Hands-on project : Experiment on GOLEM

1. What is GOLEM?

GOLEM is one of the very first tokamaks and the oldest tokamak in operation in the world. It started its carreer as TM1 at the Kurchatov Institute in Moscow in the early 60's. It was moved to the Prague Institute of Plasma Physics in 1977, where it was operated under the name of CASTOR until 2006. It was then moved again to the Czech Technical University (CTU) in Prague where it was renamed GOLEM, a parabolic reference to a legend about a powerful creature made by a rabbine in Prague in order to serve and protect the Jewish community.

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 for GOLEM and by organising remote experiments with groups in various places around the world [V. Svoboda et al., Fusion Eng. Design 86 (2011) 1310-1314].

1.1. Characteristics of the tokamak

The main parameters of GOLEM are listed in the table below:

Plasma major radius	40 cm
Plasma minor radius	8.5 cm
Max. toroidal field	0.8 T
Max. plasma current	10 kA
Typical plasma duration	15 ms
Working gas	H_2

The plasma cross section is circular.

The vacuum vessel is made of stainless steel. It is usually baked with a series of cycles at 200°C before an experiment and is operated at room temperature.

As an example of the recent developments, the machine has been equipped with a high temperature superconducting poloidal coil, which is still in test.

With the provision that a responsible officer be in the tokamak surroundings for reliability and safety reasons, operation of the tokamak can be performed entirely remotely. This can be done either via a web interface or by secured access to the local linux server which controls the machine. The high repetition rate allows to perform a discharge every 2-3 mn.

1.2. Adjustable parameters

The hydrogen pressure in the vessel is monitored with the help of a pressure gauge.

The other parameters which can be adjusted are:

- the toroidal field on the axis B_{Tor};
- the electric field at the breakdown E_{BD};
- the electric field during the discharge E_{CD};
- and the vertical magnetic field B_{ST} which allows horizontal stabilisation of the plasma.

Each of these quantities is controlled through a capacitor bank supplied with an adjustable voltage (denoted U_{Tor}, U_{BD}, U_{CD} and U_{ST} resp.).

In addition to these physical quantities, it is possible to set a delay between U_{BD}, U_{CD}, and U_{ST} (i.e. E_{BD}, E_{CD}, and B_{ST}) and U_{Tor} (i.e. the toroidal magnetic field) onset.

1.3. Diagnostics and measurements

• GOLEM is equipped with a set of coils for magnetic measurements:
- a coil around the transformer core for the loop voltage measurement;
- a Rogowski coil around the vessel for the total current measurement $I_{tot} = I_P + I_{chamber}$;
- a flux loop around the vessel in a poloidal section for the toroidal field measurement;
- 4 Mirnov coils in a poloidal section inside the vessel for local magnetic field measurements.

• A photodiode viewing a poloidal slice of the plasma through a midplane port window measures (in relative units) the visible radiation intensity.

• A fast camera can be mounted behind a window for imaging of a poloidal slice of the plasma.

• A set of 20 aligned AXUV detectors (bolometers) for measurements of the radiated power profile.

The measurements are stored in a database and can be read using the linux server. A pulse summary with the main plasma parameters is also displayed on the experiment webpage.

2. How to determine the main plasma physical quantities from the measurements?

2.1. Total current

It can be deduced from the Rogowski coil measurements with 3 operations: offset subtraction, time integration and multiplication by a calibration factor $C_I = 5000$. The offset is the bias of the coil before the plasma starts.

→ You will have to explain every step of the calculation of the total current from the Rogowski coil measurement.

2.2. Plasma current

Due to the fact that the vessel is metallic, the current induced in the tranformer after the breakdown flows both through the plasma and through the vessel.

→ How can the plasma current be deduced from the total current and the other available quantities?

→ You will also determine the plasma resistivity.

2.3. Toroidal magnetic field

→ Using the same principle as for the total current and replacing U^R with the appropriate voltage and C_I with $C_B = 170$, you will determine the toroidal magnetic field.

2.4. Injected power

→ You will deduce the injected power from the physical quantities determined above.

2.5. Electron temperature

The total plasma current is the integral of the plasma current density over a poloidal section of the plasma. From the Ohm's law using the conductivity, the plasma current can be written:

$$I_P = \int_{section} j.dS = \int_0^a \sigma_{//} E_{ind} .2\pi r.dr$$

An expression of the parallel conductivity can be found in [J. Wesson, Tokamaks, Oxford Science Publications, 3rd edition (2004), Section 2.16], from which we deduce:

$$I_P = 1.13 \times 10^3 \times \frac{U_{loop}}{2\pi R_0} \frac{1}{Z_{eff}} \int_0^a T_e(r)^{3/2} 2\pi r.dr$$

where I_P is in A, U_{loop} in V, T_e in eV and the induced electric field has been expressed as a function of the loop voltage. Note that, due to the lack of information about the local electric field, we assume here a uniform electric field.
→ Using the appropriate assumptions, you will determine the central temperature (in eV) as a function of the measured quantities (in SI units).

2.6. Electron density

As there is no specific diagnostic for density measurements, we will assume that the gas injected in the vessel prior to the discharge is not adsorbed in the vessel wall, and that it is completely ionised (this can be justified a posteriori by the high value of the central temperature compared with the H ionisation potential).
→ Determine the electron density using the appropriate assumptions

2.7. Safety factor

→ Using the definition of the safety factor and recalling the appropriate Maxwell's equations, you will calculate the safety factor at the last closed flux surface.

2.8. Plasma energy content

The plasma energy content can be determined using the quantities estimated above. It can also be determined entirely from the magnetic measurements (using the pressure equilibrium equation and the Ampère's law).
→ You will compare the values obtained with each method and comment on the results.

3. What will your objectives be?

GOLEM with its remote control capability is a unique opportunity for students to apply their academic knowledge of the tokamak principles to a real situation. Below we make a few suggestions. Apart from the first step, you can pick up whatever ideas seem interesting to you or design your own experiment. Remember that a measurement without the associated uncertainty is meaningless.

3.1. As the plasma current plays an important role, you will have to follow the method indicated in §2.2 :
- first, determine the vacuum vessel resistivity and inductance using discharges without plasma;
- then, use these values to determine the plasma current in the discharges with plasma.

3.2. The experimental set-up is particularly suited for optimisation of the main plasma parameters: plasma duration, electron density and temperature, plasma current, radiated fraction,, loop voltage, effective charge... Decide which set of these quantities you choose to maximise or minimise. By exploring the accessible range of the chosen quantities, you will help define the operational domain of GOLEM.

3.3. When you get to a reasonable understanding of the relationship between the plasma quantities and the adjustable voltages, you can also try to optimise the discharge more globally (e.g. maximise the pressure, the total injected energy, confinement time, the radiated power fraction...). Again, choose which quantity you will try to optimise and explain how it will be determined (if it is not directly accessible from the measurements).

3.4. Afterwards, you can use the experiments you have performed to compare the plasma behaviour in GOLEM with the so-called Neo-Alcator confinement scaling law [Goldston, Plasma Phys. Control. Fusion 26 (1984) 87]:

$$\tau_E = 7.1 \times 10^{22} \bar{n}_e a^{1.04} R^{2.04} \sqrt{q_a} \, .$$

4. How will you reach the objectives?

When you have set the objectives of the experiment (or at the same time), you must make a discharge plan: the number of discharges you plan to perform for each objective, the parameters which will be varied, their range. You can also schedule breaks in order to look at the data and analyse them before taking the next step.

NB: In order to minimise the uncertainties, the measurements indicated in 2.2 require to perform a series of discharges. You can try with 5 discharges and assess the expected gain with more discharges.