Study of the toroidal magnetic foeld voltage and the current drive voltage in GOLEM tokamak

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Abstract

We present results of the remote experiment performed on the GOLEM tokamak in the frame of the Cadarache Winter event 2021. Impact of engineering parameters such as the charging voltage of condenser banks for generation of the Toroidal magnetic field and the Current in the primary winding of the GOLEM transformer was studied. In particular, we focus on the plasma breakdown and on shot duration.

1. Introduction

A tokamak is a device which uses magnetic field to confine plasma in the shape of a torus. The GOLEM[1] tokamak is located at the **F**aculty of **N**uclear **P**hysics and **P**hysical **E**ngineering (**FNPPE**), Czech Technical University in Prague. It was manufactured in the Soviet Union as *small tokamak n°1* and then moved to the **I**nstitute of **P**lasma **P**hysics (**IPP**[2]) as TM-1 MH in 1977. Today, the tokamak is primarily an educational device who can be controlled remotely via an internet interface. This peculiarity earned this device the name of *the smallest tokamak with the biggest control room*. It is a small tokamak with major radius $R = 0.4$ m and minor radius of the vacuum vessel $b = 0.1$ m[3]. It has been used in several works such as to study runaway electron measured from X-rays[4]. The breakdown regime is the initial phase of the tokamak plasma discharge. It is defined by a low rate of ionization and low plasma current. Experiment work for study the breakdown phase in the GOLEM tokamak has been done previously by Y.SIUSKO *et al.* to investigate the impact on plasma performance affected from breakdown voltage and the time delay between the trigger of the toroidal magnetic field B_t and the trigger of toroidal electric field E_t. The best plasma performance on GOLEM can be achieved by the lowest time delay. This work investigated breakdown phase when chamber pressure is varied. The report is organized as follows: In section 2, the experimental set-up of the GOLEM tokamak is presented. Section 3 discusses on the plasma parameters profile resulting from the pressure, current drive and toroidal magnetic field voltage. Section 4 discusses on the discharge duration. The summary is given in section 5.

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2. Experimental set-up

The GOLEM tokamak was a small tokamak with a circular cross section. Now it operates as a device for research and education. It has a major radius of 0.4 m and minor radius of 0.1 m. Material for vacuum vessel for GOLEM is stainless steel. The main parameters of tokamak GOLEM are shown in table 1. In this experiment, Hydrogen is used for the working gas. To generate free electrons inside the tokamak vessel, pre-ionization is made by using a tungsten filament. By applying current in the primary winding of the tokamak transformer, the pre-ionization electrons are accelerated by the toroidal electric field $E_t = U_{loop}/2\pi R$, where U_{loop} is the loop voltage. The working gas is ionized by these high energy electrons resulting the secondary electron. Consequently, the secondary electron is accelerated and ionizes a neutral atom of H_2. This mechanism allows the breakdown of the a gas and the vessel is filled by fully ionized plasma. Mainly this work studies the dependence of discharge duration on the working gas pressure, toroidal magnetic field (B_t) and the electric field are controlled through the capacitor bank supplied with an adjustable voltage U_{Bt} which can be varied from 500-1200 V and U_{CD}, in a range of 400-700 V.

For our study, we need to have the value of the plasma current inside the tokamak. We can represent our system as an electrical circuit where the plasma and the vessel are in parallel and represented by a couple of a resistance and an inductor. U_{loop} is the tension of this circuit.

The circuit equations are:

$$U_{loop}(t) = R_{vessel}I_{vessel} + L_{vessel}(\frac{dI_{vessel}}{dt}) \qquad (1)$$

$$U_{loop}(t) = R_{plasma}I_{plasma} + L_{plasma}(\frac{dI_{plasma}}{dt}) \qquad (2)$$

where R_{vessel} and R_{plasma} are the vessel/plasma resistivities. L_{vessel} and L_{plasma} are the vessel/plasma inductances.

Table 1: Main parameters of tokamak GOLEM

Plasma minor radius	$a \approx 0.06$ m
Toroidal magnetic field	$B_t < 0.5$ T
Plasma current	$I_p < 8$ kA
Central electron density	$n_e \approx (0.2$ - $3) \cdot 10^{19}\ m^{-3}$
Effective ion charge	$Z_{eff} \approx 2.5$
Electron temperature	$T_e < 100$ eV
Discharge duration	$\tau_p < 25$ ms
Energy confinement time	$\tau_e < 50\ \mu s$

By performing a discharge without plasma, we can measure the total current with a Rogowski coil and deduce the value of $I_{vessel} = I_{total}$, and the value of U_{loop}. Those measurements are sufficient to deduce L_{vessel} and R_{vessel} which are characteristics of the vessel. We can now perform a discharge, deduce I_{vessel} from U_{loop} and obtain the plasma current using:

$$I_{total} = I_{vessel} + I_{plasma} \tag{3}$$

There are several systems, which consist of magnetic diagnostics, a visible spectrometer, a microwave interferometer, hard X-ray (HXR) sensor, an array of bolometers and a fast camera for pictures of the visible emission[5; 6]. However, only the most important diagnostics were operational during the described remote experimentation.

3. Experimental results

3.1. Preselected discharge parameter

The temporal evolution of main plasma parameters measured by the set of basic diagnostics of GOLEM is shown in Fig. 1.

The power supply of the toroidal magnetic field winding is switched on at $t = 0$ ms, and B_t starts to increase as $\sim sin\ t$. After a time delay, the power supply of the tokamak primary winding is switched on. This time delay can be presented prior the discharge, however in our case, this time delay is fixed to 1 ms.

The toroidal current is measured on GOLEM by a Rogowski coil surrounding the tokamak chamber.

The initial plasma discharge can be separated to three phases, breakdown, plasma formation and current rise. In the breakdown phase, the rate of ionization and the plasma current, which is proportional to the electron density, is very low, see Fig.2. The plasma breakdown is characterized by an abrupt drop of the loop voltage and a sharp increase of the plasma current in the tokamak due to the avalanche effect. At the breakdown, the plasma resistivity drops below the resistivity of the vacuum vessel, so it

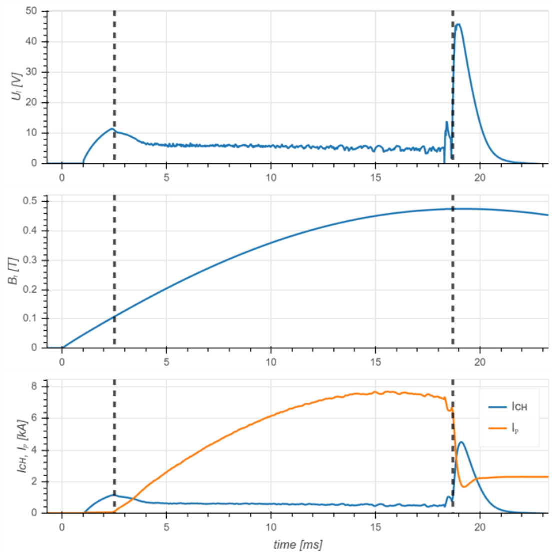

Figure 1: Evolution of the main plasma parameter (#35551). From top to bottom: U_l is loop voltage; B_t is toroidal magnetic field and I_p is plasma current.

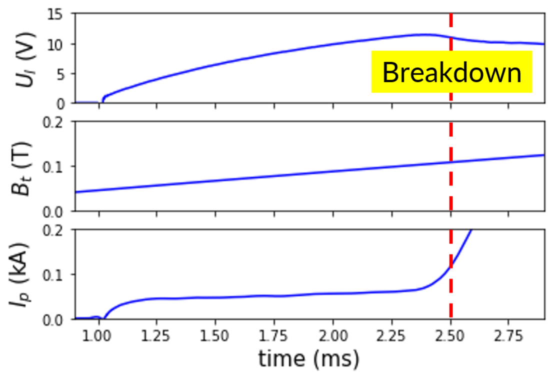

Figure 2: Zoomed plot of the main plasma parameter #35551.

became much lower to the vessel resistivity. And because we have the relation:

$$R_{vessel} + R_{plasma} \approx R_{vessel} = \frac{U_{loop}}{I_{chamber}} \tag{4}$$

Note that the plasma current inside the chamber increases during the avalanche phase, it explains the small dump of U_{loop} at the breakdown. The dotted line corresponds to the Breakdown.

3.2. Pressure scan

From the results of pre-ionization, the pressure in the chamber is the first parameter we will study its effect on the breakdown voltage.

The breakdown voltage by varying the pressure is shown in Fig.3. We can observe two phenomena. First, we see that the breakdown voltage increases with the pressure

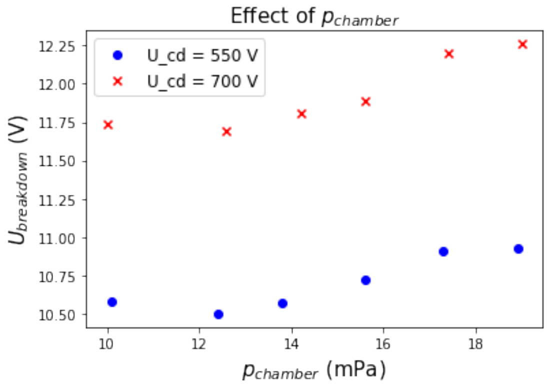

Figure 3: Plot of the effect of the gas pressure (from which the plasma is formed) on the breakdown voltage. For two different values of the current drive voltage U_{CD}.

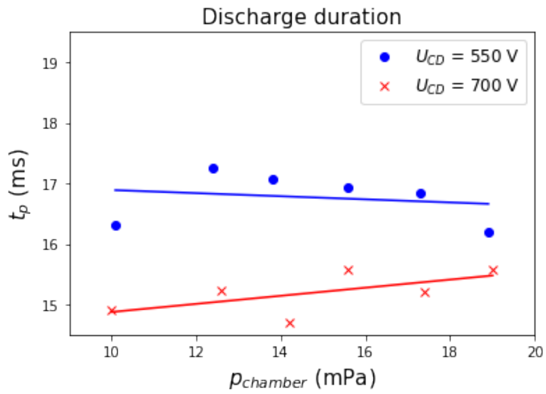

Figure 4: Duration of the discharge versus the working gas pressure for two different values of the current drive voltage U_{CD}. The toroidal field voltage $U_{Bt} = 1200\ V$.

of the working gas. We can explain this behavior by the Paschen law:

$$E = \frac{Bp}{\ln(Apd) - C} \tag{5}$$

where $C = \ln(\ln(1 + \frac{1}{\gamma}))$. E corresponds to the breakdown voltage, p to the pressure, γ is the secondary electron emission coefficient, A and B are constants which are determined experimentally. We observe that our results are in agreement with this law, indeed we observe a small dump of the curve up to a value of $p_{chamber} \approx 12$ mPa, then a quasi-linear increase of the curve. This behavior is the same for any charging voltage U_{CD}.

The discharge duration dependence by varying the pressure is shown in Fig.4. We only observe very weak dependence between the working gas pressure and the duration of a discharge. Those results are similar to the ones of the another article [3] who also studied the impact of the gas pressure on the discharge duration on GOLEM.

However, a longer discharge is observed at $U_{CD} = 550\ V$.

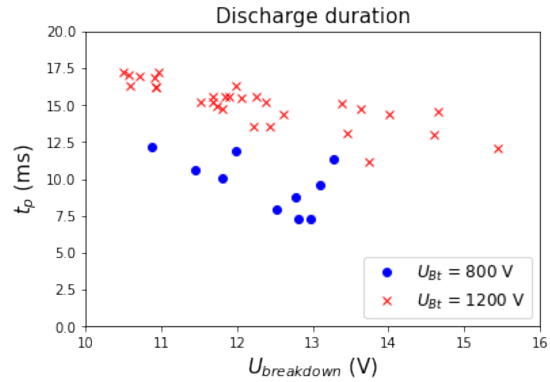

Figure 5: The discharge duration when U_{Bt} = 800, 1200 V.

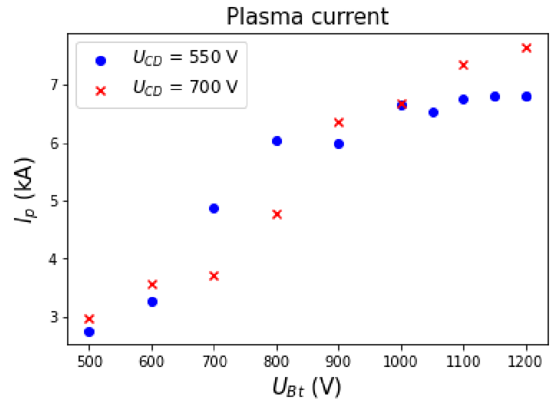

Figure 6: The maximum plasma current versus the toroidal magnetic field voltage U_{Bt} for U_{CD} = 550, 700 V, and pressure $p_{chamber}$ = 20 mPa.

3.3. Toroidal magnetic field scan

This part investigates the effect of the toroidal magnetic field voltage on plasma discharge duration and the plasma current. The discharge duration with the U_{Bt} varied is shown in Fig.5. We clearly see that the discharge duration increases with increasing of U_{Bt}. When the breakdown voltage is more than 10 V, the discharge duration has a much wider spread and has unpredictable values. This duration limit is similar to the experiment investigated by Vojtech in [3].

Fig.6. shows effect of U_{Bt} on the maximum plasma current I_p, which can be reached during the discharge. Considering in case of 500-900 V of U_{Bt}, the plasma current is dramatically increase and becomes saturation.

3.4. Current drive scan

This part investigates the effect of the current drive voltage on the discharge duration and the Ohmic heating power. The toroidal magnetic field is constant by fixing U_{Bt} at 1200 V. The pressure is pre-programmed to be 20 mPa. The electric field, induced by the U_{CD} ranges from

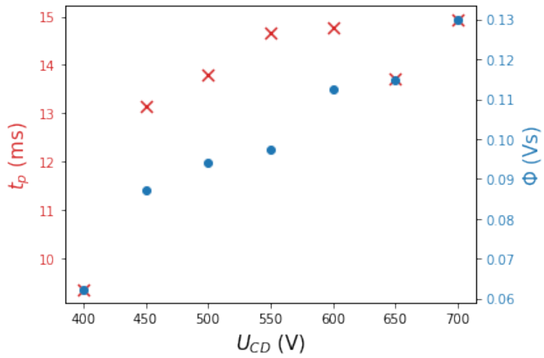

Figure 7: The discharge duration (in red) and the magnetic flux (in blue) versus the current drive voltage U_{CD} for $U_{Bt} = 1200$ V, and pressure $p_{chamber} = 20$ mPa.

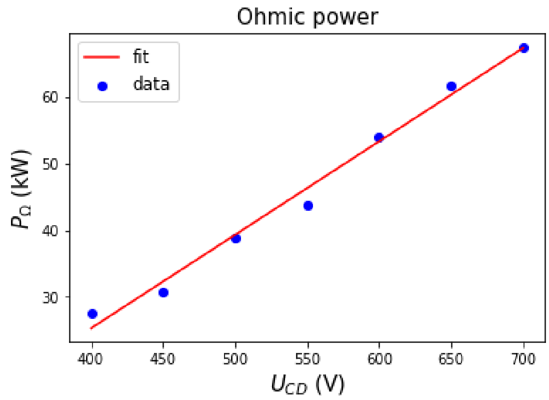

Figure 8: The Ohmic heating power versus the current drive voltage U_{CD} for $U_{Bt} = 1200$ V, and pressure $p_{chamber} = 20$ mPa.

400 to 700 V. The discharge duration with the U_{CD} varied is shown in Fig.7.

We see that the discharge duration increases with U_{CD} when of $U_{CD} \leq 550$ V and becomes saturated for higher U_{CD}.

In the same figure, we plot the maximum magnetic flux in the iron core transformer of GOLEM, which is engineering parameter limiting the discharge duration. The magnetic flux consumed by the transformer during a discharge is easily calculated from experimental data by integrating the loop voltage:

$$\Phi(T) = \int_0^T U_{loop}\, dt \qquad [Vs] \tag{6}$$

The engineering limit of the maximum magnetic flux is around $\Phi_{max} = 0.12$-$0.13\ Vs$ [3]. When the magnetic flux reaches limit, the tokamak transformer cannot transport anymore the power to plasma, and the discharge terminates.

Fig.7 shows that the magnetic flux consumed during this discharge series ranges from 0.06-0.13 Vs. Therefore, the plasma terminates by consumption of magnetic flux for $U_{CD} \geq \sim 600\ V$. For $U_{CD} < 500\ V$, discharges are terminated by another mechanism. One possibility is a large displacement of plasma column, or a drop of the edge safety factor $q(a)$ at the end of the discharge below a critical value. Unfortunately, neither displacement nor the safety factor were calculated during our experiment

The effect of the U_{CD} on Ohmic heating power is demonstrated in Fig.8. This work uses simple Ohmic law to calculate the Ohmic heating power as the product of the maximum plasma current and the mean loop voltage,

$$P_\Omega = I_{p,max} \cdot \overline{U}_{loop} \tag{7}$$

Evidently, Ohmic heating power is directly proportional to U_{CD}.

4. Conclusion

This work investigates plasma performance on the GOLEM tokamak.We have executed three systematic scans of engineering parameters of GOLEM.

• Scan over the filling pressure of the working gas (Hydrogen) in the range from 10 to 20 mPa.

• Scan over the charging voltage of the condenser bank for driving the plasma current U_{CD} in the range from 400 to 700 V.

• Scan over the charging voltage of the condenser bank for generation of the toroidal magnetic field U_{Bt} in the range from 500 to 1200 V. This systematic measurement was performed on GOLEM for the first time.

The plasma parameters which were compared in these scans are

1. The discharge duration. We found in the pressure scan that the discharge duration depend only weakly on the pressure. On the other hand, the longest discharges are achieved at the highest toroidal magnetic fields and a sufficiently high voltage applied to primary winding of tokamak transformer.
2. A shallow minimum of the breakdown voltage is observed around $p = 12$ mPa. Such optimum pressure for breakdown of the working gas is predicted by Paschen law, which is known from low temperature plasma physics.
3. The maximum plasma current as well as the Ohmic heating power proportional to U_{CD} as expected. However, we observe increase of the maximum plasma current at increasing toroidal magnetic field, which might be no so evident. We explain this feature by increase of discharge duration.

Finally, we conclude that the best plasma performance (highest plasma current > 8 kA, the maximum discharge duration about 17.5 ms) are achieved with engineering parameters $U_{Bt} = 1200\ V$, $p_{chamber} = 20$ mPa, and U_{CD} $\sim$550-700 V.

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