Space Charge Effects on the Short Pulse Beam Profile

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Summary

- We investigate **space charge effects** on the dynamics of short pulse beam profile.
- We consider **short pulses** of different initial profiles for different charge densities and pulse widths.
- We analyze the **phase-space trajectories** of the electrons sheets in the vacuum gap.
- We study the **evolution of the pulse profiles** and the current density during the transit in the gap.

Multiple-Sheet Model

A one-dimensional (1D) planar diode with gap distance d and gap voltage V_g. With M sheets inside.

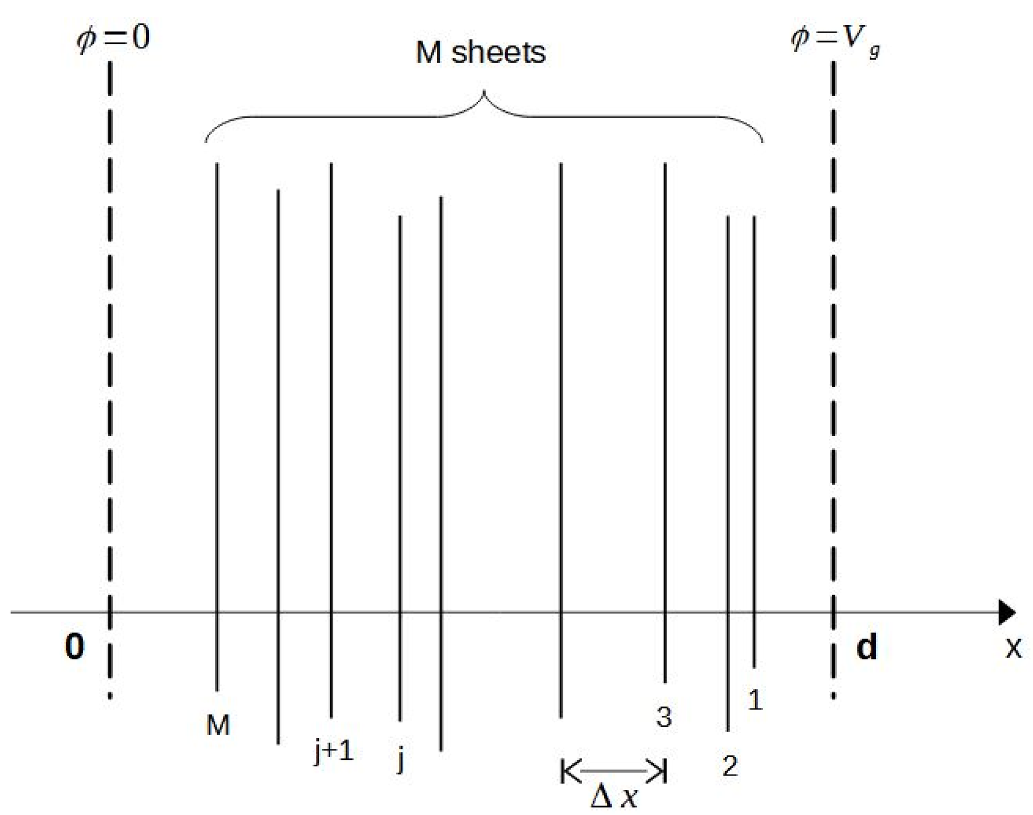

Figure 1: Sheet numbering inside the diode gap [1]

- Sheet j at $\bar{x}_j$ has a normalized charge density $\bar{\rho}_j$
- Normalized Electric field on sheet j is

$$\bar{E}_j = 1 + \left[\sum_{\mathrm{i=1}}^{\mathrm{M}} \bar{\rho}_i \bar{x}_i - \left(\sum_{\mathrm{i=1}}^{\mathrm{j\text{-}1}} \bar{\rho}_i + \frac{1}{2}\bar{\rho}_j\right)\right] \quad (1)$$

- Normalized Electric field at the cathode ($\bar{x} = 0$)

$$\bar{E}_K = 1 + \sum_{\mathrm{i=1}}^{\mathrm{M}} \bar{\rho}_i \left(\bar{x}_i - 1\right) \quad (2)$$

- The Space Charge Limited (SCL) charge density $\bar{\rho}_j^*$ is found for $\bar{E}_K = 0$

$$1 + \sum_{\mathrm{i=1}}^{\mathrm{M}} \bar{\rho}_j^* \left(\bar{x}_i - 1\right) = 0 \quad (3)$$

Square-top Profile

- All sheets with **equal charge density** $\bar{\rho}$
- The SCL charge density $\bar{\rho}^*$ is from (3)

$$\bar{\rho}^* = \frac{1}{M}\left[\frac{1}{1 - \delta\bar{x}\left(\frac{M-1}{2}\right)}\right] \quad (4)$$

- The initial pulse intervals $\delta\bar{x} = \bar{x}_n - \bar{x}_{n+1}$ are assumed to be uniform.

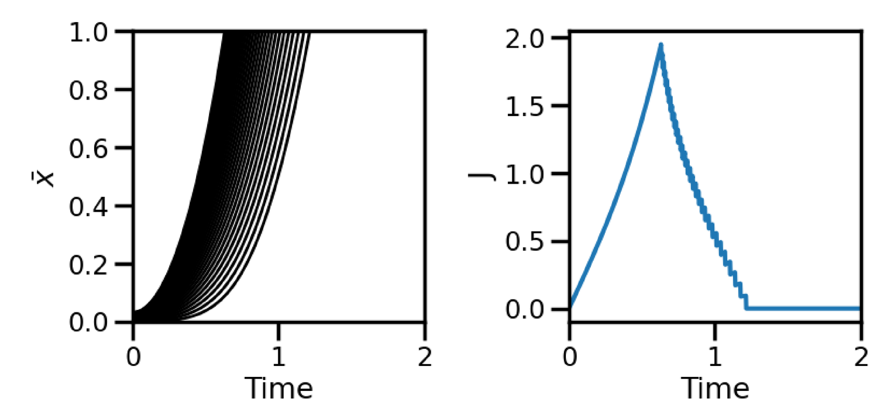

Figure: Trajectories of each sheet and current density

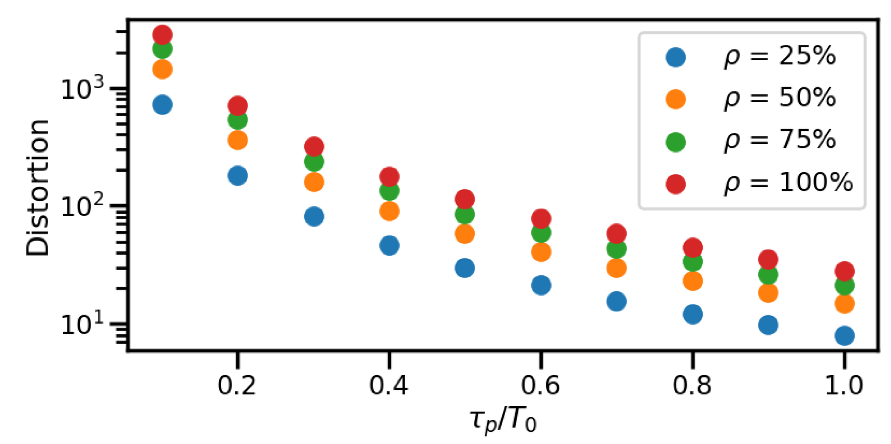

Figure: Square-top profile distortion with initial pulse length

Gaussian Profile

- Sheet j with **charge density**

$$\bar{\rho}_j = a \exp\left(-\frac{(j-\mu)^2}{b}\right) \quad (5)$$

- Where $\mu = (M+1)/2$, a and b are found solving (3) with assumption $\sum_{\mathrm{i=1}}^{\mathrm{M}} \bar{\rho}_i^* = 1$ as the bulk of sheets tends to bunch, looking like a single sheet.

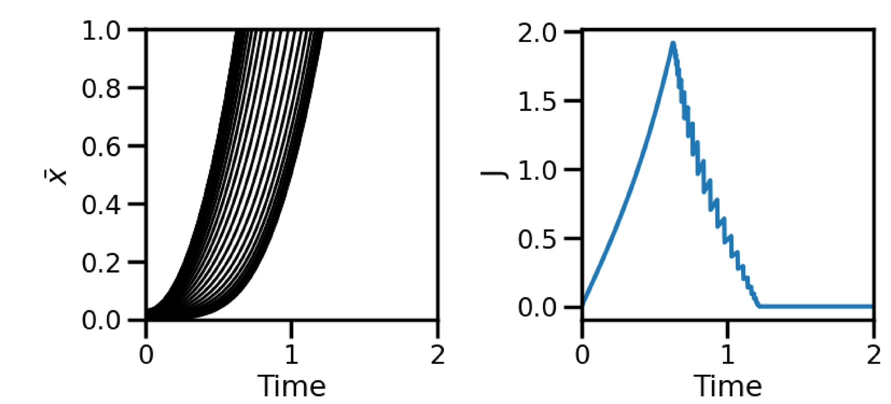

Figure: Trajectories of each sheet and current density

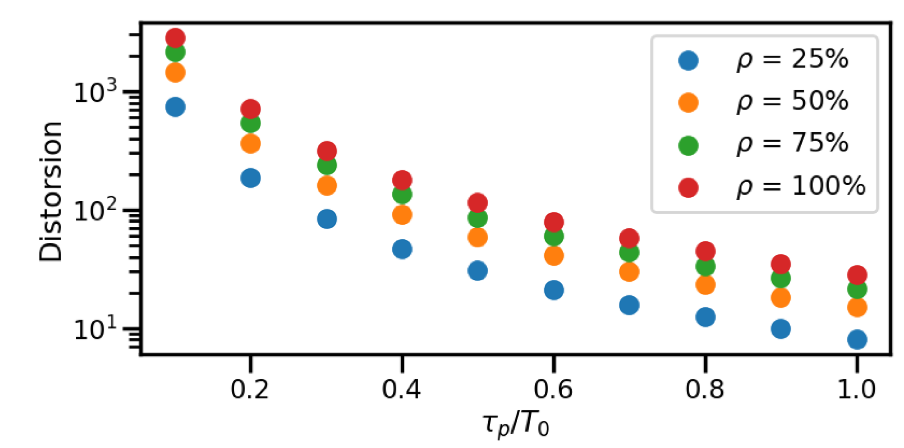

Figure: Gaussian profile distortion with initial pulse length

Evolution of the Gaussian Profiles inside the gap

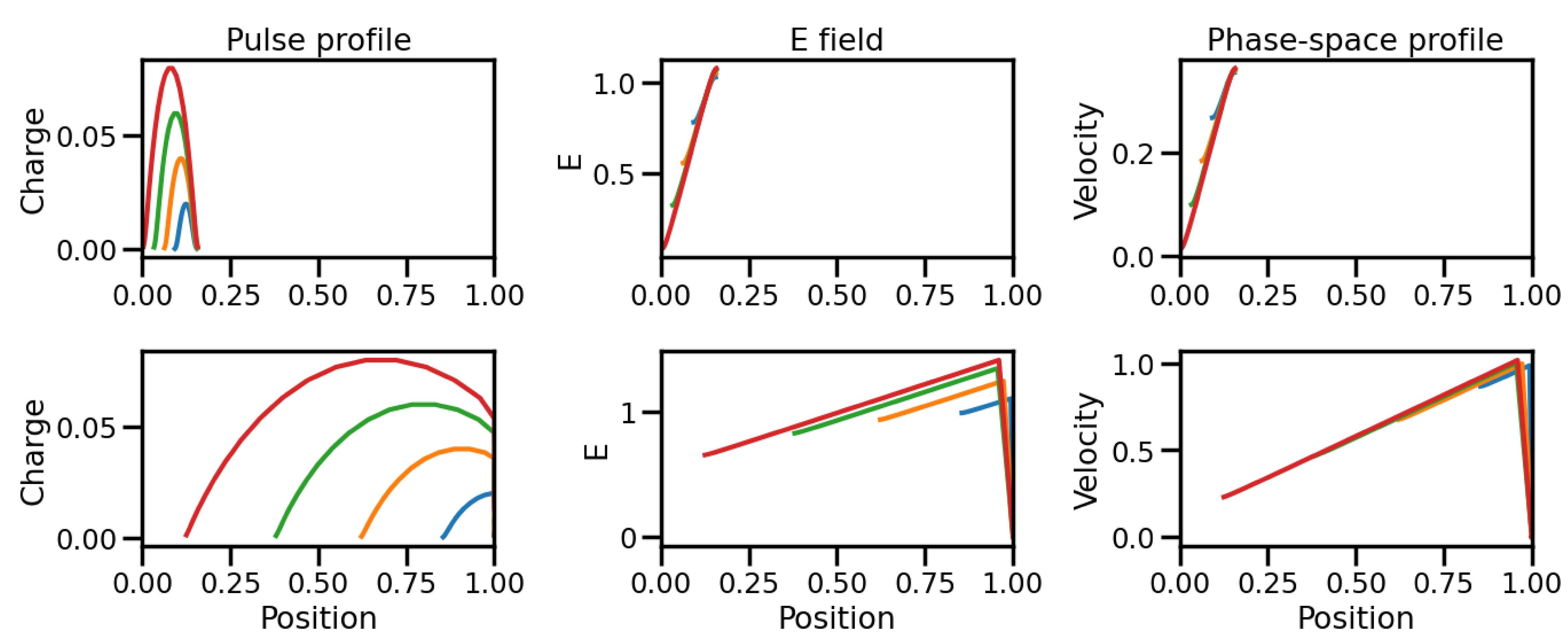

Figure: Snapshots of the evolution of pulse profile, electric field and velocity for $\bar{\rho}_j = 25,\ 50,\ 75$ and 100% of $\bar{\rho}_j^*$

Model parameters

Symbol	Meaning	Formula/Value
V_g	Gap voltage	30 kV
d	Gap distance	1.5 mm
τ_p	Pulse length	$[0.1, 1] \times T_0$
T_0	Transit time	see [3]
Δ	Distortion	$\Delta = \frac{\delta\bar{x}_{init}}{\delta\bar{x}_{final}}$
J	Current density	$J = 3\sum_{i=1}^{M}$ –

Conclusion & Future Work

1. For same total charge, both the square-top and Gaussian pulses undergo identical distortion.
2. The shorter the pulse length, the more significant the distortion becomes.
3. The smaller the charge, the faster the tail of the pulse travels through the gap.
4. In future research, assess the Child-Langmuir limit as the pulse length decreases.

References & Acknowledgement

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