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, Evans Hall, Room 61

Course Control Number:
64135

Instructors:

Lecturers:
Dr. John J. Barnard (Lawrence Livermore and Berkeley National Labs)
LBNL Room 47-0103; (510)486-6124; JJBarnard@lbl.gov
Dr. Steven M. Lund (Lawrence Livermore and Berkeley National Labs)
LBNL Room 47-0114; (510)486-6936; SMLund@lbl.gov

Faculty Sponsor:
Prof. John P. Verboncoeur (UCB Nuclear Engineering)
4167 Etcheverry Hall; (510) 642-3477; johnv@nuc.berkeley.edu

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. Take-home problem sets and a final exam are given which 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 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:

Dates and order listed are tentative and may be revised.

Week 1-2 (JJB): Jan. 21-28; W,M,W

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): Feb. 2-11; M,W,M,W

Transverse particle equations of motion:
applied fields, self fields, machine latices; paraxial approximiation; 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): Feb. 18-25; W,M,W [M, Feb. 16 UCB Holiday]

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

Week 7 (SML): Mar. 2-4; M,W

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): Mar. 9-18; M,W,M,W [Spring Break, Mar. 22-27]

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): Mar. 30 - Apr. 1; M,W

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

Week 11 (SML): Apr. 6-8; M,W

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): Apr. 13-15; M,W

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): Apr. 20-22; M,W

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

Week 14 (JJB): Apr. 27-29; M,W

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

Week 15 (SML): May 4-11; M,W,M

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. Lecture notes will be regularly posted in pdf format on the web site:

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

Paper copies of the lecture notes will also be handed out in class and pdf files of the notes can also be electronically copied in class. 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 attempt to post problem sets on the web site after they are handed out in class.

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

can be obtained for supplemental reading.

How Course Requirements Will be Met and Evaluated:

Schedule:

- Class will meet weekly MW, 5-6:30 pm, Evans Hall, Room 61 for lectures and to review problems.

Grades:

80%	Weekly Problem Sets
20%	Final Exam, Take Home

Policies:

- Lecture attendance optional, but students are responsible for all material covered in lectures including supplemental handouts and problem sets that will be distributed during the lectures.
- Problem sets will be handed out regularly and will be due on the indicated class date on the problem set at the start of the lecture.
- Students are allowed to discuss weekly problem sets with other students, lecturers, and graders, but are required to turn in their own solutions to the weekly problem sets.
- Both course lecture notes and the student's own personal notes can be used on the final exam and work must be independent. Students are not allowed to consult others other than clarification questions to the lecturers.

Office Hours:

John J. Barnard	Steven M. Lund
Friday, 1:00 -2:00 pm	Thursday, 1:00 - 2:00 pm
Lawrence Berkeley Lab	Lawrence Berkeley Lab
Building 47, Room 103	Building 47, Room 114
jjbarnard@lbl.gov	smlund@lbl.gov
(510) 486-6124	(510) 486-6936

- Schedule permitting, lecturers will make themselves available for questions and discussion immediately following classes.
- We will attempt to accommodate reasonable requests for additional help outside of regularly scheduled office hours.

Section Limit: 25

Offered:

First: Spring 2009
Future: Anticipate every other year (odd years), spring semesters

Course Background:

NE 290H is 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

Lecture notes for the June 2008 class are available at:

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

It is anticipated that NE 290H in Spring 09 will closely follow the June 2008 USPAS notes.

Additional Courses:

Other accelerator related courses that could be of interest to students in this class include:

NE 282	(3 units)	Ion Source and Beam Technology
NE 281	(3 units)	Fully Ionized Plasmas
NE 290F	(3 units)	Particle Simulation of Plasmas

Physics 205A-205B	(4 units)	Advanced Dynamics
Physics 209	(5 units)	Classical Electromagnetism
Physics 242A-242B	(4 units)	Theoretical Plasma Physics

EE C239 Partially Ionized Plasmas

US Particle Accelerator School Courses
Intensive school with sessions twice a year in variable locations.
Student support is often possible. For more information see:
http://uspas.fnal.gov