External Plasma-Breathing Magnetohydrodynamic Propulsion

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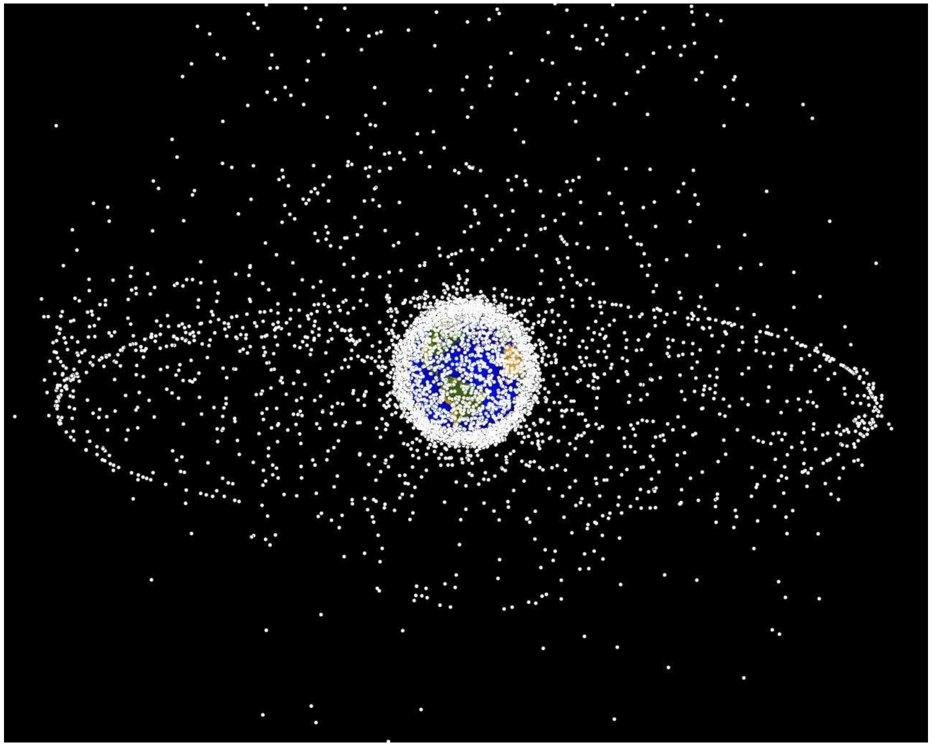
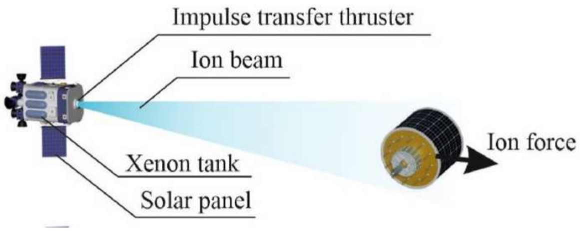
Georgia Tech Space Systems Design Laboratory

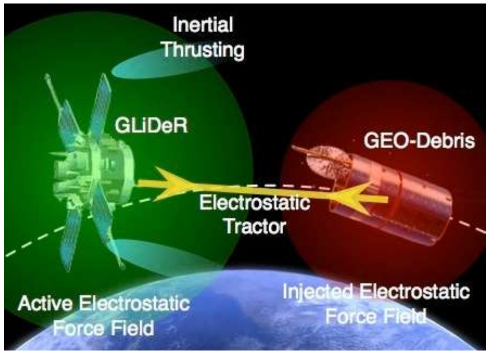
LGST Lab

Space Debris and Mitigation Strategies



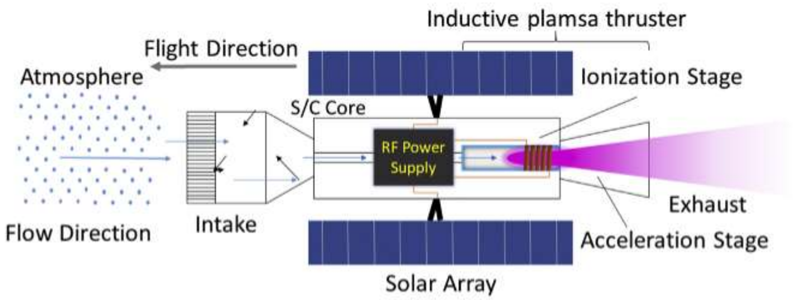
NASA Simulation

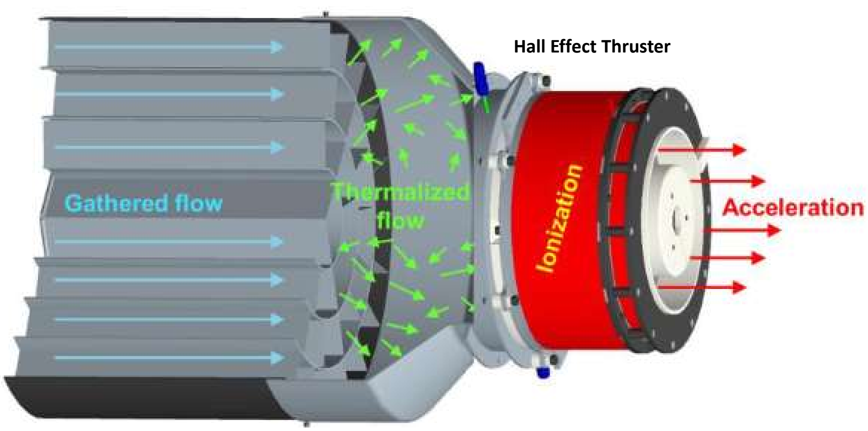


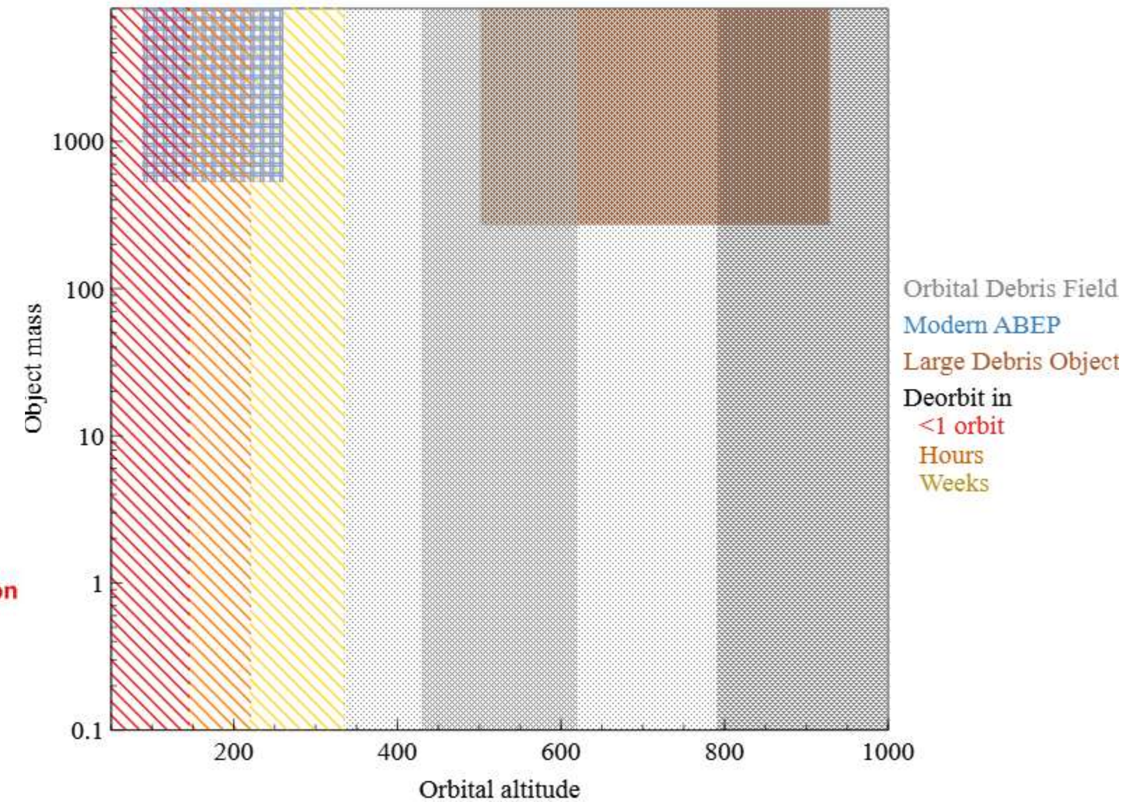


Trushlyakov, V & Yudintsev, Vadim. (2019). Rotating tethered system for active space debris removal.
Alexander S. Ledkov, Vladimir S. Aslanov (2023), Active space debris removal by ion multi -beam shepherd spacecraft
Hanspeter Schaub, Zoltán Sternovsky (2014), Active space debris charging for contactless electrostatic disposal maneuvers,

Atmosphere-Breathing Electric Propulsion (ABEP)

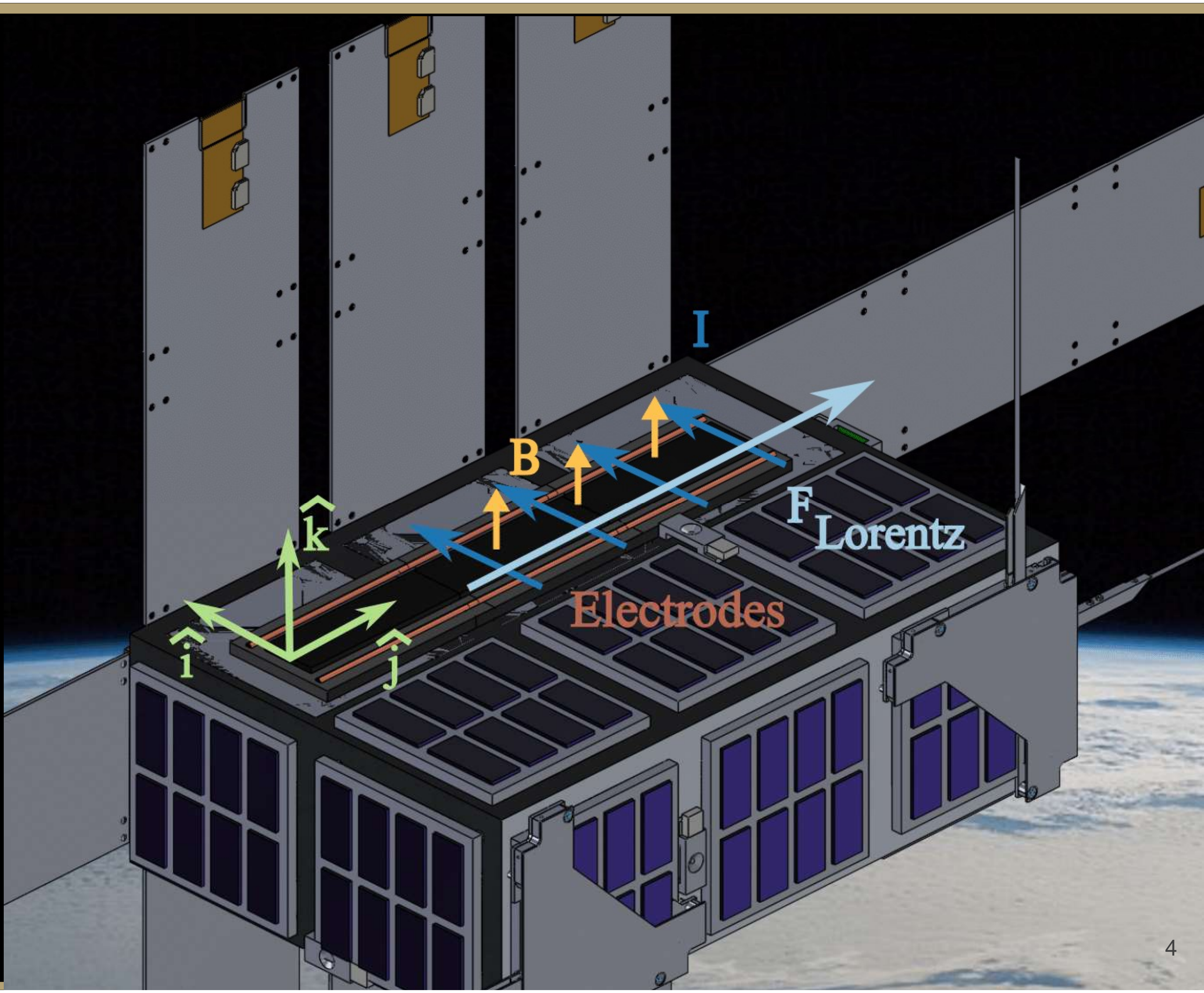






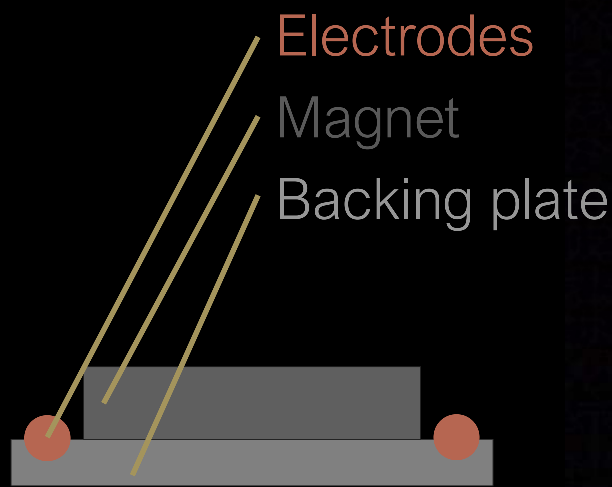
Romano, F., et al., System analysis and test-bed for an atmosphere-breathing electric propulsion system using an inductive plasma thruster (2018)
Jackson, S. W., Design of an Air-Breathing Electric Thruster for CubeSat Applications (2017)
Andreussi, et al., Development and Experimental Validation of a Hall Effect Thruster RAM-EP Concept (2017)
Souhair, et al., Prediction of the Propulsive Performance of an Atmosphere-Breathing Electric Propulsion System on Cathode-Less Plasma Thruster (2023)

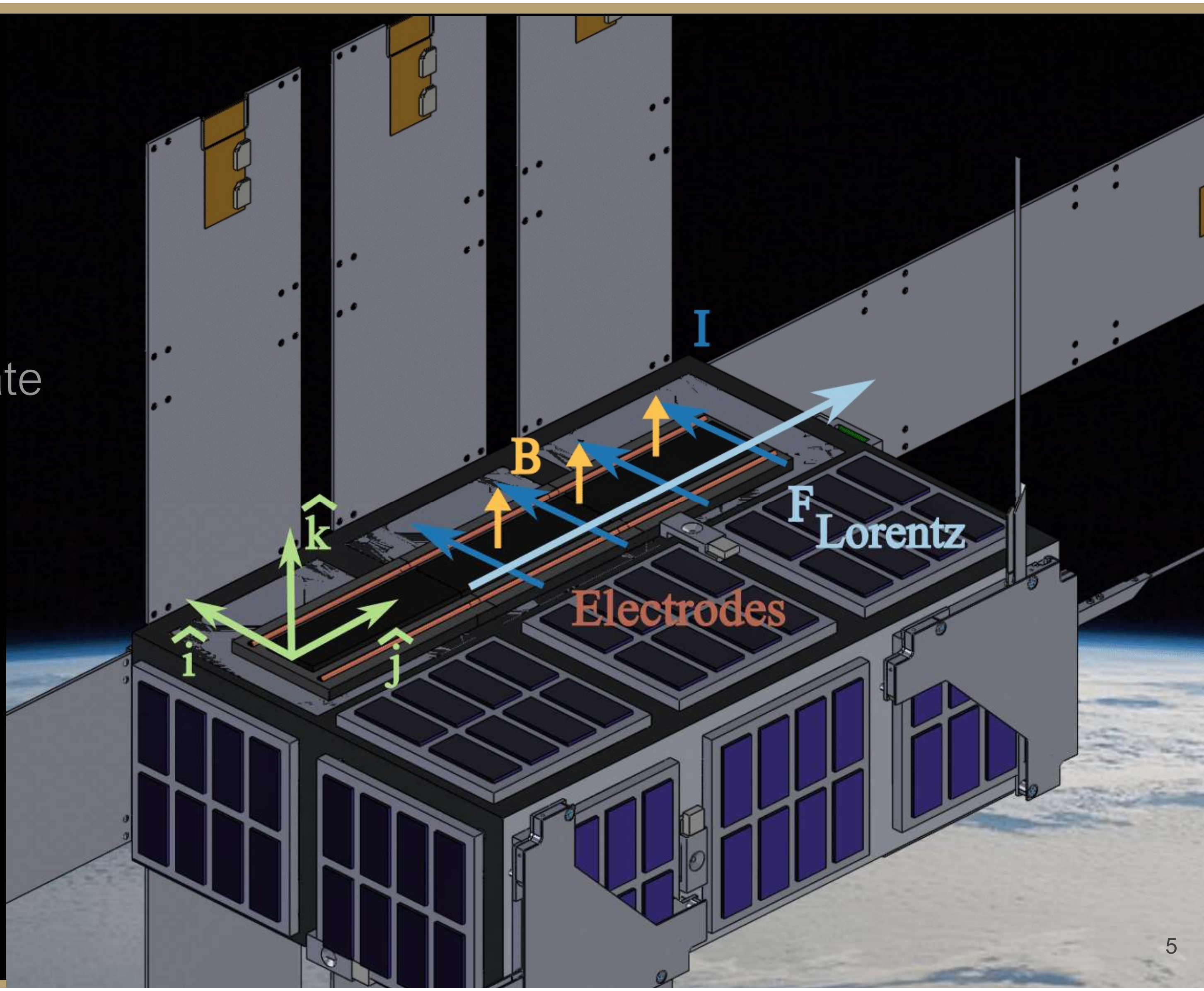
Concept Overview



Concept Overview

Cross-sectional design:





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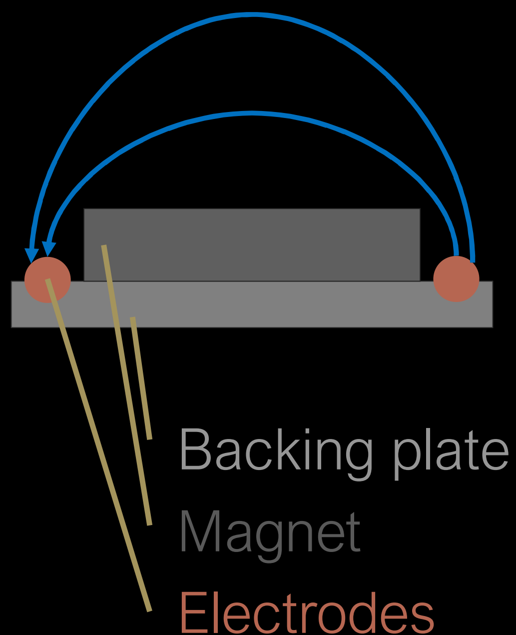
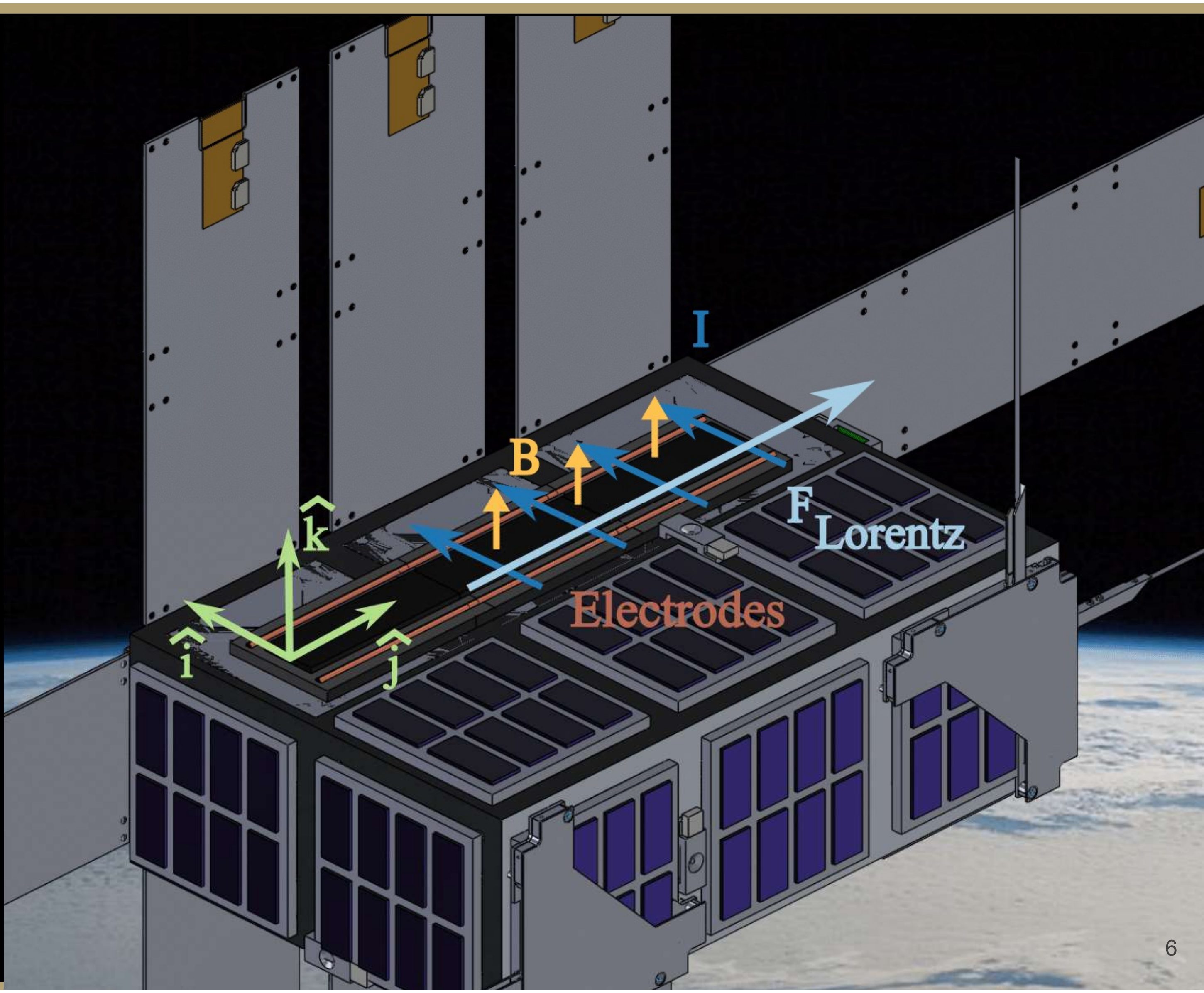
Concept Overview

Cross-sectional design:



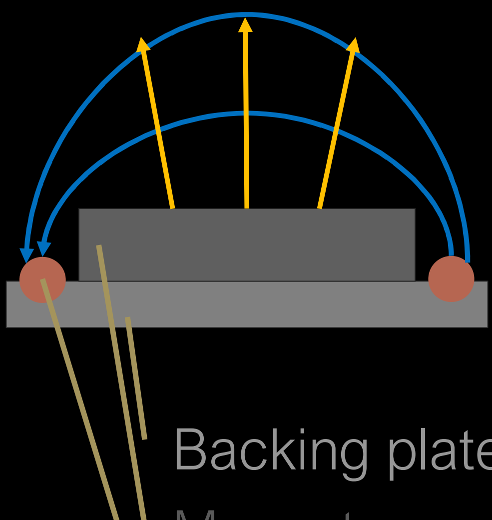


Concept Overview

Cross-sectional design:

Magnetic field

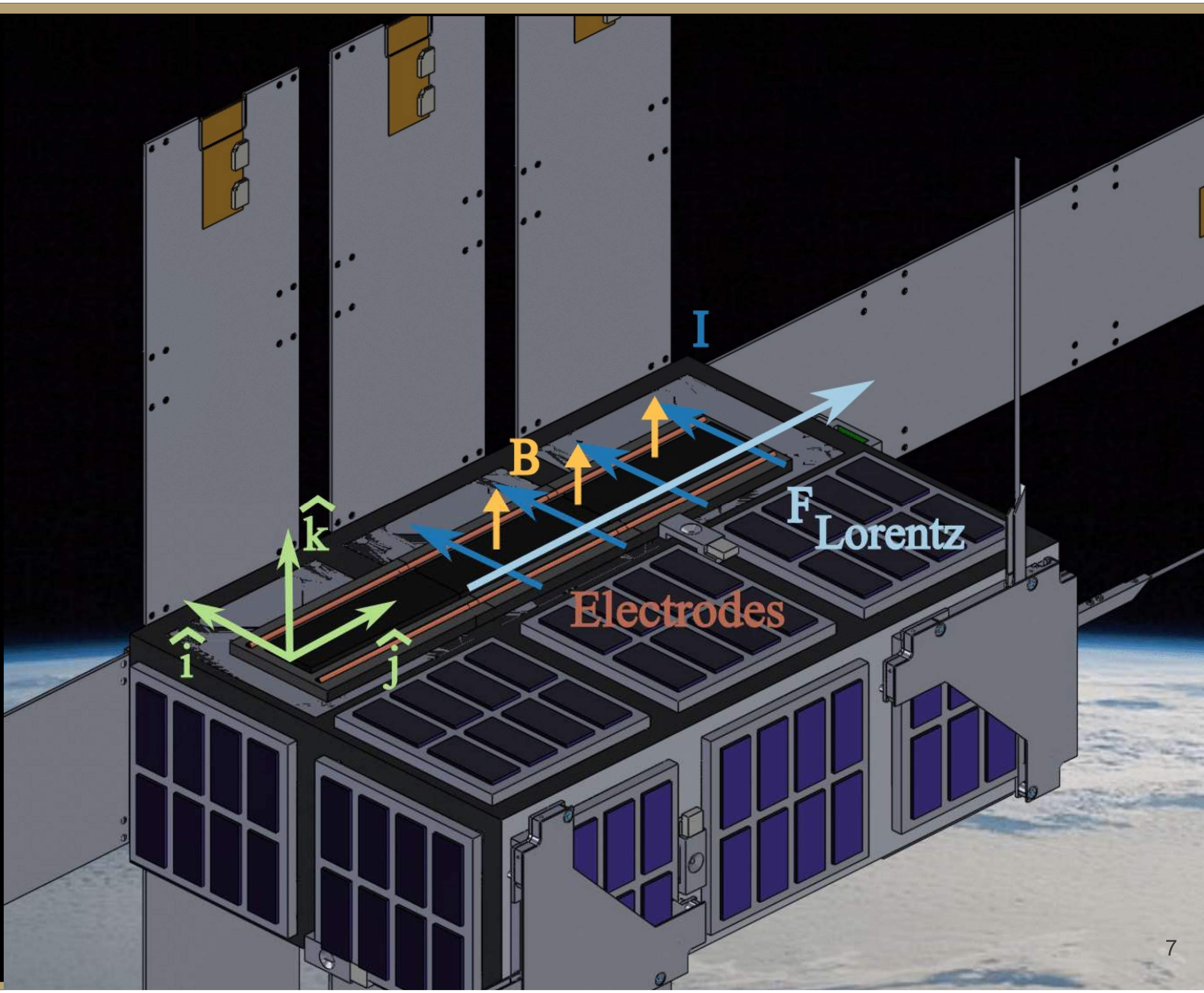
Plasma current



Backing plate

Magnet

Electrodes



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Concept Overview

Cross-sectional design:

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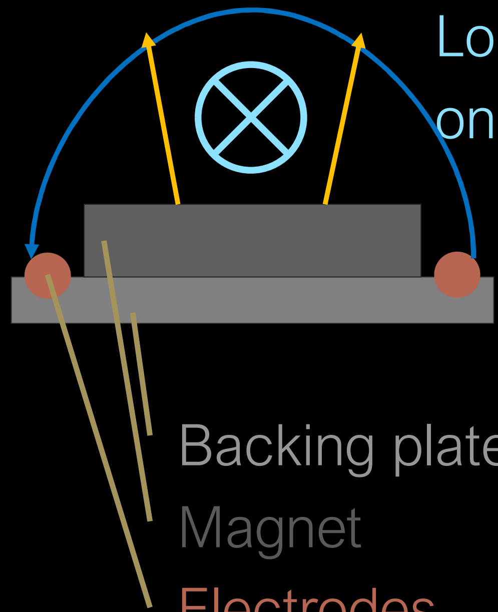

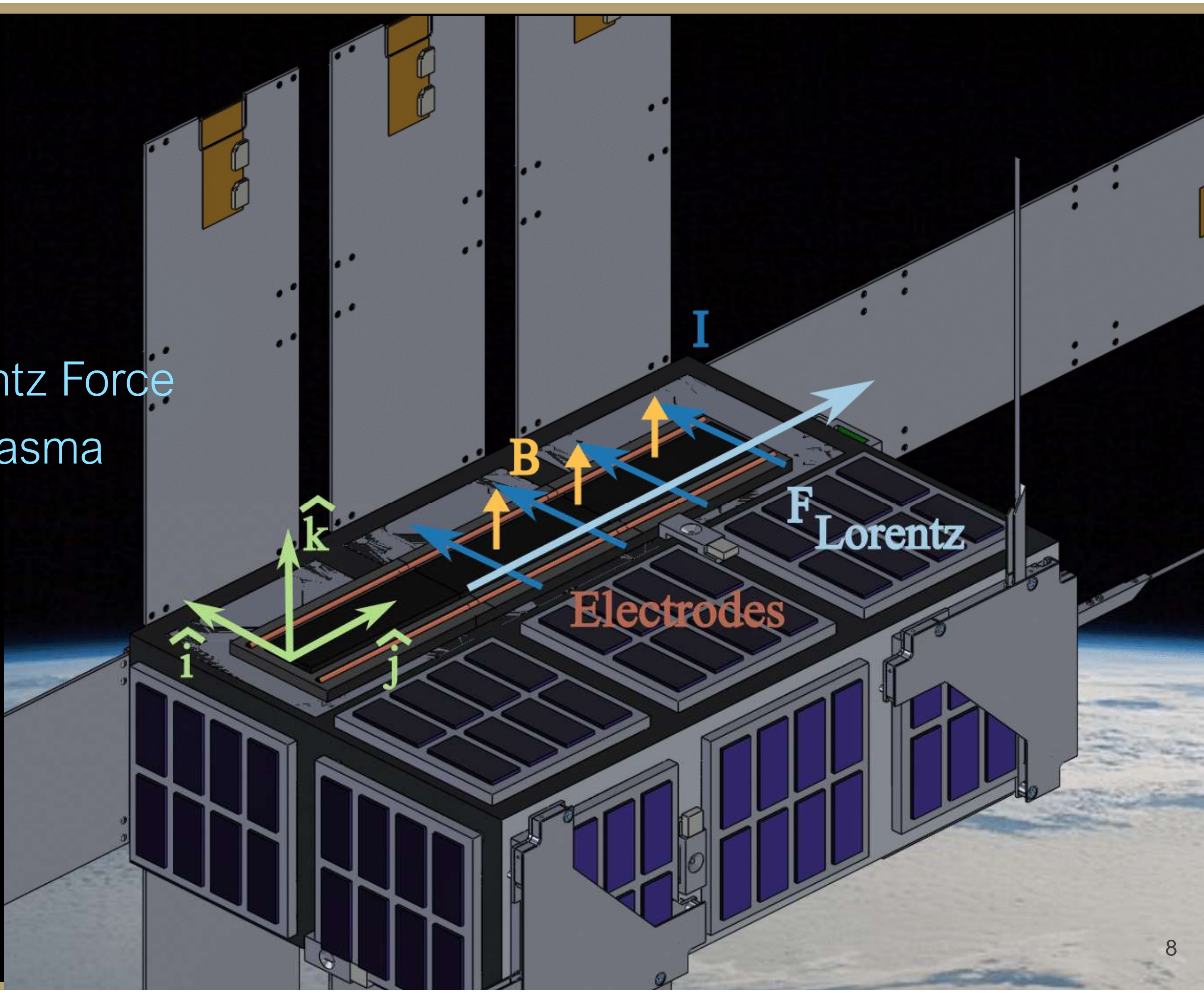

Concept Overview

Cross-sectional design:

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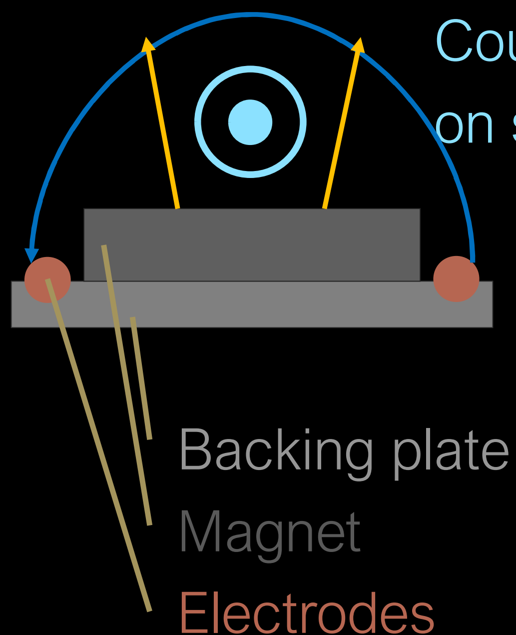
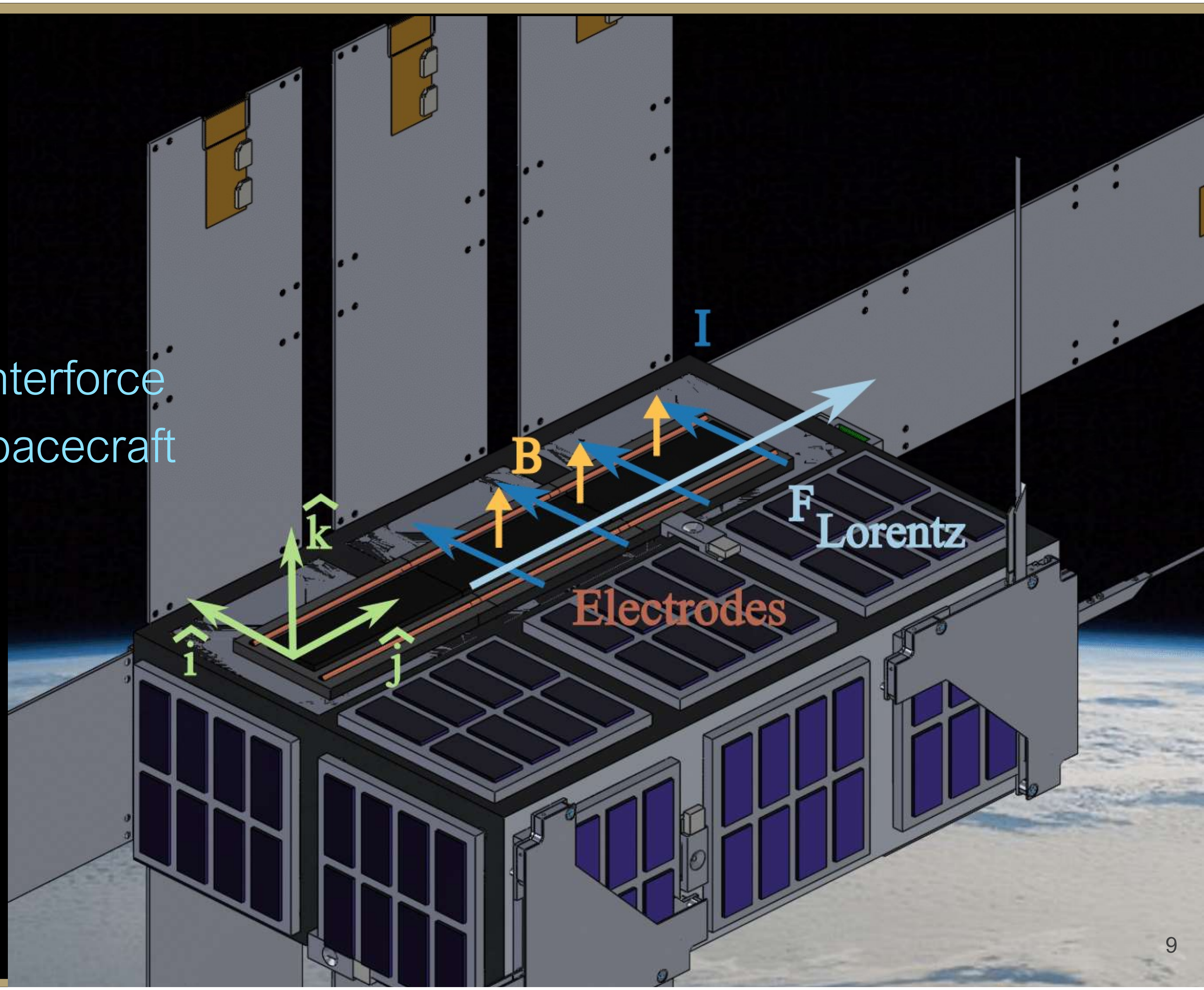
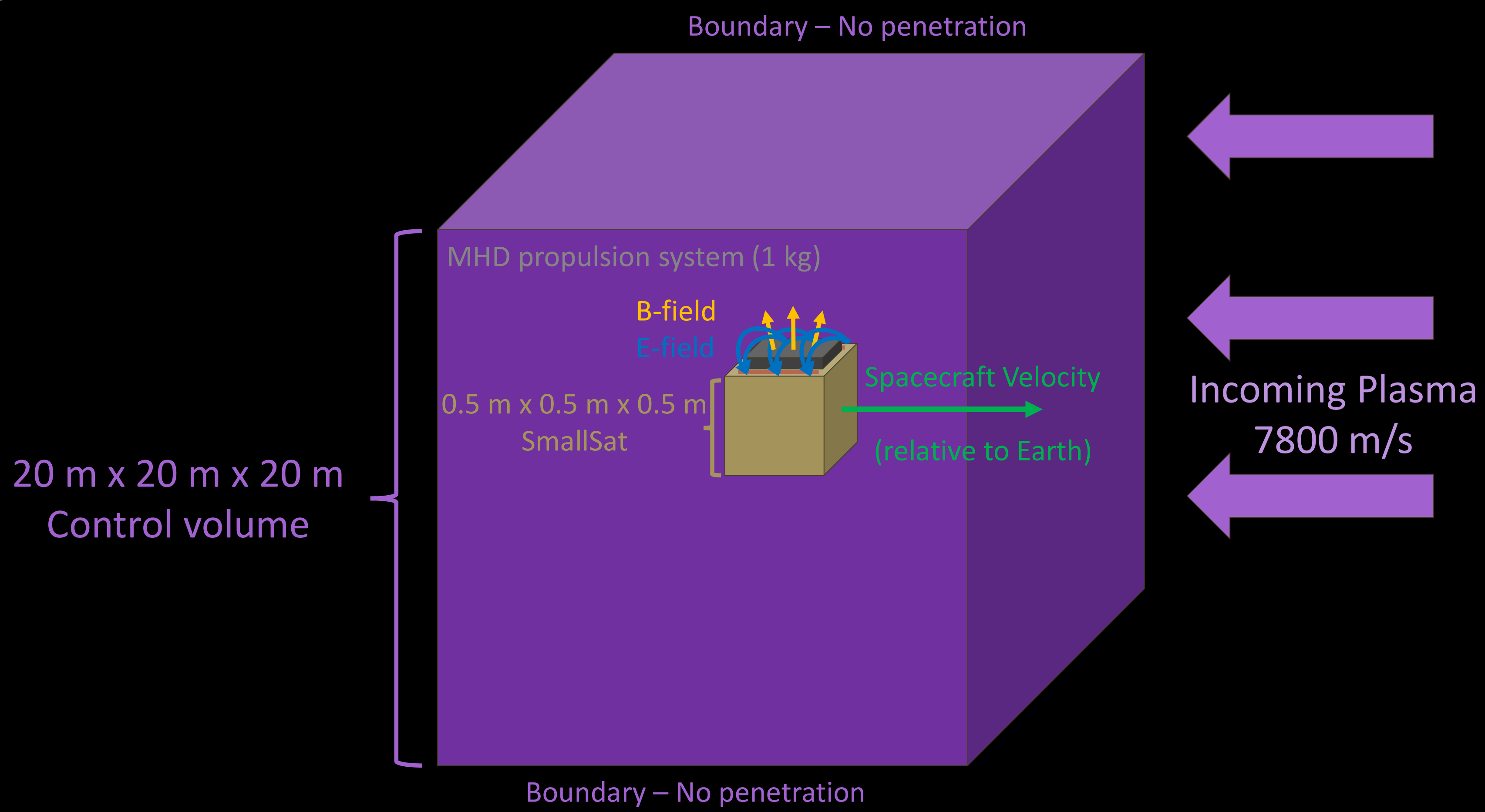




Physical problem



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Simulation techniques

$$\frac{\partial f}{\partial t} + \frac{p}{m} \cdot \nabla_x f + q\left(E + \frac{p}{m} \times B\right) \cdot \nabla_p f = 0$$

Active **Passive**

$$E + \boldsymbol{v} \times \boldsymbol{B} = \frac{J}{\sigma}$$

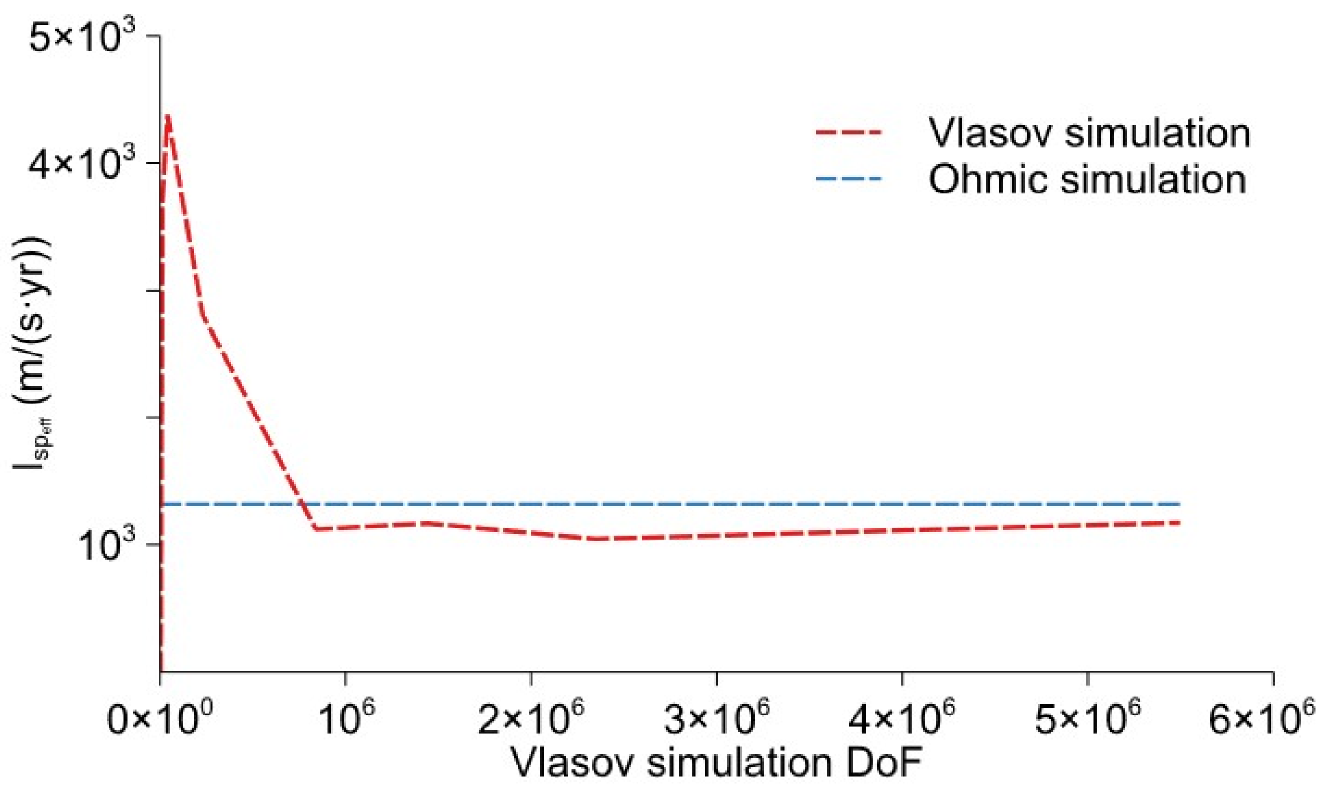
6D Vlasov	**5D** Vlasov	**3D** Ohmic analysis

• Collisionless flow simulation
• Velocity distribution tracking
• Pros
  • More accurate
  • Better physical modelling
• Cons
  • **Extremely high computational cost**
	• Magnetic forces cannot act out-of-plane
	• Out-of-plane velocities not needed
	• Pros
	  • Lower computational cost
	• Cons
	  • Potentially less accurate
		• 3D continuous model
		  • E & B fields
		  • Plasma conductivity
		• Pros
		  • Low computational cost
		• Cons
		  • Less physical modelling

Verdict: Prohibitive cost	**Verdict: Useful for verification**	**Verdict: Requires verification**

Verification and Comparison

- Test case used to verify Ohmic analysis
  - Passive drag of a spacecraft in LEO
  - Performance measured using effective I_{sp}
- 5D Vlasov simulation
  - Converges to near Ohmic result



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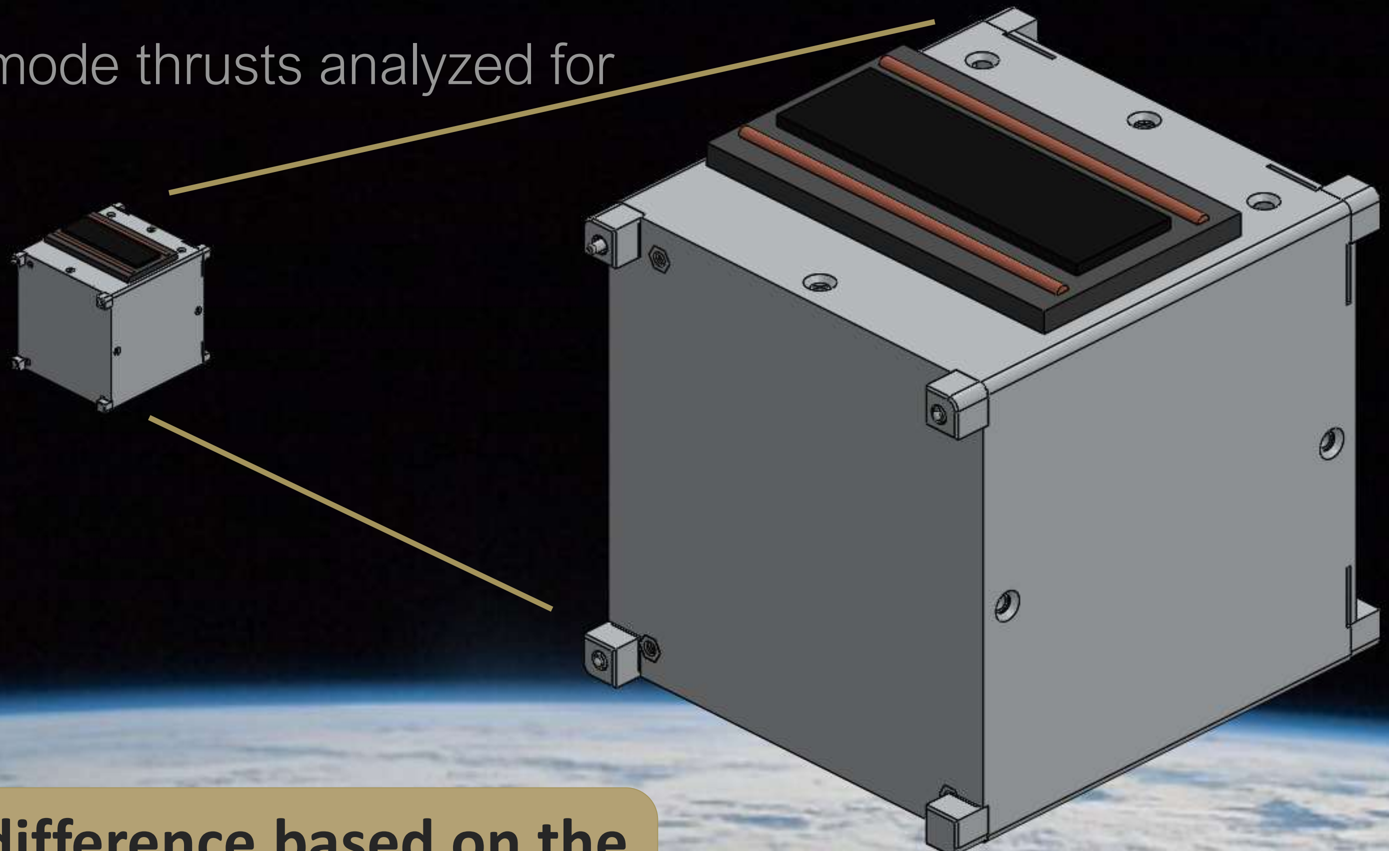
Linear scaling of Conductive MHD Patch

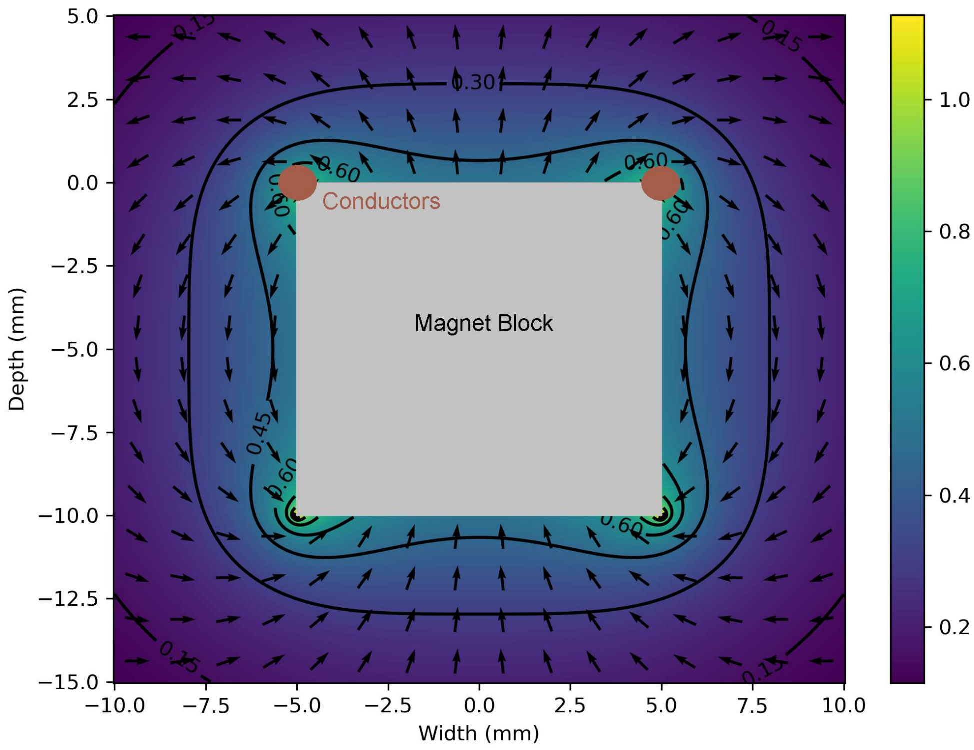
- Active and passive mode thrusts analyzed for a linear scaling
  - $M \sim L^3$
- Active thrust $F_a \sim M$
  - Power $\mathrm{P} \sim M$
  - Passive thrust $F_p \sim M$



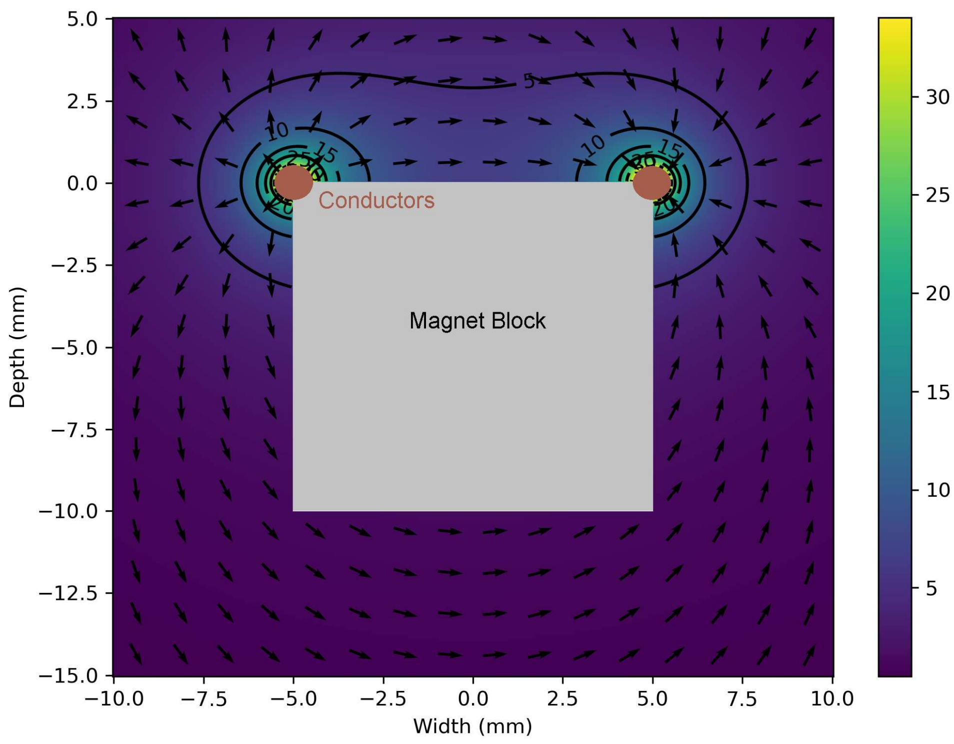
No performance difference based on the size of the satellite!

Electromagnetic Characterization

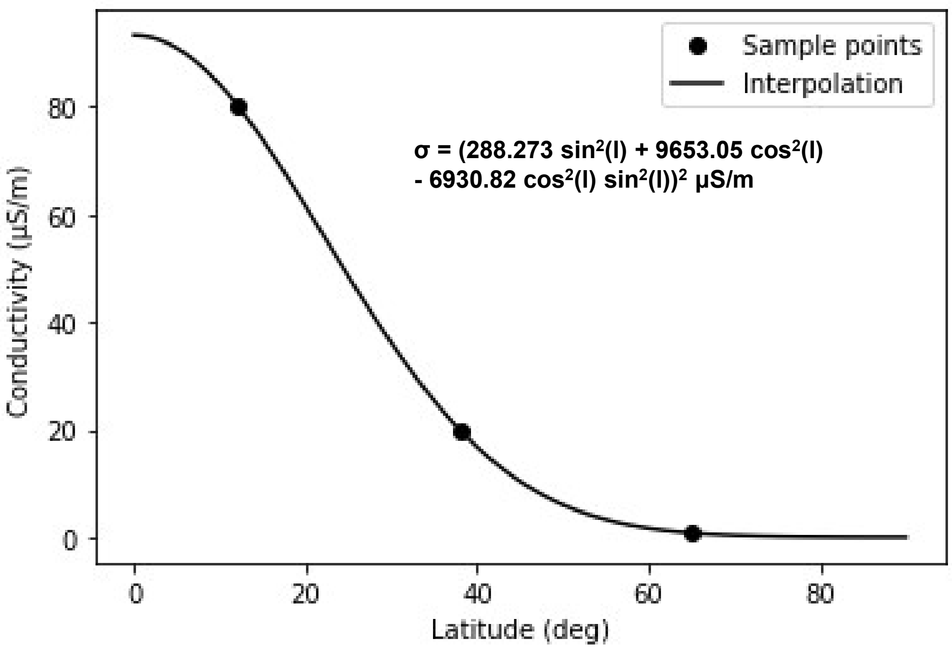
B-field (T)

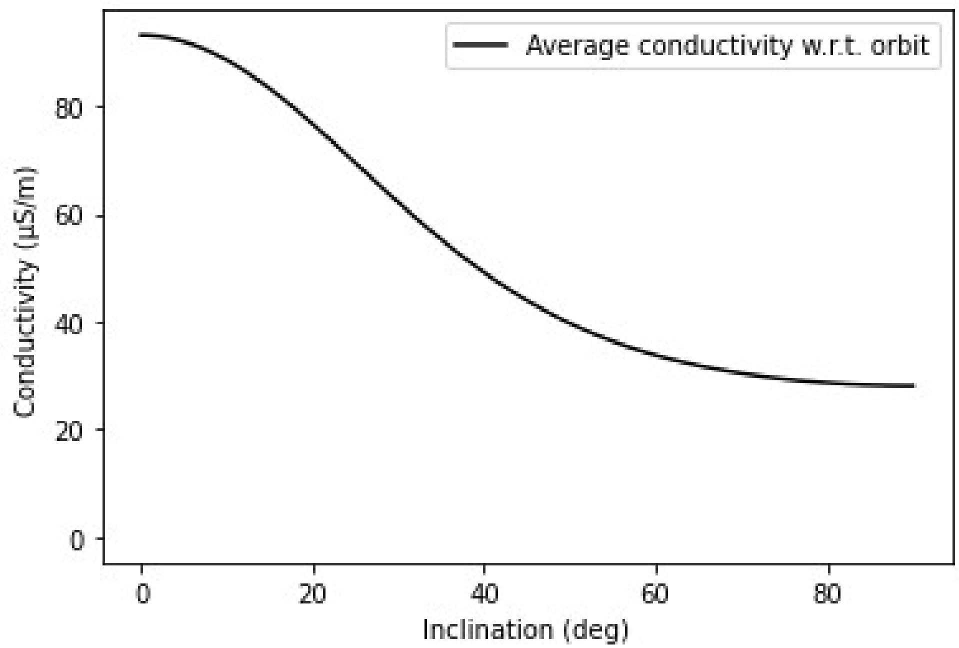


E-field (kV/m)



Plasma conductivity

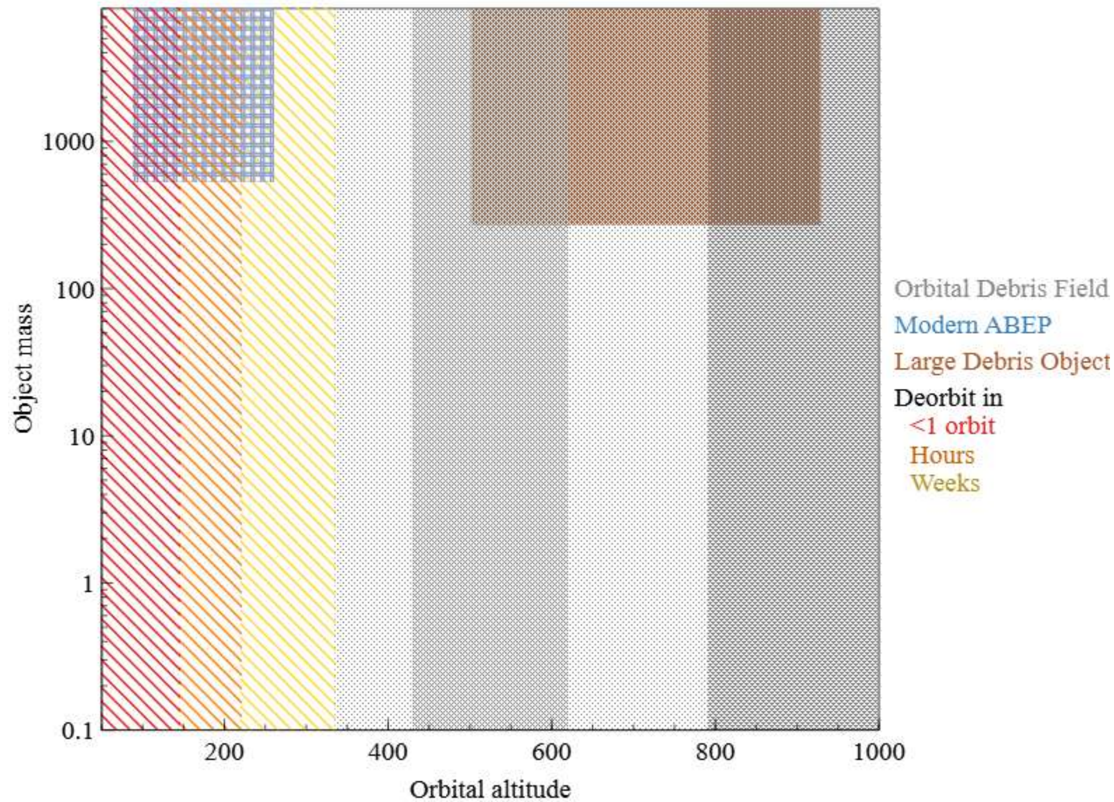




Pfaff, R. F., The Near-Earth Plasma Environment, 2012

Performance

- Similar thrust-to-mass
- Similar thrust-to-power
- Higher orbits
- Wider size range



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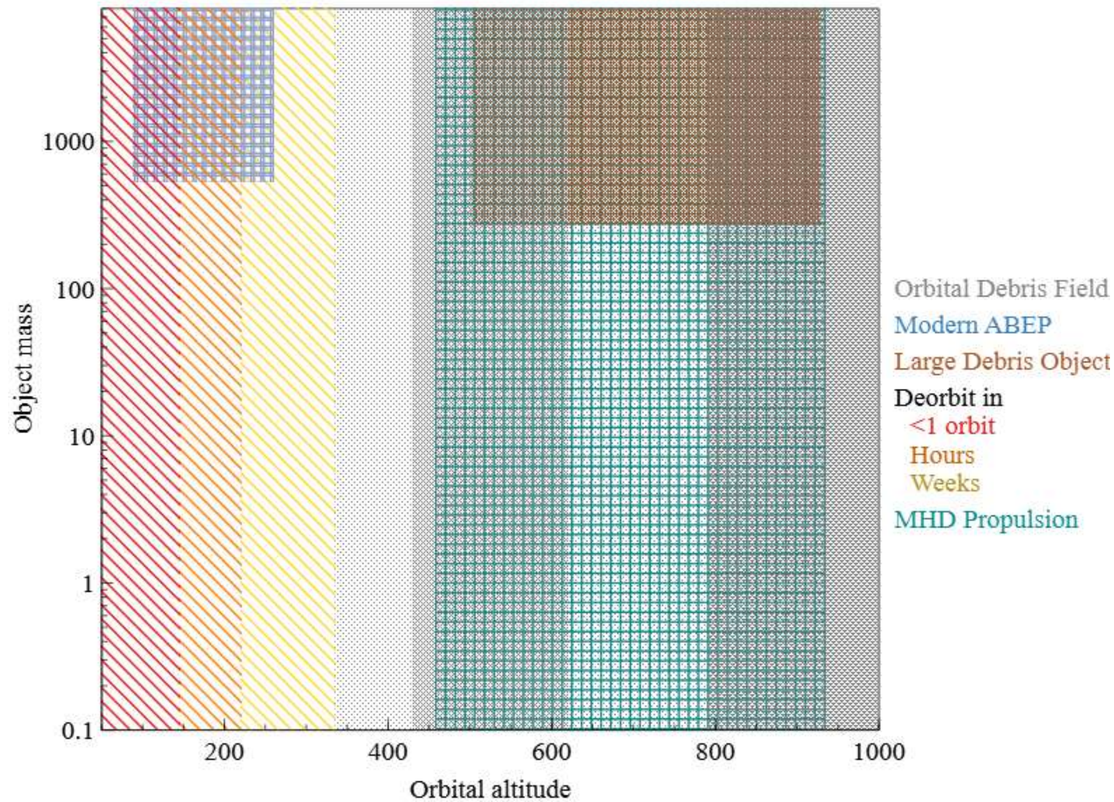
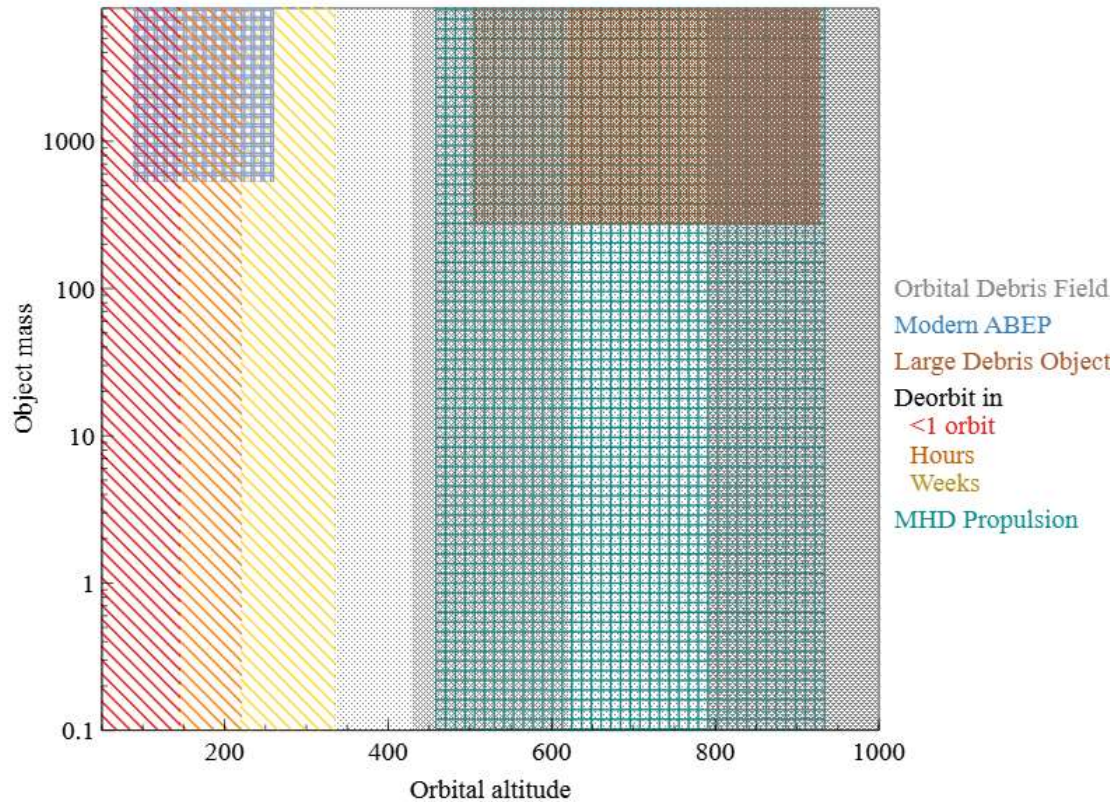


Performance

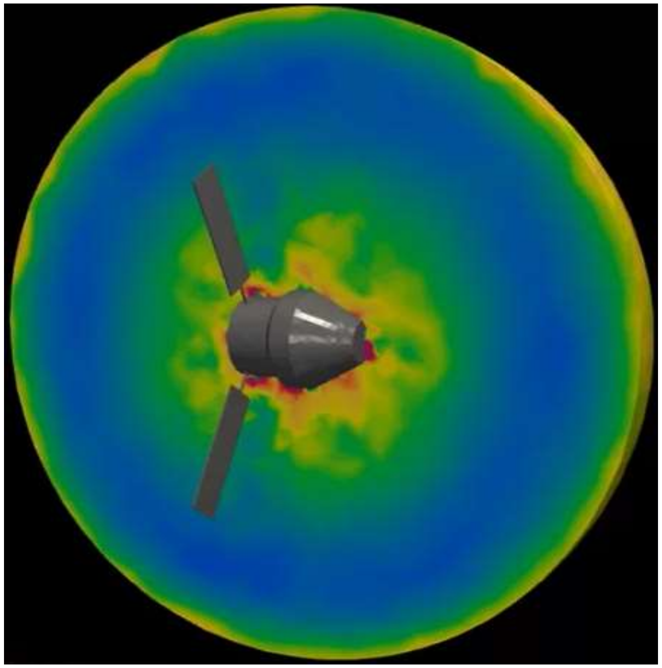
- Similar thrust-to-mass
- Similar thrust-to-power
- Higher orbits
- Wider size range

Similar performance,
More widely applicable!



Next steps

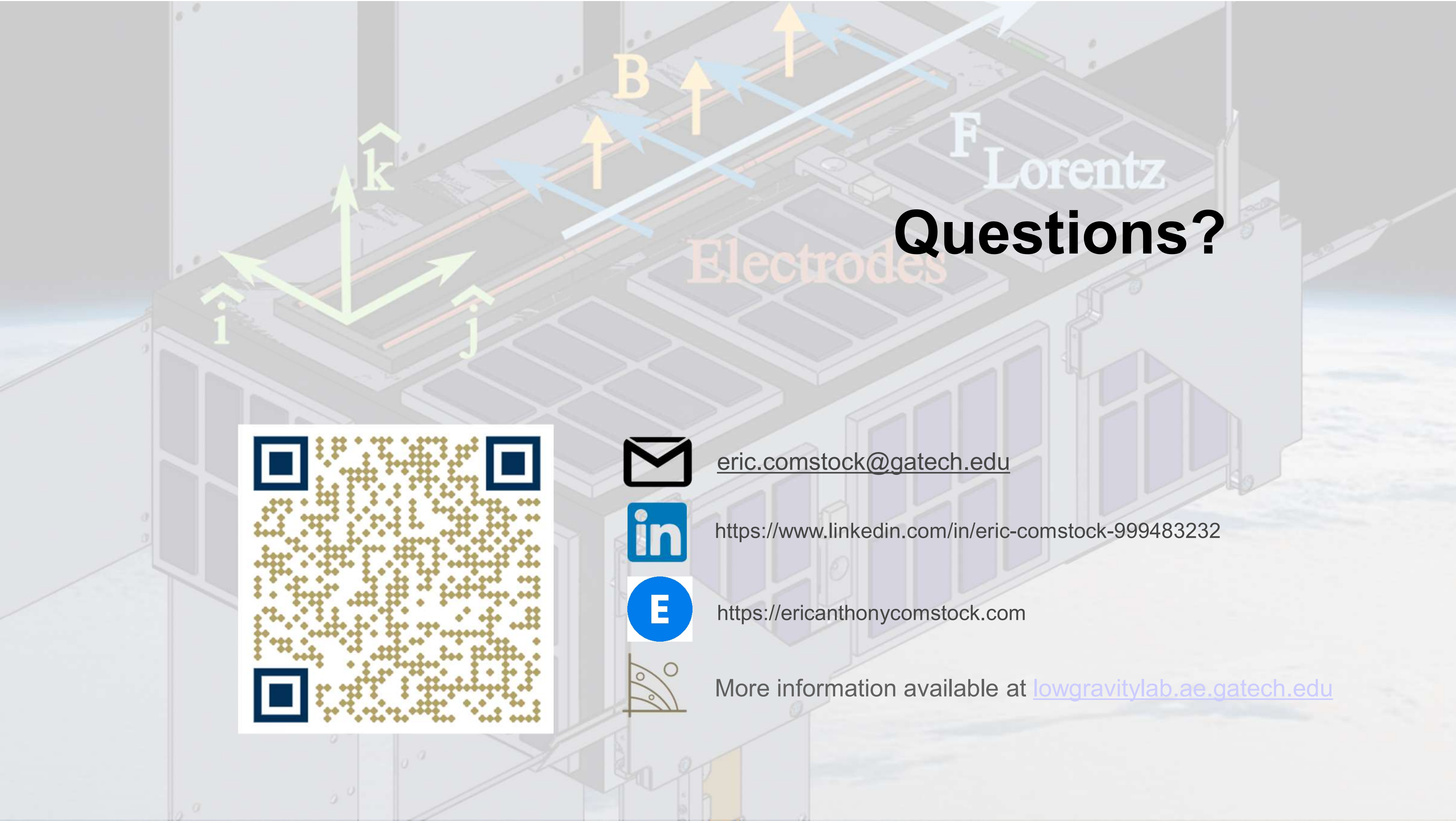
- Better quantify sources of drag
  - Higher-fidelity simulations
    - Full 6D Vlasov
    - Particle-in-cell
- Understand effects of Debye screening
  - Much more relevant at large device sizes
- Other applications
  - Station-keeping
  - Inclination changes



Ansys Blog. EMA3D Charge and Its Particle-in-Cell Solver www.ansys.com/blog/ema3d-charge-particle-in-cell-solver (2022)

Conclusion

- Space debris is a prominent challenge, especially in LEO
- Conductive MHD is effective in LEO for both small and large satellites
  - Passive vs. Active modes
  - Efficiency dependent on latitude due to plasma density variations
- MHD propulsion has few of the downsides of traditional ABEP
  - No bulky ion collectors
  - Low-volume
  - Favorable failure mode – passive drag



Questions?

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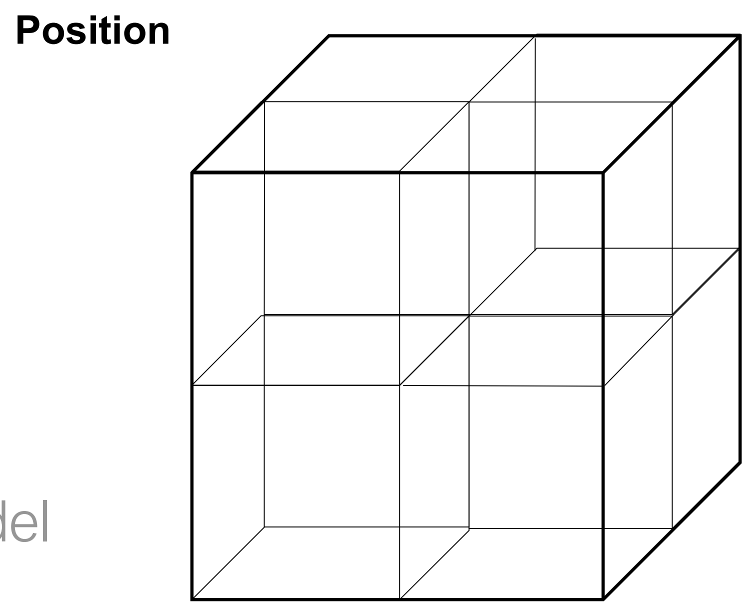
Ohmic analysis

- A simple simulation scheme assuming a 3D continuous model
  - Lorentz Force: $f = J \times B$
  - Ohm's law: $\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \frac{J}{\sigma}$

Active Passive

- Pros
  - Low computational cost
- Cons
  - Less physical modelling
    - E & B fields
    - Plasma conductivity
- Verdict: Requires verification by better model



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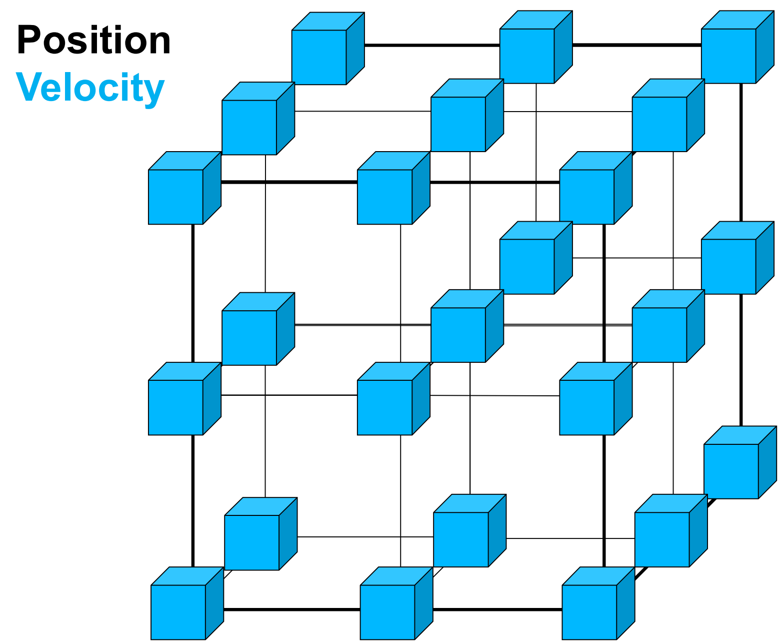
Full 6D Vlasov Simulation

$$\frac{\partial f}{\partial t} + \frac{p}{m} \cdot \nabla_x f + q\left(E + \frac{p}{m} \times B\right) \cdot \nabla_p f = 0$$

- Fully-kinetic plasma simulation
  - Collisionless flow
  - Velocity distribution tracking
- Pros
  - More accurate
  - Better physical modelling
- Cons
  - 6 dimensions
  - Extremely high computational cost
- Verdict: Computational cost prohibitive



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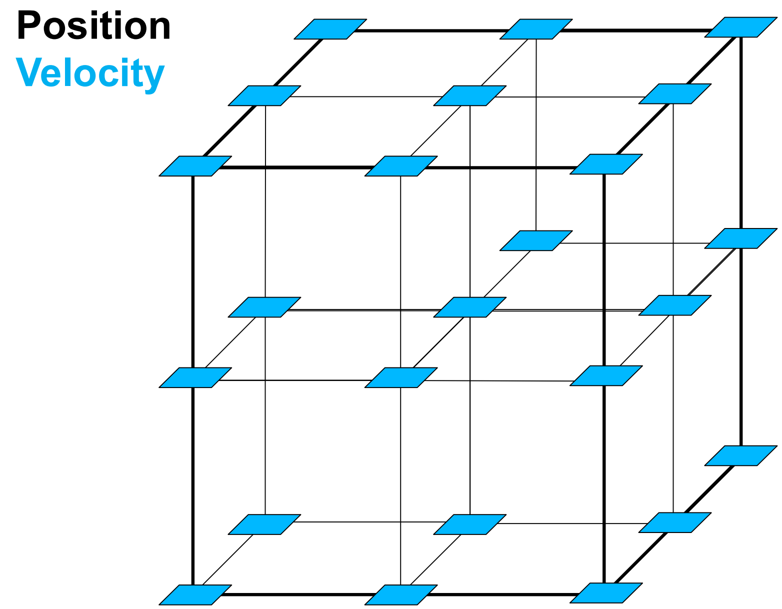
Simplified 5D Vlasov Simulation

- Simplify based on the problem
  - Magnetic forces cannot act out-of-plane
  - Out-of-plane velocities not needed
- Pros
  - Lower computational cost
- Cons
  - Still 5 dimensional
  - Potentially less accurate
- Verdict: Used for verifying Ohmic analysis



Examples

	Vehicle mass	$m_{MHD, a}$	$P_{MHD, a}$	$TSPC_a$	$I_{sp, a}$	$m_{MHD, p}$	$I_{sp, p}$
Units	kg	kg	W	W/mN	km/s	kg	km/s
Landsat 9	1512	123.3	430	130.8	4.206	51.10	10.148
TROPICS	3.9	0.232	1.5	93.57	4.360	0.04553	22.231
Zenit-2 ADR	9000	395.5	2550	198.9	10.657	395.5	10.657

- Use cases
  - Small vs. large
  - Inclined vs. equatorial
- Passive vs Active
  - Satellite lifetime