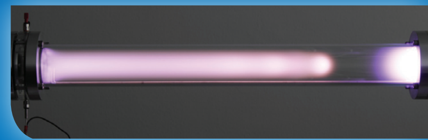
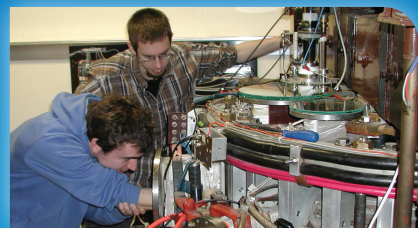
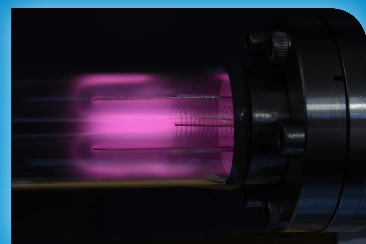
# Hands-on experiments

## on plasma physics and nuclear fusion



## Participate or build your own



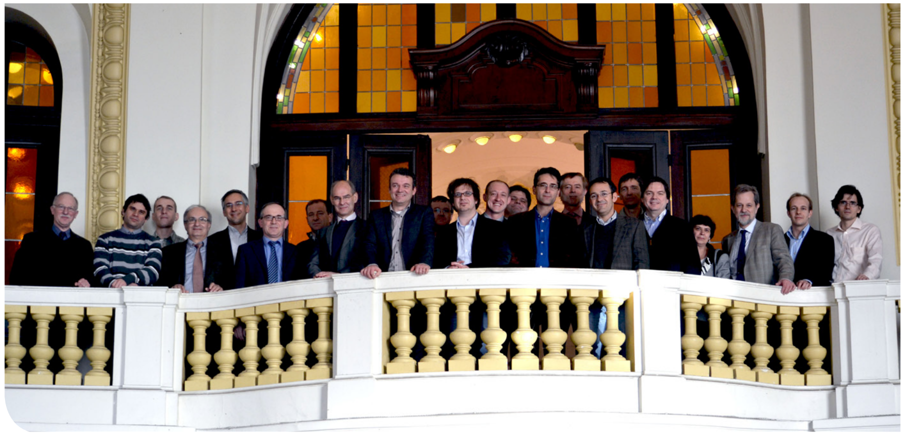


The FuseNet Project is supported by European Commission, Euratom, FP7

SEVENTH FRAMEWORK PROGRAMME

FuseNet

Association



FuseNet Association General Assembly 2013, Sofia

# Content

# Preface

Dear reader,

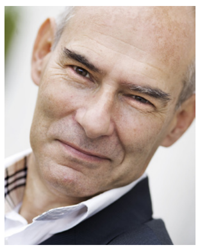
In front of you lies a booklet with short descriptions of a selection of hands-on experiments, carefully designed and built for educational purposes on an advanced academic level.

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, 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.



N Lopes Cardozo

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 continued dedication of excellent scientists and engineers and the training of a new generation.

An in-depth knowledge of specialised fields is required, usually acquired in the course of preparing a Ph.D. thesis. However, 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, carefully designed and built for educational purposes at an advanced academic level.

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 so that more proposals could be supported.

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.

Jean-Marie Noterdaeme

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

# The GOLEM Tokamak for Fusion Education

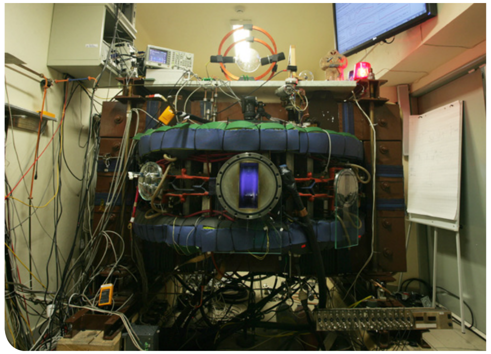
The GOLEM tokamak is located at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University (CTU). CTU hosts a Fusion Masters program, but GOLEM is for the benefit of a wider audience. It is a small-sized tokamak device equipped with basic controls and diagnostics and full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

## Target group

**Bachelors and Master Students** wanting to learn about tokamak operation.

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

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



GOLEM tokamak in operation

## Remote operation support

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

Student 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 programs. 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

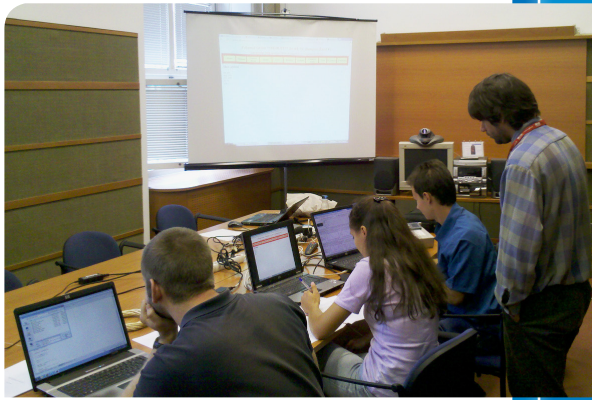
In order to introduce the GOLEM tokamak to distant users via Internet, an interactive **3D virtual model** has been created.

The virtual model is complemented by a **virtual operation interface**, where students have 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 thewhole world every year.

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

## Contact information

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# Experience all-round plasma physics education

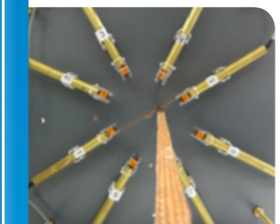
## PlasmaLab@TU/e

Eindhoven University of Technology has started a Masters program on Fusion science and technology, and now it is complemented by a plasma physics laboratory illustrating all important aspects of plasma physics.

### Target group

At Eindhoven University of Technology a hands-on plasma lab has been established with the intention to use this for multiple purposes: as an instructive example of the material taught in the different plasma physics or fusion related courses, to give the students an experimental training (on different levels: suitable projects for **both Bachelor as well as Master students** can be defined at the same setup), to use it for demonstration purposes in an outreach activity or to teach **high school physics teachers** (with or without their pupils) the principles of plasma physics.
With additional FuseNet support we offer to open this for foreign students as well and organize a 1 week hands-on plasma course.

### Magnetic diagnostic



Knowledge of the electric current in the plasma is essential for controlling and diagnosing plasmas. Magnetic pick-up coils are commonly used and magnetic measurement techniques are well established. The setup allows to calculate and verify the response of pick-up coils in the vicinity of a current-carrying conductor while experiencing similar technical difficulties as in tokamaks.

Magnetic probes around a conductor modeling plasma

### Waves in plasma

In this experiment electromagnetic wave propagation is studied in a plasma with variable density and magnetic field. The device is linear discharge tube of ~ 1 m length and a diameter of several cms equipped with small loop-antennas mounted for launching and receiving waves in the 1 GHz range. With an interferometer wave propagation can be studied as a function magnetic field and density. A Langmuir probe is also available for independent measurement of electron temperature and density.

### Zeeman splitting

The Zeeman splitting describes the effect that spectroscopic lines in excited gases are split up under the influence of a magnetic field. It provides a way to do localized measurements of the magnitude and the direction of the magnetic field by using spectroscopy. In the course of the experiment the effect of a variable orientation strong magnetic field on a light source is studied using a spectrometer.

Setup to study Zeeman splitting

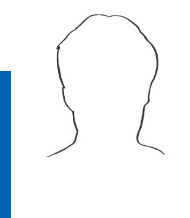
### Fusor

With an electrostatic fusor one can create and control a fusion plasma at costs and with facilities within the reach of universities. Due to loss mechanisms a fusor is not conceived as an experiment that is capable of producing net energy, but much of the physics of fusion plasmas can be studied and verified including the physics of nuclear reactions.

Fusor vessel and auxiliary units


### Use and access

PlasmaLab@TU/e is mostly used by students of the Eindhoven University of Technology and physics teachers for The Netherlands. The easiest way for European Masters students to gain access to these experiments is through the yearly hands-on course in Plasmalab@TU/e which is free if sufficient funding can be arranged. FuseNet members are also encouraged to duplicate the experiments. For this purpose detailed technical descriptions are provided.



### Contact information

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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 hosting the ASDEX Upgrade tokamak and Greifswald hosting the W7-X stellarator. Besides its research activities, it also supports education by providing access to these large 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 the ASDEX Upgrade.

## Target group

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

## Use and access

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

ICRF transmisson lines at the ASDEX Upgrade tokamak

## Contact information

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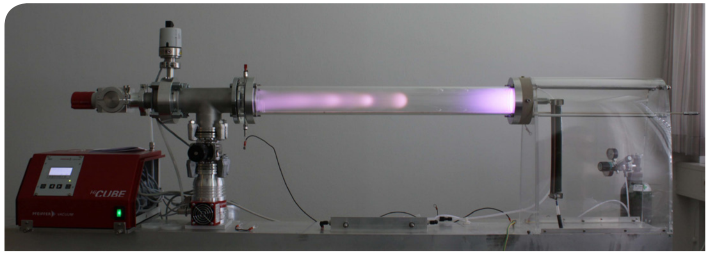
## Build your own Langmuir probe experiment

# 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 programs 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. In case of demand please contact IPP for more information on availability.
Very detailed documentation (including blueprints) is available, allowing easy replication of this experimental set-up.

## Contact information

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# A hands-on introduction to plasma physics

## PlasmaLab@UGhent

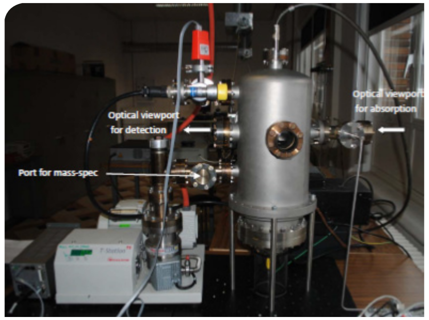
The Department of Applied Physics of Ghent University, Belgium has regular courses in both plasma physics and fusion technology on both Bachelor and Master level, and it is also coordinator of the FUSION-EP Erasmus Mundus master, a Europe-wide collaborative fusion education program.
Since the department is very well connected to plasma research laboratories, its students always 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 program.** Measurements are designed so that the experiments can be successfully performed without prior advanced knowledge of specialized 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 discharge depending on the source used.




RF plasma chamber with pumping unit

### 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 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 student can thus get acquainted with some elementary processes (ionization, dissociation, …), and also acquires knowledge on the basics of vacuum technology: they learn about the operating principles and characteristics of different kinds of pumps and pressure gauges.

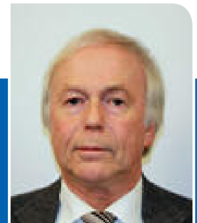
### Double Langmuir probe

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 well accepted by local students as well as students enrolled in the FUSION-EP Erasmus Mundus master program. Detailed documentations (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



### Contact information

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# Practica on all levels

## 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.

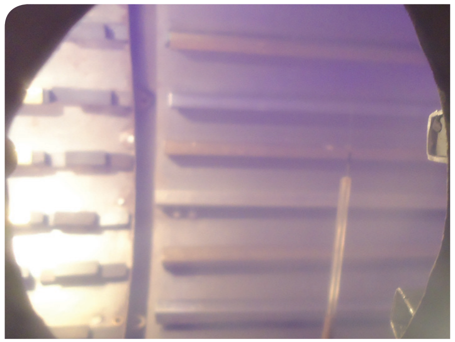
### Target group

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 reaching from popular science demonstrations to independent course work demanding knowledge of basic plasma theory.

### 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 making 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, plasma potential measurements. One practicum concentrates on studying the dependence of ion and electron saturation currents on probe geometry. Finally, a practicum is using an electrostatic analyzer to determine the ion velocity distribution.

Discharge chamber with vacuum system

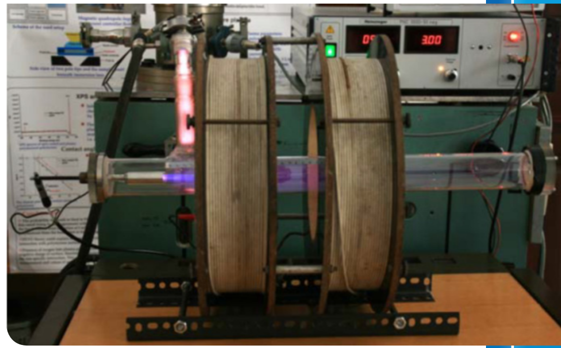


View of single Langmuir probe in magnetically confined plasma



### Magnetic confinement of an electric 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 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

### 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 days of open doors”. Access to a wider audience can be negotiated on demand. Reproduction of experiments is facilitated by providing detailed documentation and support.

2 focal points of the electron beam on the discharge axis

### Contact information

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# Experiment on complex machines

## CRPP-EPFL Plasma Devices

The Centre de Recherches en Physique des plasmas (CRPP) – Ecole Polytechnique Fédérale de Lausanne (EPFL) maintains two research infrastructures, the TCV tokamak and the TORPEX device, also frequently used in the education of Doctoral students. CRPP-EPFL has a massive doctoral education program in fusion with 8-9 graduations each year. Both TCV and TORPEX devices are capable of producing research results relevant to large tokamaks, at the same time they are flexible enough to facilitate regular coursework, as well.

### Target group

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

### Use and access

Students of a FuseNet funded international course

The TCV and TORPEX devices are normally used by EPFL students and students doing research projects, but occasionally they are open to a wider audience, for example during the FuseNet-funded one-week intensive course **"Plasma diagnostics in basic plasma physics devices and tokamaks: from principles to practice".**

### Contact information

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ivo.furno@epfl.ch



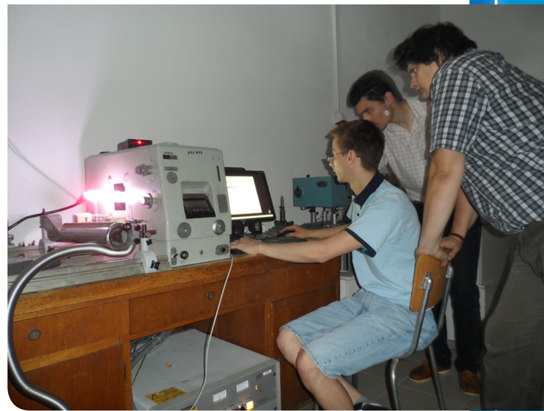
# Learn experimental plasma physics

## Sofia University Plasma Experiments

Sofia University has started a dedicated Masters program Fusion Science and Technology in 2010. 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 in students preparation 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 on 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 Master program Fusion Science and Technology includes two semesters of obligatory Plasma diagnostics practica. Bachelor students can already take these courses voluntarily, and some experiments are even demonstrated for high school students during the "Open door" day at the Faculty of Physics. Basic plasma experiments are complemented by three hands-on experiments for studying high temperature plasma on the Plasma Focus device. Use of these set-ups by external students can also be negotiated.

### Contact information

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# Experiment with plasma through the Internet

## Langmuir Probe Experiment in e-lab

Hosting the ISTTOK tokamak, the Instituto Superior Técnico has a long tradition in 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 having 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 www.athensprogramme.com and plasmasurf).

### Contact information

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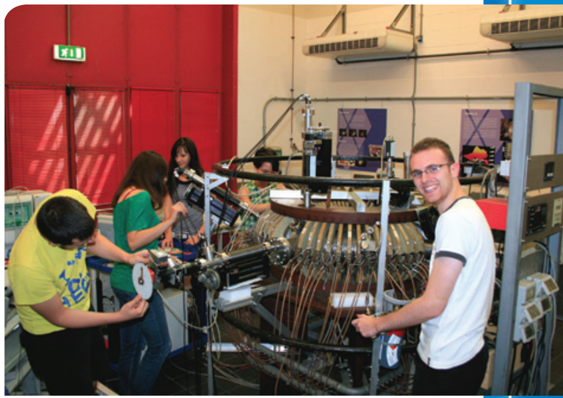
# A device to study turbulence

## Thorello device

Thorello is a simply magnetized toroidal plasma device for turbulence studies hosted at the University of Milano-Bicocca. It has the capability to produce low temperature magnetized plasmas that can be maintained stable even in hour-long operations, in a reproducible set-up. It can be employed to study and characterize the plasma state in particular the turbulent regimes that show up in magnetized plasmas, plasma-wave interactions, low temperature plasma diagnostics and anomalous transport. Main researches are 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. Gained experience is not only relevant for fusion but also for astrophysical plasmas.

### Target group

Master and Doctoral students specialized 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.

### Contact information

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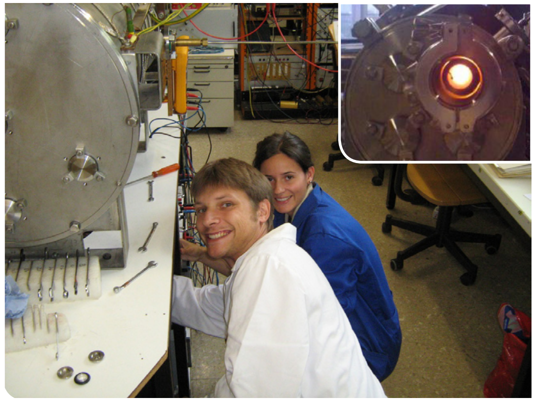
## Operate an exotic plasma source

# 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 magnetized plasma machine, in which an extremely quiescent alkaline plasma is produced by contact ionization on a hot metallic plate. The recent upgrade allows to produce 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 program are: operation of IQM and its vacuum system, basic measurements with probes and – on a amore advanced level – excitation and investigation of various instabilities.

## Target group

Students with specialization in fusion or plasma physics can either do the basic program following the practicum or do autonomous research for their Master or Doctoral thesis.



Innsbruck Q-machine in operation

## 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 programs. Access is granted to visiting students provided they have the funding to finance their stay.

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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 also 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 other locations than the ones already mentioned in the brochure.

**1. Hands-on practica on larger infrastructure, 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 turbulance studies

**2. Complete plasma laboratories, with several hand-on experiments, allowing a broad introduction**

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

**3. Smaller 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
- Non-linear plasma physics, Stuttgart
  device for plasma waves and solitons
- Plasma diagnostics, Langmuir probe, Stuttgart
  low temperature plasma with Langmuir probes

In their answer to FuseNet, most of the device hosts have 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/node/431**

# FuseNet Contribution to Experiments



FuseNet
The European Fusion Education Network


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


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