

# Numerical configuration study of Ionic Wind for Propulsion via a Two-Way Electro-Aero- Dynamic Modelling

EUCASS 2025 - Juin 30th to July 4th

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

CNRS - IMFT

IPROP EIC Pathfinder project

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Seville Chapman. Journal of Geophysical Research, April 1970.

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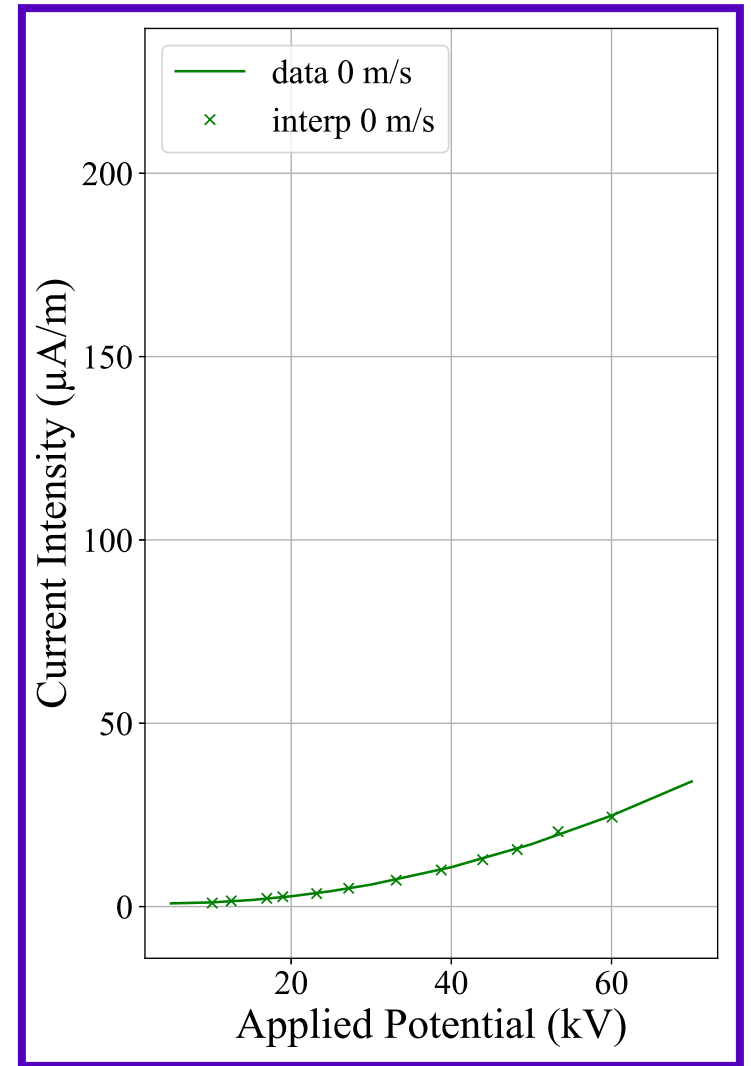
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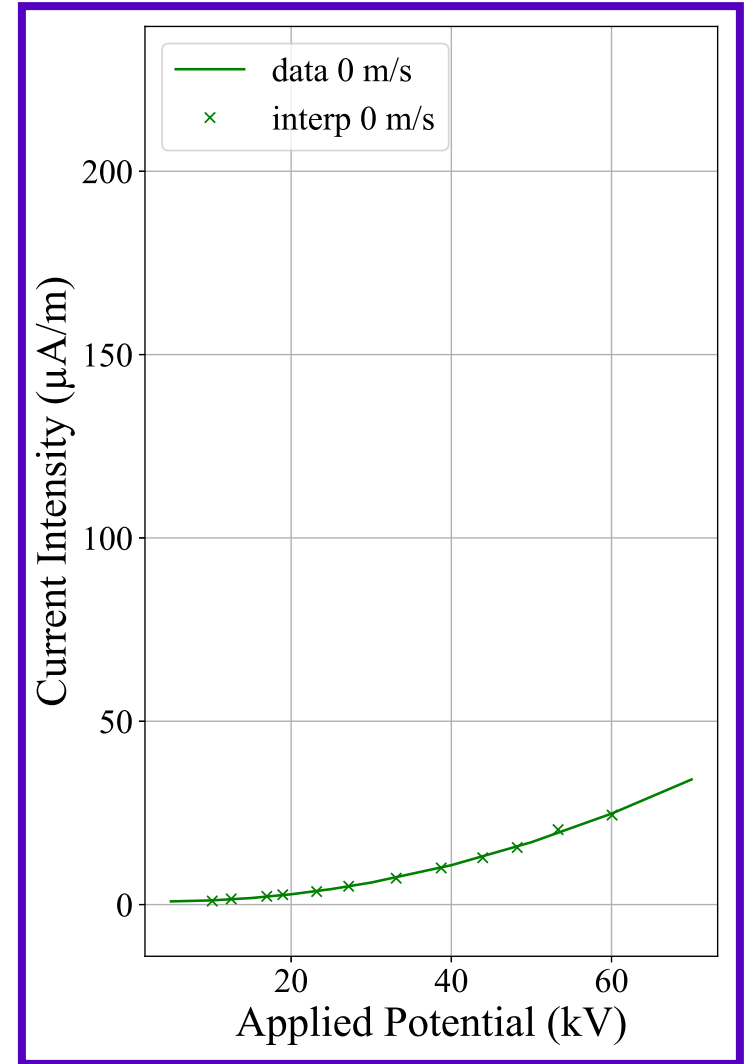


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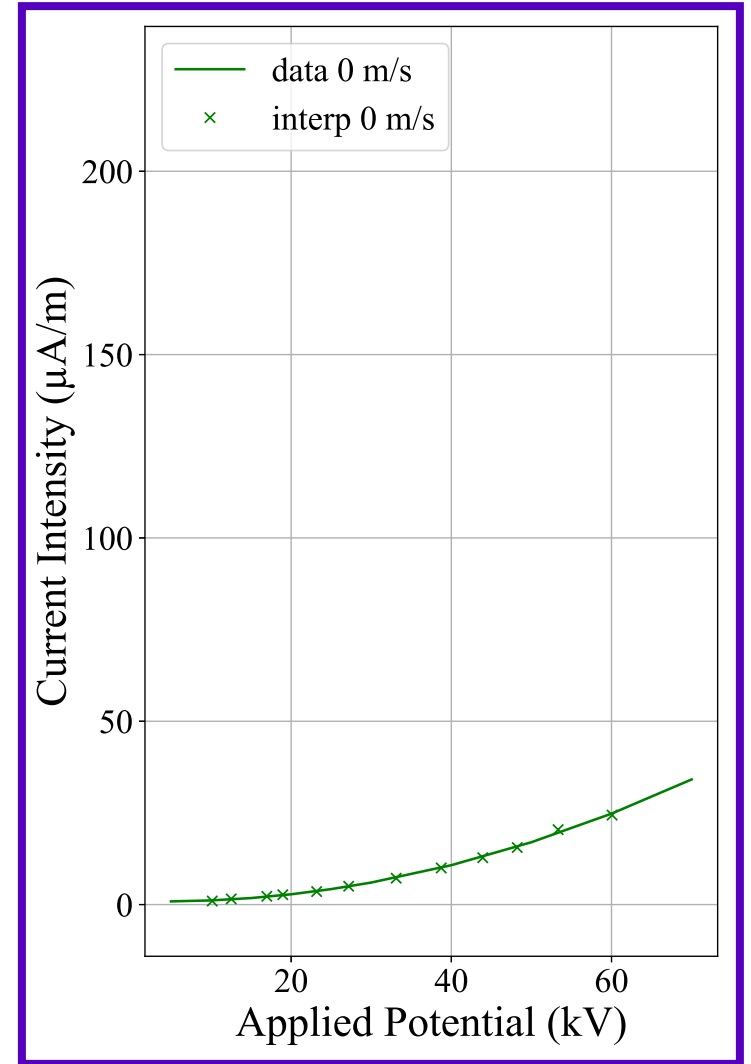
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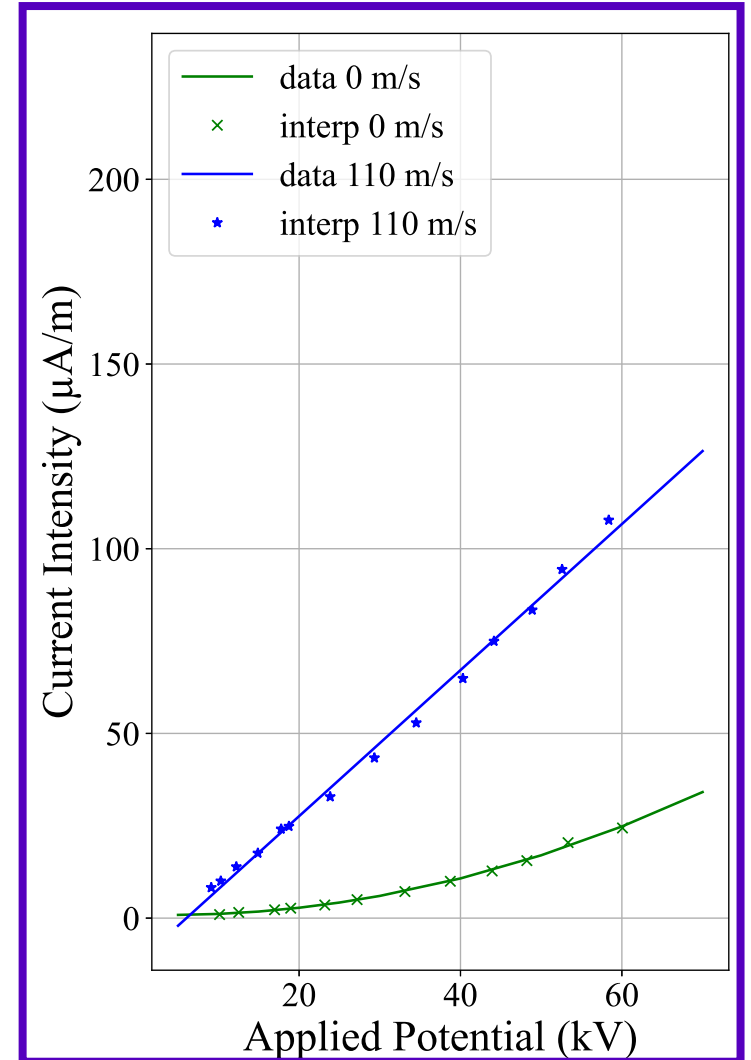
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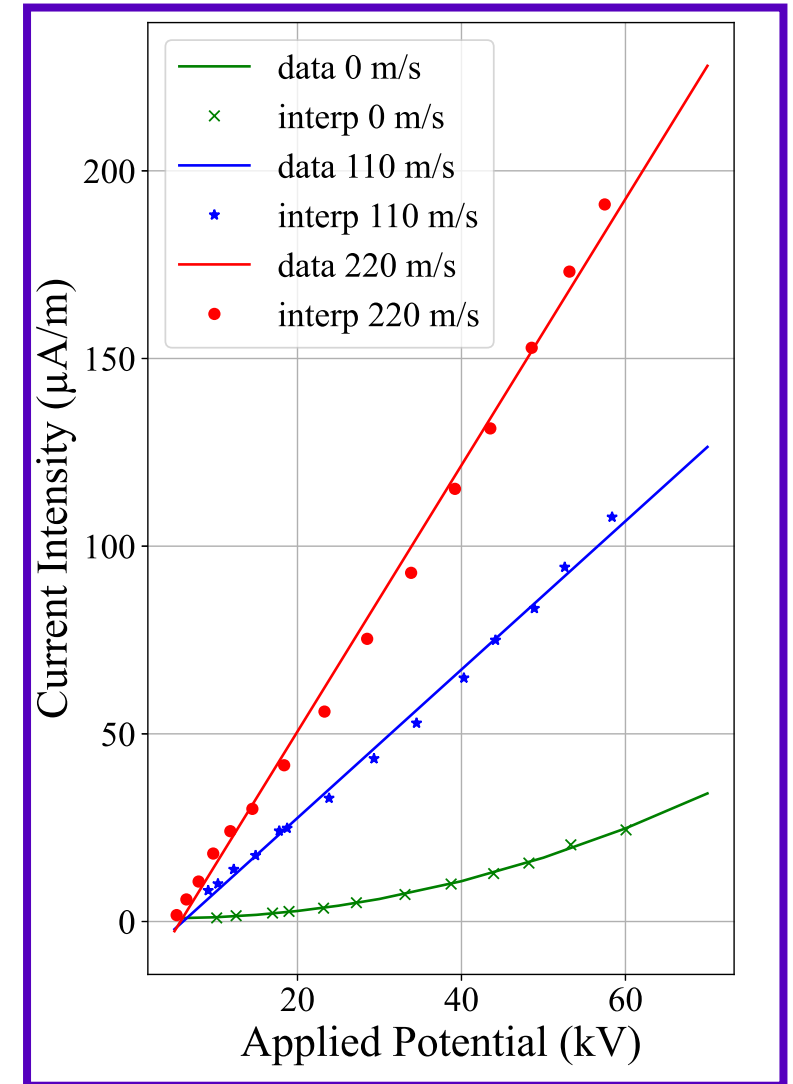
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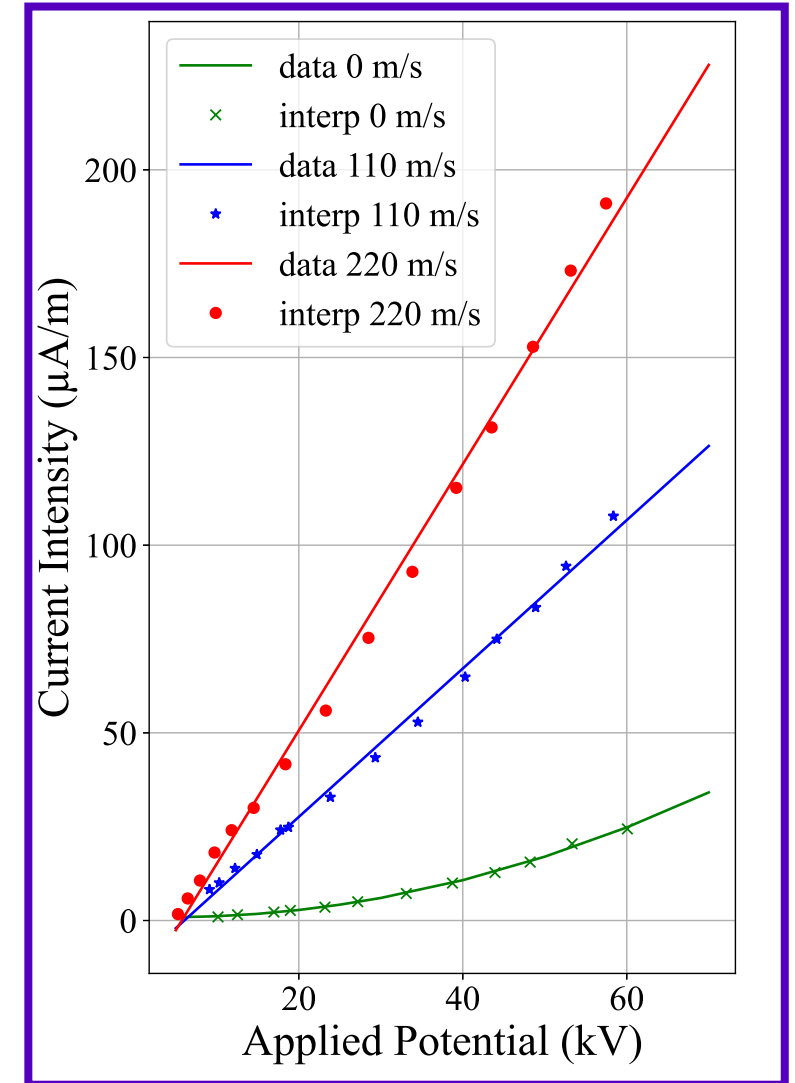
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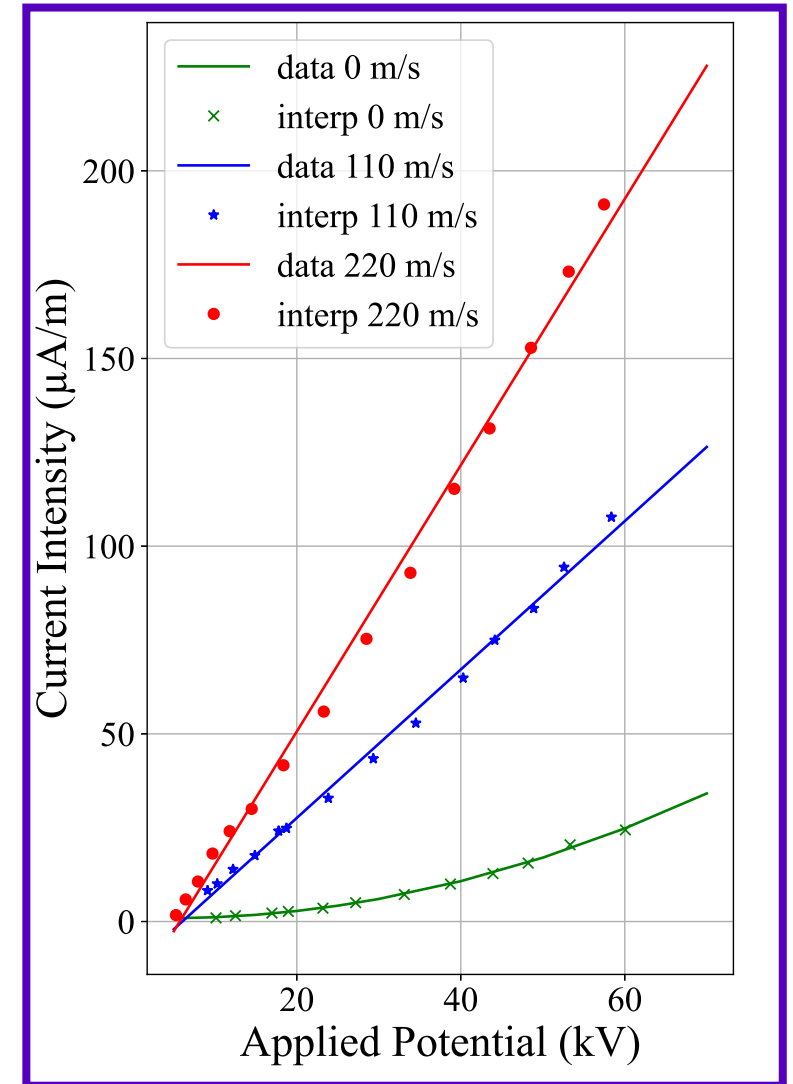
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# Outline

## I. Theoretical two-way two-domain model



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**1. Theoretical two-way two-domain model**

**2. Two NACA0012 collector configuration study**



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1. System description

2. Propulsive properties



# I. Two-Way Coupling Equations

## Physical Parameters

Electro-drift Péclet number :

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

Monrolin et al., J. of Comp. Phys., October 2021.

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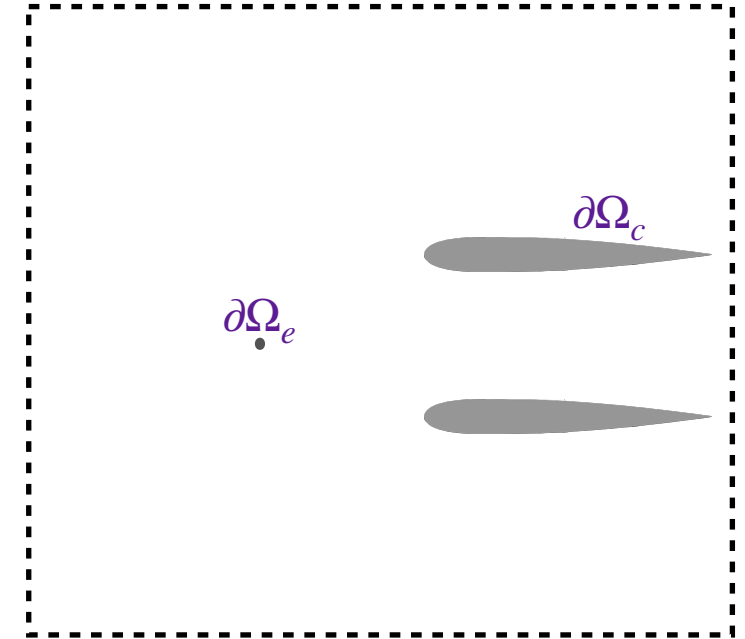
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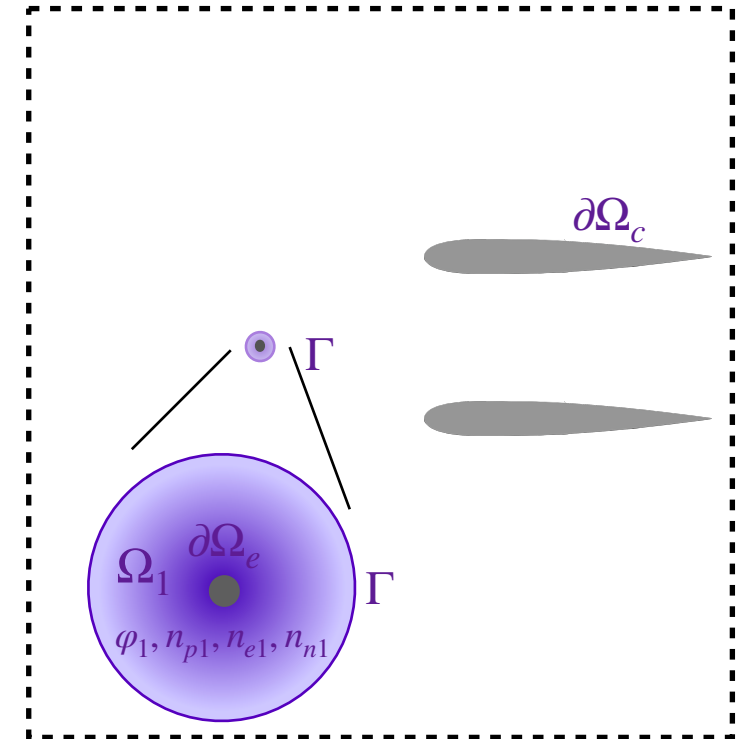
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Inner domain  $\Omega_1$

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



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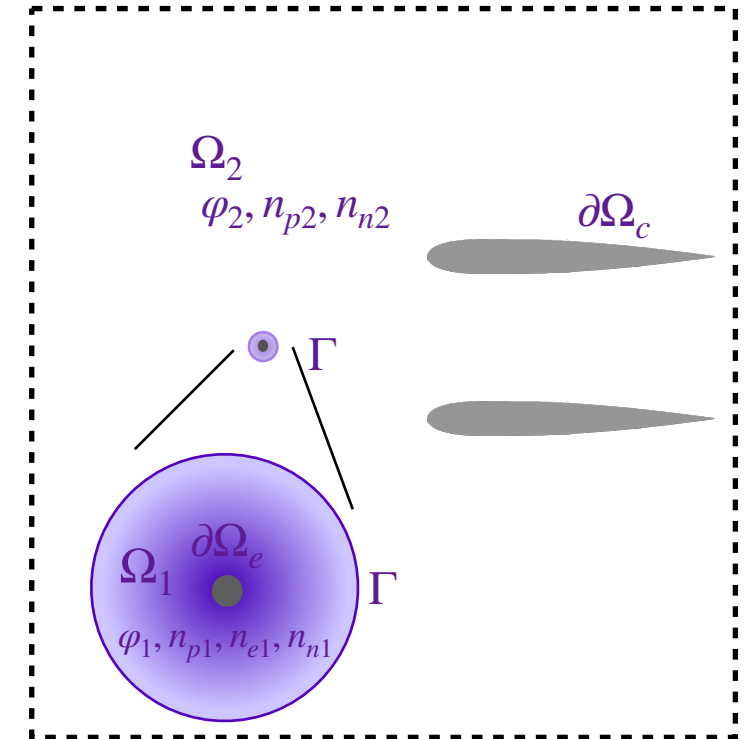
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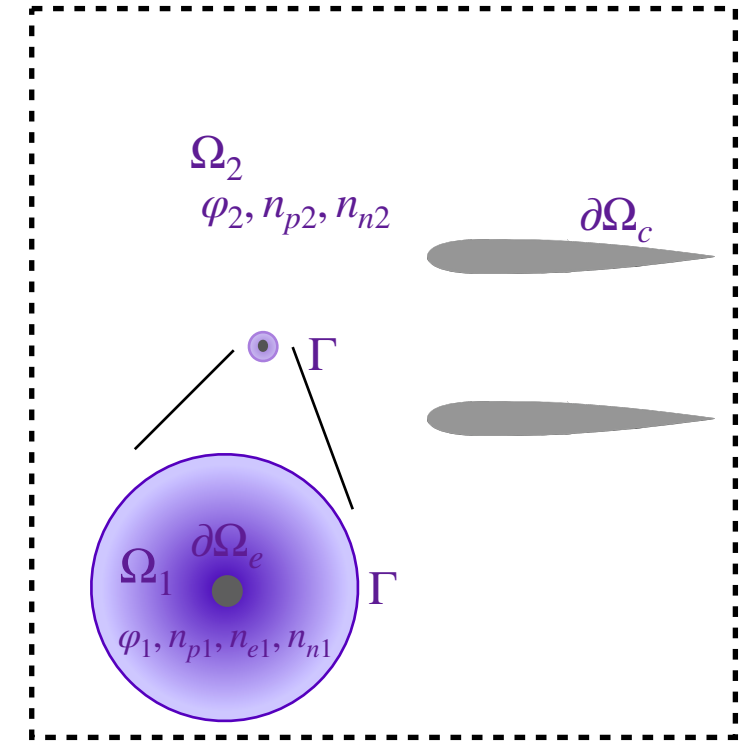
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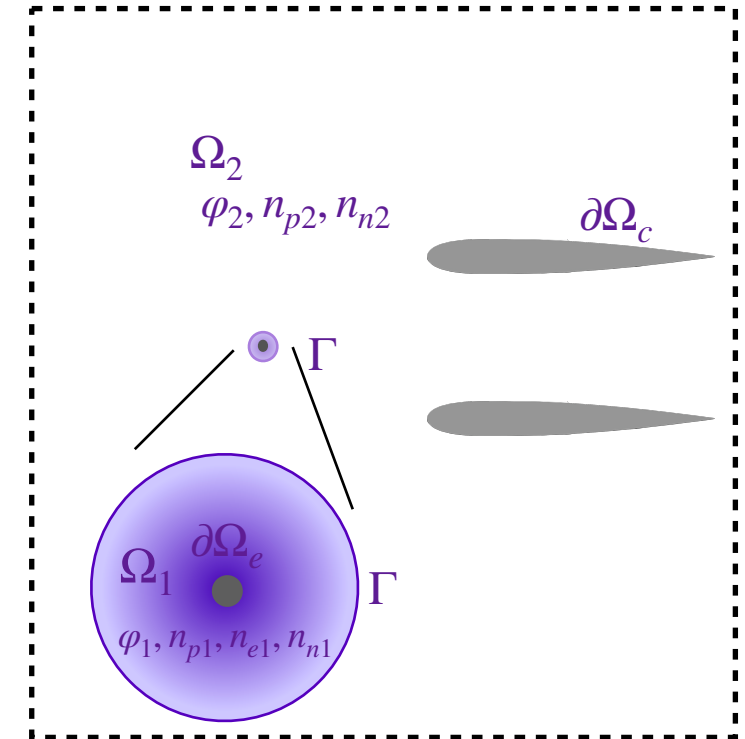
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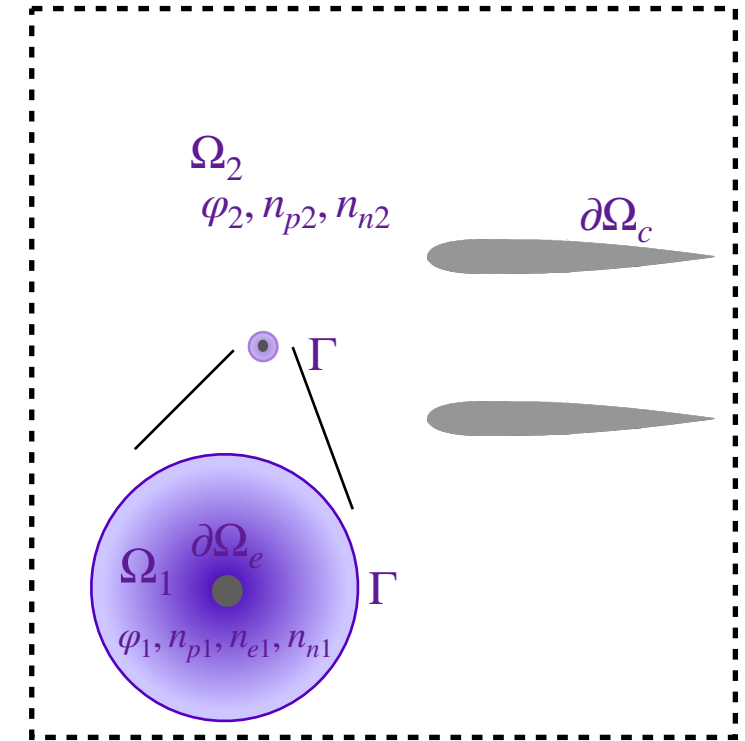
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Asymptotic expansion with respect to the EHD Mach Number :  $M_c = \frac{U_e}{\mu \varphi_a / r_c} = \frac{1}{\mu_p} \sqrt{\frac{\varepsilon_0}{\rho_f^*}} \approx 10^{-2}$

Monrolin et al., J. of Comp. Phys., October 2021.

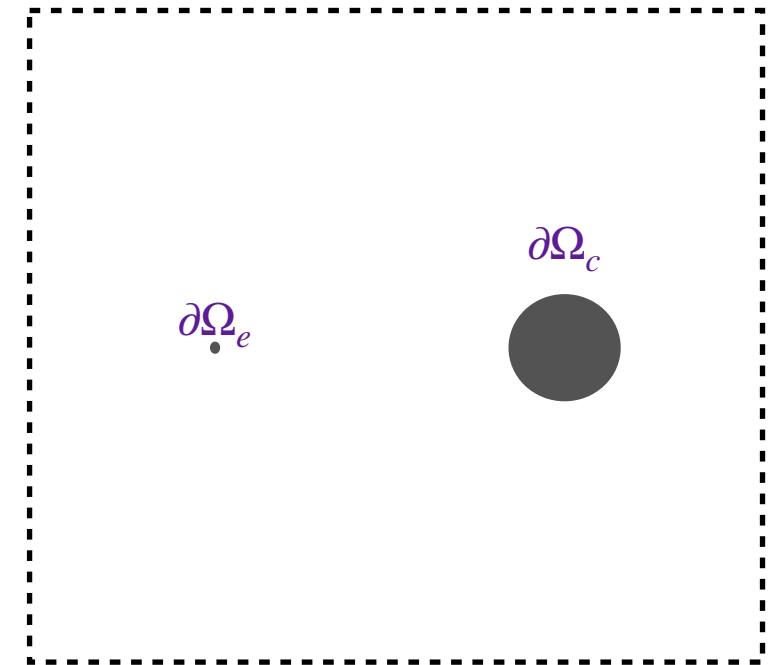
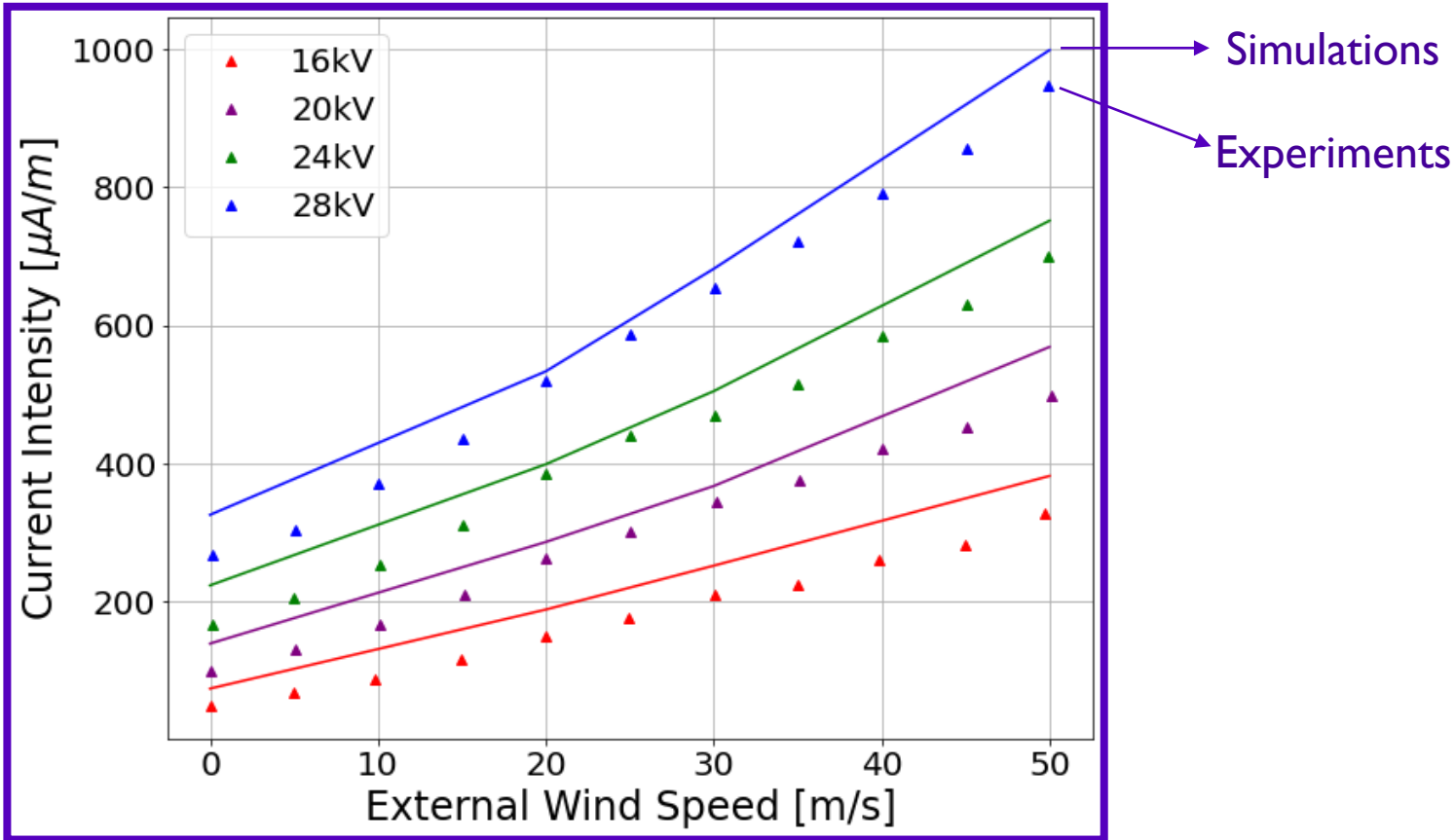
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# I. Comparison with Experiments

## Cylindrical collector



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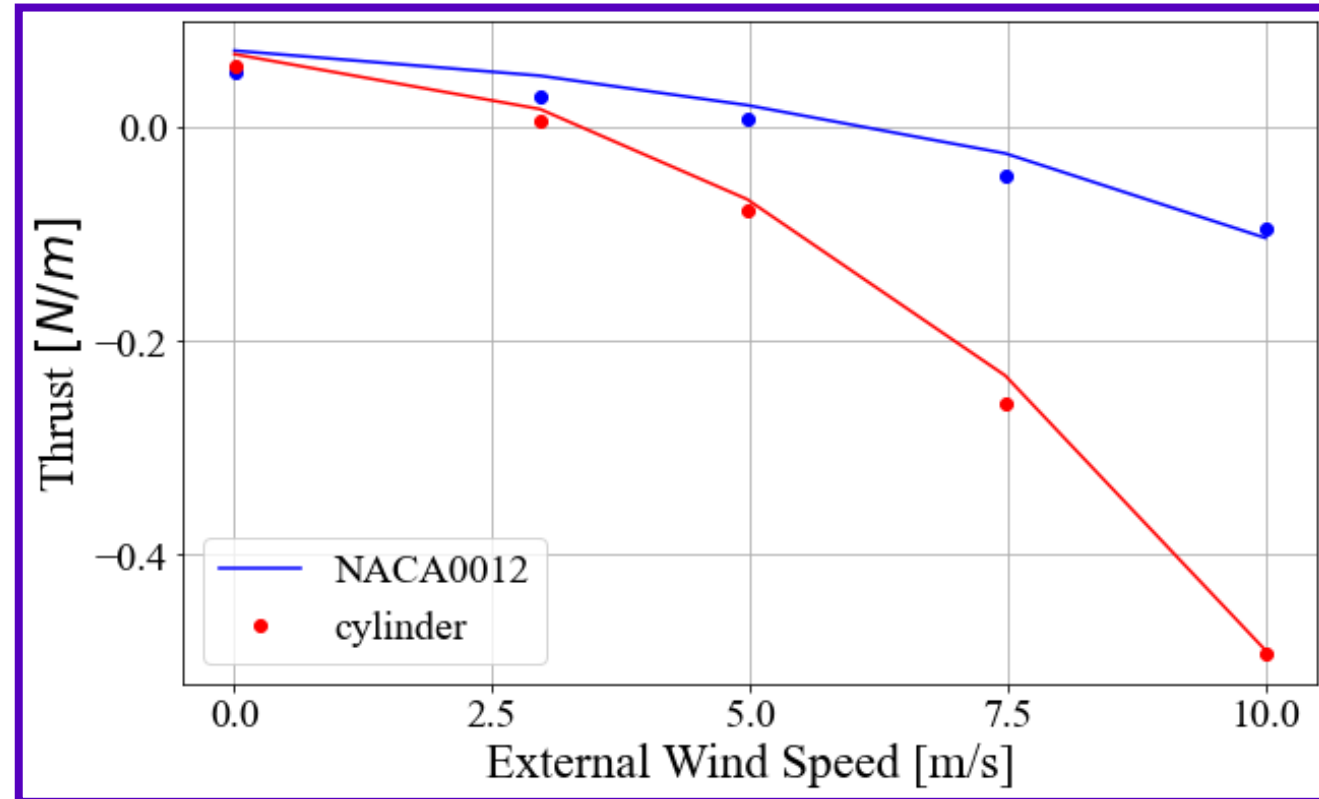
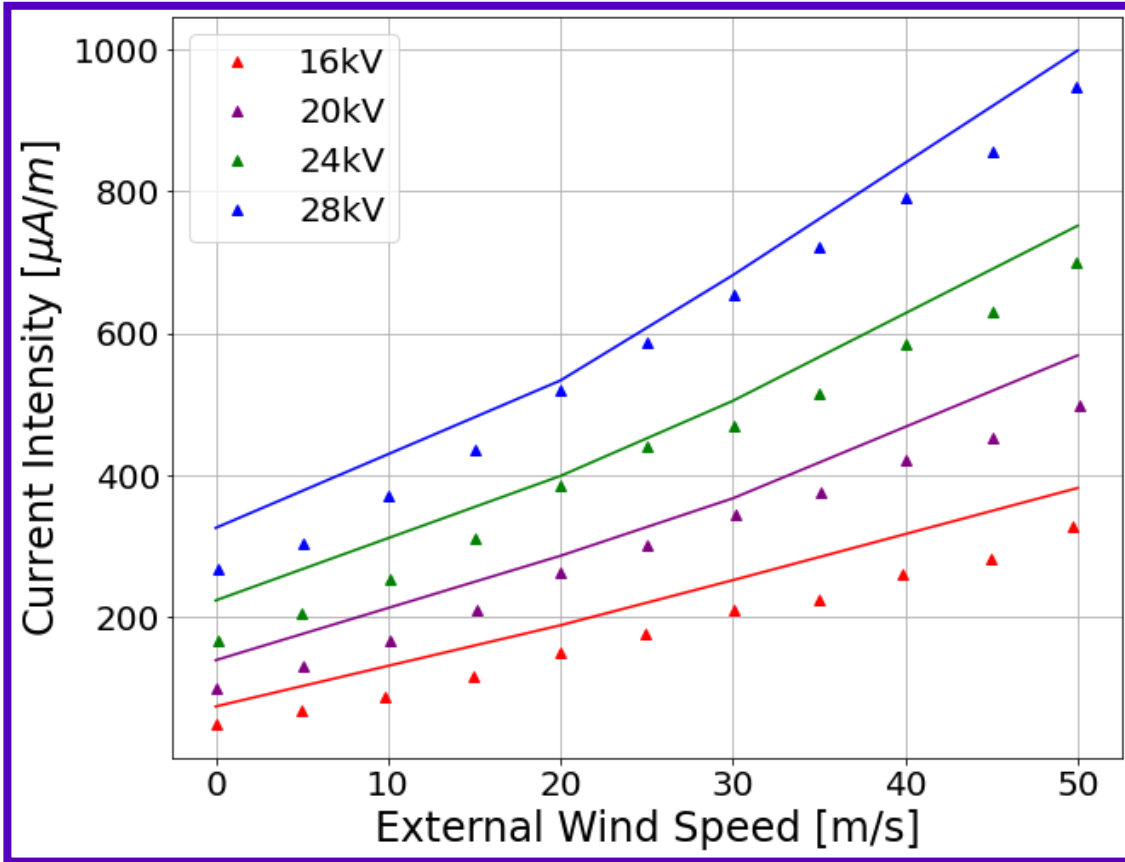
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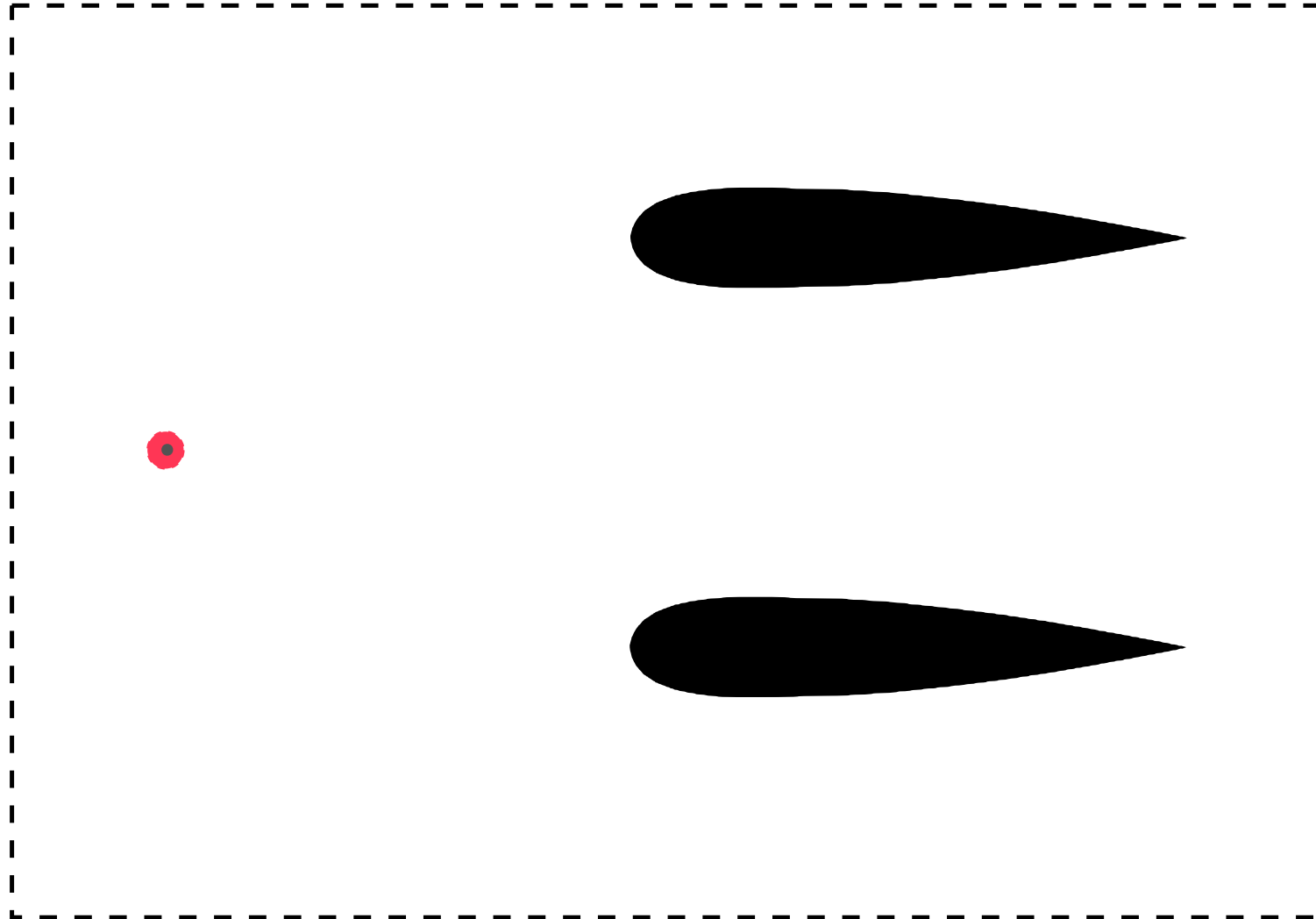
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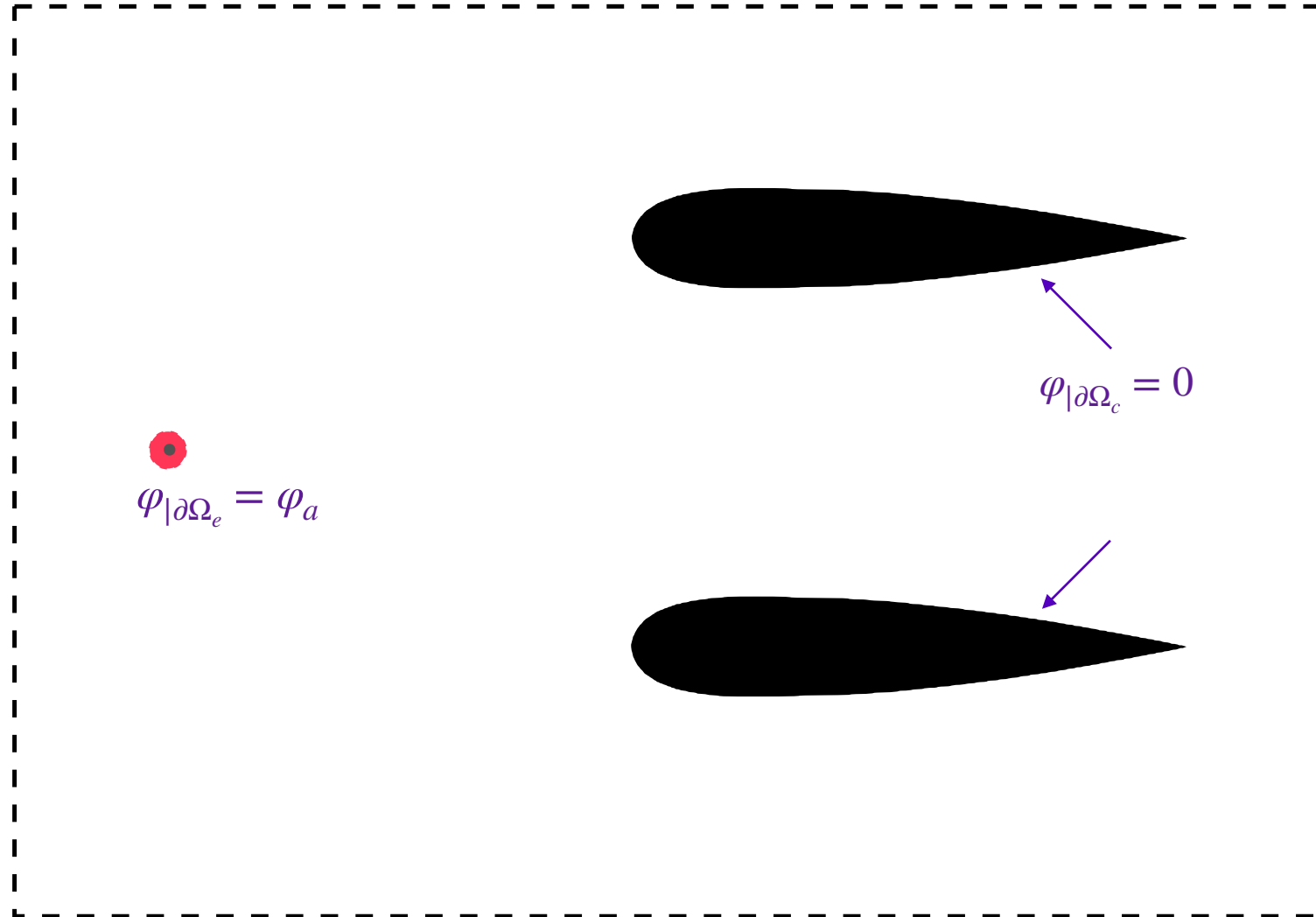


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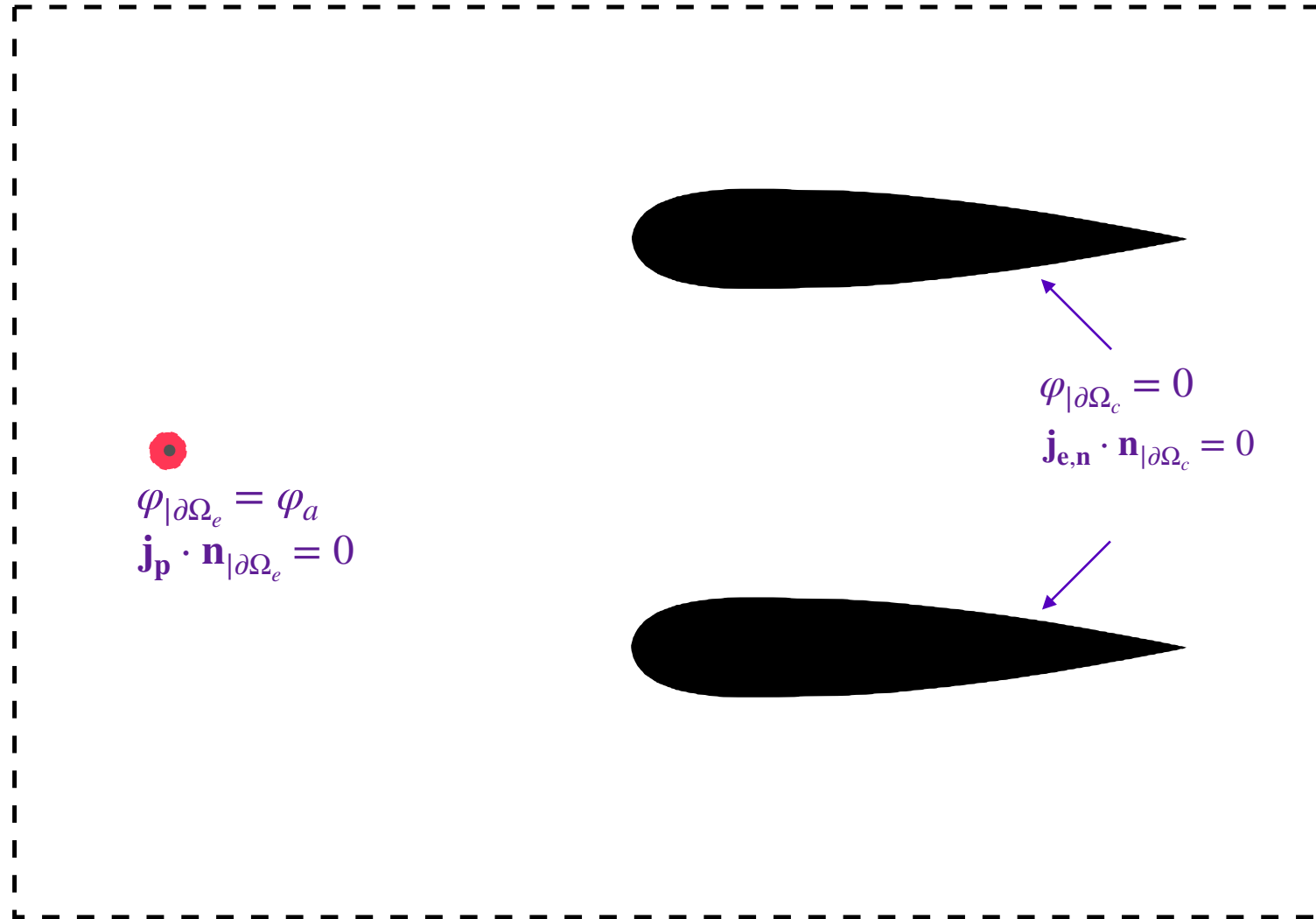
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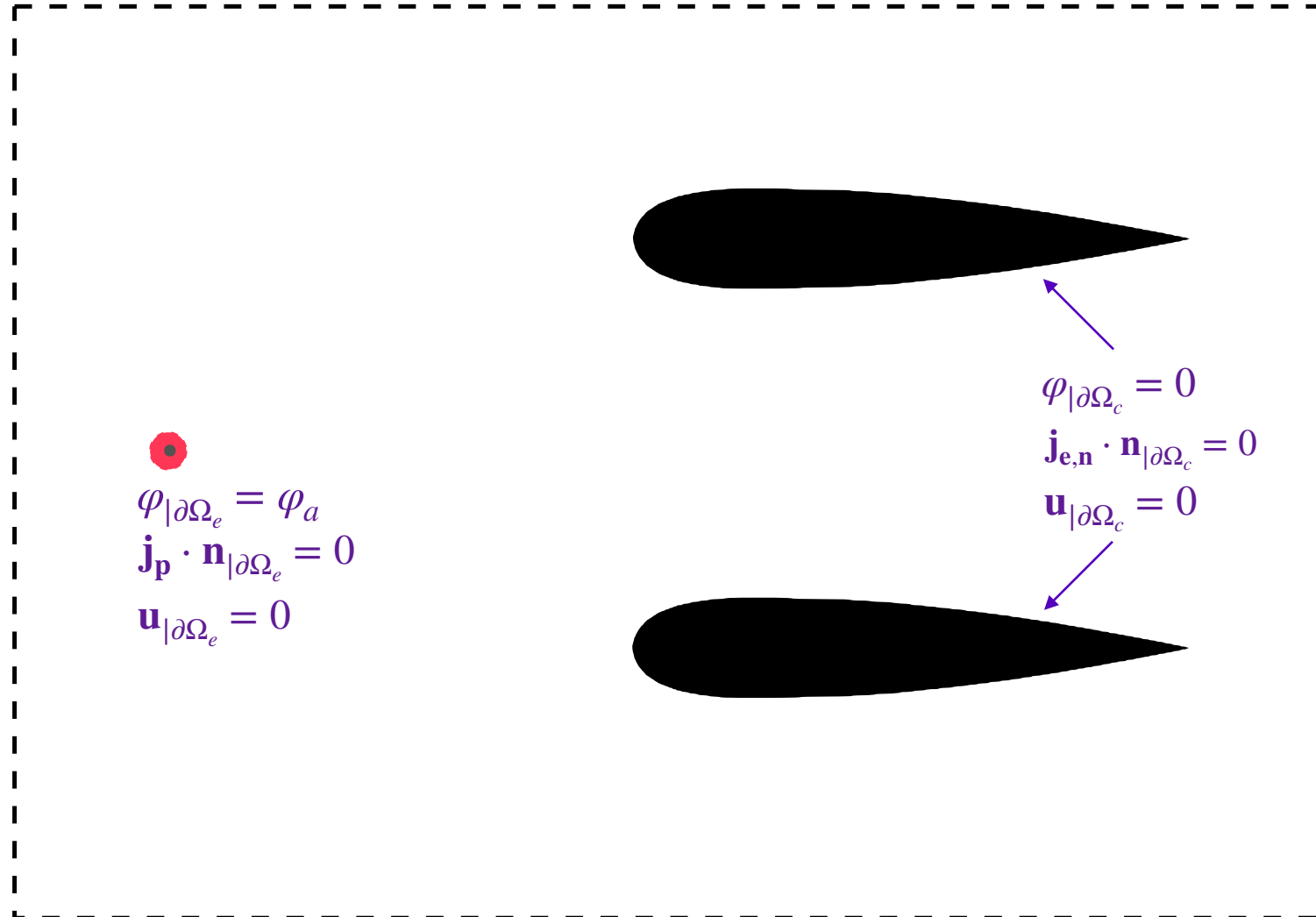
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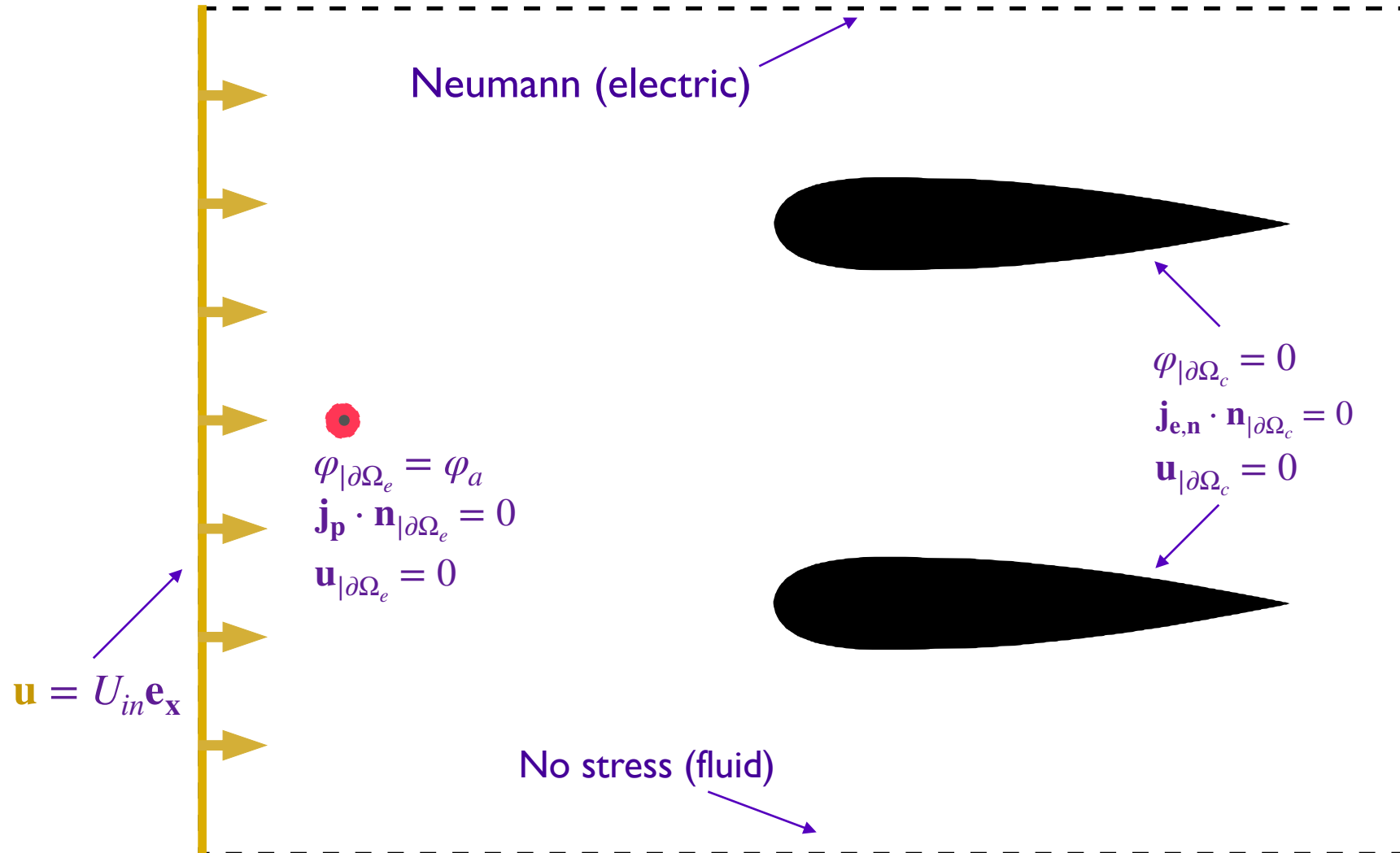
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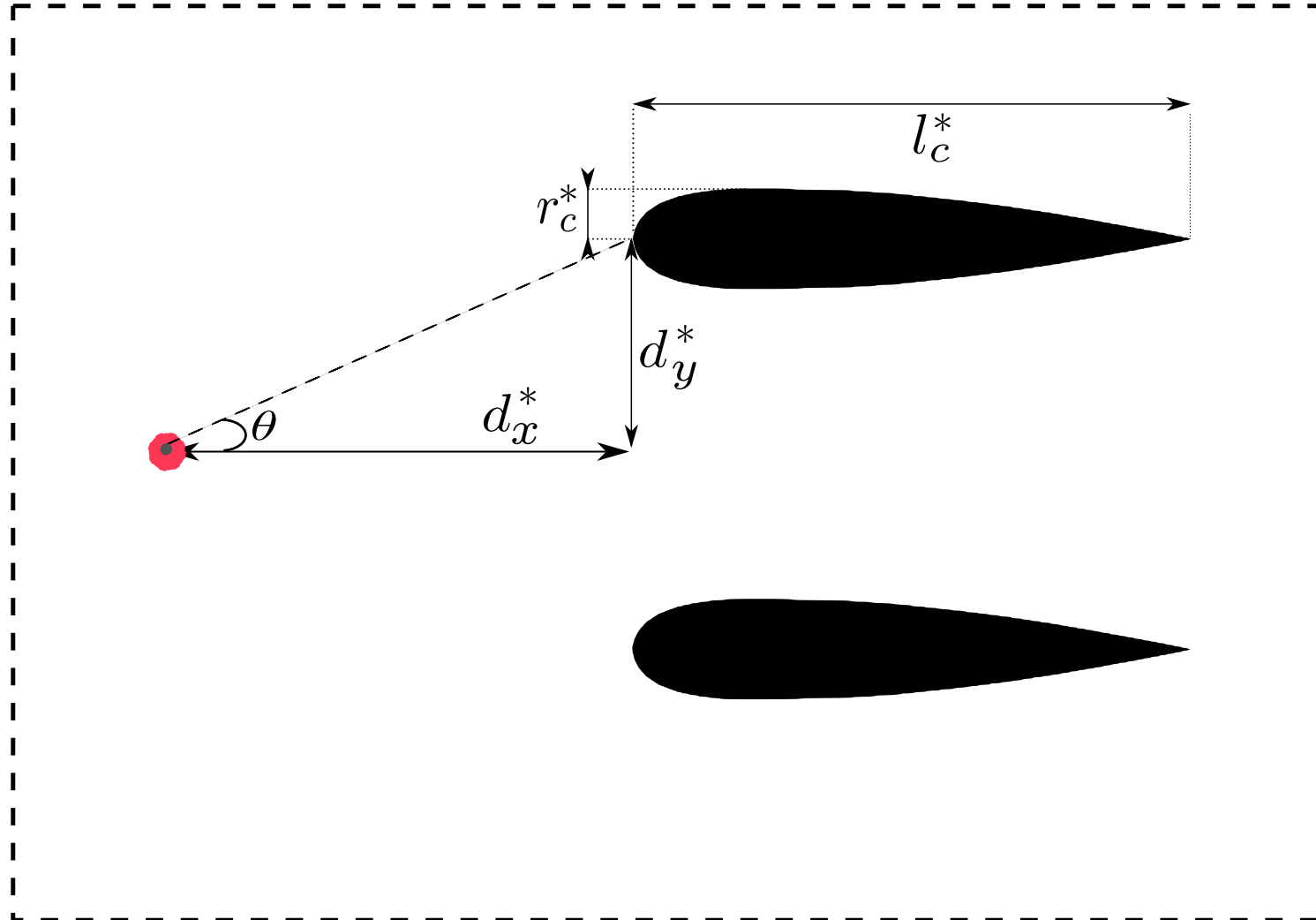


## 2. System Characteristics



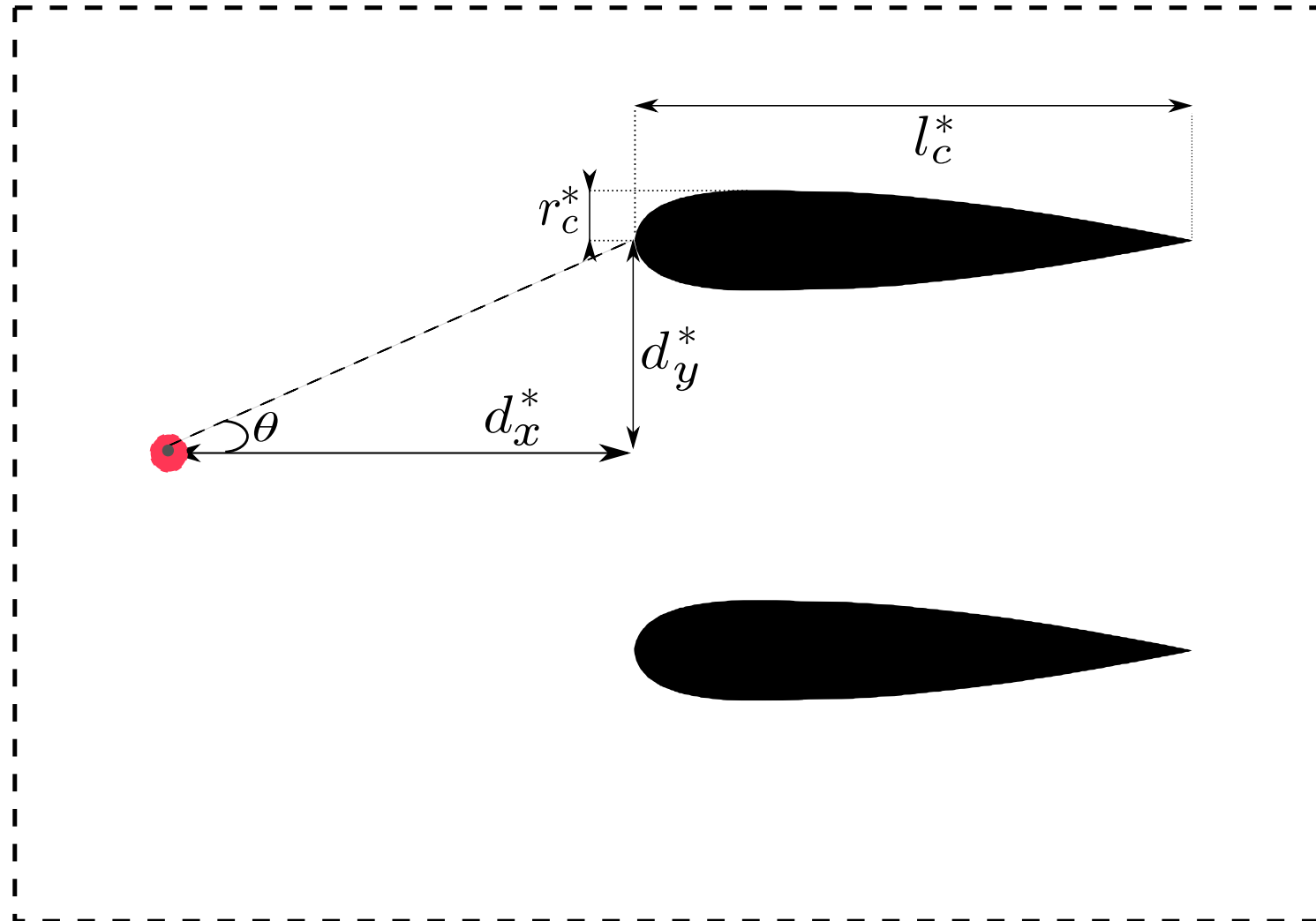
## 2. System Characteristics

- $l_c^* = 5 \text{ cm}$
- $r_c^* = 3 \text{ mm}$
- $E_{ext} = 5 \text{ kV/cm}$



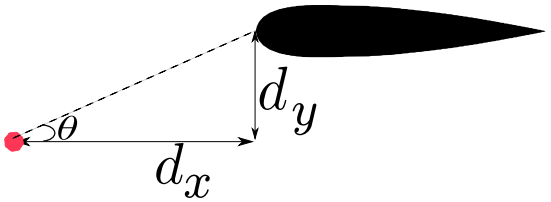
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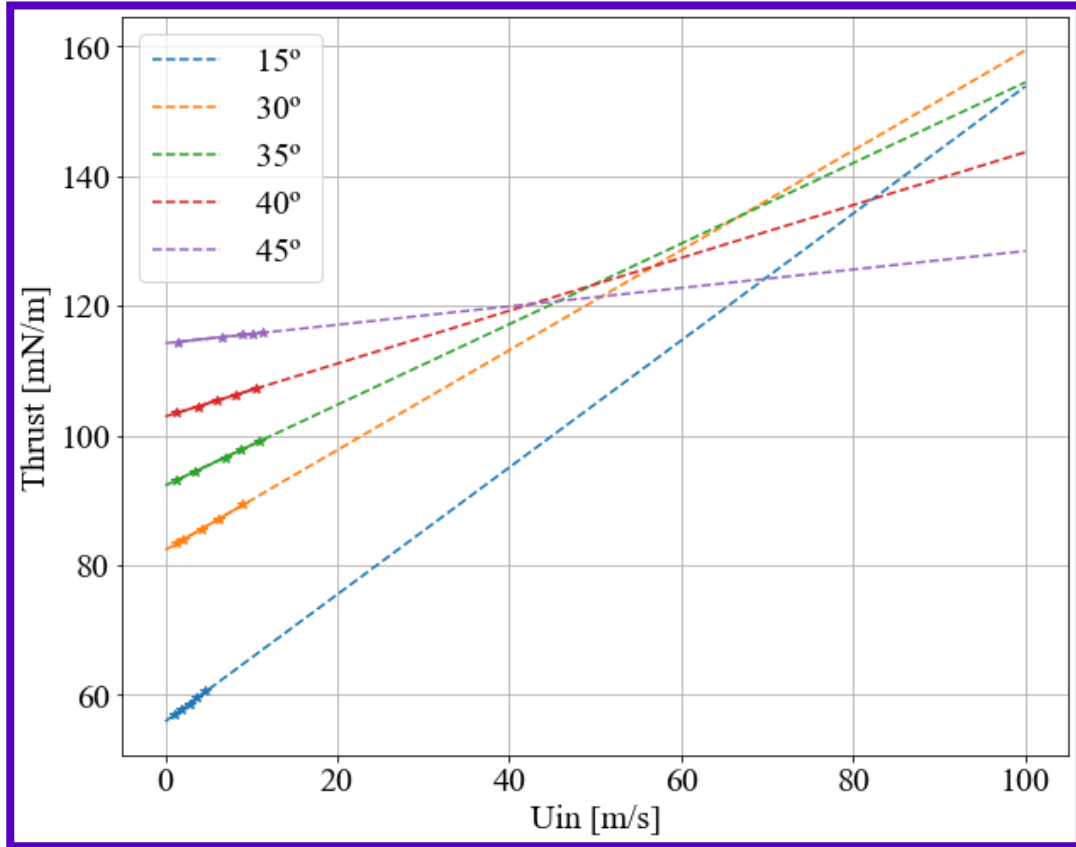


Complicated  
**experimentally !**

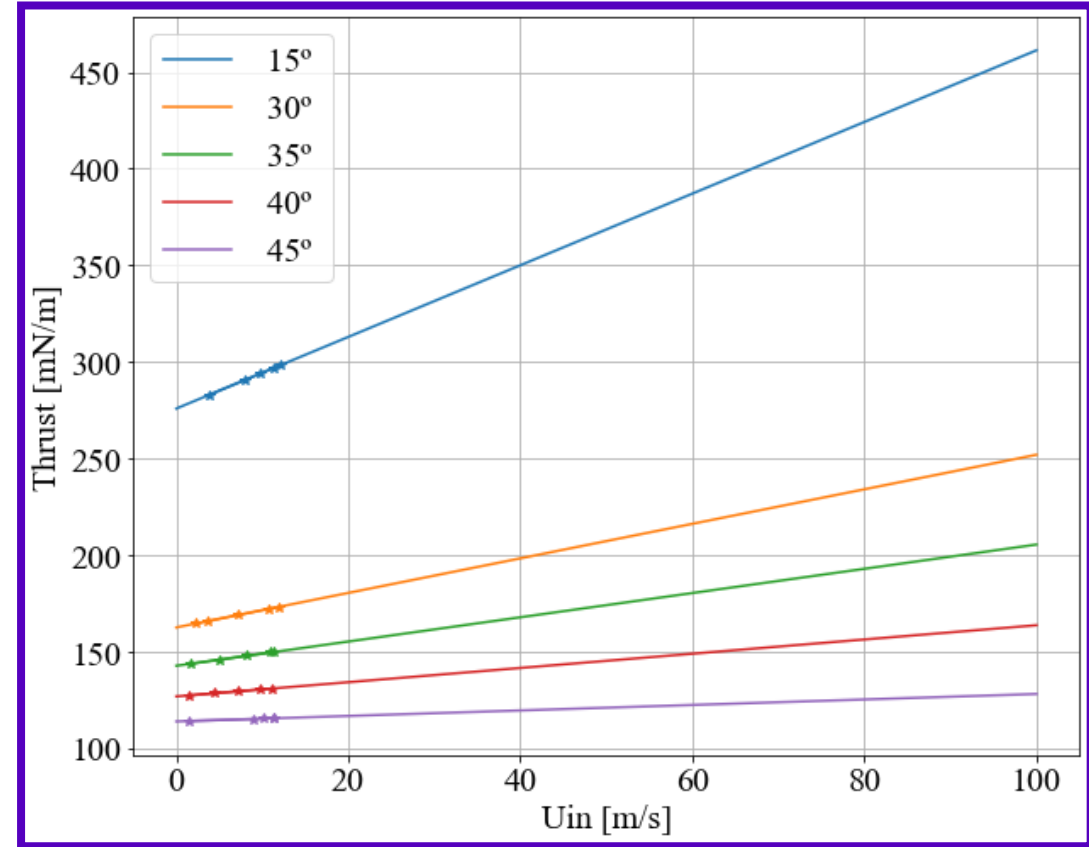
# 2. EHD Thrust



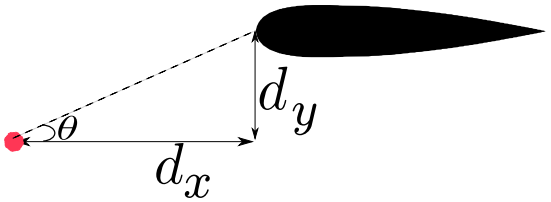
Varying  $d_y$



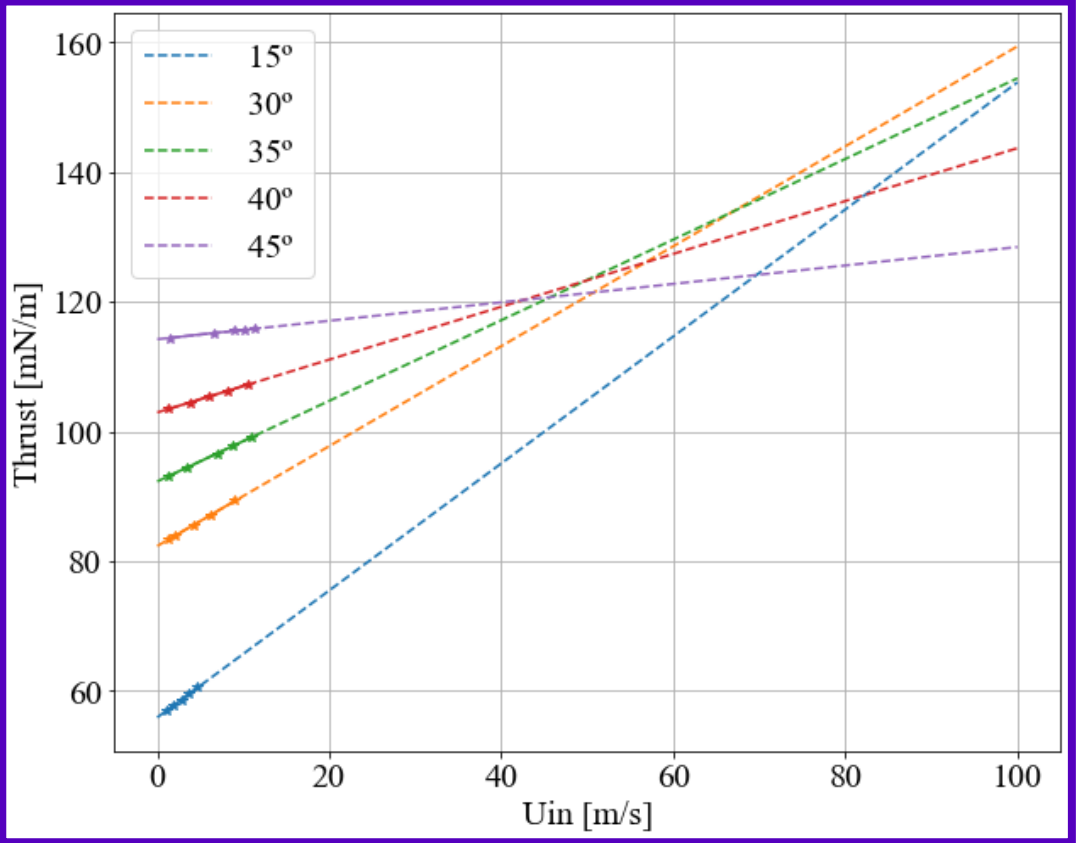
Varying  $d_x$



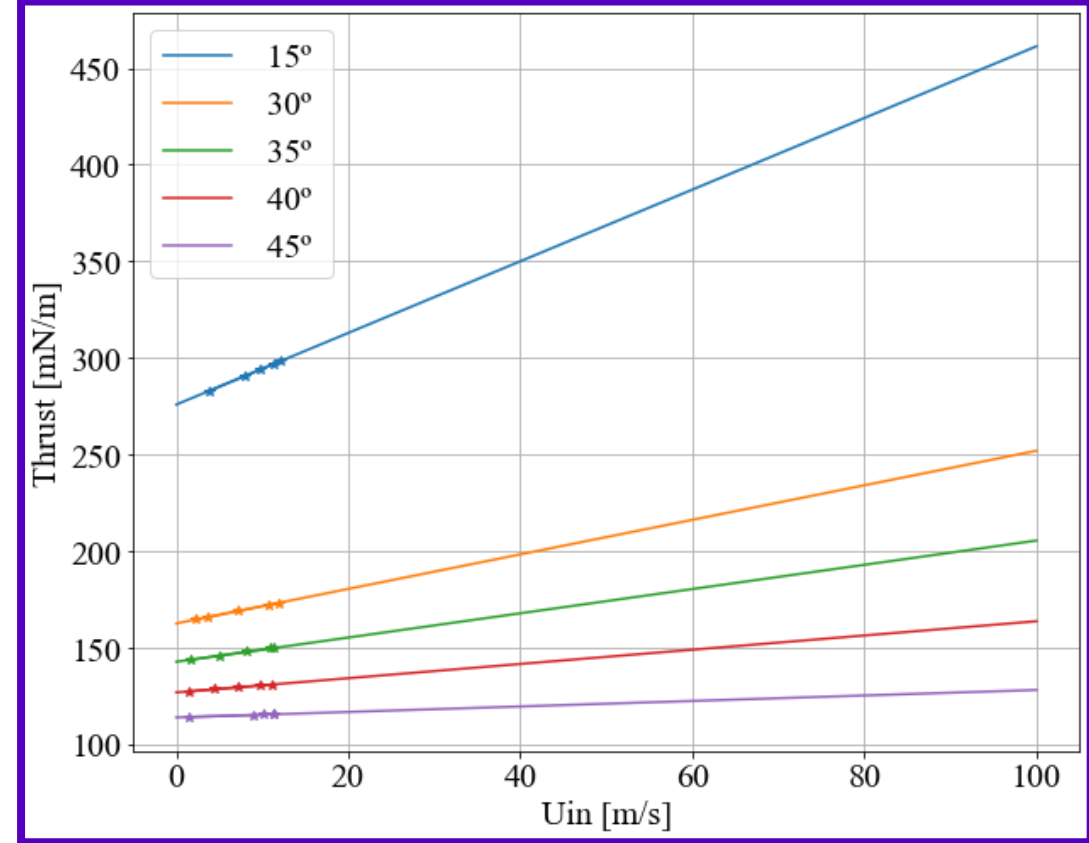
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Varying  $d_y$

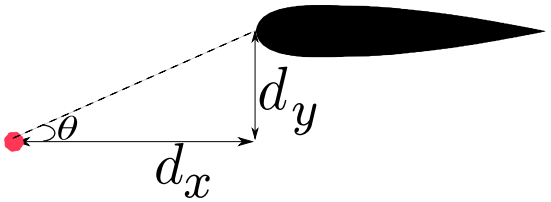


Varying  $d_x$

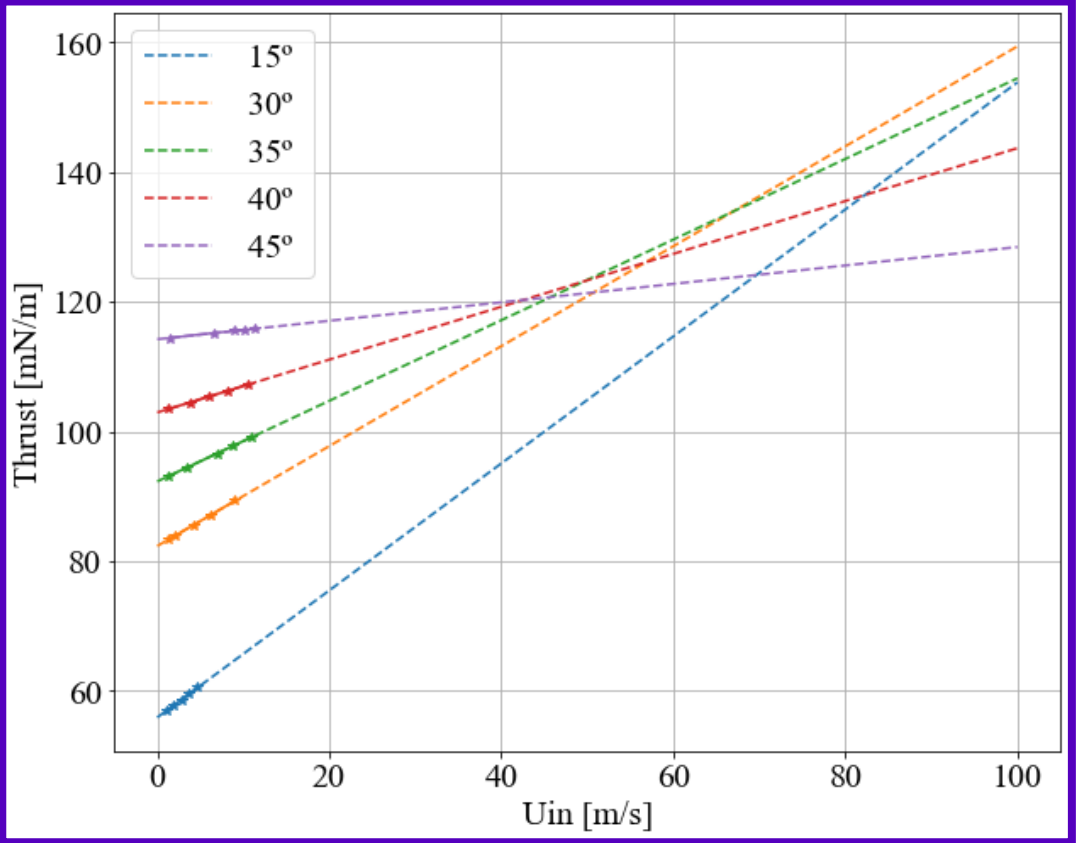


⇒  $d_x$  generates better thrust for **smaller angles**

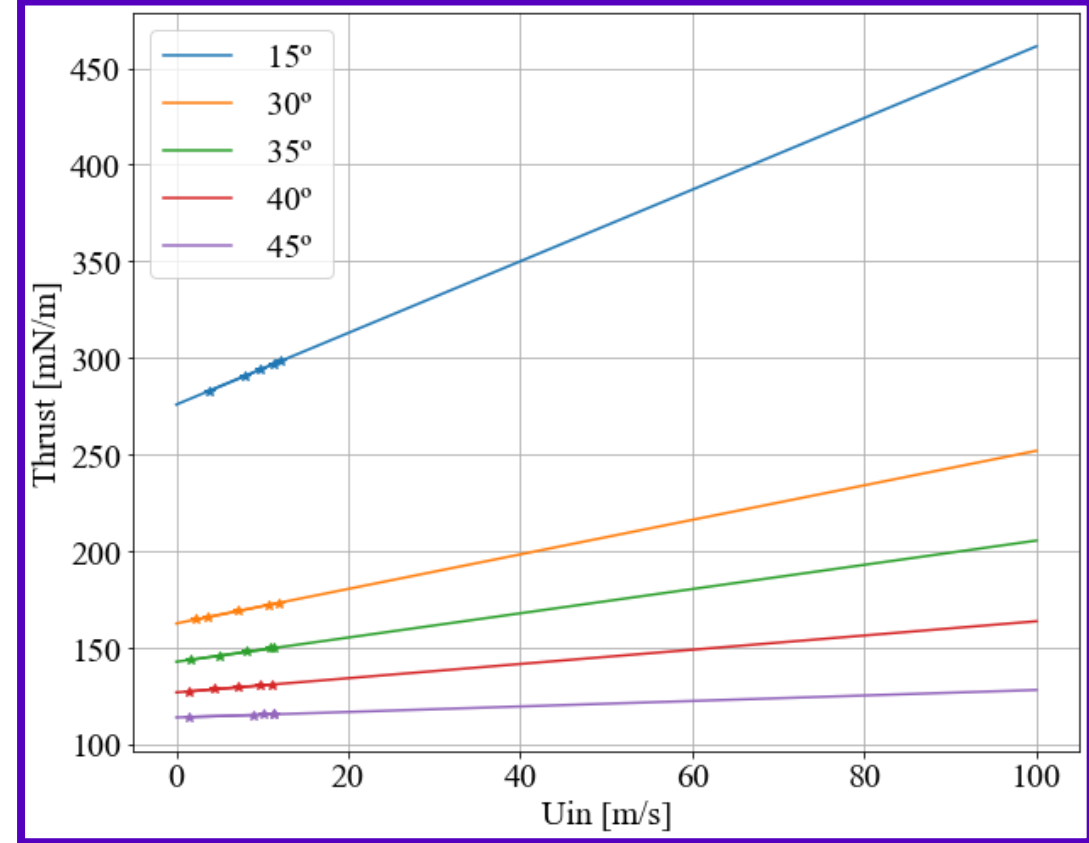
# 2. EHD Thrust



Varying  $d_y$



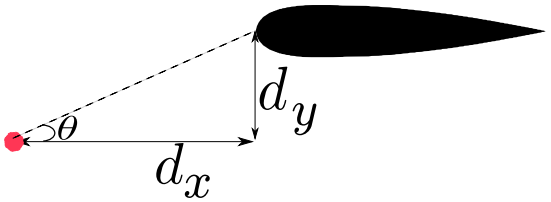
Varying  $d_x$



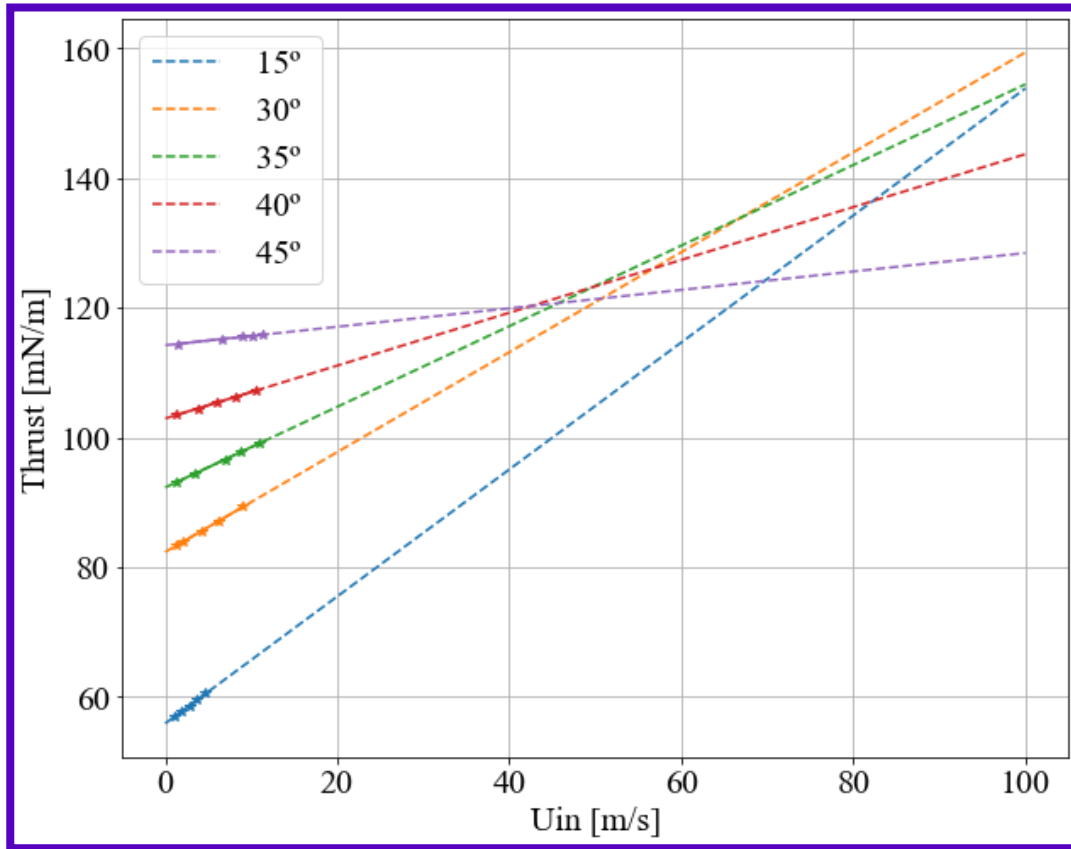
⇒  $d_x$  generates better thrust for **smaller angles**

⇒  $d_x$  generates **better thrust** than  $d_y$

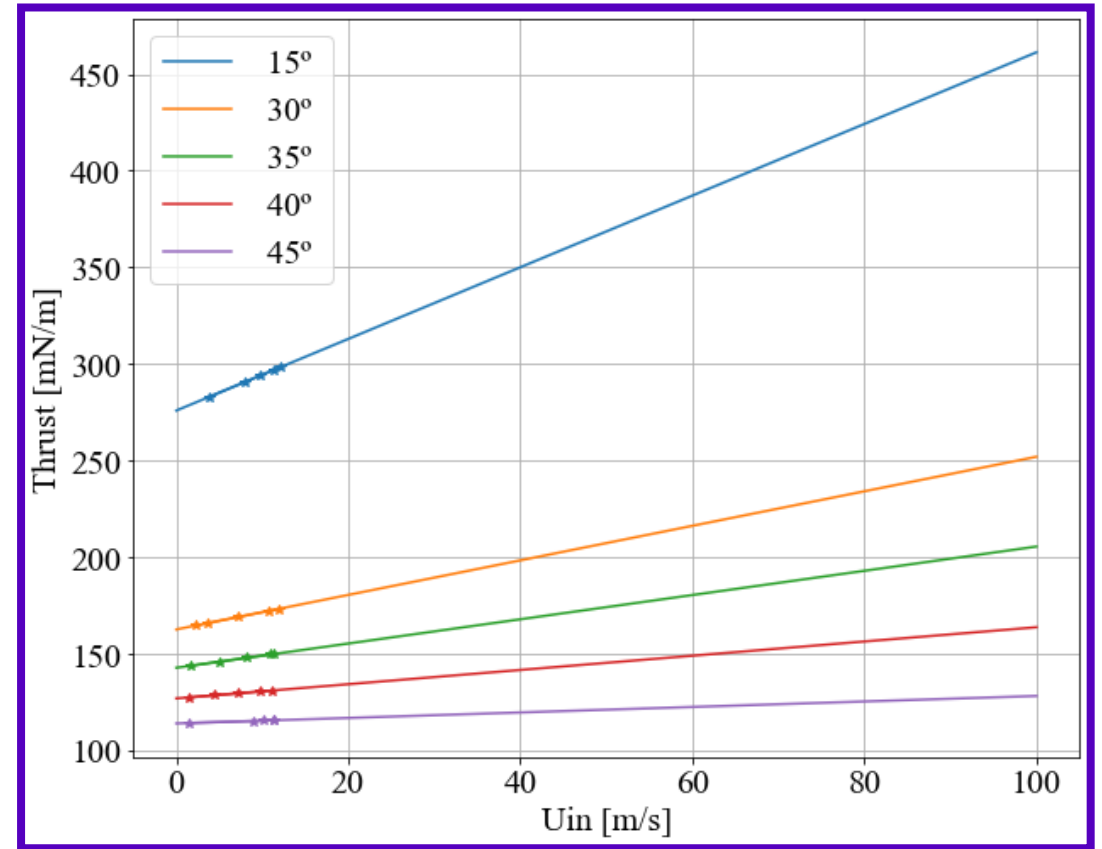
## 2. EHD Thrust



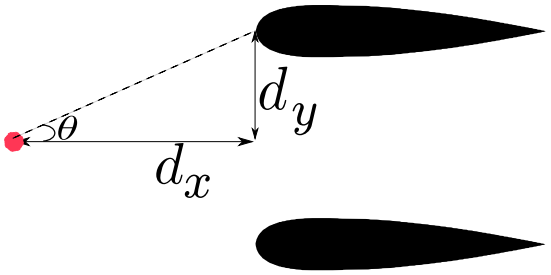
Varying  $d_y$



Varying  $d_x$

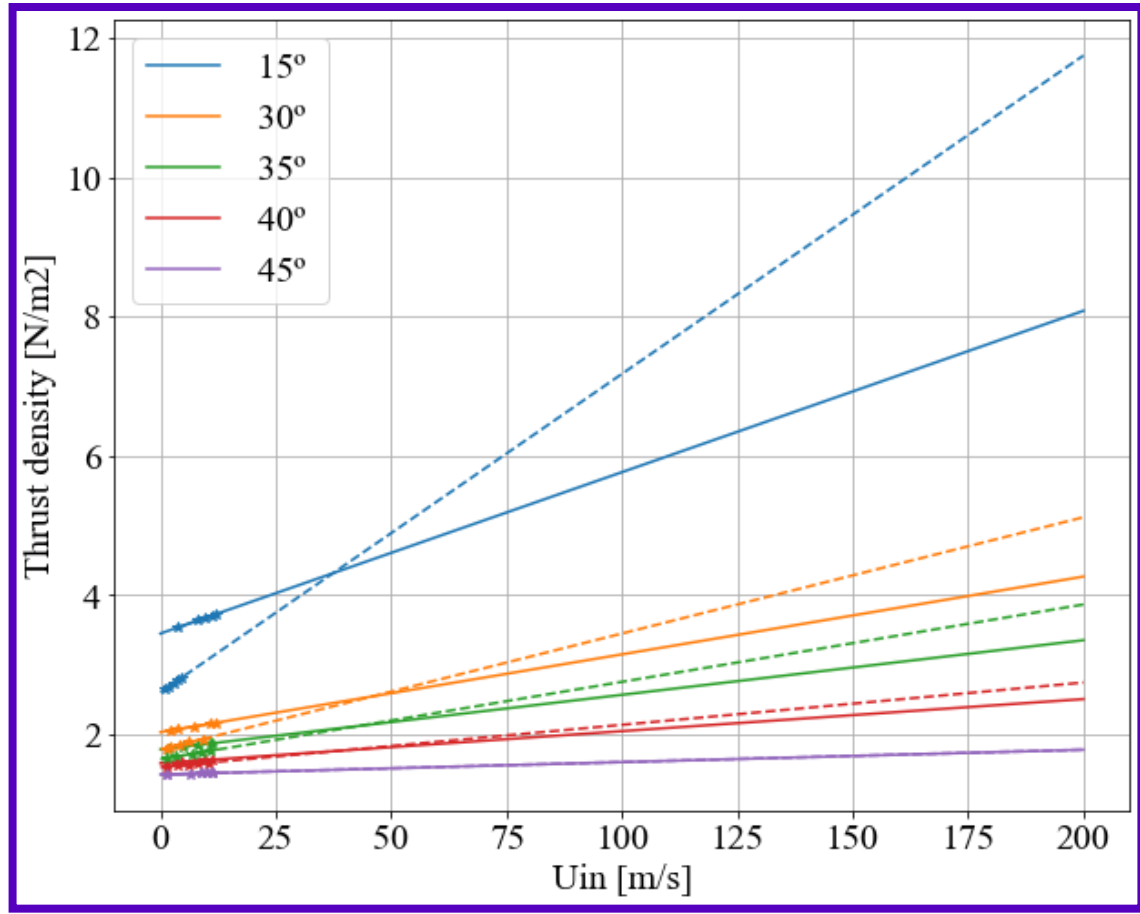


- ⇒  $d_x$  generates better thrust for **smaller angles**
- ⇒  $d_x$  generates **better thrust** than  $d_y$
- ⇒  $d_y$  more than **doubles thrust** for **small angles**



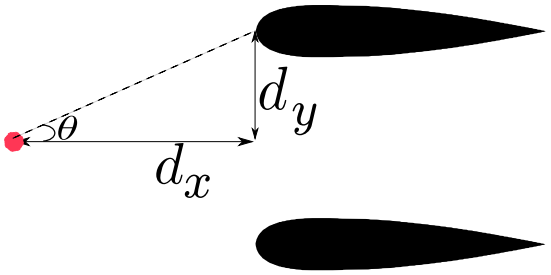
# 2. EHD Thrust Density

Varying  $d_y$  : - - - -



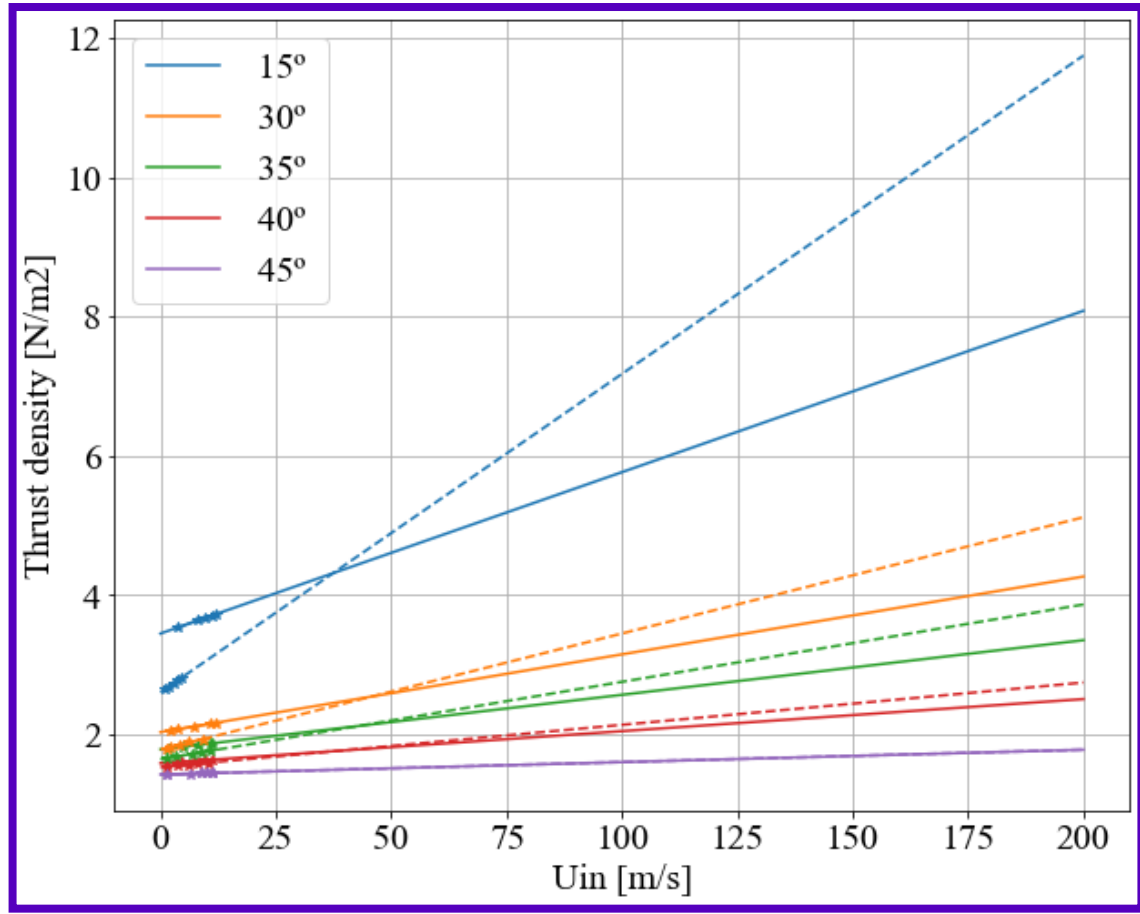
Varying  $d_x$  : ———

$E_{ext} = 5 \text{ kV/cm}$



# 2. EHD Thrust Density

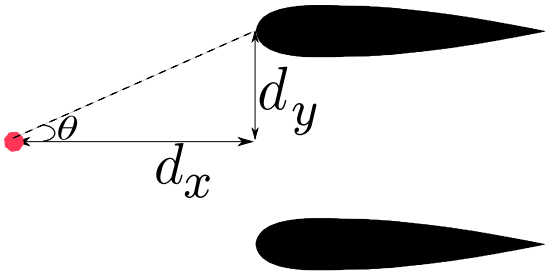
Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

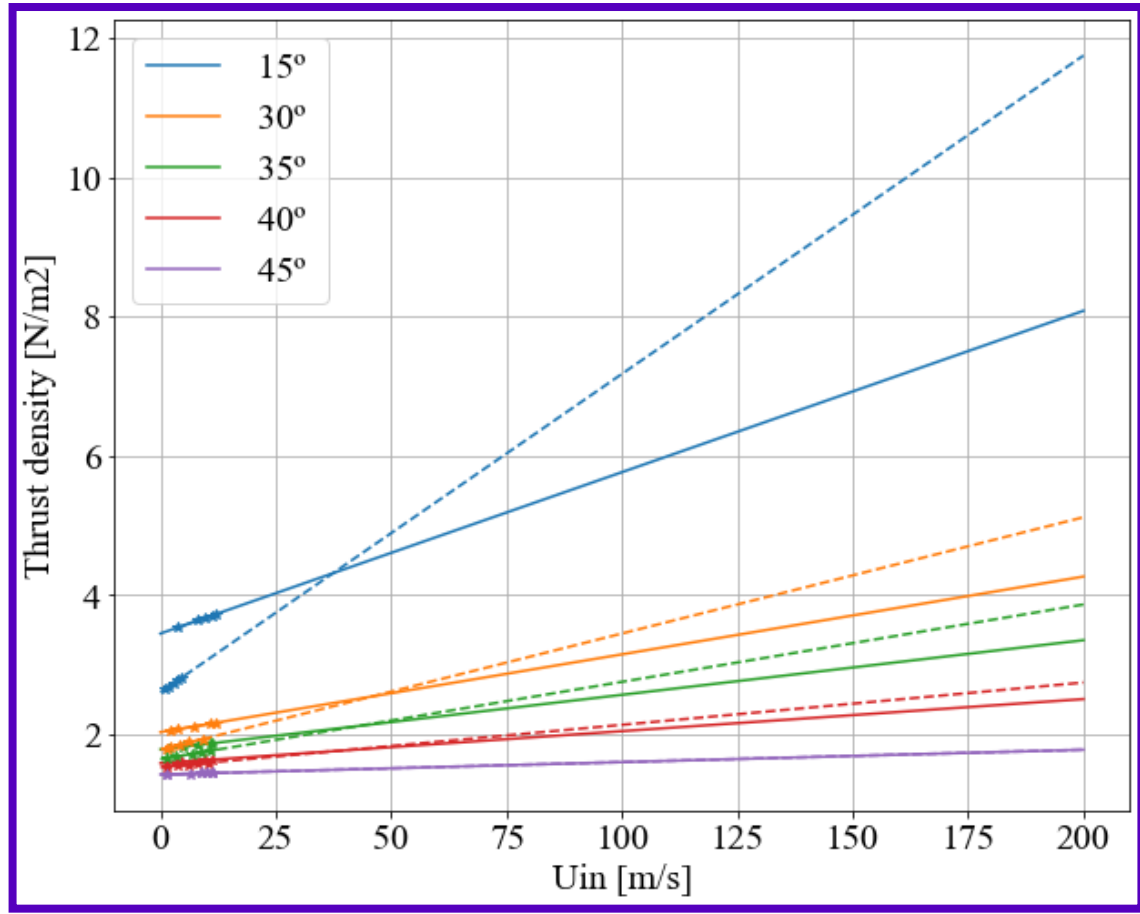
$E_{ext} = 5 \text{ kV/cm}$

⇒ **Smaller angles** are favorable.



# 2. EHD Thrust Density

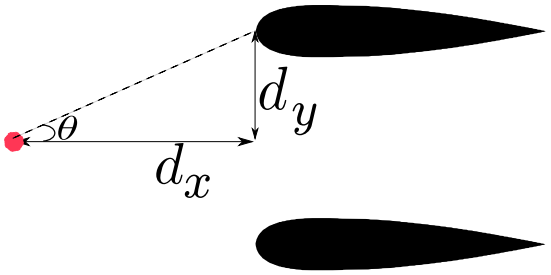
Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

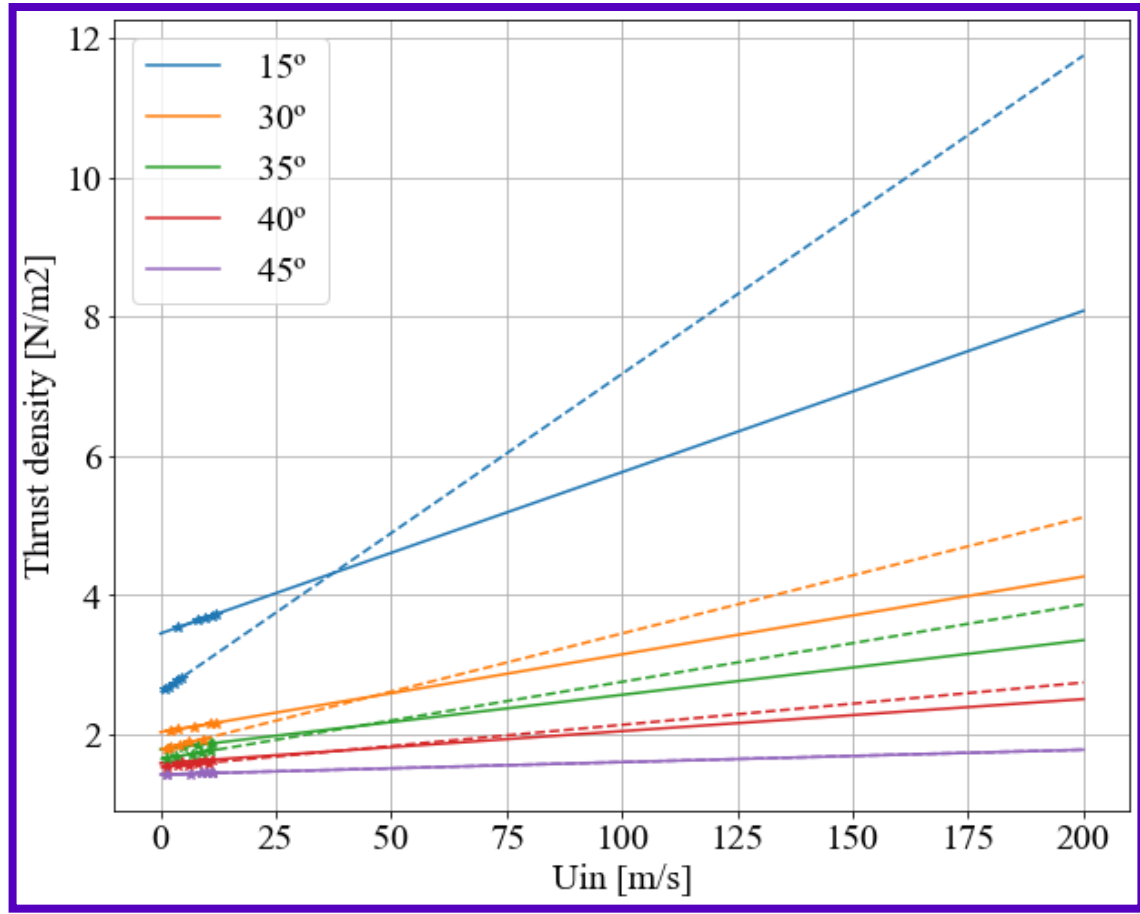
$E_{ext} = 5 \text{ kV/cm}$

- ⇒ **Smaller angles** are favorable.
- ⇒  $d_y$  better up **until almost 40 m/s**.



# 2. EHD Thrust Density

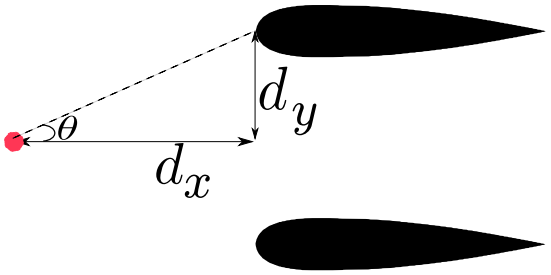
Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

$E_{ext} = 5 \text{ kV/cm}$

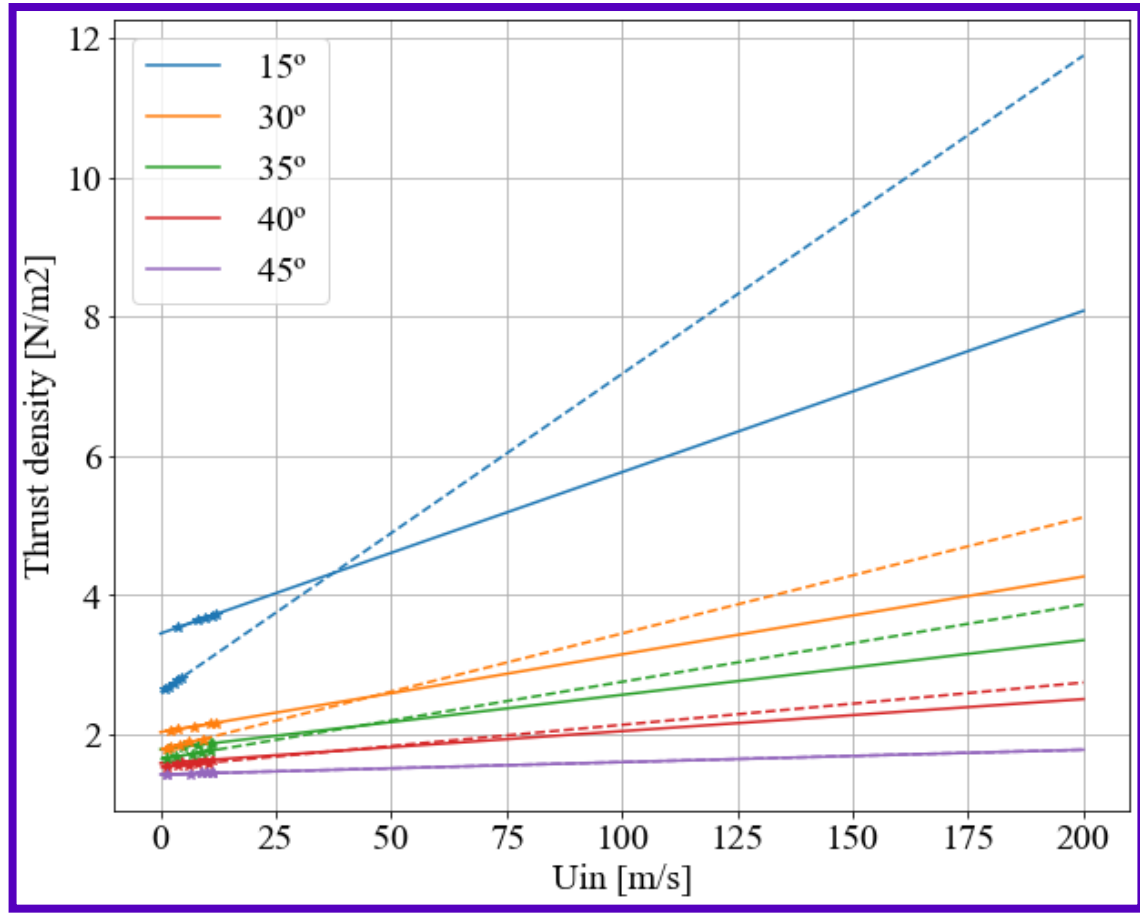
- ⇒ **Smaller angles** are favorable.
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- ⇒ Close to **10-20 N/m<sup>2</sup>**



# 2. EHD Thrust Density

Varying  $d_y$  : - - - -

Angle (°)	Applied Potential (V)	dy (cm)
15	20705	1.1



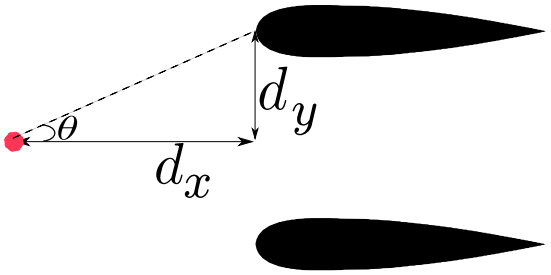
Varying  $d_x$  : ———

Angle (°)	Applied Potential (V)	dx (cm)
15	77274	14.9

Complicated experimentally !

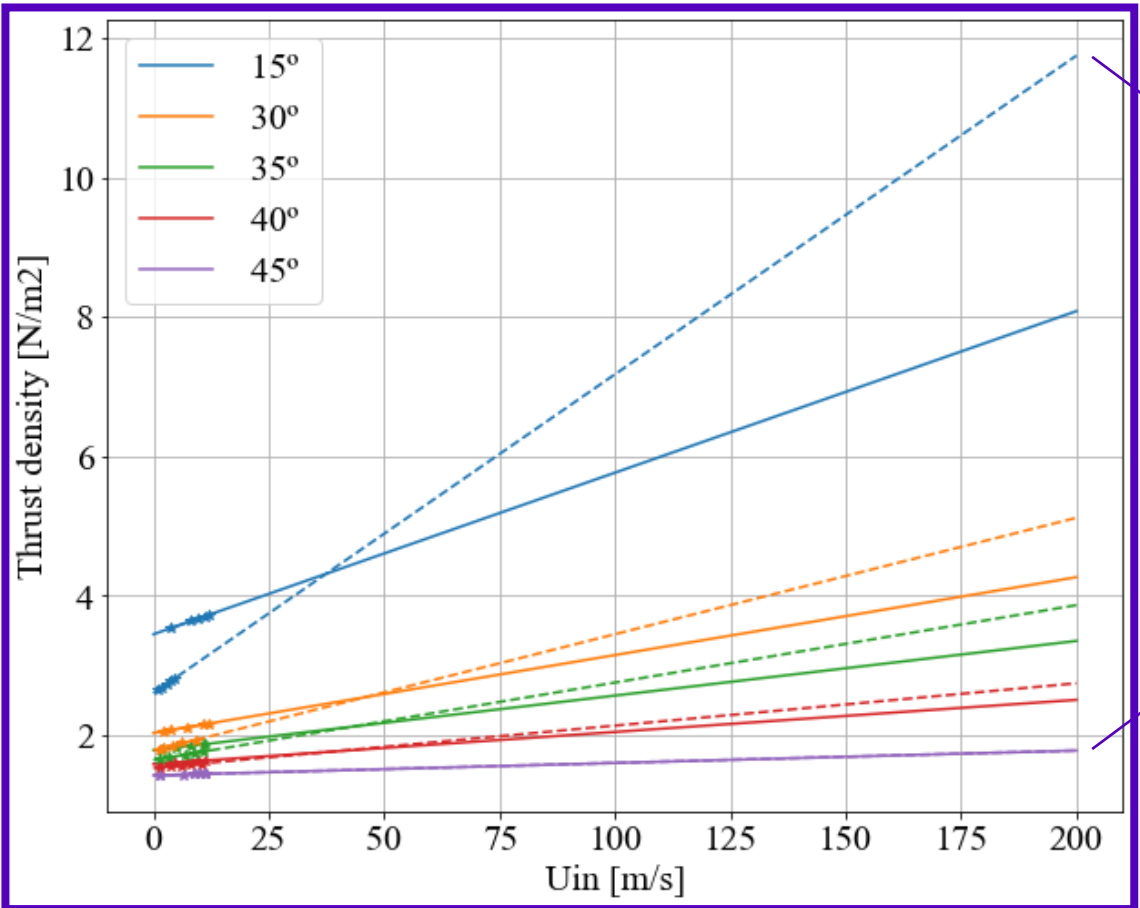
$$E_{ext} = 5 \text{ kV/cm}$$

- ⇒ **Smaller angles** are favorable.
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- ⇒ Close to **10-20 N/m<sup>2</sup>**



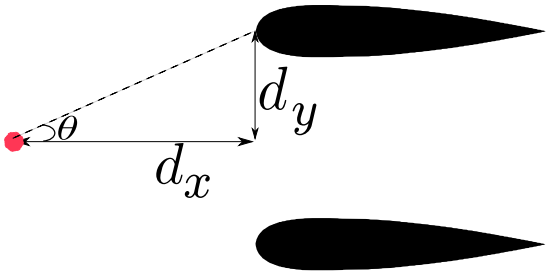
# 2. EHD Thrust Density

Varying  $d_y$  : - - - -  
 Varying  $d_x$  : ————



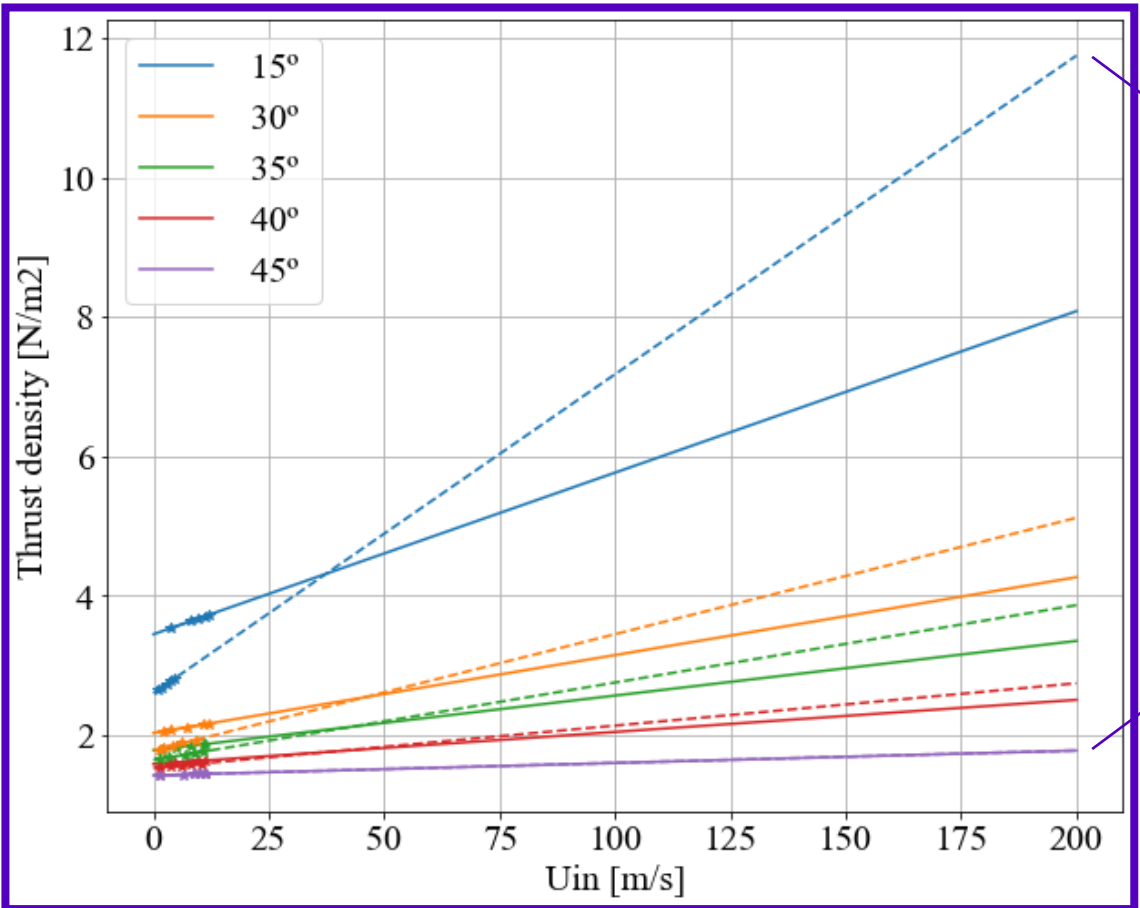
**Crucial** set up !

⇒ **Smaller angles : 5x** more thrust density



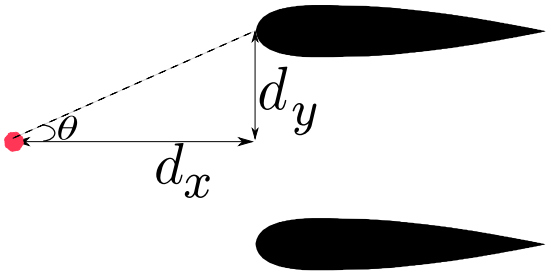
# 2. EHD Thrust Density

Varying  $d_y$  : - - - -  
 Varying  $d_x$  : ———



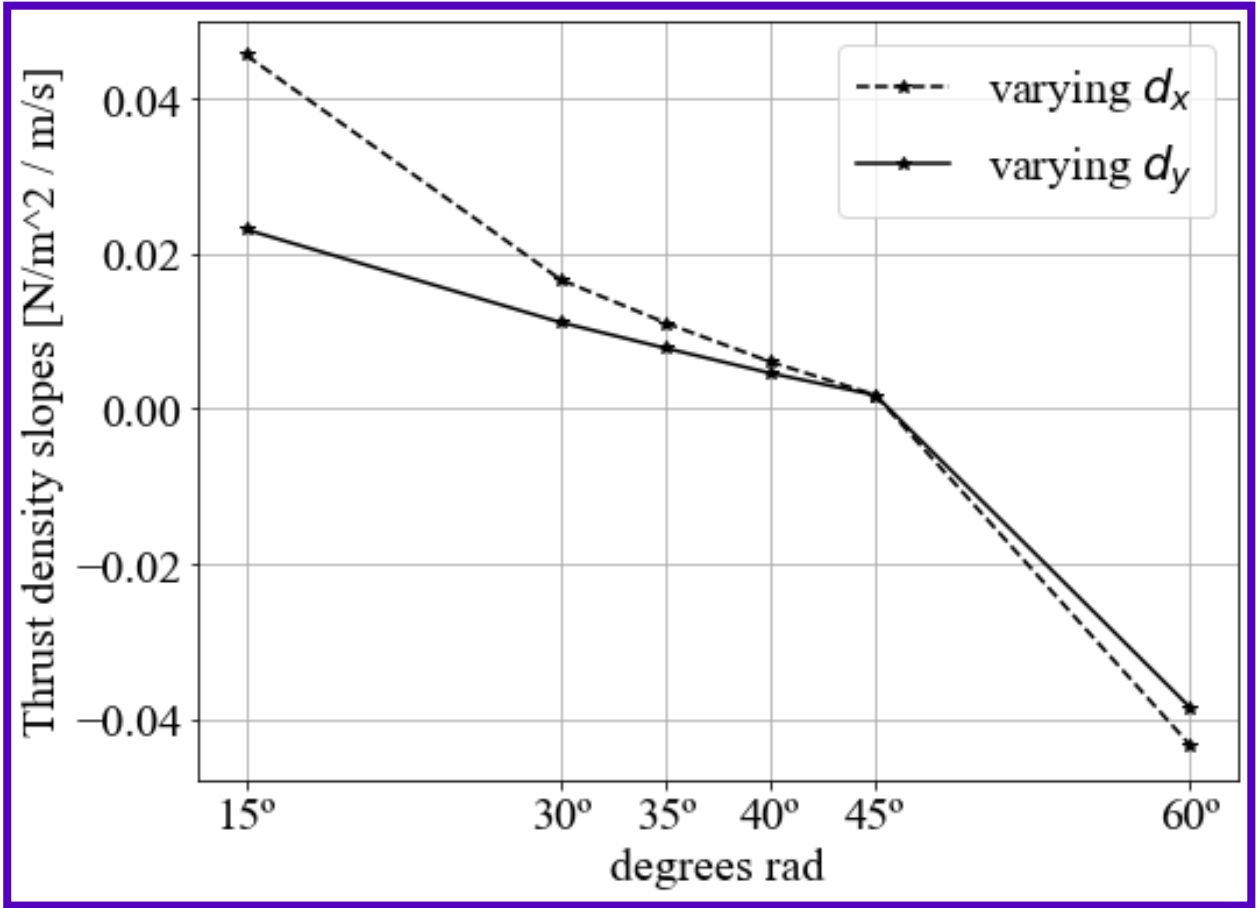
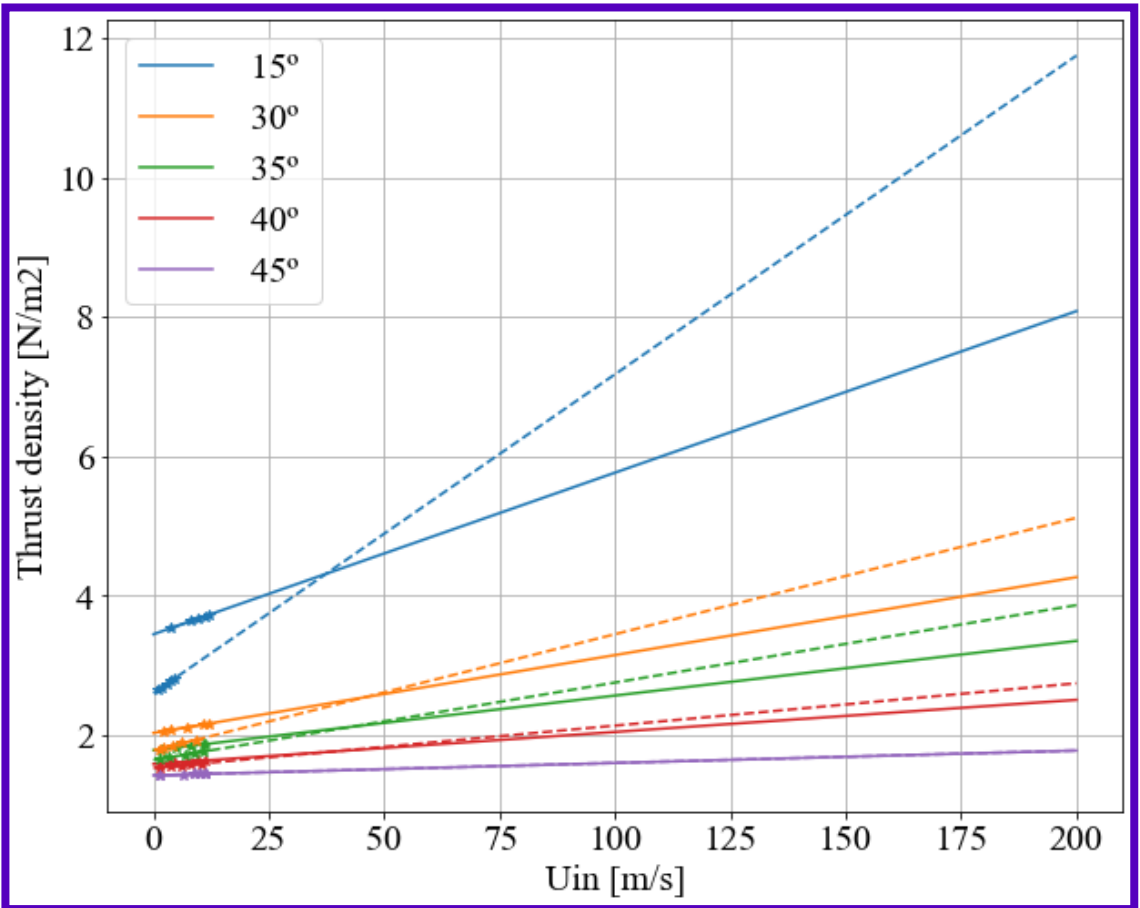
**Crucial** set up !

- ⇒ **Smaller angles** : **5x** more thrust density
- ⇒ **d<sub>y</sub>** more thrust density, due to **thruster surface decrease**



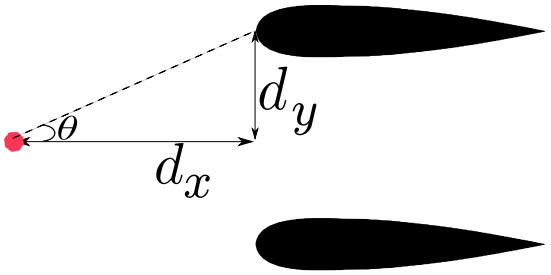
# 2. EHD Thrust Density

Varying  $d_y$  : - - - -  
 Varying  $d_x$  : ———



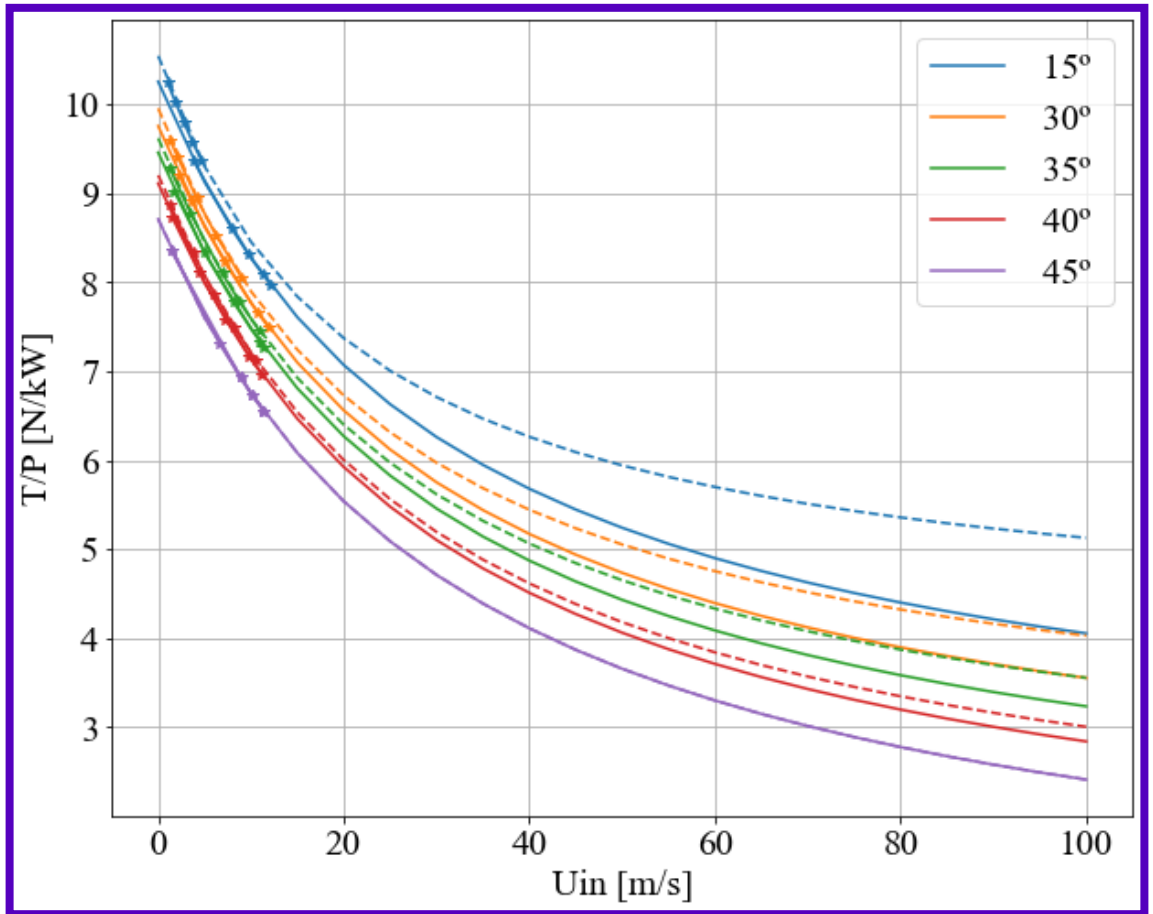
⇒ **Smaller angles : 5x** more thrust density

⇒  **$d_y$  more thrust density**, due to **thruster surface decrease**



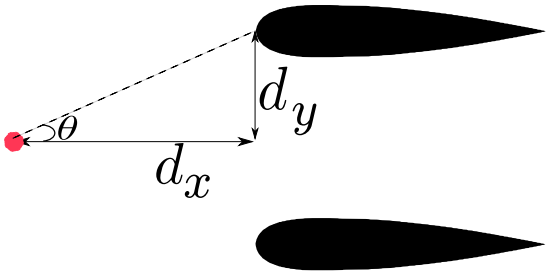
# 2. Thrust-to-Power

Varying  $d_y$  : - - - -



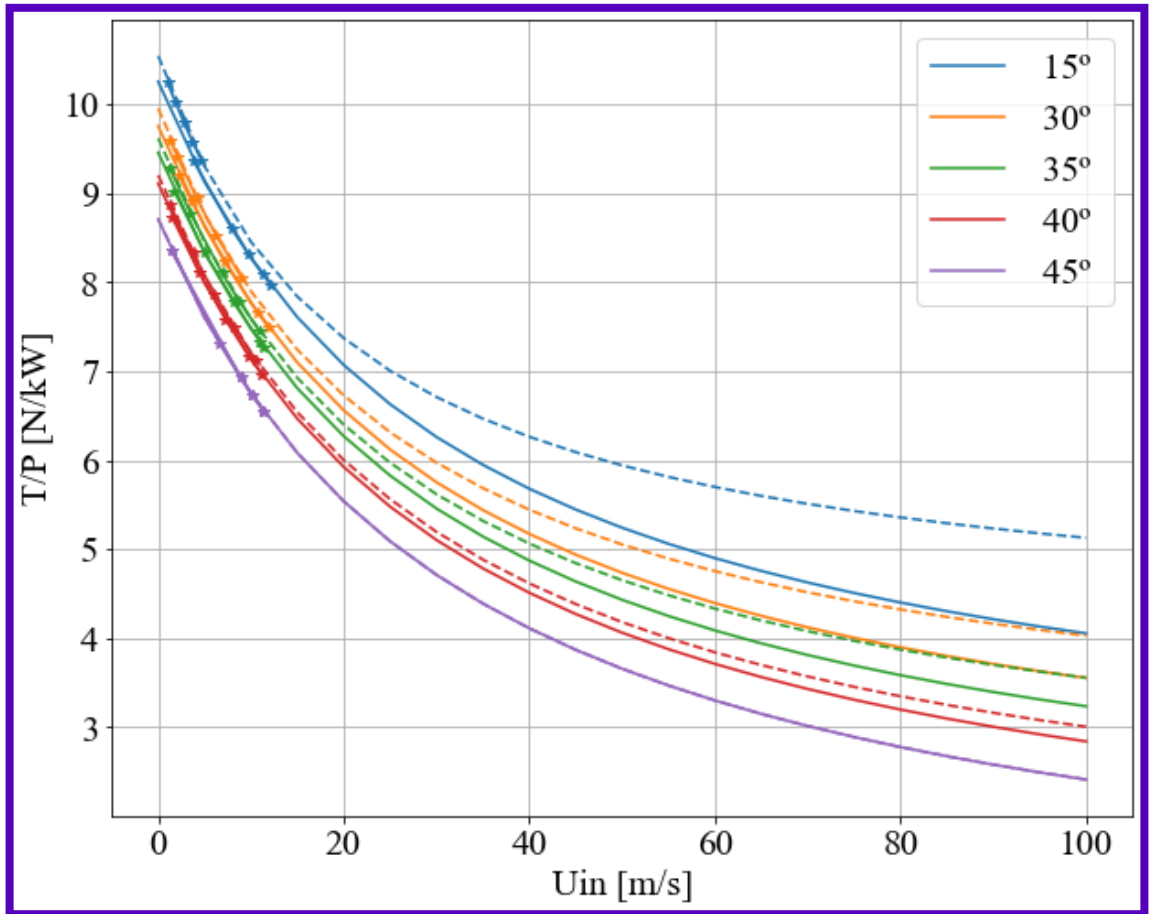
Varying  $d_x$  : ———

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# 2. Thrust-to-Power

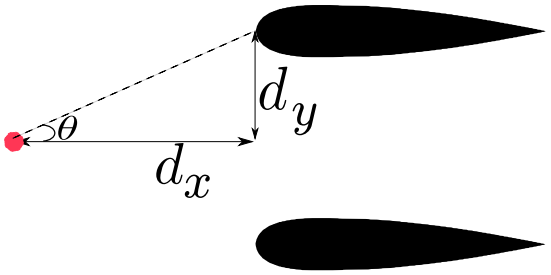
Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

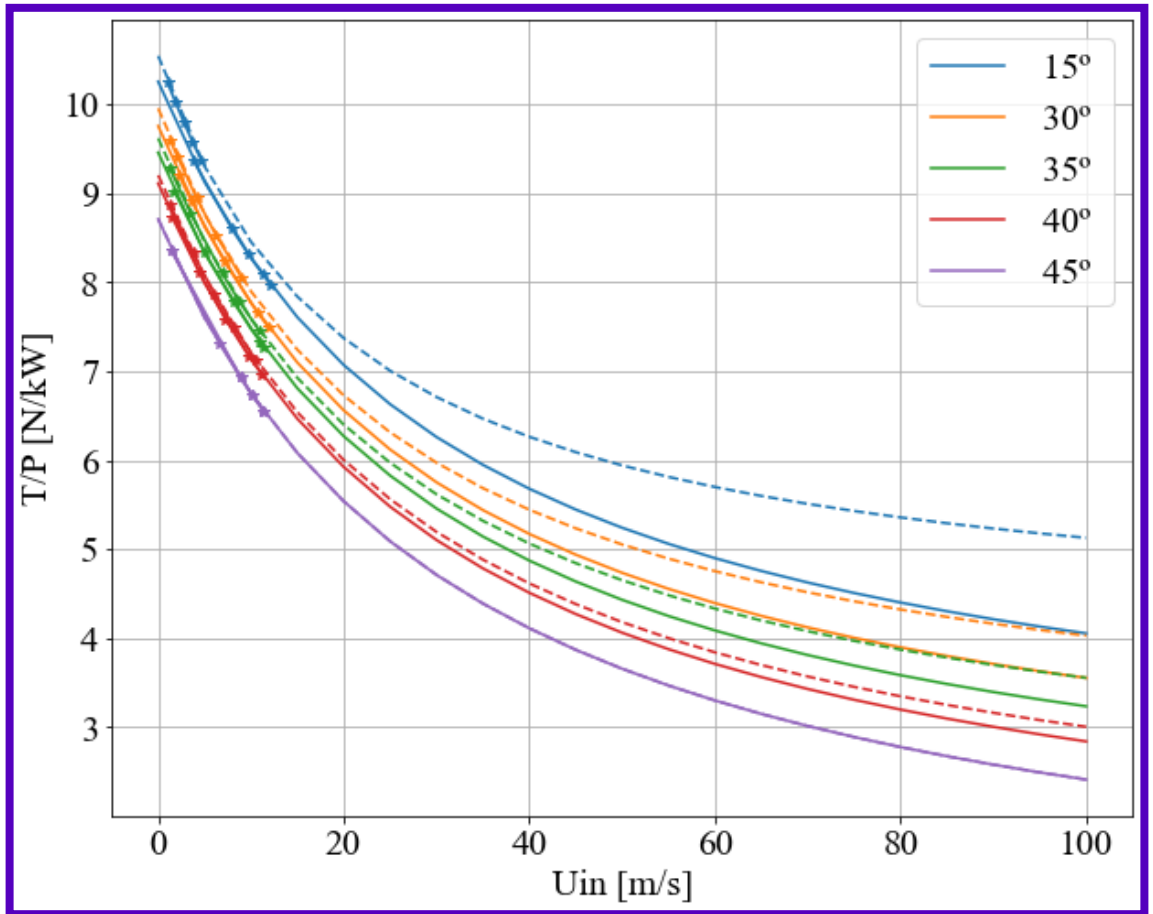
$E_{ext} = 5 \text{ kV/cm}$

⇒ **Smaller angles** : high thrust-to-power ratio



# 2. Thrust-to-Power

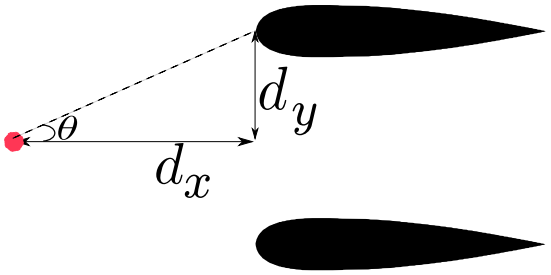
Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

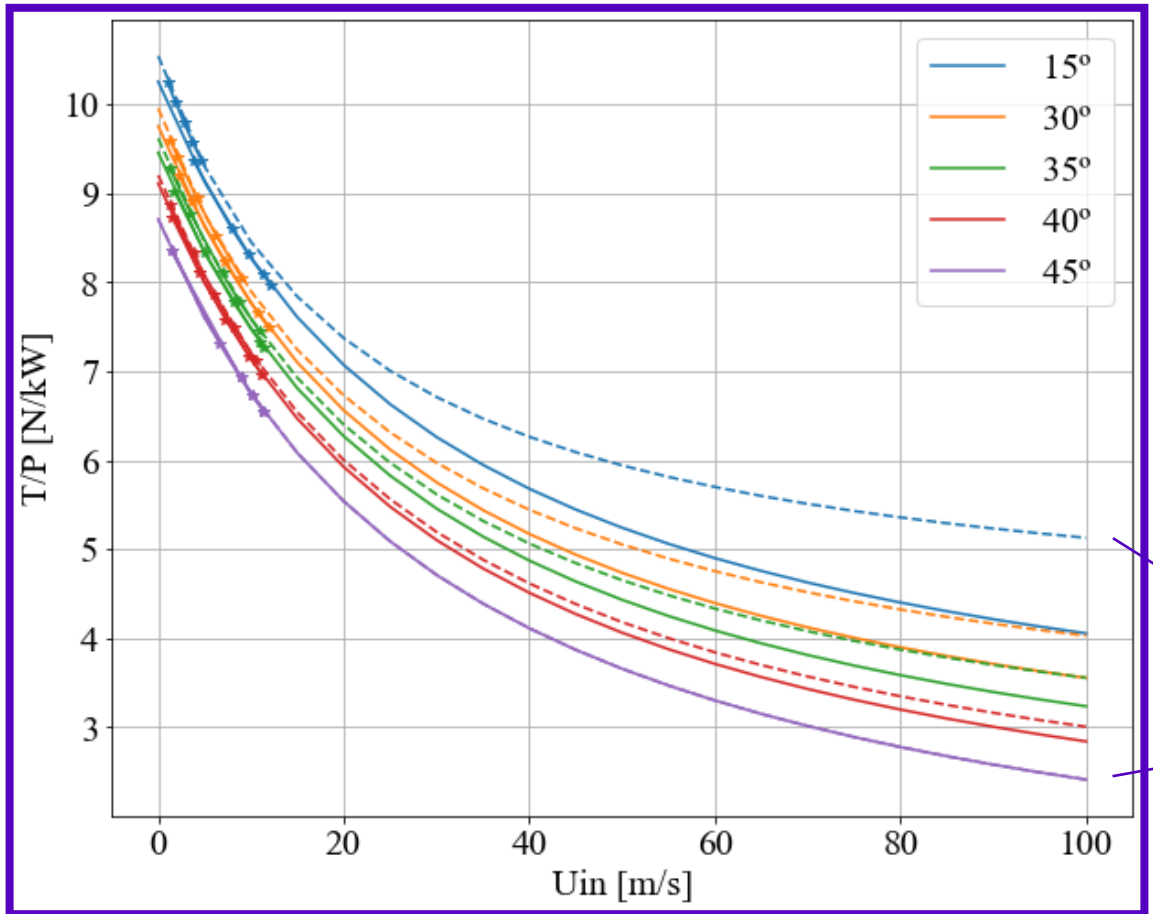
$E_{ext} = 5 \text{ kV/cm}$

- ⇒ **Smaller angles** : high thrust-to-power ratio
- ⇒ Always **larger than turbofan's 3 N/kW**



# 2. Thrust-to-Power

Varying  $d_y$  : - - - -

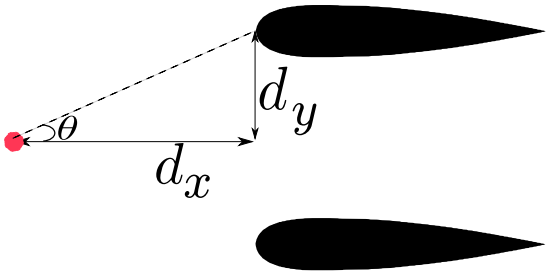


Varying  $d_x$  : ———

**Crucial** set up !

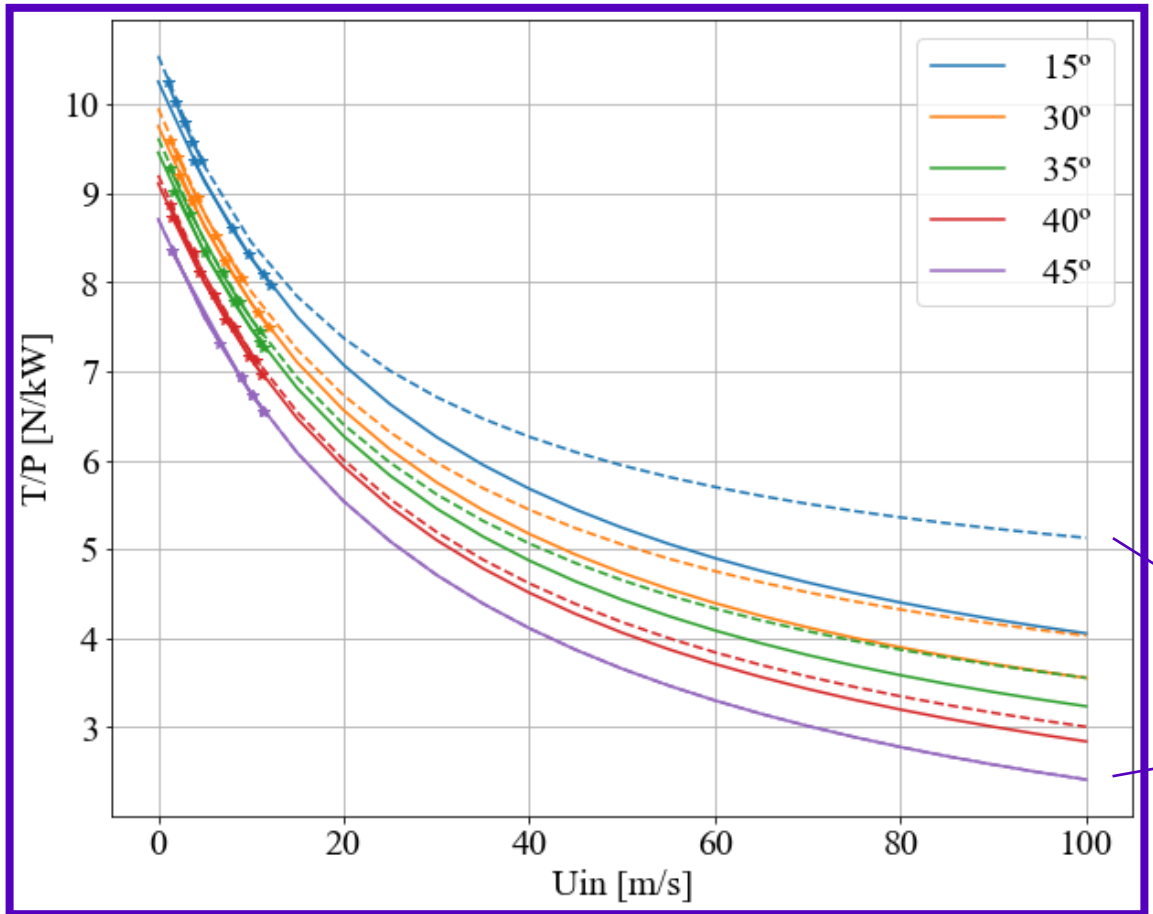
$E_{ext} = 5 \text{ kV/cm}$

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# 2. Thrust-to-Power

Varying  $d_y$  : - - - -

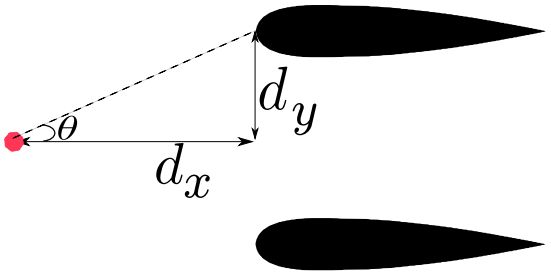


Varying  $d_x$  : ———

**Crucial** set up !

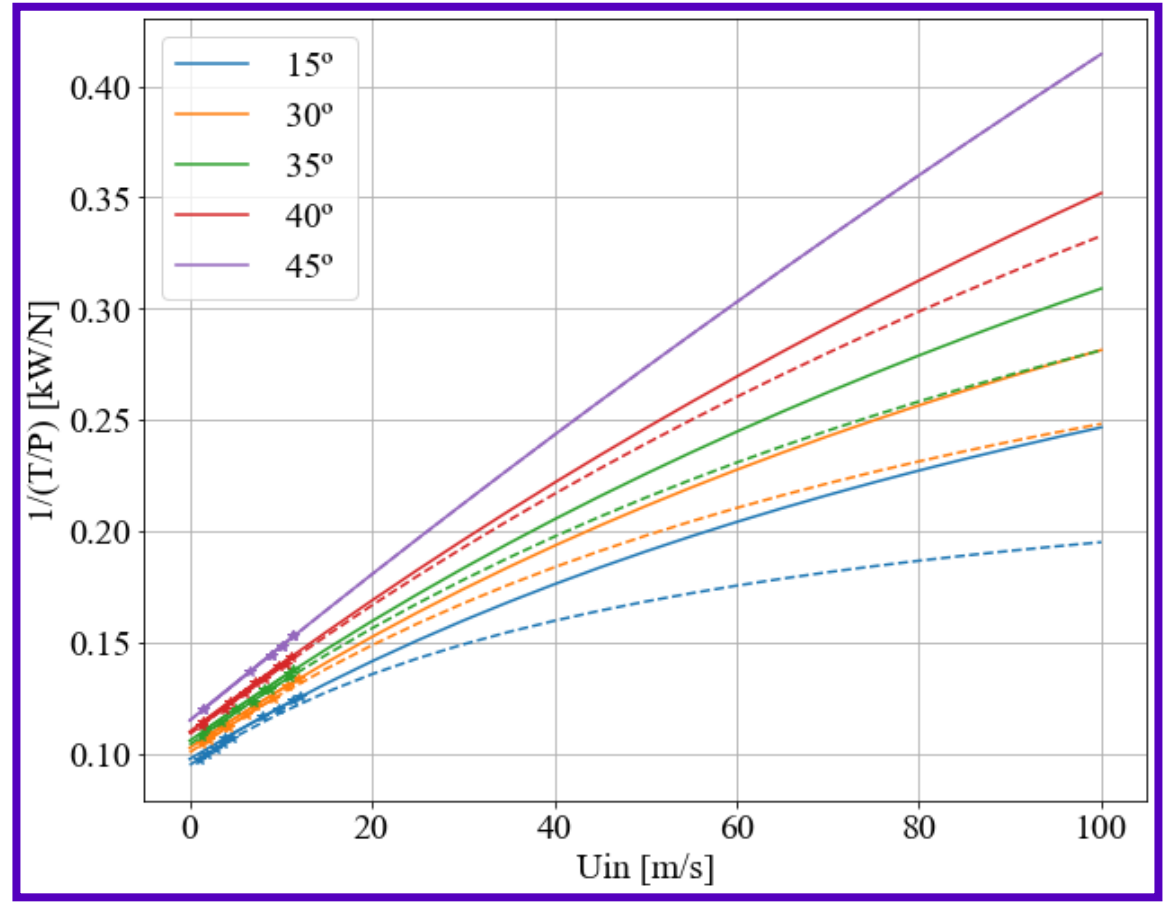
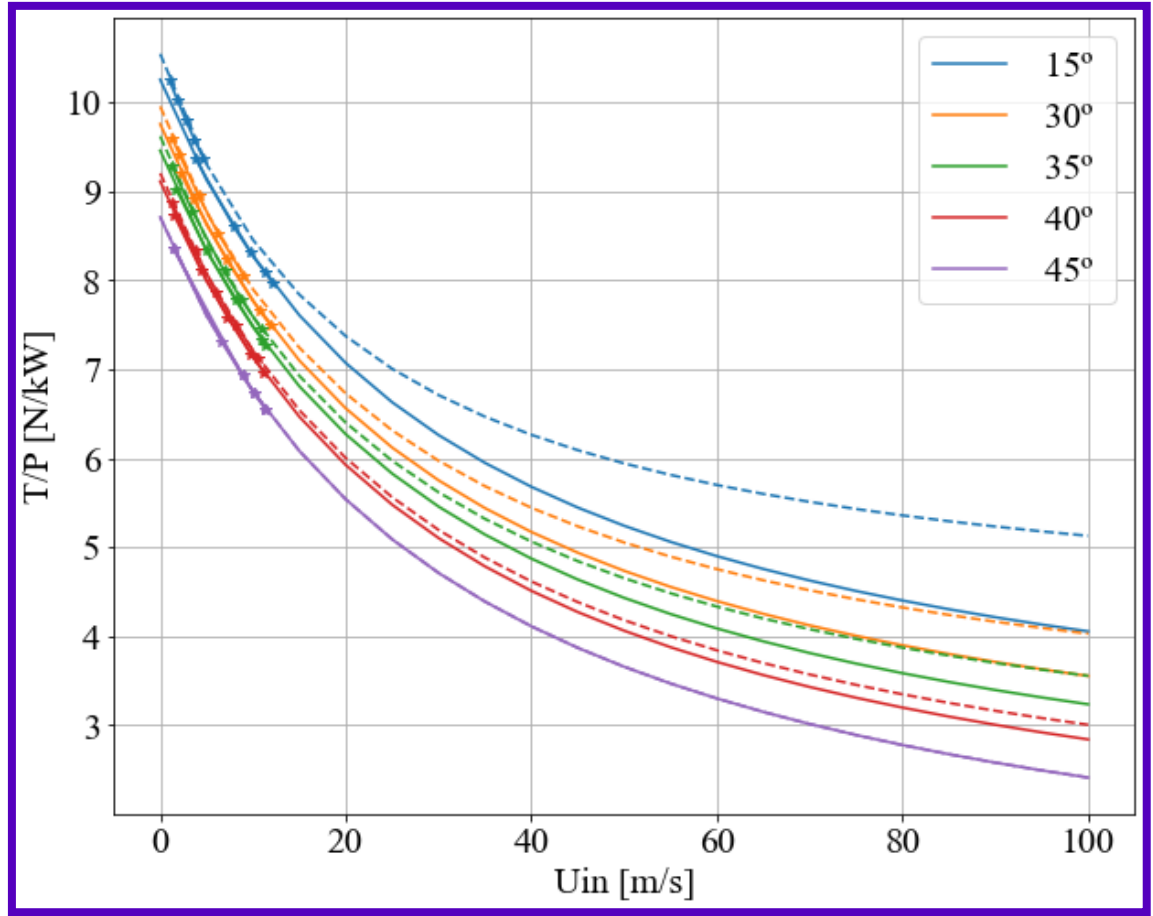
$E_{ext} = 5 \text{ kV/cm}$

- ⇒ **Smaller angles** : high thrust-to-power ratio
- ⇒ Always **larger than turbofan's 3 N/kW**
- ⇒  $T/P \sim 1/U_{in}$

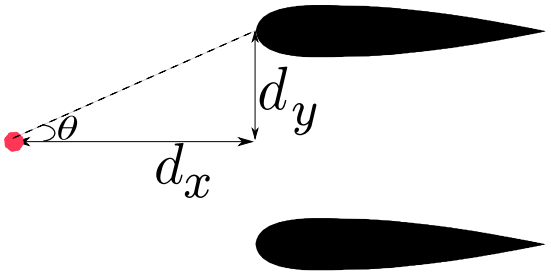


# 2. Thrust-to-Power

Varying  $d_x$  : ———  
 Varying  $d_y$  : - - - -

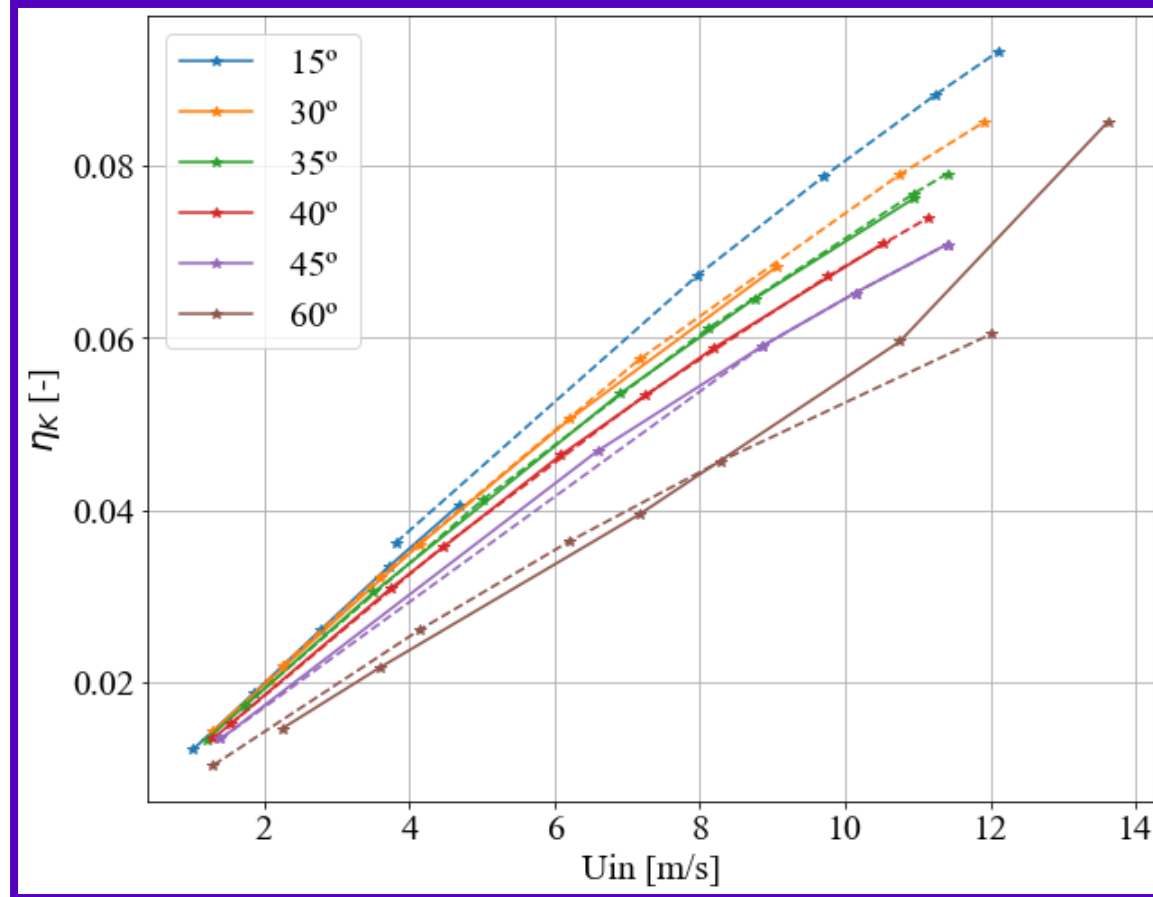


$\Rightarrow T/P \sim 1/U_{in}$  : set up **dependent** !



# 2. Efficiency

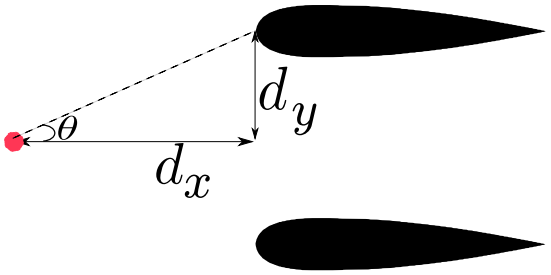
Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

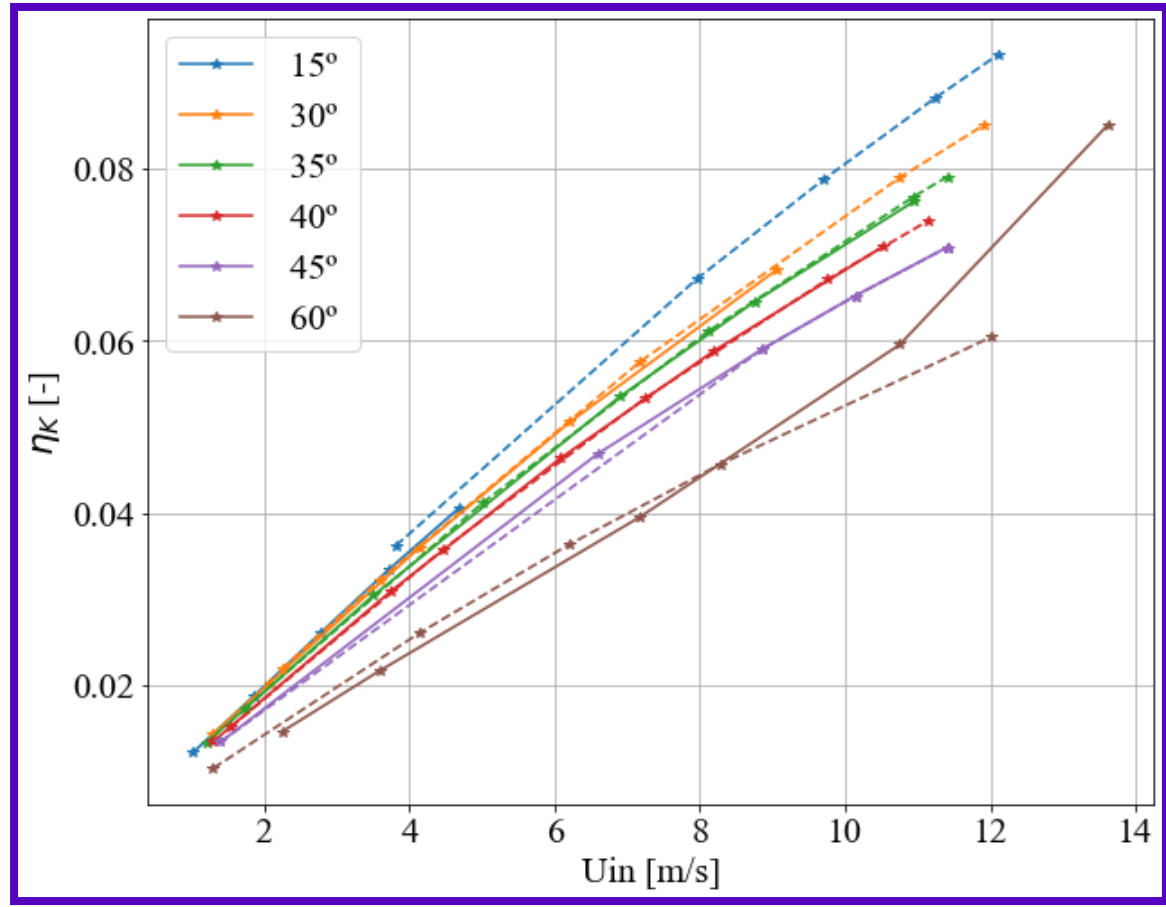
$E_{ext} = 5 \text{ kV/cm}$

⇒ **Smaller angles** : more efficient.



# 2. Efficiency

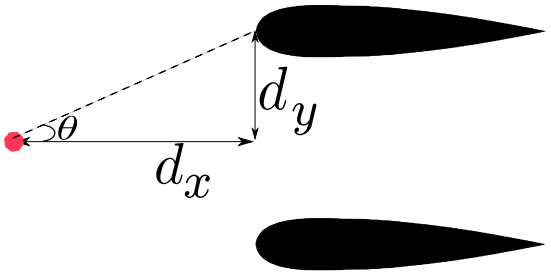
Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

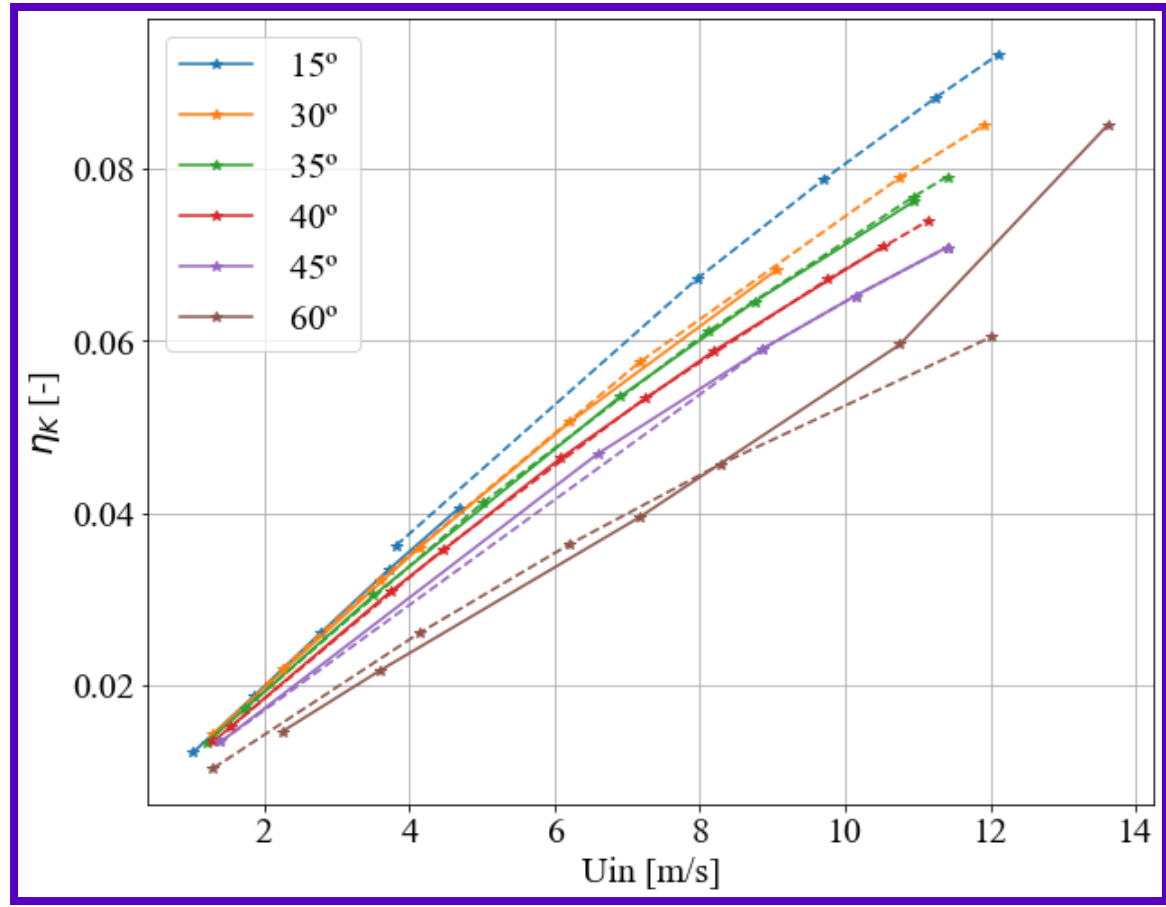
$E_{ext} = 5$  kV/cm

- ⇒ **Smaller angles** : more efficient.
- ⇒ Efficiency **increase with external flow** speed.



## 2. Efficiency

Varying  $d_y$  : - - - -



Varying  $d_x$  : ———

$E_{ext} = 5 \text{ kV/cm}$

- ⇒ **Smaller angles** : more efficient.
- ⇒ Efficiency **increase with external flow** speed.
- ⇒ **Low** efficiencies nonetheless

# Conclusion

- Numerical methods used to find **optimal configurations**.



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- Same for **Thrust-to-Power** and **efficiency**.



# Conclusion

- Numerical methods used to find **optimal configurations**.
- **Smaller angles** are **optimal** for **thrust density** generation.
- Same for **Thrust-to-Power** and **efficiency**.
- Competitive **thrust density** and **thrust-to-power**.



# Thank you !

EUCASS 2025 - Juin 30th to July 4th

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

CNRS - IMFT

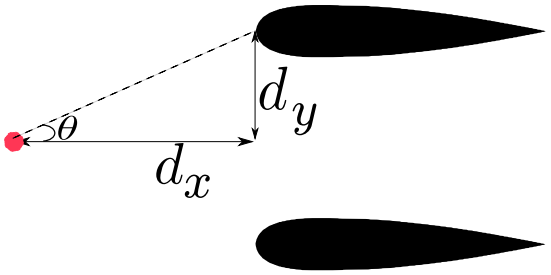
IPROP EIC Pathfinder project

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under grant agreement No 101098900. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Innovation Council and SMEs Executive Agency (EISMEA). Neither the European Union nor the granting authority can be held responsible for them.

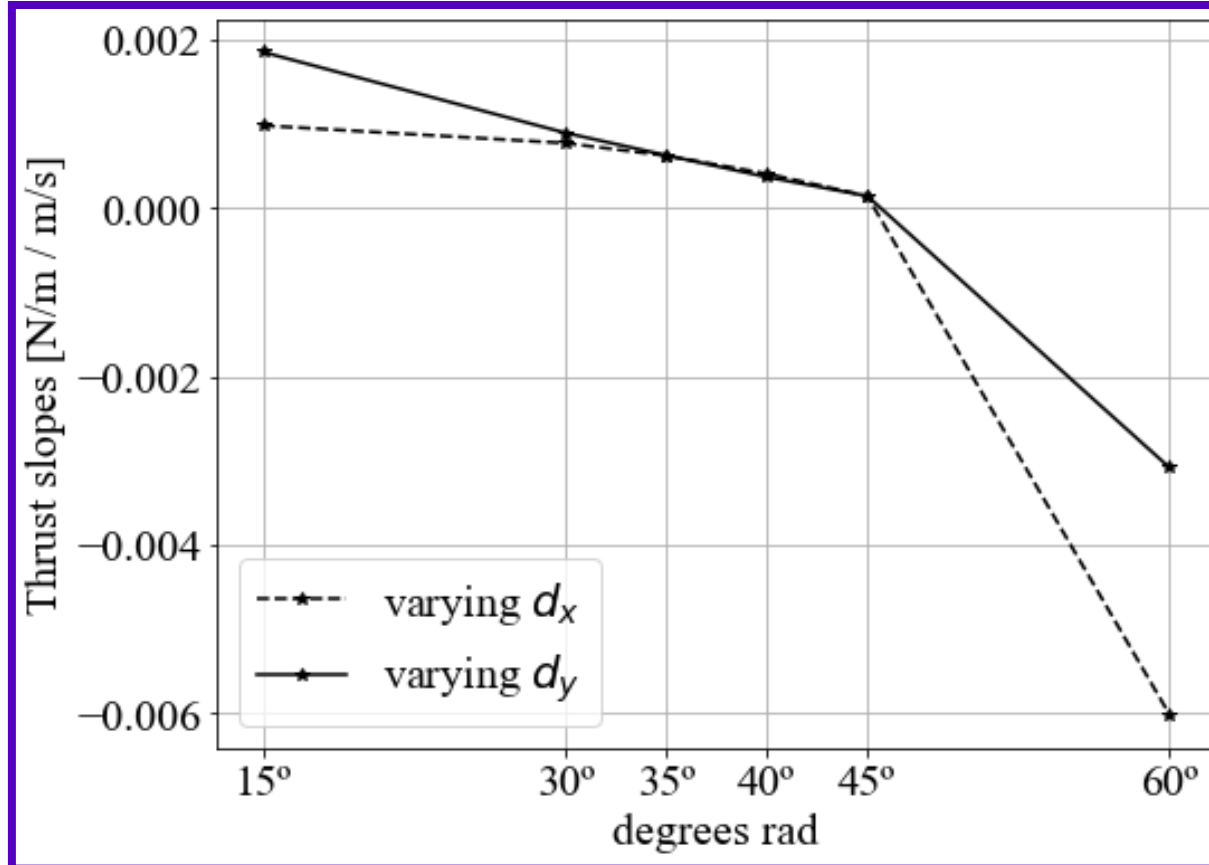
European  
Innovation  
Council

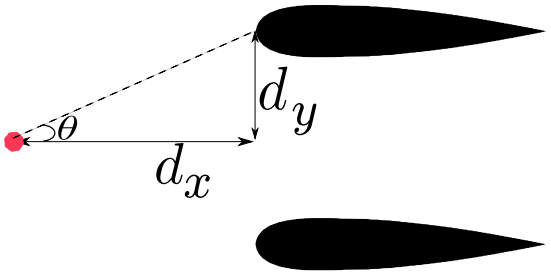


**Funded by  
the European Union**

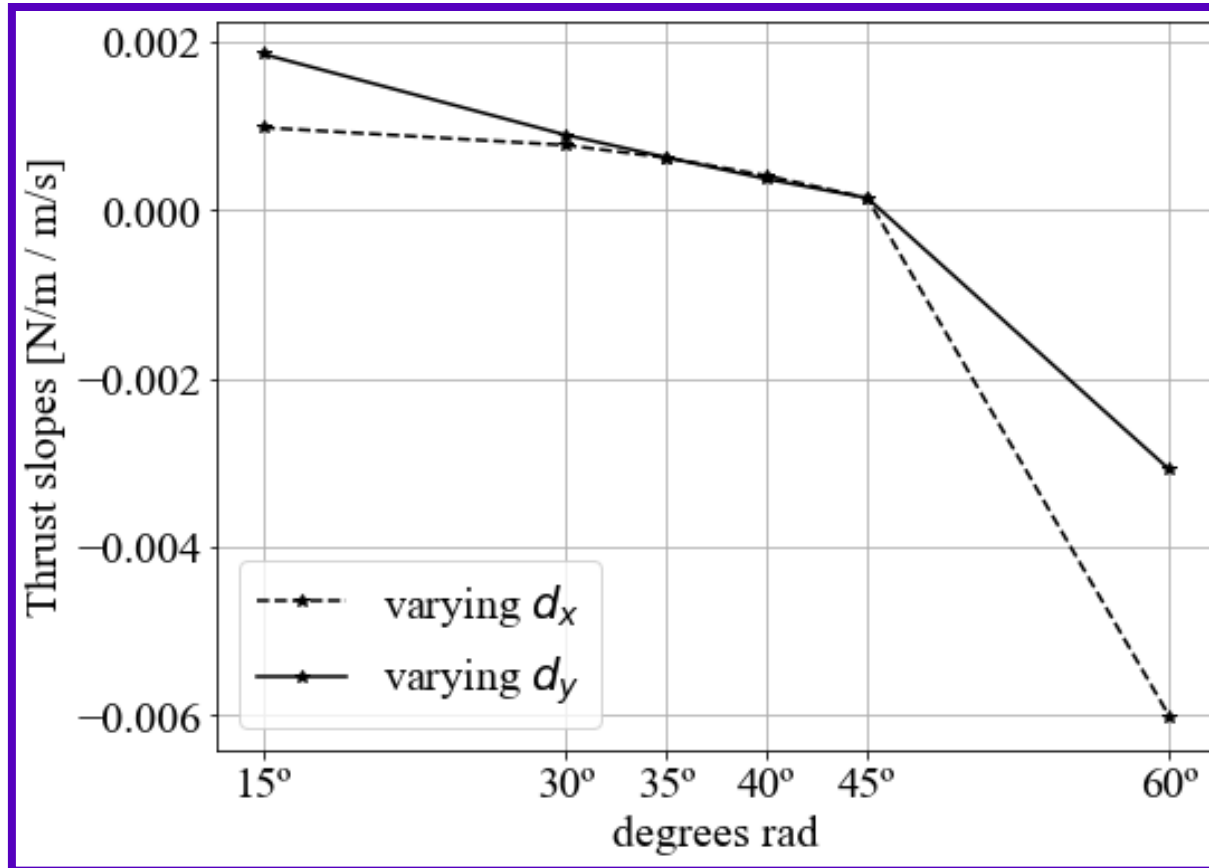


## 2. Optimal angle $\theta$ ?

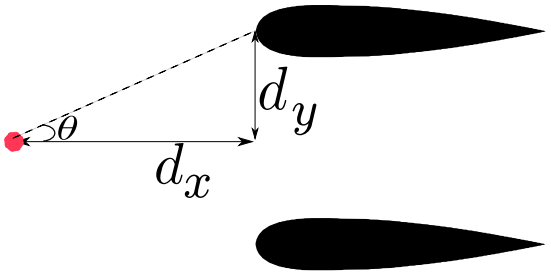




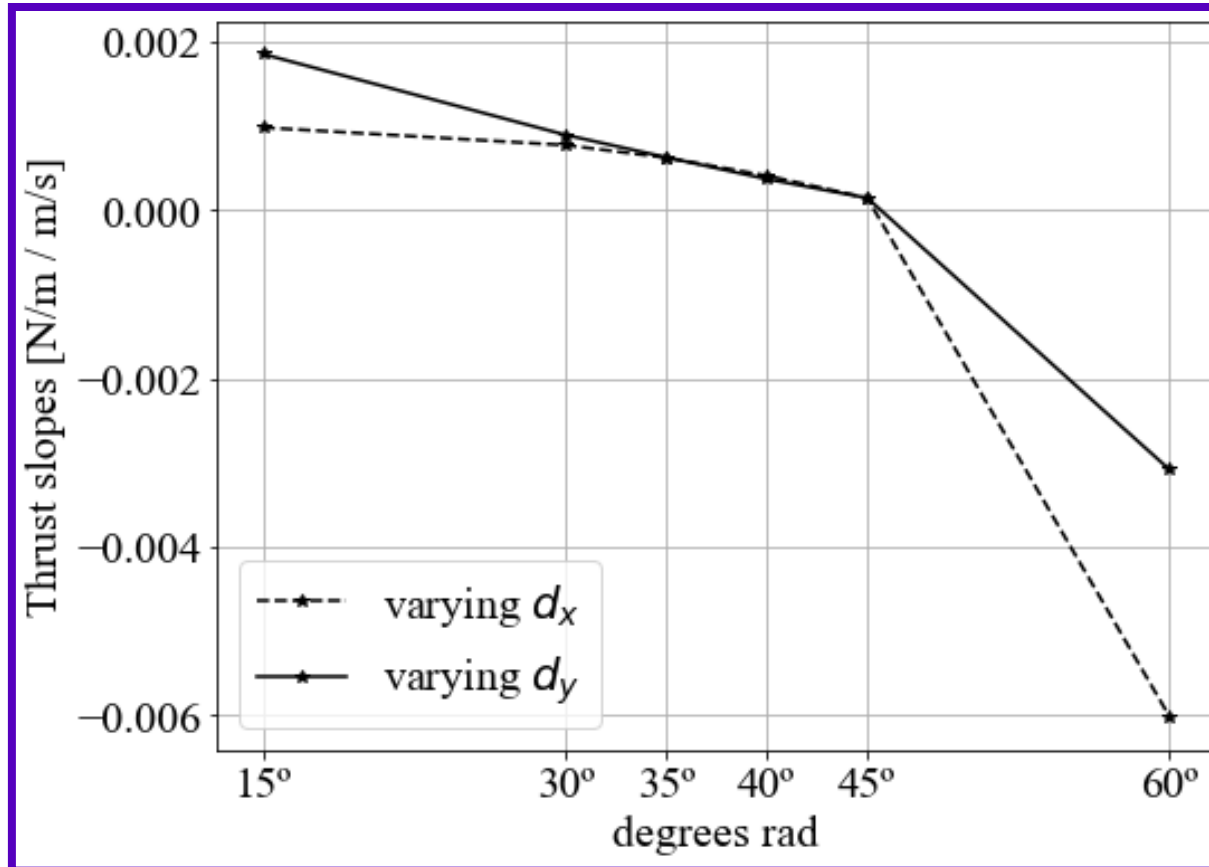
## 2. Optimal angle $\theta$ ?



⇒ **Smaller angles** : higher thrust

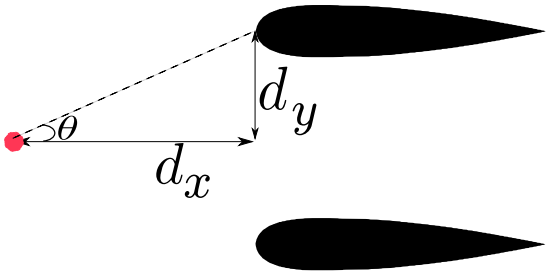


## 2. Optimal angle $\theta$ ?



⇒ **Smaller angles** : higher thrust

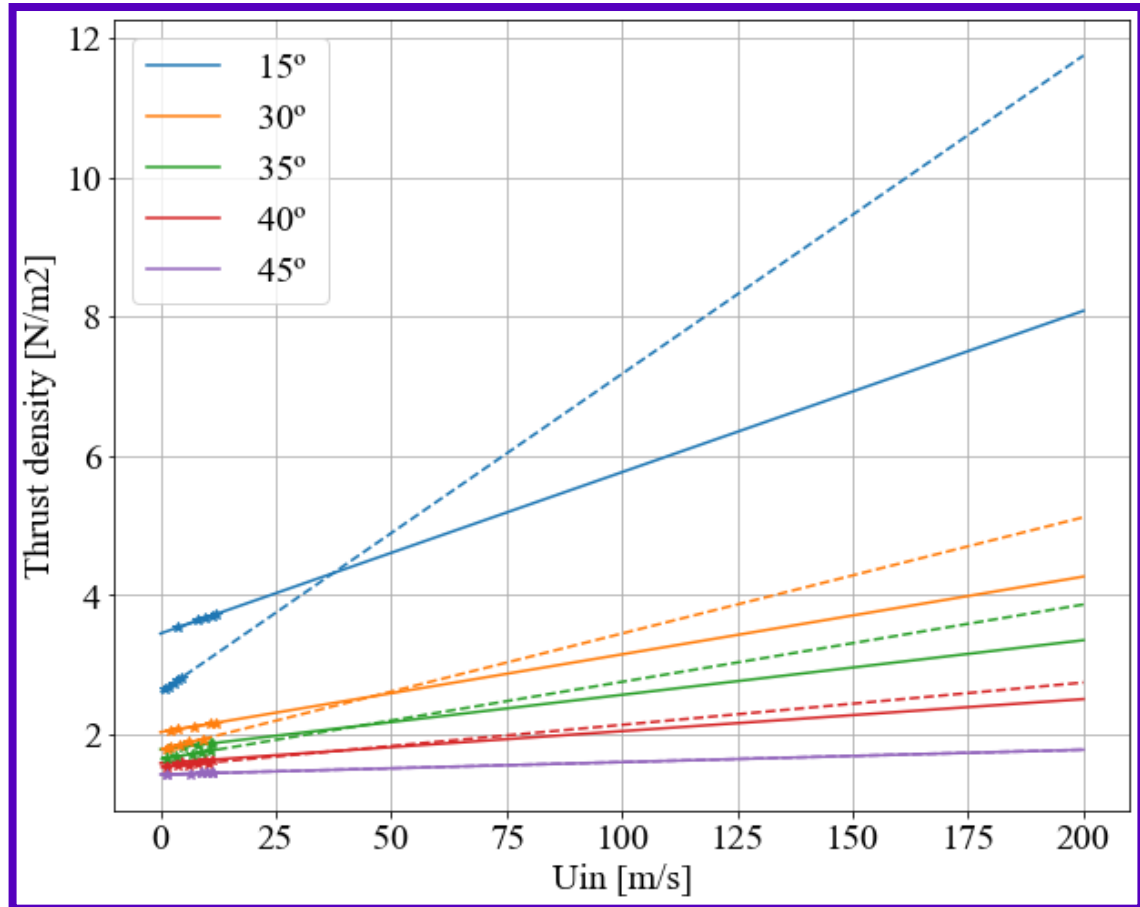
⇒  $d_y$  more than **doubles thrust** for **small angles**



# 2. EHD Thrust Density

Varying  $d_y$  : - - - -

Angle (°)	Applied Potential (V)	dy (cm)
15	20705	1.1
60	40000	6.9



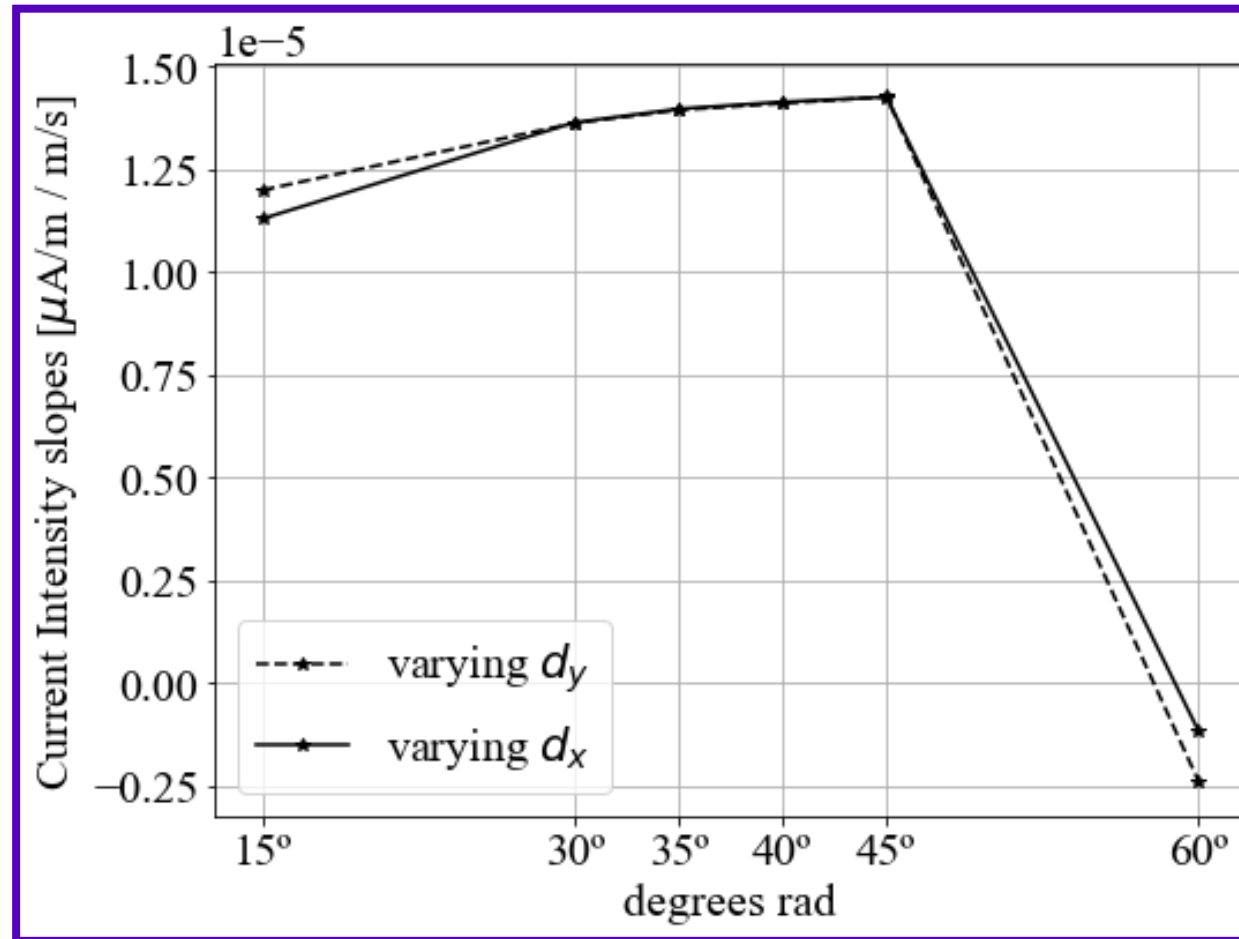
Varying  $d_x$  : ———

Angle (°)	Applied Potential (V)	dx (cm)
15	77274	14.9
60	23094	2.3

Complicated experimentally !

- ⇒ **Smaller angles** are favorable.
- ⇒  $d_y$  better up **until almost 40 m/s**.
- ⇒ Close to **10-20 N/m<sup>2</sup>**

## 2. Configuration Study : Optimal Slopes



⇒ **Optimal value** for current intensity increase with external flow at **around 50°**.

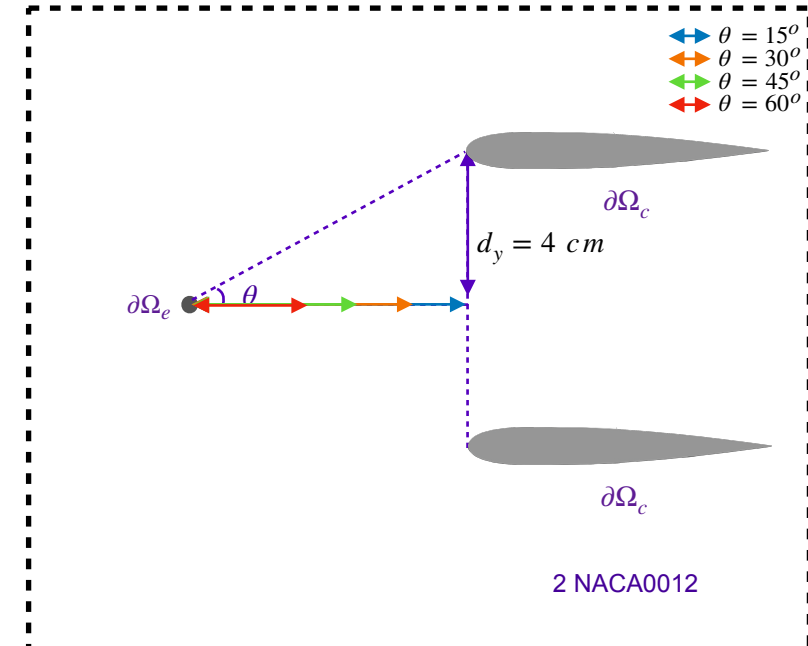
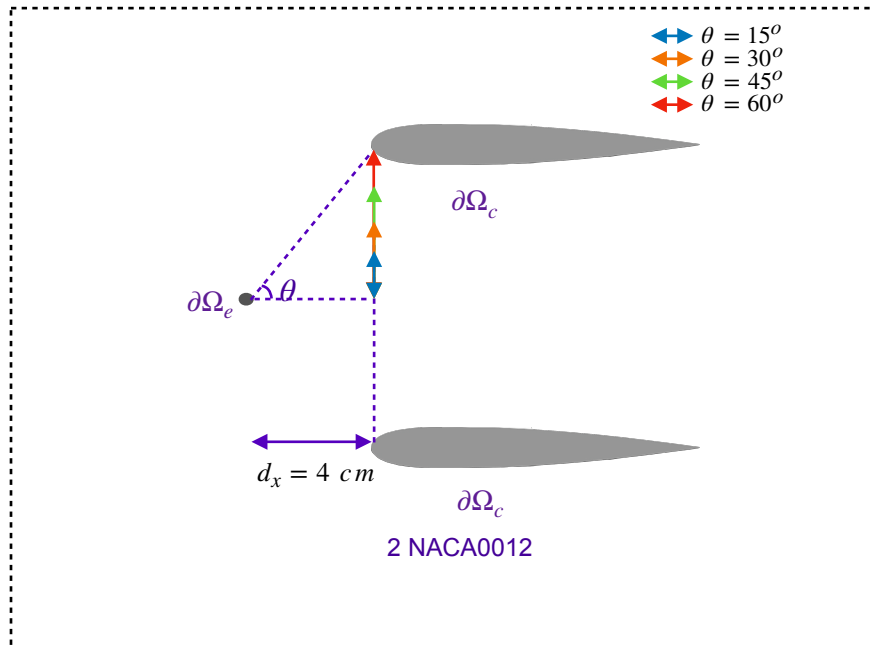
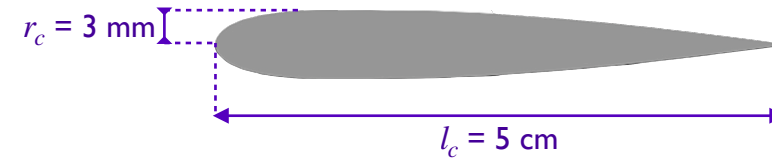
## 2. Configuration Study : Parameter Values

Angle (°)	15	30	35	40	45	60
Applied Potential (V)	20705	23094	24415	26108	28284	40
dx (cm)	4	4	4	4	4	4
dy (cm)	1.1	2.3	2.8	3.4	4	6.9

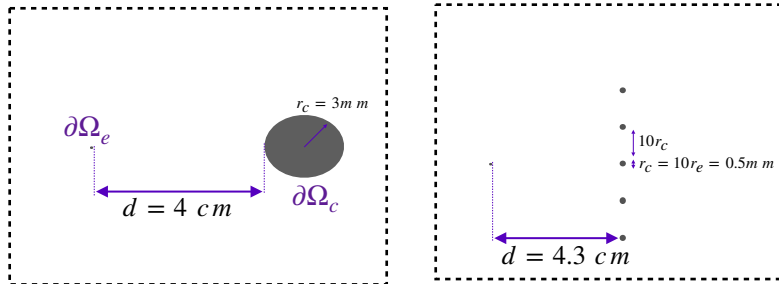
Angle (°)	15	30	35	40	45	60
Applied Potential (V)	77274	40000	34869	31114	28284	23094
dx (cm)	14.9	6.9	5.7	4.8	4	2.3
dy (cm)	4	4	4	4	4	4

# 2. Configuration Study : System Characteristics

NACA0012 collector

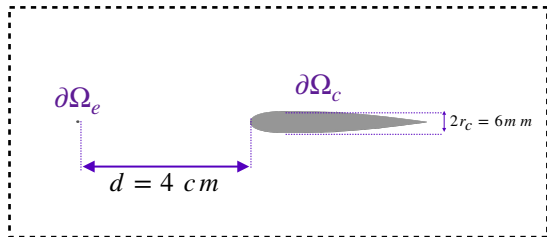


# 3. Study of different configurations

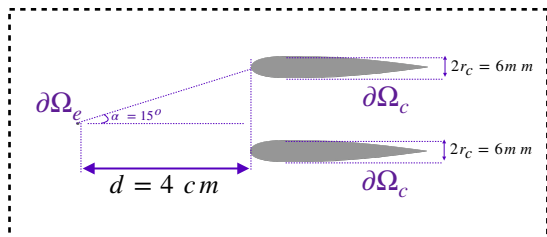


Cylindrical

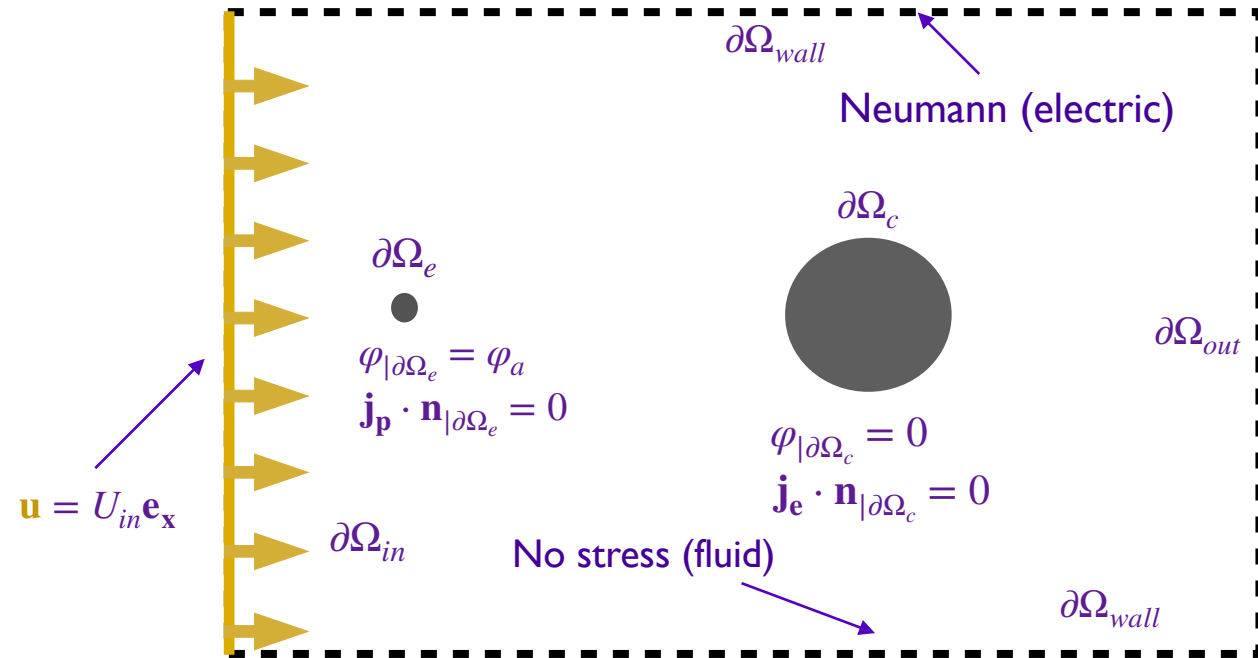
Grid



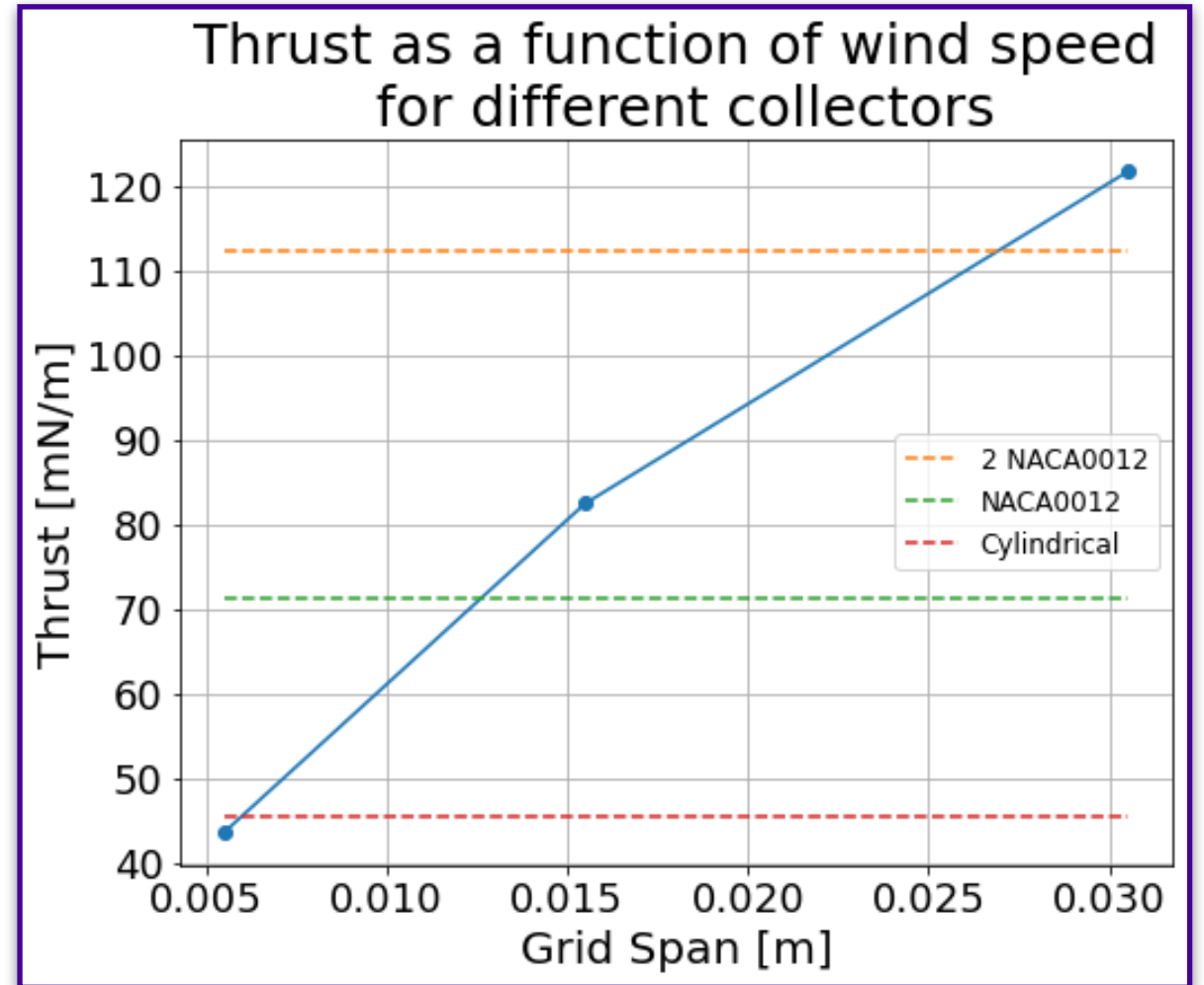
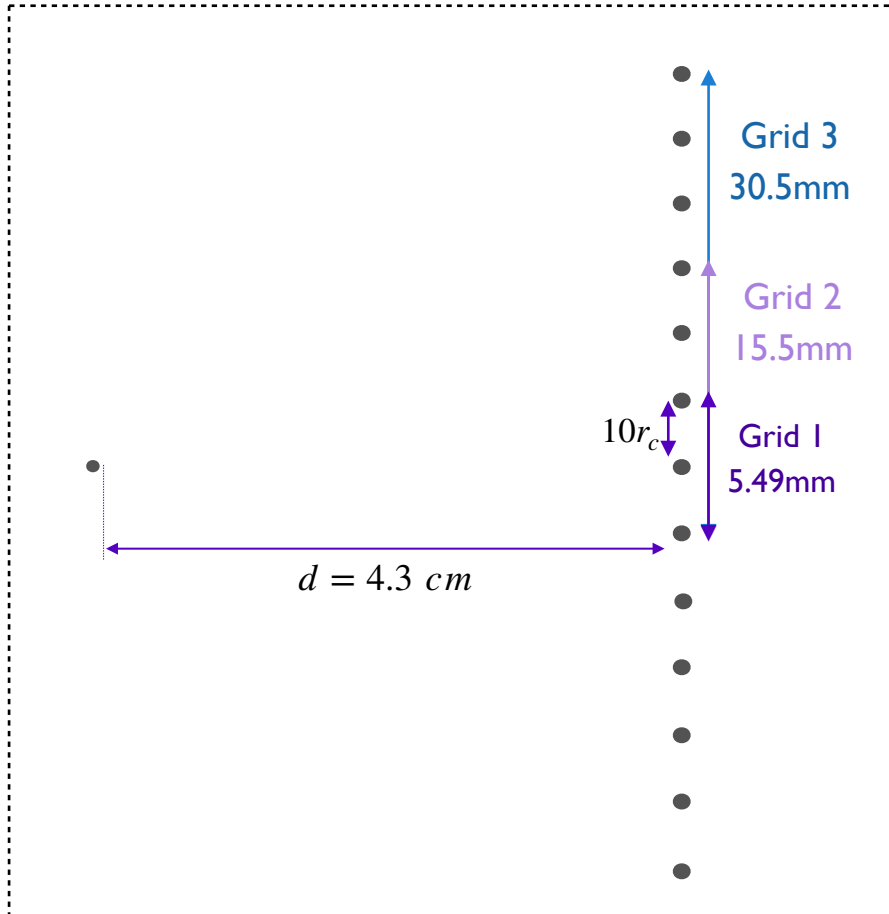
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# 3. Propulsive Properties



# 3. Numerical challenges

1. Multi-emitter configurations
2. Navier-Stokes at high speeds on large domains



# I. Two-Way Dimensionless Two Domain Model

Electric 0th-order  $\Rightarrow$  Fluid 0th-order  $\Rightarrow$  Electric 1st-order  $\Rightarrow$  Fluid 1st-order

Inner domain  $\Omega_1$

$$\Delta\varphi^0 = 0$$

$$\nabla \cdot [-n_p^0 \nabla\varphi^0] = \alpha^0 n_p^0 |\mathbf{E}^0|$$

$$\nabla \cdot [-n_e^0 \nabla\varphi^0] = (\alpha^0 - \eta^0) n_e^0 |\mathbf{E}^0|$$

Outer domain  $\Omega_2$

$$\Delta\varphi^0 = -n_p^0$$

$$\nabla \cdot [-n_p^0 \nabla\varphi^0 - \frac{1}{P_e} \nabla n_p^0] = \gamma S^0$$

Full domain  $\Omega$

$$\mathbf{u}^0 \cdot \nabla \mathbf{u}^0 = -\nabla p^0 + \frac{1}{R_e} \Delta \mathbf{u}^0 - n_p^0 \nabla \varphi^0$$

$$\nabla \cdot \mathbf{u}^0 = 0$$

Inner domain  $\Omega_1$

$$\Delta\varphi^1 = 0$$

$$\nabla \cdot [-n_p^1 \nabla\varphi^0 - n_p^0 \nabla\varphi^1] - \alpha^1 n_p^0 |\mathbf{E}^0| - \alpha^0 n_p^1 |\mathbf{E}^1| - \alpha^0 n_p^0 |\mathbf{E}^1| = -\nabla \cdot (n_p^0 \mathbf{u}^0)$$

$$\nabla \cdot [-n_e^1 \nabla\varphi^0 - n_e^0 \nabla\varphi^1] + (\alpha^1 - \eta^1) n_e^0 |\mathbf{E}^0| + (\alpha^0 - \eta^0) n_e^1 |\mathbf{E}^0|$$

$$+ (\alpha^0 - \eta^0) n_e^0 |\mathbf{E}^1| = 0$$

Outer domain  $\Omega_2$

$$\Delta\varphi^1 = -n_p^1$$

$$\nabla \cdot [-n_p^1 \nabla\varphi^0 - n_p^0 \nabla\varphi^1 - \frac{1}{P_e} \nabla n_p^0] = \gamma S^1 - \nabla \cdot (n_p^0 \mathbf{u}^0)$$

Full domain  $\Omega$

$$\mathbf{u}^1 \cdot \nabla \mathbf{u}^0 + \mathbf{u}^0 \cdot \nabla \mathbf{u}^1 = -\nabla p^1 + \frac{1}{R_e} \Delta \mathbf{u}^1 - n_p^1 \nabla \varphi^0 - n_p^0 \nabla \varphi^1$$

$$\nabla \cdot \mathbf{u}^1 = 0$$



# 2. Numerical Methods : Stabilized FEM

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

$$\Rightarrow \int_{\Omega} \frac{1}{R_e} \nabla \mathbf{u}_h \cdot \nabla \mathbf{v}_h + (\mathbf{u}_h \cdot \nabla) \mathbf{u}_h \cdot \mathbf{v}_h - p_h \nabla \cdot \mathbf{v}_h - q_h \nabla \cdot \mathbf{u}_h + n_p \nabla \varphi \, d\Omega + \text{BC}$$

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

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

SUPG/PSPG  $- \sum_{t \in T_h} \int_{T_h} \tau_{SUPG} M_a n_{p,h}^0 \nabla \varphi_h^0 ((\mathbf{u}_h^0 \cdot \nabla) \mathbf{v}_h + \nabla q_h)$

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

$$\tau_{SUPG} = \frac{4R_{e,fluide}}{h_T^2} \delta_{SUPG}$$

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

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