LASER HEATER AND COHERENT SYNCHROTRON RADIATION: ANALYTICAL AND NUMERICAL RESULTS

G. Dattoli, ENEA Centro Ricerche Frascati, Rome, Italy,
M. Migliorati, Rome University 'LA SAPIENZA' and INFN - LNF, Rome, Italy,
A. Schiavi, Rome University 'LA SAPIENZA', Rome, Italy.

Abstract

We develop some considerations allowing the possibility of deriving the conditions under which laser heater devices may suppress the Coherent Synchrotron Radiation Instability without creating any prejudice to the use of the beam for FEL SASE or FEL Oscillator operation. We discuss the problem using either numerical and analytical methods. The analytical part is aimed at evaluating the amount of laser power, necessary to suppress the instability. We use methods already developed within the context of FEL-storage rings dynamics, with particular reference to the interplay between FEL and Saw Tooth Instability. The numerical method employs a procedure based on the integration of the Liouville equation, describing the coupled interaction between electron beam and wake-fields, producing the instability, and the laser producing the heating. Particular attention is devoted to the competition between instability and heating. The comparison between numerical and analytical results is discussed too and the agreement is found to be satisfactory.

INTRODUCTION

The laser heater mechanism, proposed to suppress the Coherent Synchrotron Radiation Instability (CSRI) in FEL SASE devices [1], has been predicted for Storage Ring-FEL interaction [2] and observed at Super Aco [3]. The experiment has reported the observation of the damping of the saw tooth instability at the onset of the laser operation. The mechanisms underlying CSR or saw tooth instability suppression by a superimposed laser can be ascribed to Landau damping effects, through the macroscopically detectable heating associated with the induced energy spread [4].

The heater device for SASE FEL operation should meet the characteristics to have a sufficiently large laser power to inhibit the growth of the instability and to induce an energy spread small enough not to create problems to the SASE FEL operation. The compromise between the above points determines the amount of the power of the laser dedicated to the heater. In Fig. 1 we have reported two different conceptions of a laser heater: an external laser or a FEL oscillator, generated by the beam itself.

The solution b) is made possible only if the repetition rate of the electron bunches is such that it meets the cavity round trip requirements. If viable, the second scheme may offer several advantages, as, for example, the control of the laser intra-cavity power.

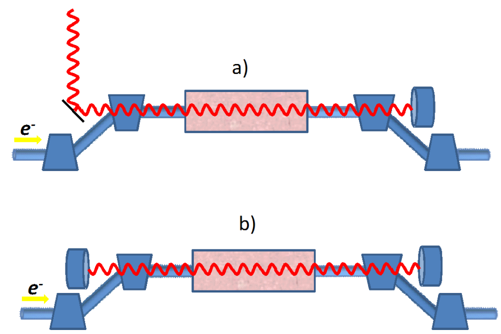

Figure 1: Laser heater schemes a) external b) FEL.

The considerations we will draw, regarding the amount of power required for the CSRI suppression, are however independent on the type of adopted solution. In both cases the interaction is of FEL type, it occurs indeed between a laser beam and an electron bunch co-propagating in an undulator, quasi resonant with the laser frequency.

FEL - CSRI INTERPLAY

All the physics concerning the FEL-CSRI interplay stays in a nut shell and can be expressed as it follows: both effects are characterized by a linear gain which is counteracted by the induced energy spread, which determines a kind of gain saturation. The dependence of the gain on the energy spread (induced or not) is ruled in both cases by the function

$$f(\sigma_\varepsilon) \propto e^{-\alpha\sigma_\varepsilon^2} \quad (1)$$

where σ_ε is the relative energy spread and α is a coefficient depending on whether we are dealing with CSR or FEL.

For the particular case of an electron beam with a Gaussian longitudinal distribution, the CSR and FEL induced energy spreads are given by [5, 6]

$$\begin{aligned} \sigma_{CSR} &\simeq \frac{0.246}{\gamma}\frac{N_e r_e}{R^{\frac{2}{3}}\sigma_z^{\frac{4}{3}}}L \\ \sigma_{FEL} &\simeq \frac{0.433}{2N}\sqrt{\pi x} \\ x &= \frac{I}{I_S} \end{aligned} \quad (2)$$

where N_e is the number of electrons in the bunch, r_e the classical electron radius, γ the relativistic factor, σ_z the bunch r.m.s. longitudinal length, R and L respectively the bending magnet radius and length.

The number of undulator periods where the interaction occurs is denoted by N, furthermore I is the laser intensity (be it that of an external laser or the intra-cavity FEL intensity) and I_S is the FEL saturation intensity, which is linked to the electron beam power density P_E and to the FEL small signal gain coefficient g_0 by

$$I_S g_0 = \frac{P_E}{2N} \tag{3}$$

We make now the assumptions that

- the two induced energy spreads combine quadratically, and yield a total energy spread denoted by σ_T;
- the beam is further accelerated and compressed to get a larger peak current to drive a FEL SASE operation (see Fig. 2).

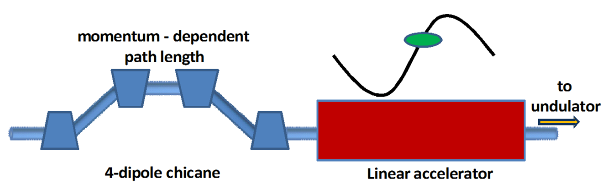

Figure 2: Sketch of the machine devices used in our study.

During the compression the electron bunch length is reduced by a factor δ_z^{-1} (compression factor) and the relative energy spread is reduced by a factor $\delta_\gamma^{-1} = \gamma_i/\gamma_f$, where the subscripts i, f stand for initial (before acceleration and compression) and final (after acceleration and compression).

The FEL will grow in the undulator only if the total energy spread will be such that

$$\tilde{\mu}_T \simeq \frac{2\sigma_{T,f}}{\rho} < 1 \tag{4}$$

where ρ is the SASE FEL gain parameter. In these conditions the required power intensity necessary to suppress the CSRI, without creating any prejudice to the SASE FEL operation is given by

$$\begin{aligned} I^* &\simeq \xi \rho I_{SASE} \\ I_{SASE} &\simeq \sqrt{2}\rho P_E^f \end{aligned} \tag{5}$$

where P_E^f is the electron beam power density in the undulator. The physical meaning of eq. (5) is quite clear since it relates the laser power of the heater to the SASE output power, by means of the ρ and ξ parameter specified as [7]

$$\begin{aligned} &\xi = \frac{N}{b^2}\left(\hat{\mu}_T^2 - \hat{\mu}_{0,CS}^2\right)\frac{\delta_\gamma \delta_z}{2\sqrt{2}g_0} \\ &\hat{\mu}_{0,CS}^2 = 4\frac{1+\alpha_{CS}^2}{\rho^2\delta_\gamma^2}\sigma_{\varepsilon,0}^2 \qquad b \simeq 0.433\sqrt{\pi} \\ &\alpha_{CS} = \frac{\sigma_{CSR}}{\sigma_{\varepsilon,0}} \qquad \delta_z = \frac{\sigma_{z,f}}{\sigma_{z,i}} \end{aligned} \tag{6}$$

where $\sigma_{\varepsilon,0}$ is the energy spread of the electron beam before being affected by heating and CSRI.

The parameter ξ depends on the compression factors in energy spread and current; however if we assume that the laser power density be of the order of the FEL (heater) saturation intensity, we find for the ξ parameter the following reference value

$$\xi = \frac{1}{2\sqrt{2}g_0 N\rho^2}\frac{\gamma_i}{\gamma_f} \tag{7}$$

where N and g_0 are relative to the FEL heater and therefore we may conclude that ξ is of the order unity.

MICRO BUNCHING INSTABILITY

An analogous procedure can be exploited to evaluate the power necessary to damp the microbunching instability. In this way we find [7]

$$\begin{aligned} I^* &\simeq \chi P_E^f \\ \chi &= \frac{\phi}{n\beta b^2}\frac{\sqrt{2}\delta_z}{2\delta_\gamma}\frac{k|R_{56}|}{\left|\frac{d\Psi}{d\gamma}\right|}\frac{1}{Ng_0} \end{aligned} \tag{8}$$

which has been derived by taking into account that the bunching coefficients b_n are related to the energy dispersion and energy spread by the relation

$$\begin{aligned} &b_n \propto J_n\left(\Delta\gamma\frac{d\Psi}{d\gamma}\right)e^{-\frac{n^2}{2}\sigma_{T,f}^2\left(\frac{d\Psi}{d\gamma}\right)^2} \\ &\frac{1}{\sqrt{2}}n\sigma_{T,f}\left|\frac{d\Psi}{d\gamma}\right| \simeq \phi \end{aligned} \tag{9}$$

VLASOV SOLVER SIMULATIONS

The validity of the previous analysis has been checked by means of a Vlasov solver [8] that, based on the solution of the Liouville equation and by exploiting the Lie algebraic techniques, allows us to study problems of beam transport in presence of non negligible wake fields effects.

The code uses a representation of the longitudinal beam density in phase space on a grid and, in contrast to macroparticle tracking codes, yields a relatively noise-free time evolution.

The magnetic compressor and the beam parameters used for our study are reported in Table 1.

The gain curve of an initial amplitude modulation due to the combined effects of the compressor and the CSRI can be obtained by solving an integral equation in the linear regime [9]. In Fig. 3 the black line shows such a curve. In the same figure we compare the linear theory with the results of the Vlasov solver (blue squares). Such a behavior can be well represented by eq. (1). In fact if we consider the dynamics of the magnetic compressor only determined by the beam optics, an initial energy modulation $\Delta\gamma$ is transformed to a density modulation as [10]

$$\rho_{mod} = \delta_z^{-1}k|R_{56}|\frac{\Delta\gamma}{\gamma_i}e^{-\frac{1}{2}\delta_z^{-2}k^2R_{56}^2\sigma_\varepsilon^2} \tag{10}$$

Table 1: Magnetic compressor and beam parameters

bending radius	3.125	m
bending length	0.2	m
first and last drift	3	m
middle drift	0.2	m
beam energy	420	MeV
initial beam current	100	A
bunch length	2.25	ps
uncorrelated initial energy spread	3×10^{-5}	
linear chirp	34	1/m
R_{56}	0.025714	m
compressor factor	8	

If we make the further hypothesis that the initial energy modulation $\Delta\gamma$ is determined by the CSR of the bending magnets and is concentrated before entering in the compressor, we can write an approximated expression of the gain curve (that overestimates the effect), as

$$G = \delta_z^{-1} k |R_{56}| \frac{I_0}{I_A \gamma_i} \frac{|Z_{CSR}|}{Z_0} e^{-\frac{1}{2}\delta_z^{-2} k^2 R_{56}^2 \sigma_\varepsilon^2} \quad (11)$$

where I_0 is the uncompressed beam current, I_A the Alfven current, Z_{CSR} the impedance due to the CSR, Z_0 the vacuum impedance. The above equation is represented in red in Fig. 3 and demonstrates that the gain has the dependence on the energy spread as reported in eq. (1).

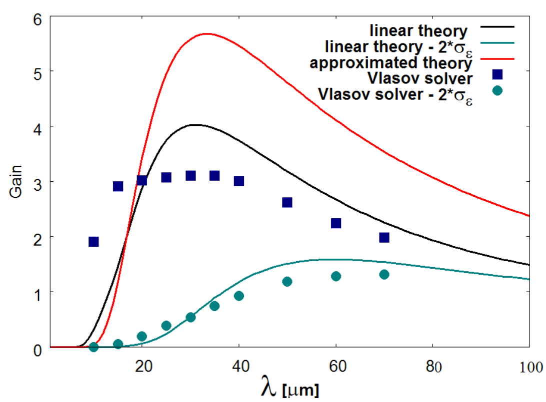

Figure 3: Gain curve of an initial density modulation with the parameters of Table 1.

By inspecting eq. (11), we can argue that a reduction in the gain is obtained by increasing the exponential argument. For example, if the presence of the laser heater doubles the uncorrelated energy spread, the reduction of the gain is more than doubled, as shown with the green line in Fig. 3. A good agreement also in this case has been obtained with the simulation code (green dots).

Using the same argument as before, we find that the inhomogeneous broadening parameter, induced by the energy spread, is now doubled (see eq. (4)), and, by assuming that such an energy spread does not significantly affect the SASE operation, eq. (6) allows us to find the optimum laser power to suppress the instability. In fact, if we notice that generally the energy spread increase due to the CSR for a high correlated bunch distribution is negligible compared to that due to the compression, we obtain again that the parameter ξ is of the order of unity (or even less), so that the laser intensity, necessary to switch off the instability, is just the fundamental FEL parameter times the output SASE power, that is just a small fraction ($\sim$0.1%) of the FEL output power.

We must, however, emphasize that the condition of eq. (4) becomes more difficult to be satisfied when the fundamental FEL parameter becomes less than 10^{-3}.

CONCLUSIONS

The results obtained in this paper are related to the condition which a laser power should satisfy in order to damp the micro bunching instability, without lowering the SASE performance. The considerations we have developed lead to a kind of criterion to optimize the heater power, which holds independently of the nature of the heater (external laser or FEL oscillator).

The calculations we have presented are simplified and indeed we did not take into account three dimensional effects, which can, however, be accounted for by a proper redefinition of the fundamental FEL parameter ρ. The electron beam energy spread may have different origins, which all contribute to the damping of the instability. For this reason the presence of the CSR contribution and of the spread from injector also reduce the request on the beam heater power.

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