MŰEGYETEM 1782

Budapest University of Technology and Economics

Measurement logbook
Measurements on the GOLEM tokamak

Alexander Šafár
NSN6EA

András Szabolcs Ványi
NYCQ3U

Supervisor: Dr. Gergő Pokol
GOLEM Supervisor: Dr. Vojech Svoboda
Date of measurement: 9. 11. 2017.

Abstract

During the measurement program we made contact with the Faculty of Physical and Nuclear Engineering of the Czech Technical University, then via remote control we operated the GOLEM tokamak under the supervision of the Czech colleagues and our local professor.

1 Introduction

The theoretical description of thermonuclear fusion started as late as the 1920s. In 1920 using Einstein's discoveries and Aston's measurements Eddington proposed a theory which described the stars' energy production as the fusion of large amounts of small nucleis. In 1928 Gamow introduced quantum tunneling as a solution to alpha decay, later this theory proved to be the base of describing nuclear reactions in stars. In 1932 Mark Oliphant made the first direct demonstration of fusion in his laboratory when accelerated hydrogen-2 at various targets and found helium-3 and hydrogen-3 isotopes afterwhile [1].

Since then we described the precise reactions taking place in the stars and we also made advances in plasma physics as according to our current knowledge thermonuclear fusion can only take place amid so high temperature that matter is in plasma state. In 1952 mankind unleashed the power of fusion in the form of the hydrogen bomb. The huge amount of energy dissipated during the process made scientists wonder whether they could use this energy in a peaceful way as a primary energy source. The main difficulty proved to be sustaining the stability of the plasma before it breaks down. To do so in the early 1950s soviet scientists Sakharov and Tamm introduced the tokamak concept, a type of magnetic confinement fusion device.

Tokamak (toroidalnaya kamera i magnitnaya katushka – toroidal chamber with magnetic coils) is a toroidal design. The confining magnetic field is the result of two components: on the one hand circle shaped field lines (B_t) generated by the external coils are passing through round the torus while on the other hand there is a poloidal field (B_p) generated by the plasma current (I_{pl}) which is introduced by the transformer coil. The superposition of the two components is a field helically winding around the torus following embedded surfaces, called magnetic surfaces. A tokamak illustration can be seen in Figure 1.

In this paragraph we are going to introduce a few quantities and formulas usually used to describe tokamaks. The helical structure is often characterized by the so called *safety factor* (q) which gives the number of toroidal turns necessary for a given magnetic field line to reach its original poloidal position. Let R be the major, r_0 the minor radius of the torus. On large aspect ratio circular tokamaks (where $R \gg r_0$) the safety factor can be approximated:

$$q(r,t) = \frac{r_0}{R}\frac{B_t(t)}{B_p(r,t)}\,.$$

The energy loss of a tokamak is best described by the so called energy confinement time:

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

where W_{pl} is the total energy of the plasma while P_{loss} is the lost power. The threshold for self-sustained thermonuclear fusion plasma burn at optimum temperature is described by the Lawson criterion (published in 1957):

$$n\tau_E > 10^{20} \text{ sm}^{-3} \, ,$$

where n is the density of the plasma ($[n] = \text{m}^{-3}$).

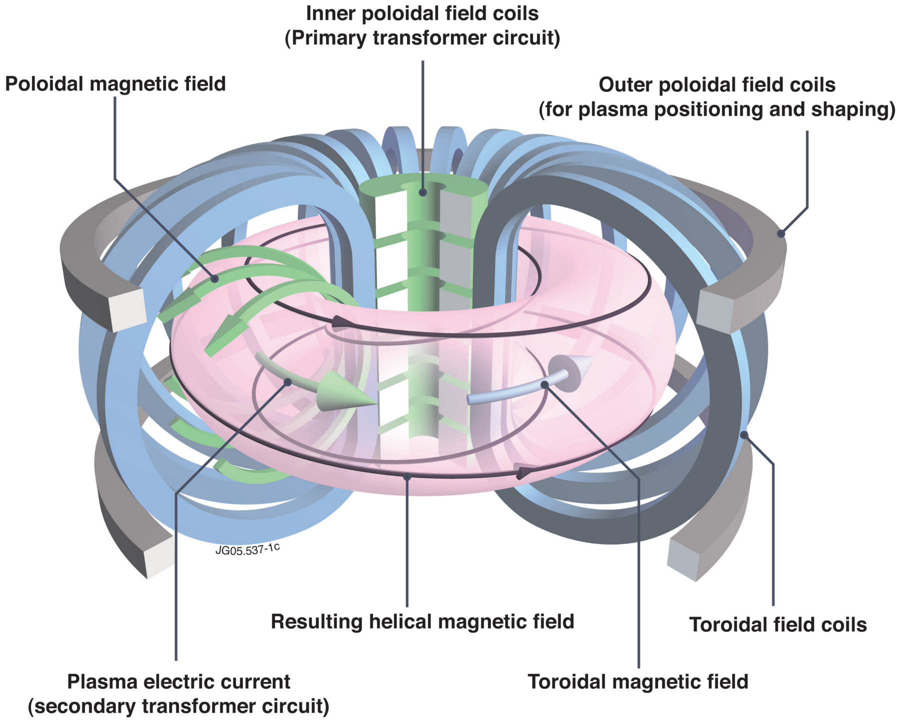

Figure 1: Tokamak with its magnetic fields and coils [2]

1.1 GOLEM

GOLEM (shown in Figure 2) is a large aspect ratio circular tokamak, based in Prague, constructed in the Soviet Union. The tokamak underwent several modifications and modernizations since its construction. Since 2007, it is operating at the Faculty of Physical and Nuclear Engineering of the Czech Technical University. It can be fully operated remotely which capability serves educational purposes.

Technical parameters and details:

- The major radius at the magnetic axis: $R_0 = 0.4$ m;
- the minor radius: $r_0 = 0.1$ m;
- the radial position of the limiter: $a = 0.086$ m;
- the toroidal magnetic field can be set through the voltage of the toroidal field capacitor bank, its range: 400–1400 V;

- the toroidal electric field can be set through the capacitor bank for the current drive, its range: 100–600 V;
- a time delay can be set up between the triggers of the toroidal magnetic field and the current drive, its range: 0–20000 μs;
- the type of gas and its pressure can be set, pressure range: 0–100 mPa, materials: hydrogen and helium;
- a preionizator (electron gun) can be turned on or off according to wishes of the user.

The built in sensors measure the followings:

- Time resolved loop voltage (U_t);
- time resolved total toroidal current by Rogowski coil (I_t);
- time resolved toroidal magnetic field by coil measurement (B_t can be obtained by $\oint U_l \mathrm{d}t = B_t$);
- time resolved plasma radiation by photodiode;
- the pressure of the vacuum chamber (p_{ch});
- the temperature of the vacuum chamber (T_{ch}).

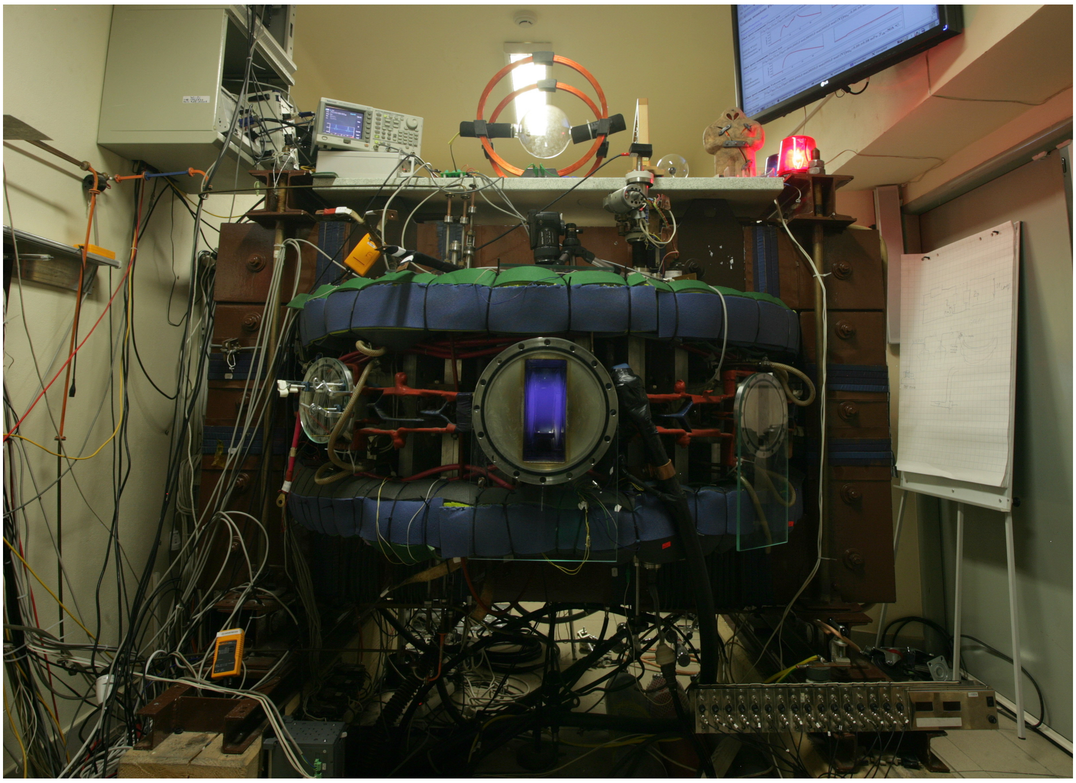

Figure 2: Recent photo of the GOLEM tokamak [3]

2 Measurement procedure and results

At 15:02 we made contact with the Czech colleagues and at 15:30 we were granted with the permission to control the tokamak remotely. We started the actual measurements at 15:44 and finished at 18:39. During our measurement session a local Czech student have made a few discharges, too, but we made sure that our results would not get mixed with his work. In the rest of this section we specified the tasks we got and published our results.

For evaluation we received two packages of functions. The first contained basic functions such as data collector, offset corrector, cropper, integrator and differentiator algorithms. Meanwhile the second package consisted of algorithms which are calculating the physical parameters we actually need. Table 1 contains the used and slightly modified functions and their tasks.

Function name	**Input parameters**	**Description**
GOLEM_get_data	shot number	Load the raw data to Matlab.
GOLEM_get_rawdata	shot number	Plots the time varying raw data.
GOLEM_offset_correction	raw data, time vector, start and end time	Transforms raw data into offset corrected data.
GOLEM_cut_data	raw data, time vector, start time, end time	Cuts irrelevant starting and ending time ranges.
GOLEM_integrate	time vector, data	Integrates the given data.
GOLEM_diff	x data, y data	Calculates the $\frac{\mathrm{d}x}{\mathrm{d}y}$ derivative.
GOLEM_chamber_current	I_t, U_l, R_{ch}, L_{ch}	Calculates the chamber current.
GOLEM_M_chamber_parameters	shot number	Calculates the chamber resistance and inductivity.
GOLEM_M_breakdown	shot number	Plots each shot's U_l^{max} against the gas pressure.
GOLEM_M_othre_parameters	chamber parameters	Calculates the followings: plasma heating power, central electron temperature, electron density, plasma energy, energy confinement time and Hugill diagram.

Table 1: Functions used for the evaluation

2.1 Determination of vacuum chamber parameters

In the case of GOLEM a part of the toroidal current always flows in the vacuum vessel. This current component must be calculated and taken into account in later measurements. To do so we have to determine the vessel resistance, which can be easily calculated if we do not create plasma. This way all the current measured by the Rogowski coil flows in the vessel. The circuit equation can be approximated:

$$U_l(t) \approx R_{ch} \cdot I_{tot}(t) \,,$$

where I_{tot} and U_l are measured. We made 5 shots with different parameters in order to obtain sufficient data, we also made sure that plasma was not formed in any of these cases. Later we also had shots which did not result plasma, in order to have a better estimate of R_{ch} we also used these cases while calculating.

For evaluation we used the *GOLEM_M_chamber_parameters*. This method does not neglect the inductive part of the equation above. It performs a line fit on the processed (offset corrected, calibrated) data. We used this method for the following shots: 25030, 25032, 25033, 25034, 25035, 25036, 25038, 25039, 25040, 25045, 25046, 25047, 25051, 25052, 25053, 25060, 25061. The calculated ($mean \pm \sqrt{variance}$) results:

$$R_{ch} = (9.533 \pm 0.057) \cdot 10^{-3}\ \Omega$$

$$L_{ch} = (8.634 \pm 0.295) \cdot 10^{-7}\ \mathrm{H}$$

The detailed resistance and inductivity results can be studied in Table 2.

Shot number	Resistance (10^{-3} Ω)	Inductivity (10^{-7} H)
25030	9.552	8.518
25032	9.489	8.865
25033	9.626	8.386
25034	9.523	8.517
25035	9.535	8.544
25036	9.369	9.617
25038	9.533	8.589
25039	9.559	8.433
25040	9.580	8.439
25045	9.550	8.478
25046	9.517	8.600
25047	9.518	8.645
25051	9.540	8.544
25052	9.550	8.340
25053	9.529	8.623
25060	9.479	8.864
25061	9.615	8.778

Table 2: Detailed resistance and inductivity results

2.2 Plasma breakdown

In this section our task was to create plasma amid varying amount of H gas and loop voltage. Our 30 designated shots were supposed to concentrate around the critical line which separates breakdown and non-breakdown shots. According to our instructions pre-ionization was supposed to be turned on to produce more reproducible results. The experience of the recent years showed that the electron gun does not make a difference. Knowing about the constant upgrades of the tokamak our supervisor urged us to test it anyway. As it turned out pre-ionization does make a difference when one is aiming to create plasma.

Using the *GOLEM_M_breakdown* function we evaluated the following shots: 25038, 25039, 25040, 25041, 25042, 25043, 25044, 25045, 25046, 25047, 25048, 25049, 25050, 25051, 25052, 25053, 25054, 25055, 25056, 25058, 25059, 25060, 25061. The *GOLEM_M_breakdown* function plots each shots U_l^{max} against the actual chamber pressure, the function also marks if there was or was not plasma and whether the electron gun was turned on or off. The final plot can be seen in Figure 3. It can be observed that with the exception of one shot the plasma and the non-plasma regions are well separated. We also succeeded in making our shots close to the critical line which separates the two regions.

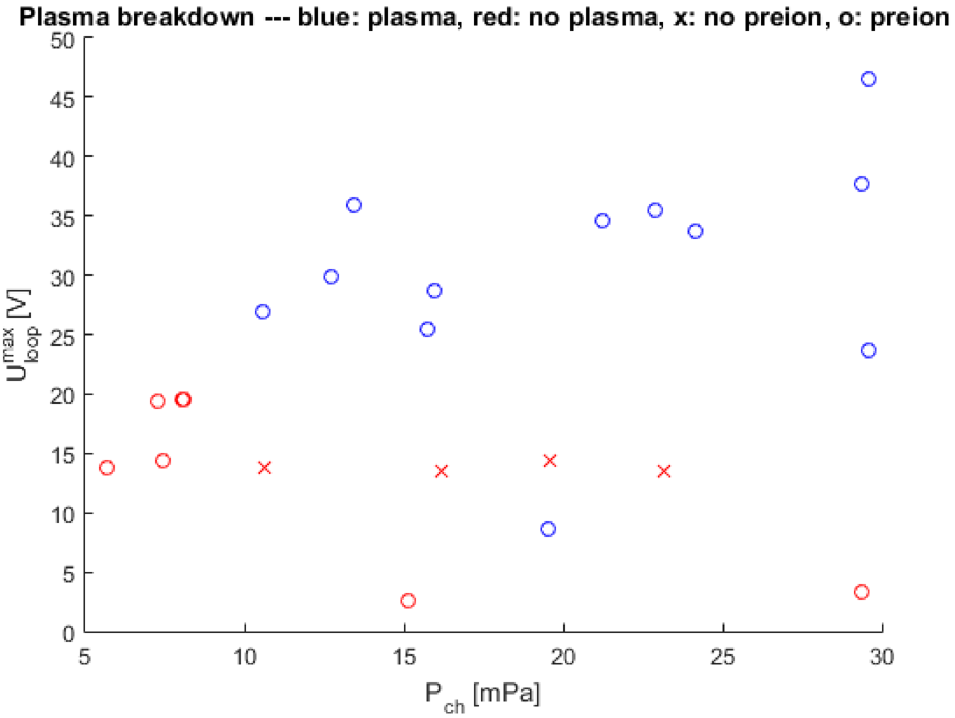

Figure 3: Plasma breakdown test

2.3 Estimation of main plasma parameters

Our next task was to study the effect of different parameters to the discharge performance and to achieve discharges with the highest central temperature, plasma energy and energy confinement time.

For evaluating the measured data we used the *GOLEM_M_other_parameters* function which calculated all the quantities needed. The function first progressed the raw data (offset correction, calibration) then using the equations below calculated the final estimates.

The basic circuit equations for the system are the followings:

$$U_l(t) = R_{ch} \cdot I_{ch}(t) + L_{ch}\frac{\mathrm{d}I_{ch}(t)}{\mathrm{d}t}\,,$$

$$U_l(t) = R_{pl}(t) \cdot I_{pl}(t) + L_{pl}\frac{\mathrm{d}I_{pl}(t)}{\mathrm{d}t}\,,$$

$$I_{tot} = I_{pl}(t) + I_{ch}(t)\,.$$

The inductance of the chamber and the plasma are negligible compared to the ohmic components, so we can simplify the equations:

$$U_l(t) = R_{ch} \cdot I_{ch}(t)\,,$$

$$U_l(t) = R_{pl}(t) \cdot I_{pl}(t)\,,$$

$$I_{tot} = I_{pl}(t) + I_{ch}(t)\,.$$

The heating power can be easily determined, as Ohmic heating is the only heating in GOLEM, and this can be calculated from the loop voltage and the plazma current:

$$P_{OH}(t) = U_l(t) \cdot I_{pl}(t)$$

For calculating the central electron temperature (T_{e0}) we were given a formula derived from Spitzer's resistivity formula:

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

where Z_{eff} is the effective charge, a is the plasma small radius, $R_{pl}(t)$ is in Ohms and $T_{e0}(t)$ is in electronvolts. For calculating the electron density we can use a rough estimate by assuming the electron gas as an ideal gas:

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

where T_{ch} can be estimated with the current room temperature. Now we can easily calculate the total energy of the plasma:

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

For estimating the energy confinement time first we have to calculate the power loss:

$$P_{loss} = P_{OH}(t) - \frac{\mathrm{d}W_{pl}}{\mathrm{d}t} .$$

By using its definition the energy confinement time can be now calculated:

$$\tau_E(t) = \frac{W_{pl}(t)}{P_{loss}(t)} .$$

For getting larger central electron temperature the plasma resistance needed to be decreased. While for getting larger plasma energy the central electron temperature and the electron density had to be increased. To do so we set larger gas pressure, larger current drive and larger toroidal field (in order to keep the plasma together for a longer period of time). We had 8 shots for this exercise Table 3 shows the most important calculated parameters. For proper results we had to smooth the data multiple times and also neglect Dirac delta like parts. To do so we used MatLab's built-in *smooth()* function for smoothing and *medfilt1()* function for removing the spikes. We executed both functions 10 times on plasma resistance, central electron temperature and plasma energy datas.

Shot number	T_{e0}^{max} (eV)	n_{avr} (m^{-3})	W_{pl}^{max} (J)	τ_E (ms)
25062	89.595	$6.86 \cdot 10^{18}$	1.731	0.0465
25063	87.211	$13.5 \cdot 10^{18}$	3.367	0.0927
25064	127.495	$13.7 \cdot 10^{18}$	4.910	0.1908
25065	158.514	$13.6 \cdot 10^{18}$	6.300	0.4168
25066	197.446	$8.36 \cdot 10^{18}$	4.450	0.2372
25067	141.484	$9.20 \cdot 10^{18}$	3.517	0.1314
25068	30.408	$8.63 \cdot 10^{18}$	0.794	0.0548
25069	30.959	$8.76 \cdot 10^{18}$	0.822	0.0529

Table 3: Main plasma parameters

Shot 25065 proved to have the highest plasma energy and energy confinement time. In Figure 4 you can see its time resolved main parameters.

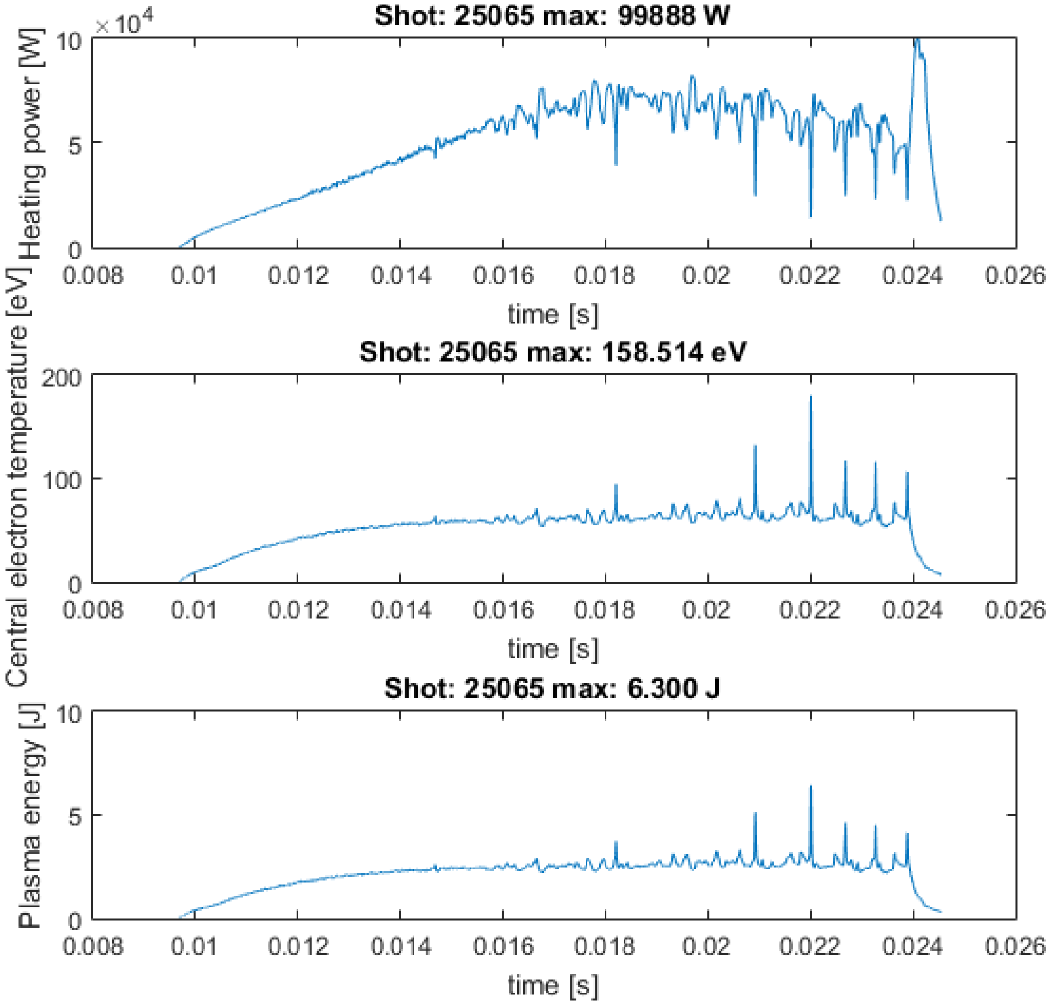

Figure 4: Time resolved parameters of shot 25065

2.4 q=2 disruptions

Our final task was to have a $q = 2$ disruption. With our last 4 shots we were aiming to achieve one, however, unfortunately none of these discharges were successful in this aspect. The main idea was to reach as large plasma current as possible, so the safety factor would be low. According to our task we evaluated each successful shot and plotted the so called Hugill diagram (Inverse edge safety factor − Murakami parameter). As it can be seen in Figure 5, none of our shots reached the $1/q = 0.5$ value, so we did not have any $q = 2$ disruptions.

The *GOLEM_M_other_parameters* function can also calculate the parameters needed for the Hugill diagram. The algorithm calculates the edge safety factor ($q(a,t)$) and the Murakami parameter (Mu):

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

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

For the Hugill diagram we used the data of all of our successful shot (shot numbers: 25031, 25037, 25041, 25042, 25043, 25044, 25048, 25049, 25050, 25054, 25055, 25056, 25058, 25059, 25062, 25063, 25064, 25065, 25066, 25067, 25068, 25069). For the plot we assumed that the disruptions occured at the highest $1/q$ values in each case. The diagram can be seen in Figure 5.

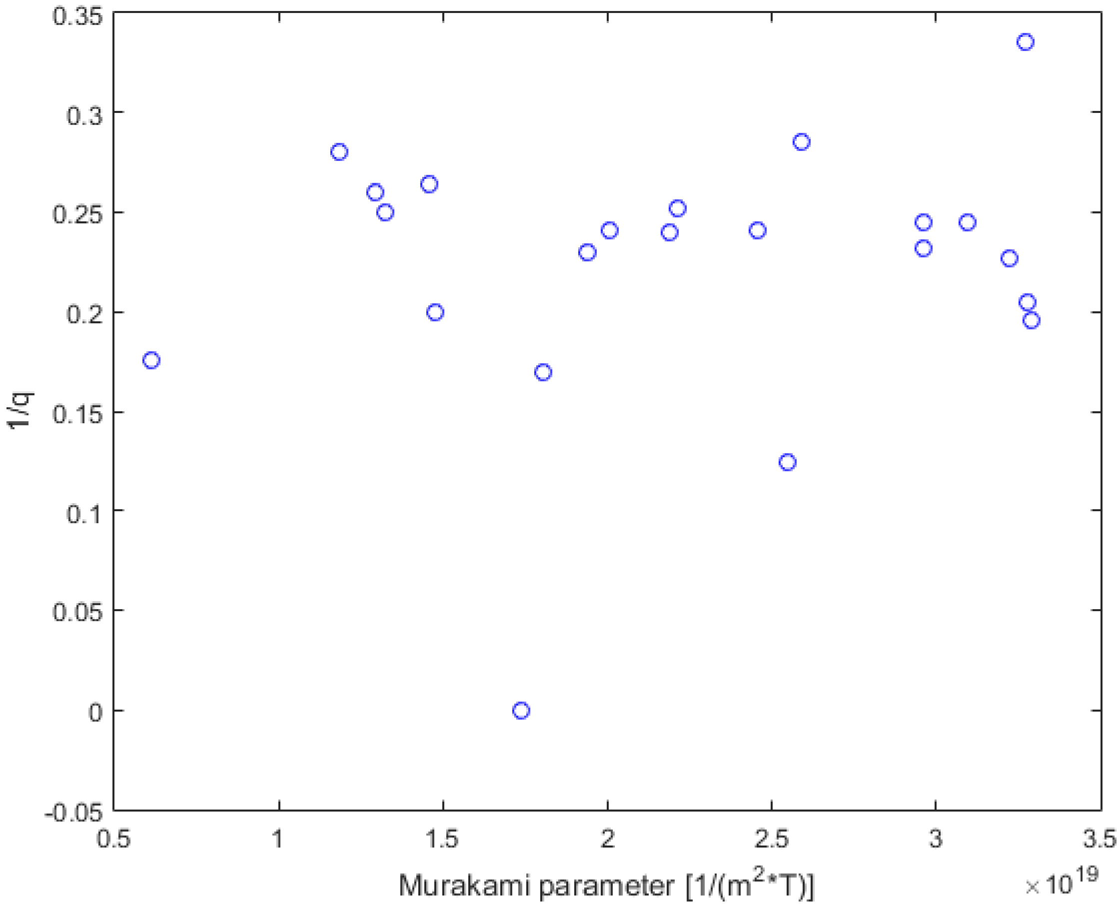

Figure 5: Hugill diagram

2.5 Shot summary

In Table 4 we summarized all our shots, those parameters which we have set manually (toroidal magnetic field – U_B, current drive – U_{CD}, chamber pressure – p_{ch}) and the calculated plasma parameters where plasma occurred.

Shot No.	U_B (V)	U_{CD} (V)	p_{ch} (mPa)	PreIon (Y/N)	Plasma (Y/N)	T_{e0}^{max} (eV)	n_{avr} (m^{-3})	W_{pl}^{max} (J)	τ_E (ms)
25030	600	500	10.61	N	N	–	–	–	–
25031	600	600	11.08	Y	Y	42.437	$4.95 \cdot 10^{18}$	0.638	0.0169
25032	600	500	6.10	N	N	–	–	–	–
25033	1100	500	2.56	N	N	–	–	–	–
25034	0	500	1.76	N	N	–	–	–	–
25035	600	700	1.53	N	N	–	–	–	–
25036	600	50	1.48	N	N	–	–	–	–
25038	600	500	10.61	N	N	–	–	–	–
25039	600	500	16.17	N	N	–	–	–	–
25040	600	500	23.14	N	N	–	–	–	–
25041	600	500	24.14	Y	Y	49.697	$10.8 \cdot 10^{18}$	1.627	0.0538
25042	600	500	22.86	Y	Y	59.816	$10.2 \cdot 10^{18}$	1.831	0.0727
25043	600	500	21.23	Y	Y	54.615	$9.50 \cdot 10^{18}$	1.544	0.0565
25044	600	500	13.46	Y	Y	58.967	$6.02 \cdot 10^{18}$	1.051	0.0346
25045	600	500	7.42	Y	N	–	–	–	–
25046	600	500	5.70	Y	N	–	–	–	–
25047	600	500	19.58	N	N	–	–	–	–
25048	600	500	29.35	Y	Y	60.510	$13.1 \cdot 10^{18}$	2.345	0.0866
25049	600	700	29.57	Y	Y	57.844	$13.2 \cdot 10^{18}$	2.230	0.0608
25050	600	700	12.70	Y	Y	36.722	$5.68 \cdot 10^{18}$	0.633	0.0377
25051	600	700	7.26	Y	N	–	–	–	–
25052	600	700	8.08	Y	N	–	–	–	–
25053	600	700	8.02	Y	N	–	–	–	–
25054	600	700	10.59	Y	Y	33.778	$4.73 \cdot 10^{18}$	0.485	0.0339
25055	600	700	15.95	Y	Y	32.921	$7.13 \cdot 10^{18}$	0.712	0.0421
25056	600	700	15.76	Y	Y	28.852	$7.05 \cdot 10^{18}$	0.614	0.0479
25058	600	300	19.56	Y	Y	59.562	$8.75 \cdot 10^{18}$	1.583	0.1058
25059	600	300	29.60	Y	Y	52.934	$13.2 \cdot 10^{18}$	2.127	0.2340
25060	600	50	29.34	Y	N	–	–	–	–
25061	600	50	15.12	Y	N	–	–	–	–
25062	800	700	15.32	Y	Y	89.595	$6.86 \cdot 10^{18}$	1.731	0.0465
25063	800	700	30.17	Y	Y	87.211	$13.5 \cdot 10^{18}$	3.367	0.0927
25064	1100	700	30.60	Y	Y	127.495	$13.7 \cdot 10^{18}$	4.910	0.1908
25065	1100	700	30.34	Y	Y	158.514	$13.6 \cdot 10^{18}$	6.300	0.4168
25066	1100	700	18.72	Y	Y	197.446	$8.36 \cdot 10^{18}$	4.450	0.2372
25067	800	700	20.57	Y	Y	141.484	$9.20 \cdot 10^{18}$	3.517	0.1314
25068	500	700	19.31	Y	Y	30.408	$8.63 \cdot 10^{18}$	0.794	0.0548
25069	500	700	19.61	Y	Y	30.959	$8.76 \cdot 10^{18}$	0.822	0.0529

Table 4: Shot summary

3 Acknowledgements

We would like to express our deepest gratitude to the colleagues at the Faculty of Physical and Nuclear Enginnering of the Czech Technical University. We would like to extend our thanks to Dr. Vojtech Svoboda in particular without whom this measurement could not have taken place.

4 Bibliography

References

[1] *Timeline of fusion*
http://https://en.wikipedia.org/wiki/Timeline_of_nuclear_fusion [2017. 11. 26. 9:33]

[2] *Tokamak figure*
https://www.euro-fusion.org/wpcms/wp-content/uploads/2011/09/JG05.537-1c.jpg [2017. 11. 26. 12:39]

[3] *GOLEM photo*
http://golem.fjfi.cvut.cz/wiki/PhotoGallery/Misc/0512GolemActionBD.jpg [2017. 11. 26. 13:42]

Appendix A – Skype log

```
[15:02:24] Tokamak GOLEM: Hi Gergo ...
[15:02:36] Gergő Pokol: Hi Vojtech!
[15:02:47] Tokamak GOLEM: Regards from Prague
[15:02:56] Gergő Pokol: We are connecting the students to Skype.
[15:03:02] Tokamak GOLEM: When do you want to start ?
[15:04:49] Gergő Pokol: In 5 minutes.
[15:05:02] Gergő Pokol: JUst having some problems with the Skype.
[15:05:58] Tokamak GOLEM: #MeToo
[15:06:26] Tokamak GOLEM: .... and with GOLEM as well, so maybe few more minutes ...
[15:20:49] Gergő Pokol: We will now use my computer, the pthers don't work.
[15:21:08] Gergő Pokol: Can you send us a link to the controll room?
[15:21:28] Tokamak GOLEM: http://golem.fjfi.cvut.cz/wiki/TrainingCourses/Universities/BUTE_Budapest.hu
/17/index
[15:22:51] Gergő Pokol: I will now let the students communicate with you.
[15:23:05] Tokamak GOLEM: OK
[15:23:44] Gergő Pokol: S: Hello Professor! How are you and how is GOLEM?
[15:23:49] Tokamak GOLEM: Regards to Budapest students from Prague
[15:24:44] Tokamak GOLEM: ... now I am a mirror of the GOLEM condition. We will see ...
[15:25:57] Gergő Pokol: S: We can see the control room via webcam, let us know whenever you are ready.
[15:26:30] Tokamak GOLEM: I will make a control discharge .. so wait a minute ...
[15:30:23] Tokamak GOLEM: So now the tokamak is ready for your control ..
[15:36:16] Gergő Pokol: S: Thank you! So can we start our first shot? We were also wondering if we could
really use helium instead of hydrogen.
[15:37:41] Tokamak GOLEM: I would recommend start with hydrogen and the switch to He
[15:38:01] Tokamak GOLEM: You can start ..
[15:44:52] Tokamak GOLEM: Congratulation to plasma ..
[15:45:27] Gergő Pokol: S: Thank you!
[16:09:44] Tokamak GOLEM: Tokamak is now under your control, so there is no need to ask my approval
for each shot. So make the discharges freely. I only ask you to check after each discharge if everything
seems OK. If not, stop submitting discharges and notice me about the problem ... Enjoy it ..
[16:11:13] Gergő Pokol: S: Alright, thank you. We will be careful!
[16:14:34] Tokamak GOLEM: One more thing .. I have a master student here and he is willing to make
some discharge from time to time. I hope it is not problem for you, isn't it?
[16:16:04] Gergő Pokol: S: It's perfectly ok for us. He might want to comment his own shots, too. So we
certainly won't mix our datas.
[16:37:36] *** Gergő Pokol új csoportos üzenetváltást indított a következőkkel: nti.hallgato2.
Csoportos beszélgetés megjelenítése ***
[16:45:05] Tokamak GOLEM: Everything OK? Are you happy with tokamak GOLEM remote control?
[16:46:10] Gergő Pokol: Yes, thank you we are having fun.
[17:15:51] Gergő Pokol: Have you ever seen something like the result of shot no. 25055? We are a little bit
puzzled about it.
[17:17:33] Gergő Pokol: Because looks like it conducts before the breakdown.
[17:21:12] Tokamak GOLEM: This is SW analysis problem (made by students). There is some current
through the chamber as well (before and during the discharge) and in this case this chamber current was
not properly subtracted ...
[17:51:23] Tokamak GOLEM: What are your plans ??
[17:51:37] Tokamak GOLEM: Any other discharge ??
[17:56:35] Gergő Pokol: We just had a short break. Yes. We are planning some further discharges.
[18:39:05] Gergő Pokol: We have finished. Thank you for the opportunity. Have a good night!
[18:39:18] Gergő Pokol: Hi Vojtech, it's Gergo
[18:39:30] Gergő Pokol: Thans for today's session!
[18:39:44] Gergő Pokol: I will send you some pics, and the logbook when ready.
[18:41:28] Tokamak GOLEM: Dear all, it was nice to have you operating the GOLEM tokamak remotely.
```

Hope you've enjoyed it. Regards from Prague and looking forward to see the pics and reports. V. Sv.
[18:41:32] Tokamak GOLEM: Good night
[18:41:47] Tokamak GOLEM: Stopping the remote operation ..
[18:42:06] Gergő Pokol: Thanks, bye!

Appendix B – Modified instructor routine

```
function data = GOLEM_M_other_parameters(chamber_params)

%Add directory of subroutine to search path
%————————————————
addpath(fullfile(’..’, ’student_routines’))

%Reading input
%————-
disp(’Please add the requested shotnumbers in an array!’);
disp(’(for example: [8379,8381,8383])’);
shot_nums = input(’The requested shots: ’);

%Create directory for output figures
%—————————————
isdir = exist(’./results’,’dir’);
if (isdir == 0)
mkdir(’results’);
end

%Constants
%———

k_b = 1.38d-23; % Boltzmann-contans [J/K]
R_0 = 0.4; % Major radius [m]
a = 0.085; % Minor raidius [m]
Z_eff = 2.5; % Z_eff
mu_0 = 4*pi*1d-7; % vacuum permeability [VÂ·s/(AÂ·m)]

%Calculate basic_parameters for each shot
%——————————————

n = length(shot_nums);
for i = 1:n

%Load basic parameters
%++++++++++++++++++++
shotno = shot_nums(i);
[t, U_l, dI_t, I_t, B_t, rawdata] = GOLEM_M_basic(shotno);

%Calculate plasma and chamber current
%++++++++++++++++++++++++++++++++++
I_ch = GOLEM_chamber_current(t, I_t, U_l, chamber_params(1), chamber_params(2));
I_pl = I_t - I_ch;


%Calculate for the time period, when plasma exists
%+++++++++++++++++++++++++++++++++++++++++++++++
URL = strcat(’http://golem.fjfi.cvut.cz/operation/shots/’,num2str(shotno),’/basicdiagn/PlasmaStart’);
[plasmastart, status] = urlread(URL);
if (status == 0) %reading failes
disp(’Loading data from GOLEM database failed!’);
return
end
```

```
plasmastart = str2num(plasmastart);

URL = strcat(’http://golem.fjfi.cvut.cz/operation/shots/’,num2str(shotno),’/basicdiagn/PlasmaEnd’);
[plasmaend, status] = urlread(URL);
if (status == 0) %reading failes
disp(’Loading data from GOLEM database failed!’);
return
end
plasmaend = str2num(plasmaend);

U_l = U_l(find((t > plasmastart) & (t < plasmaend)));
dI_t = dI_t(find((t > plasmastart) & (t < plasmaend)));
I_t = I_t(find((t > plasmastart) & (t < plasmaend)));
B_t = B_t(find((t > plasmastart) & (t < plasmaend)));
I_ch = I_ch(find((t > plasmastart) & (t < plasmaend)));
I_pl = I_pl(find((t > plasmastart) & (t < plasmaend)));
t = t(find((t > plasmastart) & (t < plasmaend)));

%Calculate plasma heating power
%++++++++++++++++++++++++++++++

dI_pl = GOLEM_diff(I_pl,t)’;
R_pl = (U_l-chamber_params(2)*dI_pl*0)./I_pl;
P_oh = R_pl.*I_pl.^ 2;


for j=1:10
P_oh=smooth(P_oh);
P_oh=medfilt1(P_oh);
end

max_P_oh = max(P_oh);

%Calculate central electron temperature
%++++++++++++++++++++++++++++++++++++++

%Central electron temperature
T_e0 = ((R_0*8*Z_eff)./(a^ 2*1544*R_pl)).^ (2/3);

for j=1:10
T_e0=smooth(T_e0);
T_e0=medfilt1(T_e0);
end

max_T_e0 = max(T_e0);

%Calculate electron density
%++++++++++++++++++++++++++
n_avr = 2*1d-3*rawdata.pressure/(k_b*rawdata.T_ch);

%Calculate plasma energy
%+++++++++++++++++++++++
W_pl = (11604.5*n_avr*k_b*T_e0*2*pi*R_0*a^ 2*pi)/3;

for j=1:10
```

```
W_pl=smooth(W_pl);
W_pl=medfilt1(W_pl);
end

max_W_pl = max(W_pl);
max_W_pl_abscissa = find(max(W_pl) == W_pl);
max_W_pl_abscissa = max_W_pl_abscissa(1);

%Calculate energy confinement time
%++++++++++++++++++++++++++++++++++
t_e = max_W_pl/P_oh(max_W_pl_abscissa);

%Calculate Hugill diagram
%+++++++++++++++++++++++++

%Safety factor
q = (a^ 2*2*pi*B_t)./(R_0*mu_0*I_pl);

%Murakami parameter
murakami = n_avr*R_0./B_t;


%Return variables
%++++++++++++++++

eval([’data.shot_’,num2str(shotno),’.t = t;’]);
eval([’data.shot_’,num2str(shotno),’.P_oh = P_oh;’]);
eval([’data.shot_’,num2str(shotno),’.T_e0 = T_e0;’]);
eval([’data.shot_’,num2str(shotno),’.n_avr = n_avr;’]);
eval([’data.shot_’,num2str(shotno),’.W_pl = W_pl;’]);
eval([’data.shot_’,num2str(shotno),’.t_e = t_e;’]);
eval([’data.shot_’,num2str(shotno),’.q = q;’]);
eval([’data.shot_’,num2str(shotno),’.murakami = murakami;’]);

%Plot results
%++++++++++++

close all
plotted = figure;

subplot(3,2,1)
plot(t,P_oh)
xlabel(’time [s]’)
ylabel(’Heating power [W]’)
title([’Shot: ’, num2str(shotno), ’ max: ’, num2str(max_P_oh, ’%6.0f’), ’ W’]);
subplot(3,2,2)
plot(t,T_e0)
xlabel(’time [s]’)
ylabel(’Central electron temperature [eV]’)
title([’Shot: ’, num2str(shotno), ’ max: ’, num2str(real(max_T_e0), ’%6.3f’), ’ eV’]);
subplot(3,2,3)
plot(t,W_pl)
xlabel(’time [s]’)
ylabel(’Plasma energy [J]’)
title([’Shot: ’, num2str(shotno), ’ max: ’, num2str(real(max_W_pl), ’%5.3f’), ’ J’]);
```

```
subplot(3,2,4)
plot(murakami,1./q)
hold on
plot(murakami(1),1./q(1),’go’);
plot(murakami(length(murakami)),1./q(length(q)),’ro’);
hold off
xlabel(’Murakami parameter [1/(mˆ 2*T)]’)
ylabel(’1/q’)
title([’Shot: ’, num2str(shotno), ’ Start: green point, End: red point’]);
subplot(3,2,5)
title([’Shot: ’, num2str(shotno), ’ Electron density: n_avr = ’, num2str(n_avr, ’%4.2e’), ’ 1/mˆ 3’]);
subplot(3,2,6)
title([’Shot: ’, num2str(shotno), ’ Energy confinement time: t_e =’, num2str(real(1d3*t_e), ’%6.4f’), ’ ms’]);

%Save to file
print(plotted,’-dpng’,fullfile(’results’,[num2str(shotno),’_other_parameters.png’]));

%Calculating the Hugill diagram
hold off
figure
myCounter=0;
j=1;
myq(i)=min(q);
while q(j) =min(q)
myCounter=j;
j=j+1;
end

mymurakami(i)=murakami(myCounter);
end
plot(mymurakami,1./myq, ’bo’)
xlabel(’Murakami parameter [1/(mˆ 2*T)]’)
ylabel(’1/q’)
end
```