Syllabus for Doctoral Course
Variable Energy Cyclotron Centre
Department of Atomic Energy
1/AF Bidhan Nagar, Kolkata 700 064

Doctoral course work at VECC is divided into 3 semesters each of 4months as described in table below. Duration of complete course work is ONE year.

Semester-I (CORE)	Semester-II (BASIC)	Semester-III (Advanced)
1. Mathematical Physics 2. Classical Mechanics 3. Quantum Mechanics 4. Statistical Mechanics 5. Numerical techniques and applications 6. Experimental Techniques and Methods	1. Basic Field Theory 2. Basic Condensed Matter Physics 3. Basic Nuclear Physics 4. Basic Accelerator Physics 5. Laboratory Experiments 6. Research and Publication ethics (RPE)	Advance Courses offered 1. Advanced Accelerator Physics-I&II 2. Advance Nuclear Theory Advance Nuclear Experiment 3. Advanced Materials Science 4. Advanced Condensed Matter Physics 5. Advanced Course on Relativistic heavy-ion collision experiments & quark-gluon plasma 6. Advanced Course on Quantum Chromodynamics (QCD) and Relativistic Heavy Ion Physics 7. Self study Project Work
All course are Compulsory		In addition to project work among advance courses offered including self-study course, total requirement of 8 credits to be completed.
21 credits	21 credits	18 credits
Aug-Nov	Dec-March	April-July

- Lecture hours mentioned includes tutorial.

Semester-I (CORE)

1. Mathematical Physics (Credit: 3, about 25 hours) PHYS04-001-C

Linear vector spaces, Linear operators and matrices, Systems of linear equations. Eigen values and Eigen vectors.

Tensors: Introduction and definition, Symmetric and anti-symmetric tensor, Cartesian & Non-Cartesian tensors and covariant derivative, Christoffel symbol, irreducible representation, Direct product and contraction, Tensors in Newtonian mechanics and Relativity.

Linear ordinary differential equations, Linear partial differential equations in physics, Green functions, Separation of variables method of solution, Special functions and their applications in physics.

Complex variable theory; Analytic functions. Taylor and Laurent expansions, Analytic continuation, Contour integration, Dispersion relations.

Integral equations: Fredholm and Volterra equations, Transformation of differential equation to integral equations, Methods for solving integral equation.

Introduction to finite and continuous groups. Group representations and operations, Permutation group and its representations, Lie group.

Suggested Books:
1. Mathematical Methods for Physicists: A concise introduction, T L Chow
2. Methods of Mathematical Physics Vol. I & Vol. II, R Courant & D Hilbert
3. Complex variables & applications, J W Brown & R V Churchill
4. Group Theory in a Nutshell, A. Zee
5. The Mathematics of Classical and Quantum Physics, F. W. Byron and R W Fuller
6. Mathematical Methods for Physicists, G B Arfken, H J Weber and F E Harris
7. Mathematical Physics: Applications and Problems, V. Balakrishnan

2. Classical Mechanics (Credit: 3, about 25 hours) 04PHYS04-002-C

Introduction to dynamical systems, Discrete dynamical systems (Maps), Continuous dynamical systems, Classifications: autonomous, non-autonomous, Linear, Non-linear systems, Phase space and phase portraits, Fixed points and stability , 1^{st} order system-phase line, 2^{nd} order system-phase plane, Examples- Logistic growth, Simple harmonic oscillator, Prey-predator system etc., Limit cycle, linearization of non-linear systems, Lyapunov stability, Linear Stability analysis.

Hamilton's equations of motion, Liouville's theorem, Poisson brackets and Canonical transformations, Generating functions, Action-Angle variables, Hamilton-Jacobi equation, Perturbation theory

Michelson-Morely Experiment, Time-like, Space-like, Light-like Intervals, Invariant Hyperbolae, Light cone, Minkowski Diagrams, Four Vectors, Lorentz Transformation and Kinematics of Special Relativity, Transformation of electromagnetic fields, Maxwell-Farady tensor.

Suggested Books:

1. Nonlinear dynamics and chaos, Steven Strogatz
2. Classical Mechanics, T W B Kibble and F H Berkshire
3. Classical Mechanics, H Goldstein
4. Classical Mechanics, L D Landau and L M Lifshitz
5. Mathematical Methods of Classical Mechanics, V I Arnold
6. Classical Dynamics: A Modern Perspective, E. C. G. Sudarshan and N. Mukunda
7. Chaos : Introduction to dynamical systems, K. T. Alligood, T. D. Sauer and J. A. Yorke
8. An Introduction to Relativity, J. V. Narlikar, Cambridge University Press

3. Quantum Mechanics (Credit: 3, about 25 hours) 04 PHYS04-003-C

Introduction, Vector spaces, Matrix Representations, Similarity transformation, Inner Product space, Spectral decomposition, Schmidt decomposition (Singular Value decomposition), Infinite dimensions and Hilbert spaces, Symmetric operator, Self-Adjoint operator, Positive operator, Tensor product of vector spaces, Partial Trace, Partial Transpose

Stern-Gerlach experiment, Postulates of Quantum Mechanics Postulates, Bloch sphere, Projective Measurement, Positive Operator Valued measure (POVM), Discriminating the states, Commutators, The expectation value and the uncertainty, Heisenberg uncertainty relations, Self-adjoint extension, von-Neumann's prescription.

General properties of the Schrodinger Equation, Complete set of commuting operators (csco), Evolution operator, Schrodinger, Heisenberg, and Interaction pictures, Two state system, Rabi-Oscillation, Density Operator, Quantum entanglement, Entanglement entropy.

Infinite potential well, Particle moving on a ring, Particle moving on a ring enclosing a magnetic flux, Aharonov- Bohm effect, Charged particle in a magnetic field, Landau levels, Periodic potential, Bloch's Condition, Kronig-Penney model.

Suggested Books :

1. Modern Quantum Mechanics, J. J. Sakurai
2. Non-Relativistic Quantum Mechanics, R. R. Puri, Cambridge University Press; First edition
3. Principle of Quantum Mechanics, R. Shankar

4. Lectures On Quantum Mechanics, Steven L. Weinberg
5. Quantum Mechanics, Vol. 1, 2 & 3, Claude Cohen-Tannoudji, Bernard Diu,and Franck Laloë

4. Statistical Mechanics (Credit: 3, about 25 hours) 04PHYS04-004-C

Information entropy, Maximization of Information entropy to derive classical ensembles. Equivalence of different ensembles. Introduction to Density matrix. Quantum statistics, Bose-Einstein condensation. Degenerate Fermi gas, White dwarf.

Phase transitions and critical phenomena: The Ising model-critical exponents and the universality, Lee-Yang theory for first order phase transition.

Non-equilibrium statistical mechanics: Linear response theory, Phase space densities; Liouville's theorem, BBGKY hierarchy, the Boltzmann equation, transport phenomena; Stochastic Processes, Fokker-Planck Equation and Brownian motion; Fluctuation-Dissipation theorem

Suggested Books:

1. Introduction to Statistical Physics, Slivio Salinas, Springer
2. Statistical Physics of Particles, Mehran Kardar, Cambridge University Press
3. An Introductory Course of Statistical Mechanics, Palash B. Pal, Narosa Publishing
4. Thermodynamics Kinetic Theory and Statistical Thermodynamics, F. W. Sears and G. L. Salinger
5. Statistical Mechanics. Huang, Kerson. 2nd ed. Wiley
6. Statistical Mechanics. Pathria, R. K. Pergamon Press
7. Statistical Physics, Part 1. Landau, L. D., and E. M. Lifshitz. Pergamon Press
8. Fundamentals of Statistical and Thermal Physics., Reif, Frederick, ed. McGraw-Hill.
9. Statistical Dynamics: matter out of equilibrium, R. Balescu, World Scientific
10. Non Equilibrium Ststistical Mechanics, D.N. Zubarev, Studies in Soviet Science

5. Numerical techniques and application: (Credit: 3, about 25 hours) 04PHYS04-005-C

Numerical Root Finding: Solution of polynomial equations: Bisection method, False position method, Newton-Raphson method and Secant method, Multidimensional Newton's method.

Interpolation and Least Square Fitting: Linear Interpolation, Newton and Lagrange Interpolation, Linear and non-linear curve fitting.

Matrix and Solution of system of simultaneous equations: Matrix diagonalization and matrix inversions, Eigen value problems, Gauss elimination, Gauss Jordan elimination method, Pivoting.

Numerical Differentiation and Integration: Numerical formulae for ordinary derivative and partial derivative, Trapezoidal formula and Simpson's formula for numerical integration, Numerical multiple integral.

Numerical techniques for solving Differential Equation: Ordinary differential equation, Initial value problems and boundary value problems, Taylor series method, Euler's method, Runge-Kutta fourth order method, Shooting method, Finite difference method, Partial differential equation, Application of numerical techniques to solve Poisson's equation, Wave equation, Heat equation, Schrödinger equation.

Random numbers and Monte-Carlo Simulation: Introduction to random numbers, Monte-Carlo simulations, Evaluation of π by Monte-Carlo method, Monte-Carlo technique of numerical integration, Metropolis algorithm.
Machine Learning: Introduction to machine learning. Application.

Books:
Introductory Methods of Numerical Analysis, S. S. Sastry, PHI Learning; 5th edition, 2012
Computer Oriented Numerical Methods:V. Rajaraman, PHI Learning; 4th edition, 2019
Numerical Recipes in C++ : The Art of Scientific Computing; William H. Press, Saul A. Teukolsky, William T. Vetterling and Brian P. Flannery, Cambridge University Press; 2nd edition, 2002
Scientific Computing in Python by Abhijit Kar Gupta

6. Experimental techniques and methods (Credit 6, about 48 hours) 04PHYS04-006-C

Philosophy of experimental science
Laboratory safety, measurement of various physical properties with appropriate transducers, Vacuum - production methods and measurement techniques, Cryogenics - production and measurement, Workshop practice and basics of engineering drawing.

Material Characterization techniques
Electrical and Magnetic, measurements, X-ray diffraction, neutron scattering and electron scattering techniques, Surface structure and topography (Scanning Electron Microscopy)
, Mechanical property measurement: Tension and compression testing, Micro and Nano-indendation techniques,

Characterization of defects and their detection (Positron Annihilation Spectroscopy, Transmission Electron Microscopy)

Detectors and Techniques for Nuclear and High Energy Physics

Interaction of Radiations with matter: Interaction of charged particles, Electrons, photons, Neutrons, Muons and neutrinos with matter. Radiation exposure and Dose.

Basics of detectors: General properties of radiation detectors, Simplified detector model, Modes of detector Operation, Pulse height spectra, Energy resolution, Detector efficiency, Working principle and properties of different types of detectors - Gas detectors, Scintillation Detectors, Semiconductor Detectors.

Basics of nuclear electronics: Pre-amplifier, amplifier, discriminators, gate and delay generators, Analog to Digital Converter, Time to Amplitude Converter and the basics of data acquisition systems.

Experimental Nuclear physics techniques and detectors: Charged particle spectroscopy and particle identifications, Gamma ray spectroscopy, Fast neutron spectroscopy and detectors related to the different techniques.

Experimental High Energy Physics techniques and detectors: General concept of building a HEP experiment, coverage and options, tracking detectors, calorimeters, vertex detectors, muon chambers, neutrino detectors, particle identification detectors in HEP. Data analysis in HEP: General approach of data cleanup, calibration, track reconstruction, reconstruction of events, challenges in each stage.

Suggested books:

1. Materials Characterization: Introduction to Microscopic and Spectroscopic Methods, Yang Leng
2. Characterization of materials, Elton Kaufmann
3. Radiation Detection and Measurement, Glenn F. Knoll
4. Nuclear Radiation Detectors, S.S. Kapoor and V. S. Ramamurthy.
5. Techniques for Nuclear and Particle Physics Experiments: A How-To Approach, William R. Leo
6. Experimental Techniques in High-energy Nuclear and Particle Physics edited by Thomas Ferbel
7. Introduction to Experimental Particle Physics, Richard Clinton Fernow
8. Data Reduction and Error Analysis for the Physical Sciences, Philip Raymond Bevington, D. Keith Robinson
9. Data Analysis Techniques for High-Energy Physics, edited by R. Frühwirth, M. Regler.

Semester-II (BASIC)

1. **Basic Field Theory (Credit 3, about 25 hours) 04PHYS04-001-B**

Basis ideas of Lorentz invariance and Relativistic kinematics.A preview of fundamental particles and their interactions.Review of classical field theory : Principle of least action, Lagrangian formulationfor continuous system and fields, symmetries and conservations laws, Noether's theorem.

Introduction to field quantization:Canonical quantization of scalar, spin one-half and gauge fields.Principle of gauge invariance:Global and local gauge transformations, Abelian gauge fields.Interacting fields : Perturbation expansion of correlation functions, Wick's theorem, Feynmandiagrams, S-matrix and cross section, Calculations of cross section and decay rates for elementary processes in quantum electrodynamics.

Suggested Books :

1. Quantum Field Theory, F Mandl and G Shaw
2. Lectures on Quantum Field Theory, Ashok Das
3. An introduction to Quantum Field Theory, M. E. Peskin and D. V. Schroeder
4. Quantum Field Theory L. H. Ryder
5. Quantum field theory lectures by Sidney Coleman

2. **Basic Condensed Matter Physics (Credit 3, about 25 hours) 04PHYS04-002-B**

Crystal structure and crystallography: Bravais lattice – Primitive vectors, Primitive unit cell, Conventional unit cell, Reciprocal lattice and Brillouin zone, X-ray diffraction, Comparison with electron and neutron diffraction.

Electronic structure of solids:Concept of classical, semi-classical and quantum electrons in solids, nearly free electron model and origin of band gap, Bloch's theorem, tight binding model, concept of many body problem, HartreeFock theory, introduction to Density Functional Theory.

Lattice vibrations**:** Phonons-Debye model for specific heat of solids-lattice dynamics-phonon spectrum. Electrical & thermal transport in solids,

Magnetism:Origin of magnetism, Quantum theory of diamagnetism and paramagnetism, Heisenberg's exchange interaction and ferromagnetism,

Superconductivity &Superfluidity:Phenomenological description of superconductivity, Interaction between electron and phonon, Cooper pair, Meaning of energy gap, Meissner effect, London theory, Classification of superconductors, High temperature superconductors, Outline of the microscopic BCS theory, Ginzburg-Landau theory.

Strength of materials:Cohesion in solids, Elasticity and Plasticity, Defects in solids, point defect, line defect, planar defects, 3D defects Concept of dislocations, role of dislocations in material behaviour,.

Irradiation effects in solids:Material behaviour under irradiation, Concept of DPA, Introduction to nuclear reactor materials**.**

Suggested books:

1. Solid State Physics : N. Ashcroft and N. D. Mermin
2. Introduction to Solid State Physics : Charles Kittel
3. Introduction to Superconductivity :A.C.Rose- Innes, E.H. Rhoderick
4. Solid State Physics : A.J. Dekker
5. Irradiation Effects in Crystalline Solids : J.H. Gittus,

3. Basic Nuclear physics (Credit 3, about 25 hours): 04PHYS04-003-B

Chart of nuclei, nuclear ground state properties (mass, binding energy and symmetries), nucleon-nucleon interactions., electric and magnetic moments,

Introduction to nuclear models: liquid drop model, concept of mean field and single-particle shell model, nuclear deformation and deformed shell model, Electromagnetic transitions

Fermi-gas model, nuclear level density and temperature, reactions at intermediate energy; nuclear multi-fragmentation and liquid-gas phase transition

Nuclear excitations and decay; collective rotations and vibrations, giant dipole resonances, alpha decay, beta decay, gamma decay, selection rules for decay.

Elementary kinematics and conservation laws, reaction cross section. Types of nuclear reactions: coulomb scattering, nuclear scattering, compound nuclear reactions, fusion-evaporation, fusion-fission, quasifission, spontaneous fission

The optical model, Resonances, Breit-Wigner formula, astrophysical s-factor and reactions of astrophysical interests.

Introduction to experimental probes for nuclear structure study, Experimental probes in nuclear reactions to study different reaction observables and their detections. Production of rare isotope beams and their applications in nuclear physics.

Suggested Books:

1. Nuclear models, by W Greiner and J AMaruhn
2. Nuclear structure Vol I, by A Bohr and B Mottelson
3. Introductory Nuclear Physics by Kenneth S Krane

4. Theoretical Nuclear Physics Blatt, Weisskopf
5. Physics of the nucleus : Preston &Bhaduri
6. Nuclear Physics in a nutshell, C.A.Bertulani

4. **Basic Accelerator Physics (Credit 3, about 22 hours) ; 04PHYS04-004-B**

Introduction to Accelerators: History of accelerators. Basic principle of DC and RF accelerators. Accelerators in India. Application of accelerators.

Ion Sources for Particle Accelerator: Principle of ionization, Ion sources for positive ions – Duoplasmatron, PIG, ECR, Ion sources for negative ions- surface, volume and charge exchange, ECR ion source and beam transport line. Ion sources for K130, K500 and Medical cyclotron at VECC.

Transverse Beam Dynamics: Accelerator coordinate systems, Maxwell equations, Charged particle motion in electric and magnetic field, Quadrupole and Solenoid focusing, Hill's equation, Periodic focusing lattices, Transfer matrix technique, Transfer matrices for drift space, dipole, quadrupole, Stability criterion, Beta function, Courant-Snyder invariant and Twiss parameters, Beam emittance. Familiar with TRANSPORT code.

Longitudinal Beam Dynamics: Longitudinal Equation of Motion, Off-momentum orbits in synchrotrons, Transition energy and Momentum compaction, Phase stability, Synchrotron oscillation, Longitudinal emittance.

Linear Accelerator: Principle of LINAC, Wideroe and Alveraz linac, Transit time factor, Shunt impedance, Quality factor, Ion and electron Linac, Empty cavity and Loaded cavity, Travelling wave and standing wave structures, principle of RFQ. Linac in RIB at VECC.

Cyclotron: Basic principle, AVF cyclotron, Synchrocyclotron, Betatron tunes, Shape of the cyclotron magnet, Injection, Extraction, Beam quality, time structure, energy resolution and emittance. K130, K500 and medical cyclotron at VECC.

Synchrotron and Radiation Source: Basic principle of Synchrotron, Electron and ion Synchrotron, Synchrotron radiation source, Total radiated power, Properties of Synchrotron radiation, Insertion devices. Indus 1 and Indus 2 at RRCAT.

Suggested Books

1. An Introduction to Particle Accelerators (Oxford University Press 2001) Edmund Wilson
2. Principles of Charged Particle Acceleration (Wiley 1986) Stanley Humphries, Jr.
3. Principles of Cyclic Particle Accelerators (Van Nostrand, NJ 1961) John Jacob Livingood

5. Laboratory Experiments: (Credit 5, about 40 hours); 04PHYS04-005-B

The students will perform 5 experiments out of those listed below.
OR participate in one ONLINE experiment using VECC accelerator facility
Each experiment is for '1' credit

1. Calibration, Energy resolution and Efficiency of Different Types of Radiation Detectors for Gamma Spectroscopy :

   The characterization of HPGe detectors with different configuration and scintillator detectors will be carried out. The detectors will be characterized with respect to their energy calibration, energy resolution and photopeak efficiency. For this purpose, coaxial HPGe detector, Low Energy Photon Spectrometer (LEPS) in planar configuration and CeBr3 scintillator detectors will be used. The energy calibration, resolution and efficiency will be determined using standard radioactive sources. The energy resolution and photopeak efficiency of different detectors will be compared.

2. X-ray diffraction analysis of deformed samples:

   X-ray diffraction analysis to understand the effect of deformation on the microstructure of materials will be carried out. Two types of deformed (rolled sheet and ball-milled powder) of copper samples used for the study. X-ray diffraction data will be collected using laboratory X-ray source. Instrumental broadening of the X-ray diffractometer will be determined using NIST standard. The diffraction peaks from the XRD data of the samples will be analysed to extract the coherent domain size and microstrain and compared.

3. Understanding the performance of detectors for charge particle spectroscopy.

   Energy resolution measurement of charge particle detector will be carried out. Energy calibrations and thin film thickness measurements will be carried out. Measurement of activity of radioactive source will be performed using the calibrated detector. Finally, depletion depth measurement in a semiconductor detector for 5.5 MeV alpha particle will be carried out.

4. Characterization of liquid scintillator based fast neutron detector:

   Experiment will be performed to calibrate the pulse height response of a liquid scintillator based neutron detector using 22Na and 137Cs gamma -ray sources. Neutron gamma discrimination using pulse shape discrimination technique will be performed using a fission neutron source. Pulse shape discrimination will be achieved using Zero Cross Over (ZCO) technique. ZCO and pulse height data will be acquired to determine the Figure Of Merit (FOM) of the neutron gamma discrimination. FOM will be determined for different pulse heights thresholds.

5. Characteristic study of plastic scintillator detectors and measuring cosmic flux using a coincidence setup.

   The students will be introduced to basic functioning of plastic scintillator detectors. Characteristic dark current curves of three different scintillators with varying threshold and applied voltages will be obtained. A coincidence unit will be setup by the students to measure the cosmic muon flux. Associated NIM modules generally used in experiments will be introduced.

6. Introduction of SEM and EDS: as a tool for material characterization

   The working principle of Scanning Electron Microscope (SEM) and energy dispersive spectrometer (EDS) set up will be explained. Good quality images captured previously will be shown to explain the important characteristics. One sintered ceramic sample (if available) or any alloy sample(s) will be used to obtain images using SEM and the composition using EDS. The analysis of the SEM images and EDS data will be explained.

Each experiment will include hands-on performance of the experiment, data collection, analysis, report writing and submission. A presentation on one of laboratory experiments performed will be followed by viva voice examination covering five experiments performed.

6.Research and Publication ethics (RPE) 04PHYS04-005-B

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Semester-III (ADVANCED)

1. **Advanced Accelerator Physics-I: (Credit:4, about 30 hours) 04PHYS04-001-A1**

Introduction: Sources of charged particle, Hamiltonian of a charged particle, Equations of motion, Planer diode without and with space charge. Beam parameters: - Beam energy, Beam current, Time structure, Peak and average beam current, Beam size, Transverse beam dimensions, Bunch length, Energy spread, Beam emittances.

Beam Transport: Accelerator coordinate system, Paraxial ray equation and solutions, Electrostatic lenses, Solenoidal magnetic lens, Larmor frame, Aberrations, transfer matrix of transport elements, Stability condition, Beam envelope, Beam matrix, Basic focusing modules and different kinds of imaging, Coupled systems, Skew quadrupoles. Quadrupole doublet and Triplet.

Beam Dynamics: Beam envelope equation, Courant-Snyder invariant and emittance, Twiss parameters, Liouville's Theorem, Periodic system, FODO Cell, Dipole field and Quadrupole gradient errors, Resonances. Off momentum orbit, Dispersion function, Momentum compaction, Transition energy, Negative mass, Dispersion matching, Chromaticity and its corrections. Longitudinal equation of motion, Phase stability and synchrotron oscillations, Bucket, Separatrix.

Intense Beam Dynamics: Space charge effects, Uniform beam model, Applied and self-fields, Beam envelope equation with space charge, Pervience, Beam transport in a uniform and periodic focusing channel, Tune shift and current limits, Envelope oscillations, Linear beam model with charge neutralization, Space charge compensation. Vlasov model, K-V and Waterbag distribution, Concept of equivalent beams, RMS envelope equations, emittance growth.

RIB Accelerator Science: Introduction and overview of RIB facilities, Different types of RIB facilities, Ion sources & charge breeder, Ion guides and gas-jet systems, RFQ cooler, Mass Separators, RFQ linac, Heavy Ion LINAC, Applications of RIB in different fields (Nuclear physics, Material science, Medicine, Industrial applications), RIB facilities worldwide.

Synchrotron radiation: Radiation from moving charges, Coulomb regime, Radiation regime, Radiation sources, Bending magnet radiation, Wavelength shifter, Wiggler magnet radiation, Undulator radiation, Radiation power and angular distribution, Beam lifetime.

Advance accelerators: Free electron laser, Plasma accelerators, Spallation neutron sources, Accelerators driven subcritical systems (ADSS),

References:

1. Accelerator Physics - (World Scientific 2019) S.Y. Lee.
2. RF Linear Accelerators - (Wiley 2008) Thomas P. Wangler
3. Theory and Design of Charged Particle Beams (Wiley 2008) Martin Reiser.

2. Advanced Accelerator Physics-II: (Credit:4, about 30 hours) 04PHYS04-002-A1

Vacuum: Equations governing vacuum systems, Creation of vacuum – Different types of pumps (Rotary, Roots, Dry, Diffusion, Cryo and ion pumps), Measurement of vacuum – Different types of gauges, working principles, range of operation, Leak testing, Different materials and their physical properties for vacuum systems, Sealing techniques, Design of simple vacuum systems. Vacuum systems in VECC cyclotrons.

Beam Diagnostics: Measurement of beam current (Faraday cup, Wall current monitors, CT, DCCT), Measurement of beam profile (Scanners, scintillators etc.), Measurement of time structure (Fast Faraday cup, Harp monitor), Measurement of beam phase, Measurement of beam energy (Spectrometer, TOF, Nuclear techniques)

Electrostatic lenses: Dipole, Quadrupole, Einzel lens, Wien filter etc.

Room Temperature Magnets: Maxwell equations, Magnetic materials and their properties, Basic equations governing magnet design, Design of different types of magnets for accelerators (Dipole, Quadrupole, Sextupole , solenoid, steering magnets), Permanent magnets, Magnet design codes, characterisation of magnets (Hall probe, NMR probe, magnetic coils, magnet test bench and harmonic coils), Examples of special magnets (RTC, MCP etc.)

Super-conductivity in accelerators: Super-conductivity, Different types of super-conductors and their properties, Super-conducting coils and their selection in magnet design, AC loss & magnetization, Stress analysis, Quench and quench protection, Current lead design, Practical design examples of superconducting magnets, High-Tc superconductors and their application in accelerators

Superconducting cavities – why it is required, Design considerations, 4K and 2K cavities, different types of superconducting cavities (QWR, HWR, elliptical cavities), Practical design examples of SC cavities (VECC QWR, proton accelerator for IIFC, VECC SC e-LINAC).

References:

1. Vacuum Technology, 3rd edition - (North Holland, 1990) A. Roth.
2. CERN Accelerator School on Vacuum for Particle Accelerators, 2017, Paolo Chiggiato.
3. CERN Accelerator School on Beam Diagnostics, 2008, Editor D. Brandt.
4. Lecture Notes on Beam Instrumentation and Diagnostics, Peter Forck, Joint Iniversity Accelerator School, 2003.
5. CERN Accelerator School Proceedings: Magnets, 2009, Editor: D. Brandt
6. M. N. Wilson, Superconducting Magnets, New York: Oxford University Press (1983).
7. YukikazuIwasa, Case Studies in Superconducting Magnets: Design and Operational Issues, Springer Science.

Advance Nuclear Theory (Credit 4, about 30 hours) 04PHYS04-001-A2

Theoretical models for heavy-ion induced reactions, concept of nuclear dissipation. Nuclear thermodynamics, calculation of density of states, different phase transitions in nuclei, statistical model theory for nuclear multi-fragmentation.

Stochastic dynamics for heavy-ion reactions. Theory for direct reactions. Dynamical theories at intermediate energies: QMD and BUU.

Small amplitude collective dynamics and Bohr's theory. Electromagnetic transitions. Theory for large angular momentum.

Quantum many-body theory for nucleus: Hartree-Fock theory. Introduction to nuclear energy density functional. Nuclear pairing, BCS and Hartree-Fock-Bogoliubov theory. Introduction to time-dependent models.

Advance Nuclear Experiment

Experimental Nuclear Reaction I (Credit 2, about 16 hours): 04PHYS04-002-A3_1
Heavy-ion induced reactions and their classifications, Fusion fission, quasi-fission, deep inelastic reactions - experimental probes and measurements. Major challenges in the search of super heavy elements. Fusion evaporation and Hauser Feshback model. Nuclear level density and its experimental determination. Heavy-Ion Induced Transfer reactions, their implication to fusion fission dynamics, Giant dipole resonances and GDR as a probe to study shape of nuclei, nuclear dissipation.

Experimental Nuclear Reaction II (Credit 2, about 16 hours): 04PHYS04-002-A3_2

Direct reaction study, Different types of light ion induced transfer reactions, transfer reactions as a spectroscopic information tool, Complex fragment emission mechanisms and their experimental characterisations, Structure and decay of particle unbound state using multi-particle correlation, Nuclear reaction in intermediate & Fermi energy domains, experiments with large arrays, Nuclear thermometry, isoscaling

Nuclear Structure Studies-I (Credit 2, about 16 hours) 04PHYS04-002-A3_3

Introduction to high resolution gamma spectroscopy and gamma detector arrays: relevant parameters; Methods for production of excited states; Experimental observables and properties of discrete excited levels; Techniques for construction of level scheme: measurement of gamma-gamma coincidence, angular distribution & correlation, linear polarization; Ancillary detectors and tagging;

Nuclear Structure Studies-II (Credit 2, about 16 hours) 04PHYS04-002-A3_4

Nuclear Isomerism, transition probability, lifetime and moments; Nuclear structure and its interpretation from lifetime and moments; Direct & Indirect lifetime measurement techniques: Doppler shift techniques, Electronic techniques and Fast timing techniques; Perturbed angular correlation methods for moment measurements: TDPAC and IPAC;

Nuclear Structure Studies-III (Credit 2, about 16 hours) 04PHYS04-002-A3_5

Theory of beta decay; Physics of decay rate changes, □-delayed particle emissions & double □ decay; Experimental probes : Decay- half-life, endpoint energy, and transition probability; Measurement techniques: Beta-gamma spectroscopy, Total Absorption Gamma Spectroscopy (TAGS), Decay spectroscopy for reaction cross section measurement; Application in nuclear physics and nuclear astrophysics

Nuclear interactions and mass measurement techniques (Credit 2, about 16 hours) 04PHYS04-002-A3_6

Introduction to mass models, techniques of mass measurements, Introduction to Ion trapping, Penning Ion Trap (PIT), Ion Manipulation in PIT, Loading and cooling of ions, Frequency measurement techniques, Mass measurement using PIT, Other applications of PIT.

Suggested Books:

1. Shell-Model applications in nuclear spectroscopy, by P J Brussaard and P W M Glaude-mans.
2. Nuclear shell theory, by A de-Shalit and I Talmi
3. The nuclear many-body problem, by P Ring and P Schuck
4. Nuclear models, by W Greiner and J AMaruhn
5. Nuclear structure from a simple perspective by R F Casten
6. Theory of nuclear structure by M K Pal
7. Direct nuclear reactions, by N K Glendenning
8. Theory of nuclear fission, by H Krappe and K Pomorski
9. Nuclear structure Vol I and Vol II, by A Bohr and B Mottelson
10. Introduction to Nuclear Reaction G. R. Satchler
11. Theroetical Nuclear Physics Blatt, Weisskopf
12. Nuclear Fission R. Vandenbosch and J. R. Huizenga
13. Giant Resonances, Fundamental Highfrequency Modes of Nuclear Excitation, By M.N. Harakeh, A. van der Woude, Clarendon Press, Oxford, 2001.
14. Treatise on Heavy Ion Science, Volume 2, Fusion and Quasi-Fusion Phenomena, Edited by D. Allan Bromley
15. Treatise on heavy-ion science. Vol. 3: compound system phenomena, Edited by D. Allan Bromley

16. Heavy Ion Collisions at Intermediate Energy: Theoretical Models", by S. Das Gupta, S. Mallik and G. Chaudhuri, World Scientific Publishers, Singapore (2019)
17. Nuclear Dynamics in the Nucleonic Regime By D Durand, E Suraud, B Tamain
18. Treatise on heavy-ion science. Vol. 8: Nuclei far from Stability, Edited by D. Allan Bromley
19. In-beam gamma ray spectroscopy: H. Morinaga and T. Yamazaki
20. Alpha Beta and Gamma Ray spectroscopy: Ed K. Siegbahn
21. Handbook of Nuclear Spectroscopy: J. Kantele
22. Gamma Ray and Electron spectroscopy in nuclear physics: H. Ejiri and M. J. A de Voigt
23. Lecture Notes and Recent Literatures
24. Atomic Masses and Fundamental Constants edited by Jerry A. Nolen, Walter Benenson
25. Ion Traps by P. K. Ghosh

Advanced Materials Science (Credit 4, about 32 hours) 04PHYS04-003-A4_1

Interaction of radiation with matter: Interaction of electromagnetic radiation, neutrons and charged particles with matter, Concept of nuclear and electronic energy loss, Differential cross section in projectile target collision

Radiation Damage Event: Neutron-nucleus interactions, Interaction between ions and atoms, Ionization collisions. The displacement of atoms: Elementary displacement theory, Modification to Kinchin-Pease displacement model, Displacement cross-section Damage cascade: Displacement mean free path, Primary recoil spectrum, Cascade damage energy and cascade volume, stages of cascade development, behaviour of defects within the cascade

Radiation induced defect formation: Point defect formation, Thermodynamics of point defect formation, Diffusion of point defects, Dislocations. Radiation enhanced diffusion and reaction rate theory: Point defect balance equation, Radiation enhanced diffusion, Defect reactions, Reaction-rate controlled processes.

Radiation induced segregation (RIS): RIS in concentrated binary alloys and ternary alloys, Effect of local composition changes on RIS.

Phase stability under irradiation: Radiation induced segregation, Radiation induced precipitation, Meta-stable phases, Amorphization.

Unique effects of ion irradiation: Ion irradiation techniques, Composition changes, Other effects of ion implantation like grain growth, Texture, Dislocation microstructure.

Simulation of neutron damage with ions : Aspects of radiation damage relevant to ion irradiation, Advantages and disadvantages of various particle types, Emulation of neutron irradiation damage with proton, Irradiation parameters for particle irradiation,

Effects on mechanical properties due to irradiation hardening, Embrittlement, Irradiation creep and growth.

Suggested Books:

1. GARY S. WAS Fundamentals of Radiation Materials Science : Metals and Alloys (2017)
2. Comprehensive Nuclear Materials, Elsevier, Editor-in-Chief Rudy J.M. Konings (2020)
3. J.H. Gittus, "Irradiation Effects in Crystalline Solids", Applied Science Ltd., (1978)

<u>Advanced Condensed Matter Physics (Credit 4, about 32 hours) 04PHYS04-003-A4-2</u>

Nano-particle Physics:Introduction to nanoscale physics, nano mechanics, nano electronics, nano photonics, spintronics, various nano structured materials and their synthesis processes, probing of nano materials by advanced tools, applications of nano materials. Development of irradiation induced nanostructure and its characterization by AFM.

Advanced oxide materials :Crystal field splitting, John Teller distortion, Zener double exchange model, Mott Insulator, High temperature superconductor, Manganites, Density functional theory, Magnetic property of a solid, d^0 ferromagnetism, Defect in materials.Characterization of defect by Positron annihilation spectroscopy.Mossbauer spectroscopy.

Tight binding model, Graphene band structure, Su–Schrieffer–Heeger Model, Anderson Localization, Integer Quantum Hall Effect, Anomalous Integer Quantum Hall Sequence in Graphene

1. Solid State Physics, A. J. Dekker.
2. Physics of Nanostructures, Dresselhaus and Dresselhaus.
3. Transition Metal Oxides: An Introduction to Their Electronic Structure and Properties, P. A. Cox.
4. Modern Condensed Matter Physics, Steven M. Girvin, Kun Yang, Cambridge University Press, 2019
5.Solid State Properties: From Bulk to Nano, Mildred Dresselhaus, Gene Dresselhaus, Stephen B. Cronin, and Antonio Gomes Souza Filho, Springer, 2018.
6.Condensed Matter in a Nutshell, Gerald D. Mahan, Princeton University Press, 2010
7. Fundamentals of Condensed Matter Physics, Marvin L. Cohen, Steven G. Louie, Cambridge University Press, 2016.

Advanced Course on Relativistic heavy-ion collision experiments & quark-gluon plasma (Credit 4, about 32 hours): 04PHYS04-004-A5-1

Introduction to relativistic heavy-ion collisions and quark-gluon plasma (QGP)

Relativistic kinematics: Lorentz transformation: frequently used reference frames, four vector notation, rapidity and pseudo-rapidity variables, light cone variables, collision and decay, relativistic invariants

Thermodynamics: Relativistic gas (hadrons, quarks and gluons) and its statistical and thermodyamical properties, MIT Bag model, Hagedron gas, phase diagram of QCD, criteria for formation of QGP in the laboratory

Collision dynamics: different stages of space-time evolution like pre-equilibrium, formation of QGP, chemical and thermal equilibria, freeze-out and particle production; Bjorken's model for energy density;

Basics of different Monte-Carlo event generators: Pythia, Hijing, AMPT, EPOS (can be part of mini-projects)

Experiments: a general overview of past, present and future experimental facilities dedicatedto search for QGP, data analysis technique, extraction of 4 momentum, control variables(centrality, root(s), system size)

Signals of QGP:

Global Observable: Multiplicity, ET, Ef, (pseudo)Rapidity, Pt distributions: explanations of various regions and connections with particle production mechanism; Correlations and fluctuations; Collective flow: radial, directed, elliptic and higher order flow harmonics extraction and interpretations; Heavy quark and quarkonia suppression, strangeness enhancement, jet quenching and electromagnetic signals (photon and di-lepton).

Suggested books:

1. Introduction to High-Energy Heavy-Ion Collisions, C. Y. Wong, World Scientific
2. The Physics of the Quark-Gluon Plasma: Introductor Lecture, Sourav Sarkar, Helmut Satz, BikashSInha (Eds.), Springer
3. A Short Course on Relativistic Heavy Ion Collisions, Asis Kumar Chaudhuri, IOP Publishing
4. Data Reduction and Error Analysis for the Physical Sciences, Philip R. Bevington and D. Keith Robinson, McGraw-Hill
5. Introduction to Experimental Particle Physics, Richard Fernow, Cambridge University Press
6. Quark-Gluon Plasma Lectures, Bikash Sinha, Santanu Pal, SibajiRaha (Eds.), Springer-Verlag

Advanced Course on Quantum Chromodynamics (QCD) and Relativistic Heavy Ion Physics (Credit 4, about 32 hours): 04PHYS04-005-A5-2

Part - I (Quantum Field Theory and QCD)

Renormalization in quantum field theory: One loop radiative corrections in quantum electrodynamics (OED), Power counting and the index of Divergence, dimensional regularizations and renormalizations. Calculations of one loop diagrams in QED.

Deep Inelastic Collisions: Proton form factor, Deep inelastic scattering of electron off proton, Parton evolutions.
Quantum Chromodynamics (QCD): Non-abelian guage theory, one loop diagrams and running coupling, Pertubative QCD.

Part - II(Relativistic Heavy Ion Physics)

Heavy Ion collisions at Ultra Relativistic Energies:Quark Gluon Plasma, Hadrons in thermal bath, Thermodynamics of strongly interacting matter, QCD phase transition in the laboratory, Space time evolution, Relativistic hydrodynamics and signals of quark gluon plasma.

Suggested Books :

1. An introduction to Quantum Field Theory, M. E. Peskin and D. V. Schroeder
2. Quantum Field Theory, L. H. Ryder
3. Field Theory, P. Ramond
4. Gauge Field theory, S. Pokoroski
5. Quantum field theory, L. S. Brown
6. Introduction to High Energy Heavy Ion Collisions, C. Y. Wong
7. Quark Gluon Plasma from Big Bang to Little Bang, K. Yagi, T. Hatsuda and Y. Miyake

After completion of this 42 credit, a student may either choose advance courses equivalent to 8 credit or advance course equivalent to 4 credit + Self Study Course equivalent to 4 credit.

Self Study Course : 04PHYS04-007-S (Maximum 4 credits)

Completion of course work requires a Project work equivalent to 10 credit.
04PHYS04-006-A7

Total credit: 60

Contact:Dean-Academic (Physical Sciences)
Variable Energy Cyclotron Centre
Department of Atomic Energy
1/AF BidhanNagar, Kolkata 700 064