Magnetic confinement of high temperature plasma at the GOLEM tokamak

Abstract: The instructions present an introduction to the physics, technology, diagnostics and operation of the (GOLEM) tokamak. The purpose of the measurement is to demonstrate the very basics of tokamak operation, and to demonstrate the basic scaling properties of magnetic confinement.

1   Tools

The device for the generation and magnetic confinement of high temperature plasma - GOLEM tokamak, working gas - hydrogen, U_l wire, B_t coil, Rogowski coil, photodiode, H_α filter, vacuum gauge, data acquisition systems, oscilloscope RIGOL.

2   Tasks

1. <u>Homework before the measurements</u>: Learn how to access and manipulate the remote data files from GOLEM measurements according to [**?**]. This will greatly simplify the massive data analysis in the last task. If you can, please bring with you to the measurement your laptop with the remote file access already set up and tested. Use the link at [**?**], to access the web-based virtual control room and get yourself familiar with the web interface.

2. <u>In the tokamak laboratory</u>, explore the GOLEM tokamak and identify the basic elements mentioned in this document. With the help of an assistant test the function of the following individual components of the tokamak facility:
   - Turn the vacuum pumping of the tokamak off and on again
   - Fill the tokamak vacuum vessel with the working gas
   - Test the pre-ionisation system (electron gun / light bulb wire)

3. <u>In the tokamak laboratory</u>, install the 4 basic diagnostic tools on the tokamak (a piece of wire to measure the loop voltage U_l, a small coil dedicated to the toroidal magnetic field B_t measurement, Rogowski coil for the measurement of the total chamber and plasma current I_{ch+p} and a photodiode with a H_α filter). Connect all the diagnostics to the 4-channel oscilloscope RIGOL (or dedicated data acquisition channels) and record the time evolution of the individual diagnostic signals.

4. Run the following exploratory experiments (in order to access data on the remote server, use the method from task **??**):
   - Create a discharge with the toroidal electric field E_t only and record the time evolution of the voltage on the loop voltage measuring loop of wire $U_l(t)$ and the voltage on the Rogovski coil U_{RC}. Comparing with the GOLEM basic data acquisition system calibrate your Rogovski coil (specify the C_{RC}).
   - Create a discharge with the toroidal magnetic field B_t only and record the time evolution of the voltage on the measuring coil $U_B(t)$. Comparing with the GOLEM basic data acquisition system calibrate your B_t measuring coil (specify the C_{B_t}).
   - Execute a "vacuum" discharge (no working gas and no pre-ionization) and from the time evolution of U_l and I_{ch+p} estimate the vessel resistance R_{ch}.
   - Execute a full plasma discharge and using the measured $U_l(t)$, $I_{ch+p}(t)$, the previously estimated R_{ch} and neglecting plasma inductance calculate the time evolution of the plasma current $I_p(t)$. Calculate and plot the time evolution of the electron temperature $T_e(t)$.

   Crosscheck all the signals obtained from your improvised diagnostic system with the standard diagnostics system of the GOLEM tokamak.

5. Using the remote control room, execute 10 discharges with 5 different levels of the magnetic field parameter and 2 different levels of the current drive parameter. Estimate the confinement time in the quasistationary phase of the discharges as the average in this phase and errorbars as the standard deviation. Plot the observed confinement time (with errorbars) versus the average (in the same phase window) magnetic field B_t and compare the observed trends with the published scaling laws.

3 Theoretical introduction

3.1 Tokamak (GOLEM)

The basic mission of the tokamak technology is to *heat* and *confine* for a sufficiently long time the fusion fuel (deuterium-tritium mixture) up to ≈ 100 milions degrees Celsius - a sufficient temperature to fuse these light nuclei into a heavier Helium nucleus and a neutron. At these high temperatures the fuel is in a state of matter called plasma: a collection of ionized nuclei and free electrons. These charged particles are confined by a strong magnetic field. The fusion reaction products have a significantly higher kinetic energy and heat the surrounding plasma. This fusion-generated heating power can then be used for electricity production.
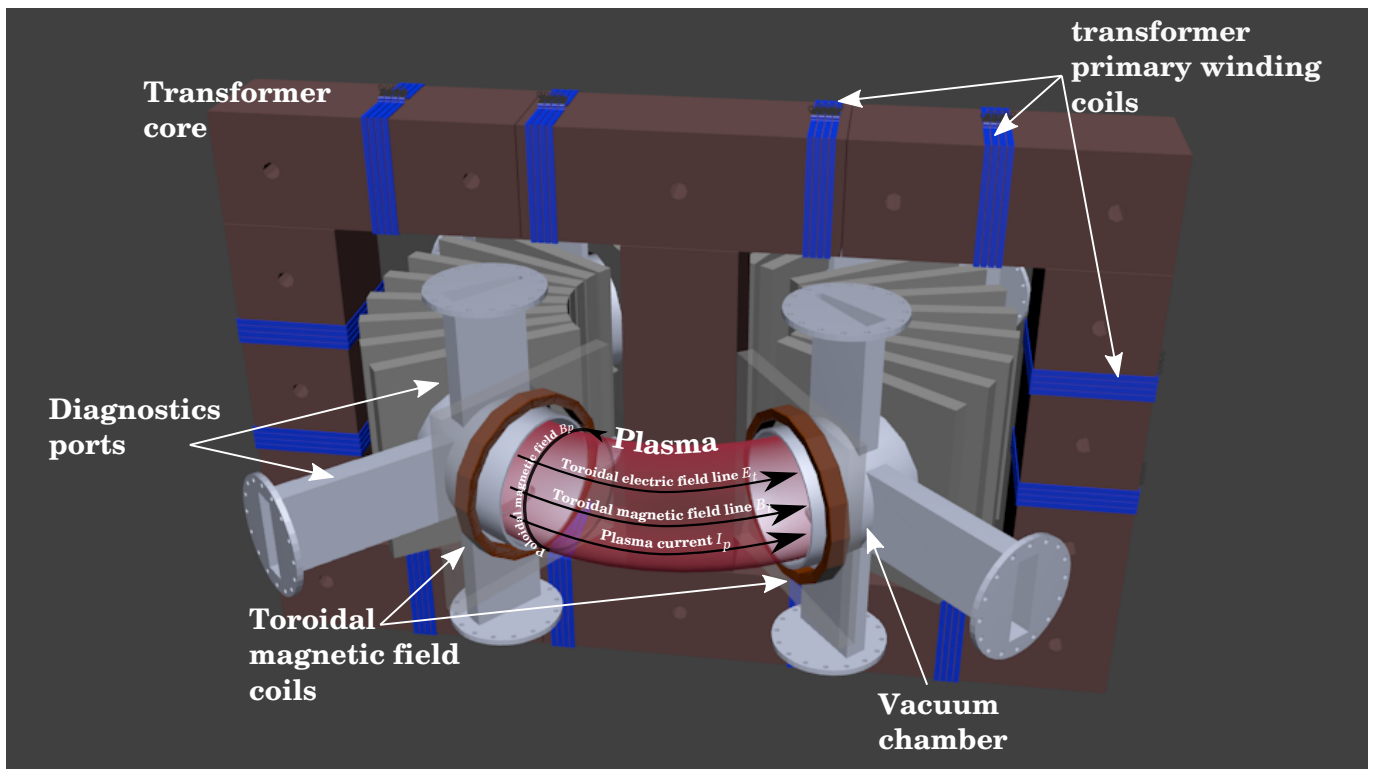

Figure 1: Basic components of the (GOLEM) tokamak

The basic structure of a tokamak (see e.g. [**?**]) can be seen in Figure 1. The confining magnetic field structure is the result of the superposition of the toroidal magnetic field B_t generated by external coils and the poloidal magnetic field B_p generated by a strong toroidal plasma current I_p induced by the transformer.

The major radius (from the central column axis to the center of the vessel) of the GOLEM tokamak is $R = 0.4$ m and the minor radius (the maximum radius of the plasma from the vessel center) is $a = 0.085$ m. The toroidal magnetic field B_t can rise up to 0.5 T and plasma current I_p can reach almost 8 kA. The discharge length T is typically not longer than 25 ms. Electron densities n_e are of the order of 10^{18} m^{-3}, while electron temperatures T_e can reach several tens of electron-volts (1 eV ≈ 11600 K or $11300\,^o$C).

The quality of plasma confinement is characterized by the energy confinement time τ_E which is the characteristic time constant of the decay of thermal plasma energy W_p due to net energy losses characterized by the loss power P_{loss} in the absence of any heating power P_H, see Figure 2. At the GOLEM tokamak τ_E can be estimated in the quasi-stationary phase ($dX/dt \approx 0$) of a plasma discharge (highlighted in Figure 3) where W_p can be estimated from T_e and $P_{loss} = P_H$ assuming power balance. The only significant contribution to the heating power is the ohmic heating power $P_{OH} = P_H$ given by the induced plasma current.
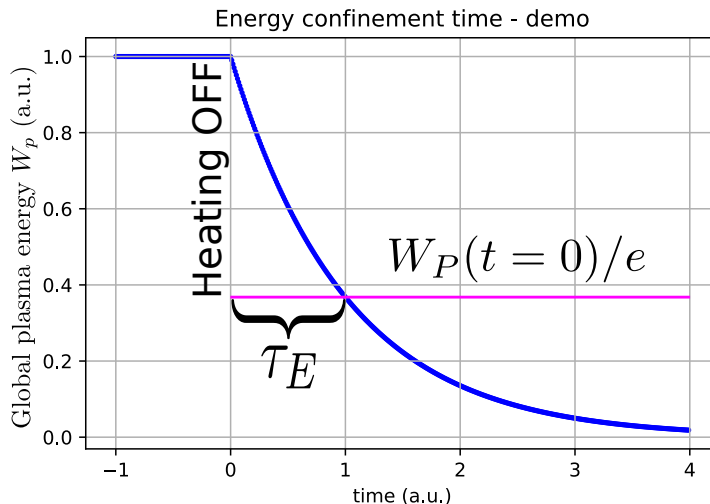

Figure 2: The τ_E as a characteristic time constant of the thermal plasma energy W_p decay.

3.2 Plasma heating power P_{OH}

In the GOLEM tokamak the only heating mechanism is the ohmic heating power P_{OH} resulting from the plasma current I_p flowing in a conductor (plasma) with finite resistance R_p. P_{OH} can be simply calculated as

$$P_{OH}(t) = R_p(t) \cdot I_p^2(t) \tag{1}$$

The explicit time dependence $X(t)$ highlights that the quantities strongly vary with time.

The current is driven in the plasma by the toroidal electric field E_t induced by the transformer. This field integrates along the plasma loop into the easily measurable loop voltage $U_l = E_t 2\pi R$. In the quasistationary phase of the discharge where $dI_p/dt \approx 0$ inductive effects can be neglected and plasma resistance can be simply estimated as $R_p = U_l/I_p$.

3.3 Central electron temperature T_{e0}

Specific plasma resistivity of a fully ionized plasma only depends on its electron temperature and scales as $\propto T_e^{-3/2}$. This dependence is quantified by the Spitzer formula [?]. For the GOLEM tokamak geometry, assumed parabolic T_e profile and pure hydrogen plasma the Spitzer formula for the central (in the plasma center) electron temperature T_{e0} reduces to

$$T_{e0} = 0.9 \cdot R_p^{-\frac{2}{3}}, \qquad [eV; \Omega] \tag{2}$$

It must be noted that the ion temperature can be very different from the electron temperature.

3.4 Thermal plasma energy W_p

The total thermal energy content is given by the average plasma pressure p_p confined in the plasma volume V_p as $W_p = p_p V_p$. The plasma volume is approximately $V_p \approx 80$ l. The average plasma

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pressure can be approximated by the electron pressure calculated from T_{e0} (with the assumed profile) and the average electron density n_e under the assumption of ions and electrons being in thermal equilibrium. The fact that the magnetic field reduces the degrees of freedom of particles to 2 must be also taken into account. Under these assumption the formula for W_p reduces to

$$W_p(t) = V_p \frac{n_e(t) k_B T_{e0}(t)}{3}. \tag{3}$$

The evolution of the plasma thermal energy W_p is governed by the power balance between the net heating power P_H and the loss power P_{loss} as

$$\frac{\mathrm{d}W_p}{\mathrm{d}t} = P_H - P_{loss} \tag{4}$$

The loss power P_{loss} characterizes the net energy losses, primarily in the form of escaped particles and radiation.

3.5 Energy confinement time τ_E

In the absence of heating power $P_H = 0$ the plasma energy would decay due to P_{loss}. Under the assumption that the loss mechanisms are the same in the whole plasma it is assumed that P_{loss} is proportional to W_p as

$$P_{loss} = \frac{W_p}{\tau_E} \tag{5}$$

where τ_E is the energy confinement time. After substituting (5) into (4) with $P_H = 0$ and solving it is seen that τ_E is the characteristic time constant of the exponential decay of W_p as visualized in Figure 2. In the quasistationary phase of the tokamak discharge, where $\mathrm{d}W_p/\mathrm{d}t \approx 0$ and using $P_H = P_{OH}$ the confinement time can then be estimated as

$$\tau_E = \frac{W_p}{P_{OH}}. \tag{6}$$

The dependence of τ_E on global plasma parameters is currently unknown and still is the subject of active research. Large databases of experiments from tokamaks all over the world were analyzed and the result is the scaling law for confinement with ohmic heating at low density [?]

$$\tau_E \propto n_e B_t^{0.5} I_p^{-0.5} \tag{7}$$

4 Experimental Setup

4.1 The GOLEM tokamak - technological scheme

The experiment is composed of the following fundamental sub-systems (see Fig. 3):
- Circuit for the generation of the toroidal magnetic field B_t consisting of a capacitor bank ($C_B = 81$ mF) charged up to $U_B = 1300$ V (recommended value in the $< 800, 1000 >$ V range). The capacitor bank is discharged by a computer-controlled thyristor into a set of 28 magnetic field coils which generate a toroidal magnetic field up to $B_t \approx 0.8$ T in the vacuum vessel.
- Circuit for the generation of the toroidal electric field E_t ($C_{CD} = 11.3$ mF , $U_{CD} \le 700$ V, recommended value:$< 400, 600 >$ V). The capacitor bank is discharged by a computer-controlled thyristors into the primary winding of the transformer. The time delay with respect to the magnetic field T_{CD}) can be selected independently.
- Triggering system, allowing to set-up the time delay between the triggers of the toroidal magnetic and electric fields (T_{CD}), range: $0-20000$ μs (recommended value in the $< 0, 10000 >$ μs range).
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- Pre-ionization of the working gas is performed by an electron gun (heated tungsten filament).
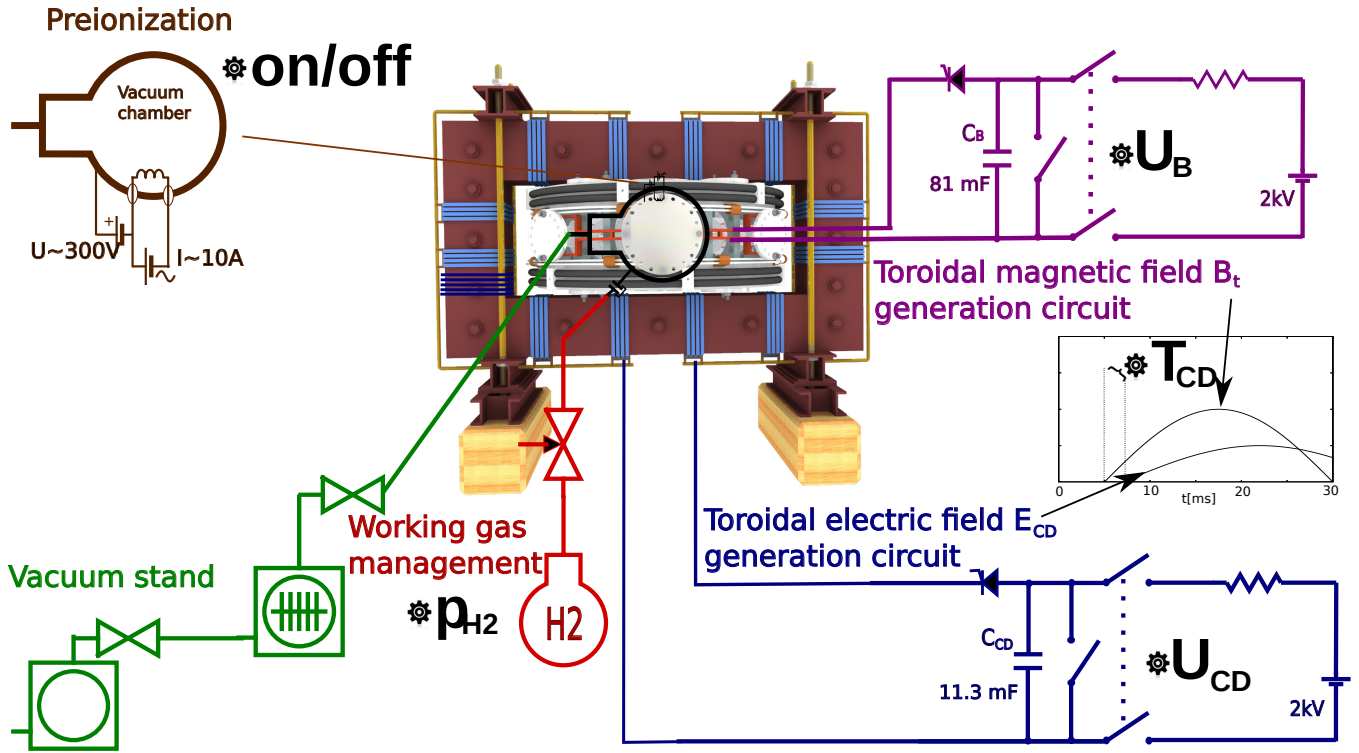
Figure 3: Experimental set-up: schematic of the GOLEM tokamak with its various sub-systems.

- Vacuum system, which allows reaching the background pressure in the vacuum vessel ≈ 0.2 mPa.
- Gas handling system (again computer controlled) to control the pressure of the working gas (hydrogen) in the vessel in the range of $p_{H_2} \approx$ 0 - 50 mPa, with recommended value in the $< 15, 40 >$ mPa range). .

4.2   Discharge procedure

The discharge procedure is controlled by a computer according to the parameters requested by the user in the remote control room described in subsection 4.4. First the capacitor banks are charged up to the requested voltage. This takes up to 1 minute. Meanwhile the vacuum vessel is filled with the selected working gas type up to the requested pressure above the background pressure. This stationary pressure balance is then maintained by the vacuum and working gas filling system. The working gas pressure must be high enough for any plasma to form, but low enough for the neutral gas to breakdown into plasma according to Pachen's law.

   Once the capacitors are charged the filament (electron gun) is heated and emits electrons which locally ionize the neutral working gas. Without any pre-ionization, no plasma can form a a so called "vacuum discharge" (useful for calibration) would be executed. The data acquisition systems are armed (made ready) and after a 10 second countdown the capacitor banks are discharged into the coils. This generates a pulse of strong magnetic field B_t in the chamber. The higher the voltage, the larger the magnetic field confining the plasma. The generated electric field E_t first through and avalanche process (ionized particles are accelerated and collide with neutrals, ionizing them, etc.) almost fully ionizes the gas and "breaks it down" into a plasma. The E_t field then continues to induce a current in the plasma which heats and further ionizes the plasma. The plasma continues to exist while the confinement is sufficient or until it touches the vessel wall.
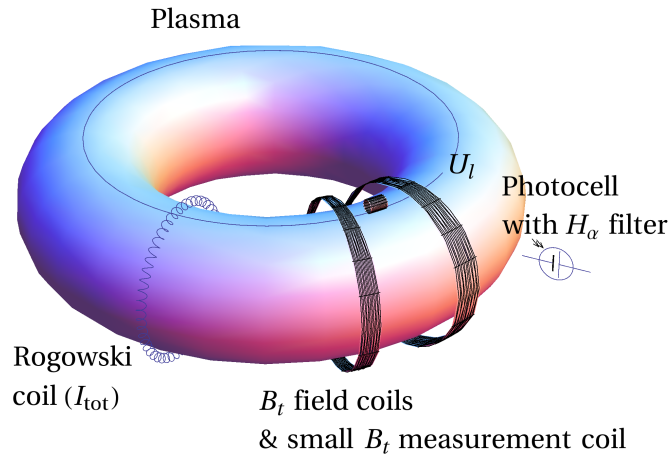
Figure 4: The GOLEM tokamak diagnostics

4.3 The GOLEM tokamak diagnostics

The basic characteristics of the discharge are measured with the following diagnostics (shown in Figure 4)
- a wire loop laid toroidally along the plasma ring measuring the loop voltage U_l
- a small coil located on the vessel measuring the voltage proportional to the toroidal magnetic field flux derivative
- a Rogovski coil surrounding vessel (and the plasma) ring poloidally measuring the voltage proportional to the total vessel and plasma current I_{v+p} derivative
- a photodiode measuring the visible plasma radiation of the H_α spectral line.
- an micorwave interferometer system (not shown) measuring the line averaged density n_e

An example of the time evolution of the measured quantities is shown in Figure 5.

4.4 Remote Control

Measurements are to be set up and shots initiated using the web interface of the GOLEM tokamak, which can be seen on figure 6. The URL address of this web interface is `http://golem.fjfi.cvut.cz/remote/control_room` However, it is recommended to use the URL provided by the remote experiment personnel, because it will likely include the necessary access token.

When visiting the control interface for the first time, a form is displayed asking for the **Identification** and (if not included in the URL) the **Access token**. The Identification is a user-name by which the current user wishes his discharges to be identified in the database. The access token is a (secret) string of characters giving access at a specific level of device control.

The left part of the top navigation bar contains links to 4 pages of the remote control interface. These are in order:
- **Introduction:** This page features video and other materials introducing the user to the GOLEM tokamak and its handling.
- **Control room:** This is the actual page shown in Figure 6 for setting up discharge configuration requests and submitting them to the requests queue. This page is described in greater detail below.
- **Live:** This page displays a live, real-time (up to a ~ 10 s delay) view of the tokamak chamber and room IP cameras, the current state of the machine (capacitor voltages, working gas pressure, discharge procedure progress) and the discharge requests queue.
- **Results:** This page lists a table of executed discharges for the currently logged-in user. The table contains links to discharge results as well.
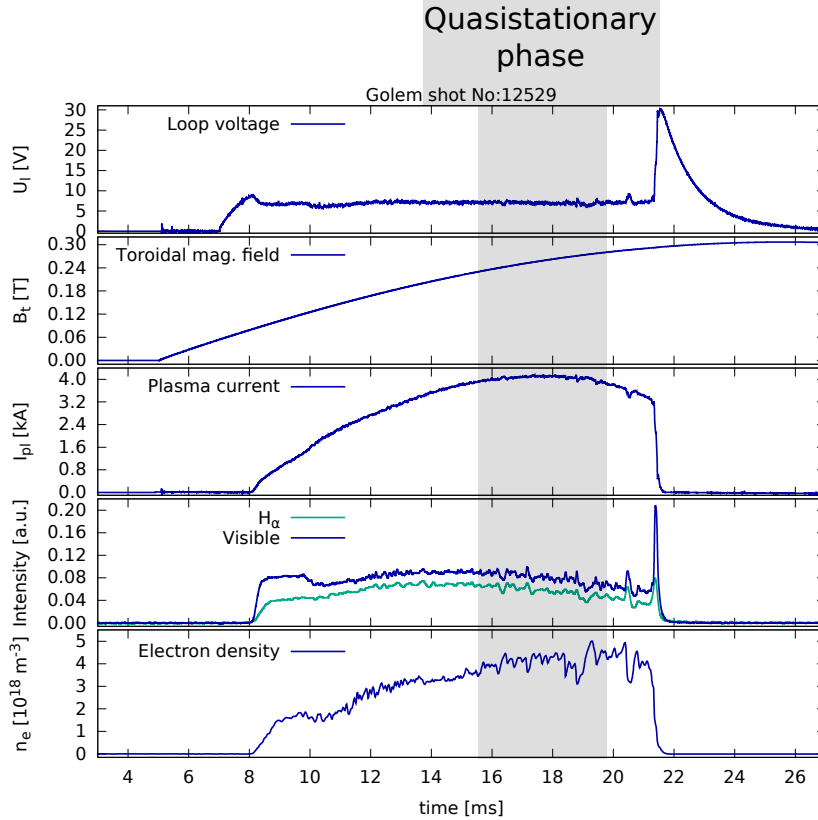
Figure 5: Evolution of a well executed GOLEM discharge. From top to bottom - the loop voltage U_l, toroidal magnetic field B_t, plasma current I_p, the signal of photo-diode with H_α interference filter and electron density n_e.

The remote control room interface shown in Figure 6 consists of 2 panels. The left panel contains a panel with 6 tabs at the top. Each tab corresponds to a step in the discharge setup procedure configuring a given tokamak sub-system. It is possible to arbitrarily switch between tabs, for instance when one wishes to go back to a previous setup step.

The right panel contains a rendering of the 3D tokamak model which dynamically changes according to the currently selected tab.

4.5 Discharge setup procedure

The discharge setup procedure consists of several steps/tabs corresponding to the subsystems described in subsection 4.2. The control page serves as a walk-through which guides the user through the setup procedure. **All settable parameters are perfectly safe.** At each step the user selects a value of some numeric parameter and/or a given option with a checkbox. The **Set recommended value** will select a predefined setting. Then the user moves to the next step by clicking the **Next** button.

The final *Submit* step is where the selected discharge configuration is submitted into the discharge requests queue along with a comment describing the configuration (i.e. the scientific aim). The comment is mandatory and must be put into the input field above the **Submit** button. Once the comment filed is filled, clicking the **Submit** button will send the discharge request into the queue. The panel also features button links to the Live real-time view of the experiment and the Introduction step to restart the walk-through. It is also possible to just go back to a specific step via the tabs at the top and change some parameters and then go back to the Submit step and submit the modified configuration.
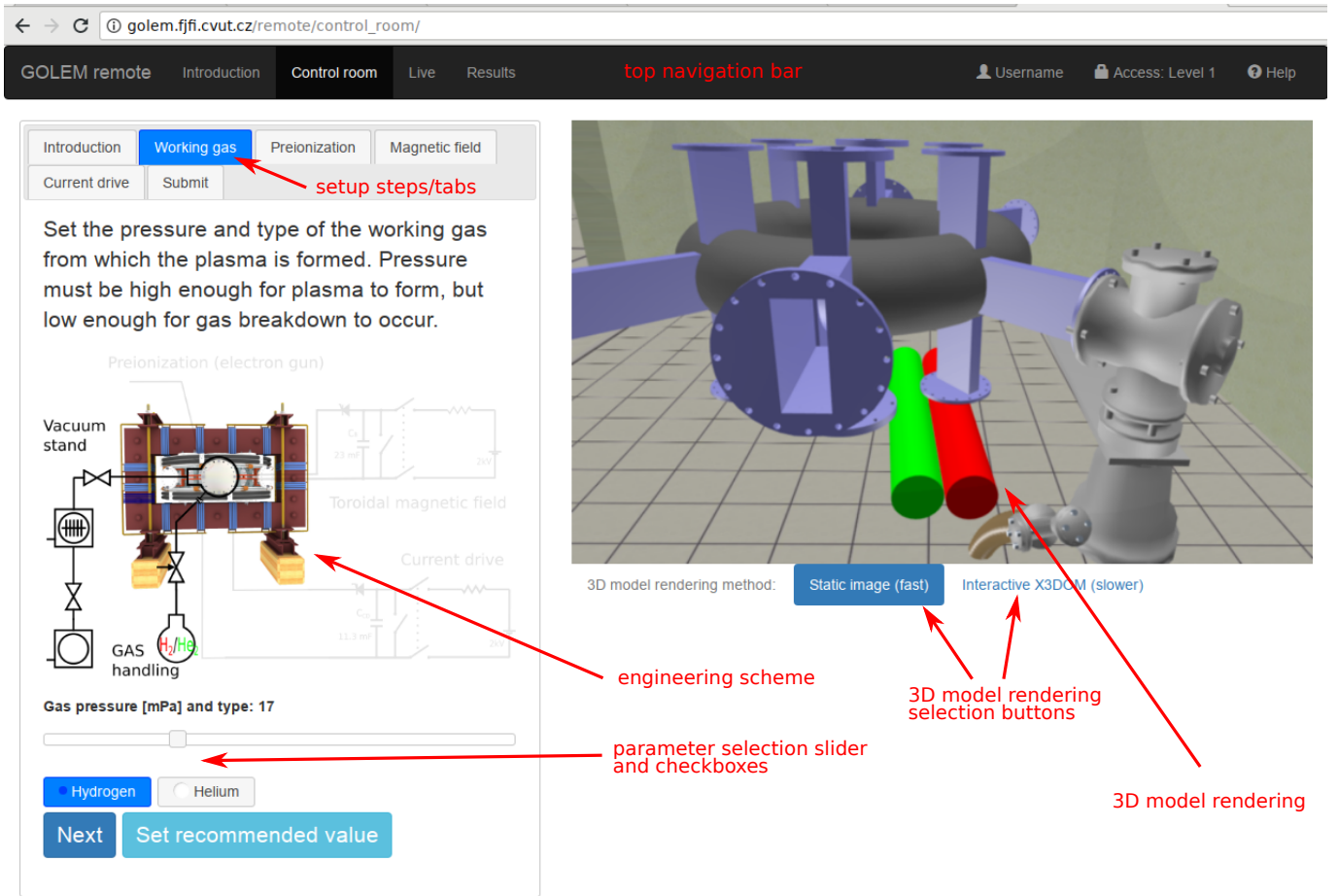
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Figure 6: Remote control interface of the GOLEM tokamak. The control room interface at the working gas setup step is shown.

5 Measurement procedure, method of evaluation

5.1 General strategy

The flow chart of the τ_E evaluation procedure is depicted at the figure 7. Due to the fact that the vessel is metallic, the current induced in the transformer after the breakdown flows both through the plasma and through the vessel and thus we need to perform two discharges: i) vacuum discharge (with no gas injected into the vessel) to get Chamber resistivity R_{ch} and calibrate B_t and Rogowski measuring coils (C_{Bt}, C_{RC}) and ii) plasma discharge to get other physical quantities necessary for the experiment mission: loop voltage U_l, plasma current I_p and electron density n_e for the τ_E evaluation and toroidal magnetic field B_t as an independent variable.

The sampling rate of the time resolved measurements $f_{DAS} = 1$ MHz, time delay between starting diagnostics and toroidal magnetic field drive $T_{DAS} = 5$ ms and time delay between toroidal field and inductive current drive T_{CD} are Data Acquisition System (DAS) time parameters.

5.2 Magnetic measurements

The toroidal magnetic field $B_t(t)$ measured by the B_t coil and the currents $I_{ch+p}(t), I_{ch}(t)$ measured by the Rogowski coil (generally diagnostics $D(t)$) measurements are from the magnetic diagnostics family and the corresponding measured raw signals (analog $U_r(t)$ or, respectively, it's discretized digital U_i counterpart form) must be specialy maintained: i) corrected for the DC bias U_{offset} of the measurement circuit, ii) integrated (pure diagnostics signal voltage $U_d(t)$ is induced by the time derivative of the appropriate magnetic flux), and iii) multiplied by calibration factors C_d (C_Bt, C_{RC}). We can express the basic relationship in this form:
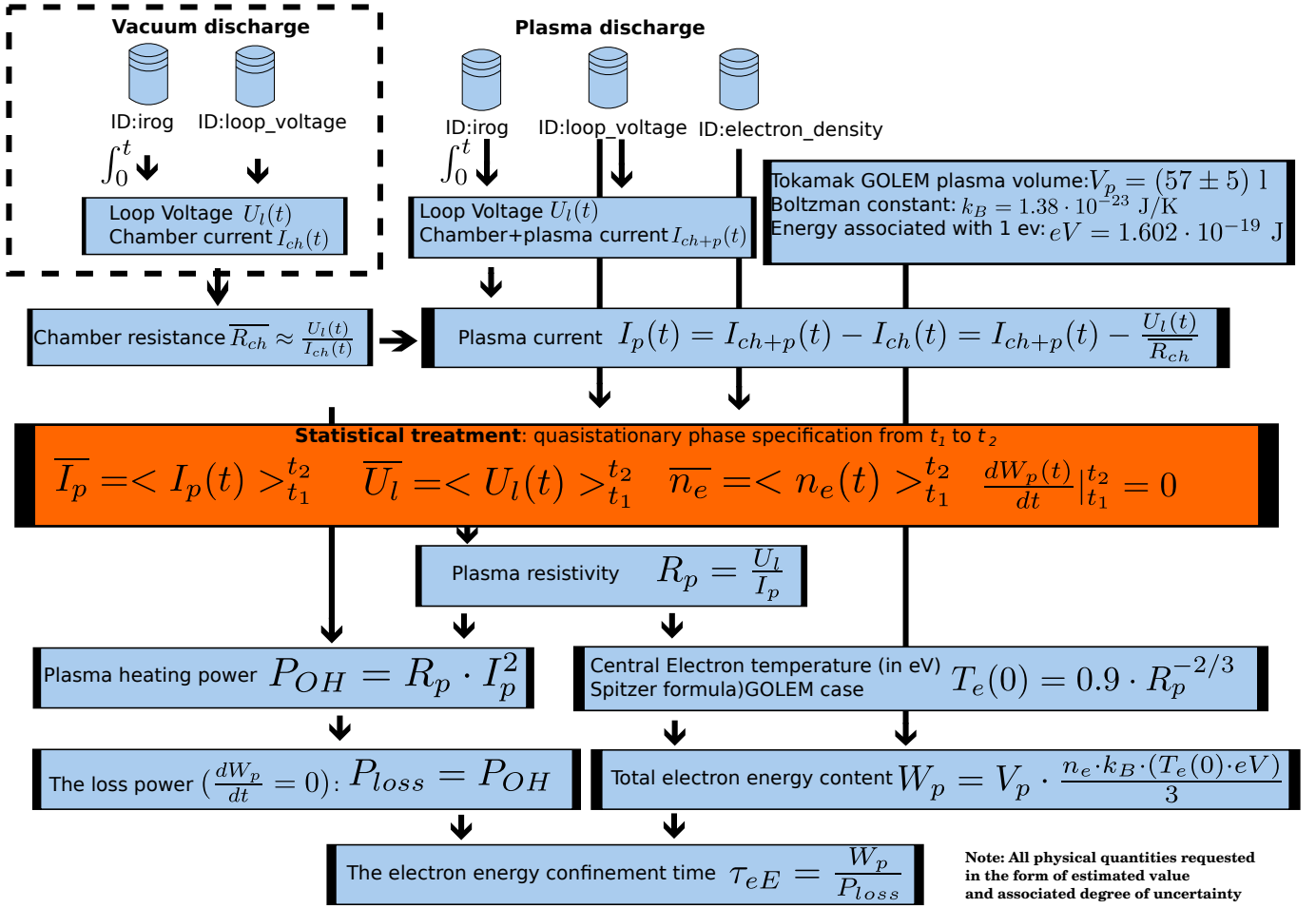
Figure 7: The flow chart of the τ_E evaluation procedure

$$U_r(t) = U_d(t) + U_{offset}$$

The measured signal $U_d(t)$ is proportional to the time derivative of the original physical quantity $D(t)$ signal (it is a magnetic measurement):

$$U_d(t) \propto \frac{dD(t)}{dt}, \text{ or } U_d(t) = C_d \frac{dD(t)}{dt}$$

Where the linearity coefficient C_d is called a calibration factor.

To determine the desired physical quantity $D(t)$, we just have to perform an integration over time:

$$D(t) = \frac{1}{C_d} \int_0^t U_d(t')dt' = \frac{1}{C_d} \int_0^t \left(U_r(t) - U_{offset}\right) dt'$$

This is a theoretical formula: in reality, the measurement is not continuous. The system performs a series of measurements U_i separated by a small time interval $\Delta t = 1$ us. In practice, to determine the desired discretized evolution of the physical quantity D_i, we replace the integral by a sum, assuming that the quantity $D(t)$ does not change during narrow time intervals:

$$D(t) = \frac{1}{C_d} \int_0^t \left(U_i(t') - U_{offset} \right) dt'$$

$$D_i = \frac{1}{C_d} \sum_{j=0}^{t/\Delta t} \left(U_i(t_j) - U_{offset} \right) \Delta t$$

$$D_i = \frac{1}{C_d} \left(\sum_{j=0}^{t/\Delta t} U_i(t_j) \right) - U_{offset} t$$

The offset U_{offset} can be specified from the beggining of the data series before switching on the discharge when there is a only background noise in the signals. If the sampling rate is 1 MHz, and the shot starts at 5 ms, we have 5000 samples from the background noise. It is better to exclude a few samples around the swithing time point.

$$U_{offset} = \frac{\sum_{i=1}^{4500} U_i}{4500}$$

6 Acknowledgments and feedback

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