STUDY OF THE HYDROGEN PLASMA BREAKDOWN PHASE IN THE "GOLEM" TOKAMAK REACTOR

THESIS

To meet one of the requirements to achieve a Strata One (S-1) education degree as Bachelor of Science at the Department of Physics

Compiled by:

Derap Pena Mukti Sari

24040120140127

PHYSICS STUDY PROGRAM
DEPARTMENT OF PHYSICS
FACULTY OF SCIENCE AND MATHEMATICS
DIPONEGORO UNIVERSITY
SEMARANG
January, 2024

PERSETUJUAN UJIAN TUGAS AKHIR

Yang bertanda tangan di bawah ini Dosen Pembimbing dari:

Mahasiswa	: Derap Pena Mukti Sari
NIM	: 24040120140127
Jurusan/Fakultas	: Fisika/FSM
Judul Skripsi	: Kajian Fase *Breakdown* Plasma Hidrogen pada Reaktor Tokamak "GOLEM"

Menyatakan bahwa mahasiswa tersebut telah melaksanakan Ujian Seminar Hasil Skripsi sehingga menyetujui dan layak untuk melaksanakan Ujian Tugas Akhir.

Semarang, 4 Januari 2024

Dosen Pembimbing I,

(Prof. Dr. Drs. Muhammad Nur, DEA)
NIP. 195711261990011001

Dosen Pembimbing II,

(Qidir Maulana BS., M.Sc., Ph.D)
NIP. 198603142012121006

PERNYATAAN ORISINALITAS

Dengan ini saya menyatakan bahwa dalam skripsi ini tidak terdapat karya yang pernah diajukan untuk memperoleh gelar akademis di suatu perguruan tinggi, dan sepanjang pengetahuan saya juga tidak terdapat karya atau pendapat yang pernah ditulis atau diterbitkan oleh orang lain, kecuali secara tertulis diacu dalam naskah ini dan disebutkan dalam daftar pustaka.

Semarang, 4 Januari 2024

Derap Pena Mukti Sari
NIM. 240401120140127

HALAMAN PENGESAHAN
SKRIPSI

Kajian Fase *Breakdown* Plasma Hidrogen pada Reaktor Tokamak "GOLEM"

Disusun Oleh:
Derap Pena Mukti Sari
24040120140127

Telah diujikan dan dinyatakan lulus oleh Tim Penguji
Pada tanggal Januari 2024
Tim Penguji,

Dosen Pembimbing I,

(Prof. Dr. Drs. Muhammad Nur, DEA)
NIP. 195711261990011001

Dosen Pembimbing II,

(Qidir Maulana BS., M.Sc., Ph.D.)
NIP. 198603142012121006

Penguji I,

(Zaenul Muhlisin, M.Si., F.Med.)
NIP. 197806082003121001

Penguji II,

(Pandji Triadyaksa,Ph.D., F.Med.)
NIP. 198101272006041002

Penguji III,

(Prof. Dr. Heri Sutanto, SSi., M.Si., F.Med)
NIP. 197502151998021001

Skripsi ini telah diterima sebagai salah satu persyaratan untuk memperoleh gelar Sarjana Sains (S.Si)
Tanggal, 12 Januari 2024

Ketua Departemen Fisika,

Prof. Dr. Heri Sutanto, SSi., M.Si., F.Med
NIP. 197502151998021001

PERNYATAAN PERSETUJUAN
PUBLIKASI SKRIPSI UNTUK KEPENTINGAN AKADEMIS

Sebagai civitas akademik Universitas Diponegoro, saya yang bertandatangan di bawah ini:

Mahasiswa	: Derap Pena Mukti Sari
NIM	: 24040120140127
Program Studi	: Fisika
Jurusan	: Fisika
Fakultas	: Sains dan Matematika
Jenis Karya	: Skripsi

Demi pengembangan ilmu pengetahuan, menyetujui untuk memberikan kepada Universitas Hak Bebas Royalti Noneksklusif atas karya ilmiah saya yang berjudul:

Kajian Fase *Breakdown* Plasma Hidrogen pada Reaktor Tokamak "GOLEM"

Beserta perangkat yang ada. Dengan Hak Bebas Royalti Noneksklusif ini Program Studi Fisika Fakultas Sains dan Matematika Universitas Diponegoro berhak menyimpan, mengalih media/ formatkan, mengelola dalam bentuk pangkalan (database) merawat, dan mempublikasikan skripsi saya selama tetap mencantumkan nama saya sebagai penulis/pencipta dan sebagai pemilik hak cipta.

Dibuat di : Semarang

Pada Tanggal : 4 Januari 2024

Yang menyatakan

METERAI TEMPEL
18DAKX782531238

Derap Pena Mukti Sari
24040120140127

FOREWORD

Alhamdulillah hirabbil 'alamin, praise be to the author to the presence of Allah Subhanahu Wa Ta'ala the ruler of the universe and its content, who has given strength so that the author can complete this Final Project, entitled " Study of The Hydrogen Plasma Breakdown Phase in The "Golem" Tokamak Reactor".

The completion of this Final Project is not solely due to the efforts made by the author himself, behind it all there are many parties involved in encouraging the author to be able to complete this work. Therefore, the author gives a big thank you to:

1. Both parents who ceaselessly offer prayers for the author, who always provide support in every path that the author chooses, who have given infinite love to the author, may they always be given health and blessings in their lives.
2. Prof. Dr. Drs. Muhammad Nur, DEA as supervisor I who has patiently directed the author in the process of making the Final Project, and always provides motivation and inspiration to the writer.
3. Mr. Qidir Maulana Binu Soesanto, S.Si., M.Sc., Ph.D as supervisor II who has been patient in guiding the author in compiling the Final Project.
4. Hutama Wahyu Nugraha and Dewinya Aminnata, as brothers and sisters who always give full support and love the author sincerely, may they always be given health and happiness.
5. Mr. Fajar Arianto, S.Si., M.Si., as a lecturer who is very humble and has patiently given input to the author in compiling the Final Project.
6. Dr. Philippe Moreau, as a mentor who inspired and guided the author during his fusion school in Thailand.
7. Dr. Vojtech Svoboda, as the chief operator of Tokamak GOLEM who has authorized the use of tokamak in ASPNF 2023 activities.
8. Thailand Institute of Nuclear Technology (TINT), Electric Generator Authority of Thailand (EGAT), International Atomic Energy Agency (IAEA),

as an organization that has organized the activity of ASEAN School on Plasma and Nuclear Fusion 2023.

9. Lara Zefani, who had been playing together, sought inspiration, provided shelter, and accompanied the writer during her studies.
10. Naqwa Mumtazah Purba, who always provides joy, support, input, and assistance to the author, especially during the preparation process to the presentation of this Final Project.
11. Mega Suci Lestari who has taught many things about patience and happiness to the author, reality is what stands in between...
12. Angelita Shinta who always covers the author with encouraging jokes and provides support and assistance to the writer.
13. Pricha Aisha who has been a friend during KKN, who always supports and patiently listens to the author when telling stories about the same problem.
14. Elisabeth, Vita, Enji, friends of Radiation Physics 2020, friends of ASPNF 2023, and friends of KKN Desa Wiroko, who have donated fragments with beautiful colors on the tapestry of the author's life.
15. Those who the author did not mention, for all the good and bad things that make up the pile of life learning are priceless for the author to become a better person.
16. Derap Pena Mukti Sari to be able to complete this Final Project, to be able to rise many times, to be able to see hope, to be able to try and keep trying.

"Out beyond ideas of wrongdoing and rightdoing, there is a field. I'll meet you there…"

(Rumi)

Semarang, 2 January 2024

Writer

TABLE OF CONTENTS

TABLE

LIST OF IMAGES

ATTACHMENT LIST

MEANING OF EMBLEMS AND ABBREVIATIONS

H	: Hydrogen
He	: Helium
T	: Tritium
Li	: Lithium
p	: Pressure (Pa)
n_e	: Electron density (m^{-3})
D	: Deuterium
E	: Energy
m	: Mass (kg)
ITER	: International Thermonuclear Experimental Reactor
q	: Particle charge (C)
v	: Particle velocity (m/s)
B	: Medan magnet (T)
CASTOR	: Czech Academy of Science TORus
R_0	: Radius major tokamak GOLEM (m)
a	: Issued-Issued Tokamak Golem (m)
E	: Electric field (V/m)
α	: Townsend's first coefficient
λ	: The average clearance of particles (mean-free-path)
e	: Electron load (C)
Vi	: Ionization potential (V)
η	: Efficiency
γ	: Townsend's second coefficient
d	: Gap width (m)
U_{BD}	: Tegangan breakdown (V)
U_{BT}	: Toroidal voltage (V)
U_{CD}	: Voltage on transformer core (V)
T_{CD}	: Time delay between capacitor and $U_{BT}U_{CD}$(s)
T_e	: Temperature electron (K)
P_{OH}	: Ohmic heating (W)
q(a)	: Edge safety factor
Z_{eff}	: Effective payload number
U_{loop}	: Loop voltage (V)
I_p	: Arus plasma (A)
μ_0	: Magnetic permeability constant ($4\pi \times 10^{-7}$ m/A)
B_t	: Medan magnet toroidal (T)
t	:Time (s)
T_{dis}	: Discharge duration (s)
$I_{p,max}$	: Maximum plasma current (A)

ABSTRACT

The breakdown phase of plasma in a tokamak is a crucial stage before achieving fusion conditions. This stage will influence the quality of electron production, plasma purity, plasma stability, and more. This study aims to determine the optimum parameters during the breakdown phase in the GOLEM tokamak by examining the effects of gas pressure and transformer core voltage on breakdown voltage, discharge duration, and maximum plasma current. The research is conducted remotely using a computer to access the website connected to the GOLEM tokamak. Eighty discharge data points from the GOLEM tokamak website database are plotted into graphs. The optimal gas pressure falls within the range of 7-15 mPa. In this pressure range, the discharge duration (T_{dis}) and maximum plasma current ($I_{p,\ max}$) reach relatively the highest values $(11{,}59 - 13{,}56\ \text{ms};\ 2{,}6 - 3{,}82\ \text{kA})$. An increase in the transformer core voltage (U_{CD}) results in an elevation of breakdown voltage ($U_{breakdown}$), discharge duration (T_{dis}), and maximum plasma current ($I_{p,\ max}$).

Keywords: *Fusion, Plasma, GOLEM Tokamak, Breakdown phase, Paschen curve, Relationship between Pressure and Breakdown Voltage.*

CHAPTER I
INTRODUCTION

1.1 Background

In 2018 fossil energy accounted for 67% of energy consumption globally, and 99% of total CO_2 emissions came from energy consumption, and without a doubt CO_2 is a major contributor to the problem of climate change and environmental damage over the past 50 years (International Energy Agency, 2020), (BP Statistical Review of World Energy, 2022), (Ehiagimusoe *et al*., 2019), (Holecheck *et al*., 2022). It is predicted that crude oil and natural gas reserves globally are only enough to last for 41.8 years and 60.3 years (Behrouzi, 2016). These problems all encourage researchers in the world to create a renewable energy source that can meet future needs. One of the breakthroughs to deal with this problem is technology by utilizing nuclear reactions.

Current nuclear technology utilizes two types of reactions called fission and fusion reactions. More than 400 fission power plants have been operating for more than half a century (Knapp, 2018). Nuclear fission is the process of splitting heavy nuclei such as uranium or plutonium by firing neutrons, the nuclei then split into two lighter nuclei and at the same time release two or three neutrons and energy, which are then converted into heat to be used as power generation (NEA, 2003). Although fission technology does not produce air pollution or the greenhouse effect, its production process poses many problems such as radioactive waste and the risk of fatal accidents. On the other hand, fusion technology is relatively safer, although both produce radioactive waste, the problem of waste treatment in the fusion process is much less when compared to fission. The waste from the fusion reaction is tritium with a half-life of 12 years, while fission as one example of plutonium has a half-life of about 24000 years. No less important advantage of fusion technology is its abundant fuel source, which can be extracted from seawater easily, cheaply and its unlimited existence (Ariola and Piranti, 2008).

Fusion is a source of energy produced by the sun and stars by combining hydrogen atoms into helium atoms, a process that occurs releasing large amounts of energy. In fusion power plants, the atomic elements combined are tritium and deuterium. This process will produce helium nuclei with a larger mass, neutrons, and also the difference in mass released in the form of kinetic energy of the nuclei of the α products of 17.59MeV which then the energy will be collected for use in electricity production (Kikuchi *et al*., 2012).

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 17.59\mathrm{MeV} \tag{1.1} $$

Fusion reactor fuel is available in abundance and unlimited on the scale of human civilization, deuterium can be found naturally abundant in water with a scale of 1:6000, this means that there is 1 atom of deuterium in 6000 atoms of hydrogen. Although tritium cannot be found naturally, it can be produced by utilizing lithium which is also available abundantly in the earth's crust and oceans (Kikuchi *et al*., 2012). The energy released from the fusion reaction with deuterium and tritium fuel weighing 1-gram is equivalent to the energy produced by 7.4-tons of petroleum, or also equivalent to 1-ton of coal (Walker *et al*., 2020).

The temperature required to reach the desired conditions for a thermonuclear reaction to take place, ranges from 10 keV ($1\, eV \approx 11604\, Kelvin$) or about 100 million degrees Celsius. At that temperature the fuel will be fully ionized and reach a state with equal numbers of electrons and ions resulting in a neutral gas state called plasma (Wesson, 2004). The large temperature value needed to achieve the fusion reaction causes a machine wall material alone to be unable to hold the plasma from escaping. TOKAMAK, which comes from the Russian "*toroidal kamera ve magnetnaya katushka*" or "toroidal chamber with magnetic coil", offers a method of confinement of plasma in a toroidal by a magnetic field and rotating in a small orbit. In this way, it is possible for plasma to travel a distance of one million times the size of the engine, with the concept of TOKAMAK such high-temperature plasma will not touch the reactor wall (Wesson, 2004).

The start-up process is a complex but has little attention in the history of TOKAMAK's research. Many experiments have not succeeded in producing fusion reactions even though high temperatures have been reached. In the 2009 JET experiment, there were more than 100 failures in the initial phase (non-sustained breakdown shots). Plasma breakdown is a condition when the plasma current and degree of ionization are low but the collision between electrons and neutral molecules is high (Siusko *et al.*, 2021). Breakdown is quite an important phase in the initial operation of the tokamak because it will affect the later stages: production of moving electrons, impurities, equilibrium, stability, etc. (Siusko *et al.*, 2021). This research will discuss the breakdown phase and the influence of the pressure and also the transformer core voltage on the breakdown voltage produced using a type of hydrogen gas.

1.2 Research Objectives

1.2.1 Specifies the optimal value of hydrogen gas pressure on the Paschen curve in the breakdown phase of hydrogen plasma on the GOLEM tokamak.

1.2.2 Analyze the effects of hydrogen gas pressure and core transformer voltage on breakdown voltage, discharge duration, and maximum plasma current in the hydrogen plasma breakdown phase on the GOLEM tokamak.

1.3 Research Benefits

This research is expected to help understand the condition of hydrogen plasma in the breakdown phase of tokamak. Knowing the optimum plasma condition in the breakdown phase is expected to help realize optimal conditions in the next phases such as burn burn-trough phase, current rump-up, and better tokamak performance.

CHAPTER II
THEORETICAL BASIS

2.1 Plasma

When a solid is heated to a thermal motion in the atoms to damage the structure of the crystal lattice, a liquid is usually formed. When the liquid is heated enough for the atoms to evaporate from the surface and faster than their process to condense, then a gas is formed. When a gas is heated enough for atoms to collide with each other and give up their electrons in the process, a plasma is formed, referred to as the 'fourth state of matter' (Goldston, 1995).

Plasma is usually only found in a vacuum, because air can cause plasma to cool and it can trigger a recombination event or the recombination of ions and electrons into atoms. But plasma can also be found on Earth, such as lightning flashes, Aurora Borealis light, fluorescent lamps, pixels from plasma TVs, or thermonuclear reactors. Media containing a charged particle cannot always be said to be plasma, a fairly precise definition according to Chen (2016) is, plasma is a quasineutral gas of charged particles and neutral particles that show collective behavior.

A gas can be said to be quasineutral if it is composed of equal amounts of positive charge (ions) and negative charge (electrons).

$$n_e \approx n_i \tag{2.1}$$

With n_e the electron density and n_i the positive ion density, under plasma conditions, the electron density will be equal to the positive ion density. In ordinary air molecules, where molecules are in a neutral state, no electromagnetic force will be found acting on them. Air molecules

It can move without interference until it collides with other molecules, this collision is what regulates the movement of these molecules. Plasma, on the other hand, is composed of charged particles. As these charged particles move they can give rise to an area composed of positive or negative charges, which is what causes an electric field. The movement of the charge can also cause currents, and the current will cause a magnetic field. It is this electric field and magnetic field that will then affect the movement of charged particles even over long distances. The influence of this field causes plasma to have a different behavior from molecules or gases that are neutral in general, this is called collective behavior. The collective behavior exhibited by plasma is generated by the presence of long-distance Coulomb forces between its constituent charges. The effect produced by the charges on each other is likened to (Figure 2.1).

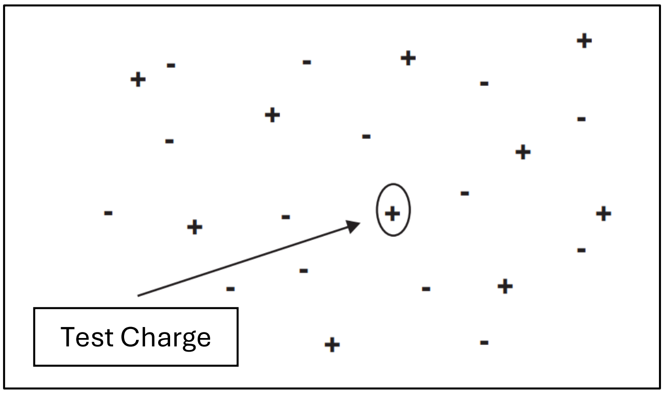

Figure 2.1 Charged particles (ions) test in plasma (Nur, 2011)

The test charge introduced into the plasma will get the potential force from the plasma around it. This means that each particle in the plasma interacts with many other particles. Elements in plasma can generate forces between one and another even at long distances. This is what causes the emergence of collective behavior from plasma and also provides a lot of space to be studied in plasma science (Chen, 2016) and (Piel, 2010).

Plasma is classified into three types based on its temperature range, namely cold plasma with a temperature of about 1000 K which is commonly used in agriculture, microelectronics, pollutant cleaning etc. Thermic plasma has a temperature of >3000 K which is often used for metal cutting, welding etc. Hot plasma or plasma with temperatures above 10 million kelvins intended for producing electrical energy (Nur, 2011).

2.1.1 Breakdown Phase

In the laboratory, electrical discharge is carried out in a tube containing gas with a certain pressure at the end of which there is a plate parallel to the electrode and connected to a high voltage DC (direct current), which will then occur electrical discharge between the electrodes (Figure 2.2).

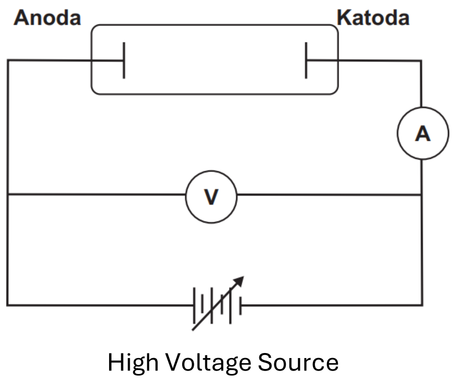

Figure 2.2 Gas discharge cylinder (Nur, 2011)

Plasma bursts are formed by electrical breakdown events in gases. Gas whose basic nature is an insulator, in the breakdown state will turn into a conductor. This generation process causes the next current flow to produce an electrical discharge.

The breakdown condition is a term to represent the process of electron multiplication in gases and the release of electrons from the cathode caused by ion collisions (towards the cathode). As the first electrons are released from the cathode which is then accelerated by an electric field, they can ionize the gas atoms they pass through. When this process occurs, an ion-electron pair is formed, and then two electrons are accelerated and then again collide with the gas and produce four electrons and will continue to create a chain ionization and electron collapse (electron avalanche) (Figure 2.3). Electrons will be accelerated by the electric field towards the anode and positive ions will be accelerated towards the cathode and produce new electrons.

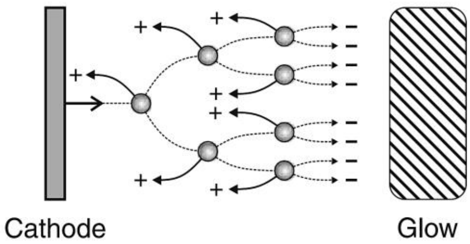

Figure 2.3 The process of electrons being emitted from the cathode and producing new pairs of electrons (Piel, 2010)

Low voltage will not have a significant effect on the current. But when the voltage begins to increase, the particles will have additional energy and the ionization process begins to increase so that the electric current will increase with the voltage, this is referred to as Townsend discharge (named after John S. Townsend, 1868-1957).

When the voltage is increased and more ionization occurs which then produces electrons due to photoelectric events, there will be a change in gas conditions to be conducting (conductors) which is called the breakdown state (Figure 2.4). In this phase, there begins to be a beam of light (emission) at the cathode due to the bremstrahlung event caused by ion collisions accelerated by the electric field. After this state, there will be an increase in current due to the number of electrons produced or what is called the normal state of glow discharge. Emissions occur that cover only a small part of the cathode surface. In this discharge ionization will occur in a chain, the voltage is lower and almost constant because it no longer requires additional voltage from outside for ionization to occur with a current range $I \approx (0.1 - 10)$ mA (Figure 2.4). The current will continue to increase until the cathode is completely covered by light emission. Furthermore, the voltage rises again with a higher current which then forms anomalous/abnormal glow discharge (Nur, 2011) and (Piel, 2010).

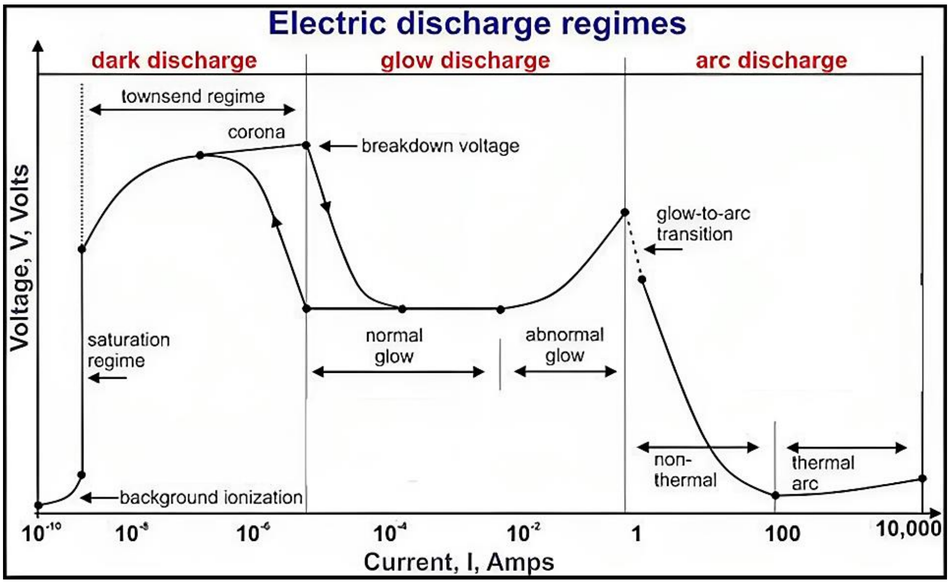

Figure 2.4 V-I curve for low pressure gas discharge (Magaldi *et al*., 2021)

If the voltage is continuously increased, the temperature at the cathode will increase further as high-energy ions continue to pound it and produce more electrons. As the electron overflow current also increases, the type of discharge formed in this state becomes unstable (depicted by a dotted line on the curve). In the next state the voltage will decrease and the current continues to increase which is called arc discharge, formed with a discharge current above 1 A.

2.1.2 Average free path

Mean free path (λ) is a term to represent the average distance traveled by a particle (ion, electron or atom) before colliding with another particle, which is formulated with (Piel, 2010):

$$\lambda = \frac{1}{n \cdot \sigma} \tag{2.2}$$

with n as the density of the particles and as (m^{-3}) and σ as a cross-section (m^2) or collisions that occur between particles or areas effective for collisions to occur.

2.2 Fusion & Thermonuclear Fusion Reactors

The path to the use of nuclear fusion energy opened in 1958 at the 2nd Atoms for Peace Conference, when scientists from around the world gathered and shared the results of their research in what was "one of the most collaborative scientific efforts ever undertaken" (Folwer, 1997). The purpose of all this is simply to be able to use the energy produced from the fusion of deuterium and tritium nuclei as an energy source to operate power plants.

Deuterium and tritium nuclei that collide with large energies in the tens of keV have a high probability of coming together to produce alpha particles (helium nuclei) and neutrons (Figure 2.5).

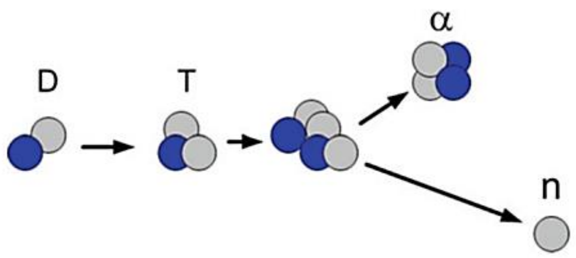

Figure 2.5 Diagram of the D-T reaction (Chen, 2016)

Possible reactions involving deuterium and tritium nuclei are:

$$D + T \rightarrow\ {}^{4}He + n + 17.6\ MeV \quad (2.3a)$$

$$D + D \rightarrow\ {}^{3}He + n + 3.3\ MeV \quad (2.3b)$$

$$D + D \rightarrow T + H + 4.0\ MeV \quad (2.3c)$$

$$D +\ {}^{3}He \rightarrow\ {}^{4}He + H + 18.3\ MeV \quad (2.3d)$$

In equation (2.3), it represents helium, and as neutrons resulting from the fusion process. In equation (2.3a) tritium is needed, tritium undergoes radioactive decay with a half-life of 12.3 years so that it cannot arise naturally, therefore tritium will be produced from lithium in the Henreactor blanket component by the following reaction:

$${}^{6}Li + n \rightarrow\ {}^{4}He + T + 4.8\ MeV \quad (2.4)$$

After the fusion reaction occurs, the total mass produced after the reaction will be less than the mass before the reaction, this "lost" mass is then turned into energy, which can be calculated by Albert Einstein's famous equation:

$$E = (m_r - m_p)c^2 \quad (2.5)$$

Where E represents the energy produced from the fusion reaction, m_r represents the total mass of the nucleus before the reaction, and m_p is the mass of the nucleus after the reaction, and c is the speed of light. The energy produced in the D-T fusion reaction is 17.6 MeV, most of the energy carried away by neutrons of 14 MeV. The energy carried by these neutrons will be captured and utilized for electrical power sources. The blanket on the components of the power plant will capture neutrons and convert their kinetic energy into heat which then rotates the turbine on the electric generator and also produces tritium fuel again. While the remaining 20% (3.5 MeV) of energy from α particles (helium) is trapped in the magnetic field that holds the plasma and will heat the plasma itself (Ariola and Pironti, 2008).

The way to realize the occurrence of this reaction is to make a plasma with a density on a scale of 10^{20} m^{-3} and the average energy of particles in tens of keV. The time limit for the thermal energy contained by the plasma to escape to the surface of the surrounding material must exceed about five seconds, so that the power generated by alpha particles can maintain the temperature of the plasma. In the 1990s researchers have succeeded in making fusion power of 2-10 MW in deuterium-tritium plasma with temperatures of 20-40keV and able to hold energy for 0.25-1 seconds. This can be compared to the 10MW power range produced by a deuterium plasma with a temperature of 1 keV with a holding time of only 5 milliseconds in the 1970s (Goldstone, 1995).

The result of a significant fusion reaction depends on the kinetic energy of the paired nuclei in overcoming the repulsive force (Coulomb) between nuclei that have the same charge. The cross-sectional relationship of the fusion trajectory as a function of the energy of particles in a mass center system with an energy range between 10 and 100 keV is shown in (Figure 2.6). It was found that at the same energy, the cross-section of the trajectory for the D-T (Deuterium-Tritium) reaction is much larger when compared to the D-D or ^{3}He-D reactions. This is the reason why all experiments today use D-T mixtures to produce fusion reactions (Piel, 2010).

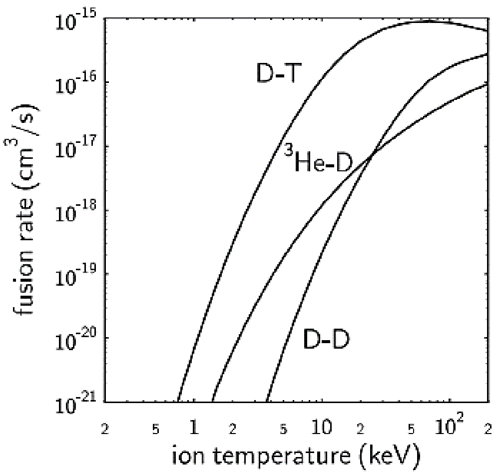

Figure 2.6 Cross section for fusion reactions D-T, D-^{3}He and D-D as a function of mass center energy (Chen, 2016)

A particle accelerator is not enough to create fusion reactions between D-T nuclei. The interaction between the projectile nucleus fired (think of it as the tritium ion) and the material of the object (electrons from the deuterium atomic beam) causes a considerable loss of energy because the projectile is unable to penetrate the object so that all initial energy is lost as heat in the shot deuterium beam (Figure 2.7).

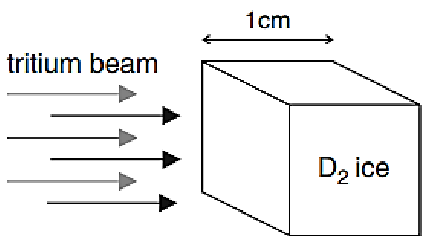

Figure 2.7 Illustration of a deuterium ice beam with a stream of tritium ions fired (Piel, 2010)

Nuclear fusion uses a different concept, heat does not become an energy that is lost during the collision process. In magnetic confinement, the D+ and T+ ions that make up the plasma are in thermal equilibrium that satisfies the Maxwellian distribution. Collisions that do not result in fusion, will only cause collisions between their partners (between individuals of charge) so that as not to change the heat content of the plasma itself, the energy gained and lost in elastic collisions is returned to the thermal distribution. Although there is still an energy leak through the bremstrahlung event during the collision process. But unlike the concept of particle accelerators with energy spread out on a microsecond scale, plasma energy in a magnetic confinement can be maintained on a second scale.

Although the D-T hot plasma is diluted, the results provided will be significant when the reactor can withstand particles and their kinetic energy for a long time. Such confinement can be achieved using a strong magnetic field called a tokamak. In this way, each projectile has the opportunity to repeatedly collide with the nuclei and form a fusion reaction.

2.2.1 Lawson's criteria

A fusion reactor will be useful when the power produced from the reaction is greater than the power used to heat the plasma and to operate it. The net output power produced by a fusion reactor can be measured by the term power gain or Q factor, which is defined as the ratio of the fusion output power (P_{output}) to the supplied input power (P_{input}), formulated by:

$$Q = \frac{P_{output}}{P_{input}} \tag{2.6}$$

Therefore, in order for fusion power to be able to reach the desired state as a value power plant. The state known as $Q > 1Q = 1$the break-even condition or Lawson's criterion is the condition when the resulting fusion output power is equal to the supplied input power, which is formulated as:

$$n\tau_E = 10^{20}\ s \cdot m^{-3} \tag{2.7}$$

As (n) the density of the particle and (τ_E) as the energy confinement time or length of time the plasma is able to survive before it is lost. Lawson's criterion provides information about the conditions of the density (n) and energy confinement time (τ_E) that must be met at a given temperature, for example the density and time of the confinement to achieve a D-T fusion reaction with a temperature value, formulating Lawson's criterion into ($T_e = 15 keV$ Kikuchi *et al*., 2012; Ariola and Pironti, 2008):

$$nT_e\tau_E > 1{,}5 \times 10^{21}\ keV \cdot s \cdot m^{-3} \tag{2.8}$$

2.3 Tokamak

The concept of the tokamak was invented in the Soviet Union in the late 1950s by scientist Igor Tamm and his former student Andrei Sakharov. Tokamak is an abbreviation of the Russian "*TOroidalnaya KAmera ee MAgnitaya Katushka*" which means "toroidal chamber with magnetic wire". A tokamak is a giant transformer, which contains the torus (geometric shape like a doughnut ring) of plasma forming a single secondary winding. The plasma is loaded inside a toroidal vacuum chamber, which is surrounded by coils of magnetic field to confine charged particles. Tokamak also became a promising device for the development of nuclear fusion power plants. Currently the tokamak is the subject of international research on the ITER (International Thermonuclear Experimental Reactor) project. An overview of the working principle of the tokamak is shown in (Figure 2.8).

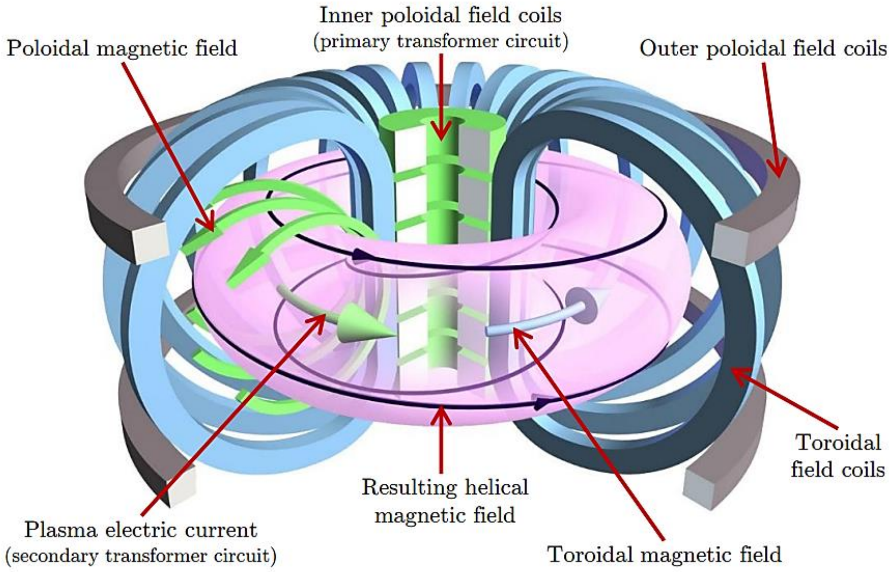

Figure 2.8 The principle of work of tokamak (Dubus, 2014)

The illustration above (Figure 2.8) shows the working principle of tokamak, which contains the main components in the form of:

- Vacuum vessel, the plasma space is represented by the area around the purple component in (Figure 2.8);
- Blanket, plays a role in absorbing 14 MeV neutrons and producing tritium which is also needed for the reaction in equation (2.3a), this component is made of lithium material so that the reaction in equation (2.3) can occur, the blanket will be in the inner layer of the tokamak (the inside of toroidal field coils);
- Toroidal field coils or coils of toroidal wire, which will conduct current and generate a toroidal magnetic field along the torus used to confine the plasma, represented by a blue component along the torus on (Figure 2.8);
- Outer poloidal field coils or outer poloidal wire coils, which will produce a poloidal magnetic field that functions to prevent high-temperature plasma from interacting with the wall on the Vacuum vessel, represented by gray components on (Figure 2.8);
- The green coil in the middle of the machine (Figure 2.8) is referred to as central solenoids (CS) or inner poloidal field coils which function to induce

plasma electric current along the torus formed by the action of the transformer, with CS being the main transformer and the plasma itself acting as a secondary transformer.

In the presence of a magnetic field, charged particles will show the rotation of the cyclotron simply around the magnetic field lines. The movement of these charged particles is formulated by the Lorentz force:

$$m\frac{d}{dt}v = q(v \times \boldsymbol{B}) \tag{2.9}$$

With m and q is the mass and charge of the particle, v is the velocity of the particle, and $\boldsymbol{B}$ as the magnetic field. When the velocity component is parallel to the magnetic field, which is also not affected by the Lorentz force, the path of the charged particle will take the form of a helix (Figure 2.9). The particles in this case will fall to the end of the magnetic field line, incompatible with the purpose of holding them on the trajectory. To solve this problem, the tokamak uses curved field lines and forms a torus (doughnut-like geometry) so that the trajectory of the particles does not end. The magnetic field will deflect the trajectory of charged particles around the tokamak to form a helical structure (Figure 2.9).

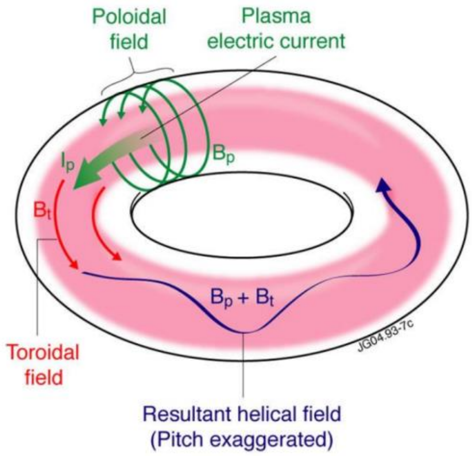

Figure 2.9 The combination of toroidal and poloidal magnetic fields that form a helical field along the torus (Twarog, *et al*. 2011)

The tokamak is a pulse machine (Figure 2.10), plasma is formed at each pulse ("start-up" phase), which is then pumped with a constant amount of current, referred to as a "flat-top" current, which is maintained in a burning state throughout the main phase of the initial discharge, and eventually the current decreases dramatically and plasma production ends. To initiate the discharge, hydrogen gas is flowed into the tokamak vacuum chamber and the current from the toroidal field coil will increase to create a magnetic field in a stable state which will later become a plasma site. Then a strong electric field is formed inside the torus using ohmic heating of the coils. This electric field breaks down neutral gas atoms which then form plasma. The current formed in the plasma is caused by a trasnformator. The collision of ions in the plasma causes the plasma to be resistive. It is this resistance that then heats the plasma (the origin of the term "ohmic heating").

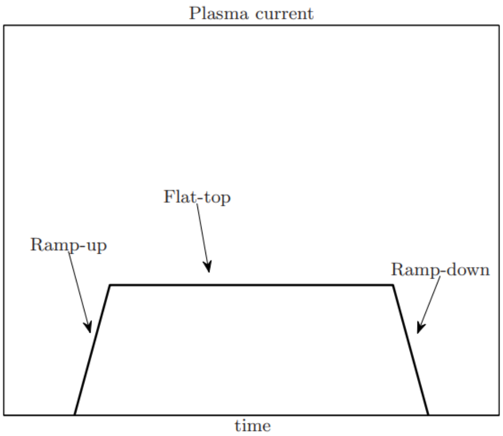

Figure 2.10 Scheme for plasma current during the initial discharge process (Ariola and Piranti, 2008)

As the temperature increases, the resistance decreases and ohmic heating is no longer effective. To enhance the fusion reaction, the temperature of the plasma must be more than 100 million degrees, which is six times hotter than this of a sun. This heat can be achieved by particle beams (injecting strong ions) or by radio frequency or microwaves (heating ions or electrons). After the discharge process begins, additional gas is flowed back into the vacuum chamber to increase the density and/or pressure to reach the desired level.

2.3.1 Tokamak GOLEM

Tokamak GOLEM operates at the Faculty of Nuclear Physics and Engineering Physics (FNPPE), Czech Technical University in Prague. GOLEM is a small tokamak built in the late 1950s at the Kurchatov Institute in Moscow under the name TM-1-MH. The tokamak was transferred to the Institute of Plasma Physics in Prague in 1977 and changed its name to CASTOR: Czech Academy of Science TORus, after its reconstruction in 1985. After 30 years of operation and decommissioning in 2006, CASTOR was transferred to FNPPE and reinstalled for educational needs for students which was later renamed GOLEM shown in (Figure 2.11).

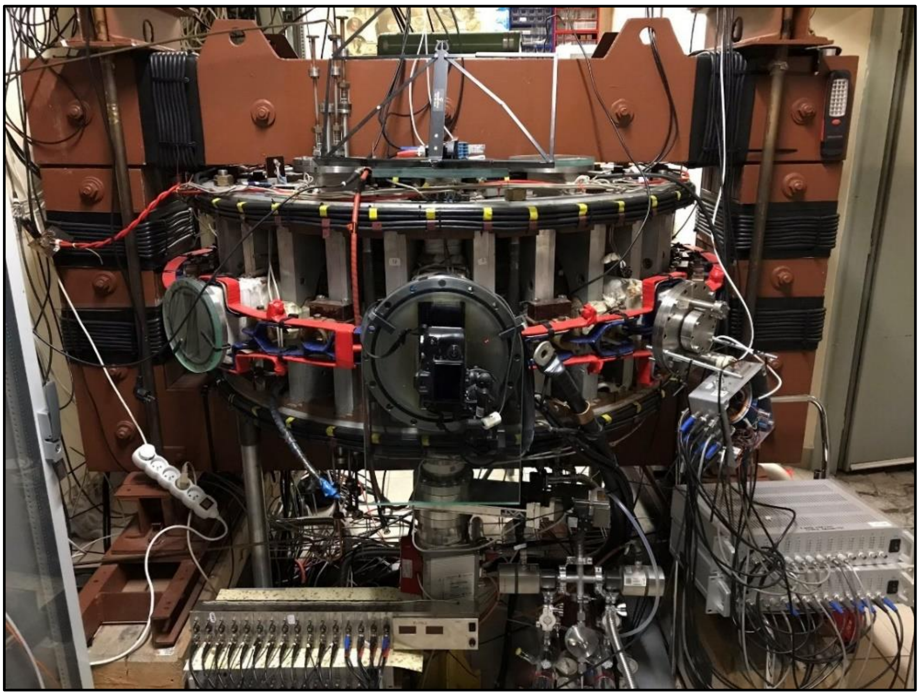

Figure 2.11 Tokamak GOLEM (Grover *et al*., 2016)

The GOLEM tokamak has a circular cross section, with the radius of the main vessel sized and the minor vessel $R_0 = 0.4\ m.\ r_0 = 0.1$ Vessels made of stainless steel are equipped with poloidal dividers made of molybdenum, with radius $a = 0.085\ m$. Tokamak has features that can measure loop voltage, plasma current, toroidal magnetic field, and visible emission. GOLEM is also equipped with Mirnov coils, visible spectrometers, a series of bolometers, fast cameras, and so on. Tokamak operates at a maximum toroidal magnetic field of up to 0.5 T. The central temperature of the electron is less than 100 eV, the maximum average line density is ~10^{19}m^{-3}, and the maximum pulse length is about 18 ms.

GOLEM has long been known for its operations that can be done remotely. Measurements and set-up of shots to charge can be set through the GOLEM tokamak website page (Figure 2.12). All systems have been arranged in such a way that the inputted parameters will not damage the GOLEM tokamak. The system is protected with some kind of token to access it provided by the operator for certain activities. In the experiment conducted for this study, the operator will send a link (URL) containing a token to access tokamak operations remotely.

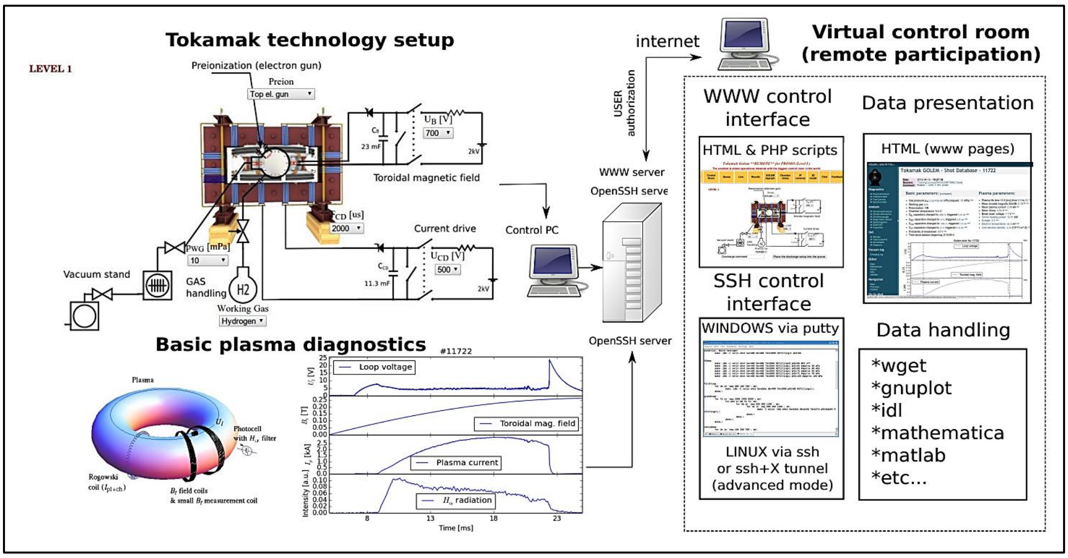

Figure 2.12 A comprehensive scheme of experiments on the GOLEM tokamak (Grover *et al*, 2016)

The Tokamak GOLEM website has several features such as (see Figure 2.13):

(i) **Home**, is a page that provides remarks and brief explanations regarding the facilities owned by Tokamak GOLEM,

(ii) **GOLEM wiki**, contains documentation, information related to set-up and parameters related to Tokamak GOLEM,

(iii) **Control Room**, on this page the user can s*et al*l the parameters needed for the discharge (discharge) of the desired experiment (such as, and will be passed to the $U_{BT}, U_{CD}, T_{CD}, p_{WG}, WG$)discharge queue.

(iv) **Queue**, a page for users to monitor all discharges with an estimated completion time.

(v) **Live**, a page that shows the current condition of tokamak operation, such as the current pressure in the tokamak vessel, the actual status of the tokamak (discharge queue, pre/due/post discharge phase),

(vi) **Result**, loads a database of all settings that have been inputted with an attachment of links to the corresponding main discharge page .

(vii) **IP camera**, a page with two parts, namely (a) provides a real-time view into the tokamak chamber (b) the display of the tank (vessel) inside, the user can see the discharge status that is on, the preionization filament light illuminates the vessel in the pre-discharge phase, and the plasma flash during the discharge.

(viii) **Chat**, giving access to a pre-prepared IRC protocol, allows many-to-many or one-to-one interactive discussions.

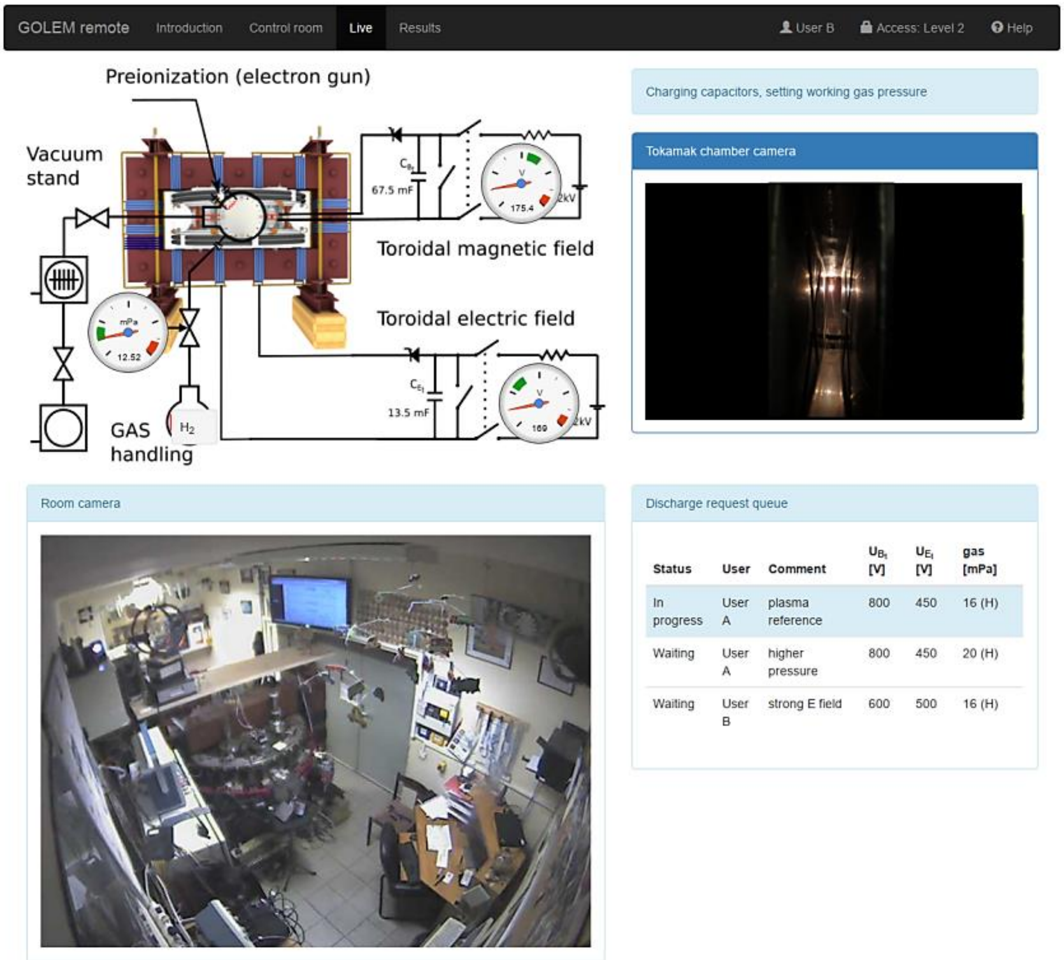

Figure 2.13 Website display during the shooting process discharge tokamak GOLEM live (Grover, 2019)

In the control room, there is access to adjust the charging voltage of the condenser bank used to power the toroidal field winding (UB) and transformer primary winding (UCD). Then, the time delay between UB and UCD trigger pulses is also pre-selected (tCD). In addition, the working gas (Hydrogen or Helium) and charging pressure (pWG) are also selected, as well as the type of pre-ionization you want to use (microwave or electron gun). This tokamak is designed to be used on groups or users who want to research at the same time. This is very possible because GOLEM has the ability to perform repeated operations every 2 minutes, and the operating limit is up to 200 discharges in one day (Grover, *et al.*, 2016).

2.3.2 Breakdown phase in tokamak

The avalanche breakdown condition is an important stage in the early stages of release in tokamak operation in order to achieve good plasma performance. The start-up phase of a tokamak consists of three phases: breakdown or avalanche, burn-trough phase or the phase when the plasma is dense and hot enough to be able to sustain its own fusion reaction, and the increase in plasma current (plasma current rump-up). The breakdown phase is characterized by a low degree of ionization, but is dominated by collisions between electrons and neutral molecules. The plasma current at the breakdown condition of the avalanche is very low as shown by the graph (Figure 2.14) of one of the shots in the early stages (start-up) of the golem tokamak.

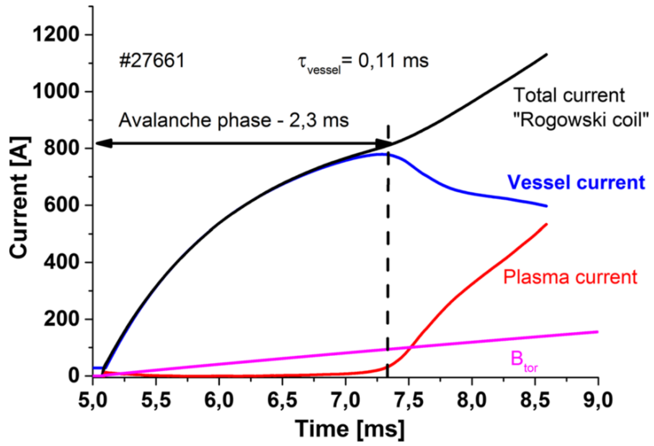

Figure 2. 14 Early-stage evolution (Start-up) on tokamak GOLEM (Svoboda, 2019)

To reach the breakdown phase, several conditions are needed in the vacuum chamber.The breakdown in tokamak generally depends on parameters: the value and size of the area with a low poloidal magnetic field, the value of the toroidal magnetic field, the toroidal electric field, and also the pressure of the gas used (Chektybayev, 2021). Based on breakdown modeling that has been done by Song *et al.*, (2017), free electrons will first be accelerated by a toroidal electric field (E) in a time span called breakdown time (τbd) until it reaches an avalanche state. There are several events that can affect, a common example is the deterioration of the reactor walls. τbd

Townsend's avalanche theory on a tokamak with a finite field and its application as early as 'ITER-Design 1998' (plasma current 21 MA, main radius 8.14m, minor radius 2.8 m, monolithic central soleid) resulted in a formula for a minimum electric field of toroidal at the growth of the (E_{min})avalanche process of a gas or or at room temperature state (300K) with pressure, for a length of $H_2 D_2 Tp$ (Pa)free-streaming-electrons, given with the equation:L (m)

$$E_{min} = 950p/ \, ln(3.88pL) \, Vm^{-1} \tag{2.10}$$

The ideal breakdown state should meet the criteria $E \geq E_{min}$. ITER is predicted to produce Townsend's 'Ohmic' avalanche breakdown that is reliable on the conditions, $E_{min} = 0.3\, Vm^{-1}, p = 1{,}4\, mPa \ (\approx 1.1 \times 10^{-5} Torr)$ and $L = 500\ m$ (Gribov *et al.*, 2007).

2.3.2 Edge safety factor q(a)

The edge safety factor $q(a)$ expresses the number of revolutions on the toroidal axis to achieve one turn of the poloidal axis. This illustrates how the shape of the magnetic field changes as it begins to reach the edge of the tokamak. Simply put, the helix shape of a magnetic surface is represented by $q(a)$ that illustrated in (Figure 2.15).

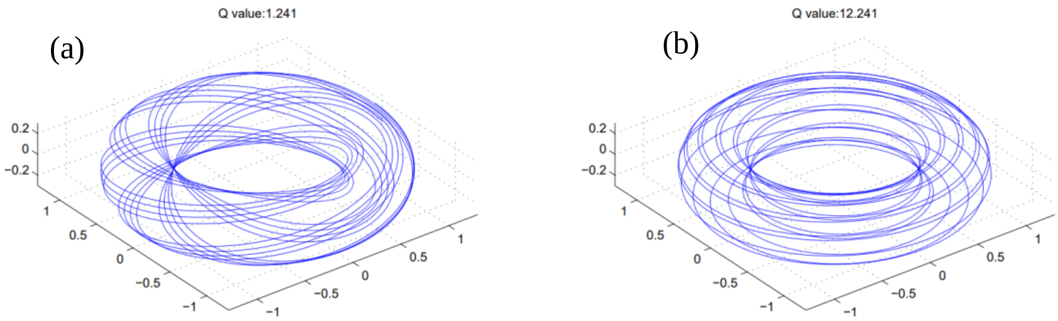

Figure 2.15 The magnetic field line in the tokamak for (a) the value q(a) 1,241 and (b) the value of q(a) 12,241 (Pokol *et al.*, 2014)

Based on the Hugill diagram, disturbances begin to form when $q(a) = 2$, when the current is given so large the value $q(a)$ produced will decrease which indicates instability in the plasma or known as tearing mode (Wesson, 1999).

2.4 International Thermonuclear Experimental Reactor (ITER)

One of the major projects involving many countries to develop tokamak is ITER. Some of the countries that contribute to this development are the European Union, Japan, China, India, Korea, USA, Russia. The size of the ITER is estimated to be several times larger than the size of the current tokamak. The design for the construction of ITER was approved in 2001 and is expected to produce the first plasma in 2025. ITER is located in the European Union precisely at the research site of Cadarache, the city of Aix-en-Provence in the southern part of France.

Figure 2.16 The site where ITER was built (a) the form of architectural design and (b) the original construction (Dubus, 2014)

The purpose of ITER development is to demonstrate the scientific and technological feasibility of realizing the utilization of fusion energy for peaceful purposes. Some of the missions to achieve these goals are:

- First, ITER must produce power greater than the power it consumes, the way is to produce fusion energy with energy gain (Q) being at a value of about 10 (equivalent to 500MW) for a few hundred seconds, and Q greater than 5 to about an hour, for comparison JET reactors have values $Q < 1$.
- Second, ITER must validate the basic design for future commercial use by demonstrating the use of superconducting magnets and remote maintenance.
- Third, ITER had to test the concept of tritium formation in reactors.

ITER will burn its fuel (deuterium-tritium) to produce 500MW of power over a long period of time, with an input energy of 50MW. ITER weighs 16 times that of the previous tokamak (more than 5000 tons) and is 2 times the size of the JET (almost 30 meters), which is equipped with superconducting magnets. The shape of the ITER tokamak is illustrated by (Figure 2.17).

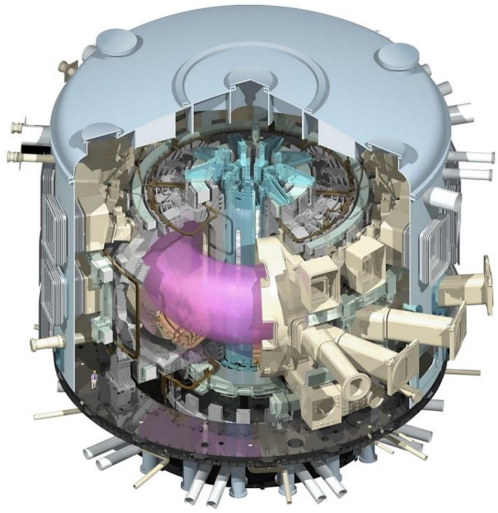

Figure 2.17 Illustration from ITER tokamak (Dubus, 2014)

The Central Solenoid (CS) of ITER is one of the important components that will produce strong currents. In the JET reactor, CS produces a plasma current of about 5 MA with plasma pulses able to last up to 60 seconds. The plasma volume in ITER will be 8 times greater than JET, therefore the magnetic energy required in CS will also increase. This will be able to maintain a plasma current of 15 MA with a time ranging from 300-500 seconds.

2.5 Model Townsend

Collisions in plasma come from the movement of ions and electrons. When an electric field (E) is applied, ions will accelerate in the direction E, while electrons will move in the opposite direction. Based on the speed of electrons as they collide with atoms, ionization collision effects are possible.

The average energy of the electron becomes dependent on the value of the electric field (E), and is inversely proportional to the value of density (N) (or pressure p, due to, so that (Magaldi *et al.*, 2021).

$$Energi = \frac{E}{p} \tag{2.11}$$

The value of this ratio E/p, defined as the average energy obtained at collisions between electrons per unit of particle average clearance (mean-free-path), also determines whether or not the gas splits occur.

Townsend provides a model for events occurring in the Townsend area (Figure 2.12) with a low-pressure parallel plate electrode case. Townsend's model assumes that at any collision that occurs caused by an electric field greater than the ioniation potential of the atom (or moleku) that forms the gas, the electron will transfer all its energy to the pounded atom and then ionize it with a probability in each collision equal to 1. The factor of electron multiplication or the number of electrons (dn) produced at the distance (dx) between the electrodes is proportional to the initial number of electrons (n) and the distance traveled (dx), represented by the following equation (Magaldi *et al*., 2021),

$$dn = \alpha n dx \tag{2.12}$$

which then leads to exponential growth $n = n_0 e^{\alpha x}$, where the constant α (Townsend's first coefficient) is the number for the number of ionizations per unit distance, $\alpha = \lambda^{-1}$ or the gas multiplication factor introduced by Townsend. The conditions for atoms and electrons to be able to collide and obtain energy above from the ionization potential energy of gas particles will be achieved if they can satisfy the following equation (Magaldi *et al*., 2021).

$$eE\lambda_i \geq eV_i \tag{2.13}$$

Where e is the fundamental charge (electron), E is the electric field, λ_i is the mean free-path, V_i as the potential of ionization, so that:

$$\lambda_i = \frac{V_i}{E} \tag{2.14}$$

Townsend's first coefficient or denoted by α or a constant representing the number of collisions that occur per unit distance. According to Magaldi *et al*., 2021, Townsend's first coefficient has a relationship with the average clearance of particles (mean-free-path) as follows:

$$\alpha = \frac{1}{\lambda} e^{-\frac{\lambda_i}{\lambda}} \tag{2.15}$$

It is known that ${}^{1}/_{\lambda}$ sebading with pressure (p), using the equation (2.14), obtained (Magaldi *et al.*, 2021):

$$\alpha = Ape^{-\frac{ApV_i}{E}} \tag{2.16}$$

Where A is a constant for temperature, assuming $B = AV$, the equation becomes (Magaldi *et al.*, 2021):

$$\frac{\alpha}{p} = Ae^{-\frac{B}{E/p}} \tag{2.17}$$

by ${}^{\alpha}/_{p}$ being defined as the multiplication of electrons that occurs per unit of the average free-path of the particle (mean-free-path). Townsend's model describes the multiplication of electrons in the process of rupture in gases, with values A and B (constants of the characteristics of the gas used), as well as breakdown voltages, can only be determined experimentally (Magaldi *et al.*, 2021).

2.6 Paschen Curve

Phase breakdown occurs when the avalanche process can take place on its own (without additional voltage from outside). This can be explained by the following equation (Chen, 2016):

$$\gamma(e^{\alpha d} - 1) = 1 \tag{2.20}$$

Where γ (Townsend's second coefficient) represents the probability of electrons being detached from the cathode due to ion collisions, which is also defined as the ratio of electron emission flux to incident ion flux and α (Townsend's first coefficient) is the number for the number of ionizations per unit distance. Using (Equation 2.20) and (Equation 2.17), and also defining $U_{bd} = E_{bd}d$, we obtain Paschen's law (Equation 2.21), named after Friedrich Paschen (1865–1947) (Chen, 2016).

$$U_{bd} = \frac{Bpd}{C + ln\,(pd)} \tag{2.21}$$

with

$$C = ln\left[\frac{A}{ln\,(1 + {}^{1}/_{\gamma})}\right] \tag{2.22}$$

The number of ionization events in the discharge gap is similar to the density value of the neutral gas and the width of the gap. (d)The Paschen curve has minimum characteristics to express an optimal state of a plasma for each type of gas used. Paschen's law describes the behavior of breakdown voltages as a pd function. When describing the breakdown (U_{bd} stress curve (pressure multiplied by the gap width pd or in this study will be the circumference of the golem tokamak) a curve known as the Paschen curve will be obtained (Figure 2.18).

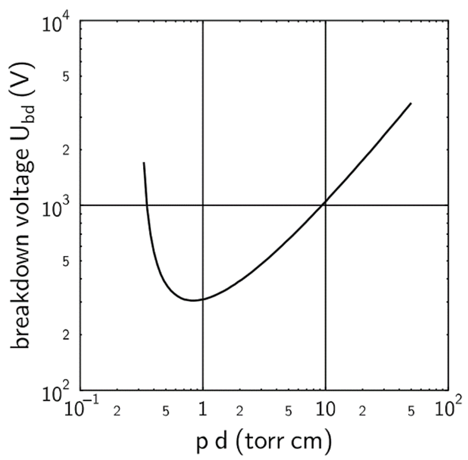

Figure 2.18 Breakdown voltage (U_{bd}) on the type of air gas as a function of pd ($1\ torr\ cm = 1.33\ Pa\ m$) (Piel, 2010).

The left part of the curve shows the presence of too few atoms to allow ioniation, while the right part of the curve explains that the mean-free-path becomes too narrow for electrons to retain the energy needed before ioniation. Both of these cases require a solution by increasing the electric field to be able to generate a higher breakdown voltage. The minimum voltage will depend on the type of gas material and cathode used.

CHAPTER III
RESEARCH METHODS

3.1 Place and Time of Research

This research was conducted at Srinakharinwirot University, Bangkok, Thailand, on May 29 – June 2, 2023, and at the Plasma Physics Laboratory, Diponegoro University, Semarang from November to December 2023.

3.2 Research Tools and Materials

Research conducted in the form of quantitative research using tools and materials:

3.2.1 Research tools

1. Tokamak GOLEM

Tokamak is used as a reactor where experiments take place, plasma formation processes occur and fusion reactions with the breakdown phase being one part of the process.

2. Computer

The research was conducted remotely using a computer connected to the internet, then accessed the golem tokamak website page. Computers are also used to collect experimental data that is stored automatically 2 minutes after charging (Figure 3.1).

3.2.2 Research materials

The experimental results will be displayed on the Tokamak GOLEM database website (Figure 3.1) approximately 2 minutes after discharge, the experimental results will be displayed on the Tokamak GOLEM database website (Figure 3.1) which will provide information data related to the value of several parameters such as plasma average current, average loop voltage, average Ohmic heating power, average electron temperature during the discharge processtake place, and so on. Some of the experimental data collected consisted of 43 primary data and 37 secondary data, all of which were accessed through the opensource GOLEM tokamak website.

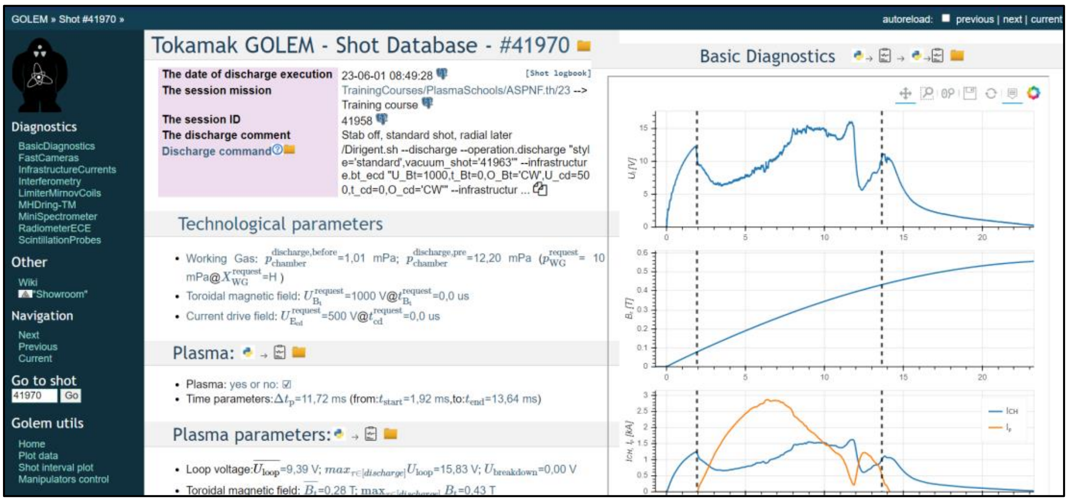

Figure 3.1 Tokamak GOLEM database website display for experimental results discharge No. 41970

3.3 Research Procedure

This research procedure will begin by preparing a computer connected to the internet with permission from the chief operator of Tokamak GOLEM, determining the input parameters of the Tokamak GOLEM experiment (gas used, pressure, toroidal voltage, delay time, etc.), collecting output data from the Tokamak GOLEM database website, and analyzing the data.

3.3.1 Computer preparation (as remote control of GOLEM)

Preparation begins by connecting a computer with an internet connection, after obtaining permission from the chief operator of Tokamak GOLEM. Next, access the Tokamak GOLEM website. Each participant or group who wants to conduct experiments will be given a special code to be able to access the control room on the website connected to Tokamak GOLEM (Figure 3.1).

There are several access or parameters set in the control room section of the GOLEM tokamak website, including see (Figure 3.1):

- **Introduction**: This section provides a brief description of the configuration procedure and shows the complete schematic of the technique as well as the visualization of the golem tokamak.
- **Working gas:** In this section will be determined the value of gas pressure (in units of mPa) and also the type of gas (Hydrogen or Helium) to be used see (Figure 3.1).
- **Pre-ionization:** The selection of the pre-ionization method (electron gun turned on/off) is carried out in this section. The electron gun will ionize some of the gas which is then used to form plasma.

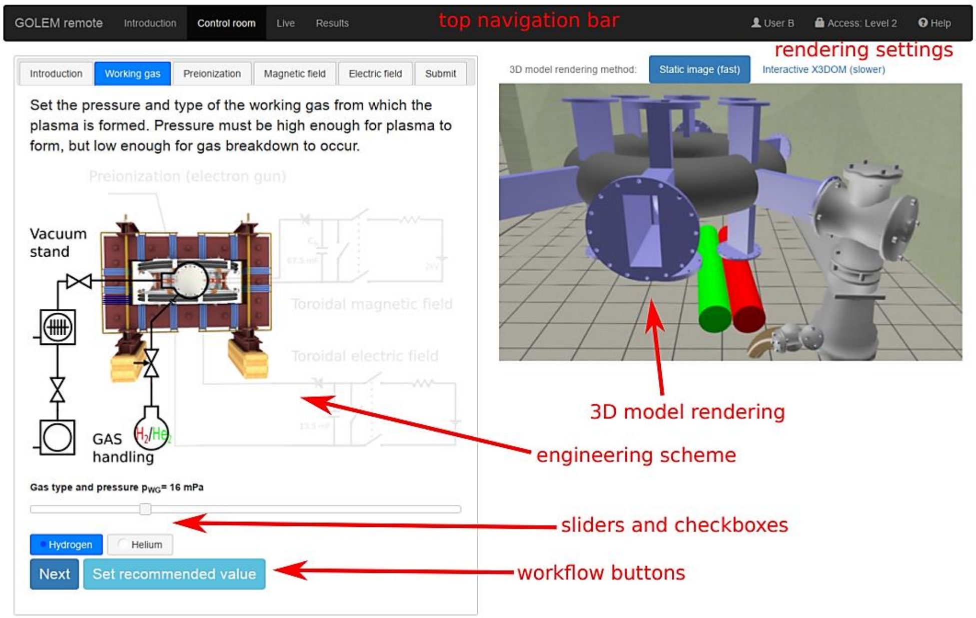

Figure 3.2 Display when setting experiment input via GOLEM tokamak website (Grover, 2019)

- **Magnetic field:** This section will contain the setting for the amount of voltage U_{Bt} (in Volts) on the capacitor to be flowed to the toroidal field coil. The higher the voltage applied, the greater the magnetic field that holds the plasma.
- **Electric field:** In this section the voltage value U_{CD} to flow to the winding of the primary transformer is set. The higher the voltage applied, the electric field.

- **Submit:** The last stage where all discharge parameters that have been set are then sent to the queue list for further execution. After successful queue delivery, a green box will appear informing the queue number and estimated time before execution is carried out.

The tokamak will work according to the command after the parameter values set as desired in the control room through the Tokamak GOLEM website. The process that takes place can be seen live on the website, which will display the flash process of plasma discharge that occurs in the tokamak, the type and value of input used, the queue of the next shot request, and also the tokamak storage space that will be visible directly (see Figure 2.13 on page 22).

3.3.2 Determining the input parameters of the GOLEM tokamak

The parameters to be set in this study are contained in (Table 3.1).

Table 3.1 Parameters that can be set remotely on the GOLEM tokamak

Settable parameters remotely	Maximum value	Enter value
The amount of voltage to power the toroidal coil (U_{BT})	$1300\ V$	$900 \leq U_{BT} \leq 1000\ V$
The amount of voltage to power the transformer core coil (U_{CD})	$700\ V$	$350 \leq U_{CD} \leq 500\ V$
Time delay (T_{CD})	$20\ ms$	$0 \leq T_{CD} \leq 0{,}5\ ms$
Pressure of the working gas (p)	$50\ mPa$	$0 \leq p \leq 40\ mPa$
Pre-ionization electron-gun	On/Off	On
Working gas	H_2/He	H_2

The parameters set or constant for each discharge in this experiment are the type of gas acting (hydrogen or H_2), pre-ionized using an electron-gun (on), and by setting the remaining parameters (Table 3.1) according to the recommended range of values.

3.3.3 Data analysis

This research will use input parameters in the form of: type of hydrogen gas (H_2), type of electron-gun pre-ioniation activated (on), gas pressure in the range $(0 \leq p \leq 40\,)\; mPa$, time delay between capacitor U_{BT} and U_{CD} $(0 \leq T_{CD} \leq 0.5)\; ms$, toroidal voltage $(900 \leq U_{BT} \leq 1000\,)\; V$, and voltage applied to the primary winding of the transformer core $(350 \leq U_{CD} \leq 500)\; V$. Output data to be collected in the form of values: discharge duration (T_{dis}), maximum plasma current $(I_{p,max})$, breakdown voltage (V_{BD}).

The study used 80 discharge data that stored in the Tokamak GOLEM website database, with 43 of them being primary data inputted directly at the time of experimentation, and the remaining 37 being secondary data accessed through the opensource Tokamak GOLEM database. All data are contained in (Appendix A) with primary data being Nos. 33-75 in the table.

The values of discharge duration (T_{dis}), maximum plasma current $(I_{p,max})$, breakdown voltage (V_{BD}) generated at each discharge will be collected one by one until up to 80 data is collected for each parameter on each discharge. Next, the data will be entered into an Excel worksheet and plotted into a graph using Origin software. Furthermore, an analysis will be carried out related to the effect of gas pressure and transformer core voltage on the breakdown phase, discharge duration and maximum plasma current on the GOLEM tokamak.

3.4 Research Flow Chart

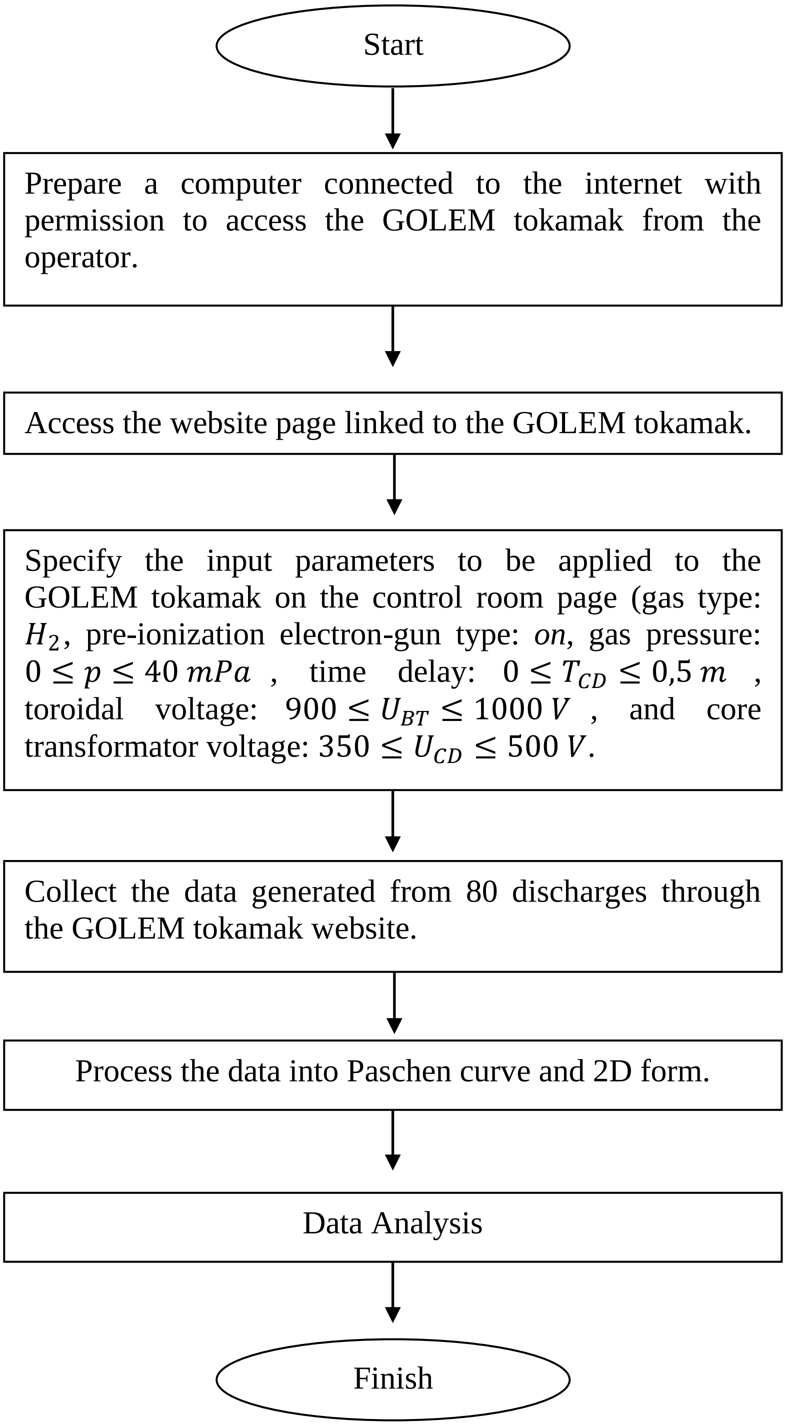

Figure 3.3 Research Flow Chart

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Parameters Used to View Breakdown Conditions.

This research has been conducted by establishing several input parameters such as: the type of gas used is H_2, the type of electron-gun pre-ioniation that is activated (on), the gas pressure is exerted on the range $(0 \leq p \leq 40\ )\ mPa$, the time delay between the capacitor U_{BT} and U_{CD} on $(0 \leq T_{CD} \leq 0.5)\ ms$, toroidal voltage $(900 \leq U_{BT} \leq 1000\ )\ V$, and the voltage applied to the primary winding of the transformer core $(350 \leq U_{CD} \leq 500)\ V$.

This study used 80 discharge data stored in the Tokamak GOLEM website database, with 43 of them being primary data and the remaining 37 being secondary data (contained in Appendix A: No. 33-75). Here's one example of the data generated in this experiment (Figure 4.1).

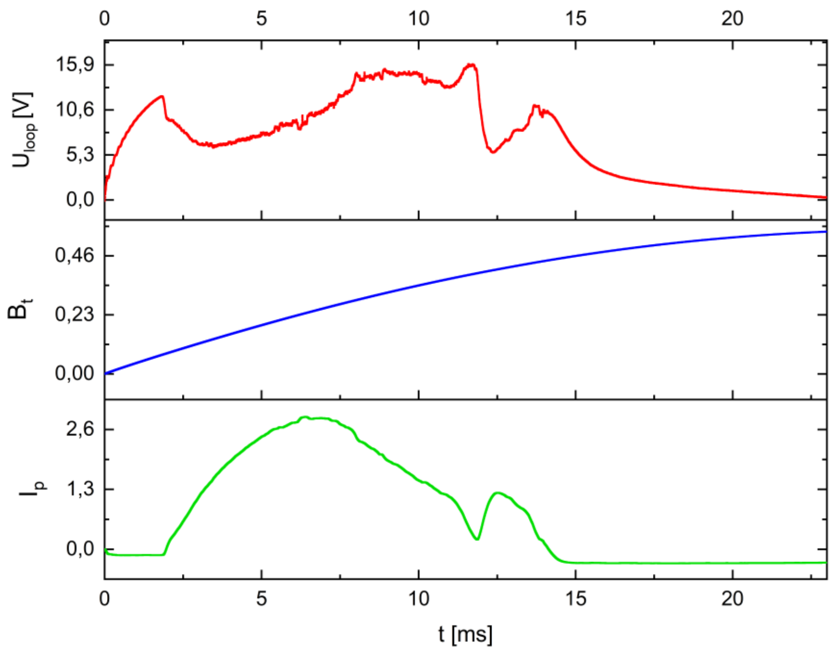

Figure 4.1 Graph of loop voltage change (U_{Loop}), toroidal magnetic field (B_t) and plasma currents (I_p) against time, discharge (No. 41970)

The parameters set in this discharge (No. 41970) are: hydrogen gas with a requested pressure of 10 mPa; $U_{BT} = 1000\ V$; $U_{CD} = 500\ V$, and the time delay between the capacitor bank U_{BT} and U_{CD} is $0\ ms$. Three basic measurements (Figure 4.1) were calculated on each discharge, loop voltage, toroidal magnetic field, and plasma current. Data for parameters, discharge duration, maximum plasma current, breakdown voltage, and toroidal magnetic field at breakdown state will be recorded and stored automatically. Figure 4.2 shows several parameters automatically generated at this experimental diagnosis: plasma density (n_e), electron temperature (T_e), ohmic heating (P_{OH}), and edge safety factor (*q(a)*).

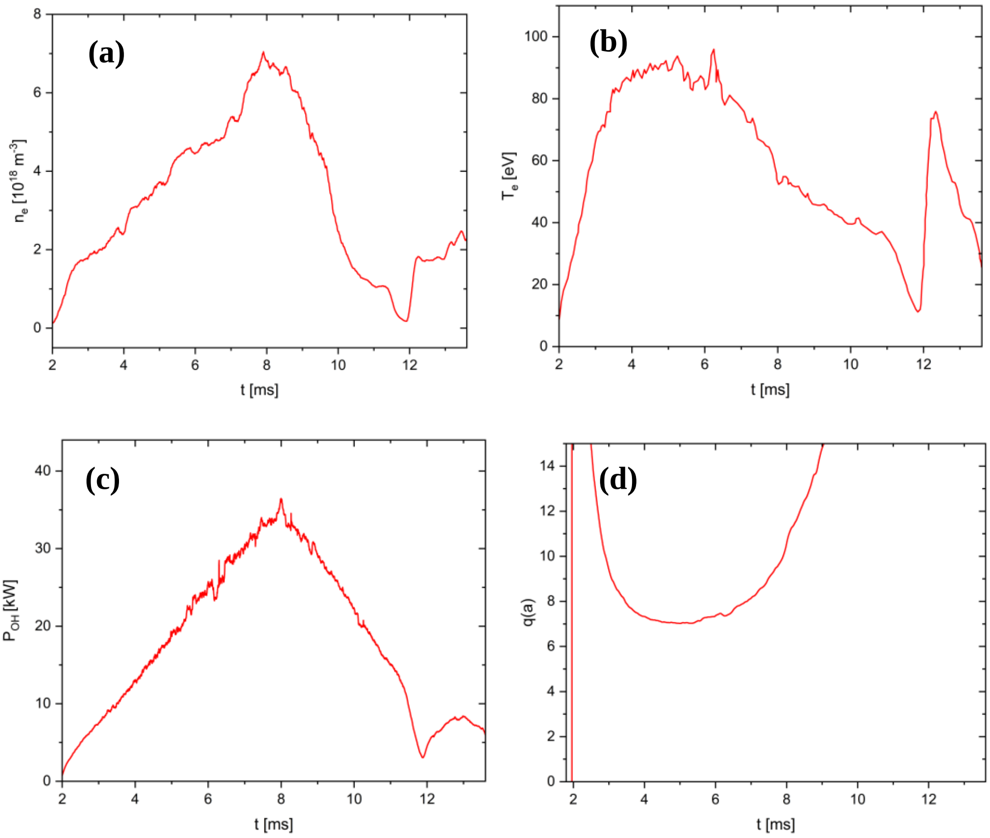

Figure 4.2 Transient changes in (a) plasma density (n_e), (b) temperature electron (T_e), (c) ohmic heating (P_{OH}), and (d) edge safety factor (q(a)) at discharge (No. 41970)

The GOLEM tokamak does not have an instrument to measure plasma density, but density is measured using the ideal gas law approach, which results in a maximum density of approximately $6{,}195 \times 10^{18}\ m^{-3}$ (Figure 4.2.a). The breakdown condition in the GOLEM tokamak requires an ambient plasma density $\sim(10^{17} - 10^{18})$ (Siusko, 2021). The resistivity of a fully ionized plasma depends on the electron temperature and effective charge number (Zeff) (the degree to which particles in the plasma interact with electric and magnetic fields). The plasma in the center of the reactor center has a higher temperature, and low resistivity with a higher current density, making the calculation of electron temperature unclear. The electron temperature (T_e) is calculated using Spitzer's resistivity equation, which yields the maximum value at this discharge at 96.133 eV (Figure 4.2.b). The ohmic heating that occurs in GOLEM tokamak comes from the current flowing through the conductor with a certain resistivity. The maximum ohmic heating at this discharge reaches 39.876 kW (Figure 4.2.c) which can be measured by the following equation:

$$P_{OH} = U_{loop} \times I_p \tag{4.1}$$

The edge safety factor q(a) will reach a value of 1 when the plasma current is so high, when q(a) begins to touch the value of 2 the plasma begins to become unstable. In this experiment q(a) on average obtained a value of 22.114 or above the value of 7 (Figure 4.2.d) which is very stable because the current used is relatively low. The edge safety factor q(a) can be obtained using Ampere's law, as follows:

$$B_P(a,t) = \frac{\mu_0}{2\pi}\frac{I_p(t)}{a} \tag{4.2}$$

by substituting it into the safety factor equation for a tokamak with a large circumference ratio such as GOLEM to:

$$q(r,t) = \frac{r}{R}\frac{B_t(t)}{B_p(r,t)} \tag{4.3}$$

The equation for edge safety factors is obtained into:

$$q(r,t) = \frac{a_0}{R_0}\frac{2\,B_t(t)}{\mu_0 I_p(t)} \tag{4.4}$$

where $a_0 = 0{,}085$ is the radius of the poloidal limiter, $R_0 = 0{,}4\ m$ is the major radius of the vessel, B_t is the toroidal magnetic field, I_p is the plasma current, and $\mu_0 = 4\pi \times 10^{-7} m/A$ which is the magnetic permeability constant (Pokol et al., 2014).

4.2 Paschen Curve in the Tokamak GOLEM Breakdown Phase

After the input parameters are set and entered the queue for execution, the GOLEM tokamak will then be pumped until it reaches ambient pressure. The $(10^{-4} - 10^{-3})\ Pa$ vacuum vessel on the tokamak will be heated for $\sim 180°C$ up to 60 minutes, and then cleaning by discharge emission from Helium particles is applied for 30 minutes to clean impure molecules (impurity moleculs) from the inside of the wall of the golem tokamak vessel.

Data from all parameters start to be stored at time $t = 0\ ms$ (Figure 4.3). The capacitor will work after a delay time $(0\ ms)$ to provide power to the primary winding of the transformer which will then be used to generate loop voltage (U_{loop}). Increasing the loop voltage will accelerate the electrons generated from the pre-ionization source using tungsten filaments which then produce electrons (electron-gun) which then the process causes an avalanche ionization event.

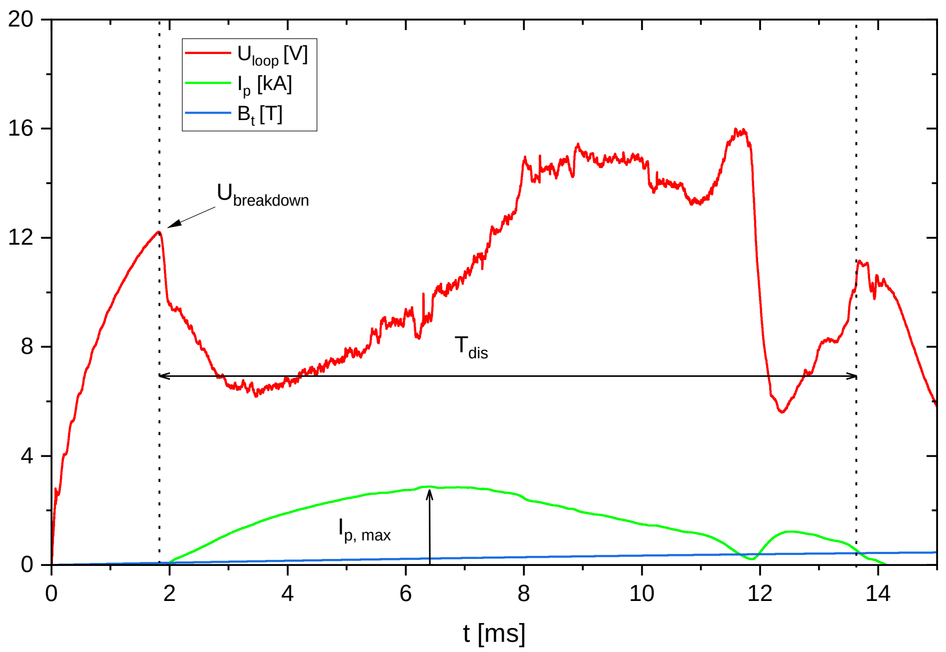

Figure 4.3 Discharge duration and maximum plasma current (No. 41970)

After an interval of time $(1 - 2\ ms)$, the density or density of plasma will become quite high which then occurs a state of breakdown in plasma accompanied by an increase in plasma current. In the breakdown state, the loop voltage will be at its maximum before falling back down due to an increase in plasma current, this decrease is caused by decreased resistance. The plasma current continues to increase because there is no system to control this situation in the Tokamak GOLEM. The time interval from the breakdown to the loss of plasma current is referred to as the discharge duration (T_{dis}) in (Figure 4.3) plasma can last for 11.72 ms. During the discharge process, the plasma current increases and reaches its maximum point ($I_{p,\ max}$) which in this experiment is 2.87 kA.

4.2.1 Townsend avalanche region

The Townsend area starts from the moment the loop voltage is applied until it reaches the breakdown point or commonly referred to as the Townsend avalanche phase, or simply the process towards a breakdown state. At discharge (No. 41970) it takes 1.8 ms to reach the breakdown state or duration during the Townsend avalanche process. Loop voltages begin to be applied $t = 0$ to cause acceleration in electrons along magnetic field lines by toroidal electric fields of:

$$E_t = \frac{U_{loop}}{2\pi R} \tag{4.5}$$

The drift speed of electrons moving along the medium affected by the electric field becomes:

$$v_D = \frac{E_t}{p} \tag{4.6}$$

with is the pressure on hydrogen gas. When the electron energy is able to unbind (ionize) molecular atoms from hydrogen gas atoms/molecules, the density n_e of p the plasma will increase which also causes an increase in plasma currents at $t = 2\ ms$, in accordance with:

$$I_p \sim n_e v_D \tag{4.7}$$

The plasma current in its initial state increases slowly due to the loss of charged particles caused by a stray magnetic field that causes collisions between particles to change their trajectory along the magnetic field which then inhibits the movement of charge. Impurities in plasma are also the cause of the loss of charged particles. Impurities can be caused by charged particles ionizing wall material (Zhou, 2019).

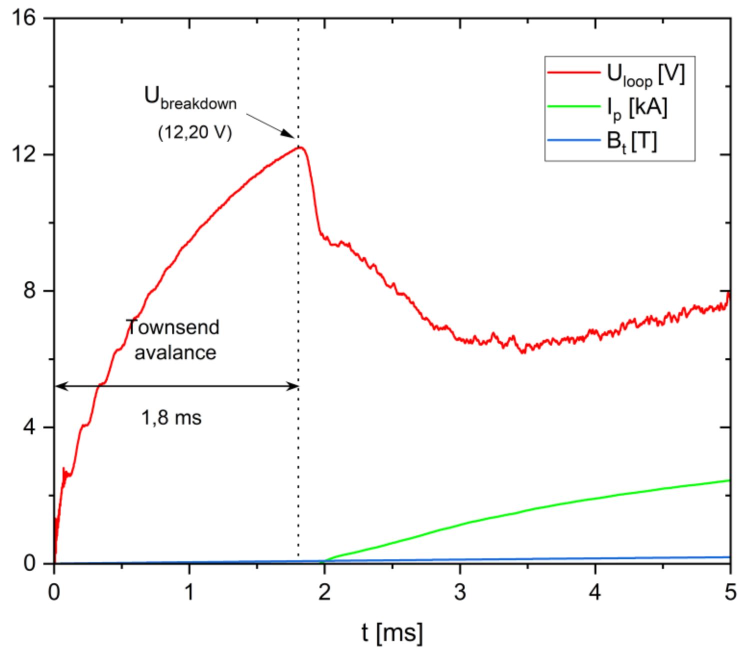

Figure 4.4 Townsend avalanche phase in discharge (No. 41970)

Plasma with high impurity conditions will cause an increase in resistivity, thus favoring an increase in loop voltage and ohmic heating. As the density of free electrons increases produced during the Townsend avalanche process, charged particles will move more freely in the plasma and cause a decrease in resistivity in the plasma. The decrease in resistivity is also due to a smaller cross-section of electron and ion interactions when compared to the cross-section of electrons and atoms (hydrogen). Decreased resistivity will cause a decrease in the loop voltage and increase the current in the plasma according to Ohm's law:

$$I_{plasma} = \frac{U_{loop}}{R_{plasma}} \tag{4.8}$$

4.2.2 Paschen Curve

The results of each breakdown ($U_{breakdown}$) voltage that occurs at 80 discharges are summarized into 2D form at (Figure 4.5). The minimum breakdown voltage occurs in the region $(7 - 15\ ) \, mPa$, for each voltage variation applied to the transformer core ($U_{CD} = 350 - 500$).

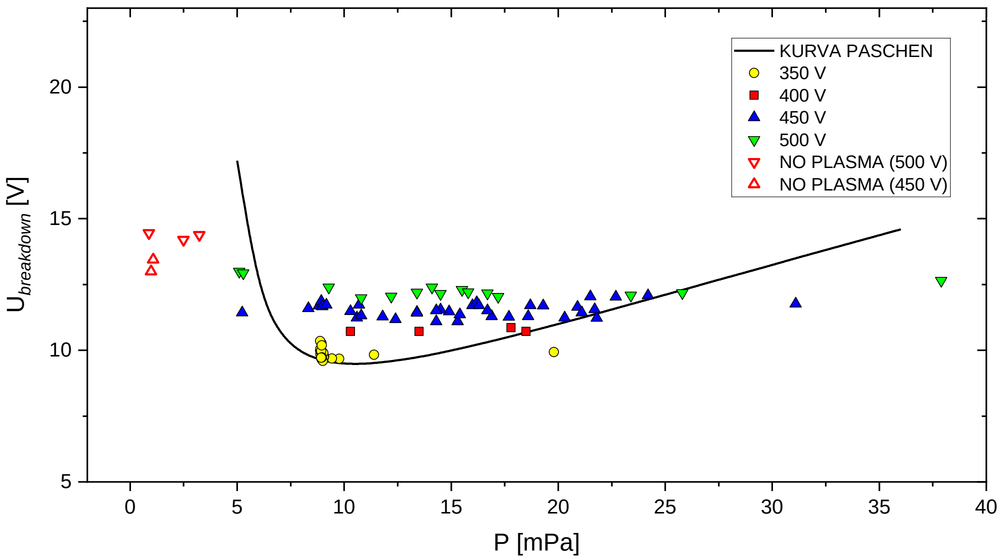

Figure 4.5 The relationship between voltages breakdown ($U_{breakdown}$) and stress on the Paschen curve for each type U_{CD}

In the region ($P < 5 \, mPa$) where no breakdown voltage is found, this is because the pressure that is too low causes a low cross-section value or the possibility of the collision of electrons produced by electron-gun with hydrogen gas atoms to ionization of the electrons that make up the atom, so that the breakdown voltage required would be very high to allow this to occur and is evidenced by the increase in breakdown voltage for each type U_{CD} as it begins to approach part of the area ($P < 5 \, mPa$) (Figure 4.5). The voltage required in the region ($P > 20 \, mPa$) will also require a higher voltage because the pressure possessed by hydrogen gas will cause a narrowing of space for electrons to move from the electron-gun and gather energy to be able to ionize atoms in hydrogen gas, this is also evidenced in (Figure 4.5) by increasing the breakdown voltageAs the gas pressure increases for each type. The data contained in (Figure 4.5) proved to consistently follow the curve lines of Paschen's law for U_{CD}breakdown stresses, defined by the following equation:

$$U_{breakdown} = \frac{Bpd}{C + ln\ (pd)} \tag{4.9}$$

where $B = 0{,}36107$ and $\mathrm{C} = -2{,}2673$ is a constant determined by the characteristics of the gas used and also the breakdown voltage produced in this experiment, p is the gas pressure, d is the distance between the trajectories traversed by the cathode particles to the anode, or is the circumference of the GOLEM tokamak, which is $2\pi R = 2{,}513274\ mR$, by being the major radius of the GOLEM tokamak, namely $0{,}4\ m$.

The minimum breakdown voltage ($U_{breakdown}$) produced at each U_{CD} produces different values for each increase (50 V) as evidenced in (Figure 4.5) and (Figure 4.6), which $U_{breakdown}$ increases with the increase from used U_{CD}.

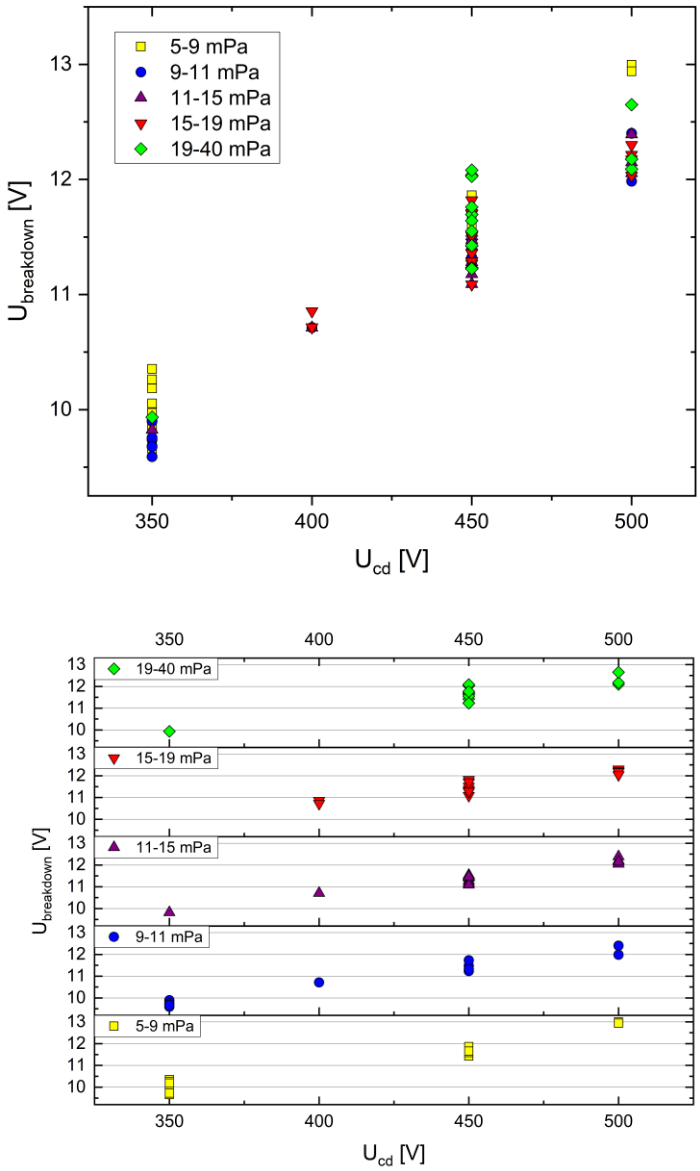

Figure 4.6 The relationship of the voltage acting on the core of the GOLEM transformer (U_{CD}) with the voltage breakdown ($U_{breakdown}$)

The highest breakdown voltage value (Figure 4.6) is at 12.996 V with a voltage applied to the transformer core of 500 V. This increase in hydrogen gas breakdown voltage follows Faraday's law of electromagnetic induction.

$$\varepsilon \sim \frac{\Delta \Phi}{\Delta t} \tag{4.10}$$

With ε as an induced voltage, $\Delta\Phi$ the magnetic field changes. When voltage (U_{CD}) is induced into the transformer core (primary winding), the flowing magnetic field will be directly proportional to the voltage value. When the magnetic field increases it will cause an increase in voltage in the plasma (secondary winding) according to the Ampere law in equation (4.2). It is also what causes an increase in the maximum plasma current as it increases U_{CD} (Figure 4.7).

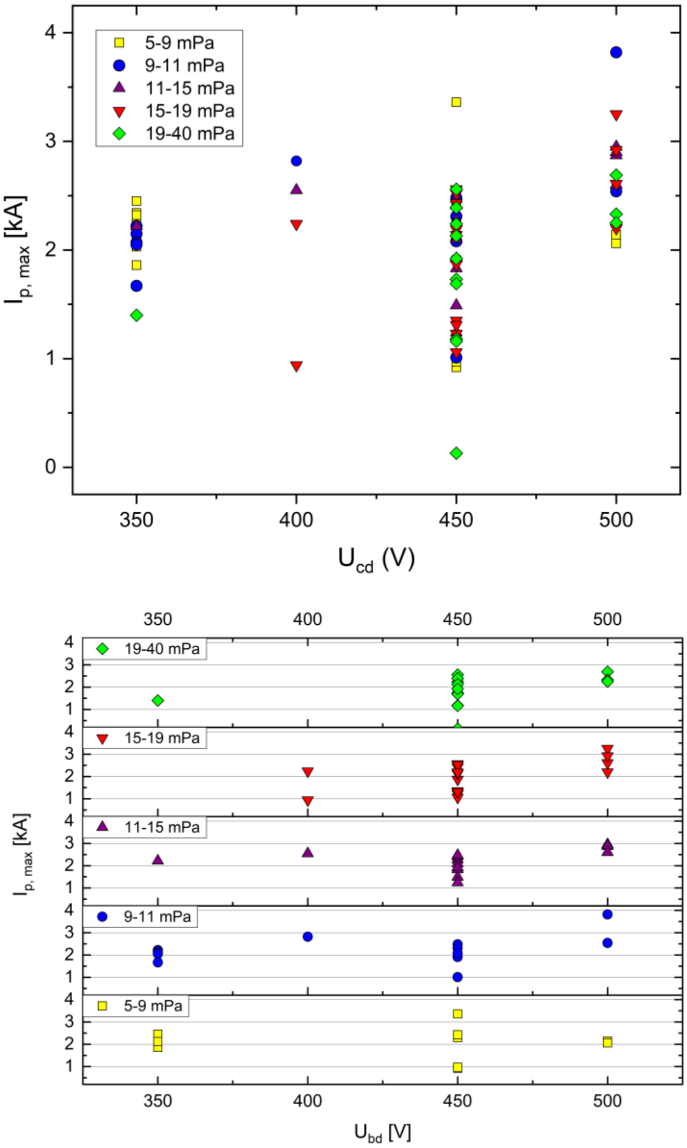

Figure 4.7 The relationship of the voltage acting on the core of the GOLEM transformer (U_{CD}) with the maximum plasma current ($I_{p,max}$)

4.3 Relationship of Pressure to Discharge Duration and Maximum Plasma Current

4.3.1 Discharge duration

The discharge duration is an important parameter in the GOLEM tokamak, which states the length of time for plasma to be able to survive on the inner wall of the tokamak. The relationship between discharge duration and hydrogen gas pressure in this experiment is represented by (Figure 4.8), seen in the gray area showing the optimum pressure $(7-20\ mPa)$ parameter to produce a longer discharge duration.

Along with the increase in pressure, the duration of discharge also decreases. The duration of discharge is limited by the quality of the SLEM transformer iron core, which is designed to transmit magnetic flux to the $0{,}12\ Vs$ maximum, if it exceeds this value then the transformer core will reach the saturation point (oversaturated) and is unable to conduct power or voltage from the primary winding (U_{CD}) to the secondary winding for plasma loop voltage.

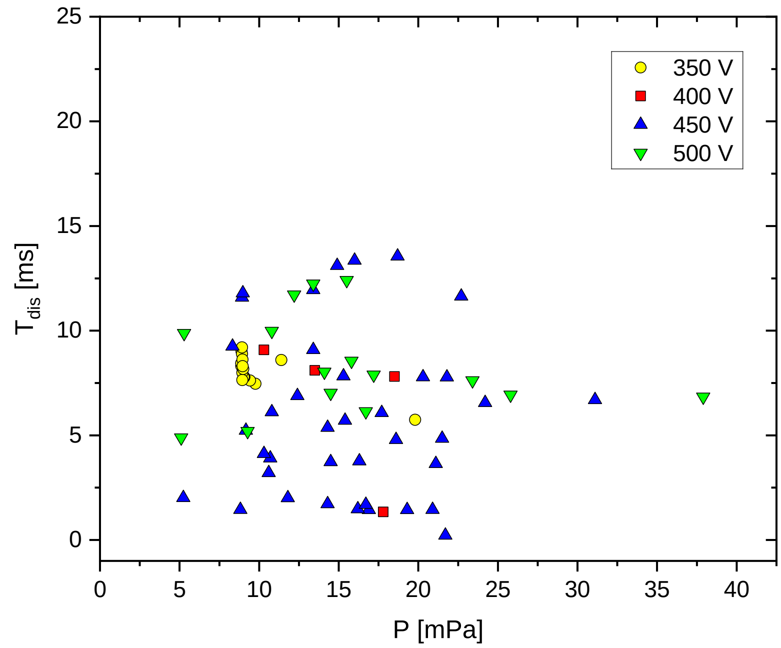

Figure 4.8 The relationship between the pressure (P) acting on hydrogen gas and the duration of discharge (T_{dis}) from the plasma to survive

In (Figure 4.8) it is seen that the pressure range $(7 - 15)\ mPa$, which is used for the minimum breakdown stress region of the Paschen curve (Figure 4.5) has a discharge duration value in a relatively high region, stating that the pressure meets the criteria for achieving the optimum state of the GOLEM tokamak.

There is a significant increase in the duration of discharge along with the increase in plasma current (Figure 4.9), this can be connected with high density can increase the time of plasma to survive, and also the voltage applied to the transformer core (U_{CD}) is clearly seen to provide an increase in the duration of plasma hydrogen discharge which is also in accordance with the circumstances in the pressure relationship and discharge duration on (Figure 4.8).

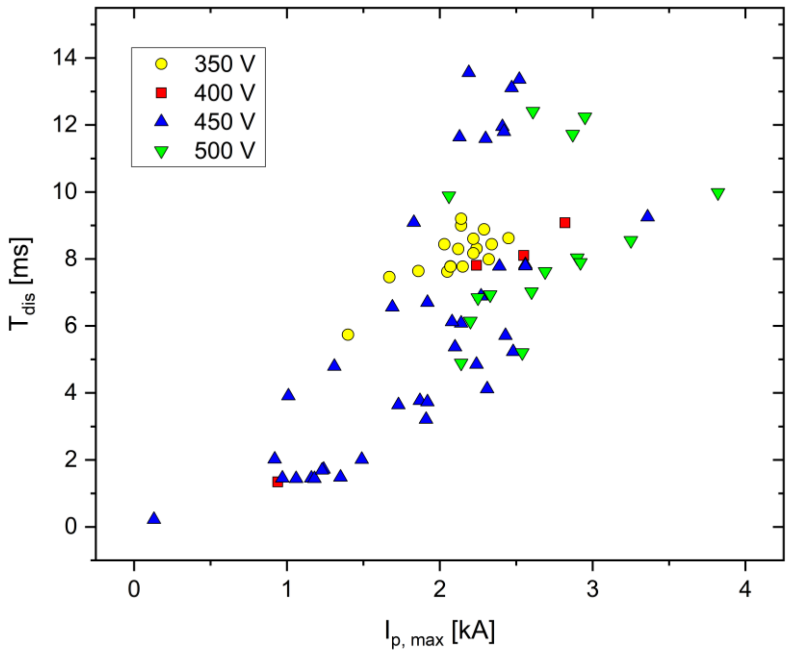

Figure 4.9 The relationship between the maximum plasma current $(I_{p,max})$ and the discharge duration (T_{dis})

4.3.2 Maximum plasma current

The illustration in (Figure 4.10) shows the maximum plasma current distribution with applied pressure, for each voltage variation applied to the primary winding at the core of the GOLEM transformer (U_{CD}). There is a decrease in the maximum plasma current with an increase in pressure in hydrogen gas. This can be due to the fact that the plasma of the GOLEM tokamak is not fully ionized and the degree of ionization decreases with increasing pressure. However, there was an increase in the system along with the increase from U_{CD}. This is also in accordance with the discussion in (Figure 4.7).

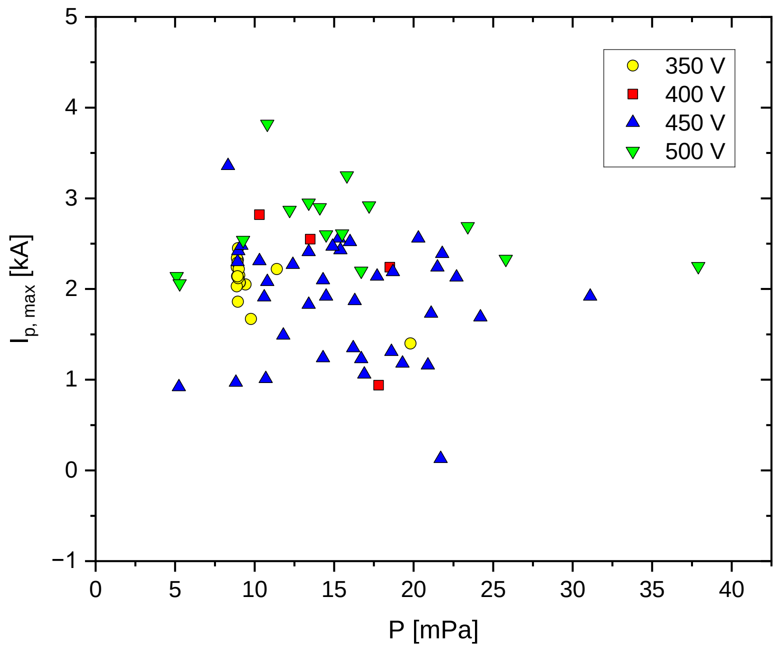

Figure 4.10 The relationship between the pressure (P) exerted on hydrogen gas and the maximum plasma current $(I_{p,max})$

The relationship that occurs at maximum plasma pressure and current indicates that the ideal pressure used is in the region $(7-17)\ mPa$. It also amplifies the pressure used at the minimum breakdown $(7-15)\ mPa$ stress on the Paschen curve (Figure 4.5) as the ideal pressure to achieve the optimum state of the GOLEM tokamak.

CHAPTER V
CONCLUSION

5.1 Conclusion

1. The Paschen curve provides information about the minimum breakdown voltage on hydrogen gas in Tokamak GOLEM reached at a given pressure. The minimum breakdown voltage ($U_{breakdown}$) for each type of voltage applied to the transformer core (U_{CD}) has different values, but they are all at an ambient optimum pressure $7 - 15\, mPa$ that results in the maximum discharge duration (T_{dis}) and plasma current values ($I_{p,max}$) at the highest area.

2. The higher the pressure (p) exerted on hydrogen gas, the discharge duration (T_{dis}) and maximum plasma current ($I_{p,max}$) will decrease. An increase in the voltage applied to the primary winding in the core of the GOLEM tokamak transformer (U_{CD}) will cause an increase in the value of the breakdown voltage ($U_{breakdown}$), discharge duration (T_{dis}) and maximum plasma current ($I_{p,max}$).

5.2 Recommendations

1. A sufficient amount of data or more than 80 data and proportional for each variation used for the voltage applied to the GOLEM tokamak core transformer (U_{CD}), will result in a more accurate analysis.

2. Set the control variable, which in this study is time delay, with a constant range of values or narrow the range of values, so as not to interfere with the interpretation of other variables in the research results.

BIBLIOGRAPHY

Ariola, M to Pironti, A. (2016). Magnetic Control of Tokamak Plasmas. New York: Springer Cham.

Behrouzi, F., Nakisa, M., Maimun, A. dan Ahmed, Y. M. (2016). Renewable energy potential in Malaysia: Hydrokinetic river/marine technology. Renewable and Sustainable Energy Reviews, 62, 1270-1281.

Benesch, J.F. (1981). Breakdown in the PRETEXT Tokamak (Ph.D. Thesis Texas Univ., Austin. Department of Physics.

BP. (2022). BP Statistical Review of World Energy. London. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html. Diakses pada 10 Oktober 2022.

Chektybayev, B., Sadykov, A., Batyrbekov, E., Skakov, M., Zarva, D., Tazhibayeva, I., *et al*. (2021). Study of breakdown and plasma formation in the KTM tokamak with the massive conductive vacuum chamber. Fusion Engineering and Design, 163, 112167.

Chen, F. F. (2016). Introduction to Plasma Physics and Controlled Fusion. Edisi ketiga. New York: Springer Cham.

Dubus, Gregory. (2014). From Plain Visualisation to Vibration Sensing: Using a Camera to Control the Flexibilities in the ITER Remote Handling Equipment. Disertasi. Tampere University of Technology. Finlandia.

Ehigiamusoe, K.U., Lean, H.H. dan Lee, C. (2019). Moderating effect of inflation on the finance–growth nexus: insights from West African countries. Empirical Economics, 57(2), 399–422.

Fowler, T.K. (1997). The Fusion Quest (Johns Hopkins University Press, Baltimore MD.

Gribov, Y. Humphreys, D., Kajiwara, K., Lazarus, E.A., Lister J.B., Ozeki, T., *et al*. (2007). Chapter 8: Plasma operation and control. Nuclear Fusion, 47(6): S385-S403.

Grover, O., Kocman J., Odstrcil M., Odstrcil T., Matusu M., Stöckelet J., *et al*. (2016). Remote operation of the GOLEM Tokamak for Fusion Education. Fusion Engineering and Design, 112 1038–1044.

Grover, O., Svoboda, V. dan Stockel, J., (2019). Online experimentation at the GOLEM Tokamak. International Conference. University of Madeira, Portugal.

Holechek, J.L., Geli, H.M.E., Sawalhah, M.N. dan Valdez, R., (2022). A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050?. Sustainability, 14(8), 4792.

International Energy Agency (IEA). 2020. Report Extract Final Consumption, World Total Final Consumption 2020. Diambil dari https://www.iea.org/reports/key-world-energy-statistics-2020/final-consumption (accessed June 23, 2023).

Islam, M.M., Irfan, M., Shahbaz, M. dan Vo, X.V., (2022). Renewable and non-renewable energy consumption in Bangladesh: The relative influencing profiles of economic factors, urbanization, physical infrastructure and institutional quality. Renewab le Energy, 184, 1130-1149.

Jiang, W., Peng, Y., Zhang, Y. dan Lapenta, G., (2016). Numerical modeling of tokamak breakdown phase driven by pure Ohmic heating under ideal conditions. Nucl. Fus., 56(12), 126017.

Kikuchi, M., Lackner, K. dan Tran, M.Q., (2012). Fusion Physics, International Atomic Energy Agency, Vienna.

Levko, D. Arslanbekov, R.R. dan Kolobov, V.I., (2019). Modified Paschen curves for pulsed breakdown, Phys. Plasmas 26, 064502.

Magaldi, B.V., Pessoa, R., Cesare, M.P., Ribeiro, A.A., Martins, C., dan Sobrinho, A.S.S., (2021). Control and data acquisition system to study dielectric breakdown in low-pressure DC plasma reactor with parallels electrodes. Rev. Bras. Apl. Vac., Campinas, Vol. 40, e1821.

Moriarty, P., dan Honnery, D. (2012). What is the global potential for renewable energy?. Renewable and Sustainable Energy Reviews, 16, 244-252.

Nuclear Energy Agency (NEA). 2003. Nuclear Energy Today. OECD PUBLICATION, Prancis.

Nur, M. 2011. Fisika Plasma dan Aplikasinya. Undip Publishing Agency.

Piel, A. 2010 Plasma Physics: An Introduction to Laboratory, Space, and Fusion Plasmas. New York: Springer.

Pokol, G. Horvath, L., Buday, C., Refy, D.I., (2014). Instructions for student measurements on the GOLEM Tokamak. Department of Nuclear Techniques, Budapest University of Technology and Economics.

Sarancha, G.A., Drozd, A.S., Emekeev, I.A., Ganin, S.A., Kropackova, D., Kudashev, I.S., *et al*. (2021). Hydrogen and Helium Discharges in the Golem Tokamak. Probl. At. Sci. Technol. Ser. Thermonucl. Fusion, 44 (4), 92.

Siusko, Y., Svoboda, V., Stockel., J., Garkusha, I.E., Solyakov, D., Girka, I., *et al*., (2021). Breakdown Phase in the GOLEM Tokamak and Its Impact on Plasma Performance. Ukrayins'kij Fyizichnij Zhurnal (Kyiv), 66(3), 231-239.

Song, X., Duan, X.R., Song, X.M., Zheng, G.Y., Wang, S., Li, B., *et al*. (2017). Experimental results of plasma breakdown and flux optimization on HL-2A Tokamak, Fusion Engineering and Design, (125) 195-198.

Svoboda, V., Zhekova, M., Dimitrova, M., Marinova, P., Podolnik, A., dan Stockel, J., (2019). Operational Domain in Hydrogen Plasmas on the GOLEM Tokamak. Journal of Fusion Energy 38: 253–261.

Twaróg D., Stankiewicz, R. dan Drozdowicz, K., (2011). Test of the European Transport Solver in the frame of Integrated Tokamak Modeling. IFJ Report, 2051/AP.

United Nations Department of Economic and Social Affairs, Population Division. (2022). World Population Prospects 2022: Summary of Results. New York: UN DESA/POP/2022/TR/NO. 3.

Walker, M.L., Vries, P.C.D, Felici, F. dan Schuster, E., (2020). Introduction to tokamak plasma control. American Control Conference (ACC), 2901–2918.

Wang, Tianbo. (2018). Reconstruction of Soft X-Ray and Tungsten Concentration Profiles in Tokamaks Using Gaussian Process Tomography. Ghent University.

Wesson, J., (1999). The Science of JET. Oxfordshire, England.

Wesson, J., (2004). Tokamaks, 3rd edition. Oxford.

Zhou, Yushan. (2019). Impact of Surface Structures on Deposition and Erosion in a Tokamak. Disertasi. School of Electrical Engineering and Computer Science. Swedia.

APPENDIX A

DATA DISCHARGE EXPERIMENT TOKAMAK GOLEM

No	Shot	Input				Output			
		p (mPA)	U_{BT} (V)	U_{CD} (V)	T_{CD} (ms)	T_{dis} (ms)	$I_{p,max}$ (kA)	V_{BD} (V)	Plasma Formed
1	41834	21,7	1000	450	0	0,22	0,13	11,551	Yes
2	41835	18,6	1000	450	0	4,79	1,31	11,287	Yes
3	41836	21,1	1000	450	0	3,64	1,73	11,425	Yes
4	41837	16,3	1000	450	0	3,77	1,87	11,702	Yes
5	41839	14,5	1000	450	0	3,73	1,92	11,536	Yes
6	41840	10,7	1000	450	0	3,91	1,01	11,728	Yes
7	41842	10,3	1000	450	0	4,12	2,31	11,477	Yes
8	41843	8,93	1000	450	0	11,59	2,3	11,862	Yes
9	41844	8,98	1000	450	0	11,8	2,42	11,66	Yes
10	41846	9,17	1000	450	0	5,23	2,48	11,723	Yes
11	41848	13,4	1000	450	0,35	9,09	1,83	11,418	Yes
12	41849	14,3	1000	450	0,35	1,72	1,24	11,505	Yes
13	41850	16,7	1000	450	0,35	1,69	1,23	11,51	Yes
14	41852	21,5	1000	450	0,35	4,85	2,24	12,037	Yes
15	41853	22,7	1000	450	0,35	11,64	2,13	12,028	Yes
16	41863	8,82	1000	450	0	1,45	0,97	11,692	Yes
17	41865	14,9	1000	450	0	13,11	2,47	11,472	Yes
18	41867	0,98	1000	450	0	-	-	13	No
19	41868	15,4	1000	450	0	5,71	2,43	11,359	Yes
20	41919	16,7	900	500	0	6,14	2,2	12,173	Yes
21	41926	5,29	1000	500	0	9,88	2,06	12,94	Yes
22	41927	5,1	1000	500	0	4,89	2,14	12,996	Yes
23	41928	9,28	1000	500	0	5,2	2,54	12,4	Yes
24	41936	11,8	1000	450	0	2,01	1,49	11,28	Yes
25	41937	17,7	1000	450	0	6,08	2,14	11,268	Yes
26	41938	17,8	1000	400	0	1,34	0,94	10,855	Yes
27	41940	19,3	1000	450	0	1,44	1,18	11,696	Yes
28	41941	20,9	1000	450	0	1,45	1,16	11,641	Yes
29	41945	16	1000	450	0	13,36	2,52	11,7	Yes
30	41946	16,2	1000	450	0	1,48	1,35	11,818	Yes
31	41949	16,9	1000	450	0	1,44	1,06	11,29	Yes
32	41951	18,7	1000	450	0	13,56	2,19	11,707	Yes
33	41958	5,24	1000	450	0	2,02	0,92	11,43	Yes
34	41959	10,6	1000	450	0	3,21	1,91	11,23	Yes
35	41960	12,4	1000	450	0	6,89	2,27	11,177	Yes
36	41961	14,3	1000	450	0	5,37	2,1	11,09	Yes

37	41962	10,8	1000	450	0	6,12	2,08	11,32	Yes
38	41963	1,08	1000	450	0	-	-	13,447	No
39	41964	13,4	1000	450	0	11,95	2,41	11,446	Yes
40	41967	15,5	1000	500	0	12,41	2,61	12,3	Yes
41	41968	14,5	1000	500	0	7,02	2,6	12,148	Yes
42	41969	13,4	1000	500	0	12,24	2,95	12,2	Yes
43	41970	12,2	1000	500	0	11,72	2,87	12,053	Yes
44	41971	14,1	1000	500	0	8,03	2,9	12,391	Yes
45	41972	25,8	900	500	0	6,93	2,33	12,177	Yes
46	41975	23,4	1000	500	0	7,62	2,69	12,09	Yes
47	41976	15,3	900	450	0	7,83	2,56	11,088	Yes
48	41977	17,2	900	500	0	7,89	2,92	12,034	Yes
49	41979	37,9	900	500	0	6,84	2,25	12,65	Yes
50	41980	20,3	1000	450	0	7,79	2,56	11,234	Yes
51	41982	18,5	1000	400	0	7,81	2,24	10,715	Yes
52	41983	13,5	900	400	0,5	8,1	2,55	10,712	Yes
53	41989	19,8	900	350	0,5	5,74	1,4	9,935	Yes
54	41990	9,77	900	350	0,5	7,46	1,67	9,678	Yes
55	41991	9,43	900	350	0,5	7,62	2,05	9,682	Yes
56	41992	9,07	900	350	0,5	7,78	2,07	9,755	Yes
57	41993	9,06	900	350	0,5	7,77	2,07	9,74	Yes
58	41994	9,03	900	350	0,5	7,77	2,15	9,898	Yes
59	41995	8,95	900	350	0,5	7,99	2,32	10,262	Yes
60	41996	8,95	900	350	0,5	7,64	1,86	9,662	Yes
61	41997	8,9	900	350	0,5	9	2,14	9,847	Yes
62	41998	8,88	900	350	0,5	8,31	2,24	9,979	Yes
63	41999	8,89	900	350	0,5	8,44	2,34	10,054	Yes
64	42000	8,88	900	350	0,5	8,44	2,03	10,353	Yes
65	42002	8,93	900	350	0,5	8,88	2,29	9,97	Yes
66	42003	9,01	900	350	0,5	8,17	2,22	9,59	Yes
67	42004	8,96	900	350	0,5	8,62	2,45	10,184	Yes
68	42005	8,97	900	350	0,5	8,3	2,12	9,73	Yes
69	42006	8,93	900	350	0,5	9,2	2,14	9,72	Yes
70	42009	11,4	1000	350	0	8,6	2,22	9,824	Yes
71	42013	31,1	900	450	0	6,7	1,92	11,76	Yes
72	42014	21,8	900	450	0	7,78	2,39	11,224	Yes
73	42030	0,88	900	500	0	-	-	14,45	No
74	42032	2,49	900	500	0	-	-	14,196	No
75	42033	3,24	900	500	0	-	-	14,379	No
76	43409	10,8	1000	500	0	9,98	3,82	11,984	Yes
77	43456	10,3	1000	400	0	9,08	2,82	10,713	Yes
78	43457	8,33	1000	450	0	9,25	3,36	11,588	Yes
79	43509	15,8	1000	500	0	8,55	3,25	12,214	Yes
80	43518	24,2	1000	450	0	6,56	1,69	12,081	Yes