Measurements on GOLEM tokamak

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Introduction

The world needs more and more energy day after day, and tries to find something what could easily satisfy this huge demand. The thermonuclear fusion could be a possibility for mankind, but there is a long way ahead. Several experimental devices have been built, so they could improve their knowledge about the physical processes. The GOLEM is such device for academic purpose in CTU. Our student group had the task to measure some basic properties of the plasma state inside the GOLEM tokamak (Fig.1).
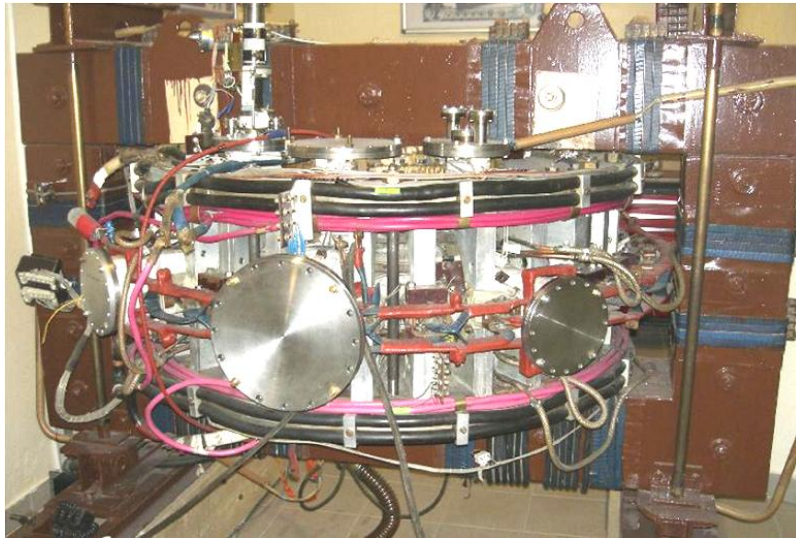

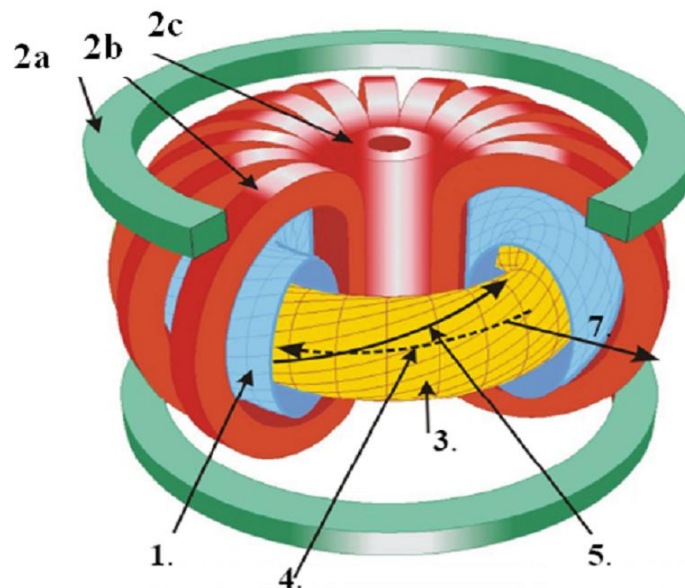Figure 1: Photo of the GOLEM tokamak.

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

Tokamak uses magnetic fields to confine the plasma as we can see on Figure 1. The transformer coil induces the toroidal plasma current, which causes twisting in the magnetic field lines stabilized by the additional coils. Nested magnetic surfaces compose the magnetic field, and on each surface one can define the safety factor (q) by the number of toroidal turns necessary for the magnetic field line to reach its original poloidal position. It can be approximated, when the tokamak has large aspect ratio as in GOLEM (A=4) by :

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

where R is the major radius, B_t (t) is the toroidal and B_p (r,t) is the poloidal magnetic field, and r is the radius of the surface.

The characteristic time of energy loss alias energy confinement time (τ_E) is an important property of the tokamak and it is from the equation:

$$P_{loss} = \frac{W_{pl}}{\tau_e}$$

where P_{loss} is the power lost and W_{pl} is the total plasma energy. Lawson criterion is a threshold for self-sustained thermonuclear fusion plasma burn at optimum temperature, and as a product of the plasma density (n) and energy confinement time (τ_E) should be greater than $10^{20} sm^{-3}$.

Our team operated on the GOLEM online at a given link by Dr. Vojtech Svoboda. Figure 3 shows the control panel, where we could set the initiating parameters for the current drive, the toroidal magnetic field, the time delay between them, the injected hydrogen gas pressure and we could decide whether or not want to preionization. The parameters were chosen according to the measurement tasks.
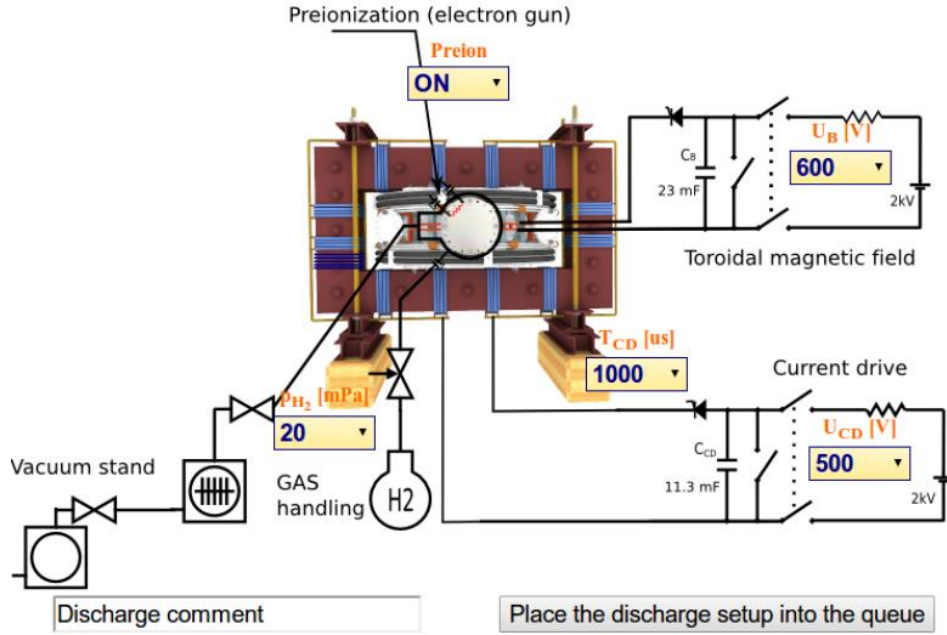
Figure 3: Remote control interface of GOLEM tokamak.

Measurements

First of all, the Tokamak is in Czech Republic. During the measurements, we were in contact with Dr. Vojtech Svoboda through Skype instant messaging who is the local support.

Firstly we calculated the main values from the signals. The main values were U_l (loop voltage), B_T (toroidal magnetic field) and I_{tot} (total current). We applied a correction for the DC bias. Because the sampling rate was 1MHz and the measurements started at 5ms so we needed to exclude 5000 samples from the beginning of the signal. Otherwise we needed to calibrate also our signals by the calibration factors. These calibration factors were given by the data collecting MATLAB file (GOLEM_get_data).

Determination of vacuum chamber parameters

For further calculation we need to determine the parameters of the vacuum chamber. We consider that the vacuum chamber has one resistance (R_{ch}) and one inductance (L_{ch}) in its circuit. We can use the next equation to illustrate the circuit:

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

To determine R_{ch} et L_{ch} we use up two different ways.

1. A simple method is the following: Just after switching on the toroidal electric field, the toroidal current is still close to zero ($I_{tot} \approx 0$), so $U_l \cong L_{ch} \frac{dI_{tot}}{dt}$, so L_{ch} can be

determined. On the other hand, at the flat top of the current curve $\frac{dI_{tot}}{dt} \cong 0$ equation (1) simplifies to so $U_l = R_{ch}I_{tot}(t)$ so R_{ch} can be estimated.

2. An other method: If we divide equation (1) by I_{tot} we can simplify the task to a 1D least squares linear fit, which can be easily implemented in MATLAB

We took 5 discharges in vacuum shot, when plasma wasn't formed.

Results:

	2nd way			1st way	
shot number	L_{ch} (10^{-7}H)	R_{ch} (mΩ)		L_{ch} (H)	R_{ch} (Ω)
12956	3,25	5,52		0,00225	0,05528
12957	0,85	6,12		0,0124	0,00629
12958	5,58	5,35		0,0032	0,1066
12959	-11,83	4,97		0,245	0,316
12960	5,34	5,37		0,021	0,11

Average	5,46	5,36	

Table 1: Chamber resistance and inductivity

The order of magnitude change very much in the first way that's why we kept the table that was made by the second way.

We think that the value with the yellow background is impossible because of the negative sign. Furthermore we consider that the best measures were the shot number 12958 and the shot number 12960 because int he case of shot number 12956 and 12957 we have a large dispersion of the values around zero while int he case of shot number 12958 and 12960 this dispersion much less juste a tiny loop. So we took the shot number 12958 and 12960 to determine an average value to L_{ch} et R_{ch} chamber parameters.

Shot number 12956

Shot number 12957

Shot number 12958
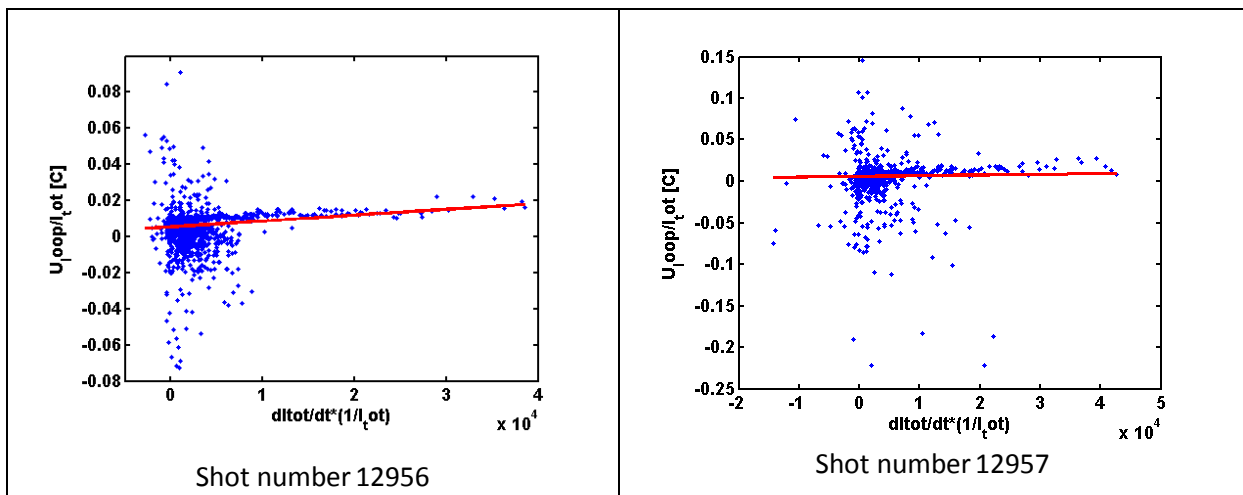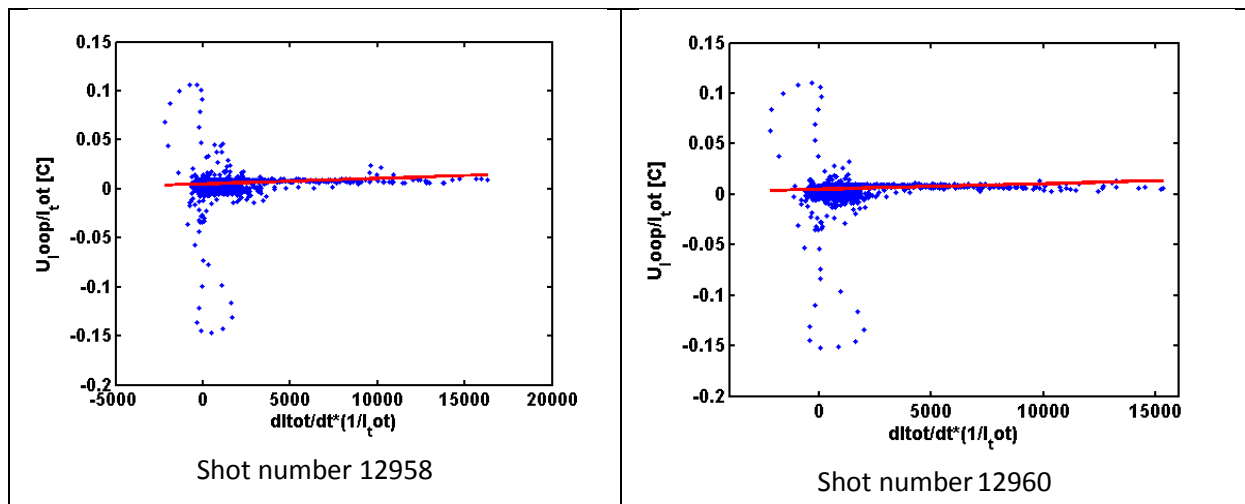
Shot number 12960

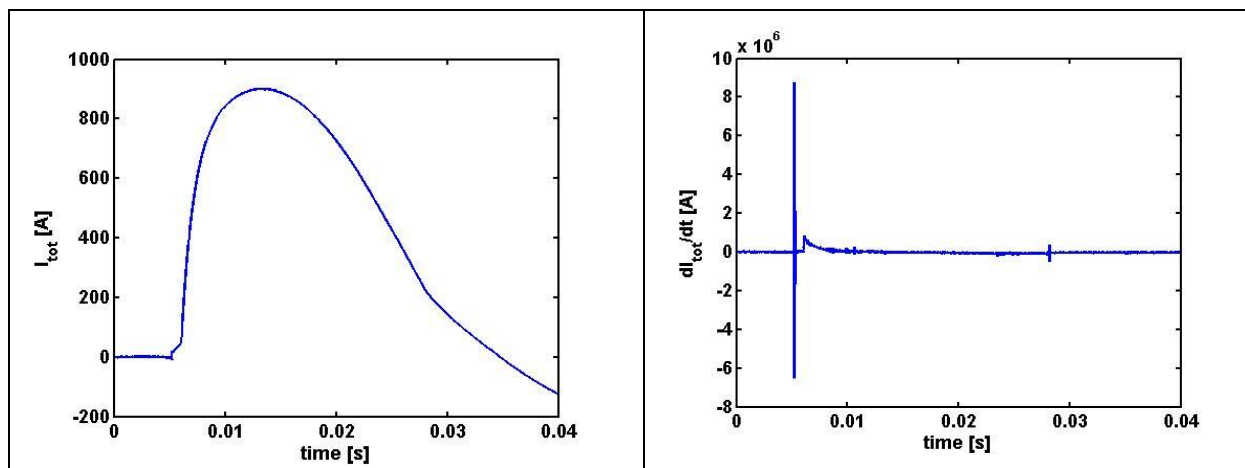The evolution of the Chamber current and Current time derivate time for the shot number 12958:

Figure 4. Evolution of the I_{tot} and its derivate (shot number 12958)

Plasma Breakdown

After the determination of the chamber parameters, we let H_2 gas into the chamber to promote the creation of the tokamak plasma. We could control pressure of the H_2 gas into the toroid. We know also that 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 (plasma breakdown)

We plot the p_{ch} against the maximum of the loop voltage spikes in the beginning of the discharges. We needed to enter the pressure when we launched an experiment. While the measurement gave us a value different from the entered value. So, after this, we used all the measured pressure values in the next. For the experiments we put on the ionisation.

Our aim was to vary the Loop Voltage (U_{cd}) and the pressure (pH_2) to have a figure where we can well distinguish the two regions (breakdown and non-breakdown). In consequence we get a line which shows the border of these two regions.

Our measurements:

| shot number	pH_2 [m.Pa]	pH_2 [m.Pa] measured	T_{cp} [μs]	U_{cd} [V]	U_e [V]	Pre-ion	Plasma
12961	6	5,4754	1000	400	600	ON	1
12962	12	11,3103	1000	400	600	ON	1
12963	18	17,8587	1000	400	600	ON	0
12964	18	17,4521	1000	300	600	ON	0
12965	12	11,4853	1000	300	600	ON	0
12966	12	11,4413	1000	450	600	ON	1
12967	12	17,5866	1000	450	600	ON	1
12968	18	17,4521	1000	500	600	ON	1
12969	24	24,0922	1000	450	600	ON	0
12970	24	24,0922	1000	500	600	ON	0
12971	6	5,2895	1000	300	600	ON	1
12972	6	5,3098	1000	350	600	ON	1
12973	12	11,3975	1000	350	600	ON	1
12974	18	17,5192	1000	350	600	ON	0
12975	24	24,0922	1000	550	600	ON	1
12976	6	5,0903	1000	250	600	ON	1
12977	12	11,3975	1000	250	600	ON	0
12978	6	4,9363	1000	200	600	ON	0
12979	6	4,9174	1000	150	600	ON	0
12980	12	11,4413	1000	350	600	OFF	0
12981	2	2,6003	1000	200	600	ON	0
12982	6	2,5903	1000	400	50	ON	0
12983	6	2,8512	1000	400	200	ON	0
12984	6	5,4754	1000	400	600	ON	1
12985	6	5,5176	1000	400	800	ON	1

Table 2. Breakdown experiments
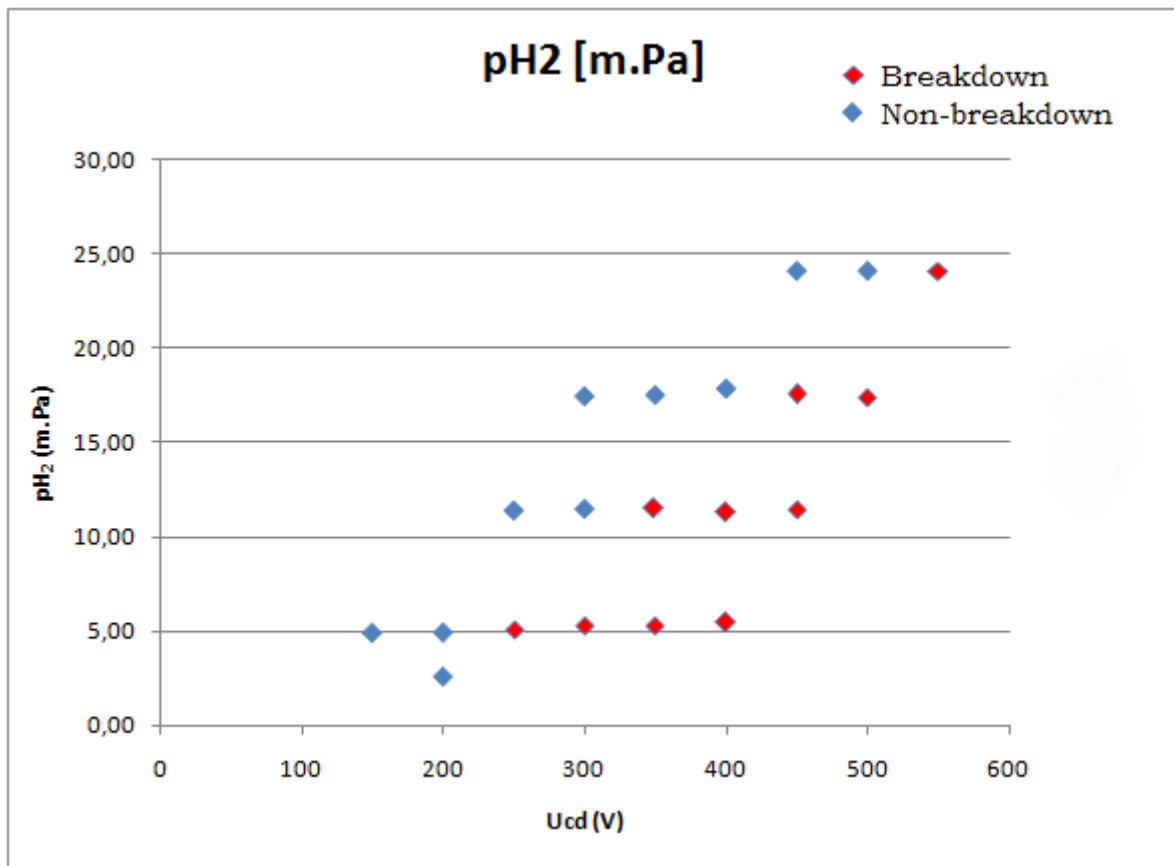
Figure 5. Breakdown dependency

We find a line which distinguish the two regions. We can deduce that if we have enough U_l (threshold - Loop Voltage) and relatively low pressure it depends on the magnitude of the Loop Voltage, then the plasma will occur.

In the end we tried to modify just the U_e (Toroidal magnetic field) on the same pressure and with same U_{loop}. We left the Loop Voltage on a high value (400V). Unfortunately the toroid had a great variation in the pression value even if we didn't vary the input pression. So we can not conclude credible laws from this measurements. We can add that if the U_{loop} and the U_e are high and the pressure is relatively low the plasma occurs.

Estimation of main plasma parameters

Due to the lack of time, we took only 10 measurements for this exercise instead of 25 discharges. During the analyse of these data, we noticed that in the last 3 measurements, there were no plasma and beyond the first 3 measurements the other measurements give strange curves. We can add that during the Skype conversation **Dr Svoboda** said that at [19:19:32] Tokamak GOLEM: „We have a strange noise, Hard to say now, where is the origin .." so we think that's why our last measurements were not good enough.

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Despite all of these errors we made all the analyses with these data. But we consider credible just the first 3 data so we show only them in the following parties. For our data we apply a filter to smooth the noises.

Plasma current

So far, we managed to determine the parameters (L_{ch}, R_{ch}) of the vacuum chamber. Now we establish some other parameters which are related to plasma. Fortunately the vacuum chamber and the plasma are modeled by LR circuits (Figure 6).
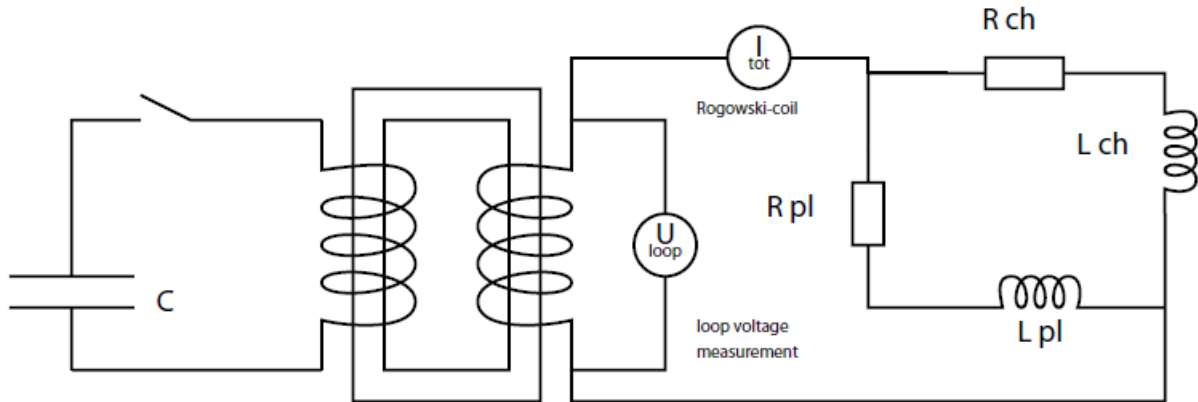

Figure 6. Model of the inductive current drive circuit

We can describe this circuits with these equations

$$U_l = R_{ch}I_{ch}(t) + L_{ch}\frac{dI_{ch}}{dt} \qquad (2)$$

$$U_l = R_{pl}I_{pl}(t) + L_{pl}\frac{dI_{pl}}{dt} \qquad (3)$$

$$I_{tot}(t) = I_{ch}(t) + I_{pl}(t) \qquad (4)$$

To get I_{ch} we use equation (2), in this case we assume that $L_{ch} \cong 0$ (it's an approximation). This operation is automatized in MATLAB. After that according to equation (4) we can easily calculate $I_{pl}(t)$. We define a threshold for plasma current which determine the beginning and the end of plasma discharge, it means when $I_{pl}(t)$ reaches 150 A we consider that time as the beginning and when $I_{pl}(t)$ oversteps the maximum and reaches 150 A is the end of plasma discharge.
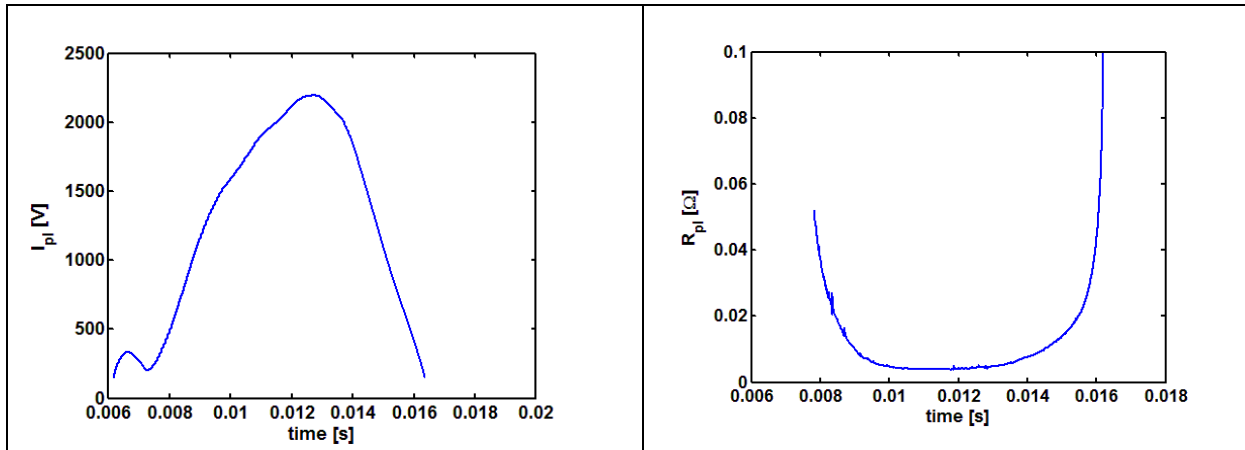
Figure 7. . Evolution of the I_{pl} and of the R_{pl} during the plasma (shot number 12988)

Plasma heating power

It's relatively easy to determine the plasma heating power. In the GOLEM Tokamak the only heating mecanism of the plasma is ohmic heating resulting from current flowing (I_{pl}) in a conductor with finite resistivity (R_{pl}).

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

In this expression $R_{pl}(t)$ is the plasma resistance and $I_{pl}(t)$ the plasma current.

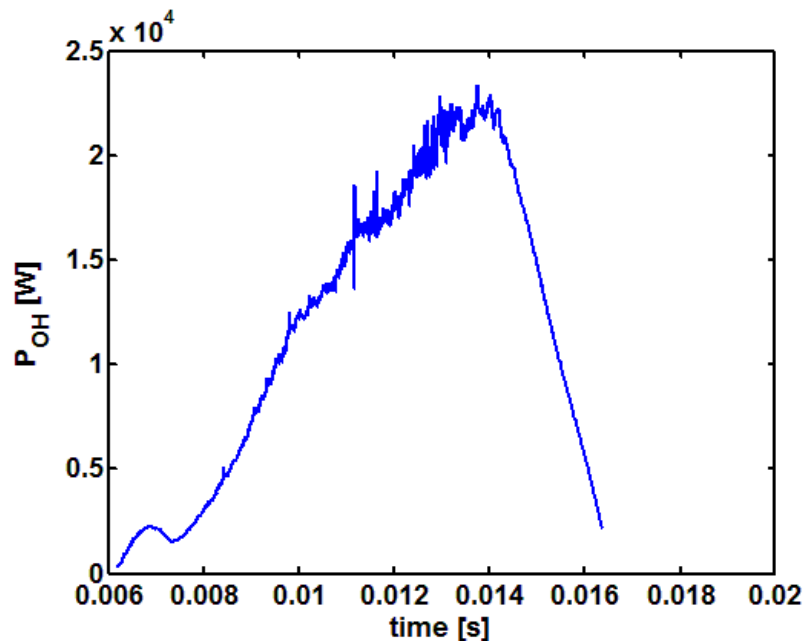Among the first three shots we reached the biggest value of P and the value was 23351W.

Figure 8. . Evolution of the P_{OH} (shot number 12987)

Here P_{oh} is not linearly propotional to current that's why the biggest current cause the biggest performance.

Central electron temperature

We used an approximation, the Spitzer's resistivity formula to calculate the Central electron temperature:

$$T_{e0}(t) = \left(\frac{R_0}{a^2} \frac{8Z_{eff}}{1544} \frac{1}{R_{pl}(t)} \right)^{2/3} \qquad (6)$$

In this formula R_0 is the major radius of the toroid (in meter), Z_{eff} is the effective charge number $Z_{eff} \approx 2.5$, a is radial position of the limiter (in meter) and at last but not at least R_{pl} is the resistivity of the plasma (Ω), it was calculated above. This formula give T_{e0} in electronvolts.

In our case R_0=0.4 m and a=0.085 m .This method increase the uncertainty of the measurements because there are some factors which are already estimated. Actually we accumulate the uncertainty.

We chose the shot number 12986.In this case the maximum of the data is at 43,86 eV. This value correspond to 508776 K as electron temperature .
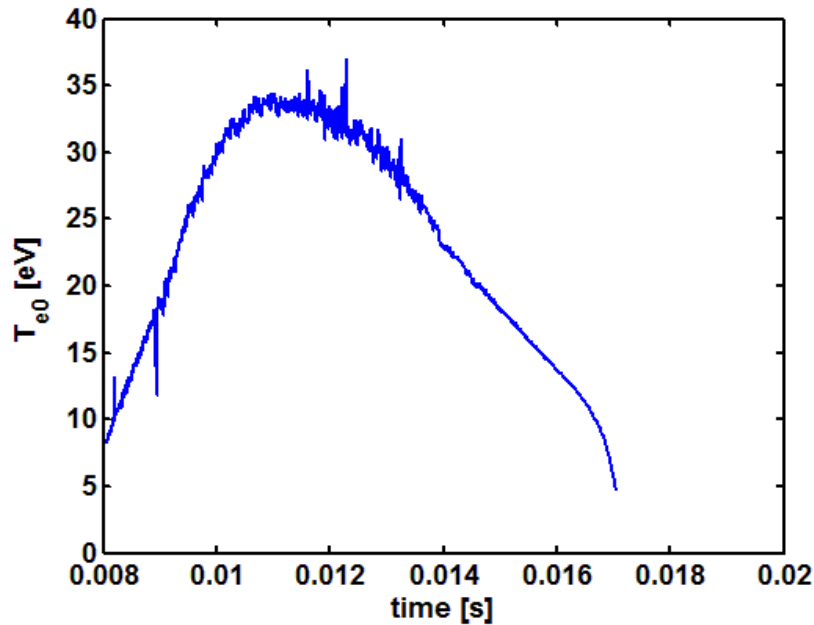

Figure 9. Evolution of T_{e0} (Shot number 12986)

The only parameter that changes from measure to measure is $R_{pl}(t)$ and in additonal this number is in the denominator so the smallest $R_{pl}(t)$ causes the greatest T_{e0}

Electron density

As the GOLEM tokamak doesn't have any density measurements and for further calculations we need to the electron density we will estimate it. We suppose that the electron density is constant in the whole place of the tokamak. We know that this is a rough estimation but we need to this condition to have an estimation at least.

The formula:

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

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where p_{ch} is the pressure of the chamber (m.Pa), T_{ch} is the temperature of the room and k_B is the Boltzmann constant.

Plasma energy

The total energy content can be simply calculated from the temperature, density and volume (V),based on the ideal gas law.

The formula follows:

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

where V is the volume of the tokamak $\quad V = 2\pi^2 \cdot R \cdot r^2$

r=a; and R=R$_0$ in our case, and the other parameters are known already.

The greatest energy was reached by the 12988 shot number. The energy maximum was 0,803162 J
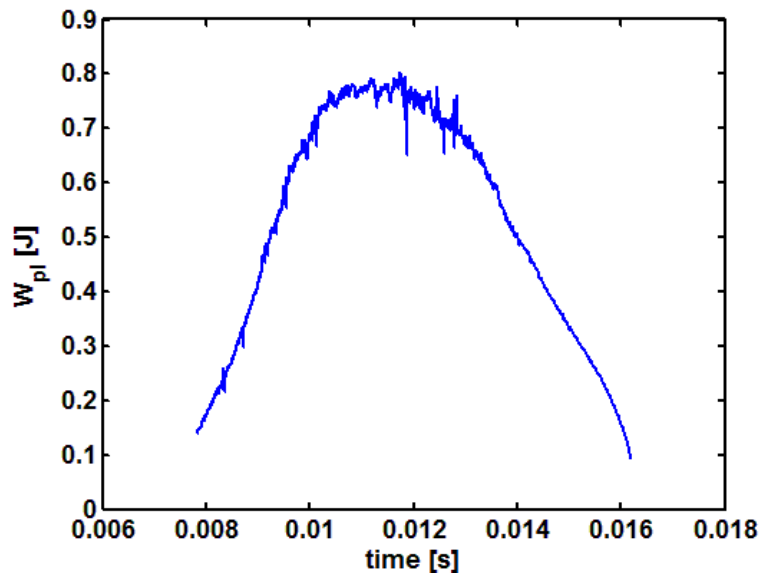
Figure 10. Evolution of W$_{pl}$ (Shot number 12988)

Energy confinement time

To estimate the energy confinement time, firstly we need to calculate the loss power. The loss power is given by the formula

$$P_{loss}(t) = P_{OH}(t) - \frac{dW_{pl}}{dt}$$

To establish the energy confinement time we apply the formula follows:

$$\tau_e = \frac{W_{pl}}{P_{loss}}$$

We chose the shot number 12986 to show the comportement of this function.
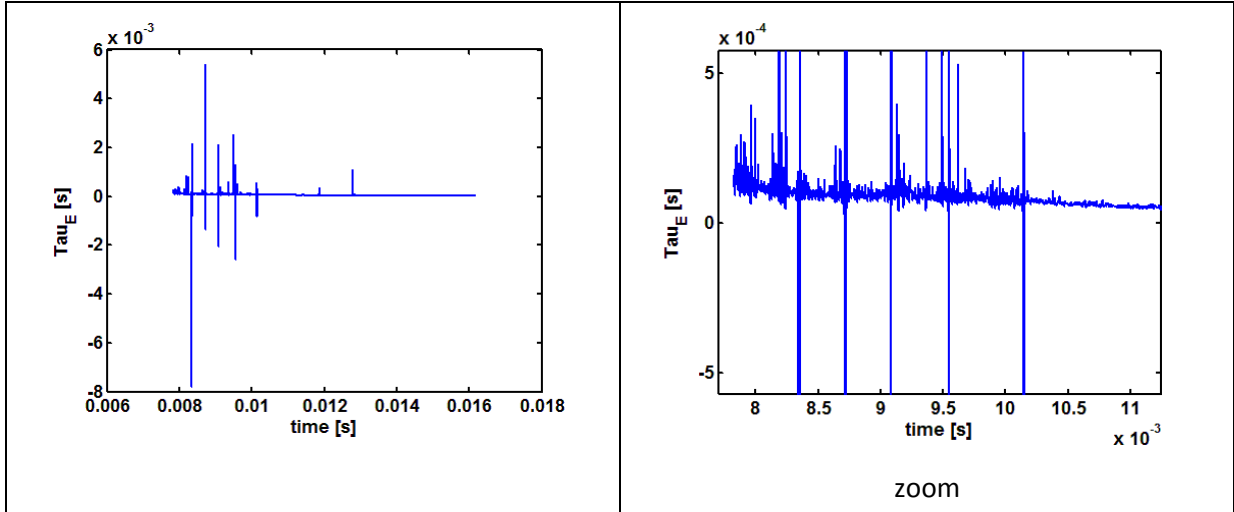
Figure 11. Evolution of Tau$_E$ (Shot number 12988)

q=2 distributions

Our task is to creat a plasma in which the safety factor equal to 2, in this case a plasma instability resonant to the q = 2 rational surface destabilizes, and a discharge terminating disruption occurs.

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

We obtained from the following expression:

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

In our case we didn't have time to try to approch q = 2 so we take one of our measurements where we consider the q is the smallest. q = 7 for shot number 12988

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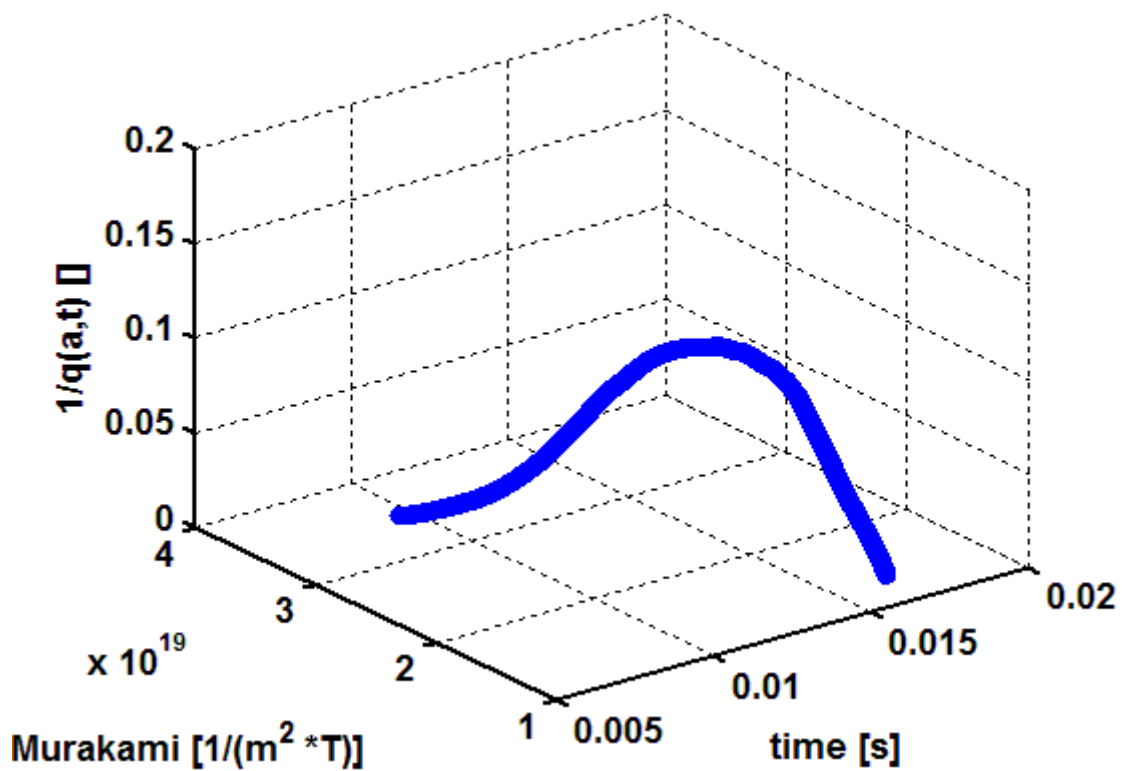
Figure 9. q = 7 distributions (shot number 12988)

Conclusion

In the beginning, we managed to characterize our equipement.

In the second part of the laboratory we managed to have some really good results, and we managed to have a good distinction between the region where we can creat plasma and where we can not creat plasma.

In the third part, we were in lack of time, that's why we couldn't make many measurements. In spite of this, we have some data which show some good correspondences to our expectations.

Appendix

Summary table

shot number	I_{pl} max (A)	R_{pl} max (Ω)	P_{OH} max (W)	T_{eo} max (eV)	n_{aver}	W_{pl} (J)	E confinement (s)	q_{min}
12961	1266,46	0,0722	8878,85	29,72	2,65E+18	0,331226	5,42E-05	0,0000
12962	1501,35	0,0952	11138,74	1916850,47	5,46E+18	44124,72	0,003362874	7,6568
12966	1253,26	0,0996	8759,00	1,00E+14	5,53E+18	2,33E+12	3,141137403	0,1855
12967	1118,07	0,0935	7302,05	8,95E+13	8,50E+18	3,2E+12	5,091750714	0,0621
12968	1256,92	0,1135	8775,87	1543215,38	8,43E+18	54814,29	0,000212952	0,1208
12971	1110,07	0,1902	5864,37	32,24	2,56E+18	0,347031	9,24E-05	-0,0126
12972	1331,49	0,0689	8367,22	34,96	2,57E+18	0,377839	5,80E-05	8,8648
12973	910,16	0,1373	6331,52	12,86E+5	5,51E+18	29740,53	0,000242173	7,1488
12975	1918,08	0,0754	15542,65	3289,53	1,16E+19	161,2985	0,000267999	0,0131
12976	938,24	0,0278	4391,36	34,49	2,46E+18	0,357351	0,000136179	0,0901
12984	1448,12	0,0859	10198,50	31,94	2,65E+18	0,355933	5,14E-05	10,8052
12985	1560,42	0,0315	11070,14	39,34	2,67E+18	0,441816	1,40E-05	6,6374
12986	1497,31	0,0722	10845,356	36,96	2,65E+18	0,411851	5,46E-05	9,96037
12987	2195,22	0,0952	23351,97608	33,94	2,66E+18	0,379723	2,68E-05	7,06431
12988	2125,57	0,0996	22688,60376	33,19	5,74E+18	0,803162	5,66E-05	7,00295
12989	2375,82	0,0654	30561,99267	118,24	2,65E+18	1,317653	3,03E-05	7,72319
12990	2085,83	0,0795	21688,36541	36,02	1,58E+18	0,239992	1,52E-05	7,73474
12991	1339,20	0,0433	69909,25696	7076,21	3,50E+18	104,3578	0,000837711	5,69029
12992	760,56	0,0384	4292,50713	2327,14	2,57E+18	25,24562	0,003202582	6,71892
12993	408,92	0,0466	4952,720591	1117,40	1,25E+18	5,890852	5,72E-05	14,0565
12994	706,18	0,0916	10623,30751	3725,80	4,48E+18	70,2476	0,056651519	9,69338
12995	831,46	0,0822	4773,271724	6420,85	4,58E+18	123,8817	0,001029171	7,8157

Table of the resultats

Skype log 20.09.2013

[14:55:35] *** Gergő Pokol meghívta NTI Hallgató-t a konferenciára ***

[14:57:02] Gergő Pokol: Control room:

http://golem.fjfi.cvut.cz/roperation/tasks/TrainingCourses/HUNTRAIC/0913BUTE/Level_I/index.php

Session archive:

http://golem.fjfi.cvut.cz/utils/session_list?session_list=190913:TrainingCourses/HUNTRAIC

[14:57:04] NTI Hallgató: hy Vojtech! Here is NTI hallgto

[14:58:34] Tokamak GOLEM: Sorry, I have a connection problem

[14:59:32] Gergő Pokol: Vojtech, are you here?

[14:59:40] Gergő Pokol:

http://golem.fjfi.cvut.cz/roperation/tasks/TrainingCourses/HUNTRAIC/0913BUTE/Level_I/index.php does not open

[15:00:17] Gergő Pokol: Link "Level I (Basic: Gas management+Toroidal magnetic field+Current drive operation)" seems to point at itself

[15:00:53] Tokamak GOLEM: Gergo, Ihad a connection problems, sorry

[15:01:43] Tokamak GOLEM: Gergo, do you have still problems with control room? It works for us ..

[15:02:04] Tokamak GOLEM: Please, click on control room button!

[15:03:10] Tokamak GOLEM: Are you OK?

[15:03:36] Gergő Pokol: Thanks, it os ok.

[15:03:45] Tokamak GOLEM: Fine

[15:24:36] NTI Hallgató: So, can we start our first measuring?

[15:24:55] Tokamak GOLEM: Yes, go on.

[15:29:49] Tokamak GOLEM: Maybe, if you want vacuum shot, switch off preionization ... This can help ..

[15:39:19] NTI Hallgató: We turned off the preionization, can we shot again?

[15:41:21] Tokamak GOLEM: Yes, it is not necessary to ask us for approval for every shot, go ahead

[15:41:48] NTI Hallgató: Noted

[16:15:13] NTI Hallgató: unfortunately we don't know, why there is plazma... any guess?

[16:16:34] Tokamak GOLEM: In #12960 there is not a plasma

[16:21:33] Gergő Pokol: We get the wrong shot number on the Live screen, and it seems to print the data for that shot number at the end of the shot. We have looked at the results in the Results screen, and vacuum shots seem to be ok.

[16:29:39] Tokamak GOLEM: I am not sure if I understand well, but ... what about to use the session log http://golem.fjfi.cvut.cz/utils/session_list?session_list=190913:TrainingCourses/HUNTRAIC ?

[16:30:39] Gergő Pokol: session log looks ok, we are using that now.

[16:35:18] Tokamak GOLEM: Congratulations, very nice plasma

[16:55:14] Gergő Pokol: It is no problem for the currelt lab, just for debugging info: on the Live screen we get the message: "Now doing... Shot No: 12687, Job for BUTE" After the shot is executed, the page visualizes data for shot 12686. The timing of the messages is correct, just the shot numbers are false.

[16:59:41] Tokamak GOLEM: Possibly you are using some older web browser that somehow fetches old data. We are sorry for the trouble, please use the Results page.

[17:36:52] Tokamak GOLEM: Just for the record, 20 mPa might be quite a lot with the current state of the chamber. We usually operate around 10 mPa.

[17:38:38] NTI Hallgató: is this a safety limit?

[17:39:44] Tokamak GOLEM: no, just the values we usually use and appear to work if you want plasma

[17:42:26] NTI Hallgató: we are trying to find the borderline between plasma and non-plasma. with normal operation we will stick to the limit you said.

[17:43:49] Tokamak GOLEM: ok, good, we just didn't want you to get "lost"

[17:44:03] NTI Hallgató: noted

[18:34:24] Tokamak GOLEM: what are you plans for the upcoming hours ?

[18:36:37] Gergő Pokol: we have cut on the lenght of the exercises, so we would like to have about 10 more shots. Does it work with you?

[18:37:21] Tokamak GOLEM: would that be the last 10 for today ?

[18:37:49] Gergő Pokol: yes

[18:53:39] Tokamak GOLEM: Gergo please, can you make a photo of students working remotely with tokamak GOLEM? Thank you in advance .

[18:54:14] Gergő Pokol: sure

[19:17:18] *** Gergő Pokol ezt a fájlt küldte: IMG_20130919_185651.jpg ***

[19:19:32] Tokamak GOLEM: Thank you for the photo. We have a strange noise, Hard to say now, where is the origin ..

[19:19:53] Gergő Pokol: We have finished for now, thanks.

[19:20:20] Gergő Pokol: Also, the last results seemed a bit strange.

[19:21:20] Tokamak GOLEM: So Good bye to Budapest, I hope it was usefull. Best regards.

[19:22:35] NTI Hallgató: Good Bye! and thanks a lot for the GOLEM :)

MATLAB code :

```matlab
function [Lch,Rch]=get_RCH_and_LCH(shot_nr)
% function to get Lch et Rch with two methods
[LA,rawd]=get_UBI(shot_nr);
Y=LA(:,2)./LA(:,4); %Ul/Itot
Y = GOLEM_cut_data(Y, LA(:,1), 0.0055, 0.03); %  1st method
Y_Lch = GOLEM_cut_data(LA(:,2), LA(:,1), 0.0053, 0.006);%Ul_Lch 2nd method
[ertek,hely]= max(LA(:,2));%Ul_Lch
%plot(LA(:,1),Y);


der_prime=GOLEM_diff(LA(:,4),LA(:,1)); %dItot/dt
der=der_prime';
X=der./LA(:,4); %(dItot/dt)/Itot
X = GOLEM_cut_data(X, LA(:,1), 0.0055, 0.03); % 1st method
X_Lch = GOLEM_cut_data(der_prime', LA(:,1), 0.0053, 0.006);% 2nd method
figure
plot(X,Y,'b.') % 1st method
xlabel('dItot/dt*(1/I_tot)')
ylabel('U_loop/I_tot [C]')
hold on
pol=polyfit(X,Y,1);  % determination of constants with 1st method
f = polyval(pol,X);
plot(X,f,'r-')
pol_Lch=polyfit(X_Lch,Y_Lch,0);
pol_Rch=LA(hely,2)/LA(hely,4);
```

```matlab
Rch=pol(1);
Lch=pol(2);

figure
plot(LA(:,1),LA(:,4))
xlabel('time [s]');
ylabel('I_t_o_t [A]')
dI_t=GOLEM_diff(LA(:,4),LA(:,1));% dItot/dt
figure
plot(LA(:,1),dI_t)
xlabel('time [s]');
ylabel('dI_t_o_t/dt [A]')
end


%    UBI(:,1)=time;% time
%    UBI(:,2)=U_l_cal;%Uloop
%    UBI(:,3)=Bt_calib;%Bt
%    UBI(:,4)=It_C;%Itot


%-------------------------------------------------------------------




%Plasma Current
for shot_nr=12988:12988
[UBI,rawdata]=get_UBI(shot_nr); %get data
I_ch = GOLEM_chamber_current(UBI(:,1), UBI(:,4),  UBI(:,2), 0.00536,
5.46*10e-7);
figure
I_pl=UBI(:,4)-I_ch;
subplot(3,1,1)
plot(UBI(:,1),I_pl);
hossz=length(I_pl);
[I_pl_glo_max,I_pl_glo_max_hely]=max(I_pl); %searching of the maximum value
of Iplasma
[sorszam_elol]=max(find((I_pl(1:I_pl_glo_max_hely))<150))% from 150 A we
consider  the appearance of plasma
[sorszam_hatul]=I_pl_glo_max_hely+(min(find((I_pl((I_pl_glo_max_hely+1):hos
sz))<150))) % above 150 A the plasma disappear

if (isscalar(sorszam_hatul)==0)% if there is a strange curve we take the
maximum value
    sorszam_hatul=I_pl_glo_max_hely;
end

I_pl_cut =
GOLEM_cut_data(I_pl,UBI(:,1),UBI(sorszam_elol,1),UBI(sorszam_hatul,1))
[ertek_I_pl_max,hely_I_pl_max]=max(I_pl_cut); % calculation of maximum
value
ertek_I_pl_max

A(i,1)=abs(ertek_I_pl_max);% we creat a matrix to save the data
R_pl=(UBI(sorszam_elol:sorszam_hatul,2)./I_pl_cut); % calculation of
Rplasma
[ertek_R_pl_max,hely_R_pl_max]=max(R_pl)
A(i,2)=abs(ertek_R_pl_max);
```

```matlab
figure %plotting of Iplasma et Rplasma
plot(UBI(sorszam_elol:sorszam_hatul,1),I_pl_cut)
xlabel('time [s]')
ylabel('I_p_l [V]')
figure
plot(UBI(sorszam_elol:sorszam_hatul,1),R_pl)
xlabel('time [s]')
ylabel('R_p_l [\Omega]')

%Plasma heating
P_OH=R_pl.*((I_pl_cut).^2);% calculation of Poh for every time
[ertek_maxp,hely_maxp]=max(P_OH);
plot(UBI(sorszam_elol:sorszam_hatul,1),P_OH)
xlabel('time [s]')
ylabel('P_O_H [W]')
P_OH_max=ertek_maxp;
A(i,3)=abs(ertek_maxp);
I_pl_max=I_pl_cut(hely_maxp);
R_pl_max=R_pl(hely_maxp);

%central electron temperature
R0=0.4;
Zeff=2.5;
a=0.085;
r0=0.1;
Teo=((R0*8*Zeff/(a*a*1544))^(2/3))*1./((R_pl).^(2/3));% calculation of Teo
for every time
figure
plot(UBI(sorszam_elol:sorszam_hatul,1),Teo)
xlabel('time [s]')
ylabel('T_e_0 [eV]')
[ertek_maxT,hely_maxT]=max(Teo);
Teo_max=abs(ertek_maxT);
A(i,4)=Teo_max;

%Electron density
V=pi*r0*r0*2*pi*R0; % volume of toroid
kB=1.380*1e-23;
n_aver=((2*rawdata.pressure*1e-3)/rawdata.T_ch/kB); % density
A(i,5)=abs(n_aver);


%Plasma energy
% 1K = 8.621E-5 eV ratio between K et eV
W_pl=V*n_aver*kB*Teo/(3*8.621E-5);
figure
plot(UBI(sorszam_elol:sorszam_hatul,1),W_pl)
xlabel('time [s]')
ylabel('W_p_l [J]')
[ertek_max_W_pl,hely_max_W_pl]=max(W_pl);
A(i,6)=abs(ertek_max_W_pl);

%Energy confinement
dWpl_dt=GOLEM_diff(W_pl,UBI(sorszam_elol:sorszam_hatul,1));
P_loss=((P_OH)-(dWpl_dt'));
Tau_E=W_pl./P_loss;
figure
plot(UBI(sorszam_elol:sorszam_hatul,1),Tau_E)
xlabel('time [s]')
ylabel('Tau_E [s]')
```

```matlab
[Tau_E_max_ertek]=mean(Tau_E);
A(i,7)=Tau_E_max_ertek;


% q distributions
mu0=4*pi*1e-7;
Bt =
GOLEM_cut_data(UBI(:,3),UBI(:,1),UBI(sorszam_elol,1),UBI(sorszam_hatul,1));
q=(a^2*2*Bt*pi/(R0*mu0)./I_pl_cut);

figure
plot(UBI(sorszam_elol:sorszam_hatul,1),q)
xlabel('time [s]')
ylabel('q []')
[value,location]=min(q);
A(i,8)=value;

%Hugill diagram
g=1./q;
murakami=n_aver*R0./Bt;
A(i,9)=t(i);
i=i+1;

figure;
scatter3(UBI(sorszam_elol:sorszam_hatul,1),murakami,g);
xlabel('time [s]');
ylabel('Murakami [1/(m^2 *T)]');
zlabel('1/q(a,t) []');
end
```