

Measurement log for the 2010.01.14. GOLEM  
experiment from BME-NTI

Csaba Buday  
Gergo Pokol  
Daniel Imre Refy

January 28, 2010

# Chapter 1

## Introduction

The measurement series presented herein was performed with the aim to explore the possibility of developing a regular student measurement program in the Budapest University of Technology and Economics (BME), Institute of Nuclear Techniques (NTI) making use of the remote measurement potential of the GOLEM tokamak. The student measurement is to be developed for students at the nuclear technology branch of the physics MSc program at BME. The purpose of such measurement would be to demonstrate the very basics of tokamak operation, and to get the students acquainted with basic properties and operational limits.

The experiment was remote controlled by the Hungarian party: Csaba Buday, Daniel Imre Refy and Gergo Pokol, and supervised by the Czech party: Dr. Vojtech Svoboda. Measurements were performed on the 14th January 2010. 9:20-13:45 by controlling the GOLEM tokamak from the Electronics laboratory of BME NTI.

### 1.1 Measurement conditions

The GOLEM is a small size tokamak device equipped with basic controls and diagnostics having dimensions:

- Major radius at the magnetic axis:  $R_0 = 0.4$  m.
- Minor radius:  $r_0 = 0.1$  m.
- Radial position of the limiter:  $a_0 = 0.085$  m.

The parameters that can be set (most of them remotely) are:

- Toroidal magnetic field ( $B_t$ ) through the voltage of the toroidal field capacitor bank ( $U_B$ ).
- Toroidal electric field ( $E_t$ ) through the capacitor bank for the ohmic heating ( $U_E$ ).
- The time delay between the triggers of the toroidal field and the ohmic heating ( $\tau$ ).
- Hydrogen gas pressure ( $P_{H2}$ ).

- Vessel pressure through the vacuum system ( $P_v$ ). Local!
- The temperature of the vacuum chamber ( $T_{ch}$ ). Local!

The diagnostics we would like to use during our session:

- Loop voltage.
- Total toroidal current by Rogowski coil.
- Toroidal field measurement coil.
- Plasma radiation by photodiode.

## Chapter 2

# Measurement evaluation

During the reported session, measurements were set up and shots were initiated using a SSH connection to the *buon.fjfi.cvut.cz* control computer. On the Budapest side the SSH shell was provided by a Putty program running on a Windows system. Shots were programmed into a text file named *makefile* by the Hungarian party following the examples found at the beginning of the file. After confirmation from the Czech party, shots were started by the Hungarian party using the `makefile tag` command in the SSH shell, where `tag` is the label of the shot series in the file named *makefile*. The file used is copied into Appendix 4. Communication between the parties was by Skype instant messaging involving three parties. The Skype log of the session is copied into Appendix 5. Using these tools, remote control and communication went smoothly.

After executing the `firsttrial` and `scndtrial` trial shots, the measurement program unfolded as follows.

### 2.1 Data sources

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

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

Basic data of the present shot series is collected at:

```
http://golem.fjfi.cvut.cz/operation/tasks/Practica/  
BudapestBME-NTI/140110_0850/
```

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

- /basicdiagn/usbscopes (time-dependent measurements:  $U_{loop}$ ,  $dB_t$ ,  $dI_{total}$ , photodiode signal)
- /Aktual\_PfeifferMerkaVakua (initial pressure [mPa])
- /Td\_aktual (time delay between toroidal field and inductive current drive [us])

- $\frac{\text{/Aktual\_TermoclanekNaKomore}}{\text{(compared to room temperature)}} [\text{K}]$  (relative temperature of the chamber)

We have a direct measurement for the loop voltage, while the toroidal magnetic field and the total current signals must be integrated and multiplied by a calibration factor.

The sampling rate is 100 kHz, and the shot starts at 5 ms, so we have 500 samples from the background noise. This is important, because using this we can measure the bias, and correct the integrated values with this factor. The Rogowski coil measurement, for example, has a large negative bias needing correction. The algorithm is the following: we average the first 450 data points ( $\langle bkg \rangle$ ), and subtract it from the measured value ( $D(t)$ ):

$$\langle bkg \rangle = \int_0^{4.5 \text{ ms}} D(t') dt' \approx \sum_{i=0}^{450} D(i); \quad (2.1)$$

$$I_{total} = c_1 \left( \int_0^t D(t') dt' - \langle bkg \rangle t \right) \quad (2.2)$$

This bias correction has to be calculated in each shot.

For the evaluation, it is important to know the time of the flat-top window. We simply define the flat-top by taking the maximum of the total current.

## 2.2 Vacuum shot evaluation

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

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

The circuit equation is then

$$U_l = R_{ch} \cdot I_{tot} + L_{ch} \frac{dI_{tot}}{dt}. \quad (2.3)$$

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

Let us notice, that this is a linear model:

$$\begin{bmatrix} I(0) & dI(0)/dt \\ I(1) & dI(1)/dt \\ \dots & \dots \end{bmatrix} \cdot \begin{bmatrix} R_{ch} \\ L_{ch} \end{bmatrix} = \begin{bmatrix} U_{loop}(0) \\ U_{loop}(1) \\ \dots \end{bmatrix} \quad (2.4)$$

$$\underline{R} \cdot \underline{a} = \underline{g}$$

This means, we can use the linear least squares method to approximate the values of the  $\underline{a}$  vector:

$$\tilde{\underline{a}} = (\underline{R}^T \underline{R})^{-1} \underline{R}^T \underline{g}$$

Because we know both the total current and its time derivative, we know everything on the right hand side of the equation, meaning we can evaluate it.

This way, we determined the internal inductance and the resistance of the chamber, which are:

$$R_{ch} = 9.81 \text{ m}\Omega \quad L_{ch} = 7.5 \cdot 10^{-4} \text{ mH}$$

Experiment was conducted by running the shot series labeled `vacuumseq` (see Chapter 4). Shot numbers of vacuum shots: #1554-1556, #1558-1561 and #1613.

The tokamak has an inductive heating system, mainly for baking the vacuum vessel, but it can also be used to alter the resistance of the chamber. By heating up the chamber with the baking system, and doing vacuum shots, we can measure the chamber resistance at different chamber temperatures. This way, vacuum chamber resistivity calculations can be checked.

#	$t[s]$	$U_i[V]$	$B_t[T]$	$I_{tot}[kA]$	$R_{ch}[m\Omega]$	$L_{ch}[mH]$
1554	0.0060	10.5	0.037	1.03	10.32	0.00107
1555	0.0061	18.9	0.045	2.01	9.20	0.00083
1556	0.0080	14.0	0.112	1.29	8.79	0.00029
1558	0.0061	4.1	0.047	0.53	7.38	0.00047
1559	0.0060	10.5	0.039	0.94	11.31	0.00088
1560	0.0061	18.7	0.043	1.96	9.96	0.00077
1561	0.0061	25.5	0.041	2.45	10.91	0.00088
1613	0.0060	29.5	0.038	2.92	10.61	0.00084
1620	0.0060	20.4	0.038	1.93	10.93	0.00082
1622	0.0059	20.1	0.037	1.76	11.44	0.00114

Table 2.1: Table of resistivity and impedance values from vacuum shots

Experiment was conducted by running the shot series labeled `vacuumheated` (see Chapter 4) after heating the chamber to 100 ° deg C (shot #1620) and 200 ° C (shot #1622) relative to room temperature. The room temperature is assumed to be 300 K. Calculated resistivity and impedance values are summarized in Table 2.1 for all vacuum shots.

It can be concluded that resistivity seems to be higher at higher temperature, which is in good agreement with the expectations, however, resistivity values at room temperature show the large uncertainty of the measurement. Making more measurements at higher temperatures could make this experiment more conclusive, but it is probably not worth the effort to do it remotely, as it inevitably requires manual local control of the vacuum chamber heating.

## 2.3 Plasma shot evaluation

Knowing the resistance ( $R_{ch}$ ) and inductance of the chamber ( $L_{ch}$ ), we can proceed to the plasma current evaluation. A simple electrical model of the tokamak is a time-varying voltage source ( $U_{loop}$ ) which is connected to two parallel LR circuits. One circuit is the chamber, the other one is the plasma.

Because of the parallel connection, the voltage is the same on both circuits:

$$U_{loop} = R_{ch} \cdot I_{ch} + L_{ch} \frac{dI_{ch}}{dt} \quad (2.5)$$

$$U_{loop} = R_{pl} \cdot I_{pl} + L_{pl} \frac{dI_{pl}}{dt} \quad (2.6)$$

$$I_{pl} + I_{ch} = I_{tot} \quad (2.7)$$

$$\frac{dI_{ch}}{dt} + \frac{dI_{ch}}{dt} = \frac{dI_{tot}}{dt} \quad (2.8)$$

$$(2.9)$$

All parameters are known in the (2.5) differential-equation, so it can be solved with the initial conditions: both the current and its time derivative being equal to zero at  $t=0$ . The plasma current is just the difference between the total and the chamber current.

Both the resistance and the internal inductance of the plasma vary in time, so there is no straightforward way to determine them from the (2.6) equation. If we assume that the inductance term is negligible compared to resistance term, plasma resistance ( $R_{pl}$ ) can be calculated.

The Ohmic heating power can be calculated as follows:

$$P_{OH}(t) = U_{loop}(t) \cdot I_{pl}(t). \quad (2.10)$$

The safety factor at the edge can be estimated as:

$$q_{edge} = \frac{a_0^2}{R_0} \frac{2B_t \pi}{\mu_0 I_{pl}}, \quad (2.11)$$

where  $a_0$  is the plasma minor radius.

For the average density we assumed, that it was constant during the discharge, apart from the dissociation of the hydrogen gas. There is a 30 second delay between the gas filling and the actual shot, which was supposed to be enough for the gas to reach thermal equilibrium with the chamber wall. Chamber temperature was monitored with respect to the room temperature, and the difference was found to normally be zero. The room temperature is again assumed to be 300 K. The ideal gas law is used to calculate the density (in particle/ $m^3$ ):

$$n = \frac{p}{k_B T}. \quad (2.12)$$

The central plasma temperature ( $T_{e0}$ ) is calculated from equation (3.20) of [1], which itself is based on Spitzer's resistivity formula, and an assumed temperature profile:

$$T_{e0} = \left( \frac{R_0}{a_0^2} \frac{8Z_{eff} \cdot I_{pl}}{1.544 \cdot 10^{-3} U_{loop}} \right)^{2/3} \quad (2.13)$$

The energy content of the plasma is calculated from the temperature, density and volume, based on the ideal-gas law, taking into account the assumed temperature profile:

$$W_{pl} = \frac{fnk_B T_e(0)}{6}. \quad (2.14)$$

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

$$\tau_E = \frac{W_{pl}}{P_{OH}}. \quad (2.15)$$

The experiment was conducted according to plans: shot series labeled `grandloop_nti` (see Appendix 4). Some shots needed to be repeated (`repeatseq`), and the  $U_B$ - $U_E$  grid was refined at areas of special interest (`detailed_loop1`). Finally, runaway electrons were searched for (`runaway_seq`, `runaway_seq2`). Results for each shot are summarized in the Tables 2.2 and 2.3. Table 2.2 shows parameters of shots having no breakdown due to too low  $U_E$  values, and Table 2.3 shows parameters of shots successfully generating plasma.

It can be concluded that all parameters estimated with the above simple methods are in the right order of magnitude therefore a similar evaluation procedure can be suitable to demonstrate the most important parameters of the tokamak plasma. The experiment can be declared to be successful in that sense, despite having some difficulties: some discharges failed and reproducing discharges had some uncertainties. *No runaway electron discharges* were found probably due to the lack of pre-ionization and/or large enough toroidal electrical fields. We speculate that pre-ionization might also improve on the reproducibility of the discharges, and make runaway discharges possible.

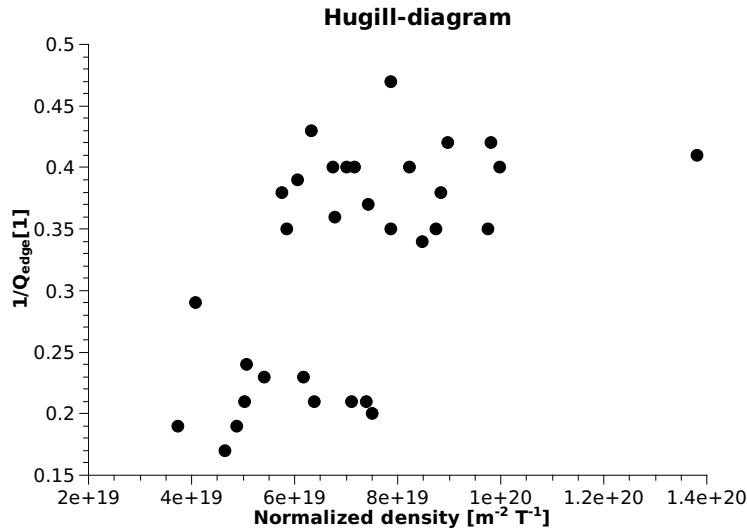


Figure 2.1: Shots with beakdown in the coordinate system of the Hugill diagram

Shots with beakdown were plotted in the coordinate system of the Hugill diagram. The  $1/q$  region is completely consistent with the criterion that  $q_{edge}$  must be greater than 2. The normalized density of  $n_e^{avr}R/B_t$  seems to be little high for GOLEM, so it might needed to check if it is in the right order of magnitude, and if there exists a better way of estimating it.

Figures 2.2 and 2.3 show the temporal evolution of the plasma current and the edge safety factor respectively for shot #1610. This is the discharge shown on the 2.1 Hugill diagram most closely approaching the value of  $q_{edge} = 2$ . In



#	$t[s]$	$U_l[V]$	$B_t[T]$	$I_{tot}[kA]$	$Photo.[a.u.]$
1548	0.008	-30.0	0.108	1.58	0.011
1549	0.008	14.2	0.100	1.37	0.004
1551	0.008	14.0	0.107	1.38	0.006
1553	0.003	-0.1	0.000	0.01	0.011
1554	0.006	10.5	0.037	1.03	0.004
1555	0.006	18.9	0.045	2.01	0.001
1556	0.008	14.0	0.112	1.29	0.008
1558	0.006	4.1	0.047	0.53	0.006
1559	0.006	10.5	0.039	0.94	0.001
1560	0.006	18.7	0.043	1.96	0.011
1561	0.006	25.5	0.041	2.45	0.008
1562	0.007	4.1	0.080	0.65	0.008
1563	0.007	10.2	0.075	1.05	0.008
1565	0.007	23.4	0.083	2.37	0.015
1566	0.007	4.1	0.125	0.30	0.004
1567	0.007	10.9	0.125	1.35	0.001
1570	0.007	4.4	0.140	0.33	0.004
1571	0.011	-0.1	-0.001	0.05	0.004
1574	0.008	4.1	0.091	0.34	0.001
1575	0.007	10.5	0.076	1.15	0.008
1578	0.007	4.1	0.117	0.61	0.006
1579	0.007	10.2	0.106	1.34	0.004
1582	0.007	4.1	0.142	0.82	0.006
1583	0.007	10.9	0.145	1.12	0.008
1586	0.007	4.4	0.073	0.34	0.008
1587	0.007	10.5	0.077	1.23	0.011
1590	0.000	-0.1	0.000	0.00	0.006
1591	0.027	0.1	0.000	0.07	0.004
1594	0.007	4.1	0.159	0.20	0.008
1595	0.007	10.2	0.147	1.22	0.013
1598	0.007	10.2	0.142	0.81	0.004
1599	0.007	4.1	0.116	0.42	0.013
1600	0.007	10.9	0.110	1.02	0.004
1613	0.006	29.5	0.038	2.92	0.011
1614	0.006	28.6	0.038	2.68	0.001
1615	0.006	28.4	0.040	2.85	0.008
1616	0.006	28.6	0.042	2.87	0.008
1617	0.006	28.4	0.040	2.93	0.008
1618	0.006	28.6	0.040	2.78	0.006
1619	0.006	28.6	0.047	2.78	0.013
1620	0.006	20.4	0.038	1.93	0.001
1621	0.005	0.1	0.000	0.01	0.018
1622	0.006	20.1	0.037	1.76	0.013

Table 2.2: Shots without breakdown

#	$t$ [s]	$U_l$ [V]	$B_t$ [T]	$I_{tot}$ [kA]	$Photo.$ [a.u.]	$I_{pl}$ [kA]	$q_{edge}$ [1]	$P_{OH}$ [kW]	$T_{e0}$ [eV]	$\tau_E$ [s]
1550	0.011	9.3	0.156	3.33	0.076	2.39	5.0	22	36	1.010E-4
1552	0.010	8.8	0.160	3.44	0.084	2.52	4.8	22	39	1.100E-4
1557	0.010	9.3	0.162	3.53	0.086	2.59	4.8	24	38	9.600E-5
1564	0.009	12.1	0.128	4.65	0.102	3.40	2.9	41	39	5.000E-5
1568	0.009	11.2	0.197	4.70	0.109	3.57	4.2	40	42	5.500E-5
1569	0.009	17.5	0.189	7.31	0.138	5.52	2.6	97	42	2.500E-5
1572	0.009	12.4	0.244	4.81	0.109	3.57	5.2	44	39	4.300E-5
1573	0.008	17.8	0.230	6.73	0.124	5.00	3.5	89	39	2.100E-5
1576	0.009	12.1	0.134	4.75	0.095	3.51	2.9	42	39	5.500E-5
1577	0.009	19.2	0.139	5.95	0.128	4.19	2.5	81	33	2.400E-5
1580	0.009	11.4	0.197	4.26	0.107	3.08	4.9	35	38	7.100E-5
1581	0.009	18.0	0.185	7.82	0.140	6.07	2.3	109	44	2.500E-5
1584	0.009	10.9	0.264	4.47	0.107	3.32	6.0	36	41	7.200E-5
1585	0.009	16.6	0.246	5.56	0.128	3.86	4.9	64	34	3.500E-5
1588	0.009	12.4	0.133	5.48	0.109	4.21	2.4	52	44	5.800E-5
1589	0.009	18.0	0.134	5.42	0.107	3.57	2.9	64	31	3.300E-5
1592	0.009	10.9	0.210	4.73	0.102	3.63	4.4	40	43	7.500E-5
1593	0.009	16.1	0.192	7.55	0.131	5.84	2.5	94	46	3.300E-5
1596	0.009	11.4	0.263	5.01	0.109	3.87	5.2	44	44	6.700E-5
1597	0.009	16.6	0.238	5.83	0.131	4.15	4.4	69	36	3.500E-5
1601	0.009	13.8	0.139	5.46	0.116	4.06	2.6	56	40	4.600E-5
1602	0.009	16.8	0.133	5.29	0.107	3.60	2.8	60	32	3.300E-5
1603	0.009	20.4	0.122	6.13	0.102	3.92	2.4	80	30	2.200E-5
1604	0.010	15.4	0.152	5.54	0.102	4.20	2.8	65	38	3.200E-5
1605	0.009	15.2	0.147	6.10	0.095	4.48	2.5	68	40	3.200E-5
1606	0.009	18.2	0.151	6.16	0.114	4.25	2.7	77	34	2.600E-5
1607	0.010	14.0	0.172	6.41	0.109	5.12	2.6	72	46	3.500E-5
1608	0.010	15.4	0.180	6.29	0.109	4.85	2.8	75	42	3.100E-5
1609	0.009	18.2	0.164	6.87	0.102	4.97	2.5	90	38	2.500E-5
1610	0.008	24.8	0.099	5.94	0.046	3.49	2.1	86	24	1.100E-5
1611	0.008	23.2	0.091	5.17	0.069	2.77	2.5	64	22	1.600E-5
1612	0.007	24.8	0.072	4.80	-0.015	2.26	2.4	56	18	1.700E-5

Table 2.3: Shots with breakdown

fact, given the uncertainties of the measurements used, it might well even reach  $q_{edge} = 2$ . This later assumption is supported by the fact that the plasma current starts to decay and the discharge terminates shortly after reaching the lowest  $q_{edge}$  value. Even is shot #1610 ended with a  $q_{edge} = 2$  *disruption*, this was a rare occasion as it required a very steep plasma current rise to overcome the effect of the growing toroidal field on the edge safety factor according to equation (2.11).

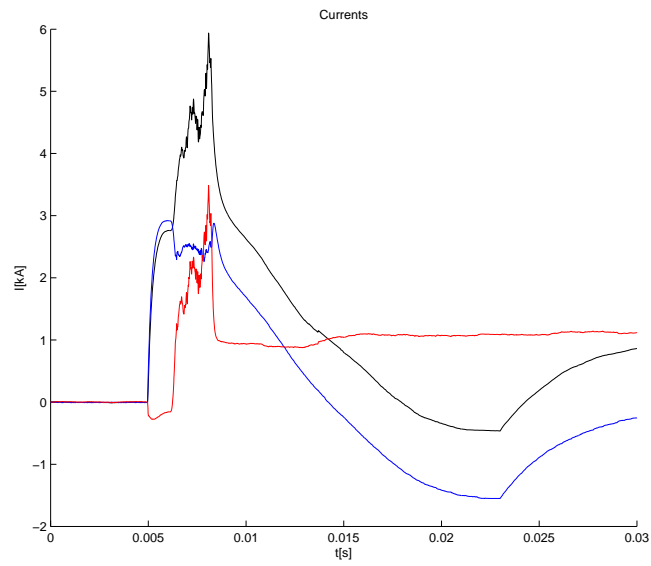


Figure 2.2: Time evolution of the total (black), chamber (blue) and plasma (red) currents for shot #1610

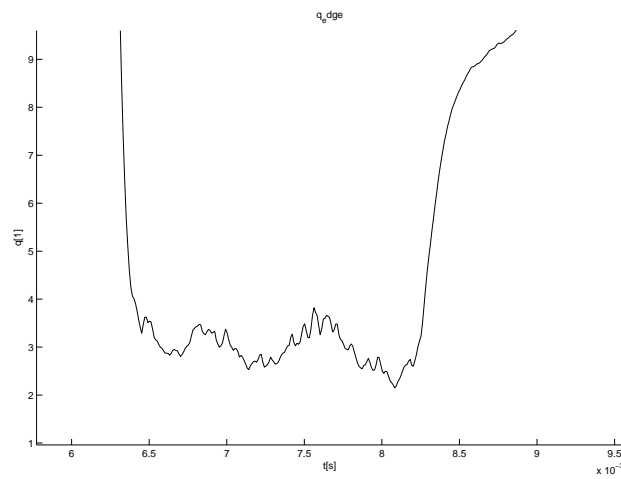


Figure 2.3: Time evolution of edge safety factor for shot #1610

# Chapter 3

## Discussion

Authors of this measurement log have discussed results with colleagues from KFKI-RMKI (Gabor Veres and Gabor Petravich), former operators of the MT-M1 tokamak. Some of the main conclusions are to be summarized in the following:

1. Inductance of the plasma could be estimated instead of neglecting it.
2. Best practice at the MT-M1 tokamak dictates that the  $\tau$  time delay between the inductive current drive and toroidal magnetic field condensers should be set so that the flattop of the toroidal magnetic field is made use of, in order to achieve the best performance discharges.
3. At the very low temperature plasma of GOLEM discharges, ionization is only partial and the Spitzer formula for conductivity should be used with care. In fact, the formula could be applied to the central, higher temperature part of the plasma, but such a calculation requires the knowledge of an estimate of temperature profile. Such a profile could be taken to be the equilibrium profile presented in [1]. In such a way, a rough estimate of the maximum temperature could be calculated from the plasma resistivity.
4. There appears to be no flattop during the discharge, so equilibrium profiles cannot develop and even the  $a_0$  plasma radius changes in time in an unmonitored way. Physical quantities derived using these data have huge uncertainties and can only be used for demonstration purposes.
5. It appears that measurements presented above could conclusively detect only the plasma breakdown operational limit. This could be interesting, however other operational limits of the Hugill diagram could also be attempted to be systematically measured:
  - (a) The low density runaway limit could be attempted to be measured. Toroidal electric field in GOLEM is calculated to be well above the critical electric field for runaway electron generation. The physical mechanism of runaway electron generation requires pre-ionization of the plasma, so such a measurement would require to switch it on. (It was always switched on in MT-M1.) A runaway discharge should be recognizable from the measurements having plasma current but no signal on the photodiode.

- (b) The  $q = 2$  disruption limit could be attempted to be demonstrated by setting the discharge time to the downslope of the toroidal magnetic field. This would cause a rapid decrease in the boundary safety factor.
- 6. It would be nice to demonstrate the meaning and calculation of the  $\tau_E$  energy confinement time. Having no diamagnetic loop measurement, this requires the calculation of total kinetic plasma energy from the ideal gas law, which requires the density as a parameter. The order of magnitude of the average density can be estimated from pre-discharge chamber pressure. (The influx from the wall is expected to be limited in the GOLEM tokamak due to low edge temperatures.) Taking the equilibrium profile from [1], one can estimate the total kinetic energy, and so the energy confinement time at the "flattop", where total kinetic energy curve has its maximum.

Based on these remarks, a proposal for a GOLEM discharge series will be prepared shortly. Such a measurement series is necessary before writing the instructions for the student measurement.

# Bibliography

- [1] Jana Brotánková. *Study of high temperature plasma in tokamak-like experimental devices*. PhD thesis, Charles University in Prague, 2009.

## Chapter 4

# Appendix: Remote control file

```
firsttrial: #without hydrogen
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=0 pH2=68

scndtrial: #with hydrogen
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=1 pH2=66

H2seq:
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=0 pH2=66 #H2 off
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=1 pH2=66 #approx 30 mPa
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=1 pH2=68 #approx 40 mPa
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=1 pH2=70 #approx 50 mPa
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=1 pH2=72 #approx 70 mPa
make -iBs -C velin shot Ue=400 Ub=400 Td=2000 H2filling=1 pH2=100 #approx 100 mPa

firstloop:
for Ue in `seq 300 100 700`; do\
make -iBs -C velin shot Ue=$$Ue Ub=400 Td=2000 pH2=68 H2filling=1;\
done;\

grandloop:
  for Td in `seq 2000 2000 8000`; do\
    for pH2 in 68 70 72; do\
      for Ub in `seq 600 300 1200`; do\
        for Ue in `seq 600 300 1200`; do\
          make -C velin -iBs shot Ue=$$Ue Ub=$$Ub Td=$$Td pH2=$$pH2 H2filling=1;\
          done;\
        done;\
      done;\
    done;\
  done;\

vacuumseq:
for Ue in `seq 100 200 700`; do\
make -iBs -C velin shot Ue=$$Ue Ub=400 Td=0 pH2=66 H2filling=0;\
done;\

grandloop_nti:
for pH2 in 66 70 100; do\
for Ub in `seq 400 200 800`; do\
for Ue in `seq 100 200 700`; do\
make -C velin -iBs shot Ue=$$Ue Ub=$$Ub Td=1000 pH2=$$pH2 H2filling=1;\
done;\
done;\
done;\

repeatseq:
make -iBs -C velin shot Ue=300 Ub=800 Td=1000 H2filling=1 pH2=66
```

```
make -iBs -C velin shot Ue=100 Ub=600 Td=1000 H2filling=1 pH2=100
make -iBs -C velin shot Ue=300 Ub=600 Td=1000 H2filling=1 pH2=68

detailed_loop1:
for pH2 in 66 ; do\
for Ub in `seq 400 50 500`; do\
for Ue in `seq 600 100 800`; do\
make -C velin -iBs shot Ue=$$Ue Ub=$$Ub Td=1000 pH2=$$pH2 H2filling=1;\
done;\
done;\
done;\

runaway_seq:
for pH2 in 60 62 64 ; do\
make -C velin -iBs shot Ue=800 Ub=400 Td=0 pH2=$$pH2 H2filling=1;\
done;\
make -iBs -C velin shot Ue=800 Ub=400 Td=0 H2filling=0 pH2=60

runaway_seq2:
for pH2 in 58 59 60; do\
make -C velin -iBs shot Ue=800 Ub=400 Td=0 pH2=$$pH2 H2filling=1;\
done;\

vacuumheated:
make -iBs -C velin shot Ue=500 Ub=400 Td=0 H2filling=0 pH2=68
```



## Chapter 5

# Appendix: Log of conversation during the experiment

```
[2010.01.14. 9:32:02] svobovoj: Hi Daniel .. Golem
[2010.01.14. 9:32:13] Refy Daniel: hi!
[2010.01.14. 9:32:25] Refy Daniel: it was fast :)
[2010.01.14. 9:32:41] svobovoj: Hi Daniel, can we chat this way?
[2010.01.14. 9:32:55] Refy Daniel: we try to make a vacuum shot, via putty
[2010.01.14. 9:33:01] Refy Daniel: yes, it is perfect!
[2010.01.14. 9:33:14] svobovoj: Perfect, go on
[2010.01.14. 9:36:15] svobovoj: OK, charging ...
[2010.01.14. 9:37:06] svobovoj: Perfect ..
[2010.01.14. 9:37:59] Refy Daniel: can i try scndtrial?
[2010.01.14. 9:38:08] svobovoj: Yes, go on ..
[2010.01.14. 9:40:15] svobovoj: OK, you have plasma, congratulation ..
[2010.01.14. 9:40:25] Refy Daniel: :)
[2010.01.14. 9:40:58] Refy Daniel: i thought there will be no plasma @ these parameters...
[2010.01.14. 9:41:00] Refy Daniel: ok
[2010.01.14. 9:41:30] Refy Daniel: ok we check the proposal and make a batch file
[2010.01.14. 9:41:45] svobovoj: OK ..
[2010.01.14. 9:45:40] Refy Daniel: what -C velin means?
[2010.01.14. 9:47:10] svobovoj: This is a directory, where all the subroutines are. I think it is of no use for you ..
[2010.01.14. 9:47:39] svobovoj: velin ... in czech "control room"
[2010.01.14. 9:47:48] Refy Daniel: i see
[2010.01.14. 9:48:08] Refy Daniel: ok we try the vacuum shot sequence, which was proposed
[2010.01.14. 9:48:44] svobovoj: wait a moment. I would like to check your modifications to makefile ..
[2010.01.14. 9:49:00] Refy Daniel: ok
[2010.01.14. 9:49:13] Refy Daniel: i already saved
[2010.01.14. 9:51:07] svobovoj: So, I have corrected it a bit, refresh the editor please and you can try it ..
[2010.01.14. 9:52:09] Refy Daniel: we try to make the shots!
[2010.01.14. 9:52:16] svobovoj: ok
[2010.01.14. 9:53:28] svobovoj: I have jus added missing -C velin. OK go on ..
[2010.01.14. 9:54:29] Refy Daniel: this shot was not ok...
[2010.01.14. 9:54:37] Refy Daniel: 1553
[2010.01.14. 9:55:19] svobovoj: You are right, I don't know what was wrong, you have to repeat it ..
[2010.01.14. 9:55:42] Refy Daniel: how can we stop the shot?
[2010.01.14. 9:55:59] svobovoj: Try Ctrl-C
[2010.01.14. 9:56:21] Refy Daniel: i tried
[2010.01.14. 9:56:31] Refy Daniel: seems to work
[2010.01.14. 9:57:07] Refy Daniel: i make the sequence again!
[2010.01.14. 9:57:13] svobovoj: Ok, but use it carefully, especially no in charging process
[2010.01.14. 9:57:23] svobovoj: just a moment
[2010.01.14. 9:57:38] svobovoj: interuption like this shoul be inspected a bit
[2010.01.14. 9:57:54] svobovoj: i will try a shot myself ..
[2010.01.14. 9:58:01] Refy Daniel: ok
[2010.01.14. 10:05:04] svobovoj: So 1556 and 1557 were mine. It seems to be OK, continue, I have added sleep command
at the end of the shot, where you can interupt loops
```

[2010.01.14. 10:05:04] Refy Daniel: i made the plasma shot sequence  
[2010.01.14. 10:05:16] Refy Daniel: check it please!  
[2010.01.14. 10:06:45] Refy Daniel: until that can i make the vacuum shots again?  
[2010.01.14. 10:06:55] svobovoj: moment ..  
[2010.01.14. 10:10:59] svobovoj: OK, so .. when you edit makefile, you have to use tabs instead blank char, secondly, please, at this moment 800V max for both Ue and Ub. I wrote you that compared to our last measurement two months ago, we have uncovered bug in calibration. So you have to half the values from last measurements. Then 800V is pretty enough.. You can now repeat vacuum shots ..  
[2010.01.14. 10:12:25] svobovoj: Please I have modified makefile, refresh the editor ..  
[2010.01.14. 10:12:59] Refy Daniel: ok, what are the limits of the Ue and the Ub?

[2010.01.14. 10:14:23] Refy Daniel: Gergo Pokol joined us  
[2010.01.14. 10:14:25] svobovoj: 800V  
[2010.01.14. 10:14:35] Refy Daniel: and the lower limits?  
[2010.01.14. 10:15:10] svobovoj: Ue, you can try 100V, Ub 400V because DAS is triggered from it  
[2010.01.14. 10:16:45] Refy Daniel: ok, i make the vacuum shots again  
[2010.01.14. 10:16:47] Refy Daniel: ok?  
[2010.01.14. 10:17:33] svobovoj: ok  
[2010.01.14. 10:22:34] Refy Daniel: done  
[2010.01.14. 10:22:49] svobovoj: It looks fine  
[2010.01.14. 10:23:02] Refy Daniel: yes:)  
[2010.01.14. 10:23:19] Refy Daniel: no i make the plasma shot sequence, if it is ok?!  
[2010.01.14. 10:23:29] Refy Daniel: now  
[2010.01.14. 10:23:35] svobovoj: i'll check it, moment  
[2010.01.14. 10:24:05] svobovoj: go on  
[2010.01.14. 10:24:54] Refy Daniel: now we about an hour right?  
[2010.01.14. 10:24:57] Refy Daniel: bit more...  
[2010.01.14. 10:25:04] Refy Daniel: we have  
[2010.01.14. 10:25:22] svobovoj: Yes .. it can take a hour ..  
[2010.01.14. 10:43:52] svobovoj: 1571 problem. let's continue, we will see ..  
[2010.01.14. 10:45:15] Refy Daniel: ok  
[2010.01.14. 10:45:28] Refy Daniel: 72 ok  
[2010.01.14. 10:45:54] svobovoj: So , things are sometimes this way ..  
[2010.01.14. 10:47:58] svobovoj: 73 ok. Have you noticed, that you can use IP camera to see the Golem ?  
[2010.01.14. 10:48:46] Refy Daniel: yes, we saw you 'running' after trigger :)  
[2010.01.14. 10:53:50] svobovoj: Is this a measurement with students?  
[2010.01.14. 10:54:13] Refy Daniel: no, this is only a trial  
[2010.01.14. 10:54:20] Refy Daniel: to see what we can do...  
[2010.01.14. 10:54:33] Refy Daniel: we will evaluate data today  
[2010.01.14. 10:54:50] gergo\_pokol: hello  
[2010.01.14. 10:55:03] svobovoj: OK  
[2010.01.14. 10:55:09] gergo\_pokol: I am pretty much responsible for the future student mes  
[2010.01.14. 10:55:16] gergo\_pokol: measurements.  
[2010.01.14. 10:56:00] gergo\_pokol: based on todays experience we will write a measurement instruction for students.  
[2010.01.14. 10:57:01] svobovoj: Fine, are you going to write it in english? I am very interested ..  
[2010.01.14. 10:57:09] gergo\_pokol: I hope that we can do it, and the whole measurement, in English.  
[2010.01.14. 10:57:45] gergo\_pokol: after all, this is an international measurement, so communication should be done considering this.  
[2010.01.14. 10:59:03] gergo\_pokol: after measurement, students will write a log book including all calculated results.  
[2010.01.14. 10:59:25] gergo\_pokol: I hope these to be also in English, so that I can directly send it to you.  
[2010.01.14. 10:59:53] gergo\_pokol: Our today's logbook will definitely be in English.  
[2010.01.14. 11:01:00] gergo\_pokol: You can expect to receive it tomorrow the latest.  
[2010.01.14. 11:01:24] svobovoj: Very good, thank you.  
[2010.01.14. 11:21:12] gergo\_pokol: problem with 1590  
[2010.01.14. 11:21:26] Refy Daniel: the problem i mentioned in my email is still not solved  
[2010.01.14. 11:22:15] Refy Daniel: you wrote me that integrated and final data are the same  
[2010.01.14. 11:22:31] Refy Daniel: integrated data is available on the webpage  
[2010.01.14. 11:23:17] Refy Daniel: for example shot nr. 1564 the maximum of the I\_tot is about 90kA  
[2010.01.14. 11:23:27] gergo\_pokol: problem with 1591  
[2010.01.14. 11:24:12] Refy Daniel: but it is about 5kA on the graph on the webpage  
[2010.01.14. 11:24:25] Refy Daniel: my question is: which data is valid?  
[2010.01.14. 11:25:21] gergo\_pokol: 1592 ok  
[2010.01.14. 11:34:58] gergo\_pokol: grandloop is over  
[2010.01.14. 11:35:14] gergo\_pokol: we are now preparing to repeat shots that went wrong  
[2010.01.14. 11:37:01] gergo\_pokol: please say, when we can go on with it  
[2010.01.14. 11:37:58] svobovoj: sorry, from time to time i have to do some things outside. Malfunction of some shots .. it is a reality of experiment like this. We here encounter these problems with the same probability. It is very difficult to identify the origin of these "shots". I\_p .. I have calibration to multiply it with 0.55. Note that I must admit that we plan recalibration of this data.  
[2010.01.14. 11:38:44] svobovoj: Thing are here OK. Go on ..  
[2010.01.14. 11:40:25] Refy Daniel: is the calibration factor 0.055, isn't it?  
[2010.01.14. 11:40:46] svobovoj: Sorry, .. of course  
[2010.01.14. 11:42:25] svobovoj: Do you intend to finish it within two shots?  
[2010.01.14. 11:43:21] gergo\_pokol: if you have time, we would try some other ones

[2010.01.14. 11:43:30] svobovoj: OK

[2010.01.14. 11:45:55] Refy Daniel: i have a couple of questions

[2010.01.14. 11:46:41] gergo\_pokol: the questions:

[2010.01.14. 11:48:31] Refy Daniel: gergo asks the questions

[2010.01.14. 11:48:56] Refy Daniel: can we make another sequence?

[2010.01.14. 11:49:06] Refy Daniel: 9 shots

[2010.01.14. 11:50:40] gergo\_pokol: 1: For the Hugill diagram, we would like to have a rough estimate of average electron density. This we imagined to calculate from H2 pressure using ideal gas approximation and full ionization. Do you have a rough estimate of pre-shot gas temperature? What is your opinion about this estimate?

[2010.01.14. 11:52:07] gergo\_pokol: 2. Chamber temperature is relative to room temperature?

[2010.01.14. 11:55:01] gergo\_pokol: Are you there? Can we proceed with the shots?

[2010.01.14. 11:56:18] gergo\_pokol: I suppose, "OK" meant, that we can proceed.

[2010.01.14. 11:56:55] svobovoj: Hi, I am back again

[2010.01.14. 11:56:56] gergo\_pokol: waiting.

[2010.01.14. 11:57:17] gergo\_pokol: can we go on with the shots?

[2010.01.14. 11:57:39] svobovoj: Yes, go on

[2010.01.14. 11:58:06] gergo\_pokol: started.

[2010.01.14. 11:59:10] Refy Daniel: can we make some vacuum shots with different chamber tempertaure after these shots?

[2010.01.14. 12:02:26] svobovoj: Unfortunately I have no idea about H2 pre-shot temperature, because the chamber is filled from the reservoir with the pressure \approx 100 bar. Volume is 10 litres, The chamber volume is approx 80 litres. So ... equation of state for the first rough approximation? Chamber temperature is relative to room temperature.

[2010.01.14. 12:03:17] svobovoj: Yes we can heat the chamber up to 200 grades of Celsius

[2010.01.14. 12:04:33] gergo\_pokol: before doing that

[2010.01.14. 12:05:17] gergo\_pokol: do you think, it is possible to operate GOLEM in the runaway limit?

[2010.01.14. 12:13:24] Refy Daniel: we thought that we will reach the runaway limit with low  $U_b$  and high  $U_e$  but it seems we did not

[2010.01.14. 12:13:37] Refy Daniel: can we lower the H2 pressure?

[2010.01.14. 12:13:51] svobovoj: Yes

[2010.01.14. 12:14:00] Refy Daniel: what is the minimal H2 pressure?

[2010.01.14. 12:14:20] svobovoj: Moment

[2010.01.14. 12:21:59] Refy Daniel: i made a runaway sequence with max  $U_e$ , min  $U_b$  and varying pressure 'seq0 10 50'

[2010.01.14. 12:22:21] Refy Daniel: can i start?

[2010.01.14. 12:26:09] svobovoj: No it has not sense

[2010.01.14. 12:26:46] Refy Daniel: what is the problem with it?

[2010.01.14. 12:26:56] Refy Daniel: pressure too low?

[2010.01.14. 12:28:12] svobovoj: It is nonlinear electromagnetic ventill, by my opinion 0, 10 and 50 will be the same, better, let's say, try e.g. 60 62 64

[2010.01.14. 12:28:48] Refy Daniel: ok

[2010.01.14. 12:29:09] Refy Daniel: i try, and a vacuum shot as well

[2010.01.14. 12:30:46] Refy Daniel: can i start?

[2010.01.14. 12:31:05] svobovoj: I'll check it, momnet

[2010.01.14. 12:31:27] svobovoj: Go ..

[2010.01.14. 12:35:16] svobovoj: 40 mPa is a surprise for me now ..

[2010.01.14. 12:35:37] gergo\_pokol: it is interesting.

[2010.01.14. 12:35:58] gergo\_pokol: what is your conclusion about this shot?

[2010.01.14. 12:36:21] svobovoj: So You can go even down 54 56 58

[2010.01.14. 12:37:12] gergo\_pokol: Can you interpret this  $I_p$  time series?

[2010.01.14. 12:43:29] Refy Daniel: i try another runaway seq with those lower pressures, you advised!

[2010.01.14. 12:43:34] Refy Daniel: ok?

[2010.01.14. 12:47:24] gergo\_pokol: if your time is up, just tell us, and we can go on in a later occassion.

[2010.01.14. 12:52:03] svobovoj: Sorry, I have a student here. You can go on

[2010.01.14. 12:54:55] svobovoj: I think we have reached the limit here

[2010.01.14. 13:01:30] Refy Daniel: no plasma at these shots

[2010.01.14. 13:01:53] Refy Daniel: i try pH2 in 58 59 60

[2010.01.14. 13:01:58] Refy Daniel: ok?

[2010.01.14. 13:01:59] svobovoj: OK

[2010.01.14. 13:08:45] Refy Daniel: do you have more time for us now? we would like to make some vacuum shots with varying chamber temperature

[2010.01.14. 13:11:18] svobovoj: half an hour, I have one more measurement with our seniors and one measurement from Costa Rica in the evening. So .. 50 100 150 200 grades will be OK?

[2010.01.14. 13:12:45] Refy Daniel: 100 and 200 will be far enough

[2010.01.14. 13:14:01] Refy Daniel: we will run the vacuumseq on both temperatures

[2010.01.14. 13:14:02] svobovoj: Now I will heat the chamber. You can see evolution here .. The third graph: <http://golem.fjfi.cvut.cz/cgi-bin/golem/aktual/index.cgi>. DO NOT make shots during the heating. I will tell you, prepare only the one row in makefile.

[2010.01.14. 13:14:26] Refy Daniel: ok

[2010.01.14. 13:14:56] svobovoj: Started ..

[2010.01.14. 13:17:07] svobovoj: Please, after we finish .. there are two unusual "conclusion" habits besides the report. If you are satisfied and willing, then please, fill the form <http://golem.fjfi.cvut.cz/hodnoceni.html> how you enjoy the measurement and add your comments, remarks and proposals. Secondly, please send a postcard from the "town of measurement" to the address: Tokamak GOLEM, Brehova st. 7, Prague 1, Czech republic. Thank you in advance

[2010.01.14. 13:18:20] gergo\_pokol: fair enough!

[2010.01.14. 13:19:31] svobovoj: Now you can try the first shot .. 100 grad. C

[2010.01.14. 13:19:40] Refy Daniel: i start

[2010.01.14. 13:21:14] svobovoj: OK, I continue heating, do not make shots ..  
[2010.01.14. 13:21:18] Refy Daniel: well done  
[2010.01.14. 13:21:21] Refy Daniel: ok  
[2010.01.14. 13:22:43] svobovoj: heating on again ..  
[2010.01.14. 13:31:00] Refy Daniel: can i start?  
[2010.01.14. 13:31:09] svobovoj: moment  
[2010.01.14. 13:33:12] svobovoj: go on  
[2010.01.14. 13:33:28] Refy Daniel: started  
[2010.01.14. 13:34:29] svobovoj: It went down very quickly, I will go up to 200 once more again  
[2010.01.14. 13:35:02] Refy Daniel: ok  
[2010.01.14. 13:40:57] svobovoj: 1621 was bad!  
[2010.01.14. 13:41:31] Refy Daniel: yes...  
[2010.01.14. 13:41:53] Refy Daniel: can i start the next shot?  
[2010.01.14. 13:42:14] svobovoj: go  
[2010.01.14. 13:44:04] Refy Daniel: well done  
[2010.01.14. 13:44:15] svobovoj: So 72 shots for Budapest, ok, can we finish?  
[2010.01.14. 13:44:25] Refy Daniel: yes, thank you!  
[2010.01.14. 13:45:45] svobovoj: Best regards, I am looking forward to your report (and postcard). And you are welcome for the next time. You are the very first so heavily working remotely on the GOLEM tokamak. Thank you. Vojtech Svoboda  
[2010.01.14. 13:46:09] gergo\_pokol: Thank you for the opportunity! Best regards!  
[2010.01.14. 13:46:33] Refy Daniel: best regards! have a nice day!  
[2010.01.14. 13:46:34] Refy Daniel: bye  
[2010.01.14. 13:46:41] svobovoj: Bye