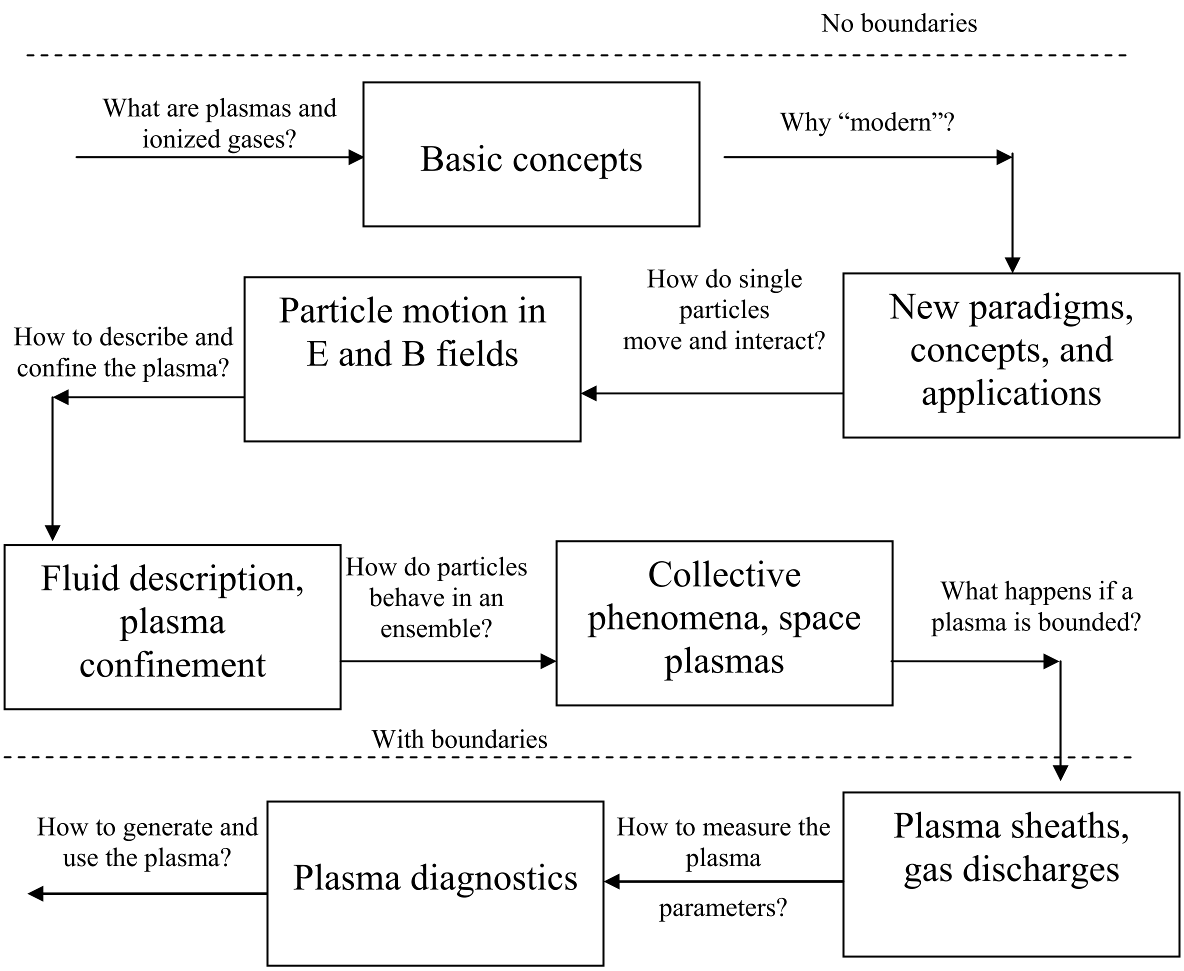
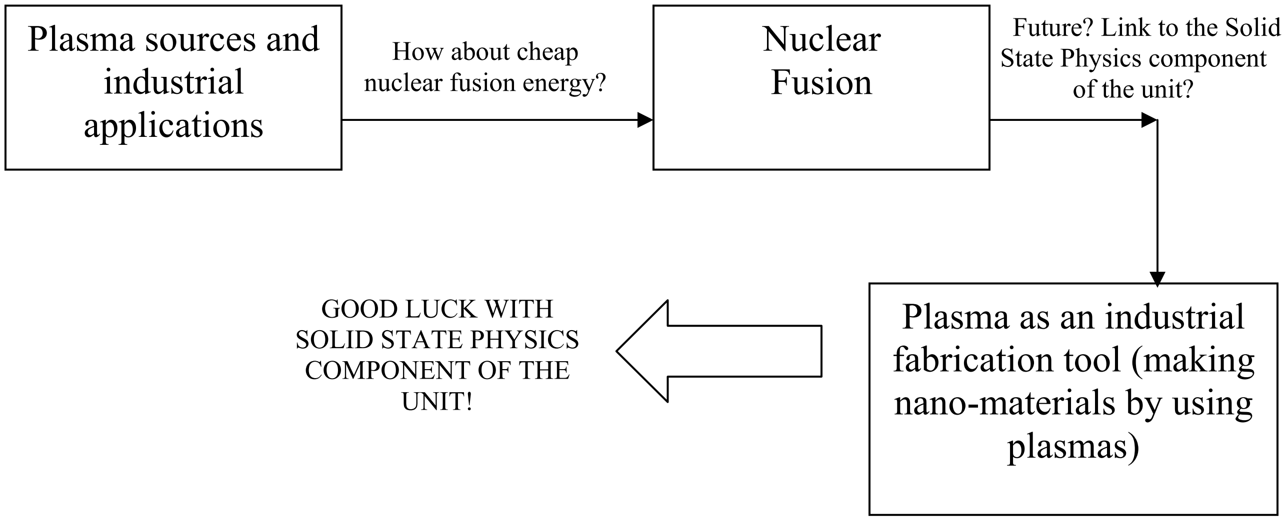
MODERN PHYSICS OF PLASMAS (19 lectures)

Course coordinator and principal lecturer: *Dr Kostya (Ken) Ostrikov*
Lecturer (normal student stream): *Dr Joe Khachan*
Guest lecturers: Dr Ian Falconer, Prof Iver Cairns

This series of lectures introduces the basic concepts of modern physics of plasmas and ionized gases. Ionized gaseous matter, which is a collection of charged and neutral particles, is the main constituent of the Universe and is a cause of a vast variety of astrophysical, space and terrestrial phenomena. The course details how unique and unusual fundamental properties of plasmas and ionized gases can explain such phenomena and translate into existing and future industrial applications including nuclear fusion energy, materials synthesis and modification, environmental remediation, aerospace, nano- and biomedical technologies. The senior electromagnetism course is assumed knowledge for the modern plasma physics component of this unit. For more details on this course see the Unit of Study Outline. This course is offered for the advanced and normal student streams. 17 lectures are the same for both streams and 2 lectures are different.

COURSE OUTLINE AND LOGIC FLOW CHART





REFERENCE MATERIALS:

- **F. F. Chen**, *Introduction to Plasma Physics and Controlled Fusion*, Plenum Press, New York, 1984.
- **Michael A. Lieberman, Allan J. Lichtenberg,** *Principles of Plasma Discharges and Materials Processing,* Wiley, New York, 1994.
- Alexander Fridman and Lawrence A. Kennedy, *Plasma physics and engineering*, Taylor & Francis, New York, 2004.
- D. A. Gurnett and A. Bhattacharjee, *Introduction to plasma physics: with space and laboratory applications,* Cambridge, UK; New York: Cambridge University Press, 2005.
- S. V. Vladimirov, K. Ostrikov, and A. Samarian, *Physics and Applications of Complex Plasmas,* Imperial College Press, London, Singapore, 2005.
- K. Ostrikov, *"Colloquium: Reactive plasma as a versatile nanofabrication tool",* Reviews of Modern Physics, v.77, 489 - 511 (2005).

COURSE STRUCTURE
(6 sections, 19 lectures, 2 assignments, and a laboratory tour)

Section 1:

PLASMAS AND IONISED GASES: BASIC PROPERTIES AND CONCEPTS
(3 lectures)

Lecture 1.1; Mon, 24 July 2006: Introduction – what is a plasma; occurrence of plasmas and ionised gases in nature and laboratory and major industrial applications. New paradigms and challenges in physics of plasmas and gas discharges.

Lecture 1.2; Thu 27 July 2006: Collision processes in plasmas.

Lecture 1.3; Fri 28 July 2006: Basics of plasma generation and gas discharges.

Section 2:

SINGLE PARTICLE MOTIONS
(2 lectures)

Lecture 2.1; Mon 31 July 2006: Particle motions in uniform electric and magnetic fields. Characteristic radius of particle motion in magnetic fields (Larmor radius).

Lecture 2.2; Thu 3 Aug 2006: Particle motions in non-uniform magnetic fields. Adiabatic invariants, magnetic mirror, gradient drift.

Section 3:

FLUID DESCRIPTION OF A PLASMA
(3 lectures)

Lecture 3.1; Fri 4 Aug 2006: Elements of fluid mechanics. Plasma fluid equations.

Lecture 3.2; Mon 7 Aug 2006: E x B and diamagnetic drifts. Generalized Ohm's law.

Lecture 3.3; Thu 10 Aug 2006: Principles of plasma confinement. Tokamaks and stellarators.

Section 4:

COLLECTIVE PHENOMENA IN PLASMAS
(3 lectures)

Lecture 4.1; Fri 11 Aug 2006 : Plasma waves and oscillations as collective phenomena. Waves in unmagnetised plasmas.

Lecture 4.2; Mon 14 Aug 2006: Waves in magnetised plasmas.

Lecture 4.3; Thu 17 Aug 2006: MHD waves. Examples of plasma collective phenomena in laboratory and space.

Section 5:

WALL PHENOMENA: DIFFUSION AND SHEATHS
(3 lectures)

Lecture 5.1; Fri 18 Aug 2006: Plasma screening and sheaths: basic concepts.

Lecture 5.2; Mon 21 Aug 2006: Types of sheaths. Diffusion and mobility in a plasma.

Lecture 5.3; Thu 24 Aug 2006: Examples of diffusion: ambipolar diffusion and diffusion in magnetic fields.

Section 6:

PLASMA GENERATION, DIAGNOSTICS, AND EMERGING TOPICS OF MODERN PHYSICS OF PLASMAS (5 lectures)

Lecture 6.1; Fri 25 Aug 2006: Generation and industrial applications of low-temperature plasmas.

Co-requisite of Lecture 6.1: a tour to research laboratories of the Applied and Plasma research group. The tour will be conducted during the week starting 21 August 2006.

Lecture 6.2; Mon 28 Aug 2006: Advanced plasma diagnostic techniques.

Lecture 6.3 (Advanced); Thu 31 Aug 2006: Collective phenomena in space plasmas.
Lecture 6.3 (Normal); Thu 31 Aug 2006: Problem solving: basic plasma properties.

Lecture 6.4; Fri 1 Sep 2006: Nuclear fusion: past, present, and future challenges.

Lecture 6.5 (Advanced); Mon 4 Sep 2006: Plasma-made nanomaterials: from cutting-edge research to undergraduate classroom and building bridges to the Solid State Physics section of this unit.
Lecture 6.5 (Normal); Mon 4 Sep 2006: Tutorial: collective phenomena in plasmas.

Assignment 1: covers sections 1-3; **due 5pm, Monday, 14 August 2006**

Assignment 2: covers sections 4-6; **due 5pm, Friday, 8 September 2006**

A ***tour to plasma and materials processing research laboratories*** of the Applied and Plasma research group of the School of Physics will be conducted during the week starting 21 August 2006.

COURSE TIMETABLE

LECTURE TIMES:

Monday: 10-11 am
Thursday: 1 – 2 pm
Friday: 1 – 2 pm

LECTURE ROOM:

- Lectures (for both streams) will be in LT5
- On the days of split lectures (31 Aug and 4 Sep), lectures for normal stream will be conducted in LT4

DETAILED LECTURE PROGRAM

Mon, 24 July: Lecture 1.1 (K. Ostrikov)
Thu, 27 July: Lecture 1.2 (K. Ostrikov)
Fri, 28 July: Lecture 1.3 (K. Ostrikov)

Mon, 31 Jul: Lecture 2.1 (K. Ostrikov)
Thu, 3 Aug: Lecture 2.2 (K. Ostrikov)
Fri: 4 Aug: Lecture 3.1 (K. Ostrikov)

Mon, 7 Aug: Lecture 3.2 (K. Ostrikov)
Thu, 10 Aug: Lecture 3.3 (K. Ostrikov)
Fri, 11 Aug: Lecture 4.1 (K. Ostrikov)

Mon, 14 Aug: Lecture 4.2 (K. Ostrikov)
Thu, 17 Aug: Lecture 4.3 (K. Ostrikov)
Fri, 18 Aug: Lecture 5.1 (K. Ostrikov)

Mon, 21 Aug: Lecture 5.2 (K. Ostrikov)
Thu, 24 Aug: Lecture 5.3 (K. Ostrikov)
Fri, 25 Aug: Lecture 6.1 (K. Ostrikov)

Mon, 28 Aug: Lecture 6.2 (I. Falconer)

Thu, 31 Aug: Lecture 6.3 (Advanced, I. Cairns)
Thu, 31 Aug: Lecture 6.3 (Normal, J. Khachan)

Fri, 1 Sep: Lecture 6.4 (J. Khachan)

Mon, 4 Sep: Lecture 6.5 (Advanced, K. Ostrikov)
Mon, 4 Sep: Lecture 6.5 (Normal, J. Khachan)

Laboratory tour: between 21-25 Aug 2006 (coordinators K. Ostrikov and J. Khachan)

CONTACT DETAILS OF THE COURSE COORDINATOR

Dr Kostya (Ken) Ostrikov, Office 569 (Building A29, second level above the Physics Library), E-mail: K.Ostrikov@physics.usyd.edu.au

LEARNINIG OUTCOMES

Section 1: *PLASMAS AND IONISED GASES: BASIC PROPERTIES AND CONCEPTS*

Lecture 1.1: Introduction.

- Understanding of what is a plasma.
- Appreciate the occurrence of plasmas and ionised gases in nature and laboratory.
- Learn the main plasma parameters in a number of typical situations in nature and laboratory.
- Be able to identify major industrial applications of plasmas and ionised gases.
- Use a Maxwellian distribution function to obtain the main characteristics of chaotic motion of particles.

Lecture 1.2: Collision processes in plasmas.

- Appreciate a wide variety of collision processes in plasmas and ionized gases: atom-atom, atom-electron, atom-ion, electron-electron, electron-ion, ion-ion, charge exchange, involving clusters, molecules, macromolecules, radicals, etc.
- Distinguish between elastic and inelastic collisions.
- Learn how to characterize collision processes by using energy-dependent cross-sections.
- Understanding of the notion of the mean free path; derivation of the mean time between particle collisions.
- Estimate the frequency of Coulomb collisions between charged particles.
- Calculate the electrical resistivity of a plasma column due to electron-ion collisions and understand the implications of temperature dependence of the electrical resistivity for applications in nuclear fusion devices.

Lecture 1.3: Basics of plasma generation and gas discharges.

- Explain the main mechanisms of ionisation (thermal, in electric field, photoionisation, etc.).
- Justify the applicability of the above ionisation mechanisms to specific situations in laboratory and space.
- Understand gas breakdown phenomena in different situations.
- Follow the transition of different regimes of a DC gas discharge with an increasing voltage.
- Differentiate between non-self-sustaining and self-sustaining discharges, glow and arc discharges.

Section 2: *SINGLE PARTICLE MOTIONS*

Lecture 2.1: Particle motions in uniform electric and magnetic fields.

- Be able to write down and manipulate the particle motion equations in the presence of uniform electric and magnetic fields.
- Calculate and estimate the characteristic radius of particle motion in magnetic fields.
- Understand the nature of ExB drift in a plasma

Lecture 2.2: Particle motions in non-uniform magnetic fields.

- Explain what happens to the particle motion when the magnetic field is non-uniform.
- Learn the implications of the adiabatic invariant on the particle motion in plasmas.
- Understand the physics of magnetic mirror and gradient drift phenomena.

Section 3: ***FLUID DESCRIPTION OF A PLASMA***

Lecture 3.1: Elements of fluid mechanics. Plasma fluid equations.

- Introduce and explain the principles of the plasma fluid description.
- Recall some basics of the fluid dynamics description – mass, momentum, and energy conservation.
- Understand how a plasma can be described as a fluid. In what sense it is a "fluid"?
- Continuity and momentum conservation equations - how do they work?
- Two/three - fluid equations – when should they be used?
- Understand the concept of multi-component plasmas.

Lecture 3.2: E x B and diamagnetic drifts. Generalized Ohm's law.

- Introduce and explain the generalized Ohm's law and commonly used approximations.
- Understand how the plasma drifts in crossed E and B fields.
- What happens if the plasma is non-uniform?
- Learn how to justify and use the single fluid approximation and other commonly used in plasma physics approximations.
- Justify and use the basic set of equations of "resistive" and "charge neutral" magnetohydrodynamics (MHD).

Lecture 3.3: Principles of plasma confinement. Tokamaks and stellarators.

- Be aware of the key ideas of the plasma confinement in magnetic fields.
- Explain the necessity of plasma confinement.
- Learn how to use magnetic fields for plasma confinement and quantify the major forces and pressures in the plasma.
- Pinch effect – how can a current flowing through the plasma be used?
- Understand working principles and main elements of common plasma fusion devices such as tokamaks and stellarators.

Section 4: COLLECTIVE PHENOMENA IN PLASMAS

Lecture 4.1: Plasma waves and oscillations as collective phenomena. Waves in unmagnetised plasmas.

- Understand the nature of collective phenomena in unmagnetised plasmas.
- Appreciate the origin and quantify the plasma oscillations.
- Learn the mechanisms of wave propagation in the plasma.

- Be able to derive and analyze wave dispersion relations in unmagnetised plasmas.
- How to identify and describe some of the common plasma wave modes?

Lecture 4.2: Waves in magnetised plasmas.

- Understand various wave phenomena in magnetised plasmas.
- Describe the waves in magnetoplasmas by using the conductivity tensor.
- Learn how to derive and analyze dispersion relations for propagation along the magnetic field.
- Be able to identify propagating modes, their polarization, resonances and cutoffs.

Lecture 4.3: MHD waves. Examples of plasma collective phenomena in laboratory and space.

- Introduce the very low frequency MHD waves and give some examples (and applications) of plasma collective phenomena.
- Be able to derive dispersion relations of MHD waves.
- Differentiate between Alfven, fast and slow MHD waves.
- Understand why plasma collective phenomena are so important in Space, laboratory and industry.

Section 5: WALL PHENOMENA: DIFFUSION AND SHEATHS

Lecture 5.1: Plasma screening and sheaths: basic concepts.

- Understand how the plasma screening and plasma sheaths work.
- Derive and use the Boltzmann relation.
- Explain the physics of the plasma screening and estimate the Debye length.
- Understand the necessity of the plasma sheaths.
- Derive and apply the Bohm sheath criterion.
- Calculate the potential of a wall exposed to a plasma.

Lecture 5.2: Types of sheaths. Diffusion and mobility in a plasma.

- Introduce different types of plasma sheaths and understand the basics of diffusion and mobility phenomena in a plasma.
- Differentiate between basic properties of high-voltage, matrix, and Child Law sheaths.
- Appreciate the importance of the plasma sheaths in industrial applications.
- Define and describe diffusion and mobility in weakly ionised low-temperature plasmas.

Lecture 5.3: Examples of diffusion: ambipolar diffusion and diffusion in magnetic fields.

- Understand basic features of diffusion phenomena in unmagnetised and magnetised plasmas.
- Explain why electrons and ions drift together in ambipolar electric fields.
- Learn the key features of the drift in partially ionised and fully ionised plasmas.
- Appreciate the importance of the plasma drift phenomena in laboratory and space.

Section 6: PLASMA GENERATION, DIAGNOSTICS, AND EMERGING TOPICS OF MODERN PHYSICS OF PLASMAS

Lecture 6.1: Generation and industrial applications of low-temperature plasmas.

- Appreciate a wide range of industrial applications of low-temperature plasmas.
- Justify the main characteristics of industrial plasmas and how they depend on process specifications (applicable to plasma-enhanced chemical vapour deposition of thin films and high-precision anisotropic etching in microelectronic manufacturing).
- Understand the means of generation and main parameters of various sources of industrial plasmas: capacitively coupled plasma sources, inductively coupled plasma sources, wave-driven (e.g. helicon) plasma sources, plasma-assisted magnetron sputtering devices, and cathodic vacuum arcs.

Lecture 6.2: Advanced plasma diagnostic techniques.

Learn basic principles of the following plasma diagnostic techniques:

- Electrostatic probes (Langmuir probes);
- Magnetic probes;
- Microwave and optical interferometry;
- Spectroscopic techniques;
- Mass spectrometry;
- Thomson scattering.

Lecture 6.3 (Advanced): Collective phenomena in space plasmas: shocks and associated phenomena.

- Appreciate a wide variety of plasma-related phenomena in space and astrophysical plasmas.
- Explain the origin of shocks and associated phenomena in space plasmas.
- Follow how MHD equations can be used for the description of shocks in space and astrophysics.

Lecture 6.3 (Normal): Problem solving: basic plasma properties.

- Learn some the most commonly used approaches to solve problems related to basic plasma properties
- Be able to numerically estimate the most important parameters in plasma physics and use representative temporal and spatial scales to explain a wide variety of plasma-related phenomena in space and laboratory plasmas.

Lecture 6.4: Nuclear fusion: past, present, and future challenges.

- Appreciate the importance of thermonuclear energy as a virtually unlimited source of cheap energy.
- Learn the key nuclear fusion reactions and their characteristics.
- Understand how one can gain net energy from nuclear fusion reactions.
- Explain the principles of magnetic and inertial confinement.

Lecture 6.5 (Advanced): Plasma-made nanomaterials.

- Appreciate the importance of plasma-aided nanofabrication processes.
- Learn what makes low-temperature reactive plasmas a versatile nanofabrication tool.
- Explain the sequence of steps of manipulation of building blocks and surface preparation in reactive plasma environments.
- Understand the notion of reactive plasmas and learn the variety of nanofabrication building blocks in reactive plasmas.

Lecture 6.5 (Normal): Tutorial: collective phenomena in plasmas.

- Appreciate a variety of collective phenomena in plasmas and relate them to basic plasma properties.
- Use knowledge obtained in the lectures to solve problems related to collective phenomena in plasmas.
- Develop a better awareness of the range of problems that might be offered at the exam.