PROGRAM SYLLABUS

MASTER PLASMA PHYSICS AND FUSION

SEMESTER 1 – COMPULSORY CLASSES

All students follow the following classes at the beginning of the term.

Tools for plasmas and fusion

Acronym :TC1	
EU Coordinator : Philippe SAVOINI, Laboratoire de Physique des Plasmas (LPP)	
Teaching staff : Philippe SAVOINI	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords : State of plasma. Characteristic space-time scales of plasmas (Debye length, plasma frequency, ...). Theories and models: orbit theory, kinetic theory, multi-fluid and Magnetohydrodynamics.	

This module is an introduction dedicated to fulfill two objectives: (i) to introduce the basic concepts of the "plasma state" and (ii) to present the different theoretical approaches related to the multi-scale (time and space) aspect of thermonuclear, cold and/or space fusion plasmas. This course remains at a basic level as far as the applications are concerned and focuses on giving the most precise general view of the tools used in plasma physics.

Indeed, plasma - or the fourth state of matter - constitutes 99% of the visible matter in the Universe and is essentially formed of ionized gas. This "plasma state" is thus characterized by a set of charged particles influenced by long-range electric and magnetic fields, and by their feedback on these fields.
. Plasmas are thus the result of two contradictory tendencies, a tendency to disorder due to thermal agitation and a tendency to organization due to the Coulombian interaction.

These two opposite behaviors between charged particles and electromagnetic fields makes the determination and calculation of the different space-time scales present within the plasma essential in order to understand both the dynamics of the plasma itself, but also and above all, the use of different theories and models used in plasma physics. Thus, among the different possible perimeters for this module, we have opted for a division according to these scales and their associated models in order to show the coherence and continuity of these different theoretical approaches. The course is divided into five parts:

Introduction :
- The space-time scales related to the electric and magnetic fields.
- Presentation of the different possible theories and models related to these scales.

Particle theory: a very useful approximation
- Electric and magnetic drift phenomena.
- Notion of adiabatic invariant : the mirror reflection.

Kinetic theory : a very complete statistical approach
- Statistical approach of plasmas :Klimontovitch equation.
- Vlasov and Boltzmann equations.

Multi-fluid theory: a global approach
- Determination of the fluid equations via the kinetic theory.
- Approximation and consequence on the dynamics of particles : Notion of closure laws.

MagnetoHydroDynamictheory : a "simplified" theory
- Determinations of the MHD equations from the multi-fluid theory.
- Limitations and areas of validity of MHD: use of Ohm's law.

This course is shared with the M2 "Master 2 Astronomy, Astrophysics and Space Engineering" (M2 A&A) in order to provide a common base on the "plasma state".

Magnetohydrodynamics

Acronym : TC2	
EU Coordinator : Catherine KRAFFT, Laboratoire de Physique des Plasmas (LPP)	
Teaching staff : Sébastien GALTIER, Catherine KRAFFT	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords : Theory of Magnetohydrodynamics (MHD) - MHD invariants - Cylindrical, toroidal, force-free equilibria - MHD instabilities - Magnetic containment - MHD waves - MHD turbulence - Magnetic reconnection - Kolmogorov spectrum	

The objective is to present the fluid approach of the generalized Magnetohydrodynamics (MHD) theory in which the corpuscular aspect (electrons, ions) is no longer essential to describe the linear and nonlinear physical processes in magnetized plasmas. Four main parts will be discussed: (I) Theoretical foundations of MHD; (II) Invariants and equilibria; (III) Instabilities and magnetic containment; (IV) MHD turbulence. The articulation between these parts will be facilitated by examples from astrophysical plasmas and magnetic thermonuclear fusion.

The content of the teaching unit is the following :

General introduction - Moments of the Boltzmann equation - Multi-fluid model - Bi-fluid model - Single-fluid model - MHD equations - Generalized Ohm's law - Resistivity - Conductivity - Limits of validity of the theory - Ideal and resistive MHD - Magnetic tension - Lorentz force - Pressure tensor - Resistive diffusion - Convection.

Conservation laws of mass, energy and momentum density - Alfven flow and freeze theorems - Magnetic helicity - Crossed helicity - Magnetic topology.

Wave propagation - Equations and dispersion characteristics of Alfven and magnetosonic waves - Radiation diagrams - Field, pressure and mass density perturbations.

Equilibria and magnetic containment - Cylindrical equilibria (theta and z pinches) - Toric equilibrium (Grad-Shafranov equation) - Force-free equilibrium.

Instabilities: Linear perturbation theory and limits of validity - Rayleigh-Taylor and Kruskal-Schwarzschild - z and theta pinches - Magneto-rotational instability in accretion disks - Resistive tearing instability.

Magnetic reconnection: Solar flares - Reconnection rates - Sweet-Parker model - Fast reconnection with Hall effect.

MHD Turbulence : Solar wind and tokamak - Statistical concepts and tools - Hydrodynamic turbulence with exact law and Kolmogorov spectrum - MHD turbulence with exact law and anisotropic spectrum - Intermittence and fractal.

Kynetic theory of plasmas

Acronym : TC3

UECoordinator : Jean-Luc RAIMBAULT, Laboratoire de Physique des Plasmas (LPP)	
Teaching staff : Mickaël GRECH, Pierre MOREL, Jean-Luc RAIMBAULT	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	

This course is divided into three parts presented below.

I. Kinetic theory : the foundations

Keywords : Phase space, density probability, distribution function; Kinetic equations (Liouville, Klimontovich, Boltzmann, Vlasov), BBGKY hierarchy, Hydrodynamic moments; Vlasov-Poisson and Vlasov-Maxwell models, Conservation laws, Linear theory (waves and instabilities), Wave-particle interaction, Landau damping; Coulomb collisions, Collision operators, Collision frequency, Diffusion coefficients, Conductivity, Heating and transport

This course aims to lay the basis of the kinetic theory of plasmas. It focuses on classical, non relativistic and fully ionized plasmas.

A first part introduces the notions of phase space, density probability and distribution functions, as well as the Klimontovich and Liouville equations that describe the exact evolution of the plasma. We then discuss the approximations and procedures allowing to derive, from these exact descriptions, the most useful statistical descriptions of kinetic plasmas: the plasma kinetic equation (accounting for collisions) and the Vlasov equation (for collisionless plasmas). This introductory part ends with the derivation of the hydrodynamic equations and a discussion of the links between the kinetic and hydrodynamic descriptions.

The second part of this lecture focuses on collisionless plasmas, as described by the Vlasov-Poisson (electrostatic) and Vlasov-Maxwell (electromagnetic) systems. The general properties of these descriptions are discussed: equilibrium and steady-state solutions, conservation of entropy, momentum and energy, etc. Their linearization is then discussed in details, and kinetic effects on waves and instabilities is addressed. A particular attention is paid to the Landau damping of electrostatic waves in the framework of linear theory (dispersion relation and damping rate) and nonlinear effects (particle trapping) are, though briefly, discussed.

The third and last part addresses the kinetic theory of collisional plasmas. Only elastic, Coulomb collisions are considered. The notions of cross-section, mean-free-path, collision frequency and diffusion coefficients are introduced. Various collision operators (Boltzmann, Fokker-Planck, Landau in particular) are then discussed and applied to the study of various important processes such as conductivity or heat transport.

II. Application to magnetic fusion plasmas: transport and relaxation in tokamak plasmas

Keywords : Principles of fusion and magnetic confinement – Magnetic equilibrium – Gyrokinetic Theory – Landau collision operator – Neoclassical theory – Collisional and non collisional relaxations – Micro-instabilities – Angle-action variables – Resonances – Zonal flows and geodesic acoustic modes.

The objective of the course is to study the phenomena of reorganisation of the distribution function of plasma particles, undergoing for example heating, in velocity space (relaxation) or in position space (transport). In particular, hot, low collisional, and especially fully ionised plasmas are studied here. Such plasmas are encountered in thermonuclear fusion, but also in the universe.

After introducing the basic principles of a thermonuclear fusion reactor, the case of magnetic confinement is studied in depth. The presence of a strong magnetic field allows the construction of the gyrokinetic theory and the fluid equations derived from it. The main micro-instabilities, associated with the magnetized plasma, can then be studied in the gyrokinetic framework.

The Landau collision operator is presented, and its consequences in terms of particle and heat transport is deduced in the framework of the neoclassical theory. In the presence of particles or heat sources, or instabilities, the relaxation mechanisms of the distribution function are presented in an action-angle formalism. The development of large-scale structures, their interest for confinement and their persistence over long times are finally discussed.

III. Application to cold plasmas : Introduction to the kinetic theory of discharges

Keywords : 2 terms approximation. Boltzmann collision operator and Lorentz models. Electronic transport coefficients. EEDF (Electron Energy Distribution Function) equation. Local and non-local approximations of the EEDF equation.

In cold plasmas, most of the electrical power is absorbed by the electrons which dissipate this energy by elastic and inelastic collisions with neutrals. Due to the low ionization rates observed in cold plasmas, electron-electron collisions are rare and the electron distribution function deviates significantly from a Maxwellian equilibrium distribution. This non-equilibrium character of electrons is the main reason for a kinetic description of the heating and transport of electrons in the cold plasmas studied in this course.

The dominant collisions for electrons in cold plasmas being electron-neutral collisions, the electron distribution function is quasi-isotropic. A spherical harmonic expansion of the electron distribution function is therefore convenient that leads to the so-called 2-term approximation.

We then study the elastic and inelastic electron-neutral collisions in detail using the Boltzmann collision operator. The low m/M mass ratio allows to simplify this operator in the framework of the so-called Lorentz models. Explicit expressions for the collision terms, in the kinetic or fluid frameworks, are obtained.

Using the kinetic approach developed in the framework of the 2-term approximation, we obtain general expressions for the electron transport coefficients in weakly ionized plasmas, magnetized or not, in stationary or time-dependent situations. In particular, explicit expressions of the mobility, diffusion and thermal diffusion coefficients, as well as their energy analogues, are obtained.

Finally, we establish the general expression of the evolution equation of the isotropic part of the electron distribution function (EEDF) in the position-energy phase space. From this equation, we discuss 2 approximations, valid respectively at high and low pressures, the so-called local and non-local approximations of the EEDF. Explicit solutions of the EEDF equation under these two approximations are given in the case of dominant electron-neutral elastic collisions, which lead to the Druyvesteyn distribution function in the case of the local approximation, and to the generalized Boltzmann relations in the case of the non-local approximation.

Waves and instabilities

Acronym : TC4	
EU Coordinator : Caterina RICONDA, Laboratoire de l'Utilisation des Lasers Intenses (LULI)	
Teaching staff : Jérôme FAURE, Roch SMETS, Caterina RICONDA	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords : Linear theory, nonlinear phenomena, non uniform plasmas, fluid and kinetic theories.	

This course is divided into three parts presented below.

I. Waves and instabilities in plasmas : the basics

This part aims at presenting in a very general way the theory of waves in plasmas in the framework of the fluid theory and the kinetic theory. The dispersion relations and the characteristics of the different wave solutions are calculated in the linear approximation. Several examples of nonlinear phenomena are then presented. The theory of linear instabilities is presented in non-magnetized media. The topics covered are the following:

- Fluid equations and dielectric function.
-Waves in non-magnetized plasmas.
- Electron plasma wave breaking in a cold plasma in fluid theory.
- Collisional absorption of electromagnetic waves.
- Propagation of an electromagnetic wave in an inhomogeneous medium (WKB theory).
- Resonant absorption.
- Low frequency nonlinear waves: ion acoustic solitons, non-collisional shock waves.
- Collisional shocks, Hugoniot curves, case of the perfect gas.
- Kinetic dielectric function.
- Landau damping of electrostatic waves in a Maxwellian plasma, electron plasma waves in a hot plasma, electron-acoustic waves.
- Kinetic beam-plasma instability (bump-in-tail).
- Fluid beam-plasma instability for electrostatic and electromagnetic waves (Weibel instability).
- Waves in magnetized plasmas: cyclotron resonance, right and left electromagnetic modes, whistler waves, ring instability.
- Ponderomotive force, three-wave resonant coupling.

II. Application to astrophysical plasmas: waves and instabilities

This course presents different examples of waves and instabilities in astrophysical plasmas, using the fluid and kinetic formalisms. The topics covered are the following:

-Alfvèn modes. The aim is to show how taking into account non-ideal terms in Ohm's law allows to sweep the spectrum of Alfvèn waves, firehose instability, mirror mode, kinetic Alfvèn waves and inertial Alfvèn waves.

- Magnetic reconnection. We present the physical concept, the different historical (resistive) models, the Harris layer, the resistive tearing mode and the collisionless tearing mode.

- Beam-plasma instability. The dispersion equations of electrostatic and electromagnetic waves in a magnetized plasma are obtained, by the determination of the dielectric matrix. These calculations are applied to Type III radio bursts, which are intense electromagnetic emissions coming from solar flares, and to the drift instability of cosmic rays in the interstellar medium.

- Langmuir turbulence. After a reminder of the ponderomotive force, we derive the Zhakarov equations which describe the dynamics of the strong Langmuir turbulence. These are solved in the subsonic case (nonlinear Schrödinger equation). We explain the trapping of Langmuir waves in density depletions (cavitons), the wave-matter interaction, the modulational instability and the collapse process.

III. Application to the laser-plasma interaction at ultra-high intensity (UHI)

The topics covered are the following:

- Introduction to ultra-intense lasers: ultra-short laser pulses, chirped pulse amplification. Ionization mechanisms in the short pulse regime.
- Reminders on relativity and Hamiltonian mechanics. Application of these concepts through the study of the motion of a charged particle in an ultra-intense laser field. Relativistic ponderomotive force.
- Fluid model of laser-plasma interaction in the relativistic regime: relativistic plasma wave excitation, relativistic nonlinear effects such as relativistic self-focusing, self-modulation...
- In the form of a seminar, topics currently studied in the laboratories are introduced: laser-plasma acceleration, generation of ultrafast X-rays, high harmonics generation.

Numerical methods and simulation codes

Acronym : TC5	
EU Coordinators :Andrea CIARDI et Aymeric VIE, Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique et Atmosphères (LERMA) et Laboratoire Énergétique Moléculaire et Macroscopique, Combustion (EM2C)	
Teaching staff : Anne BOURDON, Andrea CIARDI, Antoine TAVANT, AymericVIE	
Pre-requisites :First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords :Introduction to algorithms - Solving differential equations - Discretization methods - Explicit and implicit schemes - Stability and efficiency - Numerical simulations in fluid mechanics - Numerical simulations in plasma physics: fluid models (MHD codes, ...) , kinetic models (Particle-In-Cell, gyro-kinetic codes, ...) , hybrids.	

The objective of this course, both theoretical and applied, is twofold: (i) to train students in the methods and algorithms of numerical simulation by introducing them to the different mathematical models used in fluid dynamics and plasma physics, and (ii) to initiate them to numerical simulation by using specific computational codes, in order to study complex phenomena in plasma physics, which are described by fluid and/or kinetic models and which are dealt with in the different teaching units of the Master.

Numerical simulations in fluid mechanics

The objective is to present a set of numerical methods necessary to solve equations governing the dynamics of a fluid, and to put the students in the situation to build themselves a solver allowing to solve these equations in the framework of a given physical problem. On completion of the course, students will be able to solve a simple problem with a small script to implement a numerical resolution; to formalize a physical problem into equations and identify their mathematical nature; to discretize a set of differential equations; to derive an adapted numerical method in terms of accuracy and efficiency to solve the problem ; to analyze the accuracy and the stability of a numerical method; to ensure the validity of the results through hypotheses' checking and numerical errors' characterization; to have a critical interpretation of the physical results; to solve problems found in fundamental physics and in engineering applications.

Numerical simulations in plasma physics

This part is devoted to the modeling of plasmas and the physical phenomena that take place in such media. After a theoretical presentation of the main approaches used (fluid, kinetic, hybrid descriptions,…) to describe various physical processes at work in different types of plasmas (cold or hot, dense or diluted, magnetized or not, collisional or not, ...) and taking place on different scales (microscopic, mesoscopic, macroscopic), students are introduced, with the help of numerical practical work, to the study of a few examples: magnetohydrodynamic description of a plasma, discharges in a gas at atmospheric pressure, beam-plasma interaction in theframe of a kinetic code.

Instrumentation, diagnosis and analysis of plasmas

Acronym : TC6	
EU Coordinator : Thierry DUFOUR, Laboratoire de Physique des Plasmas (LPP)	
Teaching staff :Thierry DUFOUR, Gabi Daniel STANCU, Fouad SAHRAOUI	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords : metrology & sensors, vacuum techniques, gas flow techniques, Langmuir probes, signal processing, mass spectrometry, optical emission/absorption spectroscopy, plasma diagnostics.	

The objective of the course is to introduce students to the techniques of characterization, diagnosis and analysis of plasmas used in physics research laboratories. They can thus benefit from the expertise of internationally recognized researchers, professors, engineers and astronomers, who welcome them in their laboratories for several days of "Practical Work" organized within their research team.

The subjects proposed by the laboratories concern all types of plasmas (cold process plasmas, thermonuclear magnetic fusion plasmas, inertial fusion plasmas, natural and astrophysical plasmas). The practical work is very varied: instrumentation, experimental measurements on a research device, analysis of space data from a satellite, numerical modeling, use of calculation codes, etc...

Before these practical works, a theoretical course of 18 hours is given on the techniques of instrumentation, diagnosis and analysis of plasmas. Particular emphasis is placed on vacuum and gas flow techniques, but also on electrical diagnostics (Langmuir probes, ...), spectrometry diagnostics (OES, MS) and laser diagnostics (LIF, TALIF, ...).

List of the laboratory works proposed for the year 2020-2021

[1] UV spectroscopy of the solar corona
[2] Turbulent magnetic field measurements in interplanetary space: spectral analysis
[3] Tools for the visualization of data from natural plasmas
[4] Imaging and spectroscopy of hot plasmas created by laser
[5] Particle-In-Cell (PIC) kinetic simulation of plasmas
[6] Inertial confinement fusion : numerical study of an implosion
[7] Observation of instabilities in toroïdal magnetized plasmas by Langmuir probes
[8] Predator-prey oscillations in magnetically confined fusion plasmas
[9] Electron density measurements in an inductive plasma using a resonant microwave probe
[10] Study of the dynamics of an atmospheric plasma jet for biomedical applications
[11] Cold plasmas processes for life sciences: application to agriculture

Atomic, molecular and radiation physics

Acronym : TC7	
EU Coordinator : Frank ROSMEJ, Laboratoire de l'Utilisation des Lasers Intenses (LULI)	
Teaching staff :F rank ROSMEJ, Christophe LAUX	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords : atomic and molecular structure, collisional-radiative processes, radiation, fusion, lasers, discharges.	

This module has two parts. The first one recalls the quantum bases of atomic and molecular physics, and then presents the concepts of atomic and molecular ionization state distributions. The second part establishes the links with statistical physics to present the foundations of the dynamic physics of plasmas, then introduces the elements necessary for the modeling of chemical kinetics in plasmas, and finally presents the concepts of radiation and atomic and molecular spectroscopy. The course includes tutorials on the application of these concepts to different types of plasmas (hot fusion plasmas, cold process plasmas, natural plasmas).

The topics covered are the following:

Introduction. Two-level atom, amplitude model, density matrix, diagonal and non-diagonal populations, Einstein coefficients.

Atomic and molecular structure. Hydrogen like atom, multiple electron atom, mean potential and Hartree-Fock method, concept of the optical electron, H_2^+ molecule, Born Oppenheimer approxi-mation, H_2, hybrid, electronic configurations, rotation, vibration (diatomic), orders of magnitude in molecular physics.

Population of atomic and molecular states. Particle statistics, partition functions, populations of atomic and molecular states, equations of state, Boltzmann and Maxwell distributions, complete and local thermodynamic equilibrium.

Thermodynamic properties. Heat capacity, enthalpy, entropy, free energy, pressure, viscosity,… for atoms and diatomic systems.

Elementary collisional processes. Principle of microreversibility, detailed balance, Hamiltonian, CPT invariance, cross section, reaction rate, mean free path, elastic collisions, excitation / deexcitation, ionization / recombination, electronic attachment and detachment, quenching, charge transfer, dissociation / recombination.

Radiation. Spectral lines (intensities, profiles), Planck's law and radiative temperature, radiation hydrodynamics, emission and absorption coefficients, continuous radiation, radiative transport equation, collisional-radiative models.

Applications. Magnetic fusion, inertial fusion, lasers (optical and XFEL), atomic physics, molecular physics, plasma discharges.

SEMESTER 1 – OPTIONAL CLASSES

Students choose 4 optional classes from the following list.

Magnetic fusion: turbulence, transport, heating and confinement

Acronym : O1
EU Coordinator : Maxime LESUR, Institut Jean Lamour, Nancy
Teaching staff : Maxime LESUR, Yves PEYSSON, Marie-Christine FIRPO
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Particle trajectories in strong magnetic fields –Particle and fluid drifts – Quasilinear theories – Waves – Instabilities – Turbulence – Heating – Current drive.

This unit provides an in-depths study of processes underlying the dynamics of the core of a magnetic fusion plasma, with an emphasis on turbulence, anomalous transport, heating and current drive, and the current state of research. We aim at understanding the overall physics of confinementof thermal particles, of impurities, and of energetic particles (produced by NBI-type heating, and by fusion reactions).

Applications:
- predicting transport properties in modern tokamaks and stellerators, and future "burning plasma" experiments with deuterium-tritium fueling.
- control schemes, mitigating and channeling turbulence.
- design of operational scenarios to mitigate energetic particle losses (in ITER for example).
- design of future commercial reactors (the size and cost of a reactor strongly depends on a turbulent diffusion coefficient).

The teaching unit comprises three independent sub-units:
1. Turbulence, transport and confinement.
2. Heating and current drive.
3. Reduced prototype of confinement: magnetic viewpoint.

Content of sub-unit « Turbulence, transport and confinement »
1. Angle-action formalism, application toparticle trajectories in tokamaks
2. Main instabilities in magnetized plasmas
   + TD1: kinetic effects in the ITG (Ion Temperature Gradient) instability
3. Diffusion, random walk, quasilinear theory (fluid and kinetic approaches)
   + TD2: quasilinear calculation of ITG-driven transport
4. Turbulence: formation and properties – nonlinear coupling, energy cascades
5. Transport and confinement in tokamaks
   + TD3: impurity transport
   + TD4: confinement time
6. Energetic particles - instabilities, transport,and losses

Content of sub-unit « Heating and current drive »
The course first deals with a general introduction showing that to reach the thermonuclear regime, additional heating systems are necessary because ohmic heating is insufficient. We also discuss why external methods are needed to continuously maintain magnetized plasma in a tokamak. The heating and current generation methods can be separated into two categories: those using particles (injection of fast neutrals)

and those based on radiofrequency waves. We discuss the general principles for each of them, based on a kinetic description of the plasma. For radiofrequency waves, we focus on the three main methods, the ion cyclotron wave, the low hybrid frequency and finally the electronic cyclotron frequency. We describe the conditions for applying geometrical optics and the ray-tracing method to calculate the electric field that resonantly accelerate the electrons. We discuss the quasi-linear interaction within the framework of kinetic calculations to estimate the RF wave power absorbed by the plasma. Finally, we discuss the neoclassical effects and the bootstrap current on which great hopes for a self-sustained fusion reactor are based.

Content of sub-unit « Reduced prototype of confinement: magnetic viewpoint »

An overview of the consequences of the divergence-free property of the magnetic field is presented. It is shown that, at any given time, the magnetic field lines can be seen as trajectories of a Hamiltonian system having one-and-a-half degrees of freedom. The notions of Poincaré application and mappings are introduced; then we discuss the role and the importance of the chaos of magnetic field lines in tokamaks through the phenomena of transport barriers and sawteeth in tokamaks. The role played by the safety factor and the concept of resonance are highlighted.

Physics and Diagnostics in Tokamaks

Acronym : O2
EU Coordinator : Pierre MOREL, Laboratoire de Physique des Plasmas (LPP)
Teaching staff : Pierre MOREL, Cyrille HONORE, Rémy GUIRLET
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Profile measurements and other diagnostics for equilibrium and transport, fluctuation diagnostics: reflectometry, beam probing, radiation. H-mode, flow-turbulence interaction, power extraction.

The aim is to present the different methods of characterisation of Tokamak plasmas, from the core to the wall, by linking the outstanding observations to physical phenomena. Starting from remarkable experimental observations, the approach first consists in understanding the physics underlying the diagnostics used (radiation, wave probing, particles...). Then, by extending the « Tronc Commun » lessons, to understand the physical interpretations proposed.

The notion of magneto-hydrodynamic equilibrium seen in the previous courses TC2 (Magnetohydrodynamics) and TC3 (Kinetic Theory) are supported by magnetic measurements and interferometry, which allow to understand how a typical discharge in a tokamak is planned, then carried out and controlled in real time. The stability of such a discharge is then addressed : the measurements of the electron cyclotron emissions (ECE) and in soft X-rays, the principle of a tomographic reconstruction, allow to discern the sawtooth oscillations of the electron temperature, but also the instabilities of the pedestal at the edge, the "edge localized modes".

The temporal dynamics of the macroscopic profiles are further investigated by means of incoherent Thomson scattering, ECE, interferometry and reflectometry measurements that provide access to heat transport, density peaking, and the transition between linear and saturated ohmic confinements (LOC-SOC). Measurements by Langmuir probes and fast imaging at the edge of the plasma complement these observations by providing direct access to turbulent flows and fluctuation characteristics, such as their intermittency.

With a view to the first ITER plasmas, whose plasma-facing components will be made of Tungsten (W), the spectroscopy principles laid down in the teaching unit TC7 (Atomic, molecular and radiation physics) are reviewed and deepened, in the visible and ultra-violet domains, to enable the study of impurity sources, their flows, their density distribution, and their application to the case of Tungsten.

Finally, coherent Thomson scattering makes it possible to characterise the ion temperature, and in particular to study fast particles, which are particularly important in ITER. Collective laser and microwave Thomson scattering and fluctuation reflectometry, by spectrally and spatially characterising turbulence, make it possible to study its interaction with the radial electric field profile, in order to understand the high confinement mode (H mode), and the influence of zonal flows or geodesic acoustic flows (GAMs) on turbulence.

Course Outline :

1 - Magnetic equilibrium
2 - MHD stability
3 - Thomson scattering
4 - Profile dynamics
5 - Reminder of spectroscopy
6 - Spectroscopy applied to tokamaks
7 - Turbulence in the Scrape Off Layer
8 - Turbulence in the core of tokamaks

Space plasmas

Acronym : O3	
EU Coordinator : Philippe SAVOINI, Laboratoire de Physique des Plasmas (LPP)	
Teaching staff :Philippe SAVOINI, Arnaud ZASLAVSKY	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords : Space Plasmas & Astrophysics. Boundary zones and acceleration phenomena.	

The teaching unit presents the environment of magnetized stars. The concepts are presented mainly for the Earth and the planets of the Solar System - these environments, studied in-situ, are the best known. However, these concepts are applicable to more distant plasmas.

The "space" plasma closest to us is located at an altitude of about 70 km, where the ionization of the upper atmosphere by solar UV radiation produces a resistive and magnetized layer of plasma, called the ionosphere.

Much further away, the interplanetary medium is traversed by a supersonic expanding plasma (300 to 800 km/second), coming from the Sun which is called the *Solar Wind*.

Between the two regions, there is a zone controlled by the Earth's magnetic field called the magnetosphere. The plasma in this region is collisionless, continuously out of thermodynamic equilibrium and subject to irregular reconfigurations of its magnetic topology.

From an astrophysical point of view, these regions represent a model that can be used to better understand other objects for which *in-situ* exploration is rare (magnetospheres of the planets Jupiter, Saturn, Uranus, Neptune) or even impossible (exoplanets, stellar corona, environments of magnetized stars such as young stars, pulsars, supersonic / super magnetosonic jets), etc.

From the point of view of plasma physics, the magnetosphere and the solar wind are excellent laboratories for the study of collisionless plasmas, very interesting for the understanding of transport processes in systems without resistivity or viscosity, turbulence, wave-plasma interactions, acceleration phenomena, etc.

The course is mainly devoted to basic concepts, illustrated with examples of applications in space physics and astrophysics. It is divided into 4 independent sections:

The solar wind: The Parker model of the solar wind is used; the notions of fast and slow winds, the transport of the solar magnetic field, and the variability of the wind are presented. These concepts are useful for the study of the environment of all "standard" stars, stars with matter ejection (T-tauri stars, red giants) and some compact stars (pulsars).

Notions of boundaries and discontinuities: The fluid approach allows us to classify the different boundaries that can exist in collisionless plasmas. These four boundaries (contact, tangential, rotational or shock) are present everywhere in our near environment (terrestrial shock, magnetosheath, magnetopause, neutral layer, lobes, plasmasphere, auroral zones) and are of universal interest in astrophysical plasmas.

The magnetosphere model: This region separating the ionosphere from the solar wind is one of the most complex regions of our immediate environment, where very important energetic phenomena such as magnetic substorms (source of the aurora borealis and australis) can occur. All magnetized planets have a magnetosphere. The environment of some stars is also treated as a magnetosphere: neutron stars, white dwarfs, black holes.

The ionosphere: This layer of plasma in contact with the neutral atmosphere of the Earth is the region where ionization and recombination processes take place. The concepts of Chapman ionization layer, plasma/neutral coupling, ionospheric current systems and ambipolar scattering are presented. These concepts are useful for the study of all planets with an atmosphere.

High energy density astrophysical plasmas

Acronym : O4
Coordinator : Andrea CIARDI, Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique et Atmosphères (LERMA)
Teaching staff : Andrea CIARDI, Robin PIRON
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Astrophysics, natural plasmas, high-energy density plasma, thermonuclear fusion, radiation, Magnetohydrodynamics.

Stars concentrate the overwhelming majority of visible matter in the universe in the form of hot plasmas. In this course, we focus on the high energy density plasmas that are involved in the formation and evolution of stars.

The objective of this module is to explain the macroscopic physical phenomena that structure stellar plasmas and dictate their thermodynamic conditions, as well as the microscopic physics that locally determine their properties.

After an introduction, we qualitatively address the star formation process. We study the dynamics of the accretion disks and astrophysical jets that occur at the beginning of the star's existence. We study their internal functioning during the main sequence, the longest phase of their existence. We look at the heat production within the star and the transport of this heat to its surface, leading to the equations of the stellar structure. We also discuss some modeling elements that allow us to calculate properties useful for modeling stars: the equations of state and opacities. We also discuss the evolution and end of life of stars, supernovae and cosmic ray acceleration. Finally, we discuss recent works that aim at reproducing some astrophysical phenomena in the laboratory, using high power lasers or magnetic pinch machines (z-pinch).

Course outline

1. Introduction, astrophysical context

2. Phenomena involved in star formation

3. Thermonuclear fusion in stars, stellar nucleosynthesis

4. Radiative transfer in stellar interiors

5. Convective transfer in stellar interiors

6. Equations of the stellar structure 5. Thermodynamic and radiative properties 6. Stellar evolution, supernovae and cosmic rays 7. Laboratory astrophysics

Low pressure cold plasmas

Acronym : O5
EU Coordinator : Tiberiu MINEA, Laboratoire de Physique des Gaz et Plasmas (LPGP)
Teaching staff : Tiberiu MINEA, Jean-Luc RAIMBAUL
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Low-pressure plasmas. Physics of discharges - Fundamental phenomena. Plasma-wall interaction in partly ionized plasmas. Magnetic confined plasmas. RF plasmas.

This module focuses on the production of low-pressure plasmas, their maintenance, the physical mechanisms involved during their operation, but also on the interaction of plasma species with surfaces - a phenomenon that is very important for the establishment of the steady state, but also for many applications. Discharge plasmas are intrinsically sources of species, charged or not, but also of photons. Without being exhaustive, this course presents different configurations of plasmas used as sources of charged particles for accelerators or synchrotron, space ion thrusters, ion beams (positive and negative as in the FIB - Focus Ion Beam or additional heating of tokamaks), reactive ion etching reactors, etc. The 'cold' reaction kinetics of heavy species in low-pressure plasmas is also addressed - a major issue in microelectronics, thin film deposition, but also light sources (gas lasers, specific and low consumption lamps, ...), environmental applications (isotope separation, destruction of pollutants, ...), biology and medicine, etc...

This lecture is structured in 4 chapters.

Chapter I: Introduction to cold plasmas gives the definitions and presents the fundamental concepts for the understanding of the phenomena governing low-pressure plasmas. The self-sustaining condition of a discharge is introduced as well as the laws of similarity allowing to compare different discharges.

Chapter II - Fluid models and kinetics of cold plasmas are common approaches to analytically describe charged and neutral species, involving free electrons and ions of the plasma. Typical approximations due to low pressure are detailed leading to specific forms of the conservation equations, explained through examples. Power and matter balances, as universal laws, allow to understand plasma formation and to open to specific configurations.

Chapter III - Plasma confined by walls is an issue of all low-pressure plasmas, because they are created in vacuum chambers to maintain the low pressure. Plasma-wall equilibrium in confined plasmas is treated in different situations - sheath models - as well as the transport of the charged particles to the walls at low pressure and the establishment of the self-bias voltage, for radio frequency (RF) excitation of the discharge.

Chapter IV - Power source/plasma coupling is the key to creating a plasma with the expected properties. Energy provided to the plasma, ionization and production of active species are presented from a fundamental point of view through examples of typical configurations:

- RF plasmas - capacitive, inductive, and helicon ;

- microwave plasmas.

The low pressure - high density plasmas constitute a specific research field using different forms of electron confinement (electrostatic, magnetostatic and mixed), which are detailed for the case of magnetrons and ion thrusters.

Non-equilibrium plasmas at high pressures

Acronym : O6
EU Coordinator : Pierre TARDIVEAU, Laboratoire de Physique des Gaz et Plasmas (LPGP)
Teaching staff : Pierre TARDIVEAU, Joao SANTOS SOUSA
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French / English
Keywords : Out-of-equilibrium plasmas - Electrical discharges - Streamers – Townsend mechanism - High pressure diagnostics - Non-equilibrium kinetics- Atmospheric pressure.
The UE "High Pressure Cold Plasmas" aims to describe the basic concepts associated with high pressure non-equilibrium plasmas. Non-equilibrium plasmas are plasmas where an imbalance is created between the electronic population capable of acquiring energies as high as ten eV and other species (atomic and/or molecular, neutral or ionized, in their ground or excited states) which are maintained at temperatures below a few thousands Kelvin. This imbalance is most of the time generated as soon as the plasma is created by the application of a strong anisotropic electric field to which the electrons are mainly sensitive. The specificity of "high pressure" plasmas lies in the importance of collisions between species (electrons / neutrals, ions / ions, neutrals / neutrals, etc.) and their effects on the characteristics of the plasmas considered. The objectives of the course are in **the first part** to highlight the differences observed with low pressure plasmas (Townsend theory, Paschen's law, similarity laws, etc.), and to present the creation mechanisms specific to high pressures (space charge, streamer and ionization wave, Meek criterion,…) through experimental results and simulation. The techniques for characterizing these filamentary plasmas will also be presented: electrical methods, fast imaging, emission and absorption spectroscopy, laser spectroscopy, etc). A **second part** is devoted to the reaction and the radiative properties of these plasmas by focusing on the non-equilibrium kinetics and the primary chemical reactivity at high pressure. A presentation is made of the key primary species involved in this kinetics (densities, temperatures and energy distributions). The main principles according to which the energy of the plasma is distributed over the different excitation levels of atoms and molecules (electronic, vibrational, rotational) and how this energy can relax or transfer from one species to another are described. **A third part** focuses on the "techniques" used to temporally stabilize and spatially "homogenize" the properties of high pressure cold plasmas, and thus allow their use for various applications, and on the other hand on the advances in terms of research concerning, among other things, the generation of plasmas under extreme conditions of electric field, pressure, or plasmagenic medium (liquid, two-phase medium, etc.).

Relativistic laser-plasma interaction

Acronym: O7	
EU coordinator: Laurent GREMILLET (CEA/DAM)	
Teaching staff: Laurent GREMILLET, Cédric THAURY	
Prerequisites: First year of MSc in Physics or Engineering Schools.	
Credits: 3 ECTS	
Language: French/English	
Keywords: Laser-generated plasmas. Laser-driven particle acceleration. Laser-plasma and beam-plasma instabilities.	

The inception of ultrahigh-intensity lasers, delivering pulses of duration ranging from a few femtosecond to a few picoseconds and intensity exceeding $10^{18}\mathrm{Wcm}^{-2}$, unlocked the exploration of relativistic light-matter interactions, whereby the target electrons, accelerated to near-speed-of-light velocities, trigger a wealth of collective, radiative or nuclear processes. This research field has seen a boom in the past two decades due to the unprecedentedly extreme conditions that ultra-intense lasers can achieve, the unrivalled properties (brevity, energy density, etc.) of the generated particle and photon sources, and the growing number of applications of the latter in physics and beyond. The coming into operation of a new breed of multipetawatt laser facilities in Europe (e.g. Apollon in France) and Asia will further multiply the already many spin-offs of relativistic laser-plasma interactions. The purpose of this course is to provide the student with an in-depth review of the main concepts and phenomena underpinning this research field.

The following topics will be addressed:
- Electron dynamics in an intense laser wave in vacuum.
- Dispersion relation of an intense laser wave and self-induced relativistic transparency.
- Relativistic self-focusing of a laser wave.
- Relativistic laser-plasma instabilities.
- Laser-driven plasma wakefields and associated electron acceleration.
- Betatron radiation in plasma wakefields and inverse Compton scattering of laser light by wakefield-accelerated electrons.
- Electron heating in overcritical laser-plasma interactions.
- Relativistic plasma mirror and high-order harmonic generation.
- Transport of a high-current electron beam in a dense plasma: Alfvén's limit, generation of resistive fields, beam deceleration and plasma heating.
- Electron beam-plasma instabilities.
- Laser-driven ion acceleration.

Laser-Plasma Interaction and confinement inertial fusion

Acronym : O8
EU Coordinator : Sylvie DEPIERREUX, Benoit CANAUD (CEA/DAM)
Teaching staff : Sylvie DEPIERREUX, Benoit CANAUD, Frédéric PEREZ
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Laser plasma interaction. Laser-produced plasmas & Inertial fusion. Thermonu-clear fusion. Confinement.

This module consists of two parts. The first one is devoted to laser-plasma interaction. It discusses the non-linear wave mixing mechanisms inherent in the propagation of a large wave in a plasma and the resulting resonant couplings. The ponderomotive force is described as well as its effects on plasma as self-focalization. Thomson scattering is also presented as a powerful method for plasma diagnosis and various parametric instabilities such as stimulated Raman scattering. Finally various applications are presented.

The second part outlines the general concepts of inertial confinement fusion: compression, heating, ignition, gain. The fundamental concepts of nuclear physics, thermonuclear fusion and the principle of confinement are recalled. Post's temperature concepts and Lawson's criteria are introduced. Various gain fusion schemes are presented, such as isobaric ignition, fast ignition and shock ignition. The hydrodynamics of laser-created plasmas provide an opportunity to address the notions of self-similar flow or shocks. The modes of transport of thermal energy within the target are detailed.

Interaction laser-plasma

We study the non-linear mechanisms that develop when an intense laser electromagnetic wave is propagating in a plasma. For such wave, a development of the equations of propagation of the laser wave and ion and electronic plasma acoustic waves up to the second order is necessary. New mechanisms of non-linear coupling between these modes appear.

A first effect, called a ponderomotive force, leads to the expulsion of electrons from areas of higher intensity. For a beam of finite transverse dimension, the ponderomotive force leads to a modification of the optical index in the direction transverse to propagation, producing the effect of a plasma lens that concentrates beam energy on a small size (Fig. 1a). For very short-duration beams, of the order of a few femtoseconds, the finite size of the laser pulse causes the electrons propagating forward the direction of the pulse regarding the beginning of the pulse and backward for the pulse end (Fig. 1b).

A second non-linear effect generated by any incident electromagnetic wave in a plasma regards the resulting current from the oscillation of electrons in the electric field of the incident electromagnetic wave. This current is the source of a diffused electromagnetic wave. For low-intensity, it results in the probe spreading about density fluctuations in the plasma, which is still known as the Thomson scattering. It is a powerful method of characterizing plasmas. Beyond an intensity threshold for the incident beam, these two non-linear terms (ponderomotive force and non-linear current) lead to the unstable coupling of the incident electromagnetic wave with a plasma wave and a scattered electromagnetic wave. This three-wave coupling is schematically represented in Fig. 2. The energy of the incident laser wave maintains the instability that amplifies both the scattered and the plasma waves. These instabilities are called "stimulated Raman scattering" or "stimulated Brillouin scattering" depending on whether they involve an electronic plasma wave or an ion acoustic wave.

These mechanisms were first studied in the context of thermonuclear fusion controlled by laser inertial confinement (ICF). Laser-plasma interaction is one of the first themes to master as it aims to optimize the efficiency and quality of laser energy deposition. In this context, self-focalization interferes with the proper spread of the laser, while stimulated scattering instabilities lead to significant losses of laser energy in the form of backscattering. In the multi-beam configurations of direct and indirect drive in ICF, the beating between the incident laser waves themselves profoundly alters the laser-plasma interaction in the crossover regions of the laser beams. This aspect of the laser-plasma interaction will also be dealt in the course. Others applications concern the stimulated Raman and Brillouin scattering instabilities that are studied today as new technique for the amplification of short pulses. These patterns of amplification of short pulses in plasmas aim to push the limits towards ultra-high intensities beyond the technological limit of damaging optics inherent in the traditional method of amplification of pulses by drifting frequency.

Thermonuclear inertial Fusion

The second part outlines the general concepts of inertial confinement fusion as well as the main plasma physics problems associated with it. After a detailed recall of the nuclear reactions involved, the concepts of nuclear physics and the different pathways of nuclear fusion, the fundamental elements of thermonuclear fusion such as thermal reactivity and the notion of confinement that leads to the definition of Post's temperature or the Lawson criterion are introduced. Next, we discuss inertial confinement and the concept of hot spot ignition and its various variants (isobaric self-ignition, non-isobaric shock ignition, fast ignition) to look at the implosion of a target and its compression. This introduces the concept of minimal isobaric ignition kinetic energy and the different pathways of inertial confinement fusion (direct drive of the target by laser radiation or indirect drive after conversion of laser radiation into X-ray). The description of hydrodynamics of laser-created plasmas such as the flow triggered by laser-matter interaction, shocks, which play an important role in the acceleration of the internal layers, or the conduction of thermal energy, especially between the energy absorption zone and the more internal parts of the target. For the latter, we discuss the conduction of Spitzer-Herm which, in the extreme situations encountered in ICF, is no longer correct and must evolve towards a non-linear and non-local theory. Finally, we present the deleterious mechanisms of implosion that are hydrodynamic instabilities that degrade the symmetry that one would like perfectly spherical.

SEMESTER 2

Students choose a specialization among four themes. Each specialization consists of two courses, mixing theory and practical work.

INSTITUT POLYTECHNIQUE DE PARIS

SPECIALIZATION: ASTROPHYSICAL PLASMAS

Diffuse astrophysical plasmas

Acronym : A1
EU Coordinator : Patrick HENNEBELLE (CEA Saclay)
Teaching staff : Patrick HENNEBELLE
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Space plasmas & Astrophysics. Gravity, thermal balance, instability. Ideal and non-ideal Magneto-hydrodynamics. Conservation and transport of angular momentum.

The lecture goes deeper into astrophysical plasmas as the interstellar medium. Some of the classic processes and equations are derived and further discussed. Particular importance is given to the processes important in the context of structure formation. A particular emphasis is put on the dissipative and transport processes.

General introduction : the Universe, the galaxies, the stars and planets.
Complexity of baryonic matter.
Conservative form of the ideal MHD equations, the interstellar medium, qualitative discussion on the interstellar turbulence and numerical simulations.
Hydrodynamical and MHD shocks.
Cooling processes and thermal instability.
Bi-fluid approach, propagation of Alfven waves in the presence of neutrals.
Non-ideal correction of MHD.
Jeans length and Jeans mass.
Viriel theorem, isothermal clouds and influence of the magnetic field.
Equilibrium and gravitational collapse.
Accretion disks: importance of angular momentum transport, centrifugal barrier. Magnetic braking. Magneto-rotational instability (MRI), Toomre criteria.

INSTITUT POLYTECHNIQUE DE PARIS

SPECIALIZATION: ASTROPHYSICAL PLASMAS

Numerical simulations & solar magnetism

Acronym : A2	
EU Coordinator : : Guillaume AULANIER, Observatoire de Paris	
Teaching staff : Guillaume AULANIER	
Pre-requisites : First year of MSc in Physics or Engineering Schools.	
Credits : 3 ECTS	
Language : French/English	
Keywords : Space plasmas & Astrophysics. Magnetohydrodynamics. Numerical simulations. Project-based learning.	

<u>Goal.</u> Numerical simulation is an investigation tool shared by many specialties in plasma physics. This aim of this course is to expose students to handling this tool. More specifically, students will achieve a preliminary practical training followed by one long project in computational fluid dynamics (CFD).

All the proposed projects imply the magnetohydrodynamic (MHD) modeling in two dimensions of some physical processes involved in the Sun's activity, being associated with magneto-convection at the interface between the star's internal and external layers.

Le goal of this course is *not* to do programming and code development – even if some lines will have to be typed and some parameters will have to be varied depending on the project. Instead, the principle is to use an operational code written in FORTRAN as well as a distinct visualization tool with GDL, so as to fine-tune, to test, and to *conduct numerical experiments* aiming at characterizing, understanding, and quantifying some physical mechanisms.

<u>Organization.</u> No preexisting expertise in FORTAN or GDL is required. However, some experience in using LINUX is strongly recommended, and some knowledge in MHD is essential.

The first session will be a course introducing general concepts, presenting some sensitive issues in CFD, and describing the OHM code that will be used in the projects. The second session will be a practical training on the identification of the threshold for the convective instability in stratified plasmas. These two first sessions are mandatory to continue. All the other sessions will be dedicated to the projects, with students working by pairs on one single topic of their choice.

<u>Examples of projects</u>

[P1] Dynamo effect and magneto convection with thermal forcing

[P2] Transport and tearing of magnetic flux tubes floating in a stratified medium

[P3] Coronal magnetic reconnection driven by remote thermal convection

SPECIALIZATION: LASER-PLASMA INTERACTION, INERTIAL FUSION

Hydrodynamics of inertial fusion

Acronym : B1
EU Coordinator : Joao Jorge SANTOS, Université de Bordeaux
Teaching staff : Dimitri BATANI, Frédéric BURGY, Alexis CASNER, Guillaume DUCHATEAU, Emmanuel d'HUMIERES, Clément PEJOT, Joao Jorge SANTOS
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Inertial confinement fusion - Power lasers - Fusion hydrodynamics - Fast ignition – Hot plasmas.

Additional information on inertial confinement fusion is provided, as well as an introduction to the use of a hydrodynamic code for the simulation of laser implosions. The module is completed by experimental work on a power laser.

Physics and modeling of CFI
Compression of a fuel shell : velocity, implosion and stagnation, flow diagram - Hydrodynamic efficiency for a spherical target - Evolution of a hot spot: thermal transport, radiative transport and alpha particle production - CFI modeling methods - Introduction to the CHIC radiative hydrodynamics code - Description of the code modules: Lagrangian hydrodynamics, thermal transport, radiative transport, laser absorption by "ray tracing", equations of state and opacities, MHD module, fusion reaction - Fast ignition and physics of fast electron transport - Hybrid modeling for fast ignition.

Tutorial on the computer with the CHIC code
One-dimensional simulation of a pusher - Design of a 1D spherical target - Optimization of a gain target.

Experimental work on the "Eclipse" power laser
Interaction of the laser pulse with a solid target: measurements of plasma parameters with optical and particle diagnostics.

SPECIALIZATION: LASER-PLASMA INTERACTION, INERTIAL FUSION

Power and high-energy lasers

Acronym : B2
EU Coordinator : Joao Jorge SANTOS, Université de Bordeaux
Teaching staff : Dimitri BATANI, Frédéric BURGY, Alexis CASNER, Guillaume DUCHATEAU, Emmanuel d'HUMIERES, Clément PEJOT, Joao Jorge SANTOS
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Power lasers - High energy lasers - Very short pulse lasers - Laser diagnostics - Hot plasmas - Laser architectures and amplifier chains - Design and dimensioning of a PW laser.
Some notions on power lasers are given. The example of the LIL, LMJ and PETAL chains is presented. The module ends with pratical works on lasers. **Laser technology** History of lasers. High energy and high intensity lasers. Materials for the optical elements of the end chain. Diagnostics of lasers in a radiative environment. Examples : LIL and LMJ. **Laser architectures and amplifying chains** LIL and LMJ amplifier chains: implementation and diagnosis. High energy and very short pulse lasers: design and dimensioning of a PW laser, management of large lasers: LMJ and PETAL. **The Miro software** Design and dimensioning of a laser chain with the Miro software. **Experimental work on lasers** Smoothing, alignment and interferometry; Mac-Zehnder interferometer; Amplification, frequency conversion.

Advanced physics for Tokamaks

Acronym : C1
EU Coordinator : Rémy GUIRLET, Yanick SARAZIN (CEA/IRFM)
Teaching staff : Rémy GUIRLET, Julien HILLAIRET, Pierre MANAS, Jorge MORALES, Eric NARDON, Rémy NOUAILLETAS, Bernard PEGOURIE, Cédric REUX, Yanick SARAZIN, Alexandre TORRE
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Thermonuclear magnetic fusion -Tokamak - Reactor sizing - Energy efficiency – Hot plasmas.

The ambition of this module is to give students an integrated vision of the tokamak, to make tangible the interdependence of plasma physics, plasma-wall interaction, materials and superconductors in the definition of the characteristics of a fusion reactor.

The method consists in answering the following question: how to "size a tokamak" given the objectives assigned to it, mainly in terms of fusion power and energy efficiency? The work is done in small groups supervised by CEA/IRFM researchers.

The first two days are devoted to lectures that explain the topics studied during the following stages and the working methods (in particular the scaling laws, the operational regimes and the plasma-wall interaction).

In the first step of the group work, fusion performance goals and some constraints are given to all groups. Each group determines the best "engineering" parameters of the tokamak (torus radius, plasma current, magnetic field...) that allows to reach the objectives. For this, we use the scaling laws that relate the performance of a tokamak (for example the energy confinement time in the plasma) to the "engineering" parameters of the tokamak.

In the second stage, each group is tasked with examining a question of particular engineering or physical importance: the means of heating the plasma, magnetohydrodynamic equilibrium and turbulence, impurities and radiation, particle and heat fluxes on the enclosure components, sizing of the superconducting coils, etc. Each group is supervised by a subject expert.

During all the group work, the supervisors are present and available. During the two weeks, the students are encouraged to interact with the other groups and to interview all the CEA/IRFM researchers who can help them in their work.

SPECIALIZATION: MAGNETIC CONFINEMENT FUSION

Tokamaks: experimentation

Acronym : C2
EU Coordinator : Rémy GUIRLET (CEA/IRFM)
Teaching staff : Nicolas FEDORCZAK, Rémy GUIRLET Julien HILLAIRET, Joëlle ACHARD, Riccardo RAGONA, Yann CORRE, Valeria OSTUNI, Jorge MORALES, David ZARZOSO, Alain GHIZZO, Remy NOUAILLETAS, Mireille SCHNEIDER, Florian LEBLOND, Bernhard SCHMID, Mathieu PERET, Frédéric CLAIRET, Stéphane HEURAUX, Vojtech SVOBODA, Ondrej GROVER
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Thermonuclear magnetic fusion - Tokamaks – Experimentation – Hot plasmas.

Students work in pairs on practical work supervised by IRFM physicists and engineers, on the facilities those use for their own research.

Each student performs two experiments from the list below, one of which (if possible) concerns work on data from a tokamak (COMPASS, GOLEM, WEST).

These experiments are shared with the students of the Erasmus Mundus Master "Fusion-EP" (European Master of Science in Nuclear Fusion & Engineering).

The list of subjects can evolve according to the availability of the facilities and the supervisors:

- Monitoring the inner wall of the tokamak with the articulated inspection arm
- Mode conversion for the lower hybrid frequency (LH) wave
- Numerical models
- Thermomechanical qualification of the components in front of the plasma
- Heat flux on the tokamak walls exposed to the plasma - analysis by infrared thermography
- Superconducting properties of tokamak coil materials
- Contamination of components exposed to plasma - analysis by thermo-desorption
- Remote control and experiments on the GOLEM tokamak (Prague)
- Analysis of experiments on the COMPASS tokamak (Prague)
- Analysis of experiments on the WEST tokamak (Cadarache)

SPECIALIZATION: PLASMA PROCESSES AND APPLICATIONS

Plasmas for energy and aerospace applications

Acronym : D1
EU Coordinator : Christophe LAUX, **Laboratoire d'Énergétique Moléculaire et Macroscopique, Combustion (**EM2C)
Teaching staff :Christophe LAUX, Paul-Quentin ELIAS, Denis PACKAN
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Energy conversion, plasma-assisted combustion, ionic wind, air treatment, atmospheric reentry, propulsion.

The objective is to understand the principles and physical models of cold plasmas based on application examples in the fields of energy and aerospace. Recent advances and scientific and technical challenges are presented. The course alternates between a review of the basic principles and models and practical examples.

Program

1. Introduction to applications of cold plasmas.
2. Generation of plasmas: discharge types and reactors – DC discharges – AC and pulsed discharges (RF, MW, DBD, plasma jets, nanosecond discharges).
3. Fluid equations – Conservation equations–Drift-diffusion –Transport properties: mobility, free diffusion, ambipolar diffusion, electric conductivity, dielectric permittivity.
4. Two-temperature kinetic mechanisms. Generation of weakly ionized air plasmas.
5. Application A: DC and nanosecond discharges in air.
6. Application B: electro-hydrodynamic effects, ionic wind.
7. Application C: plasma-assisted combustion.
8. Application D: introduction to atmospheric reentry. Radiative flux on spacecraft during atmospheric entry.
9. Application E: absorption, reflection of waves. Blackout.
10. Application F: plasma propulsion.

SPECIALIZATION: PLASMA PROCESSES AND APPLICATIONS

Plasmas for materials, environment, biomedicine and agriculture

Acronym :D2
UECoordinator :João SANTOS SOUSA
Teaching staff :João SANTOS SOUSA, Nicole BLIN-SIMIAND, Emmanuel ODIC, Mike KIRKPATRICK, Thierry DUFOUR
Pre-requisites : First year of MSc in Physics or Engineering Schools.
Credits : 3 ECTS
Language : French/English
Keywords : Cold plasmas and processes. Low- and high-pressure non-equilibrium plasmas. Discharge physics, gas phase chemistry and surface chemistry. Physical and chemical diagnostics. Applications of plasmas to materials, environment, biomedicine and agriculture.

The objective is to present the physical principles, advances and technological barriers of the application of low- and high-pressure non-equilibrium plasmas to materials, environment, biomedicine and agriculture. Students will discover innovative applications of cold plasmas, and benefit from the expertise of researchers and professors recognized internationally for their scientific expertise.

The teaching unit is structured around seven themes, presented by five experts (researchers or professors) of the targeted fields:

– Kinetics and secondary reactivity at low- and high-pressure in non-equilibrium chemistry
– Physical diagnostics in post-discharge
– Plasma-Environment
– Plasma-Materials
– PlasmaandLiquids
– Plasma-Medicine
– Plasma-Agriculture

Kinetics and secondary reactivity at low and high pressure in non-equilibrium chemistry: secondary chemistry, production of secondary species, post-discharge physics, kinetic schemes and modeling of reactivity.

Post-discharge physical diagnostics: measurements of species and temperatures: short-lived and metastable species, gas temperatures, LIF diagnostics resolved in space and time, spatial profiles of radicals' density, optical diagnostics (emission, absorption, laser spectroscopy), mass spectrometry.

Overview of the different applications: synthesis of materials (e.g. nanoparticles) and surface treatment (etching, sputtering, deposition,...); depollution (DECOV, DeNOX, catalysis); biomedical (decontamination/sterilization, dermatology, oncology, in-vitro / in-vivo / clinical assays); agriculture (plant germination and growth,...).

Physics of low pressure RF discharges: Physics of inductive heating and EH transitions - Global models - Radiofrequency sheaths: self-polarization, IEDF - Multi-frequency capacitive reactors - tailored waveforms - High frequency electromagnetic effects - Instabilities in industrial reactors - Modeling of a capacitive reactor - Modeling of an inductive RF thruster - Physics of helicon waves and HDLT and Vasimr thrusters - Physics of Hall effect thrusters.

Physics of high pressure pulsed discharges: Dielectric barrier discharges (DBD) - Role of the dielectric on the discharge - Different types of DBD - Calculation of current - Self-organization phenomena - Microplasmas (MHCD) - Plasma-jets and guided streamers.

Plasma physics (discharges) in liquids and induced chemistry in the liquid phase (by discharge in the liquid or in interaction with the liquid).

Plasmas and surface chemistry: Gas phase reactions (low and high pressure) - Collision mechanisms (electronic collisions, quenching, recombination,...) - Kinetic diagrams and modeling of reactivity.
Surface reactions: adsorption - heterogeneous catalysis and photo-catalysis - plasma/catalyst interaction - polymerization - spontaneous etching reactions - sputtering - neutral-ion synergy - inhibition layers - selectivity - transport by diffusion –gas heating in a high temperature source - Chantry model - pulse modulated plasmas: post-discharge kinetics - deposition - thin and nanostructuredfilms by PVD - transport of sputtered species to surfaces: weakly ionized plasma / high density plasma - control of the energy of deposition precursors - substrate polarization - effect of flux - effect of energy - examples of structuring of thin films (metallic / compound) - flexible and hard layers (adhesion of films, interfaces).

Chemical diagnostics (chromatography,...), **materials diagnostics** (SEM, TEM, XPS, AFM, etc.), **biological diagnostics** (in-vitro, ex-vivo, in-vivo models; survival curves; cell viability assays; clinical trials ,…).