

Measurements on the GOLEM tokamak

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Supporters: Dr. Vojtech Svoboda

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I, Introduction:

Participants of the Czech-Hungarian joint measurement collected reliable data during operation of the GOLEM Tokamak. The instrument is a fully equipped, small sized thermonuclear reactor for educational purposes to take measurements. The Tokamak has got the following geometry and operational parameters:

- 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 (Bt) through the voltage of the toroidal field capacitor bank, range: 400-1400 V;
- Toroidal electric field (Et) through the capacitor bank for the current drive, range: 100-600V;
- The time delay between the triggers of the toroidal magnetic field and the current drive, range: 0-20000 μ s;
- Hydrogen gas pressure, range: 0-100mPa;
- Preionization is available.

II, Exact method of executing the measurements:

During the measurement procedure the live communication with Dr. Vojtech Svoboda, colleague of the Faculty of Physical and Nuclear Engineering of the Czech Technical University was carried out via Skype.

We used the GOLEM tokamak web interface to set up and initiate discharges. The recorded data was available at the website, the address of the required root directory was given by the Czech support.

The first task was to determine the vacuum chamber parameters. When no plasma is formed (vacuum shot) it is possible to get the resistance of the vacuum vessel, since all the current measured by Rogowski-coil flows in the vessel.

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

where $U_l(t)$ -loop voltage, R_{ch} -vacuum chamber resistance, $I_{tot}(t)$ -total current (in this case total current equals to I_{ch} - chamber current) , L_{ch} -vacuum chamber inductance.

We had data about the loop voltage and total current so the chamber's resistance and inductance were calculated with MATLAB. We made five discharges with different parameters, therefore we could fit a curve (the $U_l(t)$ function) to get the above mentioned parameters.

The second task was to plot the chamber pressure against the loop voltage spikes (in the beginning of the discharges for several attempts) and indicate plasma breakdown. First we set the hydrogen pressure which is a control property of the inlet valve, the actual chamber pressure value was provided by a vacuum meter. Secondly to indicate a breakdown we had to reach the critical value of the toroidal electric field. During the exercise the preionization was turned on as the Czech support suggested. We gave parameters to remote control where the plasma breakdown possibility was 100% and 0%. After these discharges we set medium parameters from the previous settings to find the minimal electric field where we surely experience plasma breakdown. Because we saw breakdown we continued the evaluation of the minimal electric field with the following method: we always halved the interval, according to the previously used settings. We determined the minimal values for various chamber pressures by repeating the method described above.

The third task was to study the main plasma parameters such as plasma current and plasma heating power. We chose different toroidal magnetic field's voltage (U_B) values and hydrogen pressure levels to reach as high as possible plasma current values. Ohmic heating power depends on the plasma current and plasma resistivity as the following equation shows it:

$$P_{OH}(t) = R_{pl}(t)I_{pl}^2(t)$$

In the following discharges we wanted to reach higher and higher plasma current values (indirectly through hydrogen pressure and voltage of toroidal electric field), as a result we got higher and higher ohmic heating power and central plasma temperature.

The fourth task included the study of the safety factor (q). Our goal was to achieve a $q=2$ safety factor, which leads to a plasma instability. At this value the plasma surface destabilizes and finally disrupts. We reduced the toroidal magnetic field gradient through the voltage of the toroidal field capacitor bank, this way the safety factor has decreased (see the equation below):

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

where q -safety factor, a -plasma small radius, R_0 -major radius, B_t -toroidal magnetic field gradient, μ_0 - magnetic permeability of vacuum, I_{pl} -plasma current.

III, Exact method of derivation of final results:

Central electron temperature:

The central electron temperature (T_{e0}) is calculated from equation, which itself is based on Spitzer's resistivity formula:

$$T_e(r, t) = \left(\frac{R_0}{a^2} \frac{8Z_{eff}}{1544} \frac{1}{R_{pl}(t)} \right)^{2/3} \left(1 - \frac{r^2}{a^2} \right)^2$$

The Z_{eff} (effective charges number) and a (plasma small radius) factors cannot be estimated precisely because of the inhomogeneous ionization of the central region and the lack of monitoring plasma stabilization. Therefore the electron temperature bears certain uncertainty.

Electron density:

In its current state, the GOLEM tokamak does not have any density measurements so we estimated from the state law of ideal gases.

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

This is a harsh estimate for two reasons:

Plasma is not fully ionized in the tokamak, which makes us overestimate the electron density. Due to the plasma wall interaction, absorbed gases are released from the surface of plasma and these atoms can re-enter the plasma and can be ionized thus making us underestimate the electron density.

Plasma energy:

Assuming the temperature profile shown above in Spitzer's formula and bear in mind the electron density the plasma energy can be calculated with the following formula:

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

Confinement time:

An important parameter of the energy balance in the tokamak is the energy confinement time, which is the characteristic time of energy loss:

$$P_{loss} = \frac{W_{pl}}{\tau_E} \rightarrow \tau_E = \frac{W_{pl}}{P_{loss}}$$

IV, Results of the measurements:

In the following section, we will present all of our result through the shot summary tables and some graphs.

1, Determination of vacuum chamber parameters:

As we mentioned previously, our first task was to measure the resistance and inductance of the chamber, so we made 5 shots with different input parameters. In this case, we didn't let hydrogen gas into the chamber and we didn't use the preionization. Using our MATLAB code, we calculated the parameters with linear fitting based on the following:

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

The quotients are known from the corrected measured data, so we get R_{CH} as the intercept and L_{CH} as the slope. Our result:

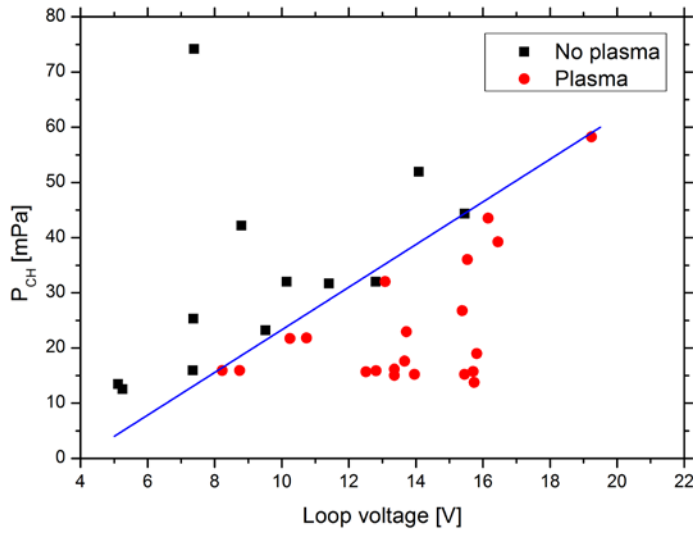
Shot number	U_B [V]	U_{CD} [V]	T_{CD} [μ s]	R_{CH} [Ω]	L_{CH} [H]
17313	0	700	500	0.0185	3.23E-6
17314	200	500	1000	0.0134	-4.55E-6
17315	200	300	1000	0.0085	4.68E-6
17316	700	300	1000	0.0084	9.9E-7
17317	700	150	500	0.0095	-4.37E-8
Average				0.01166	8.625E-07

Our results show, that this method is a bit inaccurate and gives only the order of magnitude estimate. Notice, that the inductances are really small and we got even negative numbers two times. We will use the average parameter values in the further calculations.

2, Plasma breakdown:

We turned on the preionization and let hydrogen gas into the chamber. Then the measurements were carried out at different P_{CH} , U_B and U_{CD} settings. In the following sections, we will use these data (shot number: 17318-17356) for further calculations, but the first step is to examine the plasma breakdown. We plotted the P_{CH} against the maximum of the loop voltage spikes in the beginning of the discharge for all of our discharges.

We got a really good result, because the "plasma dots" and "no plasma dots" are located separately and it defines a separator line with the equation: $P_{CH} = -15.31 + 3.86 * U_{l,max}$.



Equation	$y = a + b \cdot x$	
Weight	No Weighting	
Residual Sum of Squares	0	
Pearson's r	--	
Adj. R-Square	--	
		Value
	Intercept	-15.31034
	Slope	3.86207

3. Estimation of main plasma parameters:

We determined the basic plasma parameters for the previous 17318-17346 shots, and collected them into the shot summary table ($U_B=400V$, $T_{CD}=2000\mu s$):

Shot #	U_{CD} [V]	P_{H2} [mPa]	P_{CH} [mPa]	Max U_{loop} [V]	Max I_{pl} [A]	Discharge duration	Max P_{OH} [$\cdot 10^4$ W]	Max T_{e0} [$\cdot 10^5$ K]	Max n_{avr} [$\cdot 10^{18}$]	Max W_{pl} [J]	Max τ_e [$\cdot 10^{-5}$ s]
*18	150	2	12.55	5.25							
*19	150	4	13.44	5.12							
*20	700	4	15.20	13.96	3185	0.0065	5.716	2.972	6.476	0.6987	4.08
*21	600	4	15.67	12.51	2746	0.0066	4.163	2.861	6.678	0.6934	5.01
*22	350	4	15.92	8.74	1388	0.0066	1.313	2.478	6.781	0.6101	9.68
*23	250	4	15.92	7.35							
*24	300	4	15.92	8.22	755	0.0054	0.573	1.697	6.781	0.4179	10.75
*25	250	20	25.32	7.37							
*26	250	40	74.18	7.39							
*27	300	40	42.19	8.80							
*28	500	40	51.91	14.09							
*29	700	40	58.25	19.24	413	0.0098	0.776	0.593	24.82	0.5345	70.51
*30	700	20	26.72	15.38	3215	0.0062	5.477	2.953	11.38	1.2204	5.62
*31	400	20	31.64	11.41							
*32	350	20	32.01	10.14							
*33	500	20	32.01	13.09	1478	0.0047	2.248	1.988	13.64	0.9843	8.34
*34	450	20	32.01	12.80							
*35	550	30	44.35	15.46							
*42	650	30	39.23	16.45	2046	0.0047	3.643	2.147	16.71	1.3027	6.62
*43	600	30	36.05	15.54	407	0.0107	0.649	0.655	15.36	0.3655	43.38
*44	350	10	23.18	9.51							
*45	450	10	21.80	10.74	1976	0.0064	2.353	2.768	9.29	0.9334	8.70
*46	400	10	21.72	10.25	1373	0.0055	1.584	2.191	9.25	0.7362	9.72

To get the plasma current, we made the following calculations:

$$U_l(t) = R_{ch}I_{ch}(t) + L_{ch} \frac{dI_{ch}}{dt} \xrightarrow{int} I_{ch}(t) \rightarrow I_{pl}(t) = I_{tot}(t) - I_{ch}(t)$$

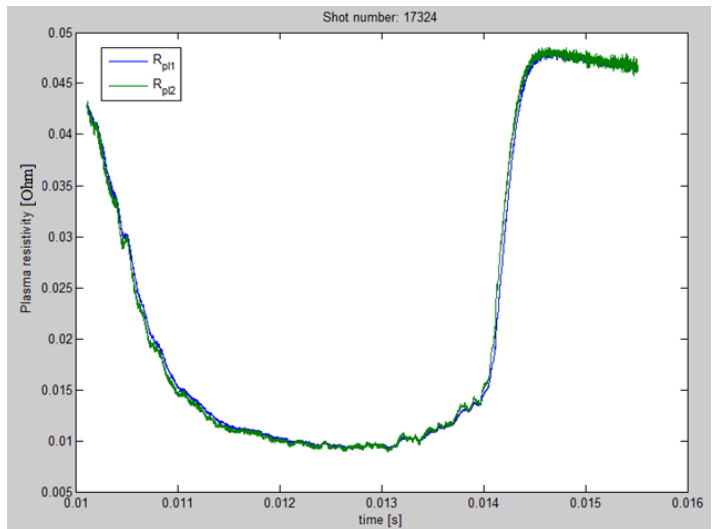
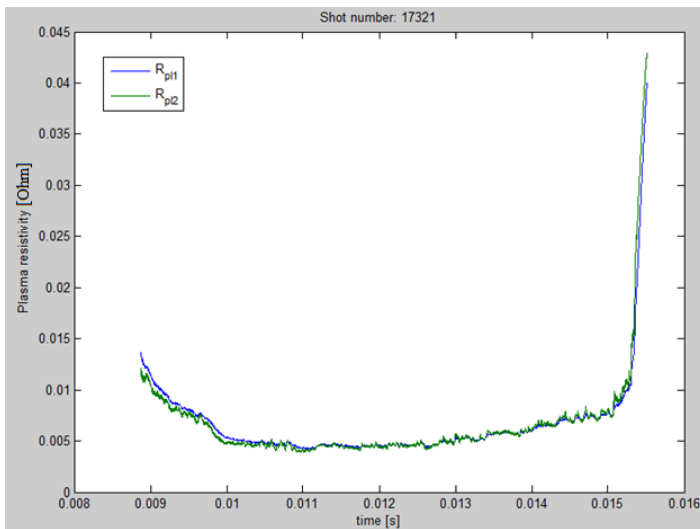
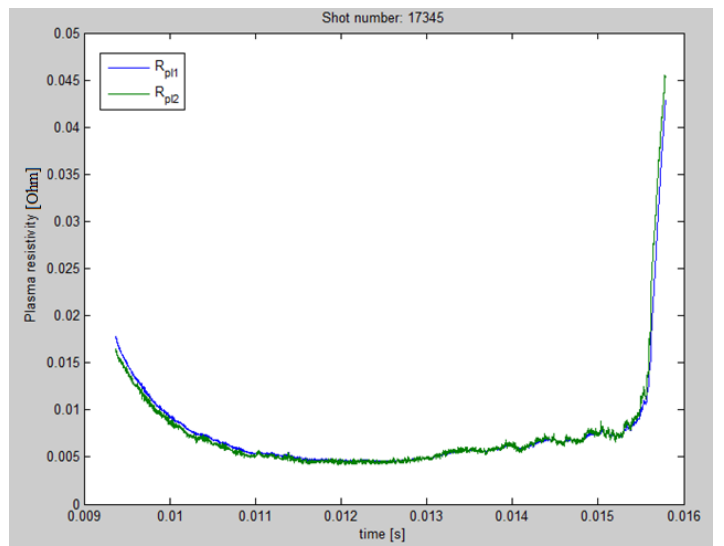
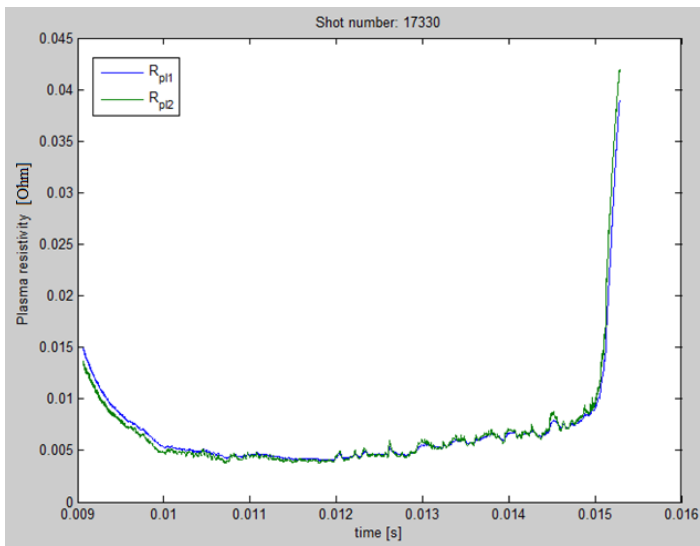
We used an appropriate threshold to get the correct discharge duration.

The plasma resistivities can be calculated with two approximations:

$$1, U_l(t) = R_{pl}I_{pl}(t) + L_{pl} \frac{dI_{pl}}{dt} \approx R_{pl}I_{pl}(t) \rightarrow R_{pl1} = \frac{U_l(t)}{I_{pl}(t)}$$

$$2, U_l(t) = R_{pl}I_{pl}(t) + L_{pl} \frac{dI_{pl}}{dt} \approx R_{pl}I_{pl}(t) + L_{ch} \frac{dI_{pl}}{dt} \rightarrow R_{pl2} = \frac{U_l(t) - L_{ch} \frac{dI_{pl}}{dt}}{I_{pl}(t)}$$

To investigate the effect of the approximation method, we plotted both of them for four random discharges:



There are no significant differences between these two methods, so we can use the much easier $L_{pl} \approx 0$ approximation.

Our next objective was to achieve as high plasma temperature as possible, so we made some extra discharges with the maximum $U_{CD} = 700V$ toroidal electric field. All of the results can be found in the shot summary table (we indicated the maximum values with red color):

Shot #	U_B [V]	P_{H2} [mPa]	P_{CH} [mPa]	Max U_{loop} [V]	Max I_{pl} [A]	Discharge duration	Max P_{OH} [$\cdot 10^4$ W]	Max T_{e0} [$\cdot 10^5$ K]	Max n_{avr} $\cdot 10^{18}$	Max W_{pl} [J]	Max τ_e [$\cdot 10^{-5}$ s]
*47	500	30	43.51	16.16	2830	0.0060	4.8009	2.5808	18.538	1.7367	7.6789
*48	500	10	22.92	13.72	3483	0.0070	5.9112	3.1489	9.7650	1.1162	5.3428
*49	500	4	17.59	13.67	3430	0.0071	5.8340	3.0925	7.4929	0.8412	4.5582
*50	400	4	16.16	13.36	3237	0.0067	5.7198	2.9742	6.8861	0.7435	4.2884
*51	600	4	15.86	12.81	3233	0.0071	5.5659	3.028	6.7552	0.7425	4.4153
*52	500	2	15.03	13.36	3234	0.0070	5.5502	3.0119	6.4018	0.6999	4.2003

We reached **3483A** plasma current and **$3.1489 \cdot 10^5 K = 27.13633eV$** plasma temperature with $U_B=500V$ and $P_{CH}=22.92mPa$ input parameters.

4, q = 2 disruption:

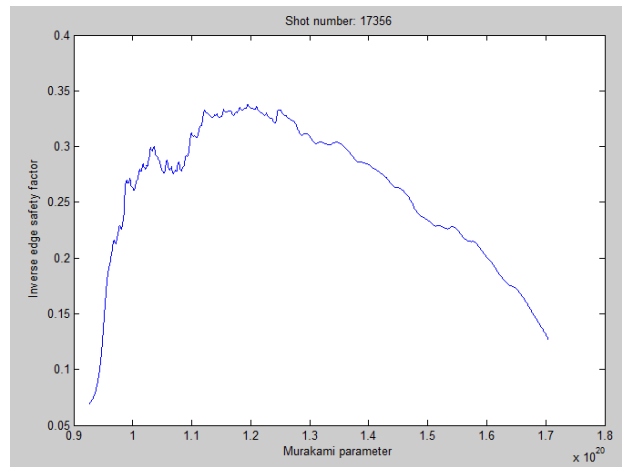
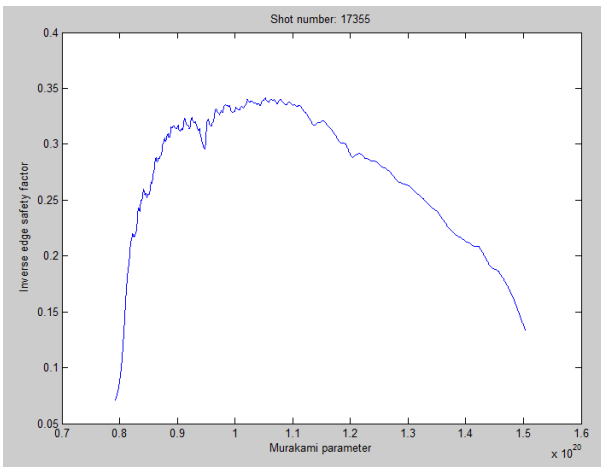
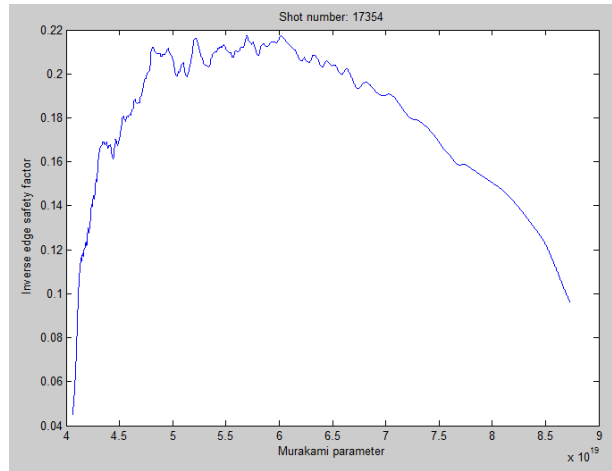
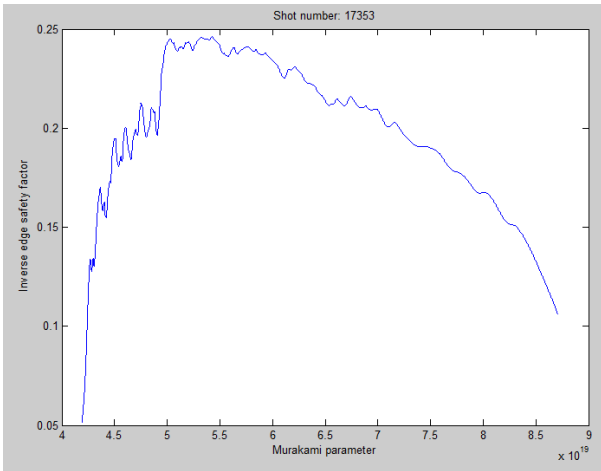
Our last task was to reach the q = 2 disruption limit and plot the results on the Hugill diagram, which serves as an operation envelope for tokamaks. On this diagram we illustrate the inverse edge safety factor against Murakami parameter:

$$\frac{n_{avg} \cdot R_0}{B_t(t)}$$

We made some final discharges to achieve this limit. The calculated results for these shots are below ($U_{CD} = 700V$):

Shot #	U_B [V]	P_{H2} [mPa]	P_{CH} [mPa]	Max U_{loop} [V]	Max I_{pl} [A]	Discharge duration	Max P_{OH} [$\cdot 10^4$ W]	Max T_{e0} [$\cdot 10^5$ K]	Max n_{avr} $\cdot 10^{18}$	Max W_{pl} [J]	Max τ_e [$\cdot 10^{-5}$ s]
*53	200	2	13.76	15.74	2858	0.0049	5.7919	2.7300	5.8609	0.5808	3.4154
*54	200	4	15.20	15.46	2853	0.0052	5.5157	2.6927	6.4759	0.6330	3.8527
*55	100	4	15.73	15.71	2377	0.0040	5.1616	2.5128	6.7036	0.6115	3.5864
*56	100	10	18.99	15.82	2264	0.0037	5.2872	2.4593	7.6412	0.6822	3.7370
*57	50	10	21.55	19.02							
*58	100	30	44.70	19.19							

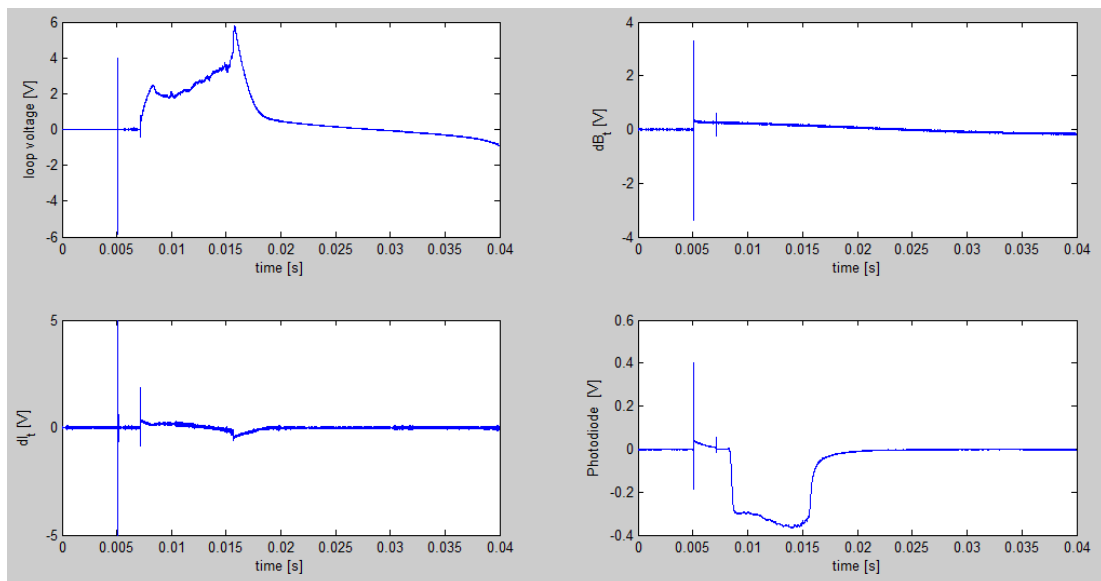
Unfortunately, we couldn't reach the q = 2 limit, but we were close to this. We plotted the results of the four successful discharges:



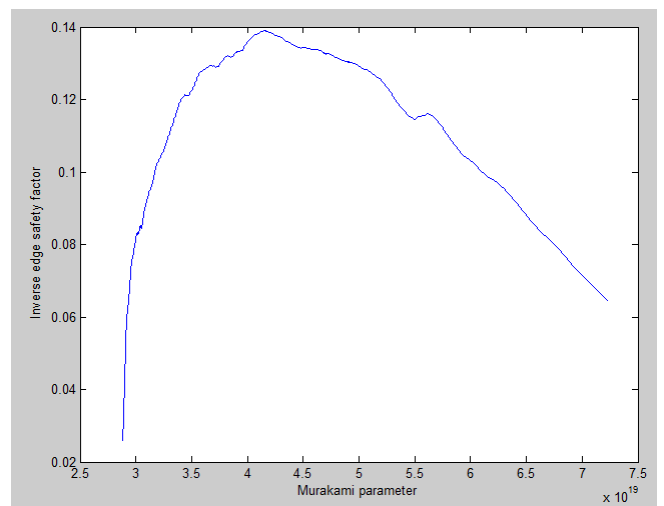
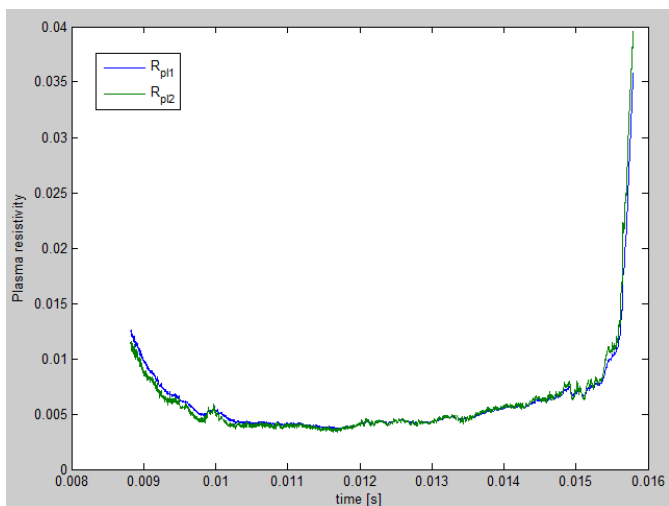
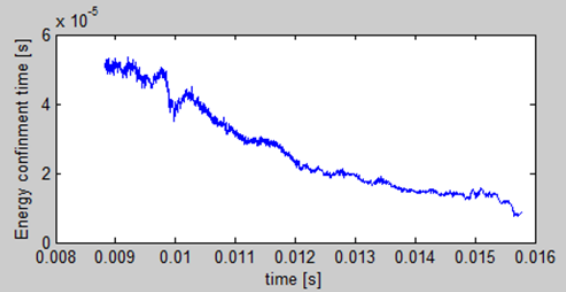
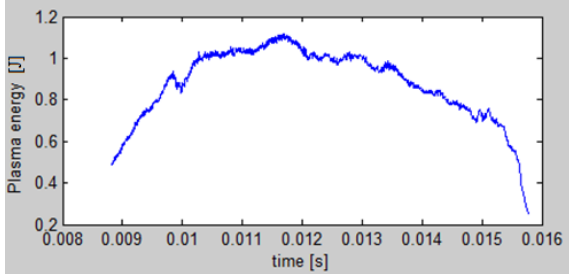
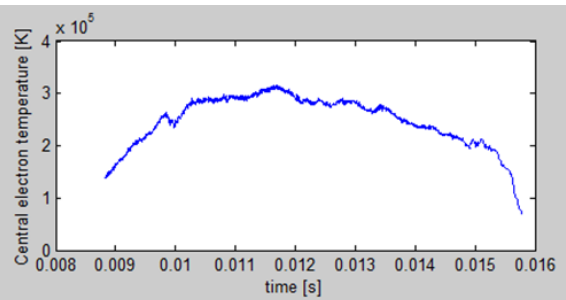
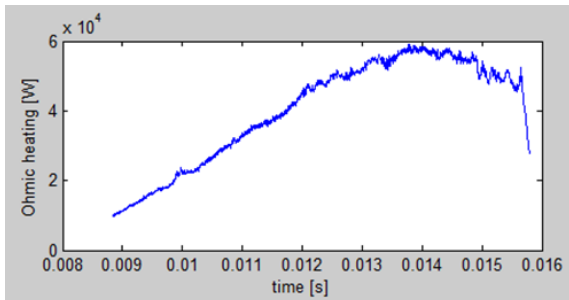
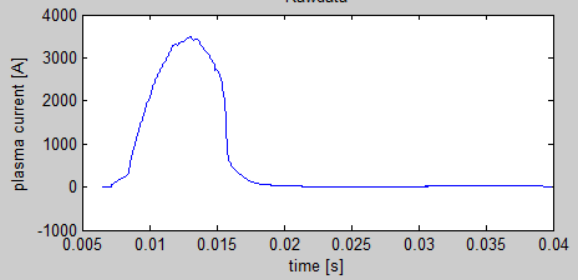
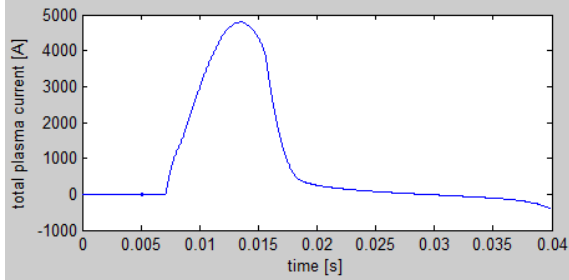
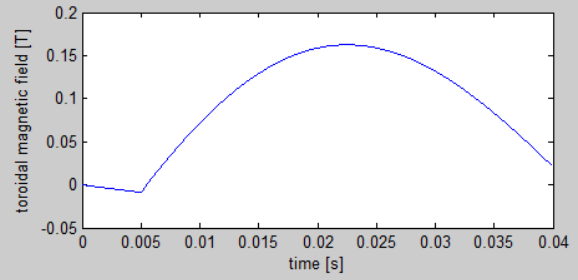
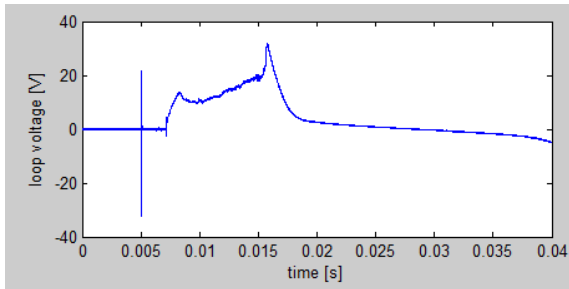
V, Time traces of shot parameters for some characteristic shots:

Shot number: 17348 was the most interesting discharge, because we reached the highest temperature and plasma current in this case, so we plotted the time traces of the parameters:

Rawdata:

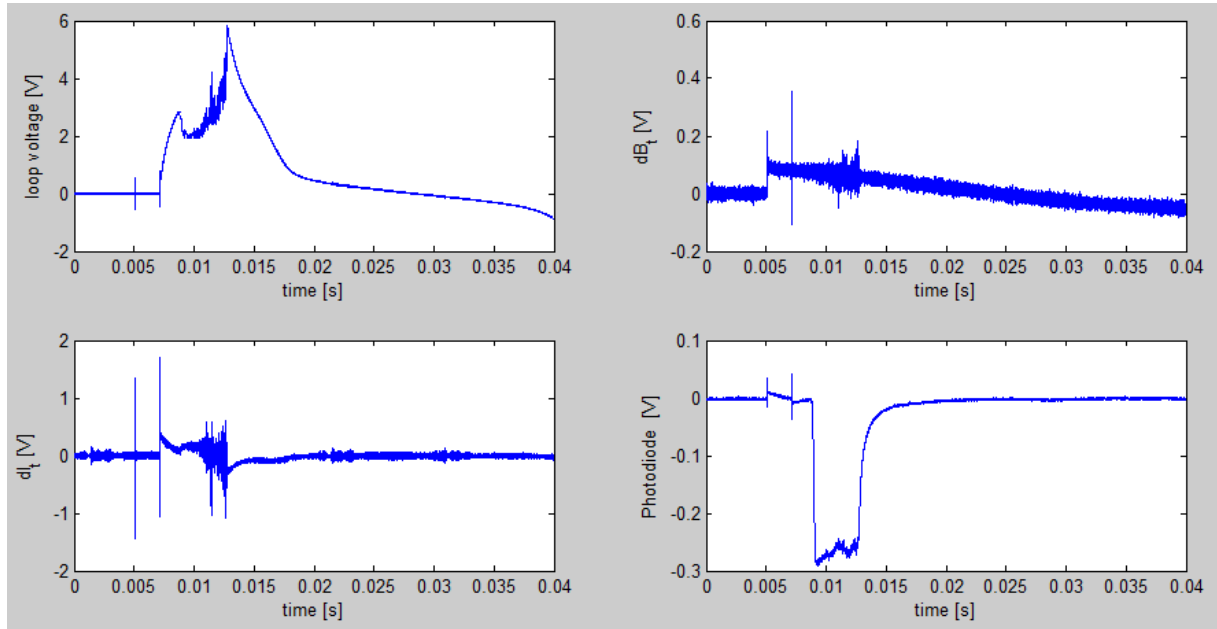


Calculated parameters:

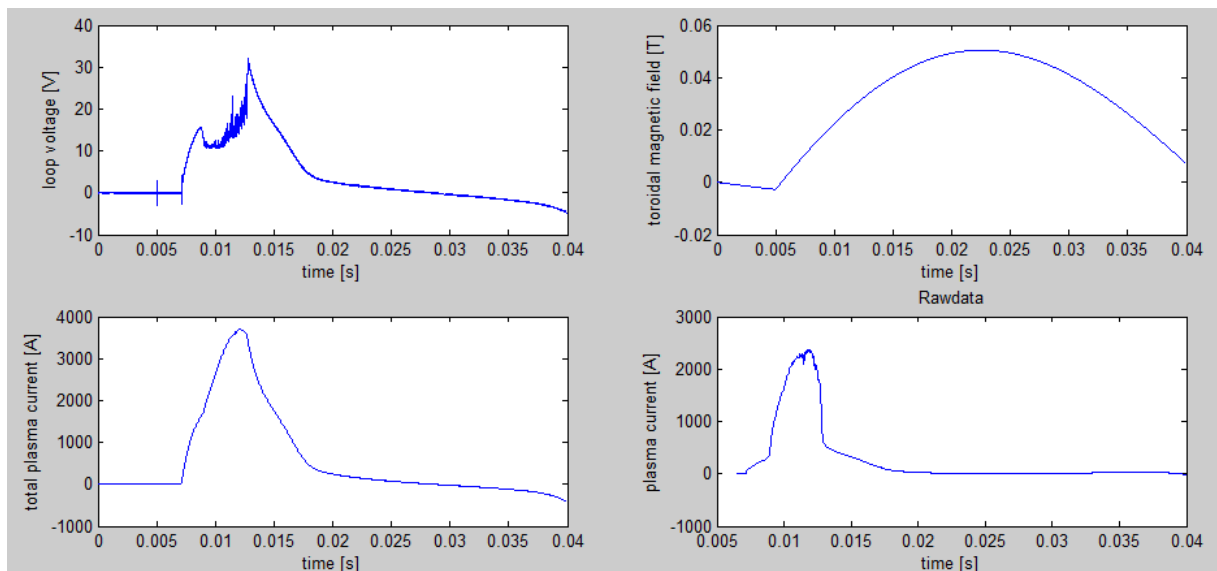


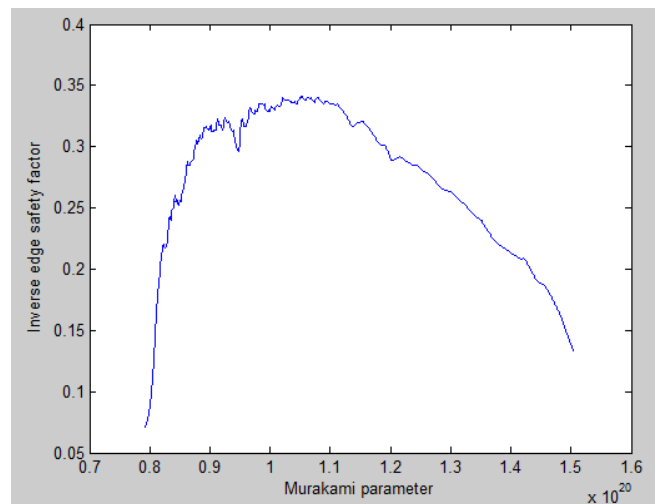
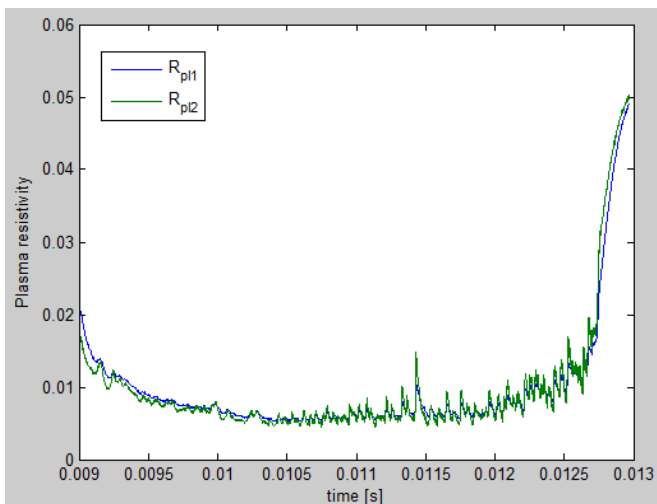
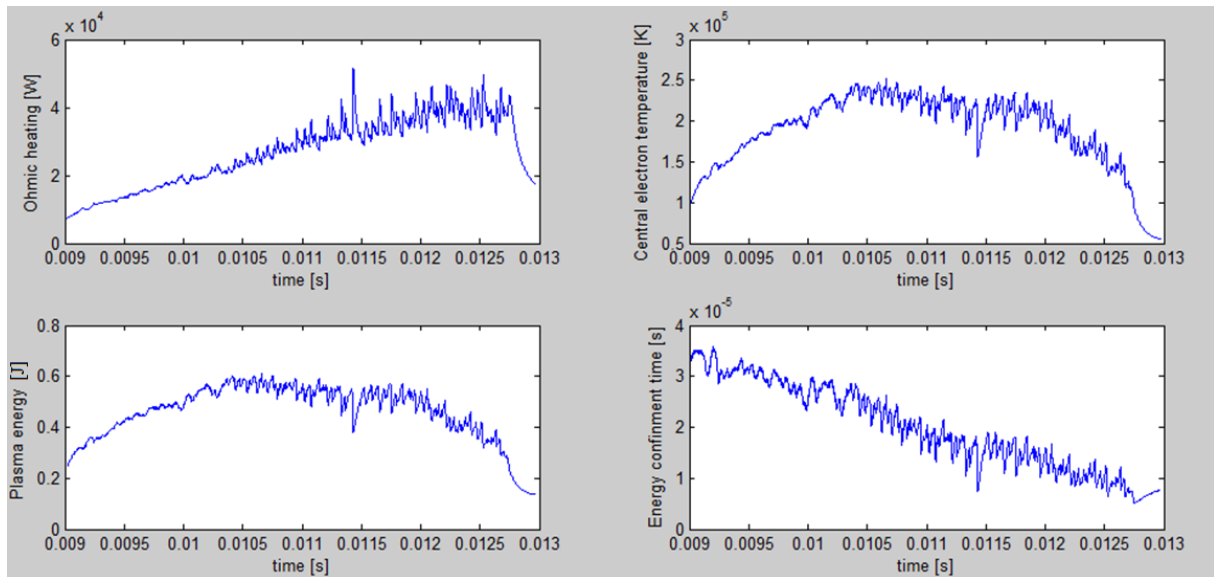
Shot number: 17355 was also interesting because of the smallest q value, so we plotted the time traces of the parameters:

Rawdata:



Calculated parameters:





VI, Appendix:

Skype log:

[15:02:53] Gergő Pokol: We are now in a conference call.

[15:03:45] NTI Hallgató: Hello Vojtech!

[15:04:43] Tokamak GOLEM: Hello. Regards from Prague, Welcome at the remote operation of the tokamak GOLEM. Enjoy it!

[15:07:50] NTI Hallgató: Thank you so much that we can do measurements of the tokamak.

[15:13:56] Tokamak GOLEM: You are welcome, so you can proceed to make discharges. The starting point is at the <http://golem.fjfi.cvut.cz/wiki/TrainingCourses/HUNTRAIC/14/index>

[15:14:49] Tokamak GOLEM: You can choose one control room, then go to Control room tab and make your discharges

[15:21:49] Tokamak GOLEM: Any problem??

[15:23:01] NTI Hallgató: No, we make our discharge parameters and we would like to do it. Can we start?

[15:23:24] Tokamak GOLEM: Yes, go on ..

[15:38:01] NTI Hallgató: We would like to do one more vacuum discharge, can we do it?

[15:42:50] Tokamak GOLEM: Yes, please ..

[15:43:43] Tokamak GOLEM: You can make your shots without asking us.

[15:44:56] Tokamak GOLEM: You have to check every discharge diagnostics if it appears OK, as expected. If not, stop submitting setups and notify us about problem ..

[15:46:20] NTI Hallgató: Okay, thank you, we do it.

[16:19:44] Tokamak GOLEM: Congratulation to your first plasma!

[16:20:54] NTI Hallgató: Thank you so much, it is amazing!

[16:21:43] Tokamak GOLEM: Have you seen the flash of the plasma at IP cameras?

[16:23:46] Tokamak GOLEM: Whe you see your results on the shot homepage, it is worth to refresh a page to let present the data from time consuming diagnostics

[16:24:15] Tokamak GOLEM: e.g. spectrometer as well as fast camera

[16:25:39] NTI Hallgató: We have seen the electron gun light just, we hope next time we can see the flash of the plasma.

[16:26:04] NTI Hallgató: ok, we check the homepage.

[16:29:15] NTI Hallgató: Wow, we have seen the flash of plasma!

[16:30:20] Tokamak GOLEM: Very good!

[16:49:29] NTI Hallgató: We have a question

[16:51:02] NTI Hallgató: What is the time delay between starting diagnostics and toroidal magnetic fild drive (trigger)?

[16:52:58] Tokamak GOLEM: 5 ms

[17:00:44] NTI Hallgató: According to results this time is cca. 5,5ms and it causes a little of problem. Can you give it us exact value?

[17:08:26] Tokamak GOLEM: I do not understand, be more specific, which results you mean?

[17:09:40] Tokamak GOLEM: OK I can see it, moment please

[17:18:18] Tokamak GOLEM: You are right! It is our problem and sorry for this. It cannot be repaired today. You have to live with it today.

[17:21:44] NTI Hallgató: We see it, thank you for your help.

[17:30:55] NTI Hallgató: We have some problem with a vacuum, can you do something?

[17:31:29] Tokamak GOLEM: You are right, moment

[17:33:00] Tokamak GOLEM: Try next shot please

[17:34:06] Tokamak GOLEM: Just a moment, we can try to fix the time delay problem. Could you please stop submitting setups?

[17:35:36] NTI Hallgató: Yes of course, we stop it, and wait with a next shot.

[17:35:48] Tokamak GOLEM: I have just stopped machine, please wait

[17:45:50] Tokamak GOLEM: Sorry we had an IT problem. So, we have just fixed 5 ms problem and you can continue making discharges.

[17:47:34] NTI Hallgató: Thanks, it is good. We continue the discharges.

[17:49:35] Tokamak GOLEM: The next discharge is yours

[17:54:26] NTI Hallgató: Thanks

[18:10:13] NTI Hallgató: Thank you for your help, the machine is working well, we have some more measurements, we hope that we do not find more problems.

[18:43:49] Tokamak GOLEM: Could you please tell us about your plans?

[18:45:33] Tokamak GOLEM: when you plan to finish?

[18:50:07] NTI Hallgató: we think, we can finish about 20 min.

[18:51:31] NTI Hallgató: we will do more some shots for a disruption. and after we are finishing.

[18:52:07] Tokamak GOLEM: OK, thanks

[19:12:48] NTI Hallgató: We are finishing.

We would like to say a huge thank you for this afternoon, it was awesome for us.

Thank you so much.

[19:13:47] Tokamak GOLEM: OK, it was nice to have you, looking forward to see the report. Best regards from Prague to you and Gergo. Good bye.

[19:14:20] NTI Hallgató: Have a nice evening. Good bye.

[19:14:24] Gergő Pokol: Thank you, Vojtech! Good bye!

[19:16:28] Tokamak GOLEM: Gergo, I will appreciate some teacher's feedback. It is important for me

...

[19:29:01] Gergő Pokol: Ok, I will certainly do it.