Hands-on project : Experiment on GOLEM - 2020

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Preamble

This document was initially composed for students having some experience in basic tokamak physics and experiments. It aimed at helping them to relate their academic lectures to a real tokamak environment and particularly the GOLEM environment. It has been adapted to suit better the participants of the ASPNF School in Bangkok.

A short description of GOLEM is given in part 1 and a list of questions is given in part 2. You will see that answers are given directly below the questions. Nevertheless, you will learn much by thinking of the question before looking at the answer! For those who did not have a specific course on tokamak physics, the vocabulary and the ideas may be new. We will have some time during the School for group discussions on this document and on GOLEM experiments.

Although we took some care preparing this document, you may find mistakes or typos. You are welcome to indicate them to the coordinators of your discussion group.

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

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 (U_{loop}) measurement;
- a Rogowski coil around the vessel for the total current measurement $I_{tot} = I_P + I_V$;
- a flux loop around the vessel in a poloidal section for the toroidal field measurement: $U_B \alpha dB/dt$;
- 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.
- Note that the diagnostics are maintained by students who work on them only part time. As a consequence, the only measurements which are always available are those of the magnetics.

The measurements are stored in a database. A pulse summary with the main plasma parameters is displayed on the experiment webpage. The data can also be retrieved as files for further analysis.

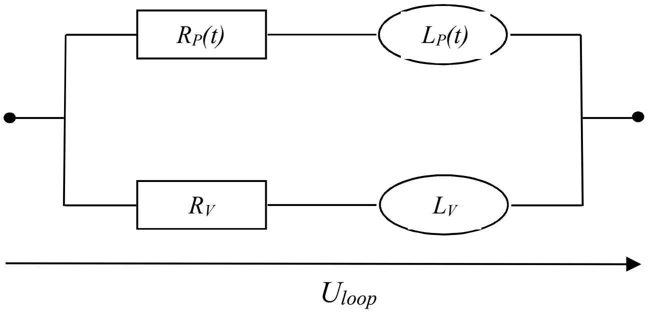
2. How to determine the main plasma physical quantities from the measurements?

2.1. Total current

The total current can be read on the GOLEM results page.

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. The system can be seen as the following electrical circuit:



where the plasma and the vessel are in parallel. On this sketch, the upper branch represents the plasma and the lower branch represents the vessel. $R_P(t)$ and R_V are the plasma and vessel resistivities and $L_P(t)$ and L_V are the plasma and vessel inductances respectively. R_V and L_V are characteristic of the vessel and thus independent of time. Note that the loop voltage $U_{loop}(t)$ is measured directly.

→ Write down the circuit equations i.e. the expressions of $U_{loop}(t)$ and $I_{total}(t)$.

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

→ Using Ohm's law (https://en.wikipedia.org/wiki/Ohm%27s_law) applied only to the plasma branch, you will also determine the plasma resistivity (in Ω.m).

2.3. Toroidal magnetic field

The toroidal magnetic field can be read on the GOLEM results page.

2.4. Injected power

In GOLEM, the only power injected to the plasma is by Joule effect (https://en.wikipedia.org/wiki/Joule_heating): as in every electrical conductor, the plasma current and loop voltage are partly converted into heat. Do you remember $P = RI^2 = UI$?

→ Using this formula and adapting it to the present situation, 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 j over a poloidal section of the plasma:

$$I_P = \int_{Section} \vec{j}.d\vec{S}$$

The local form of Ohm's law gives us:

$$j_{//} = \sigma_{//} E_{ind}$$

where $\sigma_{//}$ is the plasma parallel conductivity (meaning the component parallel to the magnetic field) and E_{ind} the electric field component in the plasma current direction.

By replacing this expression of $j_{//}$ in the expression of I_P, we find that the plasma current can also be written in the following way:

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

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).

The temperature profile $T_e(r)$ is not measured in GOLEM. We will assume a polynomial form:

$$T_e(r) = T_{e,0}\left(1 - \frac{r^2}{a^2}\right)^2 .$$

The only quantity which is not measured is the central temperature $T_{e,0}$.

→ Using the expressions of I_P and $T_e(r)$, you will determine the central temperature (in eV) as a function of the measured quantities (in SI units).

2.6. Electron density

As the diagnostic for density measurements (interferometer) is not always available and reliable, it can be useful to have another method to determine the plasma density.

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). In addition, we assume that the plasma is an ideal gas, so that the plasma ion (or electron) density is the same as the injected gas density.

→ Write the ideal gas law (https://en.wikipedia.org/wiki/Ideal_gas_law) and explain the physical quantities.

→ Determine the electron density using the appropriate assumptions.

→ Compare the experimental density value with the Greenwald density $n_{Gr} = \frac{I_P}{\pi a^2}$ (plasma current in MA, minor radius in m).

2.7. Safety factor

The safety factor (in general denoted q) is the number of toroidal turns of a field line necessary to complete one poloidal turn. Any two field lines on the same magnetic surface have the same safety factor, so q is defined for each magnetic surface. In the large aspect ratio approximation, the safety factor can be expressed as:

$$q(r) = \frac{rB_{Tor}(r)}{RB_{pol}(r)}$$

In this expression, r is the minor radius of the magnetic surface, $B_{Tor}(r)$ and $B_{Pol}(r)$ are the toroidal and poloidal magnetic fields averaged over the magnetic surface, R is the major radius of the considered surface. The only unknown in this expression is $B_{Pol}(r)$. All the other quantities are measured.

→ Reminder on Ampère's law (https://en.wikipedia.org/wiki/Amp%C3%A8re%27s_circuital_law): denoting *I(r)* the current flowing through an electrical conductor of radius r and $\vec{B}$ the magnetic field, recall the expression of Ampère's law. In this expression, an integral appears over a closed path. Explain the shape of this loop.

→ In order to determine $B_{Pol}(r)$, apply Ampère's law to the case of a tokamak plasma. In that case, *r* is the minor radius of the considered magnetic surface and the integral is over a loop of the same minor radius.

→ Using the previous results and the definition of the safety factor, calculate the safety factor at the last closed flux surface.

2.8. Plasma energy content

The plasma energy content can be determined using the temperature and density estimated above. You probably remember that in a gas, temperature is defined so that the average kinetic energy of a molecule is $\frac{3}{2}k_B T$ (https://en.wikipedia.org/wiki/Temperature).

In a plasma this must be refined. Instead of molecules, we have ions and electrons. In general they do not have the same temperature, so we define the electron temperature T_e and the ion temperature T_i. These temperatures are not uniform in the plasma but they are uniform on a magnetic surface, so we must consider their radial profiles $T_e(r)$ and $T_i(r)$.

→ What are the electron and ion energy densities on a magnetic surface of minor radius *r*?

→ How much energy is contained in a small volume *dV* around a magnetic surface of minor radius *r*?

→ What is the total kinetic energy content of the plasma?