WPMST1-CPR(17) 17183

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Preprint of Paper to be submitted for publication in Proceeding of 11th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

On the Control System Preparation for ELM Pacing with Vertical Kicks Experiments at TCV

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Abstract

High confinement plasma regimes (H-mode) are the scenarios with the highest fusion rates and the operating regime foreseen for the ITER scenario with $Q_{DT} = 10$. The steep gradients of density and temperature drive Magnetohydrodynamic (MHD) Edge Localized Modes (ELMs). Although ELMs are beneficial for controlling particle exhaust and plasma impurities, the excessive energy they deposit on the plasma facing components may lead to erosion or melting, reducing the components life cycle. By controlling the ELM frequency in an ELMy H-mode plasma it may be possible to reduce the energy expelled per ELM, mitigating damage to the tokamak parts.

One technique for mitigating these risks was first implemented successfully in TCV Ohmic H-mode plasmas, using the so called ELM pacing with vertical kicks [1]. TCV vertical stabilisation coils located inside the vessel proved to be well suited to apply the necessary perturbations to induce vertical displacements of the plasma. This method was then reproduced on AUG [2][3] and later on JET [4] with significant improvements.

During 2016 a set of experiments were planned to further study the physics of ELM pacing taking advantage of the new neutral beam heating (NBH) system installed on TCV [5]. This submission reports on the related preparation of the TCV digital vertical stabilization control system [6] actuating the in-vessel coils. A number of tools were deployed to drive a fast radial-field variation and preliminary experimental validation was carried out. The tools and simulations, as well as preliminary experiments aiming at evaluating the controller's accuracy are reported.

Keywords: ELM Mitigation, Vertical Kicks, Vertical Stabilization Control, Tokamak

1. Introduction

To achieve the ITER higher fusion rate scenarios with $Q_{DT} = 10$ and $I_p = 15MA$ it is necessary to maintain a stable H-mode confinement, avoiding the occurrence of fast energy losses due to the MHD instabilities in the plasma edge. Different options are under study to mitigate and control these Edge Localized Modes (ELMs) including [7]:

- operation in plasma regimes with small or no ELMs;
- increasing the ELM frequency reducing the energy released per ELM;
- controlling the edge with magnetic perturbations to avoid the occurrence of ELMs.

One process to increase ELM frequency is to induce magnetic perturbations that trigger the ELMs. This process of mitigating the energy release was first obtained in TCV Ohmic H-mode plasmas with Type III ELMs using a proccess that is called ELM pacing with vertical kicks[1][8]. This study was reproduced in Asdex-Upgrade (AUG) during 2004 with Type-I ELMs [2][3]. Physics studies were then conducted in several fusion devices with special relevance at the Joint European Torus (JET) with the control system preparation [9] and an in depth physics interpretation work [4].

To improve the knowledge of the physics behind ELM pacing with the vertical magnetic perturbations a set of experiments were planned for TCV. The main goals were defined in the following topics:

- Assess the type I ELMs pacing potential with vertical kicks;
- Assess the role of the displacement amplitude vs velocity;
- Evaluate the impact of ELM pacing on confinement and heat losses.

Moreover, the following assessment tools were identified:

- Estimation of the ELMs / kicks synchronisation rate;

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- Estimation of the frequency range of synchronisation;
- Evaluation of the synchronisation rate in different perturbation cases;
- Estimation of confinement and heat losses.

This paper aims at documenting the work that was developed for the preparation of the vertical control system [6] in view of the experiments with vertical kicks at TCV to further elucidate the physics of ELM pacing using the new NBH system installed at TCV [5]. An upgrade of the tools and a set of preliminary experiments were performed to evaluate the TCV capabilities to continue with the more advanced physics experiments.

The following shows the sequence of topics. Section 2 describes the TCV Tokamak with the main characteristics relevant for the implementation of a suitable control system for ELM pacing using magnetic perturbations. Section 3 presents the plasma model and simulation scheme used as well as the controller implementation. Section 4 shows the improvements achieved with the vertical stabilization system using the near optimal controller. Preliminary results and experimental data are described in section 5. Section 6 presents some power supply limitations and a proposal to overcome the limitations in future experiments. This papers ends with section 7 devoted to the conclusions and discussion of the future work.

2. Tokamak Description

The *Tokamak à Configuration Variable* (TCV) is a medium size, air core transformer, magnetic fusion device with a standard aspect ratio $1/\varepsilon = R/a \approx 3.5$ exploited by the *Swiss Plasma Center* (SPC) at *École Polytechnique Fédérale de Lausanne* (EPFL) [10]. It was designed to study the influence of the shape poloidal cross section in the plasma stability and confinement. TCV is capable of studying many different plasma configurations and shapes[10].

The importance of plasma shaping relates to the fact that plasma columns with different shapes have different stability of the plasma edge. Because higher stability permits higher plasma pressure, the research of plasma shapes and stability is an important study that aims at improving fusion power performance.

Figure 1 shows the poloidal cross-section of the TCV vacuum vessel with a reconstruction of its magnetic-flux surfaces. In TCV, the primary circuit of the transformer is composed of a solenoid around the central column, augmented by 3 additional coils; 16 poloidal field coils (E1 to E8 and F1 to F8) are used to create the toroidal magnetic field. To permit the different plasma shapes and high elongated plasmas, the vacuum vessel presents a vertical elongated cross section. To diagnose the plasma parameters several measurement equipment must access the inside of the vessel using the diagnostic windows. To vertically stabilize the elongated plasma the in-vessel toroidal coils are used (G1 to G6) represented in figure 1 in the upper and lower right corners of the vessel. These coils are driven by a Fast Power Supply (FPS). Because the coils are connected in

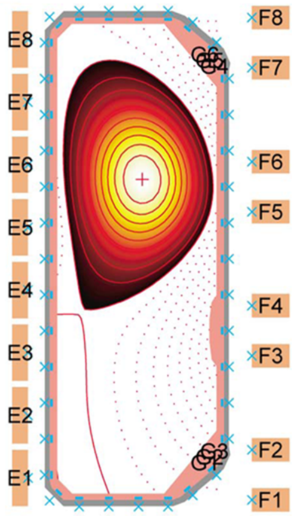

Figure 1: The TCV Tokamak

series, although with opposite current directions, only one FPS is needed to drive the coils.

3. Vertical Stabilization Algorithm and Tools

For the development of the control algorithm a control oriented plasma model was used to build the response function of the vertical plasma displacement to the control voltages applied to the TCV in-vessel poloidal field coils. RZIP [11] is a simplified plasma model that assumes a constant current distribution with rigid plasma shape and a variable total plasma current, as well as vertical and radial position. This model is derived from the radial and vertical force balance equations and the plasma current circuit equations.

Aiming at building a time optimal controller, the model was reduced and the reduction was validated by comparing the transfer function of both systems. The reduced transfer function was used to design a time optimal controller [6] and the near optimal implementation.

Figure 2 shows the system control scheme which was implemented in a simulator to make preliminary tests and validation of the controller.

With respect to the usual control scheme, a programmed feed-forward block was added to the controller in order to build the plasma vertical kicks with programmable amplitude, frequency and direction. This block foresees the possibility of introducing in the controller vertical kicks as real-time feedback reaction to the ocurrence of ELMs with a programmable delay that is the reciprocal of the desired ELM frequency.

4. Vertical Stabilization Control Improvements

As a consequence of the simulations using the control scheme in figure 2 a near-optimal variable controller was implemented and tuned with different states according to the distance

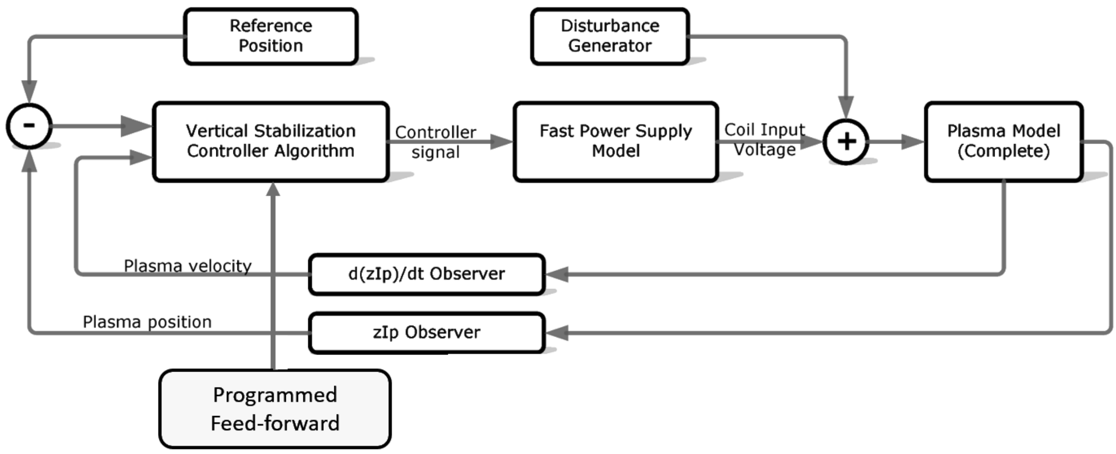

Figure 2: Simulation Control Scheme.

to the set point. The level of the controller output depends on its state, which introduces a linear behaviour to the bang-bang controller whose nature is intrinsically nonlinear [6].

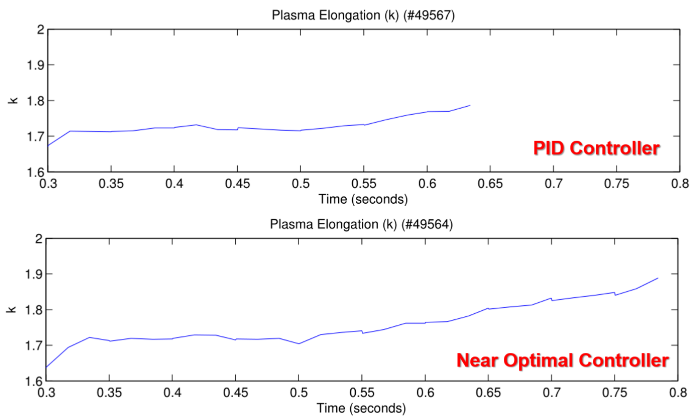

Figure 3: Increasing plasma elongation using the two different controllers.

The controller was tested in a TCV discharge with an elongation ramp after 0.5 seconds. Comparing the results of the standard PID with the near optimal implementation, an improved plasma stability over a longer period of time was achieved with the near optimal controller. Figure 3 confirms the evolution of the elongation that grows 5% more after the disruption when compared with the PID controller performance.

Figure 4 compares the PID controller (above) and the near optimal controller (below) regarding the plasma position and velocity. The blue shadow region shows the period when the plasma elongation is changing. It shows that the PID controller has difficulties coping with the instability that can be seen after $0.55s$ ending the discharge with a vertical disruption at $0.65s$. On the right, the near optimal controller maintains the plasma stable for a longer period with an improvement in time before disruption of 100% with the elongation continuously increasing until the plasma disrupts at $0.8s$.

5. First Experimental Results with Verticla Kicks

5.1. Influence on Plasma Vertical Position

To evaluate the influence of the magnetic perturbations on the plasma vertical position some experiments were performed. The first tests were made kicking the plasma in opposite directions sequence (up then down), to minimize the action of the vertical controller to recover the original position and to maintain the symmetry in the perturbations to analyse any difference in the plasma behaviour regarding the direction of the kicks.

The evaluation of the plasma displacement in response to the magnetic perturbations in figure 5 depicts a fast recovery of the plasma position after each perturbation. This shows that the vertical stabilization system behaves correctly for the displacements that were performed. However the recovering of the position is not fast enough to permit building a table relating the amplitude of the perturbation to the plasma displacement. A lower perturbation frequency should be used in order to see the stabilized plasma position value before applying the following perturbation.

Figure 6 presents a zoomed view of the influence of the FPS reference voltage on the plasma position. The sawtooth signal that can be seen in the FPS output current is due to the switching operation mode of the power supply, which causes the FPS limitation presented in section 6.

5.2. Influence on ELM Synchronisation

Figure 7 shows an ELMy H-mode plasma with non-synchronous ELMs. This discharge was then repeated using the vertical kicks. Figure 8 shows the results of the new discharge that present mild evidence of synchronism of magnetic perturbations with ELM events, represented by the peaks in D-alpha radiation in the lower plot.

Figure 8 also shows that the increase in ELM frequency due to magnetic perturbations induces lower energy release per ELM when compared with discharges without perturbations.

It is very important to note that further discharges are needed to continue this work that should confirm the present analysis

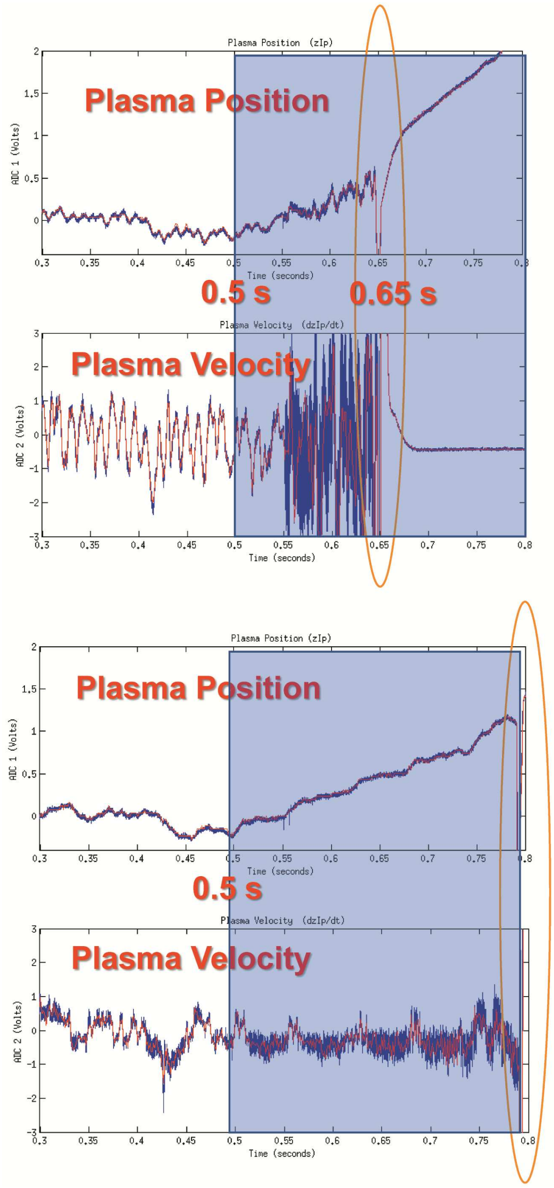

Figure 4: Comparison between PID (above) and near optimal (below) controllers in respect to plasma position and velocity.

and shed some light on the current interpretation of the available data.

6. Fast Power Supply Limits

One problem that had an impact on the planned experiments is the limited number of FPS switches possible during a discharge before the safety circuit turns FPS off. This circuit that is meant to protect the FPS from getting damaged prevented the normal duration of the plasma discharges due to loss of the vertical stabilization control and failure to induce the planned vertical kicks.

Figure 9 shows the voltage reference in the upper plot and the output FPS voltage in the middle plot. By using reference voltages that are different from the maximum FPS input voltages

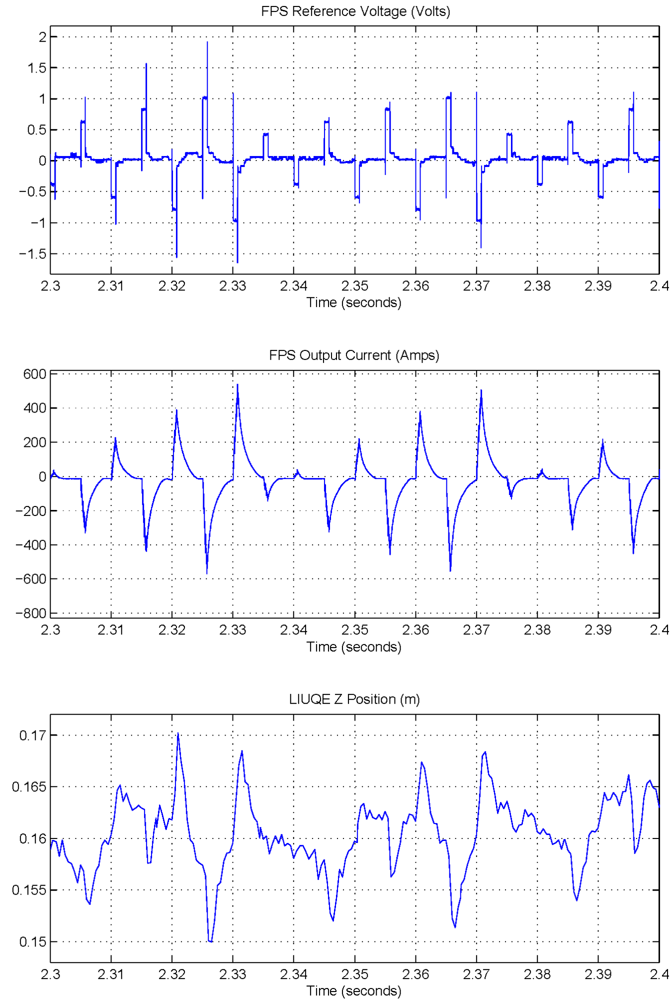

Figure 5: Influence of the vertical magnetic kicks in the plasma displacement.

we increase the number of switches of the FPS. To minimize the number of switches it is foreseen to use higher reference voltage during less time to produce similar results in the currents in the in-vessel coils, shown in the lower plot of the figure. This method shall be tested for the continuation of the research plan.

7. Conclusions and Future Work

This work presents a set of tools to simulate and predict the reaction of the plasma to the vertical kicks. These tools help the planning of the experiments during the scientific programme at TCV. An optimized vertical stability controller was also shown that improves the plasma recovery after the magnetic perturbations. The vertical stabilization system was prepared to induce magnetic perturbations at programmable frequency, amplitude and direction.

Preliminary experiments have shown evidence of the triggering of ELMs. Nevertheless, it is necessary to continue the experiments with ELMy H-mode discharges and vertical kicks at predefined frequencies to understand the physics of triggering the ELMs with magnetic perturbations.

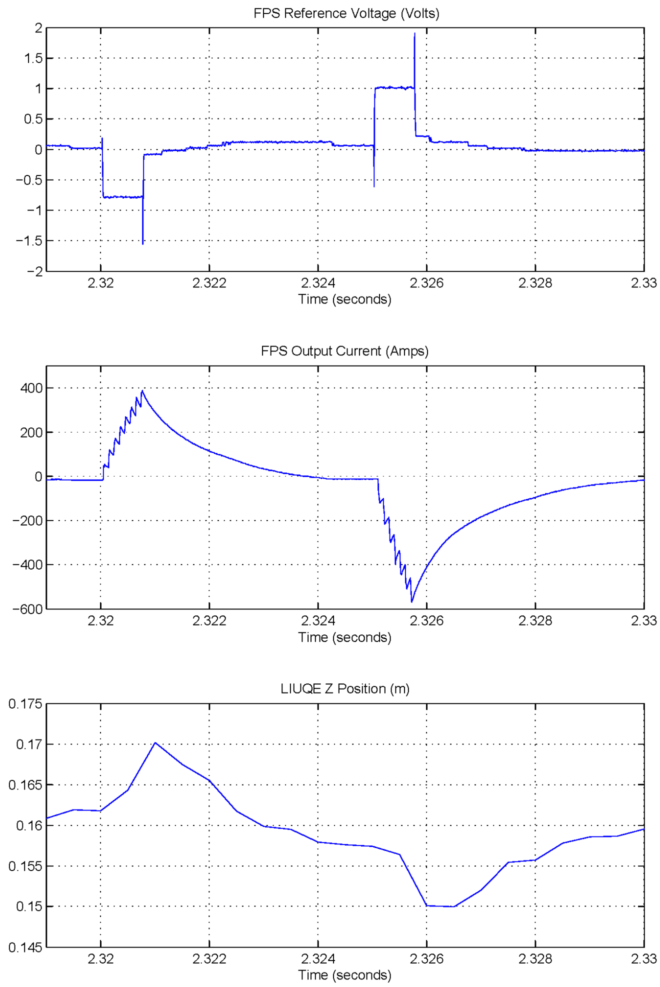

Figure 6: A zoomed view of the vertical magnetic kicks influence in the plasma displacement.

The exhaustive use of the FPS to create fast perturbations using the in-vessel coils revealed problems with the FPS protection system that prevented the use of the FPS for a thorough study during a complete discharge. Further inspection of the FPS usage and protection system is needed to continue this work, but a method for the optimized use of the FPS is proposed to mitigate the problem.

Some steps were also taken towards the use of real-time ELM detection that help the real-time synchronization between perturbation and ELMs, preventing the occurrence of ELM triggering just after a natural ELM has occurred. This shall be taken into account during the preparation of the future experiments, using the spare digital and analogue inputs of the digital controller.

The simulator in figure 2 shall also be used for improving the VS controller to overcome the inconveniences inherent to bang-bang controller and obtain an optimal algorithm that minimizes the time to target. The simulator shall test the capability of the controller in maintaining system controllability in the temporary absence of the position and velocity observer, using an adaptive controller method. This controller method shall be

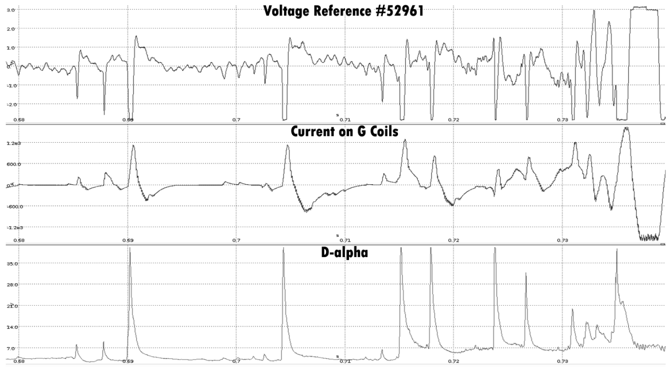

Figure 7: An ELMy H-mode plasma, with non-synchronous ELMs.

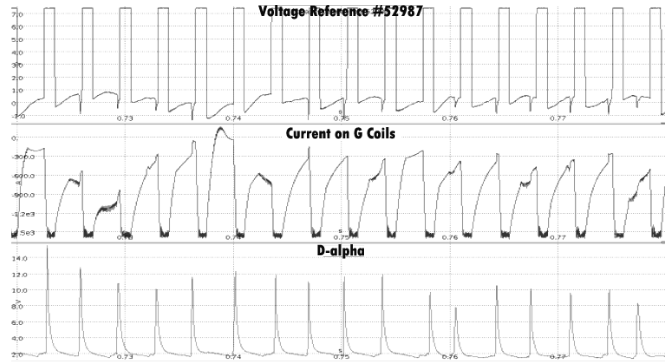

Figure 8: An ELMy H-mode plasma, with ELMs synchronous with the vertical kicks.

implemented by improving the bang-bang controller, gradually increasing the control level to the maximum permitted by the power supplies. It will also permit the real-time measurement of the vertical instability growth rates for different plasma elongations, using closed loop control.

In view of the experimental tasks defined the following planning is foreseen:

1. Re-access the near optimal controller design implemented and build new bang-bang controller with only one level of restoring control;
2. Perform a set of simulations using the designed simulator and controller for different restoring levels;
3. Implement the controller with best performance to make measurements of the growth rate for different plasma elongations and improve plasma controlability.

This research encourages a more detailed and systematic study of the influence of the perturbations in TCV plasmas in view of the confirmation of previous studies and further understanding of the physics and engineering problems of ELM pacing with vertical kicks.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under

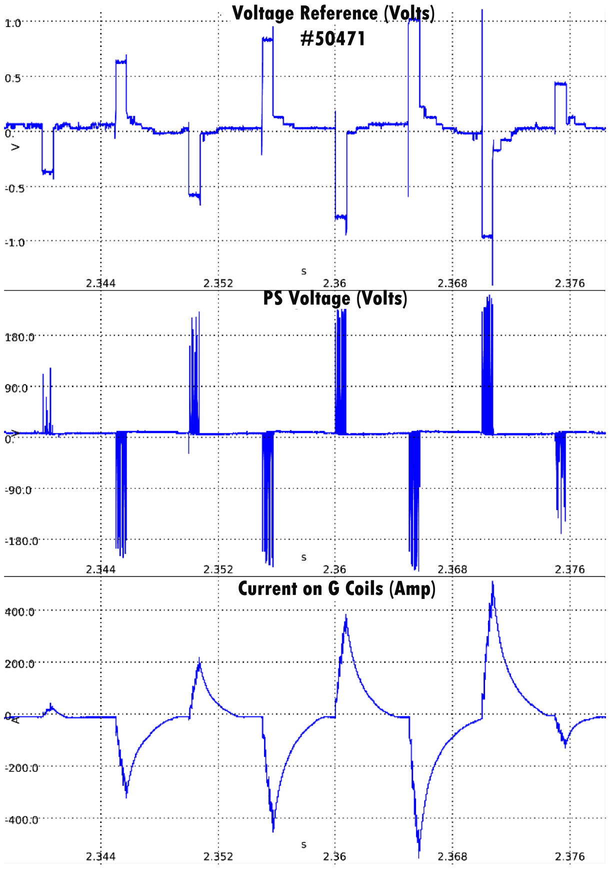

Figure 9: Limitation of the FPS due to the limited number of switches:

grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

IST activities also received financial support from ”Fundação para a Ciência e Tecnologia” through project UID/FIS/50010/2013.

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