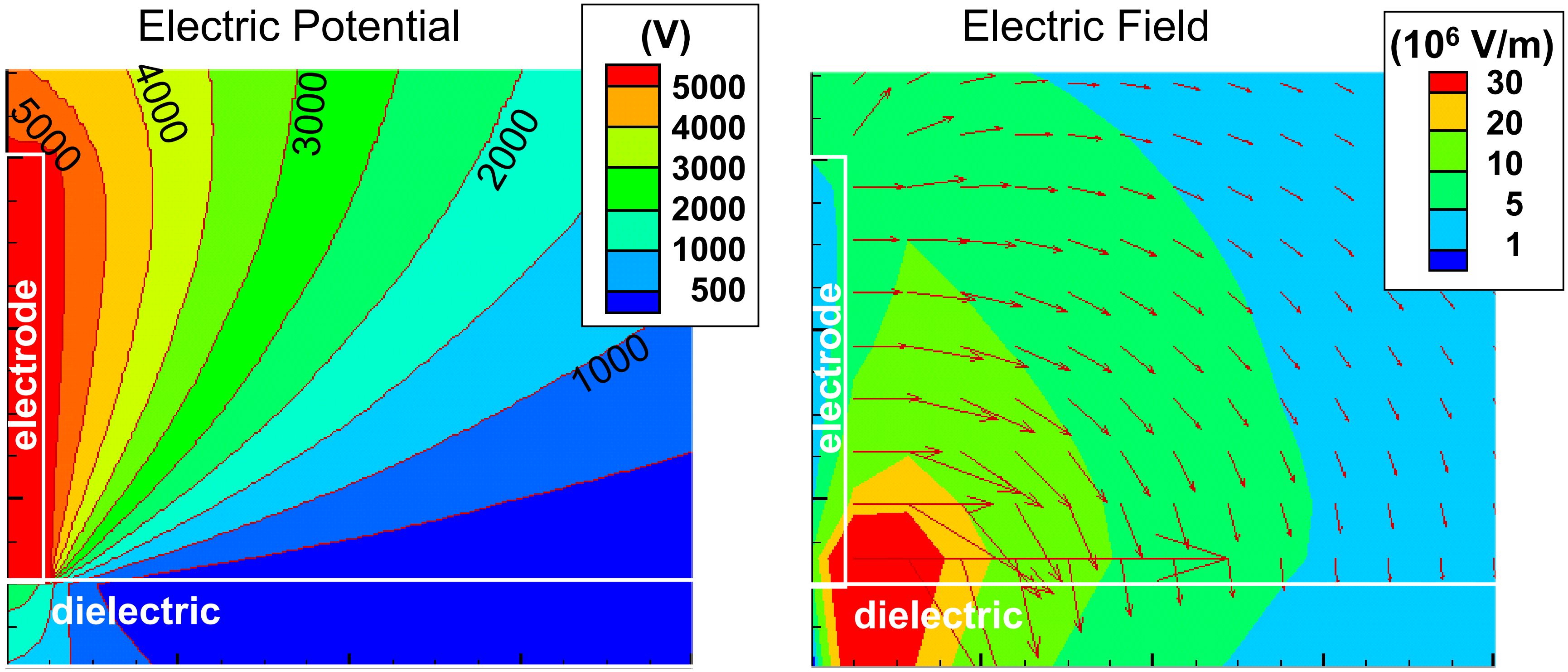
Back Discharge



- exposed electrode positive
- electrons move toward exposed electrode

COMPUTATIONAL RESULTS: BACK DISCHARGE

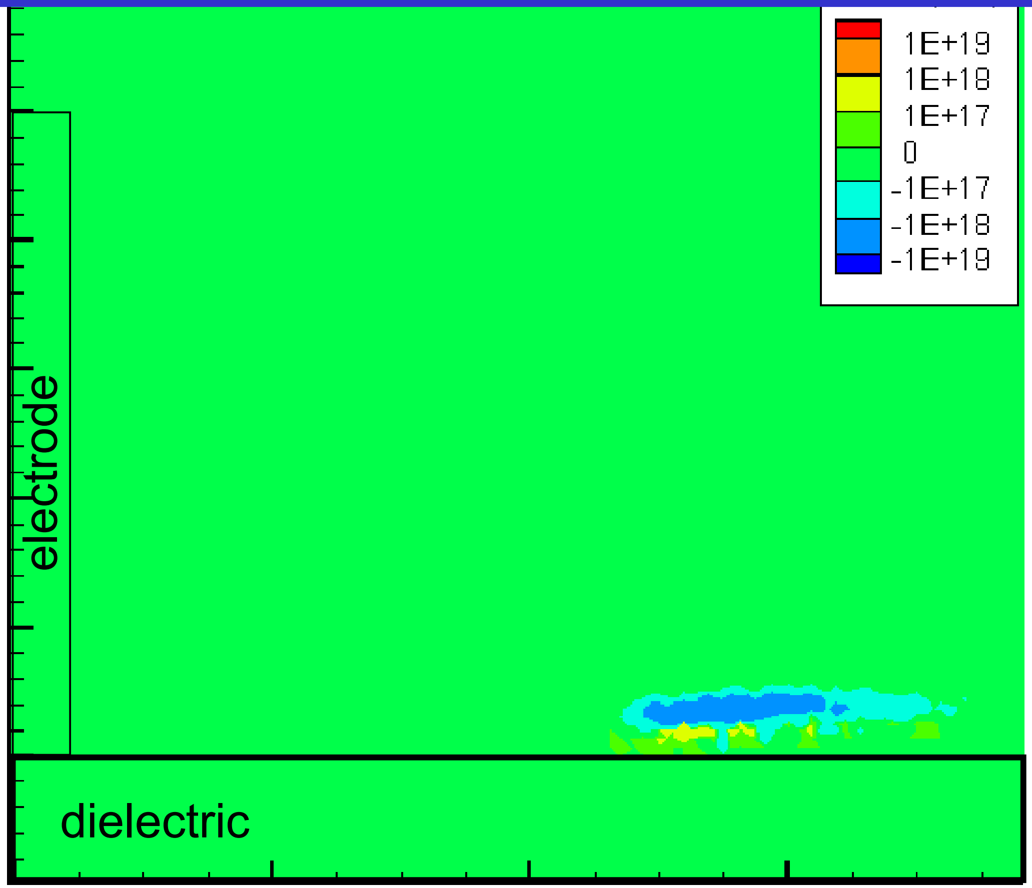
Potential Distribution and Electric Field at Start of Discharge



- Average electric field is about 10^7 V/m
- The electric field points away from the exposed electrode

COMPUTATIONAL RESULTS: BACK DISCHARGE

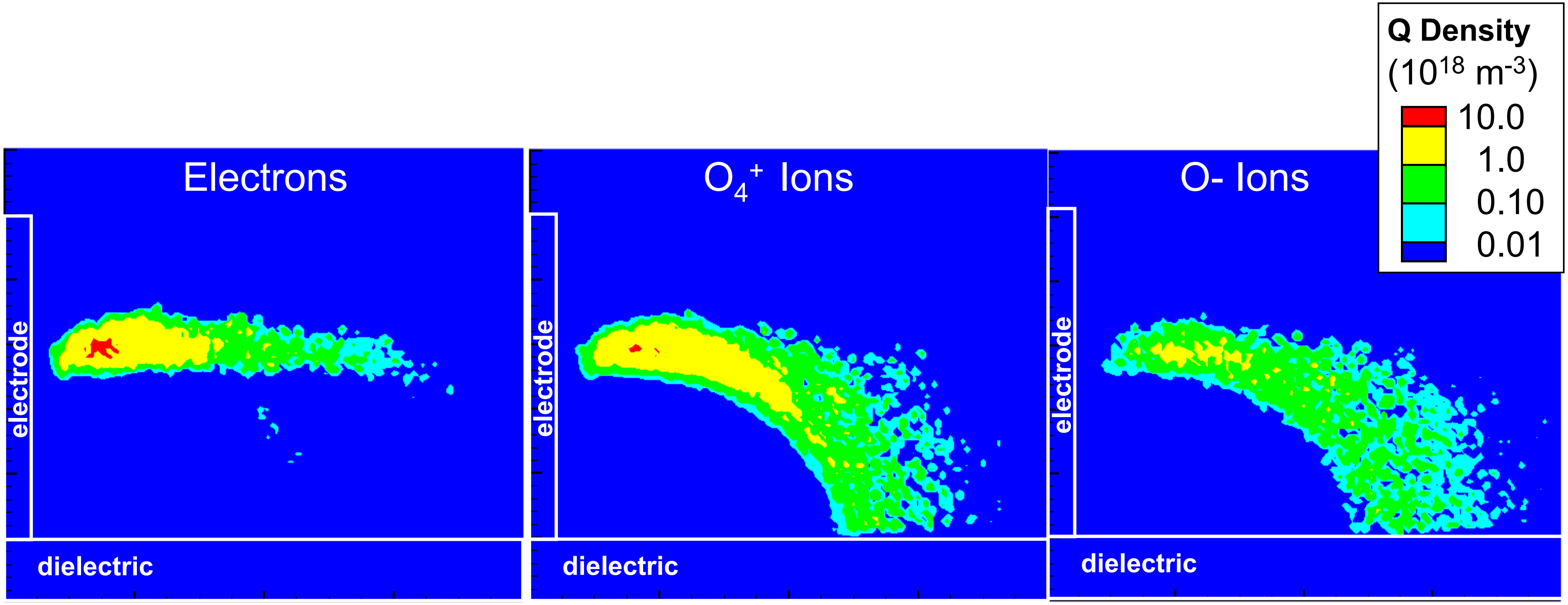
Electron Avalanche – Charge Density – 60-63 nsec



frames are 0.1 nsec apart

COMPUTATIONAL RESULTS: BACK DISCHARGE

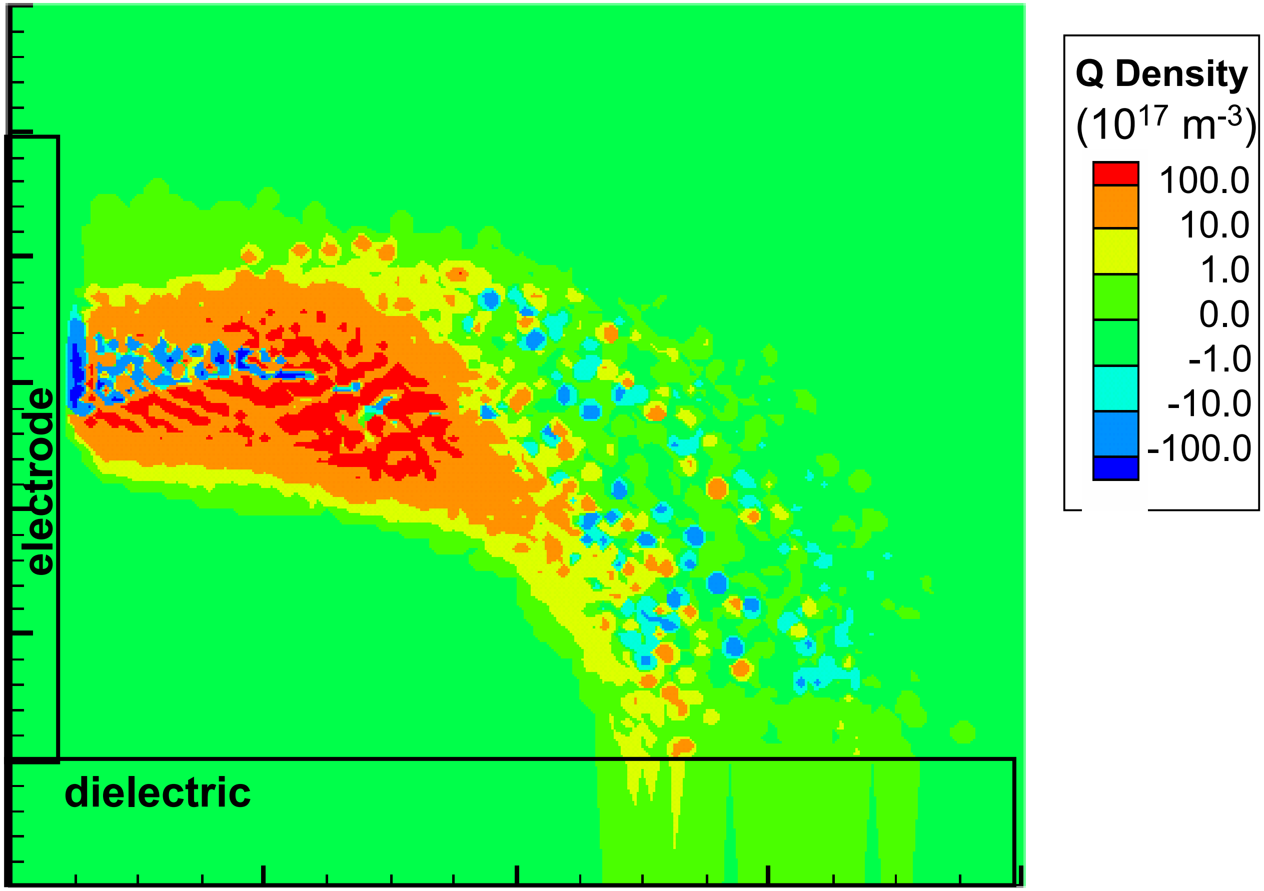
Charge Density at time = 61.1 nsec



- Electrons are concentrated at the head
- Tail is dominated by positive and negative ions
- Negative ions are 30-40% of positive ions
- Average Ion density is about 10^{18} m^{-3}

COMPUTATIONAL RESULTS: BACK DISCHARGE

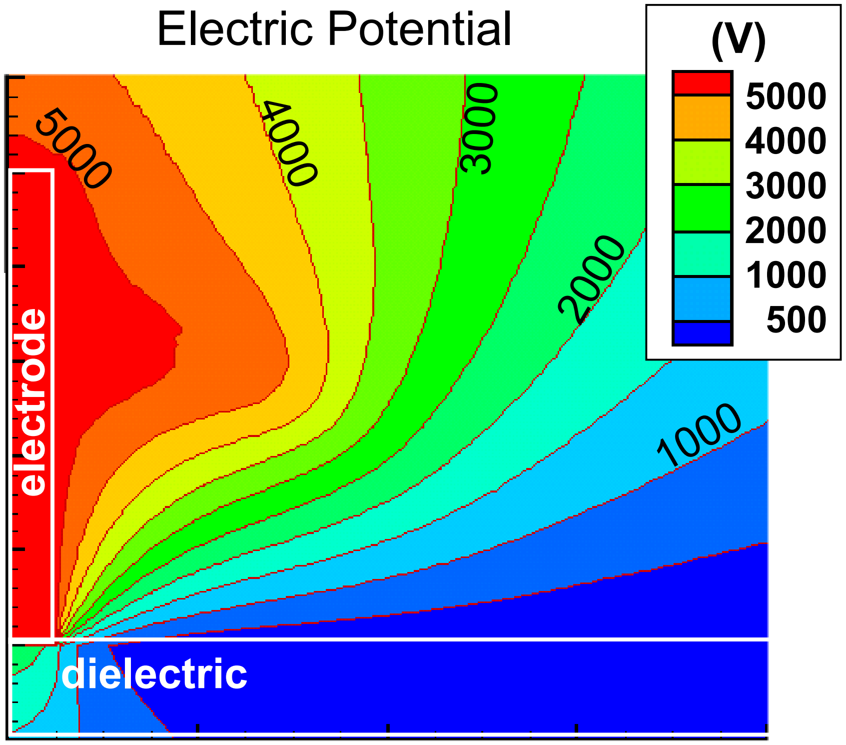
Charge Density at time = 120 nsec

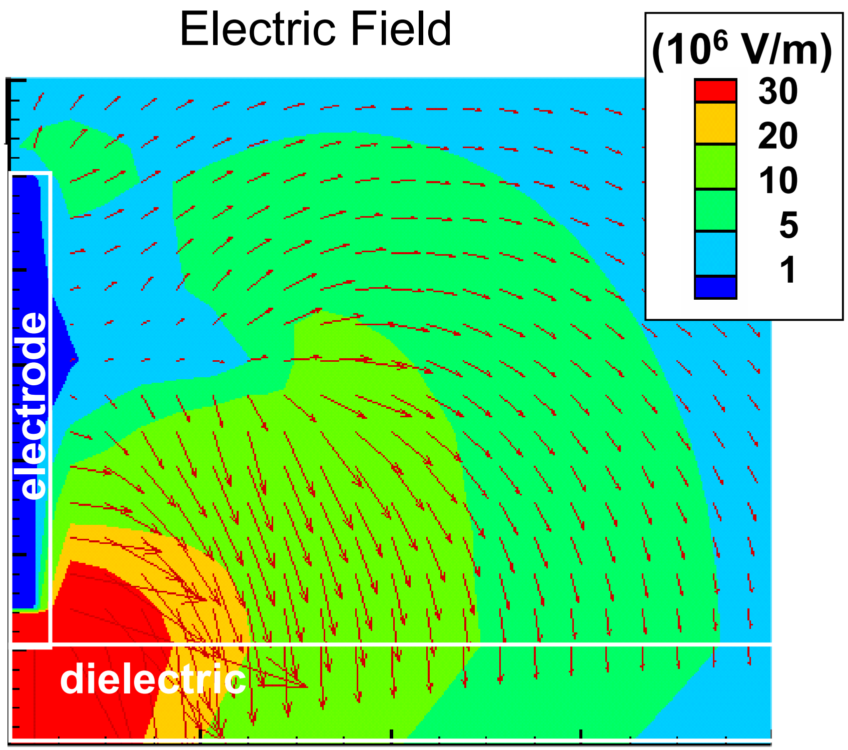


- Positive -Negative ion column decays in 3 μsec
- Average density is 10x larger than during forward discharge

COMPUTATIONAL RESULTS: BACK DISCHARGE

Potential Distribution and Electric Field at time = 120 nsec

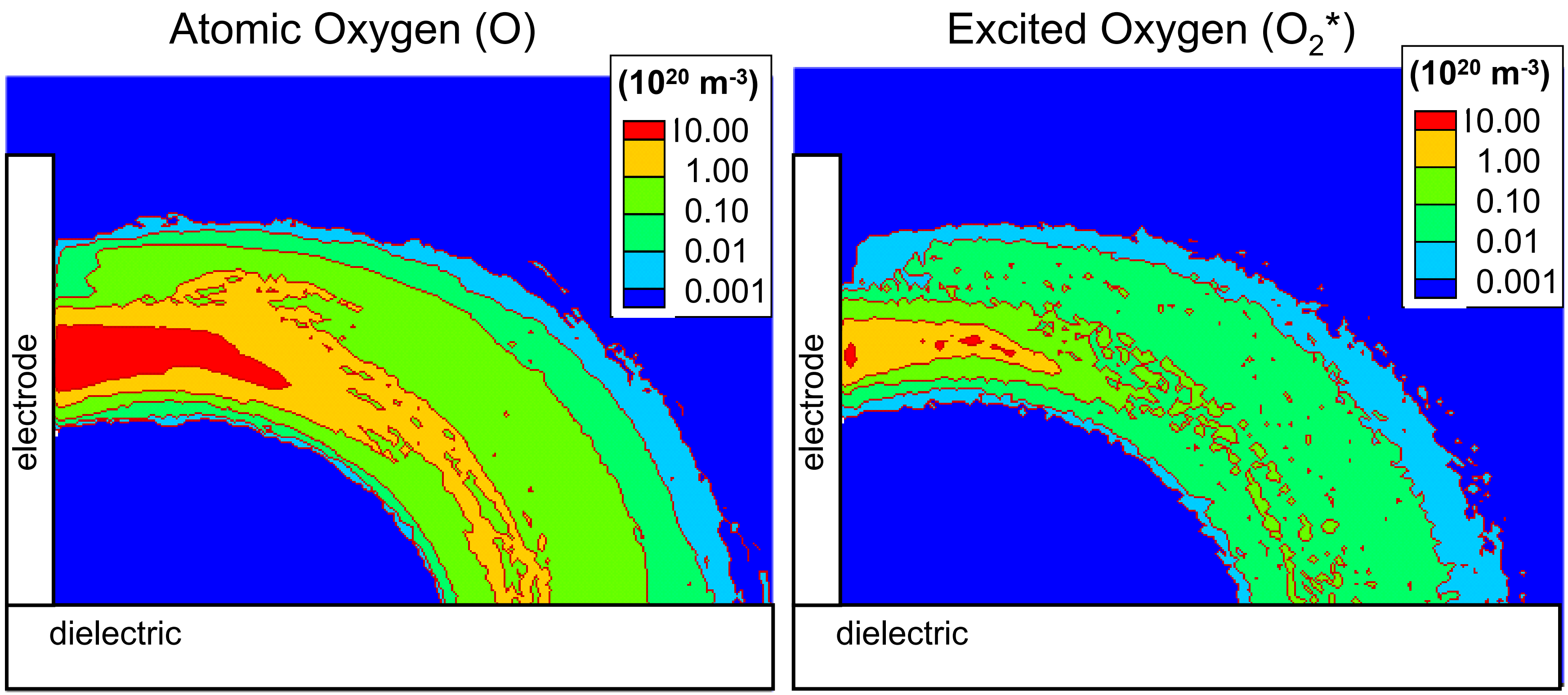




- Voltage distribution altered
- Charge density sufficiently high to begin shielding electric field

COMPUTATIONAL RESULTS: BACK DISCHARGE

Plasma Neutral Product Densities at time = 120 nsec

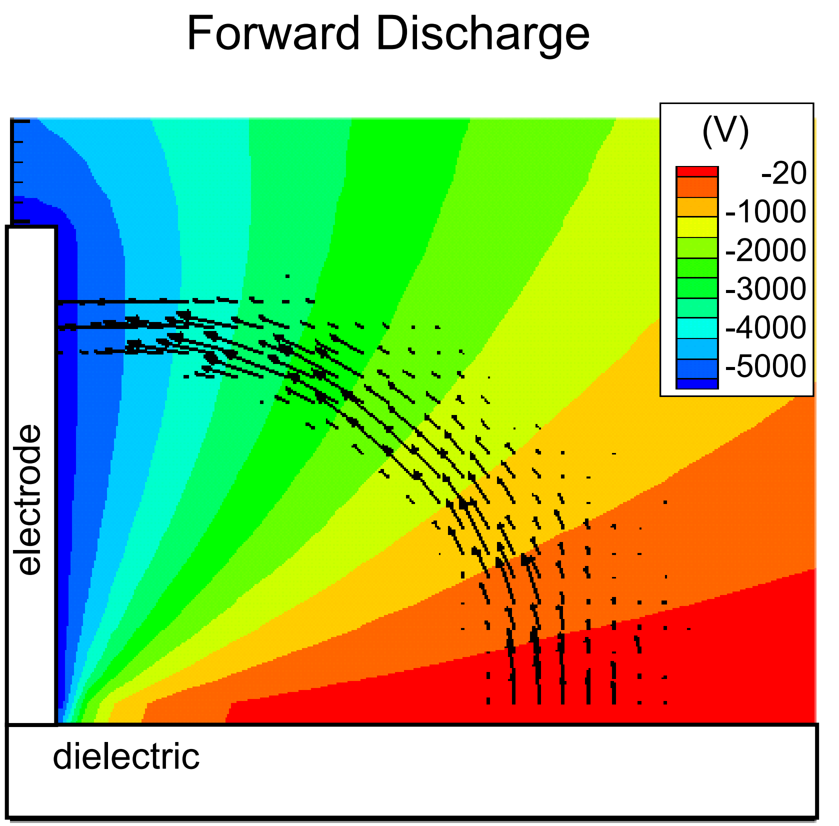


- Average excited and atomic Oxygen densities are << 1% of neutrals for one cycle
- Plasma products probably accumulate over many bias cycles

COMPUTATIONAL RESULTS:

Force Production Mechanism

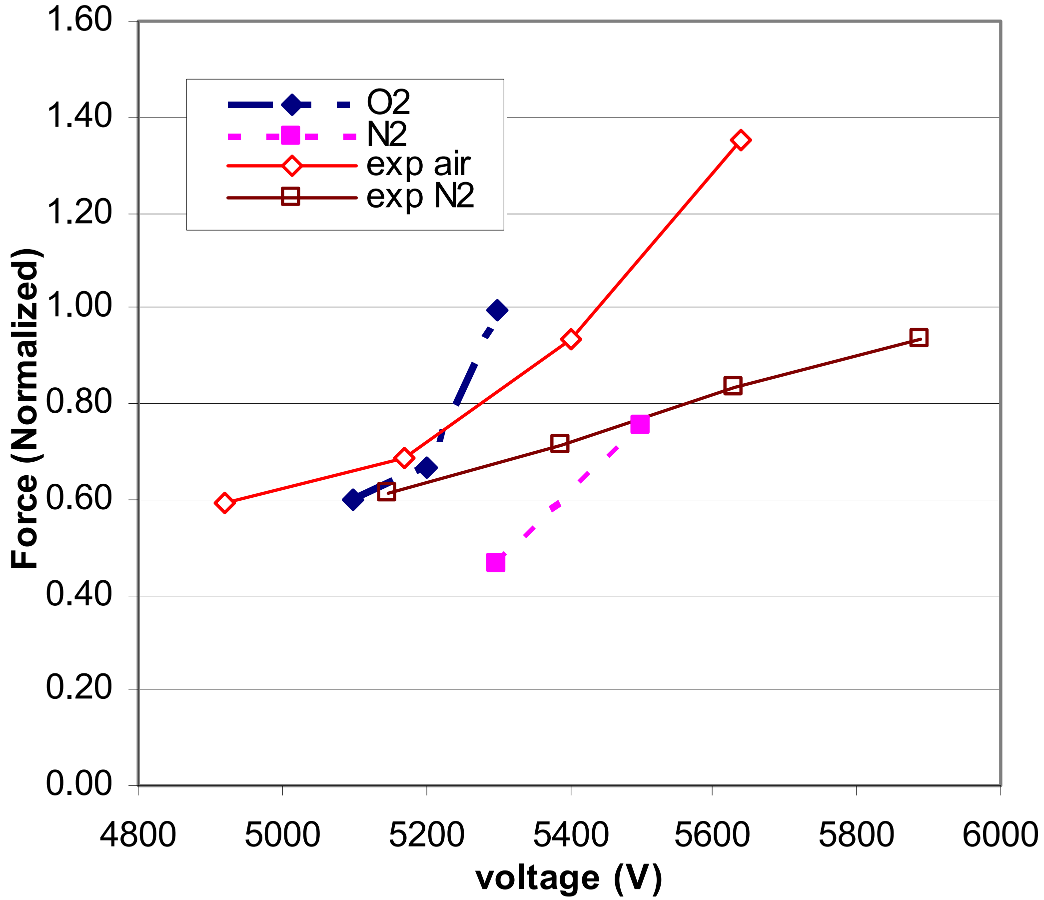
COMPUTATIONAL RESULTS:
Force Production: Force Vectors



- Forward discharge: the force is back toward the exposed electrode
- Back discharge: force away from the exposed electrode
- **NET FORCE: away from the exposed electrode**

COMPUTATIONAL RESULTS:

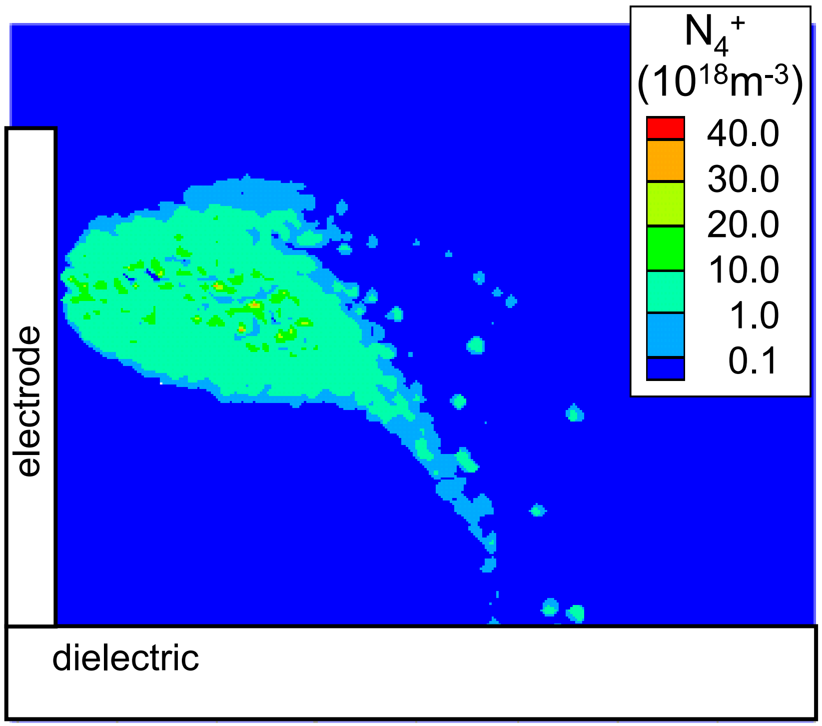
Force Production compared to an experiment



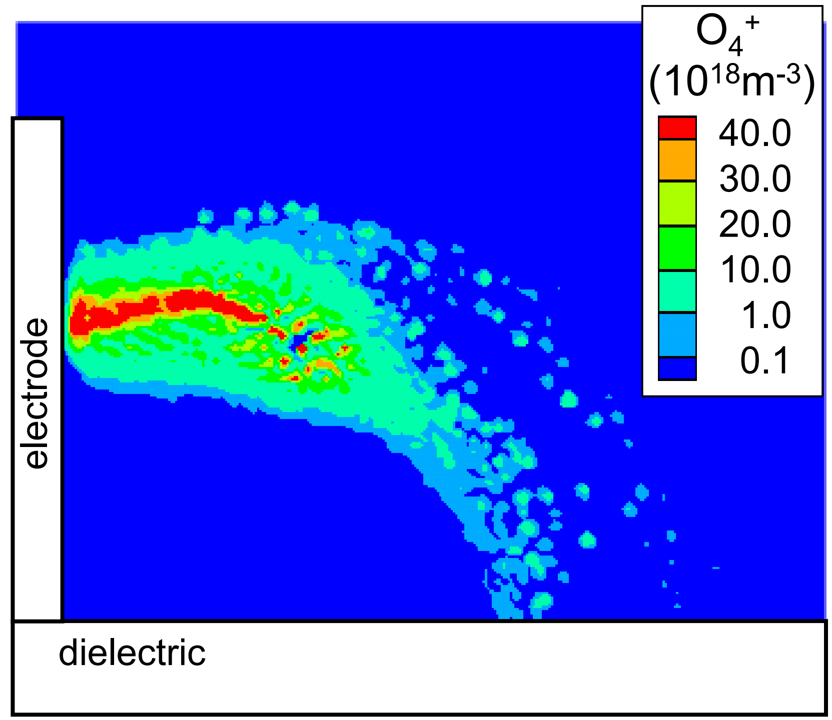
COMPUTATIONAL RESULTS:

Force Production: Oxygen vs Nitrogen

Nitrogen Discharge

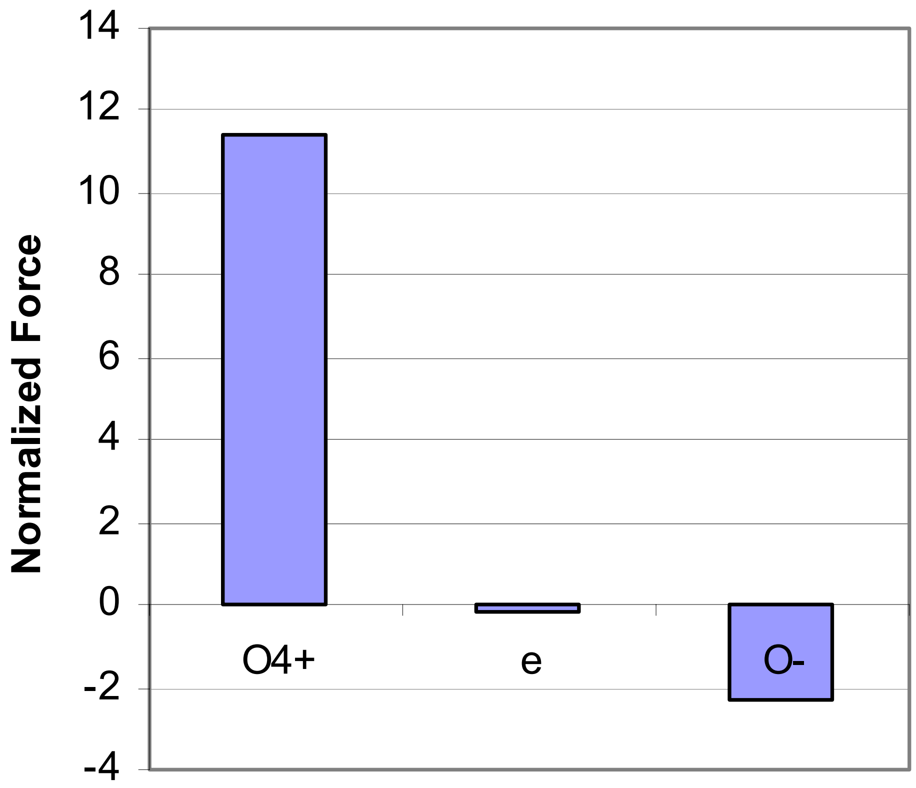


Oxygen Discharge



- Oxygen generates more force due to greater ion densities

COMPUTATIONAL RESULTS:
Role of negative ions in Oxygen



- Negative ions push in the oposite direction, but do not cancel force

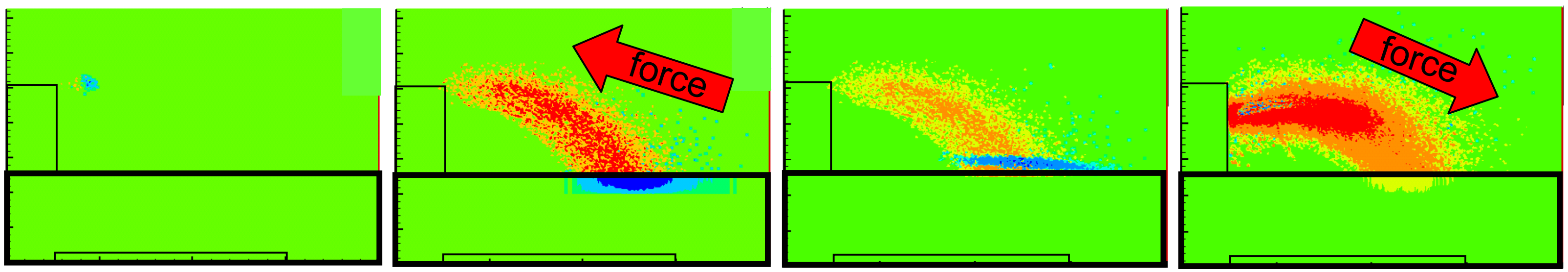
CONCLUSIONS:

- Plasma actuator is a dielectric barrier discharge that produces a plasma through an electron avalanche.
- A net force is produced by the acutator because the discharge always produces more ions in the second half of the discharge.
- The majority of the force is imparted through ion collisions due to the cross section being larger for ions than for electrons.
- Oxygen plasmas produce more force than nitrogen plasmas due to greater levels of ionization.
- Negative ions do not change the physics. They diminish the force but can not cancel or reverse it due to their lower density.
- Comparison to experiments show promise. Matched relative magnitude and differing slopes with respect to voltage.
- The accumulation of plasma products through out many bias cycles may be important to the force production.

LESSONS LEARNED:

Summary

QUESTIONS ?



Forward Discharge **Back Discharge**

Forward Discharge:

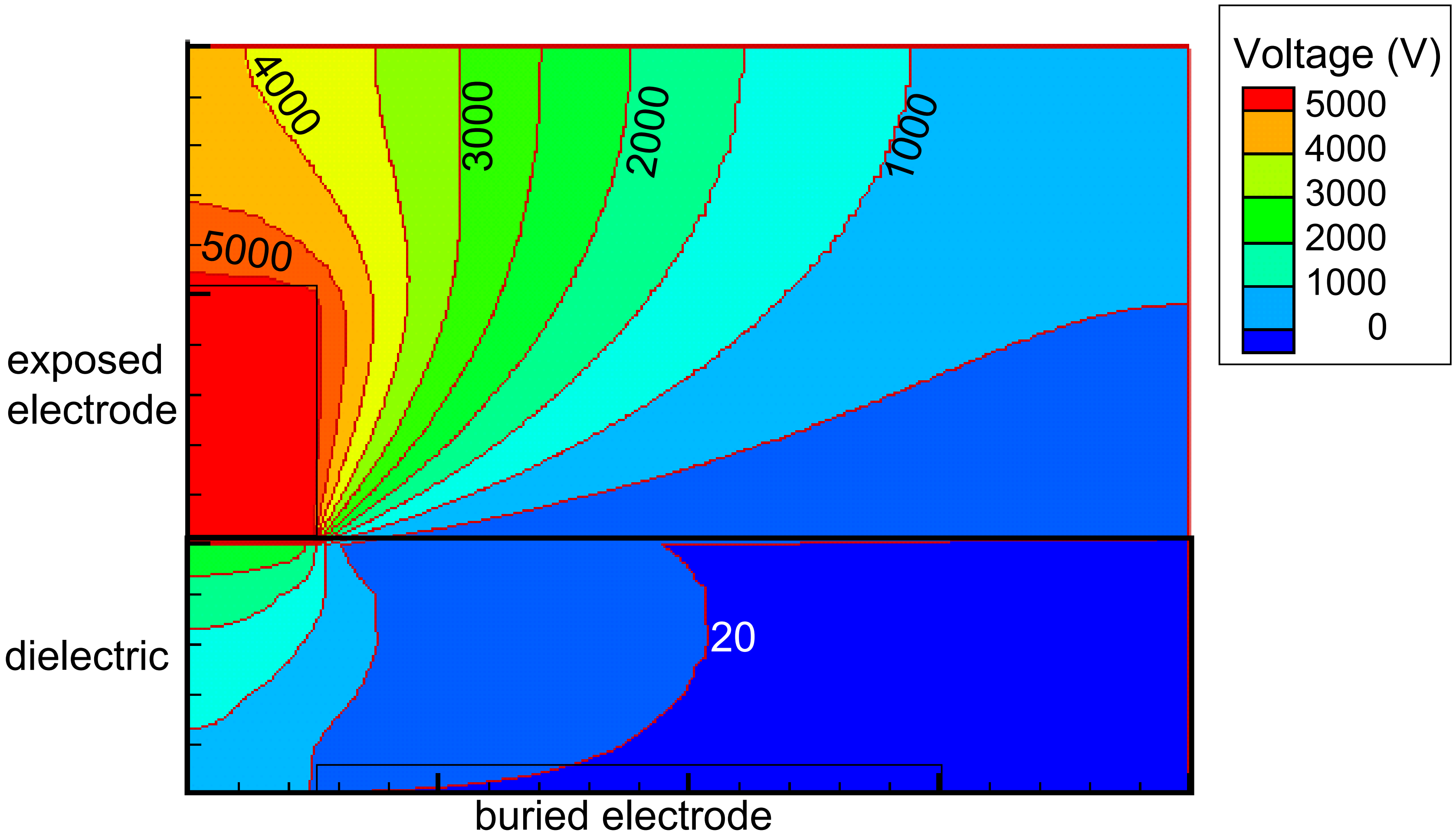
- starts with few electrons
- most generated electrons stay on the dielectric
- force is toward exposed electrode

Back Discharge:

- starts with many electrons
- most generated electrons recombine on the electrode
- force is away from exposed electrode
- greater ion density produces greater force
- repeated at each bias cycle

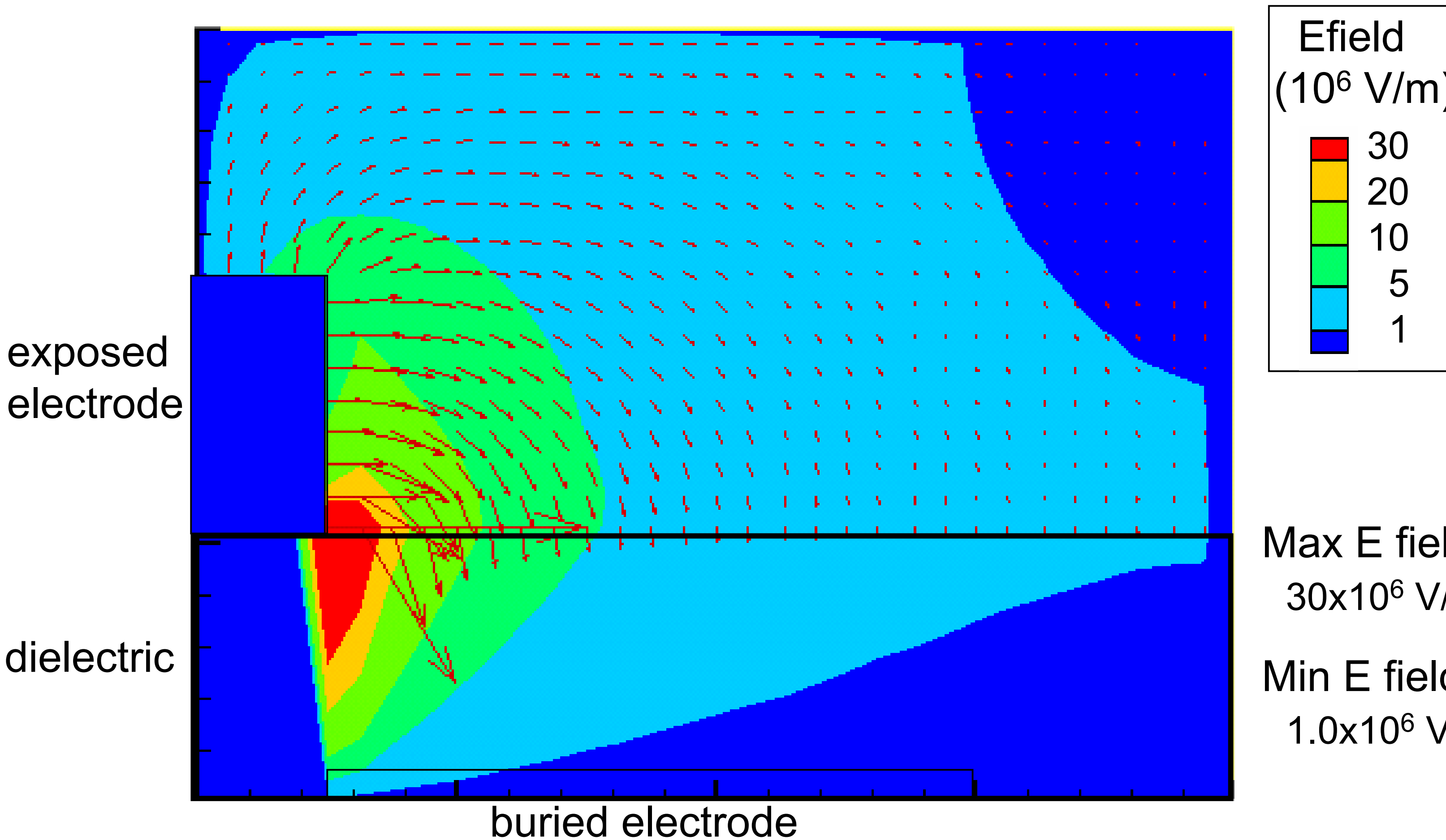
COMPUTATIONAL RESULTS: BACK DISCHARGE

Potential Distribution and Electric Field at time = 60 nsec



COMPUTATIONAL RESULTS: BACK DISCHARGE

Electric Field Magnitude and Vectors



Max E field: 30×10^6 V/m

Min E field: 1.0×10^6 V/m