Electron drift instability and secondary electron emission in Hall effect thrusters: Insights from 2D PIC simulations

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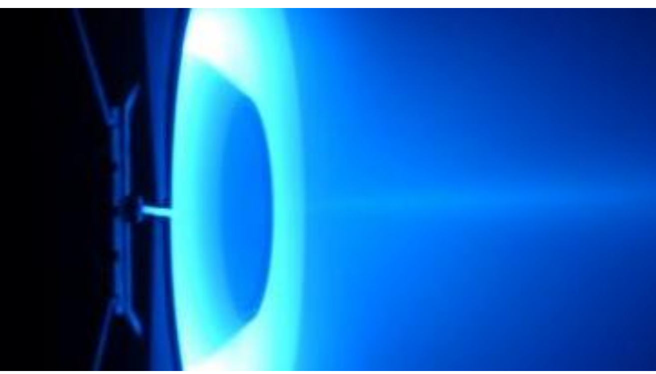
Ion Propulsion and Accelerator Industrial Application (IPAIA)
Bari, Italy

Laboratoire de Physique des Plasmas



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Safran Aircraft Engines, Vernon | Laboratoire de Physique des Plasmas, École polytechnique

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Outline

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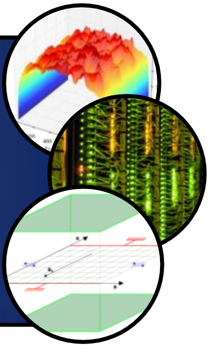
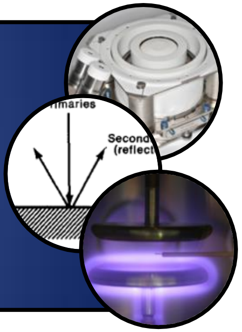
- a. Hall effect thruster (HET)
- b. Model specificities
- c. Simulation environment



II. Implementations and results
- a. Electron drift instability
- b. Anomalous electron transport
- c. Secondary electron emissions



III. Current implementations and conclusion
- a. Alternative propellants
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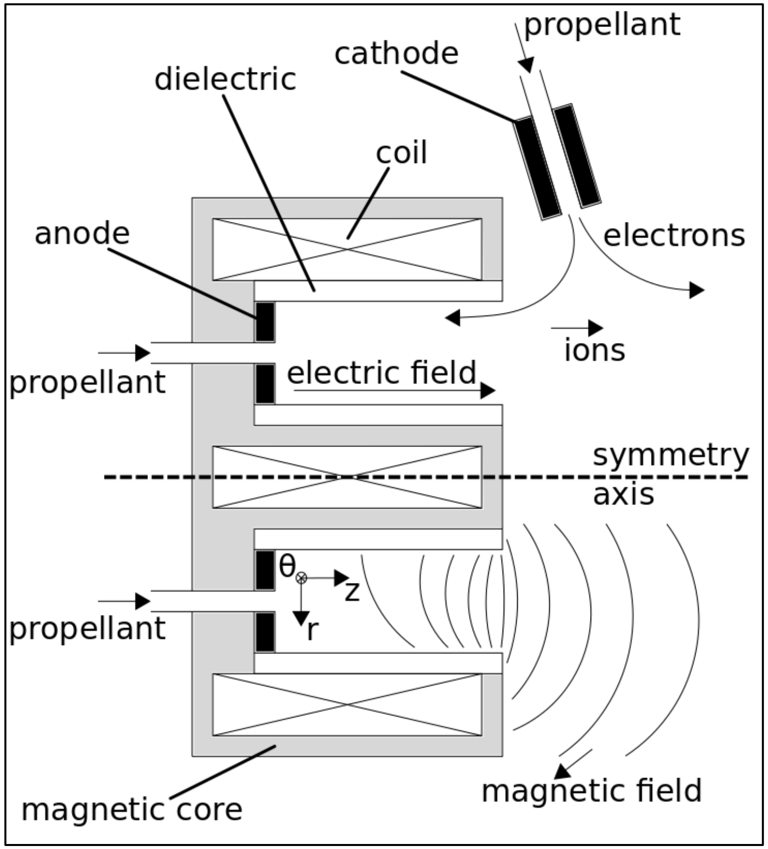
Hall effect thruster (HET)

- Difficulties to predict performance
- Role of wall materials (SEE) [1,2]
- Anomalous electron transport along (**Oz**) [1]
  - Secondary electron emission (SEE) due to e⁻/walls collisions [2]
  - Sheath instability [2]
  - Electron drift instability in the azimuthal direction [3]
  - Gradient driven fluid instability [4]



Schematic picture of a HET

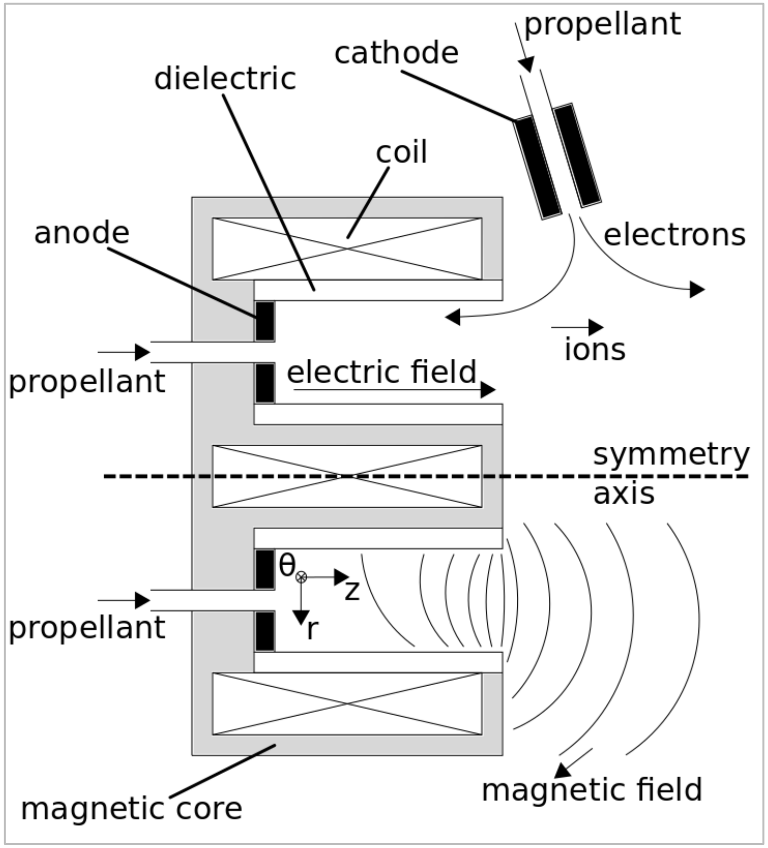
[1] D.M. Goebel, I. Katz, *Fundamentals of electric propulsion: Ion and Hall thrusters*, Wiley (2008)
[2] D. Sydorenko, A.I. Smolyakov, I.D. Kaganovich, Y. Raitses, *Phys. Plasmas*, **15**, 053506 (2008)
[3] A. Ducrocq, J.C. Adam, A. Héron, G. Laval, *Phys. Plasmas*, **13**, 102111 (2014)
[4] D. Escobar, E. Ahedo, *Phys. Plasmas*, **21**, 043505 (2014)

Hall effect thruster (HET)

- Difficulties to assess performance

- Role of wall materials (SEE): **Insufficient** [1,2]

- Anomalous electron transport along (**Oz**)
  - Secondary Electron Emission at the walls
  - Sheath instability
  - Electron drift instability in the azimuthal direction [3,4]
  - Gradient driven fluid instability

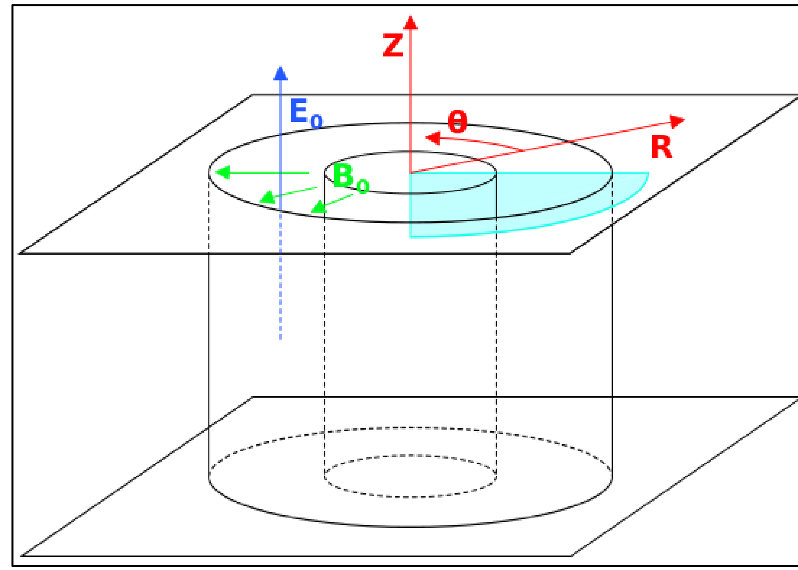


Schematic picture of a HET

[1] C. Boniface, L. Guarrigues, G.J.M. Hagelaar, J.P. Boeuf, D. Gawron, S. Mazouffre, *Appl. Phys. Lett.*, ***89***, *161503 (2006)*
[2] N.B. Meezan, M.A. Cappelli, *Phys. Rev.*, ***E66***, *036401 (2002)*
[3] M.K. Scharfe, N. Gascon, M.A. Cappelli, E. Fernandez, *Phys. Plasmas*, **13**, 083505 (2006)
[4] A.W. Smith, M.A. Cappelli, *Phys. Plasmas*, **16**, 073504 (2009)

Model specificities

Front picture of a HET (BHT-1500)



Perspective scheme of a HET

Role of wall materials [1] **+** azimuthal instability [2] **=** (**r**,**θ**) simulations

→ *Periodicity* in **θ**

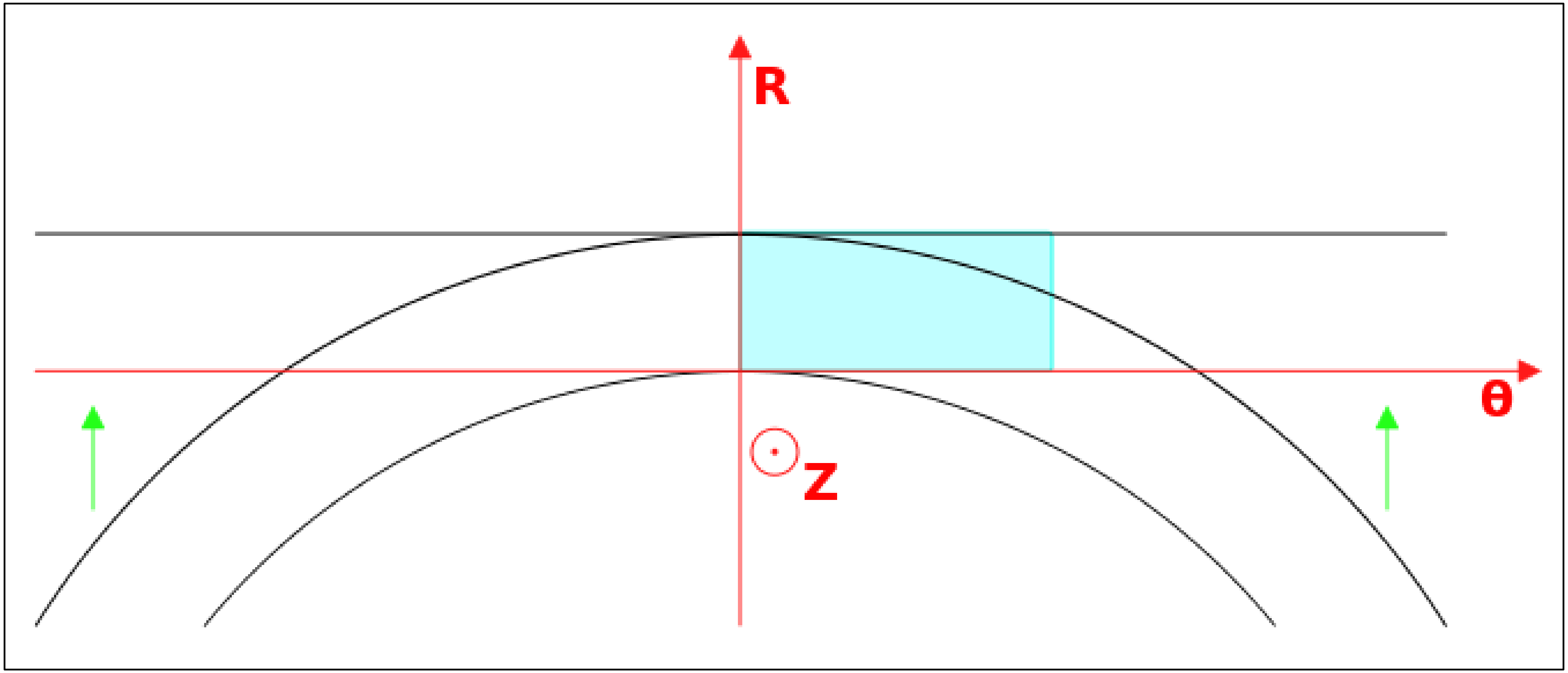
→ *Walls* in **r**

[1] D.M. Goebel, I. Katz, *Fundamentals of electric propulsion: Ion and Hall thrusters*, Wiley (2008)

[2] A. Ducrocq, J.C. Adam, A. Héron, G. Laval, *Phys. Plasmas*, **13**, 102111 (2014)

Model specificities

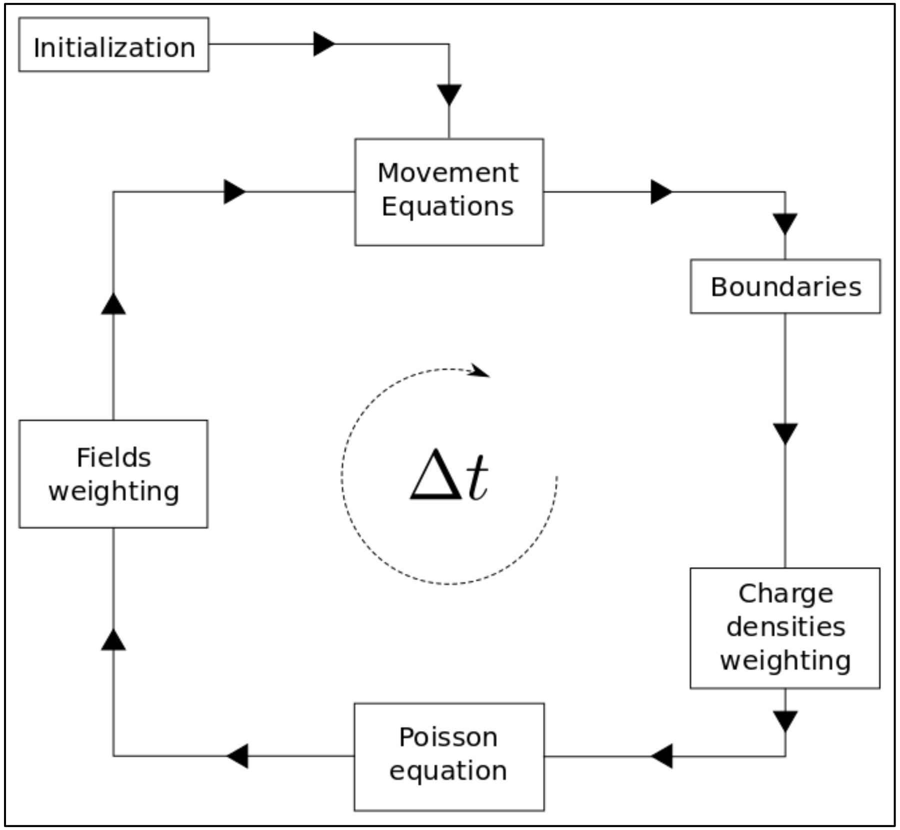
“Infinite HET” PIC/MCC model



“Infinite” radius → Cartesian coordinate system → **“Infinite” HET**

Model specificities

Particle-in-cell (PIC) method [1]



Scaling

- ✓ **NO !** ☹ [2]

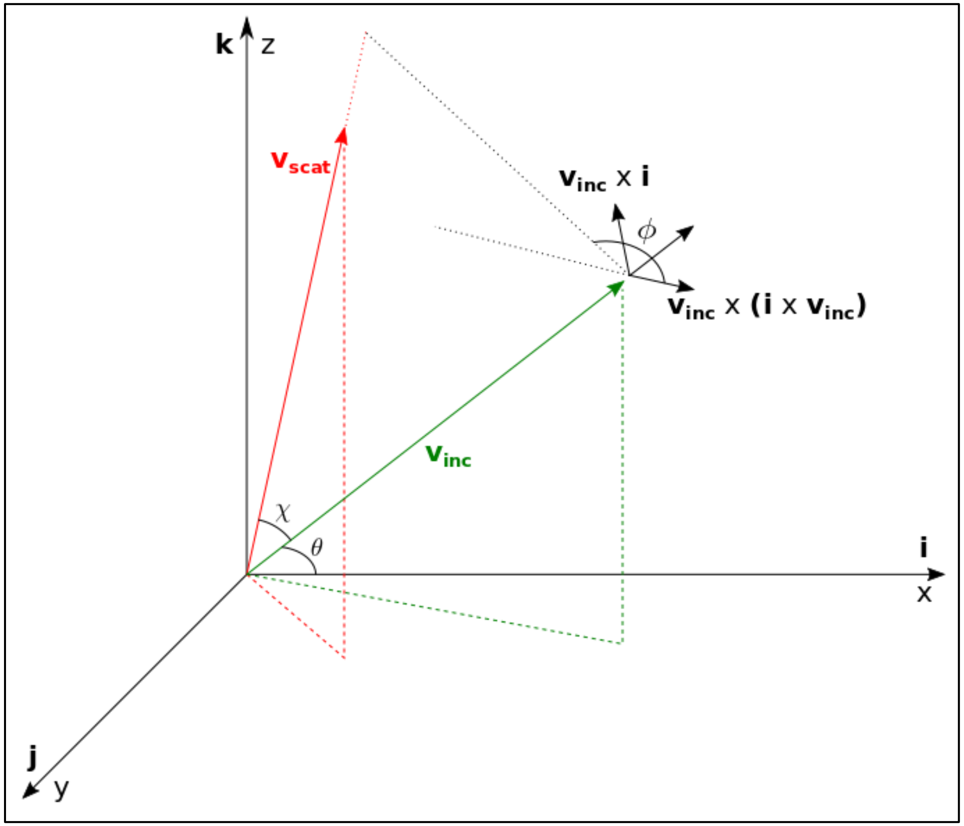
Mesh

- ✓ 2D
- ✓ Cartesian
- ✓ fixed
- ✓ structured
- ✓ uniform

[1] C.K. Birdsall, A.B. Langdon, *Plasma Physics via Computer Simulation* (IOP Publishing, Bristol, 1991)
[2] T. Lafleur, S.D. Baalrud, P. Chabert, *Phys. Plasmas* **23**, 053503 (2016)

Model specificities

Monte Carlo collision (MCC) module [1]



Neutrals

- ✓ homogeneous
- ✓ constant
- ✓ background

Collision processes [2]

- ✓ elastic
- ✓ 4 excitations
- ✓ ionization

[1] V. Vahedi, M. Surendra, *Comp. Phys. Commun.*, **87**, 179 (1995)
[2] Lxcat, Cross sections extracted from Program Magboltz, v.7.1 (June 2004)

Model specificities

LPPic2D

- ✓ Electrostatic → *Poisson* equation
- ✓ *Fixed Structured Cartesian* mesh
- ✓ Equation of motion
  - *Leapfrog* scheme [1]
  - electrons are magnetized → *Boris* scheme [2]
- ✓ *Cloud-in-Cell* scheme: Linear interpolation
- ✓ *Monte-Carlo collision* module

PIC/MCC

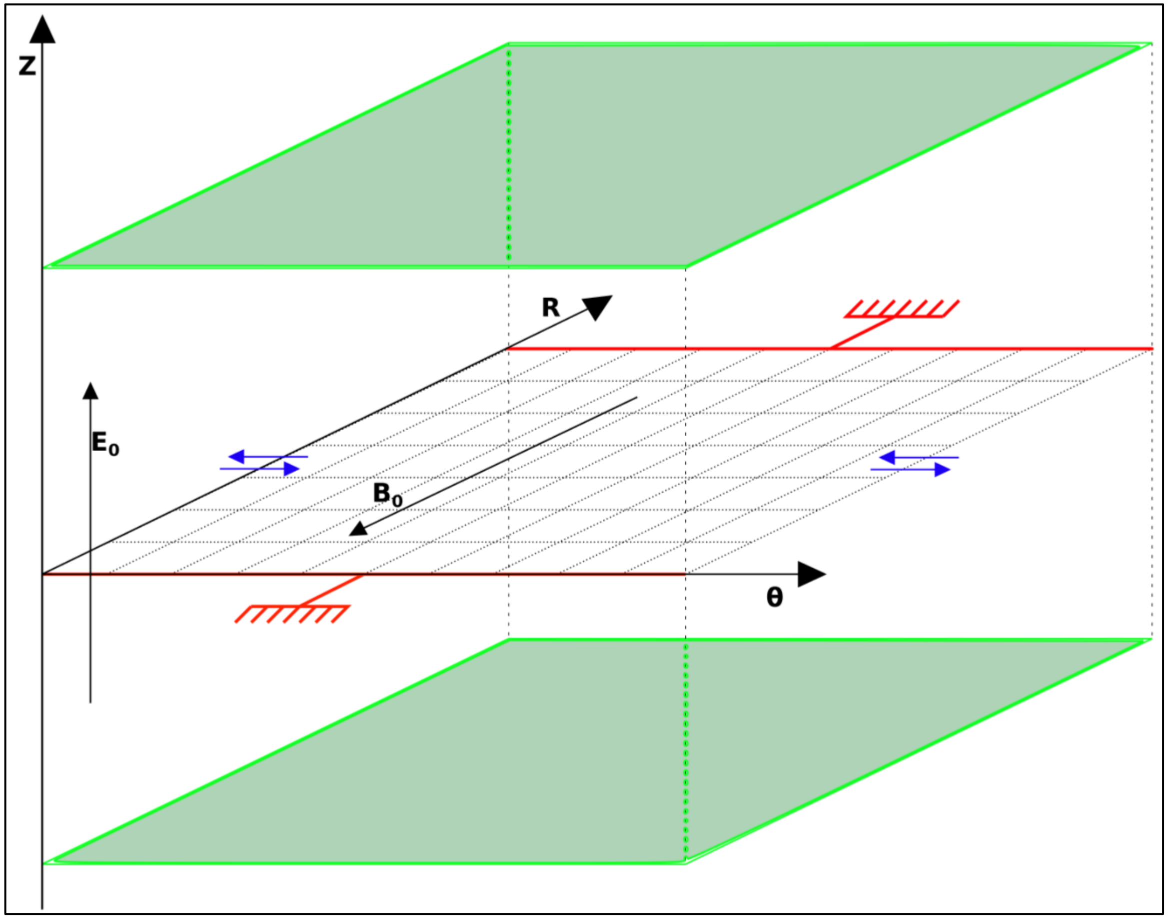
- ✓ Verified by a capacitive discharge benchmark [3]

[1] C.K. Birdsall, A.B. Langdon, *Plasma Physics via Computer Simulation* (IOP Publishing, Bristol, 1991)
[2] J. P. Boris, in *Proceedings of the 4th Conference on Numerical Simulation of Plasmas. Naval Res. Lab.* (1970)
[3] M.M. Turner, A. Derzsi, Z. Donko, D. Eremin, S.J. Kelly, T. Lafleur, T. Mussenbrock, *Phys. Plasmas*, **20** (2013)

LPP

Model specificities

"Infinite HET" PIC/MCC model



- 2.5D – 3V
- "Fake" (**Oz**) length [2]

→ Poisson only solved in the (**r,θ**) plane !

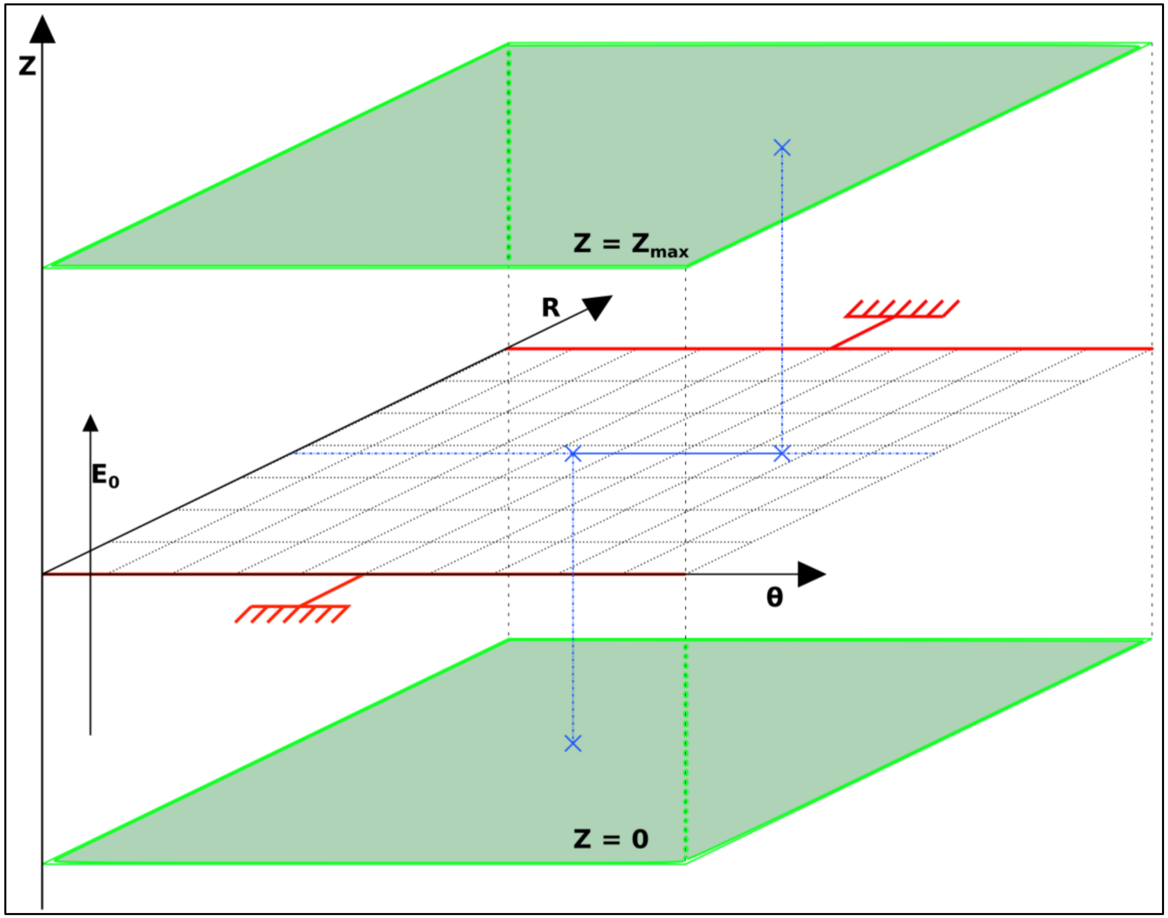
- *Not self-consistent*

→ Uniform reinjection of couples (**e**$^-$/**i**$^+$) from *grounded metallic walls* [1]

[1] J.C. Adam, A. Héron, and G. Laval, *Phys. Plasmas*, **11**, 295 (2004)
[2] J.P. Boeuf, *Front. Phys.*, **2**, 74 (2014)

Model specificities

“Infinite HET” PIC/MCC model



- Couples re-injection
  - ✓ Uniform re-injection along **θ**
  - ✓ **e$^-$** injected in **z = z$_{max}$**
  - ✓ **i$^+$** injected in **z = 0**
- Monte Carlo collision module (e$^-$/n & i$^+$/n) [1]

→ ionization [2] w/o creation of particles

[1] V. Vahedi, M. Surendra, *Comp. Phys. Commun.*, **87**, 179 (1995)
[2] Lxcat, Cross sections extracted from Program Magboltz, v.7.1 June 2004

Simulation environment

Parameter	Value
n_0 [m^{-3}]	(1 to 12) $\cdot 10^{17}$
P_n [mTorr]	30
T_e [eV]	2,6
T_i [eV]	0,026
E_0 [V/m]	$2 \cdot 10^{5}$
B_0 [G]	200
$\Delta X = \Delta Y$ [m]	$2 \cdot 10^{-5}$
Δt [s]	(1 to 4)$\cdot 10^{-12}$
t [µs]	10
L_Θ [cm]	0,5
L_R [cm]	2
L_z [cm]	1

LPPic2D

- ✓ developed *ex nihilo*

Particle In Cell

- ✓ ~ 100 particles/cell
- ✓ 255 **x** 1000 cells

High Performance Computing

- ✓ *max tested:* 1200 CPUs
- ✓ MPI library
- ✓ HDF5 library
- ✓ HYPRE/PetSc solvers
- ✓ Restart function

10 µs **+** 360 CPUs **=** 32 hours

Electron drift instability

Instability highlighting [1]

[Film of plasma potential]

[1] V. Croes, T. Lafleur, Z. Bonaventura, A. Bourdon, P. Chabert, *Plasma Sources Sci. Tech.* **26**, 034001 (2017)

Instability characteristics

Parametric study over plasma density ($n_0 = 3{\cdot}10^{17}\ m^{-3}$) [1]

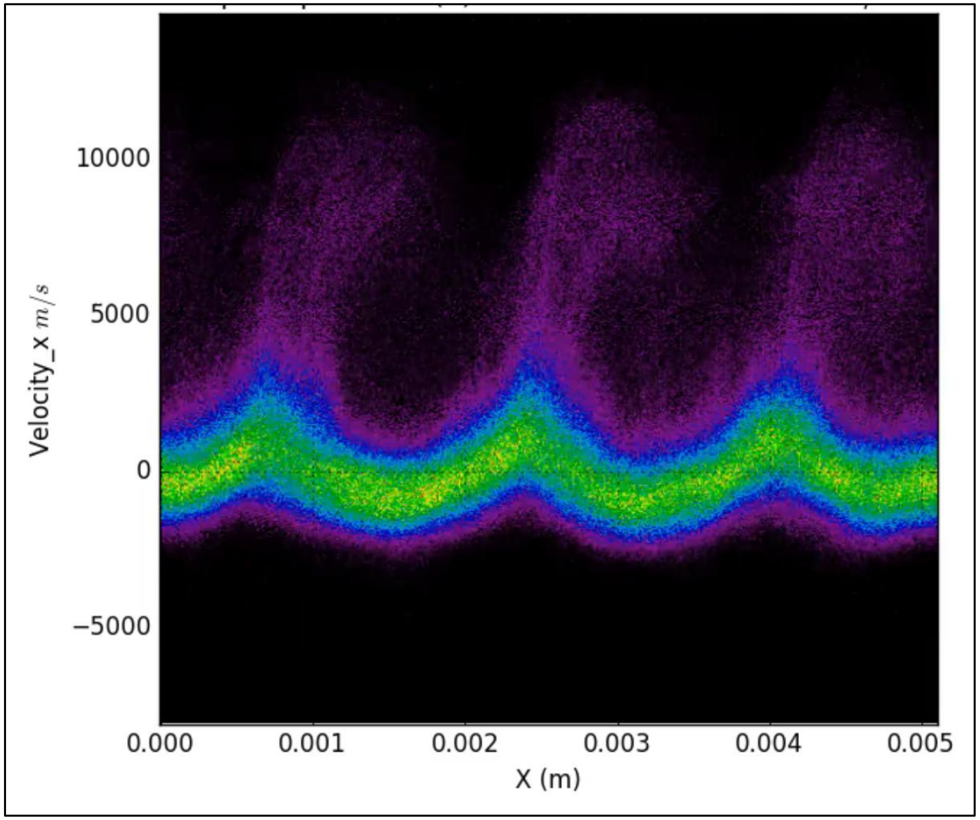
→ Confirming kinetic theory [2]

Measured Values			
Case	**λ** (mm)	***f*** (MHz)	**V_{ph}** ($10^3\ m{\cdot}s^{-1}$)
$n_0/4$	2.0	2.5	5.0
n_0	1.0	5.0	5.0
$4n_0$	0.7	10.0	5.0
Case	**$\lvert\delta n_e\rvert/n_e$** (%)	**$\lvert\delta\Phi\rvert/T_e$** (%)	
$n_0/4$	20	32	
n_0	17	25	
$4n_0$	12	15.5	
Analytical values			
Case	**λ** (mm)	***f*** (MHz)	**V_{ph}** ($10^3\ m{\cdot}s^{-1}$)
$n_0/4$	1.7	2.9	5.011
n_0	0.8	5.8	5.011
$4n_0$	0.4	11.6	5.011
Case	**$\lvert\delta n_e\rvert/n_e$** (%)	**$\lvert\delta\Phi\rvert/T_e$** (%)	
$n_0/4$	33	33	
n_0	33	33	
$4n_0$	33	33	

[1] V. Croes, T. Lafleur, Z. Bonaventura, A. Bourdon, P. Chabert, *Plasma Sources Sci. Tech.* **26**, 034001 (2017)
[2] T. Lafleur, S.D. Baalrud, P. Chabert, *Phys. Plasmas* **23**, 053503 (2016)

Electron drift instability

Ion trapping [1]



- Confirming 1D results [2]
- $V_\theta^{ions} \sim 600$ m/s > 0
- $V_\theta^{ions} \sim \sqrt{(q \cdot T_e / 96 m_i)}$ with $T_e = 2/3\ \varepsilon_e$

[1] V. Croes, T. Lafleur, Z. Bonaventura, A. Bourdon, P. Chabert, *Plasma Sources Sci. Tech.* **26**, 034001 (2017)
[2] T. Lafleur, S.D. Baalrud, P. Chabert, *Phys. Plasmas* **23**, 053502 (2016)

Anomalous electron transport

Mobility definitions

“Measured”

$$\mu_{\text{pic}} = \frac{\sum_{j=1}^{\mathcal{N}_{e-}} v_{jz}}{\mathcal{N}_{e-} E_0}$$

Classical

$$\mu_c = \frac{\frac{q}{m\nu_m}}{1 + \frac{\omega_{ce}^2}{\nu_m^2}}$$

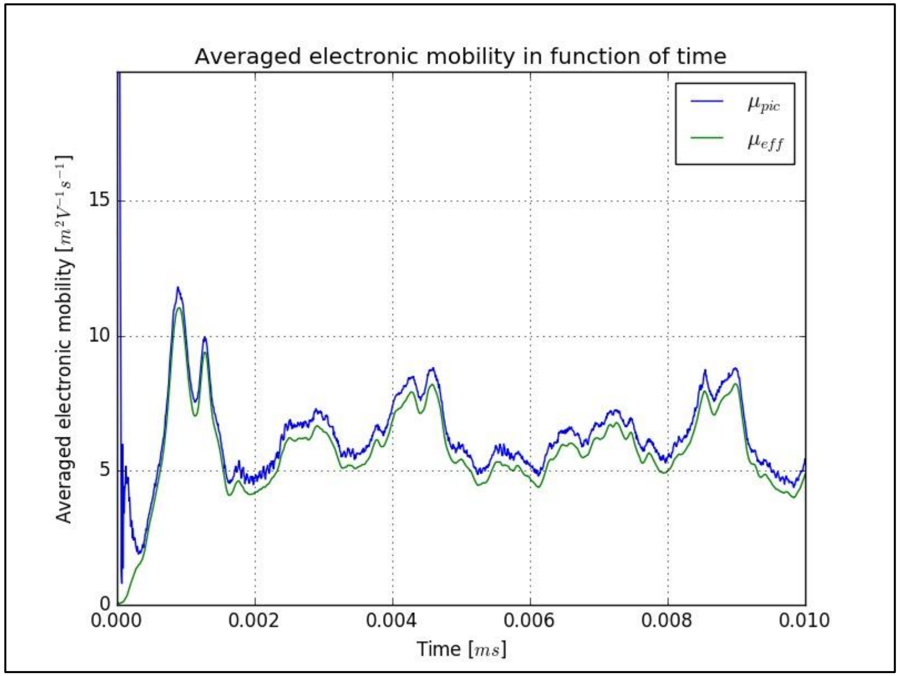
Effective [1]

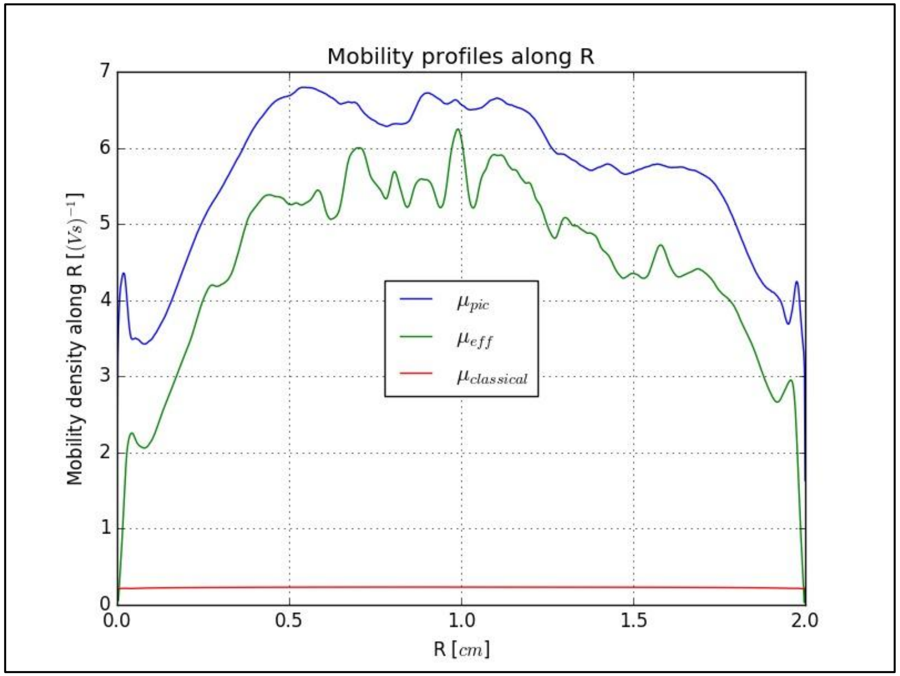
$$\mu_{eff} = \frac{\frac{q}{m\nu_m}}{1 + \frac{\omega_{ce}^2}{\nu_m^2}} \left[1 - \frac{\omega_{ce}}{\nu_m} \frac{\langle n_e E_y \rangle}{n_e E_z}\right]$$

[1] T. Lafleur, S.D. Baalrud, P. Chabert, *Phys. Plasmas*, **23**, 053502 (2016)

Anomalous electron transport

Anomalous electron cross-field mobility [1,2]





[1] V. Croes, T. Lafleur, Z. Bonaventura, A. Bourdon, P. Chabert, *Plasma Sources Sci. Tech.* **26**, 034001 (2017)
[2] T. Lafleur, S.D. Baalrud, P. Chabert, *Phys. Plasmas* **23**, 053503 (2016)

Anomalous electron transport

Friction Force at saturation, $\mathbf{R}_{ei}$ [1]

$$|\mathbf{R}_{ei}| = \frac{|q|}{4\sqrt{6}}\frac{1}{c_s}|\nabla\cdot(\mathbf{v}_{di}n_eT_e)| \Rightarrow |\mathbf{R}_{ei}| \approx \frac{|q|}{4\sqrt{6}}\frac{v_{zi}n_eT_e}{c_sL_z}$$

Effective mobility at saturation, μ_{eff}^{sat} [1]

$$\mu_{eff} = \frac{\frac{q}{m\nu_m}}{1+\frac{\omega_{ce}^2}{\nu_m^2}}\left[1-\frac{\omega_{ce}}{\nu_m}\frac{\langle n_eE_y\rangle}{n_eE_z}\right] \Rightarrow \mu_{\text{eff}}^{sat} = \frac{\frac{1}{m_e\nu_m}}{1+\frac{\omega_{ce}^2}{\nu_m^2}}\left[|q|+\frac{\omega_{ce}}{\nu_m}\frac{|\mathbf{R}_{ei}|}{n_eE_0}\right]$$

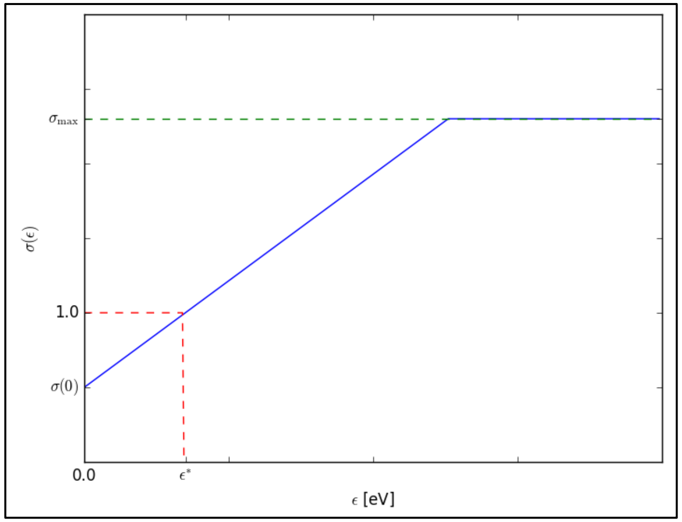
Case	Measured Values		Analytical Values	
($m^2V^{-1}s^{-1}$)	μ_{pic}	μ_{eff}	μ_{eff}^{sat}	$\mu_{classical}$
$n_0/4$	6.0	5.9	4.23	0.19
n_0	5.8	5.6	4.23	0.19
$4n_0$	6.1	6.0	4.23	0.19
plasma density: $\mathbf{n}_0 = 3 \cdot 10^{17}$ m^{-3}				

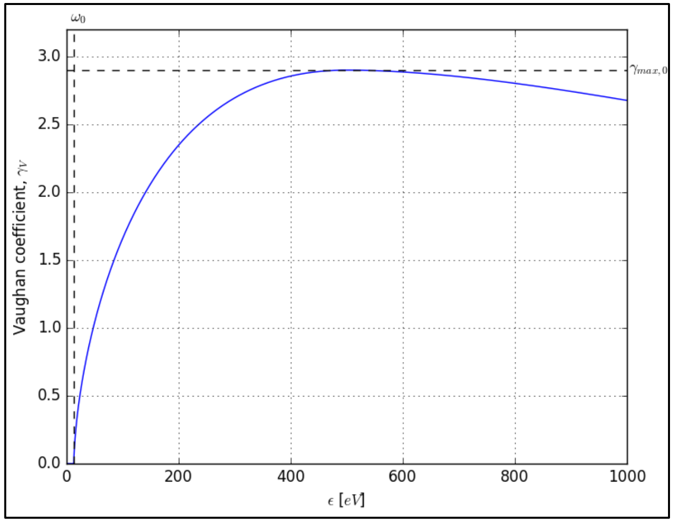
[1] V. Croes, T. Lafleur, Z. Bonaventura, A. Bourdon, P. Chabert, *Plasma Sources Sci. Tech.* **26**, 034001 (2017)

Secondary electron emissions

Available models in LPPic2D

- ✓ Constant re-emission rate — $\gamma = \gamma_0$
- ✓ Linear re-emission rate [1,2,3] — $\gamma = f(\varepsilon_e)$
- ✓ J.R.M. Vaughan [4] — $\gamma = f(\varepsilon_e, \theta_e)$





[1] A. Héron, J.C. Adam, *Phys. Plasmas* **20**, 082313 (2013)
[2] A.N. Smirnov, Y. Raitses, N.J. Fisch, *IEEE Trans. Plasma Sci.* **34** 132 (2006)
[3] S. Barral, K. Makowski, Z. Peradznski, N. Gascon, M. Dudeck, *Phys. Plasmas* **10** 4137 (2003)
[4] J.R.M. Vaughan, *IEEE Trans./Electron Devices*, 36:1963-1967 (1989)

Secondary electron emissions

Constant re-emission rate

✓ Used as verification with plasma drop equation [1]

$$\Delta\Phi_s = \frac{k_B T_{e_{//}}}{e} \cdot ln\left[(1-\bar{\sigma})\sqrt{\frac{m_i}{2\pi m_e}}\right]$$

Parameter	**Measured Values**		**Analytical Values**		
$\boldsymbol{\sigma}_{constant}$	$\mathbf{T}_{e//}$ (eV)	$\boldsymbol{\Delta\varphi}_{tot}$ (V)	$\boldsymbol{\Delta\varphi}_{p-s}$ (V)	$\boldsymbol{\Delta\varphi}_{s}$ (V)	$\boldsymbol{\Delta\varphi}_{tot}$ (V)
0.5	2.5	12	1.25	11.5	12.75
0.92	42	125	21	116	137
0.99	40	60	20	26.9	46.9

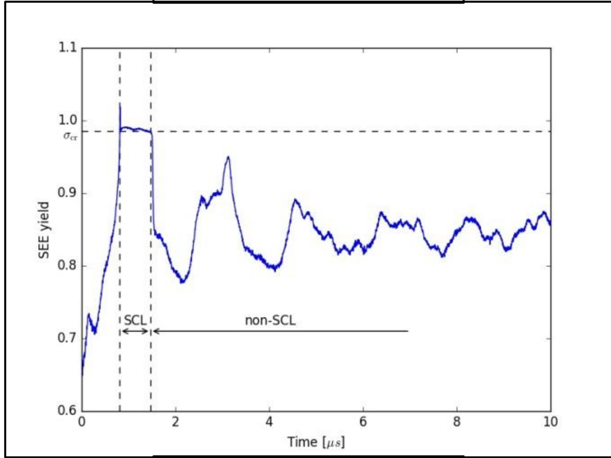
[1] S. Barral, K. Makowski, Z. Peradznski, N. Gascon, M. Dudeck, *Phys. Plasmas* **10** 4137 (2003)

Secondary electron emissions

Linear model: Identification of 3 Regimes

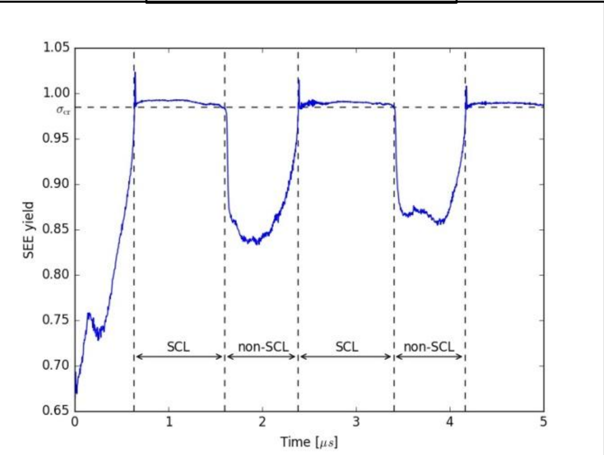
- ❑ Parametric study along ε*
- ❑ Space Charge Limited/Saturation regimes (SCL) [1,2]
- ❑ Relaxation Sheath Oscillations (RSO) [1]

Regime III



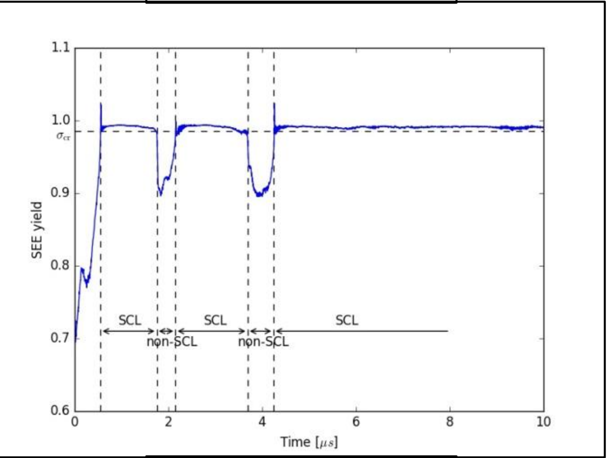
ε* = 55 eV

Regime II



ε* = 45 eV

Regime I



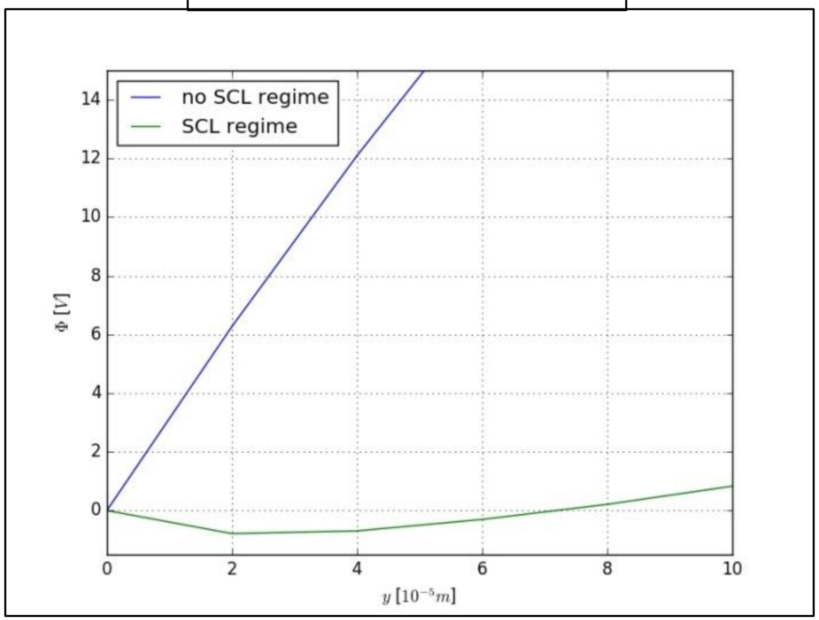
ε* = 38 eV

[1] D. Sydorenko, I.D. Kaganovich, Y. Raitses, A.I. Smolyakov, *Phys. Rev. Let.* **103** 145004 (2009)
[2] S. Barral, K. Makowski, Z. Peradznski, N. Gascon, M. Dudeck, *Phys. Plasmas* **10** 4137 (2003)

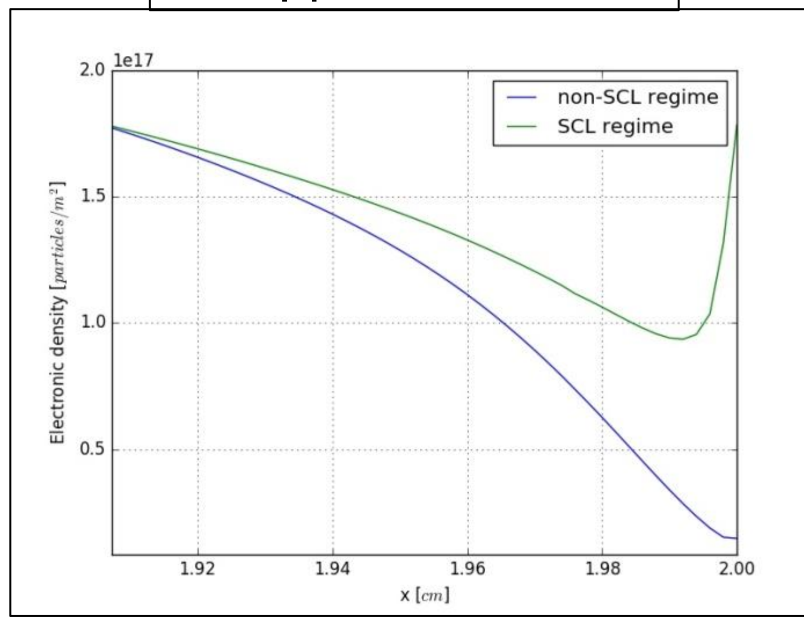
Secondary electron emissions

Space Charge Limited regime [1,2]

“Potential dwell”



“Trapped electrons”

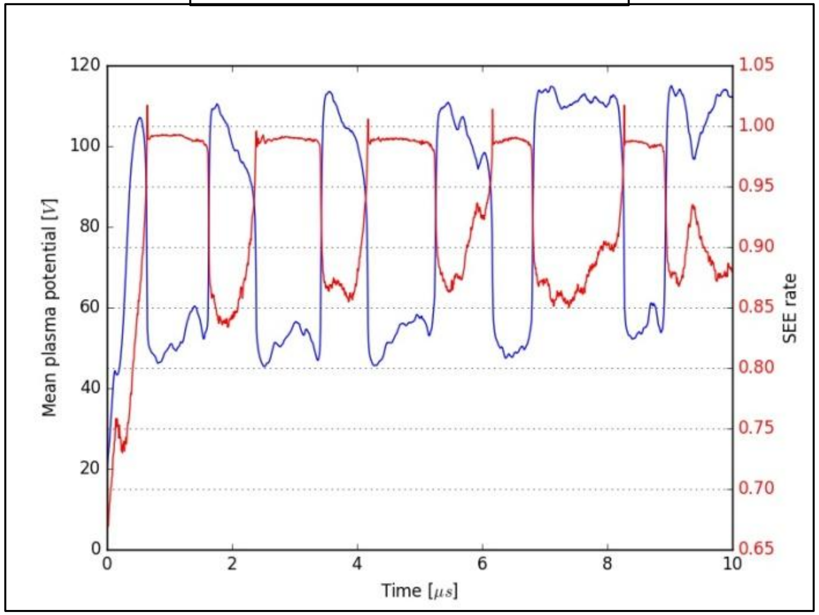


[1] D. Sydorenko, I.D. Kaganovich, Y. Raitses, A.I. Smolyakov, *Phys. Rev. Let.* **103** 145004 (2009)
[2] S. Barral, K. Makowski, Z. Peradznski, N. Gascon, M. Dudeck, *Phys. Plasmas* **10** 4137 (2003)

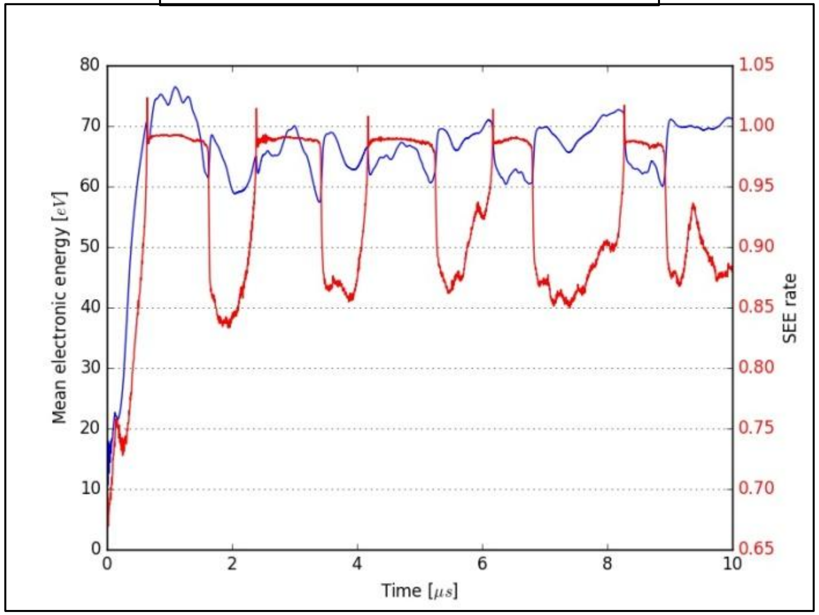
Secondary electron emissions

***Regime II*: Relaxation Sheath Oscillations** [1]

Plasma potential



Electronic energy

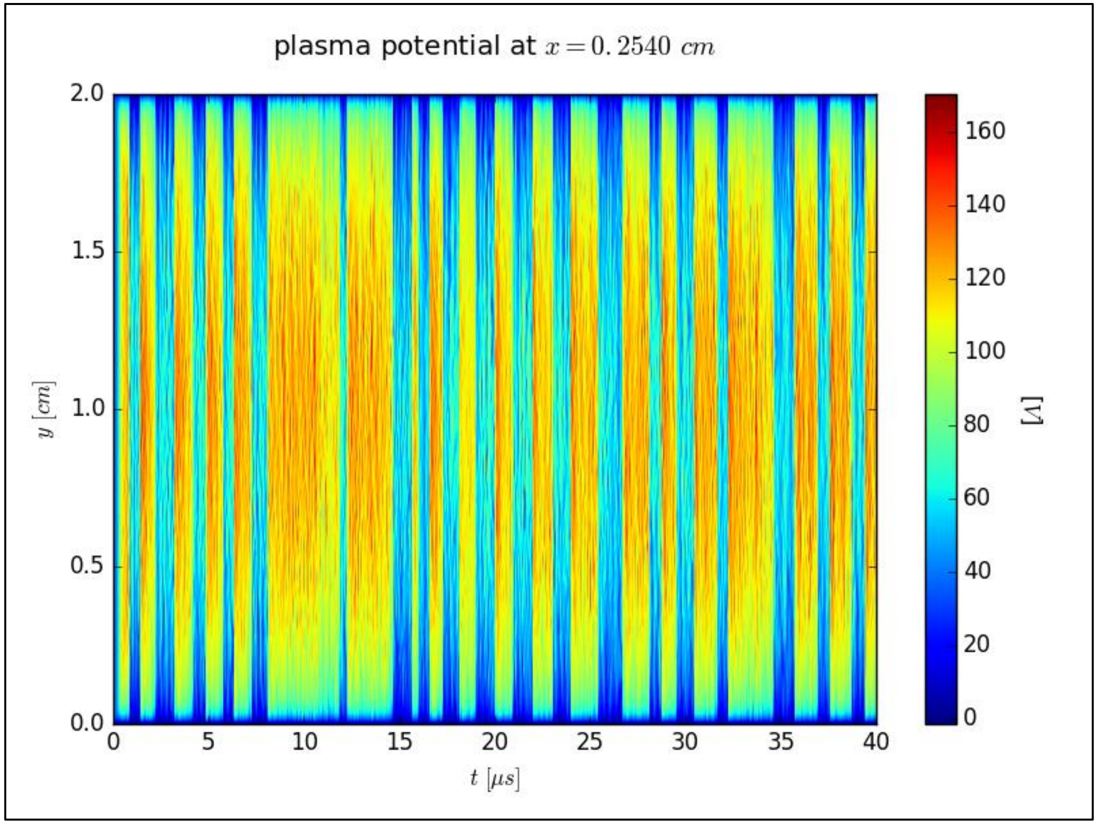


⇨ Theoretic model in development

[1] D. Sydorenko, I.D. Kaganovich, Y. Raitses, A.I. Smolyakov, *Phys. Rev. Let.* **103** 145004 (2009)

Secondary electron emissions

Effect on the instability

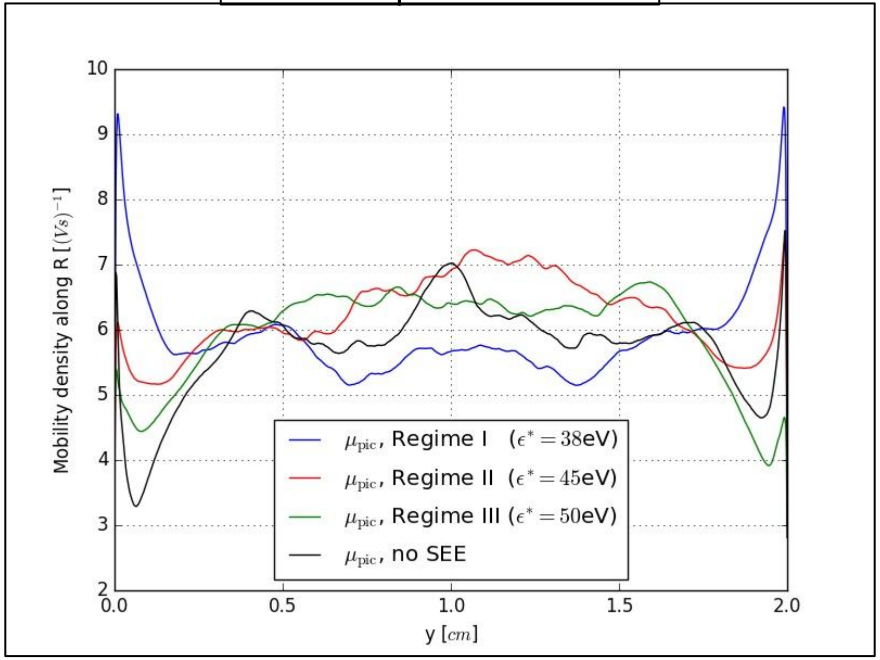


⇨ No impact on electron drift instability characteristics

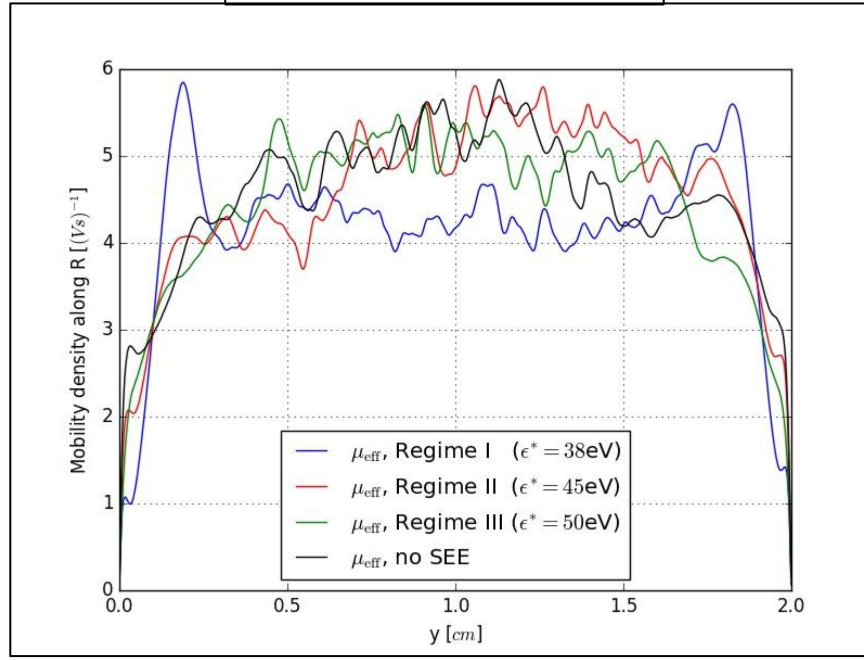
Secondary electron emissions

Effect on the anomalous transport

$\mu_{pic}(R)$



$\mu_{eff}(R)$



Secondary electron emissions

Effect on the anomalous transport

	Measured Values				Analytical Values	
Regime	μ_{pic} ($m^2V^{-1}s^{-1}$)	μ_{eff} ($m^2V^{-1}s^{-1}$)	$\mu_{classical}$ ($m^2V^{-1}s^{-1}$)	$<T_e>$ (eV)	μ_{eff}^{sat} ($m^2V^{-1}s^{-1}$)	$\mu_{classical}$ ($m^2V^{-1}s^{-1}$)
I	5.6	4.1	0.2	40	3.4	0.20
II	5.8	4.6	0.2	44	3.6	0.21
III	5.6	5.4	0.2	48	3.7	0.22
no SEE	5.8	5.6	0.2	50	4.2	0.22

Secondary electron emissions

RSO highlighting

[Film in Regime II]

Secondary electron emissions

Modeling emissions from BN walls

Regime I

❑ Linear model [1]

$\varepsilon^* = 35.04\text{eV}$

$\sigma(0) = 0.578$

$\sigma_{max} = 2.9$

Regime III

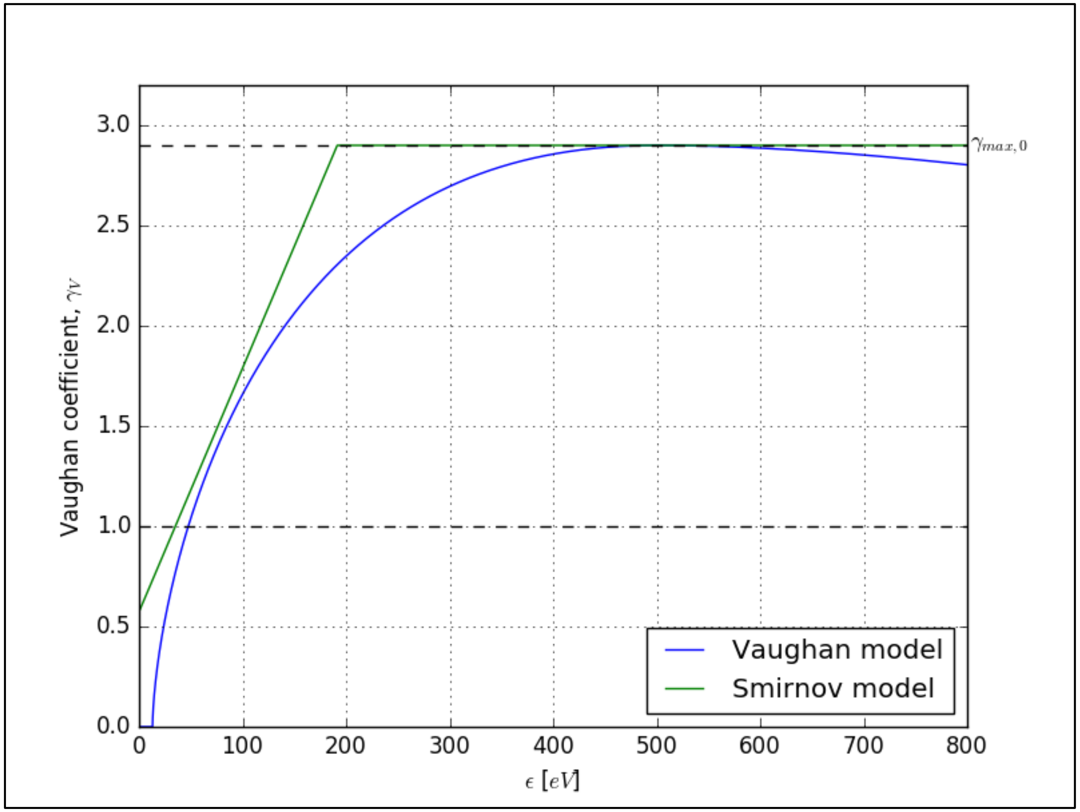
❑ J.R.M. Vaughan [2]

$ks = 1$

$\omega_0 = 13.0\text{eV}$

$\omega_{max,0} = 500.0\text{eV}$

$\sigma_{max} = 2.9$



[1] A.N. Smirnov, Y. Raitses, N.J. Fisch, *IEEE Trans. Plasma Sci.* **34** 132 (2006)
[2] J.R.M. Vaughan, *IEEE Trans./Electron Devices*, 36:1963-1967 (1989)

Alternative propellants

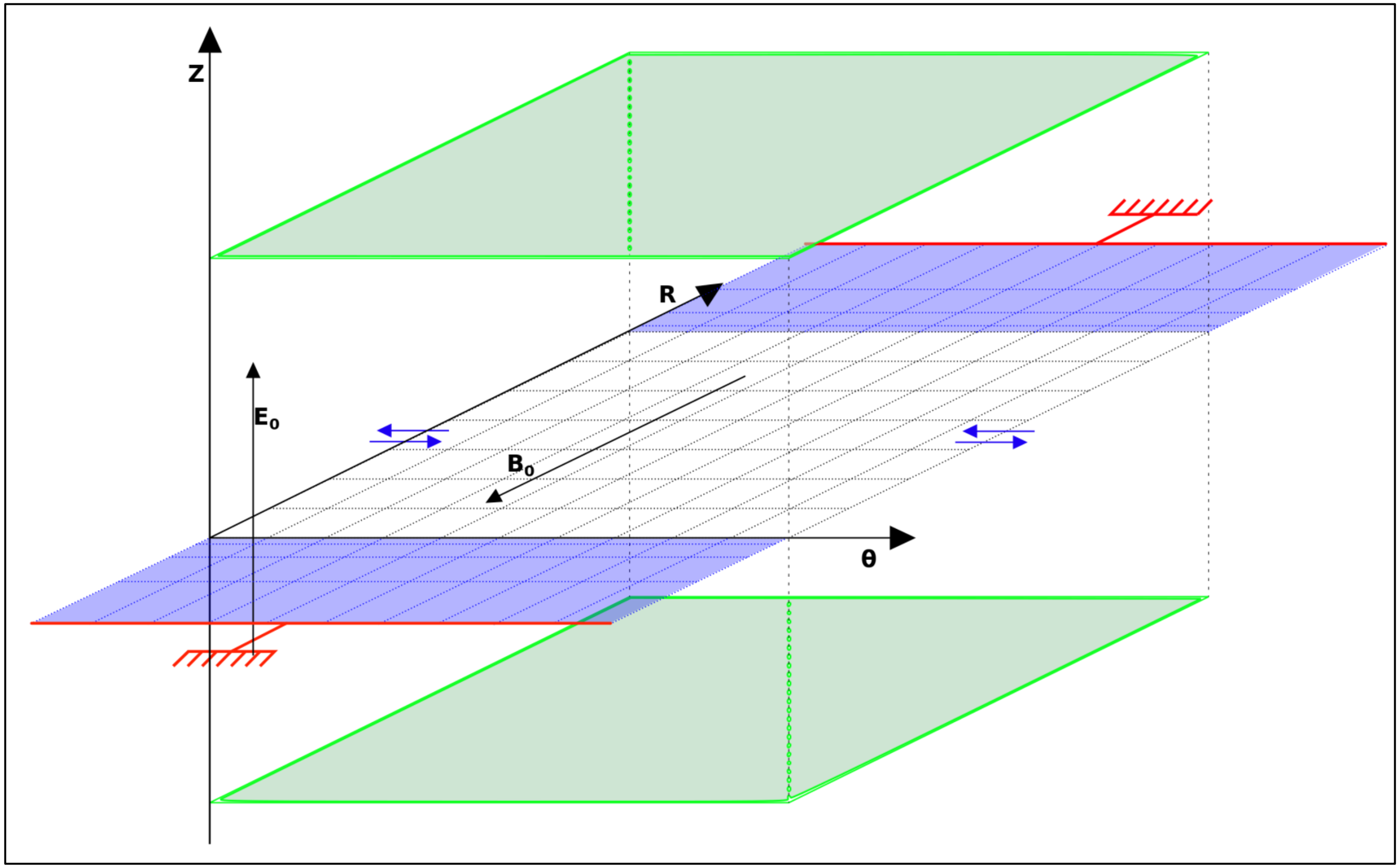
First results

- Recent implementation:
  - ✓ LPPic2D's capacity to change gas easily
  - ✓ Efficient use of *lx-cat* database [1]
  - ✓ Ar, Xe, Kr, He
- Allowed verification using CCP Helium benchmark [2]
- First results seems to confirm kinetic theory [3]
  - ✓ Instability characteristics
  - ✓ Role of collisions seems auxiliary

[1] Lxcat, Cross sections extracted from Program Magboltz, v.7.1 (June 2004)
[2] M.M. Turner, A. Derzsi, Z. Donko, D. Eremin, S.J. Kelly, T. Lafleur, T. Mussenbrock, *Phys. Plasmas*, **20** (2013)
[3] T. Lafleur, S.D. Baalrud, P. Chabert, *Phys. Plasmas* **23**, 053503 (2016)

Dielectric walls

Model implementations



- *Grounded* metallic electrodes connected to the dielectric
- Solving Poisson *in* the dielectrics
- Dielectric described by cells with an *exponential width*

Conclusion

- What is observed?
  - ✓ Electron drift instability
  - ✓ Enhanced electron mobility
- Anomalous mobility agrees well with the correlation term
  - ✓ Can be expressed as a friction force, $\mathbf{R_{ei}}$
  - ✓ Analytical expression at saturation, $\boldsymbol{\mu}_{eff}^{sat}$
- Secondary electron emission
  - ✓ SCL and RSO regimes
  - ✓ Lowers electron temperature
  - ✓ Entangled effect on anomalous transport
  - ✓ Mechanisms **?**
- Alternative propellants & dielectric walls
  - ✓ Seems to confirm kinetic theory
  - ✓ Effects on anomalous transport **?**

Acknowledgements

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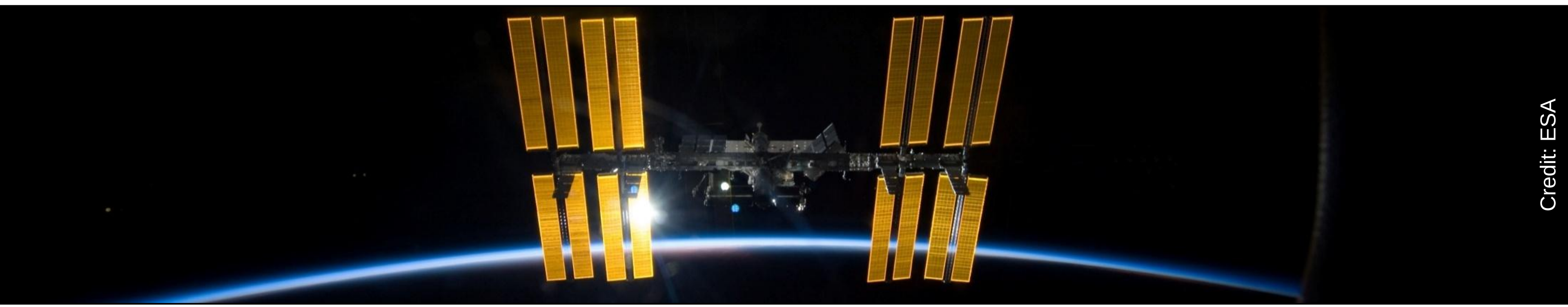
Laboratoire de Physique des Plasmas



SAFRAN
Snecma


Credit: Carlsberg

Thank you!

Questions?

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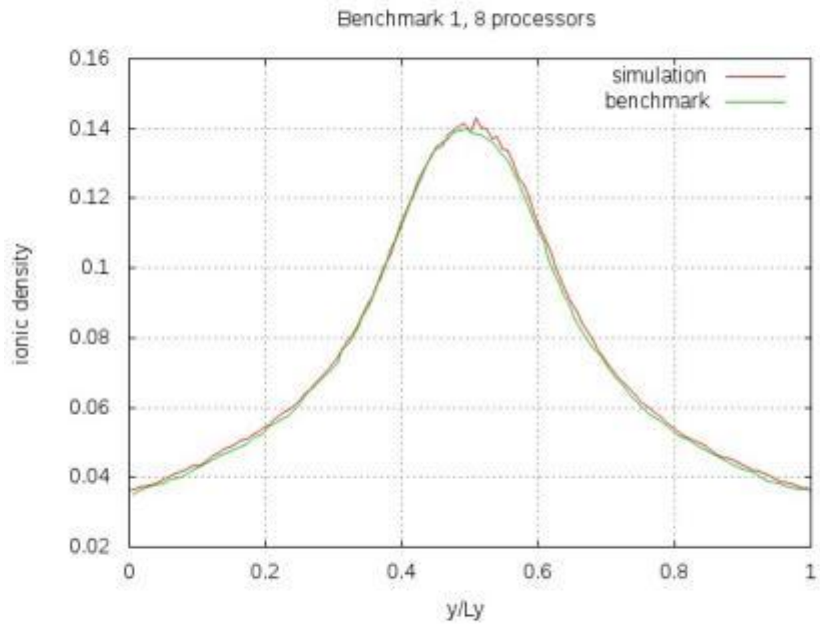
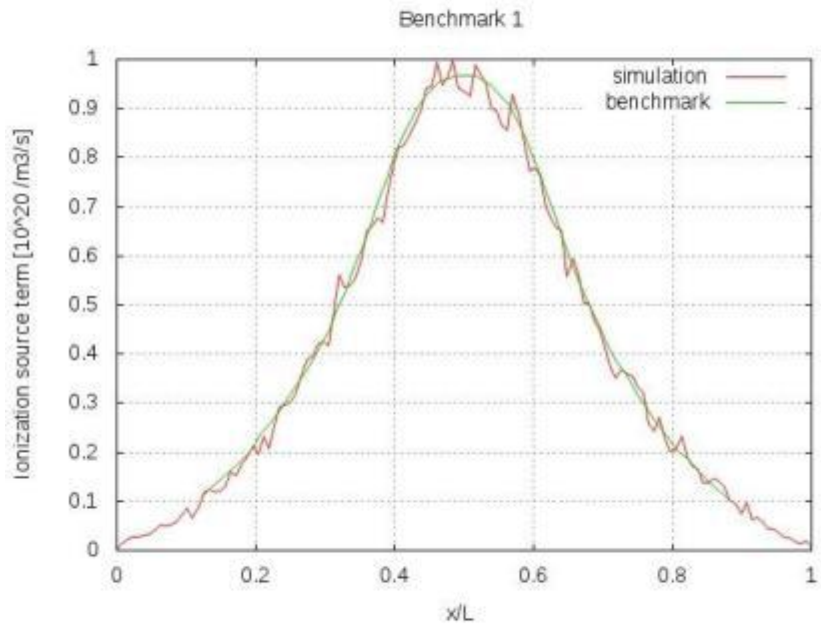
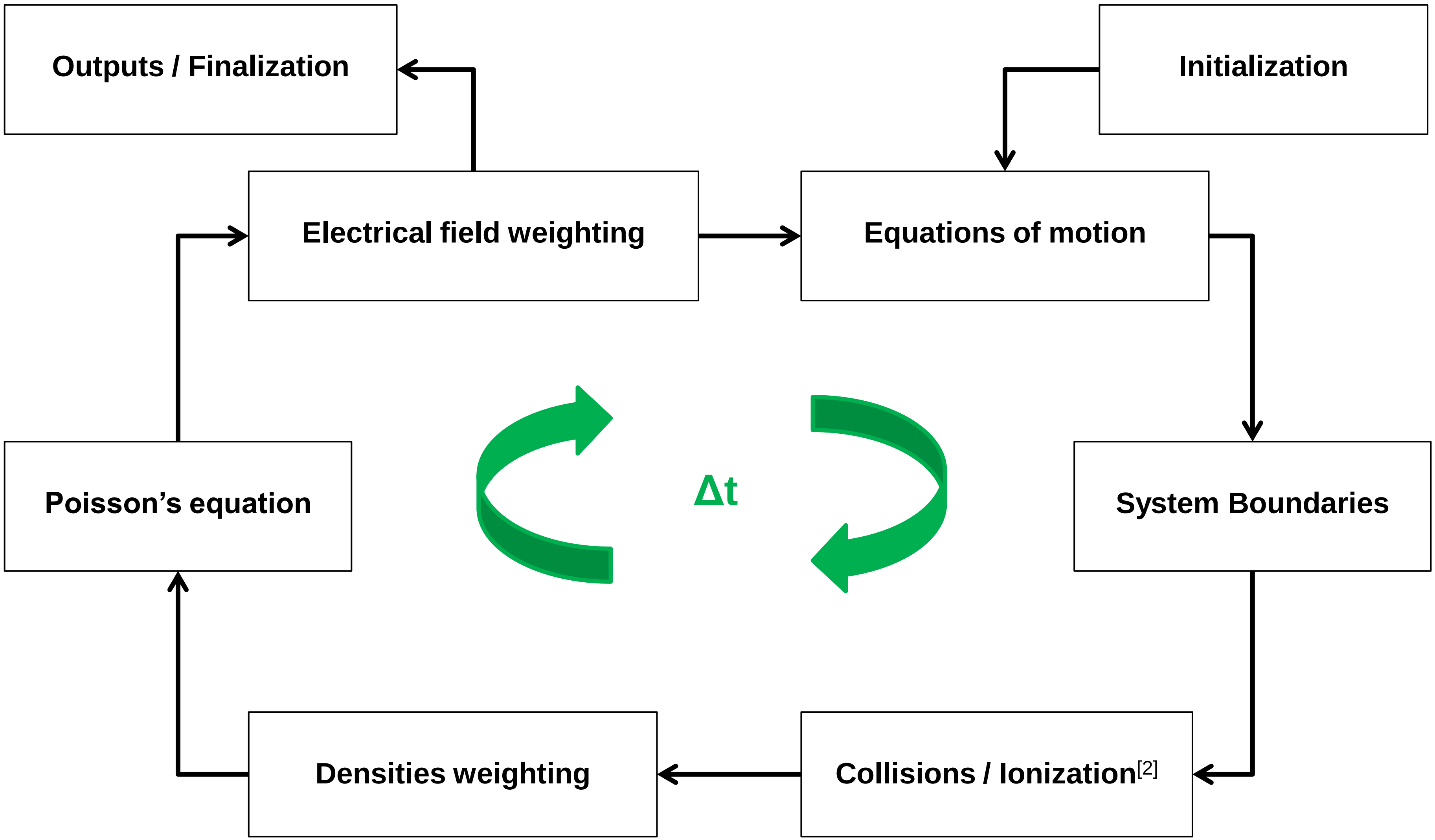
Verification (Helium capacitive benchmarks [3])





[3] M.M.Turner, A.Derzsi, Z.Donko, D.Eremin, S.J.Kelly, T.Lafleur, T.Mussenbrock, Phys. Plasmas, **20** (January 2013)

Particle-In-Cell algorithm[1]

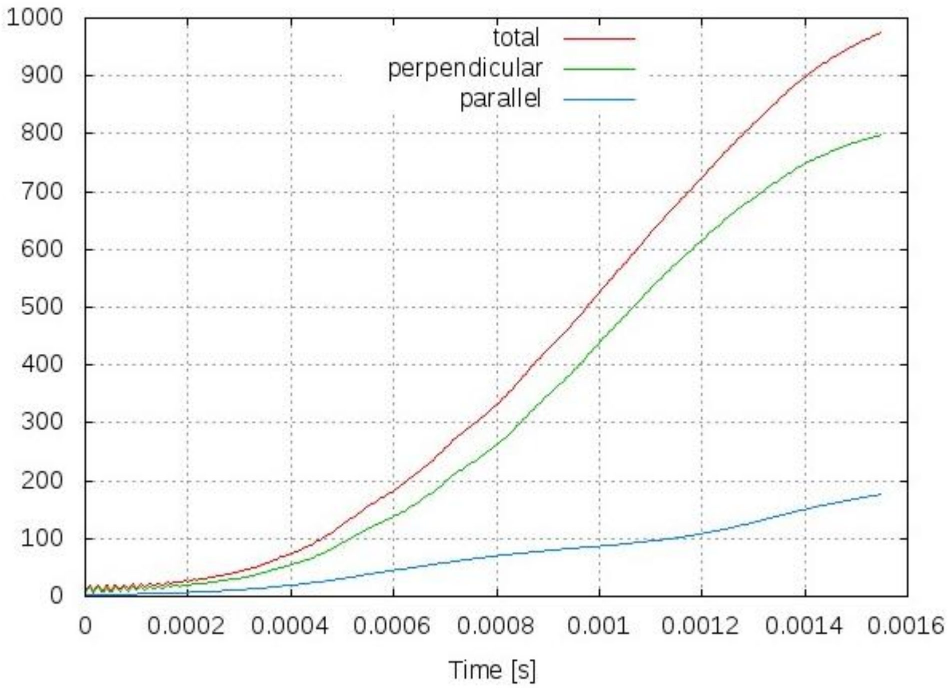


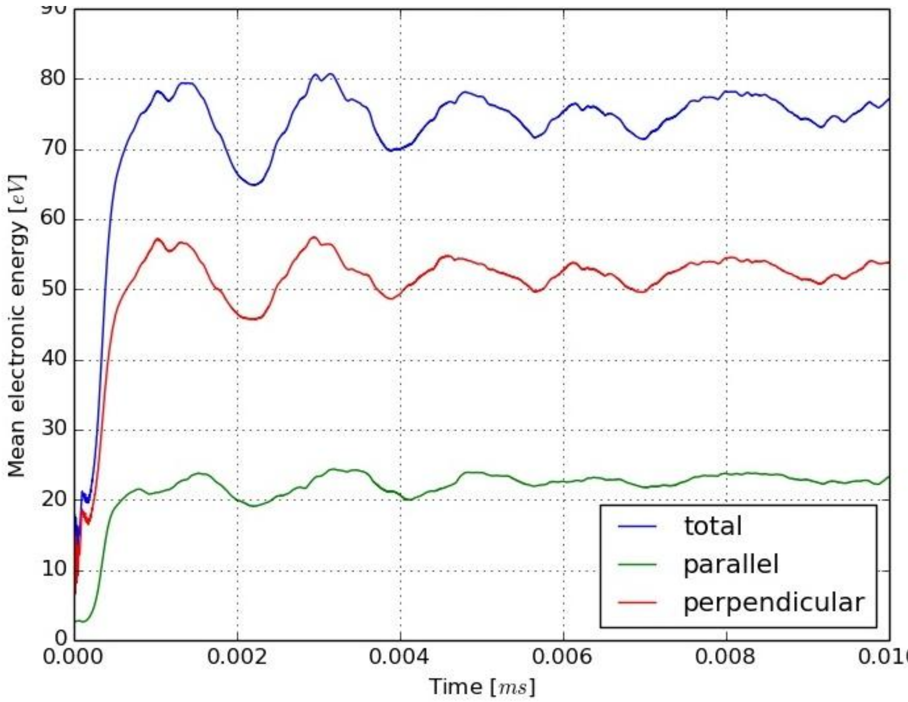
[1] C.K.Birdsall, A.B.Langdon, *Plasma Physics via Computer Simulation* (IOP Publishing, Bristol, 1991)
[2] V.Vahedi, M.Surendra, *Comput. Phys.* Commun. **87**, 179 (1995)

Vertical boundary influence

$L_z \longrightarrow \infty$

$L_z = 1\text{cm}$





Alternative propellants

Effects on the instability

Measured Values					
Propellant	**λ** (mm)	***f*** (MHz)	$\mathbf{V_{ph}}$ (10^3 m·s^{-1})	$\mathbf{\|\delta n_e\|/n_e}$ (%)	$\mathbf{\|\delta\Phi\|/T_e}$ (%)
Xe					
Ar					
fAr					
fKr					
Analytical values					
Propellant	**λ** (mm)	***f*** (MHz)	$\mathbf{V_{ph}}$ (10^3 m·s^{-1})	$\mathbf{\|\delta n_e\|/n_e}$ (%)	$\mathbf{\|\delta\Phi\|/T_e}$ (%)
Xe					
Ar					
fAr					
fKr					