Spacecraft charging via numerical simulations

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Outline

• Motivation

• Design considerations for plasma-material interaction PIC codes
  • Curvilinear PIC (CPIC)

• Selected examples

• Conclusions
Spacecraft are critical infrastructure threatened by space weather

- Society increasingly rely on spacecraft technology
  - ~1000 sc around Earth
  - ~250 commercial communication sc, $75B investment, $25B/year revenue (+consumer surplus)

- Spacecraft anomalies are common
  - Mild to catastrophic
  - Sometimes associated with environment
  - Very hard to pinpoint origin
  - Seek statistical correlation with data

- Surface charging primarily on night side
  - Link with substorms: Kp and MLT dependence
  - Correlation with 5-10 keV population [Thomsen et al, SW13]

- Simulations to identify probable cause
  - Need environment and sophisticated charging tools

Choi et al. 2011
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Plasma-material interaction (PMI) is a multiscale problem, traditionally studied with PIC

Collisionless, Vlasov-Poisson model:

$$\frac{\partial f_\alpha}{\partial t} + v \cdot \nabla f_\alpha + \frac{\vec{F}_\alpha}{m_\alpha} \cdot \nabla_v f_\alpha = 0$$

$$\vec{F}_\alpha = q_\alpha (-\nabla \phi + v \times B_0)$$

$$-\varepsilon_0 \nabla^2 \phi = \rho = \sum_\alpha q_\alpha \left[ \int f_\alpha d^3v \right]$$

PIC
- Macroparticles
- Computational grid
- Key PIC elements: mesh, solver, mover
- **Multiscale**: Runs can take hours/days/weeks depending on the problem!
For the field solver, one would want a NON-UNIFORM, structured mesh in a PMI code.

- **Uniform vs Non-Uniform**
  - Avoid small features setting grid scale

- **Structured vs Unstructured**
  - Unstructured meshes: flexibility
  - Faster solvers on structured meshes
    - x5-10 faster for a multigrid solver
    - MacLachlan et al, JCP 08
For the particles, one would want a UNIFORM, structured mesh in a PMI code

- **Uniform** vs Non-Uniform
  - Avoid particle-tracking
  - Tracking: x3-5 slower on unstructured mesh

Competitors move particles in physical space

Physical \((x,y,z)\)  \[\rightarrow\]  Logical \((\xi,\eta,\zeta)\)
Summary of design choices

Wish-list

- Solver: Non-uniform, structured mesh
- Particles: Uniform, structured mesh
- Parallelization

Curvilinear PIC (CPIC) developed at LANL follows these design choices and combines them with modern algorithms to tackle a broader set of problems
PIC with non-uniform mesh for solvers but uniform mesh for particles is possible with coordinate transformation

- **Body-fitted logical to physical space mapping**

- **Coordinate transformation:** \( x = \psi (\xi) \)
  - Physical space variables \( x = (x, y, z) \)
  - Logical space variables \( \xi = (\xi, \eta, \zeta) \)

- **Metric elements**
  - Jacobi matrix and its inverse, metric tensor
  - Operators in logical space:
    \[
    \nabla_x^2 \Phi(x) = \frac{1}{J} \frac{\partial}{\partial \xi^\alpha} \left( J g^{\alpha\beta} \frac{\partial \Phi(\xi)}{\partial \xi^\beta} \right)
    \]
Complex objects & structured mesh require multi-block meshes

- Simple geometries easy to handle
- Complex geometries require mesh generators
  - Developed in CFD community
  - Many for unstructured meshes – single-block mesh
  - Commercially available: structured mesh generators
    - Cad files → mesh
Multi-block PIC is far from trivial ...

- Many challenges
  - Mesh
    - Locally structured, globally unstructured
    - Inter-block face, coordinate orientation
    - Many-block junction points
  - Field solver
    - Mimetic discretization [Lipnikov et al., JCP 04]
  - Particles
    - Needs to know block
      - More info to be communicated among processors
    - New block orientation

... but these challenges have been met in the new version of CPIC
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Successful verification on simple charging problem

- Charging of a sphere in a plasma
- Analytic solution exists
- CPIC with multi-block mesh
- **Good agreement with theory**: collected currents, symmetry and plasma screening
Probing the Earth’s magnetosphere with an electron gun

- Goal: establish connectivity of magnetic field lines from the magnetosphere to the ionosphere

- High-power electron beam from magnetospheric spacecraft

- Spacecraft charging is a big problem: $I_e \sim \mu A$, $I_B \sim .1 \text{ A}$

\[
\frac{dQ_{sp}}{dt} = I_b + I_{e}^{bg} + I_{i}^{bg} + I_{e}^{cont} + I_{i}^{cont}
\]
The beam returns to the spacecraft if spacecraft charging cannot be mitigated.
Charging mitigation with a plasma contactor, used to increase electron collection …

- Plasma contactor: provides a high density plasma reservoir

\[ \frac{I_b}{I_{cont}} > 1 \]
... would not work! $I_b/I_{cont} = 2$

- PIC simulations: contactor, spacecraft and beam
- Contactor fired before beam
  - 3 initial configurations with different size of contactor cloud
- Fire electron beam
  - with contactor on
- Contactor fails to draw a large current from bg
In a different parameter regime, $I_b/I_{\text{cont}} < 1$, the beam can be emitted.

\[
\frac{dQ_{sp}}{dt} = I_b^e + I_b^{bg} + I_i^{bg} + I_e^{cont} + I_i^{cont}
\]
The physical explanation is the Child-Langmuir law: when the contactor cloud is sufficiently large, it emits more positive charge than the beam of negative charge.

Delzanno et al, JGR 2015a,b

(Quasi-)spherical geometry: not space-charge limited, emission of net positive charge enabled

Planar geometry: space-charge limited
Conclusions:

Curvilinear PIC (CPIC)*: a flexible, fully kinetic, 3D electrostatic PIC code in general curvilinear geometry for plasma-material interaction studies

- Features:
  - Optimal design choices
    - Non-uniform, structured meshes: fast solvers
    - Curvilinear formulation: particles move in uniform mesh
    - Optimal, scalable solver based on multigrid
  - Parallelized
  - Multi-block meshes
  - Enables tackling a broad set of plasma-material interaction problems