

University of California at Berkeley

Nuclear Engineering 290H: Interaction of Intense Charged Particle Beams with Electric and Magnetic Fields (3 units)

Location:

MW, 5:00 - 6:30 pm, Room 61, Evans Hall

Course Control Number:

64135

Instructors:

Lecturers:

Dr. John J. Barnard (Lawrence Livermore and Berkeley National Labs)

Dr. Steven M. Lund (Lawrence Livermore and Berkeley National Labs)

Prof. John P. Verboncoeur (UCB Nuclear Engineering)

Prerequisites:

Required: Undergraduate Electricity and Magnetism and
Undergraduate Mechanics

Recommended: Familiarity with plasma physics

Catalog Description:

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 students in engineering and physics.

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 no longer 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. Numerical simulations and some aspects of experimental methods will also be

covered. 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.

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 ion and proton accelerator communities. Methods covered are applicable to a wide range of applications including: high event rate colliders, 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 Syllabus:

Week 1-2 (JJB):

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

Week 3-4 (SML):

Transverse particle equations of motion:

applied fields, self fields, machine lattices; 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

Week 5-6 (SML):

Transverse Equilibrium Distribution Functions

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

Week 7 (SML):

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

Week 8-9 (JJB):

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

Week 10 (JJB):

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

Week 11 (SML):

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

Week 12 (SML):

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

Week 13 (JJB):

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

Week 14 (JJB):

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

Week 15 (SML):

Numerical Simulations
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; an optional text: "*Theory and Design of Charged Particle Beams*," Martin Reiser, (Wiley, NY) 2008 can be obtained for supplemental reading.

How Course Requirements Will be Met and Evaluated:

Schedule:

The class will meet for 3 hours of lectures and to go over problems. Approximately 6 hours of homework a week are anticipated for the students to read and study course material and work problem sets that are structured to clarify the lectures and stimulate critical thinking in intense beam physics and accelerator design.

Grades:

80%	Homework Assignments
20%	Final Exam

Section Limit: 25

Offered:

First: Spring 2009

Future: Every other year (odd years), spring semesters

Course Background:

Course based on a series of graduate level courses on space-charge effects in accelerators taught in the US Particle Accelerator School by J.J. Barnard and S.M. Lund:

06/2008 University of Maryland at College Park
Beam Physics with Intense Space-Charge

06/2006 Boston College
Beam Physics with Intense Space-Charge

01/2004 College of William and Mary
Intense Beam Physics: Space-Charge, Halo, and Related Topics

06/2001 University of Colorado at Boulder
Space-Charge Effects in Beam Transport

The US Particle Accelerator School (USPAS) is a series of intensive schools designed to educate graduate students and researchers in physics and engineering in a broad range of accelerator physics and technology. Information on the USPAS (including lecture note archives) can be found at:

<http://uspas.fnal.gov>

Extensive lecture notes for the June 2008 class are available at:

<http://uspas.fnal.gov/materials/BeamPhysics.html>

It is anticipated that the first course in Spring 09 will closely follow these notes.