Instructions for student measurements on the GOLEM tokamak using magnetic pick-up coils

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Abstract

The instructions present a 6 hour measurement program making use of the remote measurement potential of the GOLEM tokamak located at the Faculty of Physical and Nuclear Engineering of the Czech Technical University (CTU). The purpose of the measurement is to demonstrate the basic usage of the magnetic pick-up coils including plasma position monitoring and fluctuation measurements. Students are assumed to have done the Basic tokamak operation laboratory exercise preceding this practicum.

1 Introduction

A standard method for measuring the changes of magnetic field inside the plasma is a magnetic coil. Turn a piece of wire into a loop and you obtain the simplest coil for measurement of magnetic field. Increasing the number of turns of the coil, or making a larger loop higher sensitivity can be reached. Magnetic pick-up coils are small coils designed for the measurement of a component (typically poloidal or radial) of the local magnetic field.

Coils measure changes of the magnetic field and not the magnetic field directly. As a result, the voltage changes measured on the coils have to be integrated in time to be proportional to the magnetic field. In the case of fluctuation measurements is not necessary to perform the integration, one can also study the fluctuation of the time derivative of the magnetic field.

2 Magnetic pick-up coils on GOLEM

On GOLEM two sets of Mirnov coils - pick-up coils measuring the poloidal magnetic field component - are available. The first system consists of 4 magnetic coils placed inside the chamber in the distance of 93 cm from the magnetic axis as seen on figure 1. The effective area of each coil is $3,8\cdot 10^{-3}/;/rmm^2$. Ideally, their axes are perpendicular to the toroidal magnetic field, but actually they are slightly tilted and sensitive to the variations in the toroidal field, too.

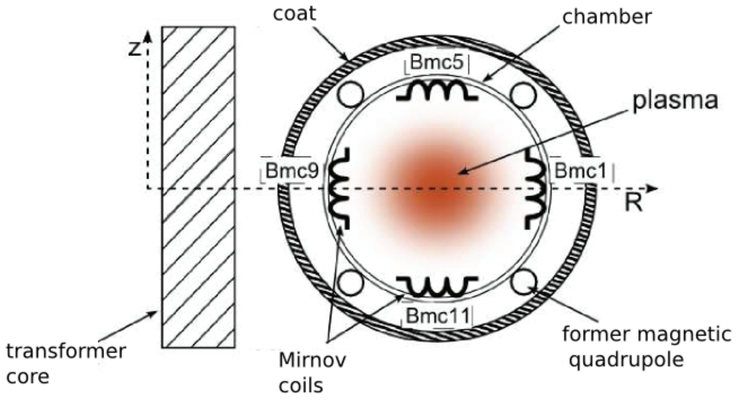


Figure 1: Poloidal cross-section of the tokamak with the places of the 4 Mirnov coils.

Recently a new system with 16 Mirnov coils (see figure 2) has been installed on GOLEM. This sensor array massively enhances possibilities of detection of large scale plasma wave activity in the tokamak.

3 Measurement procedure

This section summarizes the technical procedures necessary for the remote control of the GOLEM tokamak.

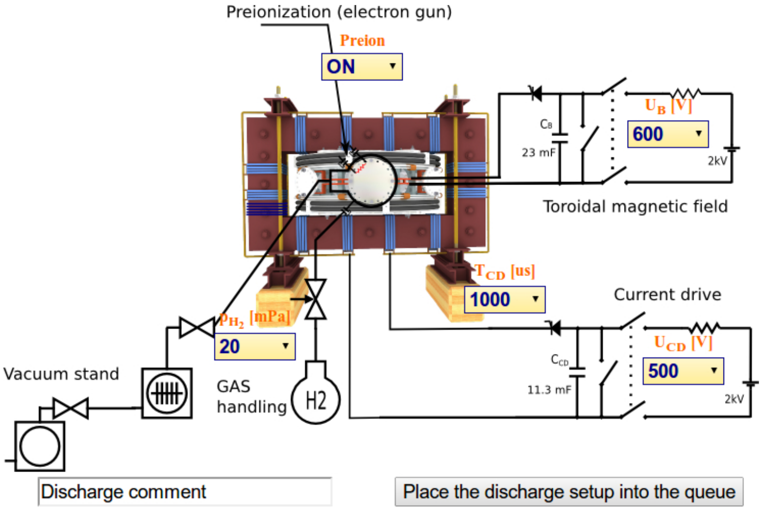
Figure 2: New set of local magnetic field sensors: 16 Mirnov coils circling the plasma column.

3.1 Communication with local support

Primary real time communication to the local support (Dr. Vojtech Svoboda) is through Skype instant messaging. For this purpose a user (name: nti.hallgato, passwd: vendeg0 or name: nti.hallgato2, passwd: vendeg1) has been created. Before starting the experiment an instant messaging conference is to be started including users nti-hallgato, gergo_pokol (Dr. Gergo Pokol, Hungarian supervisor) and tokamak.golem (Dr. Vojtech Svoboda, Czech support). After the session the conversation log should be saved and appended to the measurement log.

3.2 Remote control

Measurements are to be set up and shots initiated using the web interface of GOLEM tokamak, which can be seen on figure 3. The exact url address of it is provided by Dr. Vojtech Svoboda just at the beginning of the session.



Preion: ON

U_B [V]: 600

T_{CD} [us]: 1000

P_{H_2} [mPa]: 20

U_{CD} [V]: 500

Figure 3: Remote control interface of GOLEM tokamak.

3.3 Remote data access

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 are collected at a page to be reached at:

`http://golem.fjfi.cvut.cz/operation/currentsession/`

during the session and later archived at:

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

A MATLAB (OCTAVE) package is available for calculating main plasma parameters. These routines are to be modified to access the signals of the magnetic pick-up coils based on parameters provided by Dr. Vojtech Svoboda.

4 Plasma position monitoring

The determination of the plasma position is one of the basic tasks during the tokamak operation. Plasma tends to expand in the direction of the major radius and move in random directions influenced by various electric and magnetic fields, which are created during the discharge. The Mirnov coils are used for the determination of the plasma position on GOLEM. Present exercise aims to characterize the movement of plasma in various discharges. About a total of **15** discharges are available for this exercise.

4.1 The straight conductor approximation

It is hard to express the magnetic field analytically in a toroidal plasma geometry, therefore we take the approximation of an infinite long straight plasma column. From Ampere's law ($\nabla \times B = \mu_0 j$) it follows that the generated poloidal magnetic field decreases with distance from the column's axis as $1/r$. If we measure the poloidal field on the two opposite sides of the column, its displacement can be expressed as

$$\Delta = \frac{B_{\theta=0} - B_{\theta=\pi}}{B_{\theta=0} + B_{\theta=\pi}} \cdot b \ , \tag{1}$$

where $2b$ is the distance between the opposite measurement positions. This approximation is simple, but of sufficient accuracy for demonstration purposes.

The plasma movement is to be reconstructed in all the discharges in both the vertical and horizontal directions. Most frequent directions of movement and dependence on plasma parameters are to be studied.

4.2 Estimation of the edge safety factor

The tokamak magnetic field consists of such nested magnetic surfaces, each surface characterized by a safety factor (q). On large aspect ratio circular tokamaks (like GOLEM), where the major radius (R) is much larger than the minor radius (r_0), it can be approximated by:

$$q(r,t) = \frac{r}{R}\frac{B_t(t)}{B_p(r,t)}, \tag{2}$$

where R is the major radius of the magnetic axis and r is the distance of the magnetic surface from the magnetic axis.

In the *Basic tokamak operation laboratory exercise*, the edge safety factor has been already investigated. In that case the radius of the limiter was used instead of the real, time-dependent minor radius of the plasma ($r = r_0(t)$). Using the position of the plasma center, the minor radius of the plasma and the edge safety factor can be calculated considering that, the plasma is bounded by the limiter. Discharge evolution is to be visualized on Hugill diagrams with the corrected edge safety factor for every discharge. Most interesting discharges are to be analyzed in detail.

5 MHD mode measurement

Although several tokamaks rely on magnetic pick-up coils for plasma position measurements, their most typical application is to characterize large-scale plasma fluctuations. Due to their finite size and distance from the plasma, pick-up coils are most sensitive to the current variation of macroscopic plasma fluctuations with spatial structure comparable to the size of the machine. Fluctuations in this order of magnitude are most often described by the magneto-hydrodynamic (MHD) theory - treating the plasma as a single conductive fluid.

MHD waves are typically localized around specific magnetic surfaces, but extend to the whole of the tokamak in the toroidal and poloidal directions. In the poloidal and toroidal directions the plasma has periodic boundary conditions, which allows waves with discrete spatial spectrum in these directions characterized by the appropriate mode numbers. The excursion vector $\xi(r, \Theta^*, \phi, t)$ of an MHD eigenmode is described by the following formula:

$$\xi(r, \Theta^*, \phi, t) = \xi(r, \Theta^*) \exp\left[i(m\Theta^* - n\phi - \omega t)\right], \tag{3}$$

where Θ^* is an appropriately chosen poloidal angle and ϕ is the toroidal angle coordinated, $\xi(r, \Theta^*)$ is the amplitude, which can change sign only as function of r; m and n are the poloidal and toroidal mode numbers, respectively, and ω is the mode frequency. Positive or negative sign of m and n mode numbers determines the direction of propagation (or rotation) of the mode.

There is no fail-safe procedure to excite strong MHD eigenmodes at GOLEM, but they tend to appear in several plasma parameter regimes. **15** discharges are available for this purpose, while time intervals with strong fluctuation are to be selected by looking at the Mirnvo coil raw signals in sufficient detail.

5.1 Determination of the mode numbers

Mirnov coils measure the magnetic field fluctuation at their location, but the currents inducing the magnetic field can be at arbitrary location, which makes it a non-localized measurement. However, the current perturbation gives a magnetic response decaying with the distance, so the current perturbation can be assumed to be near the point of the magnetic surface closest to the Mirnov coil. This way, we can associate a toroidal and a poloidal coordinate to the coils. Localization in the radial direction is usually not possible.

During the coarse of the present exercise, we are going to approximate Θ^* as the geometrical poloidal angle of the probes with respect to the axis of the vacuum chamber. This approach neglects the movement of the magnetic axis and the deformation of the mode structure due to the gradient of the magnetic field, but is still sufficient to see the structure of the MHD eigenmodes.

If we plot signals from a time interval with strong fluctuations with a time axis that allows us to see the periodic changes, we can realize that there is a fixed phase between the oscillation in the different channels. By plotting the signal amplitude on the color scale on the poloidal angle - time plane, we see inclined ridges of maxima and minima (see e.g. Figure 4) . By counting the maxima in the poloidal direction at a given time point, one can determine the poloidal mode number. The goal is to find at least 5 cases, where a mode number can be determined by this procedure. Aim is to study a variety of frequencies and mode numbers.

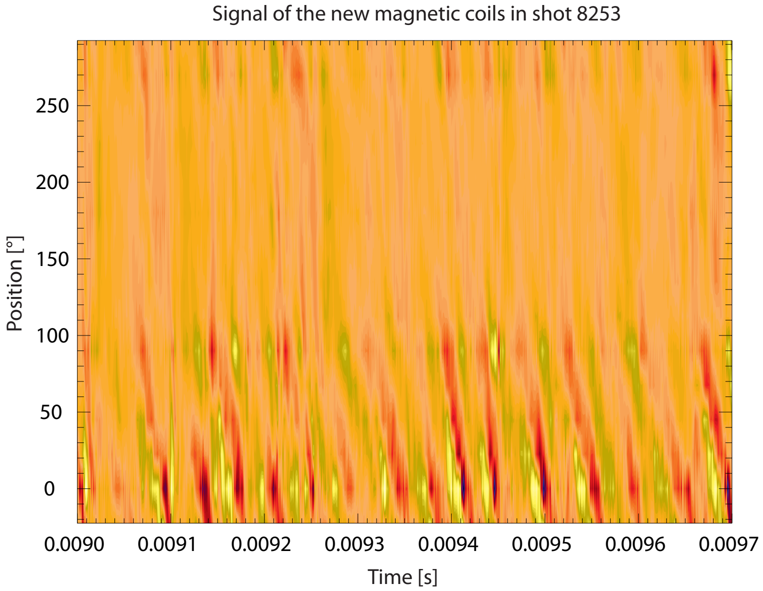


Figure 4: Raw signal of magnetic field sensors in shot 8253 [1].

5.2 Analysis in the frequency domain

MHD modes are often studied in the time domain - as above -, but having discrete frequency fluctuations it is quite natural to transfer the problem into the frequency domain. This transform is traditionally done by taking the Fourier transform of a quasi-stationary time interval. Fourier transform is implemented in discrete signal processing by the FFT algorithm. By taking the absolute value squared of the FFT, we get a spectral power density with the frequency axis going from negative to positive Nyquist frequency (half of sampling frequency). For real signals - like in our case - the spectrum is symmetrical with respect to the zero frequency axis, so we shall only plot the positive frequencies. The first task in frequency domain analysis is to produce the spectrum for a suitable time interval and identify the mode frequency or frequencies.

By producing the power spectra we have dropped the phase information in the signals, which is, however, extremely useful for the identification of fixed phase relations between signals measured by detectors in different spatial locations, and therefore to identify the spatial structure of the magnetic perturbations. At GOLEM we have a poloidal array of Mirnov coils, which makes it possible to determine of the m poloidal mode number of expression **??**. Relative phases (ξ) between signals can be calculated as the complex phase of their cross-transforms defined by expression 4.

$$\xi_{x,y}(\omega) = \arg\left(Fx(\omega)Fy^{*}(\omega)\right), \tag{4}$$

where $Fx(\omega)$ and $Fy(\omega)$ denote the Fourier transforms of signals $x(t)$ and $y(t)$ and $.^{*}$ marks the conjugate.

The only difficulty working these phases is that they are undetermined by a factor of $2\pi k$, where k is an integer. A way to overcome this problem is to arrange the phases with $2\pi k$ shifts to show monotonic increasing or decreasing trend as a function of the angular position of the corresponding Mirnov coil with respect to a reference probe. The last probe of such arrangement should be the reference probe itself with the corresponding 2π relative position. The poloidal mode number is determined by the $2\pi m$ shift of the reference probe. This method gives a positive and a negative mode number for every frequency depending on our selection of the increasing or decreasing trend, respectively. This is regardless of having a mode at the given frequency or not. If the method with different reference probe selection gives the same mode number, it is a good indication that the mode is really there. Also, mode numbers must be significantly smaller than the number of probes in the array used.

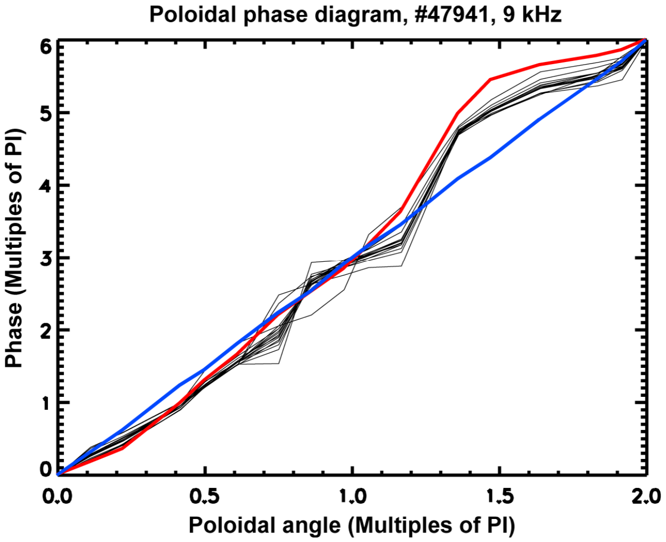


Figure 5: Example of determination of mode number from cross-spectrum phases. ($m = 3$ in Wendelstein 7-AS shot #47941 at 9 kHz) [2]

Figure 5 shows such a mode number reconstruction for the Wendelstein 7-AS stellarator: black curves connect the phases arranged in monotonically increasing order by adequate 2π shifts for different choices of reference probes, blue curve shows the ideal trend for an $m = 3$ mode if the probe positions were exactly given in the Θ^* coordinate of the MHD mode (see formula 3, and the red curve is the result of a modeling in real magnetic geometry. It can be concluded that the deviation from the ideal phase curve is due to the deviation of the magnetic Θ^* coordinate from the geometric poloidal coordinate of the Mirnov coils. A similar deviation is expected at GOLEM.

The task is to plot the relative phases between probes arranged in appropriate monotonic trend for the peaks identified in the spectrograms. Mode numbers should be attempted to be identified and compared to the ones determined from the time-domain analysis.

6 Logbook requirements

There should be a single measurement log written in English language. The measurement log should include:

- Exact method of executing the measurement.
- Exact method of derivation of final results.
- Results of the measurement tasks.

- Time traces of shot parameters for some characteristic shots.
- Shot summary table indicating all calculated parameters of all shots executed. (Unsuccessful shots also need to be recorded.)
- Skype log as appendix

All comments and proposals regarding the measurements are welcome.

It would be nice, if the participants of the session would write some thankful words to the `http://golem.fjfi.cvut.cz/hodnoceni.html` homepage, and/or send a postcard to the following address: Tokamak GOLEM, Brehova st. 7, Prague 1, Czech Republic. These activities should also be indicated in the logbook.

References

[1] L. Horvath. *Log-book of GOLEM visit*, May 2012.

[2] G. Papp, G. Pokol, G. Por, S. Zoletnik, and W7-AS Team. Investigation of transient MHD modes of Wendelstein 7-Advanced Stellarator. In *Proceedings of the International Youth Conference on Energetics, (31 May - 2 June 2007, Budapest, Hungary)*, page 109, 2007.