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, which corresponds approximately to the first 450 measurement points:

$$U_{offset} = \frac{\sum_{i=1}^{450} U_i^R}{450}$$

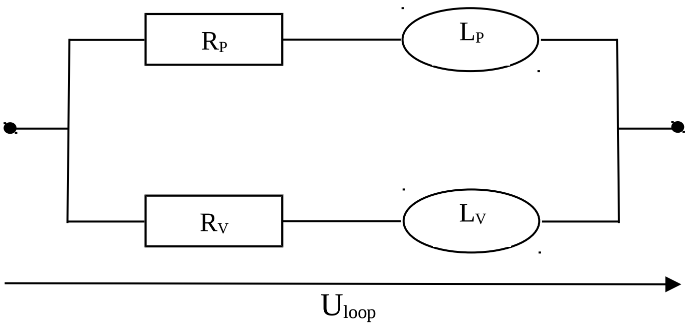
where U^R_i is the i^th^ measurement of the Rogowski coil.

The total current writes:

$$I_{total}(t) = C_I \int_0^t \left(U_i^R(t') - U_{offset} \right) dt' \approx C_I \left(\sum_{i=0}^{t/\Delta t} U_i^R(t)\Delta t - U_{offset} t \right)$$

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. In the equivalent electrical circuit, the plasma and the vessel are in parallel:



where R_P and R_V are the plasma and the vessel resistivities and L_P and L_V are the plasma and the vessel inductances. R_V and L_V are characteristic of the vessel and thus independent of time. Note that the loop voltage U_{loop} is measured directly.
The circuit equations are:

$$\begin{aligned} &U_{loop}(t) = R_V I_V(t) + L_V \frac{dI_V}{dt} = R_P(t) I_P(t) + L_P(t) \frac{dI_P}{dt}(t) \\ &I_{tot}(t) = I_V(t) + I_P(t) \end{aligned} .$$

It is possible to perform discharges without plasma (e.g. with no gas injected into the vessel). In such discharges, $I_{tot} = I_V$. Therefore, I_{tot} and U_{loop} being known, R_V and L_V can be determined.

In subsequent discharges with plasma, I_V can then be deduced from U_{loop} and subtracted from I_{tot} to obtain I_P.

Once I_P is known, the plasma resistivity $R_P \times 2\pi R_0$ (R_0 being the major radius) can be obtained using the relation:

$$R_P(t) = \frac{U_{loop}(t)}{I_P(t)}$$

2.3. Toroidal magnetic field

Same principle as for the total current, replacing U^R with the appropriate voltage and C_I with $C_B = 170$.

2.4. Injected power

The only way to provide power to the plasma is by ohmic heating, so the injected power is:

$$P_{inj}(t) = P_\Omega(t) = U_{loop}(t) I_P(t) = R_P(t) I_P(t)^2$$

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.

Assuming that the radial temperature profile is a polynome of the following form:

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

the integral can be calculated and we obtain the central temperature (in eV) as a function of the measured quantities (in SI units):

$$T_{e,0} = \left(\frac{8}{1.13\times10^3}\frac{R_0}{a^2}Z_{eff}\frac{I_P}{U_{loop}}\right)^{2/3} .$$

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). 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. The average density is obtained from the ideal gas law:

$$n_{e,av} = \frac{p_{vessel}}{kT_{vessel}}$$

where p_{vessel} and T_{vessel} are the pressure and the temperature in the vacuum vessel before the discharge.

Note that this does not take into account the impurity contribution. For a given gas pressure, a mixture of hydrogen with other gasses will likely produce more electrons than pure hydrogen, since an impurity atom will provide at least (and in general more than) one electron. The plasma density calculated as above is thus underestimated.

NB: Assuming a parabolic density profile of the form $n_e(r) = n_{e,0}\left(1-\frac{r^2}{a^2}\right)$, it is easy to calculate the relation between $n_{e,av}$ and $n_{e,0}$: $n_{e,av} = \frac{n_{e,0}}{4}$.

2.7. Safety factor

In the large aspect ratio approximation, the safety factor can be expressed as:

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

where B_{pol} is unknown. Let us apply Ampère's law to a closed poloidal loop encircling the magnetic axis at a distance r:

$$\mu_0 I(r) = \oint B.dl = \oint B_{pol}.dl = 2\pi rB_{pol}(r) \quad ,$$

where I(r) is the plasma current enclosed by the loop. We can now express q(r) replacing B_{pol} with its expression as a function of I(r):

$$q(r) = \frac{2\pi r^2 B_{Tor}}{\mu_0 I(r) R} .$$

The edge safety factor: $q_a = \frac{2\pi a^2 B_{Tor}}{\mu_0 I_P R}$ is of particular importance in tokamak experiments since it plays an important role in the MHD stability.

2.8. Plasma energy content

The average kinetic energy of a single particle is kT (T_e for an electron, T_i for an ion). The total plasma energy can thus be approximated by:

$$W_k = \int_{V_P} n(kT_e + kT_i)dV \approx 2\int_{V_P} n_e kT_e dV$$ (with n = n_e = n_i and assuming $T_i \approx T_e$)

With the same polynomial forms as above for the density and temperature profiles, the plasma energy writes:

$$W_k(t) \approx \pi^2 a^2 R n_{e,0}(t) kT_{e,0}(t) \ .$$

with W_k and $kT_{e,0}$ in J and $n_{e,0}$ in m^{-3}.

There is also a way to determine the plasma energy content from the magnetic measurements using the pressure equilibrium equation and the Ampère's law.

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]:

$$\tau_E = 7.1\times10^{22}\,\overline{n}_e a^{1.04} R^{2.04}\sqrt{q_a} \ .$$

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.