FEEDBACK CONTROL OF DYNAMICAL INSTABILITIES IN CLASSICAL LASERS AND FELs

S. Bielawski and C. Szwaj,
Lab. PhLAM/CERLA, Université de Lille 1, 59655 Villeneuve d’Ascq, France
C. Bruni, D. Garzella, G.-L. Orlandi, and M.E. Couprie,
CEA/DSM/DRECAM/SPAM, Batiment 522, 91191 Gif-sur-Yvette, France
M. Hosaka, A. Mochihashi, Y. Takashima, and M. Katoh,
UVSOR, IMS, Myodaji Okazaki 444-8585, Japan
G. De Ninno, M. Trovo, and B. Diviacco,
Sincrotrone Trieste, 34012 Trieste, Italy
D. Fanelli, Dept. of Physics, University of Florence, Florence Italy.

Abstract

We present a selected review on feedback stabilization of lasers. We concentrate on techniques based on stabilization of unstable states that preexist in the system. First we present the context of the first laser control experiments (in the beginning of the nineties), and the recent application to mode-locked lasers. Then we present the results obtained in SR-FELs, in particular the experimental results on the suppression of dynamical instabilities in super-ACO, ELETTRA and UVSOR.

INTRODUCTION

Since the beginning of the 90’s, new techniques have been developed with the aim to suppress and more generally “master” dynamical instabilities in conventional lasers. Recently, related strategies have been attempted with success on SR FEL oscillators. In this paper, we review selected topics in laser control. First we present the point of view and context (control of chaos) that led to the development of techniques in the nineties. Then we focus on one application in the context of mode-locked (ps/fs) lasers, a class of systems with strong similarities with FELs. Finally we present the results obtained these last years on the FELs of super-ACO, ELETTRA, and recently at UVSOR. Strong similarities appear between the control schemes of mode-locked lasers. However, stabilization of FEL oscillators also present specific conceptual difficulties that will be discussed.

CONTROL IN CLASSICAL LASERS

From the sixties to the nineties

Many lasers are known to undergo instabilities, that lead to nonstationary behaviors. Typical examples include lasers with constant parameters, which output present a series of spikes, because of saturable losses [1, 2], or the presence of intracavity harmonic generation [3]. Another typical example is the periodic modulation of a parameter (e.g., losses) with the aim to produce a regular train of pulse, which often leads to unwanted chaotic behaviors [4]. Two examples are represented in Fig. 1.

Figure 1: Two examples of instabilities in classical lasers. (a) Spiking of the “Q-switch type” at the output of a Nd-doped fiber laser with constant parameters (experiment of ref. [5]). (b) Output power of a CO\textsubscript{2} laser under sinusoidal loss modulation. Both lasers exhibit deterministic chaos.

Up to the nineties, the main strategy for avoiding such instabilities consisted of excluding the associated parameter regions and designs. Few feedback control techniques were used, and were applied mainly to the control of transient spiking [6, 7, 8]. No systematically rules were established for controlling laser dynamical instabilities. This can appear surprising since control theory is a well established science. An explanation can be the apparent complexity of the free running laser evolutions, with ubiquitous nonlinearities, and often chaotic evolutions. Results existed on classical control theory applied to nonlinear (chaotic) systems. However, the complexity of the schemes suggested that strong difficulties would be encountered for forcing a laser to follow a desired evolution.

The nineties and chaos control

A breakthrough occurred in 1990 when Ott, Grebogi and Yorke (OGY) [9] pointed out the possibility to take advan-
tage of a mathematical property of dynamical systems: The
existence of unstable periodic orbits and stationary states.

Originally, the focus was made on chaotic systems. A
chaotic behavior (in a deterministic system) is associated
with a complex trajectory (a chaotic attractor) in phase
space (the space constituted by its dynamical variables).

In chaotic evolutions, the trajectory in phase space visits
its periodic orbits, that are unstable leading to visible sig-
natures in the recorded signals (bursts of almost periodic
behavior, as represented in Fig. 2e).

Application of this approach (and variants) led to suc-
cessful suppression of chaos on various systems, the first
being a chaotic mechanical system (a magnetoelastique ribbon [13]). Suppression of chaos was first performed in
1992 in a YAG laser with intracavity harmonic genera-
tion [14], and in a fiber laser [15]. An example of stabi-
lization in this latter system is presented in Fig. 3. Then
the feedback loops employed evolved, and many variants ap-
peared. However a technical limitation of these techniques
was the use of a sampling at the multiples or submultiples
of the output signal frequency (the output power in the case
of lasers). The resulting process of discontinuous signals
potentially prevented any application to systems with fast
dynamics.

Since they are unstable, these periodic orbits were gen-
erally considered as mathematical objects which are inter-
esting from the fundamental point of view (e.g., for char-
acterizing dynamical chaotic attractors [11]). However the
importance of such objects for practical applications were
not obvious up to the nineties.

In 1990 [9], OGY pointed out that these unstable pe-
riodic orbits (and stationary states) can be (almost always)
stabilized, using standard feedback control techniques, thus
allowing to convert chaos into periodic motion. Schem-
atically, the principle is to use a feedback device that “mea-
sures” deviations from the target unstable periodic orbit (or
stationary state), and applies corrections on a control pa-
rameter in order to force the trajectory to approach it. Cri-
tera for stabilization are not detailed here, as it is can be
found in several review papers (see in particular [12]). The
key point of this strategy consists in stabilizing an unstable
state that preexist in phase space. This has two important
consequences:

- The control requires only simple feedback techniques
  (in particular linear control is sufficient).
- Preliminary knowledge of the system’s model is not required

Besides, other types of technique were developed, with
the aim to avoid the processing of discontinuous signal,
that are based on time-delayed signals. For example, the
chaotic CO\textsubscript{2} laser used for illustration in Fig. 1b
and Fig. 2 has been stabilized using this type of feedback [16]:

$$\mu(t) = \beta [I(t) - I(t - T)],$$  \hspace{1cm} (1)

where $I(t)$ is the power detected at the output of the laser at
time $t$, $T$ is the period of the orbit to stabilize, and the signal
$\mu(t)$ is applied on the loss modulator of the laser. Such
strategies introduced by Pyragas [17] appeared to be very
efficient, since it is very suitable to fast systems. Besides,
the presence of delays leaded to challenging problems in
the stability analysis of periodic orbits [18, 19, 20, 21].
Figure 4: Control of a periodic orbit in a chaotic CO\textsubscript{2} laser, using Pyragas method. The control signal is applied to the losses according to eq. (1), and its fluctuations represent less than 2\% of the modulation amplitude. In the absence of control, the output is precisely the signal represented in Fig. 2c.

**Stabilization of steady states: Feasibility studies and applications**

**Stabilization of steady states in conventional lasers: Feasibility studies.** The research subject initiated by OGY on the control of periodic orbits had an surprising consequence, because it triggered an activity on the control of stationary states. This stemmed from the fact that, when a dynamical system exhibits sustained oscillations (chaotic or not), there often exists an unstable steady state, which can be stabilized. In lasers this led to efficient demonstrations with surprisingly simple devices. A simple electronic derivator (i.e., a high pass filter operating in the KHz-MHz range, Fig. 5) appeared efficient to suppress the oscillations (chaotic or periodic) that appear in lasers with intracavity nonlinear losses [5]. Similarly to the case of periodic orbits, the feedback device forces the system to remain on a preexisting unstable steady state. Hence the needed correction tends to zero (if no noise is present). An example is presented in Fig. 6.

Figure 5: Experimental setup used for stabilization of a Nd-doped fiber laser subjected to Q-switch instabilities [5]. The derivator is basically a simple high pass filter with a cutoff frequency in the 100 KHz range. The bandwidth of the system is lower (in the MHz range) than the free spectral range of the laser cavity.

An application: Suppression of “Q-switch oscillations” in mode-locked lasers: In the 2000’s such approaches found applications in the case of ps/fs generation in mode-locked lasers, with potentially important commercial consequences. Indeed, one of best ways to generate ps/fs pulses with solid-state lasers, is to introduce a saturable losses (in particular SESAMs). As a side effect [22, 1, 2], the saturable losses tend to induce an instability (passive Q-switch), which is a serious drawback for different reasons:

- In the best cases, this instability leads to full-scale oscillations of the envelope of the output pulses.
- The resulting high peak powers can also lead to the destruction of the mode locker itself.
- The strategy consisting of excluding the problematic parameter regions reduces the accessible parameter domain for laser optimization (e.g., reduction of pulse duration).
- As a more subtle issue, instabilities are more likely to...
be avoided when the focusing on the nonlinear mirror is strong. This leads to operating conditions close to the damage threshold.

This technique used on non mode-locked lasers has been shown to remain efficient in the case of mode-locked lasers. First theoretical studies have concerned analyzes of the stabilization process [23, 24]. Experimental realizations have been demonstrated on a Nd:YVO₄ laser [23], a Nd:YLF laser [25] and a fiber laser [26], using a feedback on the losses. The stabilization process is illustrated in Fig. 7 on the basis of the Haus equations [24] (a model with strong similarities with the Dattolli-Eleaume approach for FELs). This subject is now the subject of intensive investigation because of its implications in the development of diode-pumped solid-state ps/fs lasers.

Figure 7: Control of a mode-locked Nd:YLF laser using derivated feedback (calculated using Haus equations from Ref. [24]). Upper figure: Transient following the application of feedback control. The figure is the numerical simulation of the image that would be recorded by a double-sweep streak camera. Each vertical line represents a pulse profile, and the horizontal axis is associated to the pulse evolution at successive round-trips. Lower figure: Example of optimization allowed by the control. The pulse duration is represented as a function of the focusing in the mode-locking device (a saturable absorber). The focusing is \(1/\nu_0^2\) with \(\nu_0\) the laser beam waist in the absorber (in adimensional units, see [27] for details). Full and dashed lines are associated with operation with and without feedback control respectively. From Ref. [27].

### STABILIZATION OF STORAGE RING FREE ELECTRON LASERS

#### Dynamical instabilities in Storage Ring Free Electron Lasers

SR-FELs are subjected to instabilities leading to full-scale fluctuations of the picosecond pulse train envelope [28, 29, 30, 31] (typically in the subkilohertz range), which remind the Q-switch instability described in the preceding section. It has been shown that these nonstationary regimes have a deterministic dynamical origin [32], which leads typically to unwanted limit cycles. A typical example is represented in Fig. 8. This instability can appear at finite detunings (i.e. synchronization between the electron bunches stored in the ring and the optical pulses bouncing in the optical resonator), as in the super-ACO and UVSOR lasers, and sometimes appear also at zero detuning (in particular in ELETTRA). Typical detuning curves of the SRFEL of Super-ACO, ELETTRA and UVSOR are presented in Fig. 9.

Figure 8: Evolution of the picosecond pulse emitted by a FEL oscillator (super-ACO) observed with a double sweep streak camera. (a) in the stable domain, near perfect detuning; (b) in the unstable domain. In these images, successive vertical cuts can be viewed as the picosecond pulse profiles at the successive round trips in the cavity (80000 cavity round trips in 10 ms).

#### Control of the FEL instabilities

A typical bifurcation diagram of the intensity of the SR-FEL in function of the detuning is presented on Fig. 10. This bifurcation diagram has been obtained using an intensity model of the FEL [31]. A stationary stable state exist near perfect tuning and for large detuning. Between these regions is the instability domain where self-pulsing occurs. However, the stability analysis of the different solutions shows that a unstable steady state exists in this region. This implies the possibility of preventing the laser pulsing by stabilizing this unstable steady state. Studies in this direction have been performed numerically [33] using direct integration of the model [31], and analytically [34].
In the latter work, a map for the pulse properties has been extracted from the full model, allowing the derivation of analytical conditions for the stabilization.

This approach has been implemented experimentally for the SRFELs of super-ACO, ELETTRA and UVSOR. In a first step, a derivative feedback has been used in the three FELs. The output power is monitored by a photodetector whose bandwidth resolves the oscillations, but not the pulse repetition rate. This signal is derived by a high-pass filter, and the output modulates the RF frequency of the ring, Fig. 11. Typical experimental transients of the output power following the application/release of the control are shown in Fig. 12. Associated streak camera recordings are presented in Fig. 13.

**CONCLUSION**

The works on control of preexisting unstable periodic and stationary states have allowed to elaborate powerful strategies for stabilizing lasers. First experiments have demonstrated the possibility of stabilizing periodic orbits with either a feedback with or without discontinuities (TDAS). In parallel, this subject has triggered an activity on the more simple question of steady state stabilization. Practical applications appeared recently in the field of mode locked lasers (Q-switch suppression).

In the case of SR-FELs, steady state suppression of the pulsed regimes has been demonstrated in the cases of super-ACO, ELETTRA and UVSOR. Future works concern improvements of the feedback schemes. Combined derivative/proportional feedback [35], as well as methods with multiple delays are now investigated (in a similar way to the case of conventional lasers [36]). Another important
perspective concerns the consideration of the noise that remains under application of control, and that originates either from spontaneous emission and technical fluctuations [37].

REFERENCES


Figure 12: Experimental transients observed when the control is switched ON and OFF (output power, the train of picosecond pulse is not resolved by the detector). (a) Super-ACO, (b) ELETTRA, and (c) UVSOR.

Figure 13: Typical transients following application of control, recorded with a double sweep streak camera. (a) and (b): cases of super-ACO and UVSOR respectively.

[158x754]Proceedings of the 27th International Free Electron Laser Conference

JACoW / eConf C0508213


