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ASTE 546, Computational Plasma Dynamics

Units: 3
Term: Spring 2024
Day & Time: Thursdays: 1:00 - 3:50 PM
Location: SOS B41 or online via Zoom

Instructors: Dr. Lubos Brieda

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Office Hours: Thursday 10:30-11:30 + by appointment
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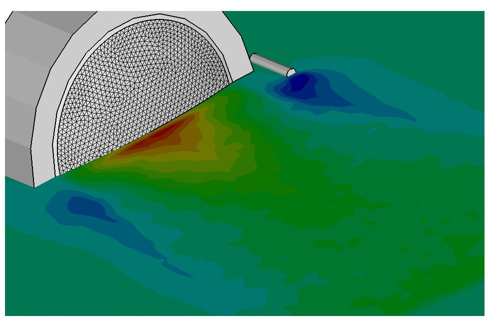
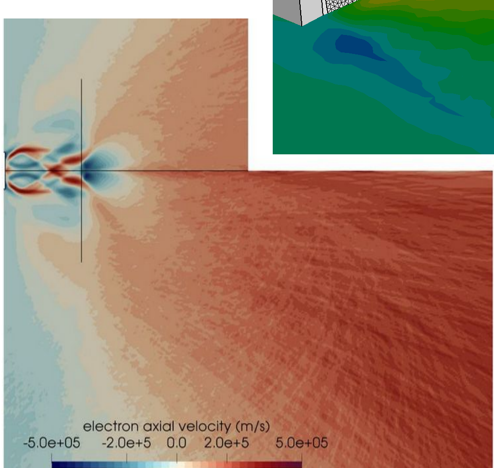
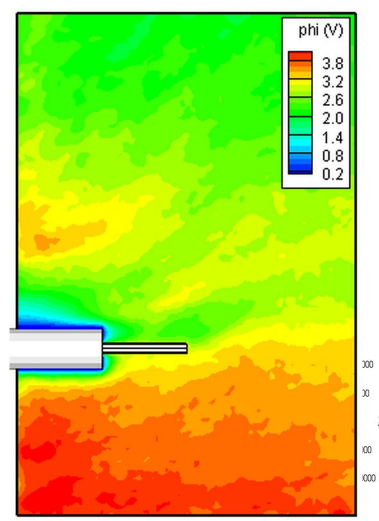
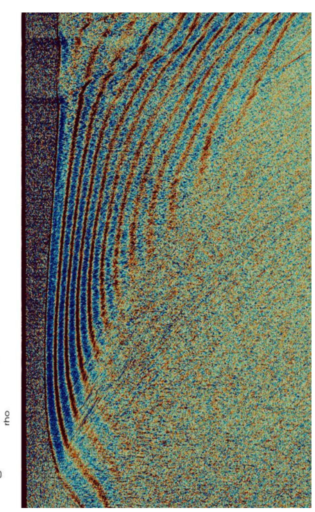
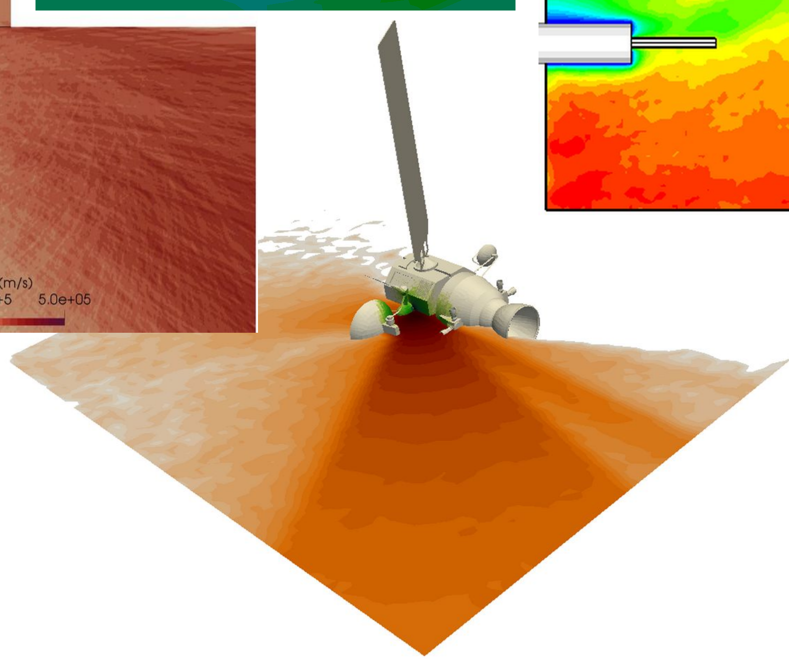
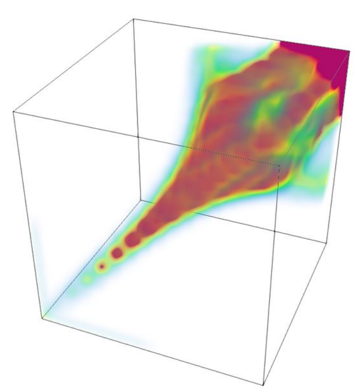
Teaching Assistant: TBD
Office: TBD
Office Hours: TBD
Contact Info: TBD

IT Help: N/A
Hours of Service: N/A
Contact Info: N/A



Course Description
The space environment is made up of ionized gas, or plasma. The interaction between this charged environment and the spacecraft can lead to adverse effects such as charging, arcing, sputtering, and contamination build up. Plasma is also utilized in electric propulsion (EP) spacecraft thrusters. These device operate by ionizing neutral propellant and accelerating it using some combination of electric and magnetic fields. Plasmas are of great importance to non-space applications. Multiple companies are currently investigating the use of high density plasma for generation of electricity in fusion reactors. Plasma etching and coating are common industrial processing techniques. Atmospheric cold plasmas are even investigated for the use in the medical setting for wound healing, sterilization, and selective cancer cell deactivation.

My objective for this course is to introduce you to the complex world of numerical plasma simulation techniques. Plasmas can be analyzed using particle or fluid approaches. These give us the Particle in Cell (PIC) and MagnetoHydroDynamics (MHD) methods. The magnetic field can be fixed or time varying due to induced currents, leading to the ElectroStatic (ES) or ElectroMagnetic (EM) formulation. We will cover the simulation techniques applicable to all these cases. We will also introduce methods for simulating the rarefied neutral environment with the Direct Simulation Monte Carlo (DSMC) method, discuss strategies for simulating interactions with complex geometries, review electric propulsion governing equations, and cover parallelization approaches with MPI and CUDA. I also plan a brief “field trip” to the plasma lab for a quick demo of glow discharge and to learn about vacuum chambers and plasma diagnostics.

Note that this class will likely take place online, due to shortage of compatible classrooms. If that is the case, I will offer in-person office hours, and we will also schedule one (optional) “field trip” to our vacuum chamber lab.

About the Instructor
My name is Lubos Brieda and I am a part-time adjunct lecturer at USC. I have been teaching at USC since Spring 2020 when I created a new course on scientific computing (ASTE-404). I am also a co-advisor to the ASPEN student club which is currently building a solid-fuel plasma thruster for Cubesat applications.

My involvement with plasma simulations dates to my time as a grad student at Virginia Tech under Prof. Wang, who now teaches here at ASTE. I next worked for 3 years at Air Force Research Laboratory at Edwards, AFB, where I developed numerical models for plasma thrusters. I then left for a PhD at the George Washington University under Prof. Keidar, where I focused on multiscale modeling of plasma thrusters. I also worked at NASA Goddard as a contamination control engineer. This gave me a lot of exposure to spacecraft vacuum testing. For the past 12+ years, I have been working as an independent consultant through my company Particle in Cell Consulting LLC, helping various aerospace firms and government agencies develop simulation codes for analyzing spacecraft environment interactions. Since 2014 I have also been teaching online plasma simulation courses, topics of which are covered in my 2019 CRC Press book. The pictures on the cover page are results from some of my past papers or from codes we will develop in this class.

Learning Objectives and Outcomes
At the end of the course, you should be able to do the following:
- Write from scratch an electrostatic particle in cell (ES-PIC) simulation code
- Know how to include particle collisions
- Be able to numerically integrate fluid MHD equations
- Develop a simple parallel code utilizing MPI and CUDA constructs
- Have a rough understanding of steps needed to simulate plasma interactions with complex objects

Prerequisite(s):
The official requirement for this course is ASTE 505a (Plasma Dynamics) or EE 507A (EM Theory). I am willing to waive these requirements if you demonstrate basic background in plasmas and fluid dynamics, which can be met by reviewing online resources on conservation laws, Maxwell’s equations, and electromagnetics.

Co-Requisite(s): N/A
Concurrent Enrollment: N/A

Recommended Preparation:

Given this is a computational class, you should have familiarity with computer programming. While we will have a crash course on programming, ASTE-404 or a class covering similar topics would be of great help. Otherwise, you should review books or online resource on C/C++, dynamic memory allocation, pointers, and custom data objects. My CRC book discusses many of the C++ concepts that will be used in the class.

Technological Proficiency and Hardware/Software Required

We will be mainly using C++ with some prototyping in Python, but will also review Fortran and C as both are frequently encountered in legacy plasma codes. You do not need any specific hardware, as we will utilize Google Colab to demonstrate parallel and GPU computing, and will also try to use the USC HPC resources. I use Linux so most of my examples will be based on gcc with Eclipse, but you are free to use any operating system of choice. Make sure to install a C/C++ compiler, such as MS Visual Studio before class 1.

Required Readings and Supplementary Materials

You do not need to purchase any of these, as the course slides posted on Blackboard/D2L will cover sufficient information. However, the material is based on the following three texts:

1. Brieda, L, "Plasma Simulations by Example", CRC Press 2019
2. Birdsal, C.K., and Langdon, A. B., "Plasma Physics via Computer Simulations", IoP, 1995
3. Bird, G.A., "Molecular Gas Dynamics and the Direct Simulation of Gas Flows", Oxford 1994

Other books I have found useful include:

1. Stroustrup, B., "A Tour of C++", Addison-Wesley, 2018
2. Jackson, J.D., "Classical Electrodynamics", Wiley, 1998
3. Chen, F.F., "Introduction to Plasma Physics and Controlled Fusion", Plenum Press, 1984
4. Tajima, T., "Computational Plasma Physics", Westview ABP, 2004
5. Sanders, J. and Kandrot, E., "CUDA by Example", Addison-Wesley, 2011

Description and Assessment of Assignments

There will be weakly programming assignments. Some of these will ask you to take an existing code and make modifications. Others will involve writing code from scratch. You will also be asked to do a short in class presentation on a journal or a conference paper that focuses on plasma simulations. You are free to select any paper of interest. The presentation should briefly summarize what numerical technique the authors used, and identify any shortcomings that you encountered. My goal with these exercises is to help you learn more about topics that are currently being investigated, but to also realize that published work may not be completely without errors. We will also have short take home quizzes and a final project. The quizzes are mainly multiple choice or short answer checks of your understanding. The project is described below.

Grading Breakdown

Assignment	Points	% of Grade
Homework		40%
Quizzes		20%
Literature Review		10%
Final Project		30%
TOTAL		

Final Project

The objective of the final project is to work in small groups of 2 or 3 students to develop a plasma simulation code and use it to run some studies that could eventually lead to a conference paper. All members are expected to contribute equally, with tasks divided among code development, testing, and documentation. You are free to pick the topic but I can also provide some if needed. This is intended to be a collaborative exercise in which you get to work closely with your TA and me, the instructor. The deliverables include the code, preliminary results, user's guide outlining the numerical model, input files, and a report similar to a 10-15 page conference paper.

Project Timeline:

- Week 3: Identify team members and project topics
- Week 6: Proposal due (team member, topics and milestone)
- Week 8: Mid-term report due (code layout, test cases, preliminary results, draft documentation)
- Finals: Project presentation (open to all faculty and students), report due.

Sample project: The ESA ExoMars Rover mission uses an ion mass spectrometer to investigate the Martian soil composition. The spectrometer uses a laser beam to desorb ions off a soil sample held at Mars atmospheric pressure. Above the sample is a long "straw" leading to a vacuum cavity containing the mass spectrometer. A sliding valve opens during the laser operation. The resulting pressure gradient accelerates the ambient gas molecules into the vacuum cavity, with ions becoming entrained in the gas flow due to collisional coupling. By coupling PIC with DSMC, you should be able to investigate the transport of ions through the collector tube to the spectrometer.

Grading breakdown of the course project:

- Proposal and mid-term updates: 20%
- Code structure: 10%
- Documentation (inline + user’s guide), examples: 20%
- Ability to generate some results: 10%
- Validation & Verification: 20%
- Presentation and final report: 20%

Grading Scale

Course final grades will be determined using the following scale, with fractional grades rounded to nearest integer.

A	93-100
A-	90-92
B+	87-89
B	83-86
B-	80-82
C+	77-79
C	73-76
C-	70-72
D+	67-69
D	63-66
D-	60-62
F	59 and below

Assignment Submission Policy

Assignments need to be submitted online to Blackboard or the D2L platform (which one is yet TBD), and need to consist of: a) a written report in a .pdf, .docx, or .odt format describing what you did and what results you got, along with plots and code snippets where appropriate, and b) the complete source code uploaded in a .zip file (if consisting of multiple files). Homework is generally due at the start of the following class, but the deadline is not going to be strongly enforced. I would rather for you to spend some extra time and learn the specific tasks, than worry about meeting an arbitrary deadline. Generally, you will not be penalized if the homework is less than a week late. Homework submitted more than a week past the deadline will incur a 50% penalty unless I know you have been actively working on it and making progress towards completion.

You may collaborate on the homework assignments but the final work needs to be your own. In other words, don't just copy other student's code or plots!

Homework will be graded as follows:

- 70% of the grade of each part is based on effort. You get full credit for a reasonable attempt at a solution.
- 30% is based on correctness. In other words, does the code do what is it supposed to?

Both of these rubrics receive partial credit. For instance, let's say a homework consists of 3 equally difficult parts, but you managed to only get to the first 2. You get the code for part 1 working perfectly, but there is a small bug in the solution of part 2. So, you would receive 100% for part 1, 70% + 25% for part 2, and 0% for part 3, for a total of 1*33.3% + 0.95*33.3% + 0*33.3% = 65%. My goal is to have the homework graded with a week but this does not always happen.

Additional Policies

While participation is not graded, I strongly suggest you to actively participate. After all, were are here to teach you something new. I have been writing plasma codes for over a decade so some things that are obvious to me may not be so obvious to you. Do not hesitate to reach out to me or the TA with any questions that come up.

(Tentative) Course Schedule:

	Topics/Daily Activities	Homework
Week 1	Introduction to governing equations, such as mass/momentum conservation equations, Maxwell's equations, Poisson's equation. Crash course on programming: installing IDE, building a simple program.	Derivations / analytical solutions
Week 2	Intro to Electrostatic Particle in Cell (ES-PIC) Method. Loading particles in a box/ quiet start. Scatter / Gather. Poisson Solver. Paraview.	Non-neutral box
Week 3	Visit to USC plasma dynamics lab to learn about vacuum chambers and probes. Continuation of topics from Week 2.	TBD
Week 4	Loading from velocity distribution functions. Mesh-averaged density and temperature. 1D and 2D codes.	1D Plasma Sheath simulation
Week 5	Review of homework / additional discussion on 1D sheath simulation. Introductions to two stream instability.	Two stream instability
Week 6	Review of 2 stream instability code. Introduction to Landau damping. 2D/Axisymmetric models.	Laundau damping
Week 7	Hybrid ES-PIC. Sugarcubing and particle removal. Flow of ions past a charged sphere.	Flow past a charged sphere.
Week 8	Surface neutralization. Collisions with MCC and DSCM.	Glow discharge
Week 9	Intro to EM. Staggered grid. Full particle EM-PIC to model wave propagation.	Wave propagation
Week 10	Continuation of EM-PIC. Simplifications / Darwin Method.	Plasma heating
Week 11	Fluid approaches / single, multi-species MHD model. Integration techniques, Crank Nicolson.	1D MHD simulation
Week 12	Meshing strategies (AMR / unstructured grid), particle-surface checks, unstructured tree codes, ion and Hall thrusters	TBD
Week 13	Vlasov solvers (possibly a guest lecture)	Vlasov two stream instability
Week 14	Parallelization strategies for clusters (MPI) and multicore architectures.	MPI sheath/ two stream instability
Week 15	Parallelization strategies for graphics cards (CUDA)	CUDA two stream instability
FINAL	**Final project presentations**	

Statement on Academic Conduct and Support Systems

Academic Conduct:

Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in SCampus in Part B, Section 11, "Behavior Violating University Standards" policy.usc.edu/scampus-part-b. Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on scientific misconduct, policy.usc.edu/scientific-misconduct.

Support Systems:

Student Health Counseling Services - (213) 740-7711 – 24/7 on call
engemannshc.usc.edu/counseling
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

National Suicide Prevention Lifeline - 1 (800) 273-8255 – 24/7 on call
suicidepreventionlifeline.org
Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-4900 – 24/7 on call
engemannshc.usc.edu/rsvp
Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity and Diversity (OED) | Title IX - (213) 740-5086
equity.usc.edu, titleix.usc.edu
Information about how to get help or help a survivor of harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants. The university prohibits discrimination or harassment based on the following protected characteristics: race, color, national origin, ancestry, religion, sex, gender, gender identity, gender expression, sexual orientation, age, physical disability, medical condition, mental disability, marital status, pregnancy, veteran status, genetic information, and any other characteristic which may be specified in applicable laws and governmental regulations.

Bias Assessment Response and Support - (213) 740-2421
studentaffairs.usc.edu/bias-assessment-response-support
Avenue to report incidents of bias, hate crimes, and microaggressions for appropriate investigation and response.

The Office of Disability Services and Programs - (213) 740-0776
dsp.usc.edu
Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

USC Support and Advocacy - (213) 821-4710
studentaffairs.usc.edu/ssa
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.
Diversity at USC - (213) 740-2101
diversity.usc.edu
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
dps.usc.edu, emergency.usc.edu
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-120 – 24/7 on call
dps.usc.edu
Non-emergency assistance or information.