INTRODUCTION TO FUSION PLASMAS

Required module for Materials and Plasma Strand

<table>
<thead>
<tr>
<th>Lecturer</th>
<th>Dr Koki Imada</th>
<th>York Plasma Institute</th>
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<td></td>
<td>Dr David Dickinson</td>
<td>York Plasma Institute</td>
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| Term 1            | 17 October 2016 to 4 November 2016 |

| Workload          | 18 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               | 7 November 2016 | Due 25 November 2016 |
| Set               | 20 November 2016 | Due 25 November 2016 |
| Set (Plasma only) | 25 November 2016 | 2 December 2016 |

| Feedback and mark | Due 9 January 2017 |

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

Core module for Plasma and Materials strands

<table>
<thead>
<tr>
<th>Lecturers</th>
<th>Dr Eugene Zayachuk</th>
<th>Delivered by Oxford staff at York Plasma</th>
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<tbody>
<tr>
<td>Dr Maria Auger</td>
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<td>Dr David Armstrong</td>
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Term 1 17 October 2015 to 4 November 2015

Workload
- 16 hours of lectures
- 3 x 1 hour problem classes
- Private study 81 hours

Assessment
- One open book assignment
  - Set: 11 November 2016
  - Due: 9 December 2016
- Feedback and mark: Due 9 January 2017

Aims

This course will give those without a background in materials science a basic introduction to the subject. 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 or high neutron fluxes. 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 August 2016
**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
INTRODUCTION TO COMPUTATIONAL TECHNIQUES

Required module for Plasma and Materials strand

<table>
<thead>
<tr>
<th>Lecturers</th>
<th>Dr David Dickinson</th>
<th>York Plasma Institute in person and by recorded presentation for those students arriving later.</th>
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<tbody>
<tr>
<td>Term</td>
<td>Term 1</td>
<td>17 October 2016 to 4 November 2016</td>
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<tr>
<td>Workload</td>
<td>9 x 1 Lectures</td>
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<td></td>
<td>3 x 1 Problem classes</td>
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<td></td>
<td>84 hours Private Study</td>
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<tr>
<td>Assessment</td>
<td>Programming assignments</td>
<td>Due: Friday week 5, 6 and 7</td>
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<td></td>
<td>Computational report</td>
<td>Due: Friday 2 December 2016</td>
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<tr>
<td>Feedback and marks</td>
<td>Assignments returned a week after submission. Report returned by 9 January 2017</td>
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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:

- Programme 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
- 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

- 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**


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


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

Numerical Recipes in C / Fortran (Cambridge University Press)
MATERIALS APPLICATIONS IN FUSION

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<th>Required module for Materials and Plasma strand</th>
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<td>Lecturers</td>
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<td>Workload</td>
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<td>Assessment</td>
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<td>Assessment</td>
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<td>Group project set</td>
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<td>Essay set</td>
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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
- Design the divertor and construct an argument for the choice of materials in this region
- Design 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 importance of materials testing, and the options available
• Understand the role of superconducting magnets in fusion devices
• Demonstrate an ability to translate knowledge
• Communicate effectively, both orally and written

Syllabus

• MCF power plant components
• ICF power plant components
• 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
• IFMIF and materials testing
• Superconducting magnets for fusion
FUSION TECHNOLOGY

Required module for Materials and Plasma strands

<table>
<thead>
<tr>
<th>Organiser</th>
<th>Prof Bruce Lipschultz</th>
<th>York Plasma Institute</th>
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<tr>
<td>Additional marker</td>
<td>Dr John Pasley</td>
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<td>Other lecturers</td>
<td>External Guest speakers</td>
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<tr>
<th>Term 2</th>
<th>16 January 2017 to 20 January 2017 for lectures, work thru end of term</th>
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<tr>
<td>Workload</td>
<td>10 lectures (25 hours)</td>
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<td>6 problem sets – 25 hours</td>
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<td>Essay assignment – 50 hours</td>
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<tr>
<td>Assessment</td>
<td>Approx 6 weekly problems (15%) and 1 essay (85%)</td>
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<tr>
<td>Hand in Due</td>
<td>Weekly problems due weekly through ~ week 7, essay due end of term</td>
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<td>Feedback</td>
<td>Within 1-2 weeks for problem questions</td>
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<td>Within one month for essay</td>
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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

Required module for Plasma and Materials Strands

<table>
<thead>
<tr>
<th>Lecturers</th>
<th>University of Liverpool Laboratories</th>
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<tr>
<td>Prof James Bradley</td>
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<td>Dr Paul Bryant</td>
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<td>Dr Karl Dawson</td>
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<td>Dr Tobias Heil</td>
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<tr>
<th>Term 2</th>
<th>23 January 2017 to 27 January 2017</th>
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<table>
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<tr>
<th>Workload</th>
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<tbody>
<tr>
<td>6 x 1 hour lectures</td>
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<tr>
<td>3 x 1 hour problem classes</td>
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<tr>
<td>73 hours private study</td>
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<td>18 hours Laboratory</td>
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<th>Assessment</th>
<th>During the course</th>
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<td>Lab books</td>
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<th>Feedback and marks</th>
<th>During the course</th>
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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) to 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 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
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.
Compulsory for all first and second year students. Third year students are welcome.

COLLABORATORY PRESENTATIONS AND SANDPIT EVENT

The collaboratory is a module that is designed to develop your research skills. It runs through the second year, and consists of a planning phase during the student conference in September of the first year; writing a research proposal by the end of September (first year); and executing the 10-week project by end June in your second year; writing a short (letter-style) journal paper by end July, which is then refereed by 3rd and 4th year students; giving an oral presentation at the student conference in September of your second year. A budget of £3k on average per student is available, but the amount awarded will depend on need and the quality of the proposal. It is essential that the collaboratory project meets certain criteria: (a) it must involve a collaboration of some sort, preferably with other Fusion-CDT students but not necessarily; (b) it must have a strong training and development aspect, and cannot simply be part of your core PhD research programme (but can be related). All Fusion-CDT students who successfully pass the taught-course modules will perform the collaboratory; those who have failed to meet the required standard for the FUSENET certificate in the taught modules will be interviewed by a panel before being allowed to take part in the collaboratory.

If there is a need to access facilities, and these are not available during the 9-month project period (Oct – end June), this will be treated on a case-by-case basis, but is expected to be an extremely rare occurrence. Such a need should be flagged to the Fusion-CDT Programme Director as soon as possible.