TrainingCourses/GOMTRAIC/13/MHD/index

Contents

Report on MHD studies

Introduction

The GOMTRAIC 2013 MHD team measured the mode number of magnetic islands appearing in the plasma of GOLEM tokamak by using magnetic diagnostics. In this report, basic theory, measurement setup and results are presented.

Basics of the theory

Magnetohydrodynamics (MHD) studies the dynamics of electrically conducting fluids, like plasma. MHD provides a good theoretical framework to describe inhomogeneities such as magnetic islands. They are present where the poloidal magnetic field flux is perturbated. At the top of the figure below, a cross section was taken of the nested poloidal magnetic flux surfaces. On these surfaces, poloidal magnetic field flux, pressure (p), temperature (T) and plasma current (J) are constant. If inhomogeneities are present, the situation changes to the one present at the bottom of the figure. Now p,T and J are short circuited where the lines intersect. As this changes plasma behavior, it is important to know where and when this happens.

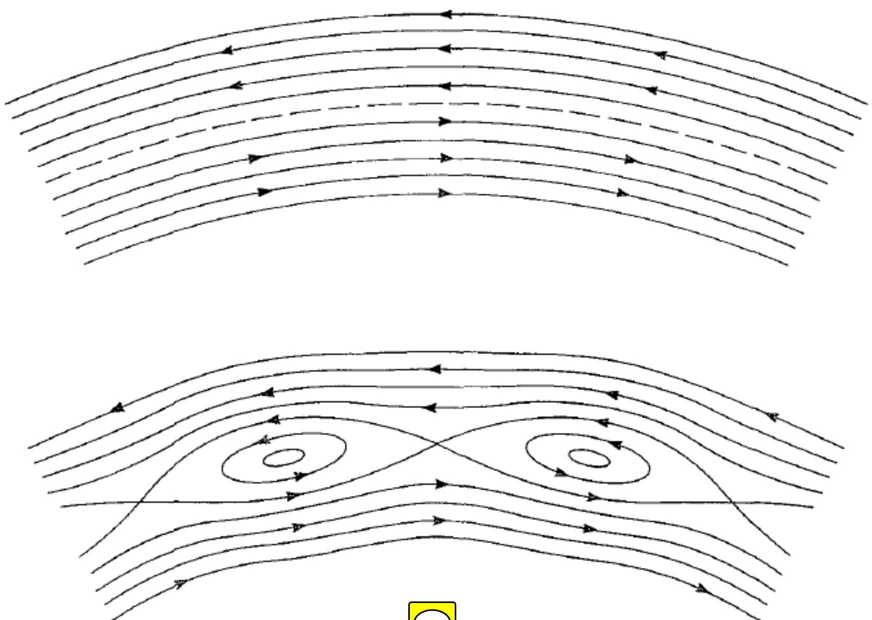

Figure 1:

These islands manifest at low safety factor q, a key parameter in MHD that gives you the number of toroidal loops for one poloidal loop. The safety factor is than equal to m/n, where m and n are natural numbers. As for GOLEM tokamak, n can be put equal to one, islands will appear if q = m. Mode number m than corresponds to the number of intersections defined above. For example, for m = 3 we get a poloidal cross section of the plasma's poloidal magnetic field flux like the one below.

Principles of the measurement

In a typical shot, magnetic islands can be identified by detection of the poloidal magnetic field temporal evolution along poloidal angle thanks a set of many sensors of local magnetic field sensors.

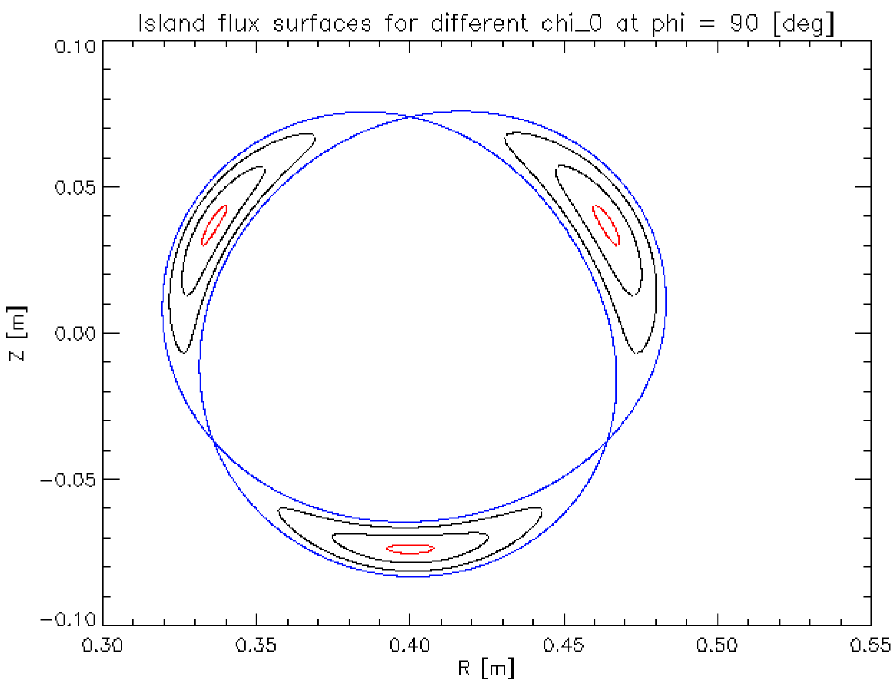

Figure 2: alt text

In GOLEM, 16 tangential magnetic probe (Mirnov coils) are installed to detect poloidal magnetic field B_θ inside the vacuum vessel.

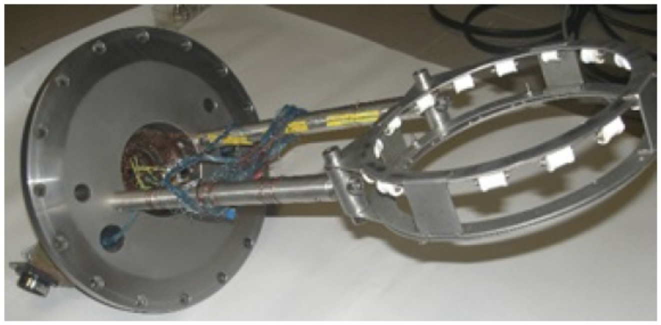

Figure 1: *Set of 16 Mirnov coils mounted in a poloidal ring to work like sensors of local magnetic field.*

Figure 3: alt text

Magnetic coil is term used for inductive sensor for magnetic field measurement based on Maxwell equations. In a region free of charges ($\rho = 0$) and no currents ($J = 0$), such as in a vacuum, Maxwell's equations reduce to:

$\nabla \cdot \mathbf{E} = 0$ Gauss's law

$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ Maxwell-Faraday law

$\nabla \cdot \mathbf{B} = 0$ Gauss's law for magnetism

$\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$ Ampere's circuital law

where c is the speed of light in vacuum.

Even though magnetic coil is used as a magnetic field sensor, it measures rate of change of magnetic induction B_θ instead of the quantity itself. This is because its principle of operation is based on integral form of Faraday's law.

The Maxwell - Faraday law establish that a time-varying magnetic field is always accompanied by a spatially-varying,non- conservative electric field, and vice-versa.

$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

where $\nabla\times$ is the curl operator and again $\mathbf{E}(r,t)$ is the electric field and $\mathbf{B}(r,t)$ is the magnetic field.

It can also be written in an integral form by the Stokes theorem

$\oint_{\partial\Sigma} \mathbf{E} \cdot \mathbf{dl} = -\int_{\Sigma} \frac{\partial \mathbf{B}}{\partial t} \cdot \mathbf{dA}$

where Σ is a surface bounded by the closed contour $\partial\Sigma$, E is the electric field, B is the magnetic field, dl is an infinitesimal vector element of the contour $\partial\Sigma$, dA is an infinitesimal vector element of surface Σ.

Changing the magnetic flux in a circuit generates a current; the direction of this current is in a direction such as to set up a magne tic flux opposing the change. The integral on the left-hand side is the electromotence or voltage $\hat{V}$ in Volts induced at the ends of the wire of coil and is equals the rate of change of $\Phi = \int B \cdot dS$ in Webers per second (product of effective area of coil S and time-derivation of averaged magnetic field magnitude in the coil B),thus mean value of B can be obtained from equation:

$$\hat{V} = -\frac{d\Phi}{dt} = -A_{eff}\frac{dB}{dt} \rightarrow dB = -\frac{1}{A_{eff}}\hat{V}dt$$

where $\Phi = B(t)A_{eff}$ is the magnetic flux and A_{eff} is the effective surface of each coils.

Experimentally $\hat{V} : \hat{V}(i)$ is a discrete signal and that voltage $\hat{V}$ obtained by the sensor will have to be integrated in order to obtain measured quantity of B.

$$B(t) \approx -\frac{\Delta t}{A_{eff}}\sum_i \hat{V}(i)$$

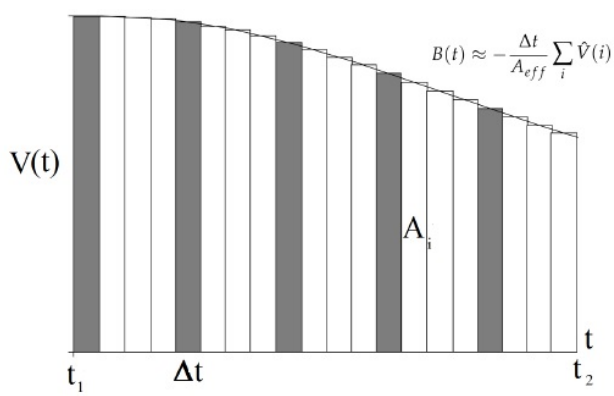

Figure 2: *Numerical integration consists of finding numerical approximations for the value* A_i

Figure 4:

where Δt is the sampling time.

Integrated magnetic measurements are very sensitive to the DC bias of the measurement circuit, which needs to be corrected for. If the sampling rate is 1 MHz, and the shot starts at 5 ms, we have 5000 samples from the background noise that we have to substracts.

$$\hat{V}(i) = V_{measured}(i) - \frac{1}{5000}\sum_{i=1}^{5000} V_{measured}(i)$$

The poloidal magnetic field perturbation is obtain eliminating a smooth signal from the original signal of the magetic field.

$$B_{per}(t) = B(t) - \text{smooth(B(t))}$$

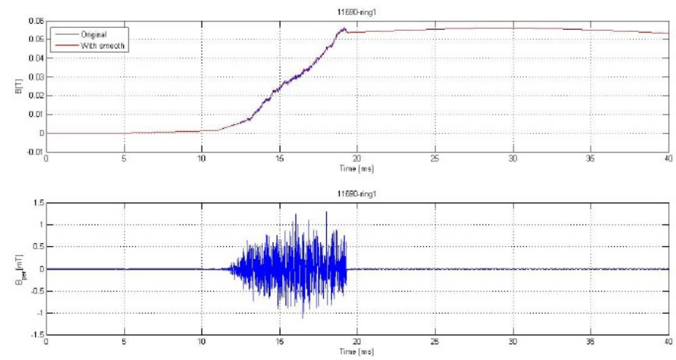

Figura 4: *Temporal evolution of the original magnetic field (blue, top panel), smooth magnetic field(red, top pannel) and the magnetic field perturbation for ring 1 obtain subtracting to the original magnetic field signal the smooth signal for the discharge # 11688.*

Figure 5:

There are currently 16 Mirnov coils placed on tokamak GOLEM. \

Each of the coils is enveloped by a ceramic cylinder made of porolite, for protection from plasma particles, as these coils are placed on a circular rack, put inside of liner. Locations of respective coils are depicted in fig. 4. Coils are placed on minor radius of 93.5 mm. Although Mirnov coils are used for measurement of poloidal field.

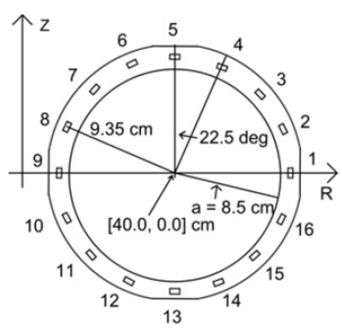

Figura 5: *On tokamak GOLEM, Mirnov coils is term used for small coils of local poloidal magnetic field measurement, placed inside of liner. The main purpose of Mirnov coils is for plasma MHD activity measurements.*

Figure 6:

There are three stated requirements that have to be met, for magnetic coil to become a reliable sensor of magnetic field:

- Have minimal perturbing efect on plasma column.
- Suficient sensitivity to overcome electric noise associated with electronics devices.
- High frequency response to follow even most rapid fluctuations of magnetic field perturbation.

However, these conditions are in confict with each other, since in order to rise sensitivity of sensor, efective area of the coil has to rise as well. For better frequency response, this area has to be in confguration of less numerous large loops, rather than large number of small loops. This, however, collides with the requirement of minimal perturbing efect on plasma.The effective area and polarity of all sensitivity of sensor are shown in the table 1.

Cuadro 1: *Characterization of Mirnov Coils*

Coil #	Polarity	A_{eff} $[cm^2]$	θ [º]	Coil #	Polarity	A_{eff} $[cm^2]$	θ [º]
1	-	68.93	0	9	-	67.62	180
2	-	140.68	22.5	10	+	142.80	202.5
3	+	138.83	45	11	-	140.43	225
4	+	140.43	67.5	12	x	x	247.5
5	-	68.59	90	13	x	x	270
6	+	134.47	112.5	14	x	x	292.5
7	-	134.28	135	15	-	139.82	315
8	+	142.46	157.5	16	-	139.33	337.5

Figure 7:

Maxwell eq, short description of magnetic diagnostics, links, Mirnov coil description

Measurement setup

geometry of the measurement, channel mapping, data acqiusition system, etc

Data processing methods

Fluctuation of raw data analysis (theta-time diagram)

We are trying to identify the mode number m and the frequency f from data because the analysis of temporal and spatial domain of Mirnov signal sensors can help us to the identification of f and m.

We have chosen shot # 11688 to explain the analysis of MHD modes using the set of Mirnov coils. Out of 16 probes, 13 probes where operational and have been used for the analysis because other 3 probe connections were inoperative. In figure 1, loop voltage, plasma current (in the unit of kA) and toroidal magnetic field measured by differents diagnostics methods.

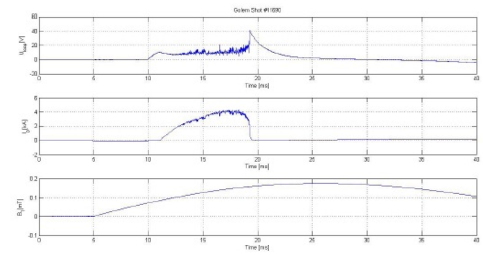

Figura 6: *Temporal evolution of whole discharge # 11688, with parameters: loop voltage (U_{loop}), plasma current (I_p) and toroidal magnetic field (B_{tor})*

Figure 8:

The perturbation of poloidal magnetic field it's given by:

$B_{per}(t) = B(t) -$ smooth(B(t))

For this shot and the ring 1 (magnetic sensor at $\theta = 0^o$) obtained:

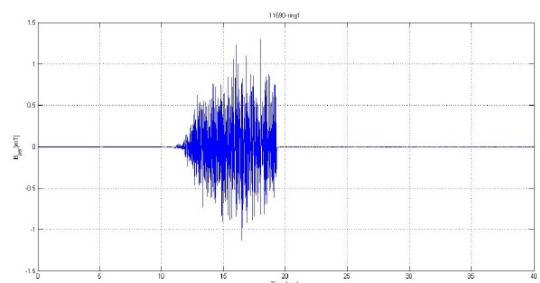

Figura 7: *Poloidal magnetic field perturbation obtain by numerical integration of the Mirnov Signal of the ring 1 for the shot # 11688. There are similar signals for all poloidal sensors at the poloidal ring.*

Figure 9:

Determining evolution in time of the magnetic field perturbation on distribution of local magnetic field sensors and then phase of oscillations between the different sensors doing θ-time diagram permit study the spatial and time behavior of a system in time and space domain.

In matlab we created a vector with the time data, another vector with the position of the polodial diagnostics and finally a vector containing B_{per} for each coil,the principal code in the matlab script was:

```
levels = linspace(-0.5e-3,0.5e-3,20);
contourf(tiempo(:,1),teta,MI,levels);
xlabel('Time(s)','FontSize',14);
ylabel('θ(deg)','FontSize',14);
colorbar
```

where tiempo is the time data vector,teta is the position vector (teta=[0,22.5,45,. . . .]) and MI is a 16x40000 matrix containing B_{per} data for each coil.

Applying this to the oscillation of poloidal magnetic field, one could estimate the mode number of the wave and so determine the number of magnetic islands appearing in the plasma. Figure 8 illustrates a typical ohmic discharge contour, with a edge safety factor is $q(a) = 3.4$ according to the edge magnetic diagnostics.

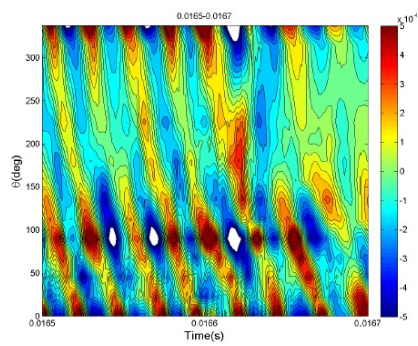

Figura 8: *Contour plot of the poloidal magnetic field oscillations in shot # 11688 and with a window time from 0.0165-0.0167 s, where the horizontal and vertical axes correspond to time and poloidal localization of the Mirnov coils. The red and blue region represent the oscillations positive and negative respectively. The color bar on the right side represents intensity of the poloidal magnetic field perturbation in T.*

Figure 10:

The method for the identification of f and m is count the number of oscillation maxima for one period time given time.

The m mode magnetic island has been directly obtained using θ-time diagram ohmic discharge for all discharges and the result are shown in table 2 .

It's proven that magnetic island informations are visible from the contour plot of poloidal magnetics field oscillations profile. Since the advantages of simple and

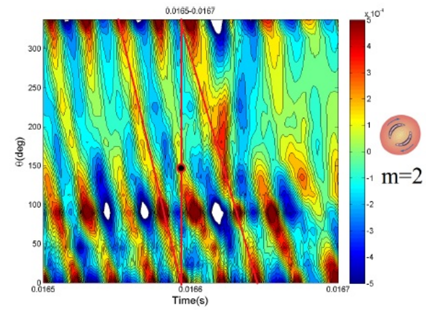

Figura 9: *Contour plot of the poloidal magnetic field oscillations in shot #11688 and with a window time from 0.0165-0.0167 s. To determinate m mode, search for a periodicity of a field line (red) and draw a vertical line and count how many maxima are "inside". The number mode m is equal to the number of maxima (minima) inside+1,in this case m=2.The big black dot mark one cut of the vertical line with a maxim inside.At the right we can see a scheme of the 2 magnetics islands who are rotating.*

Figure 11:

Cuadro 2: *Determination of m mode in the shots from the Kick-off week session*

Shot #	Island Index	$Time_d[ms]$	$Time_u[ms]$	Mode number m
11688	1	16.4	16.6	2
11689	1	14.8	15.0	2
11691	1	24.0	24.2	2
11691	2	25.8	26	2 or ¿3?
11692	1	25.3	25.5	2
11701	1	14	14.2	2
11702	1	15	15.2	2
11703	1	19.2	19.4	2
11704	1	21.7	21.9	1

Figure 12:

direct, it's proven that the θ-time diagram is an useful tool for the measurement of magnetic island .

- M = 1 island and the existence of plasma in the tokamak do not go together, even when considering the MHD ideal theory. This number is so suspect and that something in the data analysis could go wrong, for sure, we will repeat the shot in the coming sessions.

Spectrogram

Doing Fourier analysis, one can study the spatial and time behavior of a system in frequency domain. For example Fourier transformation of a sine function with frequency f corresponds to a delta peak at that frequency.

Applying this to the oscillation of poloidal magnetic field in a poloidal cross section, one could estimate the mode number of the wave and so determine the number of magnetic islands appearing in the plasma. However, as only 13 magnetic Mirnov coils where operational, not enough data points are available to do proper Fourier analysis. This can be solved by interpolating the data to poloidal angles where no detector is present.

Time domain Fourier analysis is more useful here. Now the oscillation in time of the poloidal magnetic field at a certain poloidal angle can be studied. This way it is possible to see whether an island is present or not. As it comes with sinusoidal variation in time of the poloidal magnetic field, one should look for peaks in the frequency spectrum, and this for different time windows. If peaks appear at a certain time span, further investigation of the data at that time will be useful.

Here is an example of such a spectrogram. The dark red areas are peaks. The corresponding time intervals have to be further investigated to see if magnetic islands appear.

Cross correlation analysis

Results

plots, mode number database, etc

Session log

(here should come the links to the database)

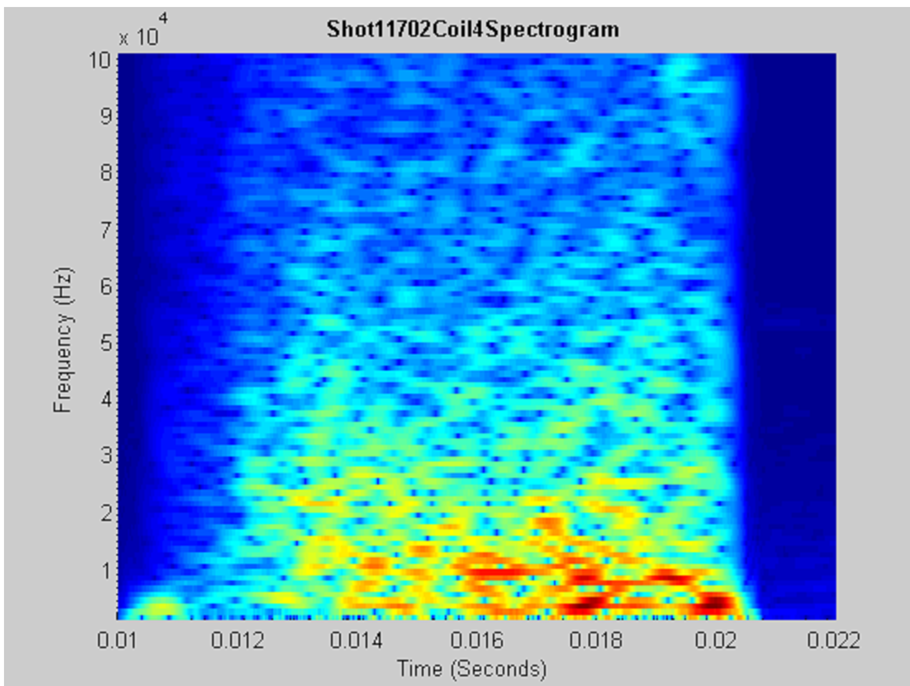
Shot11702Coil4Spectrogram
x 10^4
Frequency (Hz)
10
9
8
7
6
5
4
3
2
1
0.01
0.012
0.014
0.016
0.018
0.02
0.022
Time (Seconds)

Figure 13: