STUDY OF MICROBUNCHING INSTABLITY IN THE LINAC OF THE SHANGHAI SOFT X-RAY FEL FACILITY*

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Abstract

The microbunching instability (μBI) in the LINAC of a FEL facility has always been an issue which may degrade the electron beam quality. As the result, the whole facility may not be working properly. Therefore, learning how to control and reduce the instability is the key to the success of a FEL project. Shanghai soft X-ray FEL project (SXFEL) has been proposed and the feasibility study is finished. Once it is built, it will be the first X-ray FEL facility in China. In this article, detailed study will be given based on the design parameters of the facility to gain better understanding and control over the possible microbunching instability in SXFEL, which is critical to the success of the FEL project.

INTRODUCTION

The proposed Shanghai soft X-ray FEL facility is planned to be built in a few years. It will be a cascading HGHG FEL facility which will be working at 9 nm soft X-ray band. The electron beam energy of it at the exit of the LINAC will be around 840 MeV, the peak current will be around 600 A. The normalized emittance of the electron beam at the LINAC exit will be 2.0 – 2.5 mm.mrad.

Both the analytical and numerical studies show that μBI- induced growth of the global/slice energy spread in the LINAC is not ignorable; it also reduces the smoothness of the longitudinal beam current profile. Therefore, without proper control, the instability will be a serious problem and may impair the FEL process thereafter.

One way to control the instability is to increase the uncorrelated energy spread of the beam, which can be done by a laser heater [2][8], and it will also be implemented in SXFEL.

COMPUTATION AND ANALYSIS OF THE INSTABILITY

The basic principle of the microbunching instability in the LINAC of a FEL device has already been well-studied [1][2][3]. It is similar to the amplification mechanism in a klystron amplifier. The initial density modulation or white noise can be transferred into energy modulation by the impedances when the beam is being accelerated including the longitudinal space charge (LSC), coherent synchrotron radiation (CSR) and the structural impedance. When the beam is passing through the dispersive section such as the bunch compressor (chicane), the energy modulation will be turned back into the much stronger density modulation, in such a way that the microbunching instability is developed. Moreover, the CSR effect in the dispersive section will also form a positive feedback to enhance the instability. More dispersive sections in the LINAC will have more serious μBI problem. Figure 1 is the schematic description of the instability process.

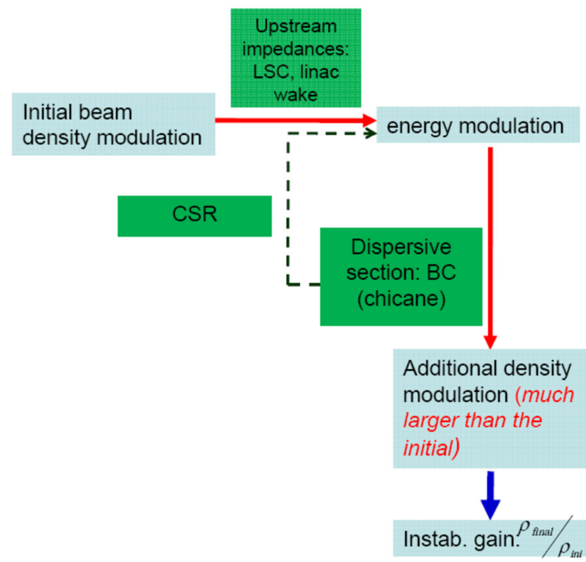

Figure 1: The microbunching instability process.

As discussed above, in the LINAC, the microbunching instability is mainly driven by the LSC, CSR and structural impedances. Since the structural impedance is more complicated and its effect on the instability is not as significant as the other two, in this article, we will be focusing on the microbunching instability introduced by the LSC and the CSR impedance.

The basic layout of the SXFEL LINAC is the following:

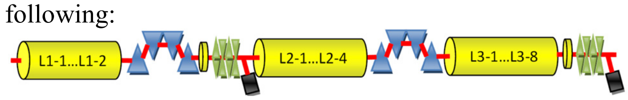

Figure 2: The layout of the SXFEL LINAC.

The SXFEL LINAC includes both S-band and C-band accelerating structures, one X-band structure to suppress the non-linear higher order mode (HOM), and two chicane-type bunch compressors (BC1 & BC2). Since there are two bunch compressors, the microbunching instability in the SXFEL LINAC is not negligible. The computation and simulation in the following is based on the design parameters of the LINAC, and the beam parameters out of the injector tracked by PARMELA [4]. Those parameters are listed in table 1.

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Microbunching Instability Driven by the Longitudinal Space Charge (LSC) Impedance

In general, the microbunching instability driven by the longitudinal impedance has already been studied in details [1]. The gain of the instability is computed by [1]:

$$G = Ck|R_{56}|\frac{I_0}{\gamma_0 I_A}\frac{|Z(k)|}{Z_0}\exp\left(-\frac{1}{2}C^2k^2R_{56}^2\frac{\sigma_\gamma^2}{\gamma_0^2}\right) \tag{1}$$

Where

$$C = 1/(1 + hR_{56})$$

is the compressing factor. For the longitudinal space charge, the impedance takes the form [5][6]:

$$Z_{\mathrm{LSC}}(k) = \frac{iZ_0}{\pi k r_b^2}\left[1 - \frac{kr_b}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right] \approx \begin{cases} \dfrac{iZ_0}{\pi k r_b^2}, & \dfrac{kr_b}{\gamma} \gg 1, \\ \dfrac{iZ_0 k}{4\pi\gamma^2}\left(1 + 2\ln\dfrac{\gamma}{r_b k}\right), & \dfrac{kr_b}{\gamma} \ll 1, \end{cases} \tag{2}$$

Table 1: Main beam parameters used in the μBI calculation for SXFEL (obtained from Elegant [10] simulation)

Parameter	Value
Electron energy before BC1 (MeV)	208.4
Uncorrelated energy spread before BC1 (keV)	7.67
Electron energy before BC2 (MeV)	425.1
Uncorrelated energy spread before BC2 (keV)	51.1
Compression ratio (BC1×BC2)	5×2
Peak current before BC1 (A)	60
Beam radius before BC1 (mm)	0.40
Beam radius before BC2 (mm)	0.26

The instability gain as a function of the initial modulation wavelength introduced by the LSC at the exit of SXFEL LINAC is shown in Figure 3 below. The gains in the 1st and 2nd bunch compressors are illustrated separately.

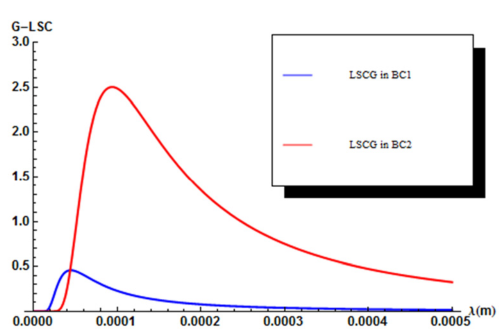

Figure 3: (color): The microbunching instability gain driven by the longitudinal space charge impedance as a function of modulation wavelength in the 1st (blue) and 2nd bunch compressors (red).

Microbunching Instability Driven by the Coherent Synchrotron Radiation (CSR) Impedance

As we already know, the electron beam in a bunch compressor can generate coherent synchrotron radiation (CSR). It can also be a source of modulation of the beam density at wavelengths small compared to the bunch length [3]. In other words, the microbunching instability can be produced from white noise due to the CSR effect in a bunch compressor.

The gain of the CSR-driven microbunching instability in a bunch compressor has already been well defined [2]. Assume a beam uniform in z and Gaussian in transverse and energy variables, the total gain induced by the CSR effect can be expressed as [2]:

$$G_f \approx \left|\exp\left[-\frac{\bar{\sigma}_\delta^2}{2(1+hR_{56})^2}\right] + A\bar{I}_f\left[\left(F_0(\bar{\sigma}_x) + \frac{1-e^{-\bar{\sigma}_x^2}}{2\bar{\sigma}_x^2}\right)\exp\left(-\frac{\bar{\sigma}_\delta^2}{2(1+hR_{56})^2}\right) + F_1(hR_{56}, \bar{\sigma}_x, \alpha_0, \phi, \bar{\sigma}_\delta)\right] + A^2\bar{I}_f^2F_0(\bar{\sigma}_x)F_2(hR_{56}, \bar{\sigma}_x, \alpha_0, \phi, \bar{\sigma}_\delta)\right| \tag{3}$$

According to reference [2], the first term on the right side of Eq. (3) represents the loss of microbunching in the limit of vanishing current, the second term is the one-stage microbunching amplification at low current, and the last term corresponds to the two-stage amplification at high current.

The computed microbunching instability gain driven by the CSR impedance as a function of modulation wavelength in SXFEL is shown in Figure 4. Again, the gains in the 1st and 2nd bunch compressors are illustrated separately.

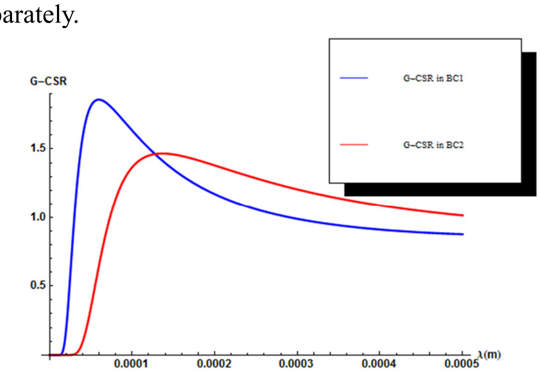

Figure 4: (color): The microbunching instability gain driven by the CSR impedance as a function of modulation wavelength in the 1st (blue) and 2nd bunch compressors (red).

Total Growth Rate of Microbunching Instability in SXFEL LINAC and Analysis

The total gain/growth rate of the instability in the SXFEL LINAC computed by analytical equations and by ImpactZ [7] is shown in Figure 5. Both the analytical solution and ImpactZ simulation peaks around ~ 100 um,

The amplitude of the two peaks looks different. It may be because of the small difference between the input parameters in the analytical computation and those in the simulation. For an example, the gain is very sensitive to the slice (uncorrelated) energy spread and R_{56} in the chicane, etc. Figure 6 below show the peak gain as a function of the relative uncorrelated energy spread of the beam before BC1. Moreover, it may be due to the excessive suppression of noises - It is known that the beam input in the simulation includes both the numerical and physical noises; it is possible that some of the "real" physical noises are incidentally smoothed out as well while we do numerical smoothing to the input beam profile.

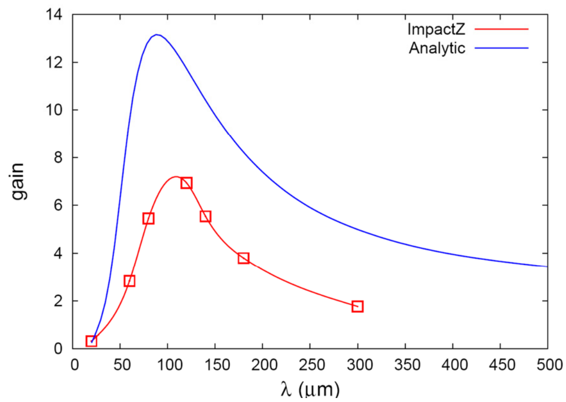

Figure 5: (color): The total μBI gain at the exit of SXFEL LINAC as a function of the modulation wavelength computed by analytical equations (blue) and ImpactZ [7] simulation (red) based on the current machine parameters.

As one can see in Figure 6, as the slice (uncorrelated) energy spread of the beam rises, the peak gain of the instability starts to fall very rapidly. It is indeed consistent with the theoretical expectation. It also tells us that in reality the gain may be very different from what we have calculated because of the possible variations of the "real" uncorrelated energy spread. Therefore, the laser heater [2] [8] is introduced to increase the uncorrelated energy spread of the beam by laser-beam interaction, in such a way to control the growth of the instability. Although the design is still not fully completed, the ongoing numerical simulation shows that it is able to reduce the gain significantly [9].

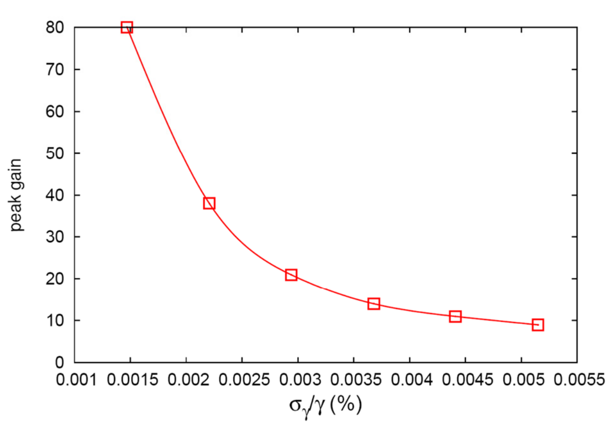

Figure 6: The peak gain computed as a function of the relative uncorrelated energy spread before the 1st chicane.

CONCLUSIONS

Microbunching instability is an important issue in the LINAC of a FEL facility. If the gain of the instability is too large, the quality of the electron beam will be destroyed and is harmful to the whole FEL device.

Both the analytical computation and numerical simulation show that the microbunching instability in SXFEL is not negligible, and the LSC impedance induced growth is larger than that driven by the CSR impedance. Moreover, the gain is very sensitive to some critical beam and lattice parameters such as the energy spread and the R_{56} in the chicanes, etc.

As a matter of fact, a laser heater is needed to suppress the instability. Further study is on the way to optimize and properly implement the laser heater into the SXFEL lattice.

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