US Particle Accelerator School
Self-Consistent Simulation of Beam and Plasma Systems

Location:
Colorado State University
Fort Collins, CO
13-17 June, 2016

Instructors:
Lecturers:

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Consultant on Warp Code:

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Course Web Site:
Contains course information including overviews, a lecture schedule, a full outline, lecture notes (pdf), and problems sets/exams (pdf) posted during the course. See:
https://people.nscl.msu.edu/~lund/uspas/scs_2016/

Prerequisites:

Required:

Undergraduate Electricity and Magnetism
Undergraduate Classical Mechanics
with Special Relativity
Undergraduate Accelerator Physics

Experience with Elementary Numerical Methods
(Finite Differencing, Quadrature,
Solution of ODEs, ...)
Basic Knowledge of the Python Programming Language*

*Requirement can be met by reading sections 1.1 to 1.4 of the Python Scientific Lecture Notes : https://scipy-lectures.github.io/

Recommended:

Familiarity with Plasma and Fluid Physics
Familiarity with Linux and/or OSX Operating Systems
Familiarity with some Compiled Programming Language
(Fortran, C, C++, …)

Overview:

"Self-Consistent Simulation of Beam and Plasma Systems" is intended to be a comprehensive introduction to numerical modeling techniques used to analyze beam and plasma systems in the context of accelerator technology. Beam intensities are considered to be high enough that self-fields cannot be neglected and collective effects can be important. This contrasts the situation in "conventional" accelerator physics where space-charge is sufficiently weak so that the particles can be modeled as a collection of single-particle orbits in applied fields with mutual interactions neglected. In addition, in "plasma accelerators," particles are accelerated in an ionized gas using resonant plasma waves which are collective by nature and call for self-consistent modeling. Self-consistent simulation methodologies are presented in a top-down hierarchy of particle, distribution, and moment methods. Emphasis is given to Vlasov model descriptions of evolution and motivating the particle-in-cell (PIC) method commonly employed to numerically evolve the system from an initial state within a Vlasov model. Needed tools to formulate a wide variety of methods are systematically developed from basic concepts borrowing methodologies from plasma and accelerator physics. Both elementary and more advanced methods are surveyed. Although the course is not on any specific code, we will employ the Warp particle-in-cell code for many illustrations and exercises and the course can also serve as an introduction to Warp. The Warp code is a highly developed open-source PIC code with a large hierarchy of models integrated under a common Python-based interpreter making it ideal for the course. More information on the Warp code can be found at:

http://warp.lbl.gov/

Warp will be set up on a limited number of shared Linux workstations in the class provided by the school for use in simulation demonstrations and exercises. Students are also welcome to build Warp on their own laptops (Mac OSX and Linux supported). Issues associated with numerical resolution and convergence are addressed. Practical issues including code organization, diagnostics, and parallel computing are also covered. The course is appropriate for upper level students and researchers in physics and engineering who have adequate background consistent with the prerequisites and recommendations.

Course Objectives:
This course is intended to give the student a broad overview of modeling accelerator systems with strong space charge and beam-plasma (as in plasma accelerator) systems. The level is sufficient to provide a solid foundation for contemporary numerical modeling of accelerator systems where intensities are sufficiently high so that mutual interactions of the particles in the beam/plasma can not be neglected. In such regimes of strong space-charge, the system can be dominated by collective effects, leading to rich wave and stability properties beyond characteristic single-particle oscillations in conventional accelerator systems. Emphasis is given on motivating methods employed in particle-in-cell simulations of beams and plasmas within a Vlasov model. Both linear (linac) and circular (ring) machine architectures, injectors and front-ends, transfer/transport lines, and beam/plasma interactions will be covered. Aspects of comparisons and benchmarking with experiments will also be discussed, but details of laboratory implementations will not be covered.

Students will become familiar with contemporary methods commonly employed to numerically model beams with strong space charge. The course is structured to provide a sound background to those providing modeling support of accelerator systems with high space-charge intensity. Daily problem/exercise sets and the final exam are structured to clarify the lectures and provide valuable examples. The open-source PIC code Warp will be applied for examples in the class. Although the class is not intended as a course on Warp, it can effectively serve as such. A sufficient number of Linux workstations with Warp installed will be setup within the class room for use in class demonstrations and problems sets. Limited support (time permitting) can be given to students wanting to setup Warp on Linux or Mac OSX laptops they may bring. Windows is not supported. The Warp code is ideal for this role since it has a wide variety of dimensional models, electrostatic and electromagnetic field solvers, particle movers, and extensively developed beam diagnostics. Warp is organized around a Python interpreter with numerically intensive routines written in fast compiled code and linked to the interpreter and much infrastructure (diagnostics, setup, …) contained in Python scripts which can be interactively modified. This highly flexible structure make Warp ideal for course instruction.

Examples of intense beams will primarily be taken from the instructors past work in intense beam transport. Methods covered are applicable to a wide range of applications including: machine front-ends and injectors, high event rate colliders for high energy physics, accelerators for nuclear physics, spallation neutron sources, nuclear waste transmutation and accelerator driven systems, material processing, intense beam-driven sources of coherent radiation, and accelerator based inertial fusion energy (Heavy Ion Fusion), plasma-wakefield accelerators, laser-wakefield accelerators, and facilities for high energy density physics. High intensity applications promise to open new applications for extensive accelerator facilities around the world that were originally intended for high energy and nuclear physics. In addition, plasma accelerators constitute a new and promising technology, that can lead to reduced system cost if substantial challenges of precisely manipulating collective effects are met. Self-consistent modeling is an essential part the ongoing effort to advance these technologies and applications.

Course Outline/Schedule:

SML:	Steven Lund Lecture	I:	Introductory
JLV:	Jean-Luc Vay Lecture	A:	Advanced
RL:	Rémi Lehe Lecture	W:	Warp / Application

Lecture times given are estimates

Monday

(SML 0:15) Course Overview
- Expectations
- Organization
- Grading

I01 (SML 0:15) Overview
- Why Numerical Simulation?
- Which Numerical Tools?

I02 (SML 3:00) Classes of Intense Beam Simulations
- Overview
- Particle Methods
- Distribution Methods
- Moment Methods
- Hybrid Methods

W1 (RL 2:00) Python Interpreter
- Overview
- Python Programming
- Numerical Python (Numpy, matplotlib/gist)
- Object-Oriented Programming in Python
- Packages/Forthon

I03 (SML 2:00) Overview of Basic Numerical Methods
- Discretization
- Discrete Numerical Operations
- Time Advance

Tuesday

I04 (SML 3:30) Numerical Methods for Particle and Distribution Methods

Overview
Integration of Equations of Motion: Leapfrog Advance
- Electric Force
- Numerical Stability
- Electric and Magnetic Force: Boris Mover
Electrostatic Field Solution
- Green's Function Approach
- Gridded Solution: Poisson Equation and Boundary Conditions
- Methods of Gridded Field Solution
- Spectral Methods and the FFT
Weighting: Depositing Particles on Field Mesh and
Interpolating Gridded Fields to Particles
- Overview of Approaches
-Approaches: Nearest-Grid-Point, Cloud-in-Cell, Area, Splines
Computational Cycle for Particle-in-Cell Simulations

A1.a (RL 1:30) Electromagnetic PIC
Electromagnetic PIC vs electrostatic PIC
- Domains of validity
- PIC loop
Finite-difference electromagnetic field solvers
- Staggering in time
- Staggering in space
- Conservation equations
Current deposition and continuity equation
- Direct current deposition and continuity equation
- Boris correction
Charge-conserving deposition

W2. (JLV 1:30) Introduction to the Warp Code
Overview
Warp Web Site
Code Structure
Example Simulations

Wednesday
A1-b. (RL 1:30) Electromagnetic waves
Numerical dispersion and Courant limit
- Dispersion and Courant limit in 1D
- Dispersion and Courant limit in 3D
- Spectral solvers and numerical dispersion
Out-going wave boundaries
- Silver-Muller absorbing boundaries
Perfectly Matched Layers

I.05 W (SML 1:45) Diagnostics
Overview
Snapshot Diagnostics
- Phase-Space Projections
- Fields
History Diagnostics
- Centroid

- rms Beam Extents
- rms Phase Space Area (Emittance)

<u>I.06 (SML 2:00) Initial Distributions and Particle Loading</u>

Overview
KV Load and the rms Equivalent Beam
Beam Envelope Matching
Semi-Gaussian Load
PseudoEquilibrium Distributions Based on Continuous Focusing Equilibria
Injection off a Source

<u>W3. (JLV 2:00) Example Warp Simulations</u>

Overview
Quadrupole Transport
Solenoid Transport
Injectors
Acceleration/Pulse Compression
Electron Cloud Effects
Plasma Acceleration

Thursday

<u>I.07 Th (SML 3:00) Numerical Convergence</u>

Overview
Resolution: Advance Step
- Courant Conditions
- Applied Field Structures
- Collective Waves

Resolution: Spatial Grid
- Beam Edge
- Collective Waves

Statistics
Illustrative Examples with the Warp Code
- Weak Space-Charge
- Intermediate Space Charge
- Strong Space Charge
- Strong Space Charge with Instabilities

<u>A2. (JLV 2:00) Mesh Refinement in Field Solvers</u>

Overview
Electrostatic
- Static
- Adaptive
- Application: Diode Simulations

Electromagnetic

<u>A3. (JLV 1:30) Special Topics in Particle/Field Moving</u>

Overview
Alternative Particle Movers
- Runge-Kutta Revisited
- Lorentz-Invariant Leapfrog
- Leapfrog with Damping
- Map Based Particle Moving

Optimal Boosted Lorentz Frame Simulations
- Savings

Friday

I.08 (SML 1:30) Practical Considerations

Overview
Fast Memory
Run Time
Machine Architectures
- Serial
- Parallel

A.4 (JLV 1:00) Introduction to Parallel Computing

Overview
MPI Libraries and Programming Techniques
OpenMP/GPU
Example Simulations

A.5 (RL/JLV 1:00) Simulation Collaborations

Overview
Software Version Control
Hosting Websites: BitBucket / GitHub
Open Sourced Collaborations
CAMPA

Reference Material/Texts:

Extensive class notes provided by the lecturers will be the primary resource. Lecture notes will be regularly posted in pdf format on the course web site:

https://people.nscl.msu.edu/~lund/uspas/scs_2016/

Paper copies of the lecture notes will also be handed out in class and updated and corrected pdf files of the notes can be downloaded from the course web site. We will attempt to regularly post material on the web site before it is covered in class and also post extensions and corrections to the notes.

Problem sets and computer exercises will be handed out in class. We will attempt to post related materials on the web site after they are handed out in class. Solution will be handed out in class but not posted on the web site.

An optional text:

"*Plasma Physics via Computer Simulation*," C.K. Birdsall and A.B. Langdon, (Taylor & Francis, NY) 2004

will be provided by the school for supplemental reading.

How Course Requirements Will be Met and Evaluated:

Schedule:

- Class will meet daily for one week of lectures. The daily schedule will be approximately:

9:00 am	- 12:00 noon	Lectures
12:00 noon	- 1:00 pm	Lunch Break
1:00 pm	- 2:30 pm	Lectures
2:30 pm	- 3:30 pm	Recitation + Lecture Carry Over
7:00 pm	- Open Ended Homework and Exercises	

  * On Friday, the course will end at approximately noon.

  Setup computer workstations with Warp installed will be present in the classroom for lecture demonstrations, exercises, and use for student homework in the evenings (classroom will be open).

  The final day will end early at 12:00 noon if the course is in the 2nd week of the USPAS session.

Grades:

60%	M-W: Daily Problems/Exercises (3 Total)
40%	Th: Final Exam, Overnight "Take Home"

Policies:

- **Lecture attendance is mandatory.**
- Problem sets will be handed out daily (Monday – Wednesday) at the lend of the last lecture and, unless otherwise noted, are due at the start of the lectures the next morning. Solutions and common issues with the problems will be reviewed in the recitation each day. We will attempt to return graded problem sets the following day after they are turned in.
- The final will be handed out Thursday at the end of the last lecture of the day and will be due Friday morning. The final will be similar in format to the problem sets. Graded finals will be mailed back to the students after the class along with course grades.
- **On the Problem Sets:** Students are allowed to discuss daily problems with other students, lecturers, and graders, but *are required to turn in their own solutions*. Use of problems and solutions of previous versions of this course, and related courses, are not permitted.
- **On the Final:** Both course lecture notes and the student's own personal notes can be used, but work must be independent. Students are not allowed to consult with others outside of clarification questions to the lecturers and grader. Use of problems and solutions from any previous versions of this course or related

courses are not permitted.

- Lecturers will make themselves available for questions and discussion immediately following lectures. Both the lecturers and the grader will regularly be present in the classroom in the evenings for further questions.

Course Background:
This course evolved from supplemental lectures given in the US Particle Accelerator School "Beam Physics with Intense Space-Charge" taught roughly every other year by SM Lund and JJ Barnard from 2001 till the present. This two-week intensive course is an extensive theory survey of the physics of beam with high space-charge intensity. At the end of the course, supplemental lectures were given on numerical simulation techniques. Time was inadequate to cover this important and central topic to the field sufficiently motivating the present course. Class notes for the course "Beam Physics with Intense Space-Charge" can be used as a supporting reference for this class. The most recent class notes dating are archived and actively updated on:

https://people.nscl.msu.edu/~lund/uspas/bpisc_2015/

Students interested in the the physics aspects of issues covered in "Self Consistent Simulations of Beam and Plasma Systems" may wish to consider also taking "Beam Physics with Intense Space-Charge."