Vienna International School - Extended Essay

To what extent is it feasible to estimate the breakdown probability for a plasma discharge in the GOLEM tokamak using a machine learning algorithm trained using precedent discharge results?

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Abstract

Fusion is the power of the future. Yet it proved very difficult to sustain it for longer periods of time. The formation of plasma in a tokamak, also known as plasma breakdown, is a key phase in the goal to create sustainable fusion. In order to understand the processes in the plasma breakdown phase and design discharges that have a high probability of success, it is important to have a model that can predict the probability of a plasma discharge, given the initial conditions. This essay has explored “**To what extent is it feasible to estimate the breakdown probability for a plasma discharge in the GOLEM tokamak using a machine learning algorithm trained using precedent discharge results?”**

To help answer the question data acquired from the GOLEM tokamak located at the Czech Technical University in Prague was analyzed using a machine learning program. The machine learning algorithm was given a training set of discharge setups and their outcomes to find trends in the data distribution by extrapolating the input. The trained program was then used to predict the probability of new discharges given previously unseen initial conditions and compare the theoretical prediction to the actual outcome.

It was found that the relationship between pressure and the current drive voltage is linked to the Paschen’s curve. Using the trained program, predictions were made on test samples and the accuracy of the prediction was assessed with respect to the number of training samples used. The conclusion was made that with a higher number of training samples, the predictions were improving. Therefore, it was concluded overall that it is feasible to estimate the breakdown probability for a plasma discharge given a sufficient number of precedent results.

(283 Words)

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Introduction

It is very difficult to imagine the world without electricity. For over one hundred years, we have used it to accomplish a wide range of tasks. Yet still our civilization does not possess a reliable and cheap source of this energy for wide use. Nuclear fission has proved to be a good candidate. However, as a side effect it produces large amounts of nuclear waste and relies on radioactive uranium fuel. Scientists are working on a better alternative - Fusion. In fission, heavy atoms are split into smaller atoms and thereby release energy. In fusion, lighter elements are forced to combine into heavier elements releasing vast amounts of energy. Besides being more energetic, the fuel is genuinely abundant hydrogen which makes the process of fusion in many ways cheaper and safer. Scientists have discovered this process along with fission. Yet it proved very difficult to duplicate it in an efficient and controlled manner on earth[1].

One the key problem at reproducing fusion in an artificial environment are the extreme conditions required. The atoms naturally repel due to the coulomb force. Only after forcing the atoms close together does the strong nuclear force take over and fuse the atoms. In our sun, gravity is responsible for this.[2] However on Earth, we are unable to create such enormous pressures. The only alternative is temperatures as high as millions of degrees where the kinetic energy of the atoms is high enough to bring the atoms close to one another[3]. This so-called Ignition temperature for a Deuterium-tritium (D-T) fusion reaction is about 4.5×10^7 K[4]. No material can withstand such temperatures. Therefore maintaining fusion over extensive periods of time requires finding a method of containing it safely in a reactor without vaporizing the walls.

Tokamak is a technology used to contain the plasma in a vacuum ring using electromagnetic coils. Fusion reactions take place in the plasma state of matter. This makes a Tokamak an ideal

[1] World Nuclear Association
[2] *ibid*
[3] *ibid*
[4] Rod Nave "Coulomb Barrier for Fusion"

device for containing fusion[5]. However to make sure the fusion is safely contained in the reactor, one must first understand the process of plasma formation in the tokamak chamber.

The plasma formation, also known as the plasma breakdown or the avalanche effect, is one of the strangest parts of plasma physics. It very much depends on the initial conditions of the experiment and thus it is difficult to simulate[6]. However, it is possible to estimate, based on previous experiments, if the breakdown of the plasma is going to be successful given some initial conditions. This essay will focus at answering the question **To what extent is it feasible to estimate the breakdown probability for a plasma discharge in the GOLEM tokamak using a machine learning algorithm trained using precedent discharge results?**

In this essay, I will present a computer method of estimating the plasma breakdown success. Using this method, it is possible to estimate the probability of plasma formation and optimize the future experiments and get the intuition of the breakdown process.

[5] World Nuclear Association
[6] Simulating ITER Plasma Startup and Rampdown Scenarios in the DIII-D Tokamak

Background information

Tokamak background

Tokamak is an abbreviation for 'toroidal chamber with magnetic coils'.[7] The history of the design reaches as far back as the 1950s when it was invented by the Soviet physicist Igor Tamm and Anrei Sakharov. [8]

The GOLEM tokamak, situated at the Czech Technical University in Prague, is one of the oldest operational tokamaks in the world. It is a relatively small device with a toroidal radius of 0.4m. However, it is capable of achieving plasma discharges as long as 13ms[9].

A tokamak consists of a toroidal chamber which is encircled by solenoid coils. When current flows through the coils a toroidal magnetic field is generated inside of the chamber. This can be used to attract the ionized gas (Hydrogen) inside of the chamber towards the center and away from the walls. The energy for the coils is stored in large capacitor banks charged to a desired voltage from now on referred to as U_b.[10]

The toroidal magnetic field B_t is defined by the following equation[11] where μ is the permeability of the core, N is the number of turns, I is the instantaneous current and r is the radius of the tokamak:

$$B_t = \frac{\mu N I}{2\pi r}$$

Substituting $I = \frac{U_n}{R}$ using Ohm's Law where R is the resistance of the toroidal coil, it appears that:

$$B_t = \frac{\mu N U_b}{2\pi r R} \rightarrow B_t \propto U_b$$

To simplify the further calculations U_b is used in place of B_t as the two values are directly proportional.

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[7] Rutherford, P 1980
[8] Bondarenko, B. D. 2001
[9] GOLEM Tokamak Wiki 2015
[10] *ibid*
[11] Nave, Rod. "Magnetic Field of Toroid."

The chamber of the GOLEM tokamak is surrounded by an iron core of a transformer. The primary winding of the transformer is linked to a second capacitor bank which is charged to a desired voltage referred to as U_{cd}.

U_{cd} stands for the current drive voltage because the transformer is positioned in such a way as to induce electric current in the area of the chamber. The area of chamber acts as the secondary winding on the transformer. If partially ionized gas is present in the chamber, its loose electrons are accelerated resulting in further ionization and rapid heating of the gas. Hence the name - current drive voltage.[12]

Plasma breakdown

The process where the gas is ionized and heated is called the plasma breakdown. It starts by the so-called avalanche phase as illustrated in *figure 1*. At the start each atom of the gas is holding onto its electrons and overall the gas is uncharged. A small amount of the gas is preionized using an electron gun. The current drive starts to accelerate the ions and the free electrons. These free charged particles collide with the gas atoms and in turn ionize these atoms as well. This 'avalanche' of electrons very quickly engulfs the entire volume of the gas. Now that all the particles of the gas are ions, and thus affected by electric and magnetic fields, the toroidal magnetic fields starts to have a compressive effect on the plasma cloud. [13] If plasma is present in the chamber, the breakdown was successful.

Whether the plasma breakdown is successful or not depends very much on the initial conditions. The higher the voltage U_t the stronger the magnetic field B_t and thus greater compression of the ionizing gas during the breakdown process. Similarly, the higher the U_{cd}, the greater the force on the charged particles resulting in greater acceleration and more rapid plasma heating.

[12] GOLEM Tokamak Wiki 2015
[13] Marguet, Fabien

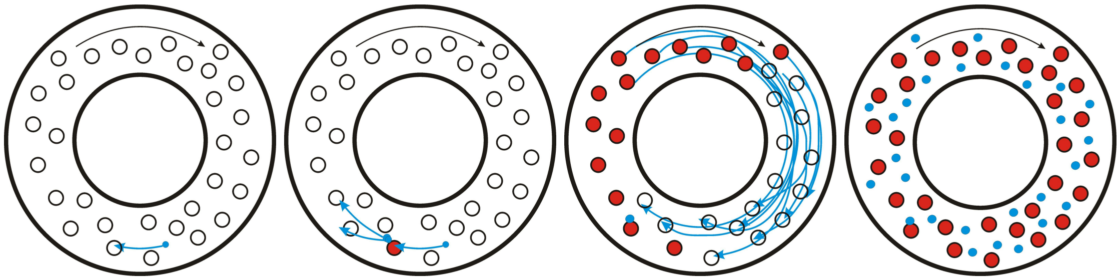

Fig 1 - Avalanche phase of gas ionization in tokamak[14]

Paschen's Law

Paschen's Law applies to the breakdown voltage of a gas between two electrodes. It predicts the minimal voltage required to create an arc[15]. According to Paschen's Law, the breakdown voltage of a gas is dependent mainly on two factors. The first being the pressure of the gas p and the second the distance between the electrodes d. The breakdown voltage V_b is given by the following formula[16]:

$$V_b = \frac{adp}{ln(dp)+b}$$

The graphical representation of this equation creates what is known as Paschen's curve as seen in *figure 2*. The constants a and b are specific for each gas.

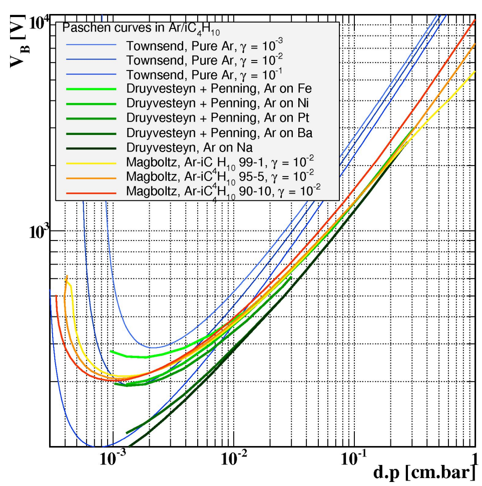

Fig. 2 - Paschen's curves for different gasses[17]

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[14] Marguet, Fabien
[15] Capacitive Discharges
[16] *ibid*
[17] "Using Gas Files: Paschen Curves"

The Paschen's Curve describes the minimum voltage required for the breakdown of plasma. That means that any voltage above the curve also represents successful breakdown. In other words, the area on and above the curve represents scenarios where the gas undergoes a breakdown.

As will come clear later in this investigation, the breakdown of plasma in tokamaks can be modeled in a very similar way. By finding the Paschen's curve for the breakdown of plasma in a tokamak, it will be possible to estimate if a combination of initial conditions results in a successful breakdown by calculating if the point lies above the curve.

Investigation

Experiment setup:

There is a number of steps involved during a discharge. This includes the preparation of the chamber and the collection of data. To ensure a high precision, all the tasks are carried out by a computer.

1. Air is pumped out of the chamber using a vacuum pump reaching pressure below 10^{-2} Pa
2. Small desired amount of working gas (H_2) is released into the chamber using an electronic pressure valve.
3. The capacitors for the U_b and U_{cd} are charged to the desired voltage.
4. The data acquisition system (DAS) initializes.
5. An electric coil acting as an electron gun pre-ionizes the gas.
6. The relays close the circuit for the toroidal coil and let the current flow from the capacitors.
7. After a small period of time (5ms), the current is supplied to the transformer coil.
8. DAS system collects the measurements and processes them.

The machine learning algorithm used in the analysis of the data requires a large training set in order to classify the discharges. To estimate the Paschen curve for the breakdown of hydrogen in the tokamak, it is necessary to obtain a large amount of data with different initial conditions and known outcomes. It would be infeasible to carry out all these experiments individually during this research. However, the tokamak GOLEM provides a database with more than 20 000 experiments carried out in the past.

These results are used in the training phase of the program. The testing of the program will be carried out on new results that have not previously been shown to the program.

The data analysis

The program (See Appendix A) loads all the data points into memory and removes experiments that have invalid data. The data points are plotted on the 3-dimensional graph of U_{cd} against pressure p and U_b. However, a 3D graph is difficult to visualize. Therefore the data is presented rather as a set of slices of simpler 2D graphs of U_{cd} against pressure p each for a different constant value of U_b. See *figure 5.*

A Support vector machine (SVM) learning algorithm is applied to the data to estimate the area where the plasma breakdown has a high probability of taking place. The internal working of the algorithm is beyond the scope of this essay, however, a simple way of describing the 'learning' process is the following[18]:

1. The algorithm is given a set of known results such as in *figure 3.*
2. Then it finds a line that splits the results into the groups (plasma was present, plasma was not present)
3. It tests how many of the results are classified correctly.
4. If the classification error is too high, the line is adjusted.
5. Steps 3 and 4 are repeated until the error margin is very small.

This process is called fitting because the algorithm attempts to fit the line to the data. The more data are available to the program, the more accurate can the line be fitted.

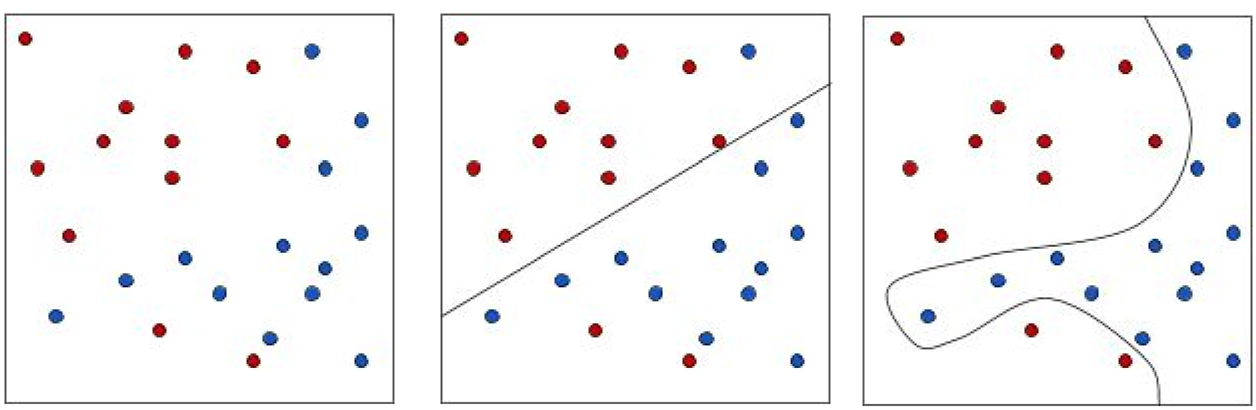


Fig. 3 - Example of a SVM machine fitting a line to known data in a 2D plane

[18] "Support Vector Machines."

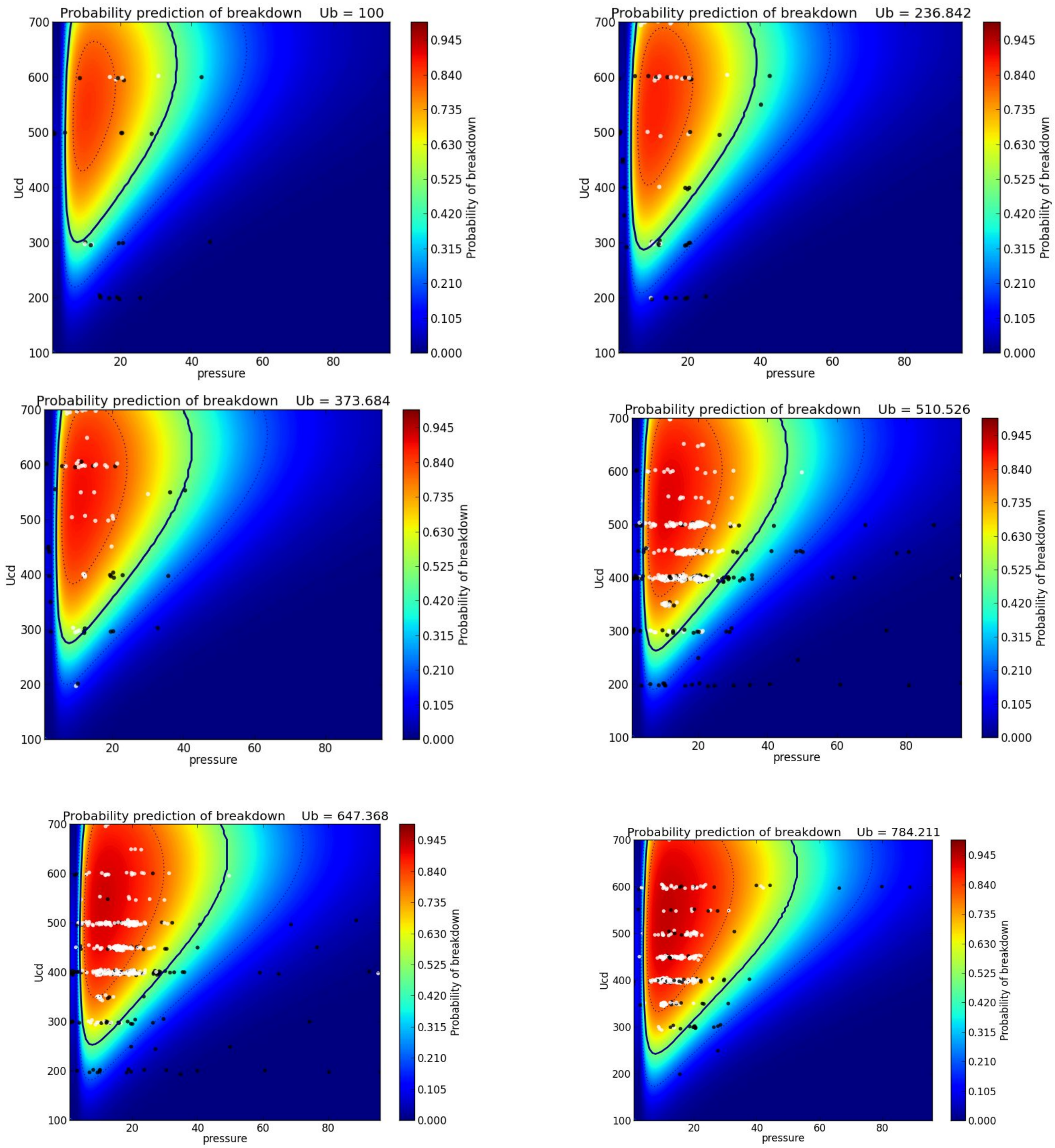


Fig. 4 - Probability maps using 10 000 training points. They show slices for different values of U_b. The color of the graph shows the estimated probability of successful plasma breakdown. The pressure is measured in [mPa], U_{cd} and U_b are in [V]. The shape of the black curve resembles a Paschen curve.

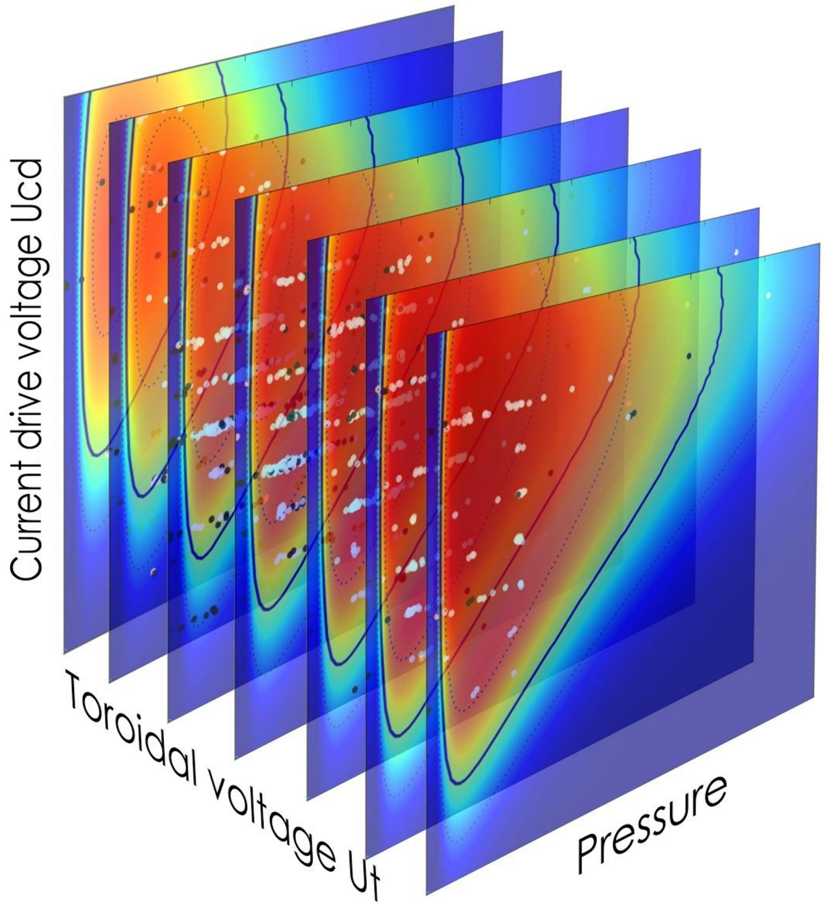


Fig. 5 - A 3D visualization of the graph slices in figure 4. Pressure [mPa], U_t and U_{cd} [V]

It can be observed that as the toroidal voltage increases, the minimum current drive voltage decreases for a given pressure and that as pressure increases, the minimum current drive voltage increases for the given toroidal voltage but not for pressures that is below the tripping point. These results, similarly to the Paschen's curve, behave almost linearly above a certain pressure threshold, the relation among the variables may be expressed in the following expressions: $U_{cd} \propto p \mid p \geq p_{min}$ and $U_{cd} \propto \frac{1}{U_b} \mid p \geq p_{min}$ where p_{min} is the lowest pressure for successful breakdown at any parameter configuration.

The possible explanation for this trend is that at higher pressure, more gas is present in the chamber. This means a larger quantity of atoms have to be ionized. This requires a greater voltage in the current drive in order to complete the ionization of the plasma.

As was already stated earlier voltage U_b is proportional to the toroidal magnetic field B_T created in the chamber. This magnetic field is responsible for the compression of the ionized gas in the chamber. With a greater magnetic field, less charged particles are able to escape the magnetic confinement. This results in a larger number of collisions and a higher probability of the plasma breakdown.

Testing the accuracy of the prediction

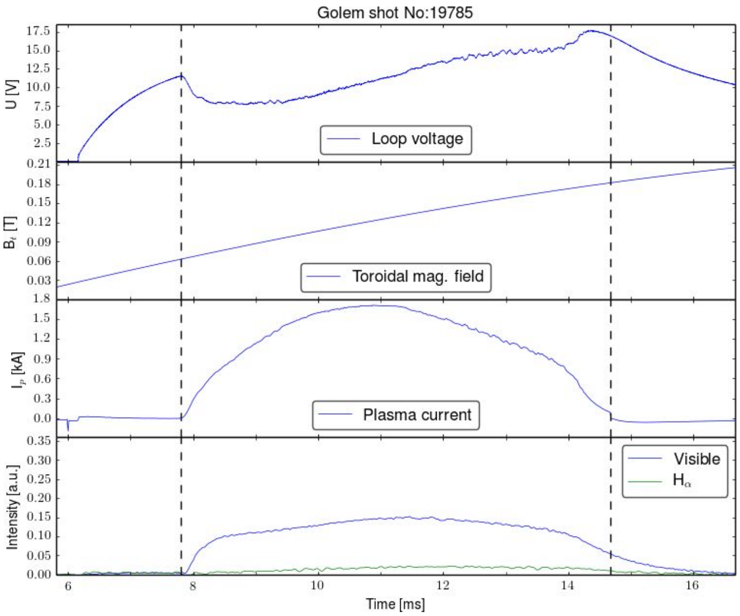
The ability to predict the outcomes of previously unknown initial conditions was examined. *Figure 6* shows a table with the results of experiments with different initial conditions and predictions using the estimated curve. It also includes the actual outcome of the experiment

Fig. 6 - Initiated shots with their estimated probability using 10 000 training samples.

Shot #	U_b [V] ±2.5%	U_{cd} [V] ±2.5%	Pressure [mPa] ±10^{-4} Pa	Estimated Probability %	Plasma present
19785	600	500	20	76	Yes
19786	200	300	30	61	Yes
19787	150	200	30	1	No
19788	200	200	30	1	No
19789	250	200	30	1	Yes

To gain a better understanding of the plasma breakdown, it is important to study some individual discharges. For the first 4 tests, the prediction of a successful breakdown was successful. However for the last shot, despite very low probability of a plasma breakdown, plasma was detected in the chamber. This is a strange outlier and has to be considered as an anomaly. Comparing the time graph of shot #19785 with #19789 in *figures 7 and 8* respectively shows major differences in the breakdown of the plasma. It can be observed that in *figure 8* the breakdown has occurred at a later point in time. The toroidal magnetic field has to reach a certain level before the breakdown can occur. It takes time before the field reached at least

0.075T and, therefore, the breakdown was delayed. In the graphs the breakdown is shown by an increase in the plasma intensity. Due to lower voltage charge in the



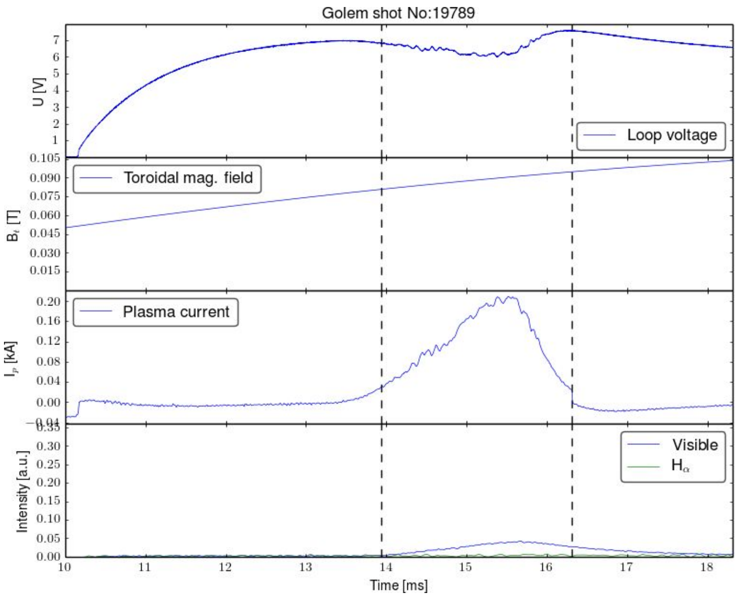


Fig. 7 - Time graph of shot #19785 *Fig. 8 - Time graph of shot # 19789*

capacitors (less than half that in shot #19785) it took longer to reach this magnetic field. Because the gas was not compressed enough, the heating was very slow. When comparing the maximal intensity of the plasma, in shot #19789 it is just 30% of that in shot # 19785. This shows that only a small number of atoms was ionized.

It must be concluded that shot #19789 was an anomaly that did not fit the system. It is possible that if more data was collected, especially in the region where the breakdown is on the edge of stability, the prediction might be more reliable.

In order to get a better picture of the performance of the algorithm with varying number of training samples, the program was trained with different number of training samples and then the predictions were made for 80 test samples. A guess was considered to be successful if the program predicted a 50% and greater probability for the breakdown and plasma was actually present and vice versa. The results were plotted on the graph in *figure 9*.

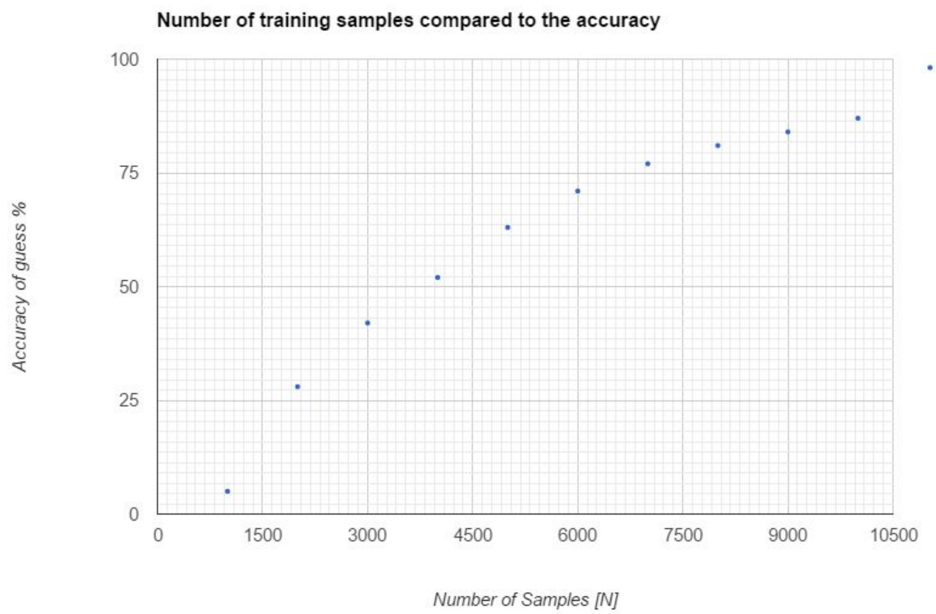


Fig. 9 - Graph of the number of training samples given to the program compared to the accuracy of the guess.

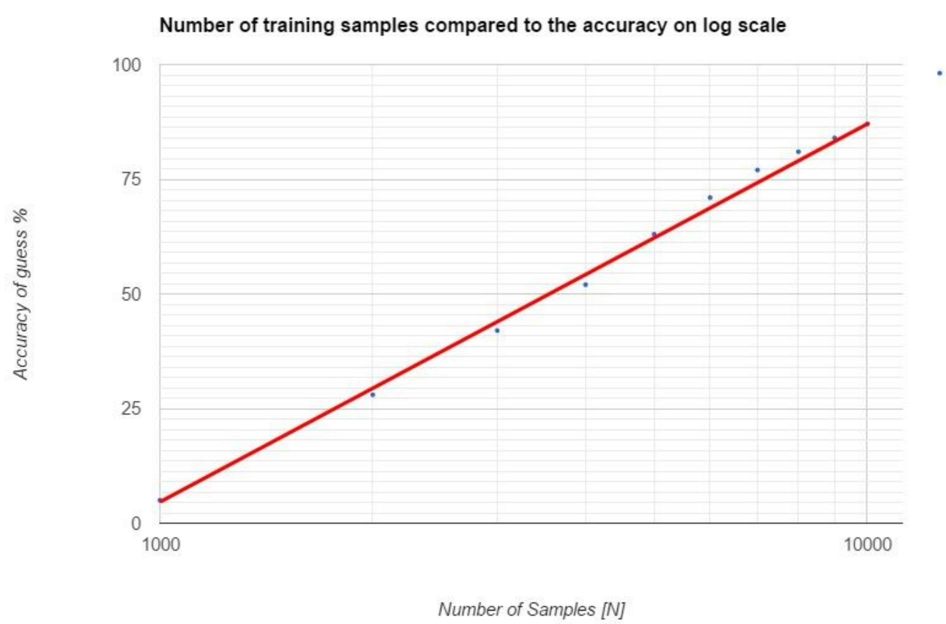


Fig. 10 - Same graph as in figure 9 with the number of samples axis plotted in logarithmic scale

The accuracy of the prediction increases with a growing number of samples. That is because in greater training samples, a larger quantity of ‘edge’ cases is present that helps to estimate more accurately the border between the two groups.

The graph in *figure 10* was plotted in order to see the relationship of the two variables on a large scale. The data points are linear which would suggest a logarithmic relationship. However, upon closer inspection, the lower half of the points are rather an ideal logarithmic plot and the upper half is above. This suggests that the relationship is described by a more complex expression.

The graph gives the intuition that greater number of training samples yields a better accuracy. At the same time, it shows that at the beginning, adding a small number of samples to the system improves the performance greater than towards the end. To illustrate, changing from 1000 samples to 2000 samples increases the guess accuracy by over 20%. However increasing the number of samples from 9000 to 10000 is only an improvement of about 3%.

Therefore much greater number of samples points have to be added in order to improve the predictions any further.

Conclusion and evaluation

This experiment attempted to find **To what extent is it feasible to estimate the breakdown probability for a plasma discharge in the GOLEM tokamak using a machine learning algorithm trained using precedent discharge results?** Experimental data were analyzed using a machine learning algorithm and the breakdown probability of the discharge was estimated. It was found, that the distribution of the probability curve resembles a Paschen curve for an arc discharge. Using this information, it is possible to estimate the outcome of an experiment with untested conditions by extrapolating the obtained graphs. In order to measure the performance of the estimations, the algorithm was trained using different number of samples and was tested against a set of testing samples.

It was found that increasing the number of training samples has the effect of improving the accuracy of the guess. The relationship was found to be approximately logarithmic which leads to several conclusions.

- The improvement is greater for smaller values and reduces, as the number of samples increase.
- This leads to the argument that in order to improve the accuracy further, much larger training samples have to be analyzed which makes the method less effective.
- With 10000 training samples, the guess accuracy is over 80% which is sufficient prediction rate. Therefore the method can be considered feasible.

Limitations of the method

One problem with this method is the fact that is generalizes the prediction and thus it fails at predicting outliers. However as was found in the second half of the investigation, the estimations accuracy increases with a growing number of samples. ‘Anomalies’ - (special cases that lie on the border between the two groups) that are rare only contribute a minor weight to the prediction when small number of training samples is used. However using larger training samples these special cases are more abundant and have a much bigger influence. This is one reason why the estimation improves with a growing number of training samples. The method is also very susceptible to outliers among the input data. This can be seen in particular in the first graph for $U_b = 100$ in *Fig. 4*. The curve is far from resembling the Paschen curve. This is mainly due to the fact that not many experiments are being conducted with $U_b = 100$. This has the effect that outliers (experiments gone wrong even under desirable conditions) have a greater influence on the data spread. Due to the very instable nature of the plasma breakdown at this voltage, a large number of anomalies affects the data. For this reason, a great portion of the data has been filtered and discarded in order to give more weight to the relevant data.

The question is if it effects the analysis. The discarded data might be useful in a way. This question could be examined in a future report.

Precision of instruments

Because the measurements deal with very small quantities and fast time intervals, it is necessary to use computers for the measurements. As a result it is difficult to estimate the uncertainty of the experimentation. For the pressure, the uncertainty is taken as ± 10^{-4} Pa because the pressure is given by 1 decimal place in mPa (10^{-3}).

According to the University, The Voltage has an uncertainty that is very much debatable. That is due to the fact that when the capacitors are sampled for voltage during the charging phase, the sampling rate is relatively low. Therefore it is the case that all the capacitors are always overcharged charged by a certain amount. This introduces a systematic error into the calculations. However the system is calibrated to take this into account. For the purpose of this experiment the uncertainty of the voltage is assumed to be ± 2.5%.

Overall the essay comes to a conclusion that the method is feasible at predicting the probability of plasma breakdown in the GOLEM Tokamak. New discharges can be added to the training sample making it ever more accurate. Perhaps one day this method may contribute to goal of creating a sustainable and cheap source of electricity using the plasma fusion in tokamaks.

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Appendix A:

The analysis programs used in this essay were written in Python 2.7 using numpy and the scikit-learn library. The source code may be found at https://github.com/zpiman/EE

The repository includes a number of scripts used to download the data, put the data in a desired form, clean up the data as well as the training script and a number of other supporting scripts that help to plot the data etc.