Comments on measurement of the current and the loop voltage on GOLEM (an example of a shot without plasma)

The measured loop voltage is composed from an inductive and resistive component

$$U_{loop} = U_{res} + U_{ind} \quad \text{where } U_{res} = I_{lin} R_L \qquad U_{ind} = L_L \frac{dI_{lin}}{dt} \tag{1}$$

According [1], the resistance of the vacuum vessel – liner is $R_L = 0.092\ \Omega$ and the inductance $L_L = 0.5\ \mu H$..

In contrast to measurements on early CASTOR (in the year 1985), the loop for measurement of the U_{loop} is not fixed at the surface of the liner, but located above it at a distanceD = ?? m, as seen in Fig. 1. In fact, two loops were used on CASTOR to determine the toroidal electric field inside the liner as

$$\overline{U}_{loop} = (U_{outer} + U_{inner})/2 = E_{tor} 2\pi R_0 \tag{2}$$

where R_0=0.4 m is the major radius of the liner.

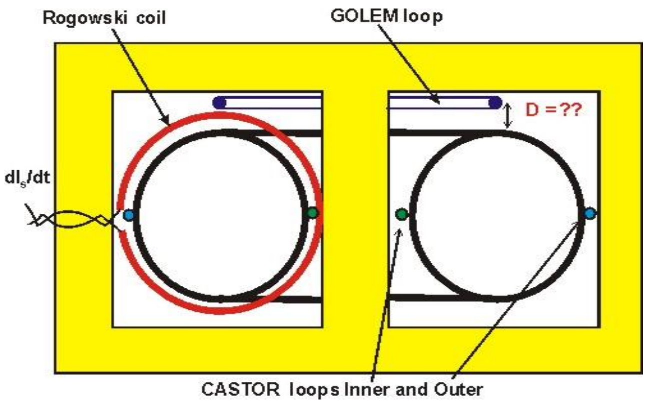

Fig. 1: *Rogowski coil and a measuring loop for U_{loop} on GOLEM/CASTOR*

It is evident that the coupling between the measuring loop and the liner is not ideal on GOLEM and we can expect a slight deviation between the measured signal from the loop and the real U_{loop} (electric field) on liner.

The toroidal current (of the liner or of the plasma) is measured by the Rogowski coil, RC.

An example of measured signals for the vacuum shot #1598, is shown in Fig. 2. The OH capacitor bank is charged to U_{OH} = 300 V in this case.

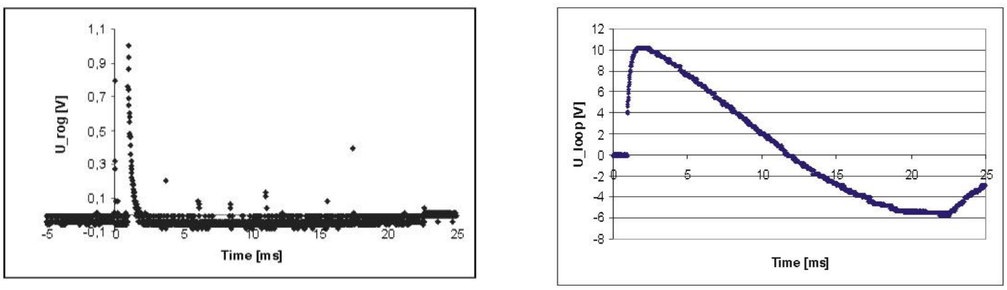

Fig. 2: *Left – signal of Rogowski coil. Right – the loop voltage. #1598, U_{OH} = 300 V*

The AD convertors are switched in t = - 5 ms. The capacitor bank for the toroidal magnetic field, BT, is switched on in t = 0. The OH capacitor bank is switched on with a time delay t = 1 ms with respect to BT. The output signal of the Rogowski coil U_{rog} is proportional to the time derivative of the liner current as

$$\frac{dI_s}{dt} = kU_{rog} \qquad (3)$$

where the constant k is k = 5.4 10^6 A/Vs. This value was determined either by calculation based on the construction of the RC, or by a precise calibration using a known current. Both was done by F Zacek on CASTOR (private communication).

The left panel in Fig 3 shows the evolution of the time derivative of the liner current calculated from eq. 3,

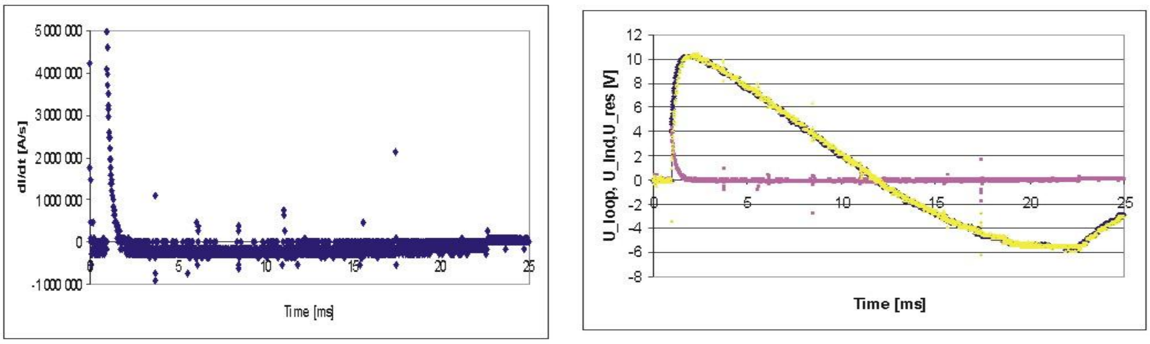

Fig. 3: *Left: Evolution of the time derivative of the liner current. Right: red – the inductive component of the loop voltage, yellow –the resistive component of the loop voltage, black – measured* U_{loop}.

It is seen that the dI_{lin}/dt reaches its maximum ~5 MA/s (5 kA/ms) at about 1-2 ms after switching on the OH bank for this shot. During the remaining time of the shot is dI_{lin}/dt much less and negative (~ -0,2 MA/s). Therefore, the inductive component U_{ind} is significant just during the start-up phase (assuming L_L = 0.077 μH). It is evident from the right panel of Fig.3 that the resistive component of the loop voltage ($U_{res} = U_{loop} - U_{ind}$) is practically identical with the measured loop voltage everywhere except the start-up.

We are interested in the absolute value of the liner current, which is calculated by numerical integration of the RC signal. At first, let us look at the raw signal of RC in more detail – see fig. 4.

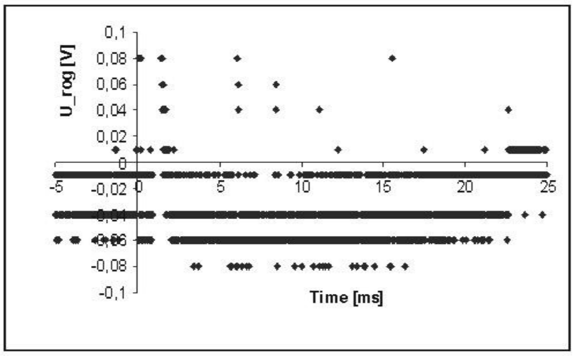

Fig. 4: *Signal of RP - the vertical scale is significantly amplified in contrast to fig. 3.*

It is evident that the digitalization of the RC signal is not correct, because individual levels of the ADC are comparable with the average level of the measured signal (except the start-up pase). Therefore, either a more sensitive ADC, or an amplifier of the RC signal has to be used before digitalization in future. Note also that the level around -0,03 V is missing for some reasons??!!!

The signal of RC is integrated numerically n GOLEM. The correct integration requires to subtract the offset of the signal U_{off}, which is between -0.02 – -0.04 V at t < 0, as apparent in fig. 4.

$$I_{n+!} = I_n + k(U_{n+1} - U_{off})\Delta t \quad (4)$$

where Δt is the sampling time Δt = 10 μs. Now, the offset is calculated as an average value of the first 450 samples. It is clear from Fig. 4 that this procedure is not sufficiently precise. For the shot # 1598 the offset is U_{off} = 0.02242 V, which is comparable with the level of the signal at > 3 ms. We show later that such offset yields a wrong result of the numerical integration. Nevertheless, the resulting liner current, determined according eq. 4, is shown by the black line in fig. 5.

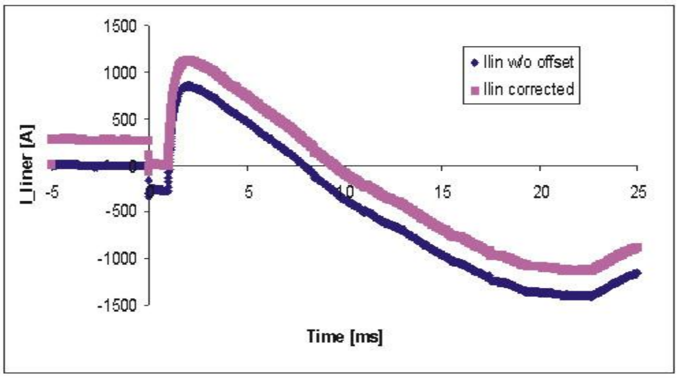

Fig. 5 *Evolution of the liner current. Black –the offset is an average of the first 450 samples. Red – result is "artificially" shifted to has* I_{lim} *= 0 before switching on the OH bank.*

It is seen that such calculation of the offset, the current is correctly equal zero at t < 0. However, after switching on of the BT, a jump of I_L (roughly by –277 A) is observed. This jump is caused by numerical integration of the spike, which is induced to the RC at the time of activation of the thyristor of BT. This jump is removed "by hand" and the result is shown in fig. 5 in red.

To avoid problems with this artificial shift, we suggest to calculate the offset differently as a average of the raw signal in the time interval

$$\Delta t = \langle t_1 ; t_2, \rangle$$

where

$t_1 = t_{BT}$ + several samples during the induced spike of the BT thyristor

$t_2 = t_{OH}$ – several samples before switching OH

The offset for the shot #1598, calculated as an average of the RC signal from 510 to 590 samples is U_{off} = - 0.0256 V. The numerical integration starts at the time t_1 and the result is shown in fig.6. by the black line.

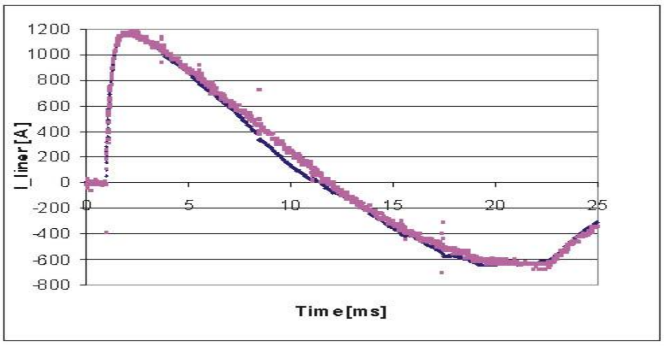

Fig. 6: *Evolution of the liner current. Black – The offset is calculated as an average between the samples 510 and 590, i.e. in the time interval between switching on the BT and OH banks. Red – Evolution of the resistive component of the loop voltage divided by R_{lin} = 0,0087 Ohm..*

The red line in fig 6 is the temporal evolution of the resistive component of the loop voltage divided by a resistance R_{lin}. The best agreement between these two curves is achieved, if we select R_{lin} = 0,0087Ohm.

Conclusions and recommendation

1. The calibration constant of the Rogowski coil is k = 5.4 x 10^6 A/(Vs)
2. How many bits has the ADC and what is its dynamic range???
3. The signal of the RC must be amplified before the ADC (at least by 5 – 10x).
4. Why some level at the output of AD converter is missing??
5. The offset signal for numerical integration of signals has to be calculated precisely. This is important namely for plasma shots. Bad offset = bad temporal evolution of the toroidal current.
6. The inductance of the liner is fund to be 0.77 μH. It agrees well with results of Hungarian practicum 0.75 μH. This value is a bit higher then reported in [1], L_{lin} = 0.5 μH. The difference can be caused by different location of the loop, which measures the U_{loop}.
7. The resistance of the liner is found to be R_{lin}.= 0,0087Ohm, which is close (but less by ~ 5%) to that, which was measured on CASTOR in [1], $R_{L(VALOVIC)}$ = 0.0092 Ohm. The difference is again caused by a different location of the loop, which measures the U_{loop}.

Jan Stockel, 15.3.2010

[1] M. Valovic, *An Ohmic Heating Circuit for the CASTOR tokamak*, Czech J Phys, 40, 1090, p. 673