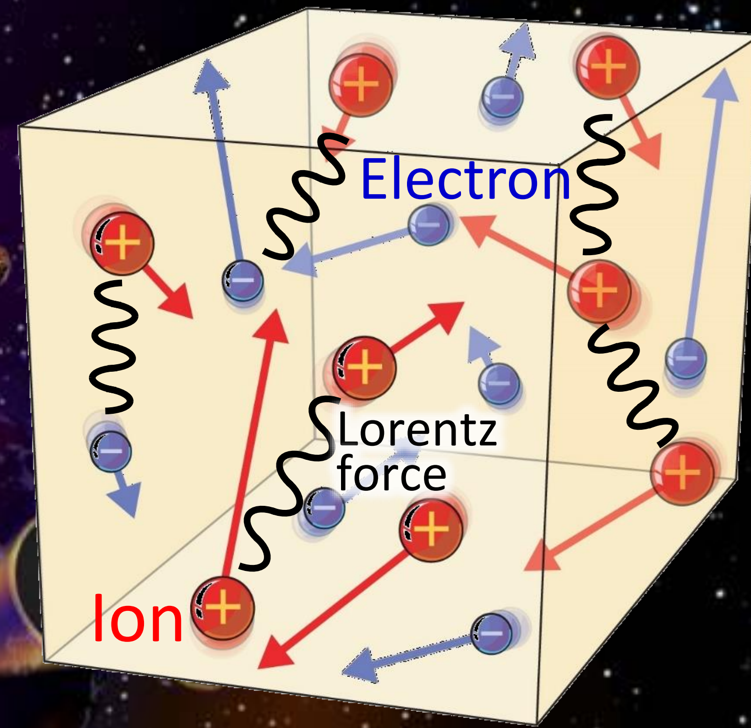
Computer Simulations on Rocket-Plasma Interactions

Yohei Miyake, Ben Whitney,
Alexis Cook, Takuya Makimura
(Contact: Y. Miyake, y-miyake@eagle.kobe-u.ac.jp)

BU-KU Simulation Summer School: final presentation on Aug. 31, 2015

Space plasma environment



Space filled with an ionized gas called "plasma"

- consisting of huge number of free-moving electrons and ions
- interactions with electromagnetic field
- interactions with rocket or spacecraft

Basic equations

Charged particle dynamics & electromagnetic evolution

Coupled

Newton's equations of particle motion

$$\frac{dv_i}{dt} = \frac{q_s}{m_s}(E + v_i \times B)$$

$$\frac{dx_i}{dt} = v_i$$

Field equations

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \mu_o J + \frac{1}{c^2}\frac{\partial E}{\partial t}$$

Full-electro-magnetic treatment

or

$$\nabla \cdot E = \frac{\rho}{\varepsilon_o}$$

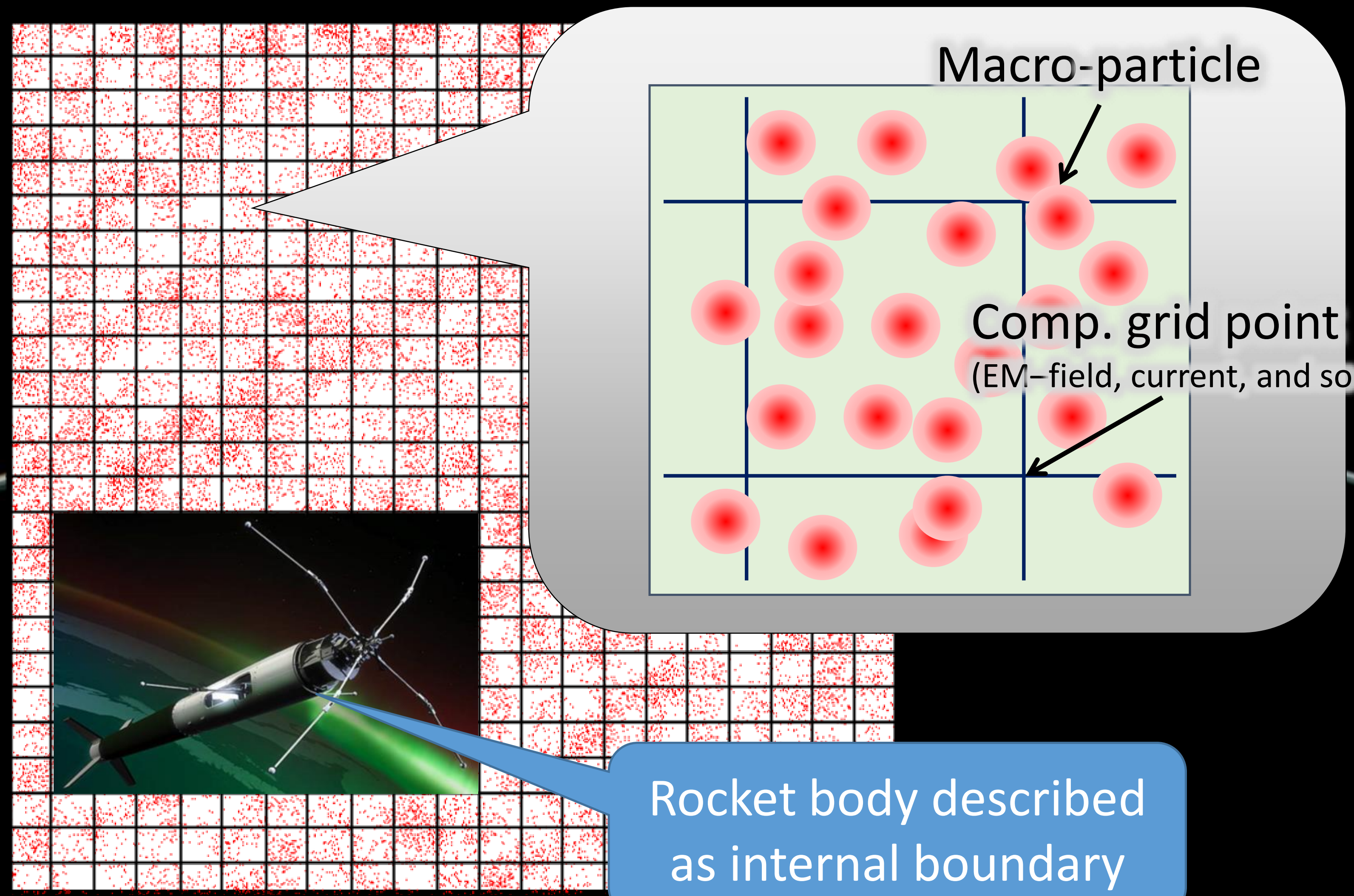
Electrostatic approximation

$$\nabla \cdot B = 0$$

These two sets of basic eq. are simultaneously solved.

Plasma particle simulation based on particle-in-cell (PIC) method

Simulation code "EMSES"



Necessity of Supercomputing

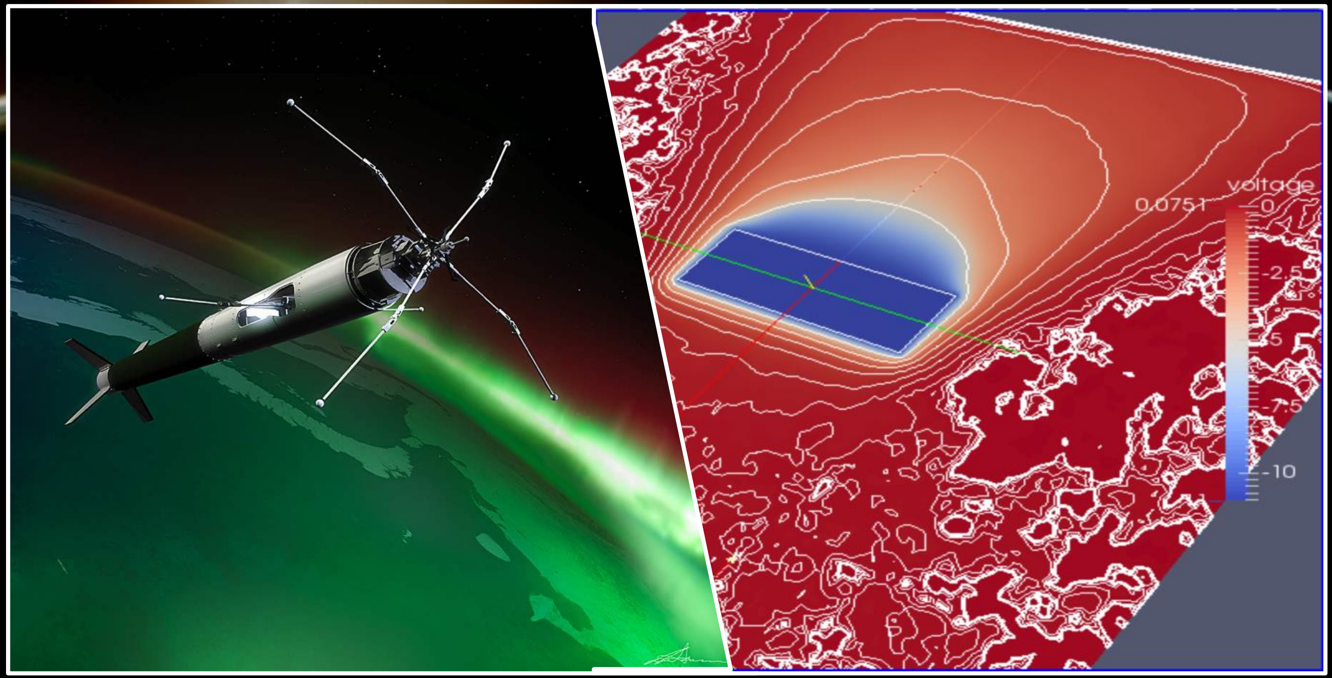
Debye length λ_D: smallest spatial scale in space plasma
System size of practical problems: 100 ~ 1000 λ_D

…need to handle
<u>Total # of grids: $10^6 \sim 10^8$ & # of particles: $10^8 \sim 10^{10}$</u>
<u>(corresponding to 100 GB ~ TB memory)</u>

Our plasma simulation code is parallelized with MPI (& OpenMP) and scales up to thousands of CPU cores.

Our goals…

To study interactions between the sounding rocket and the surrounding ionospheric plasma by means of <u>numerical simulations using supercomputers, data analysis, and scientific visualization</u>.



"Development & parallelization of new code"
... based on essence of PIC method

Alexis

"Simulation results on rocket-plasma interactions"
... presented with fascinating 3D movies

"Focused analysis on plasma particle dynamics"
... going inside details of physics

I'm so satisfied with their works!

Interactions between sounding rocket & ionospheric plasma

We focus on rocket experiments to investigate ionospheric plasma environment.

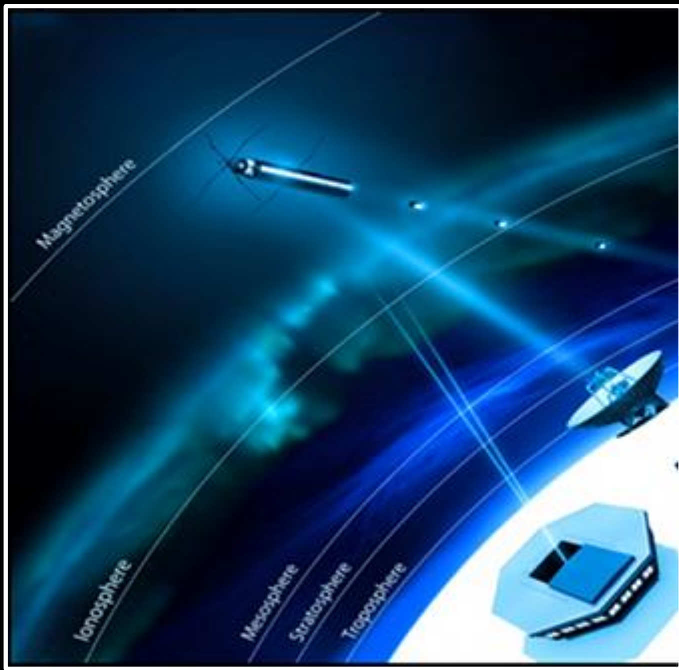
→ Understanding of rocket-plasma interactions is essential to operate such rocket experiments appropriately.

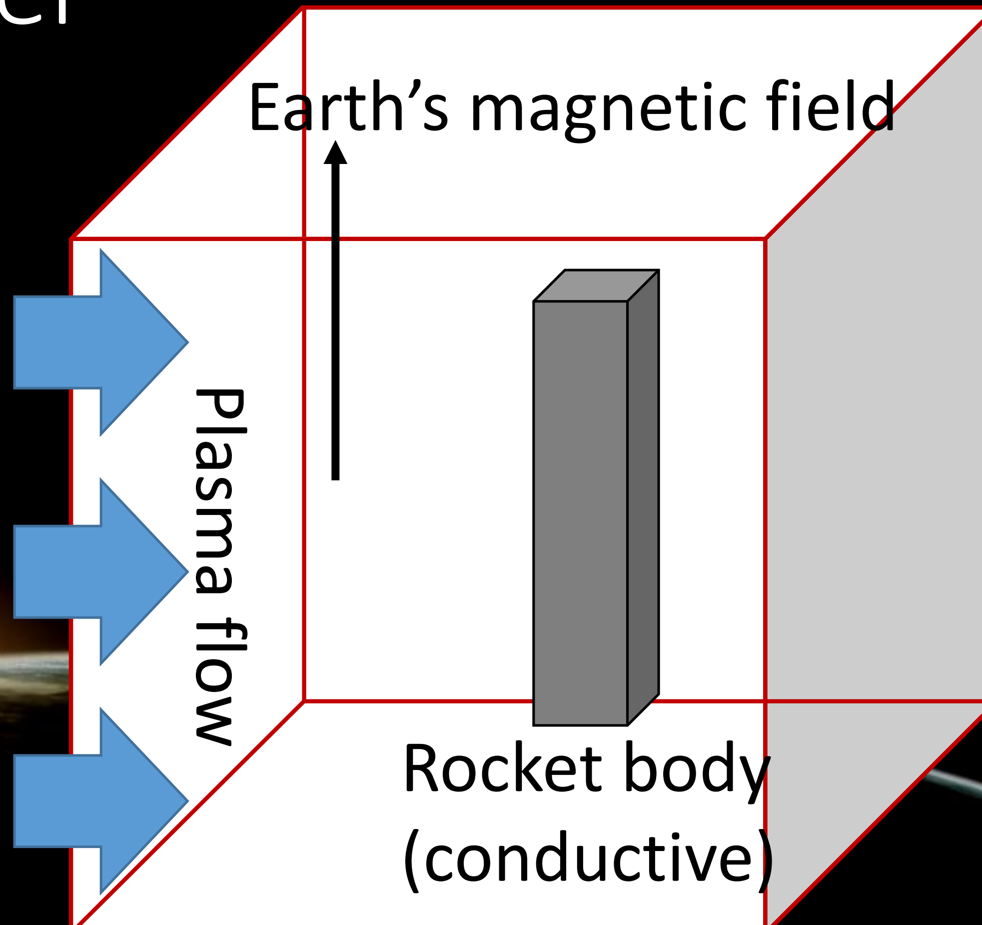
→ Aid of numerical simulations

What to see?

1. How does the rocket body charge?
2. What is the plasma (electron & ion) distributions around the rocket?
3. What is the plasma dynamics around the rocket? Is it possible to interpret the dynamics from an electric potential profile (& Earth's magnetic field) around the rocket?

Simulation model





Simulation domain

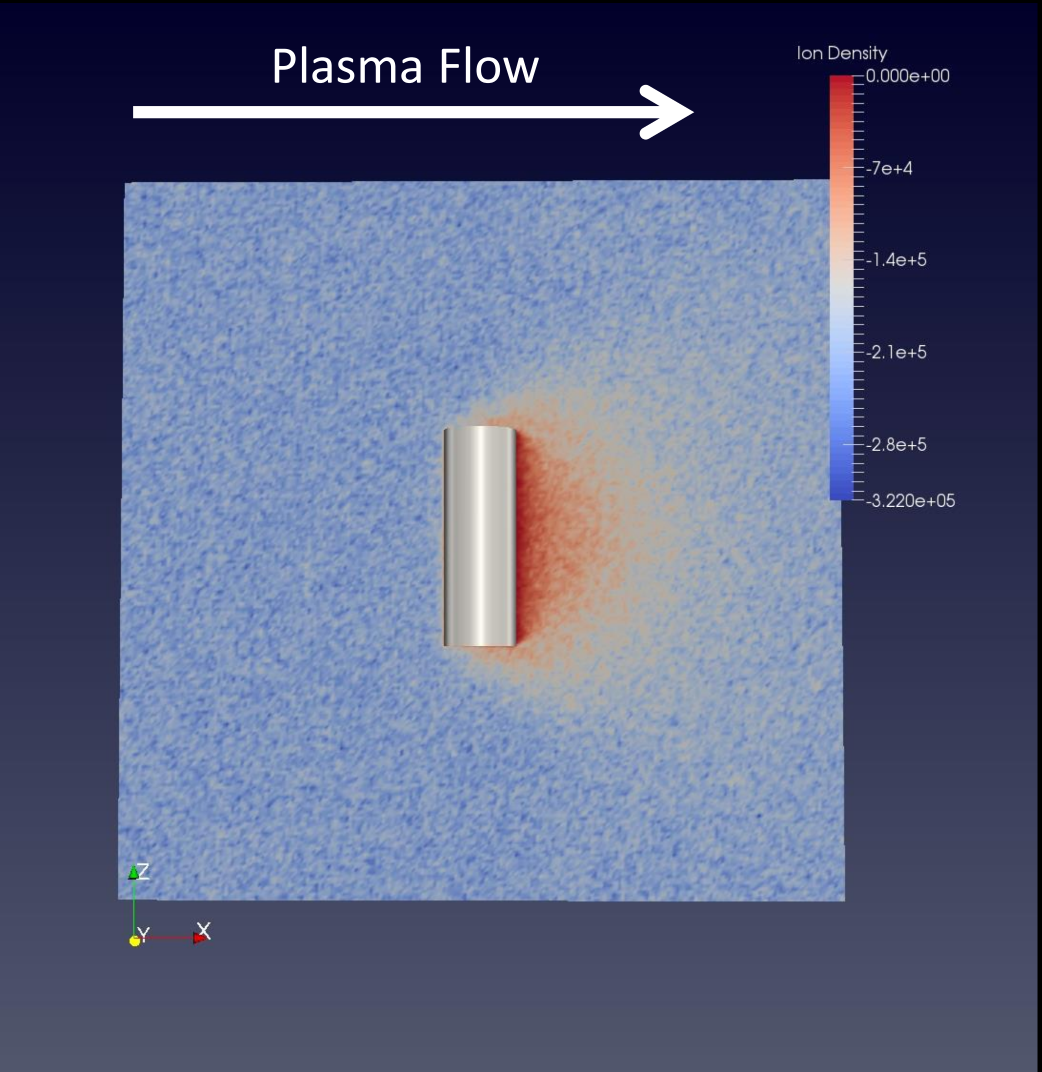
Problem size

- # of grids: 240 × 240 × 240
- # of particles: ~10^9

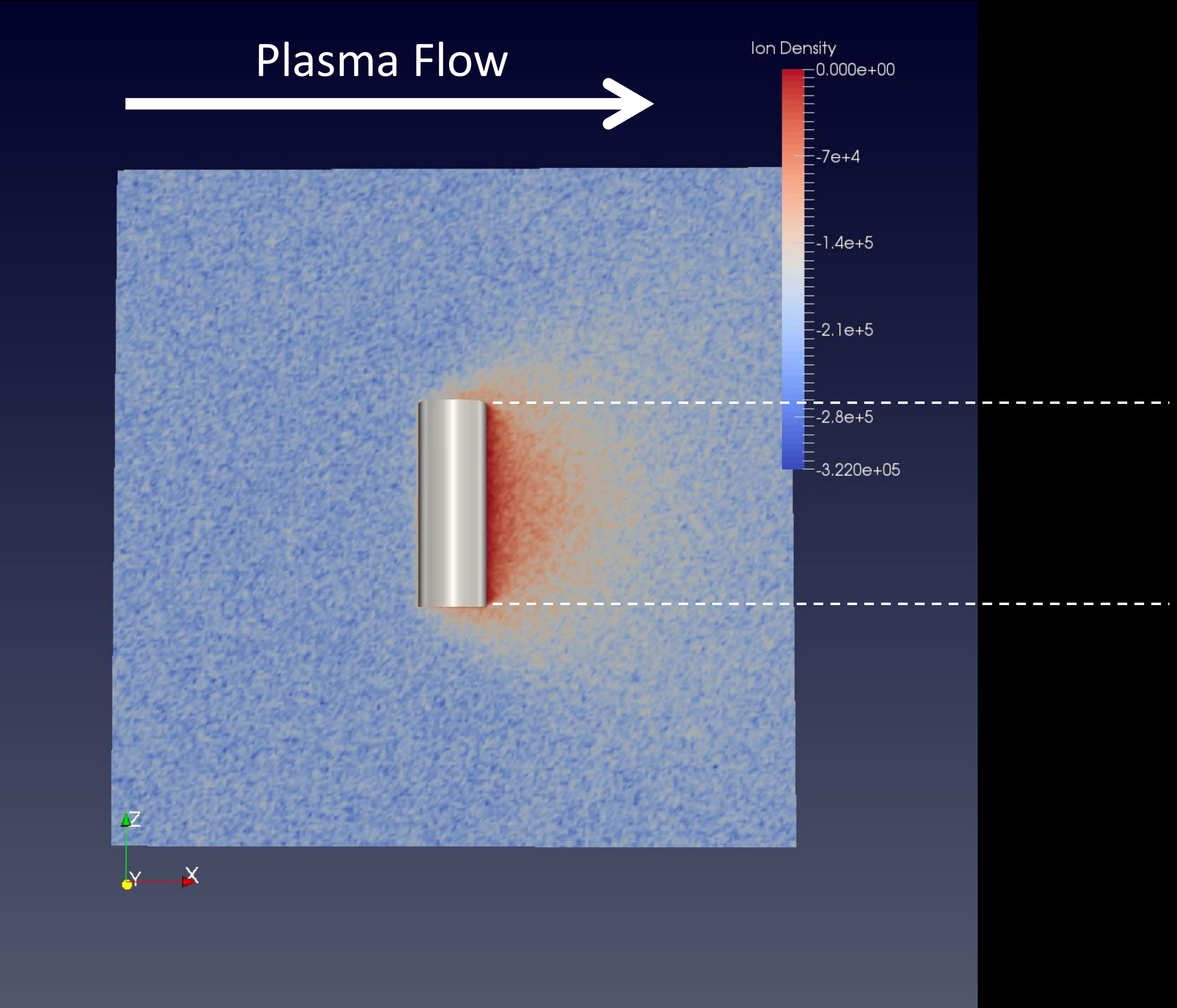
…requires >1 TB memory

Use 384 CPU-cores of Kobe FX10 supercomputer

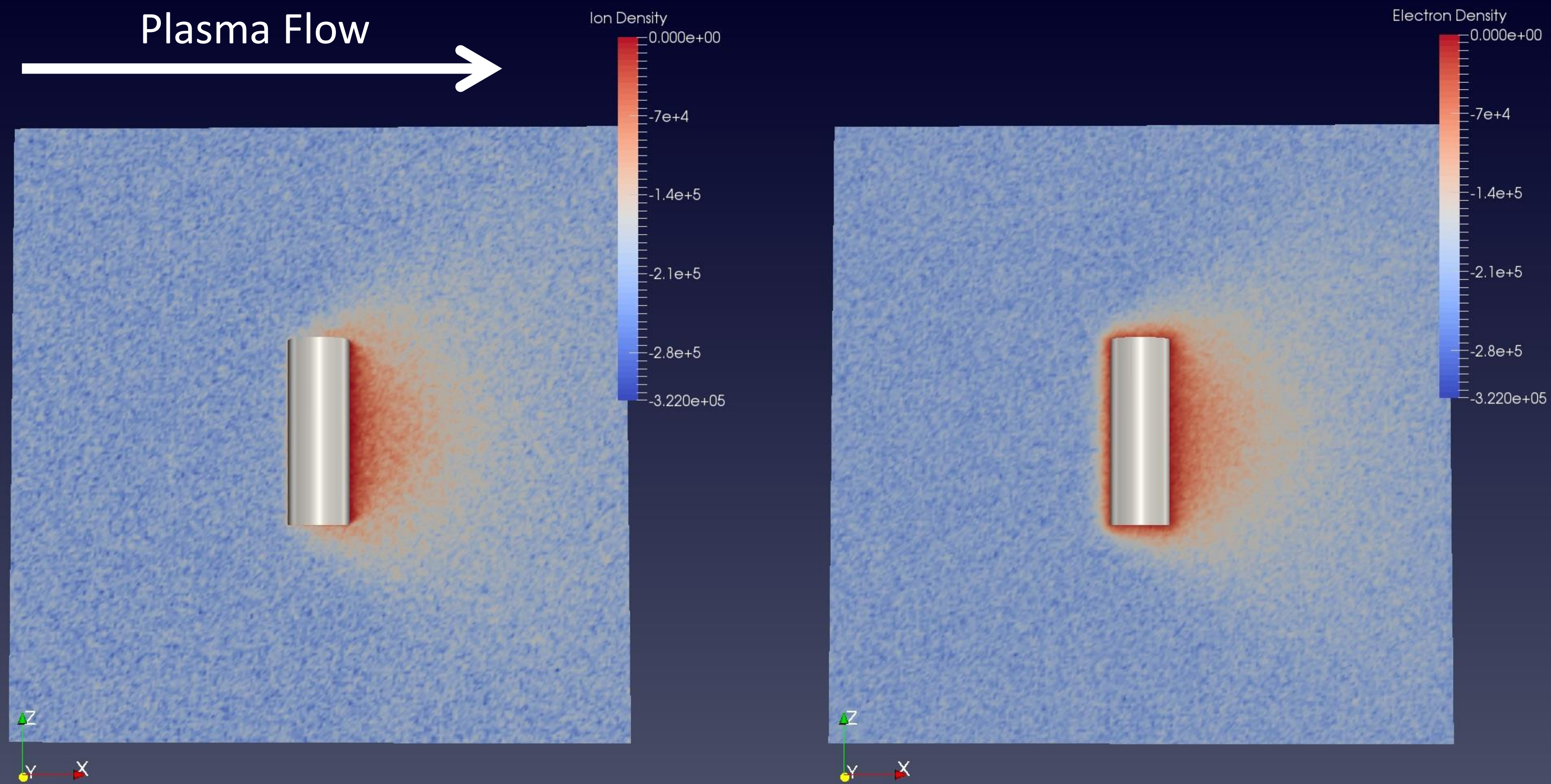
Particle Densities



Particle Densities



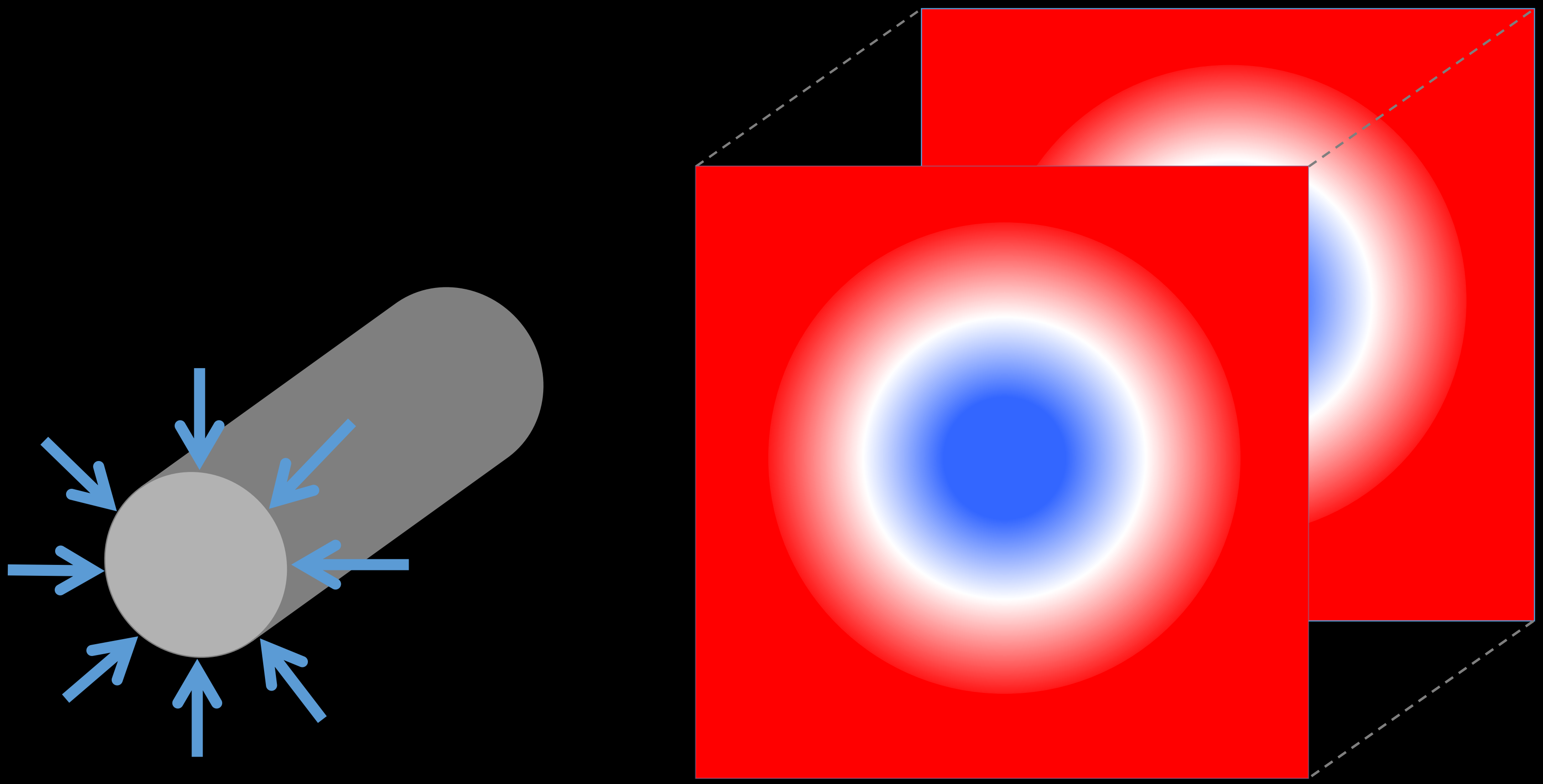
Particle Densities



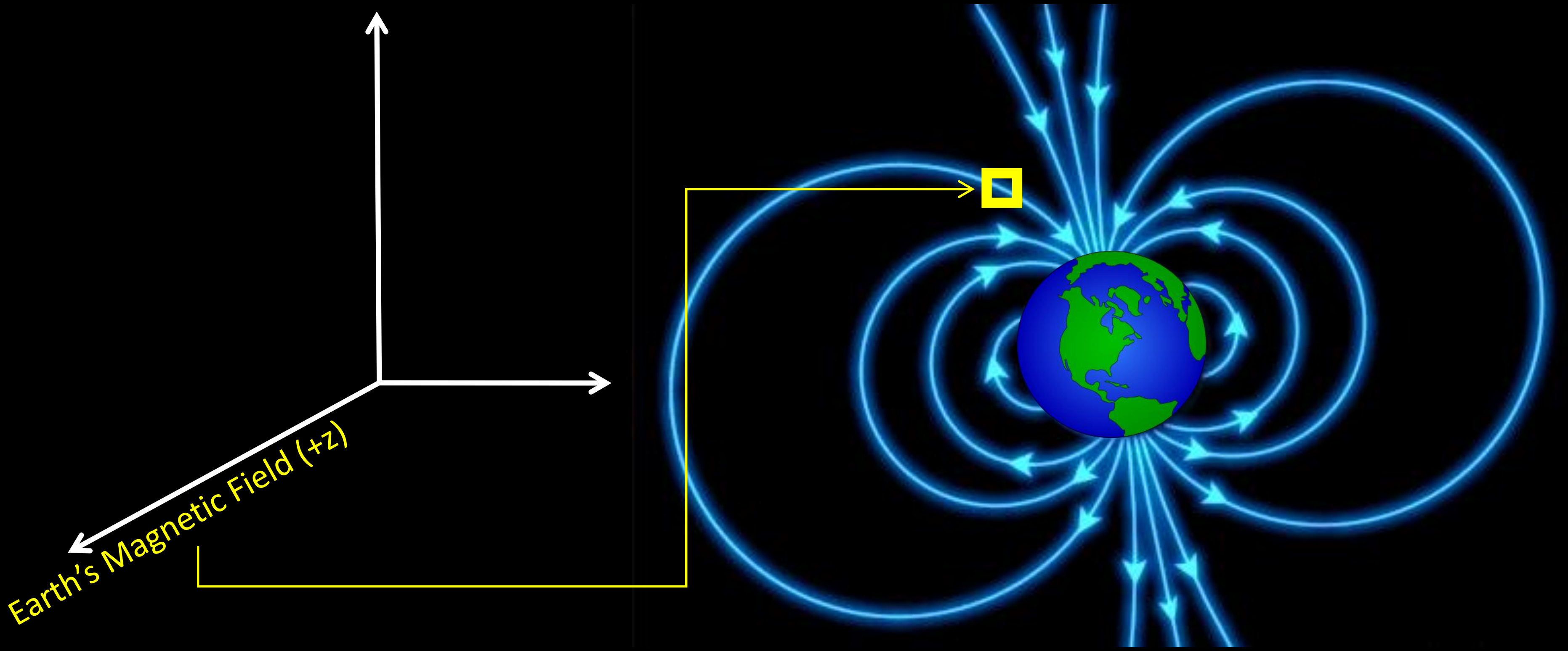
Play movie here

3D movie

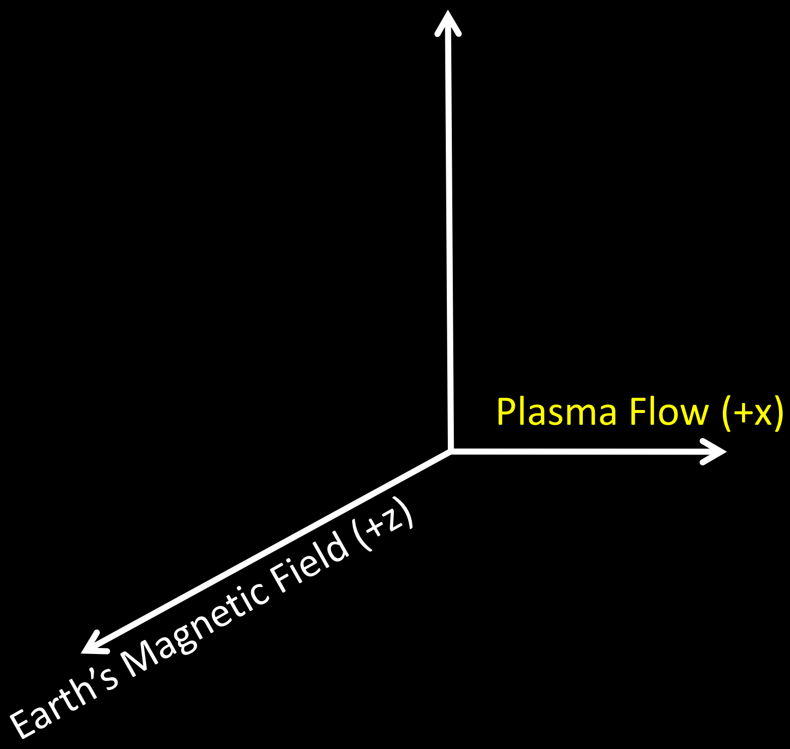
Rocket Potential



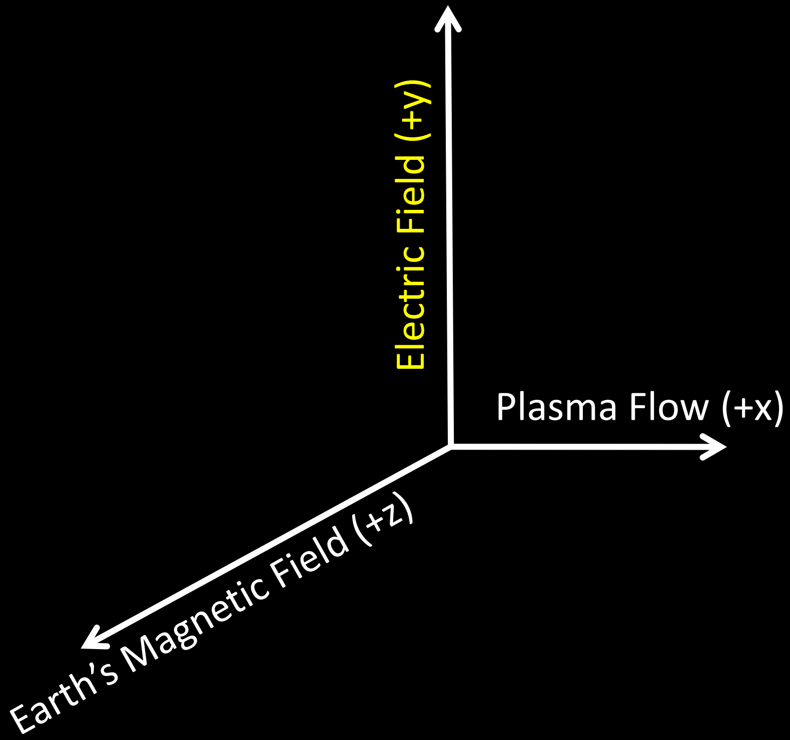
Plasma Potential



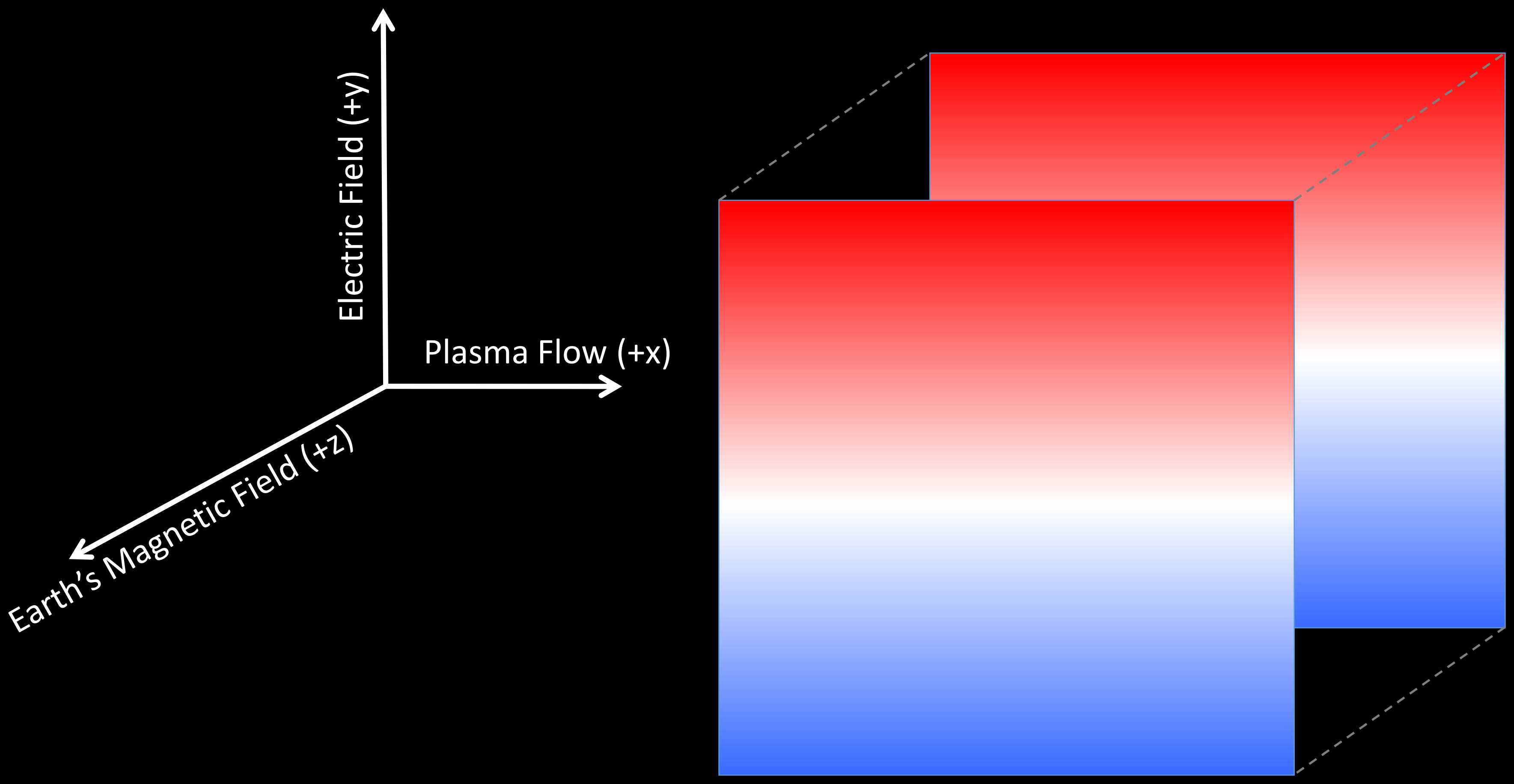
Plasma Potential



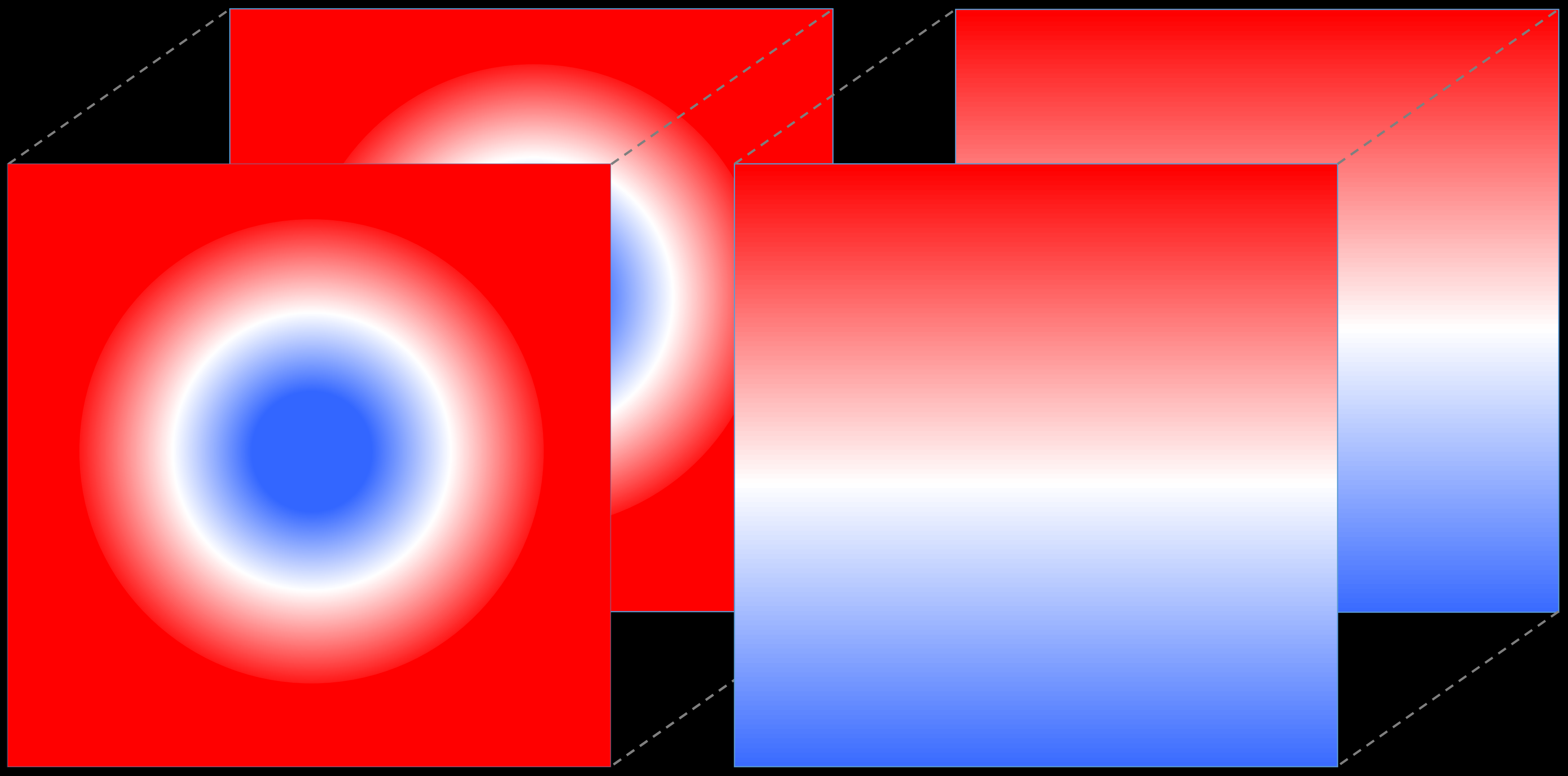
Plasma Potential



Plasma Potential



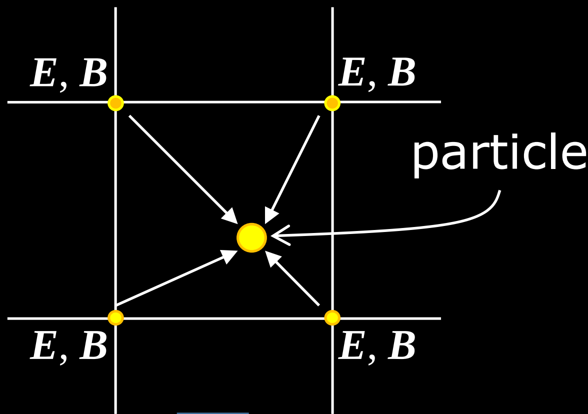
EMSES Potential



Play movie here

3D movie

EMSES plasma simulation: main loop



$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} + \mu_0 \boldsymbol{J}$$

or

$$\nabla \cdot (-\nabla \phi) = \frac{\rho}{\varepsilon_0}$$

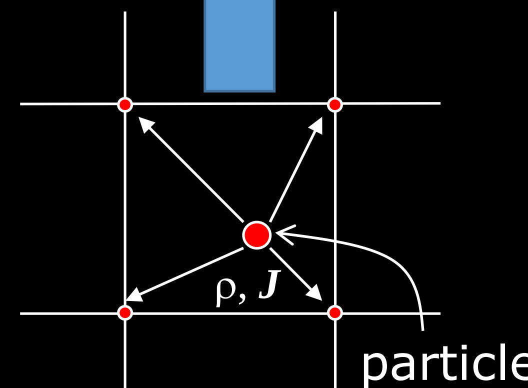
Field evolution

$$\Delta t$$

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{q_s}{m_s}(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

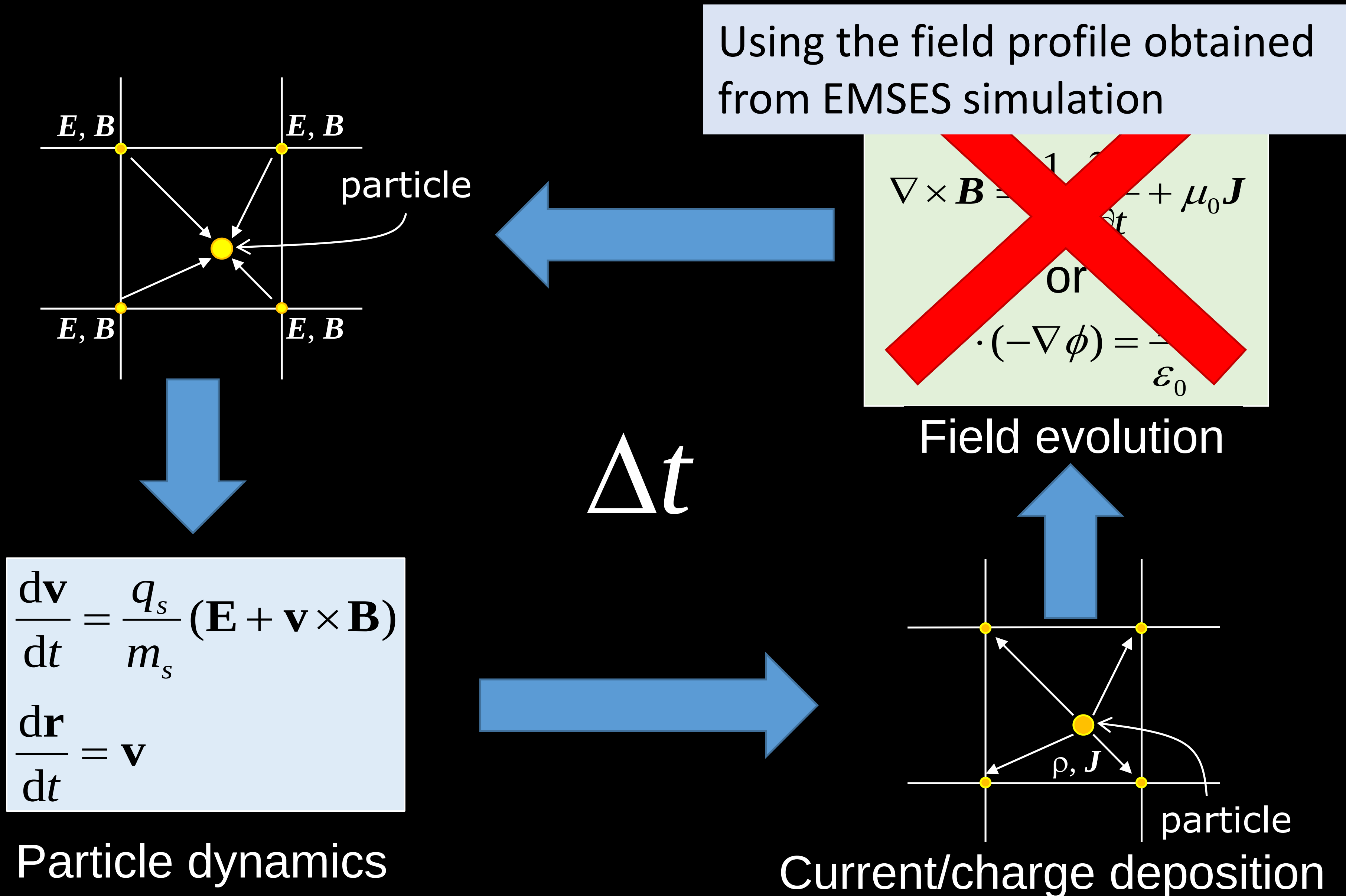
$$\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = \mathbf{v}$$

Particle dynamics



Current/charge deposition

Development of test particle code



Argument for Test Particle Code

EMSES simultaneously solves Maxwell's equations and Newton's laws (field evolution and particle motion), so we can already find where the particles are. Why should we write separate test particle code?

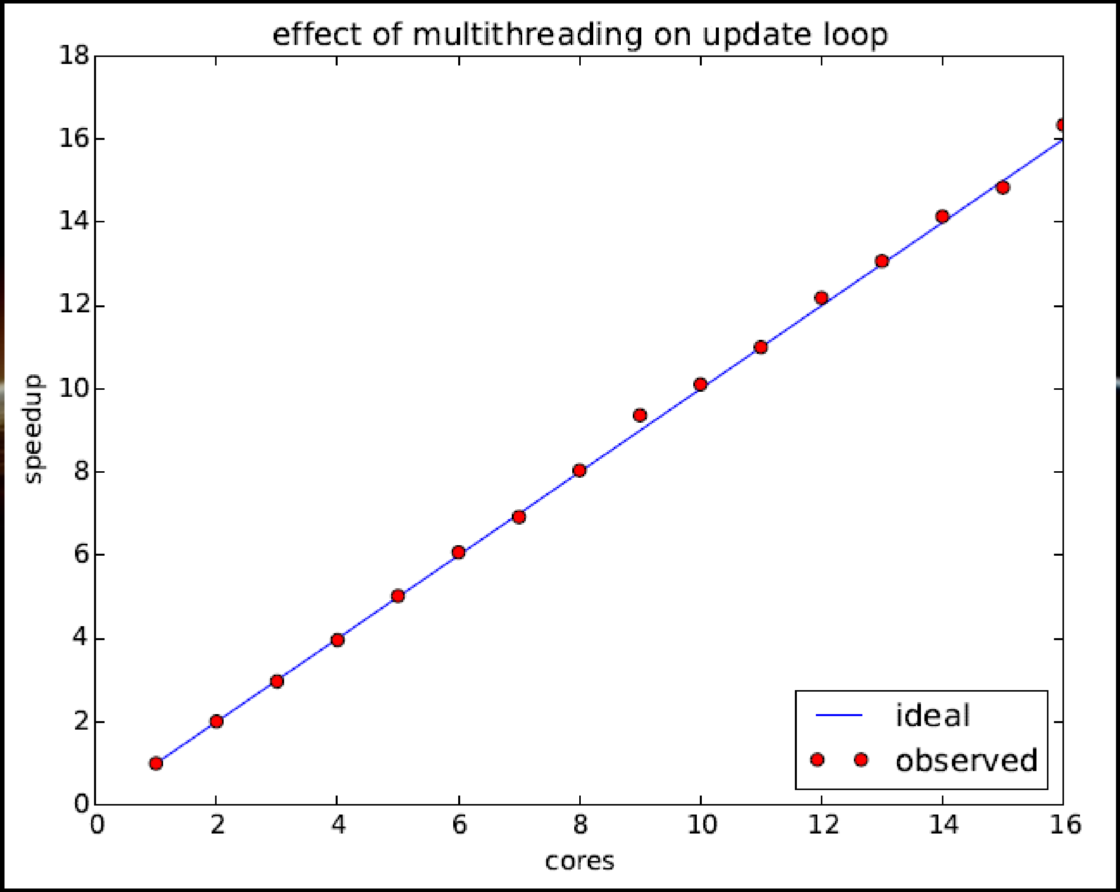
- interest in steady-state dynamics
- particles evolve according to decoupled system of ODEs (opportunity for parallelization)
- data locality and memory access

Storage of $\vec{E}$ and $\vec{B}$

- In EMSES, E_x, E_y, and E_z are stored as separate arrays (and the same for $\vec{B}$).
- If we only care about test particles, is this ideal?
- Upfront cost of restructuring storage in exchange for potential benefits during long-running computation. Profiling required.

Parallelization

Distribute particles among cores using OpenMP. Results with 2^{20} particles and 10^3 timesteps:



Takes around 24 seconds with 16 cores

Pop Quiz

Consider the following Fortran program.

```
call CPU_TIME(t0)
do i = 1, n
    u = cross_function(u, v)
end do
call CPU_TIME(t1); print *, t1 - t0
call CPU_TIME(t0)
do i = 1, n
    call cross_subroutine(u, v, w)
    u = w
end do
call CPU_TIME(t1); print *, t1 - t0
```

Similar code is used in updating particle velocities.
Which loop will be faster?

Answers

Compiled with gfortran -O3 on my laptop and with mpifrtpx -O3 -Kfast on the Kobe FX10.

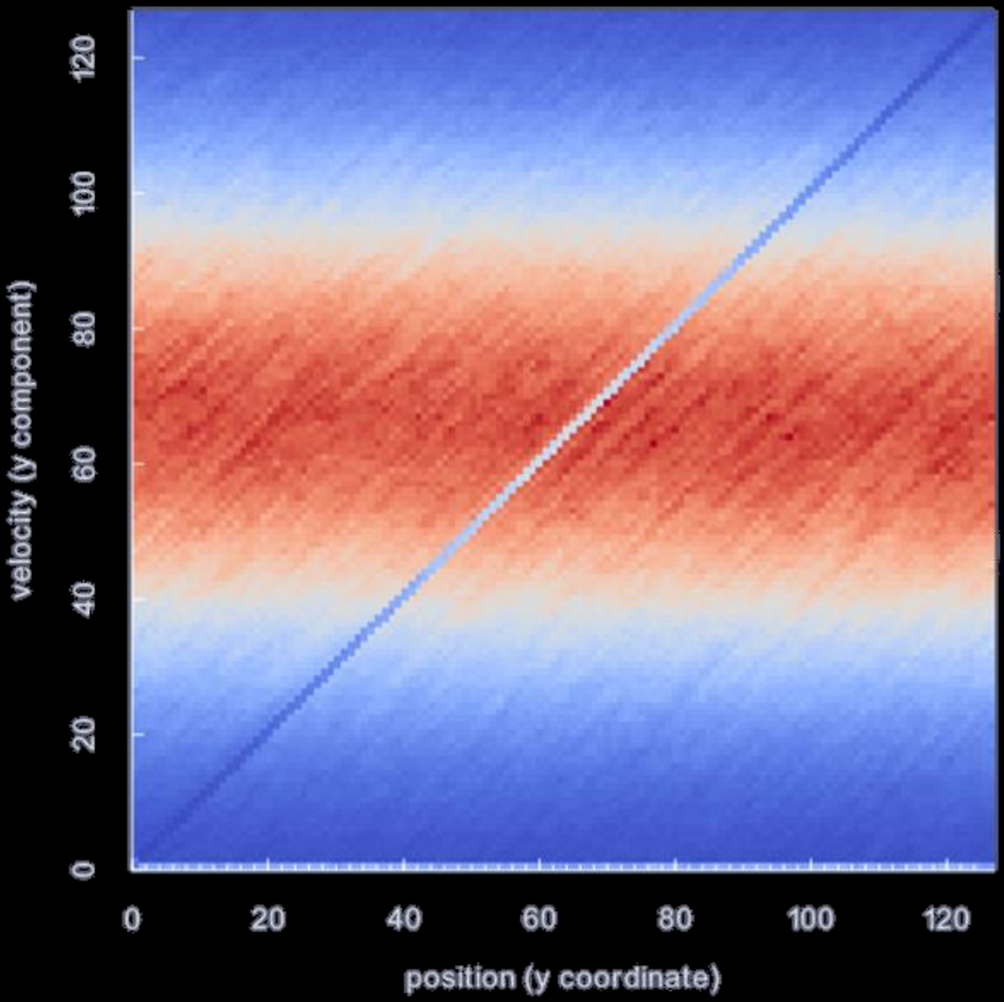
Results:

machine	function	subroutine
laptop	1.2e−1 s	1.3e−1 s
K computer	6.2e+0 s	2.1e−1 s

About 30 times slower as a function on the Kobe FX10!

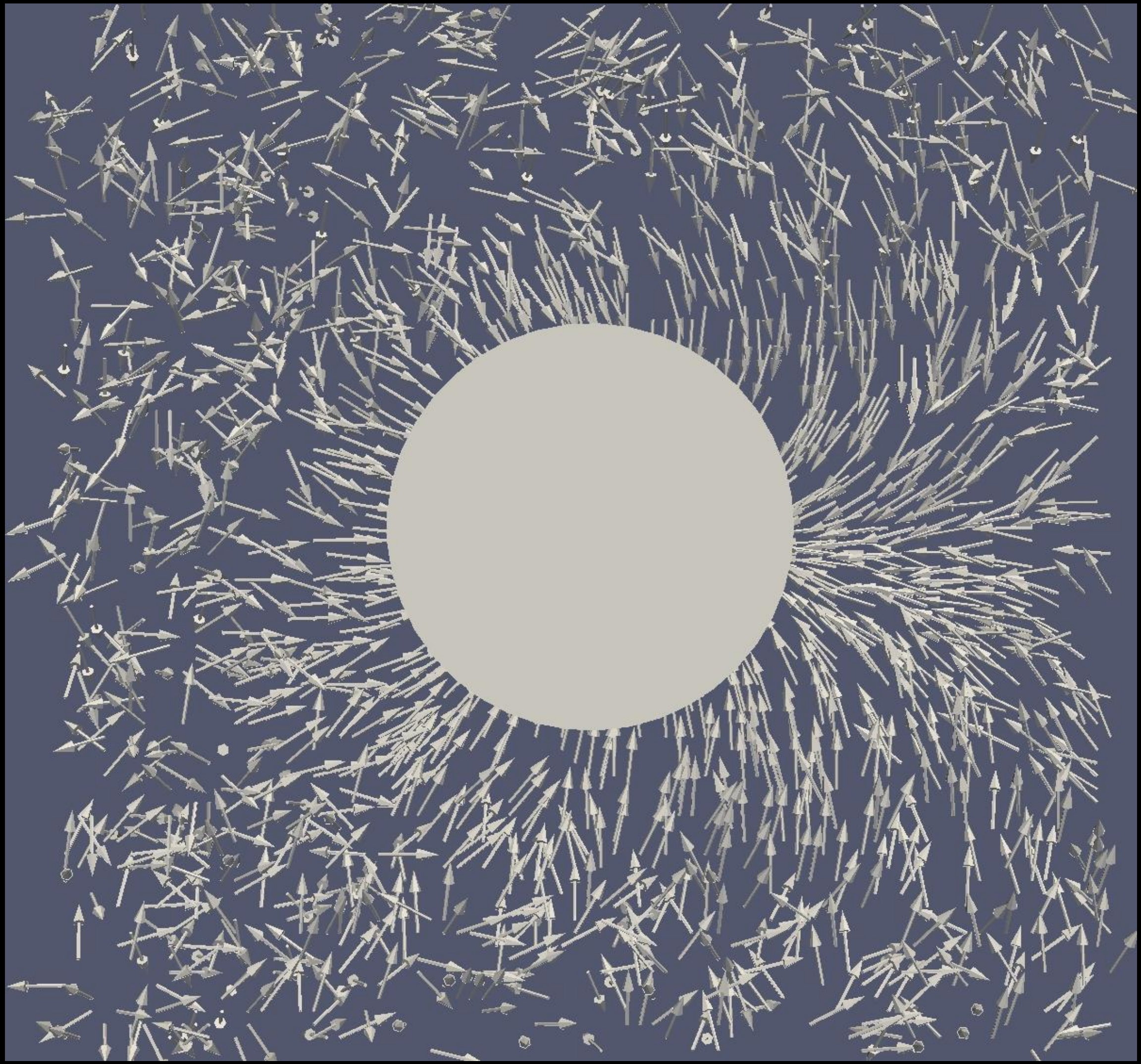
Analytics

Now that we have the particle dynamics, what next?

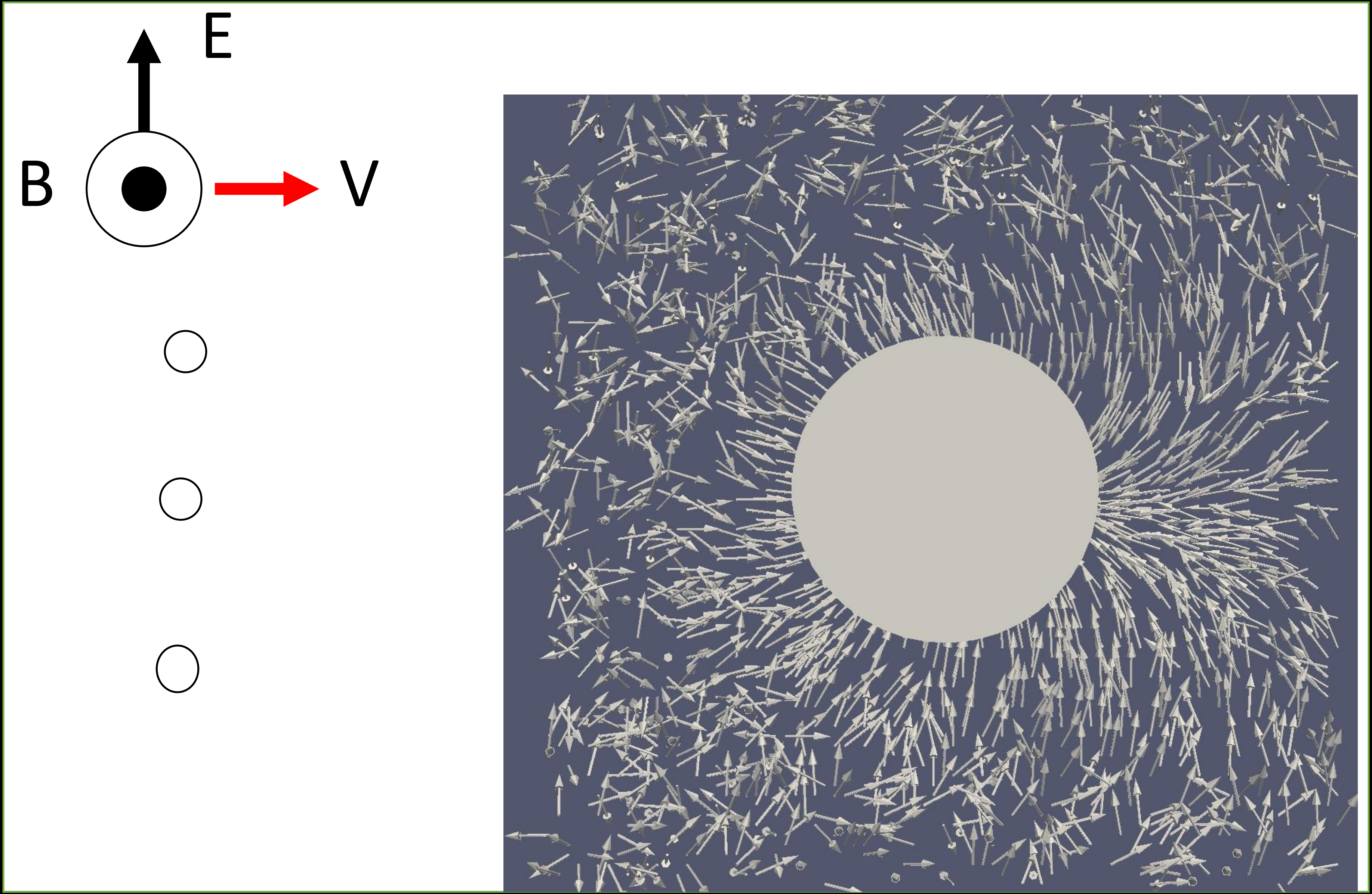


More opportunities for parallelization!

Electric field from EMSES simulation

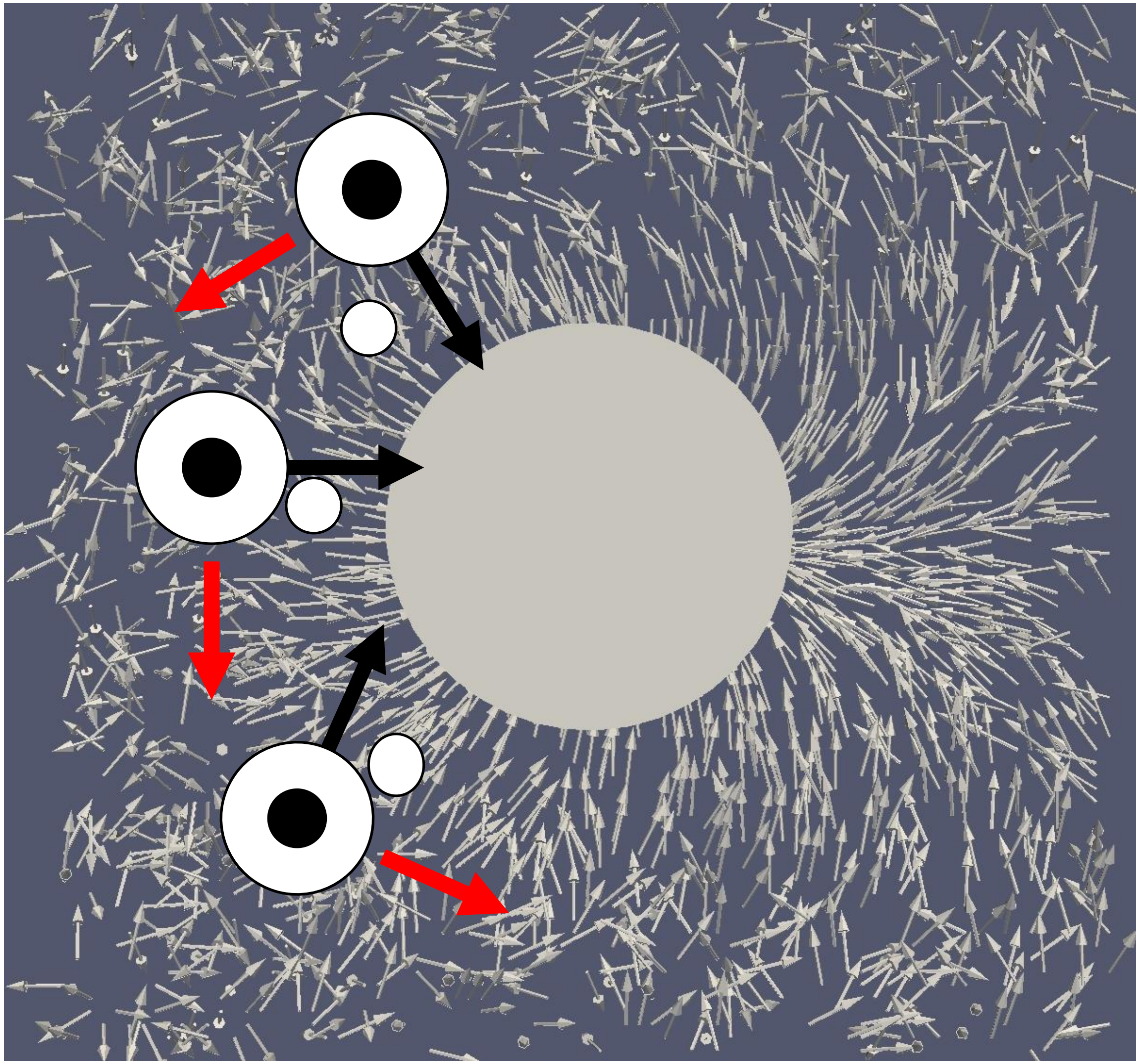


Principle



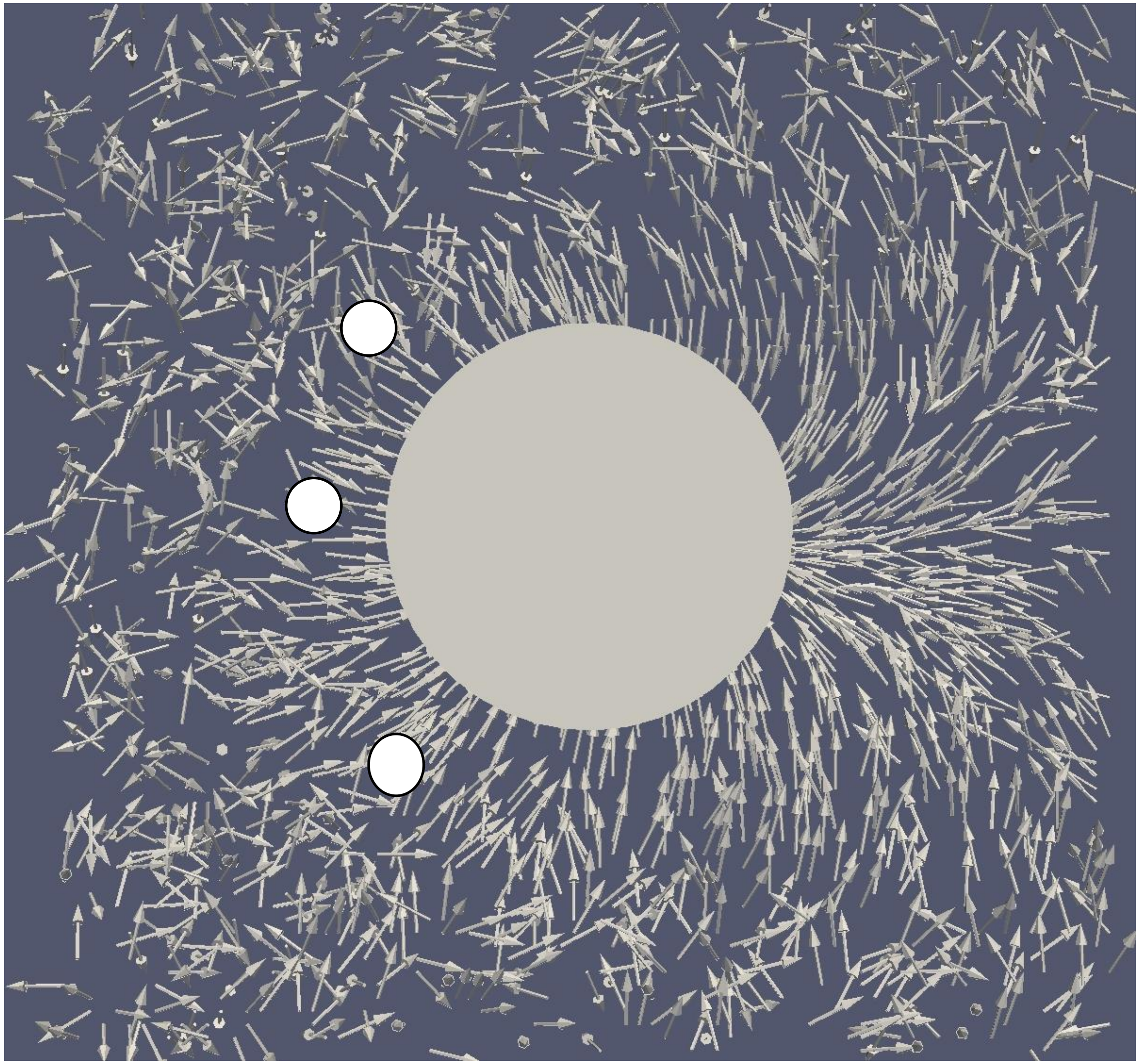
Principle

Direction Change of the electric field



Principle

Counter
Clockwise
Rotation



Summary

- We studied rocket plasma interactions by means of plasma particle simulations, data analysis and 3D visualization.

- We newly developed test particle code and parallelized the code with OpenMP.

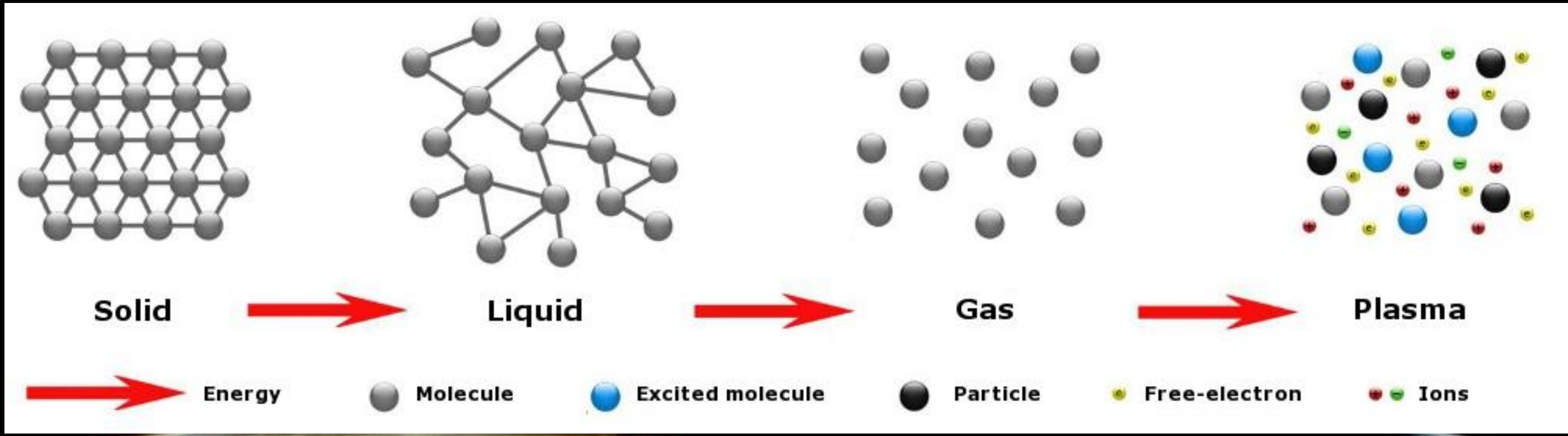
- We confirmed rocket charging and plasma perturbations, and also understood characteristic particle dynamics due to a local electric field around the rocket.


Thank you

Backup slides

What is plasma?

Plasma is "the fourth state of matter."



- Assembly of charged particles (electrons & ions)
- Quasi-neutrality
- Debye shielding
- Interactions with electromagnetic field

Rockets in plasma: What happens?

- The solid surface of a rocket introduces different boundary conditions for space plasma from its natural state
  $\Rightarrow$ Plasma density, flow velocity, etc. may change near the boundary.

- Plasma charge is deposited to its surface
  - The surface potential changes.

    ↓

  - The surface potential produces electric field.

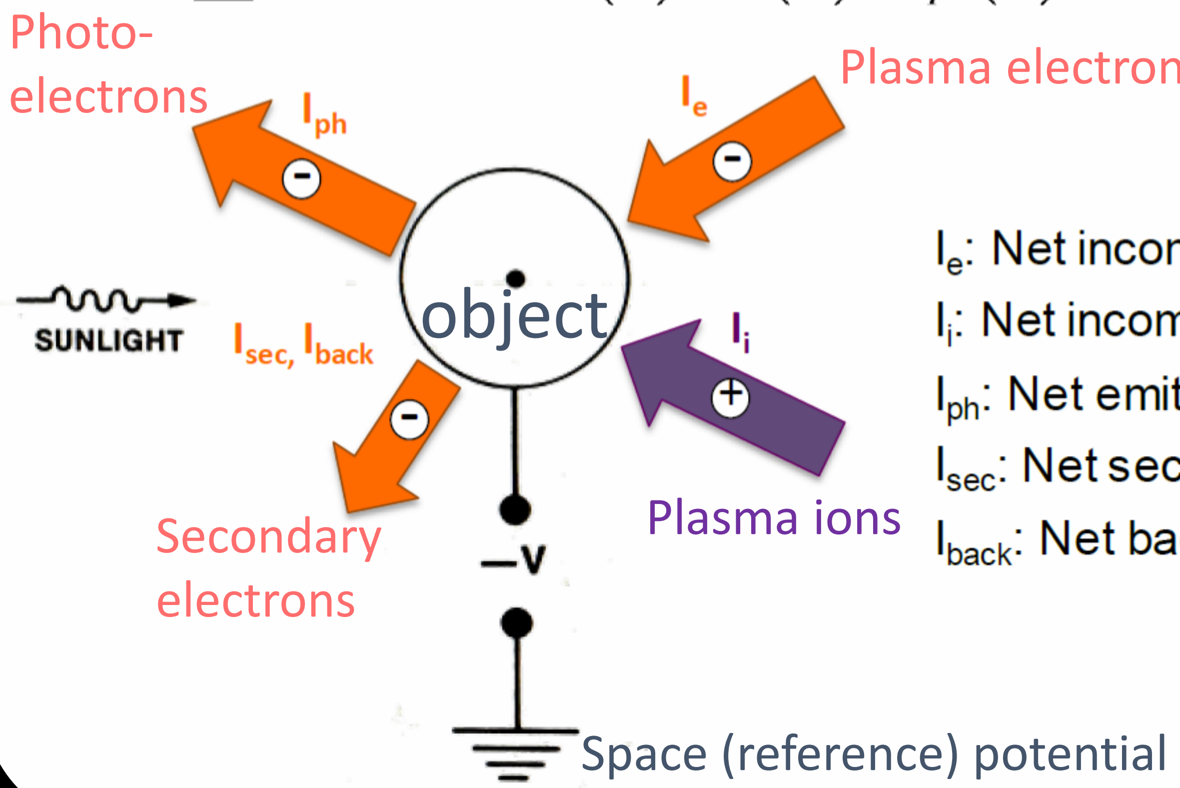
    ↓

  - Quasi-neutrality breaks down near the surface.

Equilibrium potential

Charging is a result of the current balance:

$$\sum I = 0 \;\rightarrow\; I_e(V) - I_i(V) - I_{ph}(V) - I_{sec}(V) - I_{back}(V) = 0$$



I_e: Net incoming electron current

I_i: Net incoming ion current

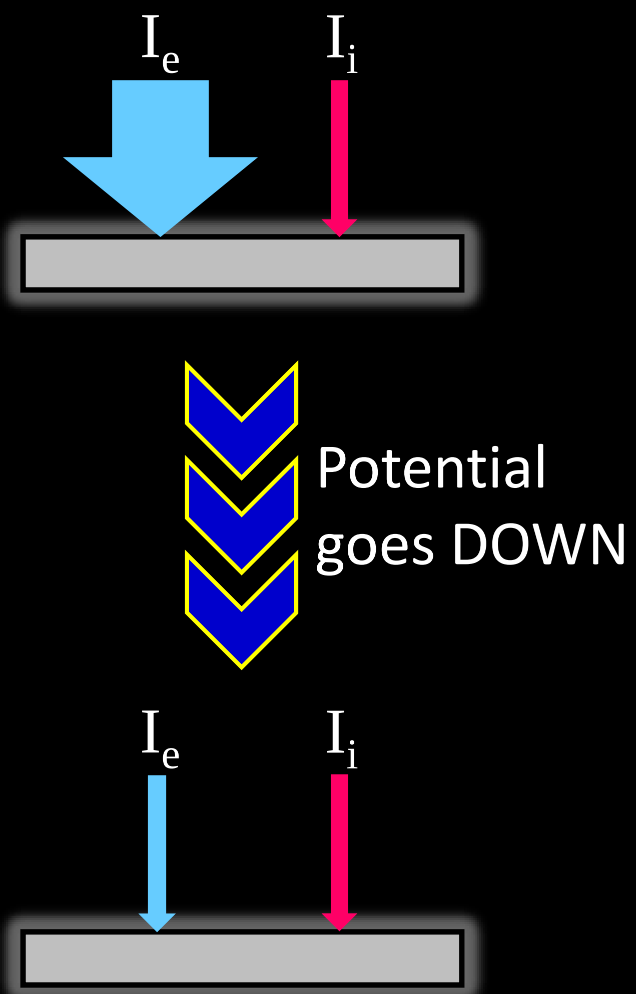
I_{ph}: Net emitted photoelectron current

I_{sec}: Net secondary electron current

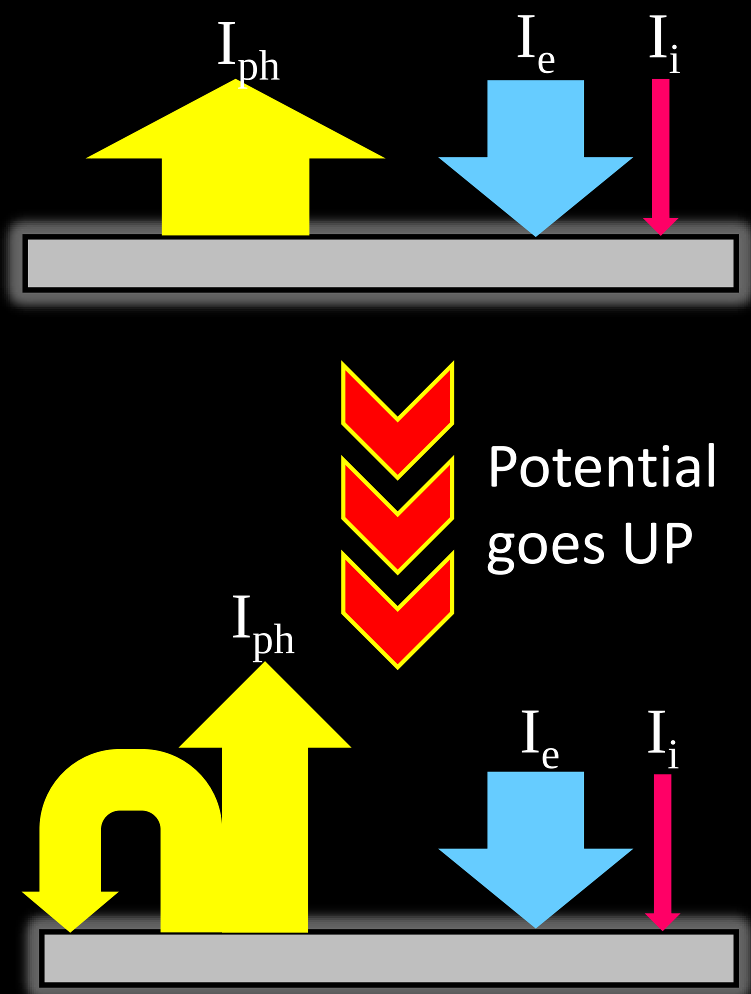
I_{back}: Net backscattered electron current

A few simple cases

Case 1. Dense plasma consisting of only electrons & ions



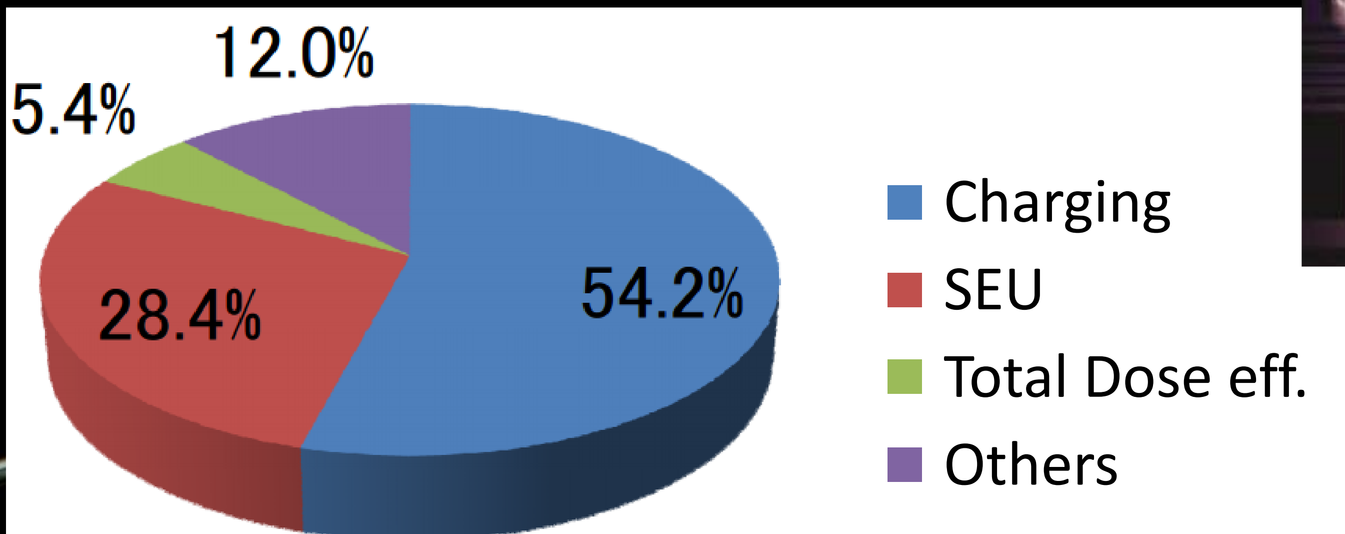
Case 2. Dilute plasma, in which photo-electron emission is NOT negligible



Current balance is established

Why charging so important?

1. Charging/discharging may cause anomalies of in-space system.



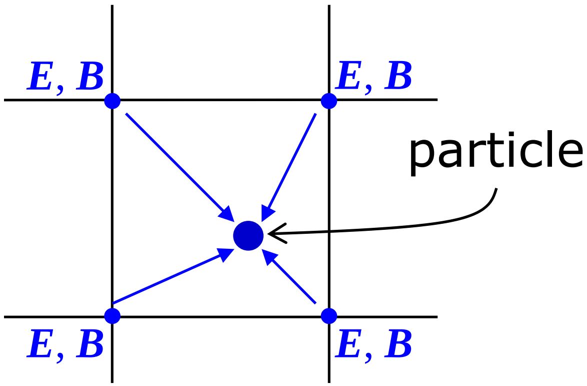
参照:Survey of spacecraft anomaly databases
(Space Architect Study: Koons他、1999)

2. Electromagnetic/plasma perturbation around rockets
   – Interference with scientific measurements (both fields and particles)

EMSES:
Electro-Magnetic Spacecraft Environment Simulator
= *Full PIC code + <u>Rocket body treatment</u>*

EMSES is an electromagnetic particle-in-cell code designed for spacecraft-plasma interaction study. It can include spacecraft/rocket surfaces <u>as an internal boundary</u>, and has capability of simulating spacecraft charging, sheath/wake formation, etc., in a self-consistent manner.

EMSES simulation: main loop



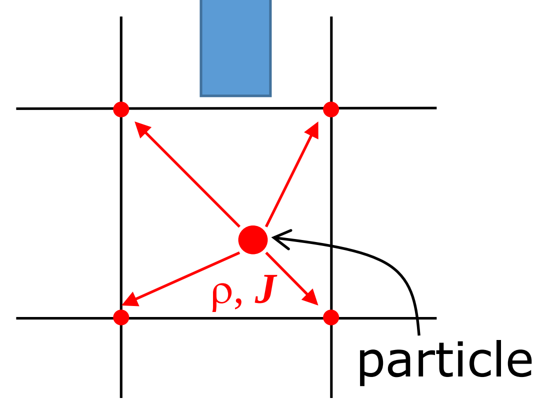
Field interpolation

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \frac{q_s}{m_s}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = \boldsymbol{v}$$

Particle dynamics

$$\Delta t$$



Current/charge deposition

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} + \mu_0 \boldsymbol{J}$$

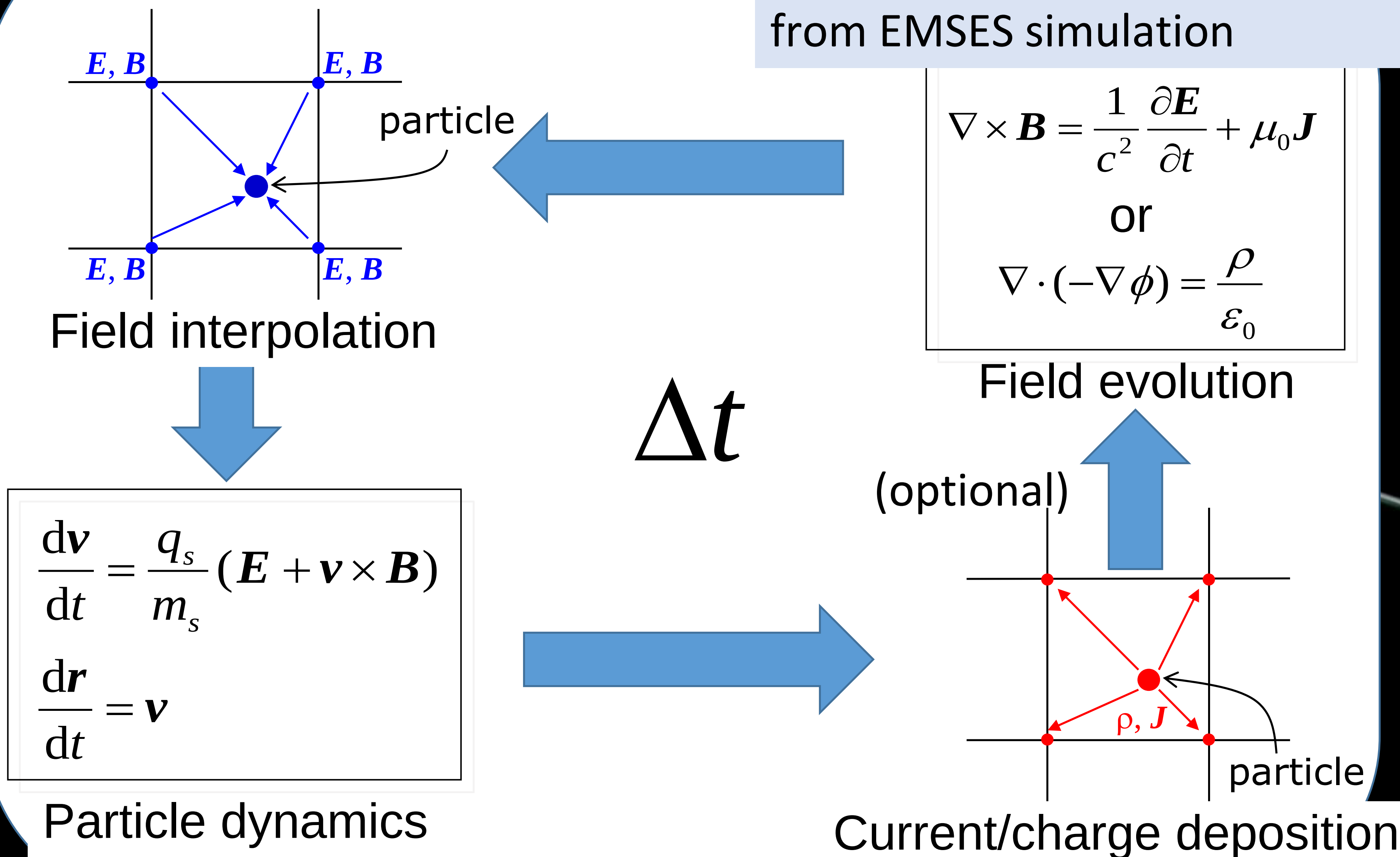
or

$$\nabla \cdot (-\nabla \phi) = \frac{\rho}{\varepsilon_0}$$

Field evolution

Mini-code: test-particle analysis

Using the field profile obtained from EMSES simulation



Test particle analysis

- Test particle analysis resolves the charged particle dynamics under the given electromagnetic field environment. (EM field is constant)
- Motion of each particle dynamics is solved individually.

Test particle analysis

(Cons) …does not include ANY plasma collective effects

(Pros) …will be instructive to understand how particles are accelerated or decelerated in the given field

(Pros) …will describe particle dynamics correctly under the assumption that the field environment reaches a steady state