Model and control fusion plasma instabilities

Concetta Barcellona, borsa di dottorato regionale in Ingegneria dei Sistemi, Energetica, Informatica e delle Telecomunicazioni, finanziato nell'ambito del PO FSE 2014/2020 della Regione Siciliana
DIEEI, University of Catania, Catania, Italy
A.Y. 2017/2018
Supervisor: Prof. Luigi Fortuna, Eng. Arturo Buscarino

Lower dimensional model of plasma instabilities

One of the most promising energy source is nuclear fusion. During the process of nuclear fusion energy production some instabilities can occur, such us ELMs (Edge Localized Modes). ELMs are characterized by the emission of large amount of energy and particles, that hitting the surrounding vessel wall, may damage and even destroy it.

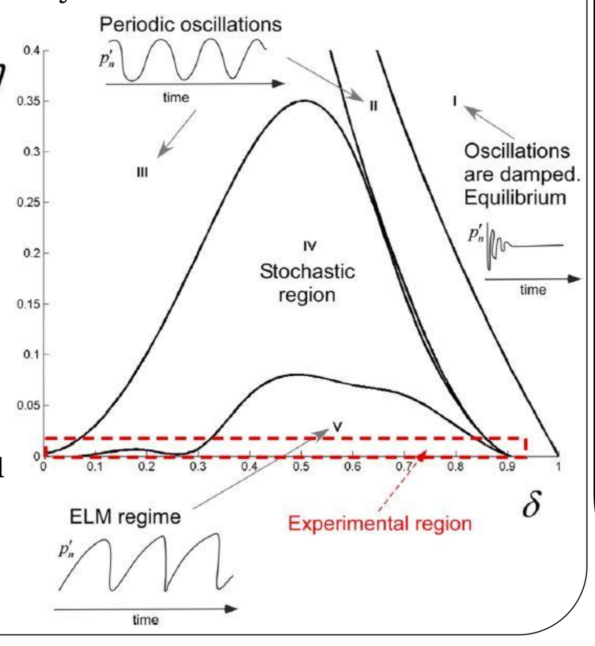
A qualitative low dimensional model has been studied in order to describe the main plasma instabilities dynamics:

$$\dot{x} = (z-1)y - \delta x$$
$$\dot{y} = x$$
$$\dot{z} = \eta(h - z - y^2z) \quad [1]$$

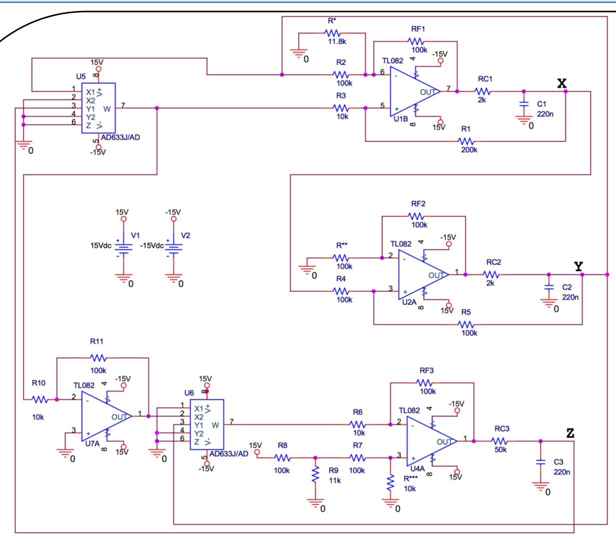
where **x, y, z** are plasma variables,. **δ, η** and **h** are system parameters, that determines its behavior:

- δ represents the dissipation/relaxation of perturbation related to ELMs burst;
- η represents heat diffusion coefficient;
- h is the normalized power input into the system and is responsible for inducing a burst.

By setting the input power as h=1.5 and δ and η as indipendent parameters, it is possible to model several dynamical regimes.

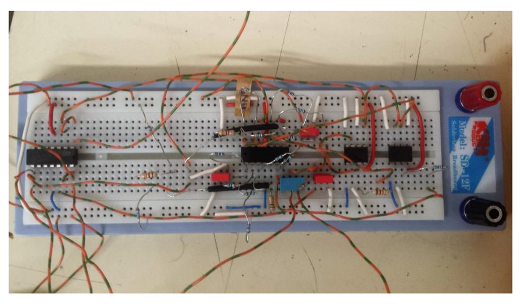


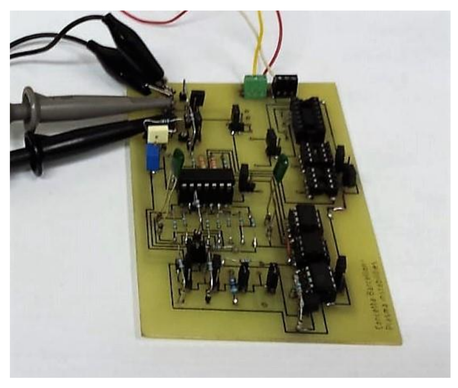
Circuit design and implementation



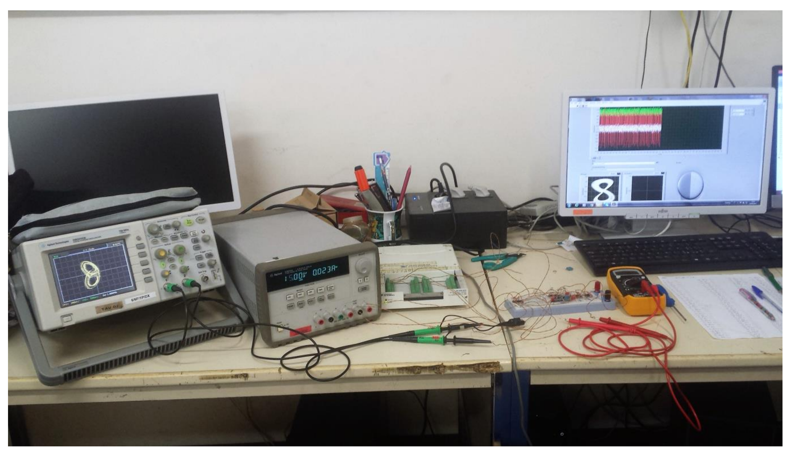
Circuital scheme of the non linear circuit

$$\dot{x} = \frac{1}{R_{C1}C_1}\left[\left(\frac{R_{F1}}{R_1}-1\right)x - \frac{R_{F1}}{R_2}y + \frac{R_{F1}}{R_3}V^*\right]$$
$$\dot{y} = \frac{1}{R_{C2}C_2}\left[\left(\frac{R_{F2}}{R_5}-1\right)y + \frac{R_{F2}}{R_4}x\right]$$
$$\dot{z} = \frac{1}{R_{C3}C_3}\left[\frac{R_{F3}}{R_7}V - z - \frac{R_{F3}}{R_6}V^{**}\right]$$



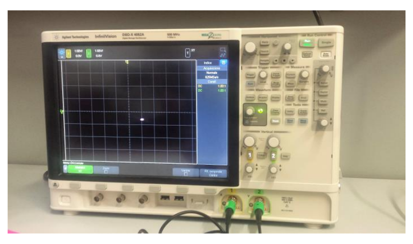


Implementation of the non linear circuit. In the first it is used a breadboard, instead in the second case a PCB implementation is realized.

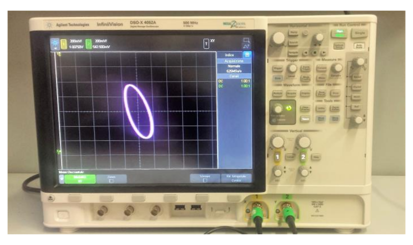


Overview of the data acquisition system used.

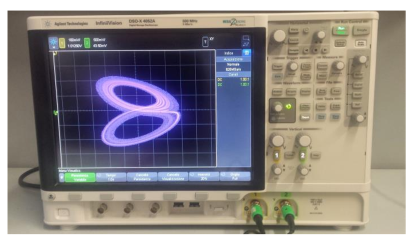
Results



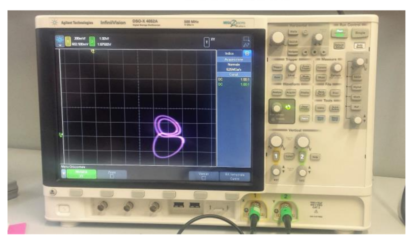
Damped oscillations (δ, η)=(0.5;0.668)



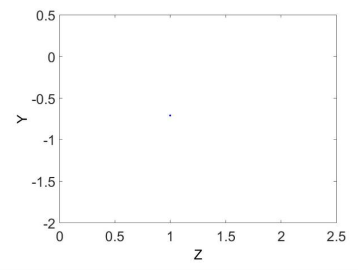
Periodic oscillations (δ, η)=(0.5;0.55)

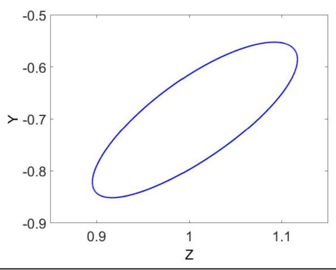


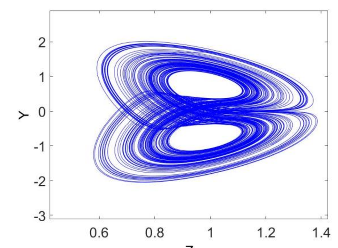
Chaotic oscillations (δ, η)=(0.5;0.08)

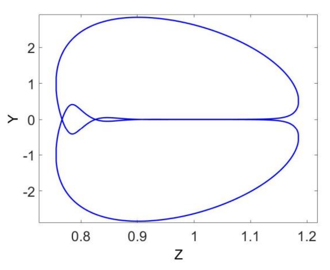


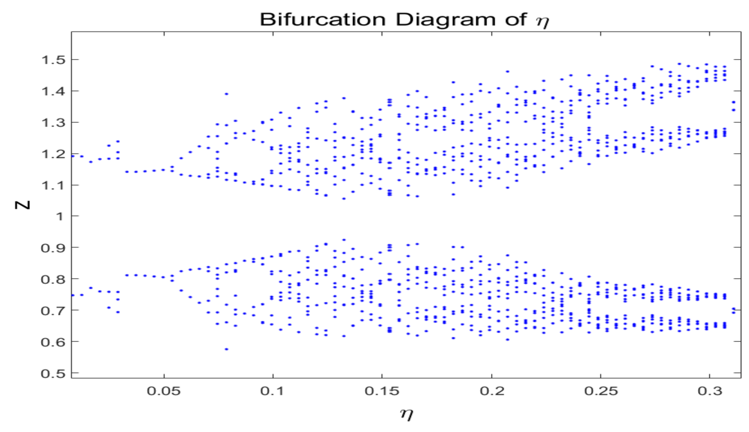
ELMs (δ, η)=(0.5;0.011)



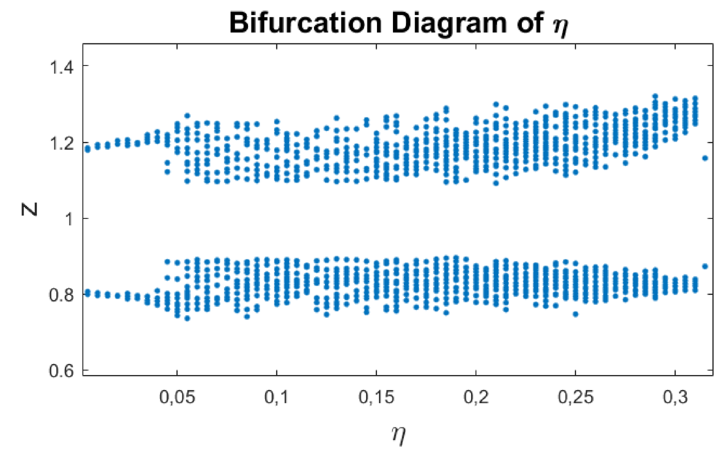








Bifurcation diagram obtained by using the ideal model.



Bifurcation diagram obtained by using experimental data acquisitions

The software Matlab is used for the simulation.

Pellet injection by using Arduino® board

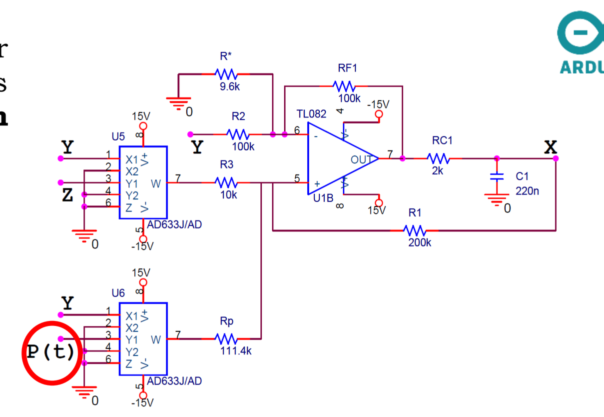
One of the strategies to **mitigate ELMs** during nuclear fusion experiments is **Pellet injection** and it is simulated in the previous ideal model with the **addiction of the P(t)** perturbation.

$$\dot{x} = -\{1 - [z + P(t)]\}y - \delta x$$
$$\dot{y} = x$$
$$\dot{z} = \eta(h - z - y^2z)$$

Perturbation

$$P(t) = \frac{a * \exp\{-\left[t - t_{period}\, int\left(t/t_{period}\right) - \delta_P\right]^2}{b}$$

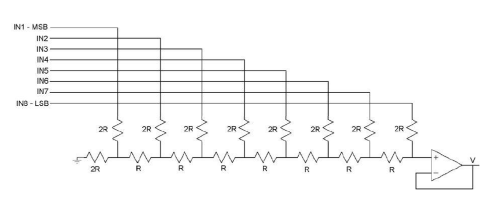
ELMs region: h = 1.5, δ = 0.5, η = 0.009

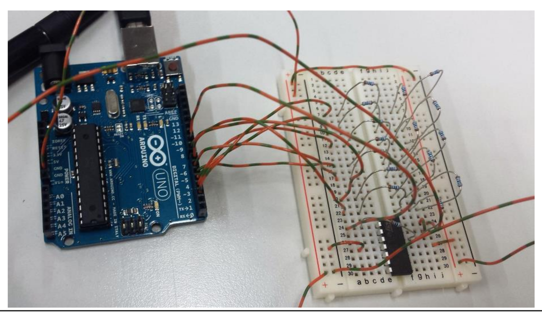


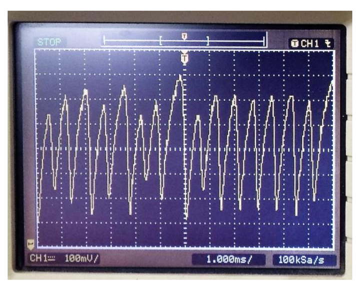
Circuital scheme if the x variable

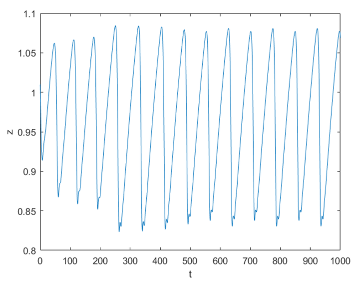
In order to implement P(t) in our analogue circuit, we have used **Arduino** as microcontrolled board .

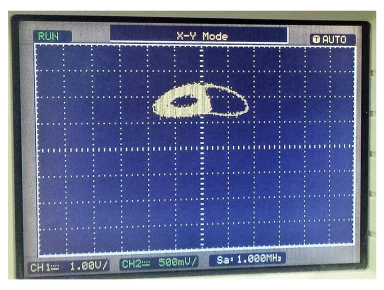
The **command lines** are shown by mean of that the P(t) is generated. The output from Arduino is a **8 bit word** and thus a DA converter has been used in order to send P(t) signal to the circuit.

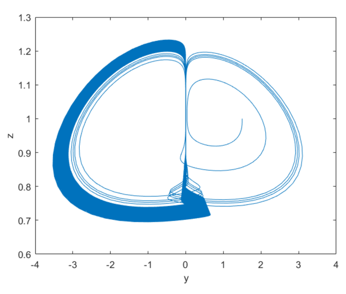


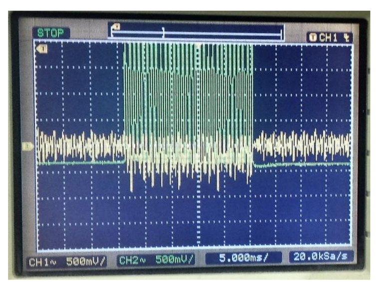


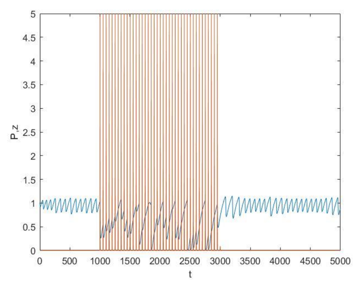


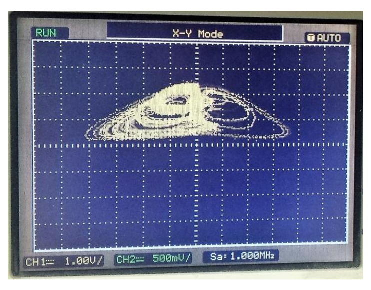


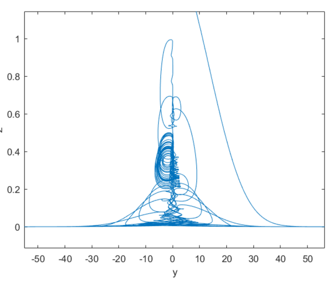












Experimental oscillascope trace of ELMs before and after Pellet injection.

Matlab® simulations of ELMs before and after pellet injection.

Experimental oscilloscope traces of the attractor before and after pellet injection.

Matlab simulation of the attractor before and after pellet injection.

Accordingly with these results, it is possible to say that the pellet injection changes **plasma stability** and increases the **ELM frequency**.

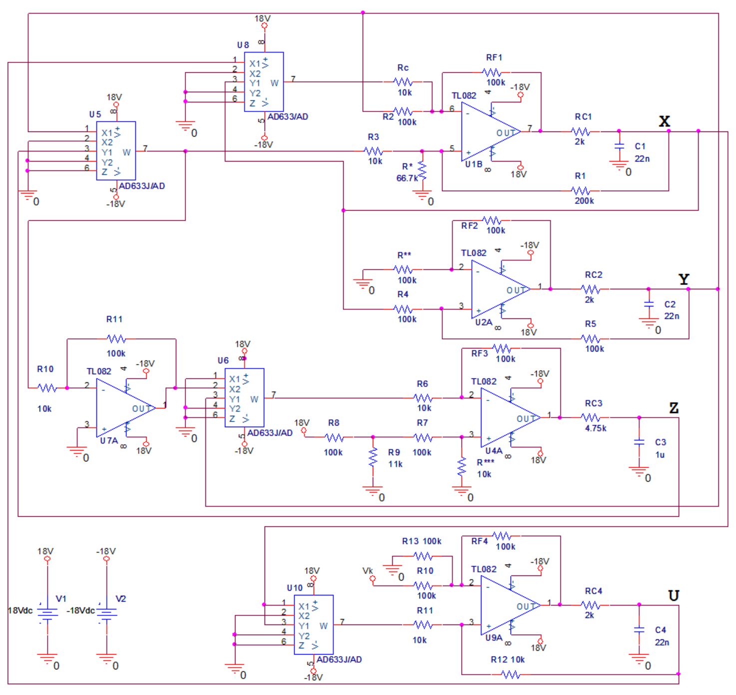
Thermostat Control

Introducing a feedback which regulates the amplitude and the frequency of the external control signal, we get a situation similar to the so-called thermostat control, illustrated by [2], [3].

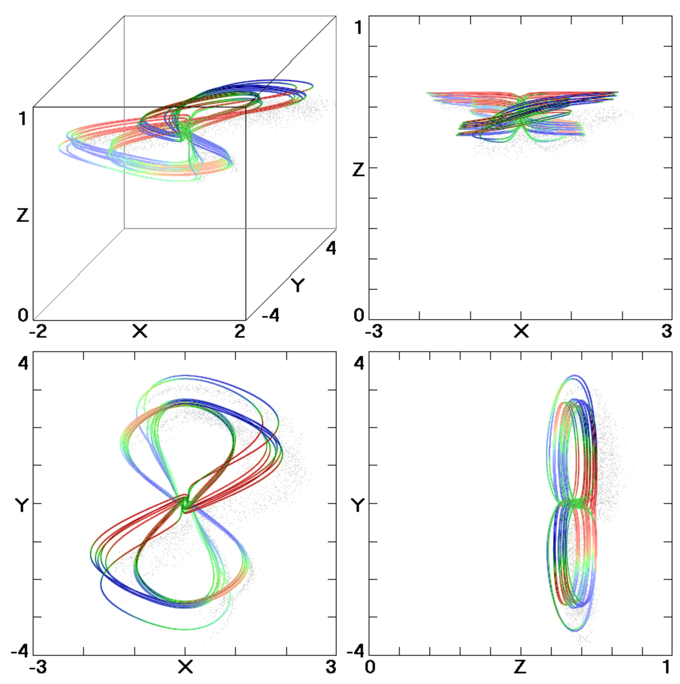
It represents a closed-loop control approach, in which a feedback is added in the original system by means of a further dynamical variable which mediates between the behavior of a state variable and the control action.

From a physical point of view, we can consider that a magnetic perturbation acts on the system, such that the original system is varied through the thermostat control.

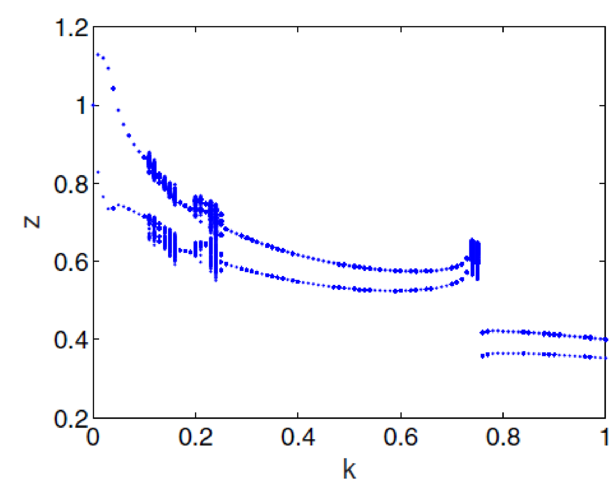
$$\dot{x} = (z-1)y - \delta x - ux$$
$$\dot{y} = x$$
$$\dot{z} = \eta(h - z - y^2z)$$
$$\dot{u} = x^2 - k$$



The circuit implementation 2 is modified in order to add a fourth equation representing the new state variable and introduce this contribution in the first equation.

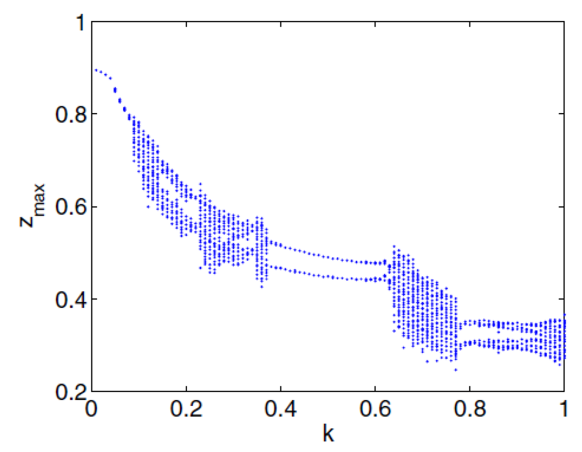


Changing the value of the control parameter **k** we pass from ELMs region to the chaotic region and the average value of z is reduced.



Simulated bifurcation diagram of z variable respect to the control parameter k.

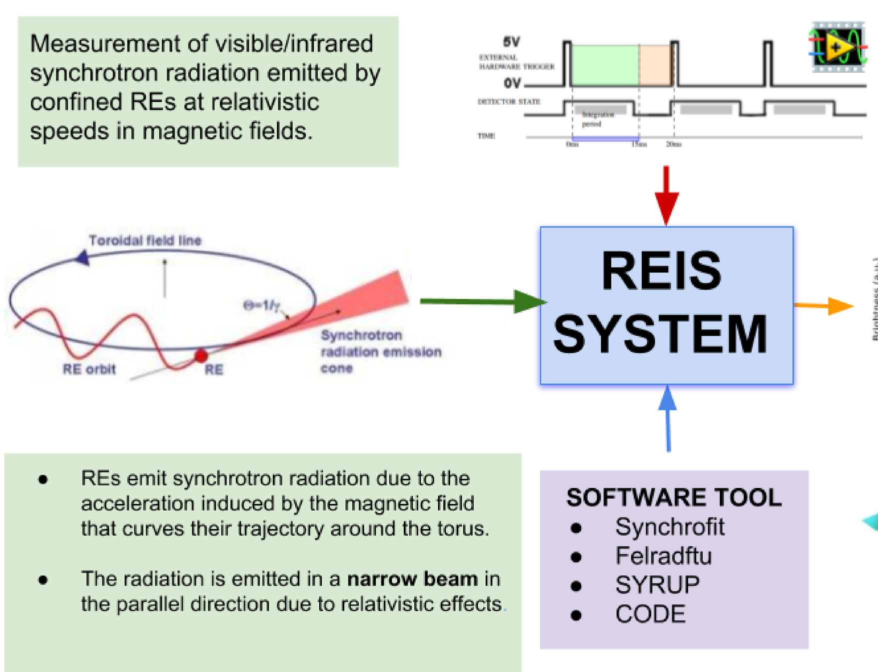
Experimental bifurcation diagram of z variable respect to the control parameter k.

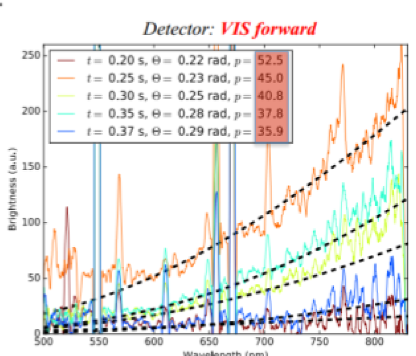


REIS software tool update

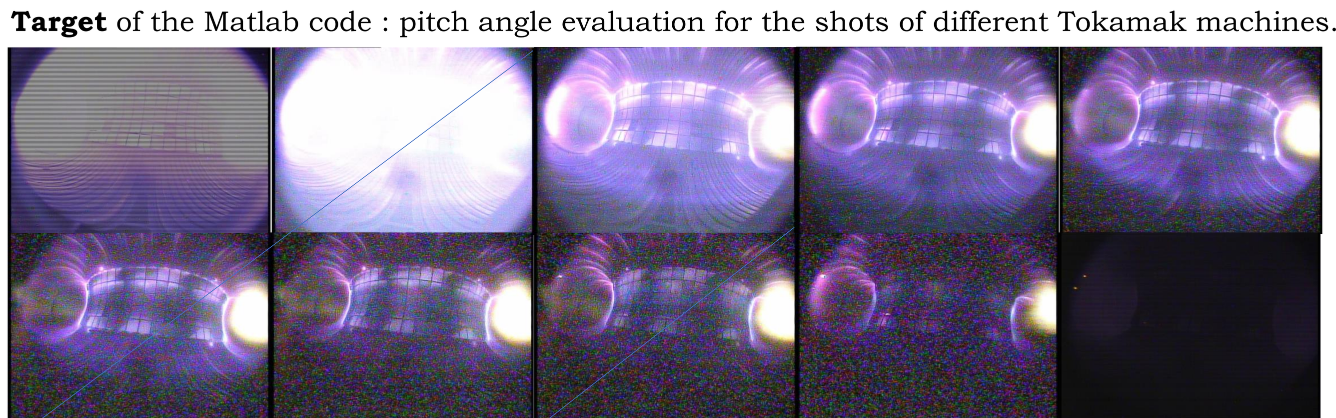
Imaging of runaway electron Beam

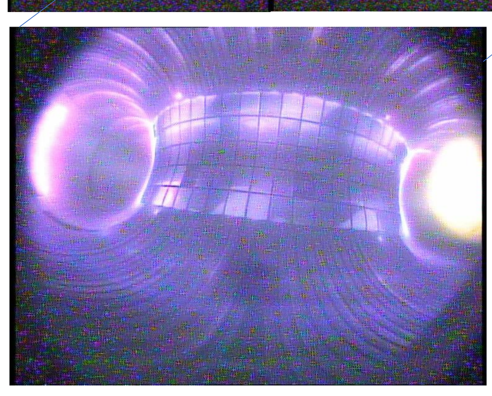
The goal of the project is the **fulfillment** of portable **Runaway Electron Imaging Spectroscopy** (**REIS**) system for use in medium size tokamaks for the measurement of visible and infrared **synchrotron radia;on** spectra and visible images produced by **runaway electrons** (**RE**) during the various phases of a plasma discharge, Including the runaway plateau phase following disrupton events.

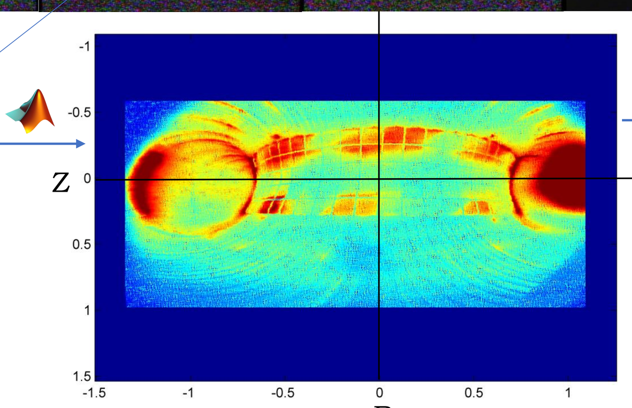


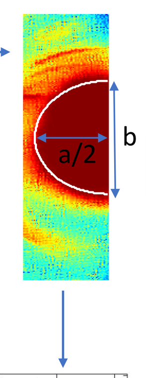


Target of the Matlab code : pitch angle evaluation for the shots of different Tokamak machines.







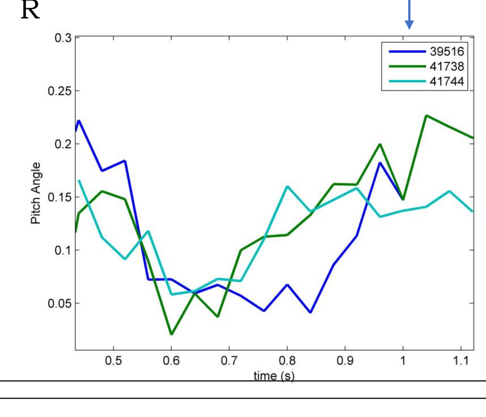


FTU Port 3 #41738 , image 28

- Scaling
- Rotation
- Mapping in RZ
- Elliptic shape Identification
- Major and minor axises computation (a and b)

- Pitch angle computation

$$\theta = \frac{\sqrt{(a-b)}}{R_0} \quad [4]$$



Measured spectra → Calibration → Savitzky-Golay filter → Emission lines filter → lmfit → REs number and energy

Measured pitch angle → lmfit

$$P_{cyl}(\lambda,\theta,\gamma) = \frac{ce^2}{\sqrt{3}\varepsilon_0\lambda^3\gamma^2}\int_{\lambda_c/\lambda}^{inf} K_{5/3}(l)\,dl$$

$$B(\lambda,\theta,\gamma) = P(\lambda,\theta,\gamma)\frac{2R}{\pi\theta}n_{RE}$$

Energy estimation: the routine *lmfit* python creates a complex fitting models for non-linear least-squares problem that wraps the brightness.

Publications

- C. Barcellona, *A new nonlinear circuit to identify plasma instabilities*, International Journal of Engineering Research and Technology, ERSA Publication, 2017, ISSN: 2278-0181.
- C. Barcellona, A. Buscarino, C. Corradino, L. Fortuna, *Hybrid circuits to model and control fusion plasma instabilities*, , 5^{th} IFAC Conference on Analysis and Control of Chaotic Systems, October 30^{th} - November 1^{st}, 2018 Eindhoven, The Netherlands
- A. Buscarino, C. Barcellona, C. Famoso, *Jump resonance: sintesi globale di sistemi risonanti*, convegno Automatica.it 2018

[1] D. Constantinescu, O. Dumbrajs, V. Igochine, K. Lackner, R. Meyer-Spasche, H. Zohm, and ASDEX Upgrade Team, A low-dimensional model system for quasiperiodic plasma perturbations. Physics of Plasmas, 18, 062307, 2011.
[2] Hoover, W. G. (1985). Canonical dynamics: equilibrium phase-space distributions. *Physical review* A, 31(3), 1695.
[3] Nos´e, S. (1984). A molecular dynamics method for simulations in the canonical ensemble. *Molecular physics*, 52(2), 255-268.
[4] Yu, J. H., Hollmann, E. M., Commaux, N., Eidietis, N. W., Humphreys, D. A., James, A. N., ... & Moyer, R. A. (2013). Visible imaging and spectroscopy of disruption runaway electrons in DIII-D. *Physics of Plasmas*, *20*(4), 042113
[5] M., Gospodarczyk, D. Carnevale, B. Esposito, L. Boncagni, *Control, diagnostics and estimation techniques for runaway electrons beams*, doctoral thesis, A.Y. 2016/2017