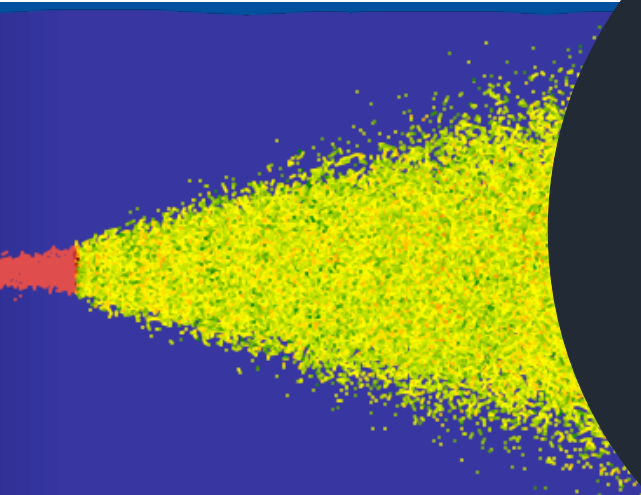




University of Stuttgart
Collaborative Research Center 1667 ATLAS



10th International Symposium on Negative Ions,
Beams and Sources - NIBS'26

PIC Simulation of Negative Ion Beamline for VLEO application

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Traditional LEO

450 km

Improved satellite communications

Rapid and safe disposal

VLEO

Aerodynamic attitude and orbit control

Reduced launch costs

Improved Earth and atmospheric science opportunities

Improved optical payload performance

Motivation

Satellites in VLEO Conditions

- Satellites in Very Low Earth Orbits (VLEO), e.g. GOCE experience atmospheric drag through the residual atmosphere
 - Primarily atomic oxygen (AO) in highly rarefied and reactive flow with high kinetic energies
 - Impact on surface → Degradation of materials
 - Atmospheric drag → Rapid deterioration of orbit
- Gaining a better understanding of the impact of AO on satellite surface materials
- Setup of an Atomic Oxygen Ground Testing Facility

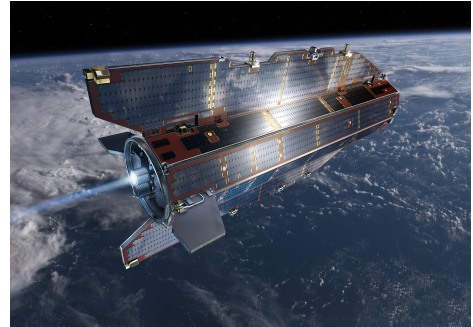
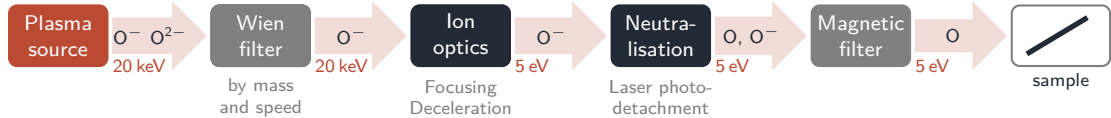


Figure: Satellite GOCE¹ operating in VLEO

¹https://www.esa.int/Applications/Observing_the_Earth/FutureEO/GOCE/Introducing_GOCE

Motivation: The Negative Ion Beamline

Bring VLEO Conditions into the Lab

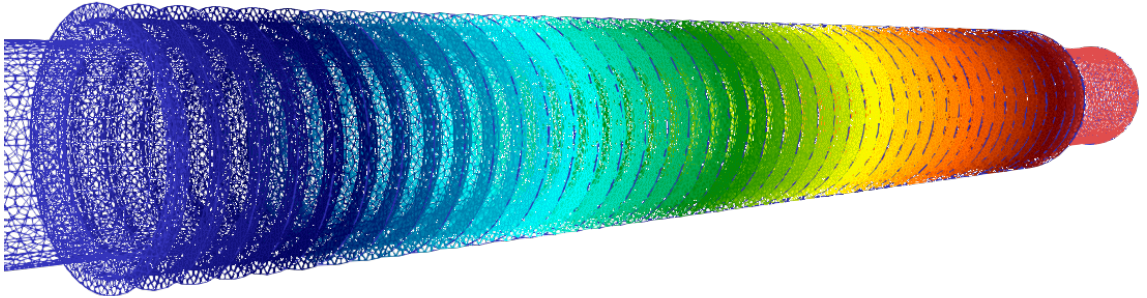


From O^- at 20 keV to O at 5 eV

- Static electric field with linearly decreasing potential along the flight path
- Distance of particles from applied cylindrical potential ensures homogenous electric field for all ions
- Realization of 5 eV energy by two grids at end of deceleration stage
- neutralization by laser photodetachment

Setup: Deceleration Unit

Realistic Simulation of Ion Optics

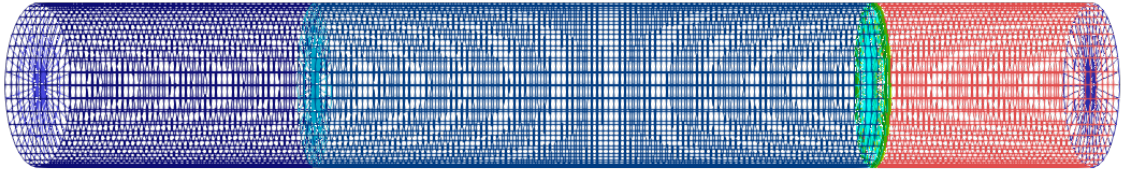


First draft: Problems

- Series of > 50 consecutive interconnected cylinders with stepwise decreasing electrical potential
- Complex geometry, e.g. curved surfaces, narrow gaps, ...
- PIC simulation on hexahedral meshes computationally expensive, direct solver not converging

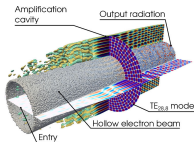
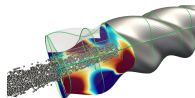
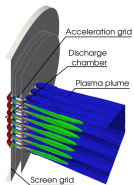
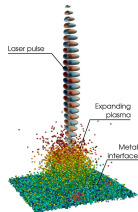
Setup: Deceleration Unit

Realistic Simulation of Ion Optics

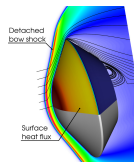


Problems

- Simplification of geometry with linear potential in resistive glass tube
 - PIC simulation on hexahedral meshes computationally expensive
- Newly implemented: unstructured tetrahedral meshes with Plasma Kinetic Code PICLas

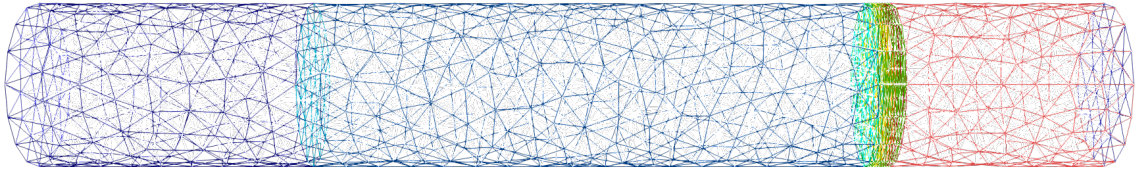


boltzplatz
numerical plasma dynamics



Setup: Deceleration Unit

Realistic Simulation of Ion Optics

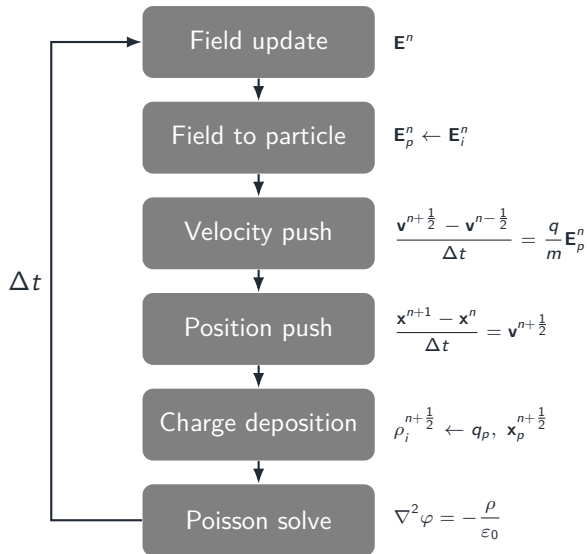


Simulations with Tetrahedral Meshes

- Same geometry with linear potential
- No splitting to hexahedral mesh necessary, less computationally expensive
- Energy conservation in the $dt \rightarrow 0$ limit with continuous galerkin solver

Theory: Leapfrog scheme

Time Discretization



Theory: Continuous Galerkin with p-Adaption

Field Discretization

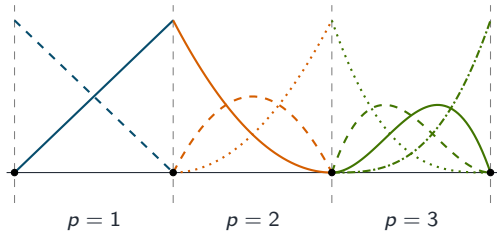
Model problem (Poisson equation)

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon_0} \text{ in } \Omega, \quad \begin{cases} \varphi = \varphi^D, & x \in \partial\Omega^D \\ \frac{\partial \varphi}{\partial n} = n \cdot E = E^N, & x \in \partial\Omega^N \end{cases}$$

$$\int_{\Omega} \nabla \varphi \cdot \nabla \Phi \, dx = \int_{\Omega} \frac{\rho}{\varepsilon_0} \Phi \, dx - \int_{\partial\Omega^N} E^N \Phi \, dx$$

p-Adaptation: the polynomial order p is chosen locally per element:

- Increase p where the gradient of φ or charge density is high
- Keep p low where not needed



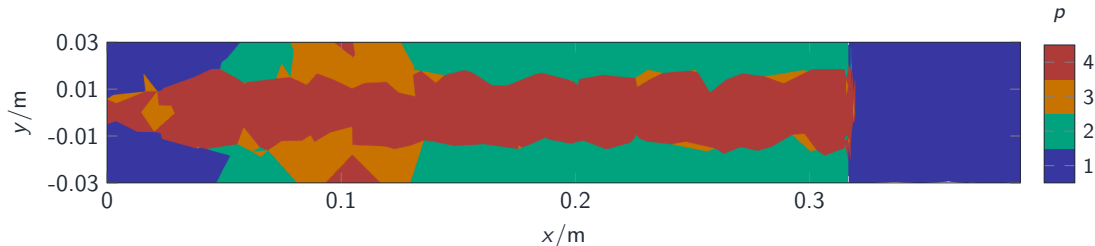
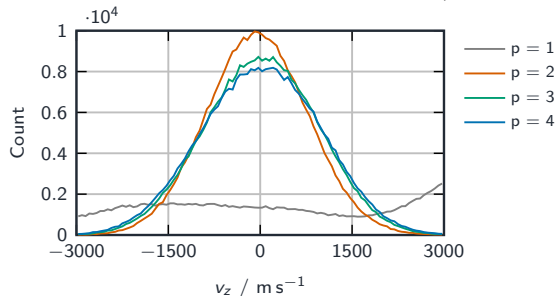
Bernstein–Bézier basis functions per element; shared endpoint values at interfaces enforce continuity across the p -adapted interfaces.

Results: $p = 1, 2, 3, 4$

Realistic Simulation of Ion Optics

Simulations for $p = 1, 2, 3, 4$

- Sampling at plane perpendicular to beam direction
- Runtimes 24min, 2h, 5h, 15h for $p = 1, 2, 3, 4$

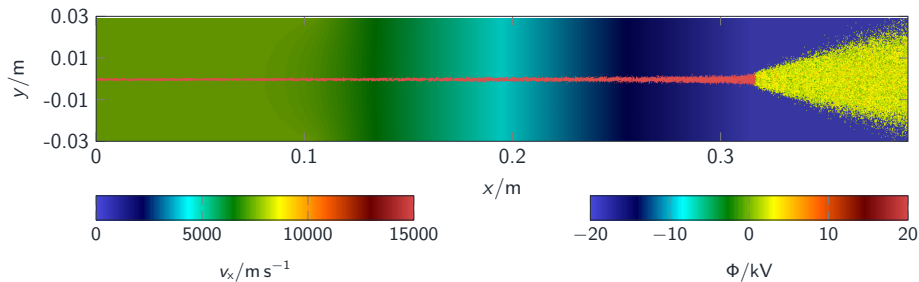
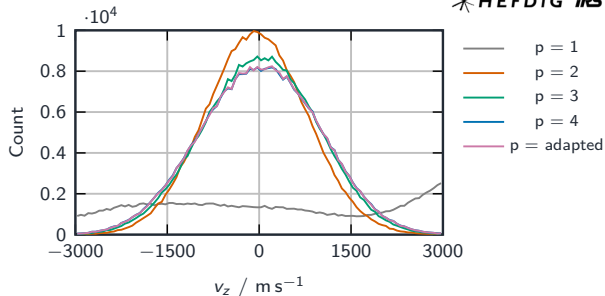


Results: $p = \text{adapted}$

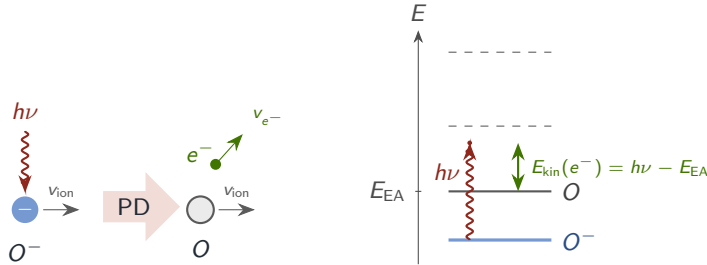
Realistic simulation of Ion Optics

Simulations for $p = \text{adapted}$

- Correct representation of effects (VLEO velocities)
- Speedup of runtime to about 5 h, 33 % compared to $p = 4$



Neutralisation: Process of laser photodetachment



(a) Reaction: $O^- + h\nu \rightarrow O + e^-$

(b) Energy diagram

Process on a particle-level view (a) and corresponding energy-level diagram (b)

- photon energy $h\nu$ must exceed electron affinity E_{EA} to realize process
- excess energy above threshold converted into kinetic energy E_{kin} of the freed electron
- photon energy must remain below threshold for detachment into excited neutral states
→ neutral beam produced exclusively in ground state

Estimation of laser-ion beam interaction region

- laser beam, incident perpendicularly to ion beam, as a band of width $2w$ centered on the z -axis
- corresponding rectangular (flat-top) laser flux profile $\Phi(y)$
- $\eta_{\text{rect}}(y) = 1 - \exp \left[-\frac{\sigma_{\text{PD}}}{v_{\text{ion}}} \frac{P}{2 w E_{\text{ph}}} \right]$ for $|y| < w$, zero outside

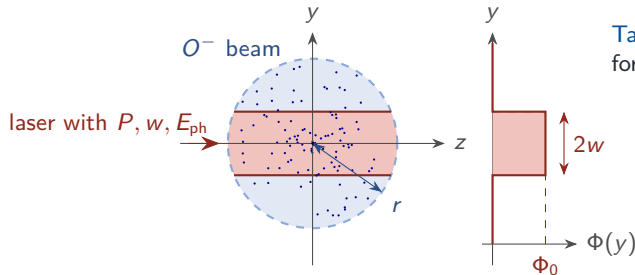
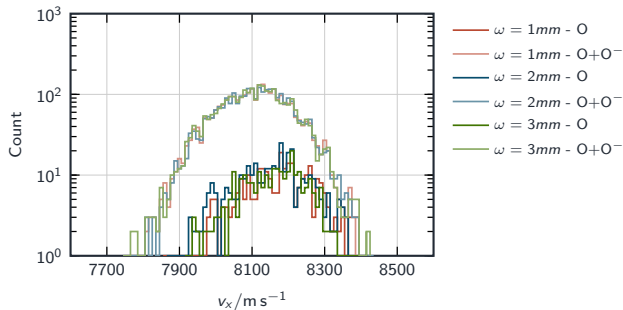
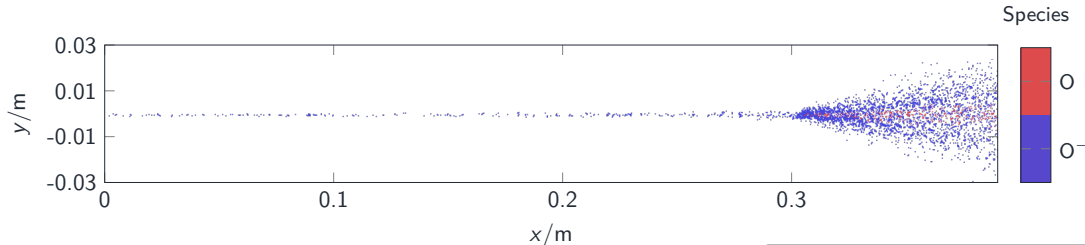


Table: Estimated photodetachment efficiency η_{rect} for different laser beamwaists w

beamwidth $2w$	η_{rect}
1 mm	30.4 %
2 mm	18.3 %
3 mm	11.4 %
5 mm	7.0 %
10 mm	3.6 %

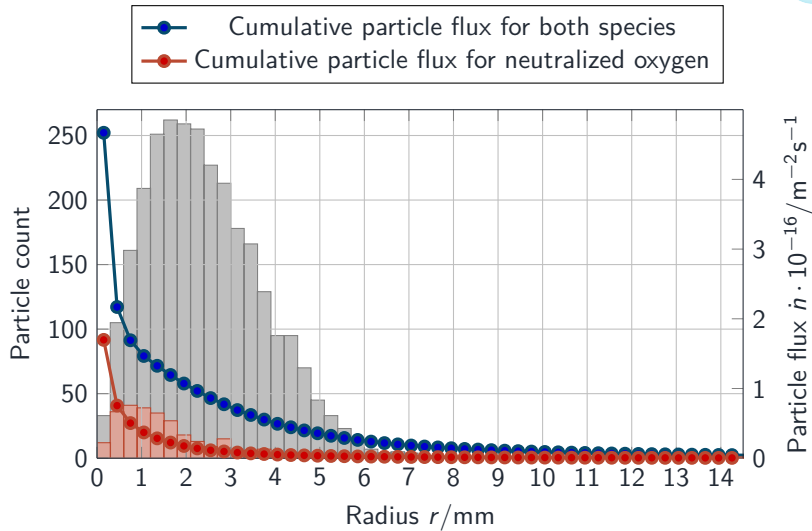
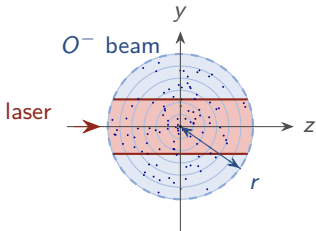
Simulation of Photodetachment



Realization in PICLas

- species swap (O^- to O) in interaction region with probability $\eta_{rect}(y)$
- neutralization of core of ion beam with velocity distributions in flight direction v_x

Neutralisation: Estimation of particle flux



Summary and Outlook

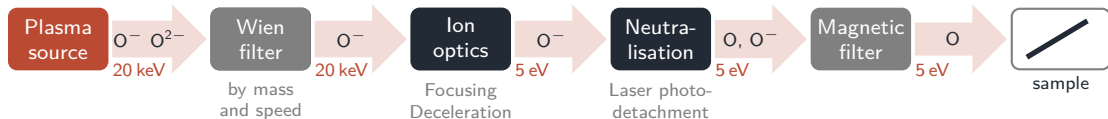
What's Next?

Summary

- Study of negative ion beamline, especially deceleration unit with neutralisation
- Efficient simulation of ion optics and laser photodetachment using tetrahedral meshes, continuous galerkin and leapfrog solver in PICLas
- Further optimization of efficiency with p-adaption

Outlook

- Comparison of experimental data with simulation results
- Further optimization of the negative ion beamline and its components
- Investigation of space charge effects with electrons after neutralisation





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Thank You!



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