Electron Current Extraction and Interaction of RF mDBD Arrays

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AGENDA

- Introduction to micro-Dielectric Barrier Discharges (mDBD)
- Current extraction
- Description of model
- Scaling of mDBD Arrays
  - mDBD sustained in N_2 (1 atm)
  - In Phase/Out-of-phase Excitation
  - Aperture Spacing, Dielectric Constants, Frequencies, Gas Mixture
- Concluding Remarks

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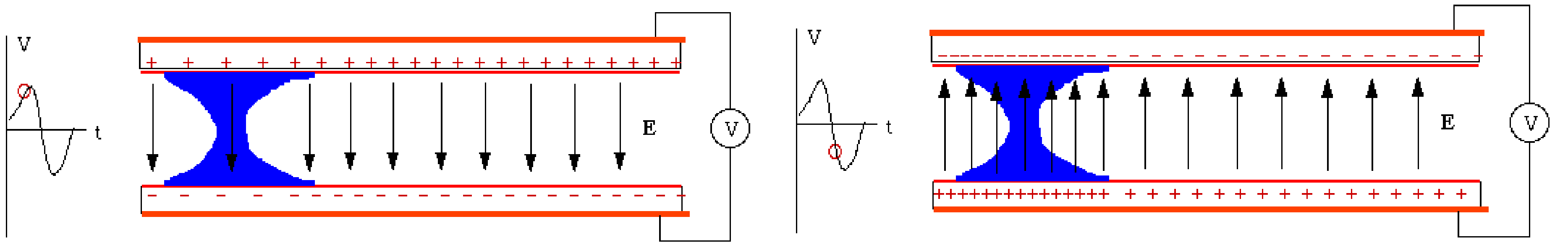
DIELECTRIC BARRIER DISCHARGES

- The plasma in DBDs is sustained between electrodes of which one (or both) is covered by a dielectric.
- When the plasma is initiated, the underlying dielectric is electrically charged, removing voltage from the gap.
- The plasma is terminated when the gap voltage falls below the self-sustaining value and so preventing arcing.
- On the following half cycle, a more intense electron avalanche occurs due to the higher voltage across the gap from previously charged dielectric.



- http://www.calvin.edu/~mwalhout/discharge.htm

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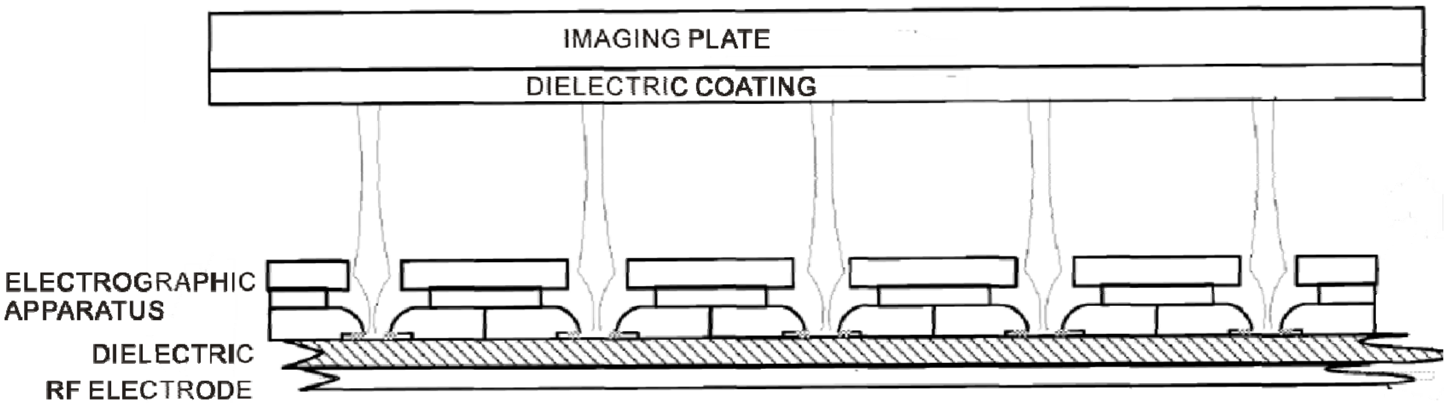
MICRO-DBD ARRAYS

- Microplasmas (10s to 100s μm) are interesting for planar current sources due to the ability of fabricating large arrays.
- Non-arcing, micro-DBDs (mDBDs) using rf voltages are attractive for arrays due to inexpensive mass or area-selective modification.



Ref:
US Patent 7764296

- mDBDs are being developed for electrographic surface patterning at atmospheric pressure.
- Electron beams extracted from arrays form charges (dots) at selected locations on the imaging surface to create the latent image.

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SCALING OF MICRO-DBDs ARRAYS

- **At atmospheric pressure, plasma formation and decay times can be a few ns whereas the rf period is 10s to 100s ns – the mDBD may need to be re-ignited with each cycle.**
- **Electron extraction from mDBD arrays may require a third electrode and so the electrode structure is important to the operation.**
- **The properties of mDBDs arrays can be optimized for producing photons, excited states or charge species by independently controlling apertures, and by choice of repetition rate, pulse shape and materials.**
- **We have computationally investigated the extraction of electron current from mDBDs arrays:**
    - **Geometry**
    - **Frequency**
    - **Dielectric materials**
    - **Gas composition**

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MODELING PLATFORM: *nonPDPSIM*

- **Poisson's equation:** $\nabla \cdot (\varepsilon \nabla \Phi) = -(\sum_j q_j N_j + \rho_s)$
- **Transport of charged and neutral species:** $\partial N_j / \partial t = -\nabla \cdot \vec{\Gamma}_j + S_j$
- **Surface Charge:** $\partial \rho_s / \partial t = [\sum_j q_j (-\nabla \cdot \vec{\Gamma}_j + S_j) - \nabla \cdot (\sigma(-\nabla \Phi))]_{material}$
- **Electron Temperature (transport coefficient obtained from Boltzmann's equation**

$$\partial(n_e \varepsilon)/\partial t = \vec{j} \cdot \vec{E} - n_e \sum_i \Delta\varepsilon_i K_i N_i - \nabla \cdot \left(5\vec{\phi}_e \varepsilon / 2 - \overline{\overline{\kappa}}(T_e) \cdot \nabla T_e\right)$$

- **Radiation transport and photoionization:**

$$S_m(\vec{r}_i) = N_m(\vec{r}_i) \cdot \sum_k \sigma_{mk} A_k \int N_k(\vec{r}_j{}') G_k(\vec{r}_j{}', \vec{r}_i) d^3\vec{r}_j{}'$$

$$G(\vec{r}_j{}', \vec{r}_i) = \frac{\exp\left(-\sum_l \int_{\vec{r}_j{}'}^{\vec{r}_i} \sigma_{lk} N_l(\vec{r}_j{}') d\vec{r}_j{}'\right)}{4\pi \left|\vec{r}_j{}' - \vec{r}_i\right|^2}$$

- **Electron Monte Carlo Simulation tracks sheath accelerated secondary electrons produced by ion and UV bombardment of surfaces.**

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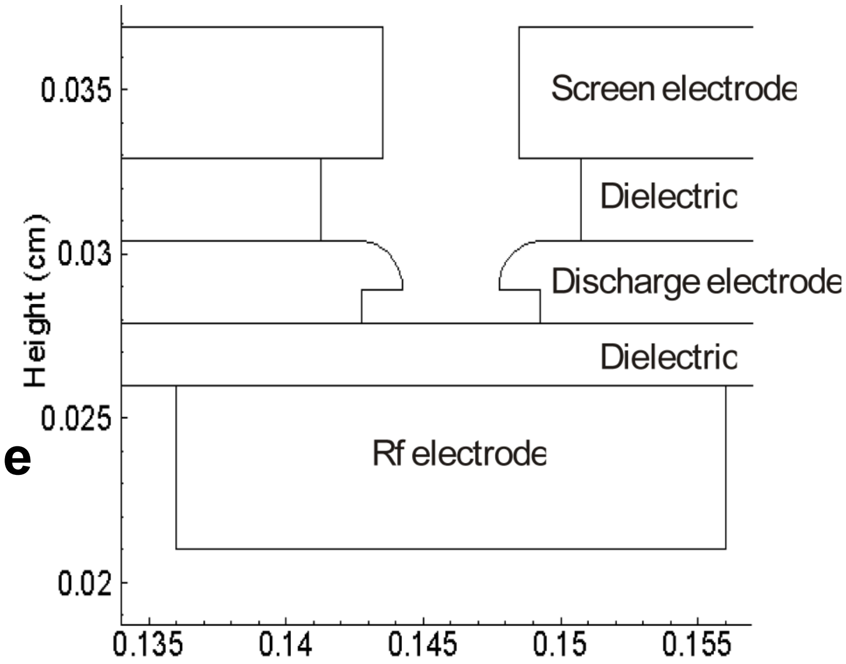
SINGLE APERTURE: GEOMETRY

- The mDBD is a “sandwich” of alternating electrodes and dielectrics.
- rf metal electrode embedded in a printed-circuit-board.
- Negatively DC biased discharge electrode separated from rf by dielectric sheet - 35 μm opening
- Less-negatively DC biased screen electrode separated from the discharge electrode acts as an anode switch
    - Extracts charge out of cavity
    - Narrow the current beam
- Apertures are circular – modeled as 2D slots to enable modeling of multiple apertures.



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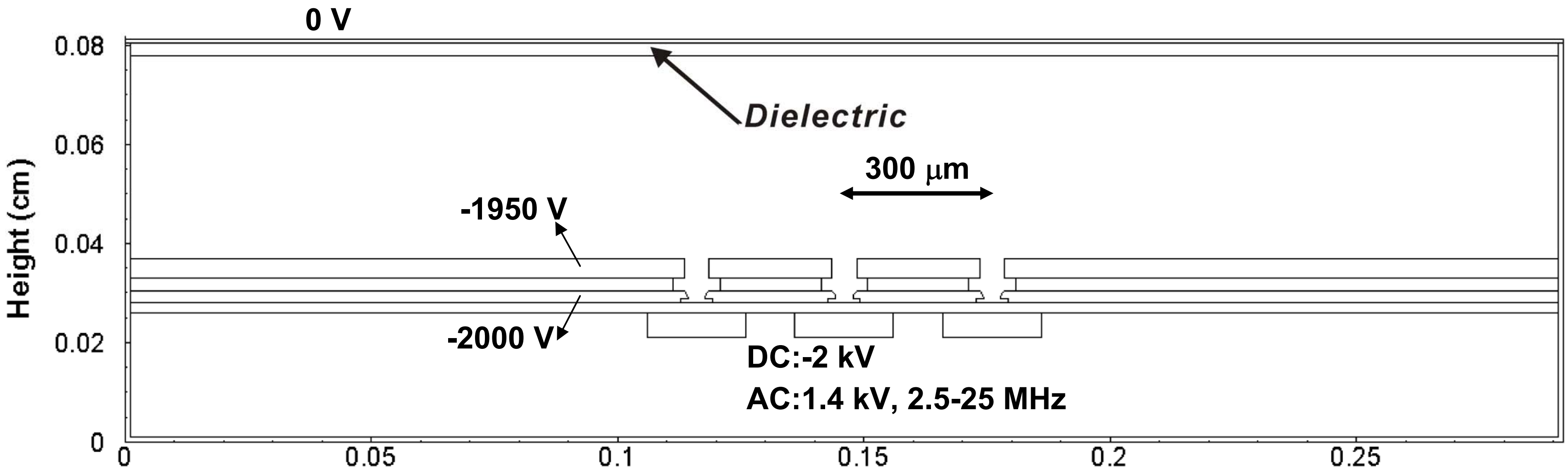
MULTIPLE APERTURES: GEOMETRY

- **Grounded electrode covered with 25 μm dielectric sheet separated from screen electrode by 410 μm gap.**
- **rf: -2 kV DC, 1.4 kV AC at 2.5-25 MHz.**
- **Discharge: -2 kV, Screen: -1950 V, top electrode grounded**



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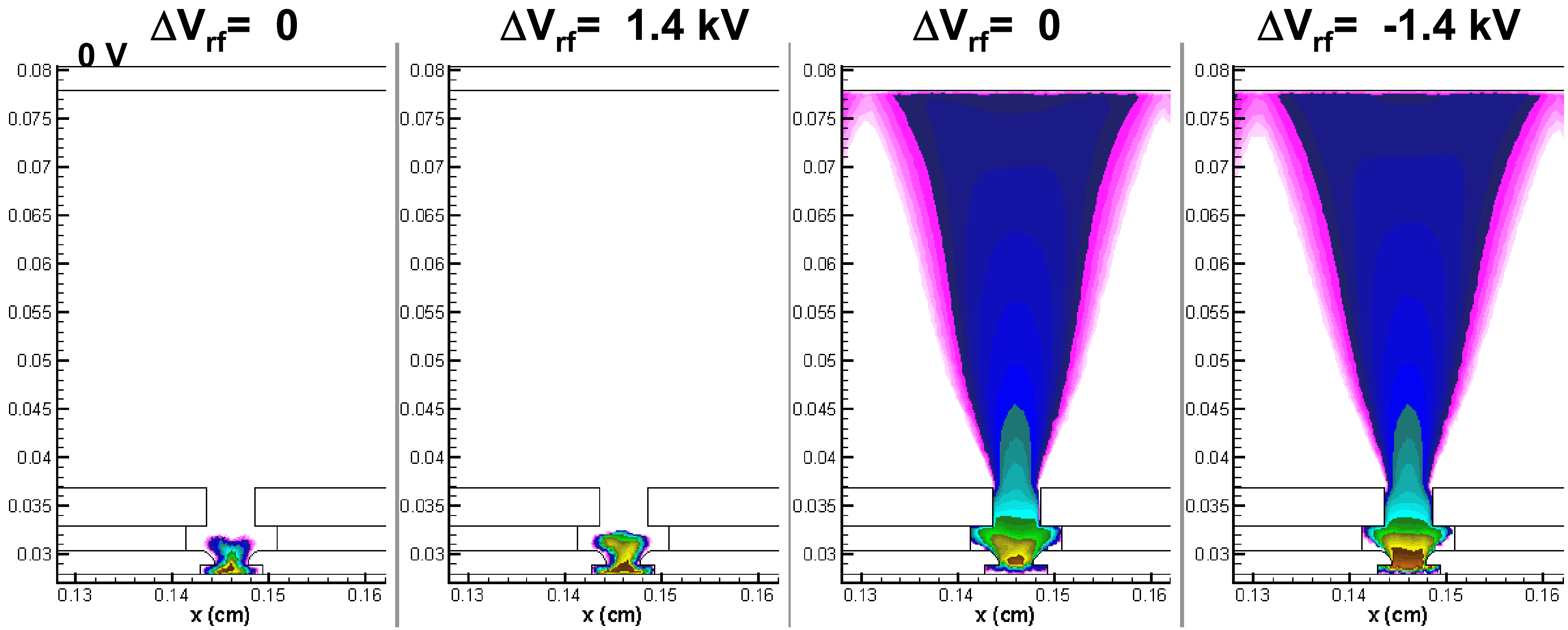
SINGLE APERTURE - 25 MHz N_2 (1 atm): [e]



- V_{rf}= -2kV DC, +1.4kV AC, 25 MHz, -2kV discharge, -1950 V screen
- ΔV_{rf}= 0 Previous positive surface charges reduce voltage drop.
  E-plume extinguishes, e-flux neutralizes positively charged dielectric.
- ΔV_{rf}= 1.4 kV Avalanche in mDBD cavity. Electrons charge dielectric negatively.
- ΔV_{rf}= 0 Grounded electrode extracts electrons from the cavity.
- ΔV_{rf}=- 1.4kV Positively charged dielectric reduces voltage drop.
  e-plume begins to diminish.

MIN  MAX

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- [e]
  (10^{16} cm^{-3}, 5 dec)

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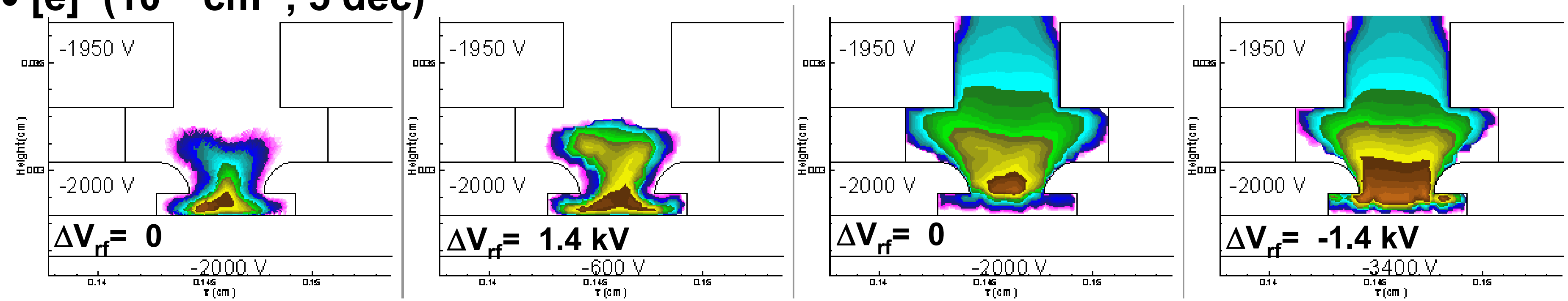
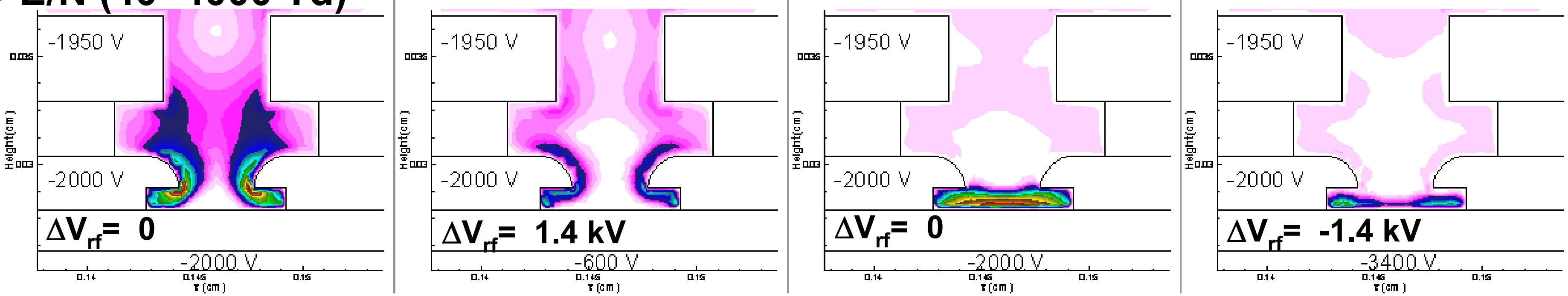
SINGLE APERTURE - 25 MHz N_2 (1 atm): [e], E/N, T_e

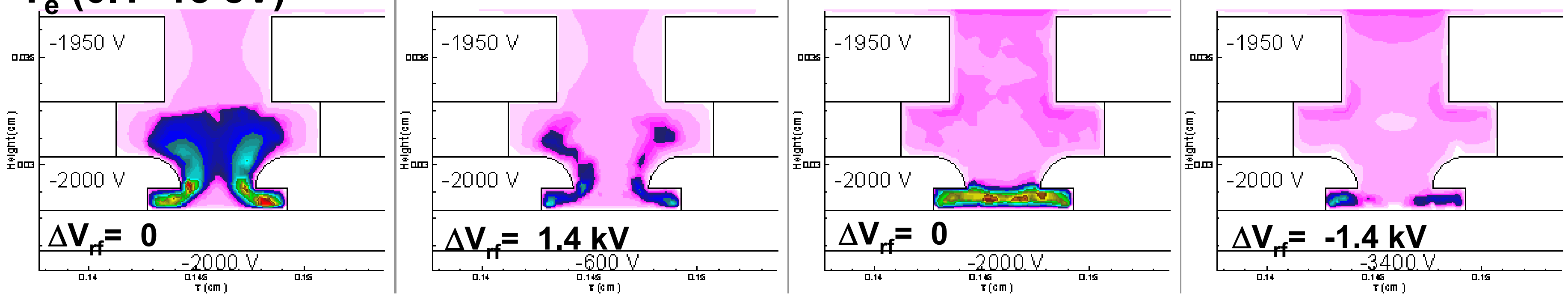
- [e] (10^{16} cm^{-3}, 5 dec)



- E/N (40~4000 Td)



- T_e (0.1~15 eV)



MIN  MAX

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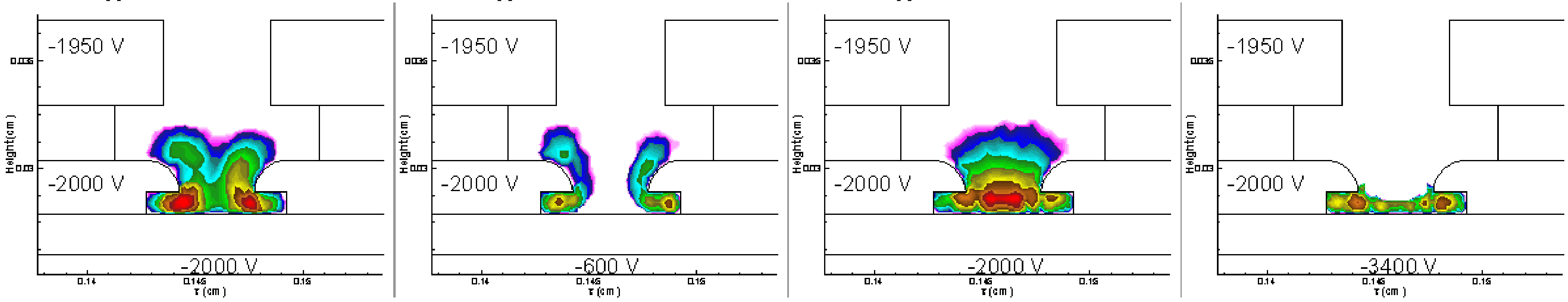
SINGLE APERTURE - 25 MHz N_2 (1 atm): $S_{e+}S_{sec}$

- $[S_e + S_{sec}]$(5×10^{24} cm^{-3} s^{-1},3dec)

ΔV_{rf}= 0 ΔV_{rf}= 1.4 kV ΔV_{rf}= 0 ΔV_{rf}= -1.4 kV



- **Larger E/N at ΔV_{rf} zero-crossing due to previously charging of dielectric. $T_{e,}$ S_e and S_{sec} follow E/N.**
- **Ionization due to secondary electrons from surface seeded by positive ions and UV photons are slightly larger than bulk ionization.**
- **Plasma shields electric field, lowers E/N, reduces ionization.**

MIN  **MAX**

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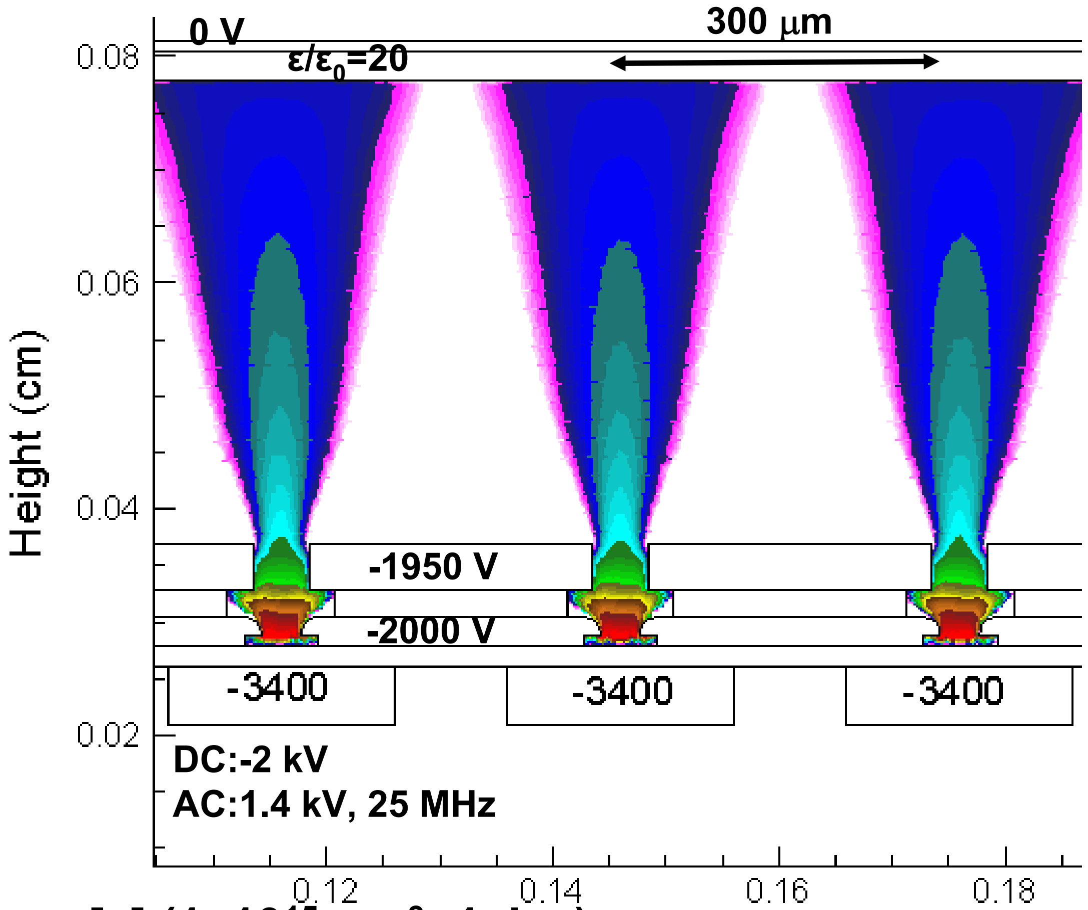
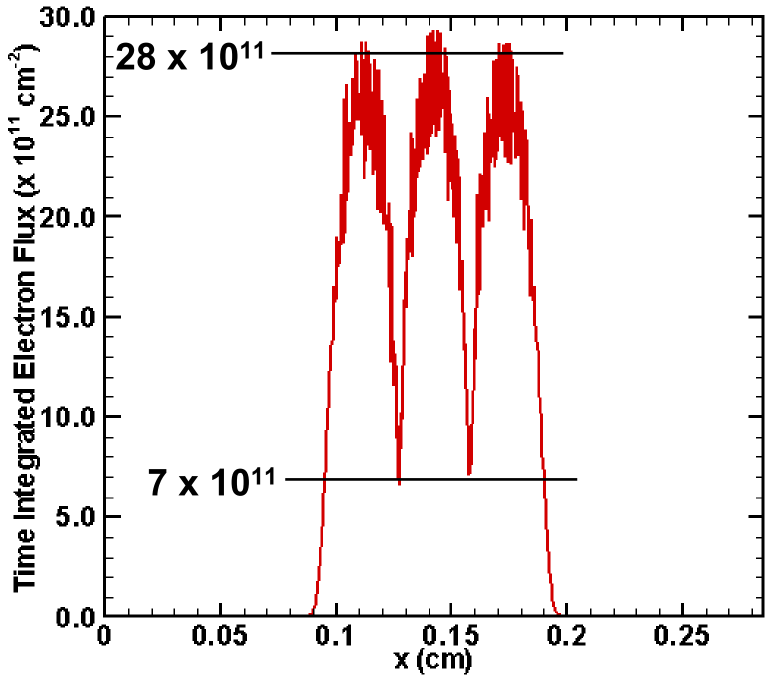
MULTIPLE APERTURES: IN PHASE EXCITATION

- With simultaneous extraction of electron current, the integrated flux can be uniform provided plumes are below the "space charge" limit of affecting their neighbors.





- Integrated Electron Flux (10th pulse)

- [e] (1×10^{15} cm^{-3}, 4 dec)
- N_2, 1 atm,

MIN MAX

Animation Slide-GIF

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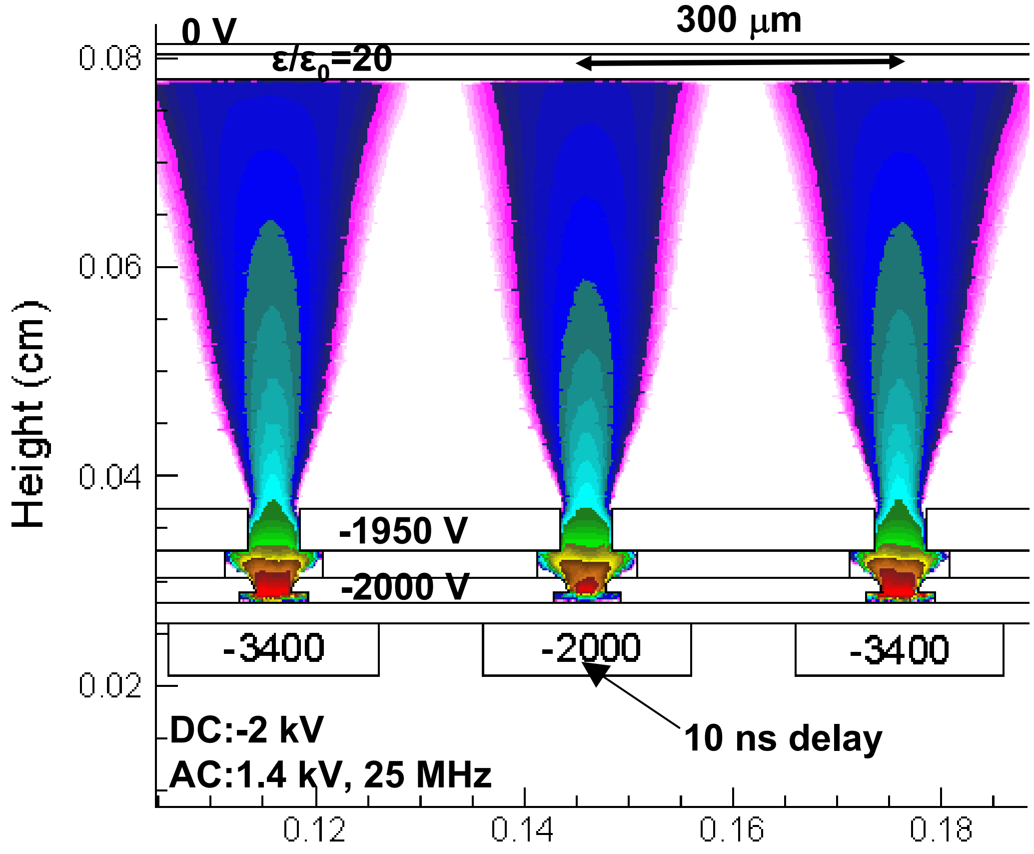
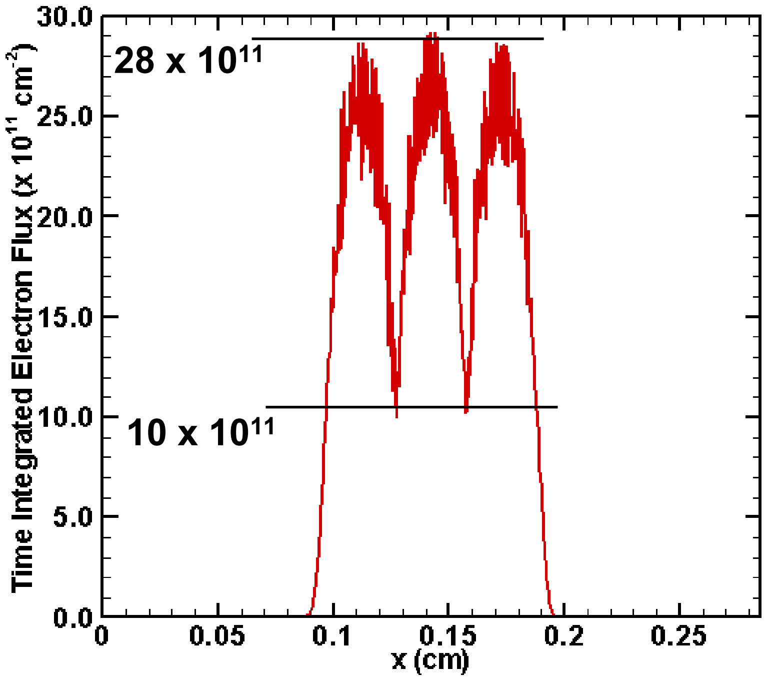
MULTIPLE APERTURES: OUT OF PHASE EXCITATION

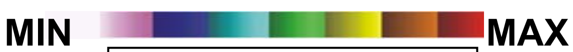
- Delaying the center aperture by ¼ cycle increases integrated electron flux between apertures; e-plume propagates with less interference. Peak fluxes are not greatly affected.





- Integrated Electron Flux (10th pulse)

- [e] (1×10^{15} cm^{-3}, 4 dec)
- N_2, 1 atm,



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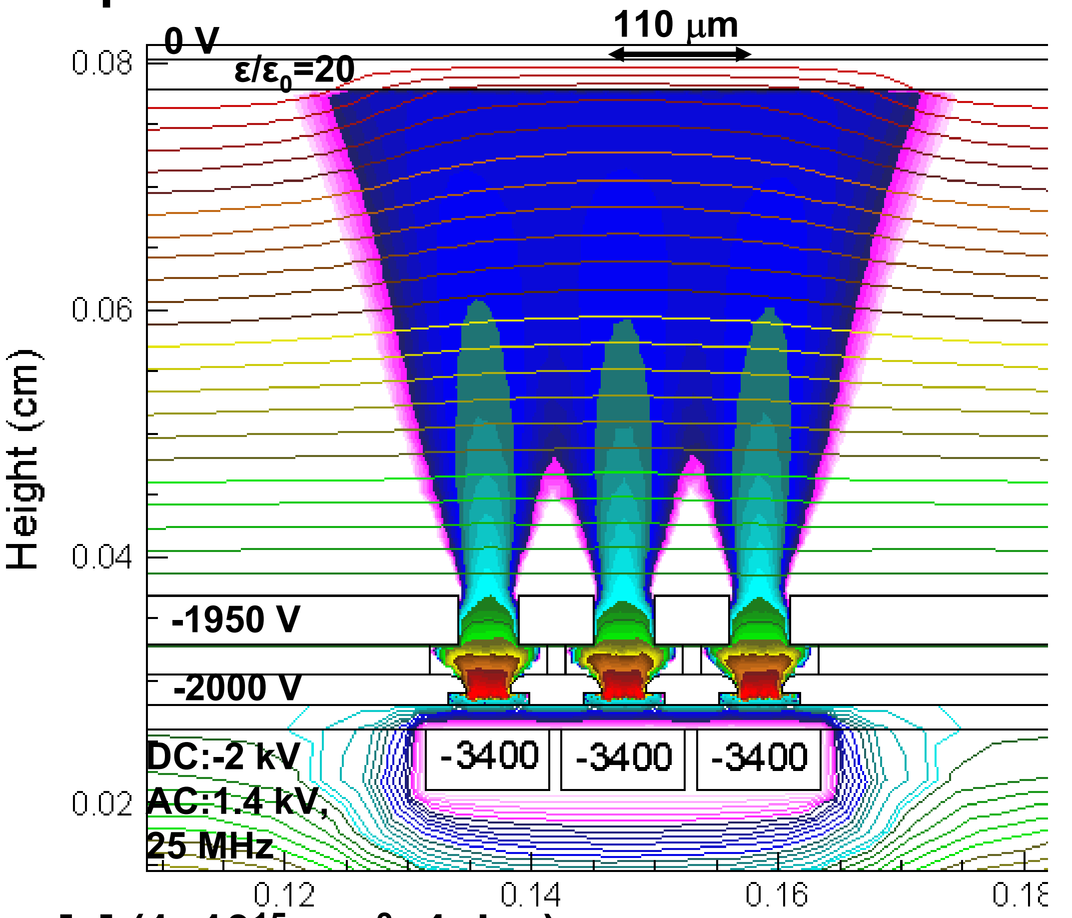
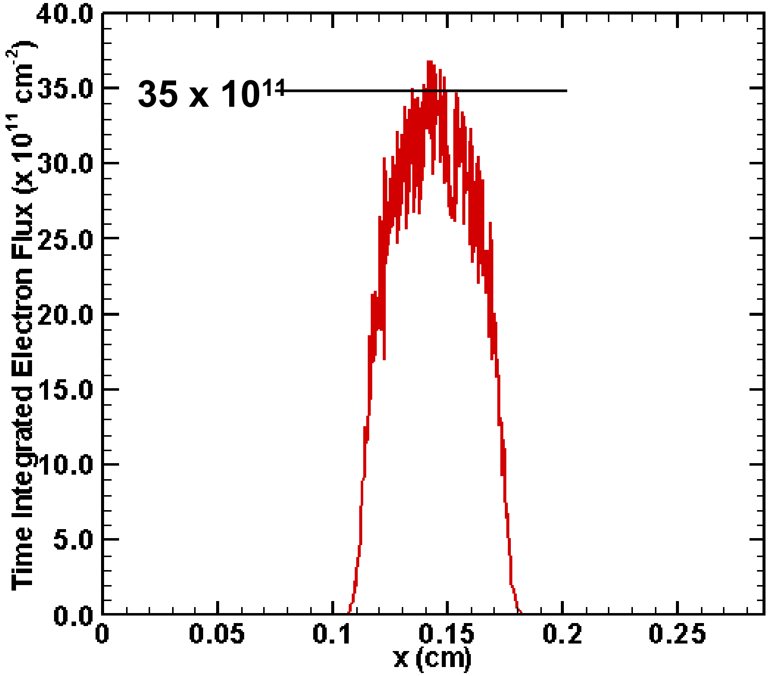
MULTIPLE APERTURES: SPACING

- Decreasing the aperture spacing (300μm → 110μm), electron plumes merge and are slightly focus in the gap due to the accumulating positive ions.





- $[e]$ (1×10^{15} cm^{-3}, 4 dec)
- N_2, 1 atm,

- Integrated Electron Flux (10^{th} pulse)

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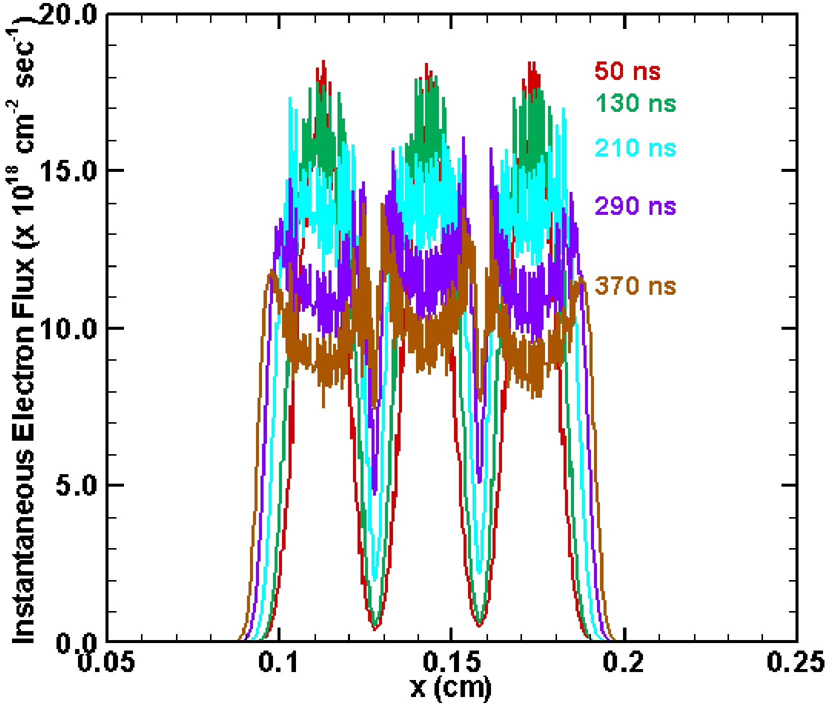
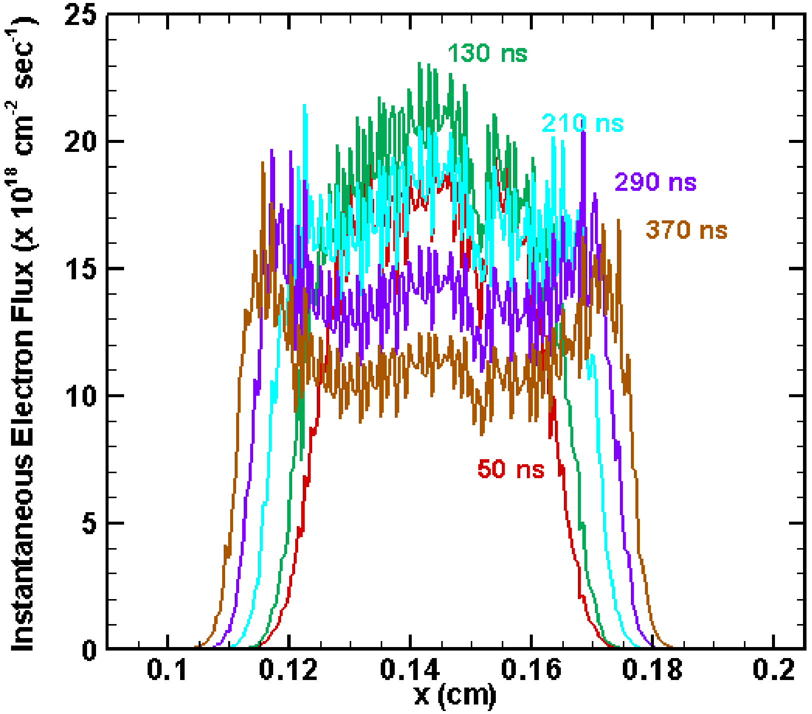
MULTIPLE APERTURES: SPACING

- By decreasing the spacing of apertures, the three e-plumes merge to form a single current beam.
- Due to the merging of three e-plumes, instantaneous electron flux is larger and broadened in width.

$\varepsilon / \varepsilon_0 = 20$



- 300 μm Spacing



- 110 μm Spacing

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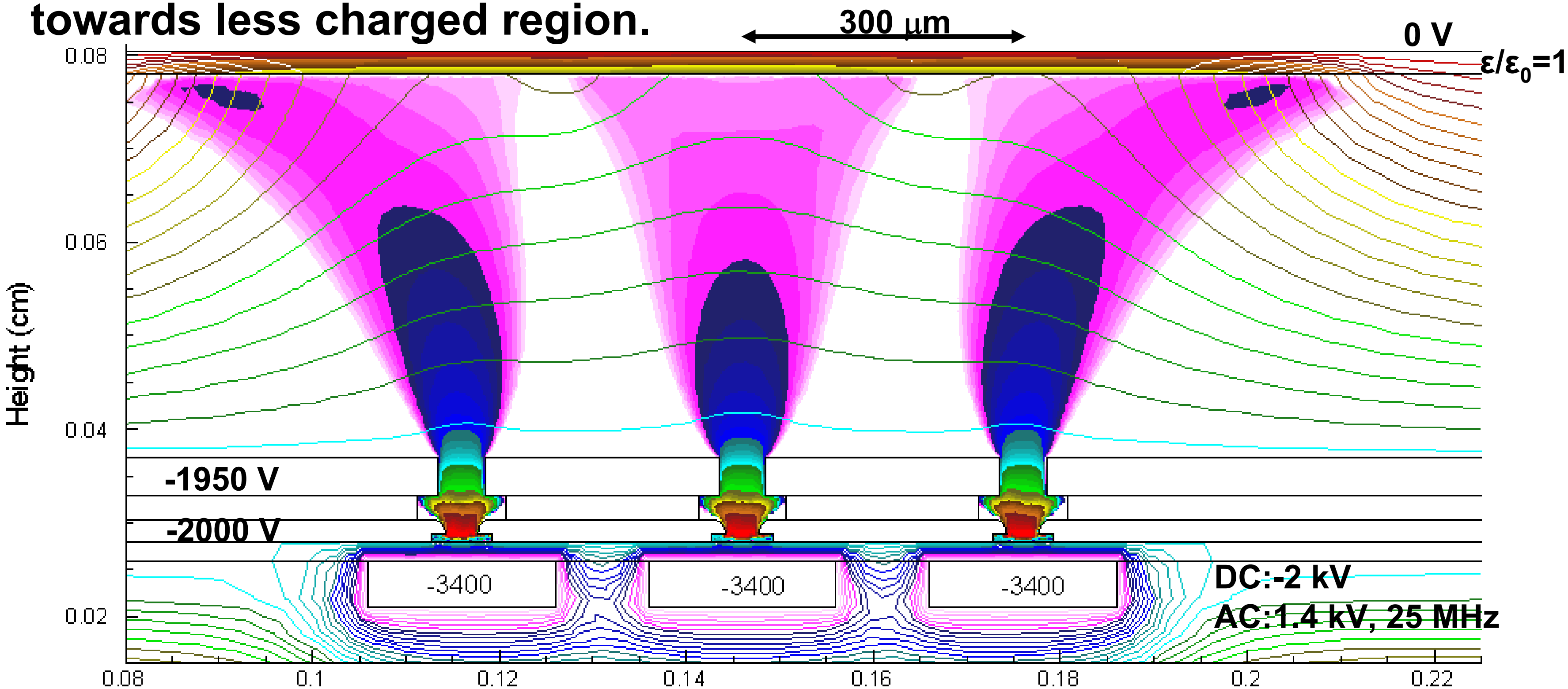
MULTIPLE APERTURES: DIELECTRIC EFFECT

- The surface charge on top dielectric creates lateral local electric fields which broaden the electron plume.
- By decreasing the dielectric constant ($\varepsilon/\varepsilon_0$=20→1), dielectric charging effect starts earlier. E-plume is not only broadened but directed towards less charged region.



- [e] (1×10^{15} cm^{-3}, 4 dec)
- [V] (-3.4kV~0 V)
- N_2, 1 atm,

MIN MAX

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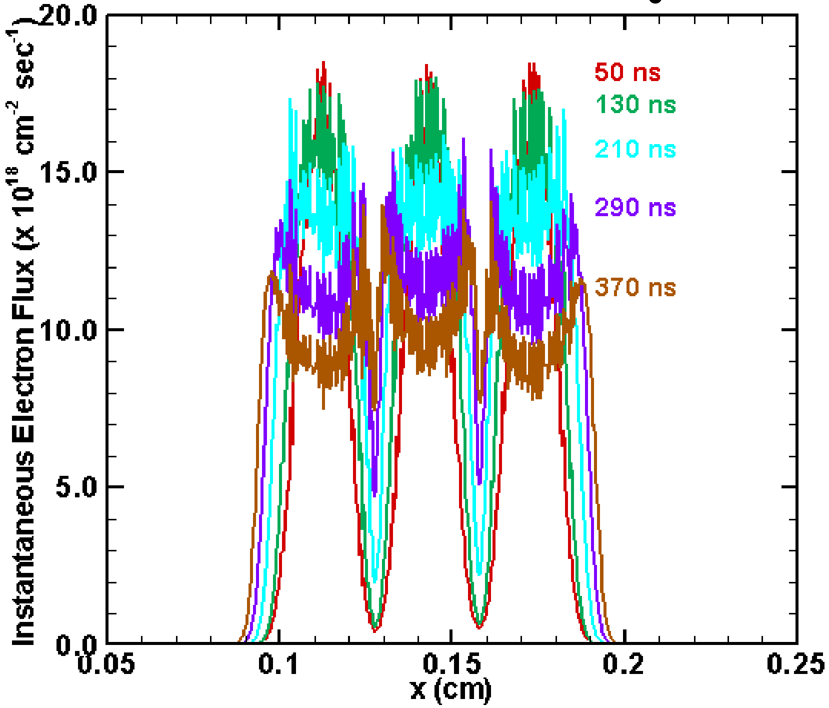
MULTIPLE APERTURES: DIELECTRIC EFFECT

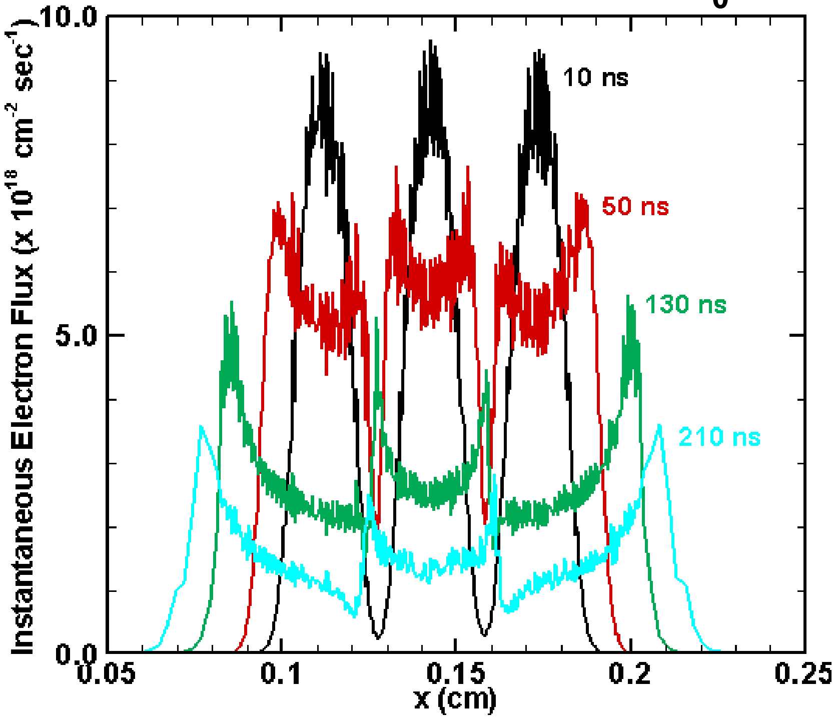
- **At high dielectric constant ($\varepsilon/\varepsilon_0$=20), e-plume initially increases due to positive charge accumulation in gap, then it decreases due to negative surface charge.**

- **At low dielectric constant ($\varepsilon/\varepsilon_0$=1), charging effect starts earlier due to lower capacitance. The e-flux is broadened and warped laterally towards less charged region.**

$\varepsilon/\varepsilon_0$=20



$\varepsilon/\varepsilon_0$=1



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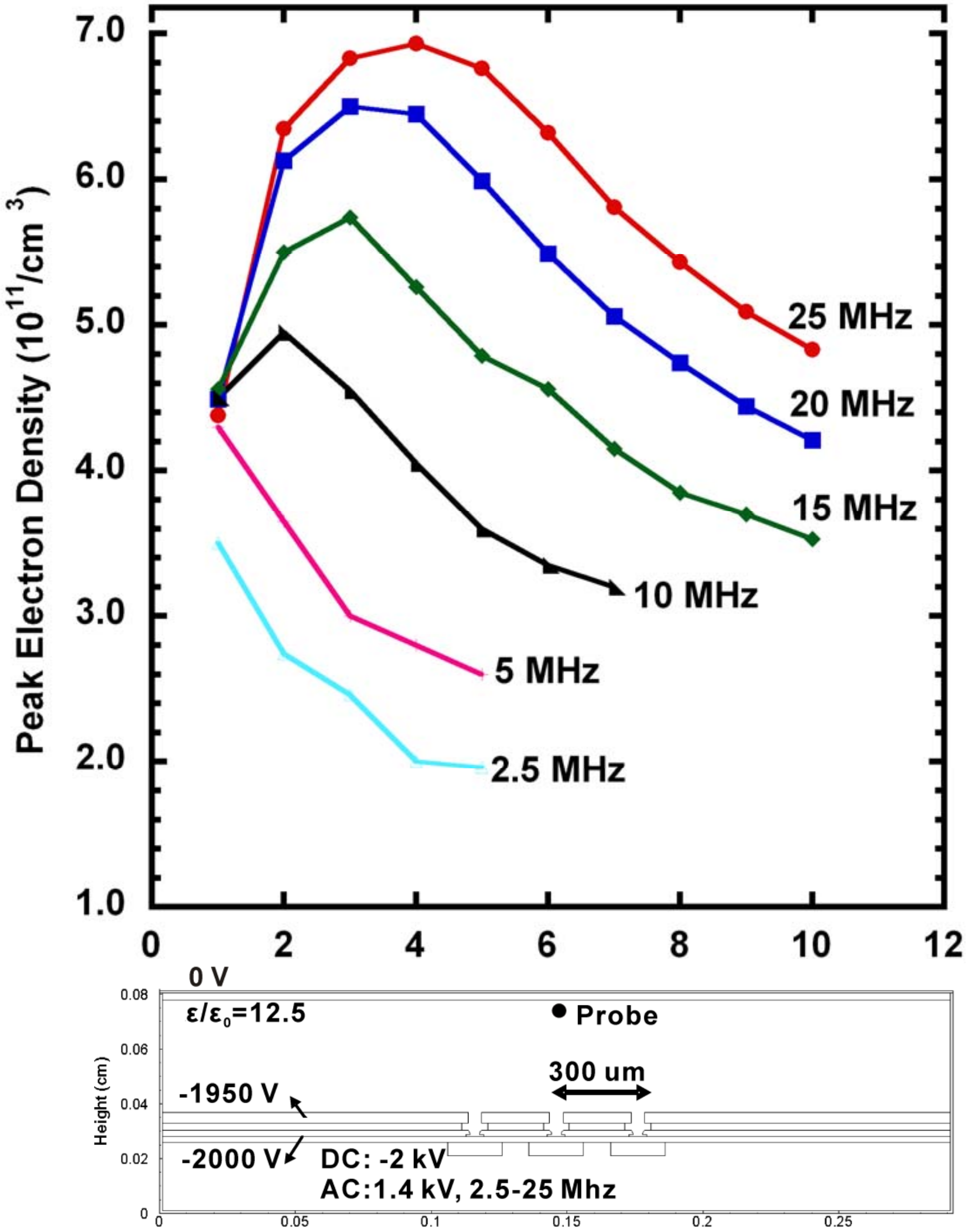
ELECTRON DENSITY vs FREQUENCY



- A probe adjacent to dielectric sheet to measure extracted electron density.
- At high frequency, e-flux is limited by rf voltage. [e] initially increases due to accumulation of positive ions, then decreases as a result of dielectric charging.
- At low frequency, e-flux limited by charging, [e] decreases.
- [e] tends to be larger at higher frequency.

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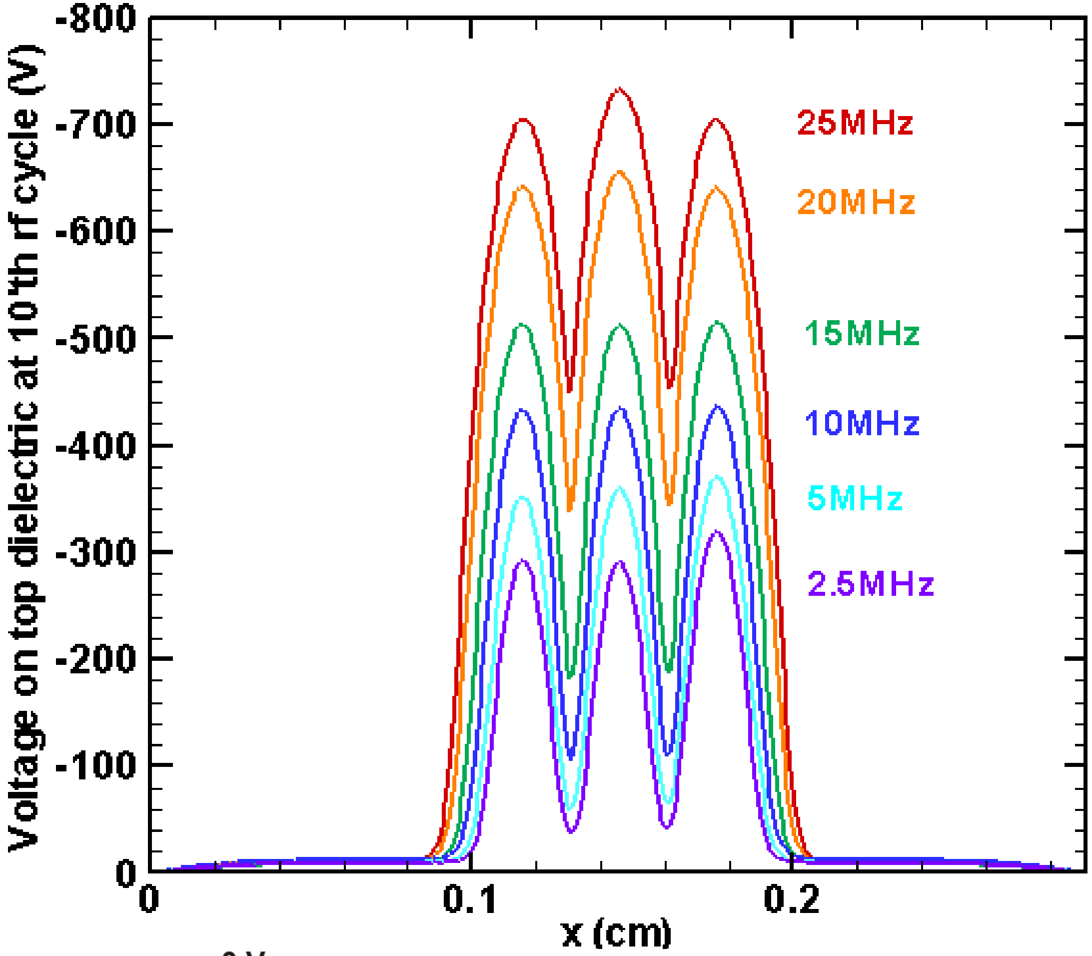
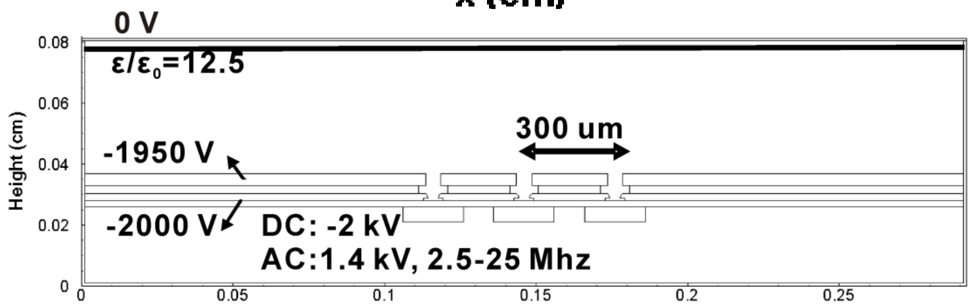
ELECTRIC POTENTIAL vs FREQUENCY





- Electric potential at surface of dielectric at 10[th] rf cycle for frequency of 2.5 - 25 MHz.
- At high frequency, electric potential is greater due to larger electron current extraction.
- At low frequency, e-flux limited by dielectric charging, electric potential decreases.

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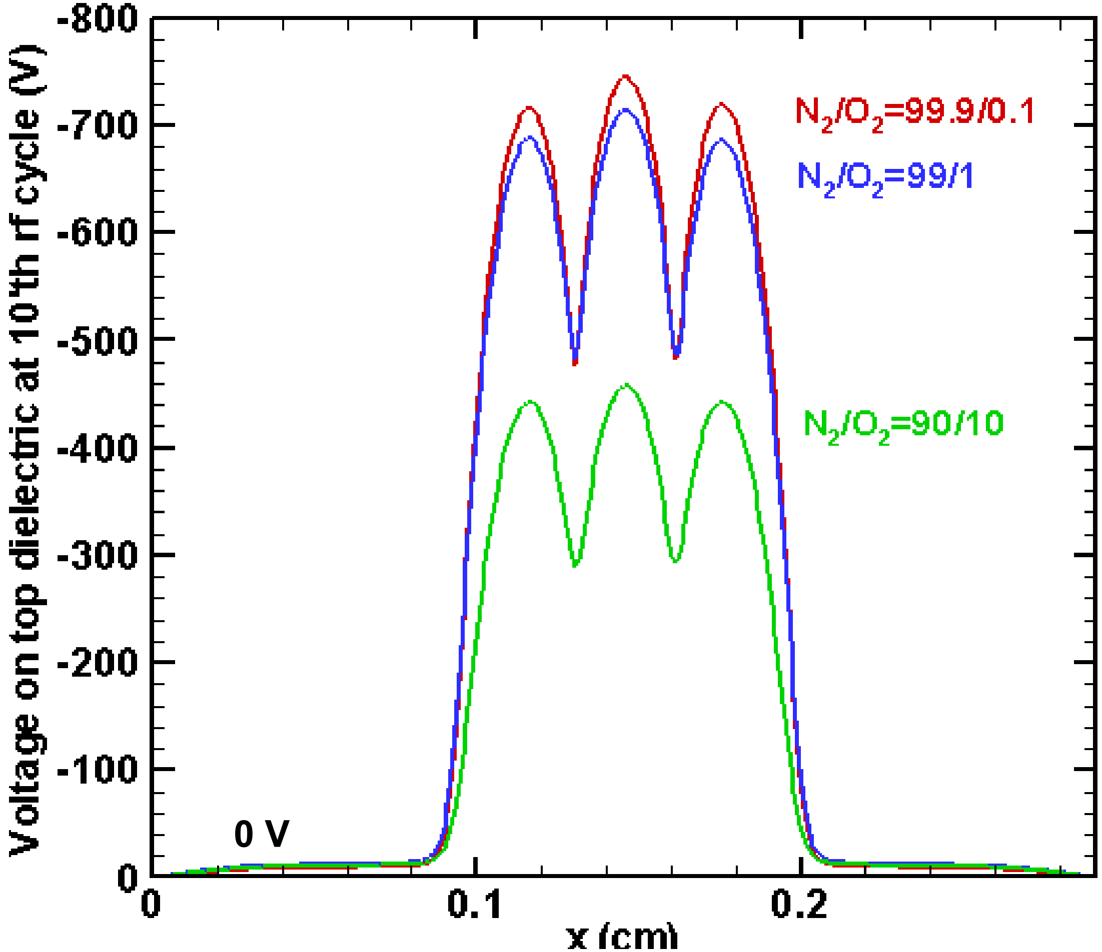
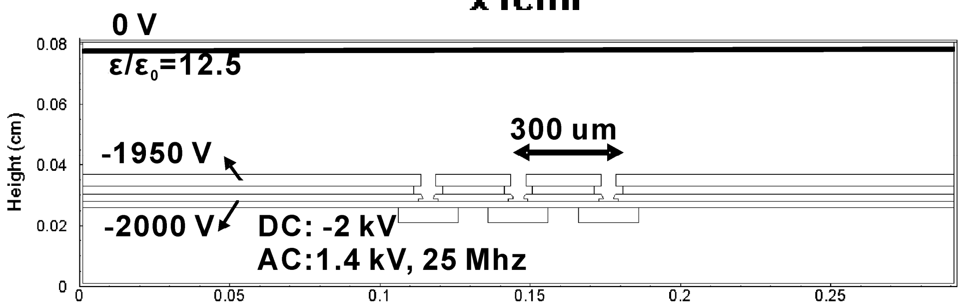
POTENTIAL PROFILE vs GAS COMPOSITION





- Electric potential at dielectric surface at 10th rf cycle for 1 atm N_2 with 0.1-10% O_2 at 25 MHz.
- N_2 does not attach electrons, electron attachment in gas mixture are due to O_2.
- At high O_2 content, surface potential is smaller due to negative ion accumulation (O^-, O^{2-}) in the gap.
- Massive negative ions reduces extraction field, electron current extraction and surface charges.

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CONCLUDING REMARKS

- Properties of multiple mDBD apertures and electron current extraction to charge polymers were numerically investigated.
- Decreasing aperture spacing merges the e-plume and increases the flux. Electron collection on dielectric creates lateral local field that broaden the e-plume and eventually stops the current extraction.
- Decreasing the dielectric constant reduces capacitance, decreasing charging time and warps the e-plume.
- At high frequency, current extraction is limited by rf voltage; current increases initially then decreases, enabling some tuning of the collected fluxes.
- Shape of voltage and charge distribution on dielectric are limited by O_2 content due to electron attachment.

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