US Particle Accelerator School
Beam Physics with Intense Space Charge

Location:
12-23 June, 2017
Lisle, Illinois
Sponsored by Northern Illinois University

Instructors:

Lecturers:
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Recitations/Grading:
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Course Web Site:

Contains course information including overviews, a lecture schedule, a full outline, lecture notes (pdf), problems sets (pdf), and the final exam (pdf). See:

https://people.nscl.msu.edu/~lund/uspas/bpisc_2017/

Prerequisites:

Required:
  Undergraduate Electricity and Magnetism:
    level Griffiths, *Introduction to Electrodynamics*
    including Special Relativity
  Undergraduate Mechanics:
    level Taylor, *Classical Mechanics*
    including Hamiltonian formulation of Dynamics
  Undergraduate Accelerator Physics:
    level *USPAS Fundamentals of Accelerator Physics*

Recommended:
  Introductory Plasma Physics:
    level: Chen, *Introduction to Plasma Physics and Controlled Fusion*
  Graduate Electricity and Magnetism:
    level: Jackson, *Classical Electrodynamics*
  Graduate or Advanced Classical Mechanics:
    level: Goldstein, *Classical Mechanics*

Overview:

"Beam Physics with Intense Space-Charge" is a comprehensive introduction to charged particle accelerator systems with high space charge intensity. Provides a foundation for research and design of systems with intensities sufficiently high so that mutual interactions of the particles in a beam focused and accelerated by applied electric and magnetic fields can not be neglected. Methodologies are systematically developed by applying dynamics, electromagnetic theory, and plasma physics. Appropriate for upper-level graduate students and researchers in physics and engineering.

Course Objectives:

This course is intended to give the student a broad overview of the dynamics of charged particle beams with strong space charge. The level is sufficient to provide a solid foundation for contemporary research and accelerator design in systems where intensities are sufficiently high so that mutual interactions of the particles in the beam can not be neglected as is often the case in conventional accelerator physics. In such regimes of strong space-charge, the beam can respond collectively as in a plasma leading to rich wave and stability properties beyond characteristic single-particle oscillations in conventional accelerator systems. The emphasis is on theoretical and analytical methods of describing the acceleration and transport of beams. Both linear (linac) and circular (ring) machine architectures, injectors and front-ends, and transfer/transport lines will be covered. Aspects of experimental methods will also be covered but details of laboratory implementations will not be covered. Time permitting, self-consistent simulation methods will be overviewed. Students will become familiar with standard methods employed to understand the transverse and longitudinal evolution of beams with strong space charge. The material covered will provide a foundation to design practical architectures. Take-home problem sets and a final exam are structured to clarify the lectures and stimulate critical thinking in intense beam physics and accelerator design.

Topics covered include: particle equations of motion, the paraxial ray equation, and the Vlasov equation; 4-D and 2-D equilibrium distribution functions (such as the Kapchinskij-Vladimirskij, thermal equilibrium, and Neuffer distributions), reduced moment and envelope equation formulations of beam evolution; transport limits and focusing methods; the concept of emittance and the calculation of its growth from mismatches in beam envelope and from space-charge non-uniformities using system conservation constraints; the role of space-charge in producing beam halos; longitudinal space-charge effects including small amplitude and rarefaction waves; stable and unstable oscillation modes of beams (including envelope and kinetic modes); the role of space charge in the injector; and algorithms to calculate space-charge effects in a range of numerical simulations from simple moment models to particle-in-cell methods for Vlasov distribution modeling.

Examples of intense beams will be given primarily from the heavy ion and proton accelerator communities. Methods covered are applicable to a wide range of applications including: high event rate colliders for high energy physics, accelerators for nuclear physics, spallation neutron sources, nuclear waste transmutation, material processing, intense beam-driven sources of coherent radiation, and accelerator based inertial fusion energy (Heavy Ion Fusion) and facilities for high energy density physics. High intensity applications promise to give new life to extensive accelerator facilities around that world that were originally intended for high energy and nuclear physics and are nearing the end of their useful lives for such purposes.

Course Outline:

In rough order of coverage:
JJB = John J. Barnard
SML = Steven M. Lund

JJB Lectures:

Introduction to the Physics of Beams and Basic Parameters
Perveance, emittance, depressed and undepressed phase advance; plasma physics of beams; Klimontovich equation; Vlasov equation

Envelope Equations
Paraxial ray equation; envelope equation for axisymmetric beams; cartesian equations of motion; quadrupole focusing; space charge of elliptical beams; envelope equations for elliptical beams

Current Limits
Current limits in accelerators for various focusing systems: continuous, electric quadrupoles, magnetic quadrupoles, Einzel lenses, solenoids

SML Lectures:

Transverse particle equations of motion:
Applied fields, self fields, machine latices; paraxial approximation; linear and non-linear fields; Hill's equation, Floquet's theorem; phase-amplitude methods; Courant-Snyder invariants; momentum spread effects and bending; acceleration and normalized emittance; acceleration and changes in gamma,beta

SML Lectures:

Transverse Equilibrium Distribution Functions
Vlasov model; Vlasov equilibria; KV distribution function; continuous focusing limit of KV distribution; continuous focusing equilbria; waterbag and thermal distributions; Debye screening; density inversion theorem

SML Lectures:

Transverse Particle Resonances with Applications to Circular Accelerators
Floquet coordinates; perturbed Hill's equation; sources and forms of perturbations; resonances; space charge effects; machine operating points

JJB Lectures:

Injectors and Longitudinal Physics I: Diodes and Injectors:
Space-charge limited flow; Pierce electrodes; injector choices

Injectors and Longitudinal Physics II:
Introduction to acceleration: space charge of short bunches; space charge of long bunches; 1D Vlasov equation; longitudinal fluid equations; space charge waves; longitudinal rarefaction waves and bunch end control

Injectors and Longitudinal Physics III
Longitudinal cooling from acceleration; longitudinal resistive instability; bunch compression; longitudinal envelope equation; Neuffer distribution function

JJB Lectures:

Continuous Focusing Beam Envelope Modes and Beam Halo
Envelope modes of bunched and unbunched modes in continuous focusing; beam halo

SML Lectures:

Transverse Centroid and Envelope Descriptions of Beam Evolution
Matched envelope solutions; envelope perturbations; Envelope modes in continuous and periodic focusing; mode launching; Centroid and envelopes based on first order coupled moment equations

SML Lectures:

Transverse Kinetic Stability
Machine operating points; Linearized vlasov equation; beam stability; KV Modes; global conservation constraints; beam stability theorem; emittance growth; collective relaxation; emittance growth from space charge non-uniformity

JJB Lectures:

Pressure, Scattering and Electron Effects
Coulomb collisions; charge changing collisions; electron clouds; multi-pacting; electron-ion instabilities

JJB Lectures:

Final Focusing and Example Applications of Intense Beams
Heavy ion fusion. Final spot size using envelope equation. Effects of chromaticity

<u>SML Lectures:</u>

Overview Numerical Simulations
Will cover select material from follow-on USPAS class on *Simulations of Beam and Plasma Systems* including as time permits: Motivation of simulation methods, classes of simulation techniques; overview of methods; particle methods; distribution function methods; diagnostics; initial distributions and particle loading; practical considerations; examples

Reference Material/Texts:

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

https://people.nscl.msu.edu/~lund/uspas/bpisc_2017/

Paper copies of the lecture notes will 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 will be handed out in class. We will post problem sets on the web site after they are handed out in class. Solution sets will be handed out in class but not posted on the web site.

An optional text:

"*Theory and Design of Charged Particle Beams*," Martin Reiser, Second Edition (Wiley, NY) 2008

http://www.wiley.com/WileyCDA/WileyTitle/productCd-3527407413.html

will be provided by the school for supplemental reading.

How Course Requirements Will be Met and Evaluated:

Schedule:

- Class will meet weekly daily for two weeks for lectures. The daily schedule will be:

9:00 am	- 12:00 noon	Lectures
12:00 noon	- 1:00 pm	Lunch Break
1:00 pm	- 2:00 pm	Lectures
2:00 pm	- 3:00 pm	Recitation + Lecture Carry Over
6:00 pm	- Open Ended	Homework

The final day (Friday) of the 2^{nd} week will end at 12:00 noon.

Grades:

80%	Weekly Problem Sets (8 Total)
20%	Final Exam, Overnight Take Home

Policies:

- **Lecture attendance is mandatory.**
- Problem sets will be handed out daily (Monday -Friday in the first week and Monday - Wednesday in the second week) at 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 in the 2nd week at the end of 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 from previous versions of this course or others taught by the lecturers are strictly not permitted.
- **On the Final:** Both course lecture notes, the student's own personal notes, and books 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 previous versions of this course and others by the lecturers are strictly not permitted.
- Lecturers will make themselves available for questions and discussion immediately following lectures and both the lecturers and the grader will regularly attend the study room in the evening for further questions.

Course Background:

Based on a series of graduate level courses on space-charge effects in accelerators taught in the US Particle Accelerator School and at the University of California at Berkeley by JJ Barnard and SM Lund:

06/2017 USPS, Northern Illinois University, held in Lisle Illinois
Beam Physics with Intense Space-Charge
01/2015 USPAS, Old Dominion University, held in Hampton Virginia
Beam Physics with Intense Space-Charge
06/2011 USPAS, Stony Brook University, held in Melville, New York
Beam Physics with Intense Space-Charge
06/2009 University of California at Berkeley
Nuclear Engineering NE290H,
Interaction of Intense Charged Particle Beams with Electric and Magnetic Fields
06/2008 USPAS, University of Maryland at College Park,
held in Annapolis, Maryland,
Beam Physics with Intense Space-Charge
06/2006 USPAS, Boston College, held in Waltham, Massachusetts,
Beam Physics with Intense Space-Charge
01/2004 USPAS, College of William and Mary
Intense Beam Physics: Space-Charge, Halo, and Related Topics
06/2001 USPAS, University of Colorado at Boulder,
held in Boulder Colorado,
Space-Charge Effects in Beam Transport

Information on the prior USPAS courses (including lecture note archives) can be found at:

https://people.nscl.msu.edu/~lund/uspas/bpisc_2017 2017
https://people.nscl.msu.edu/~lund/uspas/bpisc_2015 2015
http://uspas.fnal.gov On/Before 2011

Information on the UC Berkeley course can be found at:

http://hifweb.lbl.gov/NE290H 2009

A related simulation course is also given as part of the USPAS:

Scheduled Winter 2018:
Simulation of Beam and Plasma Systems
S.M. Lund, J.-L. Vay, and R. Lehe

Self-Consistent Simulation of Beam and Plasma Systems
S.M. Lund, J.-L. Vay, and R. Lehe
https://people.nscl.msu.edu/~lund/uspas/scs_2016/

This course extends and augments *Beam Physics with Intense Space-Charge.* Students finding this course useful who are also interested in simulations may benefit from taking this class.