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Plasma MHD Activity Observations via Magnetic Diagnostics.

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1. 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.

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

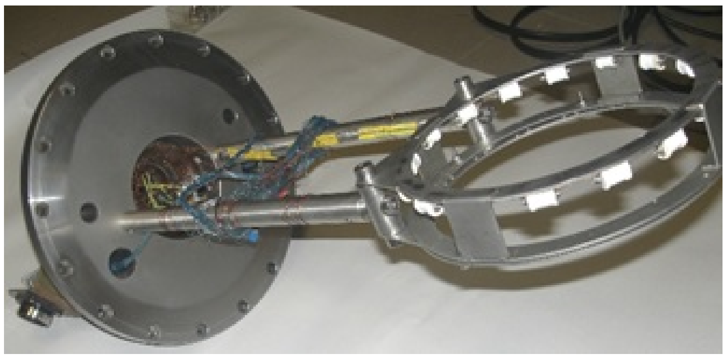

Figura 1: *Set of 16 Mirnov coils mounted in a poloidal ring to work like sensors of local magnetic field.*

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:

$$\nabla \cdot \mathbf{E} = 0 \quad \text{Gauss's law} \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{Maxwell-Faraday law} \tag{2}$$

$$\nabla \cdot \mathbf{B} = 0 \quad \text{Gauss's law for magnetism} \tag{3}$$

$$\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} \quad \text{Ampere's circuital law} \tag{4}$$

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.

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{5}$$

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

$$\oint_{\partial\Sigma} \mathbf{E} \cdot \mathbf{dl} = -\int_{\Sigma} \frac{\partial \mathbf{B}}{\partial t} \cdot \mathbf{dA} \tag{6}$$

where Σ is a surface bounded by the closed contour ∂Σ, E is the electric field, B is the magnetic field, dl is an infinitesimal vector element of the contour ∂Σ, 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:

$$\hat{V} = -\frac{d\Phi}{dt} = -A_{eff}\frac{dB}{dt} \rightarrow dB = -\frac{1}{A_{eff}}\hat{V}dt \tag{7}$$

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.

$$B(t) \approx -\frac{\Delta t}{A_{eff}} \sum_i \hat{V}(i) \tag{8}$$

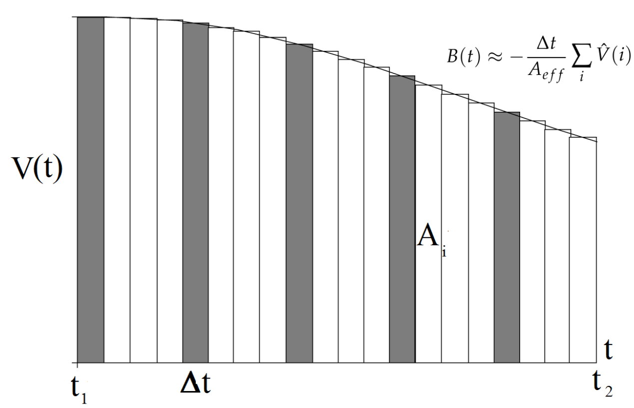

Figura 2: *Numerical integration consists of finding numerical approximations for the value A_i*

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.

$$\hat{V}(i) = V_{measured}(i) - \frac{1}{5000}\sum_{i=1}^{5000} V_{measured}(i) \tag{9}$$

The Matlab script for numerical integration is:

```
clc;
clear all;
close all;
shotnumbers = [11688,11689,11691];
coils = [1,2,3,15,16];
begin = 0.011;
final = 0.022;
DC=5000;
step = 1e-6;
AEff = [68.93e-4, 140.68e-4, 138.83e-4, 139.82e-4, 139.33e-4];
pol = [-1,-1,1,-1,-1];
for i = 1:length(shotnumbers)
out = zeros(40000,length(coils));
for j =1:length(coils)
signal=[num2str(shotnumbers(i)) 'ring' num2str(coils(j))];
nombre = ['ring_' num2str(coils(j))];
[t,v] = golem_data(shotnumbers(i),['ring_' num2str(coils(j))]);
av = mean(v(1:DC));
vNoOffSet = v-av;
b = zeros(length(vNoOffSet),1);
b(1) = vNoOffSet(1)*step/AEff(j)/pol(j);
for rr = 2:length(v)
b(rr) = b(rr-1)+step*vNoOffSet(rr)/AEff(j)/pol(j);
end
out=b-smooth(b,100);
xdata=[1:length(out)];res=[t,out];
save([num2str(shotnumbers(i)) nombre '.dat'], 'res','-ASCII')
signal2=['ring' num2str(coils(j))];
subplot(4,4,j)
plot(t,out);grid on;
title(signal2)
end
nombre1 = [ num2str(shotnumbers(i)) '.png'];
print ('-dpng', nombre1);
end
```

In fig. 3 can be seen an example of numerically integrated data obtained from one of the coils (ring 1).

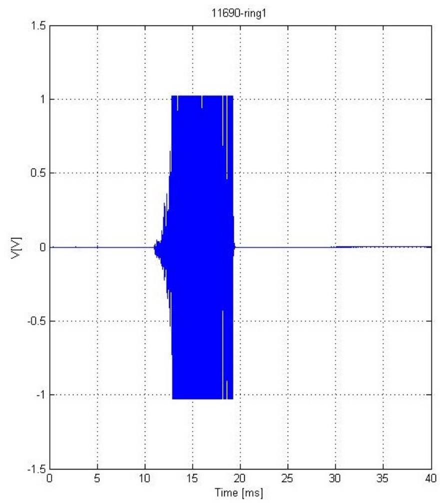

Figura 3: *Temporal evolution of the Mirnov signal $\hat{V}$ (left panel) for ring 1 and the poloidal magnetic field (right panel) obtain integrated Mirnov signal from the discharge # 11688.*

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

$$B_{per}(t) = B(t) - \text{smooth(B(t))} \tag{10}$$

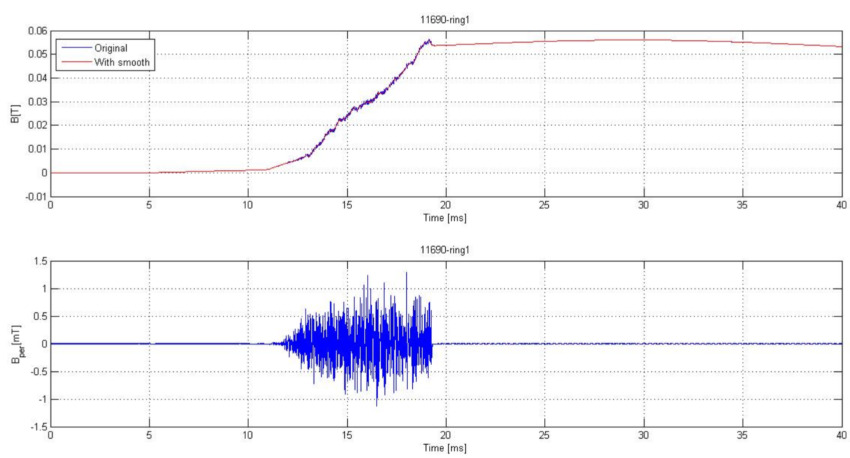

Figura 4: *Temporal evolution of the original magnetic field (blue, top panel), smooth magnetic field(red, top pannel) and the magnetic field perturbation for ring 1 obtain subtracting to the original magnetic field signal the smooth signal for the discharge # 11688.*

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.

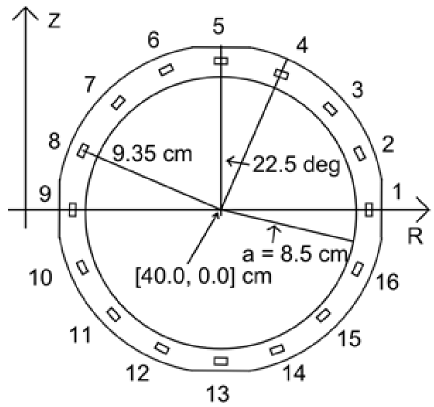

Figura 5: *On tokamak GOLEM, Mirnov coils is term used for small coils of local poloidal magnetic field measurement, placed inside of liner. The main purpose of Mirnov coils is for plasma MHD activity measurements.*

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

2. Data processing methods

2.1. 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 ionperative. In figure 1, loop voltage, plasma current (in the unit of kA) and toroidal magnetic field measured by differents diagnostics methods.

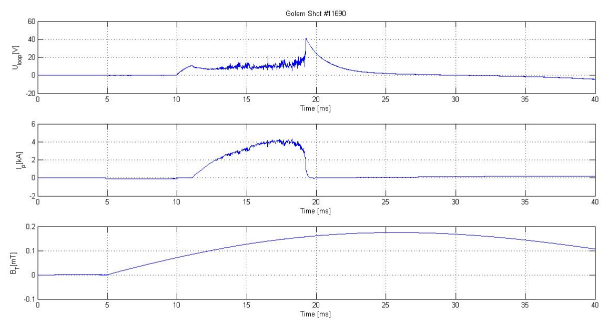

Figura 6: *Temporal evolution of whole discharge # 11688, with parameters: loop voltage (U_{loop}), plasma current (I_p) and toroidal magnetic field (B_{tor})*

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

$$B_{per}(t) = B(t) - \text{smooth(B(t))} \tag{11}$$

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

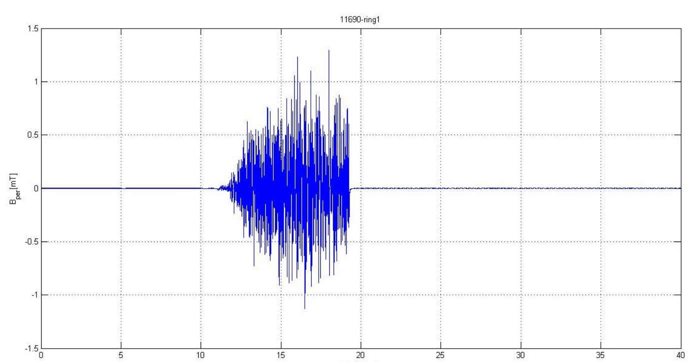

Figura 7: *Poloidal magnetic field perturbation obtain by numerical integration of the Mirnov Signal of the ring 1 for the shot # 11688. There are similar signals for all poloidal sensors at the poloidal ring.*

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. 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.

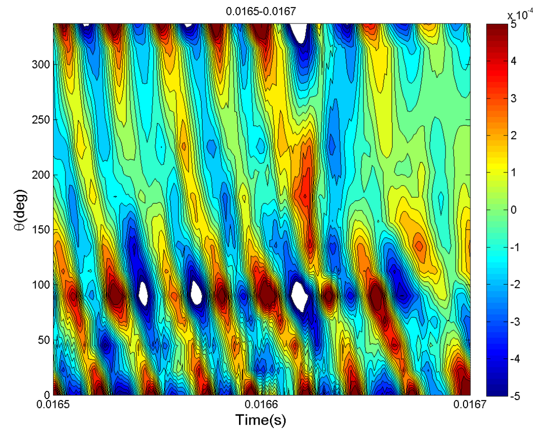

Figura 8: *Contour plot of the poloidal magnetic field oscillations in shot # 11688 and with a window time from 0.0165-0.0167 s, where the horizontal and vertical axes correspond to time and poloidal localization of the Mirnov coils. The red and blue region represent the oscillations positive and negative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

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

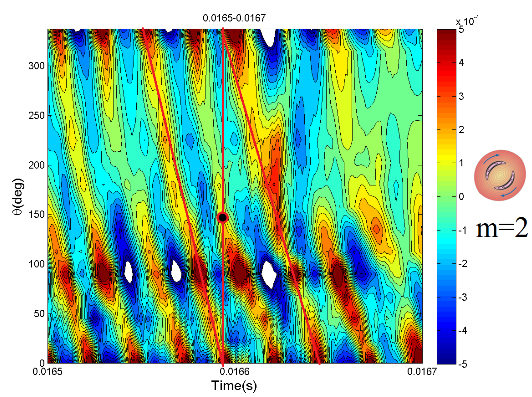

Figura 9: *Contour plot of the poloidal magnetic field oscillations in shot #11688 and with a window time from 0.0165-0.0167 s. To determinate m mode, search for a periodicity of a field line (red) and draw a vertical line and count how many maxima are "inside". The number mode m is equal to the number 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.*

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 .

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

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