Proton and Ion Linear Accelerators

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Abstract

This course is intended to give a student a broad overview of Radio Frequency accelerators and beamlines. Special emphasis is on high-current beam dynamics and linac technology for acceleration of charged particle beams. The topics include: principles of RF acceleration and focusing, self-consistent space-charge dominated dynamics of particles, halo formation in particle beams, nonlinear beam effects, beam loading effects, normal and superconducting accelerating structures, beam focusing elements, Radio Frequency Quadrupole accelerators. After taking the course, students will be able to design linear accelerators with high beam current, find optimal conditions for particle dynamics to minimize particle losses and to provide optimal beam dynamics in linacs, determine beam emittance growth and beam current limits in RF accelerators and beamlines.

1. Basics of Beam Acceleration

Principle of linear resonance acceleration

Electromagnetic field in RF cavities

Energy gain in RF gap

Transit time factor

Longitudinal particle dynamics in RF field. Frequency of longitudinal oscillations

Phase space, Liouville's theorem

Separatrix and capture of particle in accelerating regime

Longitudinal acceptance

Adiabatic damping of longitudinal oscillations

Matrix of longitudinal motion in RF gap

Phase advance of longitudinal oscillations

2. Beam Focusing

Particle defocusing in RF gaps

Matrix of transverse particle motion in RF gap

Quadrupole focusing. Single particle dynamics in focusing channel

Beam emittance, Courant-Snyder invariant, Twiss parameters

Matrix of transverse particle trajectories in quadrupole channel

Floquet theorem. Acceptance of the channel

Transverse oscillations in presence of RF field. Parametric resonances. Smith-Gluckstern stability diagram.

Averaging method in particle dynamics

Kapchinsky-Vladimirsky (KV) beam envelope equations in quadrupole focusing channel

Rms beam envelopes with space charge. Waterbag, parabolic and Gaussian distributions

Beam radius and transverse oscillation frequency in space-charge dominated regime

Beam current limit in focusing channels

Beam drift in free space

Drift of non-uniform space charge dominated beam

Beam uniforming for irradiation of large targets

Stationary beam equilibrium in linear focusing channel

Envelope instability. Even and odd mismatched envelope modes

Higher-order instabilities of KV beam. Structure resonances.

Beam current and beam position monitors (Faraday cups, beam transformers, pick-up electrodes)

Methods of beam emittance and beam profile measurements (slit - collector, “pepper pot”, Allison scanner, wire scanners and harps, scintillation screens)

3. Beam Transport in Axial-Symmetric Magnetic Field

Single-particle dynamics in magnetic field. Busch Theorem.

KV beam envelope in magnetic field.

Beam equilibrium in magnetic field. Brillouin Flow.

Lattice of periodic solenoid channel

Space-charge dominated beam in periodic solenoid channel

Instability of beam envelopes in magnetic field

4. Acceleration of Intense Beams in RF Linacs

Hamiltonian of particle motion in RF field with space charge

Required transverse focusing in RF field

Beam bunching in RF field

3D beam envelope equations

Bunched beam equilibrium

Maximum beam current in RF field

Mismatched 3D beam envelope modes

Self-consistent space charge dominated bunched beam in RF field

Beam equipartitioning in RF field

Bunched beam distribution in space charge dominated regime

Generation of RF field by a bunched beam

Beam loaded RF cavities. Effect of higher-order modes on beam dynamics

Longitudinal beam parameters measurements (beam shape monitors, dipole magnet-RF-deflector scheme, absorber-collector phase scans, delta-t time-of-flight procedure, beam energy spread measurements)

5. Radio Frequency Quadrupole (RFQ) Accelerators

Principle of operation

Acceleration and longitudinal beam dynamics

Focusing, transverse equation of motion

Matching of the beam with RFQ, Length of RFQ sections

Beam current limit in RFQ

Transverse and longitudinal parametric resonances in RFQ.

6. Low -Medium - High Energy Beam Transports (LEBT-MEBT-HEBT)

Magnetostatic and Electrostatic LEBTs

Emittance of the beam in particles sources

Space charge effects in the extraction region of particle sources.

Child-Langmuir Law

Plasma meniscus

Pierce optics

Optimization of LEBT design. Mismatch factor

Minimization of beam emittance growth in LEBT

Beam Chopping

Beam matching with RF accelerator

MEBT components

HEBT structure.

HEBT emittance measurement

Beam based alignment of transport lines

Beam injection into circular accelerator

Beam irradiation of targets

7. Emittance Growth, Halo Formation, and Beam Losses in Linacs

Effect of errors of focusing elements on beam emittance growth

Beam emittance growth in non-ideal RF structure

Emittance growth in RF field. Transverse – longitudinal coupling.

Spherical and chromatic aberrations. Beam emittance growth due to aberrations

Space-charge induced beam emittance growth in a focusing channel.

Free energy effect and charge redistribution

Emittance growth in rms –matched and rms-mismatched beams

Particle – core interaction. Beam halo formation in periodic focusing channel

Halo formation in bunched beams

Emittance exchange. Core-core resonances

Beam loss in high-intensity linacs

Effect of random errors, beam mismatch, and RF stability on beam losses

Interaction of the beam with residual gas

Negative ion stripping on residual gas, H+ capture and acceleration, intra-beam stripping, stripping in magnetic field, black body radiation

Dark currents

Mitigation of beam losses

Beam loss diagnostics (Ionization chambers, plastic scintillators, scintillation liquids, PIN diods)

High-intensity modern accelerator projects. Examples of linac design.

8. RF Accelerating Structures

Standing wave (SW) and traveling wave (TW) structures

Pillbox cavity

Disk-loaded traveling wave structures

Shunt impedance and other main parameters for SW structures

Normal conducting (NC) accelerating structures

- Low energy: RFQ, IH
- Medium energy: DTL, SDTL
- High energy: CCL, π-mode cavities

CW and pulsed accelerators

- NC and superconducting (SC) accelerating structures
- Different types of SC resonators: split-rings, QWR, HWR, spoke cavities
- Peak fields in NC and SC structures; Kilpatrick limit

General layout of a linac

- Front end: LEBT, RFQ, MEBT
- Main linac options
- High energy beam transport (HEBT)

Special features of heavy-ion linacs

- Ion sources
- Beam stripping, accelerating multiple charge states

Driver linac

Radioactive ion beams (RIB) – production and post-acceleration

Optimizing linac design parameters:

Frequency, accelerating gradient, length, RF power, and cost.

9. Linac components

Ion sources

Cavities

RF systems: RF generators, waveguides, power couplers

Magnets

Diagnostics

Auxiliary systems: vacuum, cooling, alignment