

Instructions for student measurements on the GOLEM tokamak

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Abstract

Present series of measurements are a regular student measurement program at the Institute of Nuclear Techniques (NTI), Budapest University of Technology and Economics (BME), making use of the remote measurement potential of the GOLEM tokamak located at the Faculty of Physical and Nuclear Engineering of the Czech Technical University (CTU). The student measurement is to be performed by students at the Nuclear technology branch of the Physics MSc program at BME. The purpose of the measurement is to demonstrate the very basics of tokamak operation, and to get the students acquainted with basic properties and operational limits.

1 Introduction

Participants of the present student measurement are strongly encouraged to read chapters 1 and 3 of John Wesson's *The science of JET* [3] to be downloaded from <http://www.iop.org/Jet/fulltext/JETR99013.pdf>. This reading gives an introduction to the basic concept of thermonuclear fusion and magnetic confinement.

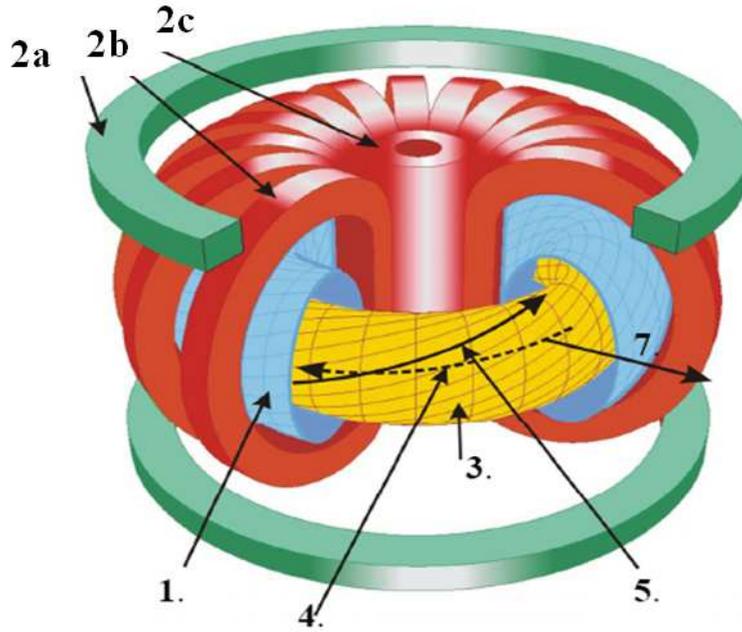


Figure 1: Structure of a tokamak: (1) vacuum chamber, (2a) vertical field coil, (2b) toroidal field coil, (2c) transformer coil, (3) plasma, (4) plasma current, (5) magnetic field line, (6) magnetic axis, (7) radial direction (r).

Basic build up of a tokamak can be seen on 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 poloidal plasma current (I_{pl}) induced by the transformer coil.

In the resulting magnetic geometry, field lines are winding helically around a torus surface, which is called the magnetic surface. The tokamak magnetic field consists of such nested magnetic surfaces. The helicity at each magnetic surface is described by the safety factor (q). It gives the number of toroidal turns necessary for the magnetic field line at the given magnetic surface to reach its original position poloidally. On large aspect ratio circular tokamaks, like GOLEM, it can be approximated by:

$$q(r, t) = \frac{r}{R} \frac{B_t(t)}{B_p(r, t)}, \quad (1)$$

where R is the major radius of the magnetic axis. An illustration for the meaning of the safety factor can be seen on Figure 2.

An important concept regarding the energy balance of the tokamak fusion reactor is the

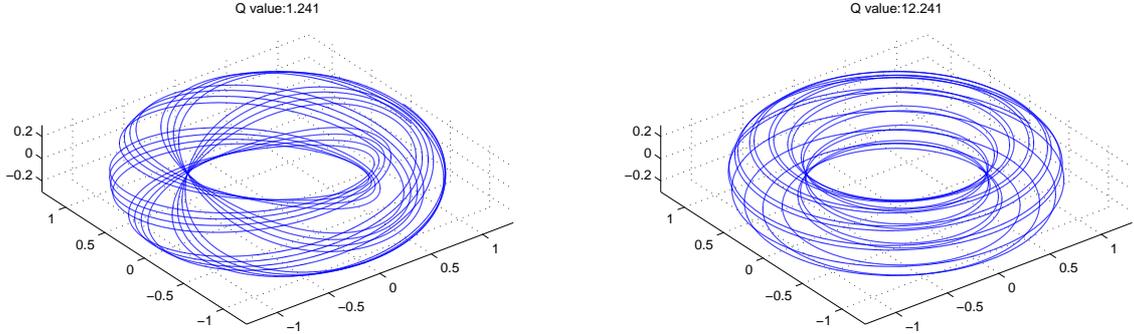


Figure 2: Magnetic field lines in a tokamak for different safety factors.

energy confinement time (τ_E). It is the characteristic time of energy loss:

$$P_{loss} = \frac{W_{pl}}{\tau_E}, \quad (2)$$

where P_{loss} is the power lost and W_{pl} is the total plasma energy. The energy confinement time is a global parameter of the confined plasma, and reaching higher values is of central interest of tokamak research.

The Lawson criterion is a simple threshold for self-sustained thermonuclear fusion plasma burn at optimum temperature, and it also includes the energy confinement time along with plasma density (n):

$$n\tau_E > 20 \text{ sm}^{-3}. \quad (3)$$

More general information on fusion power production and the tokamak concept can be found at the following sites: <http://www.magfuzio.hu>, <http://www.iter.org>, <http://www.jet.efda.org/>

1.1 GOLEM

The GOLEM tokamak is a tokamak with full remote control capability and educational purpose. It is a small size tokamak device equipped with basic controls and diagnostics having dimensions:

- Major radius at the magnetic axis: $R_0 = 0.4$ m.
- Minor radius: $r_0 = 0.1$ m.
- Radial position of the limiter: $a = 0.085$ m.

The device was originally called TM1. Designed and constructed in Kurchatov Institute of Nuclear Research (Soviet Union), it was one of the first operational tokamaks in the world. The original concept of the device did not include poloidal field coils of stabilization however, it was believed that integrating one more layer of vacuum into the chamber would help to achieve better stability of plasma column. The capacitor battery for toroidal field coils and transformer filled several rooms.

Some time later, there was a microwave heating system integrated and the device was re-named to TM1-MH. The microwave heating, in addition to ohmic heating had to heat the

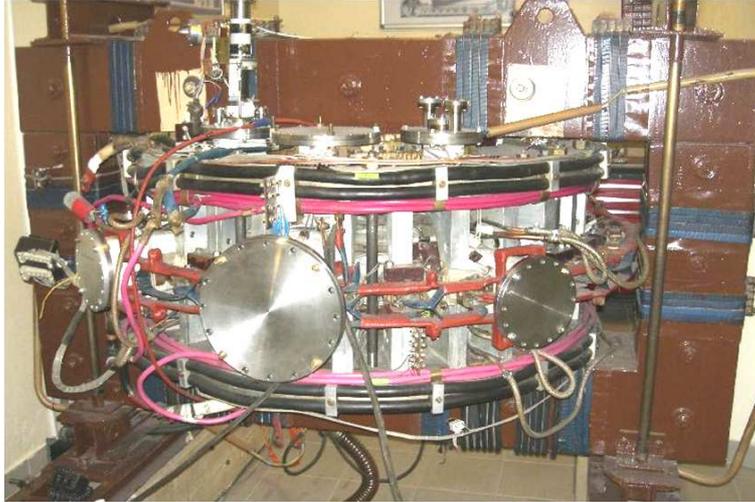


Figure 3: Photo of the GOLEM tokamak

plasma further. After the device was moved to Institute of Plasma Physics, Czech Academy of Sciences (IPP CAS) on September 1977, thanks to cooperation between the Kurchatov Institute and IPP, some changes in the engineering took place. The microwave heating system has been left in Russia, alongside with the most of the oil capacitors of the toroidal field generation, since there was not enough room in the new tokamak hall. A few years later, the device went under further reconstruction. The vacuum vessel was replaced for a new one, the layer of vacuum between the liner and coating have been fully removed and a feedback stabilization system was integrated instead. The power supply was substituted by a stronger one. The ignition was replaced by a glow discharge. Between the years 1977 and 2007 there have been several small changes over the device, such as the use of new diagnostics sensors.

In the end of 2007 the device was transferred to Faculty of Physical and Nuclear Engineering of the Czech Technical University (CTU). Now further modifications of the device are being discussed, for example improved way to distribute the power to the toroidal field coils or removing the unnecessary diagnostics sensors. Work on the reoperation of the device has been started on the 14th of July 2008 and is still underway.

More information can be reached via the home site of the GOLEM tokamak:

<http://golem.fjfi.cvut.cz>

Detailed experimental arrangement can be seen at the following link:

<http://golem.fjfi.cvut.cz/?p=exparr>

The parameters to be set remotely:

- Toroidal magnetic field (B_t) through the voltage of the toroidal field capacitor bank ($U_B = U_{C_{Bt}}$).
- Toroidal electric field (E_t) through the capacitor bank for the ohmic heating ($U_E = U_{C_{Et}}$).
- The time delay between the triggers of the toroidal field and the ohmic heating (T_d).
- Hydrogen gas pressure (p_{H_2}).

The diagnostics used during the session to be accessed online:

- Time resolved measurement of loop voltage (U_l).
- Time resolved measurement of total toroidal current by Rogowski coil (I_{tot}).
- Time resolved toroidal magnetic field measurement coil measurement (B_t).
- Time resolved measurement of plasma radiation by photodiode.
- Vacuum chamber pressure (p_{ch}).
- The temperature of the vacuum chamber (T_{ch}).

2 Measurement procedure

This section summarizes the technical procedures necessary for the remote control of the GOLEM tokamak.

2.1 Communication with local support

Primary real time communication to the local support (Dr. Vojtech Svoboda) is through Skype instant messaging. For this purpose a user (name: nti.hallgato, passwd: vendeg0) has been created. Before starting the experiment an instant messaging conference is to be started including users nti-hallgato, gergo_pokol (Dr. Gergo Pokol, Hungarian supervisor) and svboj (Dr. Vojtech Svoboda, Czech support). After the session the conversation log should be saved and appended to the measurement log.

2.2 Remote control

Measurements are to be set up and shots initiated using a SSH connection to the *buon.fjfi.cvut.cz* control computer. Login name and password is provided by Dr. Vojtech Svoboda just at the beginning of the session. On the Budapest side the SSH shell is provided by a Putty program running on a Windows system. Remote files can be edited via WinSCP.

Shots are programmed into a text file named *makefile* by the Hungarian party following the examples below. After confirmation from the Czech party, shots are started by the Hungarian party using the `makefile label` command in the SSH shell, where `label` is the label of the shot series in the file named *makefile*. The initial *makefile* starts with a short instructive comment:

```
# parameters to set:
# Ue, Ub, Td, pH2, H2filling
```

where parameters translate to the notations of the present instructions as: $U_e = U_E$, $U_b = U_B$, $T_d = T_d$, $p_{H2} = p_{H2}$ and *H2filling* is a Boolean indicating the opening of the gas valve. Here is an example for a single shot:

```
first_trial:
make -iBs -C velin shot Ue=400 Ub=400 Td=7000 H2filling=0 pH2=0
```

and an example for a shot series:

```
grand_loop:
Td=7000;\
H2filling=1;\
for pH2 in 60 100; do\
for Ub in 400 800; do\
for Ue in 'seq 200 100 800'; do\
```

```
#{SHOTCMD} -C velin -iBs shot Ue=$$Ue Ub=$$Ub Td=$$Td pH2=$$pH2 H2filling=$$H2filling;\ndone;\ndone;\ndone;\
```

Based on these examples an own *makefile* should be written and executed. Executed commands should not be deleted or overwritten, and the *makefile* is to be appended to the measurement log.

Realtime visual surveillance of the tokamak can be accomplished via the following link:

<http://147.32.4.75/cgi-bin/viewer/video.jpg>

2.3 Remote data access

All the recorded data and the settings for each shot are available at the GOLEM website. The root directory for the files is:

<http://golem.fjfi.cvut.cz/operation/shots/<shotnumber>/>

Basic data of the present shot series are collected at a page to be reached at:

<http://golem.fjfi.cvut.cz/operation/currentsession/>

during the session and later archived at:

<http://golem.fjfi.cvut.cz/operation/tasks/Practica/BudapestBME-NTI/>

During the evaluation not all the files were needed. Used ones are:

- [/basicdiagn/usbscopes](#) (time-dependent measurements: U_l , dB_t/dt , dI_{tot}/dt , photodiode signal)
- [/Aktual_PfeifferMerkaVakua](#) (initial pressure [mPa])
- [/Td_aktual](#) (time delay between toroidal field and inductive current drive [us])
- [/Aktual_TermoclanekNaKomore](#) (relative temperature of the chamber (compared to room temperature) [K])

An example download script will be given in MATLAB.

3 Measurement tasks, method of evaluation

The sampling rate of the time resolved measurements is 100 kHz. We have a direct measurement for the loop voltage (U_l), while the toroidal magnetic field (B_t) and the total current (I_{tot}) signals must be integrated and multiplied by a calibration factor: $C_{B_t} = 170$ and $C_{I_{tot}} = 5000$. The reason for this is that the voltage measured is induced in these diagnostic loops and coils by the changing of the toroidal and poloidal magnetic field respectively.

Integrated magnetic measurements are very sensitive to the DC bias of the measurement circuit, which needs to be corrected for. The sampling rate is 100 kHz, and the shot starts at 5 ms, so we have 500 samples from the background noise. This is important, because these samples measure the bias, and we can correct the integrated values with this factor.

The Rogowski coil measurement, for example, has a large negative bias needing correction. The algorithm is the following: we average the first 450 data points ($\langle DC \rangle$), and subtract it from the measured value ($D(t)$):

$$\langle DC \rangle = \frac{1}{450} \sum_{i=0}^{450} D(i); \quad (4)$$

$$I_{total} = C_{I_{tot}} \int_0^t D(t') - \langle DC \rangle dt' = C_{I_{tot}} \left(\int_0^t D(t') dt' - \langle DC \rangle t \right) \quad (5)$$

$$I_{total} \approx \sum_{i=0}^{t/\Delta t} D(i) \Delta t - \langle DC \rangle t, \quad (6)$$

where Δt is the sampling time. A higher order integration scheme can also be used instead of (6) to improve accuracy. This bias correction has to be calculated separately in each shot.

3.1 Determination of vacuum chamber parameters

In GOLEM, part of the toroidal current always flows in the vacuum vessel, which has to be taken into account during the interpretation of experimental results. In a vacuum shot, when no plasma is formed, it is possible to determine the resistance of the vacuum vessel: all the current measured by the Rogowski-coil flows in the vessel. This is an important parameter for further evaluations.

Let us denote the loop voltage with U_l , the resistance of the chamber with R_{ch} , the total current (which is the chamber current (I_{ch}) in this case) with I_{tot} and the inductance of the chamber with L_{ch} .

The circuit equation is then

$$U_l(t) = R_{ch} \cdot I_{tot}(t) + L_{ch} \frac{dI_{tot}}{dt}. \quad (7)$$

Using the loop voltage measurement and the Rogowski-coil, we have both U_l , I_{tot} and dI_{tot}/dt measured, so R_{ch} and L_{ch} can be determined.

A simple method, easily implemented for online processing, is the following: Just after switching on the toroidal electric field, the toroidal current is still close to zero ($I_{tot} \approx 0$), so $U_l \approx L_{ch} dI_{tot}/dt$, so L_{ch} can be determined. On the other hand, at the flat top of the current curve ($dI_{tot}/dt \approx 0$) equation (7) simplifies to $U_l \approx R_{ch} \cdot I_{tot}$, so R_{ch} can be estimated.

A more sophisticated method to be implemented for offline processing is a 2D least squares linear fit making use of all data points ($U_l, I_{tot}, dI_{tot}/dt$). Of course, the fitted plane has to pass through the Origin.

Values of R_{ch} and L_{ch} should be calculated for about 5 discharges having different parameters, and the results should be compiled to a single best estimate for both parameters.

3.2 Plasma breakdown

After measuring the vacuum chamber properties, we can make the next step towards creating a tokamak plasma: we can let H_2 gas into the chamber before initiation of the toroidal electric field. The p_{H_2} value, which can be set as a discharge parameter, is a control parameter for the inlet valve. The actual value of the pre-discharge gas pressure is measured by a vacuummeter p_{ch} .

As we will see, letting H_2 gas into the chamber is not always sufficient to produce a plasma. The toroidal electric field must also reach a critical value for mass ionization, in other words plasma breakdown.

The task is to plot the p_{ch} against the maximum loop voltage for several discharges, and indicate the plasma breakdown by the shape of the symbols. Shots should be concentrated around the critical line separating breakdown and non-breakdown shots. The procedure should be repeated for low and high magnetic fields. About a total of **30** discharges are to be used for this purpose.

3.3 Estimation of main plasma parameters

If plasma breakdown occurs, plasma parameters can be determined - with different accuracy - from the measured parameters. The aim of this task is to investigate the effect of different parameters on the performance of the discharge, and reach discharges with the highest central temperature, plasma energy or energy confinement time. (Best performance discharges usually utilize the time window of around the maximum toroidal magnetic field.) This task should result in about **25** discharges.

3.3.1 Plasma current

A simple electrical model for the inductive current drive is a time-varying voltage source ($U_l(t)$) connected to the plasma and the vacuum chamber in parallel can be seen on Figure 4. Both the vacuum chamber and the plasma are modeled by LR circuits. The main difference is, that while the internal inductance and resistance of the chamber are constant, and thus they can be measured separately, the parameters of the plasma differ in each discharge.

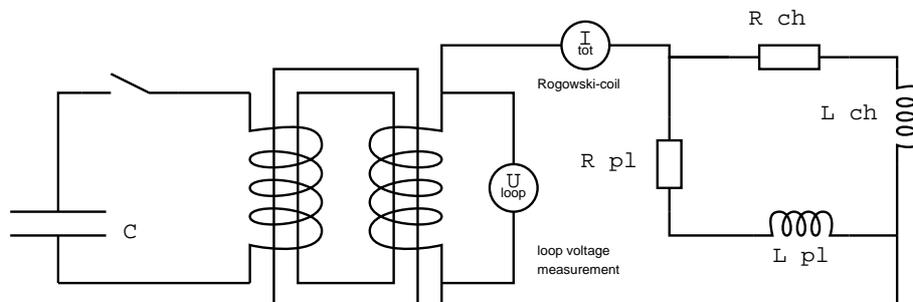


Figure 4: Model of the inductive current drive circuit

The basic circuit equations are:

$$U_l(t) = R_{ch} \cdot I_{ch}(t) + L_{ch} \frac{dI_{ch}(t)}{dt} \quad (8)$$

$$U_l(t) = R_{pl}(t) \cdot I_{pl}(t) + L_{pl} \frac{dI_{pl}(t)}{dt} \quad (9)$$

$$I_{tot}(t) = I_{pl}(t) + I_{ch}(t) \quad (10)$$

$$\frac{dI_{tot}(t)}{dt} = \frac{dI_{pl}(t)}{dt} + \frac{dI_{ch}(t)}{dt} \quad (11)$$

The chamber parameters have already been determined according to Section 3.1. As a first approximation, we can neglect the inductance of the plasma ($L_{pl} \approx 0$ H), and we can integrate the (8) circuit equation using the initial condition $I_{tot}(t = 0) = I_{ch}(t = 0)$ to arrive to $I_{ch}(t)$. This can then be used to determine the plasma current, as $I_{pl}(t) = I_{tot}(t) - I_{ch}(t)$. Plasma resistivity can be determined in turn from equation (9).

This task needs some programming that should be done parallel to the task described in Section 3.2!

It can be attempted to investigate the effect of the $L_{pl} \approx 0$ H approximation by a more careful integration of choosing $L_{pl} \approx L_{ch}$ in the time region with plasma. If significant differences are found, this later approximation has to be implemented for all further data processing.

Plasma current has to be calculated for all discharges with plasma and the maximum value has to be included in the shot summary table.

3.3.2 Plasma heating power

In the GOLEM tokamak the only heating mechanism of the plasma is ohmic heating resulting from current flowing in a conductor with finite resistivity. The ohmic heating power can be calculated as:

$$P_{OH}(t) = R_{pl}(t) \cdot I_{pl}^2(t) \quad (12)$$

Ohmic heating power has to be calculated for all discharges with plasma and the maximum value has to be included in the shot summary table.

3.3.3 Central electron temperature

Specific resistivity of a fully ionized plasma only depends on its electron temperature (T_e) and effective charge number (Z_{eff}). This dependence is quantified by the Spitzer formula [1]. It has to be noted that the ion temperature can be very much different from electron temperature. The effective charge number is determined by the amount, composition and state of impurities in the H_2 plasma, and $Z_{eff} \approx 1.5$.

Center of the plasma has higher temperature, and lower resistivity with higher current density, which makes the estimation of the electron temperature ambiguous from an integrated value of resistivity ($R_{pl}(t)$). However, if we use an equilibrium temperature

profile (13) (Figure 5), measured in more detailed measurements [2], we can estimate one parameter of the profile, which is in this case the central electron density ($T_{e0}(t)$):

$$T_e(r, t) = T_{e0}(t) \left(1 - \frac{r^2}{a^2}\right)^2 \quad (13)$$

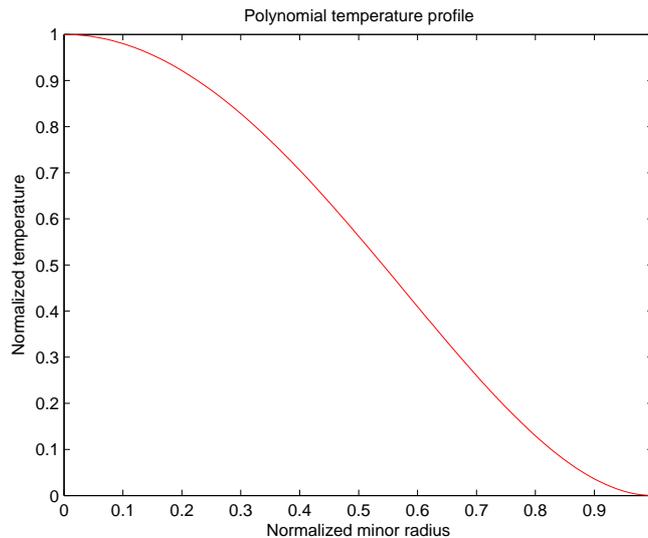


Figure 5: Equilibrium temperature profile used in the estimation of central plasma temperature

The central plasma temperature (T_{e0}) is then calculated from equation (3.20) of [2], which itself is based on Spitzer's resistivity formula:

$$T_{e0}(t) = \left(\frac{R_0}{a^2} \frac{8Z_{eff.}}{1.544 \cdot 10^{-3}} R_{pl}(t)\right)^{2/3} \quad (14)$$

It has to be noted that plasma in the GOLEM tokamak is only fully ionized in the central region, Z_{eff} can be estimated with large uncertainty and even the a plasma small radius might change in an unmonitored way due to the lack of plasma stabilization. All these factors make the estimation of the central electron temperature quite uncertain.

Nevertheless, central electron temperature has to be calculated for all discharges with plasma and the maximum value has to be included in the shot summary table.

3.3.4 Electron density

In its current state, the GOLEM tokamak does not have any density measurements. However, as electron density is needed for further calculations, we estimate its order of magnitude from the state law of ideal gases.

For the average density it is assumed, that it is constant during the discharge, apart from the dissociation of the hydrogen gas. There is a 30 second delay between the gas filling and the actual shot, which is enough for the gas to reach thermal equilibrium with the chamber wall. Chamber temperature is monitored with respect to the room

temperature, and the difference is normally be zero, but should be checked. The ideal gas law is used to give an order of magnitude estimate of the electron density (in particle/ m^3):

$$n_{avr} = \frac{2p_{ch}}{k_B T_{ch}}. \quad (15)$$

We have to note that this is a very rough estimate basically for two reasons:

1. Plasma in the GOLEM tokamak is not fully ionized, which makes us overestimate the electron density.
2. Due to the plasma-wall interaction, adsorbed gases are released from the surface of plasma facing components during the discharge. These atoms enter the plasma and can be ionized, thus making us underestimate the electron density.

The order of magnitude estimate of the average electron density has to be calculated for all discharges with plasma and included in the shot summary table.

3.3.5 Plasma energy

The total energy content can be simply calculated from the temperature, density and volume, based on the ideal gas law, taking into account the assumed (13) temperature profile:

$$W_{pl}(t) = \frac{n_{avr} k_B T_{e0}(t)}{3}. \quad (16)$$

The information that the magnetic field reduces the degrees of freedom of the particles to two has been used to derive this formula.

Uncertainty of this formula is dominated by the uncertainty of our density estimate, which makes it good for only an order of magnitude estimate.

Nevertheless, central electron temperature has to be calculated for all discharges with plasma and the maximum value has to be included in the shot summary table.

3.3.6 Energy confinement time

Having an estimate for the plasma energy, the energy confinement time can be estimated at the point where the plasma energy has its maximum. In tokamaks with more stable plasma this maximum can be taken for an extended duration of time, and this region is called the flat-top.

During the flat-top the ohmic heating power equals to the losses, this way we calculate the energy confinement time:

$$\tau_E(t_{top}) = \frac{W_{pl}(t_{top})}{P_{OH}(t_{top})}. \quad (17)$$

$$\frac{dW_{pl}}{dt}(t_{top}) = 0. \quad (18)$$

Given the uncertainty of the input parameters, this value for the energy confinement time should be taken with care. Nevertheless, it should be included in the shot summary table.

3.4 $q = 2$ disruptions

When the plasma current grows so strong that the edge safety factor, defined by (1), reaches the value 2, a plasma instability resonant to the $q = 2$ rational surface destabilizes, and a discharge terminating disruption occurs. This limit of operation is to be investigated in this task using about 5 dedicated shots.

We can calculate the poloidal field at the edge (for circular plasmas) using Ampère's law, as the enclosed current is the total plasma current:

$$B_p(a, t) = \frac{\mu_0 I_{pl}(t)}{2\pi a}, \quad (19)$$

where a is the plasma minor radius. Substituting this expression to the (1) formula, the safety factor at the edge can be estimated as:

$$q(a, t) = \frac{a_0^2 2B_t(t)\pi}{R_0 \mu_0 I_{pl}(t)}. \quad (20)$$

Discharges aiming to reach a low $q(a, t)$ need as large plasma current as possible. As we have very limited control over the evolution of plasma current in GOLEM, we can also set the T_d time delay to set up a discharge at the declining phase of the toroidal magnetic field, which will constantly decrease the edge safety factor.

In order to monitor the success of our efforts, the evolution of the discharges should be plotted on the Hugill diagram. The Hugill diagram positions a discharge on the plane of two parameters:

- Inverse edge safety factor: $\frac{1}{q(a, t)}$
- Murakami parameter (normalized density): $\frac{n_{avg} R_0}{B_t}$

The Hugill diagram serves as an operation envelope for tokamaks. If either the Murakami parameter is too high or the inverse edge safety factor reaches the value of 0.5, the plasma disrupts.

As the n_{avg} average electron density has large uncertainty, it should be substituted with the directly measured p_{ch} chamber pressure to form a Murakami-like parameter. (The uncertain Murakami parameter might also be plotted as a second scale.)

First, the temporal evolution of the dedicated shots aiming $q = 2$ disruptions should be plotted on the Hugill-like diagram described above. Afterwards, all previous shots could be plotted to check that none reach the region $1/q > 0.5$.

4 Requirements for the measurement logbook

There should be a single measurement log written. English language is highly encouraged. The measurement log should include:

- Exact method of executing the measurement.
- Exact method of derivation of final results.

- Results of the measurement tasks.
- Time traces of shot parameters for some characteristic shots.
- Shot summary table indicating all calculated parameters of all shots executed.
- makefile as appendix
- Skype log as appendix

All comments and proposals regarding the measurements are welcome.

It would be nice, if the participants of the session would write some thankful words to the <http://golem.fjfi.cvut.cz/hodnoceni.html> homepage, and send a postcard to the following address: Tokamak GOLEM, Brehova st. 7, Prague 1, Czech Republic. These activities should also be indicated in the logbook.

References

- [1] *NRL plasma formulary*. Naval Research Laboratory, 2009.
- [2] Jana Brotánková. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, Charles University in Prague, 2009.
- [3] John Wesson. The science of JET. In *JET Reports*, pages JET-R(99)13. 1999.