FEEDBACK CONTROL OF DYNAMICAL INSTABILITIES IN CLASSICAL LASERS AND FELs

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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.

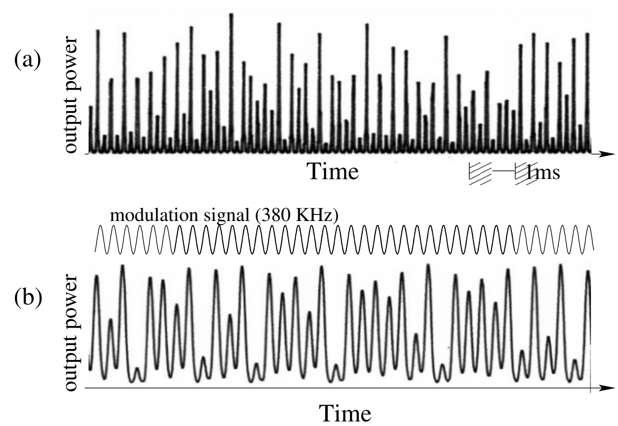

Figure 1: Two examples of instabilities in classical lasers. (a) Spiking of the "Q-switch type" at the output of a Nd-doped fiber laser with constant parameters (experiment of ref. [5]). (b) Output power of a CO_2 laser under sinusoidal loss modulation. Both lasers exhibit deterministic chaos.

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 advantage 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 signatures in the recorded signals (bursts of almost periodic behavior, as represented in Fig. 2c).

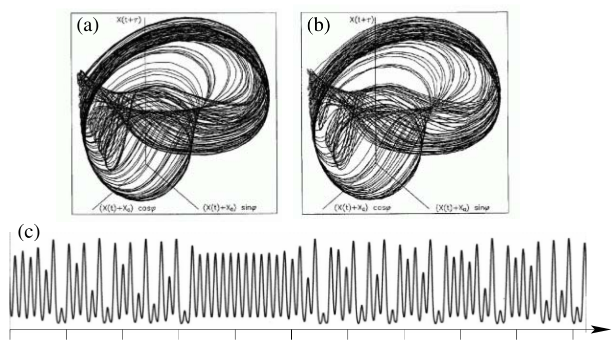

Figure 2: Existence of unstable periodic orbits in a CO_2 laser with periodic modulation (situation of Fig. 1b). (a) Chaotic trajectory in phase space, (b) set of periodic orbits embedded in the attractor. $X(t)$ is the laser intensity intensity in Log units, and φ the phase of the modulation (see [10] for details). (c): typical burst of almost periodic motion observed when the trajectory visits the neighborhood of a periodic orbit. (a) and (b) from Ref. [10].

Since they are unstable, these periodic orbits were generally considered as mathematical objects which are interesting from the fundamental point of view (e.g., for characterizing 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 periodic orbits (and stationary states) can be (almost always) stabilized, using standard feedback control techniques, thus allowing to convert chaos into periodic motion. Schematically, the principle is to use a feedback device that "measures" deviations from the target unstable periodic orbit (or stationary state), and applies corrections on a control parameter in order to force the trajectory to approach it. Criteria 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
- Once the unstable periodic orbit (or stationary state) is controlled, the corrections applied to the control parameter tend to zero (in the absence of noise).

Application of this approach (and variants) led to successful suppression of chaos on various systems, the first being a chaotic mechanical system (a magnetoelestic ribbon [13]). Suppression of chaos was first performed in 1992 in a YAG laser with intracavity harmonic generation [14], and in a fiber laser [15]. An example of stabilization in this latter system is presented in Fig. 3. Then the feedback loops employed evolved, and many variants appeared. 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.

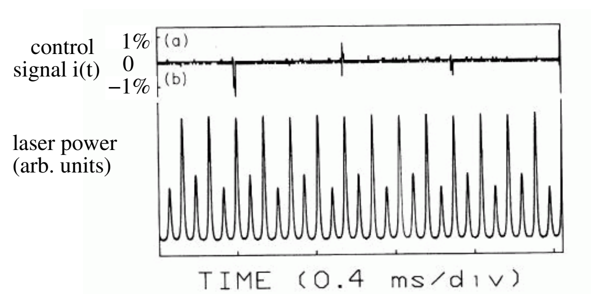

Figure 3: Control of a periodic orbit in a fiber laser. The detected output power $I(t)$ is sampled at each passage near a maximum. The resulting signal I_n is used for applying perturbations to the current $i(t)$ of the pumping diode laser (upper trace). The perturbations needed are less than 1% in magnitude. This smallness is due to the fact that a *preexisting* periodic orbit is stabilized by the feedback control (see Ref. [15] for details). Without control, the output is chaotic (of a type similar to the one of Fig. 1).

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_2 laser used for illustration in Fig. 1b and Fig. 2 has been stabilized using this type of feedback [16]:

$$\mu(t) = \beta \left[I(t) - I(t-T) \right], \tag{1}$$

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].

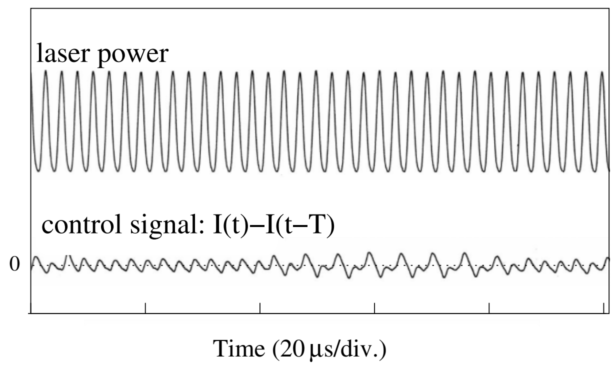

Figure 4: Control of a periodic orbit in a chaotic CO_2 laser, using Pyragas method. The control signal is applied to the losses according to eq. (1), and its fluctuations represent less than 2% of the modulation amplitude. In the absence of control, the output is precisely the signal represented in 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.

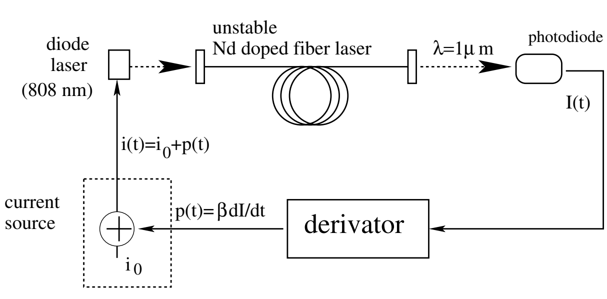

Figure 5: Experimental setup used for stabilization of a Nd-doped fiber laser subjected to Q-switch instabilities [5]. The derivator is basically a simple high pass filter with a cutoff frequency in the 100 KHz range. The bandwidth of the system is lower (in the MHz range) than the free spectral range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

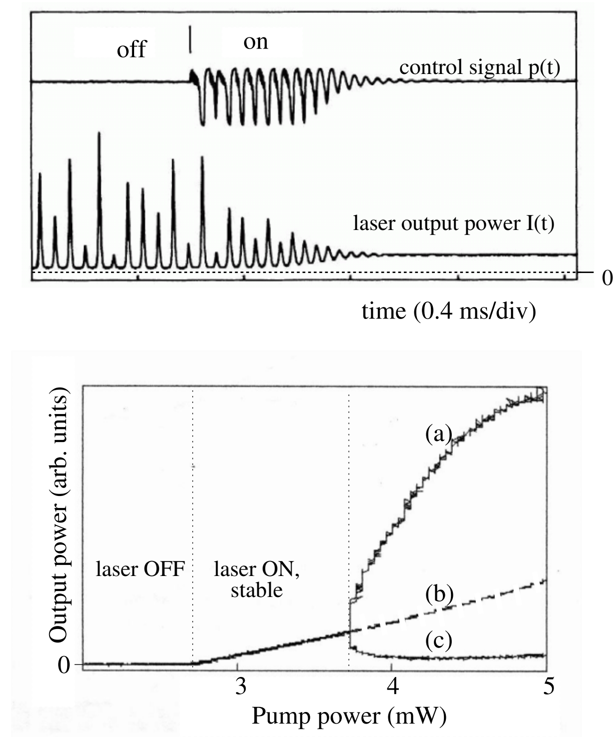

Figure 6: Feedback stabilization of the unstable steady state in a fiber laser [5]. Upper figure: Transient following the application of feedback, starting from a pulsing regime. Lower figure: Recording of the output power when the pump power is slowly swept. (a) and (c) are the maxima and minima of the oscillations when the laser is uncontrolled. (b) is the stabilized output obtained with feedback control. (b) coincides exactly with the unstable steady state that remains beyond the Hopf bifurcation (the curve is dashed for clarity).

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:YVO_4 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.

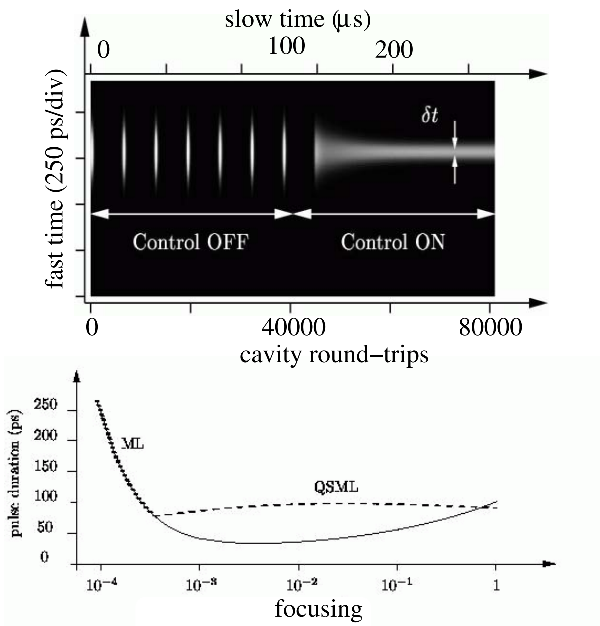

Figure 7: Control of a mode-locked Nd:YLF laser using derivated feedback (calculated using Haus equations from Ref. [24]). Upper figure: Transient following the application of feedback control. The figure is the numerical simulation of the image that would be recorded by a double-sweep streak camera. 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 $1/w_0^2$ with w_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

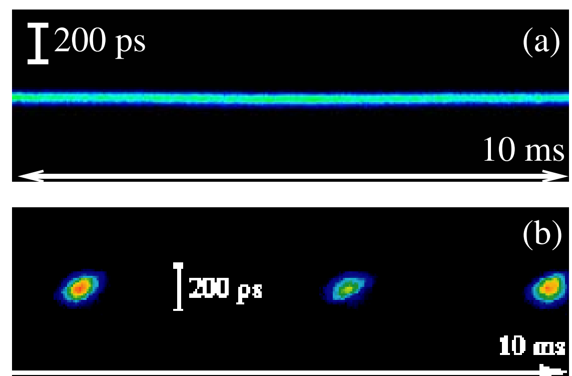

Figure 8: Evolution of the picosecond pulse emitted by a FEL oscillator (super-ACO) observed with a double sweep streak camera. (a) in the stable domain, near perfect detuning; (b) in the unstable domain. In these images, successive vertical cuts can be viewed as the picosecond pulse profiles at the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

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 SR-FEL of Super-ACO, ELETTRA and UVSOR are presented in Fig. 9.

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].

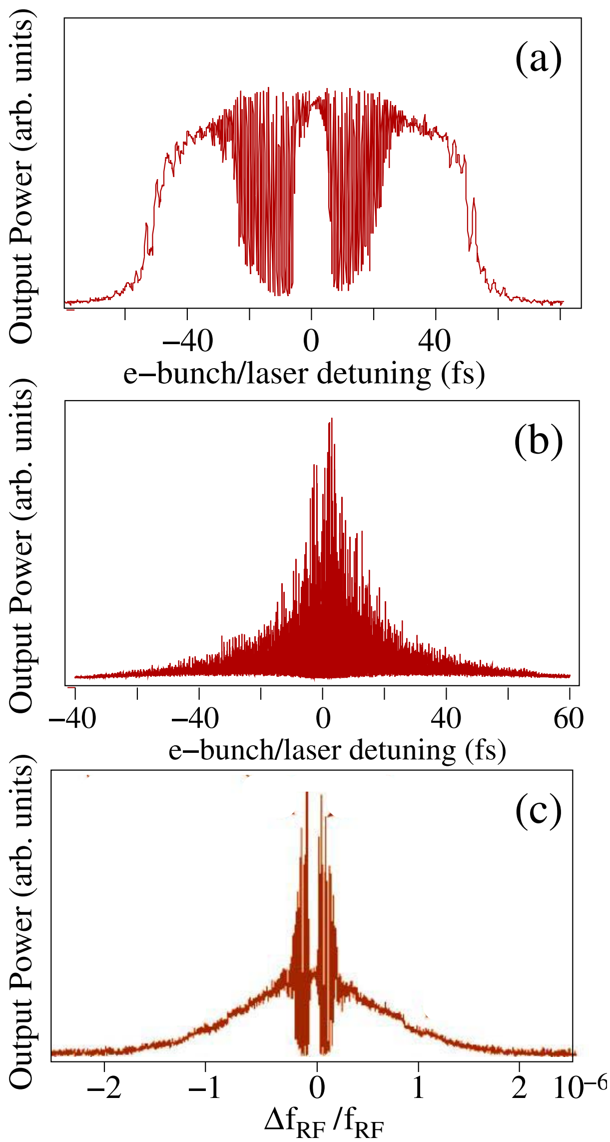

Figure 9: Output power versus detuning in the case of (a) super-ACO, (b) ELETTRA, (c) UVSOR.

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

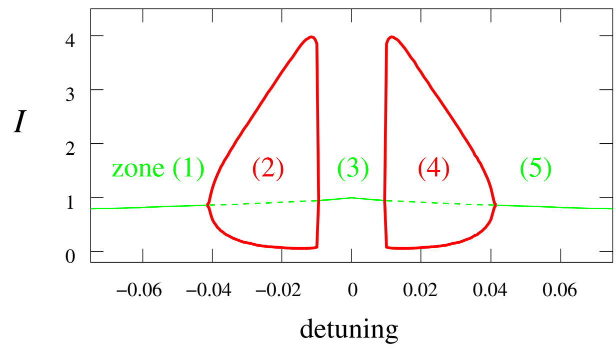

Figure 10: Bifurcation diagram of the FEL intensity model. The solid line in zone (1), (3) and (5) correspond to stable steady states. The dashed line in zone (2) and (3) correspond to unstable steady states that can be stabilized using the feedback control. The solid line in zone (2) and (3) correspond to the minima and maxima of the intensity in pulsed regime.

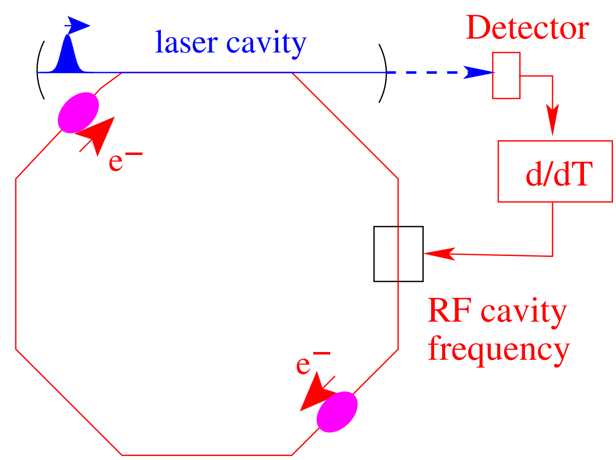

Figure 11: Setup for the feedback control system. The laser power is detected, derived, amplified and sent to the modulation frequency of the RF generator.

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

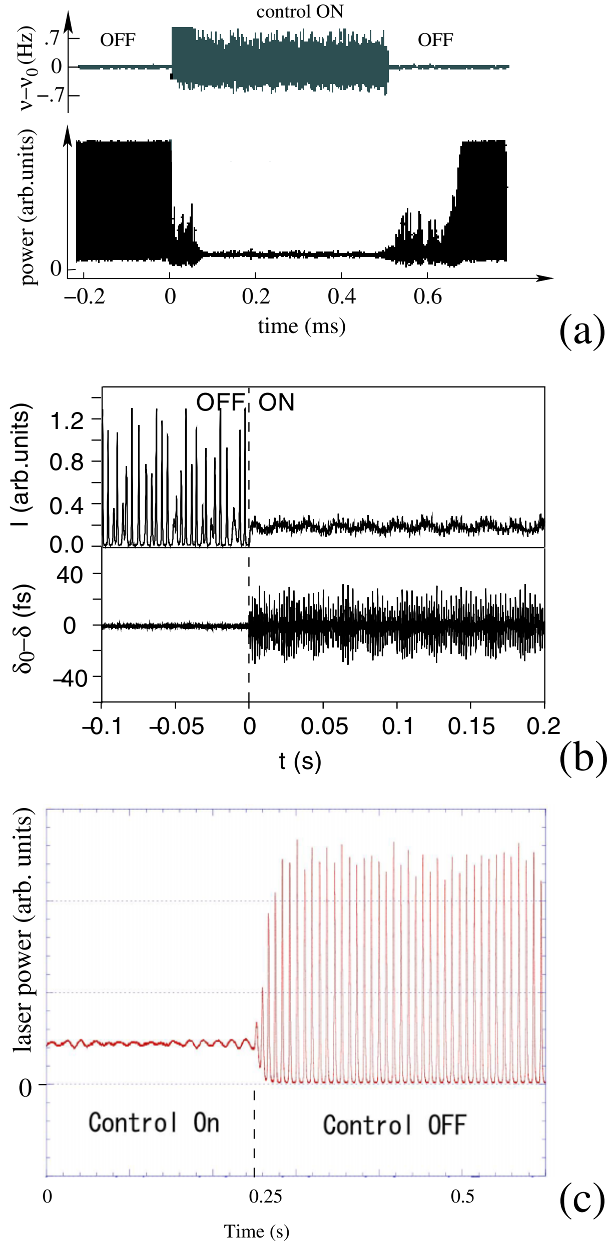

Figure 12: Experimental transients observed when the control is switched ON and OFF (output power, the train of picosecond pulse is not resolved by the detector). (a) Super-ACO, (b) ELETTRA, and (c) UVSOR.

perspective concerns the consideration of the noise that remains under application of control, and that is originates either from spontaneous emission and technical fluctuations [37].

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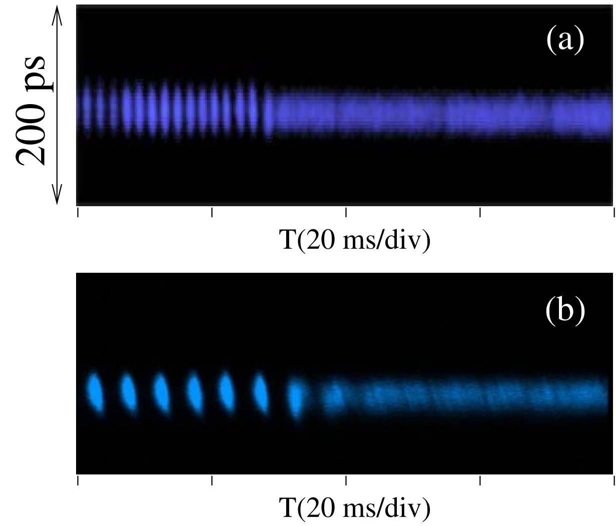

Figure 13: Typical transients following application of control, recorded with a double sweep streak camera. (a) and (b): cases of super-ACO and UVSOR respectively.

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