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Relativistic 1D PIC-MCC modeling and simulation of impedance collapse in high-voltage diodes

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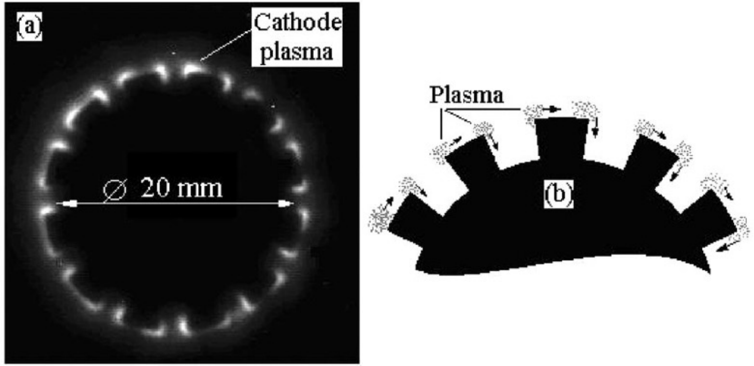
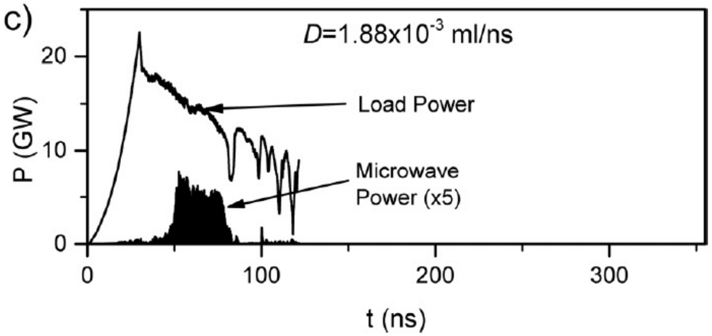
Motivation: Plasmas in High Power Microwaves (HPMs)

- Plasma (ionized gas) forms in vacuum electron devices (VEDs) as the system becomes (i) smaller device or (ii) higher energy.
- Plasma formation and expansion in anode-cathode (AK) gap causes **impedance collapse** and **gap closure,** limiting the microwave pulse.

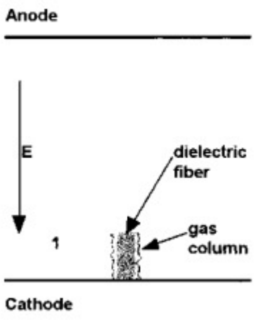


Cathode plasma formation in relativistic magnetrons (RMs) [Hadas et al. JAP 2008]

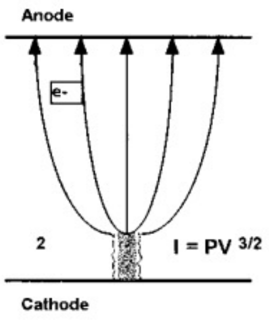


Microwave power cutoff due to cathode plasmas in magnetically insulated line oscillators (MILOs) [Rose et al. PoP 2013]

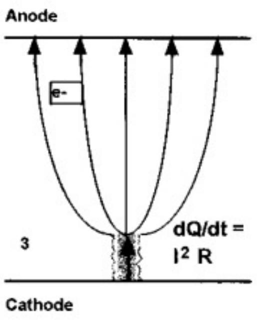
Physical Mechanisms of Plasma Formation in AK Gaps



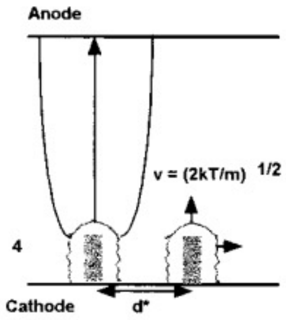
(1) Surface flashover



(2) Space charge limited (SCL) current



(3) Resistive heating of gas (plasma)



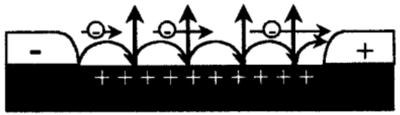
(4) Plasma expansion

[3] - R. B. Miller (1998)

Macroscopic phenomena

(i) Field emission

(ii) Secondary electron emission (SEE) avalanche



(iii) Outgassing

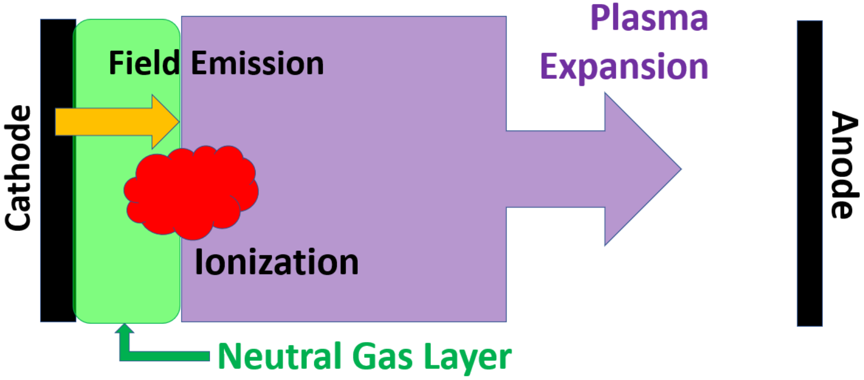
[4] - A. A. Neuber et al. (2000)

Microscopic phenomena

1D PIC-MCC Simulation Model

Goal: develop a self-consistent 1D particle-in-cell (PIC) Monte Carlo collision (MCC) model for plasma formation and expansion

- **AK gap** with a **neutral gas layer (cf. outgassing)** near the cathode
- High voltage results in **Fowler-Nordheim field emission** (FNFE) from cathode
- Emitted electrons **ionizes** the neutral layer forming the plasma near the cathode (self-consistent plasma formation; cf [1])
- Plasma **expands** towards the anode during a high-voltage pulse (~100 kV)
- Field enhancement factor **(β>1)** is considered in FNFE model to account for micro-protrusions [2]



Plasma Formation & Expansion Processes

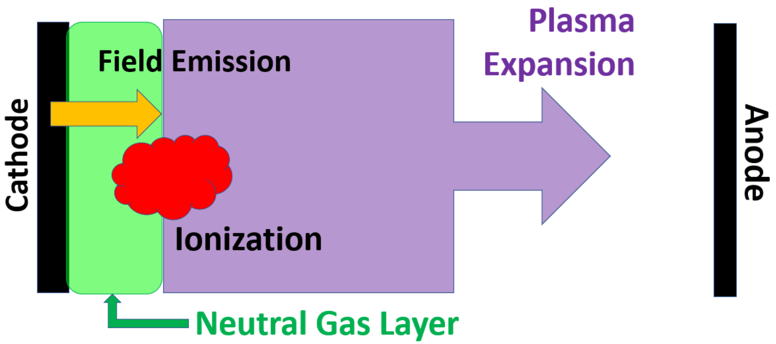
[1] D.R. Welch et al., Phys. Plasmas *16*, 123102 (2009)
[2] G.A. Farrall et al., J. Appl. Phys. *46*(2), 610-617 (1975)

Simulation: Input Parameters

Baseline conditions

Sensitivity study

- Neutral layer: **atomic hydrogen**
- Neutral layer thickness = **100 μm**
- Neutral layer density = **$2.0\mathrm{x}10^{23}$ m^{-3}**
- Field enhancement parameter **(β) = 500**



- AK gap = **1 cm**; Cells = **24000** (**dx = 0.417 μm**)
- dt = **0.167 ps**; Macroparticle weight = **$2.0\mathrm{x}10^{10}$**

Collision model

- Electron-neutral ionization, excitation, and elastic: null-collision algorithm using Monte Carlo collision (MCC) [1]
- Electron-electron and electron-ion Coulomb collisions: Langevin method based on Fokker-Planck operator [2][3]

[1] Vahedi and Surendra, Comp. Phys. Comm. *87* (1-2), 179-198 (1995)
[2] M.E. Jones et al., J. Comp. Phys. *123* (1), 169-181 (1996)
[3] W.M. Manheimer et al., J. Comp. Phys. *138*(2), 563-584 (1997)

Simulation Conditions

Grid convergence study (w/o Coulomb collisions):

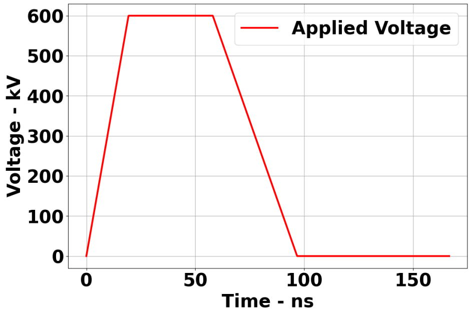
- up to **100,000** cells (**dx = 0.1 μm**) gave similar plasma expansion rates;
- computational time 7 days with 16 processors
- 24000 cells (**$dx/\lambda_d \backsimeq 1$**); 100,000 cells (**$dx/\lambda_d << 1$**)

Neutral layer density and **β** were chosen based on sensitivity study

- Experimental literature suggests ~ **10^{24} m^{-3}** neutral layer density near electrodes [1]
- β in the range of **100-600** has been reported in literature [2]

High-voltage pulse (based on experiments[3]): 100 ns pulse

- 40 ns flat-top at 600 kV
- 20 ns ramp-up; 40 ns ramp-down



[1] R. B. Miller, J. Appl. Phys. *84*, 3880–3889 (1998)
[2] S. Kobayashi et al., Appl. Surf. Science *146*(1-4), 148-151 (1999); G.A. Farrall et al., J. Appl. Phys. *46*(2), 610-617 (1975)
[3] R.K. Parker et al., J. Appl. Phys. *45*(6), 2463-2479 (1974); D. D. Hinshelwood, IEEE Tran. on Plasma Science, *11*(3), 188-196 (1983)

Grid-based Langevin Method for Coulomb Collisions

- Coulomb collision is represented as scattering of particles off the PIC grid (instead of binary collisions, e.g., Nanbu method)
- Fokker-Planck eq equivalent to Langevin eq to first order accuracy in time [1,2]
- First and second Rosenbluth potentials computed assuming a *drifting* Maxwellian VDF for the field particles, i.e., electrons and ions [3]

Dynamical Friction Vector

Diffusion Tensor

Fokker–Planck Collision Operator:

$$\frac{\delta_c f_s}{\delta t} = -\boldsymbol{\nabla}_{\mathbf{v}} \cdot \left[\left\langle \frac{\Delta \mathbf{v}}{\Delta t} \right\rangle f_s\right] + \frac{1}{2}\boldsymbol{\nabla}_{\mathbf{v}}\boldsymbol{\nabla}_{\mathbf{v}} : \left[\left\langle \frac{\Delta \mathbf{v}\Delta \mathbf{v}}{\Delta t} \right\rangle_s f_s\right]$$

Langevin Equation:

$$\Delta \mathbf{v} = \mathbf{F}_d \Delta t + \mathbf{Q}$$

Deterministic Friction

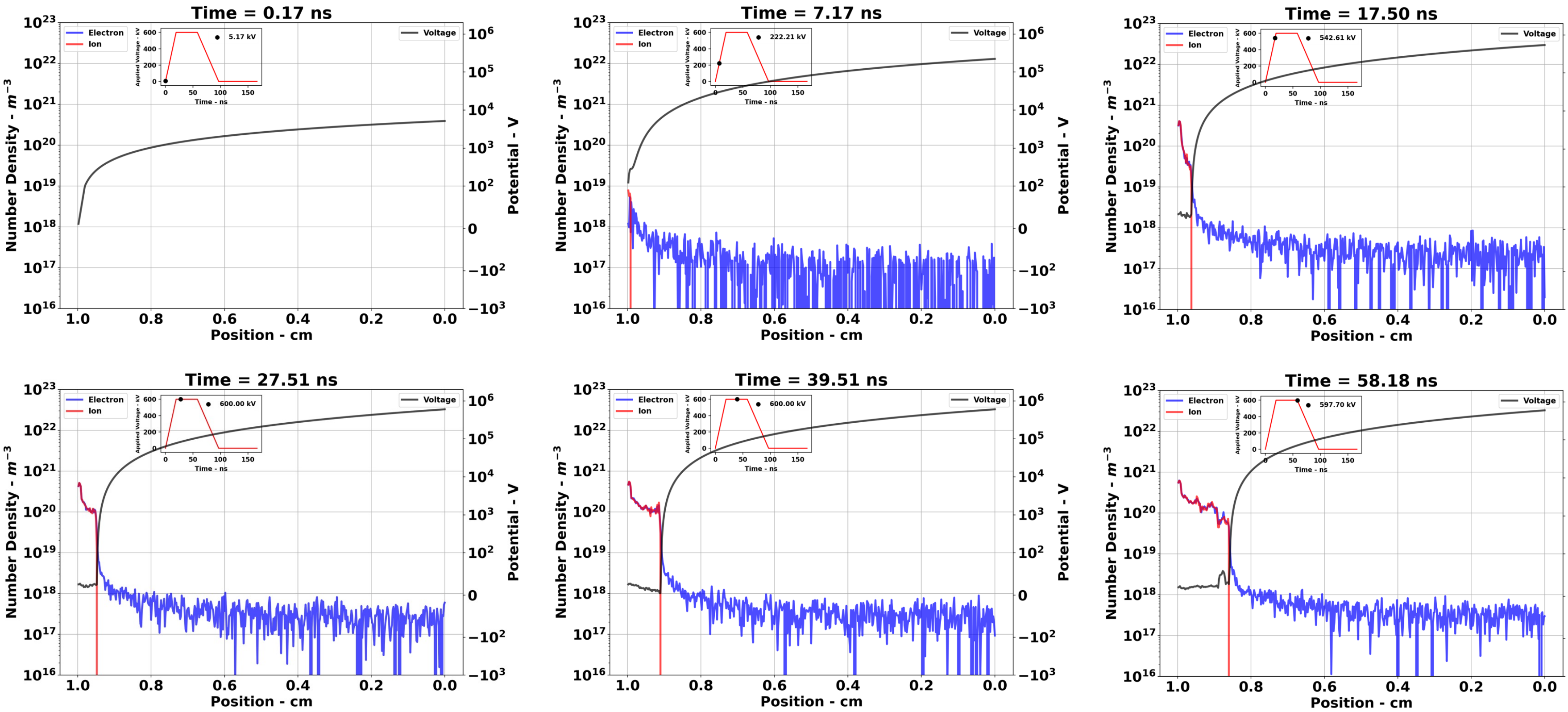
Random Diffusive Scattering

[1] S. Chandrasekhar, Rev. Mod. Phys. *15*, 1 (1943)

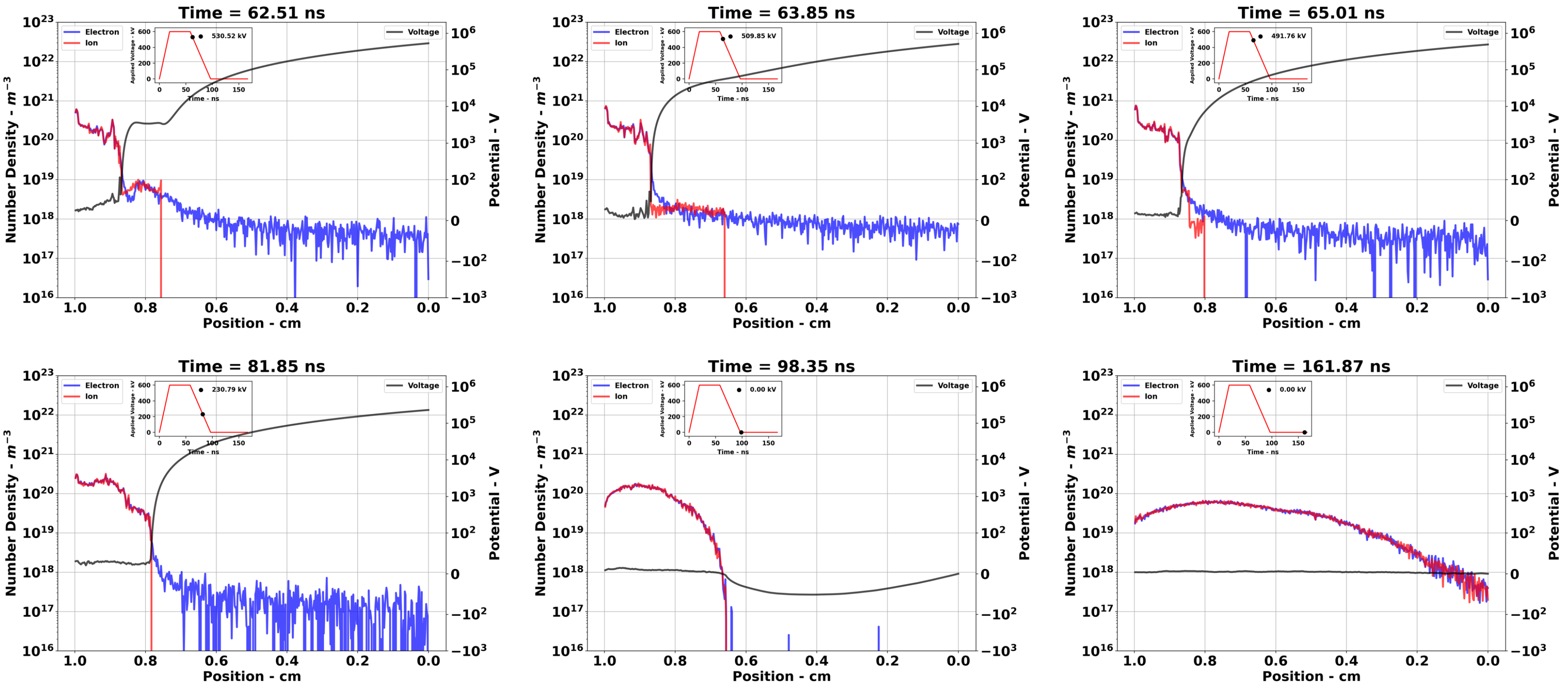
[2] M.E. Jones et al., J. Comp. Phys. *123* (1), 169-181 (1996)

[3] W.M. Manheimer et al., J. Comp. Phys. *138*(2), 563-584 (1997)

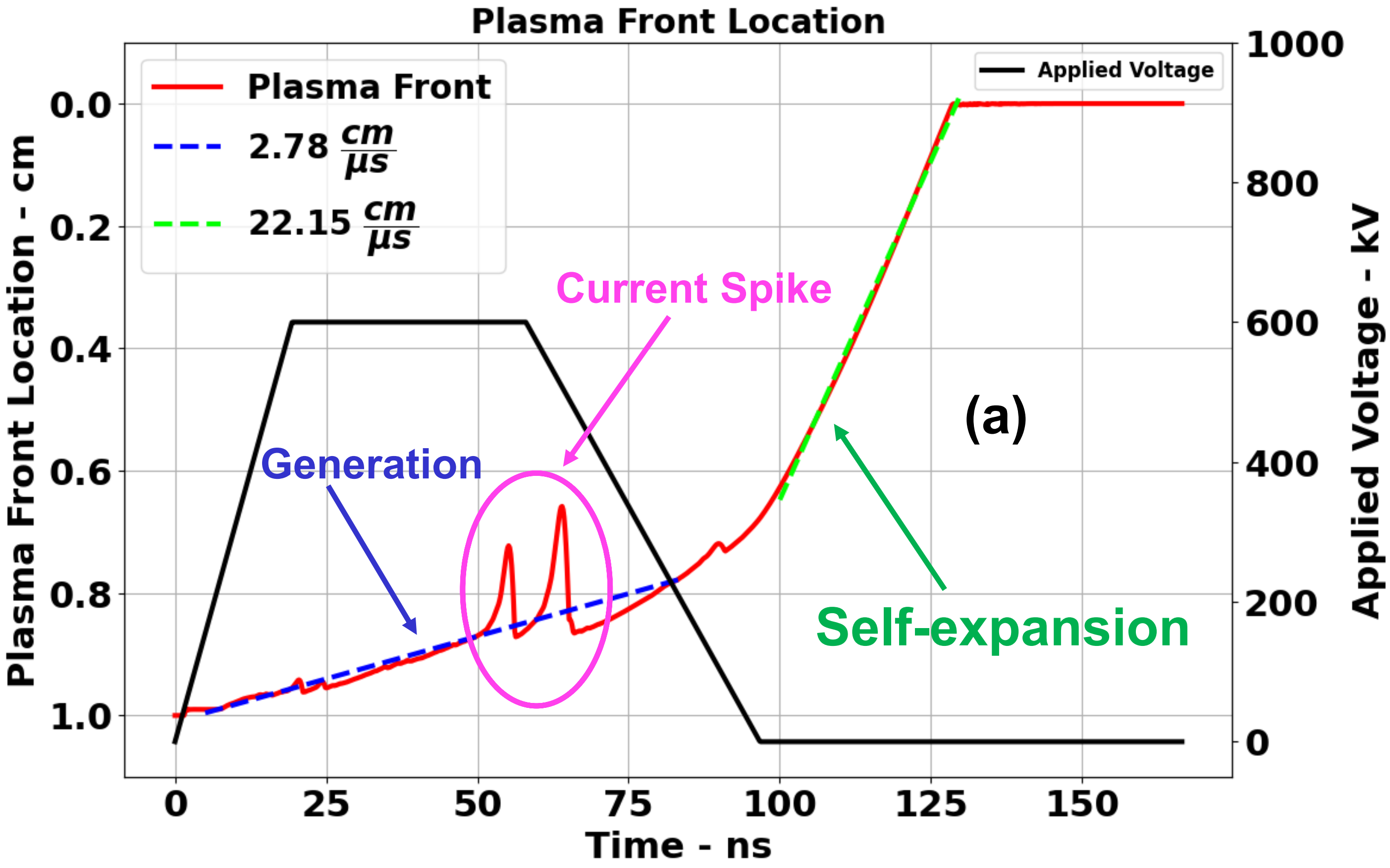
Result: Plasma Formation and Expansion



Result: Plasma Formation and Expansion



Result: Evolution of Plasma Front



Result: Evolution of Plasma Front

(a) Plasma expansion speed

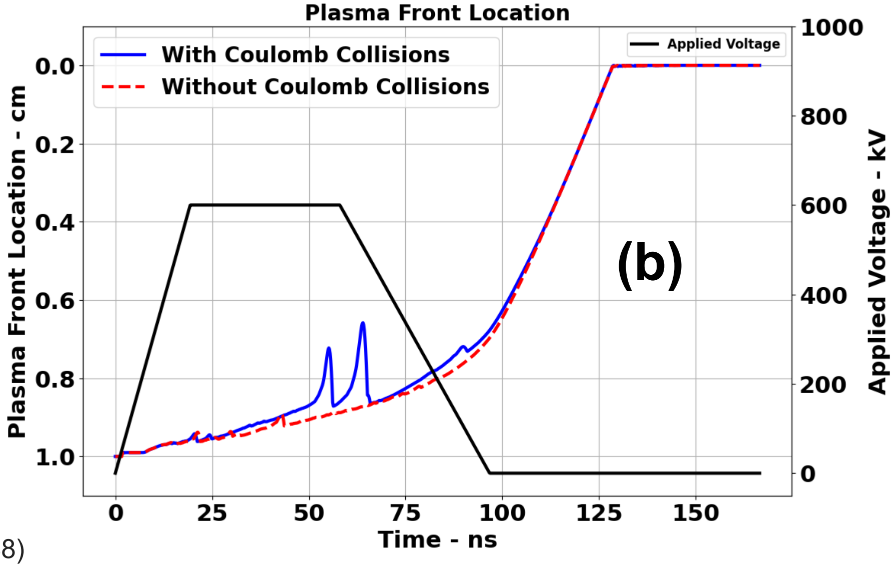
- Cf) Exp. measurement: **1-10 cm/μs** [1]

1. During pulse, **generation speed (2.78 cm/μs)** agrees well with experimental results
2. Towards the end of the pulse, **self-expansion speed (22.15 cm/μs)** due to diffusion

(b) Effect of Coulomb Collisions

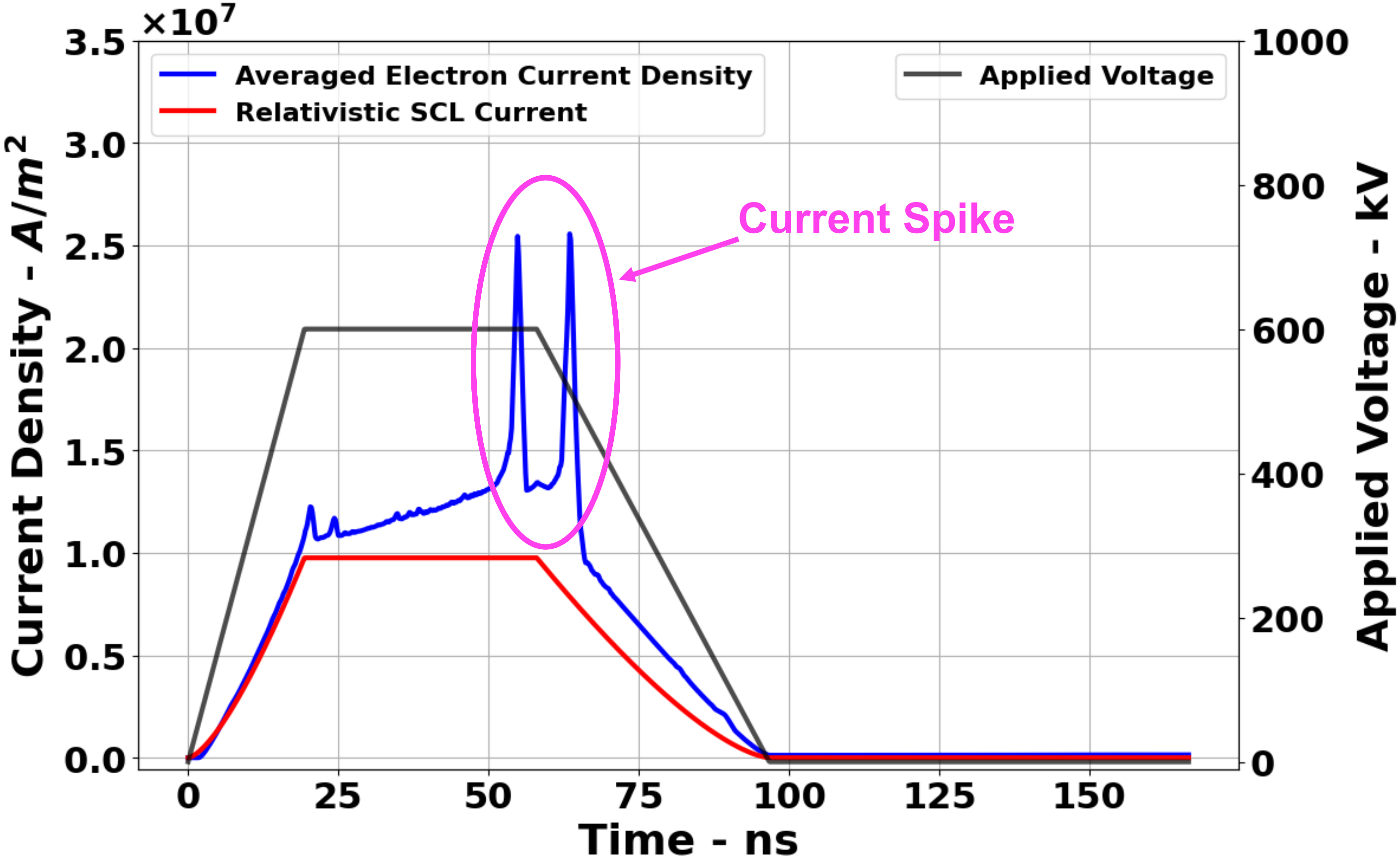
1. Plasma expansion speed unchanged
2. Current instability observed

➡ *Coulomb collisions can be important for plasma expansion!*



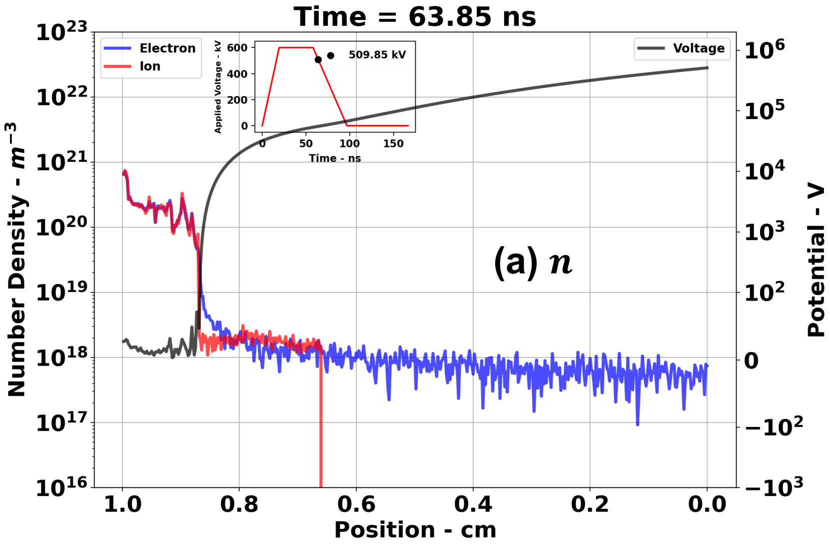
[1] R. E. Shefer et al., The Phys. of Fluids *31*(4), 930-939 (1988)

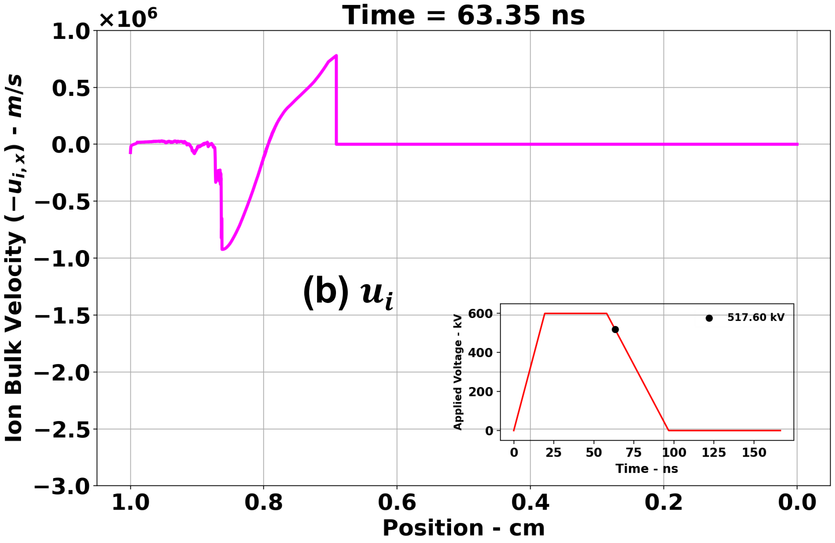
Instability: Electron Current Density



Instability: Electron Current Density

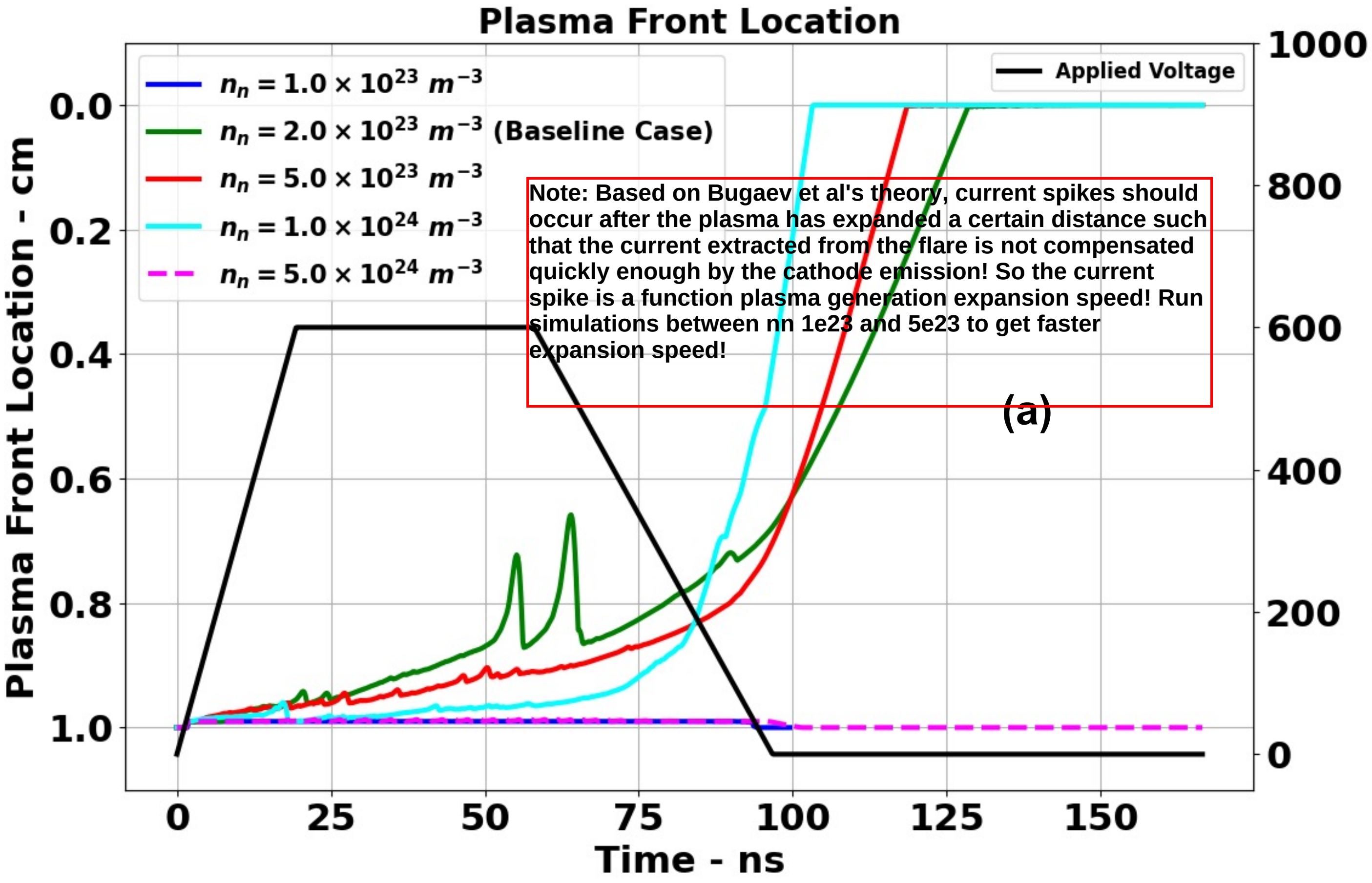
- We observe current spikes due to the acceleration of near-cathode plasma
- Experimental observation [1]: current instability can cause **x5 increase** in current density with a burst time of no more than **10 ns**





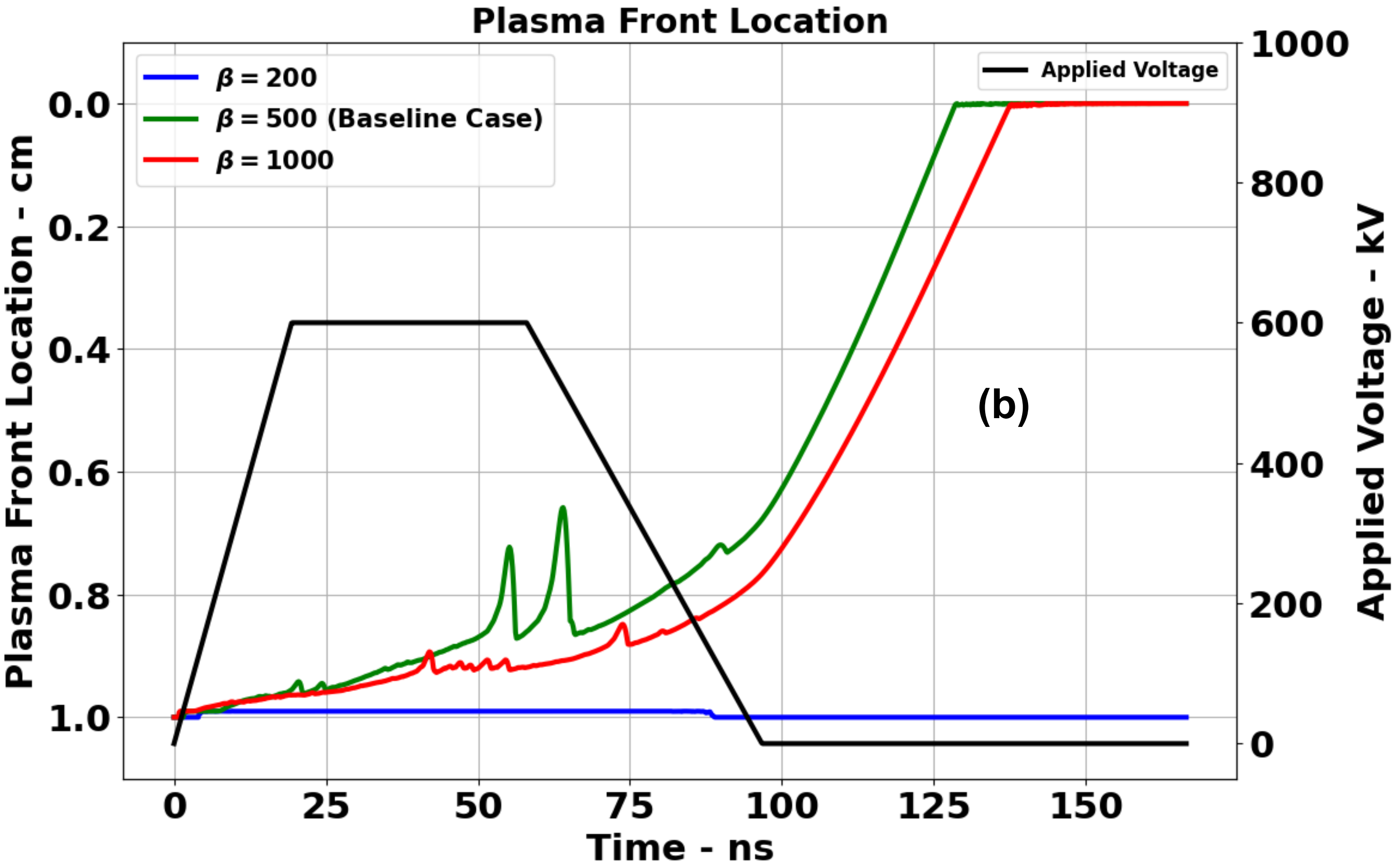
[1] S.P. Bugaev et al., Soviet Phys. Uspe. *18*(1), 51 (1975)

Parameter Sensitivity: Neutral Layer Number Density



Note: Based on Bugaev et al's theory, current spikes should occur after the plasma has expanded a certain distance such that the current extracted from the flare is not compensated quickly enough by the cathode emission! So the current spike is a function plasma generation expansion speed! Run simulations between nn 1e23 and 5e23 to get faster expansion speed!

Parameter Sensitivity: Field Enhancement Factor



Result: Parameter Sensitivity Study

Effect of varying **field enhancement factor (β)** and **neutral layer density (n)** studied

1.) Cathode plasma layer expansion not observed

(a): for high **($n>5x10^{24}$ m^{-3})** & low **($n<1x10^{23}$ m^{-3})** neutral layer number density

(b): for low field-enhancement parameters **(β<500)**

2.) Cathode plasma expansion speed sensitive to the neutral layer number density

- Generation phase: **1.5 - 2.78 cm/μs**
- Self-expansion phase: **22.15 - 42.05 cm/μs**

Summary

1D PIC-MCC model of plasma formation and expansion is developed.

- Simulation results of AK gap closure velocity in agreement with experiments: **1-10 cm/μs**
- Coulomb collisions are implemented using Langevin method (verified and tested)
- Coulomb collisions affect the plasma stability and can cause current spikes
- Current instabilities in simulation consistent with experimental observations in literature
- Plasma layer formation and expansion is a function of **neutral gas layer**, **β** (field emission enhancement factor), and **applied voltage**

Future work will take into consideration the effects of secondary electron emission, anode plasma formation, and the **surface flashover mechanism** (e.g., 2D simulations)