ENGINEERING SCIENCE

Programme Code: *ENGG00*

Programme Outcome:

This program at IPR is designed to give students the opportunity to engage with the forefront of plasma research. The initial one-year coursework helps students develop a strong, integrated foundation in plasma physics, fusion science, associated experimental, theoretical, computational methods including data analysis, and scientific computing; thus preparing students to independently conduct high-quality research. Students will learn to understand and analyze plasma behavior across multiple scales using fluid, kinetic, and magnetohydrodynamic descriptions. They will also learn to apply advanced mathematical and numerical techniques to solve complex physical problems and design, execute, and interpret plasma experiments using modern diagnostics. Additionally, instruction in research design, scientific communication, intellectual property, and publication ethics will prepare students to plan long-term research projects, present results effectively, and adhere to globally accepted ethical standards. Along with the coursework, students will initiate independent research in the form of two separate projects. In addition to the core areas of plasma and fusion, students will take a few elective courses in line with their specific research interests to gain more insight. After completing the first year of coursework, students will focus to conduct doctoral-level research under the guidance of a faculty member working in plasma and fusion research. Upon completing their doctoral research, students become independent researchers who can address challenges in plasma and fusion research as well as independent research in their area of interest.

DETAILED COURSE STRUCTURE

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1	BPP	Basic Plasma Physics	32	2
2	EPP	Experimental Plasma Physics	32	2
3	MM	Mathematical Methods	16	1
4	NM	Research Methodology: Numerical Methods	16	1
5	APP	Advanced Plasma Physics	32	2
6	PPM	Plasma Production and Measurement	32	2
7	RM	Research Methodology and Publication Ethics	32	2
8	PROJ	Project (Part A and Part B)	180	6
		CORE TOTAL	**372**	**18**

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1	LPI	Physics of Laser-Plasma Interaction	32	2
2	BTP	Basic Tokamak Physics	16	1
3	SM	Statistical Mechanics	16	1
4	ATP	Advanced Tokamak Physics	32	2
		ELECTIVES TOTAL	**96**	**6**

CORE COURSES COORDINATOR

Chief Coordinators:

Dr. Mrityunjay Kundu (, Extn.:2103 , E-Mail:mkundu @ipr.res.in)
Dr. Jinto Thomas (, Extn.: 2165, E-mail: jinto@ipr.res.in)

Course	Coordinators	Contact
Basic Plasma Physics	Dr. Devendra Sharma, Dr. Ramasubramanian	devan@ipr.res.in, mani@ipr.res.in
Experimental Plasma Physics	Dr. G Ravi, Dr. Ramkrishna Rane	gravi@ipr.res.in ramu@ipr.res.in
Mathematical Methods	Dr. Rajiv Goswami	rajiv@ipr.res.in
Research Methodology: Numerical Methods	Dr. Bahvesh Patel	bhavesh@ipr.res.in
Advanced Plasma Physics	Dr. R Ganesh	ganesh@ipr.res.in
Plasma Production and Measurement	Dr. Shantanu Kumar Karkari Dr. Pintu Bandyopadhyay	skarkari@ipr.res.in pintu@ipr.res.in
Research Methodology and Publication Ethics	Dr .C. Balasubramanian Dr .Ritesh Sugandhi	balac@ipr.res.in ritesh@ipr.res.in

ELECTIVES COURSES COORDINATOR

Chief Coordinators:

Dr. Mrityunjay Kundu (, Extn.2103: , E-Mail: mkundu@ipr.res.in)
Dr. Jinto Thomas (, Extn.: 2165, E-mail: jinto@ipr.res.in)

Course	Coordinators	Contact
Physics *of Laser*-Plasma Interaction	Dr. Sudip Sengupta	sudip@ipr.res.in
Advanced Tokamak Physics	Dr. Joydeep Ghosh Dr. Prabhakar Srivastav	jghosh@ipr.res.in prabhakar.srivastav@ipr.res.in
Advanced Tokamak Diagnostics	Dr. Shishir Purohit Dr. Jinto Thomas	pshishir@ipr.res.in jinto@ipr.res.in
Heating and Current Drive in Tokamaks	Dr. Sanjeev Kumar Sharma	sksharma@ipr.res.in
Waves In Guided Media	Dr. Varsha Siju	varsha@ipr.res.in

Fueling and plasma-wall interaction in Tokamaks (1 Credit, 15 Lectures)	Dr. Jyoti Shankar Mishra	jsmishra@ipr.res.in
Plasma Material Interaction	Dr. Sejal P Shah Dr. Mukesh Ranjan	sejal@ipr.res.in ranjanm@ipr.res.in
Physics of Low Temperature Plasma	Dr. Mainak Bandyopadhyay	mainak@ipr.res.in
Electromagnetic Theory	Dr. Rana Pratap Yadav	rana.yadav@ipr.res.in
Classical Mechanics	Dr. Anil Kumar Tyagi	aktyagi@ipr.res.in
Statistical Mechanics	Dr. Jugal Chowdhury	jugal.chowdhury@ipr.res.in
Fluid Mechanics	Dr. Amulya Kumar Sanyasi	amulya@ipr.res.in
Basic Tokamak Physics	Dr. Joydeep Ghosh	jghosh@ipr.res.in

CORE COURSES

1. Basic Plasma Physics (2 Credits, 30 Lectures)

Coordinators: Dr. Sharma(devan@ipr.res.in),
Dr. Ramasubramanian(mani@ipr.res.in)

Course Details

- **Introduction:**

  Definition of plasma, description of collective behaviour in contrast to single particle behaviour, derivation of plasma frequency (slab model), Debye length (description of Boltzmann distribution can be given here), conditions for collective behaviour (Physical basis for these conditions), binary collisions (derivation of Rutherford scattering), derivation of collision frequency νei (large angle collisions, cumulative effect of many small angle collisions, Coulomb logarithm), discussion of collective behaviour revisited with relationship between various conditions (discussion of kλD << 1, plasma parameter).

- **Single Particle Motion:**

  Lorentz force equation, Non-relativistic motion of a charged particle in constant electric and magnetic field: motion in constant E→field, constant B→field (derivation of cyclotron frequency, Larmor radius), motion in crossed E→ and B→field, drift in a combined magnetic field and a general force field (non-magnetic), Motion in non-uniform B→ field (guiding centre approximation): Grad B drift (∇B ⊥ B), curvature drift, ∇B B (magnetic mirrors, invariance of μ, concept of adiabatic invariance), Uniform B→ and spatially varying E→ field (Finite Larmor radius effects), Time and space varying E→ field (Ponderomotive force), Time varying magnetic field (adiabatic compression), Time varying E→ field (polarizationDrift)

- **Dielectric Description Of a Plasma:**

  Derivation of wave equation, dielectric constant for a cold unmagnetized plasma, normal modes (electrostatic and electromagnetic) in a cold unmagnetized plasma, dielectric constant for a cold magnetized plasma, High frequency waves in a cold magnetized plasma: waves parallel to the magnetic field (left and right circularly polarized modes, whistler mode, cut off, resonance,Faraday rotation), waves perpendicular to the magnetic field (ordinary mode, extra-ordinary mode, cut off, Cotton-Mouton effect), CMA diagram.

- **Fluid Description:**

Heuristic derivation of fluid equations (continuity equation, momentum equation), equation of state, complete set of two fluid equations, Fluid drift perpendicular to B→ (diamagnetic drift), High frequency electrostatic waves in an unmagnetized plasma (Langmuir waves, Bohm-Gross waves

), High frequency electrostatic waves in a magnetized plasma (upper hybrid oscillation), High frequency electromagnetic modes in an unmagnetized and magnetized plasma, Low frequency electrostatic waves in unmagnetized and magnetized plasma: ion-acoustic wave, ion cyclotron wave, lower hybrid oscillation.

- **MHD Description:**

Derivation of single fluid equations from two fluid equations, complete set of equations for ideal MHD, Force and motion in Ideal MHD, MHD waves (Alfven wave, magnetosonic wave), MHD energy.

Course Outcomes

Upon the completion of Basic Plasma Physics course, students will develop a comprehensive understanding of plasma as a distinct state of matter, including its collective behavior, fundamental parameters, and conditions for plasma behavior. They will be able to analyze single particle motion in electric and magnetic fields, including drifts, guiding center motion, and the effects of time- and space-varying fields, as well as understand adiabatic invariants and ponderomotive forces. The course objectives are to provide students with the ability to describe plasma using dielectric theory, including wave propagation in unmagnetized and magnetized plasmas, normal modes, cutoffs, resonances, and polarization effects such as Faraday rotation and the Cotton-Mouton effect. Additionally, students will acquire skills in fluid and magnetohydrodynamic (MHD) descriptions of plasma, including the derivation and application of two-fluid and single-fluid equations, diamagnetic drifts, electrostatic and electromagnetic wave modes, and MHD waves, such as Alfvén and magnetosonic waves. In summary, the course offers a comprehensive theoretical foundation for the analysis of plasma phenomena in laboratory and fusion research, integrating the perspectives of particles, waves, and fluids.

References:

1. Introduction to Plasma Physics and Controlled Fusion, F.F. Chen, Springer Nature, 2016.
2. Fundamentals of Plasma Physics, J.A. Bittencourt, Springer-Verlag New York Inc., 2004.
3. Plasma Physics: An Introductory Course, R.O. Dendy, Cambridge University Press, 1995.
4. Introduction to Plasma Physics, R.J Goldston, P.H Rutherford, CRC Press, 1995.

2. Experimental Plasma Physics (2 Credits, 30 Lectures)

Coordinators: Dr. G Ravi(gravi@ipr.res.in),
Dr. Ramkrishna Rane (ramu@ipr.res.in)

Course Details

- **Fundamentals of Vacuum Science:**

  Concept of vacuum and vacuum measurements pressure and flow measurements, different range of Vacuum. Concepts of vapour pressure, different types of pressure measurement devices and different pumps. Concepts of mass flow rate, conductance, pumping speed, volume flow rate, through-put.

- **Fundamentals of Gaseous Discharge:**

  Different types of collisions and collision parameters, charge Particles under constant electric field (E/p), ionization and charge exchange processes. thermionic emission, field emission, electron multiplication.

- **Gas Discharges:**
  - DC discharges DC breakdown at low pressure, Paschen law and its experimental validation, condition for self-sustenance. I-V characteristics of DC discharge: Corona discharge, normal and abnormal glows, arc discharge, etc. Regions of DC glow discharge like Cathode dark space, positive column and anode glow.
  - AC Discharges RF capacitive discharge, RF inductive discharge, ECR and wave based (Helicon) discharge, DBD discharges

- **Plasma Sheaths and various electrostatics probes:**

  Ion and electron sheaths, Bohm criteria, significance of pre-sheath, familiarity with different types of sheathsChild Langmuir, Matrix sheath Current-Voltage characteristics of a single Langmuir probe, double Langmuir probe.

- **Equilibrium Discharge Properties:**

  D.C and A.C plasma conductivity, plasma resistivity, mobility and diffusion with/without magnetic field, Ambipolar diffusion

- **Spectroscopic Diagnostics:**

  Basic introduction to spectrum and spectral lines based on Atomic and Molecular structure, Introduction to Emission, Absorption and Fluorescence spectroscopy, Einsteins coefficients for transitions, Understanding of different spectroscopic models (Corona, CR model, LTE model).

Course Outcomes

Upon completion of this course, students will gain a thorough understanding of vacuum technologies and their practical operation, including measurement, troubleshooting, and maintenance of laboratory vacuum systems. They will be able to analyze and predict gas discharge behavior under DC and RF excitation, including breakdown conditions, I–V characteristics, and glow and arc discharge regimes. The course equips students with knowledge of plasma–wall interactions and sheath formation, providing a foundation for interpreting probe diagnostics and sustaining plasma parameters such as plasma potential and Bohm velocity. Students will also develop a basic understanding of equilibrium discharge properties, including plasma conductivity, mobility, and ambipolar diffusion, with and without magnetic fields. Additionally, they will gain introductory exposure to spectroscopic diagnostics, including emission, absorption, and fluorescence techniques, enabling them to connect atomic and molecular processes with plasma behavior in laboratory settings. Overall, the course prepares students to design, operate, and analyze low-pressure plasma experiments, bridging theory and hands- on laboratory practice.

References:

1. Gas Discharge Physics, Yuri P. Raizer, Springer-Verlag Berlin and Heidelberg GmbH and Co., 2011.
2. Principles of Plasma Discharges and Materials Processing, Michael A. Lieberman and Alan J. Lichtenberg, Wiley-Interscience, 2005.
3. Principles of Plasma Diagnostics, I. H. Hutchinson, Cambridge University Press, 2005.
4. Glow Discharge Processes: Sputtering and Plasma Etching, Brian Chapman, Wiley-Interscience, 1980.

3. Mathematical Methods (1 Credit, 15 Lectures)

Coordinators: Dr. Rajiv Goswami
(rajiv@ipr.res.in)

Course Details

- **Ordinary Differential Equations (ODE):**

  First order equations, Uniqueness theorem, Lipschitz condition, Equations with separated and separable variables, Homogeneous first order equations, Equations reducible to homogeneous form, First order linear equations, Bernoullis equation, Exact differential equations, Second order linear homogeneous equations, Wronskian, Liouvilles formula, Second order linear homogeneous equations with constant coefficients, Equations equidimensional in x (Euler equations), Reduction of order, Second order linear non-homogeneous equations, Method of variation of parameters, Greens function method, Method of undetermined coefficients (for equations with constant coefficients), Nonlinear equations, Ricatti equation, Autonomous equations, Equations equidimensional in y, Scale invariant equations. Stability for a linear system of ODEs.

- **Approximate Methods for solving ODE:**

  Power series method, Picards method, Perturbative method, Poincare-Lindstedt Method, WKB method.

- **Complex Analysis:**

  Introduction to complex variables, function of a complex variable, Analytic functions, Derivatives of a complex function, Cauchy-Riemann conditions (Cartesian and polar form), Branch points, Complex integration, Cauchy’s theorem or Cauchy-Goursat theorem, Cauchy’s integral formula, Higher derivatives of analytic functions, Taylor and Laurent series, Singularities (poles and essential singularity), Residues, Cauchy Residue theorem, Contour integration, Calculation of real integrals, Trigonometric integrals, $\int \infty f\,(x)eikx$, Jordan’s lemma, Integrals with poles on real axis, Cauchy principal value, Integrals of multivalued functions (branch points and cuts), Summation of series using Contour integration. Conformal Mapping and its application to the solution of Laplace equation.

- **Partial Differential Equations (PDE):**

  Introduction, Principle of superposition, Some important equations (wave equation, heat conduc- tion or diffusion equation, Laplace equation, Poisson’s equation etc.), Classification of PDE’s (elliptic, parabolic and hyperbolic type and reduction to canonical form), Boundary conditions (Dirichlet, Neumann and Cauchy Boundary conditions), Methods of solution of a first order and second order PDE, Method of characteristics, Separation of variables technique, Integral transform techniques.

- **Integral Transforms:**

  Fourier integral, Fourier transform and its inverse, Parsevals equation, Laplace transform, Shift theorem, Transforms of derivatives, Convolution theorem, Delay theorem, Dirac delta function and its transform, Inverse Laplace transform (using contour integration; general inversion formula), Laplace inverse of functions with branch points, Solution of ODEs and PDEs using integral trans- forms, Solution of Volterra and Fredholm integral equations using integral transform techniques.

Course Outcomes

Upon completion of this course, students will strengthen their foundational mathematical skills while gaining exposure to advanced analytical techniques that are widely used in plasma physics and other areas of research. They will be able to solve ordinary differential equations (ODEs) and partial differential equations (PDEs) using both exact and approximate methods, including perturbation, power series, and WKB techniques. Students will develop proficiency in complex analysis, including contour integration, residue calculus, and conformal mapping, enabling them to tackle problems in potential theory and wave propagation. Additionally, they will acquire proficiency in integral transform methods, including Fourier and Laplace transforms, and will learn to apply these tools to solve differential and integral equations. The course's objective is to provide students with a comprehensive mathematical toolkit that can be applied to the modeling, analysis, and solution of complex problems in the fields of theoretical and computational plasma physics, as well as in related areas of science and engineering.

References:

1. Mathematical Methods for Physicists, Arfken, Weber, and Harris, Elsevier 2012.
2. Advanced Mathematical Methods for Scientists and Engineers I: Asymptotic Methods and Pertur- bation Theory, Carl M. Bender, Steven A. Orszag, Springer, 1999.
3. Advanced Engineering Mathematics, Erwin Kreyszig, Wiley, 2006.

4. Research Methodology: Numerical Methods (1 Credit, 15 Lectures)

Coordinators: Dr. Bahvesh Patel
(bhavesh@ipr.res.in)

Course Details

- **Solution of Algebraic Equations:**

  Gaussian elimination, Gauss-Jordan elimination, LU decomposition and its applications, Tridiag- onal and band diagonal system of equations, Singular value decomposition, iterative improvement of a solution .

- **Root finding and nonlinear set of equations:**

  Introduction, bracketing and bisection, Secant method, false position method, Newton Raphson method, Roots of polynomial, Newton-Raphson method for nonlinear system of equations.

- **Modeling of Data:**

  Introduction, Chi-square Fitting, Goodness of fit, Variances and co-variances of the parameters, Fitting data to a straight line, General linear least square.

- **Integration of Ordinary Differential equations:**

  Introduction, Taylors series method, Eulers method, Runge-Kutta Methods, Predictor-correction method, Boundary value problems, Finite-Difference method.

- **Fast Fourier transform (FFT) and its applications:**

  Introduction to FFT, Discrete Fourier Transform, Leakage and windows, Box-Car window, Han- ning window, Convolution and correlation, Auto power spectra, cross power spectra and coherence spectra, Data smoothing, Bi-spectral analysis.

Course Outcomes

Upon completion of this course, students will acquire a strong foundation in numerical methods, which are essential for scientific and engineering computations. They will be able to solve systems of linear algebraic equations using direct and iterative techniques, including matrix decomposition and singular value decomposition. Students will develop an understanding of and proficiency in the application of numerical methods for finding roots of nonlinear equations and systems of equations. Proficiency in data modeling and parameter estimation will be cultivated through least-squares fitting, statistical error analysis, and goodness-of-fit evaluation. Students will be equipped with the skills to numerically integrate ordinary differential equations and solve boundary value problems using finite-difference and predictor–corrector methods. Additionally, they will acquire proficiency in Fourier analysis techniques, encompassing FFT, spectral analysis, convolution, correlation, and data smoothing. This will equip them with the necessary skills to analyze and interpret experimental and computational data encountered in advanced scientific research.

References:

1. Numerical Recipes: The Art of Scientific Computing, William H. Press , Saul A. Teukolsky , William T. Vetterling , Brian P. Flannery, Cambridge University Press, 2007.
2. Numerical Methods for Scientists and Engineers, H. M. Antia, Birkhauser Verlag AG, 2002.
3. Numerical Methods in Engineering & Science with Programs in C, C++ & MATLAB, B.S.Grewal, Khanna Publishers, 2013.

5. Advanced Plasma Physics (2 Credits, 30 Lectures)

Coordinators: Dr. R Ganesh
(ganesh@ipr.res.in)

Course Details

- **Non-Equilibrium Classical Statistical Mechanics:**

  Study of Brownian motion, Random walk model, Langevins force equation, fluctuation-dissipation theorems, Fokker-Planck equation, Introduction to driven-dissipative systems.

- **Fundamentals of plasma kinetic theory:**

  Concepts of Distribution function, Maxwell-Boltzmann Distribution (Determination of the Con- stant Coefficients, moments of Maxwell-Boltzmann Distribution, RMS, Most probable speed, Speed and Energy distribution function.)

  Many body description for plasma, The Klimontovich Dupree system of equations, BBGKY Hier- archy, Liouville equation, Boltzmann equation, Moments of the Boltzmann Equation (derivation of fluid equations), Vlasov Equation, Fokker-Planck Equation, Properties of Vlasov Equation, Linear Equilibrium Solutions.

- **Vlasov theory of Waves and instabilities:**

  Derivation of electrostatic waves from linearized Vlasov-Poisson system of equations (Langmuir wave, Ion Acoustic Wave) and linear Landau Damping, kinetic two-stream instability and negative energy waves, kinetic theory of magnetized hot plasmas.

- **Nonlinear Vlasov equilibria and waves:**

  Nonlinear (nonperturbative) electrostatic waves, BGK equilibrium, wave-like nonlinear Vlasov states and trapped particle equilibria, integral and differential formulations, non-linear dispersion relation.

Course Outcomes

Syllabus is specialized to focus on concepts directly relevant for multi-time scale physics processes that are known to be important in understanding Tokamak plasmas and other fundamental phenomena, such as wave- particle resonances and nonlinear processes. A direct outcome of this syllabus is that a student once trained, would be equipped to handle advanced research topics using experiments or theory and/or computational methods. Long term ramifications are constant generation of state-of-the-art, ready-to-be-deployed manpower for country's academia as well as for domestic fusion program and industrial applications.

References:

1. Fundamentals of plasma physics, Jos´e A Bittencourt, Springer Science & Business Media, 2013.
2. Principles of plasma physics, Nicholas A Krall and Alvin W Trivelpiece, McGraww-Hill Book Company, 1973.
3. Introduction to Plasma Theory, D. R. Nicholson, Krieger Pub Co, 1992.

6. Plasma Production and Measurements (2 Credits, 30 Lectures)

Coordinators: Dr. Shantanu Kumar Karkari(skarkari@ipr.res.in),
Dr. Pintu Bandyopadhyay(pintu@ipr.res.in)

Course Details

- **Experimental Electronics:**

  Application of operational amplifier, summing amplifier (AC+DC), differential amplifier, inverting and non-inverting amplifier, design of regulated DC power supply.

- **Experimental demonstration of vacuum system:**

  Operation of rotary and diffusion pumps. Creating vacuum and its measurements, leak detection, estimation of pumping speed.

- **Characteristics of DC Discharge:**

  Validation of Paschen law of Gas breakdown, Measurements of current-voltage (DC impedance) characteristics of a discharge and demonstration of glow discharge regions.

- **B-dot probe measurement:**

  Design understanding and construction of a B-dot Probe and its measurement principle, Probe Calibration experiment and frequency response.

- **Single Langmuir Probe:**

  Design understanding and construction of a Single Langmuir Probe, Obtaining I-V Characteristic of a Langmuir probe in plasma, measurement of different plasma parameters.

- **Measurements of plasma potential using Emissive Probe:**

  Design understanding and construction of an Emissive Probe, Measurements of plasma potential using an emissive probe.

- **Excitation of Ion Acoustic Waves in Plasma and ion acoustic speed measurement:**

  Design of launcher and receiver for exciting and detecting ion acoustic wave. Measurement of dispersion relation of ion acoustic wave.

- **Spectroscopic measurements:**

  Arrangement of an experimental setup for optical emission spectroscopy. Detection of neutral and ionic species in plasma.

Course Outcomes

The Experimental Plasma Physics course, a component of the PhD (Physics and Engineering) program, is meticulously designed to develop robust experimental competence among research scholars. This objective is accomplished through immersive, hands-on training on a diverse array of plasma experiments. Upon successful completion of the course, students will be adequately prepared to operate, troubleshoot, and safely handle essential experimental subsystems, including electronic circuits, vacuum systems, and DC discharge devices. The program's practical approach will equip the students with the skills necessary to construct and utilize essential plasma diagnostic instruments, such as B-dot probes, Langmuir probes, emissive probes, and spectroscopic systems. These instruments are vital for measuring fundamental plasma parameters. Through experiments on wave excitation and discharge characteristics, students will be able to validate theoretical concepts and correlate them with experimental observations. Furthermore, the course will equip students with the ability to independently acquire, analyze, and interpret experimental data using computational tools such as Python. The course is designed to equip students with the necessary skills and knowledge to design and implement diagnostics, analyze experimental results, and engage in advanced experimental plasma research with confidence.

7. Research Methodology and Publication Ethics (2 Credits, 30 Lectures)

Coordinators: Dr. C. Balasubramanian(balac@ipr.res.in),
Dr. Ritesh Sugandhi(ritesh@ipr.res.in)

Course Details

- **Research design and methods (14 lectures)**

    - **Objectives and types of research:** Motivation and objectives - Research methods. Types of research Descriptive and Analytical; Applied and Fundamental; Quantitative and Qualitative; Conceptual and Empirical.

    - **Research Formulation:** Defining and formulating the research problem - Selecting the problem

      - Necessity of defining the problem - Importance of literature review in defining a problem - Literature review Primary and secondary sources - reviews, treatise, monographs-patents - web as a source - searching the web - Critical literature review - Identifying gap areas from literature review - Development of working hypothesis.

    - **Research design:** Basic Principles - Need of research design - Features of good design Important concepts relating to research design - Observation and Facts, Laws and Theories, Prediction and explanation, Induction, Deduction, Development of Models. Developing a research plan - Exploration, Description, Diagnosis. Experimentation: Proper approach - Importance of recording observation, maintaining the records, sample history, transparency in data recording. Determining experimental and sample designs.

    - **Statistical treatment of data and errors:** Value of Statistics; Errors and Statistics - Limita- tion of analytical methods; Accuracy; Precision; Classification of errors; Minimization of errors; Significant figures and computations; Standard Deviation; Normal Distribution; Comparison of results - students t test; F-test; Chi Square test; propagation of errors.

    - **Writing thesis and research papers:** Structure and components of scientific reports - Types of report - Technical reports and thesis - Significance - Different steps in the preparation Layout, structure and Language of typical reports - Illustrations and tables - Bibliography, referencing and footnotes - Oral presentation - Planning - Preparation - Practice - Making presentation - Use of visual aids - Importance of effective communication, Manuscript drafting based on Experimental data and Literature Survey. Where to publish?, impact factor of journals, citation databases, Metrics

    - **Intellectual Property Rights (IPR):** Integrating IPR in the innovation value-chain, Basic understanding of tools of IPR such as patents, copyright, designs registrations, etc. Role of IPR in collaborative work, technology acquisition, transfer, commercialisation & trade.

- **Research ethics and Publication ethics (10 Lectures)**

- **Research ethics:** Philosophy and ethics, Ethics with respect to Science and research, Intellectual honesty and research integrity, Scientific misconducts- fabrication, falsification and plagiarism, redundant publications- duplicate and overlapping publications, selective reporting and misrepresentation of data, Environmental impacts - Ethical issues - ethical committees - Commercialization.
- **Publication ethics:** Definition, introduction and importance, Best practices, standards setting initiatives and guidelines, Conflict of interest, Publication misconduct, Violation of publication ethics, authorship and contributorship, Identification of publication misconduct, complaints and appeals, predatory journals and publishers, Reproduction of published material - Plagiarism Citation and acknowledgement - Reproducibility and accountability.

Course Outcomes:

The course on Research Design & Methods and Research & Publication Ethics is designed to provide first-year PhD students with the essential knowledge and skills required to plan, execute, and communicate high-quality research in a systematic, ethical, and time-bound manner. Upon completion of the course, students will be able to formulate well-defined research problems, identify research gaps through critical literature review, and develop appropriate research objectives and hypotheses. The course will provide students with a comprehensive understanding of various research methodologies, experimental and sample design, data recording practices, and statistical tools for data analysis, error estimation, and interpretation of results. Students will be able to organize and present research outcomes effectively through scientific reports, theses, oral presentations, and journal publications. They will also be able to demonstrate an awareness of publication metrics, journal selection, and intellectual property rights. The course is designed to equip students with the necessary skills to recognize and adhere to ethical standards in research and publication. Students will be able to identify unethical practices such as plagiarism, fabrication, falsification, and predatory publishing. Additionally, the course will cover issues related to authorship, conflict of interest, reproducibility, and research integrity. The course is designed to equip young researchers with the knowledge and skills necessary to conduct research that is both ethically sound and meets global scientific standards. It is also intended to prepare them to withstand rigorous academic scrutiny.

References:

1. Science and methods by Henry Poincare, translated in English by Francis Maitland Source: www.archive.org/details/sciencemethod00poinuoft, 1914.
2. Research Methodology: Methods and Techniques. C.R. Kothari, New Age International 2000.
3. The Ethics of Science, An Introduction, David Resnick, Taylor and Francis, 2005.
4. Research Methods for Science, M. P. Marder, Cambridge University Press , 2011.
5. Research Methodology, R. Paneer Selvam, Prentice Hall India Learning Private Limited, 2013.
6. Ethics in Scientific Research, An Examination of Ethical Principles and Emerging Topics, Cortney Weinbaum, Eric Landree, Marjory S. Blumenthal, Tepring Piquado, Carlos Ignacio Gutierrez, 2019.
7. How to Write and Publish a Scientific Paper, R.A. Day, Cambridge University Press, 1992.
8. Avoiding plagiarism, self-plagiarism, and other questionable writing practices: A guide to ethical writing, Miguel Roig, 2015.
9. An introduction to Research Methodology, B.L. Garg, R. Karadia, F. Agarwal, and U.K. Agarwal, RBSA Publishers, 2002.
10. Research Methodology, S.C. Sinha, and A.K. Dhiman, Ess Publications, 2002.

ELECTIVE

1. Physics of Laser-Plasma Interaction (2 Credits, 30 Lectures)

Coordinators: Dr. Sudip Sengupta
(sudip@ipr.res.in)

Course Details

- **Introduction to Basics of Plasmas:**

  Collective behaviour, Debye length, Plasma frequency, Binary collision, Coulomb logarithm, Collision frequency, Fluid Equations (Continuity, Momentum, Energy/Equation of State), Maxwell's Equations.

- **Waves in Unmagnetized Homogeneous Plasmas:**

  Plasma oscillation, Bohm-Gross waves, Ion-acoustic waves, Electromagnetic waves, Wave equation in a medium, Dielectric constant (ϵ), Susceptibility (χ), Characteristic modes of oscillation (plasma oscillation, e.m. wave), Ion acoustic wave (derivation using susceptibility).

- **Propagation of E.M. Wave through Inhomogeneous Plasmas:**

  Normal incidence (Exact solution with linearly varying density), WKB analysis with general inhomogeneity, Oblique incidence (S-polarized, Exact solution with linearly varying density), Oblique incidence (P-polarized, Resonance absorption)

- **Collisional Absorption of Light Wave:**

  Collisional damping of e.m. wave propagating through a homogeneous plasma, Collisional damping of e.m. wave propagating through an inhomogeneous plasmas (normal and oblique incidence (S-polarized light).

- **Parametric Instabilities:**

  Ponderomotive Force, Oscillating two-stream and Ion-acoustic Decay instability, Dispersion re- lation and calculation of growth rate, Stimulated Raman Scattering, Dispersion relation and calculation of growth rate, Stimulated Brillouin Scattering, Dispersion relation and calculation of growth rate.

- **Plasma Heating:**

  Collisional damping of electron plasma wave, Landau damping, Large amplitude electron plasma wave, Wave Breaking

- **Relativistic Effects:**

  Single Particle motion in Intense Electromagnetic Wave, Radiation Reaction Force (Landau- Lifshitz Equation of Motion), Relativistic Ponderomotive force, Relativistic Dielectric response and Self-focussing, Interaction of Relativistically Intense Laser Pulse with Underdense Plasmas (Wake wave, Akhiezer-Polovin Mode), Interaction of Relativistically Intense Laser Pulse with Overdense Plasmas (Relativistic →j × B→heating, Vacuum heating)

Course Outcomes

Upon successful completion of this course, students will develop a strong understanding of the fundamental principles governing wave–plasma interactions. The students will be able to explain the propagation of electromagnetic waves in both homogeneous and inhomogeneous plasmas. Students will develop a comprehensive understanding of both collisional and collisionless mechanisms of electromagnetic energy absorption in plasmas, including collisional damping, Landau damping, plasma heating and other related phenomena. They will be able to analyze parametric instabilities arising from intense electromagnetic waves, such as stimulated Raman and Brillouin scattering and ion-acoustic decay, including dispersion relations and growth rates. Additionally, students will develop an understanding of the interaction of relativistically intense laser fields with plasmas. This will include relativistic particle motion, ponderomotive effects, self-focusing, wakefield generation, and laser–plasma interaction regimes in under-dense and over-dense plasmas

References:

1. "The Physics of Laser-Plasma Interactions",William L. Kruer, Frontiers in Physics Series, 1987
2. "Short Pulse Laser Interactions with Matter", Paul Gibbon, Imperial College Press, 2005
3. "High Power Laser-Matter Interaction", Peter Mulser and Dieter Bauer, Springer Tracts in Mod- ern Physics 238, 2010
4. "The Interaction of High-Power Lasers with Plasmas", Shalom Eliezer, IOP Series in Plasma Physics, 2002

2. Advanced Tokamak Physics (2 Credits, 30 Lectures)

Coordinators: Dr. Joydeep Ghosh(jghosh@ipr.res.in),
Dr. Prabhakar Srivastav(prabhakar.srivastav@ipr.res.in)

Course Details

- **Thermonuclear Fusion:**

  Basic theory of fusion, Cross-section, Power balance & Ignition, Lawson criterion, Concept of magnetic confinement, Mirror machine & Tokamak, Basic configuration of tokamak, Plasma production, Tokamak operation: pulsed & steady state. Spherical tokamak and Stellarator.

- **Tokamak Equilibrium:**

  Toroidal and poloidal magnetic fields, Concept of flux function and flux surfaces, Grad-Shafranov equation, Definition of β, Rotational transform, Safety factor, Magnetic shear, Shafranov shift, Plasma shaping, Elongation, Triangularity, Trapped particles, Banana orbits.

- **Confinement and Transport:**

  Classical transport, Neoclassical transport, Bootstrap current, Anomalous transport, Turbulence and zonal flows. Pfirsch-schlu¨ter current and diffusion, L-mode, Transport barriers, H-mode, L-H transition, Confinement scaling laws: Ohmic scaling, L-mode scaling, H-mode scaling. Radiation losses, Radiation due to Impurities. Runaway electrons.

- **MHD Theory and Macroinstabilities:**

  Definition, Energy principle, MHD theory of stability, Ideal MHD instabilities, Plasma resistivity, Resistive instabilities. Kink instability, Ballooning modes, Tearing modes, Magnetic islands, Neoclassical tearing modes. Sawtooth oscillation, Fishbone instability, Toroidal Alfven Eigenmodes, Edge Localized Modes, Resistive wall mode. Disruption physics.

- **Microinstabilities:**

  Introduction, Drift waves, Ion temperature gradient mode, Trapped electron mode, Electron temperature gradient mode, Micro/Drift-tearing modes, and Kinetic ballooning mode. GyroBohm scaling.

- **Plasma Wall Interaction:**

  Introduction, Plasma sheath, Scrape-Off Layer, Recycling, Erosion. Limiter and Divertor con- cepts. Heat load.

- **Plasma Heating:**
  Ohmic heating, Auxiliary heating. RF heating. Ion Cyclotron Resonance, Electron Cyclotron

Resonance, and Lower Hybrid Resonance heating. NBI heating, α particle heating. Current drive.

- **Tokamak Diagnostics:**

  Introduction, Measurements of: Magnetic equilibrium, Plasma current, Loop Voltage, Plasma shape, Safety factor profile, Plasma density and temperature, Distribution functions, Flows, Ra- diation from plasma, Plasma Rotation, Impurity Profiles, MHD activities, Instabilities and Fluc- tuations.

  Passive & Active diagnostics. Electric diagnostics, Magnetic diagnostics, Spectroscopic diagnostics (Visible & UV), Thomson Scattering, ECE, Bolometry, Charge exchange diagnostics, Motional Stark effect, Interferometry, Microwave, Infrared and X-ray diagnostics.

- **Important Tokamaks:**

  Indigenous tokamaks: ADITYA & SST. Design parameters, Milestones, Achievements.

  International Tokamaks: JET & MAST, DIII-D & NSTX, ASDEX-U, JT-60SA, EAST, KSTAR, TCV, ITER: Design parameters, Milestones, Achievements.

- **Tokamak Reactor Design:**

  Main components: Superconducting Magnets, Vacuum Chamber, Blanket Module, Divertor, Cryostat Assembly, (Heat exchanger, Turbine, Generator). Reactor Power, Fuel resources, So- cial and economic factors, Future.

Course Outcomes

The successful completion of this course will enable students to gain a clear understanding of the fundamentals of thermonuclear fusion and magnetic confinement. They will learn how tokamaks operate and how plasma is generated, controlled, and sustained in fusion devices. The course will also build strong conceptual insight into plasma stability, transport phenomena, and the major instabilities affecting confinement. In addition, students will become familiar with key plasma diagnostics and the role of modern fusion experiments worldwide. Overall, this course will prepare students for advanced academic pursuits and professional careers in fusion energy and plasma science.

References:

1. “Tokamaks”, John Wesson, Clarendon Press-Oxford 2004
2. “Fusion Physics”, Edited by: M. Kikuchi, K. Lackner, M. Q. Tran, IAEA Vienna, 2012
3. “Collective Modes in Inhomogeneous Plasmas”, Jan Weiland, IOP Publishing Ltd, 2000
4. “Ideal MHD”, J P Freidberg, Cambridge University Press, 2014
5. “The Theory of Toroidally Confined Plasmas”, Roscoe B. White, Imperial College Press,UK, 2001.

3. Advanced Tokamak Diagnostics (2 Credits, 30 Lectures)

Coordinators: Dr. Shishir Purohit
(pshishir@ipr.res.in),
Dr. Jinto Thomas(jinto@ipr.res.in)

Course Details

- **Introductions to Fusion Devices:**

  Tokamaks, stellarators, reverse field pinch, Z-pinch, inertial confinement devices, Hybrid concepts, tokamak components and nomenclatures, Ohmic transformer, toroidal and poloidal fields, plasma pressure and magnetic pressure, equilibrium, toroidal and poloidal beta, small and large aspect ratio tokamak. Case Study: diagnostics details of Aditya-U, SST1, EAST, JT60-SA.

- **Magnetic field Diagnostics:**

  Maxwells equation, magnetic field through a coil, One turn loop and Rogowsky coil, Calibration techniques, Hall & Faraday effect, Poloidal flux measurement and detection of MHD, plasma position and symmetry measurement, Sine-cosine coil, diamagnetic measurement, Case study: basic experimental measurement paper from early tokamaks (T3, START, JFT-2, TFTR, ADITYA).

- **Particle Diagnostics:**

  Concept of particle flux, Debye shielding, Collisionality, Sheath thickness, effect of magnetic field, gridded energy analyzers, bolometric probe, neutral particle measurement, charge exchange, neu- tral transport, example paper of neutral particle measurement, probing with neutral particles, beam attenuation, charge exchange, heavy ion beam probe, fast ion diagnostics, neutron diagnos- tics, Case study: experimental papers on NPA, Fast Ion, HIBP in tokamaks.

- **Millimeter Wave Diagnostics:**

  Waves in homogenous plasma, Appelton-Hartree formalism, wave propagation in magnetic field, non-uniform plasma and WKB approximation, CMA diagram, O-mode & X-mode waves, den- sity measurement through interferometry, Michelson, Mach-Zehnder, Fabry-Perot interferometry, issues in phase shift, homodyne, heterodyne, super heterodyne techniques, Faraday rotation, po- larization measurement, inversion techniques, Reflectometry. Case study: experimental papers on density profile measurements, pedestal measurements in H-mode.

- **Radiation Diagnostics:**

  Cyclotron radiation from electron, Broadening: Doppler, relativistic, radiation, and collisional., radiation transport, absorption, emission, wave polarization effect, effect of varying magnetic fields, Cerenkov emission, Radiation through bremsstrahlung (classical and quantum effect, Gaunt factor), recombination radiation, X-ray imaging, thermal (soft X-ray) and non-thermal (Hard X-ray) measurements, types of detection systems and relevant instrumentation, Bolometry and imaging, Case Study: Experimental techniques, data analysis and interpretation of the radiation measurements.

- **Spectroscopy Diagnostics:**

  Edge plasma characteristics: limiter & divertor, composition of edge plasma, atomic & molecular processes, collisions & cross sections, electron impact ionization, recombination, excitation in edge plasma, electron molecular-ion collision, example of these processes in He, and C impurity ions, spectral line and continuum spectrum, continuum: bremsstrahlung, properties of spectral line : central wavelength, intensity & line width, Intensity - population mechanisms of excited level via LTE, Corona & collisional radiative model, line profile: natural, Doppler, pressure, Reabsorption, line shift and split: Doppler and Zeeman, applications to basic and fusion plasma: measurements of electron and density temperature measurement, rotation velocity and Z effective, magnetic field measurement through Zeeman polarization spectroscopy. Case Study: Experimental techniques, data analysis and interpretation in a tokamak.

- **Physics study with diagnostics: Case studies:**

  Plasma equilibrium, G-S equation, plasma parameters as flux functions, profile estimation of plasma beta, internal inductance, current density and safety factor. Effect of current profile modification and transport/impurity control, H-mode pedestal studies, L-I-H transition, ELMs, Zonal flow and limit cycle oscillations.

Course Outcomes

Upon completion of this course, students will acquire a comprehensive understanding of fusion confinement devices, with an emphasis on tokamaks, their components, magnetic configuration, and operational parameters. Upon successful completion of the course, students will be able to explain the principles and applications of a wide range of advanced plasma diagnostics used in magnetic fusion experiments, including magnetic, particle, millimeter-wave, radiation, and spectroscopic diagnostics. Students will develop the ability to apply electromagnetic theory, wave propagation, atomic and molecular physics, and radiation processes to interpret diagnostic measurements in plasmas. Students will be able to analyze diagnostic data to infer key plasma parameters such as density, temperature, current density, magnetic field, impurity content, rotation, and confinement properties. By means of case studies from major tokamak experiments, students will gain practical insight into diagnostic design, calibration, data analysis, and uncertainty interpretation. The course is designed to provide students with the necessary skills and knowledge to utilize diagnostics as a means of investigating plasma equilibrium, transport processes, instabilities, and confinement regimes. Additionally, it aims to facilitate the correlation of experimental measurements with fundamental plasma physics and fusion performance.

References:

1. Wesson, Tokamaks, Clarendon Press-Oxford 2014
2. Hutchinson, Principles of Plasma Diagnostics, Cambridge U. Press, 1990
3. Janev, Atomic and molecular processes in fusion edge plasmas, Plenum Press, 1995
4. Kikuchi, Fusion Physics, IAEA Vienna, 2012
5. Freidberg, Ideal MHD, Cambridge University Press, 2014
6. Knoll, Radiation detection, radiation shielding, and radiation effects, ISBN 0471073385, 9780471073383

4. Fueling and plasma-wall interaction in Tokamaks (1 Credit, 15 Lectures)

Coordinators: Dr.Jyoti Shankar Mishra
(jsmishra@ipr.res.in)

Course Details

- **Plasma Fuelling:**

  Ionization and recombination, pressure and mean free path, connection length, particle and energy confinement, LCFS and separatrix, Tokamak SOL, sheath, extrinsic fuelling: gas puff, molecular beam injection, solid pellet injection, impurity injection, intrinsic fuelling: Wall as pump and source.

- **Cryogenic pellet fuelling:**

  Cryogenically cooled pellets (H2, D2) as particle source, Pellet-plasma interaction, gas dynamic equations and ablation models, cloud characteristics and shielding mechanism, particle homogenization and fuelling efficiency, pellets for plasma control and diagnostic, Basics of cryogenics and its role in vacuum, heat transfer methods: conduction, convection, radiation. Material properties relevant to vacuum and cryogenics. Phase diagram, gas condensation, pellet production technique, Instrumentation for pellet production and acceleration, diagnostic for pellet-plasma interaction. Case Study: pellet fuelling in tokamaks

- **Plasma facing materials:**

  Low Z and high Z impurity, tokamaks with carbon and all metal wall, tungsten and beryllium wall, limiter and divertor material, physical and thermal characteristics of PFCs, heat removal and diagnostics, material testing, neutron activation, effect of neutron on material characteristics, ODS and RAFMS materials for fusion reactors, neutron sources and IFMIF, Challenges of materials for Fusion reactors: energy content, pulse duration, duty factor, ELMs, tritium handling, Case Study: material choice in ITER

- **Plasma material interaction:**

  Particle fluxes and energies, basic particle-material interaction: reflection, implantation, defects, reemission, Plasma interaction with wall: physical and chemical sputtering, radiation enhanced sublimation, wall deposition, erosion, and recycling, hydrogen processes in metals: diffusion, trapping, precipitation, retention, Case Study: limiter and divertor interaction in Aditya/U, ASDEX, DIIID, fuel retention in TFTR carbon wall,

- **Wall damages and control:**

  Disruptions, VDEs, runaway electrons, ELMs, dusts and flakes in tokamaks, disruption and ELMs mitigation, RMP, wall conditioning and coating, GDC, EC and IC wall conditioning, lithiumiza- tion and boronization, Introduction to plasma edge, sputtering modelling

Course Outcomes

Upon successful completion of the course, students will be able to understand the fundamental principles of plasma fuelling in tokamaks, including particle sources, ionization processes, confinement, and the role of fuelling in density and plasma performance control for high-performance and burning plasmas. Students will gain knowledge of different fuelling techniques, such as gas puffing, impurity injection, and cryogenic pellet fuelling. In addition, they will learn about the underlying physics of pellet–plasma interaction, ablation processes, and fuelling efficiency. They will be able to identify key plasma-facing materials used in present and future tokamaks and explain the stringent material requirements imposed by extreme heat fluxes, neutron irradiation, erosion, and tritium retention. Students will develop an understanding of complex plasma–material interaction processes, including sputtering, erosion, impurity generation, hydrogen isotope retention, and recycling, and their impact on plasma contamination and tokamak operation. Furthermore, they will be capable of analyzing wall damage mechanisms arising from disruptions, ELMs, and runaway electrons. Additionally, they will be able to evaluate mitigation and control strategies such as pellet injection, impurity seeding, wall conditioning, and edge plasma control. These strategies are designed to enable long-pulse operation in fusion devices like ITER.

References:

1. Federici, Nuclear Fusion, Vol. 41, No. 12R (2001)
2. Pellet fuelling, S. L. Milora, Nuclear Fusion, Volume 35, Issue 6, pp. 657-754 (1995).
3. Pellet-plasma interactions in tokamaks, Physics Reports 206, No. 4 (1991) 143196. North-Holland
4. Pellet injection technology, S. K. Combs Rev. Sci. Instrum. 64 (7), 1993
5. Physical processes of the interaction of fusion plasmas with solids, Hofer & Roth, Academic Press 1996
6. Plasma-material interaction in controlled fusion, Naujoks, Springer 2006

5. Heating and Current Drive in Tokamaks (1 Credit, 15 Lectures)

Coordinators: Dr. Sanjeev Kumar Sharma
(sksharma@ipr.res.in)

Course Details

- **Introduction:**

  Tokamaks and stellartors, ignition condition and reaction cross section, confinement time, particle and energy loss, Ohmic heating and limitation. Case Study: Ohmic heating experiments in tokamaks (Aditya and JET)

- **Ion Cyclotron Heating:**

  Absorption of magneto sonic waves, R & L cut off, evanescent layer, wave tunnelling, cold plasma approximation, slow and fast waves, hot plasma dielectric tensor, absorption mechanisms, wave polarization, second harmonic heating, high harmonic heating, minority heating and ion-ion hy- brid heating, direct electron heating, Introduction to experimental system: Selection of source frequency and power, transmission lines, Antenna-plasma coupling, wave shaping through an- tenna array, matching network, introduction to codes for study of antenna-plasma coupling, wave propagation and absorption in tokamaks, full wave simulation, Plasma start-up and wall condi- tioning. Case study: basic experimental papers from tokamaks (ASDEX, Alcator C-mod).

- **Electron Cyclotron Heating:**

  O-mode & X-mode, cut off & resonances, CMA diagram and wave accessibility, fundamental and second harmonic heating, single pass absorption, mode conversion, EBW heating and current drive, preionization and start-up, fully non-inductive current drive, fast particle generation and control, NTM stabilization, Experimental set-up: Gyrotron as an oscillator, waveguide, launcher, polarization control, access to thermal and non-thermal population. Case study: Study of EC resonances in TCV, EBW heating in COMPAS-D.

- **Current drive by Waves:**

  Dispersion relation, propagation, landau damping, accessibility and spectral gap, experimental set-up: Klystron, waveguide, grill antenna, evolution of launchers in tokamaks, phasing, reflection coefficient, current drive efficiency, current profile modification, fast electron behaviour, LHCD, ECCD, FWCD, wave propagation in toroidal geometry, ray tracing: Case study: Early current drive experiments in JFT-2 tokamak, Phase reflection experiment in a grill antenna.

- **Heating & CD by Neutral beams and alpha:**

  Basic beam-plasma interaction, multi-step ionization, charge exchange, ionization cross section by ions and impurities, Lorentz ionization, importance of Beam injection geometry, Energy transfer mechanism, energetic particle particles orbits, Current Drive efficiency, fast ion behaviour at high temperature, distribution function, banana drift, ripple loss, alpha heating, Experimental method: ion source, extraction, acceleration, beam steering,negative and positive ion beam, negative ion for ITER Case study: First beam driven current experiments in DITE, TFTR, JT 60U.

Course Outcomes

Fusion energy is widely regarded as a long-term solution for clean, safe, and sustainable power generation. The tokamak is the most advanced and extensively studied magnetic confinement device for achieving controlled thermonuclear fusion. Achieving and sustaining the extreme plasma temperatures and conditions required for fusion critically depends on efficient heating and current drive systems. Key techniques such as Neutral Beam Injection (NBI), Ion Cyclotron Resonance Heating (ICRH), Electron Cyclotron Resonance Heating (ECRH), and Lower Hybrid Current Drive (LHCD) play essential roles in plasma heating, current profile control, and stability. A structured academic program focused on heating and current drive systems would provide students with strong foundations in plasma physics, wave–particle interactions, and fusion engineering.

References:

1. Stix, Waves in Plasma, AIP, 1992
2. Wesson, Tokamaks, Clarendon Press-Oxford 2014
3. Kikuchi, Fusion Physics, IAEA Vienna, 2012
4. M. Bornatici et al 1983 Nucl. Fusion 23 1153
5. Ushigusa, JAERI, 1339, 1999
6. Yamamoto, PRL 1980
7. M. Brambilla, Nucl. Fusion 16, 47 (1976).

6. Waves in Guided Media (1 Credit, 15 Lectures)

Coordinators: Dr. Varsha Siju
(varsha@ipr.res.in)

Course Details

- **Revision of mathematics for waves:**

  Vector algebra, coordinate systems (Cartesian, cylindrical, polar) and transformation, differenti- ation and integration of scalar and vector functions.

- **Electric and magnetic fields:**

  Coulombs law and electric field from charge distribution, Gausss law and calculation of potential, materials in electric field (conductor, dielectric, polarization, permittivity), Maxwells equation, eddy current.

- **Wave propagation:**

  Wave and wave equation, complex pointing vector, propagation of wave in materials (lossy dielectric, propagation in conductor, skin depth, dispersion and polarization, reflection and transmission of waves.

- **Transmission line:**

  Resistance, inductance and capacitance per unit length, transmission line equation, practical transmission lines (lossless, long, distortion-less, low resistance), field picture of lines, load reflection coefficient, line impedance, vswr, lossless matched and terminated lines, resonant transmission lines, Case study: application to tokamak and linear plasma devices.

- **Smith chart and impedance matching:**

  The smith chart, smith chart as an admittance chart, impedance matching, single and double stub matching, quarter wavelength transformer matching, transients with capacitive and inductive loading, Case Study: Impedance matching in tokamaks EAST, Alcator C-mod

- **Waveguides:**

  TE, TM, TEM modes, TE propagation in parallel plates, rectangular waveguide, attenuation in WG (dielectric loss, wall loss, cut off), cavity resonators, quality factors and applications. Case Study: Design and simulation of rectangular waveguide for tokamak experiment.

Course Outcomes

Upon completion of this course, students will be able to apply vector algebra, vector calculus, and appropriate coordinate systems to analyze electromagnetic wave phenomena. They will be able to analyze electric and magnetic fields produced by charge and current distributions using Coulomb’s law, Gauss’s law, material relations, and Maxwell’s equations. Students will understand electromagnetic wave propagation in free space and materials, including polarization, dispersion, reflection, transmission, and losses in conductors and dielectrics. They will be able to analyze transmission lines by determining characteristic parameters, reflection coefficients, standing wave ratios, and resonance conditions, and apply impedance matching techniques using the Smith chart. Students will also be able to analyze wave propagation in waveguides and resonant cavities, identify TE, TM, and TEM modes, evaluate attenuation and quality factors, and relate these concepts to practical applications in tokamak and linear plasma experiments.

References:

1. Ida, Engineering electromagnetics, Springer 2021
2. Chapman, Theory and problems of transmission lines, New York McGraw-Hill 1968
3. Moreno, Microwave transmission design data, Boston Aptech house, 1998

7. Plasma Material Interaction (1 Credit, 15 Lectures)

Coordinators: Dr. Sejal P Shah (sejal@ipr.res.in),
Dr. Mukesh Ranjan (ranjanm@ipr.res.in)

Course Details:

- **Structure and Properties of Materials:**

  Atomic Bonding and Crystal structure, Metallic bond, unit cell, atomic packing, interstitial sites, Miller indices, crystal orientation, Crystal defects in metals viz. vacancy, dislocations etc., Prop- erties of materials: Electrical, Thermal, Magnetic, Optical and Mechanical properties of materials. Surface properties like roughness, surface free energy, wettability, surface corrosion etc.

- **Plasma Material Interaction in Low Temperature Plasma:**

  Basics of Plasma material interaction, plasma sheath, plasma etching, plasma sputtering, Plasma immersed ion implantation (PIIII), Plasma Nitriding, Surface nano-patterning, Introduction to different reactive species in plasma. Basics of thin film growth, Physical Vapour Deposition (PVD), Chemical Vapour Deposition (CVD), Pulsed Laser Deposition (PLD) E-beam PVD, Plasma en- hanced PVD and CVD etc.

- **Introduction to Plasma Material Interaction in Tokamak:**

  Particle fluxes and energies, basic particle-material interaction: reflection, implantation, defects, trapping, reemission, Recycling in tokamaks, Erosion and deposition, Scrape-Off Layer, Limiter and Diverter concepts. Material modification by high power load in tokamak

- **Material Characterisations:**

  Surface Characterisations: Operating principle of Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), Scanning Tunnelling microscope (STM) and Transmission Electron Microscopy (TEM). Operating principle of Surface Profilometer, contact angle Goniometer and hardness tester. Crystallographic and identification: X-ray diffraction (XRD), Energy dispersive X-ray spectroscopy (EDX), inductively coupled Plasma Mass Spectroscopy (ICPMS) and X-ray Photoelectron spectroscopy (XPS) Optical Characterisation: Operating principle of Fourier trans- form Infrared Spectroscopy (FTIR), Ellipsometry, UV-visible spectroscopy (UV-Vis) and Raman spectroscopy Magnetic Measurements: Operating principle of Magneto-Optic Kerr Effect (Moke) spectroscopy, Vibrating sample magnetometer (VSM) Electrical and Thermal Measurements: Re- sistivity measurement by Four probe method, Thermal conductivity measurement etc.

Course Outcomes

Upon completion of this course, students will gain a clear understanding of the objectives and significance of plasma–material interaction, particularly in the context of large-scale tokamak devices. The course will provide a comprehensive understanding of the structure of materials, including atomic bonding, crystal structure, lattice parameters, and defects. Students will be able to explain the fundamental mechanisms of plasma–material interaction in low-temperature plasmas, including sheath formation, sputtering, etching, implantation, thin film growth, and surface nano-patterning. The course provide an understanding of particle–material interactions in tokamaks, including erosion, deposition, recycling, and material modification under high heat and particle fluxes in the scrape-off layer, limiter, and divertor regions. Additionally, students will develop an understanding of a diverse array of material characterization techniques and their underlying operating principles, including structural, surface, optical, magnetic, electrical, and thermal analysis. In essence, the course is designed to provide students with the necessary skills to assess the material performance in harsh plasma environments and make informed material selection decisions for plasma-based experimental systems and fusion devices.

References:

1. Materials Characterisation : Introduction to Microscopic and Spectroscopic Methods by Yang Leng
2. Principles of Plasma Discharges and Material Processing by M Lieberman and A. Lichtenberg
3. Plasma-material Interaction In Controlled Fusion by Naujoks, Springer 2006

8. Physics of Low Temperature Plasmas (1 Credit, 15 Lectures)

Coordinators: Dr. Mainak Bandyopadhyay
(mainak@ipr.res.in)

Course Details

- **Introduction:**

  Typical discharges in presence of constant electric field, Classification of discharges, Sheaths in plasmas, Drift of electrons in weakly ionized gas, Conductivity of ionized gas, Electron energy, Diffusion of electrons, Ion motion

- **Interaction of Electrons in an Ionized Gas with Oscillating Electric Field:**

  Motion of electrons in oscillating fields, Electron energy

- **Atomic Collisions:**

  Elastic and Inelastic collisions, Collision Parameters, Ionization, excitation and elastic scattering cross sections for electrons in Ar, Ion-atom charge transfer and elastic scattering

- **DC Sheath:**

  Collisionless Sheath, Bohm Sheath Criterion, Presheath, Collisional Sheath, Matrix Sheath, Child’s Law Sheath, Generalized Criterion for Sheath Formation

- **Brief Introduction of Different Heating Mechanisms:**

  Ohmic Heating, Stochastic Heating, Resonant wave-particle interaction heating, Secondary Elec- tron Emission Heating

- **Capacitive Discharges:**

  Homogeneous Model, Plasma and Sheath Admittance, Ohmic and Stochastic Heating, Inhomogeneous Model, Collisionless Sheath Dynamics, Child’s Law, Sheath Capacitance, Ohmic and Stochastic Heating

Course Outcomes:

The syllabus of "Physics of Low Temperature Plasma" is to provide a comprehensive understanding of the fundamental plasma physics and to learn the basic properties, concepts, and criteria of low temperature laboratory plasmas, including kinetic theory, plasma parameters (e.g., electron density and temperature), Debye shielding, particle motion in electric and magnetic fields, and particle collisions, considering electrons are highly energetic but the heavier ions and neutral gas remain near ambient temperature. The knowledge gained from this course will help the students to understand the design aspects different types of plasma devices for versatile applications (e.g. plasma processing, ion source, plasma etching, sustainable environment, basic plasma physics etc.). With this knowledge the student can do mathematical modeling to describe complex plasma processes and their interactions with surfaces and also for scaling up those plasma devices.

References:

1. “Principles of Plasma Discharges and Materials Processing”, Michael A. Lieberman, Allan J. Lichtenberg
2. “Gas Discharge Physics”, Yuri P. Raizer

9. Electromagnetic Theory (1 Credit, 15 Lectures)

Coordinators: Dr. Rana Pratap Yadav
(rana.yadav@ipr.res.in)

Course Details

- **Electrostatics:**

  Review of Electrostatics, Work and Energy in Electrostatics, Poisson and Laplace equations, Uniqueness of solution using Dirichlet or Neumann boundary conditions, Green theorem, formal solution of electrostatic boundary value problem with Green function, method of images, separa- tion of variables, multipole expansion. Electrostatic fields in matter.

- **Magnetostatics:**

  Review of magnetostatics, Biot-Savart law, Ampere's Law, Vector Potential, Multipole expansion, Magnetic fields in matter, Methods for solving boundary value problem in magnetostatics,

- **Electrodynamics:**

  Maxwells equations (in free space and in matter), Boundary conditions, Electromagnetic Energy and Momentum, Poynting's theorem, Maxwell stress tensor, Wave equation, Gauge transformation (Coulomb and Lorentz gauge), reflection and refraction at a plane between dielectrics, reflection at a plane conducting boundary.

- **Electromagnetic wave in bounded region:**

  General wave behaviour along guiding structure (TEM, TE, TM modes), rectangular waveguide, coaxial transmission line, dielectric waveguides, cavity resonator.

- **Radiation:**

  Radiation from localized oscillating source (dipole radiation), Radiation from an arbitrary source, Radiation by an accelerated particle: Lienard-Wiechert potentials and field, power radiated by an accelerated charge.

- **Relativistic electrodynamics:**

  Lorentz Transformations, Four Vectors, Covariant and contra- variant tensors, Electrodynamics in Tensor Notation. Relativistic Potentials. Invariance.

Course Outcomes

In this course, after a brief review on the subjects of basic Electrostatics, Magnetostatics, and Electrodynamics; students will learn various advanced topics: (i) Interaction of Electromagnetic waves with bounded medium, principle of various wave-guides and transmission lines which are useful for micro-wave applications

Radiation from accelerated charge-particles as well as Relativistic electrodynamics which are useful for studying particle-acceleration and new-light source generation via intense-field wave-plasma interaction.

References:

1. Classical Electrodynamics, John David Jackson, Wiley Publication,1998.
2. Introduction to Electrodynamics, David J. Griffiths, Cambridge University Press, 2017.

10. Classical Mechanics (1 Credit, 15 Lectures)

Coordinators: Dr. Anil Kumar Tyagi
(aktyagi@ipr.res.in)

Course Details

- **Lagrangian mechanics:**

  Review of Newtonian mechanics, Constraints, principal of virtual work, DAlemberts principle, Generalized coordinates. Lagranges equation of motion and its applications, e.g., Spherical pendulum, particle in EM fields etc., principle of least action, conservation laws.

- **Rigid Body:**

  Eulerian angles, Euler's equations, study of symmetric top.

- **Hamiltonian mechanics:**

  Legendre transform, Hamiltons equation and its applications, e.g. spherical pendulum, electromagnetic interactions etc.

- **Canonical transformations (CT):**

  Definition, generating functions, properties and examples of CT, Poisson bracket (PB) represen- tation, invariance of PB under CT.

- **Hamilton Jacobi Theory:**

  Hamiltons principal function, Hamilton Jacobi equation, action-angle variable, adiabatic invari- ants.

Course Outcomes

On completing this course, students will get an opportunity to revisit and strengthen key concepts of classical mechanics such as Lagrangian and Hamiltonian formulations, rigid body dynamics, canonical transformations, Poisson brackets, Hamilton–Jacobi theory, and adiabatic invariants. These form the foundation for advanced areas of physics and are widely used in plasma physics and related disciplines. The course will enable students to understand the connections between different formulations of mechanics and appreciate their relative advantages and limitations. After completing the course, students will gain a clear conceptual understanding of classical mechanical systems and the methods used to analyze them. They will be able to approach complex physical problems systematically by selecting appropriate coordinates, applying suitable transformations, and reducing complicated problems to simpler forms using the techniques discussed in the class.

References:

1. Classical Mechanics, Herbert Goldstein, Pearson Education, 2011.
2. Classical Mechanics, Narayan Rana, Pramod Joag, McGraw Hill Education, 2017.
3. Mechanics, Course of Theoretical Physics, L D Landau, E.M. Lifshitz, Butterworth-Heinemann, 1982.

11. Statistical Mechanics (1 Credit, 15 Lectures)

Coordinators: Dr. Jugal Chowdhury
(jugal.chowdhury@ipr.res.in)

Course Details

- **Equilibrium Classical Statistical Mechanics:**

  Foundations and Postulates, Microcanonical and Canonical ensemble with simple examples, Toy models & Introduction to phase transitions, Role of range of interaction.

- **Non-Equilibrium Classical Statistical Mechanics:**

  Study of Brownian motion, Random walk model, Langevins force equation, fluctuation-dissipation theorems, Fokker-Planck equation, Introduction to driven-dissipative systems.

- **Numerical Statistical Mechanics:**

  Chaos and low degrees of freedom statistical mechanics, Monte Carlo Simulations, Molecular Dynamics and Noose-Hoover Statistical Mechanics.

- **Advanced Classical Statistical Mechanics:**

  Introduction to Entropy Fluctuation Theorems, Introduction to Non-extensive systems, Intro- duction to Linear Response Theory and Onsager’s Regression Hypothesis, Introduction to Large Deviation Theory based Statistical Mechanics.

Course Outcomes

Upon completing the Statistical Mechanics course, students will understand the foundations and postulates of classical statistical mechanics. They will also learn about microcanonical and canonical ensembles using simple models. Students will also grasp the concept of phase transitions and the role of interaction range in many-particle systems. Students will describe non-equilibrium processes, such as Brownian motion and random walks, and understand stochastic descriptions using the Langevin equation, the fluctuation-dissipation theorem, and the Fokker-Planck equation. Students will also gain an understanding of driven-dissipative systems and their statistical behavior. Students will understand numerical approaches to statistical mechanics, including chaos in low-dimensional systems, Monte Carlo simulations, and molecular dynamics methods. Finally, students will be introduced to advanced topics such as entropy fluctuation theorems, non-extensive systems, linear response theory, Onsager’s regression hypothesis, and large deviation theory in statistical mechanics.

References:

1. Statistical Mechanics, R.K. Pathria , Paul D. Beale Academic Press Inc.(London) Ltd, 2021.
2. Monte Carlo Simulations in Statistical Physics - An Introduction, K Binder, 5th Ed, SpringerLink (2010)
3. W. G. Hoover, Computational Statistical Mechanics (Elsevier, Amsterdam, 1991).
4. W. G. Hoover, Time Reversibility, Computer Simulation, and Chaos (World Scientific, Singapore, 1999)
5. R S Ellis, Entropy, Large Deviation and Statistical Mechanics, SpringerLink (2006)
6. Statistical Mechanics, Kerson Huang,, Wiley, 2008.
7. Fundamentals of Statistical and Thermal Physics, Reif F , Waveland Press, 2010.

12. Fluid Mechanics (1 Credit, 15 Lectures)

Coordinators: Dr. Amulya Kumar Sanyasi
(amulya@ipr.res.in)

Course Details

- **Dimensional analysis and its application:**

  Techniques to generate dimensionless quantity:- Rayleighs Indicial method, Buckingham Π (PI) method; Introduction of dimensionless quantities like: Reynolds no., Froudes no., Eulers no., Webers no., Machs no., Relation between model and 1:1 size prototype, Model analysis, Similitude theory.

- **Types of flow with their mathematical description :**

  Ideal flow, Real flow, Newtonian flow, Non-Newtonian flow, Steady and Unsteady flow, Uniform and Non-uniform flow, Laminar and Turbulent flow, Compressible and Incompressible flow, Ro- tational and Irrotational flow, 1D-2D-3D flows.

- **Dynamics of flow:**

  Bernoullis theorem and its applications in real system

- **Kinematics of linear flow of incompressible fluid:**

  Introduction to Eulerian frame, Lagrangian frame, Specification of the flow field, Concept of convective field, Continuity equation, Velocity Potential function and Stream function, Flow net and their applications to analyze for superimposed flow, Vorticity distribution (line and sheet vortices). Navier- Stocks equation, Expression for stress tensor.

- **Kinematics of rotational flow of incompressible fluid:**

  Flow at large Reynoldss number, Vorticity dynamics, Kelvins circulation theorem, Lagranges theorem, Vorticity laws for inviscid fluid (having no viscosity).

- **Instabilities:**

  Introduction to Rayleigh-Taylor instability, Kelvin-Helmholtz instability in fluid.

Course Outcomes

Upon completing the Fluid Mechanics course, students will understand the principles of dimensional analysis and its applications. They will learn techniques for generating dimensionless quantities using various standard methods. Students will learn about important dimensionless numbers, such as the Reynolds, Froude, Euler, Weber, and Mach numbers, and will be able to use similitude theory for model and prototype analysis. Students will understand and be able to describe mathematically different types of fluid flow, including ideal and real flows, laminar and turbulent flows, compressible and incompressible flows, and flows in multiple dimensions. Students will learn how to use Bernoulli’s theorem to analyze practical flow systems. Students will learn the kinematics of incompressible flow through Eulerian and Lagrangian descriptions, the continuity equation, velocity potential, stream function, flow nets, and vorticity concepts. They will learn to apply the Navier–Stokes equation and stress tensor to fluid motion. Finally, students will learn about rotational flow, vorticity dynamics, circulation theorems, and basic fluid instabilities, such as Rayleigh–Taylor and Kelvin–Helmholtz instabilities.

References:

1. Fluid Mechanics, E.M. Lifshitz , L D Landau, Elsevier Exclusive, 2010.
2. Vectors, Tensors and the Basic Equations of Fluid Mechanics, Rutherford Aris, Dover Publications Inc., 1990.

13. Basic Tokamak Physics (1 Credit, 15 Lectures)

Coordinators: Dr. Joydeep Ghosh
(jghosh@ipr.res.in)

Course Details

- **Thermonuclear Fusion and Magnetic Confinement:**

  Theory of fusion, Power balance & Ignition, Lawson criterion, Concept of magnetic confinement fusion, Inertial confinement fusion.

  Mirror machine & Tokamak. Basic configuration of Tokamak, Plasma production, Tokamak operation: pulsed & steady state.

- **Tokamak Equilibrium:**

  Magnetic fields, Flux functions & flux surfaces, Grad-Shafranov equa- tion, Plasma β, Safety factor, Magnetic shear, Shafranov shift, Plasma shaping. Trapped particles, Banana orbits.

- **Confinement and Transport:**

  Classical transport, Neoclassical transport, Bootstrap current, Anomalous transport, Turbulence and zonal flows. L-mode, Transport barriers, H-mode, L-H transition. Radiation losses, Runaway electrons.

- **MHD Theory and Macroinstabilities:**

  MHD theory of stability, Ideal MHD instabilities, Resistive instabilities. Kink instability, Bal- looning modes, Tearing modes, Sawtooth oscillations. Disruption physics.

- **Microinstabilities:**

  Drift waves, Ion temperature gradient mode, Trapped electron mode, Electron temperature gradient mode, Micro/Drift-tearing modes, and Kinetic ballooning mode.

Course Outcomes

Upon completing the Basic Tokamak Physics course, students will understand the fundamental principles of thermonuclear fusion, such as power balance, ignition, and the Lawson criterion. Students will also be guided through the concepts of magnetic and inertial confinement fusion and learn about the basic configuration and operation of a tokamak. Students will understand plasma production methods and pulsed and steady-state tokamak operation. Students will learn about the various fields, flux surfaces, and the safety factor in a tokamak, as well as its role in tokamak equilibrium. Students will also learn about particle confinement, transport processes, and different confinement regimes, such as L- and H-mode. They will understand the major macroscopic instabilities and disruptions. Finally, students will learn about microinstabilities in plasma turbulence and anomalous transport.

References:

1. “Tokamaks”, John Wesson, Clarendon Press-Oxford 2004
2. “Fusion Physics”, Edited by: M. Kikuchi, K. Lackner, M. Q. Tran, IAEA Vienna, 2012
3. “Collective Modes in Inhomogeneous Plasmas”, Jan Weiland, IOP Publishing Ltd, 2000
4. “Ideal MHD”, J P Freidberg, Cambridge University Press, 2014
5. “The Theory of Toroidally Confined Plasmas”, Roscoe B. White, Imperial College Press,UK, 2001.