STORAGE RING FELS PULSE PROPAGATION EFFECTS AND MICROWAVE INSTABILITY

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Abstract

The mechanisms underlying the suppression of instabilities of microwave type by FEL interaction in Storage Rings are fairly well understood, the on set of the FEL provides a shift of the instability threshold, associated with the intensity dependent induced energy spread. Even though the intracavity power of nowadays Storage Ring FEL oscillators is sufficient to provide the conditions ensuring the complete suppression of the instability, it is interesting to investigate the regime in which the laser power is just close to the switching off threshold. This situation is particularly interesting because the instability may be eliminated without any significant increase of the e-bunch energy spread and length. We develop a dynamical description of the FEL-microwave instability interaction, by exploiting a model combining the FEL rate equations, including lethargy and pulse propagation contributions, and those accounting for the instability evolution. The obtained results confirm some controversial experimental evidences

1 INTRODUCTION

We have already pointed out that in a Storage Ring FEL Oscillator the interaction of the e-beam with the laser intracavity power may provide the conditions for the suppression of instabilities of longitudinal type[1]. We have also indicated the mechanisms underlying such an effect and we have used general consideration to derive the threshold power ensuring the instability switching off. The basic idea put forward in ref. [1] and in the subsequent investigations [2] is that the FEL and the microwave instability are competing effects, both can grow if the beam qualities are appropriate and both produce analogous beam qualities degradation. It has been shown that the dynamics of the two systems are closely similar and that both are characterized by a fast growth which is counteracted by the induced energy spread and bunch lengthening. When the FEL field grows in presence of the instability, the intensity dependent induced energy spread may be large enough to inhibit the on set of the instability. On the other side the effect of the instability may be so significant that the associated energy spread is big enough that the laser gain is not sufficient to warrant the system oscillation.

An idea of the FEL-microwave interplay is offered by figs. 1 where we have reported the damping coefficient of the exapolar longitudinal mode [3] vs a) the microwave

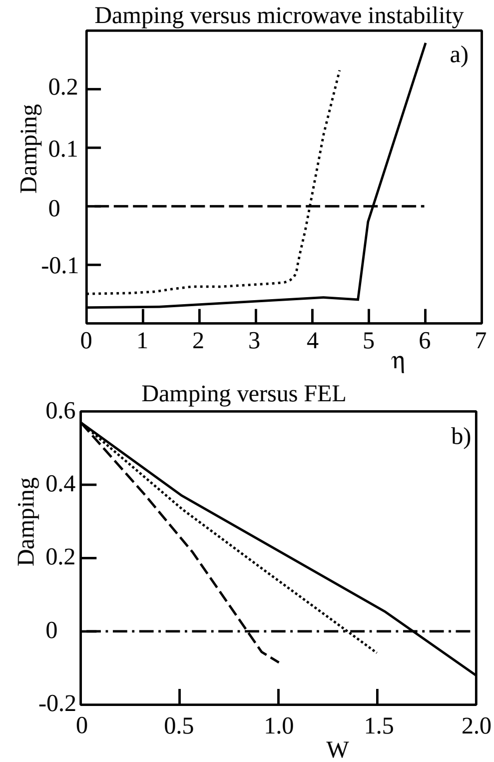

Figure 1: a) Damping term of the exapolar mode vs microwave instability strength without (dotted line) and with (continuous line) FEL contribution; b) Damping term of the exapolar mode vs FEL dimensionless intensity for different values of the detuning, $\nu = \pi/2$; (continuous line), $\nu = 0$ (dotted), $\nu = \pi$ (dashed)

strength and b) vs the FEL dimensionless power. It is evident that in case a) the presence of FEL shift the instability threshold towards larger values while in case b) the increase of the FEL power brings the system towards the stability region. It is worth noting that the instability suppression is more efficient for values of the detuning close to zero for which the beam heating effect is larger.

In the forthcoming sections we will explore the problem from a dynamical point of view and we will address the following questions

A) In the near threshold region may FEL and instability coexist?

B) After suppression may the instability have a revival?

C) What is the role of pulse propagation and slippage?

2 DYNAMICAL MODEL

In the following we will model the FEL-microwave instability dynamics by using the Storage Ring FEL oscillator equations[1] coupled to the Volterra like equations accounting for the microwave evolution [2] providing the dynamical version of the Boussard criterion [4],

$$\frac{d}{dt}\alpha = \left[\frac{A}{(1+\sigma^2)^{3/2}} - B(1+\sigma^2)^{1/2}\right]\alpha,$$

$$\frac{d}{dt}\sigma^2 = \alpha\sigma^2 - \frac{2}{\tau_s}(\sigma^2 - x), \qquad (1)$$

$$\frac{d}{dt}x = Ex\left[\frac{1}{\sqrt{1+\sigma^2}}\,\frac{1}{1+1.7\mu_\varepsilon^2(0)(1+\sigma^2)} - r\right]$$

where

$\alpha \equiv$ instability growth rate,
$\sigma \equiv$ induced energy spread normalized to the natural energy spread ($\sigma_{\varepsilon,n}$)
$x \equiv$ dimensionless intracavity power, (2)
$r = \frac{\eta}{0.85 g_0}$, $g_0 \equiv$ small signal FEL gain coefficient
$\eta \equiv$ cavity losses,

$$\mu_\varepsilon(0) = 4N\sigma_{\varepsilon,n},\ N \equiv \text{number of undulator periods}, \qquad (3)$$

The coefficients A, B, E are linked to the machine parameters by

$$A = \frac{n}{T_0}\sqrt{\frac{(2\pi)^{3/2} I_0 \nu_s \left|\frac{Z_n}{n}\right|}{\left|\frac{E_0}{e}\right|\sigma_{\varepsilon,n}}}\,,$$

$$B = \frac{2\pi}{T_0}\alpha_c\sigma_{\varepsilon,n},\ E = \frac{0.85 g_0}{T_0} \qquad (4)$$

$T_0 \equiv$ machine revolution period,
$I_0 \equiv$ beam average current.

The condition for the instability suppression is

$$\frac{d}{dt}\alpha = 0,$$

$$\sigma^* = \sqrt{\left(\frac{A}{B}\right)^{4/3} - 1} = \sqrt{\left(\frac{I_0}{I_{th}}\right)^{2/3} - 1}, \qquad (5)$$

$$I_{th} = \frac{\sqrt{2\pi}\left(\frac{E_0}{e}\right)\sigma_{\varepsilon,n}^3}{\nu_s\left|\frac{Z_n}{n}\right|\alpha_c^2} \equiv \text{Boussard threshold current}$$

We will use σ^* as reference threshold value for the FEL induced energy spread to switch off the instability. An idea of the system dynamics is offered by figs. 2 in which we report the evolution of the intracavity laser power and the induced energy spread for a Storage Ring FEL operation with and without microwave instability, for

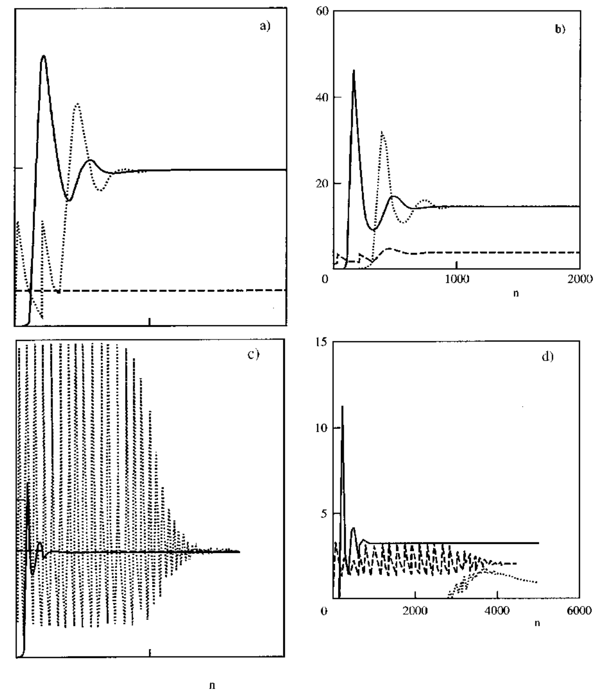

Figure 2: a) Normalized induced energy spread (σ^2) vs time for a system without instability (continuous line), with instability (dotted line) and σ^{*2} (dashed line). b) Dimensionless intracavity power vs. time (same as a)) the dashed line represents the total induced energy spread for a system including the instability effects A= $9\cdot10^4$, B=$3\cdot10^4$, E=10^4,$\mu_\varepsilon(0)$=0.1, ε=0.2, τ_s=3mδ; c) same as a); d) same as b) for r=0.45.

different values of the losses. It is evident that when the losses increase the intracavity power and the induced energy spread decrease so that it becomes increasingly difficult to counteract the effect of the instability. It is worth noting that when the induced energy spread is just below the threshold value, the FEL may start but is eventually switched off because not supported by sufficient gain, notwithstanding the instability can be counteracted. This effect is due to the genuine non linear nature of the interaction which implies a non trivial dependence of the whole system dynamics on the initial conditions which cannot be simply restored by the damping.

3 INSTABILITY AND PULSE PROPAGATION EFFECTS

In this section we will include in the system dynamics contributions due to the finite longitudinal e-bunch structure and to cavity mismatch effects which may provide a lack of overlapping between electron and photon bunches after each cavity round trip. This effect has been shown to provide a pulsed behavior of the laser operation when the system is close to saturation. The equation we will use are an extension of eqs. (1) and read

$$\frac{d}{dt}\alpha = \left[\frac{A}{(1+\sigma^2)^{2/3}} - B(1+\sigma^2)^{1/2}\right]\alpha,$$

$$\frac{d}{dt}\sigma^2 = \alpha\sigma^2 - \frac{2}{\tau_s}(\sigma^2 - \bar{x})$$

$$\frac{d}{dt}x(\tau,t) = E\left[x(\tau+\delta,t)G(\tau,\sigma) - \bar{r}x(\tau,t)\right] + S(\tau), \bar{r} = \frac{\eta}{g_0}$$

where

$$G(\tau,\sigma) = \frac{2\pi}{\sqrt{1+\sigma^2}}\int_0^1 d\xi(1-\xi)\sin(\nu\xi)e^{-\frac{(\pi\mu_\varepsilon(0))^2}{2}(1+\sigma^2)} * e^{-\frac{\tau^2}{2(1+\sigma^2)}},$$

$$\bar{x} = \int_{-\infty}^{\infty} x(\tau,t)d\tau, \tau = \frac{z}{\sigma_z} \qquad (7)$$

with τ being the longitudinal coordinate normalized to the bunch length. The function G(τ,t) denotes the gain function including the line shape (ν is the detuning parameter) and the e-bunch distribution which is assumed Gaussian at any time, S(τ) specifies the contribution from the spontaneous emission.

The results of the numerical integration is summarized in figs.(3,4). The case with $\delta = 0$ does not contain any significant difference with respect to the already discussed dynamics. While that with $\delta \neq 0$ is more interesting, as already remarked the system does not reach a real steady state operation, as indicated in figs. (3a,b)

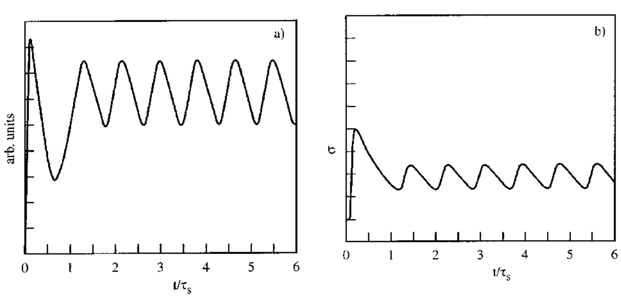

Figure 3: a) Evolution of the optical packet intensity $\bar{x}$, b) Evolution of the e-beam induced energy spread
$A = g_0$=5%, η=1%,τ_s=1.5ms,$T_0=2\cdot10^{-7}$s,δ=0.1, S~5 without instability effects.

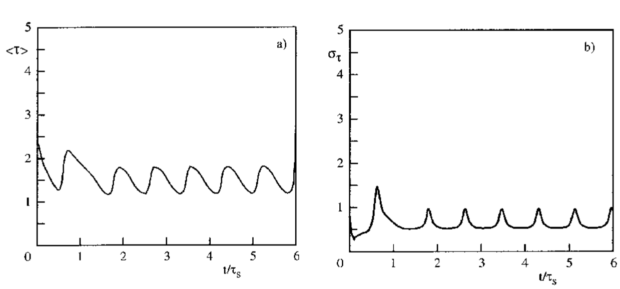

Figure 4: a) Evolution of the optical packet centroid. b) Evolution of the r.m.s. of the optical packet. Same parameters of fig. 3).

accounting for the evolution of the dimensionless optical power and the induced energy spread without the inclusion of instability effects. The evolution of the optical packet is summarized in figs.(4a,b) where we have reported the temporal behavior of the centroid of the optical packet and of its r.m.s. length, It is evident that the motion of the optical packet is characterized by a kind of breathing and by a back and forth of its centroid. The inclusion of the instability does not change the basic features of the previously described dynamics if the system has sufficient gain and the laser can start, the instability is counteracted and the evolution of the optical packet exhibits the same qualitative features of the case without instability.

The results we have obtained are based on a kind of heuristic model of the instability. We must underline that the implications of such a model have been checked by means of more complete numerical computations and the agreement has been found excellent [2].

The conclusions of the present investigation can be summarized as follows:

a) the FEL suppresses the instability when the induced energy spread is larger than the threshold value σ*,
b) the equilibrium laser power is that the FEL would reach in absence of the instability,
c) the FEL and the instability cannot cohabit,
d) in some subthreshold conditions the laser may be excited but if not adequately supported by the system gain may be switched off,
e) the present simulations cannot exclude the possibility of an instability revival
f) when pulse propagation effects are included the above conclusions are not modified except that for some values of the cavity mismatch the gain is not sufficient to ensure the growth of the laser itself,
g) the FEL may operate without inducing any significant increase of the e-beam energy spread and bunch lengthening (figs.2(c-d)).

This last fact confirms some puzzling experimental observations [5].

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