Student measurements on the GOLEM tokamak

10/10/2013
Logbook

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1 Introduction

The purpose of this measurement was to get acquainted with the basics of tokamak operation. A tokamak is a device using a helically twisted magnetic field to confine a plasma in the shape of a torus. Such a helical field is the superposition of a toroidal magnetic field produced toroidal field coils and a poloidal magnetic field generated by current that flows inside the plasma. Schematic build up of a tokamak can be seen on figure 1.

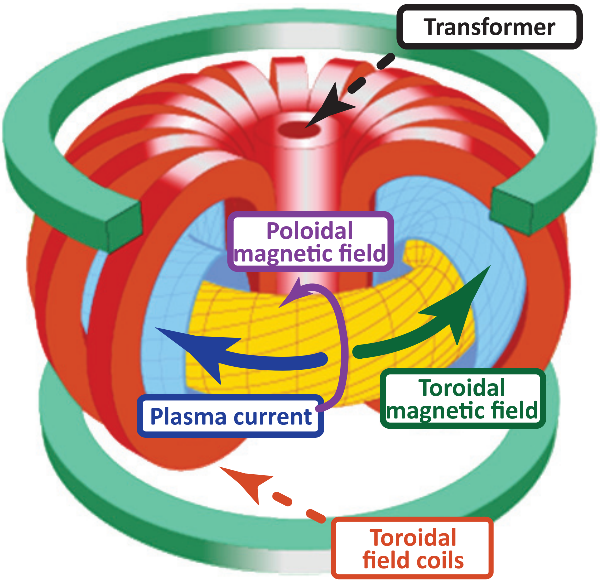

Figure 1: *Schematic build up of a tokamak. The toroidal magnetic field is produced by the red toroidal field coils. The plasma current generating the poloidal magnetic field is produced by the transformer.*

Our measurements were performed on the GOLEM tokamak. This is a small sized tokamak device equipped with basic controls and diagnostics. The main parameters of this device is the following:

- 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.
- Toroidal magnetic field: < 0.8 T
- Plasma current: < 8 kA
- Discharge duration: ≈ 10 ms

- Working gas: H_2

Presently the device is located at the Faculty of Physical and Nuclear Engineering of the Czech Technical University (CTU) in Prague. It has full remote control capability which gives the possibility to perform measurements from Budapest. The following parameters can be set remotely:

- Toroidal magnetic field (B_t) through the voltage of the toroidal field capacitor bank ($U_B = U_{C\_Bt}$), range: $400 - 1400$ V.
- Toroidal electric field (E_t) through the capacitor bank for the current drive ($U_E = U_{CD}$), range: $100 - 600$V.
- The time delay between the triggers of the toroidal magnetic field and the current drive ($T_{CD} = \tau_{OH}$), range: $0 - 20000$ μs.
- Hydrogen gas pressure (p_{H2}), range: $0 - 100$ mPa.
- Preionization ON/OFF

The discharges can be investigated by different measurements: time resolved measurement of loop voltage (U_l), total toroidal current by Rogowski coil (I_t) and magnetic field by coil measurement (B_t). The vacuum chamber pressure (p_{ch}) and the temperature of the vacuum chamber (T_{ch}) are also registered.

2 Measurements tasks

2.1 Determination of vacuum chamber parameters

The Rogowski-coil measures the time derivative of the total toroidal current. Since the vacuum chamber of the GOLEM tokamak is an electrical conductor, part of the toroidal current always flows in the vacuum vessel. Therefore in order to determine the plasma current one has to calculate the current flowing in the vacuum chamber. Vacuum shots, when no plasma is formed, give the possibility to calculate the parameters of the vacuum chamber, namely its resistance and its inductance.

The circuit equation which characterize the system is the following:

$$U_l(t) = R_{ch} \cdot I_{tot}(t) + L_{ch} \frac{dI_{tot}}{dt} \ , \tag{1}$$

where U_l is the loop voltage, R_{ch} is the resistance, L_{ch} is the inductance of the chamber and I_{tot} is the total current which in this case equals to the chamber current (I_{ch}). U_l, I_{tot} and dI_{tot}/dt can be determined from the loop voltage and the Rogowski-coil measurements. After dividing equation (1) by I_{tot} one can get a simpler form:

$$\frac{U_l(t)}{I_{tot}(t)} = R_{ch} + L_{ch}\frac{dI_{tot}}{dt} \cdot \frac{1}{I_{tot}(t)} \ , \tag{2}$$

which from the value of R_{ch} and L_{ch} can be evaluated by a 1D least squares linear fit. To make the calculations mentioned above we used four vacuum shots from #13073 to #13076. The results are summed in table 1. It can be seen that, the measured inductance of the vacuum chamber is a very small negative value, which means that the slope of the fitted linear is very close to zero. Since the negative value cannot interpreted as a physical unit we neglect the inductance of the vacuum chamber and taking only the ohmic resistance into account. So the resistance of the vacuum chamber is 0.01114 Ω.

Shotnumber	R_{ch} [Ω]	L_{ch} [H]
#13073	1.050e-02	-1.026e-06
#13074	1.252e-02	-3.863e-06
#13075	1.087e-02	-1.113e-06
#13076	1.065e-02	-9.805e-07
Average	1.114e-02	-1.746e-06

Table 1: *Parameters of the vacuum chamber measured in different vacuum shots. The average values indicated in the last row.*

2.2 Plasma breakdown

The next step was the investigation of plasma creation. The aim was to set different pressure for the H_2 working gas, set different loop voltage and decide if plasma formed or not. Unfortunately the standard turbomolecular pump was dysfunctional, so we had to use the old one. Therefore we could not make discharges at lower pressure than 16 mPa.

We did 12 discharges without pre-ionization and our results presented on figure 2, where the voltage of the capacitor bank responsible for the toroidal electric field can be seen as a function of the working gas pressure. Discharges where plasma was created are indicated with red circles and black squares indicate the vacuum discharges. As we can 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 plasma breakdown. As I mentioned above we could not make discharges at lower pressure, but a critical line is observed which separates breakdown and non-breakdown discharges.

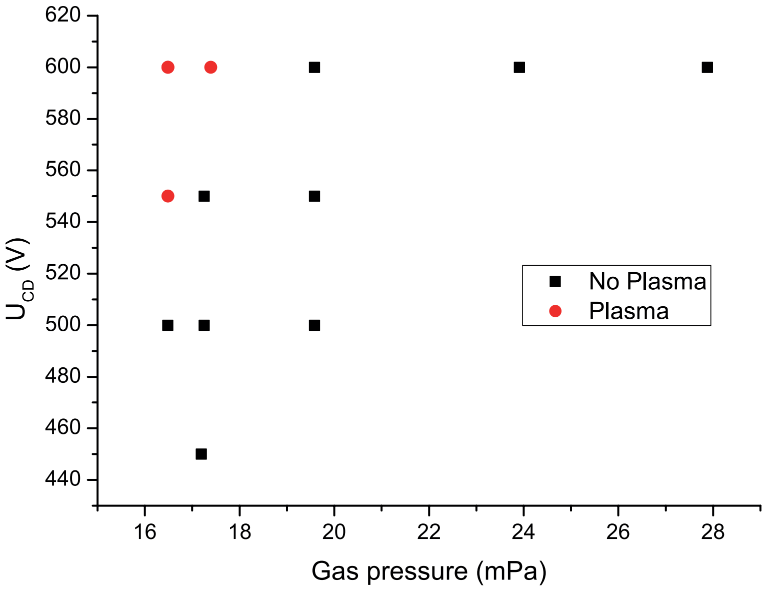

Figure 2: *Plasma breakdown studies: the voltage of the capacitor bank responsible for the toroidal electric field can be seen as a function of the working gas pressure. Discharges where plasma was created are indicated with red circles and black squares indicate the vacuum discharges.*

2.3 Estimation of main plasma parameters

Plasma current

In section 2.1. the parameters of the vacuum chamber were estimated which values can be used to evaluate the plasma current from the measured total current. Since the inductance of the vacuum chamber is approximated by zero the current flowing in the chamber can be easily calculated using the loop voltage measurements:

$$I_{ch}(t) = \frac{U_{ch}(t)}{R_{ch}} \ . \tag{3}$$

After that the plasma current is given by the following equation:

$$I_{pl}(t) = I_{tot}(t) - I_{ch}(t) \ , \tag{4}$$

where $I_{tot}(t)$ is arisen form the integral of the Rogowski coil measurement.

Calculated plasma current is presented on figure 3.c for discharge #13096. Loop voltage and toroidal magnetic field are also plotted on figure 3.a and 3.b. The maximum of the plasma current is calculated for all discharges with plasma and included in the shot summary table.

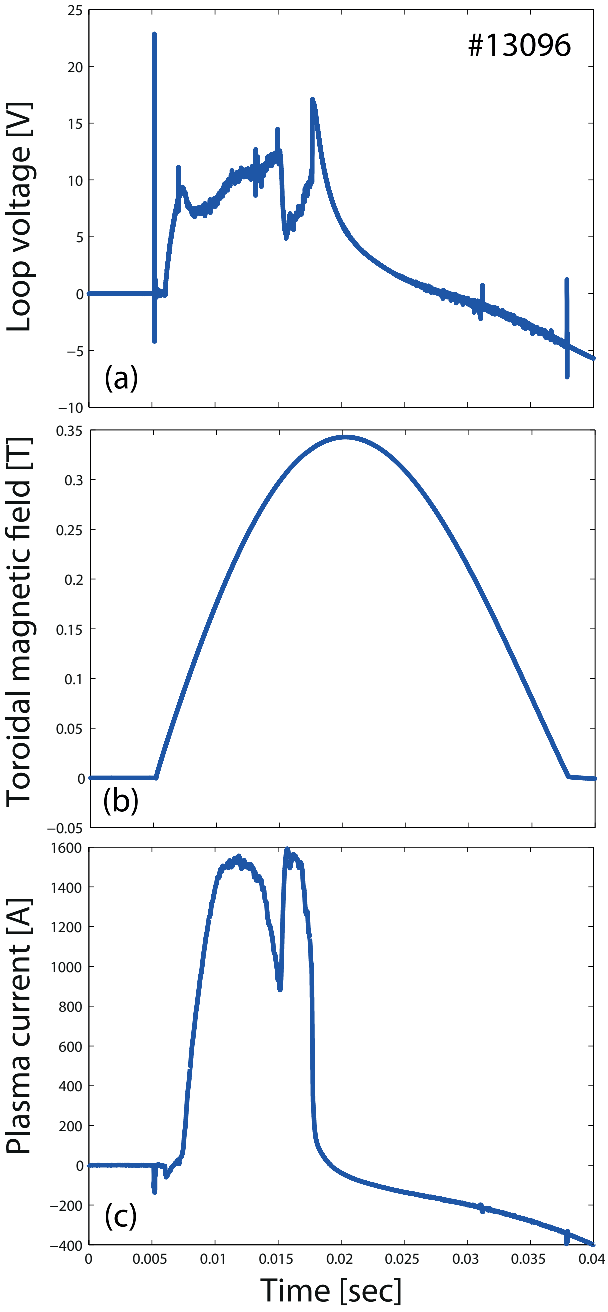

Figure 3: *(a) Loop voltage measurement in discharge #13096. (b) Toroidal magnetic field measurement in discharge #13096. (c) Plasma current in discharge #13096.*

Plasma heating power

The GOLEM is a small tokamak without any external heating power, so the only heating mechanism of the plasma is ohmic heating which resulting from the plasma current. The ohmic heating power can be calculated as:

$$P_{OH}(t) = R_{pl}(t) \cdot I_{pl}^2(t) \ . \tag{5}$$

We calculated the plasma heating power for discharge #13094 as can be seen on figure 4 and also include the maximum values in the shot summary table.

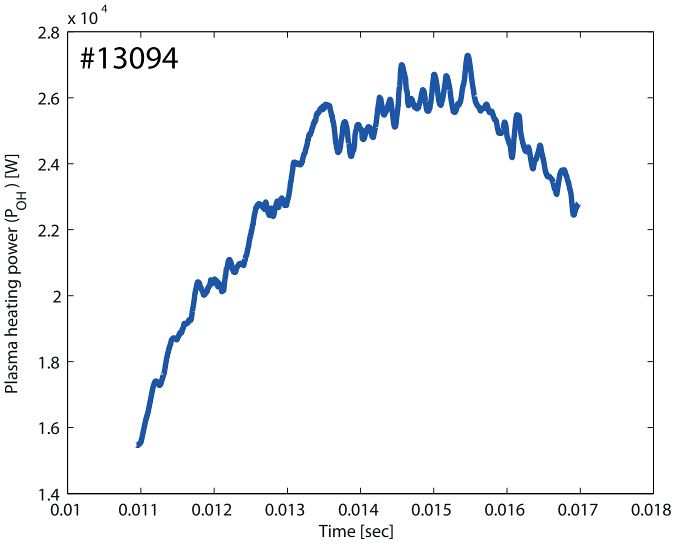

Figure 4: *The time evolution of the plasma heating power in discharge #13094.*

Central electron temperature

The electron temperature in the plasma core can be estimated by Spitzer's resistivity formula if one knows the effective charge number (Z_{eff}) and the electron temperature profile. In our calculations we used $Z_{eff} \approx 2.5$ approximations for the effective charge number and we used the equilibrium temperature profile introduced in the measurement instructions:

$$T_e(r,t) = T_{e0}(t)\left(1 - \frac{r^2}{a^2}\right)^2 \ , \tag{6}$$

where $T_{e0}(t)$ is the central electron temperature. The formula which based on Spitzer's resistivity formula used for our T_{e0} calculation is the following:

$$T_{e0}(t) = \left(\frac{R_0}{a^2}\frac{8Z_{eff.}}{1544}\frac{1}{R_{pl}(t)}\right)^{2/3} \ , \tag{7}$$

where $R_{pl}(t)$ is in Ohms, distances are in meters and we get $T_{e0}(t)$ in electronvolts.

We calculated the electron temperature in the plasma core for discharge #13094 as can be seen on figure 4 and also include the maximum values in the shot summary table.

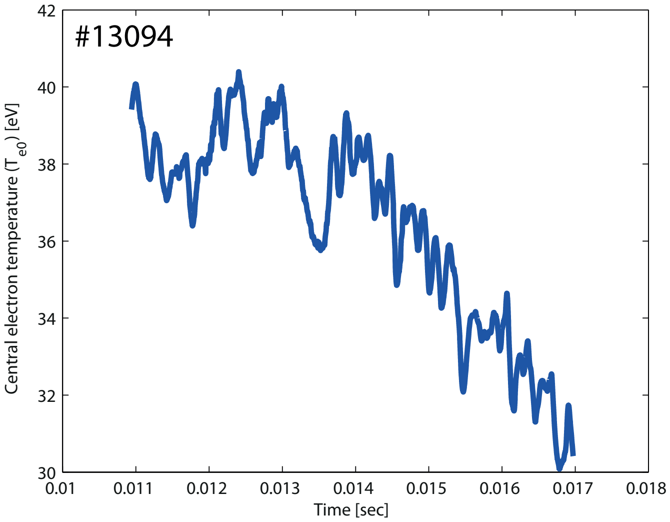

Figure 5: *The time evolution of the central electron temperature in discharge #13094.*

Electron density

Using the state law of ideal gases the order of magnitude of the electron density can be estimated. The pressure of the working gas is measured just before the discharge. The temperature of the vacuum chamber is approximated by the room temperature. So the electron density can be estimated in the following way:

$$n_{avr} = \frac{2p_{ch}}{k_B T_{ch}}. \tag{8}$$

The calculated average electron density values are included in the shot summary table.

Plasma energy

The total energy content can be simply calculated from the temperature, density and volume (V), based on the ideal gas law, taking into account the assumed (6) temperature profile:

$$W_{pl}(t) = V\frac{n_{avr}k_B T_{e0}(t)}{3}. \tag{9}$$

Plasma energy in discharge #13094 can be seen on figure 6 and maximum values of plasma energy for all discharges with plasma are included in the shot summary table.

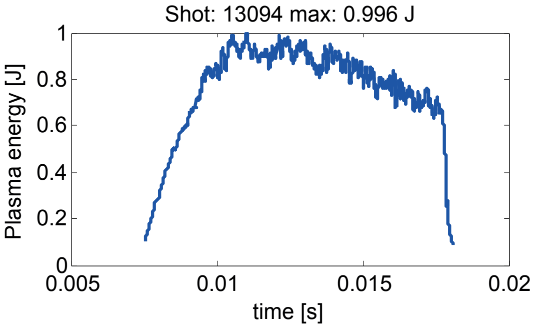

Figure 6: *The time evolution of the plasma energy in discharge #13094.*

2.3.1 Energy confinement time

We estimated the energy confinement time where the plasma energy has its maximum. At this point the ohmic heating power approximately equals the losses, allowing us to calculate the energy confinement time:

$$\tau_E(t_{top}) = \frac{W_{pl}(t_{top})}{P_{OH}(t_{top})}. \tag{10}$$

The calculated energy confinement time values are included in the shot summary table.

2.4 $q = 2$ disruptions

The last task was to investigate $q = 2$ disruptions. The helical structure of magnetic field lines is described by the safety factor (q) at each magnetic surface. It gives the number of toroidal turns necessary for the magnetic field line at a given magnetic surface to reach its original position poloidally. On the GOLEM tokamak, where the major radius (R) is much larger than the minor radius (r_0) it can be approximated by:

$$q(r,t) = \frac{r}{R}\frac{B_t(t)}{B_p(r,t)}\ , \tag{11}$$

where R is the major radius of the magnetic axis.

Theory tells us that a strong instability, which can terminate the discharge causing a disruption occurs, when the safety factor on the plasma edge is close to $q = 2$. In order to attempt this limit of operation we tried to make discharges with as high plasma current as possible and with low toroidal magnetic field. Considering Ampère's law the safety factor at the plasma edge can be calculated in the following way:

$$q_{\text{edge}}(t) = \frac{a^2}{R_0} \frac{2B_t(t)\pi}{\mu_0 I_{pl}(t)}. \tag{12}$$

The most successful discharge was #13103. The time evolution of the safety factor is calculated by using equation (12) and plotted on figure 7. It can be seen that the safety factor at 11,4 ms get close to $q = 2$ and after that the plasma collapsed. The calculated safety factor does not reach $q = 2$, but in equation (12) the minor radius was substituted by the minor radius of the vacuum chamber. If the center of the plasma is not in the middle of the vacuum chamber the minor radius is defined by the limiter. Which means that probably the minor radius of the plasma was smaller than 85 mm, so our safety factor calculation is an upper estimation.

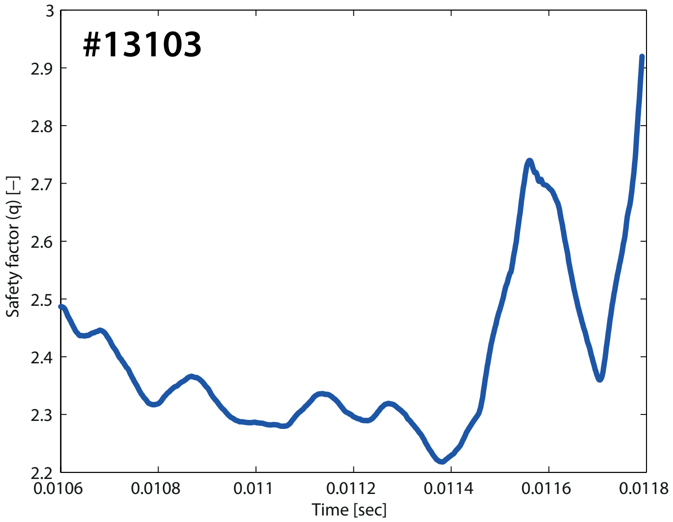

Figure 7: *Time evolution of the safety factor in discharge #13103.*

The evolution of the discharge is also plotted on the Hugill diagram. The Hugill diagram shows the evolution of a discharge as a function of the inverse edge safety factor and the Murakami parameter ($n_{\text{avg}} R_0 / B_t(t)$). The Hugill diagram of discharge #13103 can be seen on figure 8.

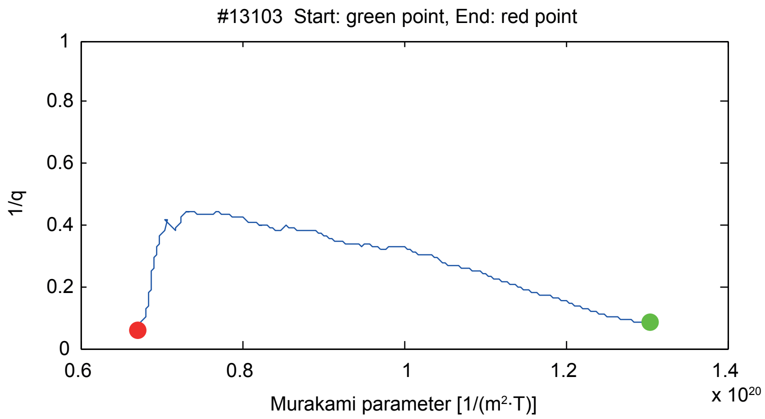

Figure 8: *The Hugill diagram of discharge #13103.*

3 Conclusion

This laboratory exercise gives a brief introduction to the basics of tokamak operation. During the measurements first we determined the resistance and inductance of the vacuum chamber. Then we successfully made discharges with plasma. After doing some programming we calculated several parameters of the plasma such as the plasma current, the central electron temperature, the ohmic heating power, the safety factor and plasma energy.

This exercise was a great opportunity to get experienced in measurements performed in an international environment.

4 Shot summary table

Shot no.	Disch. dur. [ms]	I_p^{max} [A]	P_{OH}^{max} [W]	T_{e0}^{max} [eV]	n_{avg}^{max} [1/m^3]	W_{pl}^{max} [J]	τ_E^{max} [s]
13083	4.3	964	10962.76	19.3	8.4E+18	0.41	4.4E-05
13087	4.5	1063	11774.60	18.2	8.0E+18	0.41	4.2E-05
13088	3.7	821	7404.92	17.4	8.0E+18	0.36	6.4E-05
13090	4.6	1110	12365.48	17.8	8.0E+18	0.43	4.1E-05
13092	9.9	2289	17656.50	48.2	9.5E+18	1.10	8.3E-05
13093	9.6	2821	28472.21	40.9	9.4E+18	1.21	9.6E-05
13094	10.6	2924	29802.86	44.9	7.7E+18	0.99	7.0E-05
13095	9.7	2834	30873.86	41.7	7.7E+18	1.00	5.9E-05
13096	10.5	1656	16268.03	38.2	7.7E+18	0.94	1.4E-04
13097	7.9	2173	22857.96	33.0	1.0E+19	1.01	8.0E-05
13098	8.4	2550	24423.65	44.7	8.4E+18	0.89	7.3E-05
13099	6.8	1864	17626.30	31.6	1.1E+19	0.91	7.4E-05
13101	5.6	1231	12608.86	20.4	1.2E+19	0.73	6.6E-05
13103	3.8	1790	17829.04	28.6	7.8E+18	0.69	5.2E-05
13105	4.7	1833	18862.41	28.7	9.4E+18	0.84	6.8E-05

Table 2: *Shot summary table: highest values are indicated by red.*

5 Skype log

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[15:18:31] *** Gergo Pokol meghívta Horváth László-t a
   konferenciára ***
[15:18:50] Gergo Pokol: [15:17] Tokamak GOLEM:

<<< Control room: http://golem.fjfi.cvut.cz/roperation/
   tasks/TrainingCourses/HUNTRAIC/1013BUTE
Session : http://golem.fjfi.cvut.cz/utils/session_list?
   session_list=101013:TrainingCourses/HUNTRAIC/
[15:18:51] Horváth László: Hello!
[15:19:27] Tokamak GOLEM: Hi Laszlo, regards from Prague
   !
[15:24:20] Horváth László: Regards from Budapest. We are
    almost ready to start the first shots. We need a few
    minutes.
[15:25:21] Tokamak GOLEM: OK, we are ready
[15:30:20] Horváth László: Can we start with the first
   vacuum shots in order to determine the vacuum chamber
    parameters?
[15:31:13] Tokamak GOLEM: Yes, but it will be difficult
   to reach vacuum shot, because of poor pressure in
   chamber. I guess we will have plasma in the dust. You
    can try it ..
[15:32:07] Tokamak GOLEM: I have a suggestion, I can now
    switch the orientation of E field and in this mode
   it is difficult to breakdown H into plasma, so it is
   a chance to have a vacuum shot ..
[15:34:11] Horváth László: Let's start with standard
   orientaion first
[15:34:19] Tokamak GOLEM: OK
[16:06:24] Horváth László: We are starting to make shots
    in order to investigate breakdown parameters.
[16:35:15] Tokamak GOLEM: Hi Laszlo, note, that it is
   possible to play a "chamber conditionig game", i.e.
   baking and glow discharge.
[16:44:32] Horváth László: How much time do you need to
   make the chamber conditioning?
[16:46:53] Tokamak GOLEM: It depends on you: 10 minutes
   for baking to get approx 150 gr. C. and glow
   discharge could be also 10 minutes
[16:54:03] Horváth László: We need 5-6 more shots to
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   finish breakdown studies and then chamber
   consitioning would be great. What is 150 gr. C?
[16:55:45] Tokamak GOLEM: OK,  sorry, 150 degres Celsius
   ..
[16:56:06] Horváth László: ok, :)
[16:58:54] Tokamak GOLEM: "Fast" camera added
[17:21:29] Tokamak GOLEM: Laszlo, everything without
   preionization??
[17:22:27] Horváth László: Yes, we did breakdown studies
    without preionization.
[17:22:42] Horváth László: Please make the chamber
   conditioning.
[17:22:54] Horváth László: After that we will continue
   with plasma shots.
[17:23:37] Tokamak GOLEM: Which one, baking or Glow
   discharge, or both?
[17:24:08] Horváth László: Both, please.
[17:24:16] Tokamak GOLEM: OK
[17:33:11] Tokamak GOLEM: Glow discharge is on, you can
   watch it on IP camera
[17:33:33] Tokamak GOLEM: Now baking ..
[17:36:54] Horváth László: Yes, glow discharge is well
   visible on IP camera.
[17:38:07] Tokamak GOLEM: Baking ON
[17:43:59] *** Gergo Pokol ezt a fájlt küldte:
   IMG_20131010_163101.jpg IMG_20131010_163116.jpg ***
[17:48:49] Gergo Pokol: Hi Vojtech, here goes some
   pictures.
[17:52:35] Tokamak GOLEM: Thank you very much :)
[17:58:10] Horváth László: Can we try to make some
   plasma shots?
[17:58:40] Tokamak GOLEM: Just a moment, we will test it
    after conditioning
[17:58:51] Horváth László: OK
[18:03:15] Tokamak GOLEM: Go ahead
[18:11:17] Horváth László: Just a few questions: What is
    the current status of the TMP? Why is the loop
   voltage so noisy?
[18:32:05] Tokamak GOLEM: The standard TMP is
   substituted with the old one.
[18:33:08] Tokamak GOLEM: Noise is our current problem.
   We are investigating (afetr reconstruction) the
   origin ... Sorry, I think the current operation, more
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    then 10 ms discharge is out of our today’ morning
   dreams.
[18:43:07] Horváth László: Yes, we have nice shots. I’ve
    asked these questions just for curiosity.
[18:54:45] Tokamak GOLEM: OK
[19:04:45] Horváth László: Do you know what can be the
   reason of the strange effect in the plasma current in
    shot #13096 at ~15 ms?
[19:08:17] Tokamak GOLEM: We call it double breakdown
   and we can not find any reasonable explanation .. a
   lot of theories without common agreement to any .. We
    have a lot of discharges like this, even triple
   berakdowns ..
[19:08:21] Tokamak GOLEM: http://golem.fjfi.cvut.cz
   :5001/ShowRooms/TripleBreakdown/index
[19:13:11] Horváth László: We finished our experiments.
   Thank you very much! We really enjoyed this evening!
[19:14:05] Tokamak GOLEM: Very good! Best regards from
   Prague. I am glad that you enjoyed today’ session.
   Bye
[19:14:29] Gergo Pokol: Thank you, Vojtech! We had some
   interesting results today.
[19:14:48] Tokamak GOLEM: Fine!
[19:16:09] Tokamak GOLEM: Looking to see your reports.
   Measurements from BUTE are the best of all remote
   accesses we had up to now.
[19:17:08] Gergo Pokol: We will try our best to live up
   to your expectations. :) Bye!
[19:17:31] Tokamak GOLEM: Bye
[19:17:43] Horváth László: Bye!
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