INTRODUCTION TO FUSION PLASMAS

Required module for Materials and Plasma Strand		
Lecturer	Dr Koki Imada Dr David Dickinson	York Plasma Institute York Plasma Institute
Term 1	16 October 2017 to 1 December 2017	
Workload	17 x 1 hour lectures plus 4 x 1 hour Wave lectures	
	3 x 1 hour workshops/problem classes plus 1 x Wave problem workshop	
	Private study 77.5 hours	
Assessment	Three open book assessments for Plasma strand Two open book assessments for Materials strand	
Set	6 November 2017	Due 24 November 2017
Set	13 November 2017	Due 24 November 2017
Set (Plasma only)	27 November 2017	1 December 2017
Feedback and mark		Due 8 January 2018

Aims

Fusion, whether by inertial confinement or magnetic confinement, requires deuterium and tritium to be heated to such high temperatures that the electrons are stripped from the ions. The resulting conducting gas is called a plasma. Plasmas are common place around the universe so the topic of plasma physics is important in many branches of science including astrophysics and solar physics, as well as having industrial applications. This course aims to introduce the basic plasma physics principles through a combination of physical pictures and mathematical analyses, often using examples from fusion to provide specific applications.

Plasma strand students will be expected to attend four lectures on Plasma Waves by Dr David Dickinson and complete an open book assignment relating to these lectures.

Learning outcomes: at the end of this module successful students will be able to:

●Describe, both through physical pictures and mathematics, the orbits of individual particles in magnetic and electric fields: the cyclotron frequency, the guiding centre, the ExB drift, the gradB and curvature drifts and the polarisation drift.

●Write down expressions for the quantities that are conserved when a charged particle moves in a magnetic field: energy and magnetic moment. Use this principle to show how charged particles can be trapped in a magnetic mirror. Understand the limitations of a magnetic mirror for confining plasma for fusion.

●Demonstrate an understanding of the principles of magnetic confinement in a toroidal magnetic field configuration, including the roles of both the poloidal and toroidal magnetic fields. Describe the basic principles of tokamak operation.
●Describe the process of inertial confinement fusion.
●Describe the physics of Debye shielding and be able to derive the Debye length mathematically. Write down the definitions of a plasma.
●Demonstrate an understanding of the distribution function and how to derive plasma density and flow by integrating over velocity space.
●Without rigorous mathematical derivation, describe how plasma fluid equations can be obtained from the kinetic equations for plasma evolution. Given the fluid equations, describe the physics of the individual terms. Derive the ideal MHD equations from the 2-fluid equations. Describe the concept of “frozen in” magnetic field.
●Given the fluid equations, derive the diamagnetic drift. Provide a physical explanation for the origin of the diamagnetic drift, including why it is not experienced by a single particle.
●Demonstrate an understanding of equilibria for cylindrical and toroidal plasma systems. Derive the equilibrium relations for cylindrical systems. Describe qualitatively the features of toroidal equilibria including the origin of the Grad-Shafranov equation (without rigorous proof); the concept of toroidal flux surfaces, and definitions of equilibrium quantities such as aspect ratio, safety factor, major and minor radius, etc.
●Describe the origin of trapped particles in tokamaks and the associated bootstrap current. Explain the origin of the Pfirsch-Schlüter current.
●Qualitatively describe how turbulence influences the confinement in a magnetised plasma, including an understanding of flow shear.
●Provide a description of the exhaust processes in a tokamak, including the physics of plasma-material interaction (e.g. sheath physics).
●Describe the ITER operational scenarios, including L-mode, H-mode and hybrid mode. Demonstrate an understanding of the pedestal and edge-localised modes (ELMs).

Syllabus
Charged particle orbits and drifts
Magnetic mirror and toroidal magnetic confinement
Inertial confinement
Debye shielding and formal definition of a plasma
Distribution functions and velocity space integration
Kinetic equation and fluid equations, diamagnetic drift
Ideal magneto-hydrodynamics (MHD), plasma equilibrium
Plasma turbulence
Neoclassical theory
Plasma-material interaction
ITER operational scenarios

Lecture notes: students are expected to take their own notes during lectures. A set of skeleton notes will be available at the end of the course electronically.

Reading list
Chen F F: Introduction to plasma physics and controlled fusion (Plenum)***
Wesson: Tokamaks, Oxford Science Publications ***
Atzeni and Meyer-ter-Vehn: The physics of inertial fusion (Oxford Science) **
Boyd T J M & Sanderson J J: The physics of plasma (CUP)**

Cairns R A: Plasma physics (Blackie) **
Dendy R O: Plasma dynamics (OUP) **
Goldston & Rutherford: Introduction to plasma physics (IoP)**

Preparation reading: Chen F F: Introduction to plasma physics and controlled fusion Chapters 1 and 2

INTRODUCTION TO MATERIALS [CDT:YU01]

Core Module for Plasma and Materials Strands		
Lecturers	Dr Eugene Zayachuk Dr Maria Auger Dr Dong Liu (TBC)	Delivered by Oxford staff at York Plasma Institute
Term 1	16 October – 3 November 2017	
Workload	16 hours of lectures	
	3 x 1 hour problem classes	
	Private study 81 hours	
Assessment	One open book assignment	
Set	3 November 2017	Due 8 December 2017
Feedback and mark	Due 8 January 2018	

Aims

This course will give those without a background in materials science a basic introduction to the subject and act as revision for those who have previously studied materials science. Materials are becoming increasingly important in fusion as we move to the more demanding environments of next step fusion devices, including ITER. Understanding the structure of materials and their properties is important for designing future fusion devices, whether they are based on magnetic or inertial fusion concepts. Materials need to withstand hostile environments, such as high heat loads associated with the plasma exhaust, high neutron fluxes, and high stresses during transient events. The knowledge of basic material properties that this course provides will establish the foundations for understanding how fusion reactor components perform in such harsh environments

Learning outcomes: at the end of this module successful students will have a grounding in the key areas in Physical Material science

Syllabus

Crystallography and structures: Symmetry, lattices, vectors and planes, simple structures

Crystal defects: vacancies, interstitials, diffusion, dislocations, planar defects

Mechanical properties: elasticity, yield, flow, hardening mechanisms, fracture

Phase diagrams and microstructures: Thermodynamic basis of phase diagrams, typical phase diagrams, microstructural development, alloy systems

Updated May 2017; July 2017

Reading list

C.Hammond, *Basics of Crystallography and Diffraction*
D. Hull and D.J. Bacon, *Introduction to Dislocations*
W.D Callister, *Materials Science and Engineering*
J.E Gordon, *The New Science of Strong Materials or Why You Don't Fall Through the Floor*
A Groves, G W Kelly, *Crystallography and Crystal Defects*
D.A. Porter, K.E. Easterling and M. Sherif, *Phase Transformations in Metals and Alloys*

Lecture notes

Will be supplied.

Suggested preparation

None: this is an introductory course.

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COMPUTATIONAL TECHNIQUES

Required module for Plasma and Materials strand		
Lecturers	Dr David Dickinson Dr Peter Hill	York Plasma Institute in person and by recorded presentation for those students arriving later.
Term 1	16 October 2017 to 3 November 2017	
Workload	9x1 Lectures & 3x1 lecturers week 1 – Plasma strand only	
	3x1 Problem classes & 3x1 Problem Classes week 1 – Plasma strand only	
	100 hours Private Study	
Assessment	Programming assignments	Due: Friday week 5, 6 and 7
Assessment	Computational report	Due: Friday 1 December 2017
Feedback and marks	Assignments returned a week after submission. Report returned by 8 January 2018	

Aims

An introduction to the computer simulation of plasmas. A series of lectures in the first term gives a theoretical foundation in computational methods used in plasma physics. Students will learn about both continuum (fluid) and discrete (particle) techniques, and identify which techniques are appropriate for a variety of specific problems. At the end of the first term students will carry out and write up a short computational project.

Learning outcomes: at the end of this module successful students will be able to:

- Program in Python
- Distinguish between the following types of computational systems and identify which is relevant in a given scenario: linear vs nonlinear, initial value vs boundary value, particle vs continuum and fluid vs kinetic.
- Describe the following computational algorithms: finite difference & flux conservative interpolations, Eulerian & Lagrangian grids and macroparticles with mean fields
- Assess the accuracy, stability, and convergence of numerical methods
- Apply computational techniques to solve 1-dimensional problems
- Present computational methods and results in a short journal paper format

Syllabus

3 lectures (week 1) on Linux and programming & 3 Problem Classes

- Using Linux, including the command-line. Common Linux commands
- Programming concepts: variables, conditionals, loops, functions. Debugging and version control techniques
- Introduction to the Python programming language

9 lectures (weeks 4 – 6) on computational techniques & 3 Problem Classes

- Introduction to plasma modelling, including Vlasov, gyrokinetic, and fluid approaches
- Discretisation of Ordinary Differential Equations using explicit and implicit methods
- Numerical accuracy, stability and convergence
- Discretisation of Partial Differential Equations using Finite Difference and spectral methods
- Particle in Cell techniques
- Continuum techniques for kinetic or fluid equations: Advection schemes, CFL condition, numerical diffusion and dispersion, and flux conservation.
- Introduction to advanced methods, including finite elements, implicit integration, and limiter schemes

Reading list

Stephen Jardin, Computational Methods in Plasma Physics (CRC Press 2010)

Culbert B Laney, Computational Gasdynamics (Cambridge University Press 1998)

Toshiki Tajima, Computational Plasma Physics: With Applications to Fusion and Astrophysics (Westview Press 2004)

Hans Petter Langtangen, A Primer on Scientific Programming with Python (Springer 2009)

Numerical Recipes in C / Fortran (Cambridge University Press)

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MATERIALS APPLICATIONS IN FUSION [CDT:OU03]

Core Module for Materials and Plasma Strands		
Lecturers	Guest Lecturers Organizer Dr David Armstrong, University of Oxford	
Term 1	6 November to 10 November 2017	
Workload	12 x 1 hour lectures	
	12 x 0.5 hour discussion	
Assessment	Group project	22 hours
Assessment	12 page essay	30 hours
Group project set	During the module	Presentation due on last day of module
Essay set	10 November 2017	Due 15 December 2017
Marked	8 January 2018	To be marked by Supervisor
Vetted and returned	29 January 2018	Dr David Armstrong

Aims

The choice of materials is extremely important in a fusion reactor, where there are often high heat loads and high neutron fluxes. In this module you will learn about the different areas of a fusion device where materials are particularly important. Most of the lectures will address the issues in a tokamak environment. Students will be divided into groups and asked to evaluate the implications of the lecture materials for an inertial fusion reactor, making a group presentation on their findings at the end of the week. Following the course, students will write an essay on this same subject.

Learning outcomes: at the end of this module successful students will be able to:

- Describe the key components of a magnetic confinement fusion power plant
- Describe the key components of an inertial confinement fusion power plant
- Discuss the implications of radiation damage for materials
- Demonstrate an understanding of the effect of wall materials, and how plasma and materials interact
- Discuss how transient phenomena like ELMs and disruptions affect materials
- Understand the divertor roll and construct an argument for the choices of materials in this region
- Understand key issues in the tritium breeding blanket modules
- Demonstrate an understanding of neutronics calculations and the implications for materials

- Demonstrate an understanding of the challenges of developing diagnostics for a fusion environment
- Understand the role of superconducting magnets in fusion devices including novel materials and designs
- Demonstrate an ability to translate knowledge
- Communicate effectively, both orally and written

Syllabus

- MCF power plant components
- ICF power plant components
- Basics of Radiation damage
- Wall materials and plasma-material interaction
- Effect of ELMs and disruptions on materials
- Divertor designs and materials
- Tritium breeding blanket module design
- Neutronics
- Diagnostic design for fusion devices
- Superconducting magnets for fusion

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FUSION TECHNOLOGY

Required module for Materials and Plasma strands		
Organiser **Other lecturers**	Prof Bruce Lipschultz External Guest speakers	York Plasma Institute
Term 2	15 January 2018 to 19 January 2018 for lectures, work thru end of term	
Workload	10 lectures (25 hours)	
	5 problem sets – 25 hours	
	Essay assignment – 50 hours	
Assessment	Approx 5 weekly problems (15%) and 1 essay (85%)	
Hand in Due	Weekly problems due weekly through ~ week 7, essay due end of term	
Feedback	Within ~2 weeks of submission for problem questions Within one month for essay	

Aims

To give students an overview of the complex materials science and technology issues associated with future fusion reactors and their relationship to the underlying physics. The course is designed to connect to associated plasma physics based courses on magnetic and inertial confinement fusion, by describing the major science and engineering problems that need to be overcome for fusion to become a viable source of electricity production. Course lectures are presented over one week to enable intensive concentration on relevant physics and technology issues and to enable guest lecturers from fusion laboratories to present material.

Learning outcomes: at the end of this module successful students will be able to:

- Give an overview of the main components in fusion reactor designs.
- Outline the principal technological problems that need to be addressed in order to realise the potential of fusion power as a source of electricity production.
- Be familiar with the basic software analysis tools used for modelling neutron transport in a fusion reactor.
- Describe the main features of the tritium cycle within a fusion reactor and outline methods to control the tritium inventory in a reactor.

- Identify and explain the technologies associated with heating and confinement of fusion plasmas.
- Understand the role of physics, machine size, technologies and materials drivers in the economics of a fusion reactor.
- Identify and explain the technologies associated with heating and confinement of fusion plasmas
- Understand the technologies and materials drivers in the economics of a fusion reactor.

Syllabus

- Overview of Fusion reactor design: Plasma conditions for fusion burn or ignition. Economic and environmental consequences of fusion materials and system design choices.

- First wall, plasma facing & structural materials: Neutron damage of materials. Introduction to neutronics and neutron transport calculations.

- Divertor high heat-flux and erosion handling issues and relationship to plasma and atomic physics. We will also cover the importance of tritium retention, tritium handling and safety issues.

- Specialist fusion technology systems: Heating and current drive engineering. Neutral beam systems. Wave heating and current drive systems.

- Lasers and heavy ion beam drivers for ICF systems. Targets, injection and tracking systems for ICF.

- The ITER device and DEMO reactor.

Reading reference - “Principles of Fusion Energy” by A.A. Harms et al.

PLASMA SURFACE INTERACTIONS LABORATORY [CDT:LU01]

Core Module for Plasma and Materials Strands		
Lecturers	Prof James Bradley Dr Paul Bryant Prof Karl Whittle	University of Liverpool Laboratories
Term 2	22 January 2018 to 26 January 2018	
Workload	6 x 1 hour lectures	
	3 x 1 hour problem classes	
	73 hours private study	
	18 hours Laboratory	
Assessment	Lab books	During the course
Feedback and marks	During the course	

Aims

The interaction of a plasma with surfaces, whether the walls or a substrate, is a key process underpinning the application of industrial plasma technologies. In tokamak plasmas these processes are often detrimental to the cause of generating fusion energy. This lecture and laboratory course aims to introduce the principles that govern the interaction between a plasma and a solid object. The course develops the mathematical and physical description of the plasma sheath boundary layer which drives particle fluxes to surfaces. The basic chemical and physical processes that occur as the plasma particles bombard the surface are then introduced with examples from fusion. Using these ideas via a series of laboratory experiments the course shows how diagnostics can be developed that allow the measurement of the edge plasma parameters relevant to both low and high temperature plasmas. The module provided the opportunity to see how diagnostic tools operate and develops ideas and methodology on interpretation of data from the instruments. It also has the aim of inducing surface analysis methodology and practical experience in operating surface analysis tools.

Learning outcomes: at the end of this module successful students will be able to:

- Describe the Plasma boundary and surface processes in physical terms
- Derive the Sheath/pre-sheath equations
- Apply the Bohm criterion in surface problems
- Apply Langmuir probe (inc. Tokamak geometry) theory to obtain plasma parameters and the influence of plasma fluctuations
- Understand the principles and use of Retarding field analysers (RFA) (inc. Tokamak geometry)
- Use sputtering, etching deposition, secondary electron/ion yields in calculations

- Appreciate the role of plasma in changing surface functional energy, causing surface damage and in dust formation.
- Understand the principles and use of surface analytical tools
- To operate and interpret electrical and optical diagnostic tools on a series on different low temperature plasma devices

Syllabus

Lecture:

The Plasma boundary layer

Physical properties of the presheath and sheath, derivation of governing equations, Bohm criterion for sheath formation, Floating surfaces and the floating potential, Particle fluxes and ion energy distributions (IEDs), Sheath processes (collisions, orbiting, ionisation), and effect of geometry (planar, spherical, cylindrical) on sheath properties.

Plasma - surface interaction

Sputtering, physical and chemical etching, deposition and formation of thin films, dust formation, secondary electron, ion and photon emission, negative ion formation, effect of surface particle emission on sheath properties, surface energy, bond energy and bond breaking mechanisms.
Surface Analytical Tools
Surface properties and parameters (roughness, surface energy etc.), operation principles and use of Atomic Force Microscopy (AFM), Secondary Electron Microscopy (SEM), ~~Tunnelling~~Tunneling Electron Microscopy (TEM).

Laboratory experiments

The diagnostics introduced in the laboratory experiments will be 1) Langmuir probe in linear B-fieldS, 2) Langmuir probes (with and without RF compensation) in an RF etching tool 3), RFA in an RF etching tool, 4) Atmospheric plasma jet surface modification of polymers, 5) Laser plasma, 6) SEM, 7) TEM, 8) AFM

Reading list

Chen F F, Introduction to plasma physics and controlled fusion (Plenum)*** I H Hutchinson, Principles of plasma diagnostics
I G Hughes, Measurements and their uncertainties, Oxford 2010

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INTEGRATED SYSTEMS AND PROJECT MANAGEMENT [CDT:DU01]

Core Module for Materials and Plasma Strands		
Lecturer	Dr S Rolt Ms Madeline Close Mr P Clark Prof R Sharples	
Where	Centre for Advanced Instrumentation	Mon/Tue/Wed
	Rochester Physics Durham University	Thurs/Fri
When	9 April 2018 – 13 April 2018	
Workload	50 hours taught course	
	50 hours extended project	
Assessment	Extended group project	
Set	13 April 2018 13 April 2018	25 May 2018 (report) 8 June 2018 (presentation)
Feedback and mark	One week after final submission	

Aims

Fusion reactors are complex installations which bring together a wide range of engineering disciplines. This course aims to provide an introduction to the basic optical engineering principles which underlie the design of diagnostics for burning fusion plasmas, together with the concepts of systems engineering and project management which underpin the successful completion of large engineering projects. The final part of the course will consider the methods used to interface the diagnostic systems to on-line or off-line computer systems. Where possible the course will be illustrated using examples from existing fusion tokamaks to provide specific applications.

Learning outcomes: at the end of this module successful students will be able to:

- Describe an ideal imaging system in terms of its Cardinal points and use simple matrix ray tracing techniques to derive its basic properties under the paraxial approximation
- Understand the origin of the Gauss-Seidel monochromatic aberrations and their effects on simple optical systems based on lenses and mirrors
- Understanding the influence of stop position on aberrations, and the use of aspheric surfaces to control them
- Be aware how the dispersion of optical glasses can be used to control chromatic aberrations in refractive systems
- Describe how diffraction limits the performance of optical systems and affects the propagation of Gaussian (laser) beams

- Understand the principles of radiometry and the limitations of different types of detectors employed in diagnostic systems
- Acquire knowledge of the different optical materials commonly used optics and coatings and the potential adverse effects on their properties due to temperature, radiation and plasma deposition in tokamak environments
- Understand the design principles and design philosophy used to develop new diagnostics and the software tools employed for optical, mechanical and thermal design
- Describe the limitations on optical system performance imposed by manufacturing and test procedures and the methods used for performance verification
- Understand the concepts of project management and programme management and the basics of the PRINCE2 and other project methodologies
- Undertake requirements capture, translating project descriptions into requirements and verification
- Use a project work breakdown structure to develop a project schedule, resourcing and costing
- Be aware of quality management procedures and tools for project tracking and control
- Understand the roles of systems engineering and risk management in achieving successful project completion
- Use risk management techniques to develop a risk register
- Apply project and risk management techniques to fusion projects
- Understand the main physical types of serial and parallel data interfaces
- Understand the basics of the Raspberry-Pi single-board computer and its interfaces
- Be able to write an instrumentation data I/O interface on the Raspberry-Pi using the Python programming language and send data between two Rasberry-Pis.
- Be aware of the different types of fast data links used for high speed camera interfaces and their bandwidth limitations
- Use an external trigger with a high speed camera to record high speed video

Syllabus
Optics fundamentals
Optical instrument design
Design issues for tokamak environments
Manufacture & test procedures
Case studies
Project management methodologies
Requirements capture, work breakdown structures, cost estimates & schedule
Project tracking and control, risk management, systems engineering
Control system concepts and instrumentation data I/O
Data interface programming in Python

Reading list
The course will be supplemented by an extensive set of slides and written course notes.

DiMarzio C A, Optics for Engineers (CRC Press) ** Hind
D, PRINCE2 Study Guide (Sybex) **
Hughes J, Real World Instrumentation with Python (O'Reilly) **

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FRONTIERS OF FUSION FOR FUSION CDT

Required module for Plasma and Materials Strand		
Organisers Lecturers	Prof Bruce Lipschultz Prof Howard Wilson Dr. Kate Lancaster Dr. David Dickinson 10 over the 1st 2.5 days of week	York Plasma Institute
Term 3	30 April – 4 May 2018	
Workload	Year 1 CDT students will be required to present a poster describing their research. Later years will be required to give a short oral presentation.	

An annual week-long workshop called “Frontiers and Interfaces” held in May.

This workshop will expose students to fusion research at the frontiers of the discipline, and also provide themed days, where lectures and seminars will explore the interfaces between fusion and related disciplines.
In addition, there will be presentations on future career opportunities so that students can start to think about where their PhD will take them.

A short student-led workshop will give you the opportunity to make presentations to your fellow students.

FUSION (ICF)

Required module for Plasma strand		
Lecturer	Dr Chris Murphy and Dr Kate Lancaster	York Plasma Institute
Term 1	2 October 2017 to 1 December 2017	
Workload	18 x 1 hour lectures	
	2 x 1 hour problem classes	
	Private study (60 hours)	
Assessment	3 sets of problems and exam (joint with MCF) (20 hours)	
Feedback	Two weeks after submission	

Aims

The course will provide an overview of the key plasma physics issues associated with inertial fusion research. It will enable students to make an informed decision on an appropriate research degree project, while at the same time providing the essential foundations necessary to pursue a research degree in the field. It will provide the necessary background for students to appreciate seminars in this research field. Inertial Confinement Fusion (ICF) is one of two major routes that are being pursued for fusion energy applications. It relies upon the extreme compression and heating of a tiny fuel capsule by the action of intense laser, ion or soft x-ray radiation. Students will learn about key aspects of ICF including the physics of ignition and burn, implosion physics, laser plasma interactions and hydrodynamic instabilities as well as being introduced to the latest developments in the field such advanced schemes and current state of the art.

Learning outcomes: at the end of this module successful students will be able to:

- Explain the advantages and features of various approaches to ICF including indirect drive ICF, direct drive ICF, laser driven ICF, ion beam and pulse power driven ICF and fast ignition and variants.
- Describe the following physical processes: ignition in dense fuel, shock wave propagation, laser interaction with plasmas, laser interaction with a fuel capsule, laser interaction in hohlraums, fluid instabilities and laser interaction at high intensities and energetic particle generation.

Syllabus

- Introduction to ICF (1 lecture)
- Ignition and Burn (2 lectures)
- Implosion physics (4 lectures)

- Laser plasma interactions (2 lectures)
- Hohlraum physics (2 lectures)
- Fluid instabilities (1 lecture)
- State of the art ICF (1 lecture)
- Alternative schemes (4 lectures)
- Review lecture (1 lecture)

Reading List

Lindl, The Quest for Ignition and Energy Gain Using Indirect Drive, Springer-Verlag,1998 (also available as a journal article Phys. Plasmas 2 (11), pp. 3933-4024,1995)

Atzeni and Meyer-ter-vehn, The Physics of Inertial Fusion, Oxford, 2004

Zel'dovich and Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Dover, 2002.

Lecture Notes

Students will have access to powerpoint slides via the web. Additional and explanatory material is presented in the lectures. Students should take notes in lectures.

Suggested preparation

Background reading of web material such as:
https://lasers.llnl.gov/science/icf/how-icf-works

Please be aware:

You will not be present for lectures 7 – 11 November as you will be in Oxford. Please ensure that you have access to any notes and slides used that week

Module Number Part PHY00017M

Fusion (MCF)

Stage 1
Term 2

Required module for Plasma Strand		
Module Co-Ordinator	**Dr Istvan Cziegler**	
Term 2	**22 January 2018 – 16 March 2018** (CDT students will miss Week 3 lectures and will need to catch up using the recordings)	
Workload	**Lectures:** **Practical:** **Assessment:** **Private Study:** **TOTAL:**	18 x 1 hour 2 hours 30 hours 50 hours **100 hours**
Assessment	WEEKLY assignments (including CDT PhD students)	
Feedback	One week after submission	
Pre-Requisites	A first degree in physics or similar suitable subject	

Aims

The course provides an overview of the key plasma physics issues associated with magnetic fusion research. It is intended to enable students to make an informed decision on an appropriate research project by providing the foundations essential for pursuing a research degree in the field. The standard of the module is for students to appreciate professional research seminars in the field. With magnetically confined fusion, a magnetic field confines plasmas at much lower density, but for much longer times than in inertial confinement. The course will focus primarily on tokamak physics, while other confinement schemes such as stellarators or reversed field pinches, will be introduced. Plasma waves, heating methods, transport processes, instabilities, turbulence, turbulence modelling and plasma edge physics will be treated. The motivation, physics along with the outstanding challenges and opportunities of the next generation of tokamaks, currently under construction, will be presented.

Learning outcomes: at the end of this module successful students will be able to

- Describe and contrast different toroidal confinement devices, including tokamaks, spherical tokamaks, stellarators and reverse field pinches.
- Describe the physics of waves in magnetised plasmas, including Alfvén waves and the electron drift wave. Provide a mathematical derivation of some of the basic plasma waves.

- Describe the physics of the various heating and current drive schemes employed in magnetic confinement fusion experiments including beam injection and radio-frequency waves.
- Demonstrate an understanding of basic neoclassical physics, including the role of trapped particles and different collision frequency regimes. This will include a qualitative understanding of neoclassical currents such as the bootstrap current.
- Understand the processes responsible for instabilities in magnetic confinement devices, including the kink mode, the ballooning mode, tearing mode and fast particle instabilities.
- Demonstrate knowledge of performance-limiting phenomena observed in tokamaks, and the link with plasma instabilities. This will include disruptions, operational limits, edge-localised modes (ELMs), sawteeth and fishbones.
- Describe the basics of turbulent transport in tokamaks, including a qualitative understanding of the role of flow shear in transport barrier formation (e.g. the L-H transition). Demonstrate a basic understanding of the importance and limitations of gyro-kinetic theory.

Syllabus

- Toroidal confinement devices (3 lectures)
- Neoclassical transport and currents (2 lectures)
- MHD equilibrium and waves (2 lectures)
- Heating and current drive (2 lectures)
- Plasma instabilities (3 lectures)
- Performance-limiting phenomenology (1 lecture)
- Small-scale instabilities, gyrokinetics, and turbulence (3 lectures)
- Transport barriers and L-H transition (1 lecture)
- Research for ITER and beyond (1 lecture)

Additional Reading

J. Freidberg "Ideal MHD" Cambridge University Press (2014)
J. Freidberg "Plasma Physics and Fusion Energy" Cambridge University Press (2007)
R. Goldston & P. Rutherford "Introduction to plasma physics" IoP (1995)**
J. Wesson "Tokamaks" Oxford University Press (2011) ***
P. Stangeby "The Plasma Boundary of Magnetic Fusion Devices" Taylor and Francis (2000)
(F. Chen "Introduction to plasma physics and controlled fusion" Springer (1984) *)

Lecture Notes

Additional and explanatory material is presented in the lectures. Students are expected to take notes.

Suggested preparation

Background reading of web material such as: http://www.ccfe.ac.uk/introduction.aspx

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PLASMA DIAGNOSTIC TECHNIQUES

Required module for Plasma Strand			
Lecturer	Dr Deborah O'Connell	York Plasma Institute Fusion Learning Studio	
Term 1	2 October 2017 to 1 December 2017		
Workload	18 x 1 hour lectures		
	2 x 1 hour practical class		
	50 hours private study		
Assessment	Two open book assignments		
Set	13 Nov 2017	Due: 20 Nov 2017	Feedback:18 Dec 2017
Set	27 Nov 2017	Due 11 Dec 2017	Feedback: 8 Jan 2018

Aims
Diagnostic techniques used to determine the properties of plasmas are examined. The physics behind particle and probe diagnostics, and active and passive emission spectroscopy techniques are reviewed.

Learning outcomes: at the end of this module successful students will be able to understand:
- The underlying physics behind diagnostic techniques used in plasma research.
- Methods of measuring key plasma parameters from first principles.

Syllabus
- Introduction to plasma diagnostic techniques
- Probe and electrical diagnostics of plasmas
- Particle detectors used in plasmas
- Optical emission spectroscopy
- Absorption spectroscopy
- One and two-photon laser induced fluorescence spectroscopy
- Scattering of electromagnetic radiation in plasmas and the application to plasma diagnostics

Reading List
I H Hutchinson *Principles of plasma diagnostics*, Cambridge 2001.

Lecture Notes
Additional and explanatory material is presented in the lectures. Students should take notes in lectures.

Suggested preparation
The course follows the recommended text (Hutchinson, 'Principles of Plasma Diagnostics'), so purchase of a copy before lectures commence and general reading of the text will be useful.

FUSION CDT

EPSRC Centre for Doctoral Training in the Science and Technology of Fusion Energy

Module Number PHY0002M

Further Plasma Physics

Stage 1
Term 2

Module Co-Ordinator	Professor G J Tallents	
Other Lecturers	Dr C Ridgers Dr Deborah O'Connell Prof Timo Gans	
Credit Value	10	
Credit Level	M	
Workload	Lectures: Physics Problem Classes: Assessment Private Study: **TOTAL:**	18 hours 3 hours 10.5 hours 67.5 hours **100 hours**
Dates	**29 January 2018 – 16 March 2018**	
Assessment	Weekly problems	
Pre-Requisites	A first degree in physics or similar suitable subject	

Aims

The extended nature of the dominant Coulomb force between the particles in plasma ensures that the behaviour is markedly different to that of gases where the forces are short range. As a result plasma has two distinct dynamic patterns associated with correlated long range motions - collective effects- and fluid-like flow - magneto hydrodynamics (MHD). After an introduction to these dynamics, two strands are available: (1) an introduction to laser interaction physics with an introduction to high energy density plasma physics or (2) an introduction to low temperature plasmas of technological application. Students choose which strand they would like to follow.

Learning outcomes: at the end of this module successful students will be able to:

- Derive the Vlasov equation and understand the need for a collision operator in the context of Debye shielding.

- Linearise the Vlasov equation to obtain the plasma dielectric function and understand how the form of the dielectric function gives rise to Landau damping.
- Write down the form of the Krook and Fokker-Planck collision operators.
- Derive the diffusion coefficients for a magnetised plasma and explain the origin of the Braginskii transport relations

For the laser plasma/high energy density strand:
- Understand single electron motion in an electromagnetic field with relevance to **J X B** electron acceleration and the ponderomotive potential
- Understand the underlying physics of laser absorption mechanisms in laser-plasmas – inverse bremsstrahlung and resonance absorption
- Understand basic laser scattering mechanisms important in laser-plasma interactions
- Appreciate the additional plasma physics involving radiation and pressure effects important in high energy density plasmas.
- Derive the equivalent equation to the Boltzmann ratio for ionization balance for equilibrium plasma – the Saha equation.
- Understand aspects of radiative transfer important in laser-produced plasmas and ICF.

For the low temperature plasma strand:
- Distinguish between plasmas in thermal equilibrium and non-thermal plasmas
- Describe Townsend's theory of electrical breakdown
- Sketch and explain the characteristics of a Paschen curve
- Discuss electron and ion dynamics in low-temperature plasmas
- Describe chemical kinetics and plasma surface interactions in low-temperature plasmas

Syllabus

Kinetic versus fluid description of a plasma	**(1 Lecture)**
The distribution function	
The Vlasov equation & collision operator	
Fluid quantities as moments of the distribution function	
Landau damping	**(2 Lectures)**
Krook collision operator	**(2 Lectures)**
Binary multiparticle scattering and the Fokker-Planck collision operator	
The Coulomb logarithm	
Transport theory	**(1 Lecture)**

For the laser interaction/high energy density strand

Single electron motion and the ponderomotive potential	**(2 lectures)**
Plasma absorption	**(3 lectures)**
Laser light scatter	**(1 lecture)**
Definition and regimes of high energy density plasmas	**(2 Lectures)**
The plasma coupling constant	
Ideal gas equations (revision)	
Energy and pressure of a photon gas	
Degenerate matter.	
The Saha equation	**(2 Lectures)**
Local thermodynamic equilibrium (LTE)	
Continuum lowering	
Ion sphere models	**(1 lecture)**
Thomas-Fermi model.	
Radiative transfer	**(1 lecture)**
The Rosseland and Planck mean opacities	

For the low temperature strand:

Introduction to technological applications and examples	**(1 lecture)**
The non-equilibrium nature of low-temperature plasmas and low-temperature plasma characteristics	**(1 lecture)**
Low-temperature plasma breakdown and Paschen curves	**(1 lecture)**
Low-temperature plasma sheath models	**(2 lectures)**
Low-temperature plasma sources and global particle and energy balance models	**(2 lecture)**
Electron and ion dynamics	**(2 lectures)**
Chemical kinetics and plasma-surface interactions	**(2 lectures)**
Advanced environmental and biomedical applications	**(1 lecture)**

Reading List

Plasma Dynamics, Dendy RO, OUP (1990).

The Physics of Plasmas, Boyd & Sanderson, Cambridge University Press (2003)

High Energy density physics, Drake R P, Springer (2006)

Atomic physics in hot plasmas, Salzmann D, OUP (1998)

Radiative processes in Astrophysics, Rybicki GB and Lightman AP, Wiley (1979)

An introduction to the atomic and radiation physics of plasmas, Tallents G J (2018 in press).

Physics of Radio-Frequency Plasmas, Pascal Chabert and Nicholas Braithwaite, Cambridge University Press (2011)

Principles of Plasma Discharges and materials processing, Lieberman M and Lichtenberg A 2nd edn., New York: Wiley (2005)

Lecture Notes

Additional and explanatory material is presented in the lectures. Students should take notes in the lectures.

Suggested preparation

Revision of material presented in “Plasma physics for fusion” presented in term 1.

FUSION LABORATORIES

Experimental Lab ICF, MCF and Computational Lab

Required module for Plasma Strand				
Lecturer	Dr D Dickinson Prof Kieran Gibson & Prof Nigel Woolsey Dr Andy Higginbotham		Fusion Lab – Computational Fusion Lab – Experimental Fusion lab – ICF Data Analysis	York Plasma Institute
Term 1 and 2	2 October 2017 to 9 March 2018			
Workload	104 hours practical sessions			
	Private study 117 hours			
Assessment	30 hours			
Computational Term	Lab book	Due 12 March 2018	Feedback by 17 April 2018	
Experimental ICF	Lab book	Due 1 December 2018	Feedback by 8 January 2018	
Experimental MCF	Lab book	Due 16 March 2018	Feedback by 17 April 2018	

Aims

A basic knowledge of the diagnostics, the type of data, and data analysis methods needed to interpret a magnetic and inertial confinement fusion experiment is provided. The basic diagnostics are a range of neutron, X-ray, magnetic field, and optical detectors that give spatially and/or temporally resolved measurements of a fusion experiment.

An introduction to the computer simulation of plasmas is obtained. The series of lectures in the first term gives a theoretical foundation for the techniques that will be practiced in the laboratory in the second term. Students will learn about both continuum (fluid) and discrete (particle) techniques, and identify which techniques are appropriate for a variety of specific problems. During the first term students will gradually write a continuum code, submitting a minor project report at the end of the first term. In the second term computational laboratory, students will use a particle-in-cell code for their major project.

Learning outcomes: at the end of this module successful students will be able to:

- Program in Python and other computer languages
- Present scientific research in different formats
- Outline diagnostic methodologies
- Determine appropriate software tool(s) for analysis
- Explain how different methodologies complement each other in providing a comprehensive description of an experiment
- Apply advanced analysis techniques to experimental data
- Determine limits of diagnostic techniques, including identifying spurious artefacts in data
- Calculate key plasma parameters from raw data.
- Distinguish between the following types of computational systems and identify which is relevant in a given scenario: linear vs nonlinear, initial value vs boundary value, particle vs continuum and fluid vs kinetic.
- Describe the following computational algorithms: finite difference & flux conservative interpolations, Eulerian & Lagrangian grids and macro particles with mean fields
- Discuss the physical origin and numerical implementation of a collision operator
- Write and apply a plasma particle-in-cell simulation code.

Syllabus

Introduction to the techniques used in inertial and magnetic confinement fusion experiments

- Orientation to the facilities on which the data was taken
- Description of diagnostic technology
- Scientific, technical and support roles

Inertial confinement fusion

- Time resolved and spatially resolved data
- X-ray imaging
- X-ray spectroscopy
- Particle methods

Magnetic confinement fusion

- Tokamak plant diagnostics
- Magnetics
- Passive spectroscopic and imaging techniques
- Particle and edge diagnostics
- Active spectroscopic techniques

Classification of numerical problems

- Discretisation of differential equations
- Numerical accuracy, stability and convergence
- Making tractable the problem of 10 particles
- Particle-in-cell techniques
- Fluid / MHD techniques

- Kinetic / Vlasov techniques
- Introduction to gyrokinetics

Reading List

IH Hutchinson *Principles of Plasma diagnostics,* Cambridge 2001

MAST Wiki

Toshiki Tajima , *Computational Plasma Physics: With Applications to Fusion and Astrophysics* (Westview Press 2004)

C. K. Birdsall and A. B. Langdon, *Plasma Physics Via Computer Simulation* (IoP 1991)

A. Iserles, *A First Course in the Numerical Analysis of Differential Equations* (CUP 1996)

RADIATION DAMAGE [CDT:O01]

Core Module for Materials Strand only	
Lecturer	Dr Steve Fitzgerald (TBC) University of Leeds Dr David Armstrong University of Oxford Dr Ed Tarleton University of Oxford + Guest lecturers from CCFE
Term 1	13 November to 17 November 2017
Workload	13 hour lectures
	8 x 0.5hrs Discussion
	4.5hrs Group classes
	Study/assignments 45 hours
	Total 66.5 hours
Assessment	Extended review of radiation damage in tungsten
Set	17 November 2017
Hand in due	5 January 2018
Feedback	Due 2 February 2018

Aims
Radiation damage is a complex process, which occurs over disparate length- and time-scales. Events occurring on the scales of nanometres and picoseconds give rise to effects on the scales of metres and years. This course aims to introduce the physical processes happening over these scales. It will cover the basics methods used to model radiation damage. This will be followed by an introduction to using ion implantation as a surrogate from neutron damage and some of the consideration which must be taken into account. Finally there will be an introduction to methods used to characterize radiation damage as well as the practical realities of working with radioactive materials from an experimental point of view.

Learning outcomes: at the end of this module successful students will be able to:
- Describe the fundamental processes occurring in the radiation damage event (RDE)
- Understand the basic analytical models for the RDE and their implications for damage calculations
- Use available software (e.g. SRIM) to perform DPA-based damage profile calculations

- Describe the different types of point defects that contribute to radiation damage
- Demonstrate an understanding of the concept of multiscale modelling
- Discuss the scope, advantages and disadvantages of the different approaches to computational modelling of radiation damage
- Understand the methods used to simulate ion damage with charged particles
- Introduction to test reactors and neutron sources
- Working with active materials an introduction

Reading list
- Gary Was: Fundamentals of Radiation Materials Science

FUSION CDT

EPSRC Centre for Doctoral Training in the Science and Technology of Fusion Energy

CHARACTERISATION / ANALYTICAL TOOLS [CDT:OU02]

Core Module	Materials Strand only	
Lecturers Oxford	Dr. Neil Young Prof. Pete Nellist Dr. Mohsen Danaie Prof. John Titchmarsh (TBC) Prof. Michael Moody Dr. Paul Bagot	Oxford – 21 BR Conference Room (TBC)
Term 2	5 February 2018 to	9 February 2018
Lecturers Manchester	Dr Tom Slater Prof. Bob Cernik	Oxford
Workload	14 hours of lectures	
	2 workshops/problem classes (Oxford); 1 practical session (Oxford)	
Assessment	2 x Open book assessments, 1 set by Oxford and 1 set by Manchester	
Oxford/Manchester Set	9 February 2018	Hand in due: 5 March 2018
Feedback and marks	Due 9 April 2018	

Aims

Following completion of this module, students should have a solid understanding of how Transmission Electron Microscopy, X-ray and Atom Probe Tomography, neutron diffraction and scattering, and residual stress measurement techniques work, both in theoretical terms and with hands-on experience of imaging/data analysis. Students should understand how these methods contribute to understanding key issues in nuclear materials, and should be well placed to consider how areas of their own research may benefit from the application of these methods.

Learning outcomes: at the end of this module successful students will be able to:

- Understand the basic principles of Transmission Electron Microscopy, including imaging and diffraction modes
- Understand the advantages of Scanning Transmission Electron Microscopy for chemical analysis
- Have a broad knowledge of how to use a variety of EM methods to examine radiation damage, both in theory and through a hands-on session
- Understand the basic principles of atom probe tomography (APT), and how it can be used to examine radiation damage in materials
- Examine sample APT data and appreciate the fundamentals of how to analyse the data

- Understand the basic principles of lab-based and synchrotron X-ray scattering and how these techniques are used to examine radiation damage in materials
- Understand the basic principles of neutron scattering and how these techniques are used to examine radiation damage in materials
- Decide on the most appropriate residual stress measurement technique to employ, perform simple calculations of stress, and determine appropriate mediation approaches
- Understand the basic principles of X-ray tomography and electron tomography and how these techniques can be used to study the microstructure and defects in materials

Syllabus

Background and basic principles of TEM - Imaging and Diffraction - STEM and Analysis - TEM imaging and radiation damage applications - Applications of spectroscopy to nuclear materials - Sample prep for nuclear materials - Fundamentals of atom probe tomography - Applications of APT to nuclear materials – Generation of X-rays by laboratory and synchrotron sources – Fundamentals of X-ray tomography - Fundamentals of electron tomography - Neutron sources for materials characterisation – Neutron scattering and diffraction – Residual stress measurement techniques – residual stress mediation

Lecture notes

Reading list

Preparation reading

Updated September 2017

FUSION CDT

EPSRC Centre for Doctoral Training in the Science and Technology of Fusion Energy

FINITE ELEMENT METHOD AND DESIGN CODES [CDT:MU01]

Core Module	Materials Strand only	
Lecturer	Prof Paul Mummery University of Manchester Dr Lee Margetts	
Term 1	12 March 2018 to 16 March 2018	
Workload	24 hour lectures	
	16 hour workshops/problem classes	
	Private study 60 hours	
Assessment	One open book assessment; one FEM assignment; and one problem solving assignment on supercomputer (dates for access to be given during the module)	
Open book set	16 March 2018	Due 20 April 2018
Problem solving set	FEM assignment 16 March 2018 Supercomputer tbc	Due 16 March 2018
Feedback and mark		1 May 2018

Aims

On completion of the module the students should have an appreciation of the fundamental basis and practical requirements of the finite element method; and be aware of the need for design codes and safety analysis of materials and components and how these analyses are undertaken.

Pre-requisites

Exercises will be carried out using both the UNIX and Windows operating systems. The course will also introduce some programming concepts for finite element analysis using Fortran. Attendees may find it useful to work through the online Fortran courses before arriving.

For those not familiar with UNIX (or Linux), or Fortran, please request details of introductory courses before arriving, by e-mailing kathryn.harvey@york.ac.uk

Learning outcomes: at the end of this module successful students will be able to:

- appreciate the fundamental basis of the finite element method;
- develop code to solve problems in mechanical and physical behaviour of materials and components using the finite element method;
- recognise the need for and basis of design codes and safety analysis of materials and components;
- be able to perform simple calculations based on design codes and commercial finite element packages

Syllabus
Mathematical foundations of finite element method – introduction to numerical methods – coding in ParaFEM – introduction to design codes – principles of R5, R6, RCCMX – failure assessment diagrams – safety calculations – use of Abaqus in stress analysis

Lecture notes:

Reading list
Programming the Finite Element Method, 6th edition,

The course makes use of the text book Smith, Griffiths and Margetts, “Programming the Finite Element Method”, 5th Edition, Wiley, 2014. Fusion CDT PhD students will be provided with a copy of the book. Two copies are available from the University of Manchester library.

Updated May 2017

FUSION CDT
EPSRC Centre for Doctoral Training in the Science and Technology of Fusion Energy

MATERIALS FOR NUCLEAR POWER [CDT:OU04]

Core Module for Materials Strand	
Lecturer	
Term 2	4 April 2018 to 6 April 2018
Workload	Lectures 9
	Discussion 1
	Group classes 1
	Assignments 1
	Private study
	Total
Assessment	TBD
Set	TBD
Hand in due	TBD
Feedback	Due

Aims: This course links the materials requirements for future fusion reactors with the materials solutions previously and currently deployed in fission reactors. Over the last 70 years structural materials for fission have been continually developed and studied while fusion materials have lagged behind. They have also benefited from the examination of in service components and materials, exposed to decades of radiation damage, which can lead to physical changes not observed during proxy irradiations. In many cases the fusion community can use lessons learnt in the fission materials to aid materials design and deployment.

Learning outcomes: at the end of this module successful students will be able to:

Understand the basic design of a fission reactor (PWR and AGR)
Understand the common materials issues across fission and fusion reactors
Develop knowledge of specific nuclear materials, (others may be substituted depending on lecturer availability), issues associated with their deployment and where the fusion community can learn from them:

Syllabus

- Reactor Design – (James Marrow)
- Fuel cladding (zirconium) – (Chris Grovenor)
- Fuel (uranium oxide) – (TBA)
- RPV steels – (Peter Flewitt)
- Stress corrosion cracking in aqueous environments (Sergio Lozano-Perez)

- Creep resistant steels for steam turbines (David Armstrong)
- Nuclear graphite (Dong Liu)
- Nuclear ceramics (David Armstrong)
- Waste disposal (Dirk Engleberg (Manchester)

Reading List

Fundamentals of Radiation Damage - Gary Was
An Introduction to Nuclear Materials – K. Linga Murty and Idrajit Charit
Nuclear Materials Science – Karl Whittle