Two-way perturbative coupling of plasma-fluid interactions

GEC 2025

José Marques, Toulouse Institute of Fluid Mechanics

Supervisors: D. Fabre, F. Plouraboué

IPROP EIC Pathfinder : https://www.iprop-project.eu/

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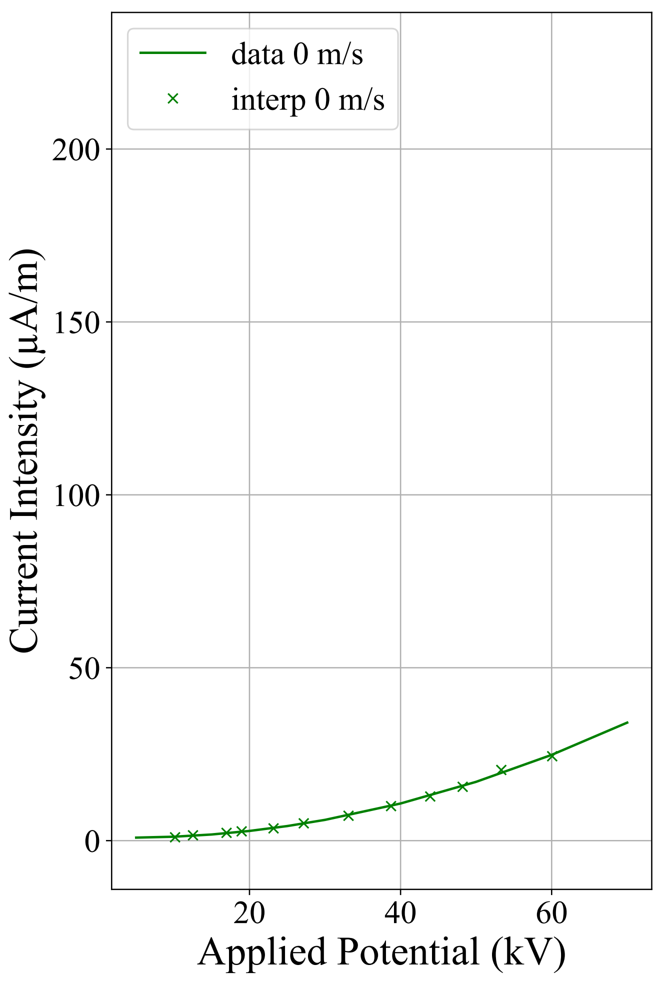
Current Intensity of DC Corona Discharge in a Flow

- Chapman's measurements in the 60's



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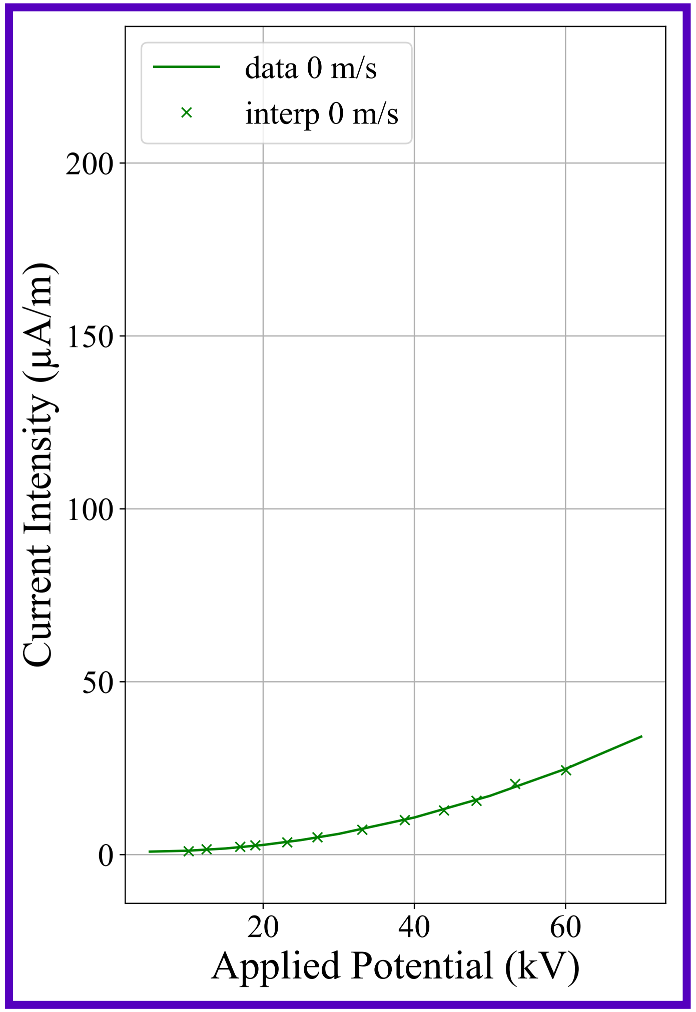

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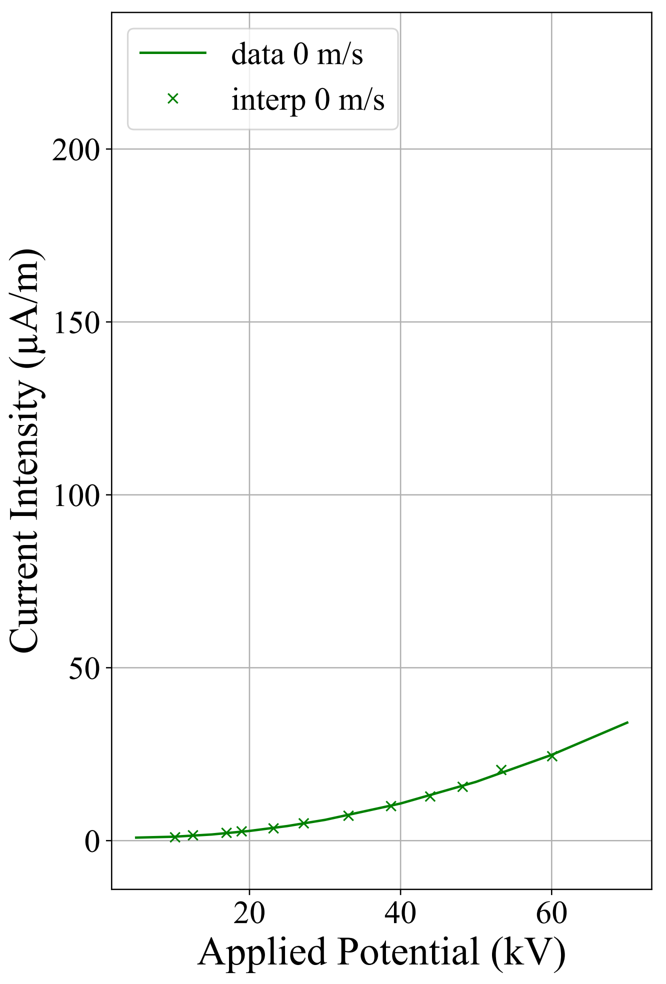

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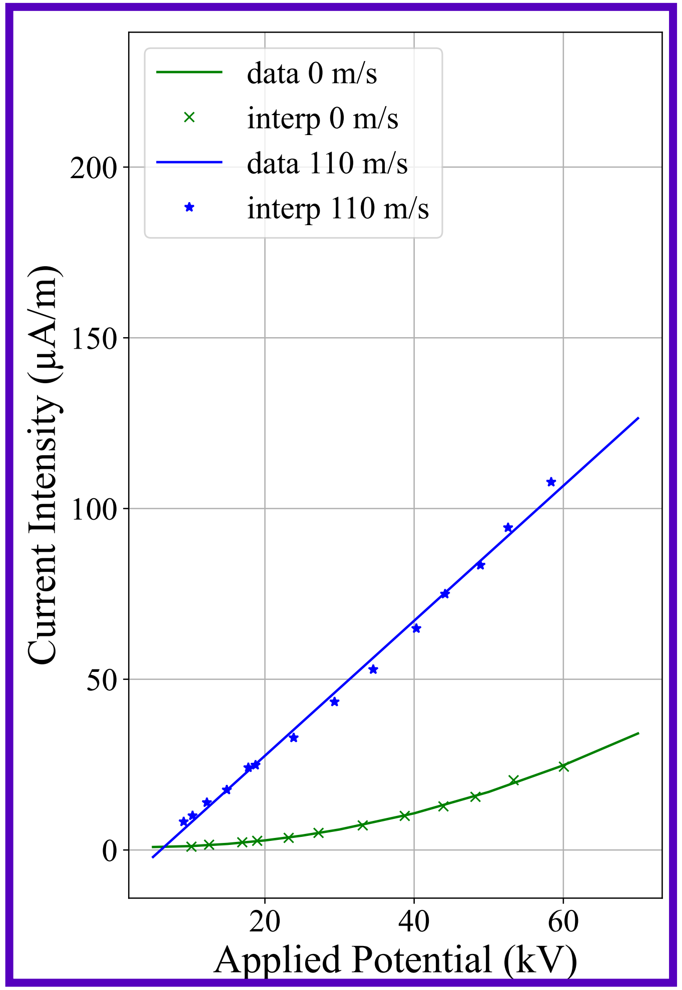

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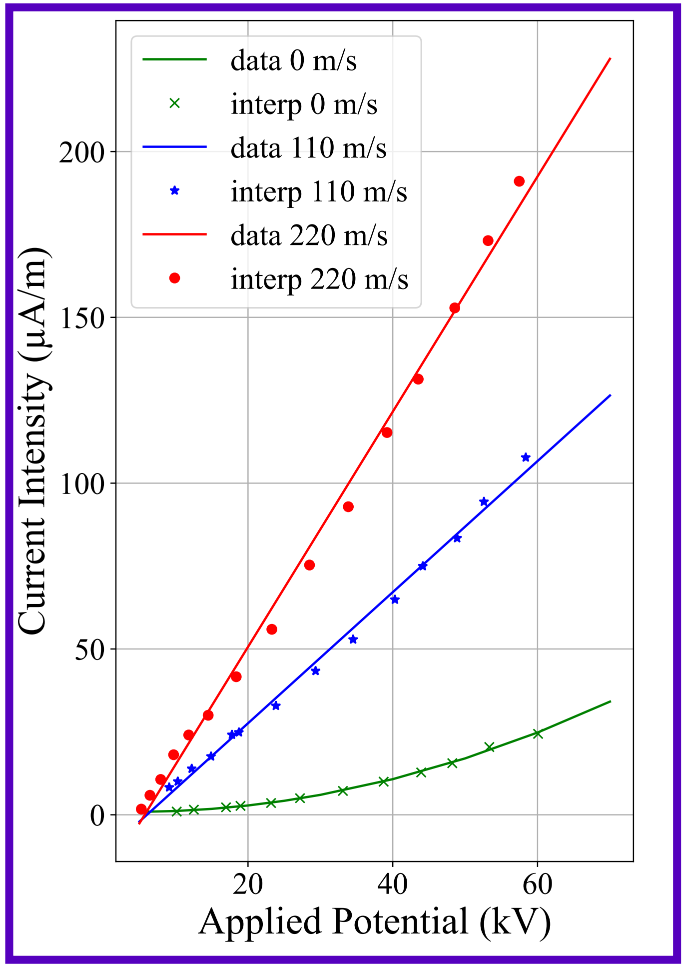

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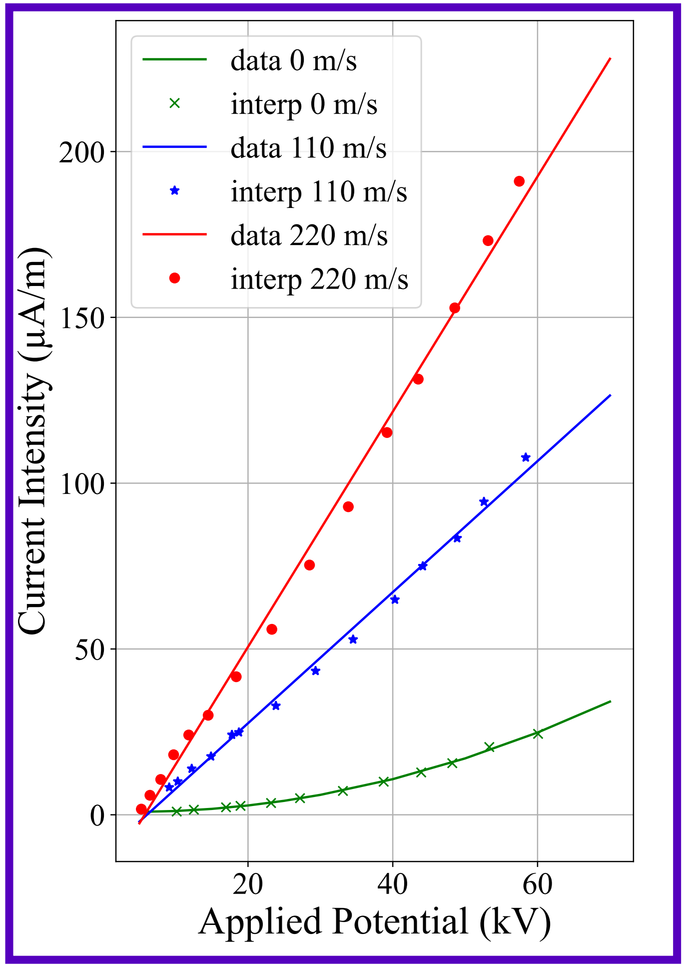

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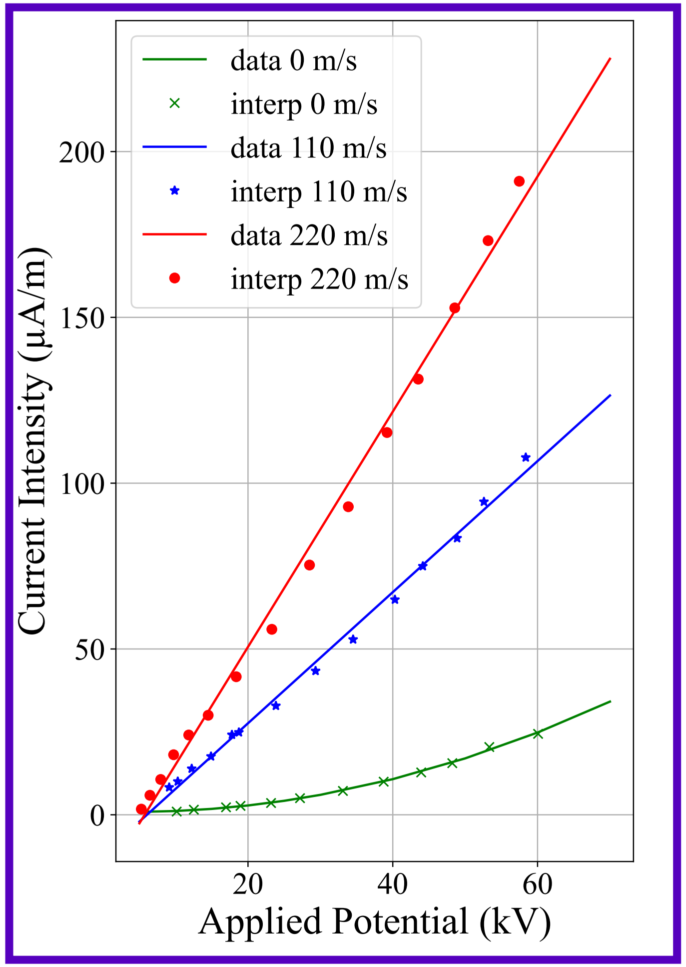

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Dimensionless Two-Way Model of Plasma & Fluid

Physical Parameters

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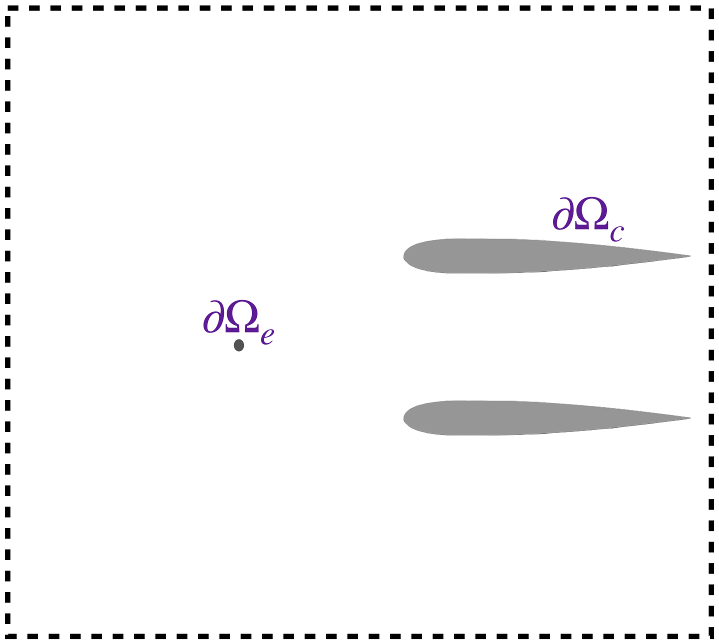

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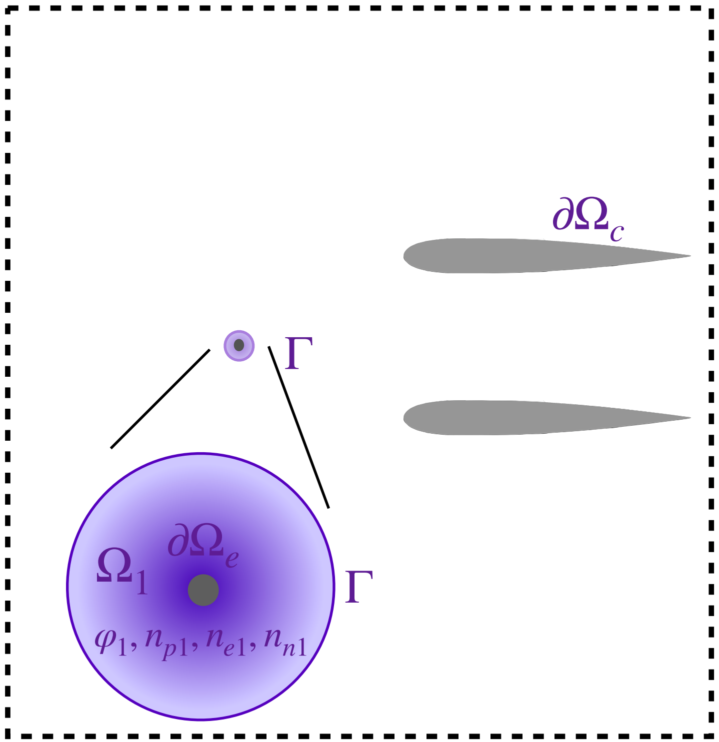

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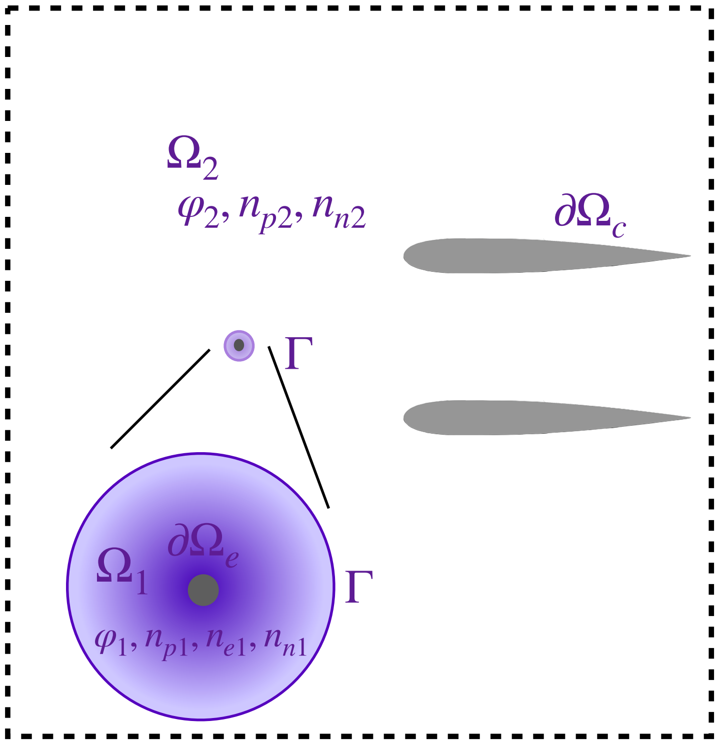

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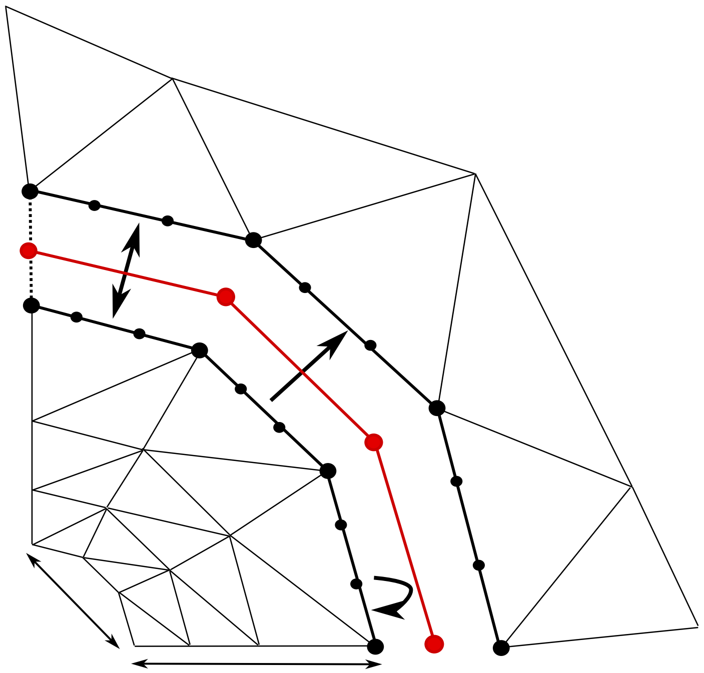
Two-Way Model (Some) Numerical Aspects



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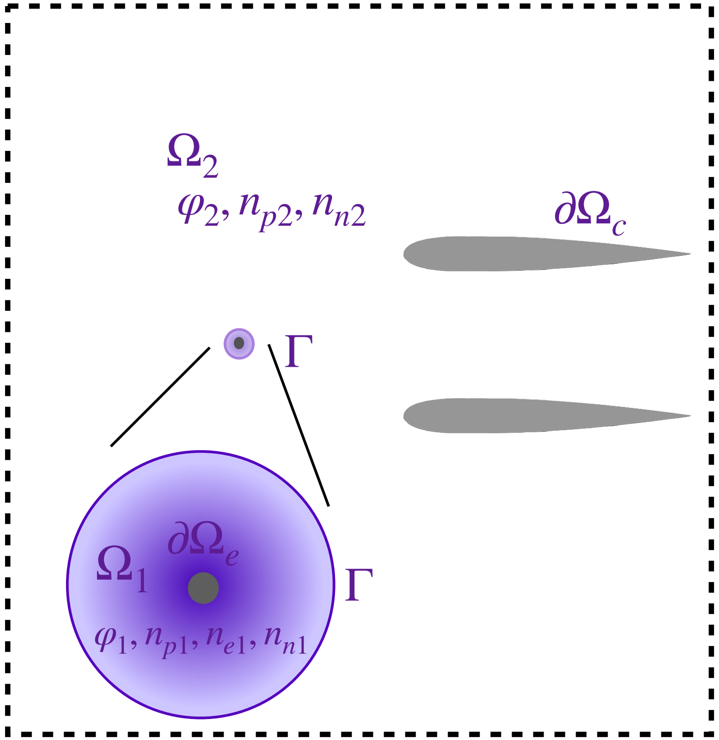

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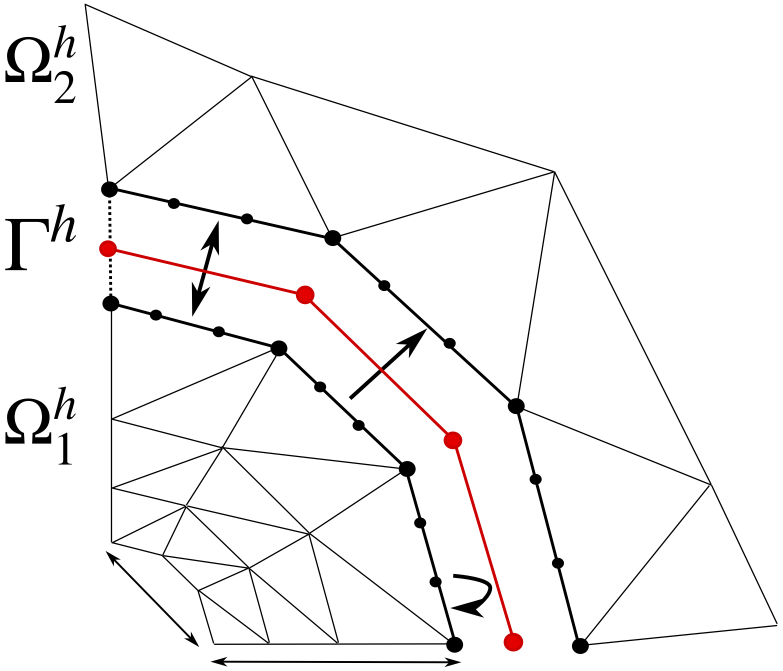

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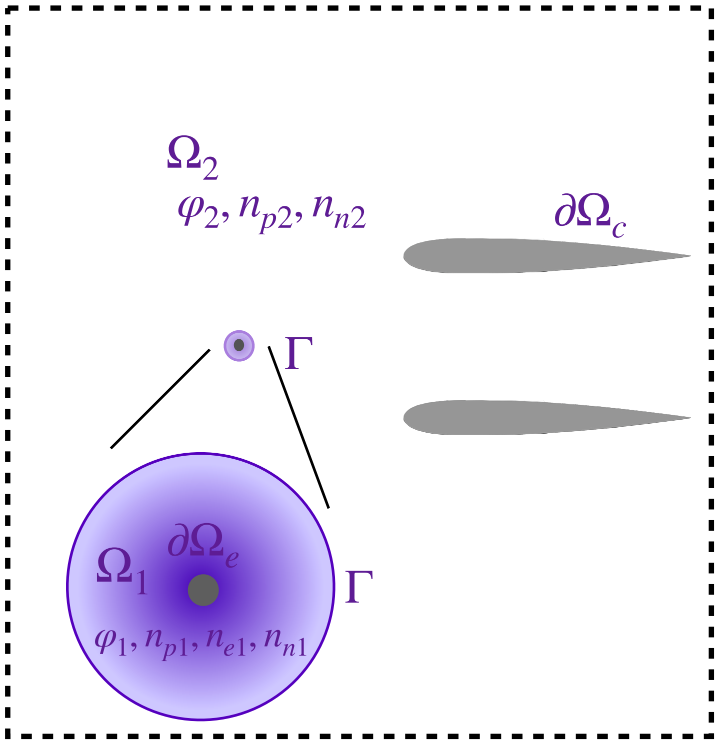

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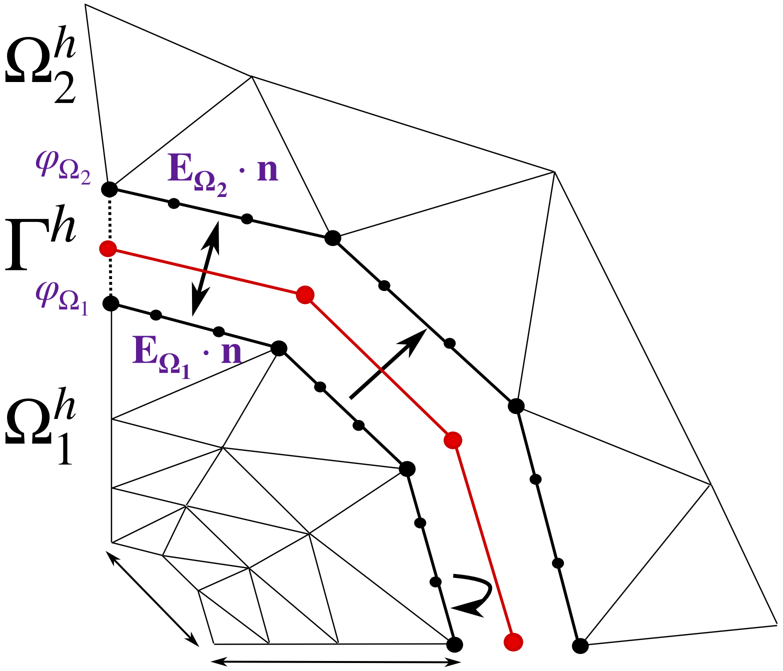

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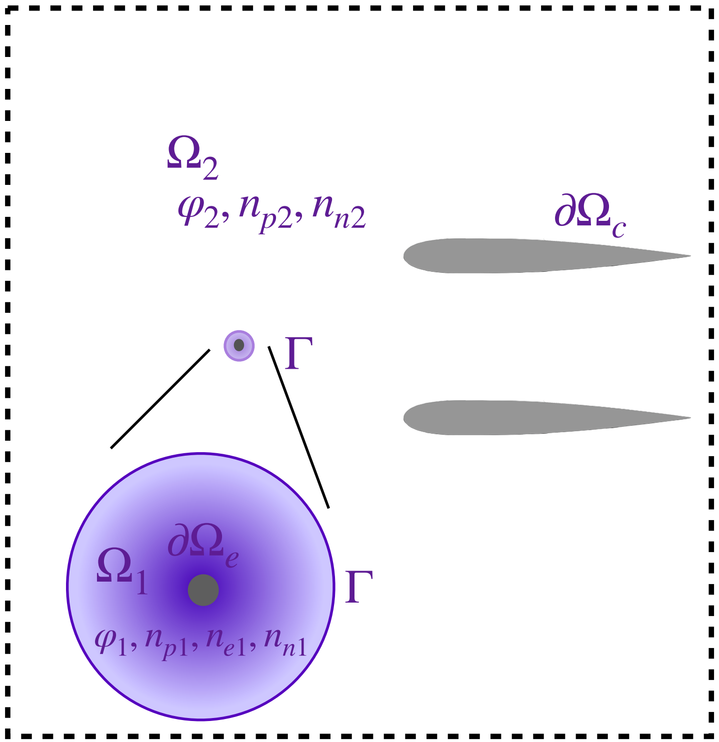

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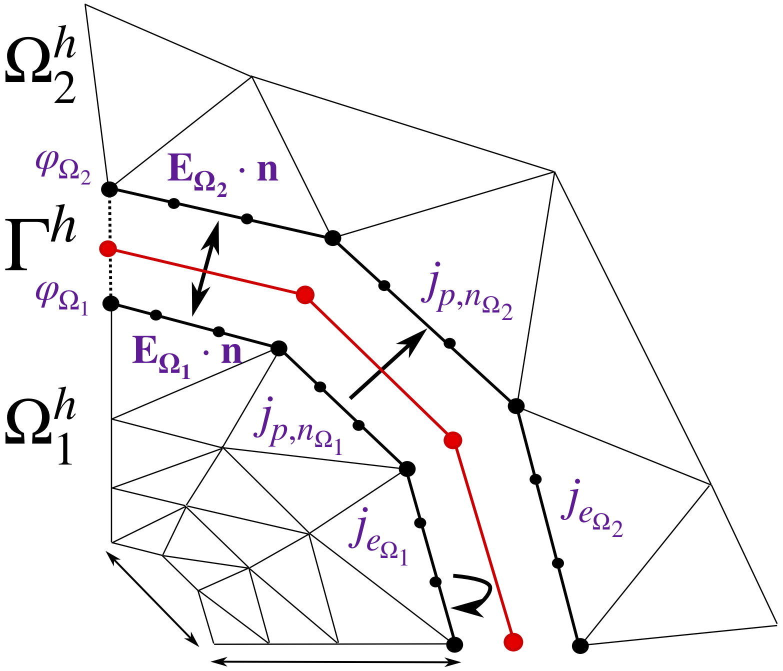

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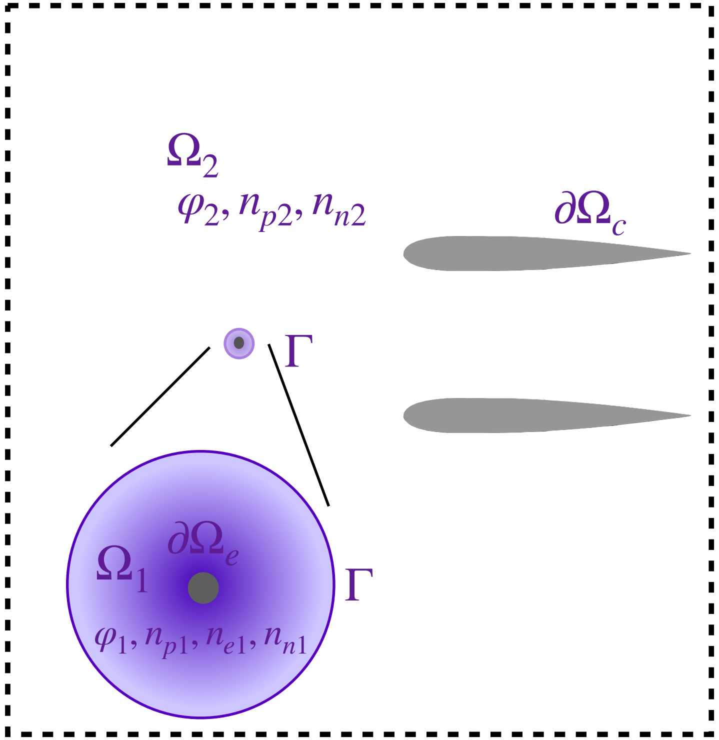

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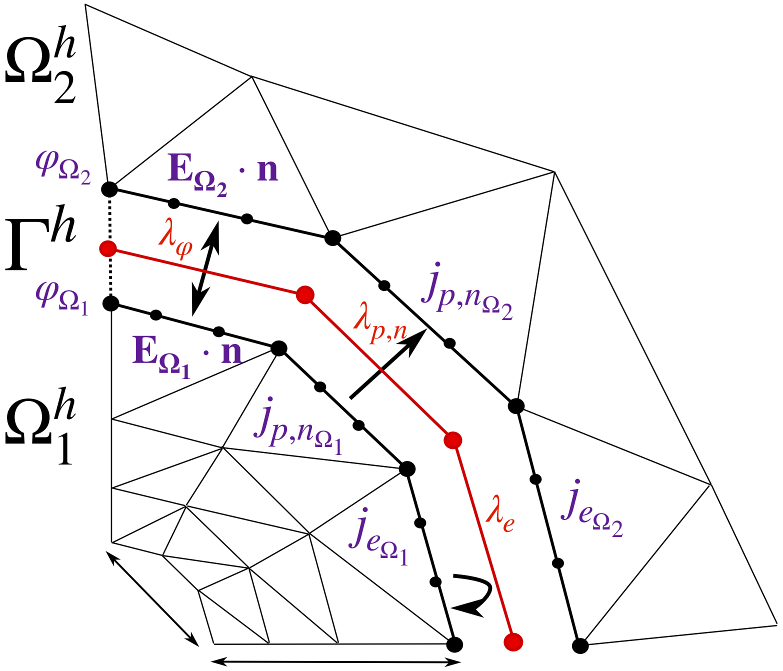

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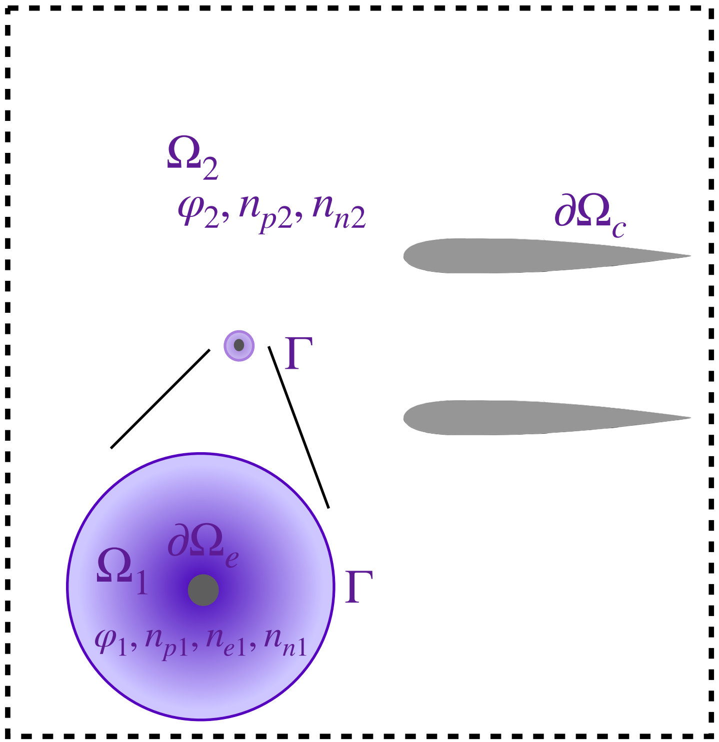

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$$\begin{cases} \Delta\varphi = -n_p + n_n \\ \nabla \cdot [n_p(-\nabla\varphi + \quad) - \frac{1}{P_e}\nabla n_p] = \gamma S \\ \nabla \cdot [n_n(\nabla\varphi + \quad) - \frac{1}{P_e}\nabla n_n] = 0 \end{cases}$$

A. Corona Discharge

Nicolas Monrolin and Franck Plouraboué. Journal of Computational Physics, 443:110517, October 2021.
Francesco Picella et al. AIAA Journal, pages 1–12, April 2024.

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Dimensionless Two-Way Model of Plasma & Fluid

Physical Parameters

Electro-drift Péclet number :

$$P_e = \mu\varphi_a / D_\rho$$

EHD Reynolds number :

$$R_e = U_e r_c / \nu_f$$

EHD electric speed :

$$U_e = \frac{\varphi_a}{r_c}\sqrt{\frac{\varepsilon_0}{\rho_f}}$$

Speed ratio :

$$\beta = \frac{U_{in}}{U_e}$$

Inner domain Ω_1

$$\begin{cases} \Delta\varphi = 0 \\ \nabla \cdot [n_p(-\nabla\varphi + \quad)] = \alpha \|n_e \mathbf{E}\| \\ \nabla \cdot [n_e(\nabla\varphi + \quad)] = (\alpha - \eta)\|n_e \mathbf{E}\| \\ \nabla \cdot [n_n(\nabla\varphi + \quad)] = \eta \|n_e \mathbf{E}\| \end{cases}$$

Outer domain Ω_2

$$\begin{cases} \Delta\varphi = -n_p + n_n \\ \nabla \cdot [n_p(-\nabla\varphi + \quad) - \frac{1}{P_e}\nabla n_p] = \gamma S \\ \nabla \cdot [n_n(\nabla\varphi + \quad) - \frac{1}{P_e}\nabla n_n] = 0 \end{cases}$$

Full domain Ω

$$\begin{cases} \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{R_e}\Delta \mathbf{u} - (n_p - n_n + n_e)\nabla\varphi \\ \nabla \cdot \mathbf{u} = 0 \end{cases}$$

A. Corona Discharge

$\Downarrow$

B. One-way coupling : Coulomb forcing

Nicolas Monrolin and Franck Plouraboué. Journal of Computational Physics, 443:110517, October 2021.
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Dimensionless Two-Way Model of Plasma & Fluid

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Outer domain Ω_2

$$\begin{cases} \Delta\varphi = -n_p + n_n \\ \nabla\cdot[n_p(-\nabla\varphi + M_m\mathbf{u}) - \frac{1}{P_e}\nabla n_p] = \gamma S \\ \nabla\cdot[n_n(\nabla\varphi + M_m\mathbf{u}) - \frac{1}{P_e}\nabla n_n] = 0 \end{cases}$$

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A. Corona Discharge

⇓

B. One-way coupling : Coulomb forcing

⇓

C. Two-way coupling : charge advection by the fluid

Nicolas Monrolin and Franck Plouraboué. Journal of Computational Physics, 443:110517, October 2021.
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Dimensionless Two-Way Model of Plasma & Fluid

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Outer domain Ω_2

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A. Corona Discharge

$\Downarrow$

B. One-way coupling : Coulomb forcing

$\Downarrow$

C. Two-way coupling : charge advection by the fluid

EHD Macro-to-Micro speed ratio : $M_m = \frac{U_e}{\mu E} = \frac{1}{\mu_p}\sqrt{\frac{\varepsilon_0}{\rho_f^*}} \approx 10^{-2}$

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$$\begin{cases} \mathbf{u}\cdot\nabla\mathbf{u} = -\nabla p + \frac{1}{R_e}\Delta\mathbf{u} - (n_p - n_n + n_e)\nabla\varphi \\ \nabla\cdot\mathbf{u} = 0 \end{cases}$$

A. Corona Discharge

⇓

B. One-way coupling : Coulomb forcing

⇓

C. Two-way coupling : **Perturbative** retroaction of charge advection by the fluid onto the discharge

Asymptotic expansion with respect to : $M_m = \frac{U_e}{\mu E} = \frac{1}{\mu_p}\sqrt{\frac{\varepsilon_0}{\rho_f^*}} \approx 10^{-2}$

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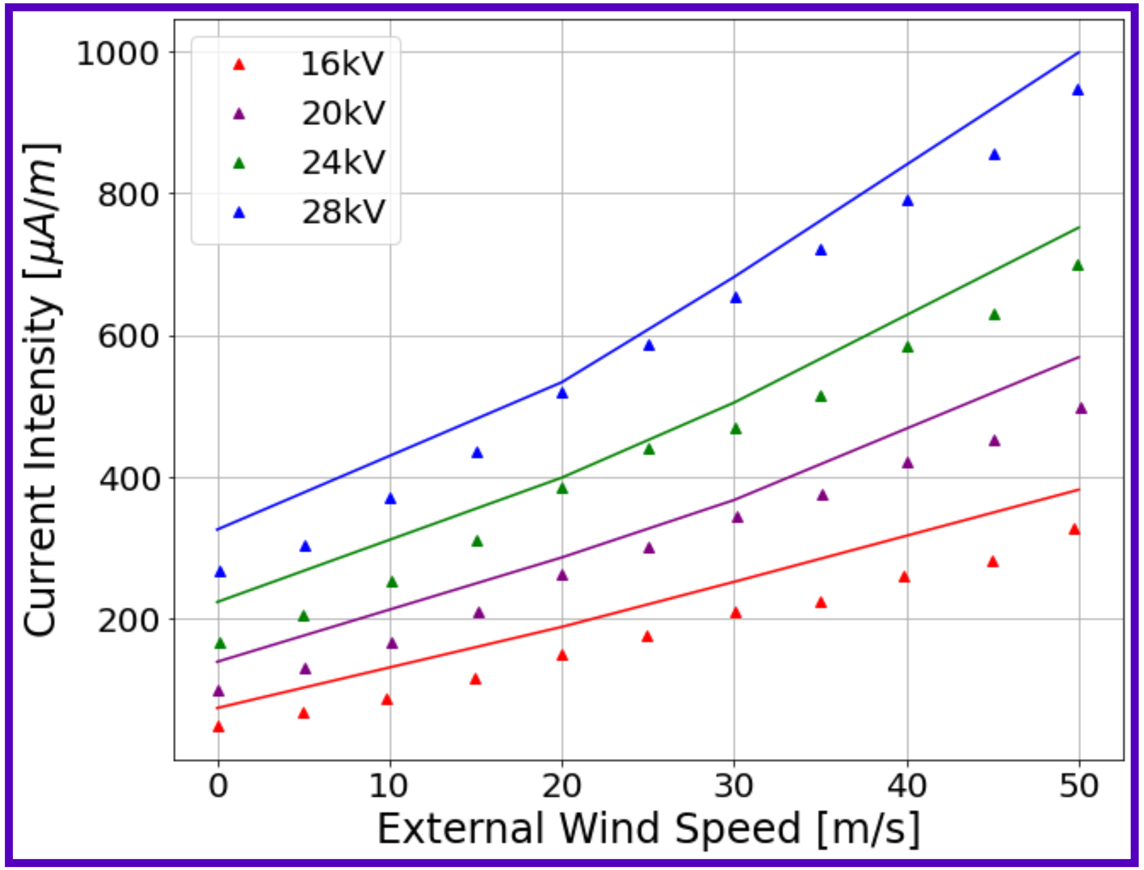
Comparison with Experiments

Cylindrical collector



Implemented with :

- FreeFem++
- StabFem++

Grosse et al., *J. Elect,* **130**-103950, 2025
Chapman. *J. Geo. Res.*, 75(12):**2165**–2169, 1970.

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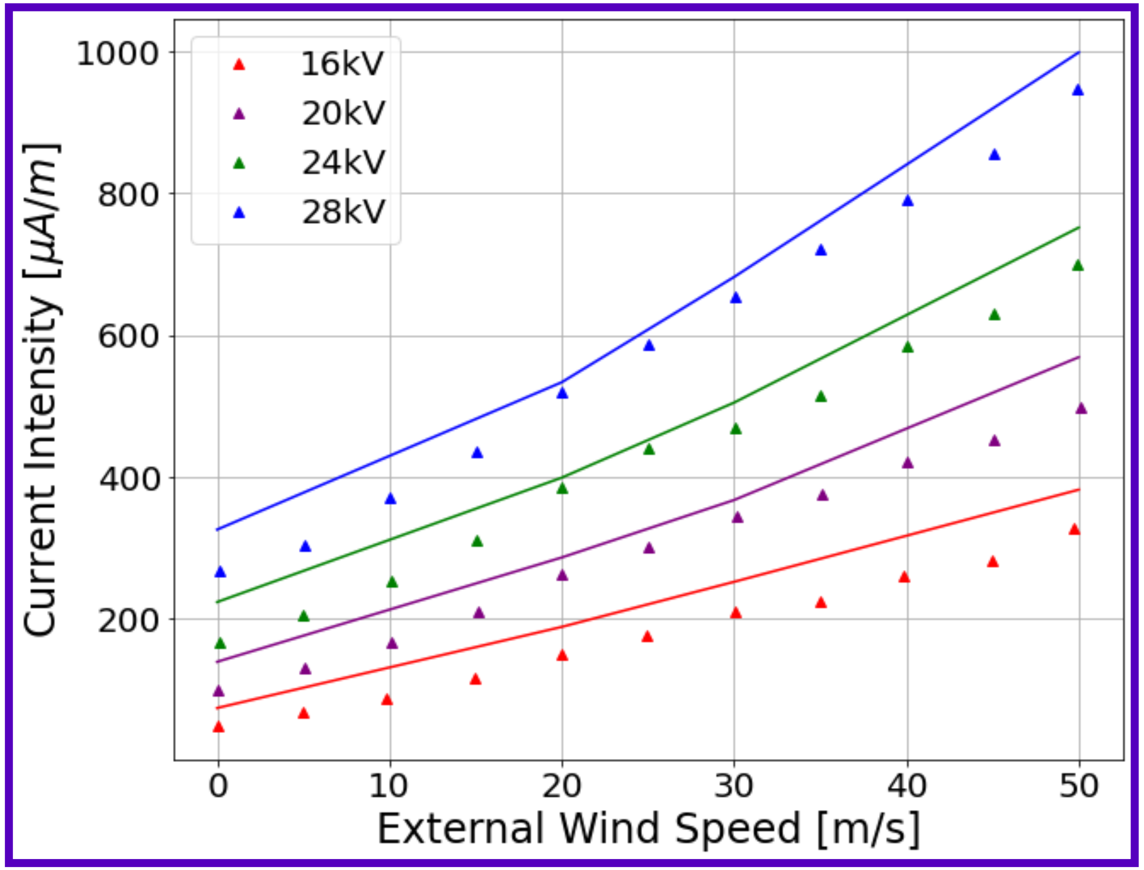

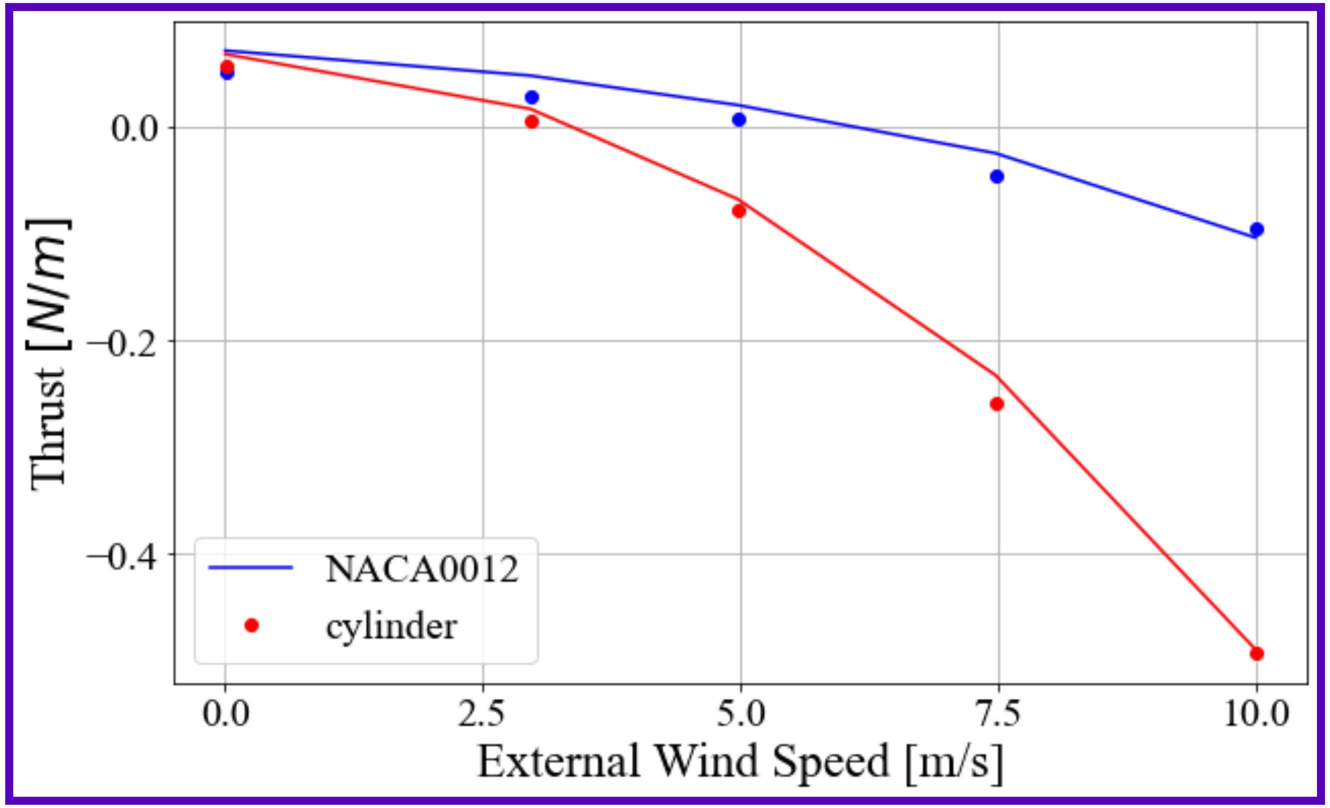

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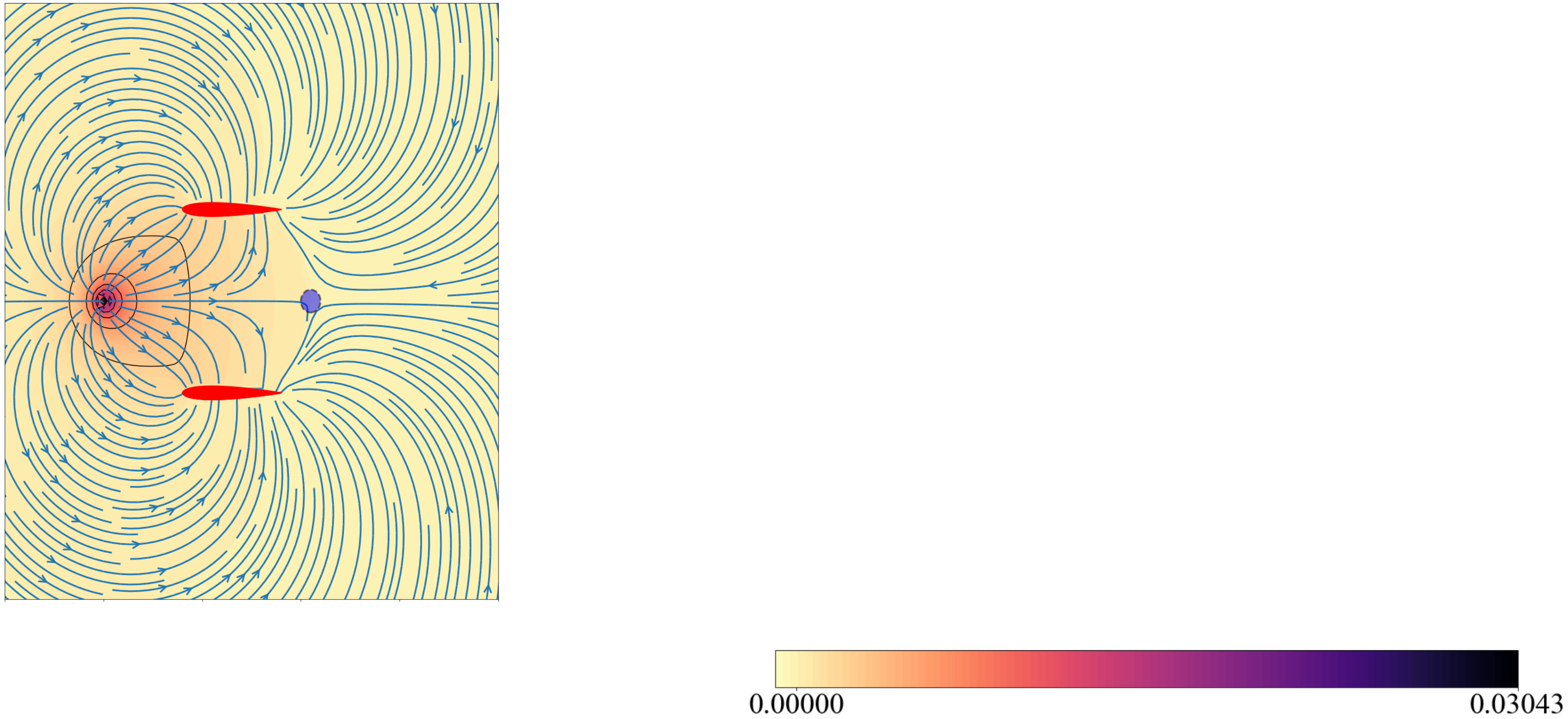
Electric Field Lines

$U_{in} = 1\ m/s$

$U_{in} = 2.87\ m/s$

$U_{in} = 5.73\ m/s$

$U_{in} = 12.26\ m/s$



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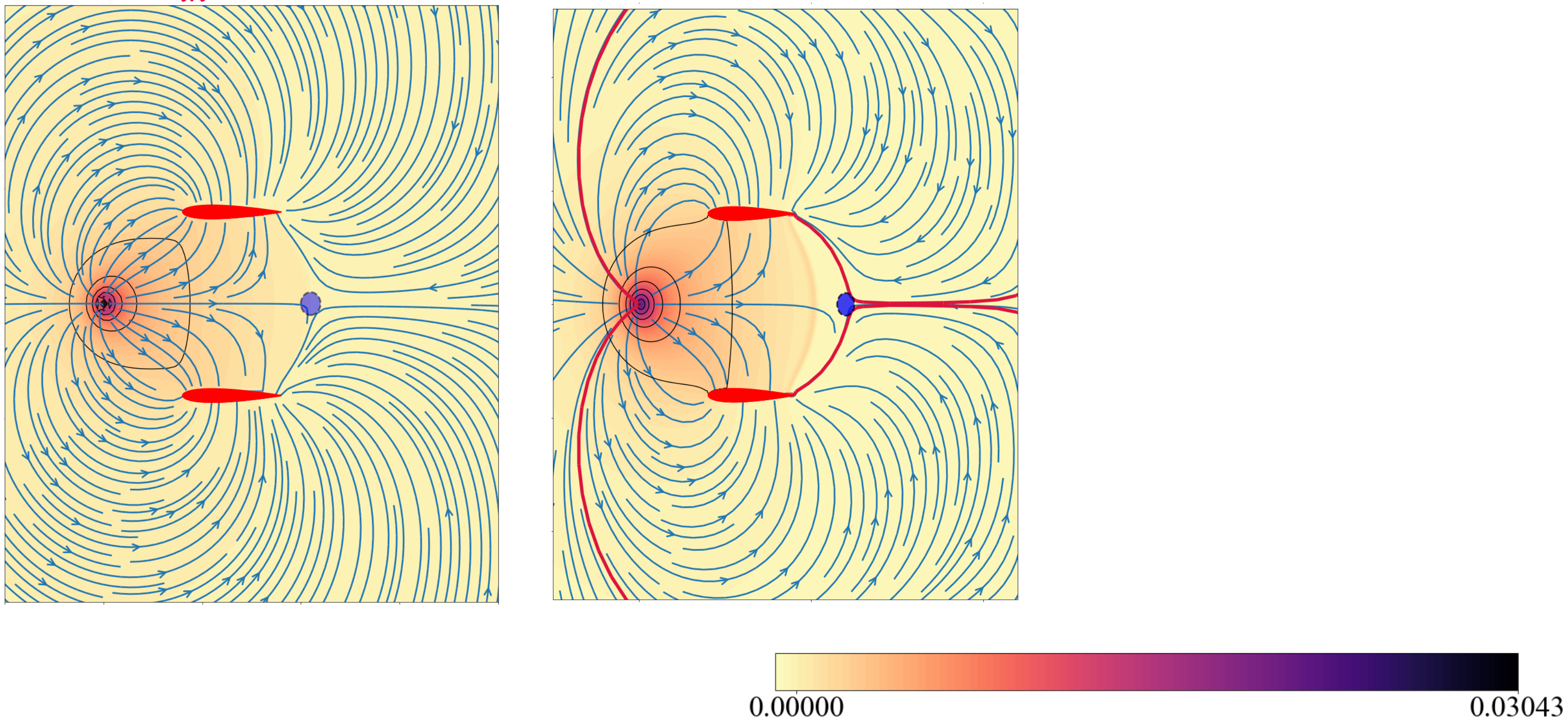

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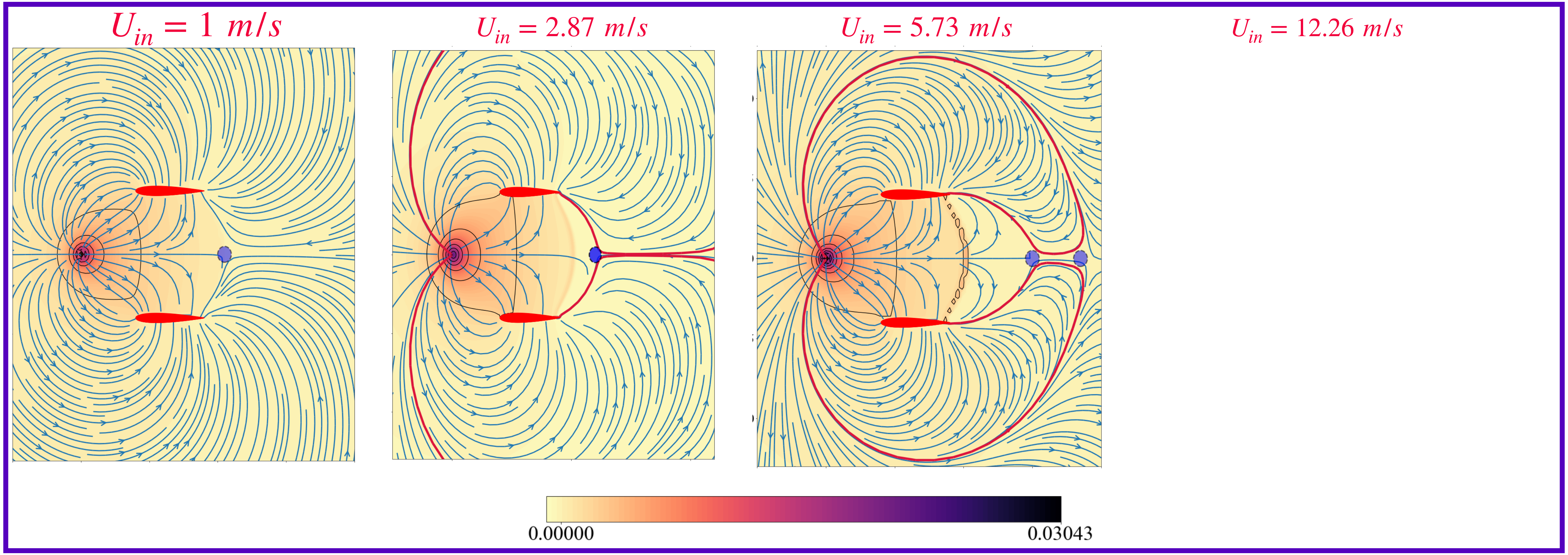
Electric Field Lines



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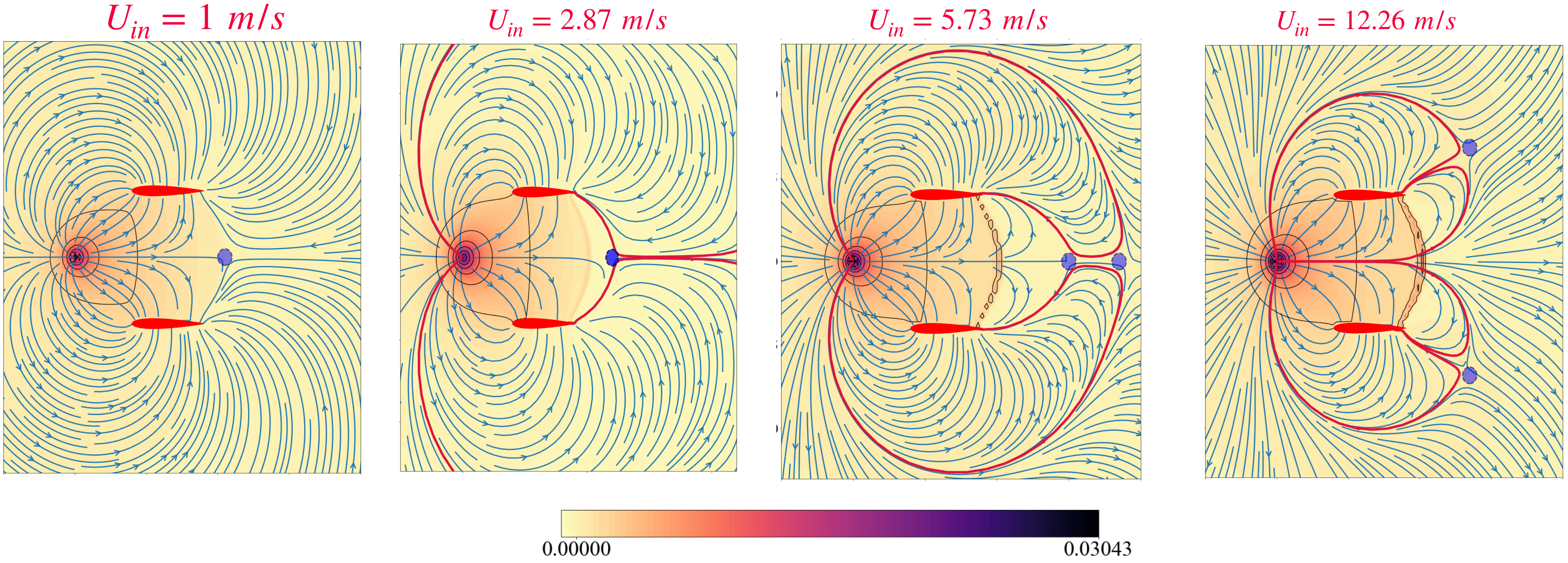
Electric Field Lines



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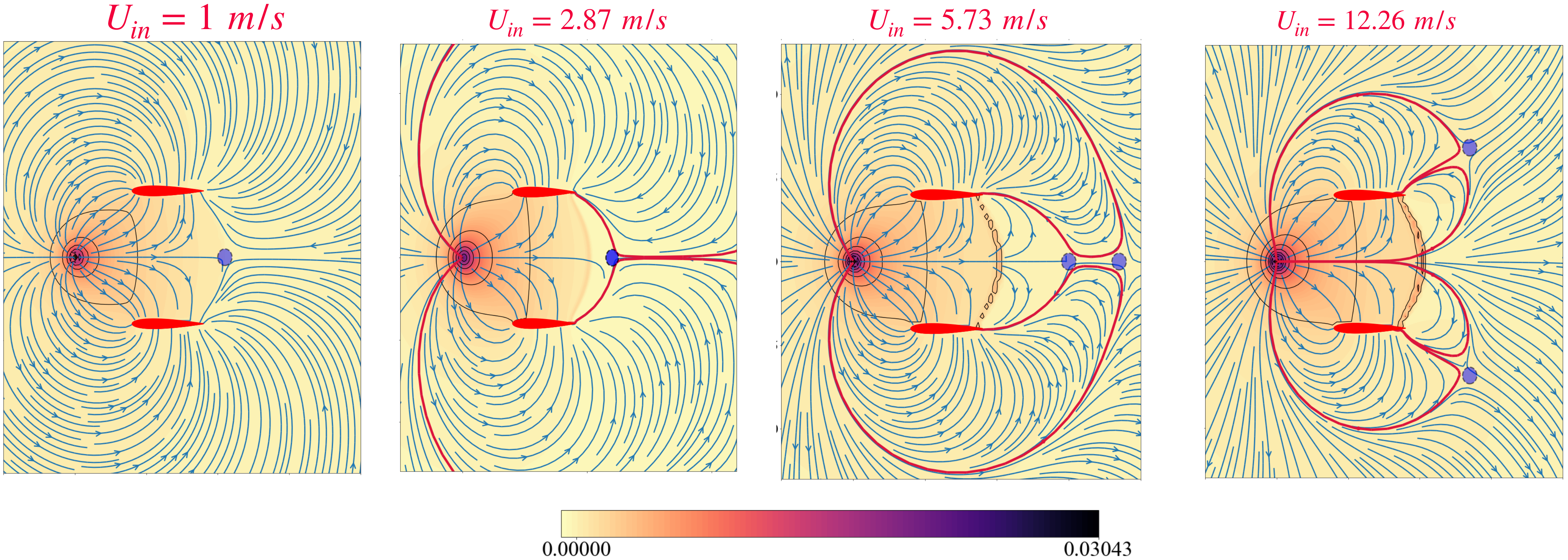
Electric Field Lines



$\Rightarrow$ Decreasing **charge collection zone**

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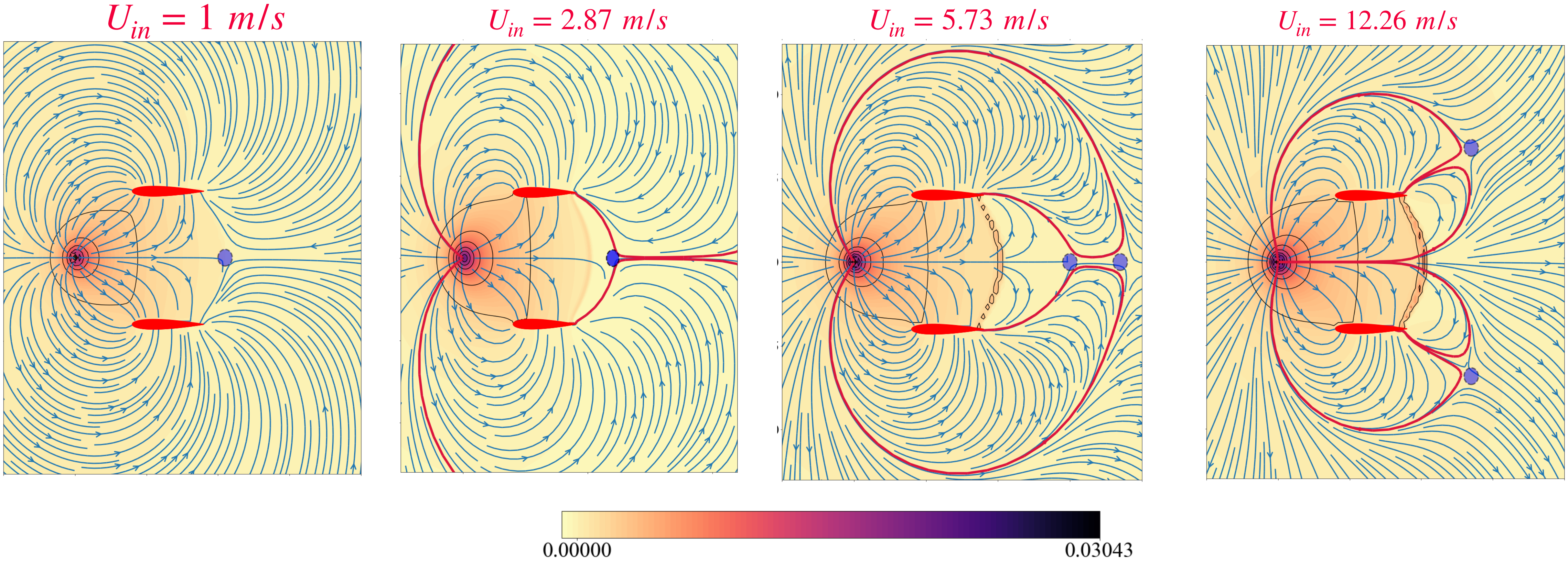
Electric Field Lines



⇒ Decreasing **charge collection zone**

⇒ Ion **boundary layer**

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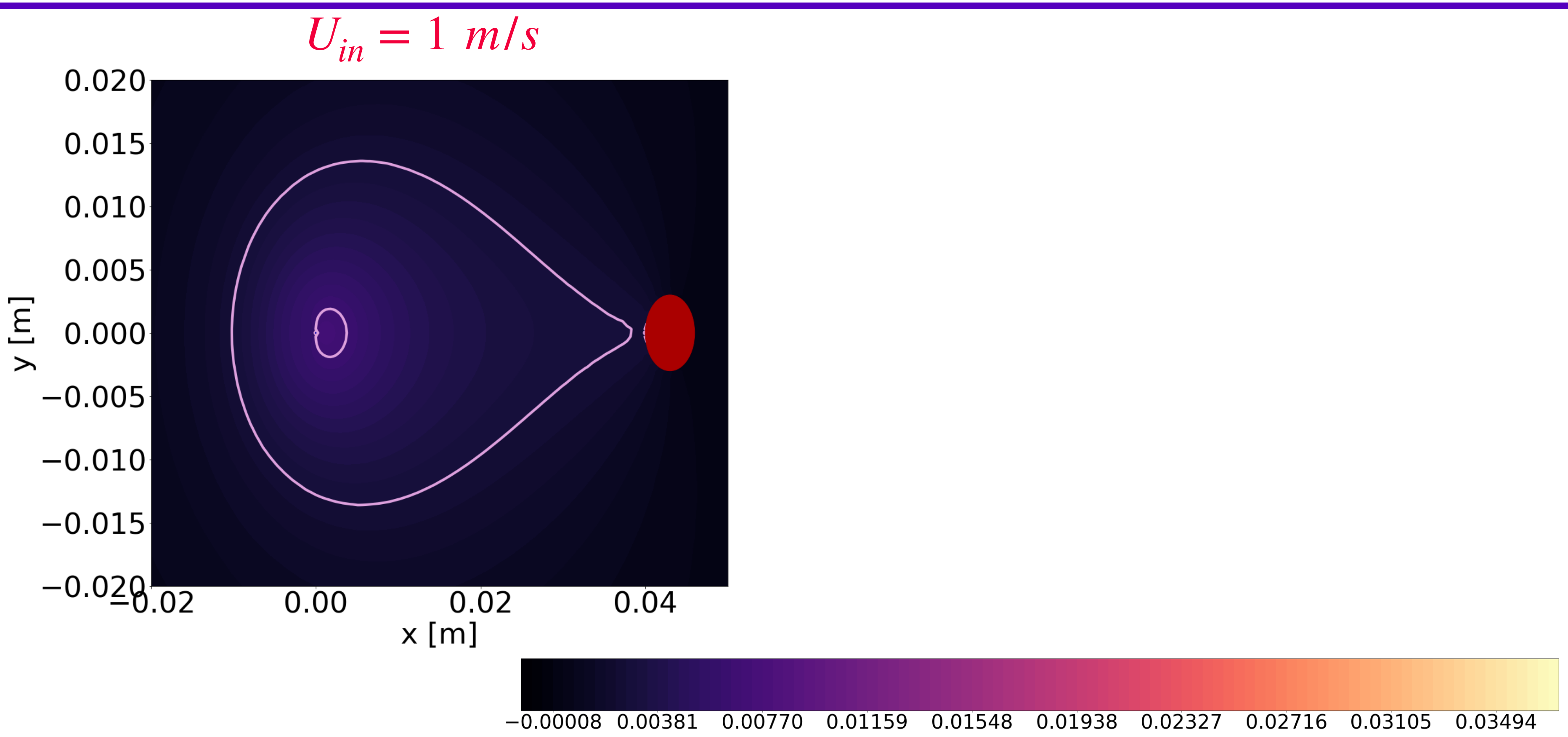
Ion Density Distributions



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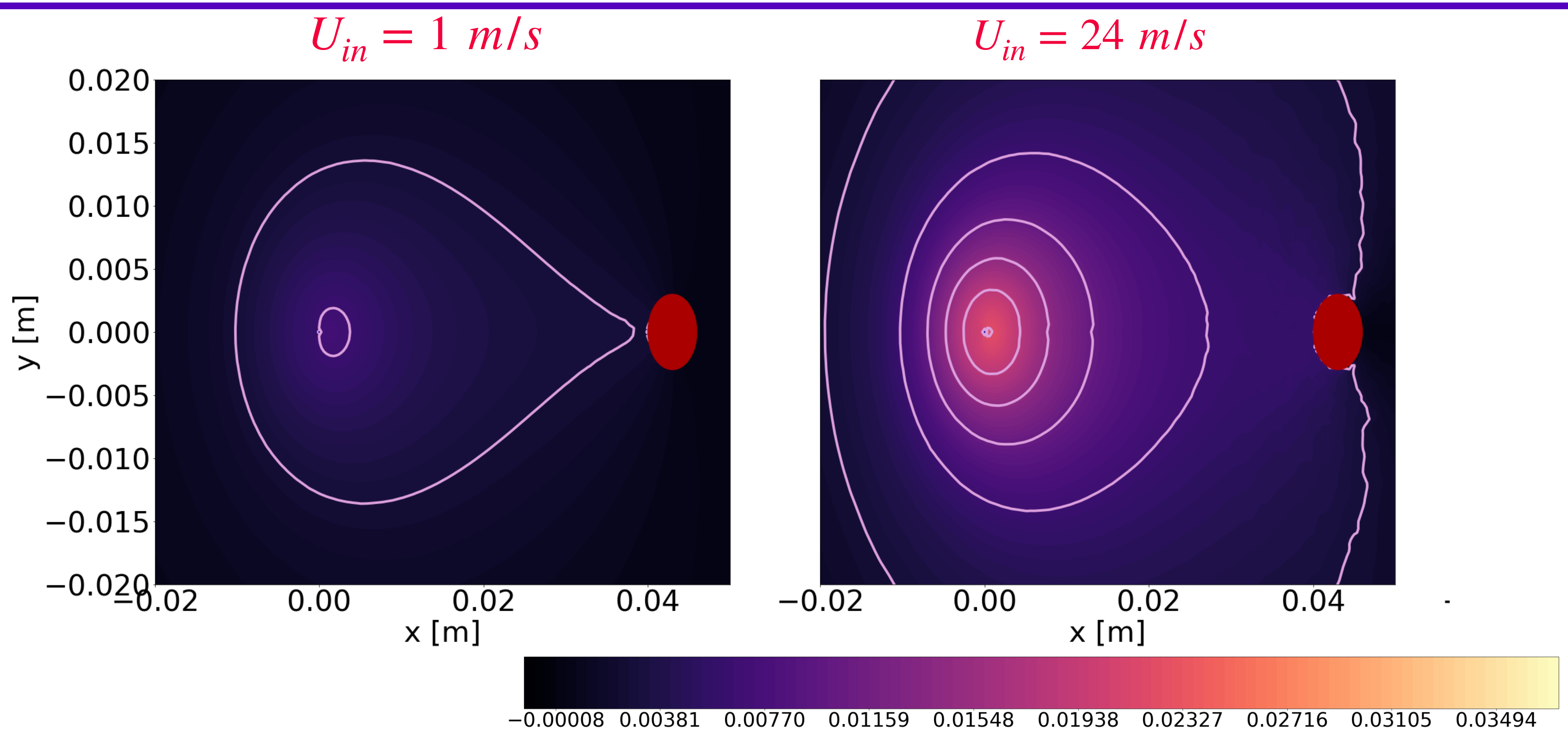

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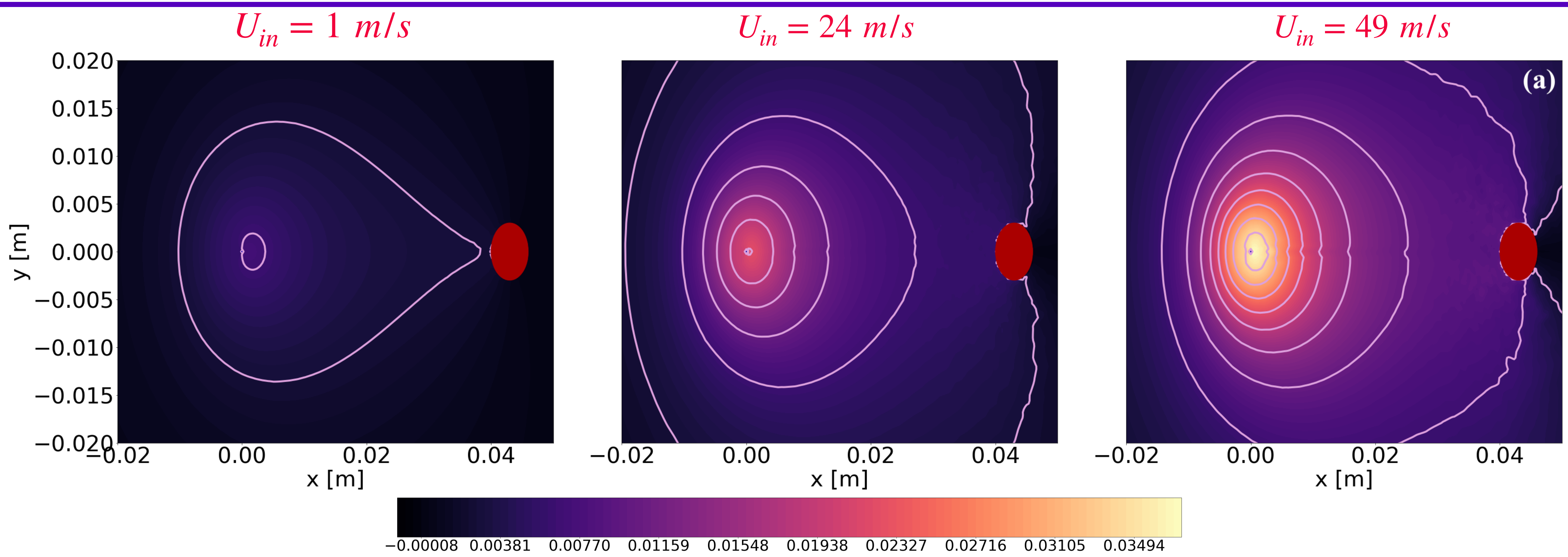

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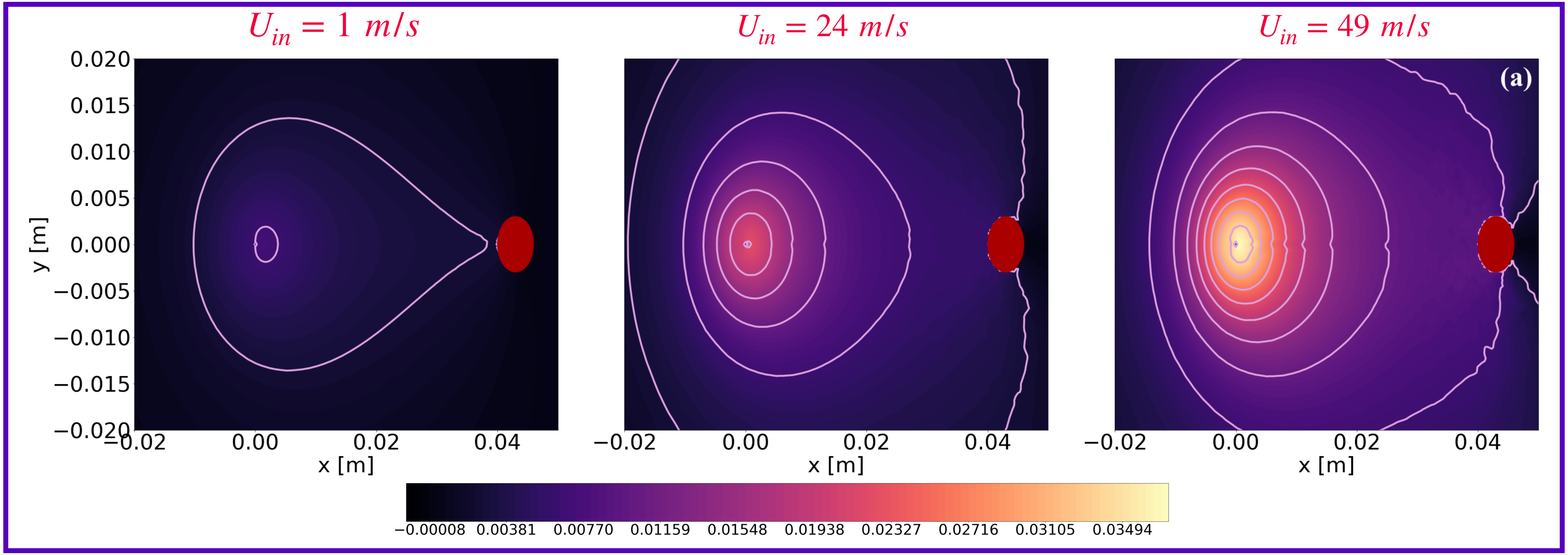

⇒ Ion **density** increase

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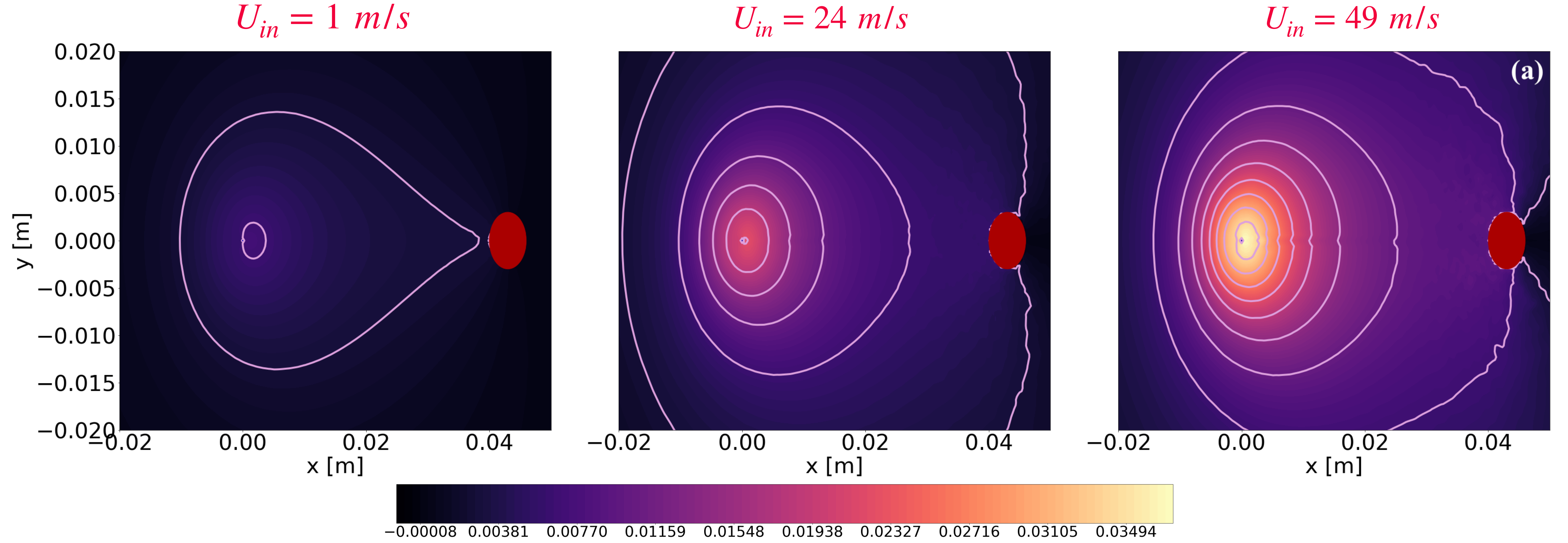
Ion Density Distributions



$\Rightarrow$ Ion **density** increase, how ?

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Ion Density and Generation Increase

$$
\begin{cases}
\Delta\varphi = \delta_{\mu_n} n_n + \delta_{\mu_e} n_e - n_p \\
\nabla \cdot [n_p(-\nabla\varphi + M_m \mathbf{u})] = \alpha \| n_e \mathbf{E} \| \\
\nabla \cdot [n_e(\nabla\varphi + \delta_\mu M_m \mathbf{u})] = (\alpha - \eta) \| n_e \mathbf{E} \| \\
\nabla \cdot [n_n(\nabla\varphi + M_m \mathbf{u})] = \eta \| n_e \mathbf{E} \|
\end{cases}
$$

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Ion Density and Generation Increase

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- Electron advection can be neglect $\delta_{\mu_e} \sim 10^{-2}$

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- Electron advection can be neglect $\delta_{\mu_e} \sim 10^{-2}$
- Charge production depends only on Townsend terms α and η

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- Electron advection can be neglect $\delta_{\mu_e} \sim 10^{-2}$
- Charge production depends only on Townsend terms α and η

$$\boxed{\alpha \propto BN\, exp^{-\frac{C}{\|E/N\|}}}$$

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- Electron advection can be neglect $\delta_{\mu_e} \sim 10^{-2}$
- Charge production depends only on Townsend terms α and η

$$\alpha \propto BN\, exp^{-\frac{C}{\|E/N\|}}$$

- Charge **generation** increases & $\alpha = \alpha(\|\mathbf{E}\|) \Rightarrow \|\mathbf{E}\|$ must increase

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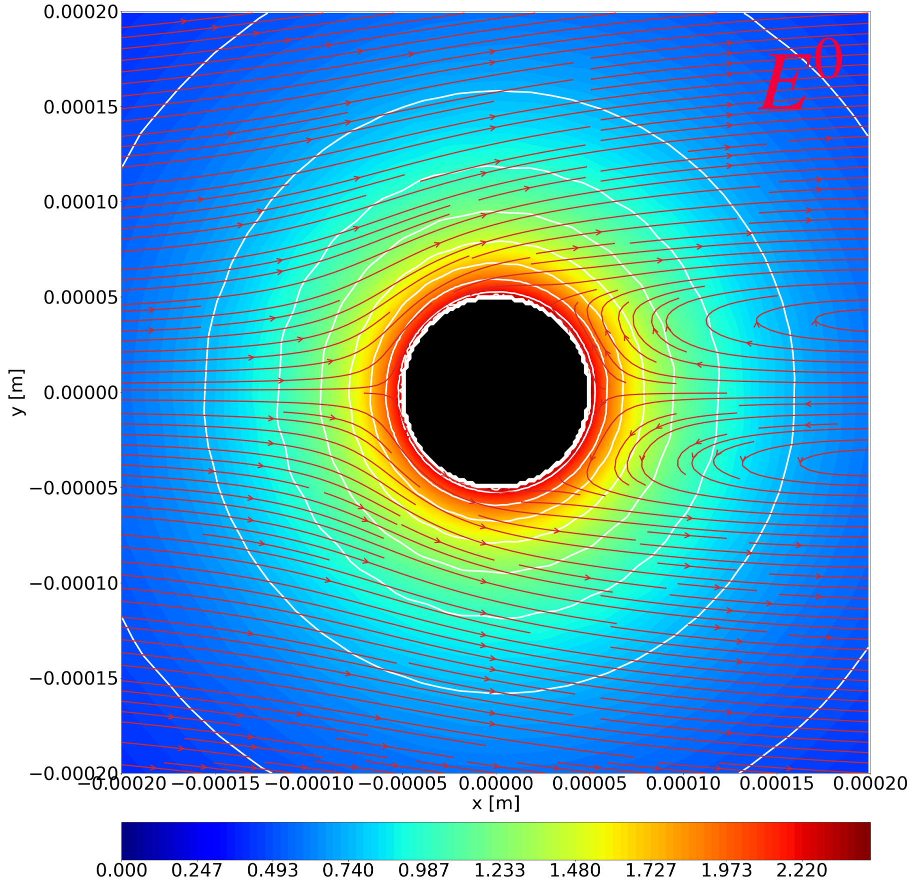
Electric Field Enhancement around the Emitter



Base $||E||$

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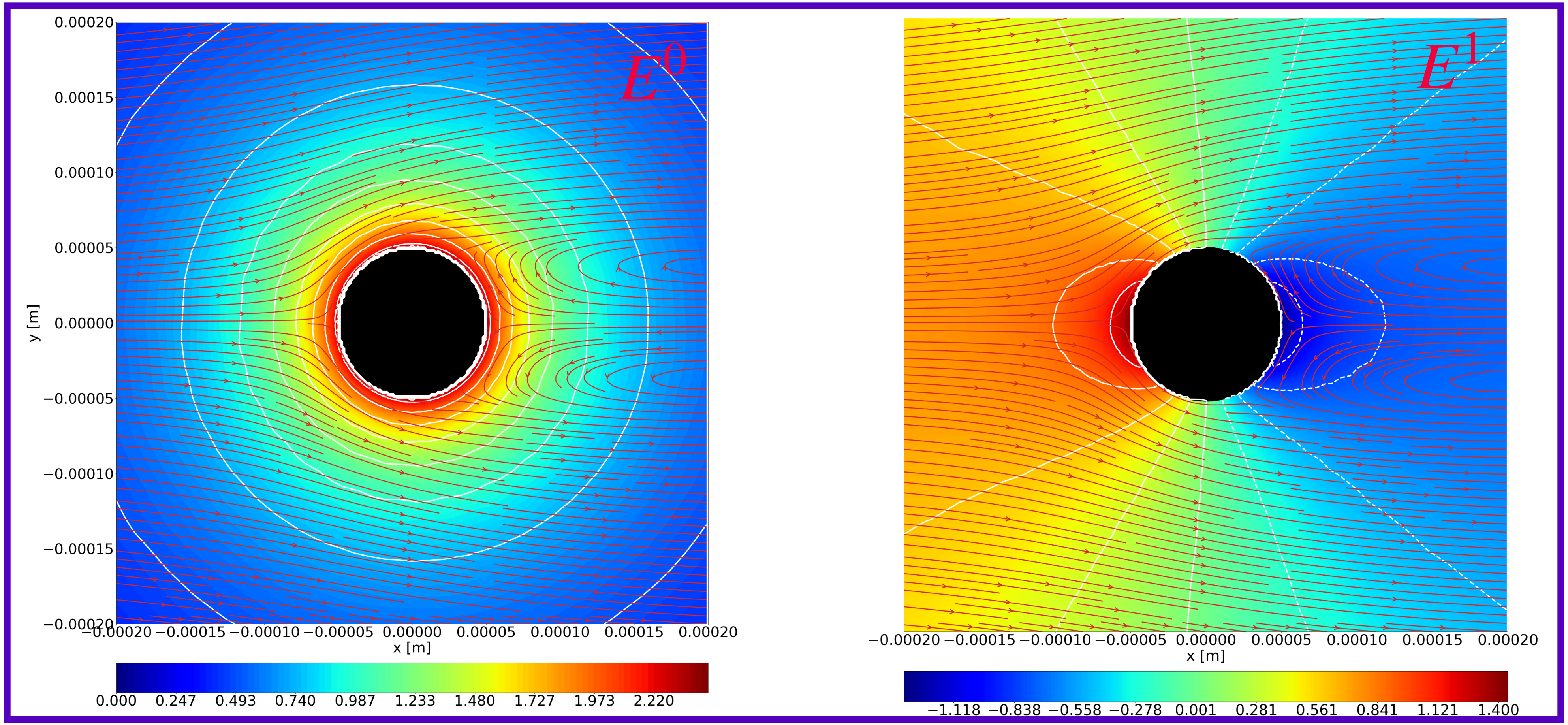
Electric Field Enhancement around the Emitter



Base $||E||$

$||E||$ Perturbation

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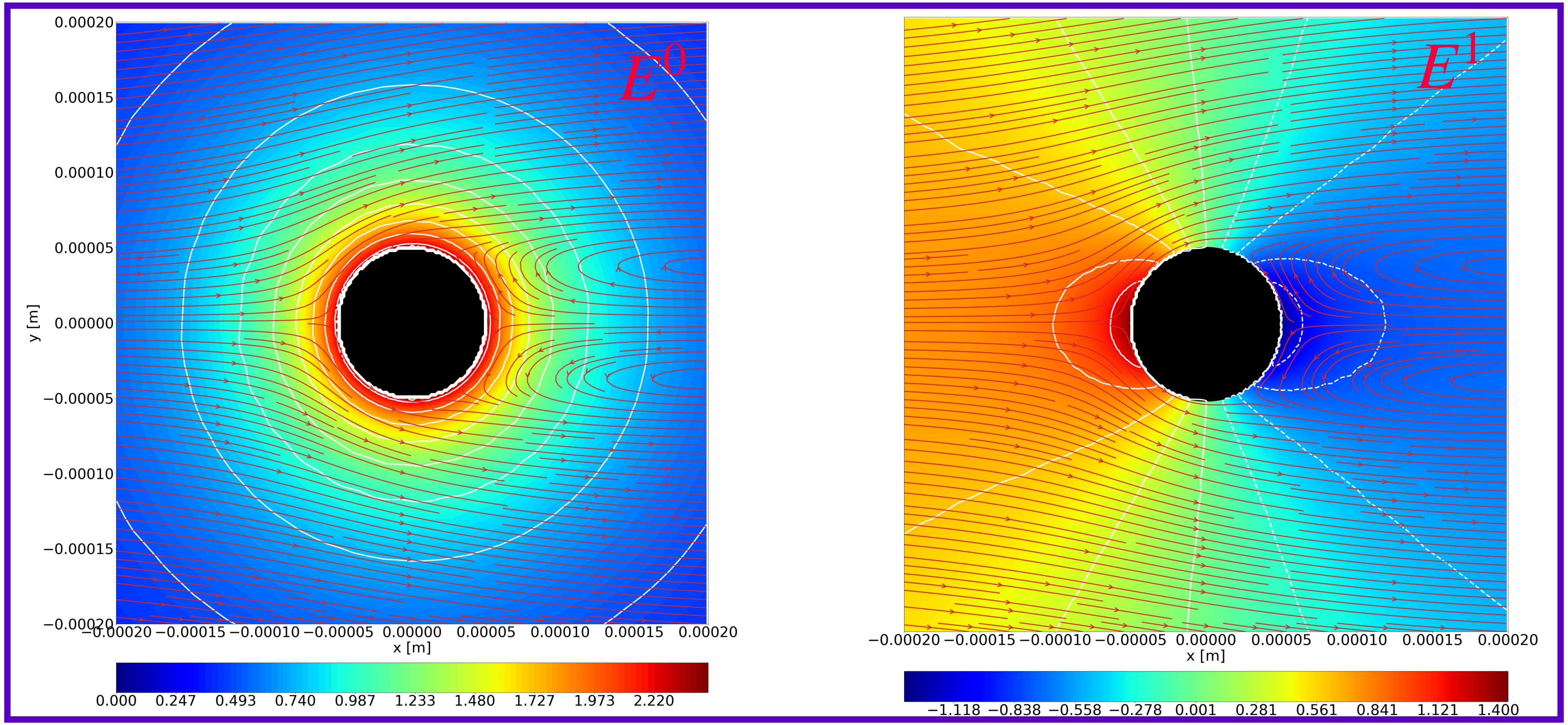

⇒ Advected charges **locally enhance** $\|\mathbf{E}\|$

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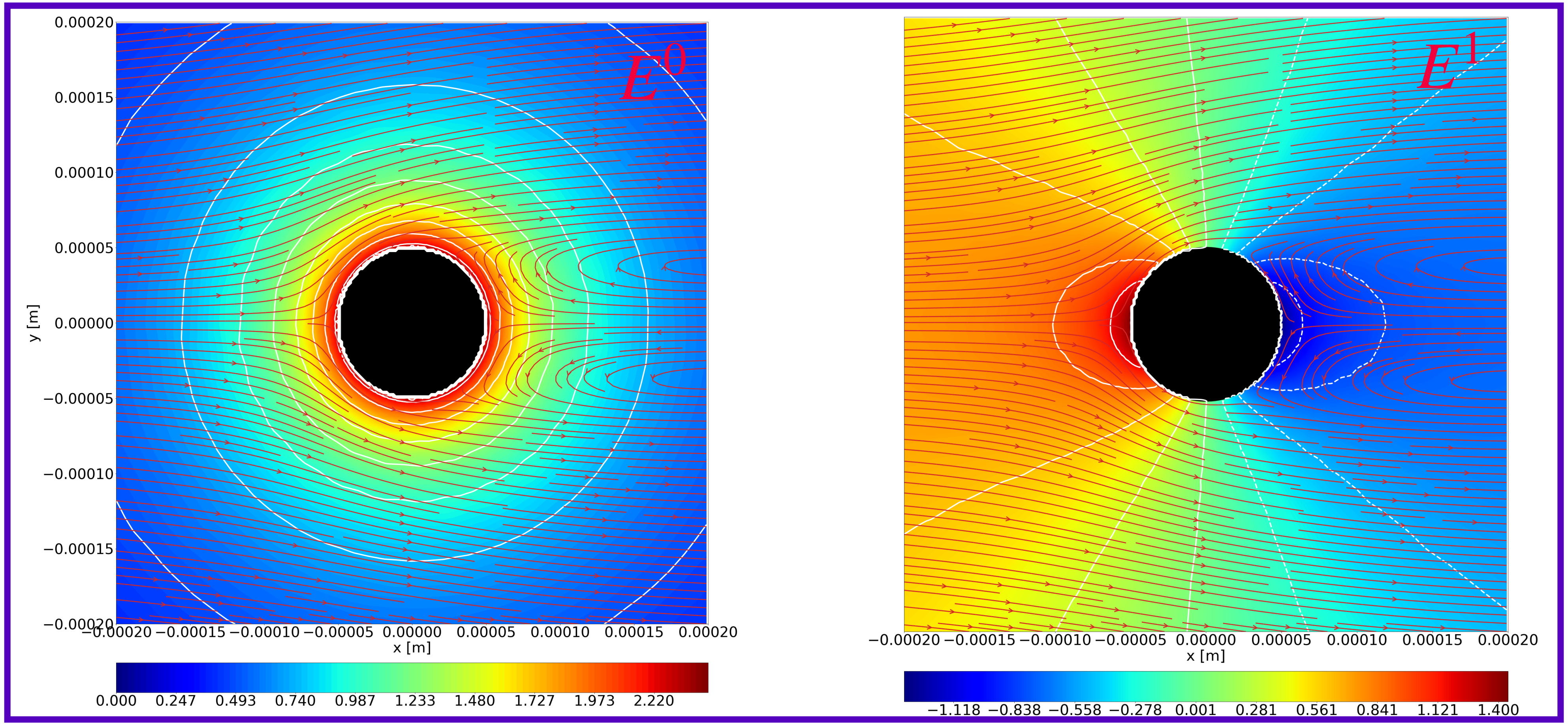

$\Rightarrow$ Advected charges **locally enhance** $\|\mathbf{E}\|$

$\Rightarrow$ Ion **generation** increases : $\|\mathbf{E}\| \nearrow \Rightarrow \alpha(\|\mathbf{E}\|) \nearrow$

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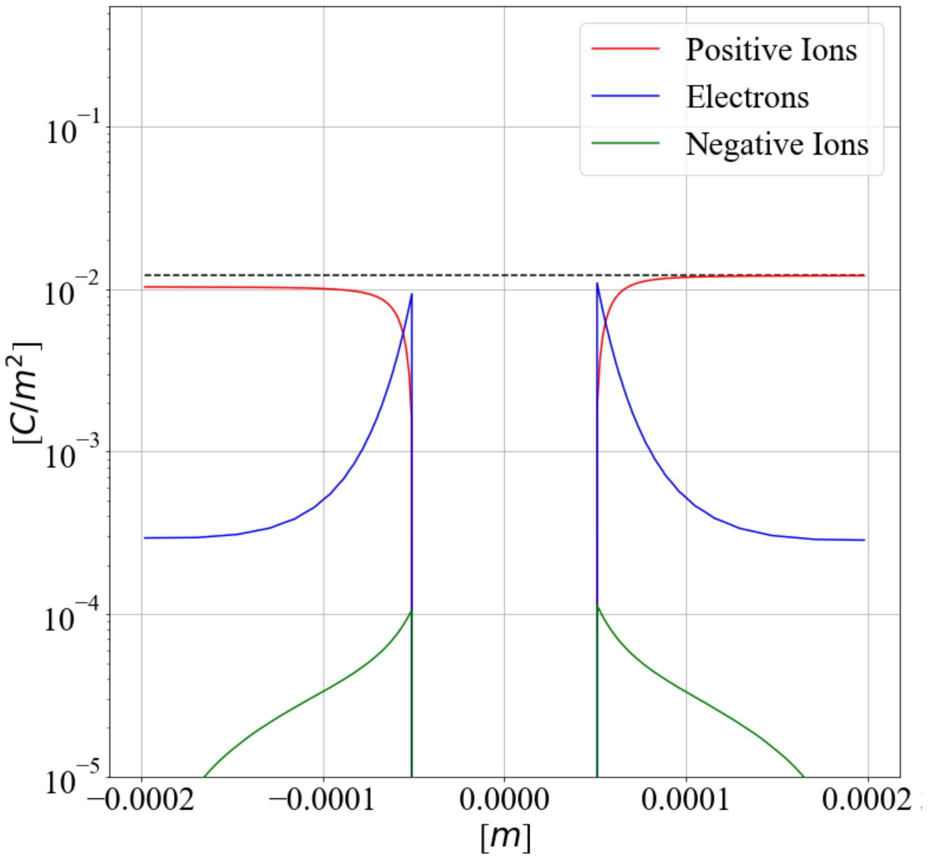
Charge Profiles around the Emitter



Collector

$U_{in} = 0\ m/s$

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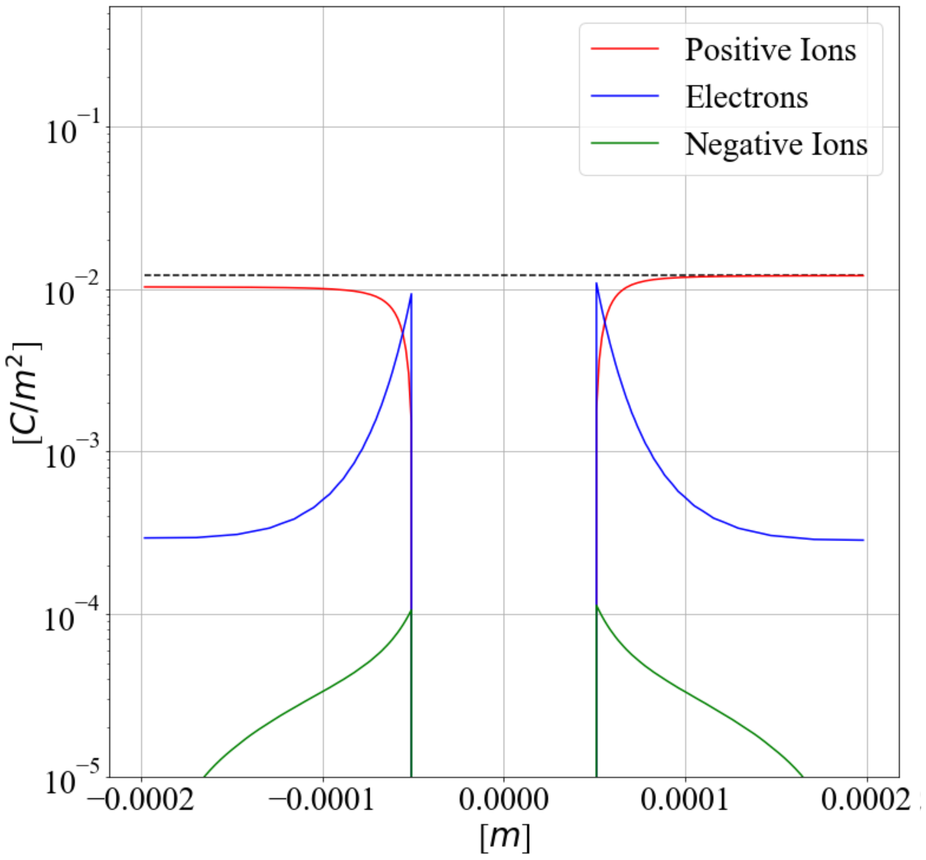
Charge Profiles around the Emitter

Flow direction



Collector

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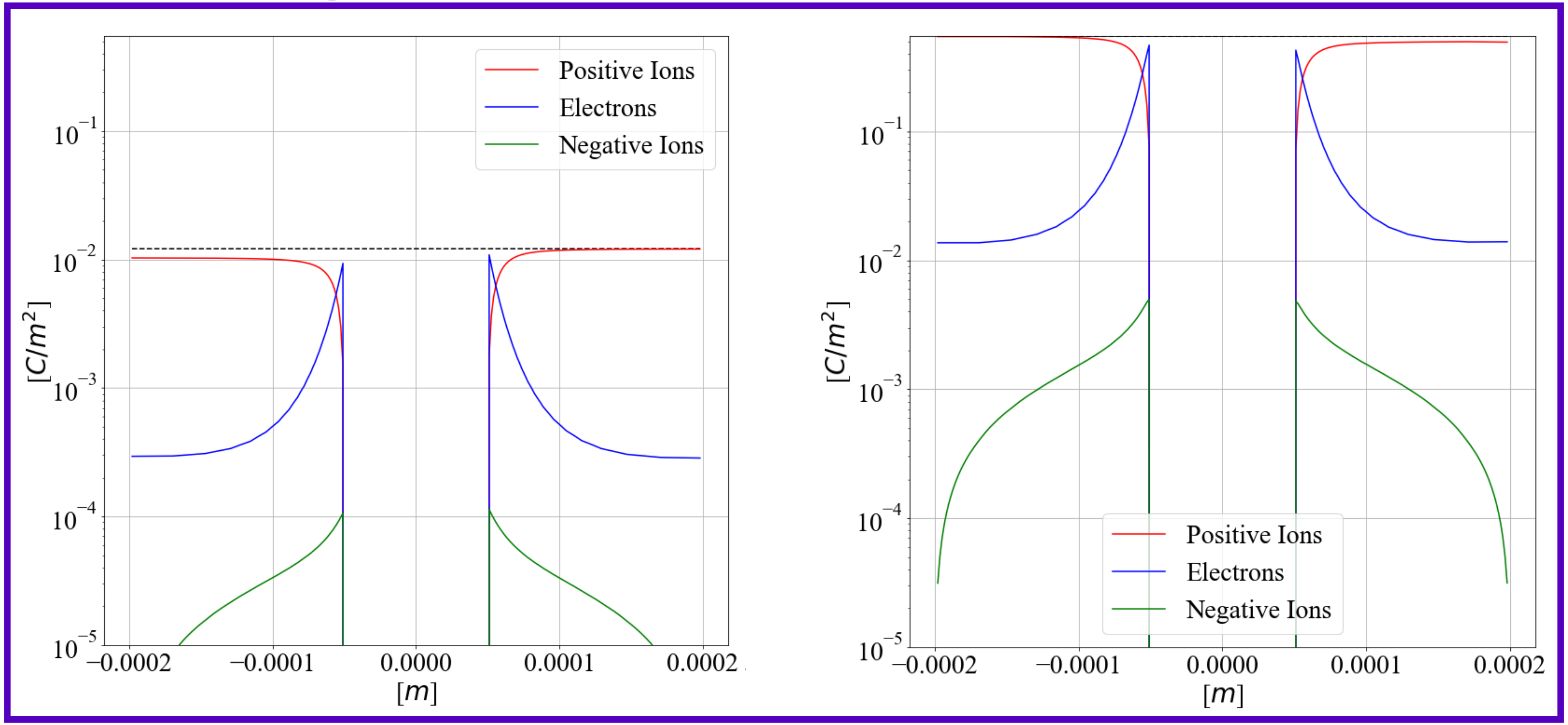
Charge Profiles around the Emitter

Flow direction



Collector

$U_{in} = 0\ m/s$

$U_{in} = 12\ m/s$

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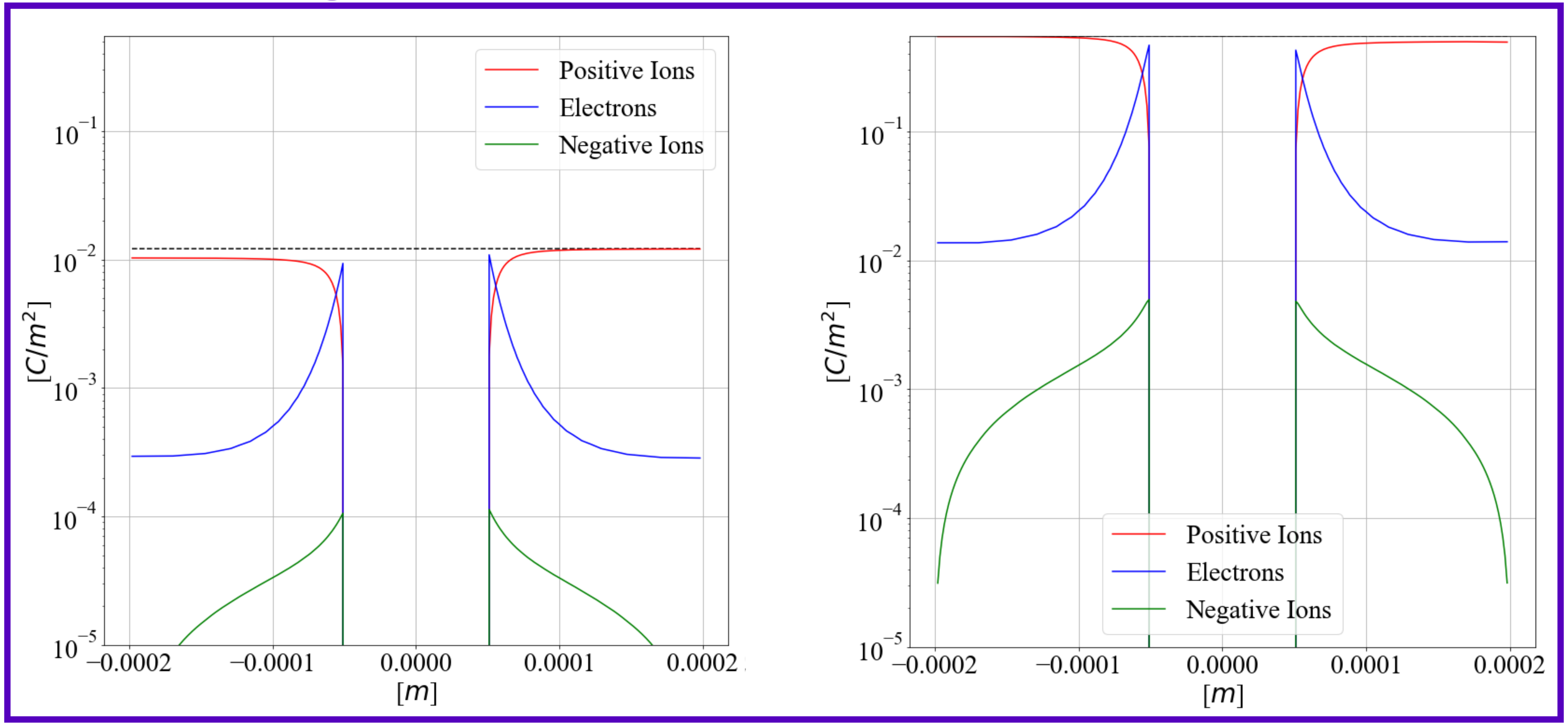
Charge Profiles around the Emitter

Flow direction



Collector

⇒ Charge **densities** increase

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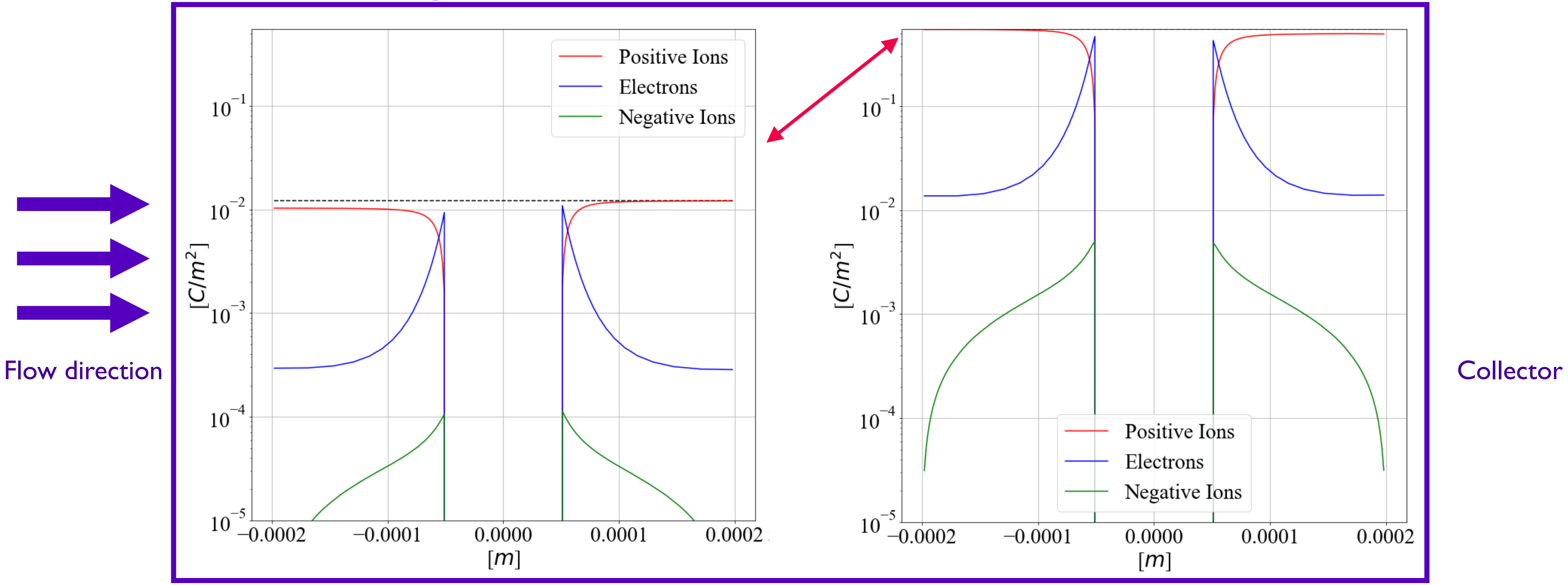

⇒ Charge **densities** increase

⇒ **Symmetry shift** around the emitter

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Conclusion

- **New method**: plasma-fluid interactions accounting with external flow

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- **New method**: plasma-fluid interactions accounting with external flow
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Conclusion

- **New method**: plasma-fluid interactions accounting with external flow
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- Flow acts as a **small perturbation** on the CD

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- **Accepted manuscript** : Marques et al 2025 *J. Phys. D: Appl. Phys.*
  https://doi.org/10.1088/1361-6463/ae07f9

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Thank you !

GEC APS 2025, Seoul, South Korea

J. M. D. C. Marques, D. Fabre, F. Plouraboué

IPROP EIC Pathfinder

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Two-Way Model (More) Numerical Aspects

$$L_{NS}(\mathbf{u};\mathbf{u},p) := -\frac{1}{R_e}\Delta\mathbf{u} + \mathbf{u}\cdot\nabla\mathbf{u} + \nabla p + n_p\nabla\varphi$$

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$$\Rightarrow \int_\Omega L_{NS}(\mathbf{u};\mathbf{u},p)L_{NS}(\mathbf{v},q)^\dagger d\Omega \;+\; \text{BC}$$

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SUPG/PSPG
(Artificial diffusion)

$$+\sum_{t\in T_h}\int_{T_h} L_{NS}(\mathbf{u}_h;\mathbf{u}_h,p_h)\cdot\tau_{SUPG}((\mathbf{u}_h\cdot\nabla)\mathbf{v}_h + \nabla q_h))$$

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Grad-div (Numerical mass conservation)

$$+\sum_{t\in T_h}\int_{T_h}(\nabla\cdot\mathbf{u}_h)\gamma_{grad-div}(\nabla\cdot\mathbf{v}_h)$$

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$$\tau_{SUPG} = \frac{\delta_{SUPG}}{\sqrt{4\frac{\|\mathbf{u^{n-1}}_h\|^2}{h_T^2} + \frac{16}{R_{e,fluide}^2 h_T^4}}}$$

$$\gamma_{grad-div} \sim o(1)$$

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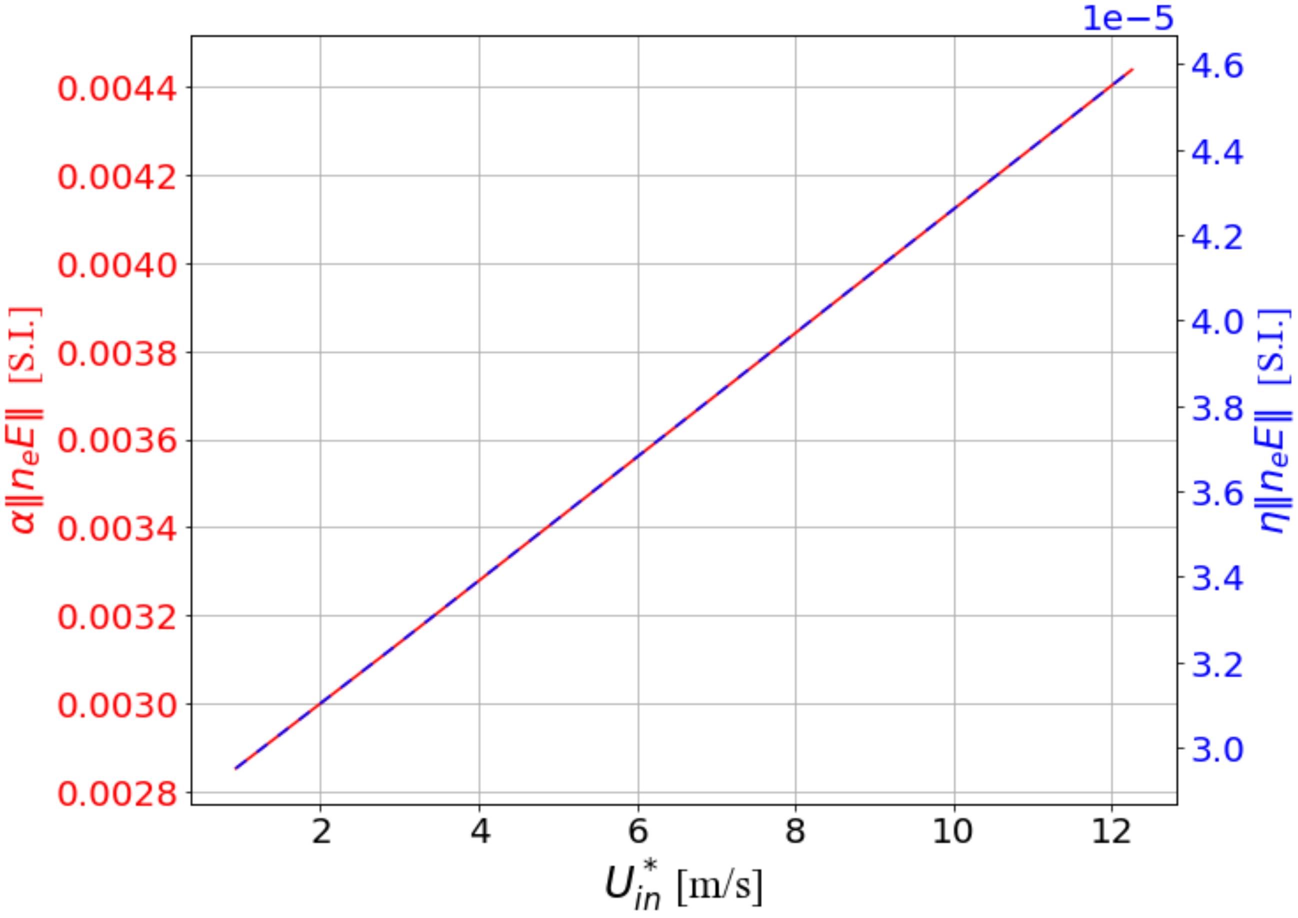
Townsend Avalanche



$$\alpha \propto BN\ exp^{-\frac{C}{\|E/N\|}}$$

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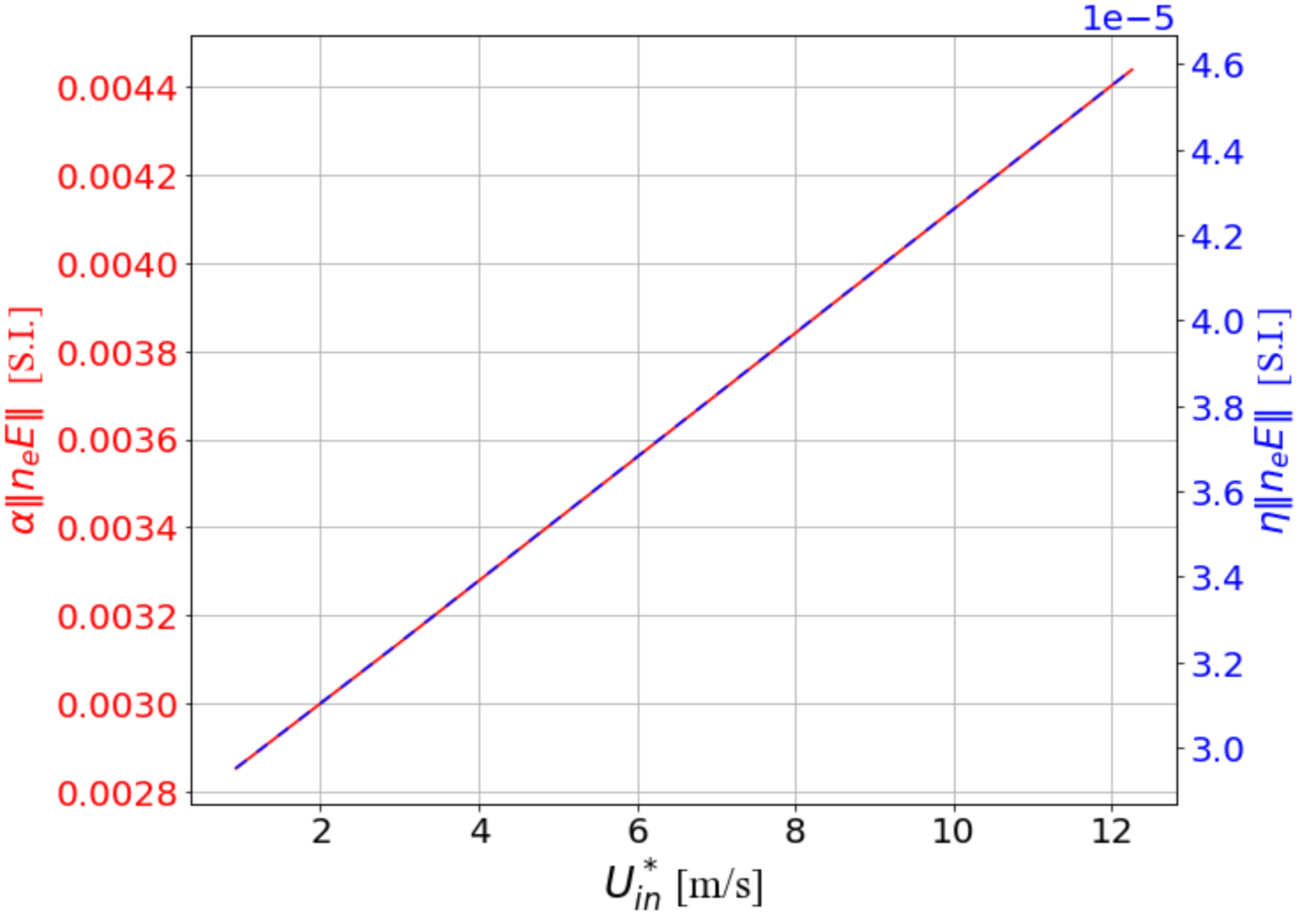

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⇒ Charge **generation** increases

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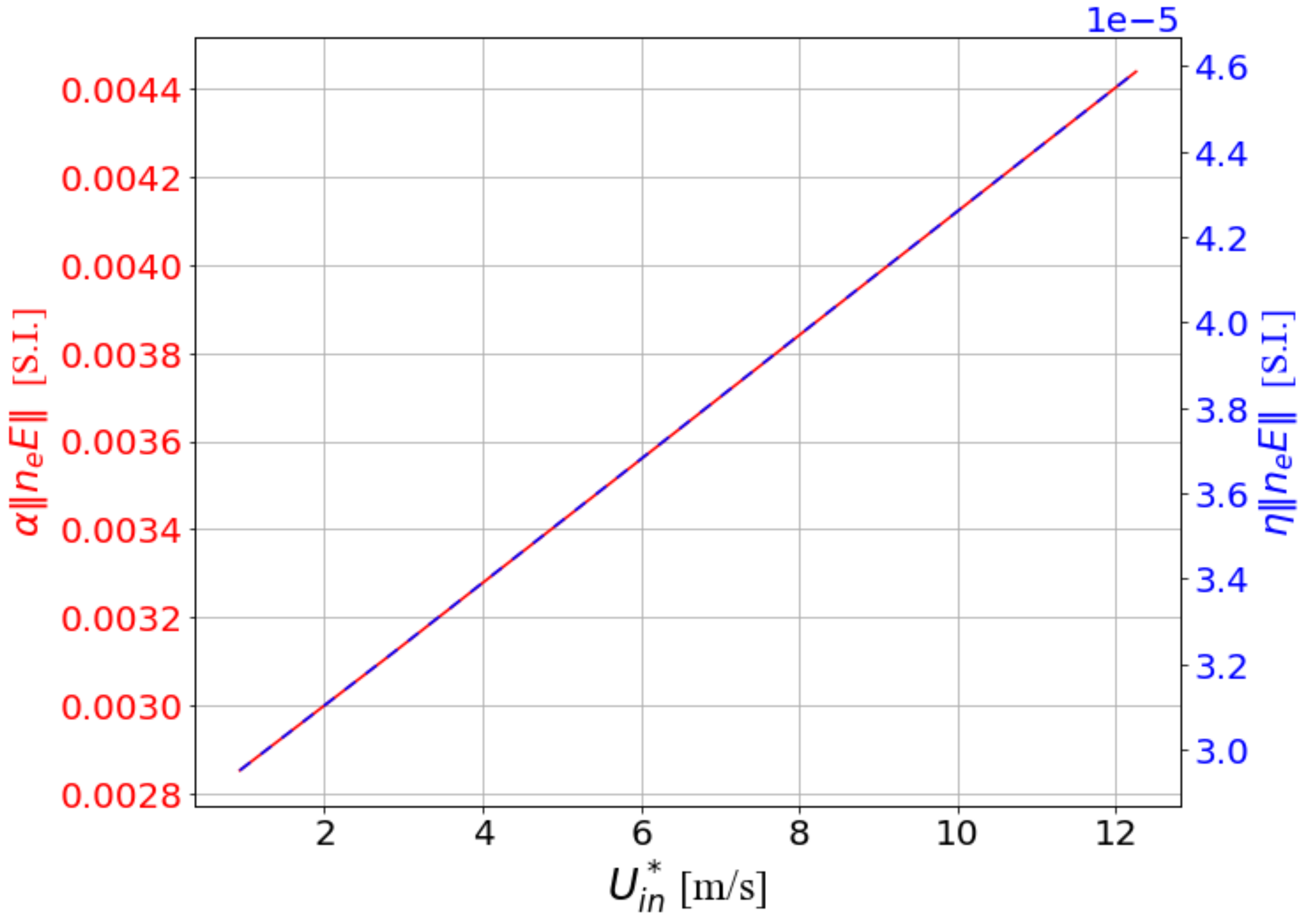

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⇒ Charge **generation** increases

⇒ Depends only on $\|\mathbf{E}\| : \alpha = \alpha(\|\mathbf{E}\|)$

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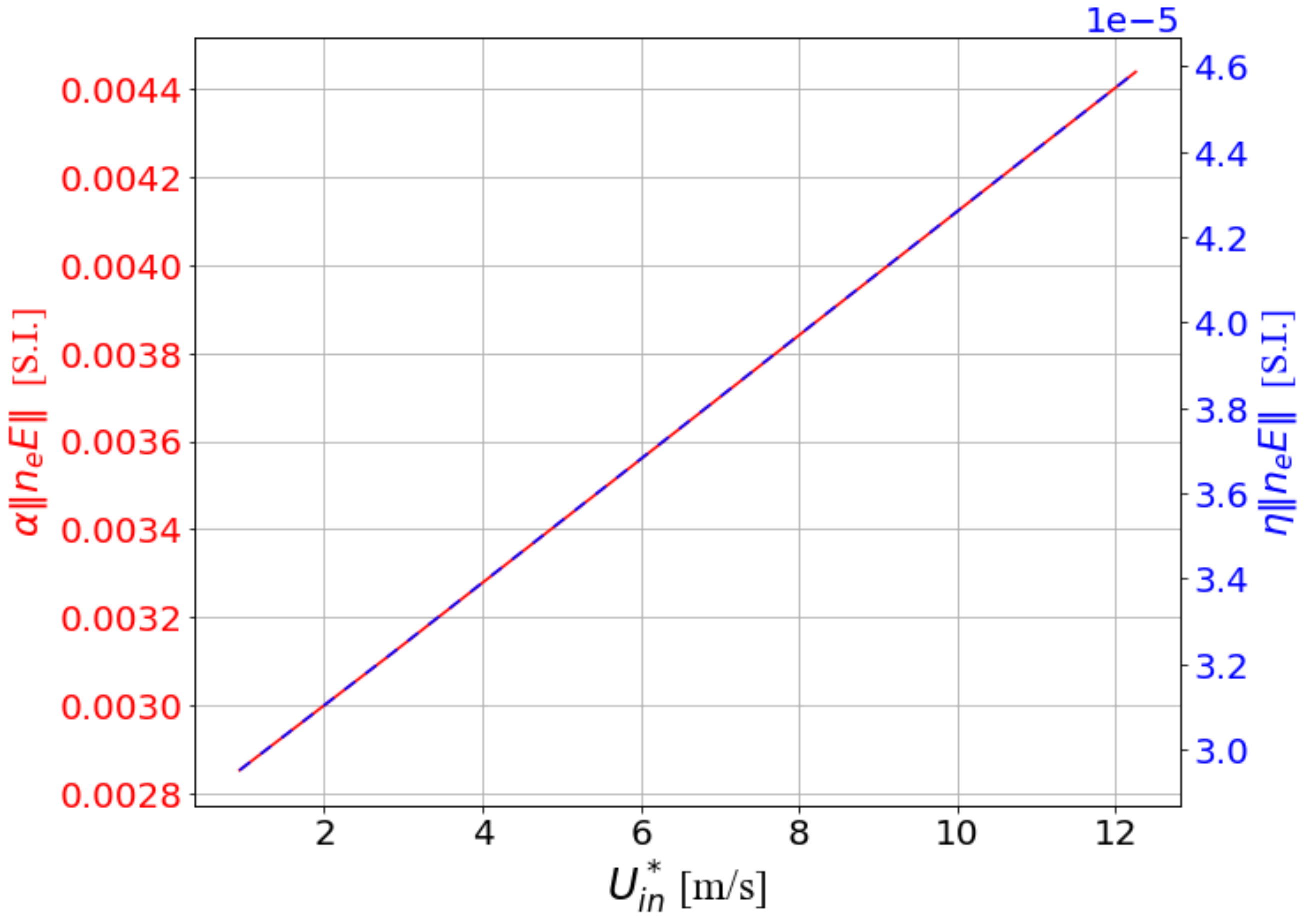

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} ⇒ $\|\mathbf{E}\|$ must increase

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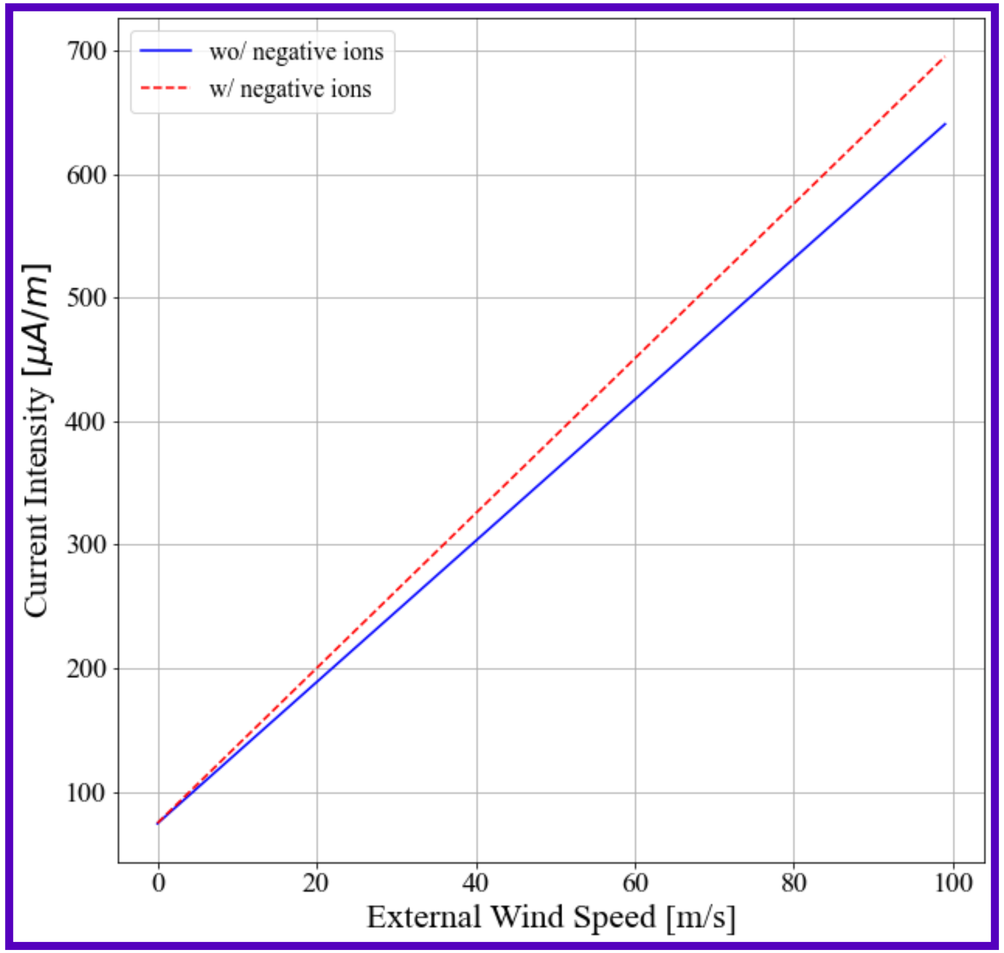
Negative ions



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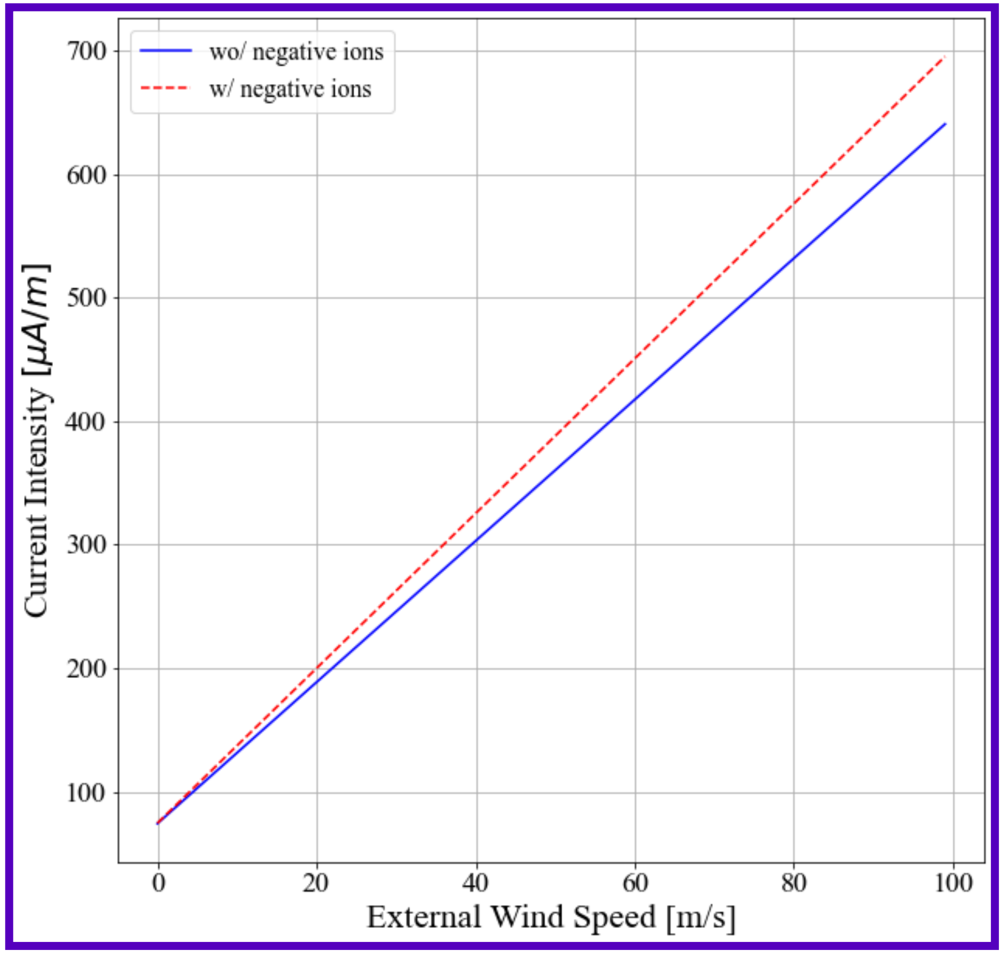

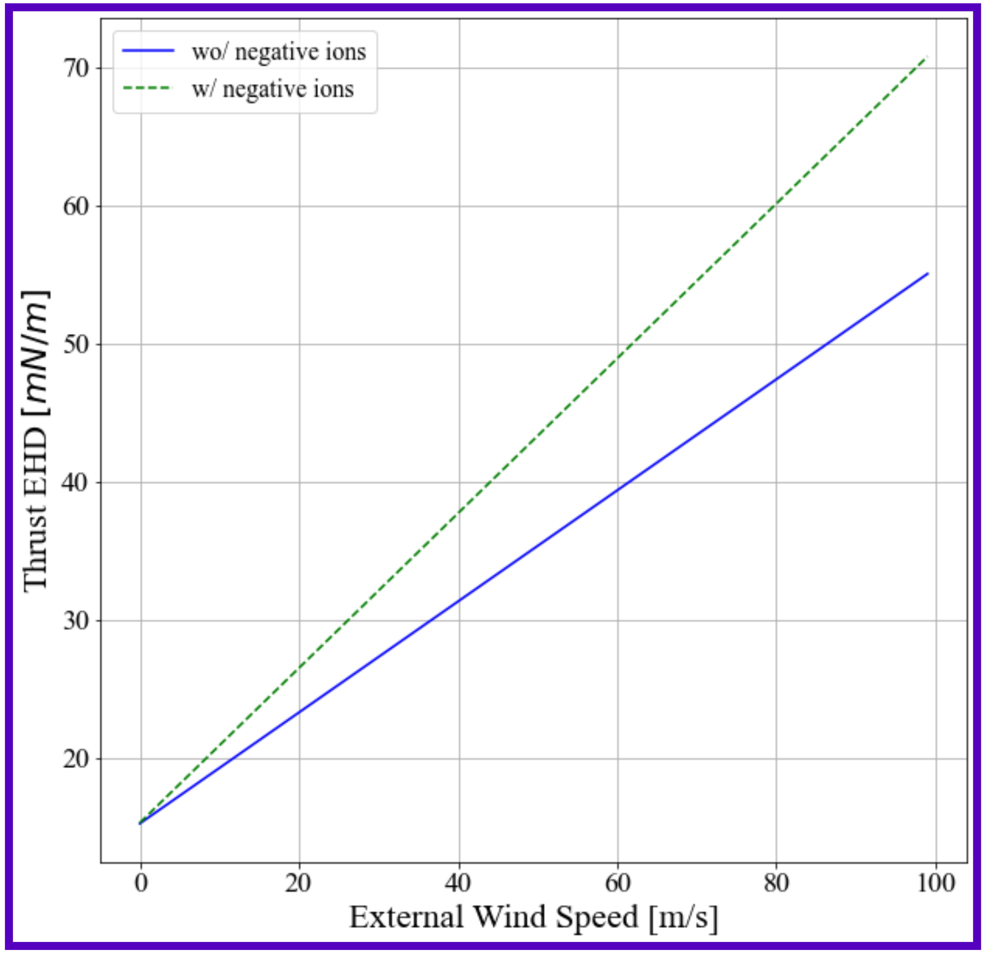

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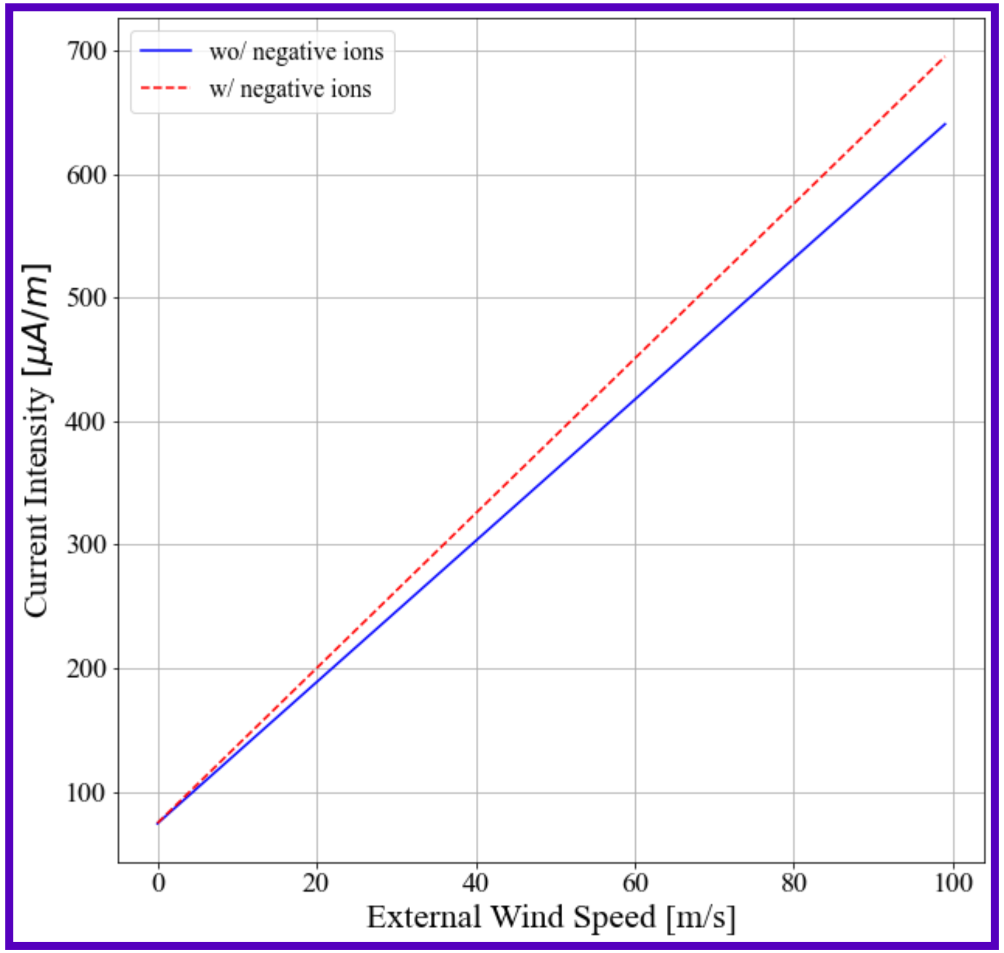

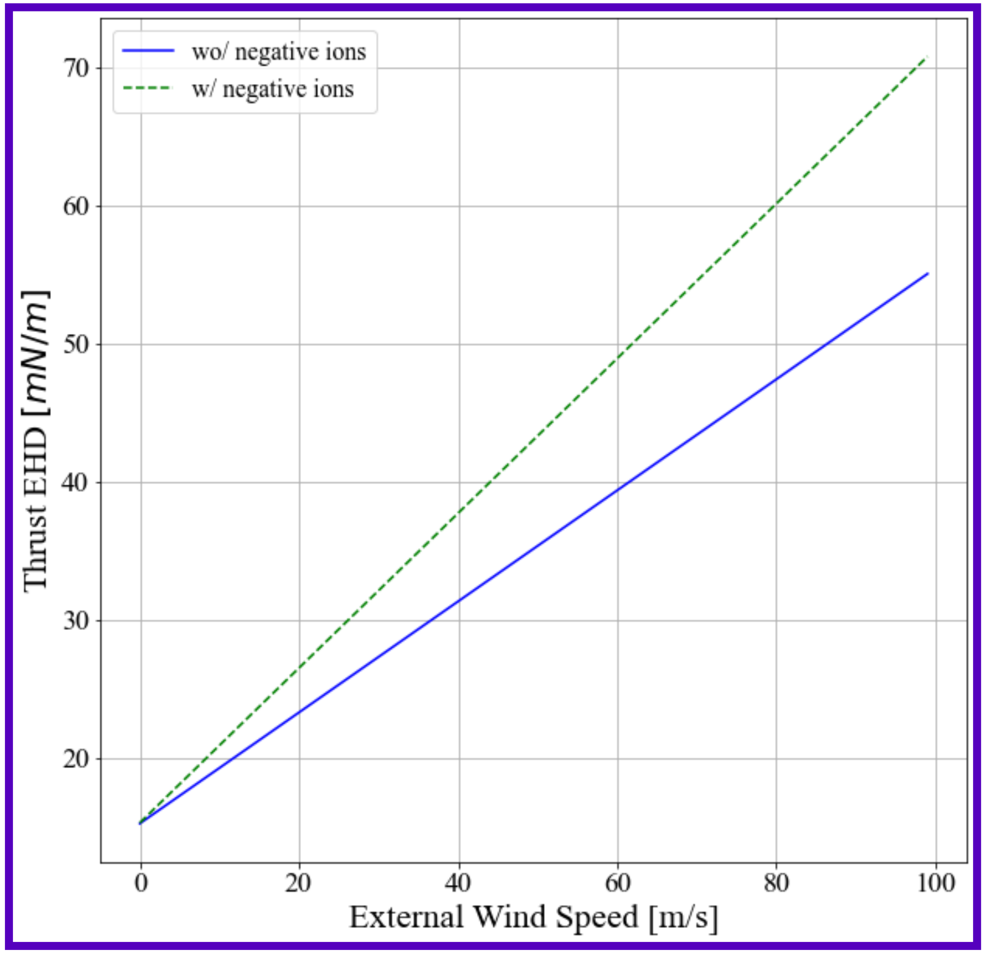

$\Rightarrow$ Negative ions also contribute to $\|\mathbf{E}\|$ enhancement

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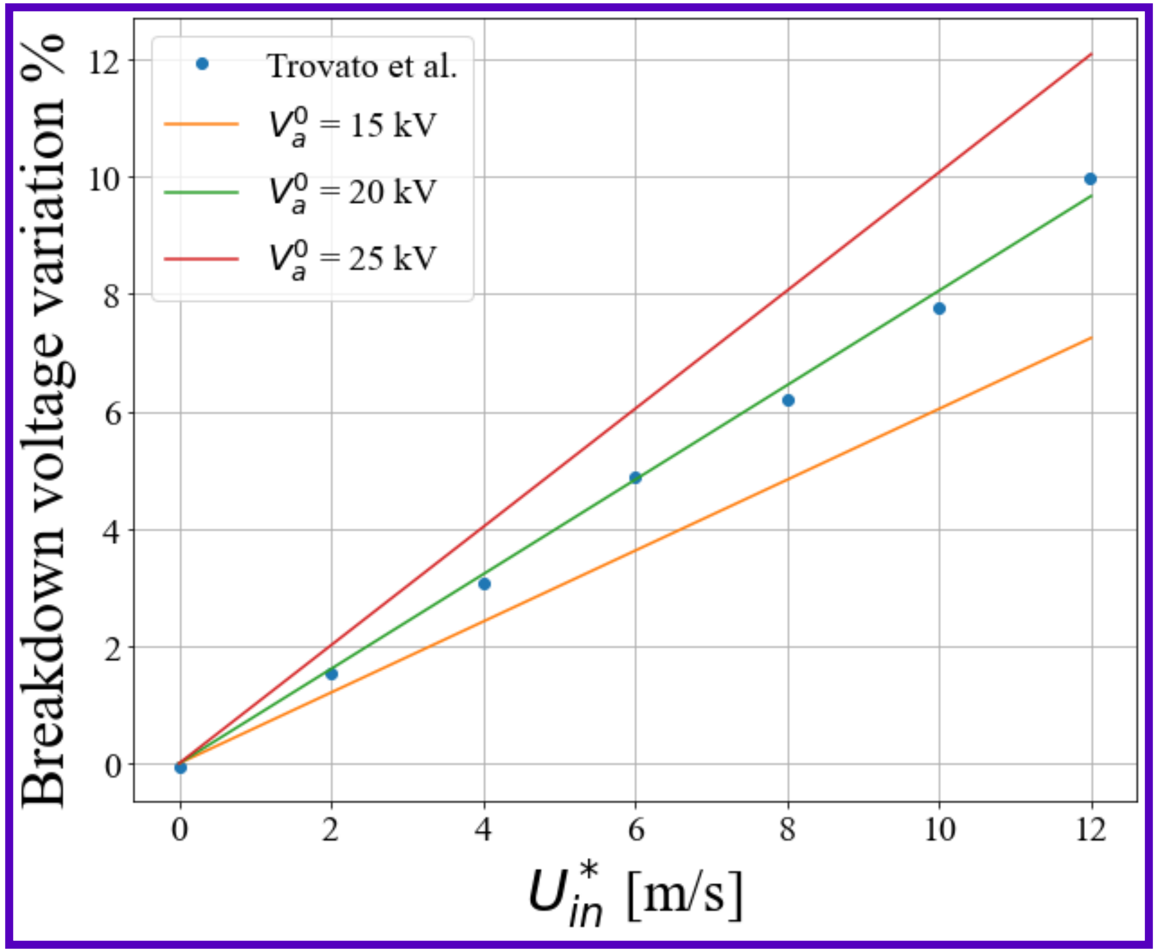
Breakdown



$$V^1 \propto U_{in}$$

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