Maximum plasma current and effect on shot duration in GOLEM tokamak

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Abstract

Using a remote experimental setup on the GOLEM tokamak, a study of the maximum plasma current I_p is carried out. The effect of maximising the plasma current on the evolution of the shot duration is explored and physical interpretations to the different observed phenomena are presented.

Theoretical scaling laws are established to predict the correlation between the two quantities and their dependencies on the experiment parameters.

Experimental setup is described, the experimental data and manipulations done on them are detailed with the physical hypothesis made. Then a physical interpretation of the results is detailed with a focus on the effect of the maximum plasma current on the confinement, the heating and the stability of the plasma.

1. Introduction

The GOLEM tokamak in Prague, built in the 60s, is the oldest tokamak still in operation today. It is now mainly used for educational purpose and is connected to the internet so that people all over the world can do experiments and measurements on its plasmas via a web interface.

This report is primarily going to be a study of how to maximize the maximum plasma current I_p and why it is important to do so in a tokamak.

Importance of plasma current

The plasma current I_p in the toroidal direction is an important parameter of the tokamak discharge, its presence in the plasma is crucial to the confinement and heating.

In the GOLEM experiment, the toroidal current is generated by a transformer winding coils.

To better assess the importance of the plasma current, one can refer to the MHD equilibrium equation

$$\nabla p = \mathbf{j} \times \mathbf{B}$$

. With the most important contribution coming from the product of the toroidal current $j_\varphi = \frac{I_p}{\pi a^2}$ and the poloidal magnetic field $B_\theta = \mu_0 \frac{I_p}{2\pi a}$ (this formula coming from the Ampere theorem), the radial pressure gradient can be written as following

$$\frac{\partial p}{\partial r} \sim \mu_0 \frac{I_p^2}{2\pi^2 a^3}$$

The confinement requires large gradients of thermal pressure which is directly and strongly related to the plasma current.

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Of course, the current has limits to the values it can take. This limit is set by multiple things. First, the technological constraints on the transformer as it can only generate moderate electric fields. The plasma resistivity also plays a role in the generation of the poloidal electric current and limiting it. The most important limitation to the plasma current is probably the safety factor q. If the plasma current is increased indefinitely, the safety factor will take high values. Consequently, kink instabilities will arise, leading to magnetic islands and magnetic reconnection thus short circuiting the pressure gradients and degrading the confinement.

Parameters of the discharge

Using the remote control room of the GOLEM tokamak, a range of parameters is set by the user. These parameters are:

- The gas pressure in the experiment P, which changes the electron and ion density n_e and n_i.
- The current in the poloidal coils U_{Bt}, which creates the toroidal component of the magnetic field $\mathbf{B}$ that is used to confine the plasma discharge.
- The current in the primary transformer circuit U_{cd}, it is used to create an electric field in the toroidal direction leading to a toroidal plasma current and the creation of the poloidal component of the magnetic field $\mathbf{B}$.
- The option to activate an ionizing electron gun, which ionizes the plasma before the discharge take place. The electron gun consists in a broken light bulb which is a continuous source of electrons to help the start of the discharge.

- The delay between the activation of the current in the poloidal coils U_{Bt} and the current in the transformer circuit U_{cd}.

This report is first going study the operation of the machine and the data collecting process.

Then, the experimental data from the shots will be exploited and interpreted from a physical standpoint.

Finally, a conclusion is made on the maximization of the plasma current and the evolution of the discharge time with it.

2. Experiment & Data

Diagnostic tools

Multiple diagnostic tools were used in this experiment in order to harvest some measurable quantities of the plasma. The diagnostics used in this experiment were:

- the Rogowski coil, which is used to measure the intensity of the current inside the plasma I_p.
- the diamagnetic loop, which is used to measure the toroidal loop voltage.
- the toroidal magnetic field coil that measure the toroidal magnetic field component.

From those measurements, one can have an idea about the discharge and the different parameters governing it. For instance, the plasma current is obtained as following:

The voltage from the Rogowski coil in written as

$$V = \mu N A \dot{I}_{tot}$$

with μ the plasma magnetic permeability, N the number of turns per unit of length and A the coil cross section area[1]. With an integrator and with the right calibration, the total current is derived. Taking into account the current through the tokamak chamber, the plasma current is $I_p = I_{tot} - I_{chamber}$, with $I_{chamber} = \frac{U_{loop}}{R_{chamber}}$. The U_{loop} is taken from another diagnostic, whereas the chamber resistance has a given value for the GOLEM tokamak.

Experimental protocol

The goal was to maximize the plasma current I_p. To do so, and after a few discharges, a choice was made to study the effect of the time delay between the toroidal magnetic field and the toroidal electric field generation on the plasma current. While fixing the other parameters of the experiment, multiple discharges were made with a varying time delay.

The main campaign of measurement was done with $10mPa$ hydrogen working gas, with $U_{Bt} = 1200\ V$, $U_{cd} = 700\ V$, with preionization.

The other parameters such as the gas pressure and the toroidal magnetic field effects were explored briefly.

Once the discharges were done, a python script was used to extract the values from the GOLEM web interface for further analysis.

Measured plasma characteristics:

The measured values are directly available from the web interface. The values include the plasma duration ($\tau[ms]$), the mean and maximal values of the toroidal magnetic field (B_t[T]), Loop voltage (U_{loop}[V]), and plasma current (I_p[kA]). A measurement sample can be found in fig. 1.

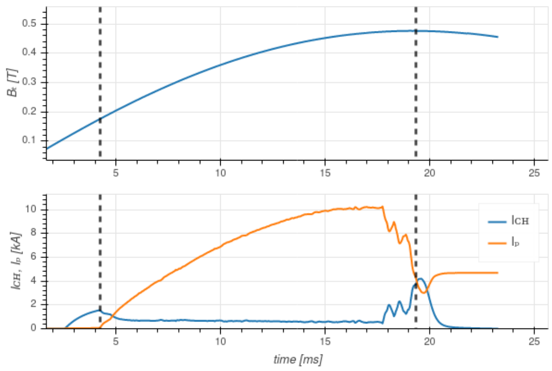

Figure 1: measurements of B_t and I_p over time. our study focused on the averages and maximums of these values.

Knowing the geometrical parameters of the tokamak, approximations of other properties of the plasma are then calculated:

Safety factor

An approximation of the mean and maximal poloidal magnetic field ($B_p[T] = \mu_0 \frac{I_p}{\pi a^2}$) was then calculated, where a is an approximation of the poloidal radius of the plasma inside the tokamak (in this case, it is the radius until the limiter).

This was then used to obtain the safety factor of the fields averages ($q = \frac{a}{R}\frac{B_{t\ mean}}{B_{p\ mean}}$), and "maximal" safety factor ($q = \frac{a}{R}\frac{B_{t\ max}}{B_{p\ max}}$). It is to be noted that these safety factors are virtual: the fields vary greatly during the discharge and ignoring the time dependence will only give a crude approximation of real life results.

The value of the safety factor is a good indication on the stability of the plasma. The smaller the safety factor, the more stable the plasma is predicted to be.

Electron temperature

One other quantity that can be important to estimate is the electron temperature T_e. For this estimation, the resistivity of the plasma is taken as the Spitzer parallel resistivity, without taking into account the neoclassical transport, $\eta_\perp = \frac{4\sqrt{2\pi}}{3}\frac{Ze^2\sqrt{m_e}\ln\Lambda}{(k_B T_e)^{3/2}}$, with $\ln\Lambda$ the Coulomb logarithm estimated for the GOLEM tokamak to be around 41. The plasma is modeled as a resistive material with a $2\pi R$ length and a πa^2 cross section, with a known resistance, which means that its resistance can be written as following $\mathcal{R} = \frac{U_{loop}}{I_p} = \frac{2\pi R}{\pi a^2}\eta_\perp$.

Given the previous equation, the electron temperature (in electronvolts) can be calculated with the following formula

$$T_e[eV] = \frac{1}{18^{1/3}\pi}\left(\frac{I_p}{U_{loop}}\right)^{2/3}\left(\frac{R}{a^2}\right)^{2/3}\frac{(em_e)^{1/3}}{(\varepsilon_0)^{4/3}}(\ln\Gamma)^{2/3}$$

The value of the electron temperature will be useful to see the efficiency of the plasma heating. It can also be used to calculate other plasma quantities such as the kinetic parallel energy and the Larmor radius.

3. Results and Exploitation

Impact of the delay on the plasma current

The importance of this delay in terms of maximizing the plasma magnetic field resides in letting the toroidal magnetic field get established before driving the plasma current. Yet, letting the toroidal magnetic field run alone for too long will drive the free charged particles to collide with the walls of the tokamak due to the drift velocities (which is ideally compensated by the poloidal magnetic field created by the toroidal plasma current).

Fewer electrons means a smaller electron cloud, this means a larger electric field needed to induce the breakdown and start the discharge, which means less energy transfered to the plasma current.

It is interesting to determine the order of magnitude of the drift velocity due to the toroidal magnetic field gradient. This drift velocity is written as following:

$$v_{\nabla \mathbf{B}} = \frac{\mathcal{E}_{K\perp}}{qB}\frac{\mathbf{B}\times\nabla B}{B^2}$$

, with $\mathcal{E}_{K\perp} = \frac{1}{2}mv_\perp^2$ the thermal energy in the direction of the magnetic field, which, in this calculation in orders of magnitude, will be taken as k_BT_e.

Taking into account only the toroidal magnetic field and estimating the gradient as a radial component equal to the magnetic field strength over the major radius $\nabla B = \frac{B}{R}\vec{e_r}$, the drift velocity in question can be written as $v_{\nabla \mathbf{B}} = \frac{k_BT_e}{e}\frac{B}{R}\vec{e_\theta}$. Given the typical values for the GOLEM tokamak, an estimate of this drift velocity is $v_{\nabla \mathbf{B}} \sim 50\ ms^{-1}$.

Given an electron starting its trajectory at the edge of the tokamak, it would need to cross a distance of $2a$ to reach the other edge and hit the wall of the tokamak and thus be lost from the plasma. This would provide an upper limit for the time delay after which it is reasonable to predict that most of the charged particles of the plasma have already hit the machine walls. With the brief physical argument and the extreme approximations made in this section, the time for a particle to hit a wall is $\tau_{wall} = \frac{2a}{v_{\nabla \mathbf{B}}} \sim 5\ ms$.

The value found for τ_{wall} is coherent with the results found in the experiment (Fig. 2). For the shots with preionization, and for a time delay over the calculated value τ_{wall}, the plasma duration and the plasma current fall drastically. No plasma discharges were observed for time delays of 12.5 ms and 15 ms and beyond.

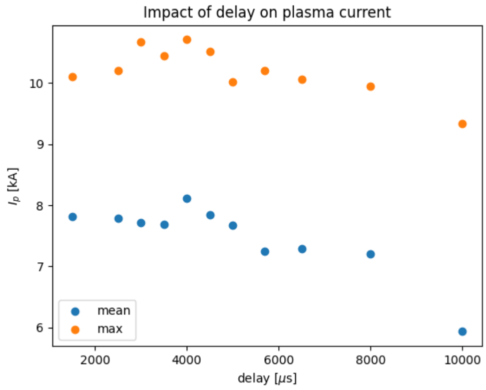

Figure 2: Plasma current with preionization: beyond $4ms$, the current falls off because there are less available electrons for preionization

Impact of the delay on the plasma duration

Similarly, the plasma duration decreases after a delay of $4ms$ (Fig 3). This is probably due to the lower quality confinement of the plasma due to the lower plasma current intensity seen in Fig 2.

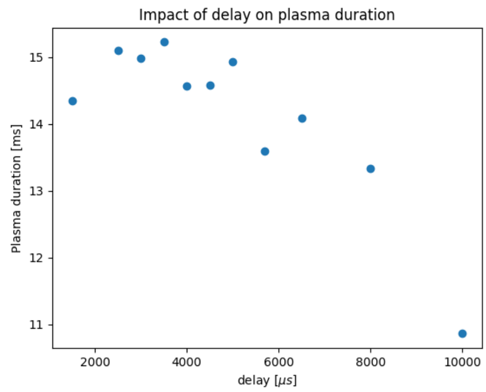

Figure 3: The confinement falls off once the delay is too big

Study of plasma confinement

To see the quality of the plasma confinement, one must look at the safety factor q. As calculated in the previous section of this report, the safety factors were determined for each shot in figure 4.

The "maximum" safety factor, calculated with the maximum values of the field and current intensity, can be considered an ideal towards which the mean safety factor should strive to go.

As the figure shows, the safety factor increases the longer the delay, which is in accordance with the previous results and would suggest that the decrease in plasma duration is caused by a worse confinement.

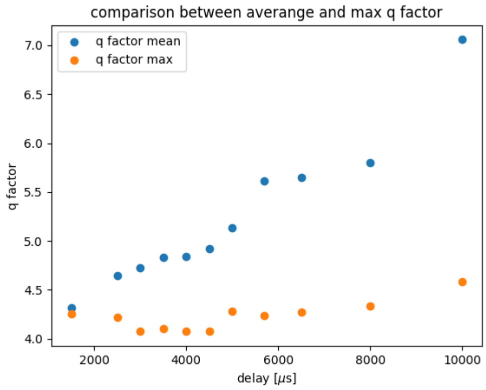

Figure 4: the q factor gets worse as the delay increases, particularly after 5ms.

Fig 5 comes as a verification of this result, in which we can see that the confinement time is effectively inversely proportional to the q factor (itself a function of the plasma current).

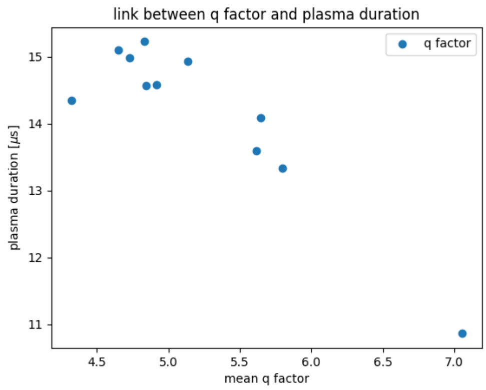

Figure 5: The confinement time is inversely proportional to the q factor

Electron temperature

The electron temperature is an indication of the efficiency of the heating. As seen in figure 6, the higher the maximum plasma current is, the higher the electron temperature T_e and the better the heating.

4. Conclusion

In this report, the basics for the operation of the GOLEM tokamak are laid out. In the goal of maximizing the plasma current, the time delay between the transformer for the toroidal magnetic field and the transformer of the toroidal electric field is taken as a parameter.

As the time delay varies, the electron cloud responsible for the conduction of the plasma current is changing. With

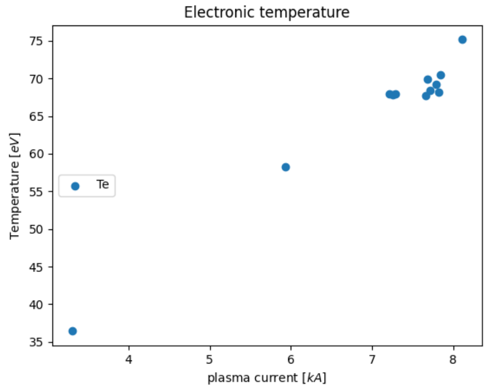

Figure 6: Time confinement with preionization

an optimal value of the delay of around $4ms$, the maximum plasma current is obtained with a value of around $10kA$.

It has been shown also that the more important the value of the plasma current is, the more stable the plasma gets (better discharge time and better safety factor) and the more efficient the heating of the plasma is (higher electron temperature).

Further studies could be done with time dependent values of I_p, B_t and q in order to verify if the q calculated from the average values of B_t and I_p is close to the time average of $q(t)$. A greater spread and increased number of measurements would also be necessary in order to verify the results and verify incertitudes.

5. Acknowledgments

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References

[1] I. H. Hutchinson. *Principles of Plasma Diagnostics, 2nd ed.* Cambridge Univ. Press, 2002.