International Baccalaureate Diploma Programme

Extended Essay

What is the dependence of plasma current on toroidal magnetic field capacitor voltage and current drive voltage in tokamaks?

Higher Level Physics

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Contents

Introduction

The current world population exceeds seven billion people and it still rises. Such an increase and technological development of society calls for higher supply of energy. Sill widely used fossil fuels do not present a satisfactory long-term solution due to their unsustainability and the effects on the environment. The alternate sources of energy also have quite serious limitations.

Nuclear engineering offers another option. Fission nuclear power plants are already established around the world, but the public remains distrustful to this technology due to catastrophes from the past (Chernobyl, Fukushima). There are other disadvantages – storage of nuclear waste and dependence on radioactive fuel. However, the nature offers one more promising solution – thermonuclear fusion. This process, where lighter nuclei fuse together to form heavier atomic nuclei and release energy, is the basis for the existence of all stars and more complex atoms.

This process releases more energy than fission, is safe and with the right fuel breeding, the fuel is easily available all around the world. For these reasons, mankind tries to tame the power of the stars in Earth's conditions. There are several paths of research, but tokamaks remain the most promising one. [1]

The Czech Republic has two tokamaks, medium-sized COMPASS and small-sized GOLEM, which is located in the building of FNSPE of Czech Technical University. This tokamak is unique as it is dedicated to educating of students. This is where I conducted my research.

This essay will explore the research question of **how is the plasma current I_p (the flow of ions and electrons of the plasma) dependent on the capacitor voltage for the toroidal magnetic field U_{BT} and the voltage for the primary winding of the transformer U_{CD} (current drive voltage) of the tokamak?** The whole time-evolution of plasma current and maximum and mean values of plasma current will be considered. The mean value can give us a general idea about the discharge, whereas the maximum value is important due to the possible formation of disruptions.

I chose this topic because tokamaks offer very tempting results in the future, however, there are still many technological problems to be solved. Therefore, we need to thoroughly understand the machines.

The plasma current is a crucial parameter as it influences the heating of plasma. The higher plasma current generally leads to the desired higher plasma heating and it is crucial for steady operation of a future power plant. On the other hand, high plasma currents can lead to disruptions, which suddenly terminate the discharge and cause damage to the vacuum chamber walls and plasma facing components. A fine balance has to be established between the many objectives. [2], [3]

Background information

Tokamaks

The desire to use fusion power plants on the Earth faces many problems. The first problem we encounter is the fusion itself – the nuclei of atoms strongly repel each other due to the Coulomb force between them. The nuclei need to be brought extremely small mutual distances where the strong nuclear force takes over.

In the stars, the plasma is confined with gravity which holds the large density in the core, therefore, the temperature in the stars does not need to reach too high values (in Sun the temperature is over 15 million kelvins).

However, such conditions cannot be met on the Earth. This limitation can be bypassed through the temperature (hundreds of millions of kelvins) – due to the extremely high kinetic energies, the nuclei are able to overcome the mutual repulsion. The ignition temperature for deuterium-tritium plasma is around 150 million K. [4], [5]

Such temperatures create another problem – no material can withstand this heat. Tokamaks strive to solve the problem with magnetic confinement.

The name of tokamaks comes from Russian: *toroidalnya kamera s magnitnymi katushkami*, toroidal chamber with magnetic coils. Those devices were first developed in 1950s in Soviet Union by physicists Igor Tamm and Anrei Sakharov. [1]

Tokamak consists of a toroidal vacuum chamber, commonly made from steel. The chamber is surrounded by solenoid coils. When current flows through them, a toroidal magnetic field is induced in the chamber, which serves as a magnetic confinement of the plasma. Since the energetic requirements to create such magnetic fields would disrupt the other users of the electrical network, the energy for the solenoid coils is supplied by a large capacitor bank charged to the toroidal magnetic field capacitor voltage U_{BT}, which is chosen by the operator of the experiment (at tokamak GOLEM). [4], [5]

Additionally, tokamaks work as transformers. The vacuum chamber is surrounded by an iron transformer core. The primary winding is charged by a dedicated capacitor bank to the voltage U_{CD}. The plasma ring itself functions as the secondary winding. As a result, plasma current is induced, which also serves as one of the heating mechanisms. The plasma current generates poloidal magnetic field, which combines with the toroidal magnetic field to form a magnetic field with helical field lines, which makes the system more stable. [4], [5], [6]

The features of the tokamak mentioned above are illustrated in Figure 1 and the engineering scheme of the tokamak with the capacitors highlighted in Figure 2.

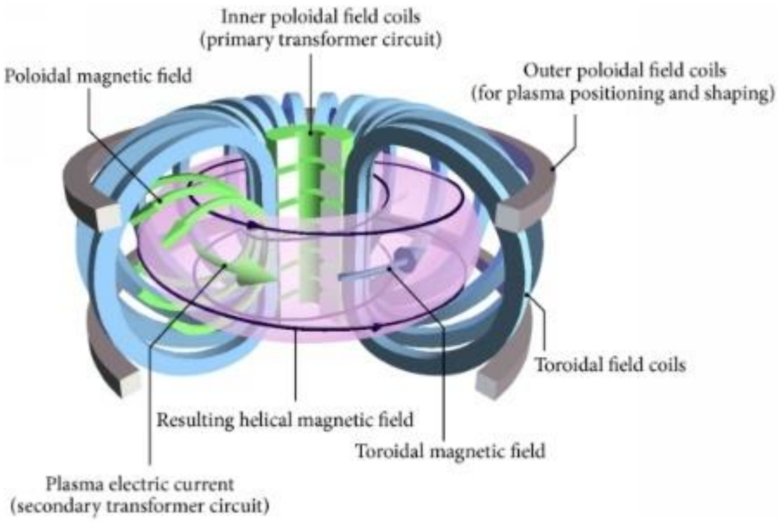

Figure 1: Working principle of tokamak [7]

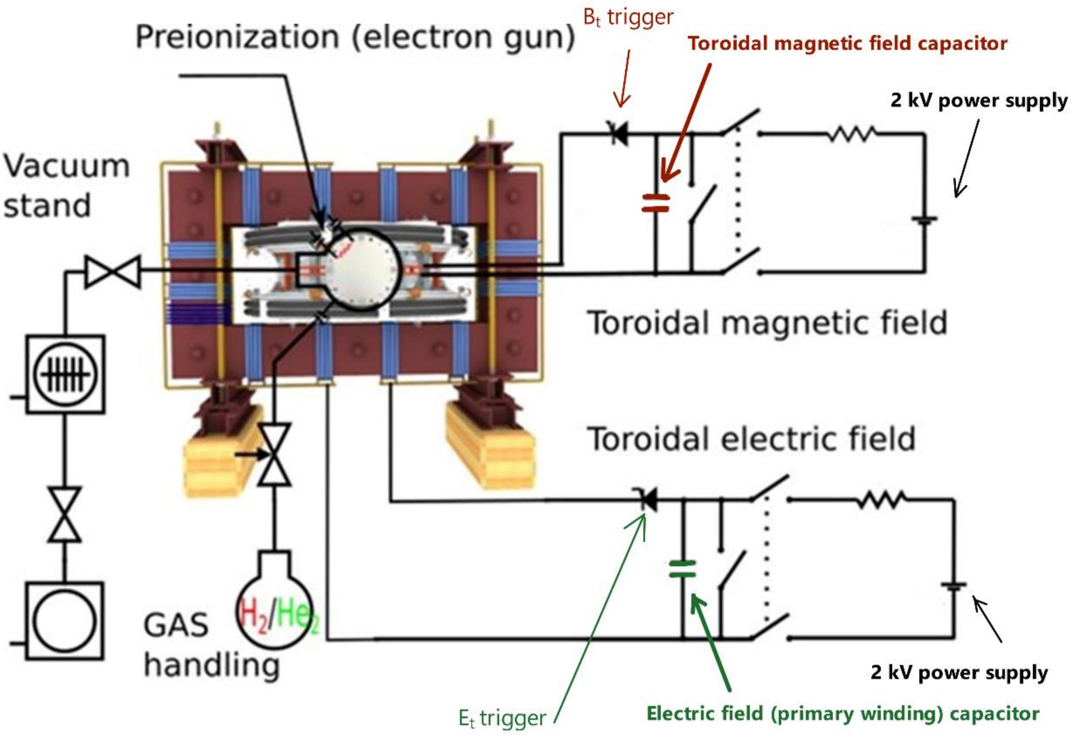

Figure 2: Engineering scheme of tokamak GOLEM [8] (edited)

The principle of creating the plasma current is that the electric field generated by induction accelerates any loose electrons present in the chamber (they either come from cosmic radiation or more commonly from deliberate ionization by an electron gun). Once the electrons reach a hydrogen ionization energy (around 13.6 eV), they start to ionize the remaining neutral working gas molecules. The ionization releases more electrons, and the avalanche mechanism is initiated, see Figure 3. The process of plasma creation is also referred to as the plasma breakdown.

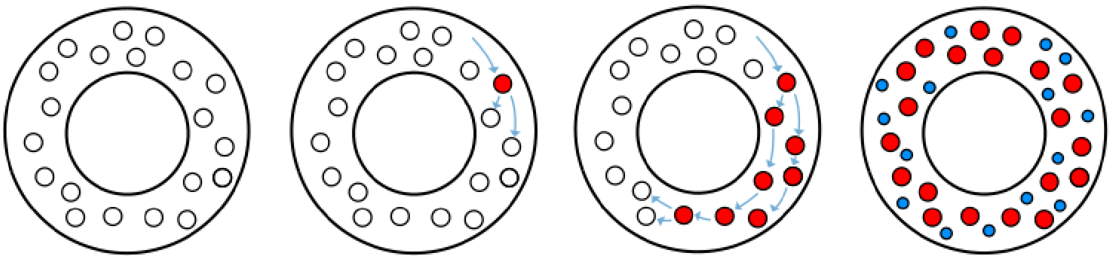

Figure 3: Ionization of working gas in a vacuum chamber where the white circles represent neutral molecules of working gas, red ions and blue electrons [9]

GOLEM tokamak

GOLEM is the oldest still functioning and the smallest tokamak in the world. It was built in the Moscow Kurchatov Institute as TM1, but currently it can be found at Czech Technical University under the name GOLEM.

Table 1 records the main parameters of the machine. The geometry of the tokamak is explained further by Figure 4 and Table 1 lists the maximum values that can be reached due to technological constrains at tokamak GOLEM.

Major chamber radius	$R_0 = 0.4\ \mathrm{m}$
Minor chamber radius	$r_0 = 0.1\ \mathrm{m}$
Plasma radius	$a \approx 0.085\ \mathrm{m}$
Discharge length	$t < 25\ \mathrm{ms}$
Toroidal magnetic field	$B_t < 0.5\ \mathrm{T}$
Plasma current	$I_P < 8\ \mathrm{kA}$

Table 1: Main parameters of tokamak GOLEM: discharge length (time of plasma breakdown until the end of the discharge), toroidal magnetic field (serves for magnetic confinement, induced by discharge of capacitor banks with voltage U_{BT}), plasma current (movement of electrons and ions) [10]

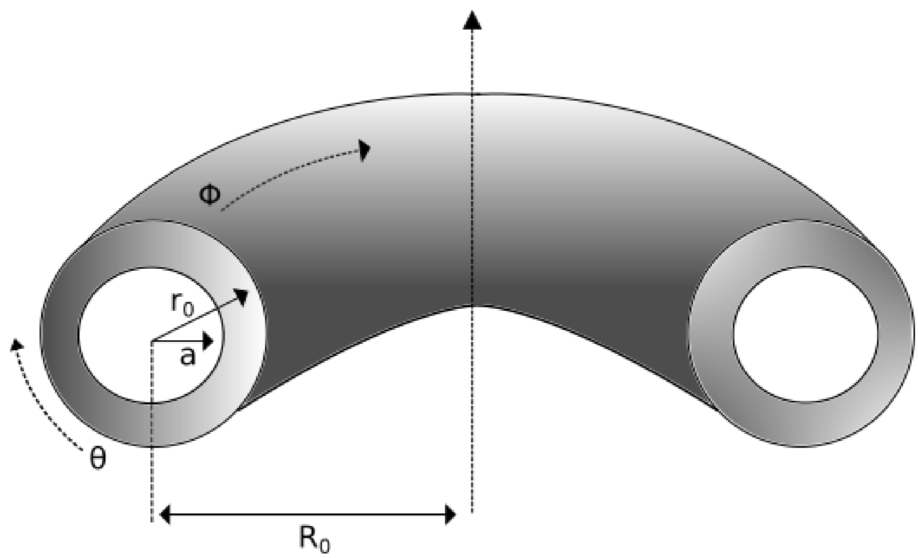

Figure 4: Tokamak geometry: R_0 – major radius (measured from the centre of the toroidal chamber to its outer wall), r_0 – minor radius (radius of the cross sectional area of the chamber), a – plasma radius (radius of the plasma column confined in the chamber), θ – poloidal direction (the "short" way around the torus), ϕ – toroidal direction (the "long" way around the torus) [6]

Plasma current

Plasma current is the flow of electrons and ions, which were created via the ionisation from the working gas.

Plasma current in tokamaks has usually more than one component:

1. Ohmic current generated by the electromagnetic induction described above (also used for ohmic heating)
2. Non-inductive current from external sources (such as neutral beam injection or radio frequency waves). This type is not present at tokamak GOLEM, although these sources also serve for heating purposes [6]
3. Self-generated bootstrap current, which originates due to the pressure gradient of the plasma [11]
4. Runaway electron current (RE) present in low-density discharges or during disruptions [12]

In our situation, the measured plasma current in the following analysis is simply considered as to be the ohmic current.

Plasma current diagnostics

Tokamak GOLEM possesses several diagnostics of the macroscopic plasma parameters. For our analysis, the most important parameter is the plasma current, which is measured by Rogowski coil, see Figure 5. It is a coil wound around the vacuum chamber in poloidal direction, which directly measures the time derivative of the poloidal magnetic field. It measures the contribution from the plasma current as well as from the chamber current. Fortunately, the chamber current can be determined and subtracted with the knowledge about chamber resistance (around 10 mΩ) and loop voltage and plasma current can then further be obtained through integration. [12]

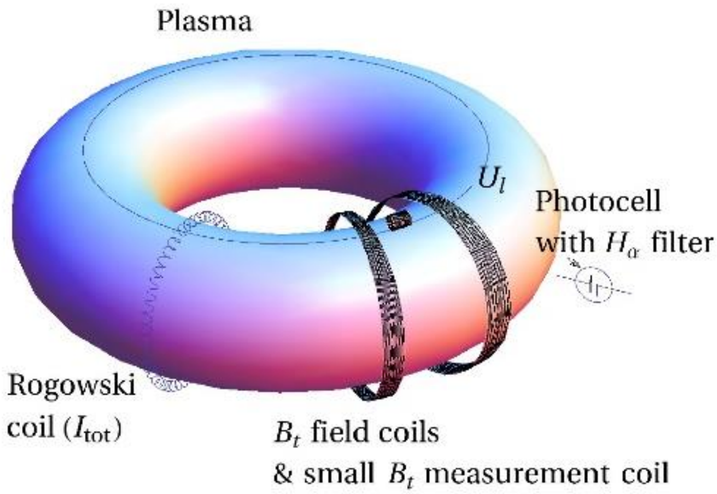

Figure 5: Macroscopic parameters diagnostics at tokamak GOLEM [13]

Safety factor and disruptions

Safety factor q (dependent on time and position in the chamber) is defined as the number of toroidal turns necessary for the magnetic field line at the given magnetic surface to reach its original position poloidally.

It serves as a stability indicator. Plasma is generally more stable with a higher safety factor value, thus preventing unwanted internal plasma mechanisms that could lead to disruptions. [14] [15]

If the plasma current or density reach a certain maximum value, magnetic field fluctuations start to rise and the plasma stability and confinement is starting to get worse. This situation can lead to the so called “saw tooth” instability or worse, to disruptions, which can immediately end the discharge. Very fast plasma current decay can induce strong destructive forces in the surrounding structures. Additionally, disruptions lead to the release of the plasma thermal energy. Such release can significantly damage the chamber walls. The already mentioned runaway electrons, which are usually produced in disruptions, also pose another risk. As electrons are no longer slowed down by collisions, they are accelerated to relativistic velocities. Beam of runaway electrons can also damage the chamber. For this reason, the plasma current must remain within the limit of the given machine. [2], [4], [5]

Hypothesis

Since the current drive voltage U_{CD} is responsible for accelerating electrons and the ionization process, it directly influences the plasma current. Therefore, **it is hypothesised that higher current drive voltage (that leads to stronger electric filed) will also lead to higher plasma current.** [15]

Apart from the safety factor, there is no direct relationship between the toroidal magnetic field capacitor voltage and plasma current, however, we think that stronger magnetic confinement (higher U_{BT}) may lead to longer and more stable discharges, therefore, an increase of the plasma current is expected. [5]

Methodology

Tokamak GOLEM was remotely controlled using command line programme PuTTY, which allows to set all the necessary parameters.

Figure 6 (identical to Figure 2) was inserted in this section to help the reader visualise better the described situation.

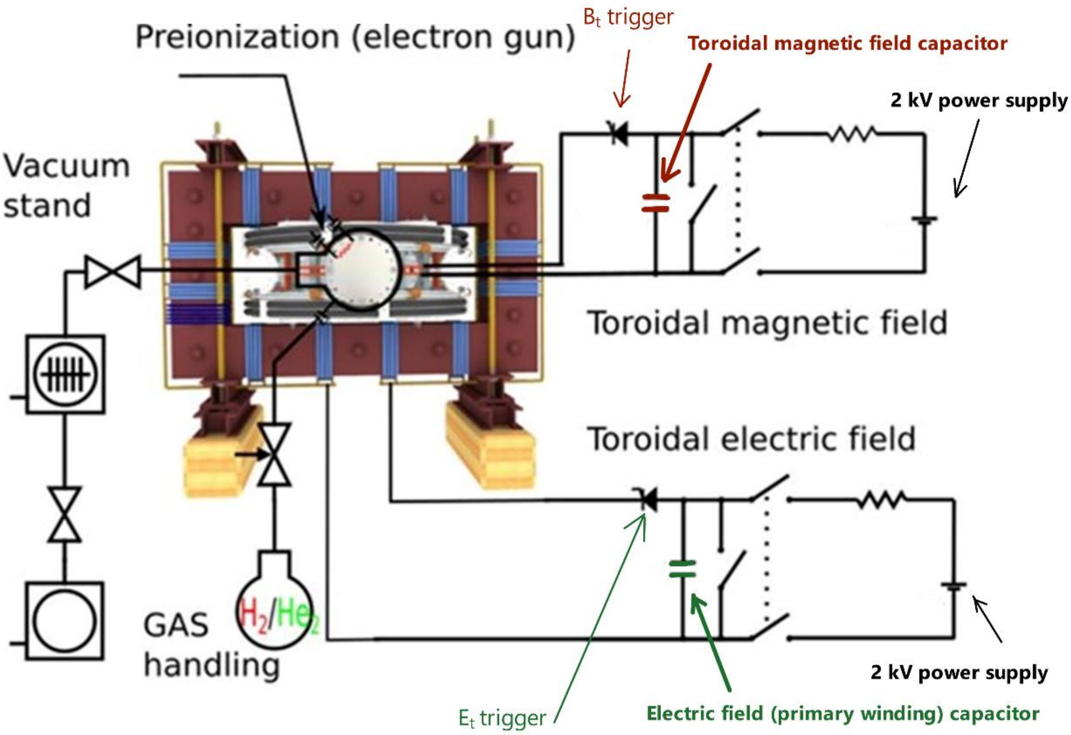

Figure 6: Engineering scheme of tokamak GOLEM [8] (edited)

There are several steps to a discharge:

1. The chamber is evacuated using vacuum pumps to a pressure below 1 mPa
2. All the necessary parameters are set: voltage of toroidal magnetic field capacitors U_{BT}, current drive voltage U_{CD}, pressure of the working gas and time delay between the connection of the magnetic capacitor trigger (T_{BT}) and current drive trigger (T_{CD})
3. The working gas (Hydrogen/Helium) is injected into the chamber
4. The capacitor banks start to charge to the desired voltage
5. The working gas is preionized by the electron gun
6. At time 0 the experimental *data acquisition system* (DAS) starts gathering data
7. At time T_{BT} the toroidal magnetic field capacitor banks start to discharge into the coils
8. At time T_{CD}, the current drive capacitor banks start to discharge into the primary winding coils and electric field is induced
9. The electrons generated by the electron gun are accelerated by the electric field and move around circular magnetic field lines

10. The working gas is ionised by collisions with the high-energy electrons. During each successful collision, another electron is generated and an avalanche succession is initiated
11. After a few milliseconds a fully ionised plasma ring is created in the chamber, which is heated by the passing current

Figure 7 visualises the time delay. As described, the toroidal magnetic field capacitors start to discharge first to ensure magnetic confinement is prepared before plasma breaks down and starts to heat up.

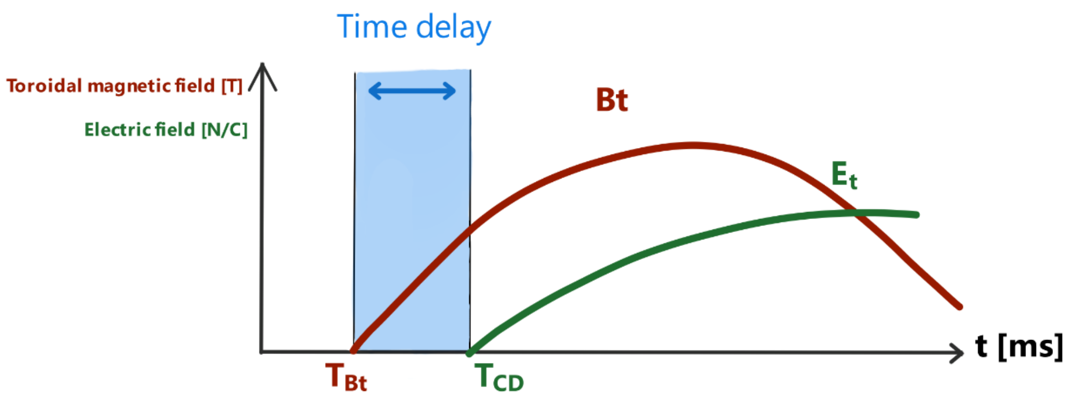

Figure 7: Times of discharge of the capacitor banks

Hydrogen plasma was chosen for this experiment.

The experiment was performed in two phases: in **the first phase, all the parameters except** U_{BT} **were fixed.** U_{BT} **was varied** from 800 V to 1300 V with a step of 100 V.

U_{CD} [V]	450
Pressure [mPa]	10
T_{BT} [ms]	1
T_{CD} [ms]	2

Table 2: Parameters for the first part of the experiment (U_{BT} variation)

In **the second phase, U_{BT} was fixed along with the other parameters, whereas U_{CD} was varied** from 300 V to 600 V with a step of 50 V.

U_{BT} [V]	800
Pressure [mPa]	10
T_{BT} [ms]	1
T_{CD} [ms]	2

Table 3: Parameters for the second part of the experiment (U_{CD} variation)

This data sample is quite small, therefore other discharge sessions, where the capacitor voltage was varied individually, were included in this work. The details about those discharges will be included in the Data and analysis section.

Analysis

The parameters were chosen from the recommended values for this machine. Tokamak GOLEM has a shot homepage (*https://golem.fjfi.cvut.cz/shots/discharge number/*) where all the information about the discharges is noted. This page additionally contains the maximum and mean values of plasma current. Both those values and the full time-evolution of plasma current will be used in the analysis.

Both parts of the experiment will be evaluated separately. Firstly, the whole time-evolution of plasma current of all the discharges from the experiment performed specially for this paper will be shown.

Secondly, the dependence of maximum and mean (averaged plasma current during the time of the discharge indicated in the database) plasma current on the capacitor voltage will be shown.

Finally, the dependence of mean plasma current from all discharge series will be plotted against the capacitor voltage. This part of the analysis also shows the other influences on plasma current.

Variables

	1st part	2nd part
Independent	U_{BT} (toroidal magnetic field capacitor voltage)	U_{CD} (current drive voltage)
Dependent	I_p (plasma current)	I_p (plasma current)
Controlled	U_{CD}, gas pressure, preionization, T_{BT}, T_{CD}	U_{BT}, gas pressure, preionization, T_{BT}, T_{CD}

Table 4: Variables for experiment (U_{BT} variation in the 1st part, U_{CD} variation in the 2nd part)

T_{BT} and T_{CD} refer to the times when the capacitor banks start discharging.

Data and analysis

The data was analysed and the graphs were plotted using the programming language Python. Since the measurement of the plasma current is rather complex, it is not possible to determine the uncertainties simply through the precision of the measuring equipment. Additionally, each value of maximum and mean plasma current comes from a unique discharge, therefore statistical measurements such as the standard deviation are not relevant. Therefore, after a consultation with the researchers at tokamak GOLEM, it was decided to use 8% as an estimation of the experimental error.

The biggest source of uncertainty in the measurement of plasma current stems from the integration of the measured signal and the determination of the Rogowski coil calibration. Moreover, the Rogowski coil is located outside the chamber, and hence, can be influenced by currents passing through other components. Other sources include noise from the measuring equipment and uncertainty in the chamber resistance.

Change in toroidal magnetic field capacitor voltage

Discharge #	U_{CD} [V]	U_{BT} [V]	I_p [kA]	Pressure [mPa]	T_{BT} [ms]	T_{CD} [ms]
38838	450	800	3.51	10	1	2
38839	450	900	3.49	10	1	2
38834	450	1000	3.39	10	1	2
38835	450	1100	3.24	10	1	2
38836	450	1200	3.22	10	1	2
38837	450	1300	2.68	10	1	2
29228	500	700	3.23	16	5	10.5
29230	500	800	2.48	16	5	10.5
29231	500	900	2.30	16	5	10.5
29232	500	1000	2.27	16	5	10.5
29233	500	1100	1.74	16	5	10.5
29234	500	1200	1.52	16	5	10.5
26059	550	800	4.52	30	5	10
26060	550	1000	4.34	30	5	10
26061	550	700	4.84	30	5	10
26062	550	600	4.33	30	5	10
26063	550	1100	5.52	30	5	10
26072	700	600	5.11	30	5	10
26073	700	700	5.70	30	5	10
26074	700	800	6.49	30	5	10
26076	700	800	6.44	30	5	10
26077	700	1000	7.10	30	5	10
26078	700	1100	7.72	30	5	10
35880	450	1300	4.25	16	1	2
35881	450	1250	4.42	16	1	2
35882	450	1200	4.94	16	1	2
35883	450	1150	5.15	16	1	2
35884	450	1100	4.72	16	1	2
35885	450	1050	5.00	16	1	2
35886	450	1000	5.07	16	1	2
35887	450	950	4.96	16	1	2
35888	450	900	5.49	16	1	2
35889	450	850	5.48	16	1	2
35890	450	800	5.45	16	1	2
35891	450	750	5.46	16	1	2
35892	450	700	5.68	16	1	2
35893	450	650	5.00	16	1	2
35894	450	600	4.50	16	1	2
35895	450	550	3.84	16	1	2

Discharge #	U_{CD} [V]	U_{BT} [V]	I_p [kA]	Pressure [mPa]	T_{BT} [ms]	T_{CD} [ms]
35896	450	500	2.58	16	1	2
35897	450	450	1.54	16	1	2
35898	450	400	1.27	16	1	2
35899	450	350	1.46	16	1	2
35900	450	300	1.32	16	1	2
35901	450	250	1.23	16	1	2

Table 5: Summary of all experiments with U_{BT} change

Table 5 records all experiments regarding the change in toroidal magnetic field capacitor voltage U_{BT} and the parameters of those discharges that may influence the plasma current. The plasma current presented here (I_p) is the mean value (I_p *mean*) obtained from the shot homepage.

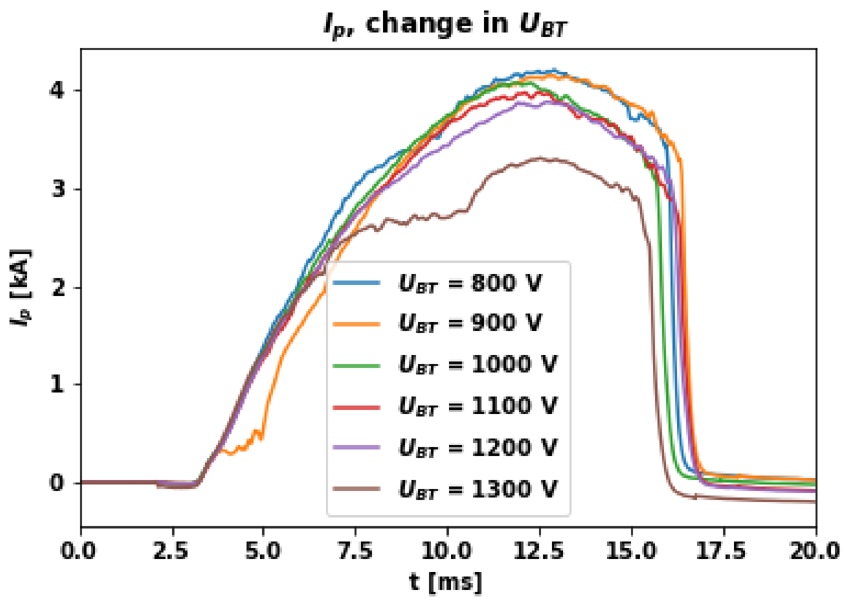

Figure 8: Plasma current time-evolution for U_{BT} change (#38834 - #38839)

Figure 8 presents the whole time-evolution of plasma current during the experiments performed for this paper (green group from Table 5). It seems, that the change of UBT voltage in this range does not have direct influence on the plasma current time evolution.

Only the discharge with the largest used voltage 1300 V slightly differs, but the difference is clearly not caused by the voltage change, because the toroidal magnetic field almost did not change compared to the previous discharge with voltage 1200 V (In both cases the mean toroidal magnetic field is 0.12 T and the maximum is 0.19 T). The current reason of this different plasma current behaviour is very hard to identify from available diagnostics and far beyond the scope of this work.

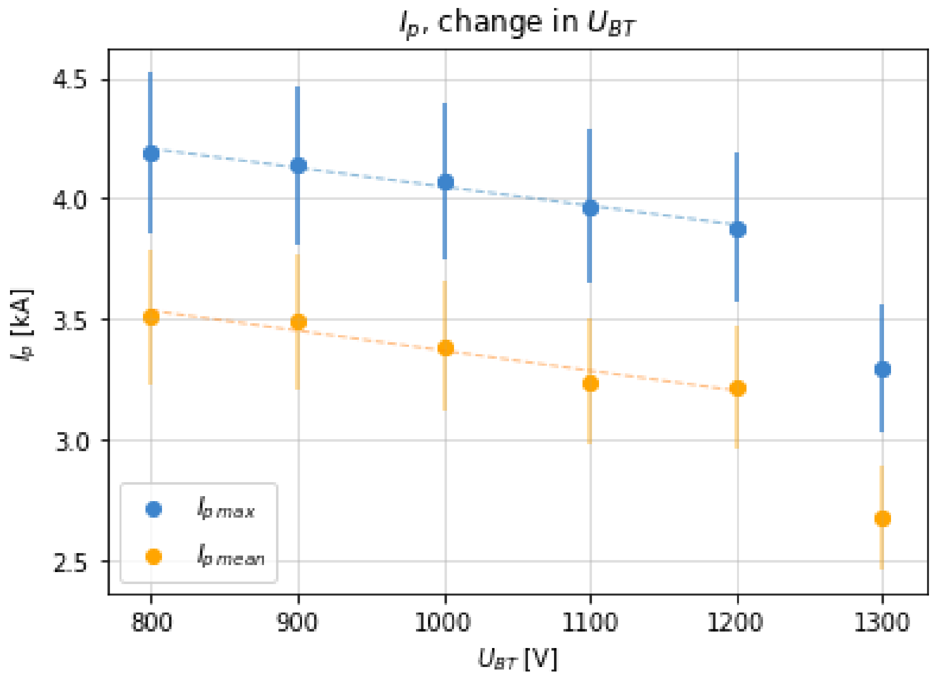

Figure 9: Mean and maximum plasma current for U_{BT} change (#38834 - #38839)

Figure 9 plots the mean and maximum values of plasma current from the same measurement. If we omit the values for the U_{BT} of 1300 V, as explained earlier, we can see a very weak decreasing trend. The change of plasma current between the lowest and the highest voltage is less than 10%, but the voltage increased by 50%. Thus we can carefully say, that U_{BT} has just a marginal influence on the plasma current in this specific range of used U_{BT} and U_{CD} voltages. Table 6 summarises the slopes and R^2 coefficients for the trend lines presented in Figure 9, which support the previous claims. The slopes for both data sets are very similar and low and the trend lines show strong correlation (red – little to no correlation, yellow – weak correlation, green – strong correlation).

	Slope	R^2 coefficient
Max	-0.0079	0.984
Mean	-0.00083	0.933

Table 6: Slopes and R^2 coefficients of trend lines from Figure 9

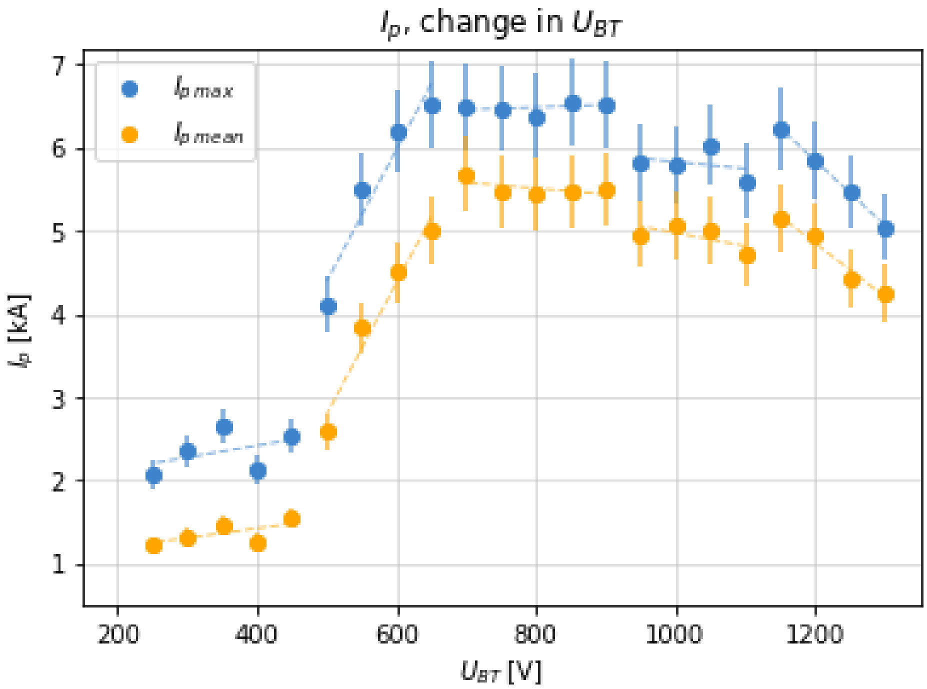

Figure 10: Mean and maximum plasma current for U_{BT} change (#35880 - #35901)

Figure 10 was constructed from discharges #35880 to #35901 (brown group from Table 5). The measuring range for these particular experiments was higher, therefore we get the full picture of the dependency. Very low values of U_{BT} sustain only small plasma current probably due to the insufficient magnetic confinement. From around 600 V to 900 V plasma current remains high and approximately constant. Then the plasma current starts to slowly decrease like in Figures 8Figure 8 and 9. However, the specific slopes in the identified intervals differ. Table 7 looks at Figure 10 piecewise and describes the parameters of the trend lines – slope and R^2 coefficients.

Interval	Range of voltages	Slope max plasma current	Slope mean plasma current	R^2 coefficient max plasma current	R^2 coefficient mean plasma current
1	250 - 450	0.00142	0.00114	0.196	0.471
2	500 - 650	0.01586	0.01584	0.921	0.953
3	700 - 900	0.0003	-0.00072	0.118	0.357
4	950 - 1100	-0.0008	-0.00158	0.086	0.450
5	1150 - 1300	-0.0078	-0.00644	0.999	0.959

Table 7: Slopes and R^2 coefficients of trend lines from Figure 10

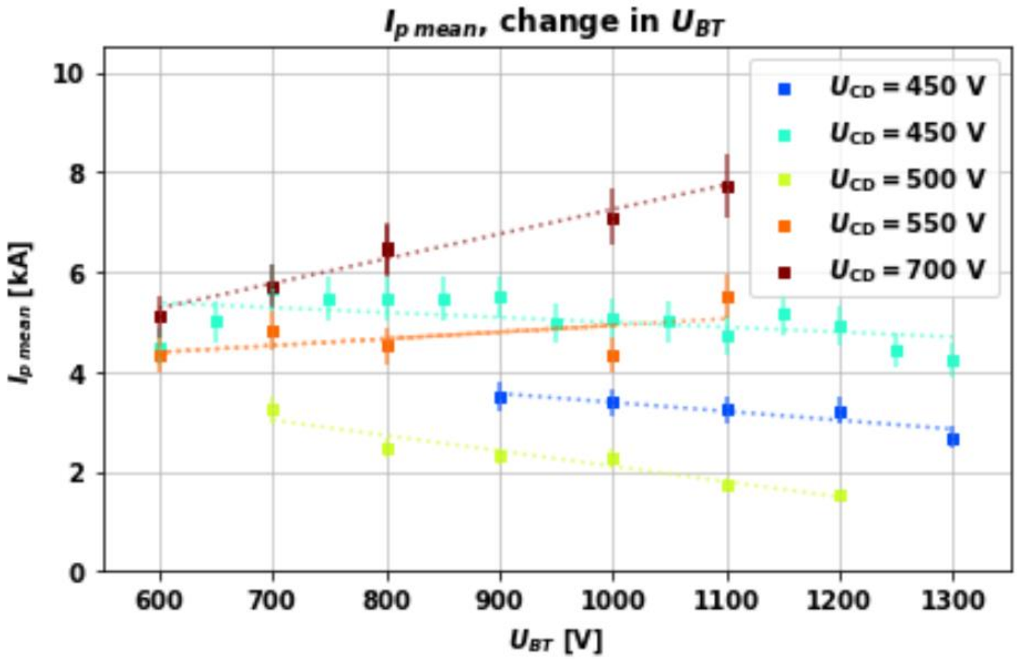

Figure 11: Mean plasma current comparison for all U_{BT} change data sets

Figure 11 summarises all of the discharges from Table 5 (for mean plasma current). Although from discharge session #35880 - #35901 (brown group in Table 5) only the discharges with $U_{BT} \geq 600$ V were used. This was done to effectively compare it with the remaining data sets, which have a smaller measuring range.

The claim that change in U_{BT} has very little influence on plasma current verified by the other graphs can be identified in Figure 11 and the parameters of the trend lines presented in Table 8.

	U_{CD}	Slope	R^2 coefficient
	450	$-1.79 \cdot 10^{-3}$	0.816
	450	$-9.81 \cdot 10^{-4}$	0.261
	500	$-3.0857 \cdot 10^{-3}$	0.921
	550	$1.3488 \cdot 10^{-3}$	0.316
	700	0.00495	0.969

Table 8: Slopes and R^2 coefficients of trend lines from Figure 11

There are some differences observed in Figure 11. These differences are caused by the different discharge parameters (pressure, time delay) summarised in Table 9.

	U_{CD} [V]	Pressure [mPa]	T_{BT} [ms]	T_{CD} [ms]
	450	10	1	2
	450	16	1	2
	500	16	5	10.5
	550	30	5	10
	700	30	5	10

Table 9: Parameters influencing plasma current in Figure 11

The biggest difference identified is with the dark red data set, U_{CD} = 700 V, where the plasma current seems to be rising, although more data with higher U_{BT} would be needed to verify this tendency. We think the rise in plasma current is cause by U_{CD}, which is significantly higher than with the other data sets. As will be discussed next, plasma current rises with rising U_{CD}.
Although the other factors influencing the plasma current are not focus of this work, certain trends are identified. A longer time delay between the discharges of the capacitor banks seem to shift the plasma current higher (comparison of dark blue and turquoise). Higher pressure may also lead to higher plasma current, although the comparison presented is not completely precise (comparison of orange and green).

Change in current drive capacitor voltage

Discharge #	U_{CD} [V]	U_{BT} [V]	I_p [kA]	Pressure [mPa]	T_{BT} [ms]	T_{CD} [ms]
38840	300	800	2.74	10	1	2
38841	350	800	2.63	10	1	2
38842	400	800	2.85	10	1	2
38843	450	800	3.81	10	1	2
38844	500	800	3.98	10	1	2
38845	550	800	4.5	10	1	2
38846	600	800	4.99	10	1	2
29219	450	750	1.8	20	5	7
29220	550	750	3.28	20	5	7
29221	650	750	3.86	20	5	7
29222	450	750	1.07	20	5	13
29223	550	750	2.27	20	5	13
29224	650	750	3.28	20	5	13
29252	550	700	3.39	20	5	10
29253	600	700	3.57	20	5	10
29254	650	700	4.01	20	5	10
29255	700	700	4.35	20	5	10
29269	500	700	3.29	40	5	10
29270	550	700	4.01	40	5	10
29271	600	700	4.29	40	5	10
29272	650	700	4.68	40	5	10
29273	700	700	5.08	40	5	10

Table 10: Summary of all experiments with U_{CD} change

Table 10 records all experiments regarding the change in current drive voltage and the parameters of those discharges that may influence the plasma current. The plasma current presented here (I_p) is the mean value (I_p *mean*) obtained from the shot homepage.

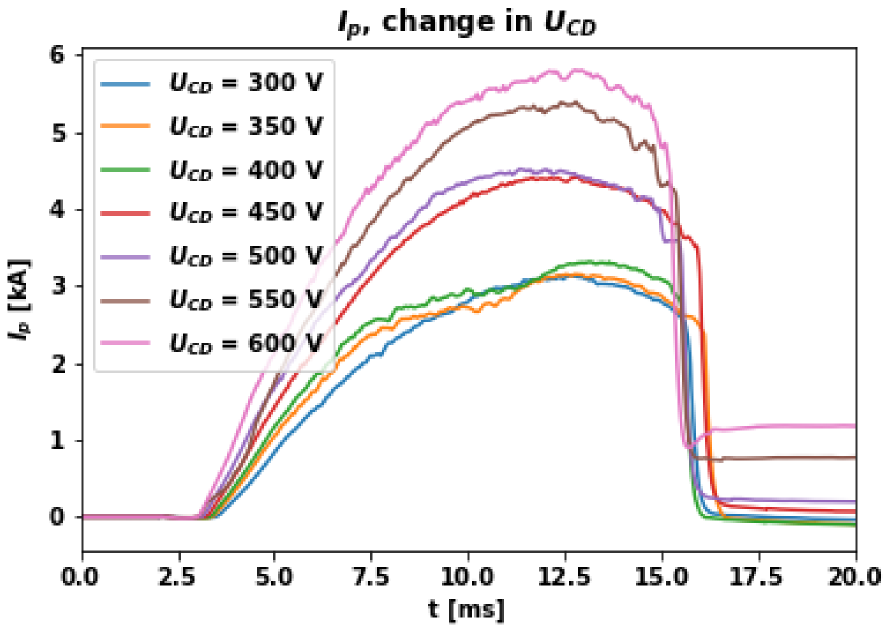

Figure 12: Plasma current time-evolution for U_{CD} change (#38840 - #38846)

The experiment performed for this paper (green group from Table 10) was again used to show the whole time-evolution of plasma current in Figure 12. The dependency here is clear: higher U_{CD} generates higher plasma current.

In the graph when the U_{CD} is high, the plasma current doesn't fall to zero. That is because the Rogowski coil diagnostic used to measure plasma current gets saturated when the plasma current is very high, which happens during a disruption.

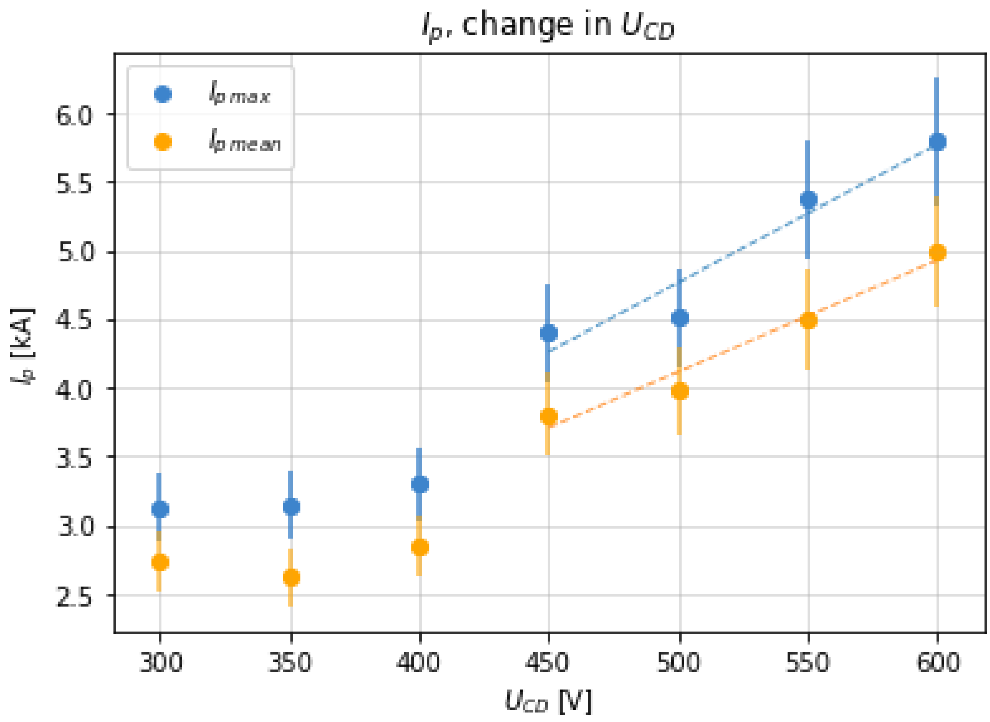

Figure 13: Mean and maximum plasma current for U_{CD} change (#38840 - #38846)

The mean and maximum values of plasma current for the same data set (green group in Table 10) are shown in Figure 13. The graph shows an overall growing trend, as was expected and confirmed through Table 11.

	Slope	R^2 coefficient
Max plasma current	0.01006	0.930
Mean plasma current	0.00812	0.962

Table 11: Slopes and R^2 coefficients of trend lines from Figure 13

In more detailed analysis, in discharges with U_{CD} of 300 V, 350 V and 400 V the plasma current had atypical time evolution, which caused lower plasma current, than was expected. If we have repeated these discharges for the purpose of eliminating unusual situations (such as MHD instability [6] or an impurity liberated from the chamber wall) and thus to measure only "standard plasma behaviour", the final plasma current would be more consistent with the linear trend of the measured data.

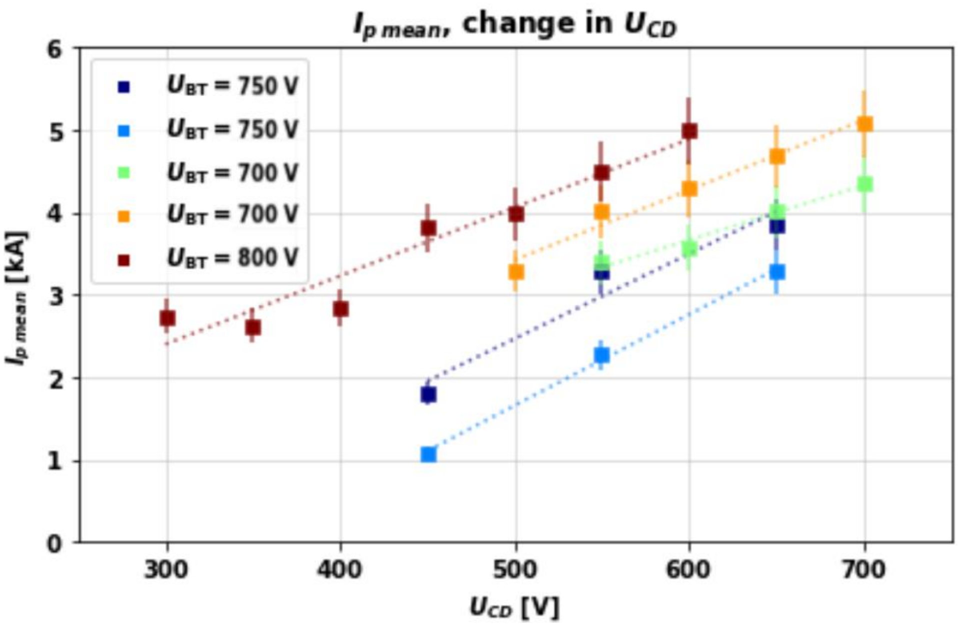

Figure 14: Mean plasma current comparison for all U_{CD} change data sets

Figure 14 shows all the data sets from Table 10 plotted together (for mean plasma current). The data sets are very close in terms of the toroidal magnetic field capacitor voltage, yet there are differences in the plasma current. That is caused by the difference in other discharge parameters summarised in Table 12 below. However, regardless of the discharge settings, the dependence of plasma current on the current drive voltage is clear – the plasma current rises as the current drive voltage rises as can also be seen from Table 13 presenting the information about the trend lines from around 400 V and above.

	U_{BT} [V]	Pressure [mPa]	T_{BT} [ms]	T_{CD} [ms]
	750	20	5	7
	750	20	5	13
	700	20	5	10
	700	40	5	10
	800	10	1	2

Table 12: Parameters influencing plasma current in Figure 14

In terms of the other parameters, higher pressure seems to increase the plasma current (comparison of green and orange). On the other hand, the claim that longer time delay leads to higher plasma current made in the previous section conflicts with the observation from Figure 14, where longer time delay seems to correlate with lower plasma current (comparison of dark blue and turquoise).

	U_{BT}	Slope	R^2 coefficient
	750	0.0103	0.940
	750	0.01105	0.998
	700	0.00664	0.677
	700	0.0085	0.975
	800	0.0083	0.934

Table 13: Slopes and R^2 coefficients of trend lines from Figure 14

Conclusion

In this essay, the influence of the toroidal magnetic field capacitor voltage U_{BT} (consequently the strength of the toroidal magnetic field) and current drive capacitor voltage U_{CD} (consequently the strength of the toroidal electric field) on the plasma current in tokamak GOLEM was examined. Plasma current is important due to its influence on other essential variables such as the electron and ion temperatures. Additionally, if a plasma current is too high, a disruption can occur, which immediately terminates the discharge and poses a risk for plasma facing components.

Through data analysis including the comparison of whole time-evolution of plasma current and comparison of mean and maximum values of plasma current under different conditions, we reached a conclusion.

With very low U_{BT} (around 200 - 400 V), the plasma current is very small probably due to the insufficient magnetic confinement. When the U_{BT} rises (400 - 600 V), the plasma current does too because of rapid improvement of the plasma magnetic confinement and stability. This piecewise analysis was shown in Figure 10. Another increase of the U_{BT} voltage seems to have just a marginal influence on plasma current behaviour, probably due to already sufficient plasma magnetic confinement and stability as shown in Figure 9 and confirmed through the low slopes in Tables 6, 7 and 8.

We have clearly measured, that the plasma current is proportional to the current drive capacitor voltage (as could be seen in Figures 13 and 14), when the sufficient toroidal magnetic field is presented. The dependency is linear as can be seen from the positive slopes and high R^2 coefficients suggesting strong correlation of the linear regression lines (Tables 11 and 13).
Considering the presented results, **the hypothesis was not falsified. In terms of U_{BT}, an increase of plasma current was observed, however, an ideal value for maximizing the plasma current did not correspond to the highest U_{BT}, as was described above. On the other hand, higher values of U_{CD} clearly lead to higher plasma current due to its dependency on the ionization of the working gas.** This conclusion seems to be in accordance with past research and theory such as [5], [6] and [15].

Discussion

Generally, there were no greater issues with the experiment since tokamak GOLEM could perform a discharge around every five minutes, therefore, if a problem arose, it could be dealt with quickly with a new discharge.
There are still certain points that need to be kept in mind when presenting the results of the experiment.
When one of the capacitor voltages was varied, the other one was kept constant. However, the variation was done only for one value of this constant. A more sophisticated experiment should include the variation of one capacitor voltage over many values of the fixed capacitor voltage. On the other hand, such an extension would be very demanding in terms of time and material.
The last graph in each section (Figure 11 and Figure 14) and the respective tables (Tables 9 and 12) showed that the other parameters chosen for the discharge can significantly influence the plasma current. Those dependencies should be properly examined, for example with the starting points seen in this paper – higher pressure seems to increase plasma current, but the results regarding the influence of time delay are conflicting and need to be verified by another experiment.
Additionally, plasma current can have more than one component and only one of them was examined in this paper. For example, the possible presence of the runaway current could

influence the measured plasma current. To fully understand this variable, more experiments should be performed.

At last, it is good to mention, that also tokamak conditions and especially the vacuum chamber condition just before the experiment has a crucial influence on plasma behaviour. Unfortunately, it is generally hard to hold these conditions unchanged during all discharges, which is important to correct data evaluation.

List of tables and figures

Tables

Figures

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