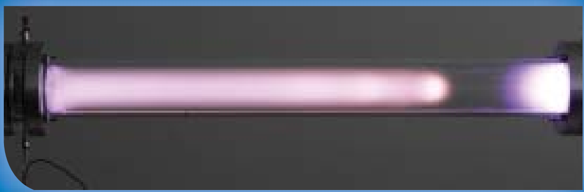
Hands-on experiments

on plasma physics and nuclear fusion



Participate or build your own

FuseNet Association

FuseNet Association General Assembly 2013, Sofia

Content

Preface

Dear reader,

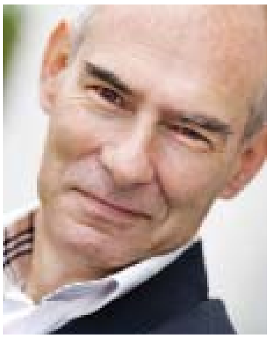
In front of you lies a booklet with short descriptions of a selection of hands-on experiments, carefully designed and built for educational purposes at an advanced academic level.

The concerted action to develop these experiments, coordinated by Prof. Jean-Marie Noterdaeme, is an excellent example of the work of the FuseNet Project, the European Fusion Education Network, a EU-funded 'coordination and support action'.

The FuseNet Project has now evolved into an Association, whose members are universities, national labs and companies that are involved in the development of ITER and fusion energy. ITER itself is a member, too. There are presently more than 40 member organizations, spread across Europe and even including the Ukraine. They have a common interest: attract the brightest students to the fusion development programme and give them the best possible education.

To achieve that goal FuseNet coordinates and supports a range of activities. The hands-on experiments that you find in this booklet are an example of the joint development of educational tools. Other examples are on-line virtual educational tools, remotely accessible experiments and a textbook on fusion technology. Another line of activities concerns the coordination and support of joint educational activities, such as a range of summer schools and the annual event for all PhD students in the fusion field. FuseNet also offers a matchmaking service for students who seek an interesting place for an internship, be it in a research institute or a company. In an effort to stimulate excellence and harmonise fusion education across Europe, FuseNet has introduced Certificates for MSc and PhD students who meet academic standards that were jointly defined by the FuseNet members, and are guarded by the independent Academic Council.

The experiments you will find in this booklet constitute, I believe, a real and lasting contribution to fusion education and training. And very importantly, they make the fusion education programmes more attractive, more interesting and more challenging to students.



Prof. N.J. Lopes Cardozo,
Chair FuseNet Association

Introduction

The realisation of controlled nuclear fusion as an energy source will require the hard work and dedication of excellent scientists and engineers and the training of a new generation.

An in-depth knowledge of specialised fields is required, usually acquired during the research leading to a Ph.D. It is also essential to get a broad view in this area characterized by its strong interdisciplinary nature: from superconductivity to spectroscopy, from RF electrical engineering to nuclear aspects. Getting this broad view is increasingly difficult.

We therefore, in one of the work packages of the Fusenet Project, coordinated and supported the development or upgrade of a wide range of hands-on experiments.

This was one of the most successful work packages of FuseNet. Its initial budget of about 1/6 of the project's entire budget was increased to more than 1/4. Indeed, from the high quality of the submitted proposals it became clear that there was a strong need, and resources released in other areas were channelled into this work package to fund more proposals.

This brochure provides an easy guide to a selection of the hands-on experiments that benefited from this financial support. It is not meant to be comprehensive. Rather its goal is to be a quick reference for teachers and students to more extensive material available on the FuseNet website.

Do you, as a teacher, want to set up an experiment to introduce your students to Langmuir probes? You will find a complete manual on how to build such an experiment, with all details, including technical drawings, even addressing the pit-falls you could encounter when setting the system up.

Do you, as a student, want to participate in a comprehensive lab course, or even operate a tokamak? You will find where this is possible and whom to contact.

We hope that this development of hands-on experiments will provide the young scientists and engineers with the broad view needed to complement their in-depth training.

Prof. Jean-Marie Noterdaeme,
Leader of the Work Package
„Hands-on Experiments"

The GOLEM Tokamak for fusion education

The GOLEM tokamak is located at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University (CTU). CTU hosts a Fusion Masters programme, but GOLEM is for the benefit of a wider audience. It is a small-sized tokamak device equipped with basic controls and diagnostics and full remote-control capability for educational purposes.

Target group

Bachelor and master students wanting to learn about tokamak operation.

At an introductory level: the very basics of tokamak operation are demonstrated, and students are acquainted with key plasma properties and tokamak operational limits.

At an advanced level: the concept of MHD equilibrium, MHD eigenmodes, turbulence and radiation are studied by making simple measurements of basic properties. Any other fields can be considered for studies based on individual proposals.

GOLEM tokamak in operation

Remote operation support

Measurements are set up and shots initiated using the **user-friendly web interface of the GOLEM tokamak.**

Students visiting GOLEM

All the **recorded data** and the settings for each shot are **available on a shot homepage**, and download routines exist in several widespread processing languages.

Student instructions and an interactive wiki page have been prepared to guide students through various measurement programmes. The aim of these guides is to demonstrate a maximum number of fusion plasma phenomena within a limited time period and using the simple tools available at GOLEM.

Virtual tools aiding the preparation

In order to introduce the GOLEM tokamak to distant users via the Internet, an interactive **3D virtual model** has been created.

The virtual model is complemented by a **virtual operation interface**, which gives students the opportunity to set up the parameters in the same way as in real operation. The only difference is that virtual operation is inspired by and results are generated from the shot database.

Use and access

Both local and remote users can make good use of the capabilities of the GOLEM tokamak. Numerous measurements have been taken from all over the world, even during regular student laboratory courses. The main use is, however, during concentrated education activities, like the **GOMTRAIC** GOlem reMote TRAIning Course attracting students from all over the world every year.

The easiest access for individual users is through the yearly GOMTRAICs, while institutions can contact the GOLEM team for regular or occasional operational windows.

Students performing remote operation exercise from Budapest

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Education by Hands-on experience

PlasmaLab@TU/e

Eindhoven University of Technology offers a master programme „Science and Technology of Nuclear Fusion". This programme is supported by a plasma physics laboratory, „PlasmaLab@TU/e", consisting of 10 different plasma experiments ranging from breakdown in gases to diagnostics and techniques as used on large fusion experiments.

Target group

The PlasmaLab@TU/e aims at supplementing the education by hands-on experience and provides the students with a reality check of the theory learned. Moreover it will develop their experimental skills and creativity. The principal target group are students that follow master-level plasma courses, but the lab material can equally well be used for teaching at other levels: bachelor, high school students or outreach activities.

Each of the 10 experiments is unique in order to optimise plasma physics coverage. Basic experiments include Langmuir probes and magnetic diagnostics. More advanced experiments include electromagnetic wave propagation in plasmas, spectroscopy and a real fusion device: the Fusor.

The hands-on experience of the students in the PlasmaLab@TU/e

Paschen curve

How do you make plasma? That is the main question to be answered by the experiment known as the 'Paschen curve'. It demonstrates the elementary processes leading to a break-down of a gas discharge. By noting the break down voltage as a function of pressure and the distance between the electrodes, Paschen's law might be reproduced, but deviations from this can be observed as well, demonstrating that reality is more complicated than the idealized theory.

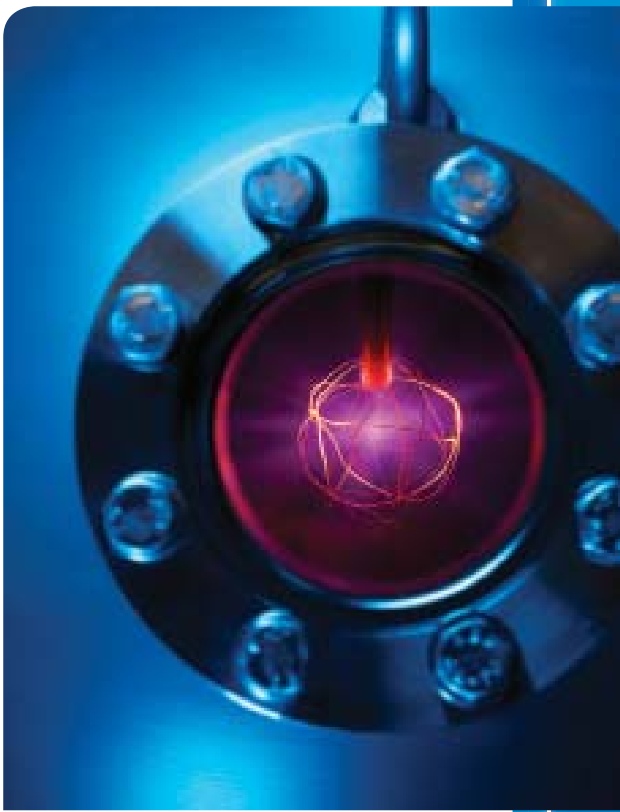
Studying the plasma breakdown in the Paschen setup

Laser spectroscopy

Lasers are a powerful tool to gain information on the plasma. To demonstrate several laser techniques a special setup has been constructed. Using a tuneable diode laser and a set of fine mechanical optical components this experiment enables the students to measure density and temperature of a gas cell with Rubidium. The physics of optical pumping, laser absorption and laser fluorescence will be reviewed with the help of this experiment.

Fusor

A table top fusion reactor impossible? No! Actually a device, called the Fusor, based on electrostatic confinement, has already been proposed several decades back in time but has been disregarded as a viable power producing machine. Nevertheless it can produce actual DD-fusion neutrons. Such a device is built by and for students in the PlasmaLab@TU/e. In the Fusor, ions are accelerated towards the centre of an inner sphere where the ion energy is high enough to cause a fraction to fuse. The educational aim of the experiment is to demonstrate the physics of fusion reactions, as well as to gain experience in diagnostic methods and ionising radiation issues.



View into the core of a table top fusion reactor the Fusor

Use and access

The PlasmaLab@TU/e is fully operational primarily as an educational facility for the plasma groups in the faculty of Applied Physics and for outreach activities. Also external users might access it, just ask about the possibilities. Moreover, 1-week hands-on PlasmaLab courses open to foreign students are organised.

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A hands-on introduction to plasma physics

PlasmaLab@UGent

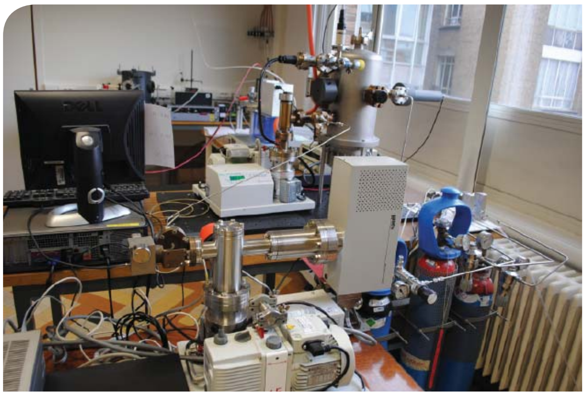
The department of Applied Physics of Ghent University, Belgium has regular courses in both plasma physics and fusion technology at bachelor and master level. The university is also coordinator of the FUSION-EP Erasmus Mundus master course, a Europe-wide collaborative fusion education programme.
Since the department is very well connected to plasma research laboratories, its students always have had the opportunity to visit large research devices, and now the department has bridged the gap between theory and large experiments with a set of carefully selected hands-on experiments.

Target group

Experiments at Ghent University are regularly used by **bachelor and master students enrolled at the university** to complement the theory courses, and by students enrolled in the **FUSION-EP Erasmus Mundus master programme.** Measurements are designed so that the experiments can be successfully performed without prior advanced knowledge of specialised fields of plasma physics.

Spectroscopic measurements

Emission spectroscopy is the most elementary non-invasive technique to measure the properties of non-fully ionized plasmas. The visible light spectrometer can be connected to either a DC glow discharge or a low-pressure RF discharge. Based on the theory of atomic and molecular physics, we can determine plasma parameters like temperature, density and plasma composition from the intensity and shape of spectral lines.
Through this experiment the student also gets some experience with elements of DC or RF discharges depending on the source used.



RF plasma chamber with pumping unit and gas system

Mass-spectrometry

Mass spectrometry is a standard method to measure plasma composition. The experimental set-up consists of a low-pressure discharge tube mounted on the inlet flange of a quadrupole mass spectrometer which serves as grounded anode for the DC-excited discharge.

Mass spectrometer coupled to a DC glow discharge tube

The discharge can be run with both a noble gas (e.g. Ar) and a chemically active gas (e.g. CO_2). The students can thus get acquainted with some elementary processes (ionization, dissociation, …), and also acquire knowledge of the basics of vacuum technology: they learn about the operating principles and characteristics of different kinds of pumps and pressure gauges.

Double Langmuir probe

Sets of Langmuir probes are used in almost every plasma device to measure basic plasma parameters in the moderate temperature region. The experimental set-up consists of a low pressure discharge tube equipped with a double Langmuir probe, located at different positions along the discharge axis. A DC noble gas glow discharge is produced in the tube at different pressures in the range 0.1-10 kPa. The experiment illustrates many of the concepts that are covered in the lecture on glow discharge physics and exposes the students to the specifics of probe diagnostics.

Use and access

The FuseNet funded experiments are routinely undertaken by local students as well as students enrolled in the FUSION-EP Erasmus Mundus master program. Detailed documentation (including laboratory manuals, blueprints and lab reports) has been produced with FuseNet support, and replication of these experiments in FuseNet member institutes is encouraged.

Discharge tube with two Langmuir probes

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Alexandru Ioan Cuza University Plasma Laboratory

Faculty of Physics at Alexandru Ioan Cuza University, Iasi, Romania hosts plasma courses at different levels and also occasionally offers education to high school students.

Target group

Experiments at Alexandru Ioan Cuza University Plasma Laboratory are regularly used by **bachelor and master students enrolled at the university** to complement their theory courses, and by students of nearby high schools. Teaching goals are therefore diverse and range from popular science demonstrations to independent course work demanding knowledge of basic plasma theory.

Discharge chamber with vacuum system

Plasma diagnostics by electrical probes

A series of eight practica is designed to benefit from the versatile experiment of electrical probes mounted on a multipolar magnetic confinement plasma. Besides getting students acquainted with the concept of confinement in a multipolar magnetic field, which is interesting in itself, the experiments demonstrate the whole range of measurements feasible with single, double and triple Langmuir probes including temperature, density and plasma potential measurements. One practicum concentrates on studying the dependence of ion and electron saturation currents on probe geometry. Finally, a practicum uses an electrostatic analyzer to determine the ion velocity distribution.

View of a single Langmuir probe in a magnetically confined plasma

Magnetic confinement of an electron beam

The key element of the experiment hardware is the fast, slightly divergent electron beam streaming from the negative glow of an electrical discharge burning in abnormal regime. The beam is generated with a hollow cathode. The effect of a magnetic field on plasma electrons and magnetic confinement is demonstrated by studying the effect of a variable magnetic field on the geometry of the electron beam. Students can also determine the velocity of the beam electrons along the magnetic field by studying the interaction between the beam and the applied magnetic field and comparing it with theory.

Helmholtz coil confining electrons in a discharge tube, 2 focal points on the discharge axis

Use and access

Along with a set of further plasma experiments, the FuseNet-funded experiments are mainly used by students enrolled at Alexandru Ioan Cuza University and ~500/ year students from Romanian high schools during the "Open House Days". Access to a wider audience can be negotiated on demand. Reproduction of experiments is facilitated by providing detailed documentation and support.

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Learn everything about RF

IPP RF laboratory

The Max Planck Institute for Plasma Physics in Germany is one of the largest fusion research institutes situated in two locations in Germany: Garching hosts the ASDEX Upgrade tokamak and Greifswald the W7-X stellarator. Besides its research activities, it also supports education by providing access to these large facilities and also to some small educational experiments.

The IPP RF laboratory consists of a series of experiments aiming at familiarizing students with HF/VHF transmission lines, matching methods, power generation and measurement equipment used for high power RF. A set of 11 hands-on experiments is complemented by a visit to the high power ion cyclotron range of frequency (ICRF) heating system of ASDEX Upgrade.

Target group

Experiments at IPP mostly address **master and doctoral students enrolled in education programmes at German universities.** Regular master courses are offered at universities making use of the capabilities provided by IPP. The experiments can also be made available on demand.

ICRF transmisson lines at the ASDEX Upgrade tokamak

Use and access

A lab session can be organised on demand for between 4 and 16 students. It can be tailored to master or doctoral students and can last between half a day and several days.

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Sofia University plasma experiments

In 2010 Sofia University started a dedicated master programme called Fusion Science and Technology. The curriculum relies heavily on experimental work during which students can not only see plasma in various plasma sources but also learn how to create it themselves, how to measure the plasma properties and the applications where it can be used. This practicum is the first step to prepare students for joining the teams working on big devices in operation in Europe.

Target group

Sofia University has a curriculum for **Fusion Science and Technology Masters**, and students can already use the experiments in their thesis work at the **bachelor** level. In complexity, the experiments reach from demonstration to building new plasma sources.

Students experimenting on a discharge tube

Use and access

The curriculum of the master programme Fusion Science and Technology includes two semesters of obligatory plasma diagnostics practica. Bachelor students can also take these courses voluntarily, and some experiments are even demonstrated for high school students during the "Open House Day" at the Faculty of Physics. Basic plasma experiments are complemented by three hands-on experiments for studying high-temperature plasmas on the Plasma Focus device. Use of these set-ups by external students can also be negotiated.

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CRPP-EPFL plasma devices

The **Centre de Recherches en Physique des Plasmas** (CRPP) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) regularly operates two plasma physics experiments, the TCV tokamak and the TORPEX device. Both devices are used, in particular, in the framework of the Doctoral programme for education and research. The CRPP-EPFL has a large Doctoral programme in magnetic fusion with 7-8 students graduating every year. Graduate students are closely involved in the development, construction and exploitation of plasma diagnostics, and conduct experiments that address important open questions in plasma physics. Doctoral courses, open to EPFL and external students, are regularly taught during the official EPFL semesters. In addition, one-week intensive courses, convenient for external students, are organised, such as the FuseNet-funded course **"Plasma diagnostics in basic plasma physics devices and tokamaks: from principles to practice"**.

Target group

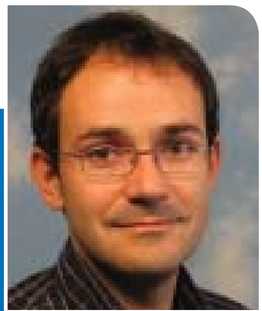
Students attending **doctoral training in fusion plasma physics or technology** either at EPFL or at a collaborating institute.

Students of a FuseNet-funded international course

Use and access

The TCV and TORPEX devices are widely open to international collaborations. TCV, in particular, has been selected in the framework of the European Fusion Roadmap, as one of the three Medium Size Tokamaks (MST) that are available to the entire fusion community.

Contact information



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Thorello device

Thorello is a simply magnetised toroidal plasma device for turbulence studies hosted at the University of Milano-Bicocca. It has the capability to produce low temperature magnetised plasmas that can be maintained stable even in hour-long operations, in a reproducible set-up. It can be employed to study and characterise the plasma state in particular the turbulent regimes that show up in magnetised plasmas, plasma-wave interactions, low temperature plasma diagnostics and anomalous transport. Most research is focused on the identification of structures or events generated by turbulence by different statistical analyses and on the study of their role in particle transport mechanisms. The experience gained here is not only relevant for fusion but also for astrophysical plasmas.

Target group

Master and doctoral students specialising in plasma physics with particular interest in plasma turbulence and advanced signal analysis methods, like conditional sampling and intermittent spectra.

Thorello device being used by students

Use and access

Thorello is used by **master students** during the course of the Plasma Physics Laboratory within the Plasma Physics curriculum at University of Milano-Bicocca. It is also available for **master and doctoral students doing research.**

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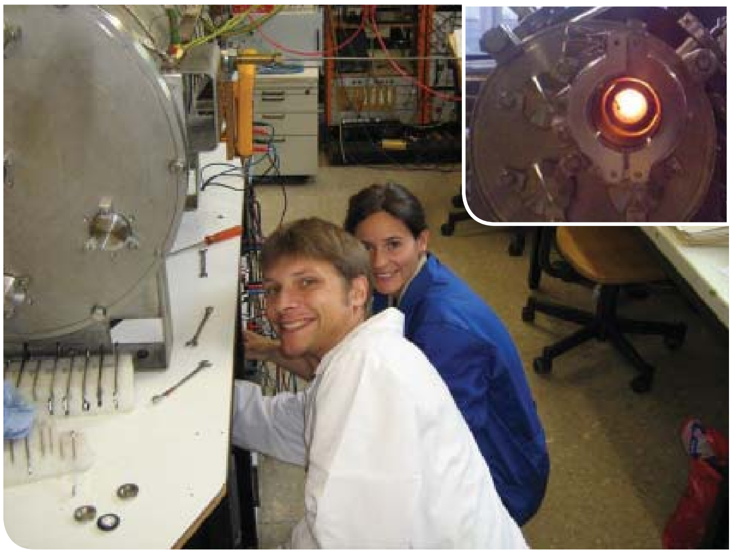
Operate an exotic plasma source

Innsbruck Q-machine

The University of Innsbruck hosts the only operational Q-machine in Europe, along with some other small experiments. The Innsbruck Q-machine is a linear magnetised plasma machine, in which an extremely quiescent alkaline plasma is produced by contact ionization on a hot metallic plate. The recent upgrade is allowing production of a more homogeneous plasma column of larger diameter in a stronger magnetic field. A typical practicum on the device lasts about 2 to 3 weeks. Included in the programme are: operation of IQM and its vacuum system, basic measurements with probes and – on a more advanced level – excitation and investigation of various instabilities.



Innsbruck Q-machine in operation

Target group

Students with specialization in fusion or plasma physics can either do the basic programme following the practicum or do autonomous research for their master or doctoral thesis.

Use and access

The Innsbruck Q-machine is used by local master and doctoral students and a large number of guest students from various international programmes. Access is granted to visiting students provided they have the funding to finance their stay.

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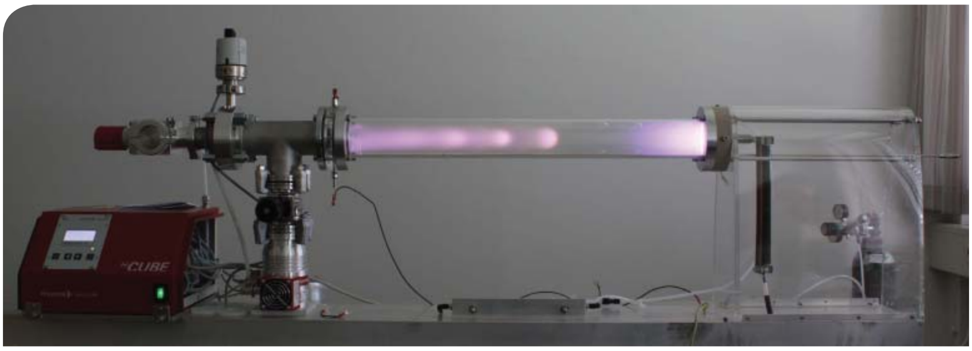
Compact Langmuir probe experiment

The Max Planck Institute for Plasma Physics has set up a new laboratory course experiment that supports master-level plasma physics education. This compact and simple experiment combines a DC glow discharge tube with a single/double Langmuir probe, making it an ideal tool to address basic plasma physics concepts in a hands-on experiment.

Target group

The experiment is mainly intended for **master students** enrolled in education programmes at German universities. The optimum group size is two to three students.



Portable glow discharge tube

Use and access

This experiment is regularly used by students attending the associated courses at German universities. Use by other institutions or students is generally possible. Please contact IPP for more information on availability.
Very detailed documentation (including blueprints) is available, allowing easy replication of this experimental set-up.

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Experiment with plasma via the Internet

Langmuir probe experiment in e-lab

Hosting the ISTTOK tokamak, the Instituto Superior Técnico has a long tradition of using plasma devices for educational purposes. Now it is possible to share this expertise with the rest of the world with the help of a remote-controllable plasma experiment. Using the e-lab framework, the "Langmuir probe" experiment can be controlled through the Internet. Students can not only practice how to handle a Langmuir probe but they can also learn how to set up remote measurements in the e-lab framework.

Target group

The experiment is intended for two groups of people: those who want to learn about Langmuir probes within a plasma physics course, and a more general public audience interested in remote measurements. In both cases a basic knowledge of data processing and some knowledge of plasma physics are assumed.

The first Plasmasurfers, using the IST remote plasma lab

Use and access

The experiment is available for anyone who has access to a PC with internet connection. Tutoring can only be provided for a limited number of students and has to be booked in advance. The device is therefore mostly dedicated to students who attend international courses in partnership with Instituto Superior Técnico (see for instance the ATHENS programme and Plasmasurf).

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More hands-on experiments for fusion training

In addition to the support of the development of hands-on experiments, the FuseNet Project has created an inventory of existing experiments available for fusion education. This covers comprehensively the opportunities that European students have to gain practice in applied fusion plasma physics during regular education activities. We list here only those at locations other than the ones already mentioned in the brochure.

1. Practica providing experience on integrated aspects and plasma operation

- Tore Supra, Cadarache
  tokamak with student access
- Practicum Plasma Physics, Prague
  practicum on tokamaks and a laser facility
- Stellarator TFJ-K, Stuttgart
  stellarator for diagnostics and turbulence studies

2. Practica with several hands-on experiments for a broad introduction

- Istituto di Fisica del Plasma „Piero Caldirola" plasma lab, Milan

3. Plasma sources where one or more aspects are taught

- Discharge tube, Budapest
  low temperature discharge tube
- VESPA, Padua
  argon plasma in a cylindrical device
- Magnetron sputtering, Padua
  magnetron with cylindrical chamber

4. Dedicated hands-on experiments to teach one specific aspect

- Superconducting test bench, Cadarache
  table-top experiment with superconductors
- Plasma interferometry, Garching
  dedicated pulsed plasma source
- Plasma spectroscopy, Garching
  spectroscopy of an inductively coupled plasma
- Non-linear plasma physics, Stuttgart
  device for plasma waves and solitons
- Plasma diagnostics, Langmuir probe, Stuttgart
  low temperature plasma with Langmuir probes

When contacted by FuseNet, most of the device hosts expressed their willingness to make these experiments available to a wider audience, under varying conditions. The list of responsible contacts is kept up to date on

the FuseNet website: http://fusenet.eu/experiments

FuseNet contribution

The GOLEM tokamak for fusion education	4-5
In the course of the FuseNet Project various hardware upgrades were financed, as well as an extensive training programme development, both resulting in a better use of the GOLEM tokamak's unique capacity for full remote operation through a simple web-based graphical interface.	
PlasmaLab@TU/e	**6-7**
The FuseNet Project has provided funding for four out of the eight experiments operating at the Plasma Laboratory of TU/e, as well as for three instalments of hands-on courses in Plasmalab@TU/e.	
PlasmaLab@UGent	**8-9**
FuseNet funding made it possible to expand the PlasmaLab@UGent and produce the detailed documentation facilitating the replication of the experiments.	
Alexandru Ioan Cuza University Plasma Laboratory	**10-11**
FuseNet supported the design of two experiments at Alexandru Ioan Cuza University and the development of associated course materials and documentation.	
IPP RF laboratory	**12**
The development of this RF lab was supported by the FuseNet Project.	
Sofia University plasma experiments	**13**
FuseNet has supported the upgrade of a part of the existing experiments in a laboratory.	
CRPP-EFPL plasma devices	**14**
The experiments at the CRPP-EPFL were already available. FuseNet has provided the funding for a pilot programme providing opportunities for international students to make use of the experiments during the course "Plasma diagnostics in basic plasma physics devices and tokamaks: from principles to practice".	
Thorello device	**15**
FuseNet has funded the personal costs of an upgrade and documentation of the Thorello device.	
Innsbruck Q-machine	**16**
FuseNet has supported an upgrade to produce a more homogeneous plasma column of a larger diameter in a stronger magnetic field, and to use this machine for teaching purposes.	
Compact Langmuir probe experiment	**17**
The Compact Langmuir probe experiment was built and documentation produced with funding by the FuseNet Project. Other experiments exist and are operated for educational purposes both at IPP Garching and at IPP Greifswald.	
Langmuir probe experiment in e-lab	**18**
Building of the Langmuir probe experiment and setting up the computer framework was financed by FuseNet, as well as the first courses that made use of it.	

FuseNet Project, 2013
Seventh Framework Programme

Hands-on experiments on plasma physics and nuclear fusion.
Participate or build your own.

Publisher:	FuseNet Project
Editors:	Prof. Jean-Marie Noterdaeme, leader of the work package „Hands-on experiments" (WP7 of the FuseNet Project) Dr. Gergő Pokol, BME
DTP:	Máté Kovács, BME
Photographs:	Photographs are property of departments marked in the contact information of each device. Photo on page 12 is courtesy of Peter Ginter (IPP).
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This publication was supported by the European Commision, Euratom, FP7.

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The FuseNet Project is
supported by
the European Commission,
Euratom, FP7

SEVENTH FRAMEWORK
PROGRAMME