Kinetic Modeling of Electrostatic Ion thrusters

Workshop on Ion Propulsion and Accelerator Industrial Applications

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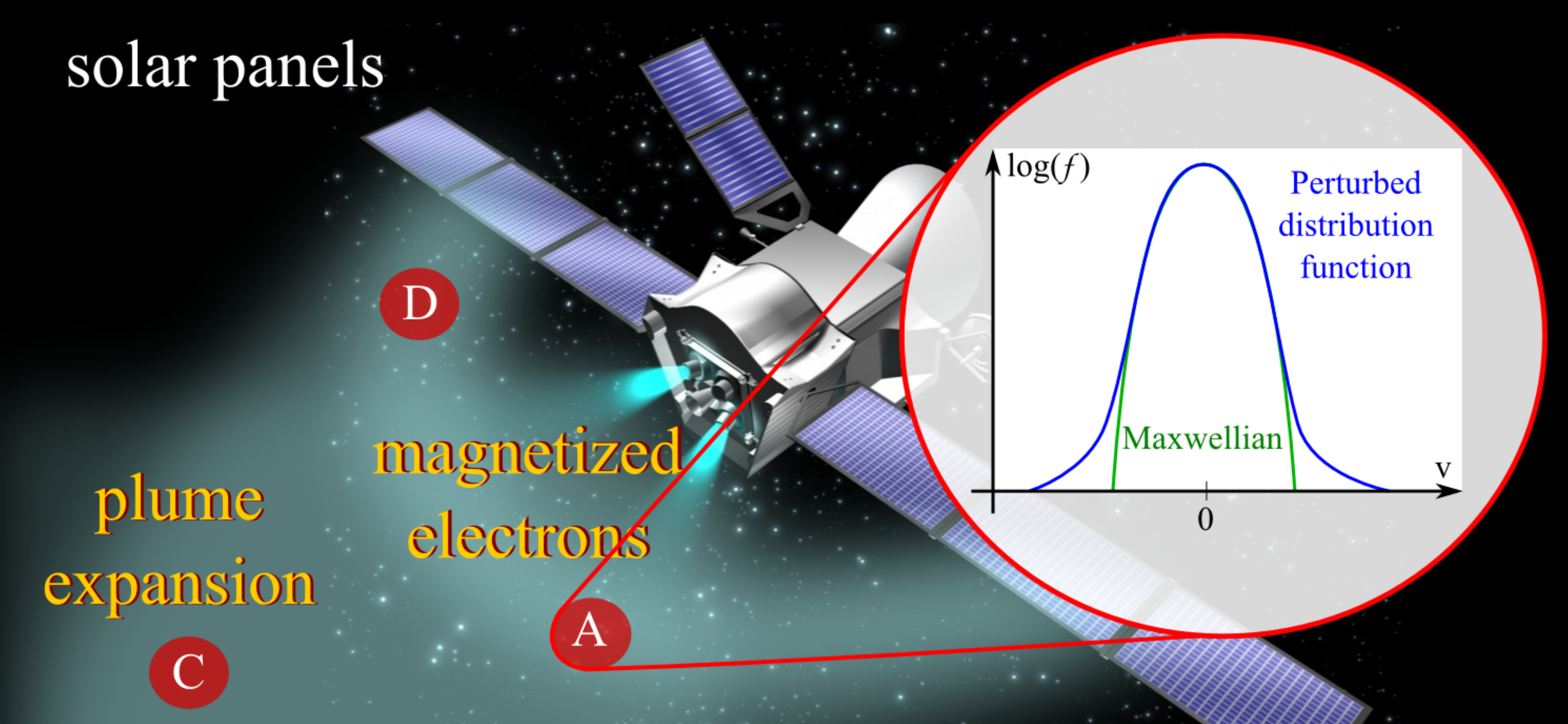
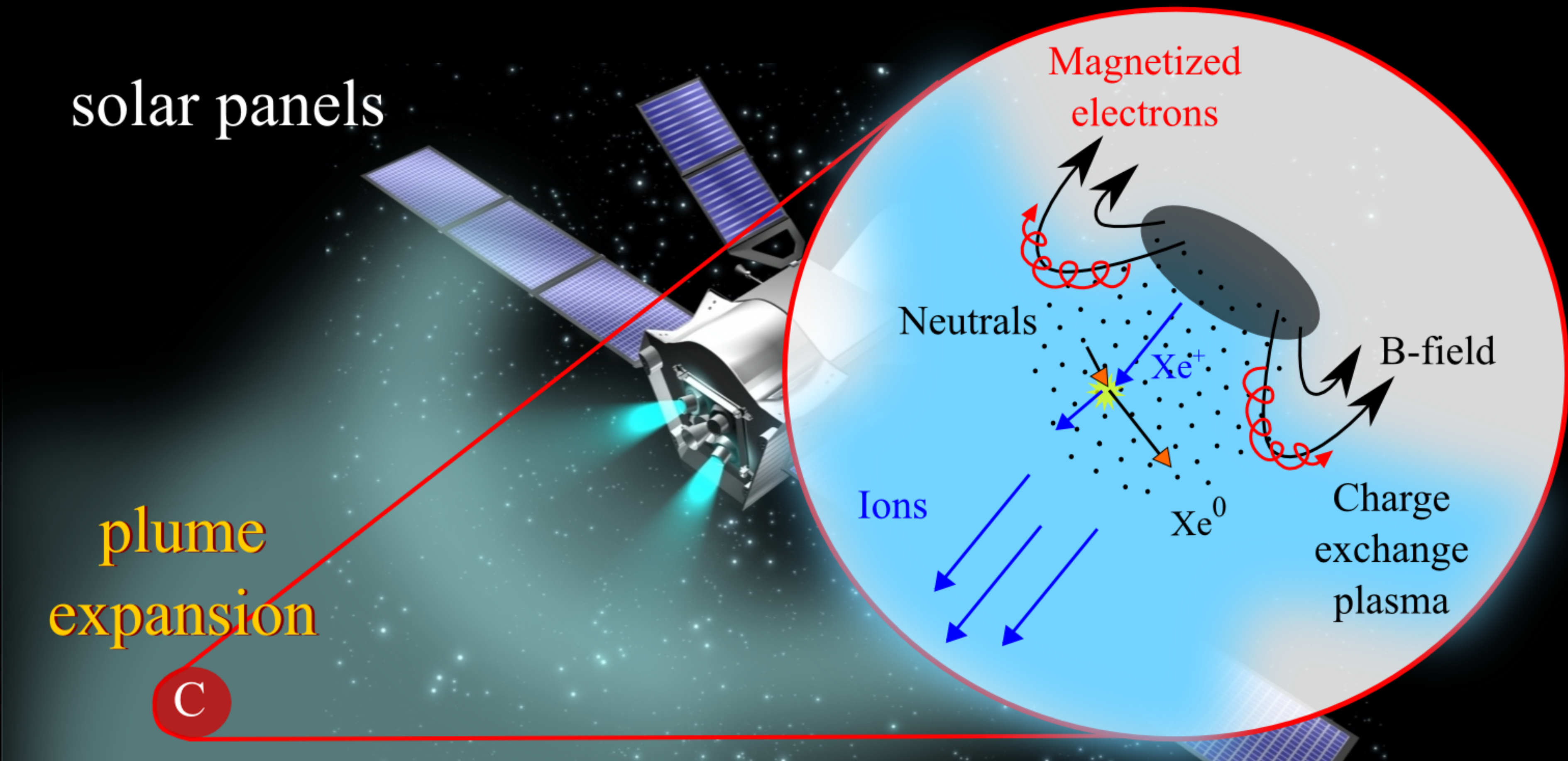
Ion thruster plume interaction with satellites



- A Non-Maxwellian plasma kinetics
- B Plasma-wall interaction
- C Non-magnetized expansion dynamics
- D Plasma & electromagnetic waves

ESA-spacecraft BepiColombo (ESA / C.Carreau)

Ion thruster plume interaction with satellites



A Non-Maxwellian plasma kinetics

B Plasma-wall interaction

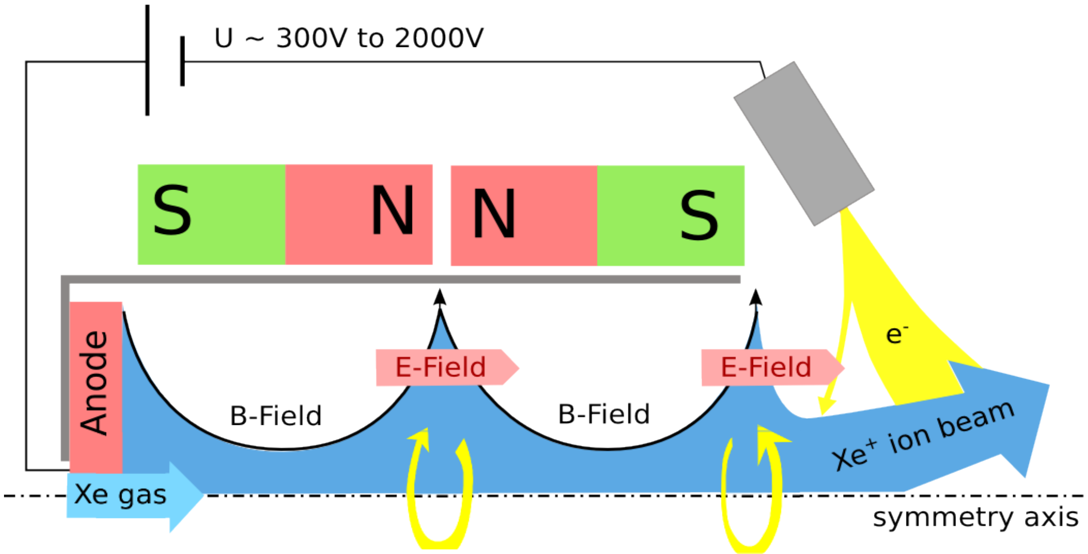
C Non-magnetized expansion dynamics

D Plasma & electromagnetic waves

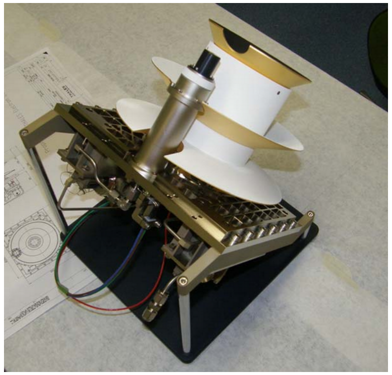
ESA-spacecraft BepiColombo (ESA / C.Carreau)

The HEMP thruster

patented by THALES Electron Devices with an initial patent filed in 1998



DLR Projects:
50 RS 0804, 50 RS1101



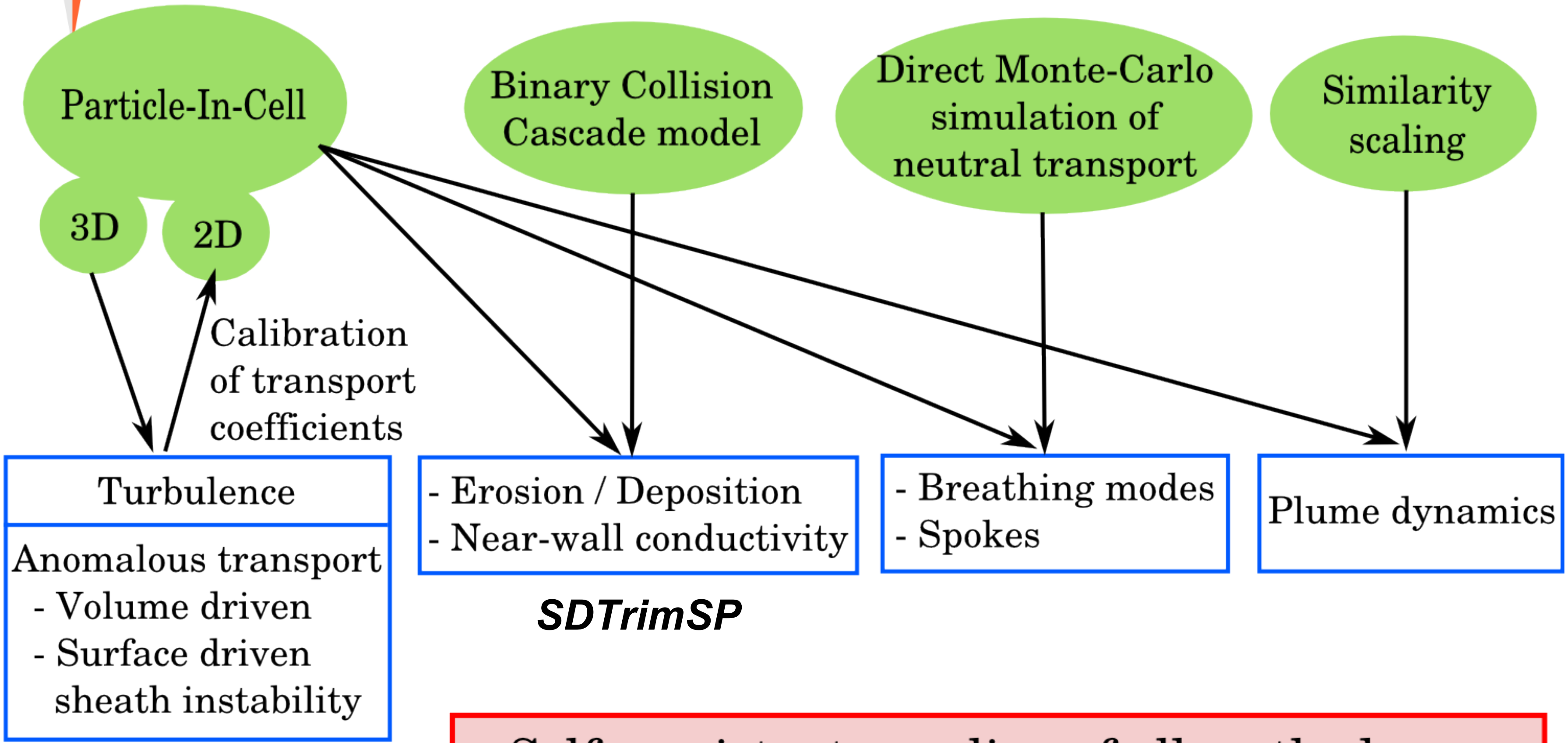
THALES

Self-consistent kinetic simulation: $\lambda_e^{mfp} \approx L_{system}$

Self consistent plasma + neutral dynamic
Anomalous transport
Secondary electron emission
Integrated model of channel and plume

System without grid and reduced wall contact

Simulation tools

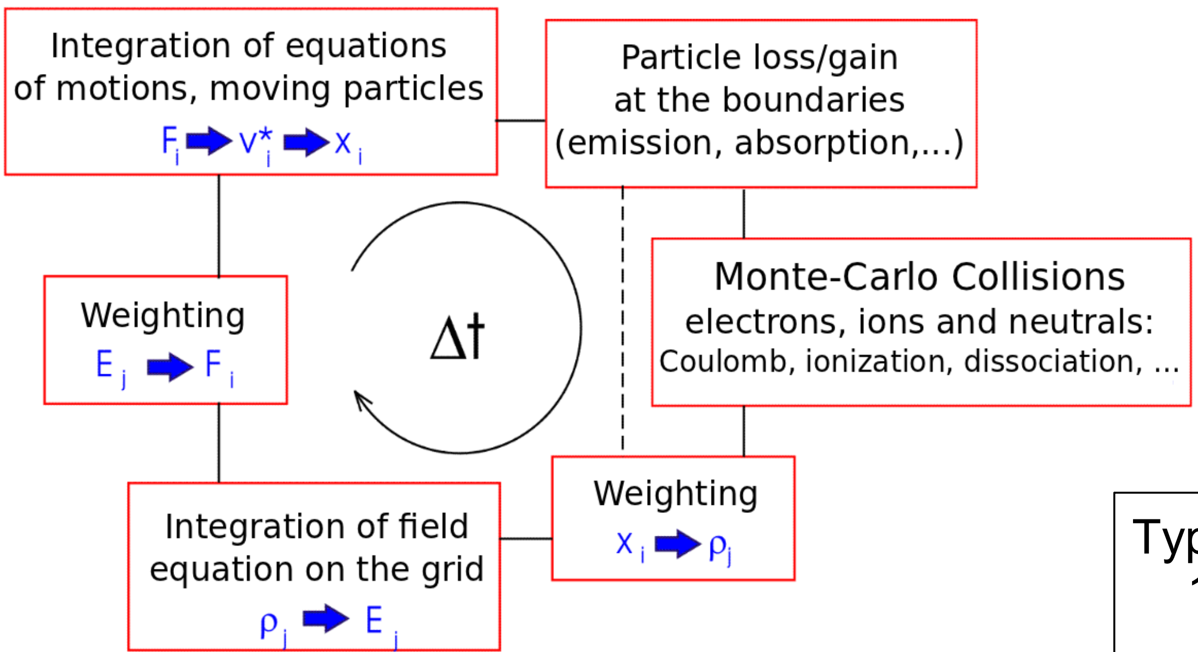


- Self consistent coupling of all methods
- Reduction of empirical parameters
- Deduction from higher hierarchical models

Own codes!

Particle-In-Cell: [1], [2]
SDTrimSP: [3], [4], [5]
Similarity scaling: [6]

MCC Particle-In-Cell simulation



Requirements:

$\Delta t = 0.2/\omega_{p,e}$ $\Delta x = 0.5\lambda_{D,e}$

equidistant mesh (self force!)

Similarity scaling:

$\frac{r_{L,e}}{L} = const.$ $\frac{\lambda_{e,N}^{mfp}}{L} = const.$

surface/volume limit

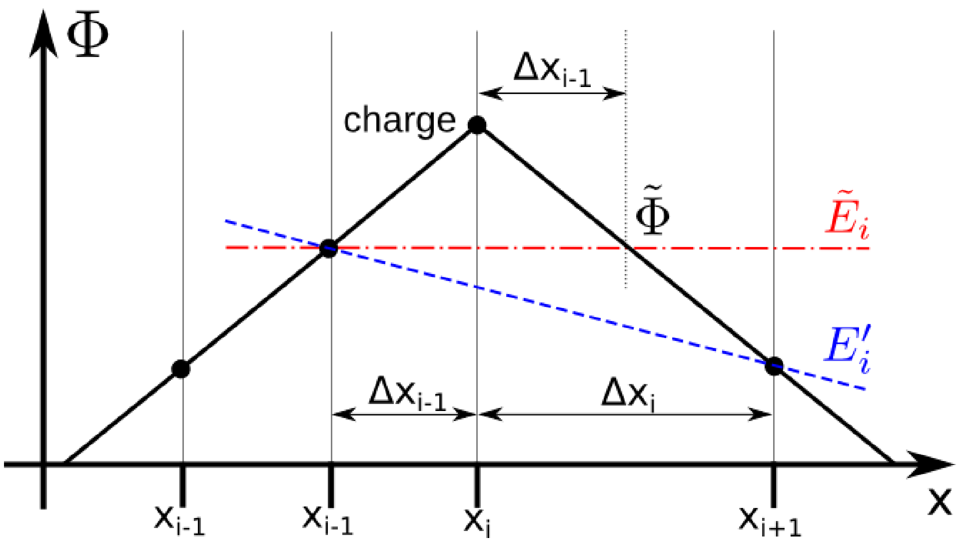
Typical parameters for HEMP:
10^5 cells, 10^8 time steps,
10^8 pseudo-particles
→ computing time ≈ 2 weeks

Direct Monte-Carlo Collisions:

$e^- + Xe \rightarrow Xe^* + e^-$	total excitation	$Xe + e^- \rightarrow Xe^+ + 2e^-$	ionization
$e^- + Xe \rightarrow Xe + e^-$	elastic scattering	$Xe + e^- \rightarrow Xe^{++} + 3e^-$	ionization
$Xe^+ + Xe \rightarrow Xe^+ + Xe$	elastic scattering	$Xe^+ + e^- \rightarrow Xe^{++} + 2e^-$	ionization
$Xe + Xe^+ \rightarrow Xe^+ + Xe$	charge exchange	Coulomb collisions (e^--e^-, Xe^+-Xe^+)	

Non-equidistant PIC

Test: 1D PIC, 1 electron



different E-field interpolation

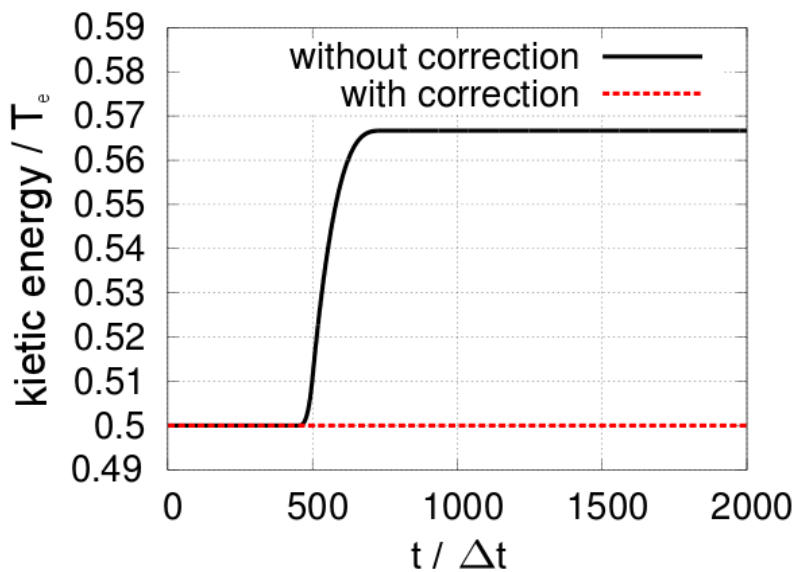
↓

self force disappears

non-symmetric situation for non-equidistant grids

↓

artificial self force

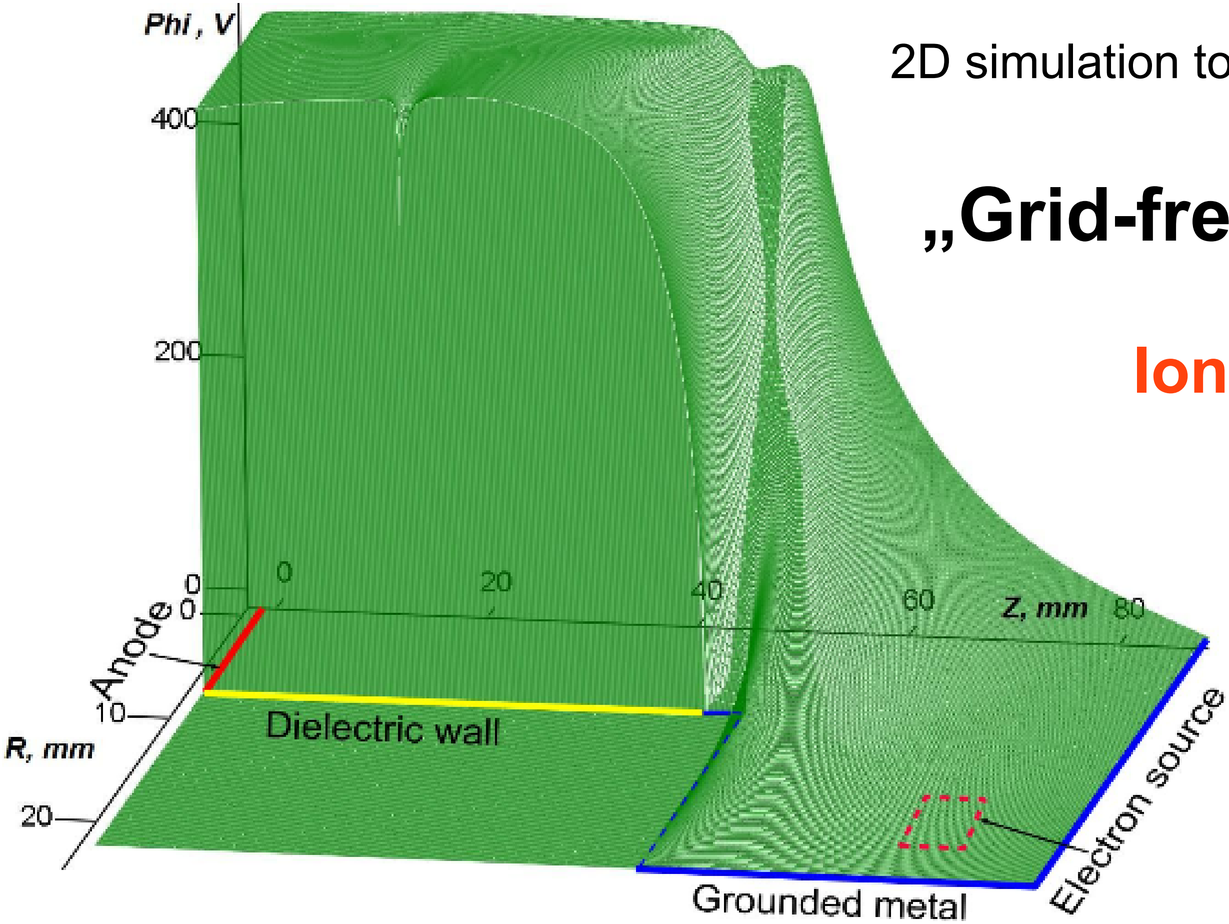


[7] Duras, Matyash; CPP (2014)

Simulation results

HEMP DM3a thruster

Potential profile:



2D simulation to reduce computational effort

„Grid-free grid thruster"

Ions accelerated at the exit

$R_{thruster}$ = 9 mm

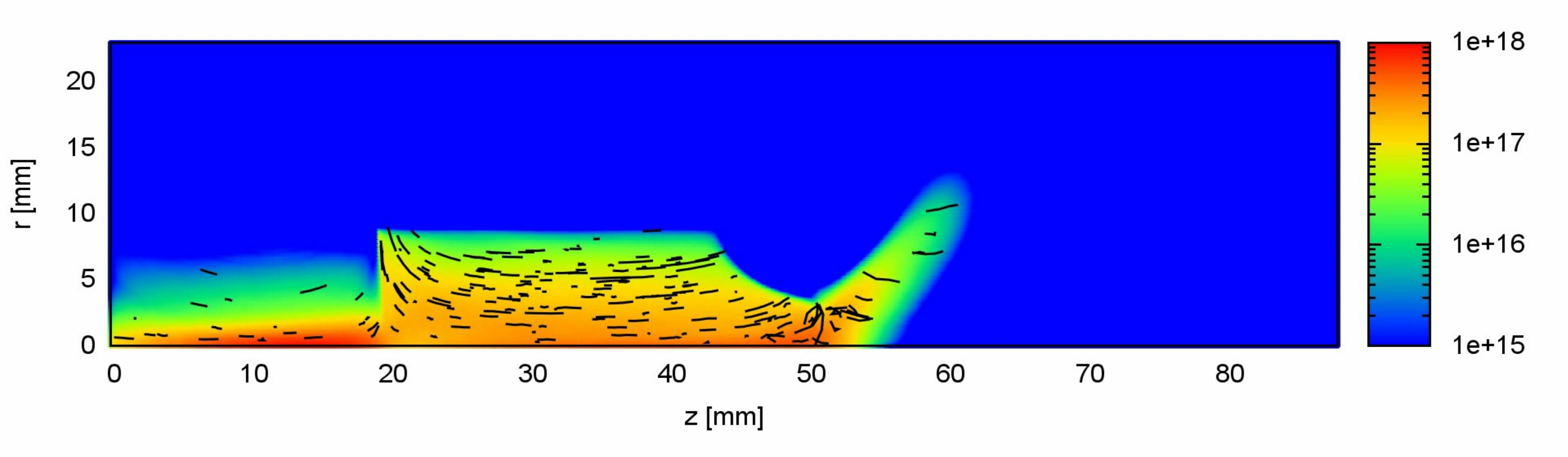
$L_{thruster}$ = 51.2 mm

[8] Matyash, Schneider; IEEE (2010).
[9] Kalentev, Matyash; CPP (2014).

Simulation results

HEMP DM3a thruster

Electron density with example particles:

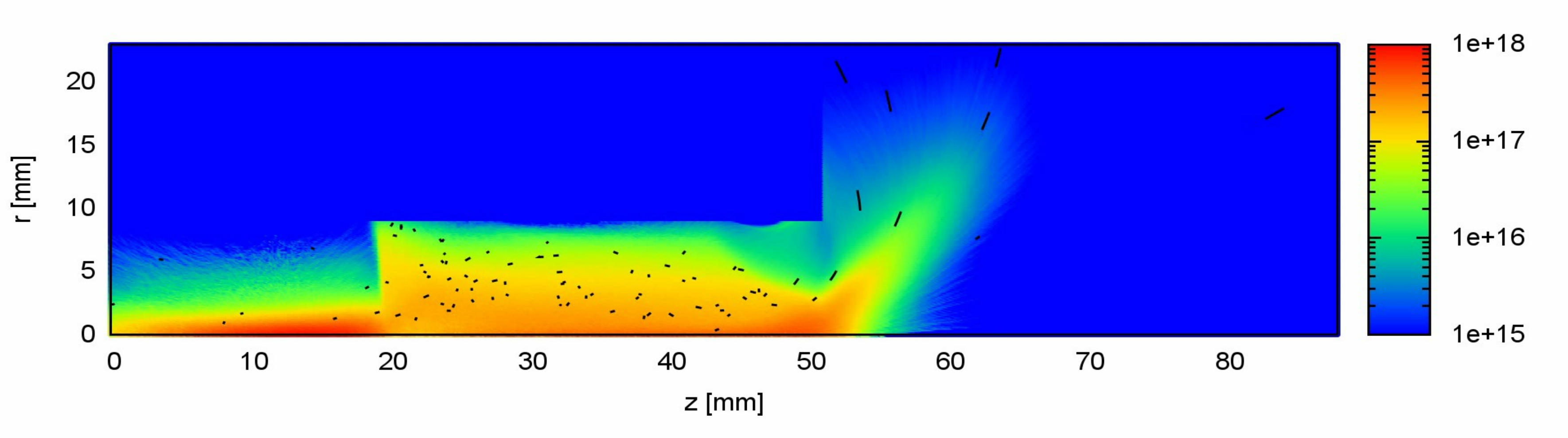


- **Magnetised electrons** $50 \cdot \Delta t_e$
- **Non-Maxwellian velocity distribution** $\lambda_e^{mfp} \approx L_{system}$
- **Oscillating in front of the exit**

Simulation results

HEMP DM3a thruster

Ion density with example particles:



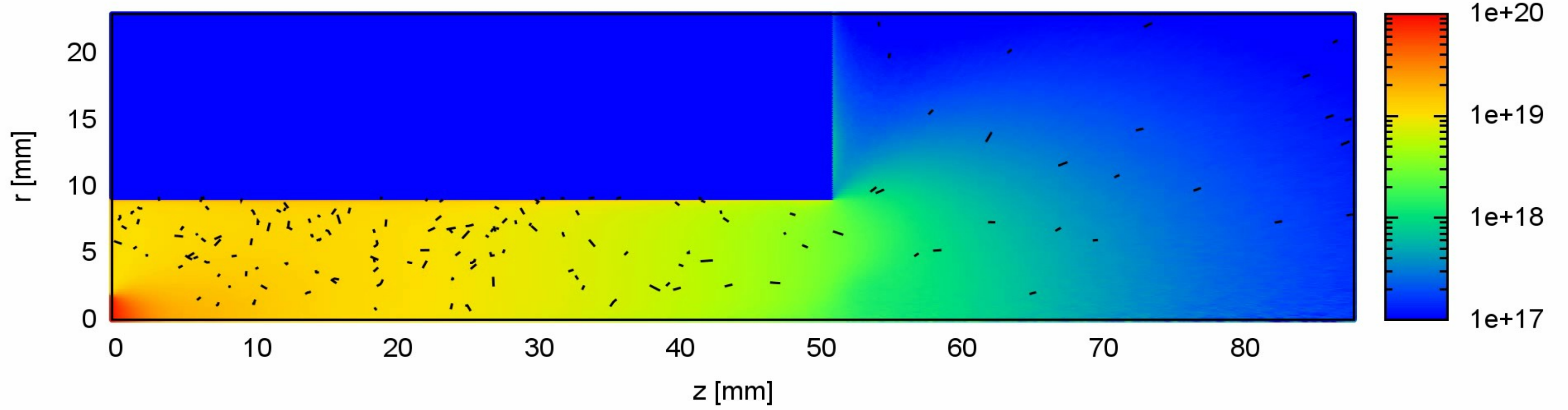
$$2.000 \cdot \Delta t_e$$

- **Not magnetized**
- **Thermal velocity distribution in the channel**
- **Acceleration at the thruster exit**

Simulation results

HEMP DM3a thruster

Neutral density with example particles:



$10.000 \cdot \Delta t_e$

- **Thermal velocity in the channel**
- **Expansion at the channel exit**

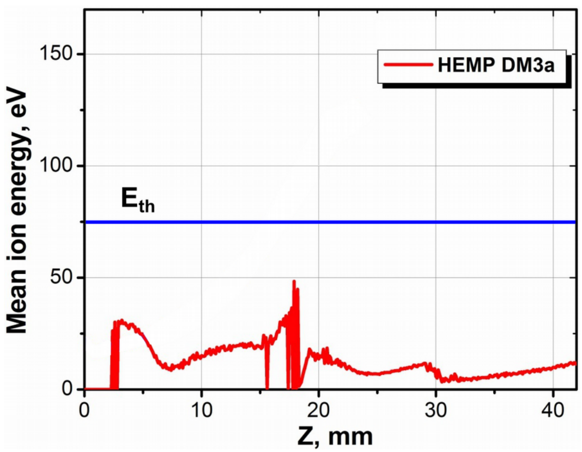
Diagnostics

HEMP DM3a thruster

Validation with experimental data

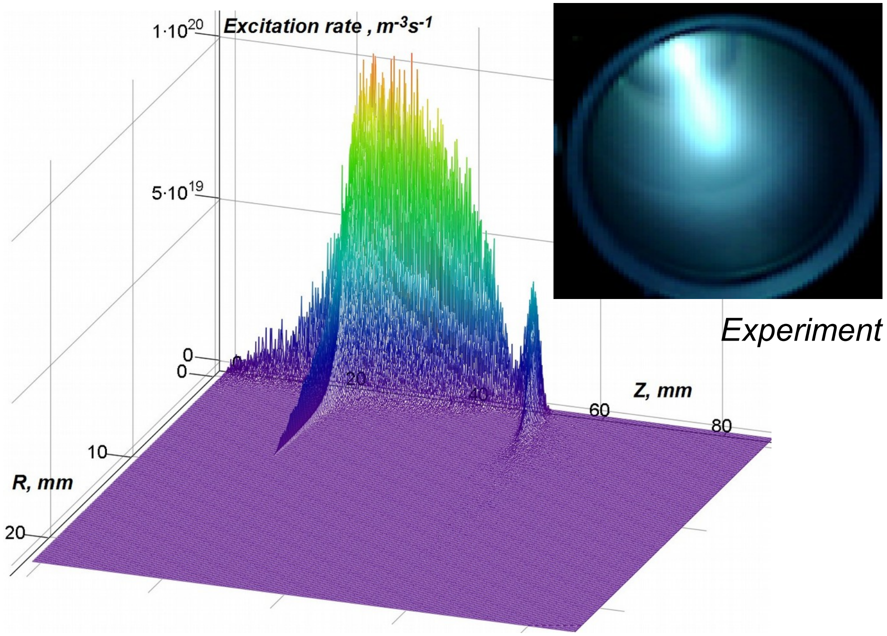
Erosion:

- Ion flux non-negligible in HEMP only at cusp positions
- Energy below the sputtering threshold (E_{th}~ 75 eV)



„Grid-free grid thruster with minimized erosion"

Total excitation:

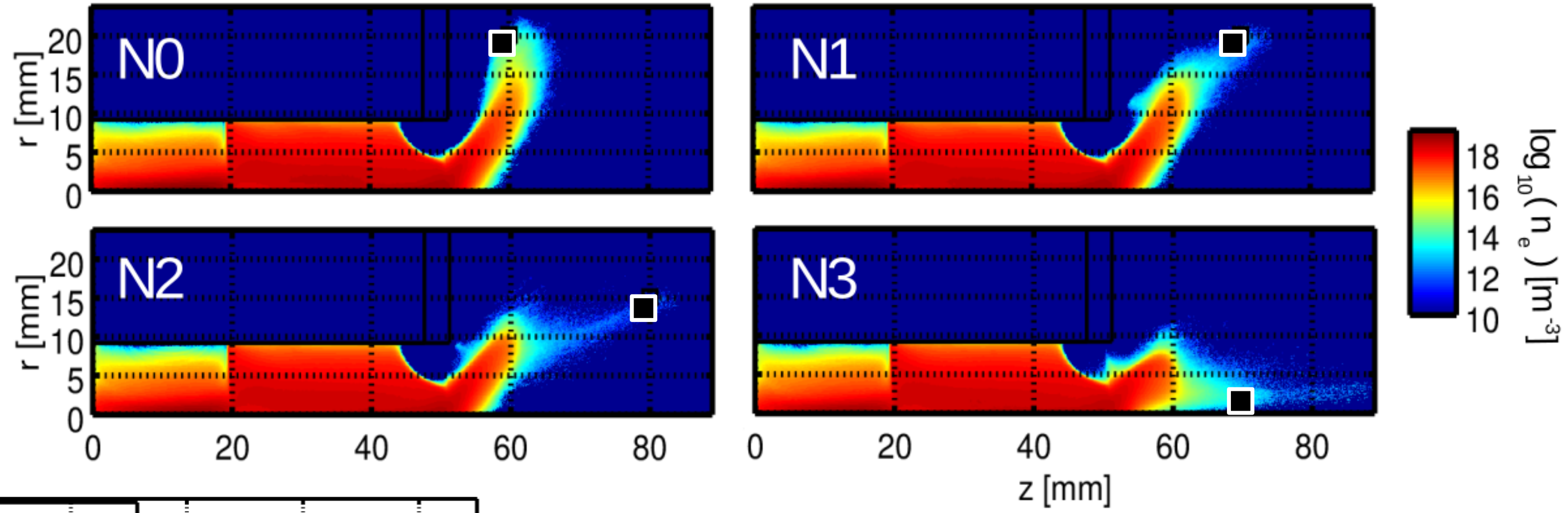


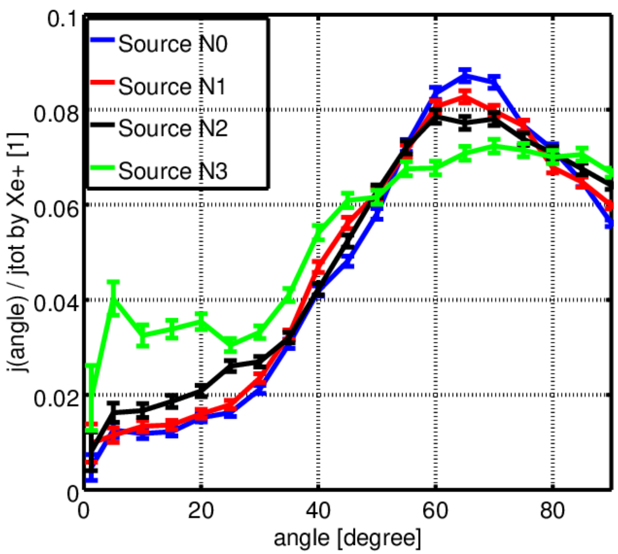
Light emission from axis and cusps

[8] Matyash, Schneider; IEEE (2010).

Influence of electron source

Thermal source with T_e=2eV and I_{src} = 0.3mA





Due to B-field, only axial source changes electron density → angular ion distribution

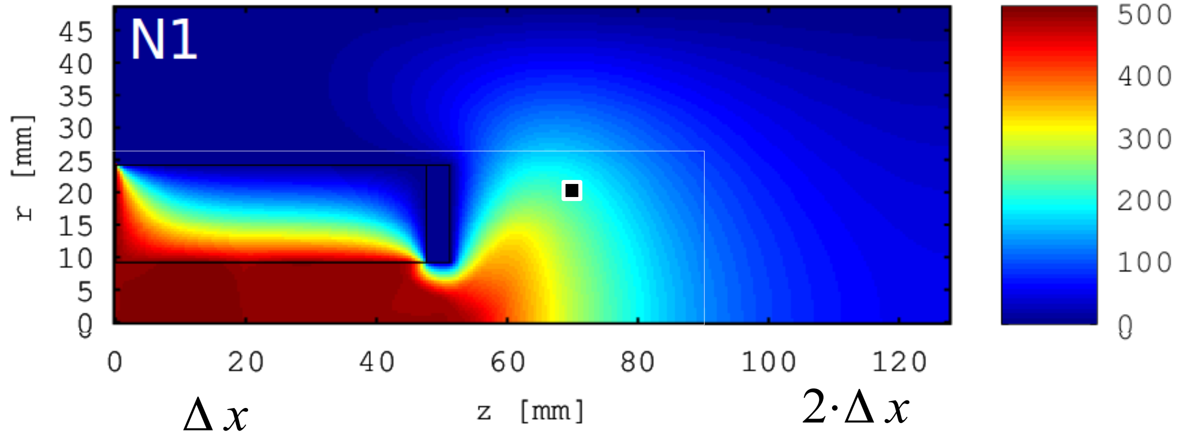
Axial electrons enter channel directly

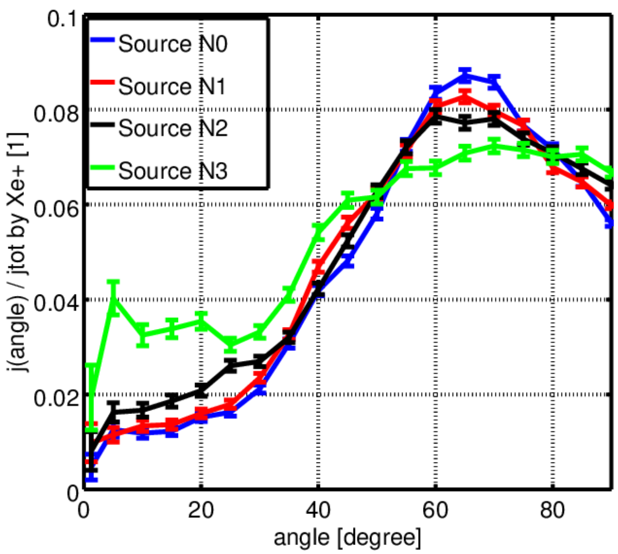
Non axial electrons = reservoir

[10] Duras, Schneider; PPT (2016).

Influence of electron source

Thermal source with T_e=2eV and I_{src} = 0.3mA





No plume plasma

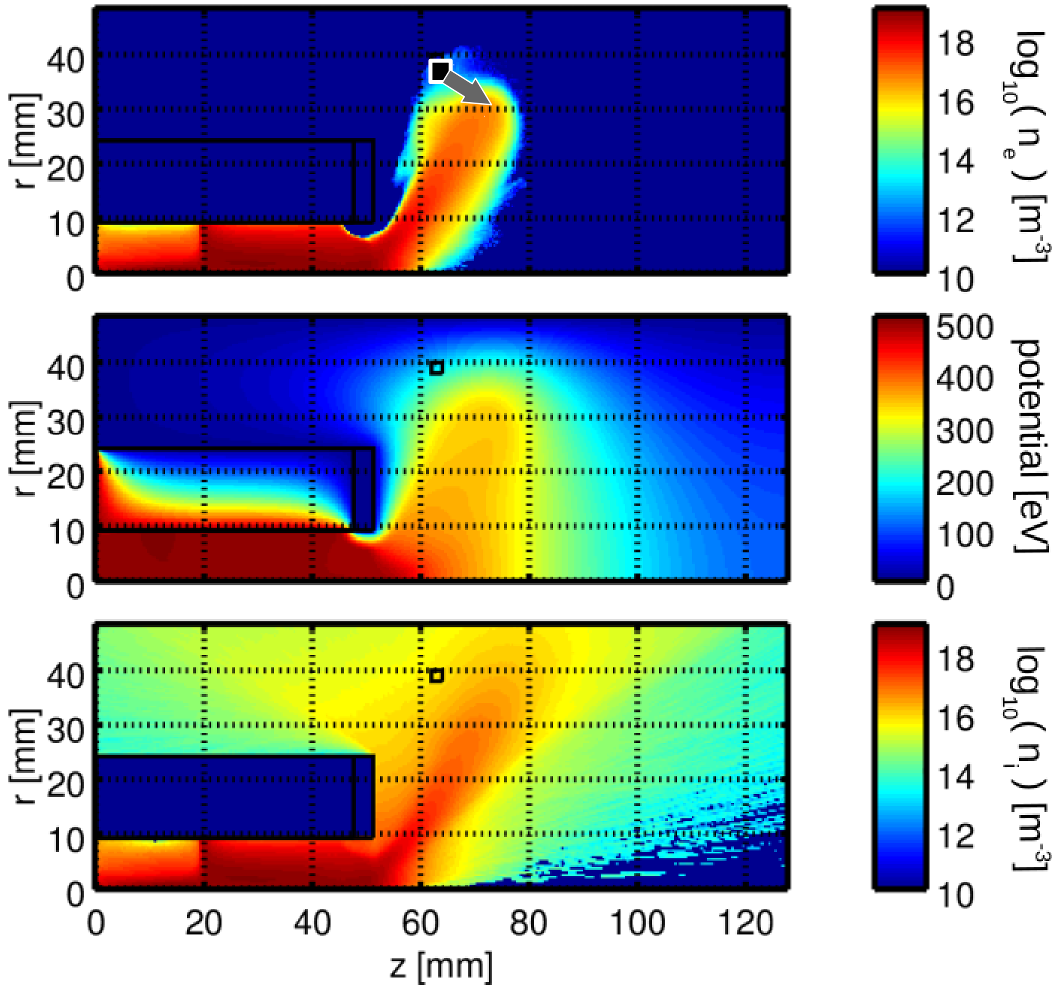
No screening of domain boundary potential

→ influences angular ion distribution

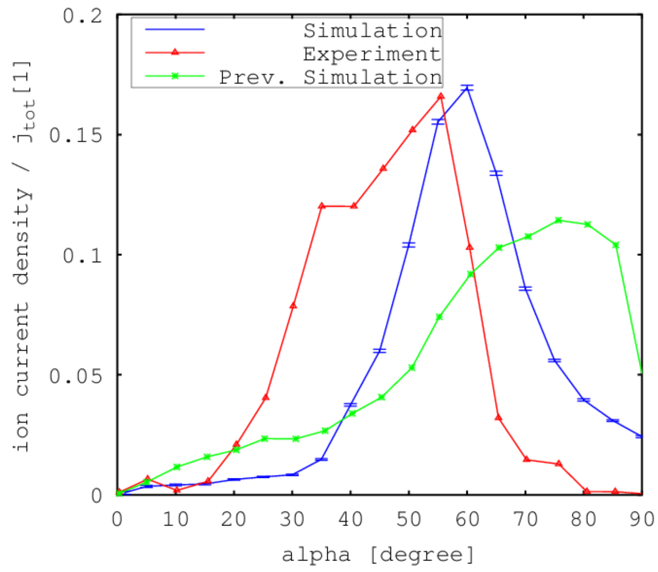
[10] Duras, Schneider; PPT (2016).

Influence of electron source

Directed source with drift velocity $v_{drift,e}$=20eV, T_e=0.1eV and I_{src}=0.3mA



Plasma screens top boundary potential = more realistic



[10] Duras, Schneider; PPT (2016).

Summary

- **Self-consistent kinetic simulation are needed**
  → computationally costly → deduction from higher hierarchies
- **Correction of E-field calculation for non-equidistant grids**
- **Validation with experiment: wall erosion & total emission**
- **Studies of electron sources:**
  - **Ion beam divergence is mainly determined by B-field**
  - **Screening of domain potential is important for simulation**

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Bayerisches Staatsministerium für
Bildung und Kultus, Wissenschaft und Kunst

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[10] J. Duras, R. Schneider, O. Kalentev, S. Kemnitz, K. Matyash, N. Koch, K. Lüskow, D. Kahnfeld, G. Bandelow: *Influence of electron sources on the near-field plume in a multistage plasma thruster*, **Plasma Physics and Technology.** 2016; 3(3):126-130.

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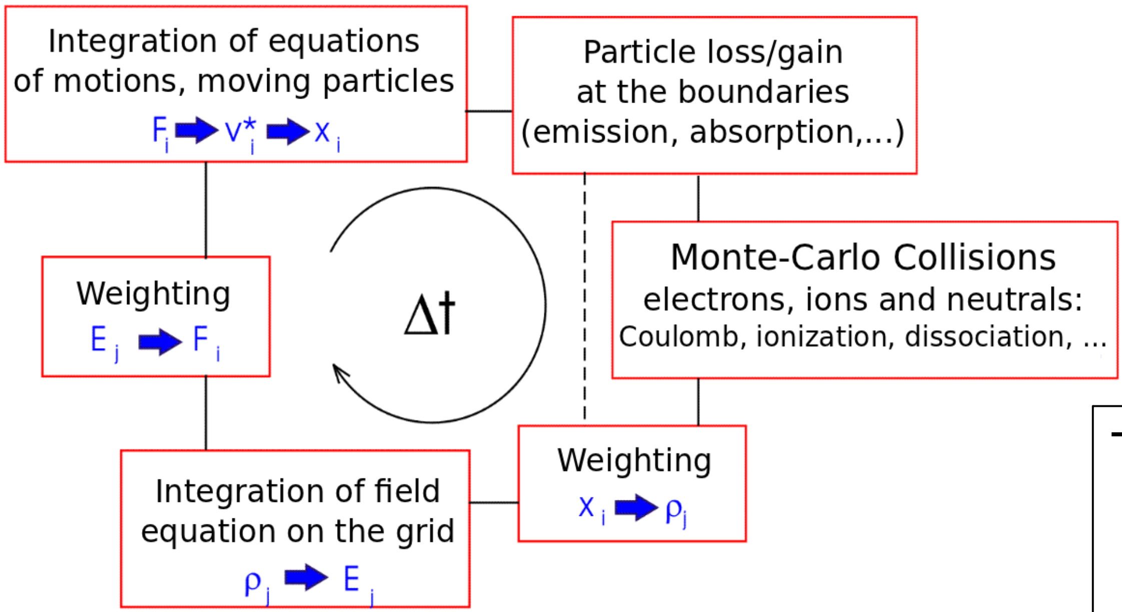
Particle-In-Cell simulation of ion thrusters



Requirements:

$\Delta t = 0.2/\omega_{p,e} \quad \Delta x = 0.5\lambda_{D,e}$

equidistant mesh for momentum conservation

Typical parameters for HEMP:
10^5 cells, 10^8 time steps,
10^8 pseudo-particles
→ computing time ≈ 2 weeks

Length	$L = f L^*$
Magnetic field	$B = f^{-1} B^*$
Cross section	$\sigma = f^{-1} \sigma^*$
Plasma density	$n_p = n_p^*$
Neutral density	$n_n = n_n^*$
Electric potential	$\Phi = \Phi^*$
Temperature	$T = T^*$

Similarity scaling:

$\frac{r_{L,e}}{L} = const. \quad \frac{\lambda^{mfp}_{e,N}}{L} = const.$ → surface/volume limit

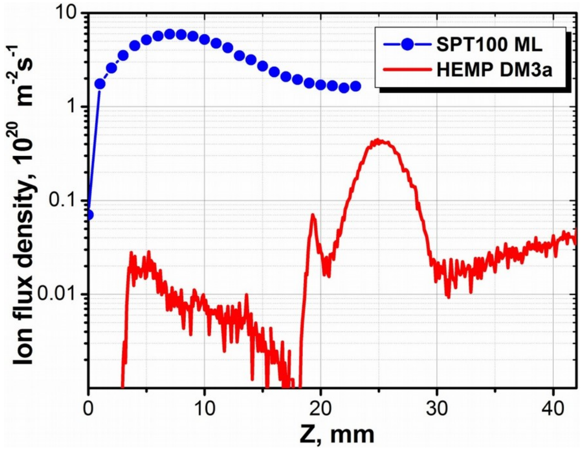
Energy not scaled → atomic physics preserved

Debye length unchanged → reduction of grid size

Channel erosion

HEMP DM3a thruster

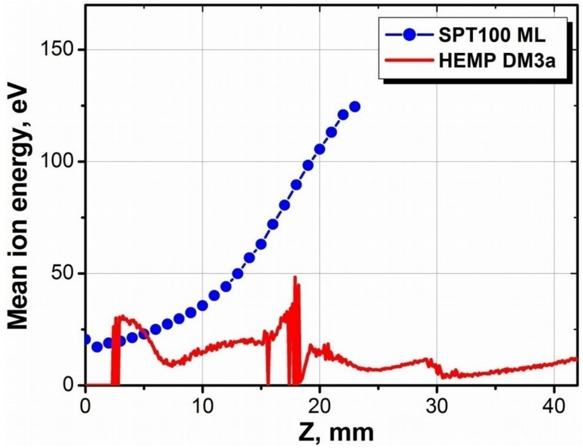
Ion fluxes to the channel wall



Ion flux non-negligible in HEMP only at cusp position Energy below the sputtering threshold (E_{th}~ 75 eV)

[7] Matyash, Schneider; IEEE (2010).

Mean energy of the ions



Erosion rate