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ORIGINAL RESEARCH

Operational Domain in Hydrogen Plasmas on the GOLEM Tokamak

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Abstract

A series of discharges in hydrogen were performed in two experimental sessions. The vessel was not conditioned before the first session, while inductive heating of the vessel and cleaning glow discharge were applied before the second session. Experimental results from both sessions are compared, and optimum operational conditions for the majority of key plasma parameters are determined. It is found that plasma performance with a properly conditioned vessel is significantly better, as expected. In particular, a noticeable increase of discharge duration, and of the electron temperature is observed.

Keywords Tokamak · Plasma · Operational domains

Introduction

The GOLEM tokamak operates at the Faculty of Nuclear Physics and Physical Engineering (FNPPE), Czech Technical University in Prague [1]. GOLEM is a small tokamak which was constructed at the end of 1950s at the Kurchatov Institute, Moscow and moved to the Institute of Plasma Physics in Prague in 1977 and re-named as CASTOR [2, 3]. After 30 years of operation, the tokamak was given to the FNPPE for education of students and renamed as GOLEM. It is the oldest operational tokamak in the word.

An important feature of GOLEM is the possibility of remote operation via Internet (see "Remote Operation of the GOLEM Tokamak" section), which is frequently used for education of young domestic as well as foreign students. Recently, such remote operation was performed with the aim to determine the operational domain of the GOLEM tokamak in a sufficiently broad range of engineering input parameters and to optimize discharge performance.

Remote experiments were performed in two sessions:

- First session: The vacuum vessel is evacuated to the basic pressure ∼ 0.1 mPa, and with tokamak operation starting immediately. Consequently, the inner surface of the vessel is covered by adsorbed molecules (mainly water). Such an operation mode is usually used for demonstration of GOLEM performance, for commissioning of newly installed diagnostics, and for educational purposes. In the following text, we refer to this vessel conditions as "dirty".
- The second session: the tokamak vessel was carefully conditioned by inductive heating for up to 200° for 60 min, which was followed by a cleaning glow discharge in Helium to remove impurities adsorbed on the inner surface. Typical parameters of the glow discharge cleaning at the GOLEM tokamak are: the pressure is 1 Pa, 20 min duration and the discharge current is 0.5 A. This operational mode is usually exploited for dedicated plasma physics studies, [e.g. 4]. This status of the vessel is referred to as "clean". The basic pressure in the clean vessel is again ∼ 0.1 mPa.

Plasma performance on the GOLEM tokamak under the both vessel conditions is compared. The main aim is to provide guidance to future GOLEM users, and thus to

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accelerate the achievement of required discharge conditions. The GOLEM tokamak together with its state-of-the-art remote operation system are briefly described in "The GOLEM Tokamak" section. Main experimental results are presented and discussed in "Experimental Results" section, and summarized in "Conclusions" section.

The GOLEM Tokamak

Description and Characteristics

The GOLEM tokamak has a circular cross section with the major/minor radii $R_0 = 0.4$ m, $b = 0.1$ m. The stainless steel vessel is equipped with a poloidal limiter (made of Molybdenum) of radius $a = 0.085$ m. The power supplies of individual windings are based on several capacitor banks. In this contribution, we perform GOLEM operation in the very basic mode, and only two capacitor banks are exploited to supply the toroidal field coils and primary winding of the iron core transformer.

The tokamak is equipped with a set of basic diagnostics, which measure the loop voltage, plasma current, toroidal magnetic field, and visible light emission. GOLEM is also equipped with Mirnov coils, a visible spectrometer, a microwave interferometer, hard X-ray (HXR) sensor, an array of bolometers, and a fast camera for time resolved pictures of the visible emission [5, 6], etc.

Engineering and plasma parameters, which can be achieved on GOLEM are quite modest. The tokamak operates at maximum toroidal magnetic field of up to 0.5 T, with plasma current less than 8 kA. The central electron temperature is somewhat less than 100 eV, and the line average density just below $\sim 10^{19}$ m^{-3}, with the maximum pulse length is around 20 ms.

Remote Operation of the GOLEM Tokamak

A unique capability of the GOLEM tokamak is that it can be operated remotely via Internet [7]. Once agreed with the chief in situ operator, the remote users connect to the web page displaying the remote control room of GOLEM, which is shown as the print screen in Fig. 1.

It is seen in the figure that just six "knobs" are used to operate the tokamak in a basic mode. Remote operators pre-select charging voltage of the capacitor banks for powering the toroidal field coils (U_B) and the primary winding of the transformer (U_{CD}). Then, the time delay between triggering pulses of U_B and U_{CD} is also pre-selected (t_{CD}). Furthermore, the working gas (Hydrogen or Helium) and its filling pressure (p_{WG}) are chosen. One can also select the type of pre-ionization (microwave or electron gun). The selected discharge is commented and placed into the queue. Once the discharge is executed, the experimental results in form of temporal evolutions of basic plasma parameters, as well as resulting data files are available, when the option "Results" is selected on the yellow banner of the screen. Other most important options seen on the yellow banner in Fig. 1: *Queue*—position of the discharge to be executed, *Live*—views by web cameras of the torus hall and through a glass window into the tokamak vessel.

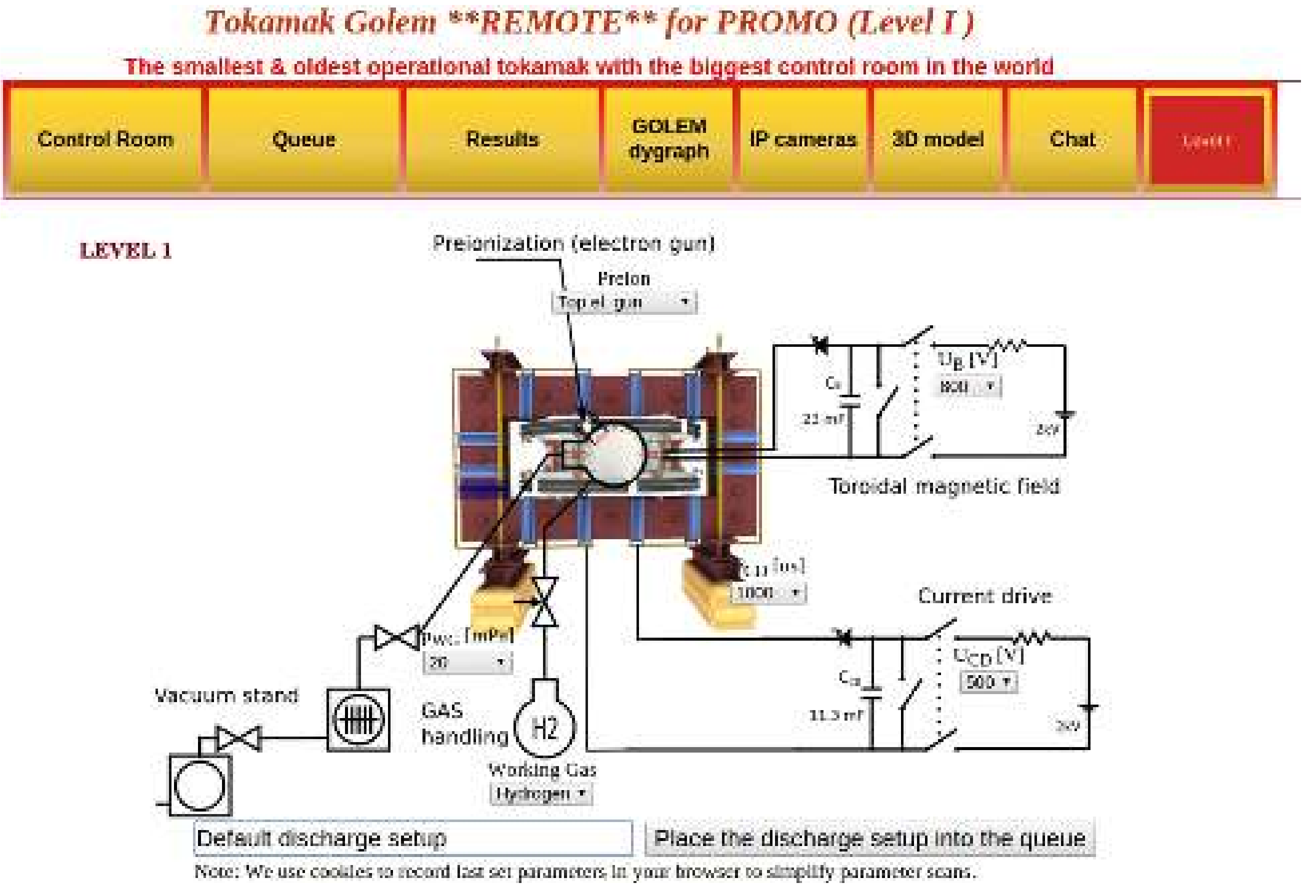
Experimental Results

This remote operation of GOLEM is focused on defining the operation domain of the GOLEM tokamak. We have fixed the charging voltage toroidal magnetic field at $U_B = 1100$ V, which generates sinusoidal waveform of the toroidal magnetic field with the maximum $B_t = 0.45$ T at $t = 25$ ms. Furthermore, the time delay between triggering the capacitor banks U_B and U_{CD} is also fixed to $t = 0$ ms. This means that both the main power supplies are triggered at the same time. The working gas is Hydrogen, and its pre-ionization by an electron gun is kept ON. Thus, only two of six "knobs" mentioned above are exploited in this experiment. The temporal evolution of a typical discharge is plotted in Fig. 2.

The left panel displays the evolution of three basic quantities measured during every discharge, the loop voltage, the plasma current, and the toroidal magnetic field. From these data, the duration of the discharge $T_{dischcharge}$, the breakdown voltage of the working gas $U_{breakdown}$, and the value of the toroidal magnetic field at the breakdown are automatically recorder and stored. Plots in the right panel of Fig. 2 show quantities derived automatically from the basic diagnostics: the electron temperature T_e (from the plasma conductivity according to Spitzer's formula [8] corrected for trapped electrons [9]), the Ohmic heating power $P_{OH} = U_{loop} * I_p$, and the edge safety factor calculated as $q(a) = 90.3 * B_t / I_p$ [T, kA]. All these data are stored in the GOLEM database and are freely available via internet for any discharge.

It has to be noted that the plasma position in vertical/horizontal direction within the tokamak vessel evolves spontaneously, because it is not actively controlled. This is a specific feature of GOLEM operation at a basic level. Consequently, the position of the plasma center is changing during a discharge, as demonstrated in Fig. 3 showing emission recorded by an array of bolometers.

Displacement of emissivity upward and shrinking of the plasma column during the discharge is evident. However, this variation of the plasma cross section is not taken into account in the present analysis.



Tokamak Golem **REMOTE** for PROMO (Level I)

The smallest & oldest operational tokamak with the biggest control room in the world

LEVEL 1

Preion: Top el. gun

U_B [V]: 800

τ_{CD} [μs]: 1000

p_{WG} [mPa]: 20

U_{CD} [V]: 500

Working Gas: Hydrogen

Default discharge setup

Note: We use cookies to record last set parameters in your browser to simplify parameter scans.

Fig. 1 Virtual control room of the Golem tokamak used for remote operation

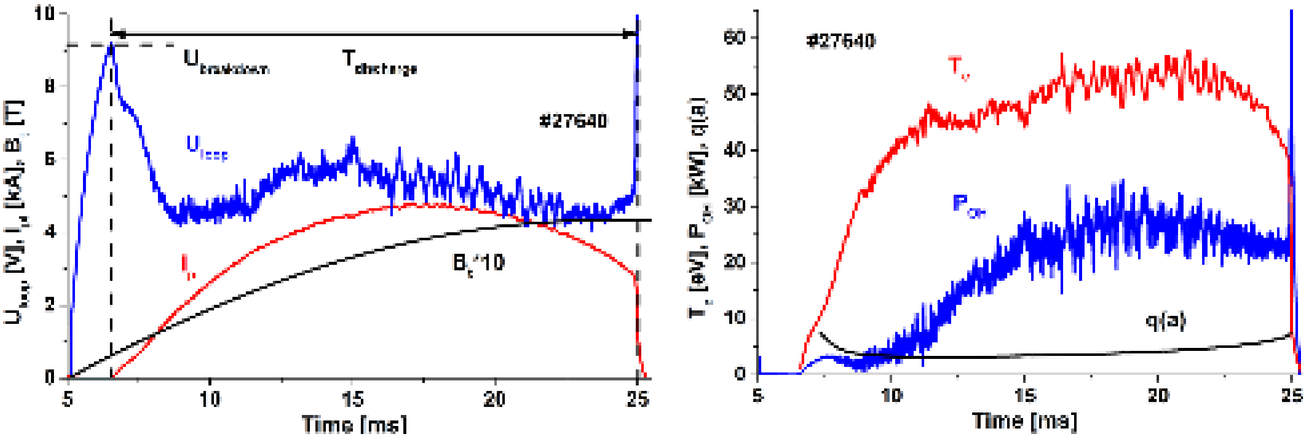


Fig. 2 Temporal evolution of the discharge #27640, $p = 23.5$ mPa, $U_{CD} = 400$ V—“clean” vessel

The GOLEM tokamak is equipped by a microwave interferometer ($\lambda = 4$ mm) which measures the line average density. Unfortunately, this diagnostics did not operate properly during these experimental campaigns. We observe “jumps” in the temporal evolution of the interferometer signal, which is a consequence of “fringe fails” that are not properly processed by its electronic system. Therefore, any systematic analysis of density cannot be performed over the scans. Nevertheless, a rough analysis of interferometer data indicates a rather low line average density, between $\sim$ 1.8 and 3.8 10^{18} m^{-3}.

About 90 discharges were executed during both remote sessions by scanning the pressure of the working gas in the range of 10–30 mPa, and the charging voltage of the capacitor bank of the primary winding of the tokamak transformer in the range of 250–600 V. We focus on

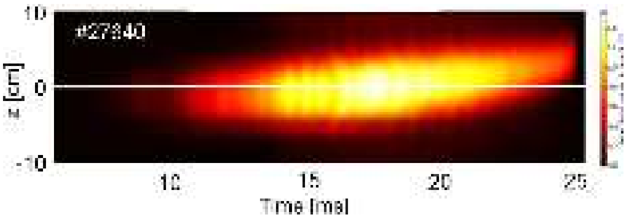


Fig. 3 Temporal evolution emission measured by the array of bolometers viewing the plasma vertically from the horizontal port (#27640)

several plasma parameters, which are also automatically derived and stored in the GOLEM database, such as the mean plasma current, the mean loop voltage, the mean Ohmic heating power, and the central electron temperature averaged over the discharge duration. Furthermore, we analyze conditions at breakdown of the working gas and behavior of runaway electrons. We search the optimum values of above-mentioned quantities to characterize plasma performance and to determine the operational domain of the GOLEM tokamak in Hydrogen discharges.

Breakdown of the Working Gas

Temporal evolution of the start-up phase of a GOLEM discharge is shown in Fig. 4. We plot here selected parameters such as the total current measured by the external Rogowski coil, the current in the conducting vacuum vessel (proportional to the loop voltage), and their difference showing the plasma current.

We can distinguish two phases during the start-up. After applying the loop voltage at t = 5 ms, the electrons from the pre-ionization source accelerate, collide with molecules of the working gas and ionize them. Consequently, the plasma density and the plasma current increases exponentially with a time constant, which is given by the balance between the ionization rate and charge particle losses due to stray magnetic fields. This phase is usually called the avalanche phase [10], and, in this particular case lasts ~ 2.3 ms. When the plasma current increases to a sufficiently high level, the rotational transform becomes dominant and the confinement of charged particles dramatically improves. This occurs when the plasma current is I_p ~ 30–40 A and the toroidal magnetic field is B_t ~ 95 mT. Then, the plasma current starts to rise faster, the degree of ionization increases, electron–ion collisions dominate, and plasma becomes ohmically heated.

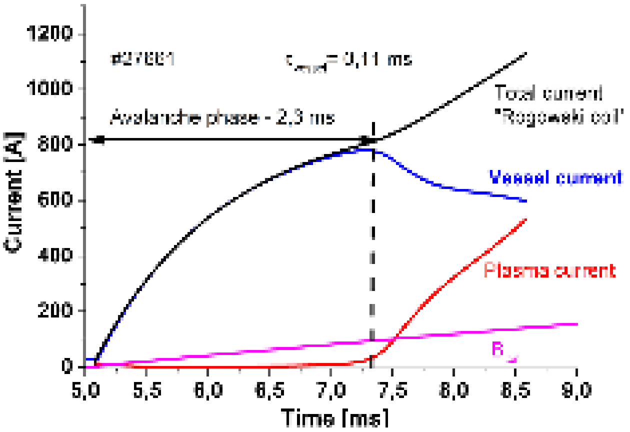


Fig. 4 Evolution of the start-up phase on GOLEM

Results of breakdown studies are summarized as 2D plots in the p–U_{CD} plane in Fig. 5.

It is evident that the lowest breakdown voltage is observed at low charging voltage U_{CD}, and depends only slightly on the pressure of the working gas. It is also seen that the status of the vacuum vessel (clean or dirty) doesn't play any significant role for breakdown, as expected.

It is also seen that the breakdown voltage increases with the pressure of the working gas for any charging voltage U_{CD}. This is in agreement with prediction from the Paschen law shown in Fig. 6, where the toroidal electric field required for breakdown is plotted versus the pressure of the working gas.

The Paschen law for breakdown voltage is described by the general expression [11]

$$E = \frac{Bp}{\ln(Apd) - C},$$

where C = ln[ln (1 + 1/γ)], and A, B are constants. If the pressure p of working gas is expressed in mPa, and the electric field $E_{bd} = U_{bd}/2\pi R$ is in V/m, then the best fit (blue line in Fig. 6) is achieved by selecting unknown constants such as A = 0.9 [m^{-1}, mPa^{-1}], B = 0.3 V/m/mPa, C = 1.2 ≥ γ ~ 0.037.

It is evident that the electric field E_{bd} on GOLEM is still by an order of magnitude higher than the limit for breakdown required for ITER [12]. It means that the conditions for breakdown are still far from optimum. This is because of perpendicular components of the toroidal magnetic field are still significant and cause losses of charged particles during the avalanche phase of the discharge before the rotational transform dominates [9]. The stray perpendicular magnetic fields on GOLEM are naturally generated by:

- Unprecise positioning of toroidal magnetic field coils.
- The electric current in the conducting vacuum vessel during the avalanche phase of the discharge.

In an ideal case, the perpendicular components of the magnetic field have to be precisely compensated by external poloidal coils to achieve optimum breakdown. This is not the case of GOLEM at a basic operational level discussed here. However, experimental analysis of stray magnetic fields and their impact on breakdown would

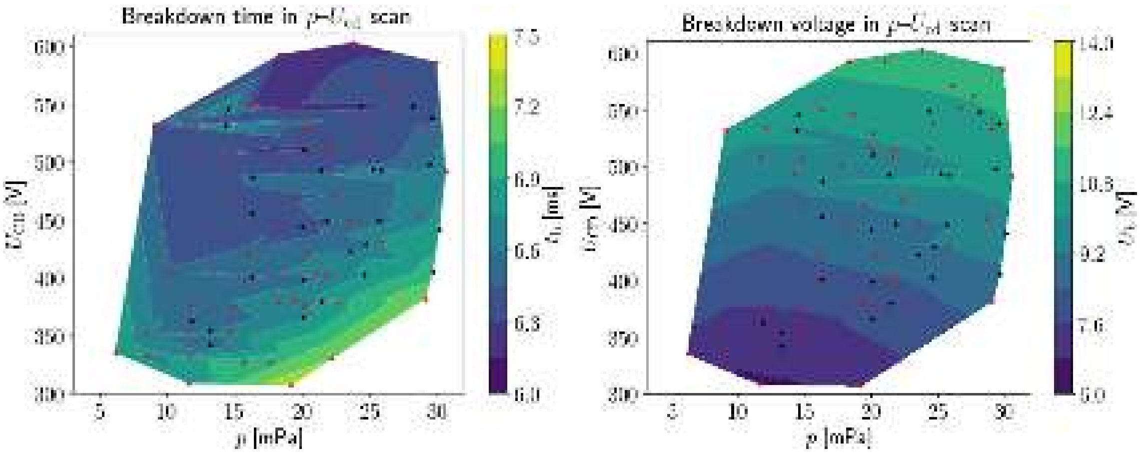


Fig. 5 2D plots in the plane of the pressure and the charging voltages U_{CD}. Red symbols—"clean" vessel, black symbols—"dirty" vessel. Left—the breakdown time, right—the loop voltage at the breakdown (Color figure online)

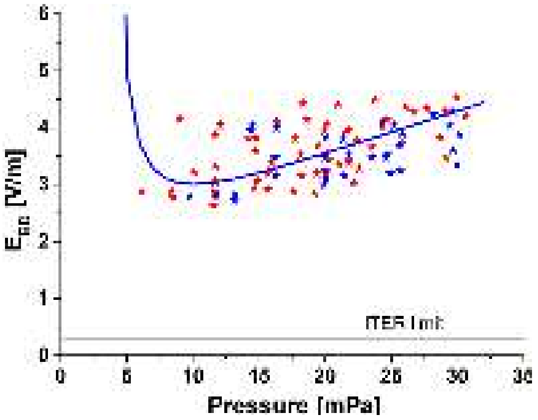


Fig. 6 Paschen diagram on GOLEM—for "clean" (red symbols) and "dirty" (blue symbols) vessel for all measured values of U_{CD}. Blue line—model Paschen law (Color figure online)

require extra effort exceeding the scope of this contribution.

Discharge Duration

The dependence of discharge duration on working gas pressure is plotted in Fig. 7.

The dependence of the discharge duration on the status of the inner wall of the GOLEM vessel is evident. It is seen that for $p > 13$ mPa, the duration of discharges for a well-conditioned vessel is longer by a factor of 2 than with the "dirty" one. On the other hand, only a weak dependence on pressure and the charging voltage U_{CD} is observed. The duration of the discharge is limited by quality of the iron core transformer of GOLEM, which is designed to transfer maximum magnetic flux $\Phi_{MAX} = 0.12$ Vs. Above this value, the transformer core becomes oversaturated and cannot transfer the power from the primary circuit to the plasma loop. The magnetic flux consumed by the iron core

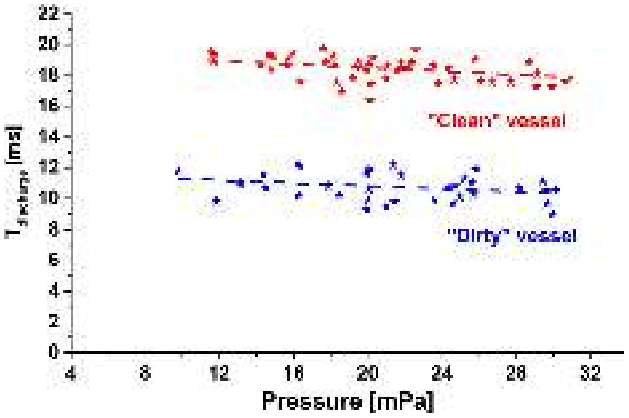


Fig. 7 Duration of a discharge versus the pressure of the working gas for "clean" and "dirty" vessel plotted for *all* values of the charging voltage of the capacitor bank used for powering the primary winding of the GOLEM transformer, U_{CD}

transformer is easily calculated as the time integral of the loop voltage,

$$\Phi(T) = \int_0^T U_{loop} dt \quad [Vs].$$

The temporal evolution of the loop voltage for two discharges is plotted in Fig. 8.

It is seen that the discharges terminate when the consumed magnetic flux approaches $\Phi = 0.8$–0.1 Vs, which is close to the limit maximum magnetic flux Φ_{max}. The loop voltage in "dirty" vessel discharges is significantly higher than for "clean" conditions, because of enhanced influx of impurities during the discharge and a consequent higher effective ion charge Z_{eff}. Therefore, duration of GOLEM discharges with a "clean" vessel are always longer than those with a "dirty" vessel, and thus more suitable for physics studies.

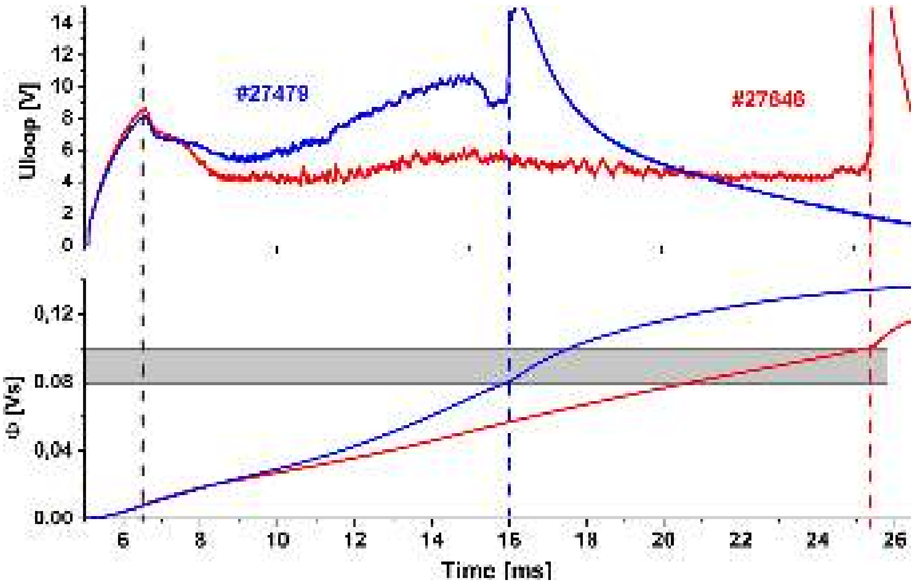


Fig. 8 Evolution of the loop voltage and the consumed magnetic flux in the GOLEM transformer for “clean” (red) and “dirty” (blue) vessel (Color figure online)

Mean Plasma Current and Loop Voltage

Figure 9 compares mean values of the plasma current and the loop voltage in sessions with “clean” and “dirty” vessels.

We again observe a higher loop voltage with a “dirty” vessel, because of higher Z_{eff} and a significantly lower plasma current than in the clean one. This is because that the plasma resistivity $R_{plasma} \sim Z_{eff}$, is higher in this case.

Ohmic Heating Power and the Electron Temperature

The Ohmic heating power is calculated as the product of the plasma current and the loop voltage and its mean value is stored in the GOLEM database. Figure 10 plots this quantity for “clean” and dirty vessels.

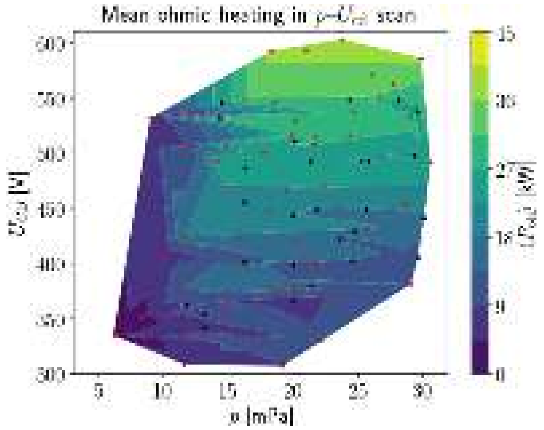


Fig. 10 2D plot of the mean Ohmic power at different pressures and charging voltages U_{CD} for “clean” (red points) “dirty” (black points) vessel (Color figure online)

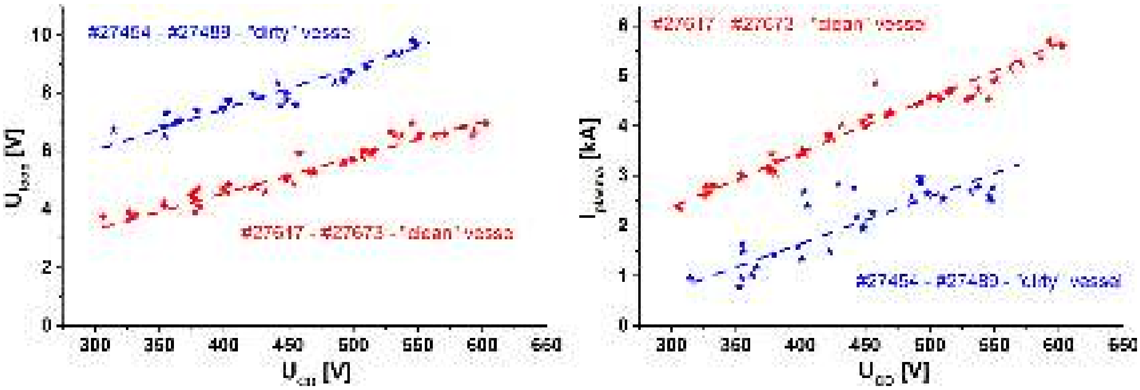


Fig. 9 Mean plasma current and the mean loop voltage versus the “real” charging voltage U_{CD}—for “clean” (red symbols) and “dirty” (blue symbols) vessel (Color figure online)

It is seen that the heating power delivered to plasma is almost independent on the status of the vacuum vessel—higher loop voltage and lower plasma current for the “dirty vessel and vice versa for the “clean” vessel.

A quite different situation is observed on behavior of the electron temperature, derived from Spitzer conductivity [8] as evident from Fig. 11.

It is evident that a significantly higher electron temperature is achieved with the well—conditioned vessel.

Runaway Electrons

The toroidal electric field $E_{tor} = U_{loop}/2\pi R$ is rather high on GOLEM and consequently runaway electrons are generated during a discharge. Figure 12 shows evolution of the signal of a HXR sensor (composed of a scintillator + photomultiplier) during a discharge.

Spikes in the HXR signal correspond to those runaway electrons (RE), which are lost from the plasma column and hit a first wall element of the tokamak vessel, mainly the poloidal limiter [12–14]. The amplitude of spikes is proportional to energy of runaway electrons, but the HXR sensor was not absolutely calibrated during this experimental campaign. Nevertheless, the maximum energy of RE can be estimated under the assumption of free-fall acceleration and neglecting collisions as

$$W_{\max} \sim c \int_0^{Tdisch\arg e} E_{tor} dt \quad [eV]$$

where c is the velocity of light. The right panel of Fig. 12 demonstrates that REs can be accelerated on GOLEM up to several MeV.

To estimate the number of RE which are generated in a particular discharge, we integrate the HXR signal during the discharge, which is plotted in the upper panel of Fig. 12.

Resulting time integrals of the HXR signal are compared in the next Fig. 13 for the campaigns with the “clean” and “dirty” vessel.

As it is evident, the highest values of the integrated HXR are observed in discharges with “clean” vessel at low plasma current. This is due to the fact that the runaway electron rate is inversely proportional to the effective ion charge Z_{eff} [15].

$$S_R \approx \exp - \left\{ \frac{kT_e}{m_e c^2} \left[\frac{1}{8} \left(\frac{E_D}{E} \right) + \frac{2}{3} \left(\frac{E_D}{E} \right)^{3/2} \sqrt{1 + Z_{eff}} \right] \right\}$$

where E_D is the Dreiser field, $E_D \cong 410^{-2} \left(\frac{n_e}{10^{13}} \right) \left(\frac{10^3}{T_e} \right)$ [V/cm, cm^{-3}, eV], and E is the toroidal electric field.

Conclusions

This contribution summarizes results of systematic measurements performed on the GOLEM tokamak at two different conditions of the inner wall of the tokamak vessel. Experiments with the “dirty” vessel (discharges #27640–#27640) are performed just after evacuation of the vessel to a basic pressure of the working gas < 1 mPa. Operation under such conditions is used typically to demonstrate tokamak operation to students (either present at the tokamak, or operating remotely from abroad), commissioning new diagnostics etc. Operation with a “clean” vessel is used for experiments which should yield physical results. In this case, the vessel is baked to ∼ 200° and the cleaning glow discharge is applied (discharges #27466–#27474). Comparison of plasma performance under such conditions is thereby used useful. We focus on comparison of selected plasma parameters which are available in the GOLEM database just after executing the discharge at http://golem.fjfi.cvut.cz/shots/#shotnumber/:

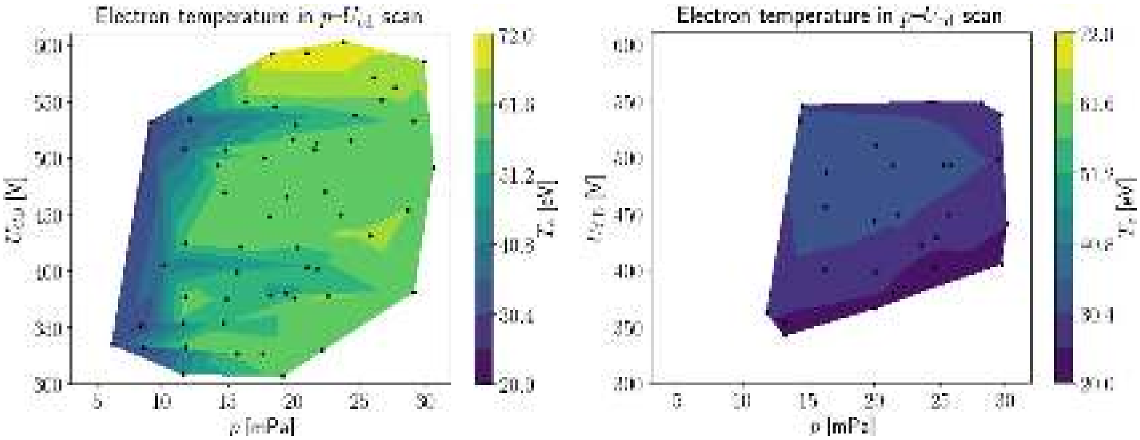


Fig. 11 2D plot of the mean electron temperature at different pressures and charging voltages U_{CD}. Left—“clean” vessel, right—“dirty” vessel

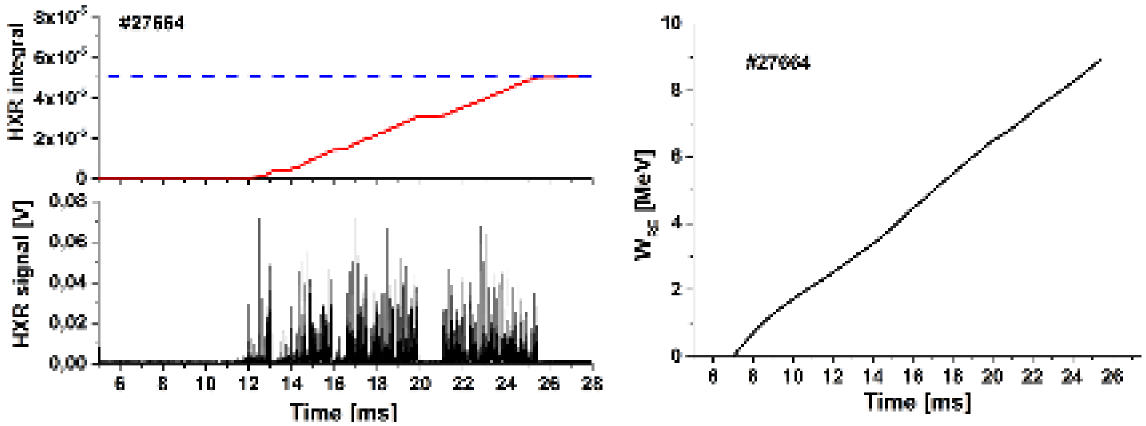


Fig. 12 Left—evolution of the HXR signal (bottom panel) and its time integral (top panel). Right—maximum energy of RE. #27664 ("clean" vessel)

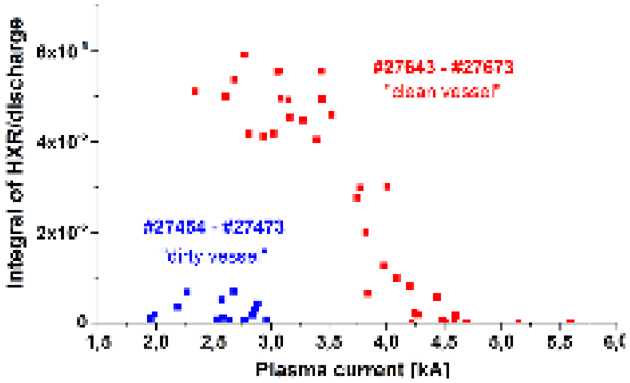
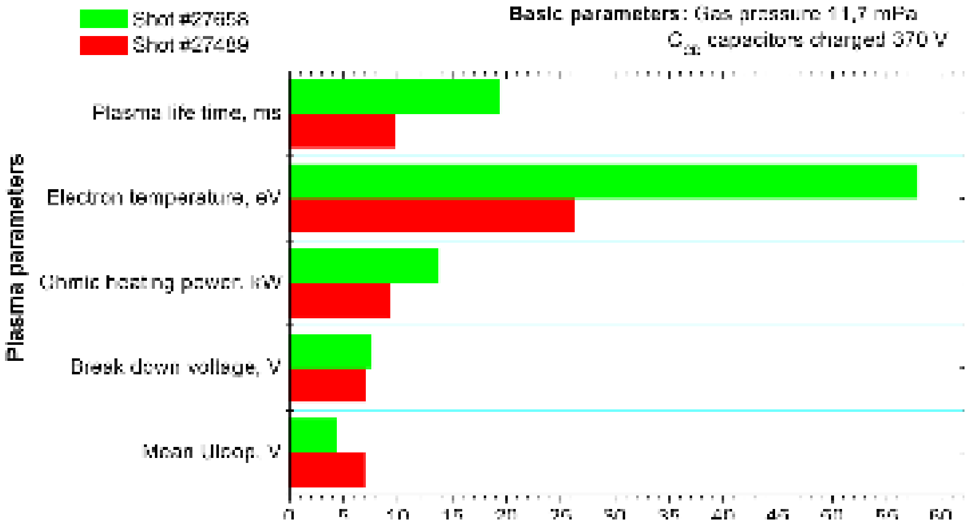


Fig. 13 Time integral of HXR versus plasma current for "clean" and "dirty" vessel

- *Loop voltage*—is significantly lower with the "clean" vessel because of a reduction of impurity influx during the discharge and consequent a lower effective ion charge Z_{eff} than with the "dirty" vessel.
- *Discharge duration*—is noticeably longer with the "clean" vessel by a factor of two than with the "dirty" vessel because of lower loop voltage. Consequently, the saturation of the iron core transformer of GOLEM, which terminates the discharge occurs later.
- *Ohmic power*—delivered to plasma is almost independent on the status of the vessel, because the plasma current is higher and the loop voltage is lower with the "clean" vessel and vice versa for the dirty vessel.
- *Mean electron temperature*—is significantly higher with the "clean" vessel. This also implies an improvement of electron confinement time $t_{eE} \sim T_e{*}ne/P_{OH}$, because the electron density as well as the ohmic power seem to be almost independent of the status of the vessel.
- *The breakdown voltage*—is independent on the status of the vessel, because the plasma wall interaction is negligible during this phase of the discharge, and

Fig. 14 Summary comparison of plasma performance with "dirty vessel" (#27489) and "clean vessel" (#27658)



impurities don't play any role for breakdown of the working gas.

Comparison of plasma performance is shown in Fig. 14 to demonstrate what was mentioned above for two typical discharges with the "clean" and "dirty" vessel.

We also compare behaviour of HXR emission, which is related to generation of runaway electrons. We achieved interesting results showing higher HXR activity with the "clean" vessel. However, understanding of this behaviour would require more experiments and improvement of diagnostics.

In summary, this contribution tries to provide guidelines for future students and young physicist for an efficient operation of the GOLEM either from in-house or remotely.

In future, we plan to perform similar analysis of plasma performance with Helium working gas.

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