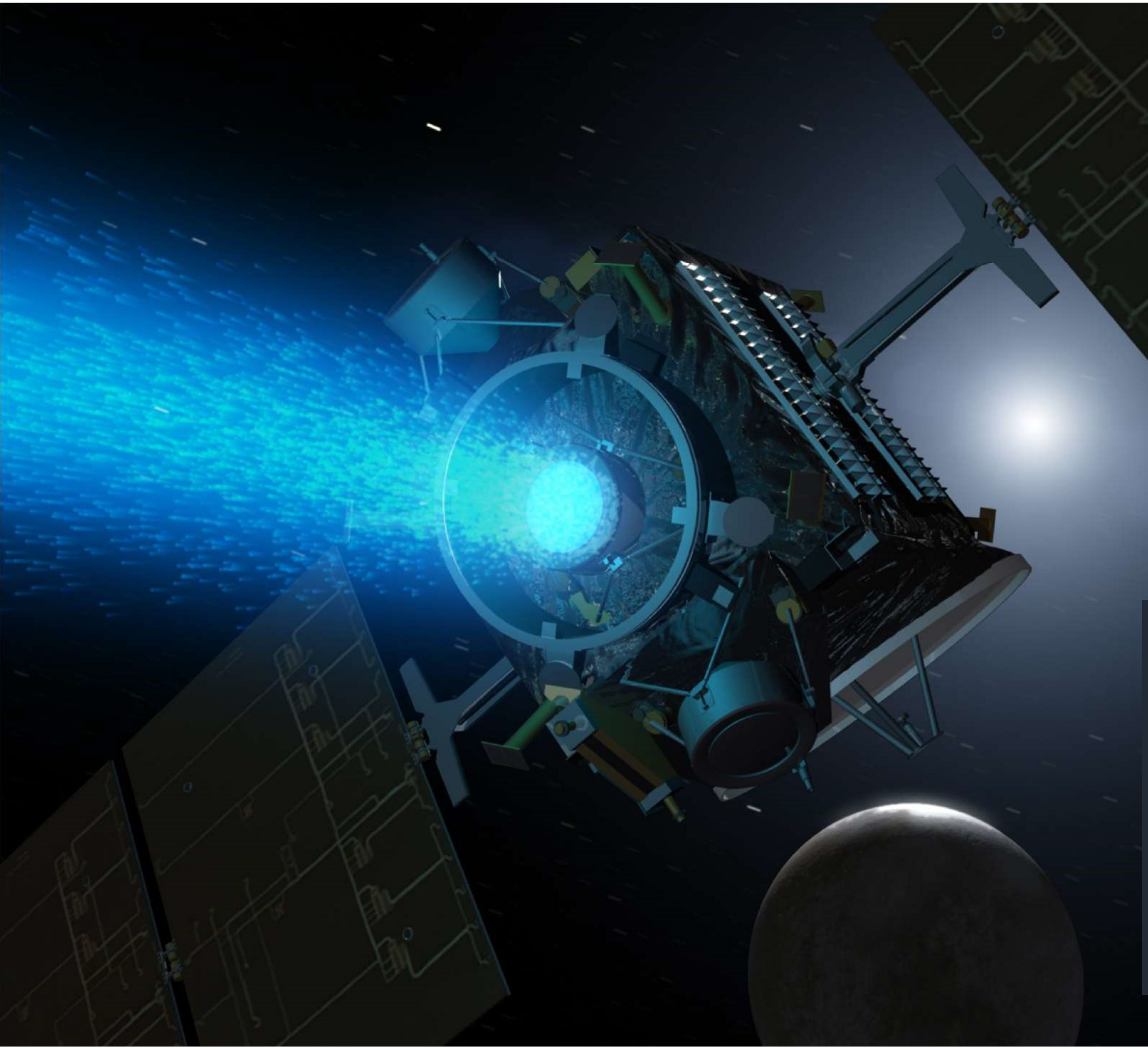


Computational Plasma Engineering of Gridded Ion Optics

28th Spacecraft Plasma Interaction Network in Europe meeting 2021

June 8th | 9th | 10th 2021

U. Siems, S. Rouwette, L. Basov, S. Chibani, R. Bouziane, B. Mockel, F. Zhu, R. Schmit, D. Petkow,

F. Taccogna,

D. Feili, and G. Deprez

Agenda

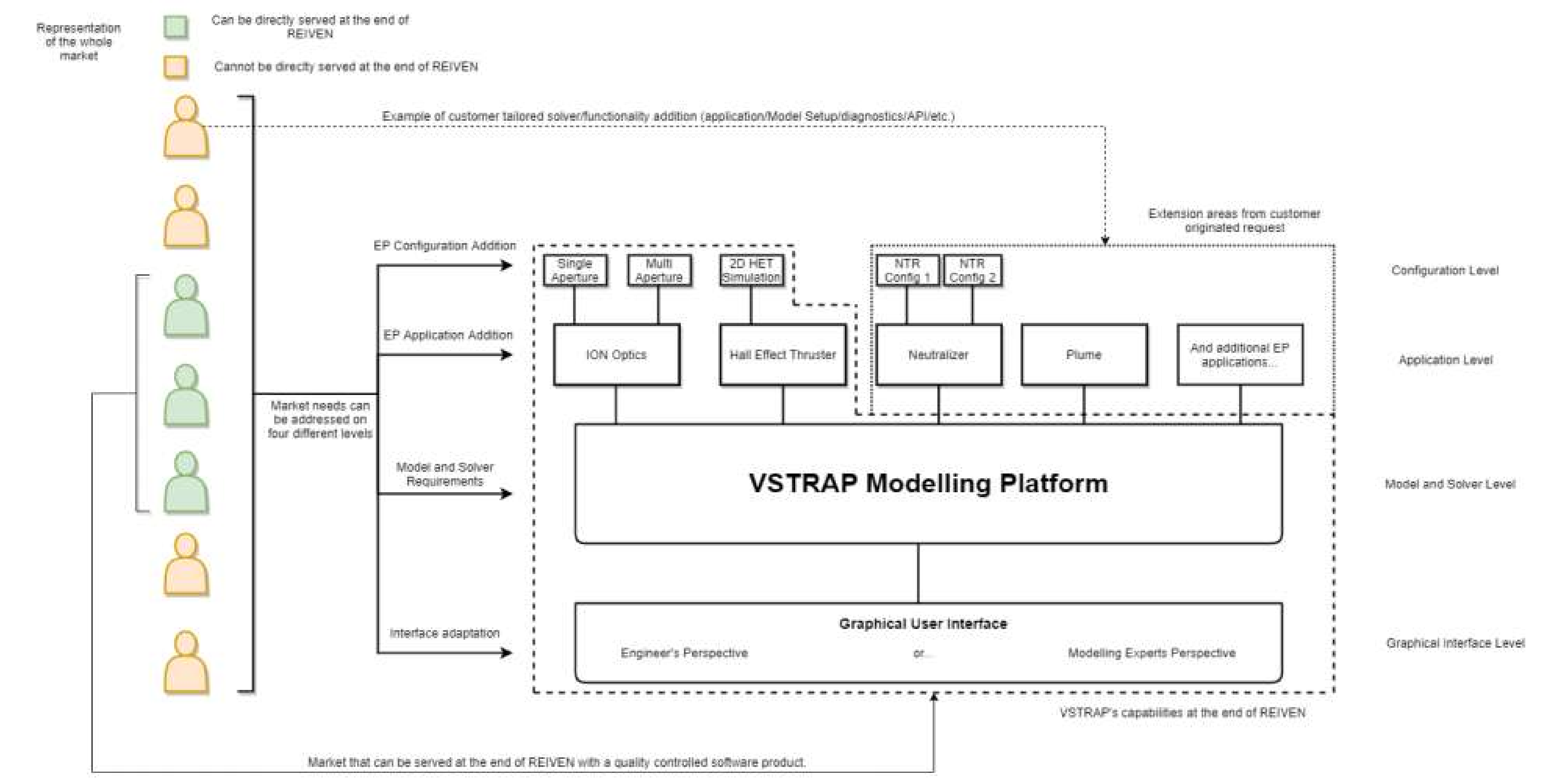
Introduction VSTRAP

Modules & Methods

Preliminary Verification & Validation Status

Outlook

VSTRAP



Representation of the whole market
Can be directly served at the end of REIVEN
Cannot be directly served at the end of REIVEN
Example of customer tailored solver/functionality addition (application/Model Setup/diagnostics/API/etc.)
Extension areas from customer originated request
EP Configuration Addition
EP Application Addition
Market needs can be addressed on four different levels
Model and Solver Requirements
Interface adaptation
Single Aperture
Multi Aperture
2D HET Simulation
NTR Config 1
NTR Config 2
ION Optics
Hall Effect Thruster
Neutralizer
Plume
And additional EP applications...
VSTRAP Modelling Platform
Graphical User Interface
Engineer's Perspective
or...
Modelling Experts Perspective
Configuration Level
Application Level
Model and Solver Level
Graphical interface Level
VSTRAP's capabilities at the end of REIVEN
Market that can be served at the end of REIVEN with a quality controlled software product.

First EP Applications

Hall Effect Truster

- 2d (r-z) fully kinetically PIC
- Simulation Domain: ionization channel + near plume
- **Neutral gas interaction: staggered**
- **Diagnostics: Thrust, ISP, anode current, surface charging, surface erosion, plasma density and plasma potential, ...**

Gridded Ion Thruster (ion optics)

- 3D plasma solver (FMM+BEM)
- Full kinetic and hybrid available
- Speed-up: Boltzmann-relation electrons
- Simulation Domain: Extraction region + acceleration of ionized plasma + near plume
- **Neutral gas interaction: staged**
- Diagnostics: Thrust, ISP, grid/beam currents, collimation angle, grid erosion, plasma density and plasma potential, ...

Gridded Ion Optics Modules

Gridded Ion Thruster (only ion optics)

- Ionization chamber is NOT simulated
- Neutralizer only as quasi-neutral outflow

Required Modules

- 3D plasma solver: FMM+BEM (+hybrid)
- Pusher: explicit **Boris schema**
- **Inflow**
- Plasma-wall interaction
- MCC neutral gas interaction (not yet included)

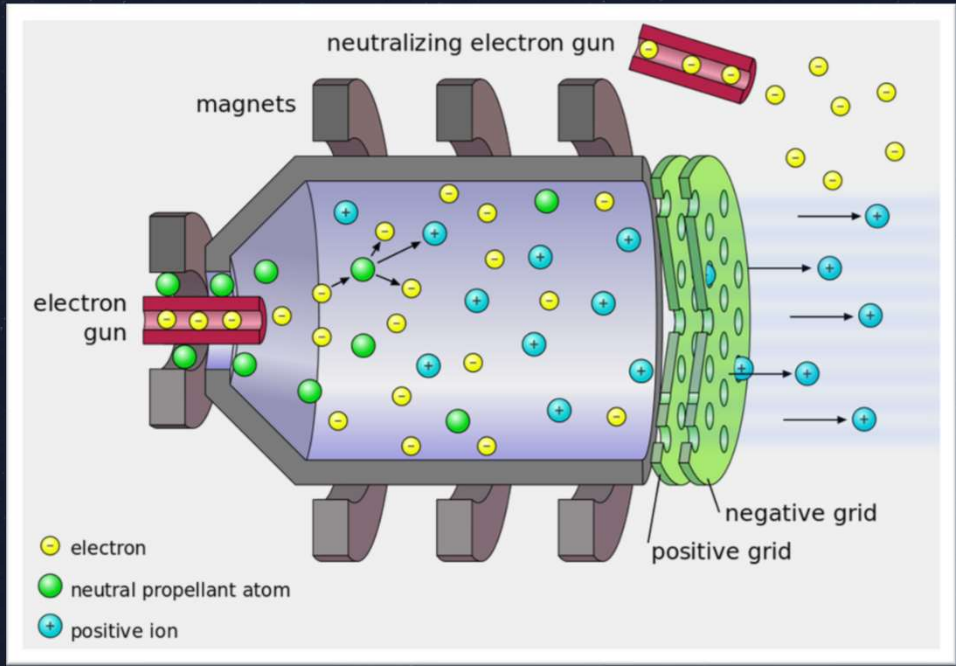


Image: Wikipedia – Gridded Ion Thruster CC BY-SA3.0

3D Plama Solver: Fast Multipole Method (FMM)

Poisson equation:

$$\Delta\Phi = -\frac{\rho}{\varepsilon_0}$$

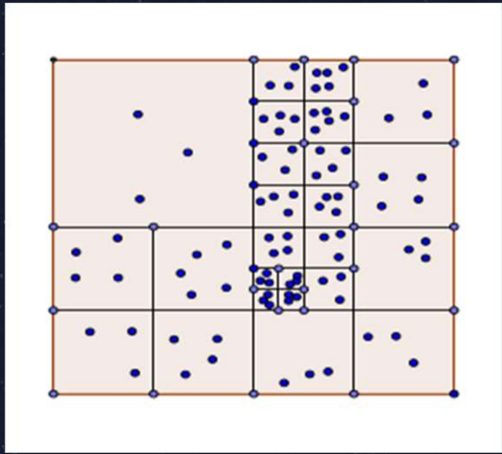
Particular solution:

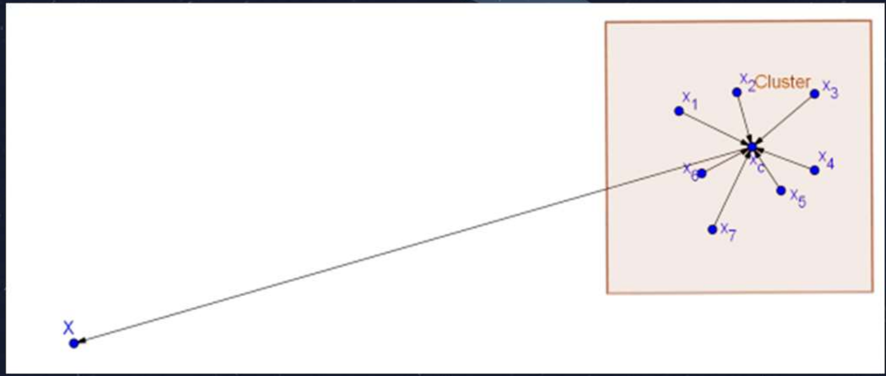
$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{N}\frac{w_i q_i}{|\mathbf{r}_i - \mathbf{r}|}$$

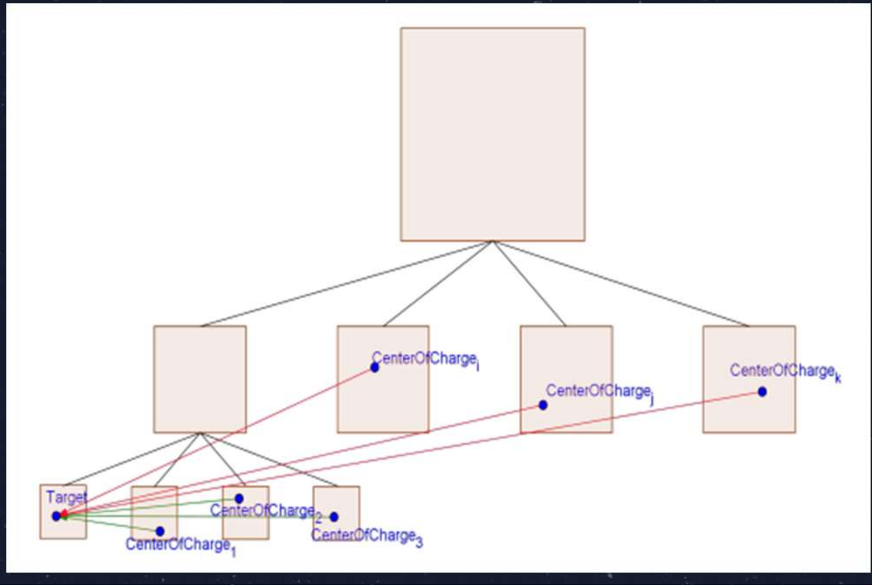
Multipole expansion of a cluster with spherical harmonics:

$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\sum_{l=0}^{\infty}\sum_{m=-l}^{l} M_l^m \cdot I_l^m(\mathbf{r} - \mathbf{r}_c)$$

Octree decomposition of the domain:







3D Plama Solver: Boundary Element Method (BEM)

Laplace boundary problem:

$$\begin{aligned} \Delta u &= 0 \text{ in } \Omega \\ u &= g_1 \text{ on } \Gamma_1 \\ \partial_n u &= g_2 \text{ on } \Gamma_2 \end{aligned}$$

Representation formula:

$$c(y)u(y) = \int_\Gamma G(x,y)q(x) - u(x)F(x,y)\,dx$$

Collocation scheme:

$$u_i c(x_i) + \sum_{j\in J} u_j \underbrace{\int_{T_j} F(x,x_i)\,dx}_{F_{ij}} = \sum_{j\in J} q_j \underbrace{\int_{T_j} G(x,x_i)\,dx}_{G_{ij}}$$

Solution in the domain:

$$u(y) = \sum_{j\in J} q_j \int_{T_j} G(x,y)\,dx - \sum_{j\in J} u_j \int_{T_j} F(x,y)\,dx$$

$$E(y) = \sum_{j\in J} u_j \int_{T_j} \nabla_y F(x,y)\,dx - \sum_{j\in J} q_j \int_{T_j} \nabla_y G(x,y)\,dx$$

3D Plama Solver: Couple BEM and FMM

Poisson boundary problem:

$$\begin{aligned} \Delta\phi &= -\frac{\rho}{\varepsilon_0} \text{ in } \Omega \\ \phi &= g_1 \text{ on } \Gamma_1 \\ \partial_n\phi &= g_2 \text{ on } \Gamma_2 \end{aligned}$$

Solution: homogeneous + inhomogeneous

$$\phi = u + v$$

Split Boundary Problem

$$\begin{array}{rcll} \Delta v &=& -\frac{\rho}{\varepsilon_0} & \text{in } \Omega \\ \Delta u &=& 0 & \text{in } \Omega \\ u &=& g_1 - v & \text{in } \Gamma_1 \\ \partial_{\mathbf{n}} u &=& g_2 - \partial_{\mathbf{n}} v & \text{in } \Gamma_2 \end{array}$$

- Inhomogeneous part v is solved with FMM
- Homogeneous part u is solved with BEM using the adjusted boundary condition

FMM+BEM vs PIC

Advantages of FMM+BEM	Disadvantages
Grid-less approach	Higher computational demand
Automated adaptivity by Octree	Less common in literature
Better energy conservation	
Consideration of the near field interaction	

Hybrid: Boltzmann solver

The electron density given by the Boltzmann relation

$$n_{br}^{el}(x) = n_{ref}^{el}\exp\left(e\frac{\phi(x)-\phi_{ref}}{k_B T_e}\right)$$

The electrons are sampled on the ion positions

Electron weight:

$$w_{el}(x_i) = n_{el}(x_i)\frac{w_{ion,i}}{\sum_j w_{ion,j}S(x_i - x_j)}$$

with shape function S(x)

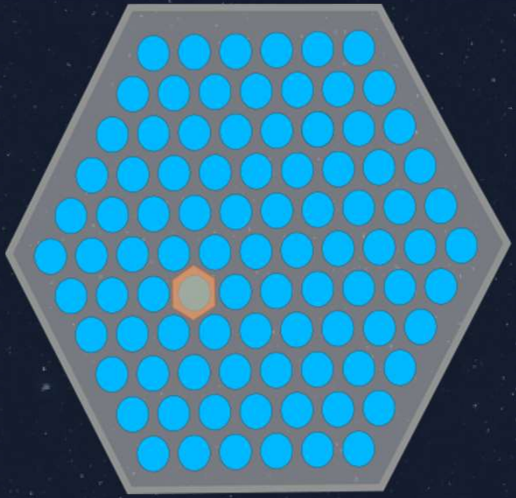
FMM uses screened weights

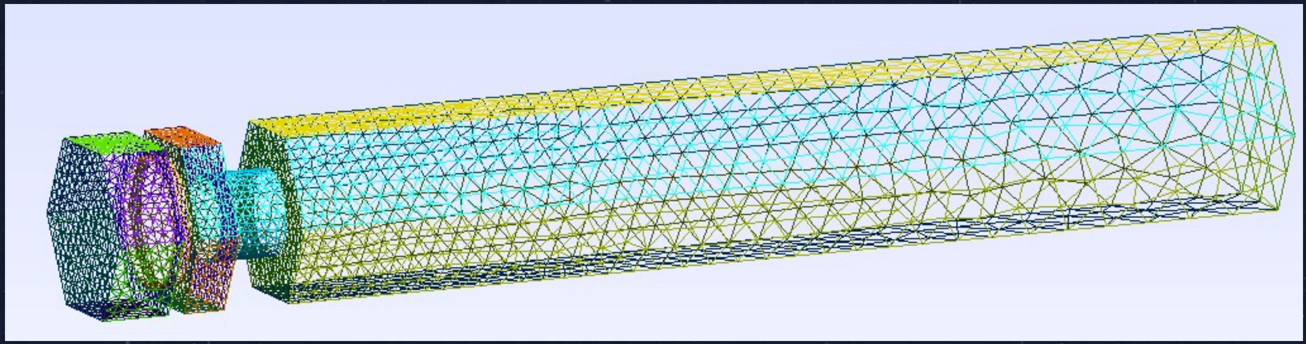
$$w^s = w^{ion} - w^{el}$$

Gridded ion Optics: Single Aperture

Single aperture ion optics

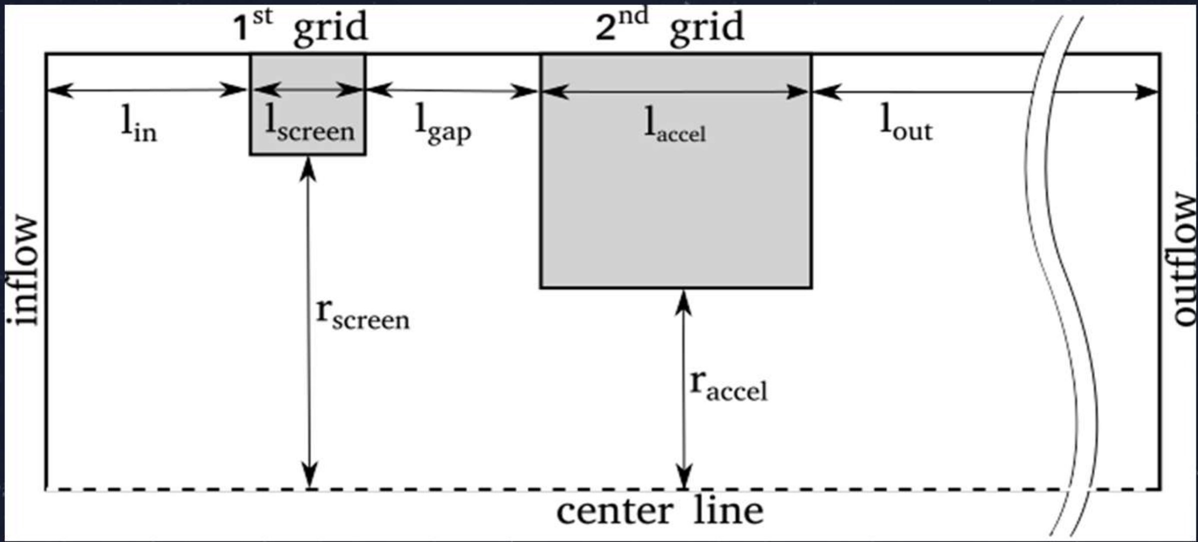
- 3D hybrid kinetic ions + BR
- Code-to-code comparison
- Single beamlet as infinite pattern
- Hexagonal cross section





Gridded Ion Optics Setup: Geometry

Code to code comparison: Binder et al. [RD1, RD2] (RIT-µX)



Parameters	Values	Description
l_{in}	1.00 [mm]	Inflow length
l_{out}	14.30 [mm]	Outflow length
l_{screen}	0.25 [mm]	Length of 1st grid
l_{gap}	0.6 [mm	Length of gap between 1st and 2nd grid
l_{accel}	1.85 [mm]	Length of 2nd grid
r_{screen}	0.95 [mm]	Aperture radius of the 1st grid
r_{accel}	0.625 [mm]	Aperture radius of the 2nd grid
d	2.4 [mm]	Distance between apertures centers

[RD1] T. Binder, M. Pfeiffer, S. Fasoulas, and H. Leiter. High-fidelity Particle-In-Cell simulations of ion thruster optics. Proceedings of the International Electric Propulsion Conference, 35, 2017.

[RD2] T. Binder Development and application of PIClas for combined optic-/plume-simulation of ion-propulsion systems, Thesis, IRS Stu 2019.

Gridded Ion Optics Setup: Operation Point

Boundary Conditions:

	Electrostatic BC	Particle Boundary Condition
Inflow	Dirichlet 1465 [V]	Open with ion inflow: $_{131}Xe^{+}$ with density n = 1.08e17 [m^{-3}] Global particle weight w = 500
1st Grid	Dirichlet 1450 [V]	open
2nd Grid	Dirichlet -300 [V]	open
Symmetry	Neumann 0 [V/m]	reflective
Outflow	Dirichlet 0 [V]	open

Two electron populations

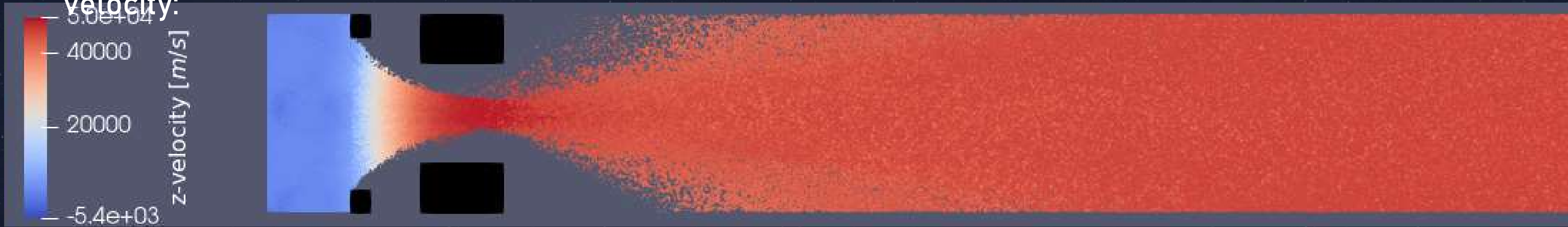
	Boltzmann relation
Inflow	$n_{ref,in}$ = 1.08e17 [m^{-3}] $T_{ref,in}$ = 3.5 [eV] ϕ_{ref} = 1465 [V]
Outflow	$n_{ref,in}$ = 4.4e15 [m^{-3}] $T_{ref,in}$ = 2.0 [eV] ϕ_{ref} = 0 [V]

Additional Parameters

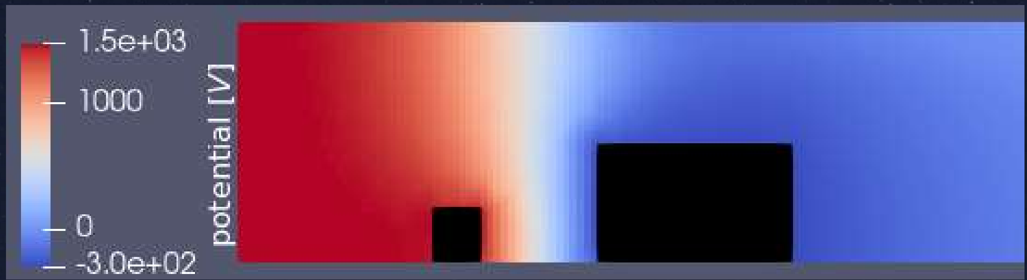
Parameters	Values
Time step	0.5e-8 [s]
Iterations	7000
Sampled Iterations	3000
Shape function	constant
Smearing radius rs	1.25e-5 [m]

Results 2d diagnostics

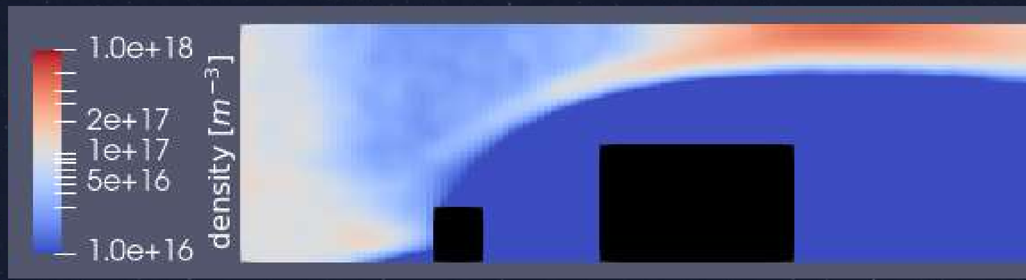
Plasma state x-z projection with color-coded velocity:



Diagnostic x-z plane: Plasma potential



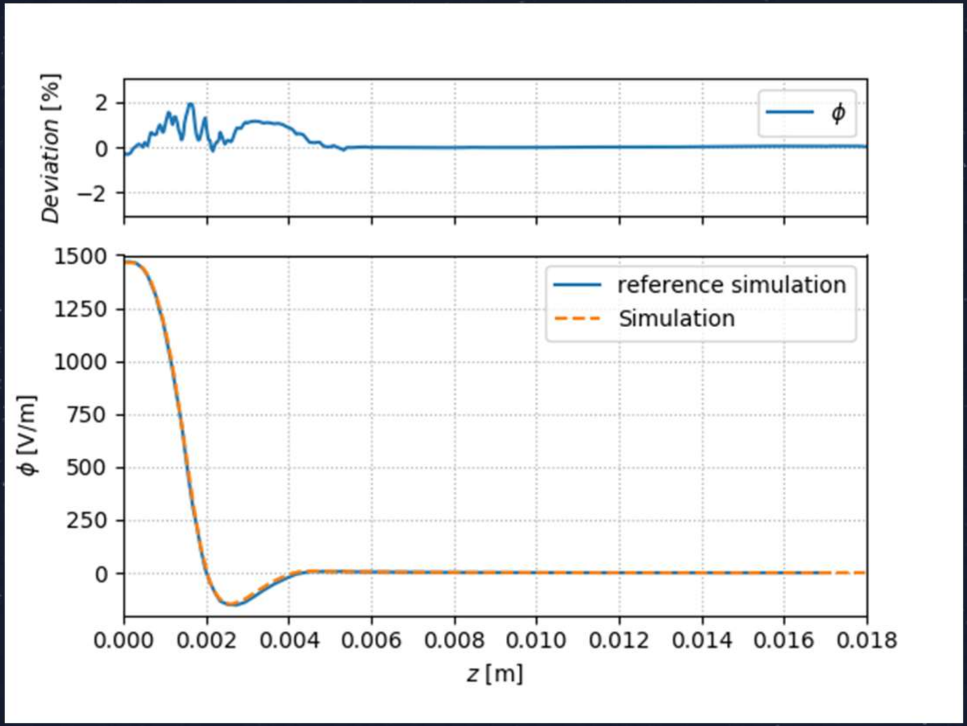
Diagnostic x-z plane: Ion density



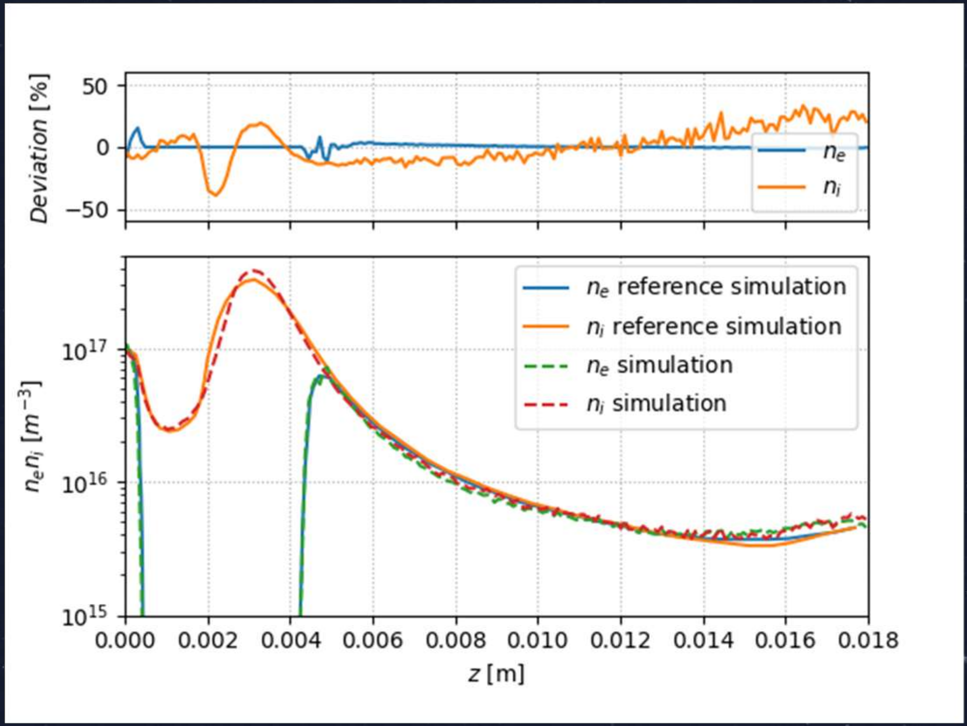
Center Line Diagnostics: Code-to-Code verification

Code-to-code comparison to reference [RD1]

Center line: plasma potential



Center line: plasma densities



[RD1] T. Binder, M. Pfeiffer, S. Fasoulas, and H. Leiter. High-fidelity Particle-In-Cell simulations of ion thruster optics. Proceedings of the International Electric Propulsion Conference, 35, 2017.

Movie: Transient Phase

Single aperture, 2 grid system

Regression tests

- **Unit tests**
- **Integration test**
  - **Inflow test,**
- **Regression tests**
  - **Two stream instability**
  - **Sheath test case**
- **Verification tests**
  - **Single aperture gridded ion optics**

Outlook

- Staged interaction with neutral gas: charge exchange and elastic scattering
- Validation simulation: 60° wedge of a full thruster – comparison to experimental results
- Additional Diagnostics:
  - Surface/beam currents
  - Erosion due to ion impact
  - Bridging to SPIS or OpenPlume (see presentation S. Rouwette)
- Performance improvements with GPUs (see presentation R. **Bouziane**)


SPARC Industries
We deliver.The future.
SPARC
INDUSTRIES SÀRL
www.sparc-industries.com
info@sparc-industries.com