Kinetic Plasma Simulation Capabilities in the MOOSE Framework: Verification of Particle-Particle Collisions

Grayson Gall[1], Logan H. Harbour[2], Casey T. Icenhour[2], Pierre-Clément A. Simon[2,3], **Amanda Lietz**[1]

[1]North Carolina State University, Raleigh, North Carolina
[2]Idaho National Laboratory, Idaho Falls, Idaho
[3]The Pennsylvania State University, University Park, Pennsylvania

Gaseous Electronics Conference 2025

Supported by the Idaho National Laboratory, Laboratory Directed Research & Development (LDRD) Program and The National GEM Consortium Fellowship Program

- Introduction and Background

- Conclusions

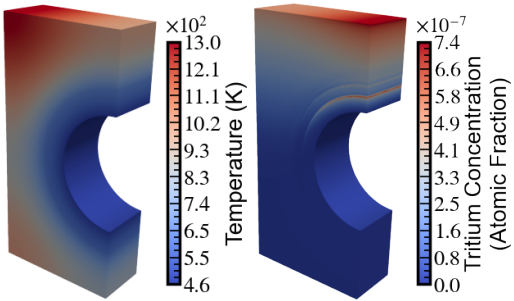
SALAMANDER

- SALAMANDER — Software for Advanced Large-scale Analysis of Magnetic confinement for Numerical Design, Engineering & Research.[1]
  - Open Source.
  - Built upon MOOSE — a massively parallel finite-element method (FEM) framework.
- FEM particle-in-cell (PIC) capabilities are being developed within SALAMANDER.
  - Built on MOOSE's Ray Tracing module.
    - Scalable with ∼18,500 MPI ranks.[2]
  - Supports structured and unstructured meshes in 1D, 2D, and 3D.

[1]Simon, P.-C., et al. 2025 *OSTI*.

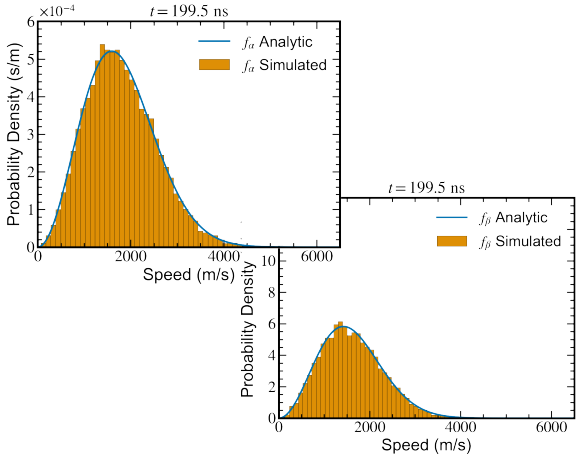
[2]Gaston, D. R., et al. 2021 *Nuclear Technology* 207 (7).

Multiphysics Divertor Monoblock Model



Software Quality and Motivation

- SALAMANDER is being developed with nuclear quality software quality assurance practices.
- Rigorous verification and testing are a core part of the development process.
- At low pressures, neutral particles are also kinetic, requiring direct simulation Monte Carlo (DSMC)[3].
- In this work, two kinetic problems demonstrate the initial implementation of the DSMC algorithm.



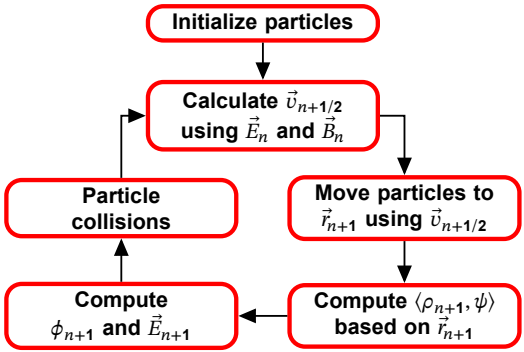
[3] Bird, G. A. 1994 Oxford university press.

PIC Design and Simulation Flow

- Particles shape functions are Dirac delta functions.
- Particles are pushed with the leap frog or Boris method.
- In an element, particle weight, w, is based on number density n, element volume V_E, and particles per element N_p.

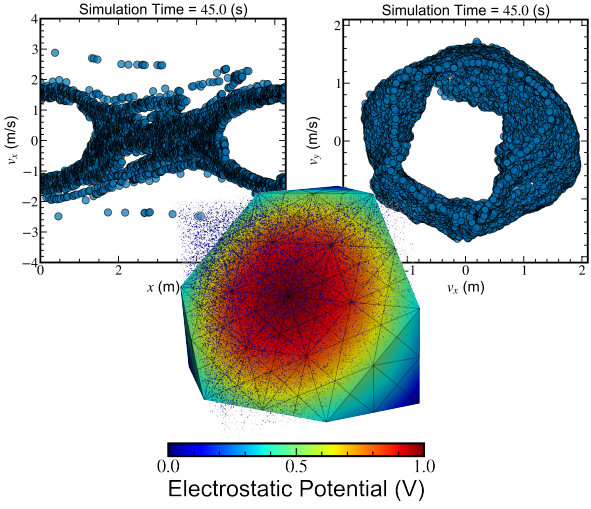
$$w = \frac{nV_E}{N_p}$$

- The DSMC method is used for collisions.



Previous Verification

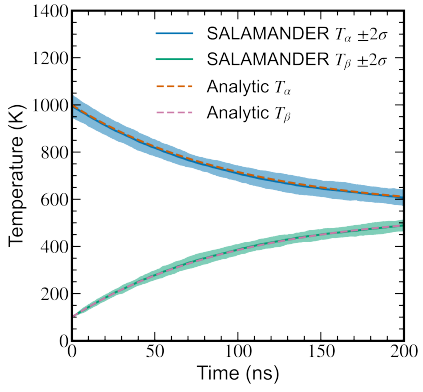
- Fundamental PIC capabilities have been verified.[4]
  - Electrostatic potential solve.
  - Density projection onto the mesh.
  - Charge conservative current density calculations.
  - Two stream and Dory-Guest-Harris instabilities.
- Previous verification is/will be available: https://github.com/idaholab/salamander



[4] Gall, G. S., et al. 2024 *OSTI*.

Concluding Remarks

- Electrostatic collisionless capabilities have been verified.
- SALAMANDER can perform simulations in 1D, 2D, and 3D.
  - Unstructured meshes may be used.
  - Utilizes the parallelization of the MOOSE framework.
- The initial version of the DSMC algorithm has been implemented and verified.
- Next steps:
  - Adding support for more particle interaction types.
  - Comparison of rates to those calculated by a muliterm Boltzmann solver.



1. Simon, P.-C., et al. 2025 “Software For Advanced Large-scale Analysis Of Magnetic Confinement For Numerical Design, Engineering & Research (salamander)” *OSTI* https://doi.org/10.11578/dc.20250611.2.
2. Gaston, D. R., et al. 2021 “Method of characteristics for 3D, full-core neutron transport on unstructured mesh” *Nuclear Technology* 207 (7), https://doi.org/10.1080/00295450.2021.1871995.
3. Gall, G. S., et al. 2024 “Kinetic Plasma Simulation in the MOOSE Framework: Verification of Electrostatic Particle In Cell Capabilities” *OSTI* https://doi.org/10.13182/PBNC24-45091.