*International Online Plasma Seminar (IOPS)*

# Expansion of plasma plumes generated by ion sources using RF grid biasing

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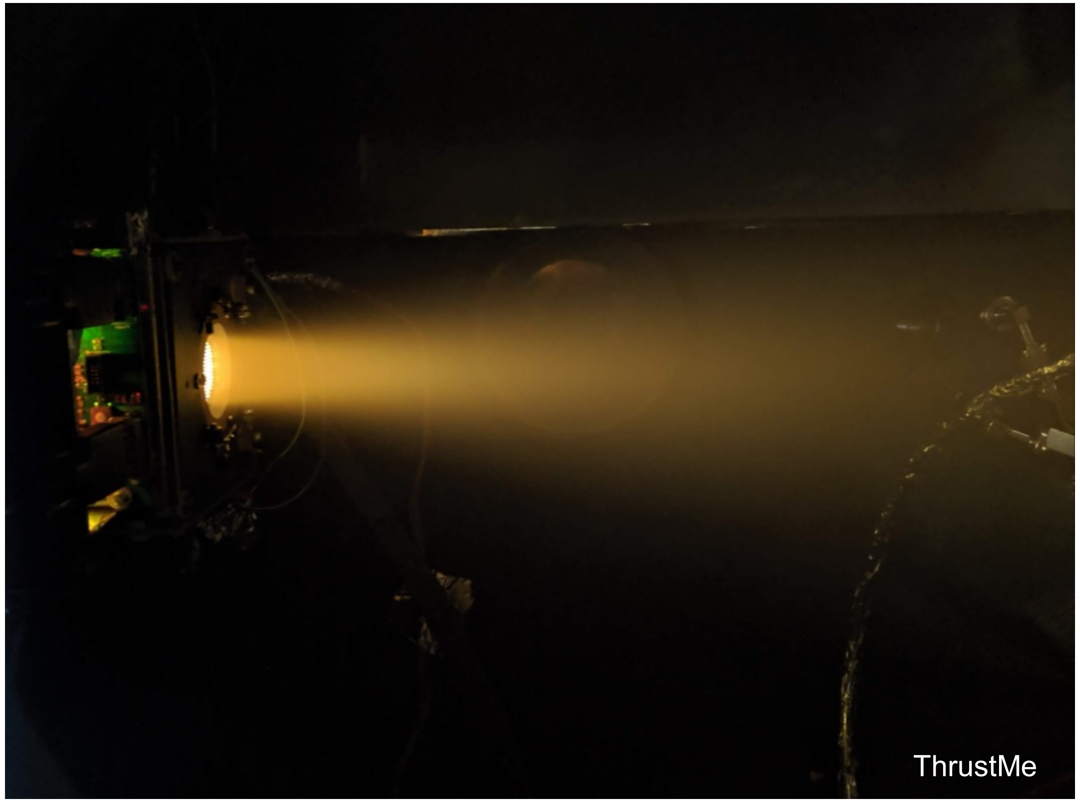
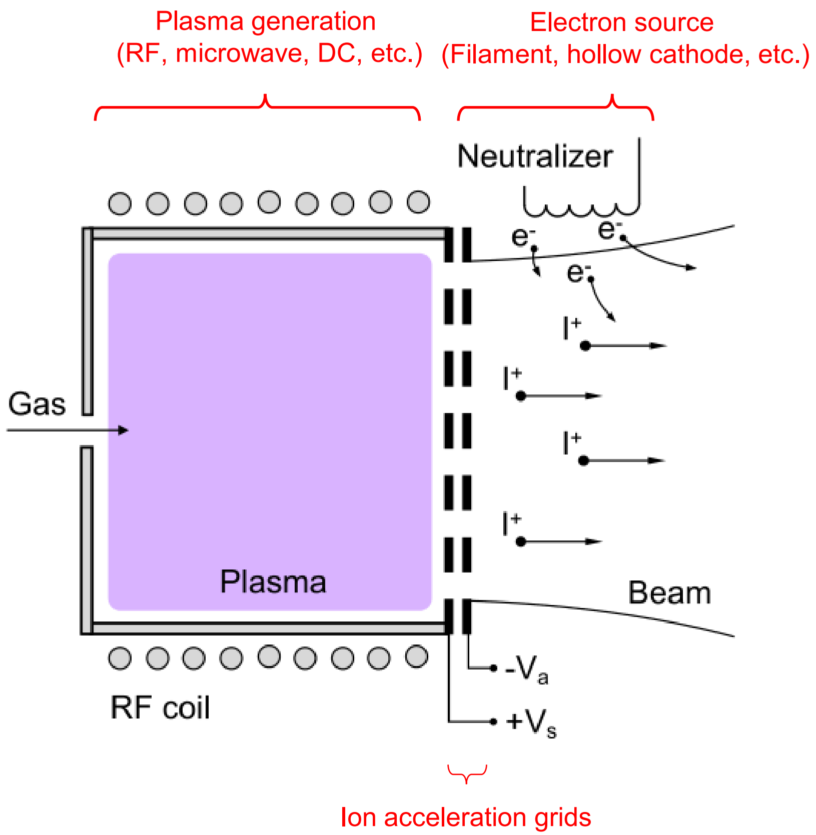
# Outline

1. Background
2. Description of particle-in-cell (PIC) model
3. Simulation conditions
4. DC / RF comparison
5. Parametric study
6. Conclusions

# Ion thrusters



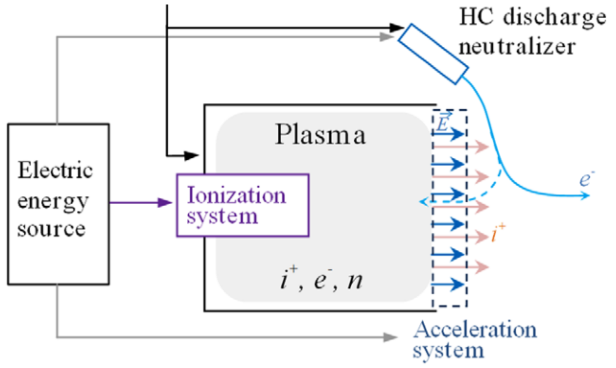



# Neutralizer-free concepts

- In **ion thrusters, neutralizers** are used for charge-balance and keep quasi-neutrality in the plume
- Usually are complex and delicate systems (e.g. hollow cathodes)
- Requires a separate power system
- Alternatives to eliminate neutralizer in ion thrusters:
  - Acceleration of positive and negative ions
  - **Positive ions and electrons**


[1] D. Rafalskyi and A. Aanesland, "Brief review on plasma propulsion with neutralizer-free systems," *Plasma Sources Sci. Technol.*, vol. 25, no. 4, p. 043001, Jun. 2016, doi: 10.1088/0963-0252/25/4/043001.

[2] T. Lafleur, D. Rafalskyi, and A. Aanesland, "Radio-frequency biasing of ion thruster grids," presented at the 36th International Electric Propulsion Conference, 2019.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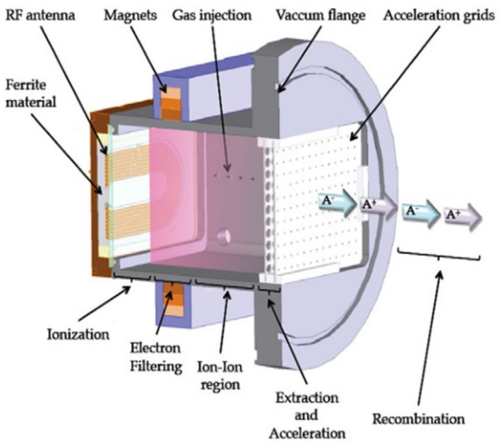


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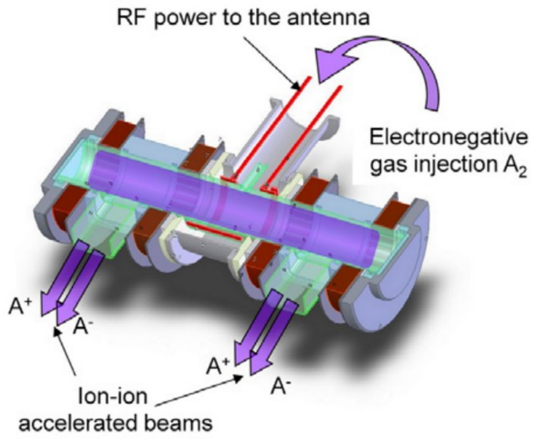


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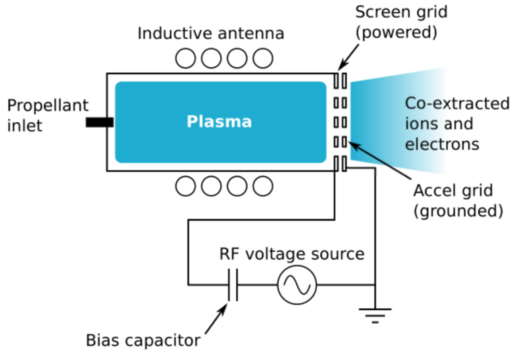


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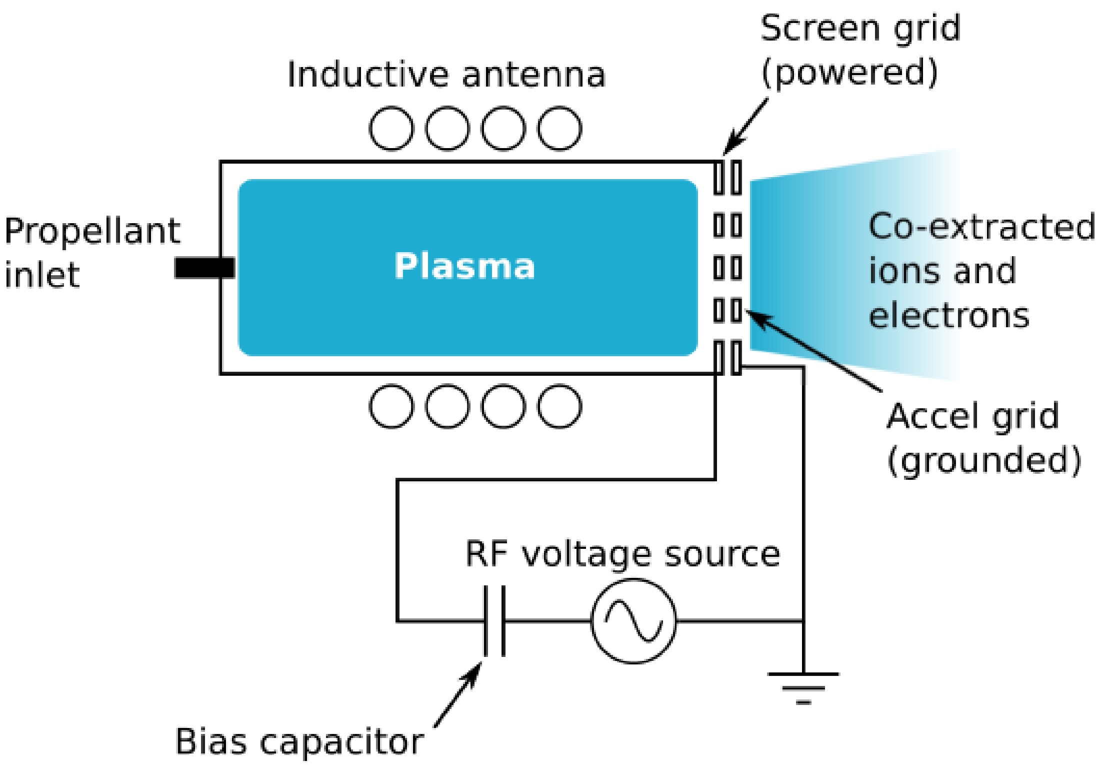
# RF grid biasing

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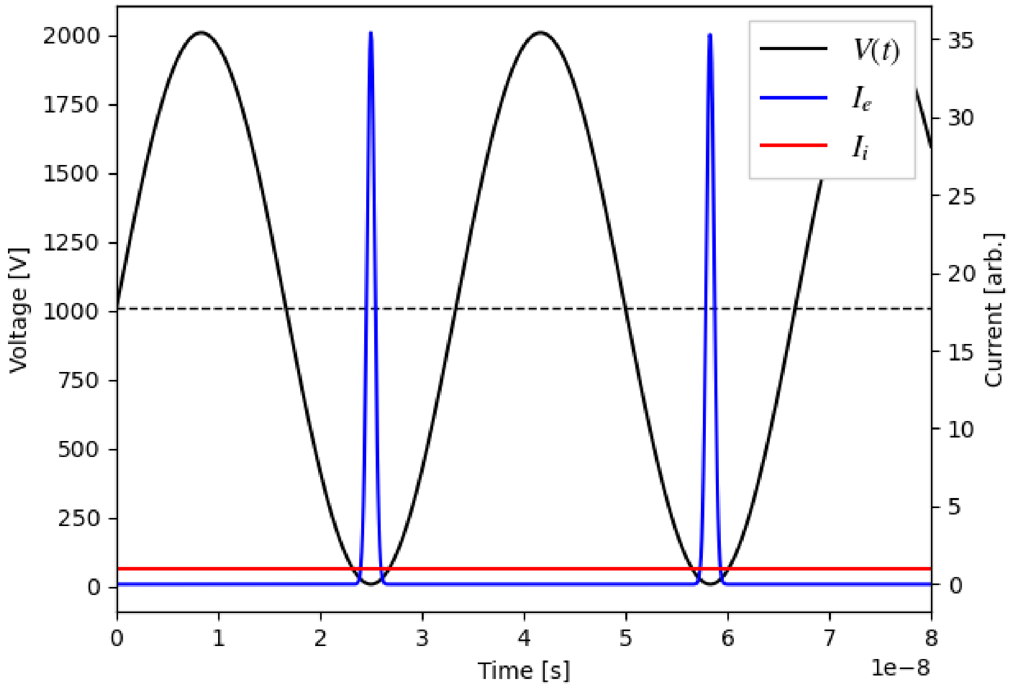
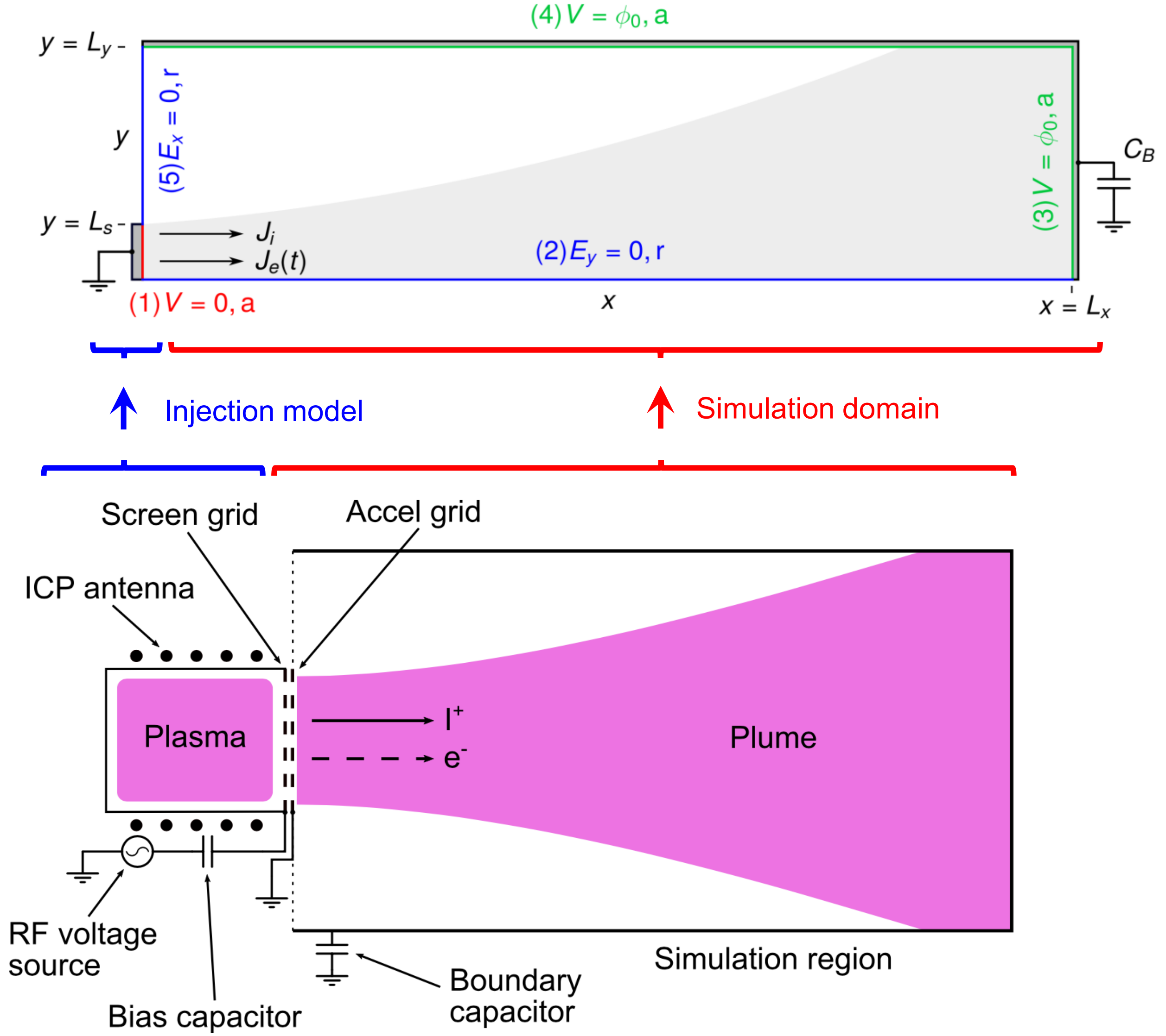



- No neutralizer
- Demonstrated experimentally
- Numerical work was mostly on particle focusing
- Plume dynamics are still unexplored


[1] T. Lafleur, D. Rafalskyi, and A. Aanesland, “Radio-frequency biasing of ion thruster grids,” presented at the 36th International Electric Propulsion Conference, 2019.

# Plume simulation

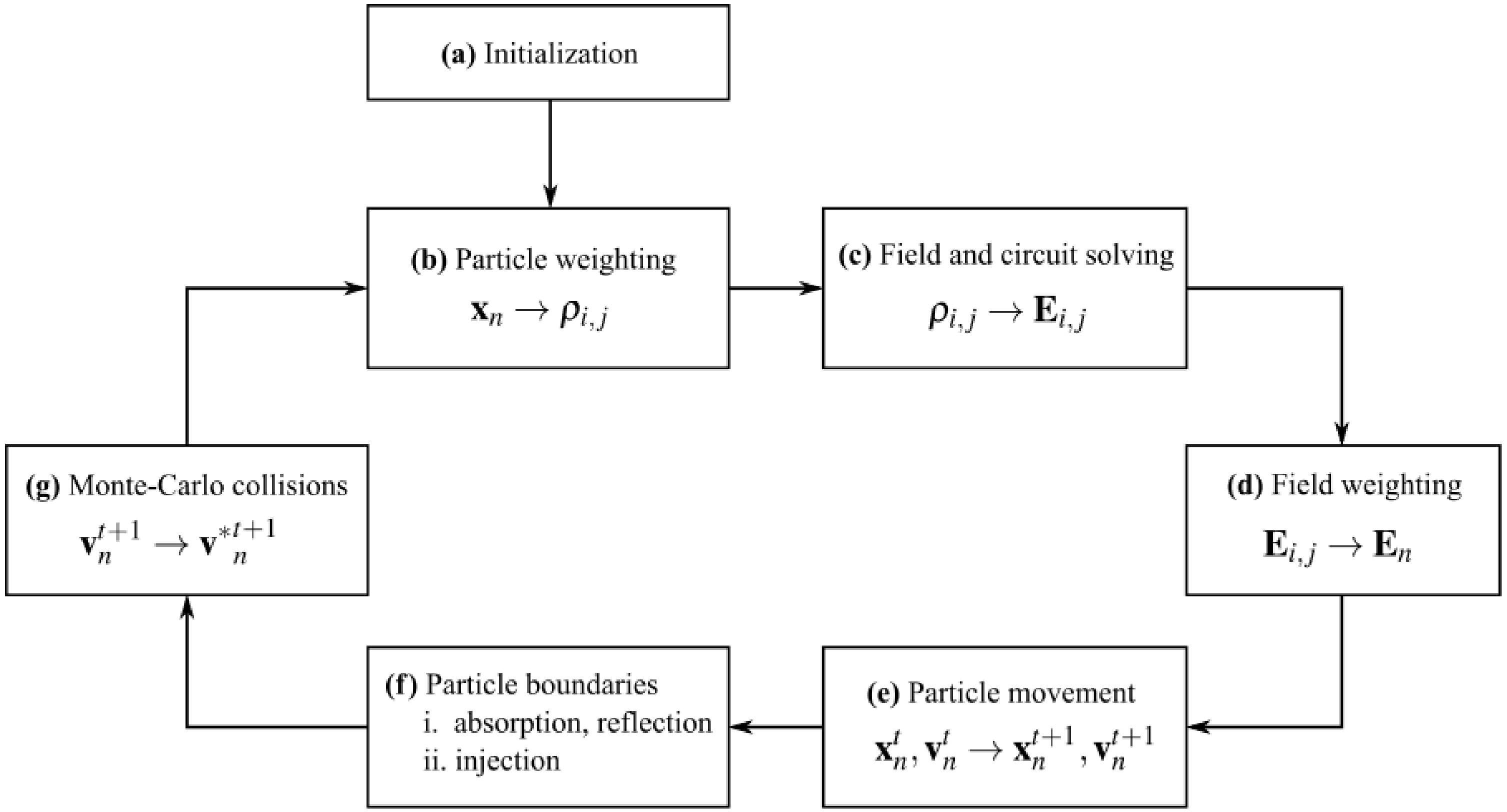
- Pulsed injection model
- Thruster floating → boundaries floating
- Floating (capacitive) boundaries ensure current free condition without artifacts
- XY symmetric domain (no major loss from cylindrical)



# Code development

**Characteristics:**
- 2D electrostatic PIC
- MCC collisions
- DSMC neutral flow simulation
- Capacitive BC

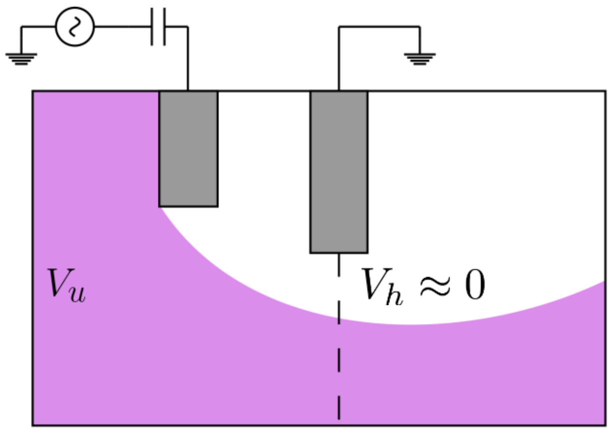
**Tools:**
- C++
- MPI
- HYPRE field solver



# Pulsed electron neutralization

**Ion current**

$$J_i = e n_i u_B$$




$$V_u \approx V_{sb} + V_{RF} \sin \omega t$$

**Electron current**

Considering upstream quasineutrality and maxwellian electrons:

$$J_e = J_i \sqrt{\frac{m_i}{2\pi m_e}} e^{-(V_u - V_h)/T_e}$$

As a first approach:

$$\langle J_e \rangle = \alpha J_i$$

We obtain:

$$J_e(t) = \frac{\alpha J_i}{I_0(V_{RF}/T_e)} \exp\left(-\frac{V_{RF}}{T_e} \sin \omega t\right)$$

# Simulation conditions

## Varied parameters

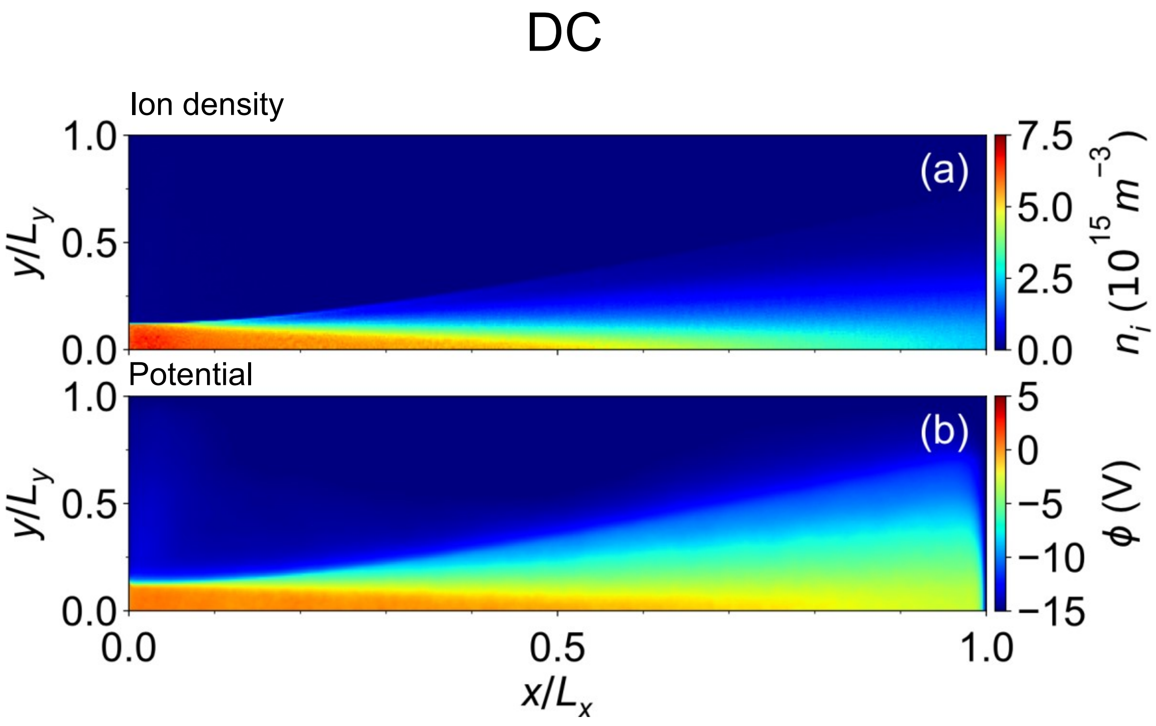
| Parameter | Value |
|---|---|
| Frequency, $f$ (MHz) | 5 – 55 |
| Electron-to-ion current ratio, $\alpha$ | 1 – 5 |
| Boundary capacitance, $C_B$ (F) | $10^{-12}$ – $10^{-8}$ |

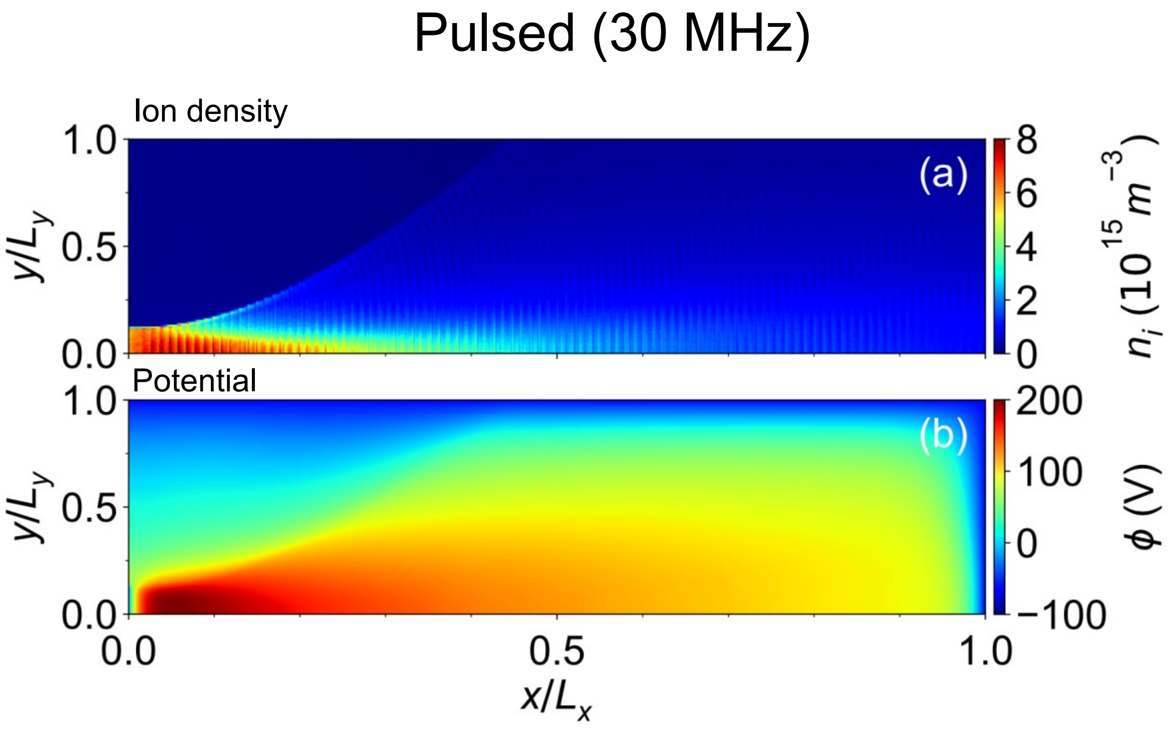
1. **Nominal case**
   - $f = 30$ MHz
   - $\alpha = 3$
   - $C_B = 10^{-11}$ F
2. **DC case**
3. **Parametric study** varying each parameter starting from the nominal case

## Fixed parameters

| Parameter | Value |
|---|---|
| Reference Debye length, $\lambda_D$ (mm) | 0.220 |
| Number of horizontal cells, $N_x$ | 512 |
| Number of vertical cells, $N_y$ | 128 |
| Horizontal domain length, $L_x$ (mm) | $511\lambda_D$ |
| Vertical domain length, $L_y$ (mm) | $127\lambda_D$ |
| Source exit length, $L_s$ (mm) | $15\lambda_D$ |
| Time step, $\Delta t$ (s) | $5 \cdot 10^{-12}$ |
| Simulated time, $t_s$ (μs) | 12 |
| Particle weight, $N_f$ | $3.2 \cdot 10^5$ |
| **Ion energy $E_i$ (eV)** | **1000** |
| Initial ion density, $n_0$ ($m^{-3}$) | $6 \cdot 10^{15}$ |
| Ion current density, $J_i$ ($A/m^2$) | 35 |
| Ion mass (Xe), $m_i$ (kg) | $2.18 \cdot 10^{-25}$ |
| Ion temperature, $T_i$ (K) | 300 |
| **Initial electron drift energy, $E_e$ (eV)** | **50** |
| Initial Electron temperature, $T_e$ (eV) | 5 |
| Neutral gas mass flow rate, $\dot{m}_g$ (mg/s) | 0.15 |

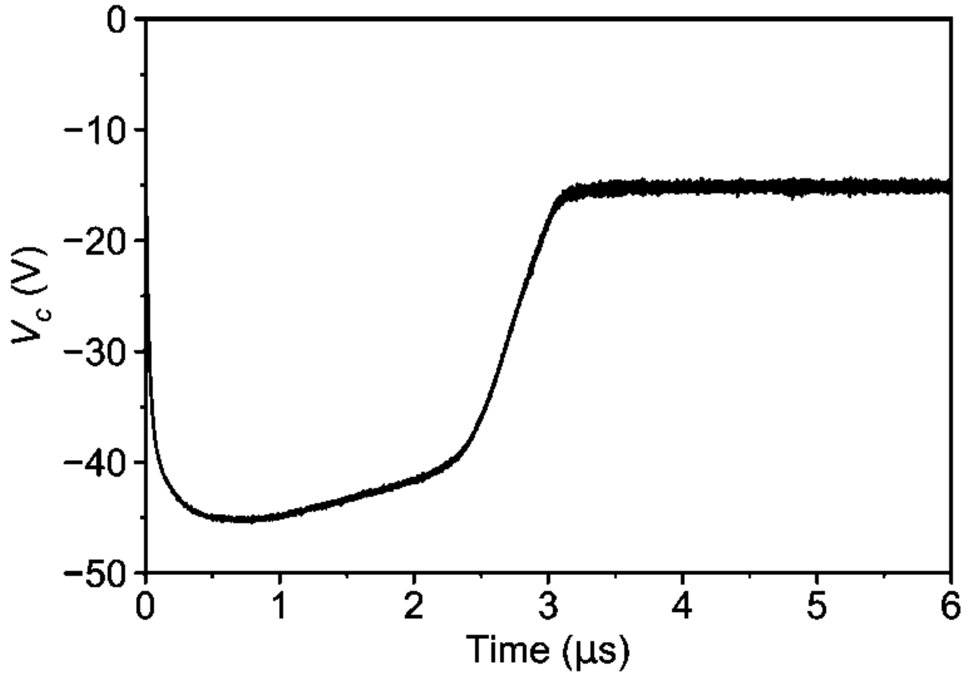
# Comparison of DC and pulsed neutralization



# Boundary capacitor

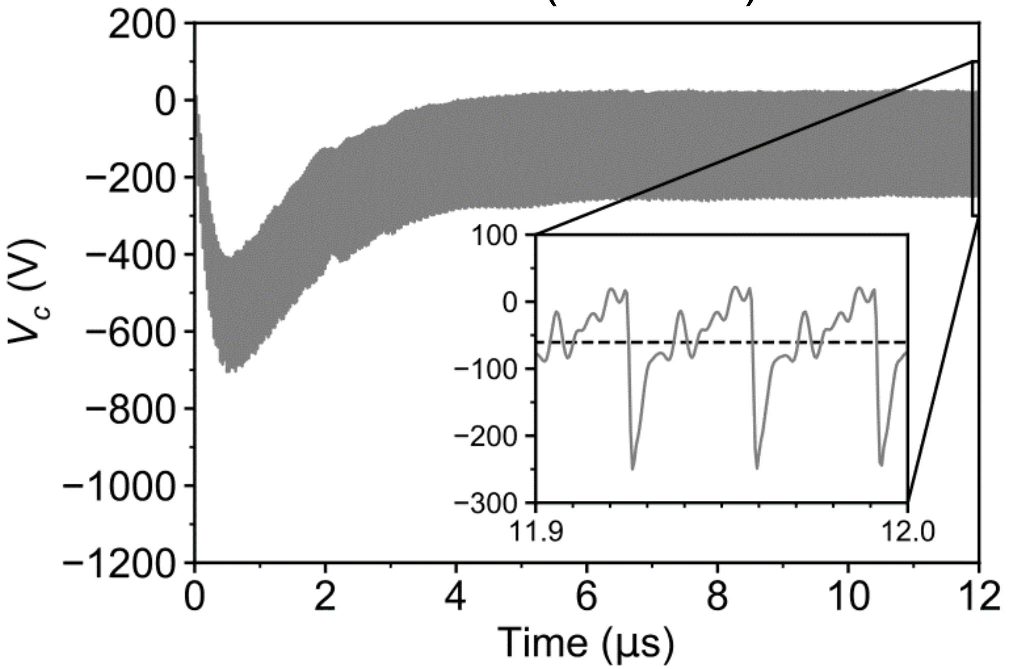
DC

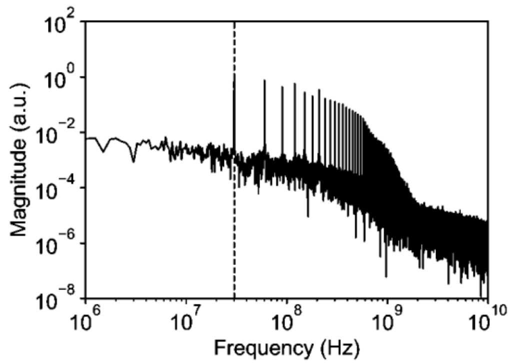



$\langle V_c \rangle \approx -15\ V$

$t_{ss} \approx 3.2\ \mu s$

Pulsed (30 MHz)

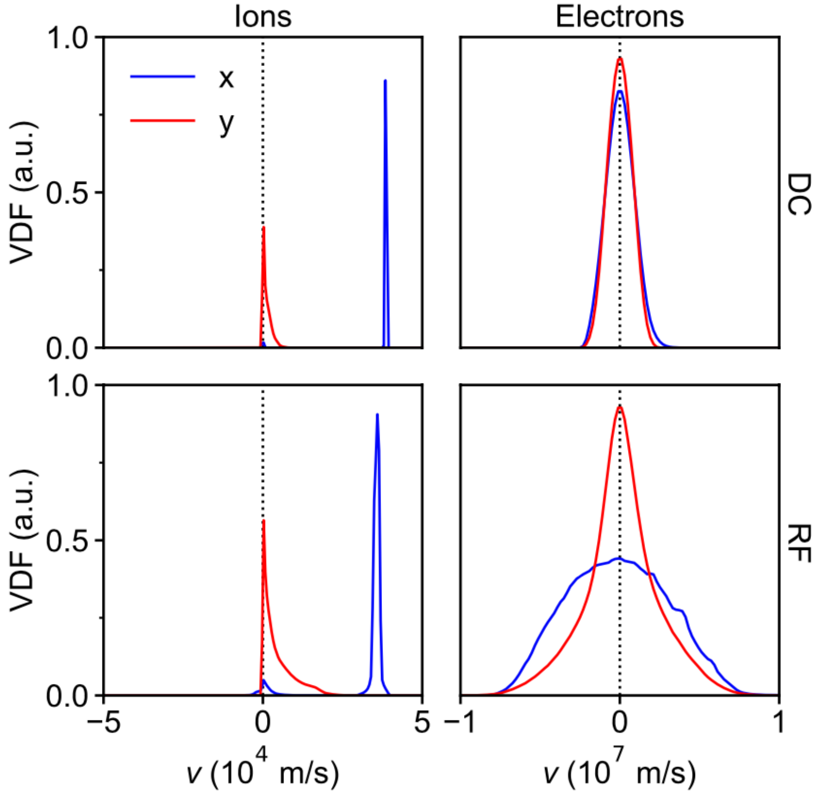


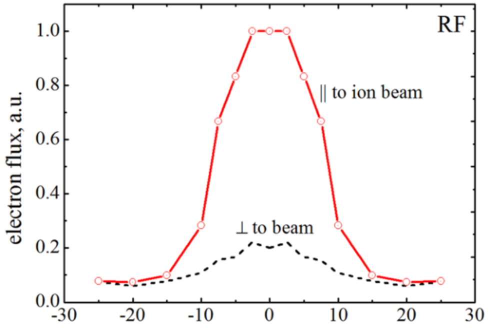




$\langle V_c \rangle \approx -60.5\ V$

$t_{ss} \approx 4.5\ \mu s$

# Comparison of DC and pulsed neutralization




Source: [3]

- Hotter electrons
- Anisotropic distribution

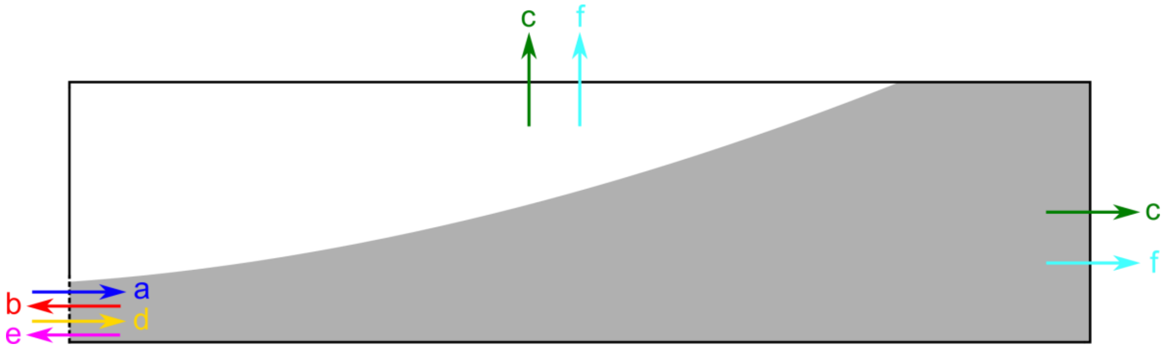
[3] D. Rafalskyi and A. Aanesland, “Brief review on plasma propulsion with neutralizer-free systems,” Plasma Sources Sci. Technol., vol. 25, no. 4, p. 043001, Jun. 2016, doi: 10.1088/0963-0252/25/4/043001.

# Currents at boundaries

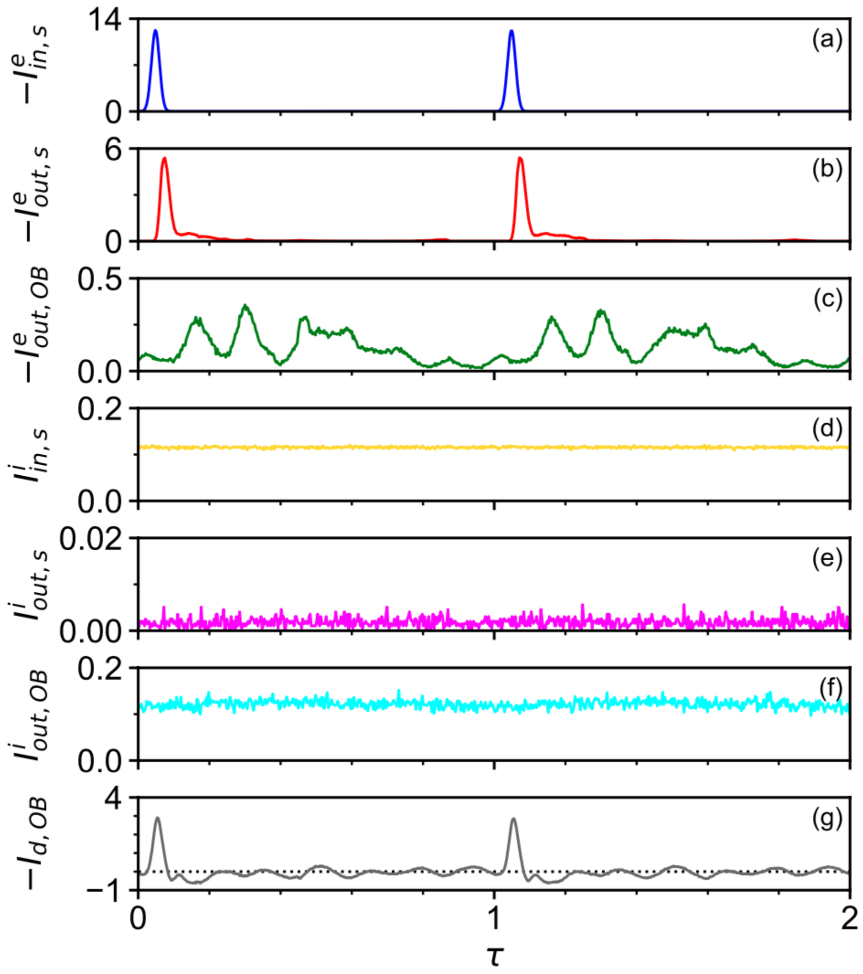
- High electron backstream due to virtual cathode

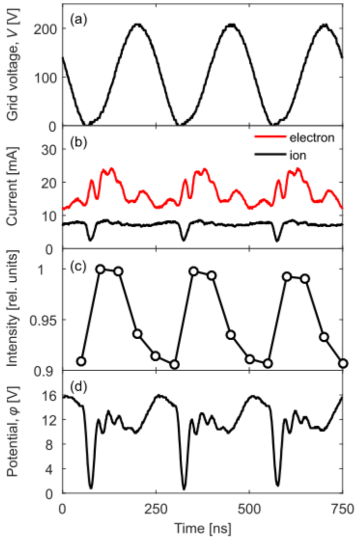
- Electron current has different harmonics probably due to interference between different electron pulses
- Shows a close resemblance to the current measured in experiment by [3]

- **Displacement current** plays an important role, dominating the capacitor charging process




Current leaving domain over 2 RF periods



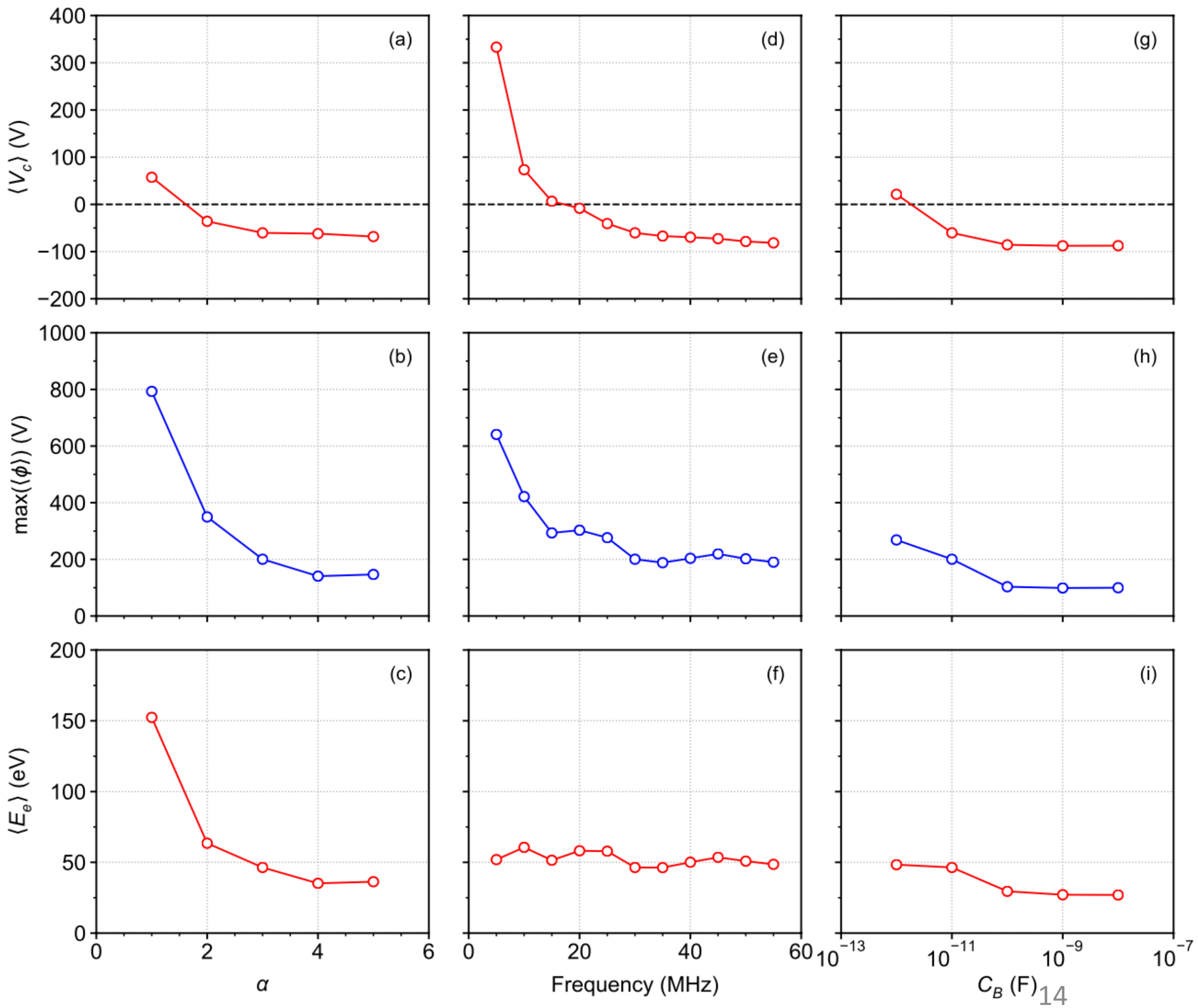




Source: [4]


[4] J. Dedrick, A. R. Gibson, D. Rafalskyi, and A. Aanesland, “Transient propagation dynamics of flowing plasmas accelerated by radio-frequency electric fields,” *Phys. Plasmas*, vol. 24, no. 5, p. 050703, May 2017, doi: 10.1063/1.4983059.

# Parametric study

- Asymptotic behavior with increasing $f$, $\alpha$ and $C_B$
- Stable behaviour of electron energy with frequency
- Increase in frequency and available electrons decrease potentials
- The boundary capacitance has the least impact on the characteristics



# Conclusion

- The RF plume expansion was simulated using a 2D PIC model
- Similar behavior to previous experiments
  - Electron anisotropy
  - Oscillatory profile of electron current to the boundaries
- Trends similar to detailed grid simulations and theory
  - Average plasma plume potential
  - Electron back streaming
  - Minimum electron current magnitude
  - Charging behavior with frequency
- Next steps include self-consistent injection and larger simulation domain

Thank you!