Sciences de la Fusion
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Hands-on project
Cadarache Winter event

FUSION-EP
Education and Culture DG
Master of Science in Nuclear Fusion and Engineering Physics
Erasmus Mundus

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Master National Sciences de la Fusion

Erasmus Mundus European Master in Nuclear Fusion & Engineering Physics

Short description of the subjects for Hands-On project.

Cadarache event – Winter 2015

- 1 - Lower Hybrid antenna

Tore Supra is a superconducting tokamak which has demonstrated the sustainment of long plasma pulses (up to 6 minutes 30 seconds). In order to sustain these long pulses, a part or all the plasma current must be generated non-inductively. This additional plasma current is driven on Tore Supra via the Lower Hybrid and Current Drive (LHCD) system. High power Radio-Frequency sources (klystrons) generate hundreds of kilo-Watts which are carried through transmissions lines (rectangular waveguides) up to the LH launchers facing the edge plasma (cf. Figure 1).

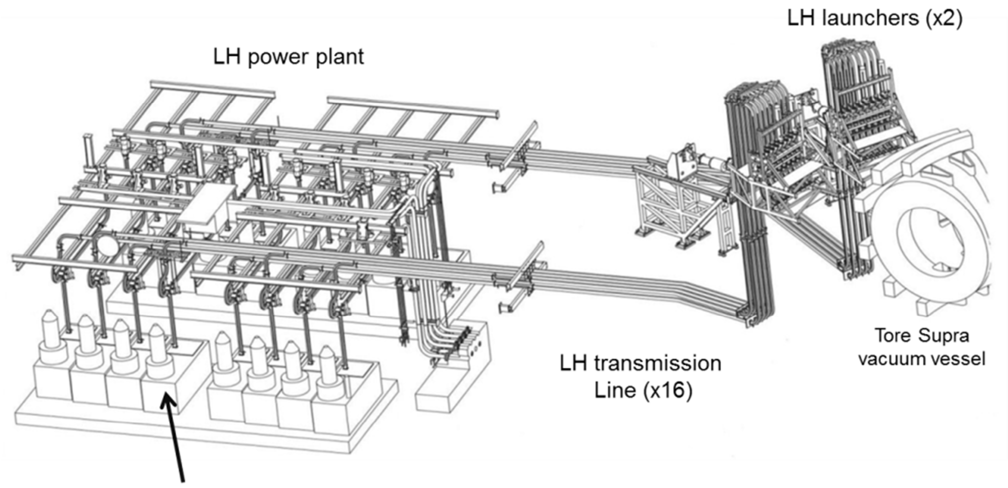

Figure 1. Overview of the Tore Supra LHCD systems. Sixteen high power sources (klystrons, at the left of the Figure) feed two antennas (at the right of the Figure, not illustrated) via sixteen 25-meters long transmission lines (rectangular waveguides).

The following two Hands-On projects focus on two RF components constituting the Tore Supra LH launchers: the mode converter (in red in
Figure **2**) and a multijunction (in blue in
Figure **2**). These RF components have multiple functions, but the main one is to divide the RF power coming from the klystron to numerous waveguides facing the plasma.

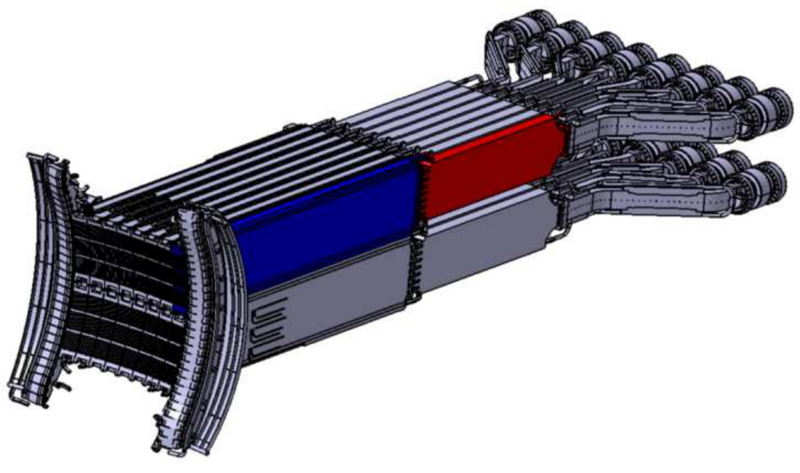

Figure 2. CAD view of a Tore Supra Lower Hybrid launcher (aka “C3”). The red part is the TE10-TE30 Mode Converter. The Blue part is the multijunction. Dimensions : approx. 0.7 x 0.7 x 5 m.

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Location (including report preparation) Building 508, 2nd floor, room 234

Schedule - 2015
MC: Mode Converter ; MJ: Multijunction

Mon 9/02	10/02	11/02	12/02	13/02
Welcome	Recall of basic RF and LH (MC/MJ)	MC: E-Fields meas.	MC: data analysis	Prepare report
		MJ: data analysis	MJ: data analysis	
Introduction to Hands-On	MC: 1.S-param meas. 2.analysis S-param	MC: end of meas. Data analysis	MC: data analysis	
	MJ: 1. Spectrum 2. S-param meas.	MJ: Short-Circuit meas.	MJ: data analysis	

Mon 16/02	17/02	18/02	19/02	20/02
Recall of basic RF and LH (MC/MJ)	MC: E-Fields meas.	MC: data analysis	Prepare report	Exam
	MJ: data analysis	MJ: data analysis		
MC: 1.S-param meas. 2.analysis S-param	MC: end of meas. Data analysis	MC: data analysis		
MJ: 1. Spectrum 2. S-param meas.	MJ: Short-Circuit meas.	MJ: data analysis		

A quick survey of the work
During these Hands-on, both measurements and data analysis will be performed. We will introduce you to the fabulous world of RF measurements and you will operate by yourself the measurements devices, such as RF network analyser. You will have to assemble yourself the waveguides elements and perform the necessary calibrations, make the measurements and then post process these results.

Figure 3. A student is performing a calibration of the Network Analyzer for the Mode Converter measurement.

Figure 4. Students are analyzing their data.

- 2 - Qualification of plasma Facing Components

The project aims at illustrating various aspects of non-destructive testing performed on plasma facing components to check their properties before being installed in a tokamak for operation. Main focus is put on actively cooled components. Active cooling is mandatory to achieve stationary long duration plasma discharges. Actively cooled components have to fulfil a number of criteria to provide the required heat exhaust capability. The project illustrates the method that is used in Cadarache to measure the characteristics of these components.
Actively cooled components are usually made of a combination of several materials assembled around a cooling pipe where pressurized water flow (Fig.1). Heat exchange between the water and the component has to be maximized. The interface layer has to be checked.

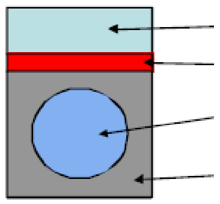


Figure 1

During the project, a sample component, comparable to that in Fig. 1, will be tested, and results compared to that from reference PFCs, to find possible defaults. The fabrication process is therefore tested before the component is installed inside the vessel for real tokamak operation, and default components can be rejected. Three test beds will be used:

1) hydraulic dimensioning & measurement of pressure drop

2) SATIR (french acronymn for Station d'Acquisition et Traitement Infra Rouge)

The surface temperature of the sample is deduced from infra-red thermography measurements. Its response to a change of temperature of the water flowing through the pipe gives an indication on the heat exhaust capability of the component.

3) lock-in thermography

As in SATIR, the surface temperature of the sample is measured from infra-red thermography, but instead of measuring the response to a change of temperature of the water in the pipe, the response to a sinusoidal heat flux excitation to the component surface is now measured. The heat flux is produced by halogen lamps.

- 3 – Thermo-desorption

Thermo-desorption is a laboratory technique in which a material sample is heated in a controlled manner, and the outgassing species are analyzed by mass spectrometry. The results are then modelled to derive a quantitative measurement of the chemical species that were trapped in the sample. In the context of fusion research, it is used to analyze the quantity of tritium trapped in the Plasma Facing Components (CFP), and to determine the trapping mechanisms.

In this project, we propose to use the thermo-desorption technique to study trapping mechanisms in material samples taken from Tore Supra PFCs.
Students will measure the total number of deuterium atoms trapped in the sample, together with their concentration. The result will be extrapolated to derive the total number of deuterium atoms trapped in the Tore Supra vessel walls, considering the total surface of PFCs. The number will be compared to already published value (Tsitrone et al, Nucl. Fusion **49** (2009) doi:10.1088/0029-5515/49/7/075011, paper will be distributed during the Hands-On work). Error bars will be estimated, and sources of errors discussed.
TDS gives also information on trapping processes. During TDS, when the sample is heated, gazeous species as deuterium are released at several temperatures, each corresponding to a trapping energy. During the Hands-On, energy spectra will be measured. The temperatures at which deuterium desorption is observed will be determined, and the consequences on deuterium recovery in a tokamak will be discussed. Comparison between carbon and tungsten walls will be made using published results (Ogorodnikova et al, Journal of Nuclear Materials 373 (2008) 254–258, Fig. 5 and Fig. 6), and the advantages of tungsten for fuel control will be analyzed.

Organisation

1) calibration of mass spectrometer

2) Tore Supra sample analysis : identification of the desorbed species and their production, discussion on possible errors.

3) reference sample, never exposed to plasma: analysis of a possible contribution to the results of spurious oxydation by air or of desorption of TDS vessel walls,

4) interpretation of results.

- 4 - Glow discharge characterisation

1. Subject/ Aim of the experiment

The tokamak walls have to prepared in a certain way for discharge initiation, for plasma purity, and to minimize retention of tritium. The preparation of the walls is called conditioning. Several techniques can be used for wall conditioning, but one of them consists in producing 'glow discharges' inside the vessel. Glow discharges are cold plasma discharges in a gaz, between an anode and a cathode, and without magnetic field. This experiment is related to the optimization of the glow discharge plasma parameters required for wall conditioning in a tokamak.

The work proposed here will include:

- Operation of the 'glow discharge'/ cleaning of the vessel walls
- scan of discharge parameters by changing gas pressure + gas species. Available gases are: argon, helium.
- Measurement of discharge parameters with Langmuir probes: determine density and temperature profiles.
- Characterization of the discharge using visible spectroscopy.

2. Experimental work to be done

2.1. Operation

Start the plasma discharge. Use argon as working gas. Choose the current to be used (manual setting of the current). Get familiar with the different settings of the device. Get familiar with Labview to visualize the data. Characterize discharge breakdown. Courbe de Paschen

Tracer U=f(P) 0.1-10 Pa, comparer à une courbe de Paschen standard. Expliquer une courbe de Paschen. Ar/ He.

2.2. Cleaning process

Run several discharges in argon, with given current. The voltage to be applied to get a given current gets lower with the number of discharges. This voltage will be used as a quantitative parameter to characterize the wall conditions. Try to find an explanation for this. Use documentation and model presented in the introduction session.

Change the control parameters (current, gas pressure, gas species) and find discharge conditions for wich best conditioning is achieved (lowest voltage).

2.3. Plasma characterization: Langmuir probe

Measure the probe (U, I) characteristics for different operating conditions. Analyze in terms of plasma electron density and temperature. Use different techniques to analyze probe (U, I) characteristics. Scan en position de la sonde de Langmuir. mesures bruitées. Utiliser méthode des pentes log(i)=f(u).

2.4. Plasma characterization: visible spectroscopy

- 5 - Reflectometry

Reflectometry is a diagnostic technique used to measure the electron density profile and its fluctuations in tokamak plasma experiments. The measurement is deduced from the properties of wave propagation in a plasma: the electromagnetic wave is reflected at the plasma cutoff layer, when the refraction index goes to zero for the particular wave frequency. In the tokamak diagnostic, the position of the cutoff layer is measured.

This subject proposes to uses the real Tore Supra reflectometers in the lab to carry on series tests and experiences to get familiar with all the details of the density profile measurements.

Fig. 1: Tore Supra reflectometer

The work will be organized as follows: 1) presentation of the physics basis of the measurement, and details of implementation as a tokamak diagnostic, 2) experimental work in the lab, 3) analysis of data already obtained on Tore Supra. Characteristics of the probe wave and of the detection technique will be discussed. Test experiments using a mirror for the reflection layer will be used to discuss the angular precision required for the measurements.

Finally, the principle of turbulence measurements will be illustrated.

- 6 - TOKAMAK EXPERIMENT: COMPASS.

COMPASS is the tokamak operated at the Institute for Plasma Physics in Prague. It is a midsize tokamak equipped with a whole set of diagnostics. All the common heating techniques are available (neutral beam injection and radiofrequency at various wavelengths). The COMPASS team is used to organising remote experiments with students and young scientists. We will start with an introductory lecture about the tokamak, its diagnostics and heating capabilities and the main topics of research. The students will then be proposed a few themes derived from the results obtained during the EMTRAIC event with the Fusion EP students in December. According to their choice, the pairs of students will elaborate an experimental plan and perform the experiments (remotely) with the help of the COMPASS team in Prague. The preliminary analysis during the experiments will allow them to modify the experimental plan if necessary. A more accurate analysis after the experiment will lead to the preparation of the oral examination.

This hands-on work is proposed only on the second week of the hands-on projects. It is a unique opportunity to get involved in a tokamak experiment fully equipped with modern diagnostics and heating devices. It is open to every student regardless of their future orientation. Some of the EMTRAIC participants may be requested to choose this project.

The students will be supervised by a senior physicist of the COMPASS team visiting IRFM for the whole week together with 3 experienced physicists of IRFM.

- 7- TOKAMAK EXPERIMENT: GOLEM.

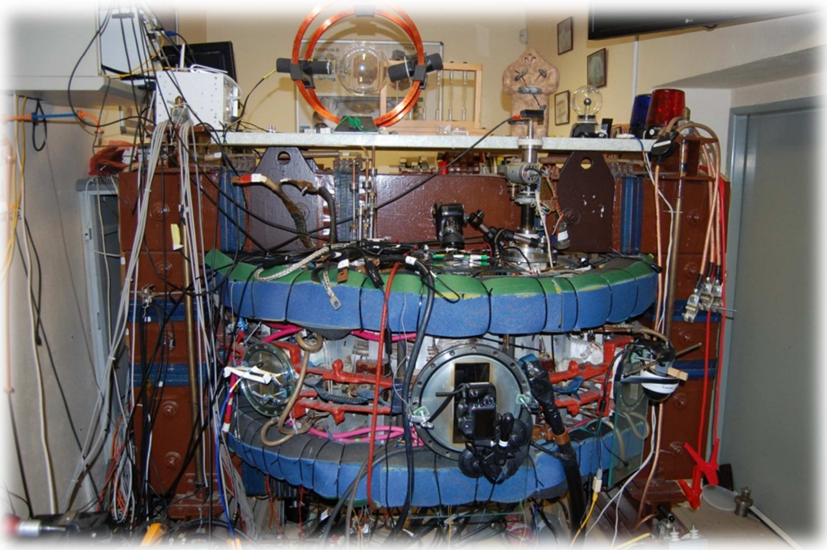
GOLEM is one of the very first tokamaks and the oldest tokamak in operation in the world. It stands in the Czech Technical University (CTU) in Prague.

GOLEM was installed, commissioned and is continuously upgraded by Vojtech Svoboda with the aim of training students and young physicists interested in thermonuclear fusion research. This is done both by allowing CTU students to develop new systems or diagnostics and by organising remote experiments with groups in various places around the world [V. Svoboda et al., Fusion Eng. Design 86 (2011) 1310-1314].

After an introductory lecture about the tokamak and its diagnostics, the pairs of students will have to devise methods to determine the main plasma parameters using the available measurements. Then they will choose a theme of study, elaborate an experimental plan and perform the corresponding experiments (remotely!) for about one day (or possibly two half-days). The preliminary data analysis during the experiments will be followed by a more accurate analysis. The results will be summarised in a short written document of about 4 pages.

This hands-on work is proposed only on the first week of the hands-on projects. It is a unique opportunity to get involved in a tokamak experiment at the very heart of operation. It is open to every student regardless of their future orientation.

The students will be supervised by 3 experienced physicists. The GOLEM project leader will be visiting us at the beginning of the work. He will operate the machine the second part



The tokamak GOLEM.

- 8 - Tore Supra experimental data analysis. scaling of the energy confinement time with plasma parameters

The project aims at 2 main goals:

- illustrating how plasma performances are investigated experimentally to find empirical scalings
- giving some insight into the measurement techniques that are required for that, the interpretation of raw data, and the necessary consistency check.

The example that is chosen is that of the dependencies ofe time (τ_E) with plasma parameters, in particular the dependence with the electron density. The experimental data obtained in various plasma scenarios on Tore Supra is used. Students have the opportunity to work with real experimental data. They have to derive the dependencies from the raw data. Emphasis is put on the measurements that are required to determine the relevant physics parameters, and on the interpretation and consistency of the data sets. The objective is that the students bring their own thinking into the subject, the analysis of the energy confinement regimes being only a guide line.

Background

τ_E is controlled by plasma parameters as plasma current, electron density or level of additionally injected power. The 'Neo-Alcator' confinement law predicts a dependence of the energy confinement time with the electron density in ohmic heated plasmas, $\tau_E \propto \bar{n}aR^2$:

- Linear Ohmic Confinement (LOC mode) at low electron density
- Saturated Ohmic Confinement (SOC mode) at higher density.

The analysis proposed here is intended first to explore the energy confinement time in ohmic regimes in Tore Supra, and determine the density at which the transition LOC/SOC occurs. The dependences of τE in additionaly heated plasmas, and with plasma current.will then be analysed. One of the goals is to use different diagnostics to check the consistency of the measurements.

Schedule

Day 1: introduction to tokamak plasma operation & diagnostics techniques, detailed subject/ focus, start learning how to access data

Day 2 & 3: Data analysis in control room

Day 4 : Preparation of oral presentation.

- 9 - Numerical Models

Objectives:

- Analytical studies and use of reduced numerical models (from 0 to 2D in phase space, either toy models or derived from 1st principles)
- Physics of resonances, of non-linearities and of chaos; dynamics of turbulent transport and self-organization
- Related modules (for Master 'Sciences de la Fusion'): FCM-3, FCM-4 & FCM-5

Means:

- Analytic calculations
- Numerical simulations on local servers (Fortran 90 and/or Matlab/Python languages)

Practical work:

- Analytic study of the reduced model properties
- Understanding of numerical methods
- Performing numerical simulations (from a few seconds to a few minutes)
- Studying numerical results (Matlab/Python programming)
- Comparison to theoretical predictions

4 proposed models:

1. Landau damping & collisions: 2D Vlasov-Poisson model f(x,v,t):
2. 2D model for bump-on-tail instability: linear and quasi-linear properties
3. Transition towards chaos: Chirikov parameter, Poincaré cross-section, etc.
4. Sand pile as a model for turbulent transport: avalanches and transport barriers

- 10- Integrated tokamak modelling:

initiation with the SPOT orbit following Monte Carlo code.

The purpose of this subject is to get a foretaste of simulation techniques for Physics research. The work plan is organized in three parts, including 1) an introduction to the context and motivation of integrated modelling; 2) basics of Monte Carlo techniques and numerical methods for simulating fusion-born alpha particles; 3) exercises around the SPOT Monte Carlo code in order to construct a complete Monte Carlo solver for evaluating the transfer of fusion power to the plasma bulk for ITER.

Since this subject is proposed for the first time, evaluating a realistic daily work plan is a bit tricky. For this reason, the exercises will be adjusted according to the efficiency of the students, i.e. the solution for some Physics or numeric issues may be brought in order to complete the Monte Carlo solver by the end of the week.

1. Context of integrated modelling:
    a. Brief reminder of tokamak magnetic device and fusion processes
    b. Transport solvers: towards simulating a complete plasma discharge
    c. Modules: physics codes for simulating a specific physics process
    d. Example: the SPOT Monte Carlo code for simulating fast ions in the plasma
    e. Integrated Tokamak Modelling : SPOT in this context, present status and perspectives
2. Numerical methods for orbit following Monte Carlo codes:
    a. The Monte Carlo technique
    b. Generating a source of alpha particles
    c. The trajectory equations
    d. The Runge-Kutta integration for orbit following
    e. The Monte Carlo operator for collisions
    f. General structure (flowchart) of the code with its time/particle loops.
    g. Particle administration (optional)
    h. Optimization: collision acceleration & energy reweighting (optional)
3. Construction of a Monte Carlo solver for alpha particles:
    a. To generate 100 new-born alpha particles from the D-T fusion reactions using the Monte Carlo technique: to evaluate their initial position, velocity, pitch angle
    b. To compute the trajectory equations and the Runge Kutta integrator
    c. To construct the time and particle loops for computing full orbits / trajectories
    d. To add a Monte Carlo operator for simulating the collisions between alpha particles and the thermal plasma (electrons and ions from the bulk)
    e. To construct two vectors for storing the fusion power and the power transferred to the bulk
    f. To export the results to a file for external display and verification

Involved computing environment and languages: Unix, Fortran 95, Matlab.