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Y.SIUSKO,[1] V.SVOBODA,[2] J.STOCKEL,[2] I.GARKUSHA,[1,3] D.SOLYAKOV,[1,3] I.GIRKA,[3] V.VOLKOV,[3] D.BONDAR,[3] V.KONDRATENKO,[3] A.BOYCHENKO,[3] A.KRUPKA,[3] D.BOLOTO,[3] D.DROZDOV,[3] O.SALMIN,[3] A.SHCHIBRYA[3]

[1] National Science Center Kharkov Institute of Physics and Technology
(1, Akademicheskaya St., Kharkov, 61108, Ukraine; e-mail: zhenya-syusko@kipt.kharkov.ua)
[2] Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering
(Brehova 7, 115 19 Praha 1)
[3] V. N. Karazin Kharkiv National University, School of Physics and Technology
(4 Svobody Sq., Kharkiv, 61022)

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BREAKDOWN PHASE IN THE GOLEM TOKAMAK AND ITS IMPACT ON PLASMA PERFORMANCE

The effect of the breakdown phase on subsequent plasma parameters was investigated remotely in GOLEM tokamak. The dependence of breakdown voltage and the breakdown time versus the time delay between the trigger of the toroidal magnetic field B_t and the trigger of toroidal electric field E_t for different groups of the pressure magnitudes is built. The performed experiments have shown that for GOLEM tokamak the shorter is temporal delay - the better mean plasma parameters are obtained. In addition, the breakdown phase was discussed more detailed. In the discussion the analysis of the avalanche phase of the breakdown was made. The dominant mechanism of particle loses during avalanche phase, future steps, tasks were discussed and set.
Keywords: GOLEM, breakdown, avalanche, tokamak, particle losses, plasma parameters

1. Introduction

The initial stage (startup) of a tokamak discharge can be divided into three phases: breakdown, plasma formation, and current rise. The breakdown phase is characterized by a low degree of ionization. Collisions between an electron and neutral molecules dominate. Plasma current is still low, and the rotational transform is negligible. After the break down the next phase starts, which is called the Coulomb phase, when collisions between charged particles dominate. Plasma current is sufficiently high, magnetic surfaces arise, and the confinement is expected to increase significantly. The start-up phase of discharge in a TM-I-MH tokamak was investigated in [1]. The mechanism of particle losses in the phase preceding the formation of rotational transform was studied in the TM-1-MH tokamak in [2], and importance of stray magnetic fields was discussed. The breakdown phase directly affected the ultimate properties of the plasma in the light of the production of runaway electrons, impurity, equilibrium, stability, etc. Breakdown phenomena was studied experimentally in the SINP tokamak [3] for different magnitudes of filling pressure, toroidal electric field, toroidal magnetic field and vertical magnetic field by using a hot filament preionization system. Also, breakdown was studied in the PRETEXT Tokamak [4]. There were investigated the effects of Limiter Bias, working gas, and pressure on breakdown. In the paper [5], tokamak breakdown phase driven by pure Ohmic heating with implicit particle were simulated by the particle in cell/Monte Carlo collision (PIC/MCC) method. The avalanche process was shown to be able to be separated into two stages. One was the fast avalanche stage, in which the plasma was heated by the induced toroidal electric field. The other was the slow avalanche stage, which began after the plasma density has reached 10^{15} m^{-3}. In this paper, the impact of working gas pressure and the toroidal magnetic field on the breakdown phase and subsequent plasma parameters are investigated. A Ukrainian group of undergraduates from the School of Physics and Technology at V. N. Karazin Kharkiv National University had carried out the experiments on studying the breakdown phase remotely due to remote control capability on GOLEM tokamak [6,7] on March, 2019.

2. Experimental set-up and diagnostics

The GOLEM tokamak (formerly CASTOR) at Czech Technical University is demonstrated to be an educational and research device for domestic and foreign students. This tokamak was brought to the IPP Prague in 1977 from Kurchatov Institute in Moscow, Russia. The name TM-1-MH was substituted by the acronym CASTOR: Czech Academy of Science TORus after reconstruction in 1985. After the shut down in 2006, CASTOR was transported to the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague and reinstalled [8]. Now it operates under a new name GOLEM as a device for education and research work. The main parameters of tokamak GOLEM are shown in table 1. The more detailed description of the tokamak is given in [9]. Diagnostics, which were used for the experiment are listed in the table 2.

2.1. Remote handling of the GOLEM tokamak

For remote handling, one needs a computer with an internet connection and agreement of the chief operator of GOLEM. After reviewing and accepting the experiment plan, the remote operators take access for the site with the remote control room of GOLEM. There they can choose parameters which they need according to the plan for the experiments. Parameters that can be pre-selected by remote users are shown in table 3. When the initial parameters of the pulse are accepted, then after a while a discharge is executed. The main experimental results and the data from all the diagnostics are loaded in a couple of minutes into the database, which is also available via the internet for everyone in this site [10]. When one wants to process data, he/she can find the corresponding shot in the database. There are utilities for faster data processing in the site [11]. These utilities help to find the necessary pulse numbers, withdraw the specified diagnostic data or some calculated values in text or graphical form. This is very comfortable and helpful when one needs to process a big massive data in the GOLEM database.

2.2. Preparing for breakdown phase

The tokamak is pumped down to the pressure $10^{-4} \div 10^{-3}$ Pa. The tokamak vessel is baked to $\sim 180°$ for 60 minutes, and the cleaning glow discharge in He is applied for 30 minutes to remove impurity molecules from the inner wall of the vessel. The working gas is H_2. The plasma density $\sim 10^{17} \div 10^{18}$ m^{-3} is required at the breakdown phase. The density of neutral atomic hydrogen should be comparable one. Therefore, the initial pressure of H_2 should be in the range $\sim 0.002 \div 0.02$ Pa. The breakdown of the working gas in tokamaks starts after inducing the toroidal magnetic field (by driving current in the toroidal field coils) and the toroidal electric field coils (by driving current in the primary winding of the tokamak transformer). However, at least a single charged particle (electron) has to be present in the tokamak vessel, which is filled by the working gas at sufficient pressure. In addition, in our case pre-ionization is

Table 1. **Main parameters of tokamak GOLEM**

Parameter	Value
Vessel major radius	$R_0 = 0.4$ m
Vessel minor radius	$r_0 = 0.1$ m
Plasma minor radius	$a \approx 0.06$ m
Toroidal magnetic field	$B_t < 0.5$ T
Plasma current	$I_p < 8$ kA
Central electron density	$n_e \approx (0.2-3) \cdot 10^{19}$ m^{-3}
Effective ion charge	$Z_{eff} \approx 2.5$
Electron temperature	$T_e < 100$ eV
Discharge duration	$\tau_p < 25$ ms
Energy confinemen time	$\tau_e < 50$ μs

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Table 2. **Diagnostics, which were used for the experiment**

• A wire loop laid toroidally along the vacuum vessel measuring the loop voltage U_{loop}.
• A small coil located on the vessel measuring the voltage proportional to the time derivative of the toroidal magnetic field.
• A Rogowski coil surrounding the vessel (and the plasma) ring poloidally measuring the voltage proportional to the time derivative of the total vessel and plasma current I_{v+p}.
• A microwave interferometer system (not shown) measuring the line averaged density n_e.

Table 3. **The parameters of GOLEM tokamak which can be selected via the internet**

Basic parameters which can be preselected remotely	Maximum value	Recommended
The magnitude of capacitors charge voltage for powering toroidal coils U_{BD}	1300	$800 \leq U_{BD} \leq 1000V$
The magnitude of capacitors charge voltage for powering the primary winding of the transformer U_{CD}	700 V	$400 \leq U_{CD} \leq 600V$
Time delay T_{CD}	20 ms	$0 \leq T_{CD} \leq 10ms$
The pressure of working gas p	50 mPa	$15 \leq p \leq 40$ mPa
Periodization	on or off	on
Working gas	H_2 or He	can be chosen

made with using tungsten filament, which generates some free electrons. This electron is accelerated by the toroidal electric field $E_t = U_{loop}/2\pi R_0$, (where U_{loop} is the loop voltage, R_0 is the major radius) and follows the circular magnetic field line. When the energy of electrons is sufficiently high (>13.6 eV in H_2), it ionizes a molecule of the working gas and creates a pair of ion and electron. The secondary electron is again accelerated and ionizes a molecule of H_2. This process further evolves as an avalanche which leads to the breakdown of a gas, and after a short time (in the range of milliseconds) the tokamak vessel is filled by "fully" ionized plasma.

3. EXPERIMENTAL RESULTS

3.1. Preselected discharge parameter via the internet for the investigation breakdown phase

In our experiments, H_2 is selected as the working gas, and the electron gun used for its periodization operates. The charging voltage of the condenser bank for the toroidal magnetic field is fixed to $U_{BT} = 1300$ V and is kept unchanged for the whole experimental series, as the charging voltage of the condenser bank for the primary winding of the transformer $U_{CD} = 500$ V. First, the pressure of working gas is pre-selected by a gate valve to be of 6 mPa, and the time delay T_{cd} between triggers of U_{BT} and U_{CD} is changed from 0 to 5000 μs by steps of 500 μs i.e. 11 shots. The same scan is performed for higher pre-selected pressures - 8, 10, 12, and 14 mPa. Therefore, 55 shots are carried out in a total in this experiment, from №29859 to №29913.

3.2. Results

Temporal evolution of a typical ("good") discharge in Hydrogen, for example, №29871, is shown in fig. 1. Pre-defined discharge parameters: pressure of the working gas (requested 8 mPa, achieved 7.88 mPa); $U_{BT} = 1300$ V; $U_{CD} = 500$ V; Time delay is 0,5 ms.

We see that the plasma life time (or discharge duration) is 16.6 ms (from 7,6 ms to 24,2 ms), the maximum plasma current is $\sim$ 6 kA, the maximum central electron temperature is up to 80 eV, the edge safety factor $q(a)$ is slightly above 3, and the maximum line average density reaches $8 \cdot 10^{18}$ m^{-3}. However, the first stage of the discharge should be examined more precisely. The breakdown time and the breakdown voltage are defined from the plot of the main plasma parameter during the discharge. The closer look at the breakdown phase of the discharge (№ 29871) is shown in fig. 2.

The plasma breakdown is manifested by an abrupt drop of the loop voltage and a sharp increase of the plasma current at t = 7.6 ms, and denoted further as U_{BD}. The breakdown time (τ_{br}) is defined as the time lag between the start of the loop voltage signal

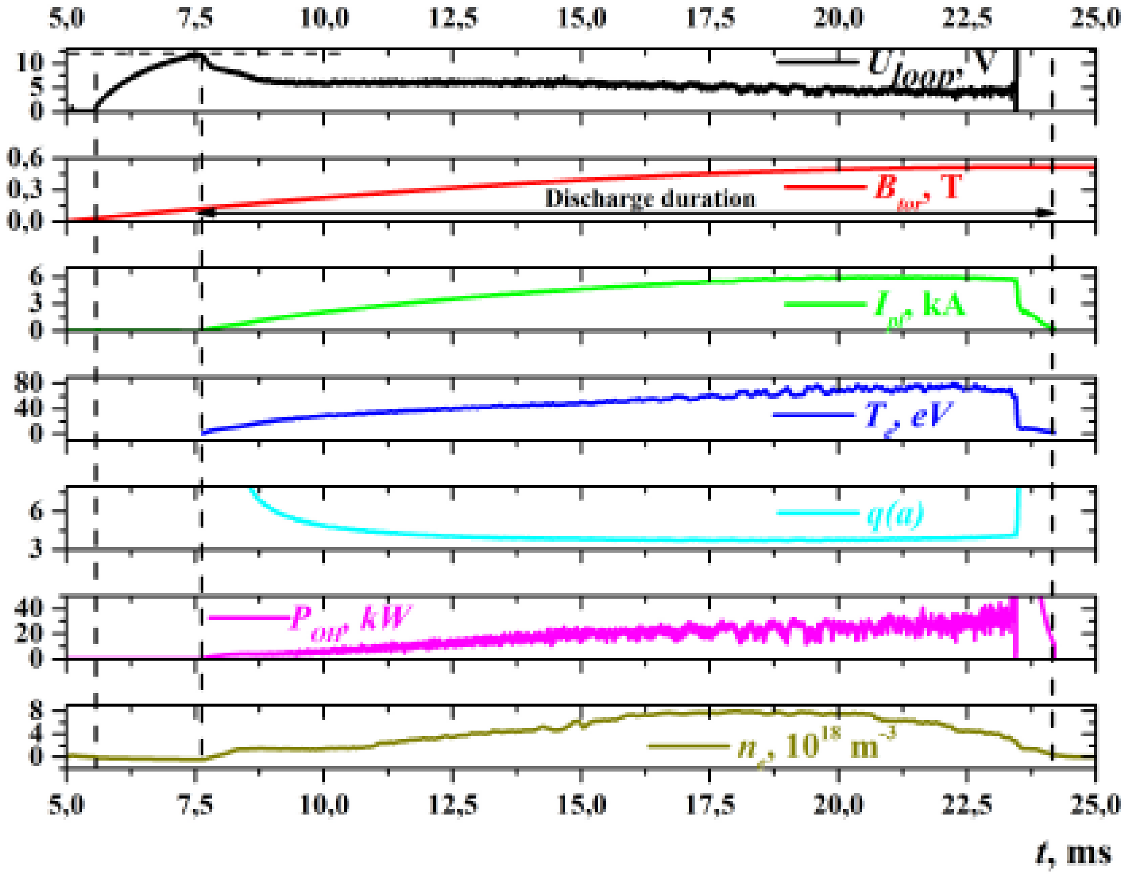

Fig. 1. Plot of the temporal evolution of a good shot №29871 containing selected traces available from the GOLEM database, where from top to bottom: Uloop is loop voltage; B_t is toroidal magnetic field; I_{pl} is plasma current; T_{e0} is central electron temperature; $q(a)$ is safety factor; P_{OH} is the Ohmic heating power; ne is line electron density.

(the trigger of U_{CD}) and the breakdown of the working gas. At the breakdown, the plasma resistivity $R_{plasma} = \frac{U_{loop}}{I_{plasma}}$ drops below the resistivity of the GOLEM vacuum vessel, which is $\sim 10\ m\Omega$. We see that the delay between the trigger B_t and the trigger U_{CD} defines the value of the toroidal magnetic field at which the loop voltage (or the toroidal electric field E_t) is applied. So, increasing this delay, the toroidal magnetic field at the start-up increases as well. Let us analyze impact of the time delay on the plasma parameters of the breakdown phase of the discharge for different values of the working gas pressure. It has to be noted that in GOLEM, one cannot set a precisely same filling pressure for a given pre-selected value. Therefore, for a more convenient presentation, the discharges are divided to the pressure into several groups: $5 \div 6\ mPa$, $7 \div 6\ mPa$, $7 \div 8\ mPa$, $8 \div 9\ mPa$ and $10 \div 11\ mPa$. Fig. 3 presents dependence of the discharge duration versus the time delay for selected groups of the pressure of the working gas. Reduction of the discharge duration with increasing of the time delay is evident. It is also seen that the optimum range of the pressure is in the range of $7 \div 11\ mPa$. Note also a rather dramatic reduction of the discharge duration for lower pressures at the time delay $\sim 5\ ms$. Fig. 4 shows the dependences of the breakdown voltage and the breakdown time on the time delay.

We clearly see that the breakdown voltage as well as the breakdown time increase with increasing of the time delay. When the time delay is more than two milliseconds, the breakdown voltage has a much

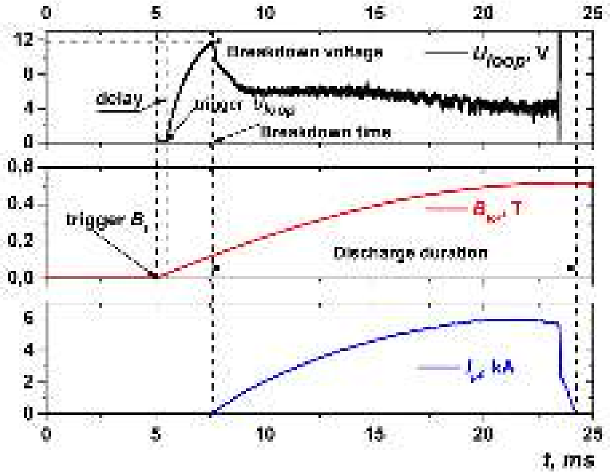

Fig. 2. Plot of the main plasma parameter. (№29871). Here from top to bottom: U_{loop} is loop voltage; B_{tor} is toroidal magnetic field I_{pl} is plasma current.

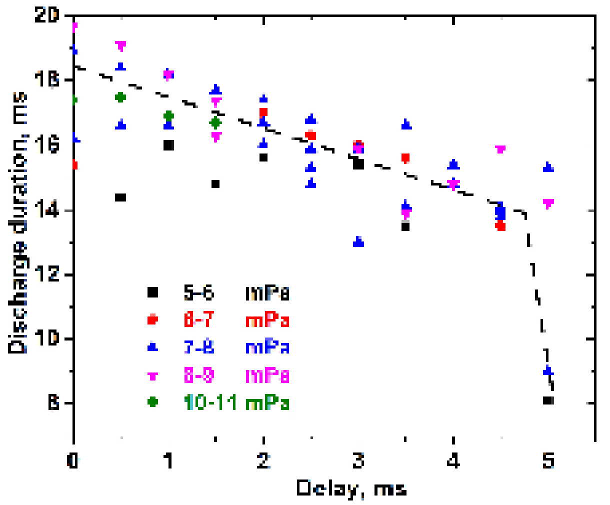

Fig. 3. Discharge duration versus the time delay for several groups of the pressure of the working gas.

wider spread and has unpredictable values. The right panel of Fig. 4 shows that the breakdown time also increases with increasing the time delay. Gas pressure increasing also leads to a later breakdown time. In the GOLEM database, mean values of various plasma parameters are automatically calculated according to software presented in wiki pages of tokamak GOLEM [11]. Fig. 5 shows dependences some of them on the time delay. It is seen that all-important mean plasma parameters are reduced when the time delay is increasing. However, it has to be noted that mean values also reflect the duration of the discharge in some way. As it was claimed before, the time delay is proportional to the toroidal magnetic field during the breakdown phase of the discharge. Therefore, we analyse this phase in more detail to have better insight into underlying physics.

4. DISCUSSION

4.1. Analysis of the avalanche phase of a discharge

The process in a tokamak, which leads to the breakdown, is called as the avalanche phase (Townsend avalanche). The avalanche phase is defined as the time interval between application of the loop voltage and the breakdown of the working gas. Evolutions of several macroscopic parameters of the discharge (№29871) during the avalanche phase are plotted in Fig. 6. We clearly observe the visible emission, which is the signature of excitation/ionization of the working gas by the avalanche of preionization electrons. These electrons are accelerated to the drift velocity by the toroidal electric field:

$$v_D = 6.910^4 \sqrt{\frac{E_T}{p_{H_2}}}, [m/s, V/m, Pa] \quad (1)$$

where $E_T = \frac{U_{loop}}{2\pi R_0}$ is the induced toroidal electric field, and $R_0 = 0.4$ m is the major radius of the GOLEM tokamak. The number of ionizations per unit length is given by the first Townsend's coefficient α:

$$\alpha = A \cdot p_{H_2} \cdot \exp\left\{\frac{B \cdot p_{H_2}}{E}\right\}, m^{-1} \quad (2)$$

where A = 3.75 and B = 99 for molecular Hydrogen [12]. The characteristic ionization time τ_{ion} is defined as:

$$\tau_{ion} = \frac{1}{\alpha \cdot v_D}, [s, m^{-1}, m/s] \quad (3)$$

An example of temporal evolutions of the mentioned above quantities is plotted in Fig. 7 for the GOLEM discharge №29871. Fig. 8 shows more detail evolution of the plasma current during the avalanche phase. During the avalanche phase, the plasma current is proportional to plasma density, because collisions between avalanche electrons and neutrals (hydrogen atoms/molecules) dominate:

$$I_p \sim n_e \cdot v_D, \quad (4)$$

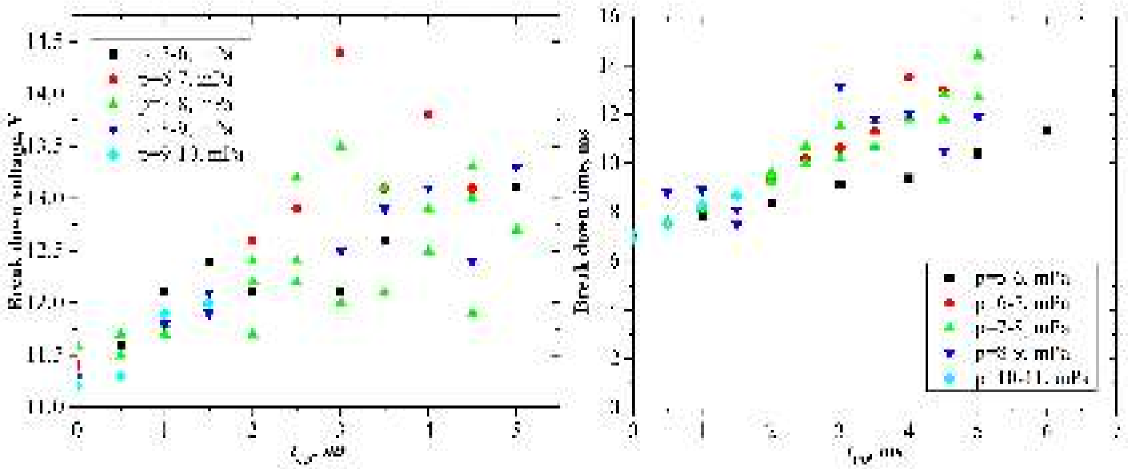

Fig. 4. The Dependencies of the breakdown voltage (left panel) and the breakdown time (right panel) on the time delay.

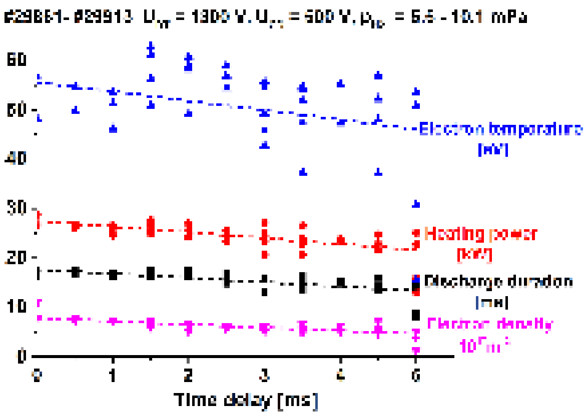

Fig. 5. Variation of mean plasma parameters with the time delay for all range of working gas pressures.

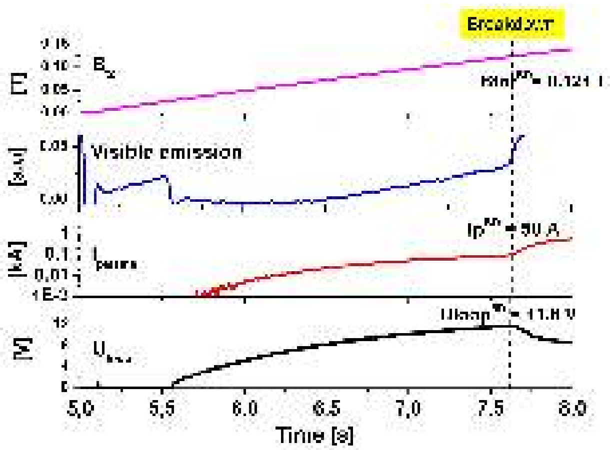

Fig. 6. Temporal evolutions of selected plasma parameters during the avalanche phase of discharge №29871.

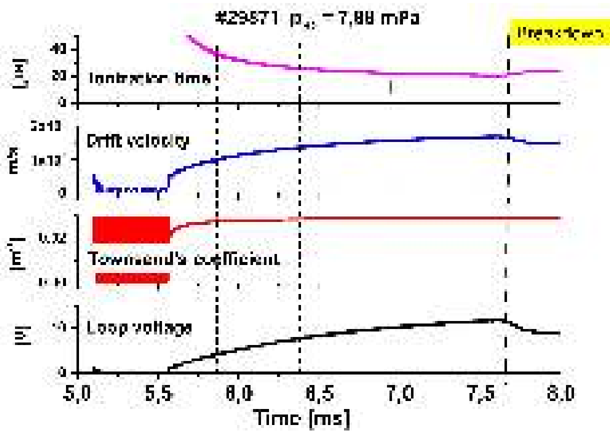

Fig. 7. Temporal evolution of selected quantities during the avalanche phase of the discharge №29871 derived according to the expressions (1-3) and loop voltage.

We see that the rise time of the plasma current at the very beginning of the avalanche is comparable with the ionization time which is in the range of $\tau_{ion} \sim 30-40\mu s$. However, we see in the same figure that the rise time of the plasma current is significantly slowed, being characterize by a time constant $\tau_a > 1ms$, which is by an order of magnitude higher than the ionization time. The evident reasons for this difference are losses of charged particle from the plasma column:

$$n_e(t) = n_{eo} \exp\left[\frac{t}{\tau_{ion}} - \frac{t}{\tau_{loss}}\right], \quad (5)$$

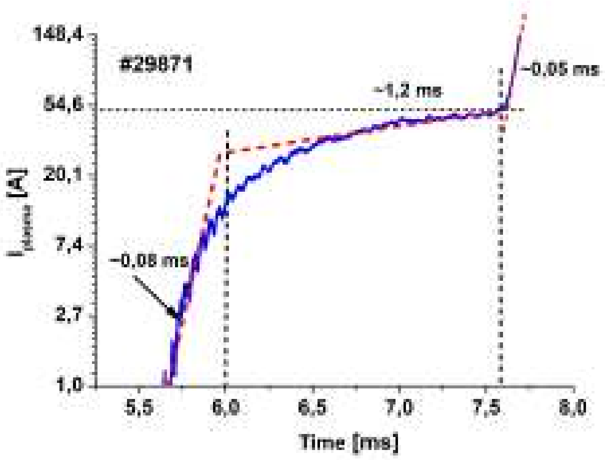

Fig. 8. Evolution of the plasma current during the avalanche phase of discharge №29871.

These particle losses can be characterized by a time τ_{loss}. The relation between the all that time constants is [13]:

$$\frac{1}{\tau_a} = \frac{1}{\tau_{ion}} - \frac{1}{\tau_{loss}}, \qquad (6)$$

If we use now experimentally measured $\tau_a \sim 10 \cdot \tau_{ion}$, we can estimate the characteristic loss time as:

$$\tau_{loss} = \tau_{ion} \frac{1}{1 - \frac{\tau_{ion}}{\tau_a}} = \frac{10}{9} \cdot \tau_{ion}, \qquad (7)$$

We clearly see that the loss time has to be comparable (but slightly higher) than the ionization time to match the experiment. The mechanism for sufficiently fast particle losses during the avalanche was proposed in the pioneering paper of Martin Valovic [14]. It was experimentaly demonstrated that plasma polarization due to perpendicular stray magnetic B_{perp} is responsible for fast particle losses during the avalanche phase. This mechanism is depicted on a schematic drawing shown in Fig. 9 assuming the stray magnetic field has only the vertical component $B_{perp} = B_z$. Perpendicular stray magnetic fields, which are always present in the tokamak vessel, cause the drift of charged particles in a perpendicular direction with respect to the toroidal magnetic field. The avalanche electrons propagate along the helical magnetic field line with drift velocity, while the ion velocity is much lower. This causes separation of electron and ion component and consequently results in the formation of the perpendicular electric field E_{perp}.

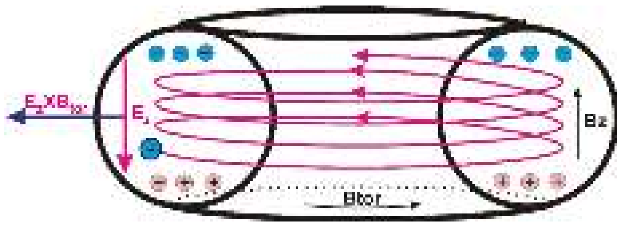

Fig. 9. Formation of the perpendicular electric field E_z and consequent losses due to cross-field drift motion $E_z \times B_tor$.

The expression for the perpendicular electric field was derived (and proved by experiment) in [15] as:

$$E_{perp} \approx \frac{E_{tor} B_{tor}}{B_{perp}} \qquad (8)$$

The corresponding cross field velocity characterizing plasma losses is $v_{loss} \approx \frac{B_{perp}}{B_{tor}}$, and the resulting loss time is:

$$\tau_{loss} \approx \frac{\alpha}{\nu_{loss}} = \frac{\alpha \cdot B_{perp}}{E_{tor}} \qquad (9)$$

where a is the minor radius of GOLEM. As a next step, we have to estimate the perpendicular stray magnetic B_{perp} field on GOLEM. There are three main sources of the perpendicular stray magnetic fields on GOLEM during the avalanche phase:

- The stray vertical magnetic field generated by the current induced in the conducting vessel of GOLEM, $I_{vessel} = \frac{U_{loop}}{R_{vessel}}$, where $R_{vessel} = 0.001\Omega$
- The stray magnetic field generated by the presence of the iron core transformer.
- The stray magnetic field generated by imperfect alignment of toroidal field coils and cables of their powering.

The stray vertical magnetic field due to the current induced in the toroidal tokamak vessel is proportional to the vessel current, estimated as [16]: $B_z = (0.4 \div 0.5) \cdot 10^{-5}$ $[T, V]$. According to the equations 8 and 9, the resulting loss time is (within some expected error bars) $\tau_{loss}^{vessel} \approx \frac{\alpha \cdot B_z}{E_{tor}} = (0.04 \div 0.05) \cdot 10^{-4} \frac{2\pi R_0 \cdot a \cdot U_{loop}}{U_{loop}} = (1 \div 1.2) \cdot 10^{-5} \cdot [s]$ is comparable with the ionization time τ_{ion}. It is important to emphasize that this loss time depends only on the geometry of the GOLEM, being independent on preselected discharge parameters. Therefore, we can assume this loss time as the basic one. It is evident that the vessel stray magnetic field is superimposed by the stray field of the iron core transformer of GOLEM τ_{loss}^{transf}. Unfortunately, we don't know how to estimate this quantity. But, definitely, the resulting loss time has to be higher. Now, we have to discuss the stray field due to the toroidal field winding. The dependence of the avalanche time on the time delay is plotted in Fig. 10. We clearly observe a linear de-

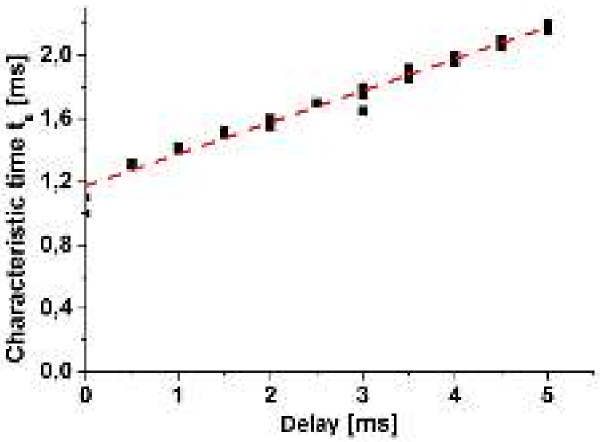

Fig. 10. The dependence of the characteristic (avalanche) time τ_a on the time delay.

pendence of the avalanche time on the time delay, i.e. on the value of the toroidal magnetic field during the avalanche phase. This demonstrates that the stray magnetic field because of TF coils is significant. However, these stray fields, which should be well below 1% of B_{tor} can be hardly measured experimentally on the high background.

5. CONCLUSIONS

A Ukrainian group of master students from the School of Physics and Technology, V. N. Karazin Kharkiv National University, held experiments on the study of the breakdown phase remotely due to remote control capability on GOLEM tokamak. The breakdown phase is investigated depending on the filling pressure of the working gas H_2, and the time delay between the start of the toroidal magnetic field and the trigger of the current in the primary winding of the GOLEM transformer. Experimentally measured dependences of macroscopic discharge parameters allow us to conclude:

- Increasing time delay leads to the reduction of the discharge duration. A rather dramatic reduction of the discharge duration for the lowest pressures at the time delay $\sim 5ms$ is also observed;

- Increasing time delay is followed by an increase of the breakdown voltage and the breakdown time. This may cause an enhanced generation of supra-thermal (runaway) electrons, which is always unwanted effect in tokamaks.

In summary, the best plasma performance on GOLEM is achieved at the lowest time delays (from 0 to 1ms) and the filling pressures of the working gas (H_2) in the range of $7 \div 9\ mPa$. The avalanche phase of the breakdown was also analyzed. Several characteristic quantities are calculated under the GOLEM conditions: the drift velocity of electrons in molecular Hydrogen, the number of ionizations per unit length (Townsend's coefficient α) and the characteristic ionization time τ_{ion}. It was observed that the characteristic (avalanche) time τ_α increases linearly with increasing the time delay. We conclude that the dominant mechanism of particle loses are caused by plasma polarization due to stray magnetic fields which occur during the avalanche phase.

Ukrainian team sincere thanks the Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering for the opportunity to perform remote control and exploitation of the GOLEM tokamak. This work has been supported by IAEA CRP F13019 "Network of Small and Medium Size Magnetic Confinement Fusion Devices for Fusion Research" as well as the European Fusion Education Network (FuseNet). This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.' Work performed under EUROfusion WP EDU.

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Фаза пробою на токамаці GOLEM та її вплив на параметри плазми

Р е з ю м е

На токамаці GOLEM було досліджено вплив фази пробою на подальші (після пробійні) параметри плазми. Для різних під-груп тиску, побудована залежність напруги та часу настання пробою від періоду затримки між моментом включення тороїдального магнітного поля B_t та моментом включення тороїдального електричного поля E_t. Проведені експерименти на токамаці GOLEM показали, що чим коротша часова затримка між полями - тим кращі середні параметри плазми. Крім того, фаза пробою була обговорена більш детально. В ході обговорення було зроблено аналіз лавинної фази пробою. Встановлено домінуючий механізм втрати частинок під час лавинної фази, обговорені майбутні кроки досліджень, поставлені нові завдання.