ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP016

# STUDY OF MICROBUNCHING INSTABILITY IN SHINE LINAC*

Dazhang Huang†, Duan Gu, Meng Zhang, Shanghai Advanced Research Institute, Shanghai, China

*Abstract*

Microbunching instability usually exists in the linear accelerator (linac) of a free electron laser (FEL) facility. If it is not controlled effectively, the beam quality will be damaged seriously and the machine will not operate properly. As a typical example, the microbunching instability in the linac of the proposed Shanghai high repetition rate XFEL and extreme light facility (SHINE) is investigated in detail by means of both analytical formulae and simulation tools.

## INTRODUCTION

As the beam passes through a bunch compressor, for example, a magnetic chicane, the energy modulation introduced by those effects is transformed into density modulation and may thus introduce the so-called microbunching effects. In certain situations, the microbunching effects can be so large that the microbunching instability can also take effects, and the final gain of the instability can become significant. On the other hand, the FEL process has a high demand for electron beam quality in terms of peak current, emittance, energy spread, etc. Therefore to preserve the beam quality, the microbunching effects must be studied in the design stage of the machine. In this paper, the study of microbunching instability in the linear accelerator (linac) of Shanghai high repetition rate XFEL and extreme light facility (SHINE) is reported, the comparison between numerical and analytical results shows very good consistency, given the gain curve of the instability. Meanwhile, the preliminary study of the laser heater to suppress the instability is also illustrated. The paper is organized as the following: first the basic methods to study the microbunching instability is introduced and the results are shown, followed by the study of the laser heater including its effect on the instability and the transverse matching. The conclusion is drawn as the last part.

## METHODS

The recently approved SHINE project is a high repetition rate hard X-ray free electron laser (XFEL) facility based on the superconducting radio-frequency (SCRF) technology. In order to fulfil the goal of the project, a high energy, high peak current and low emittance electron beam is required as an output of linac. The main design parameters are illustrated in Table 1, and the schematic layout of the whole facility is shown in Figure 1 as well.

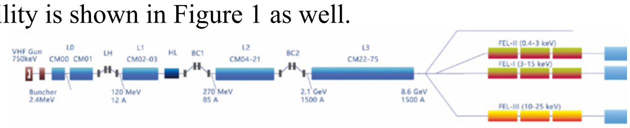

Figure 1: Layout of SHINE facility.

Table 1: Main Design Parameters of SHINE Linac

| Parameter | Value |
|---|---|
| Beam energy (GeV) | 4 - 8.6 |
| Bunch charge (pC) | 10 - 300 |
| Peak current (kA) | 1.5 – 3 |
| Repetition rate (MHz) | Up to 1 |
| Pulse length (fs) | 5 - 200 |

The microbunching instability starts from the initial beam current/density modulation, turned into the energy modulation by a variety of impedances such as linac wake, longitudinal space charge (LSC), coherent synchrotron radiation (CSR), and gets amplified by the dispersion in a bunch compressor (chicane). As usual, the SHINE linac includes multiple stage of bunch compression. In the physical design, two bunch compressors are employed and the third one is reserved as a spare to compress the bunch current up to 3 kA. The main parameters of the bunch compressors are listed in Table 2.

Table 2: Main Parameters of Bunch Compressors in SHINE Linac

| Parameter | BC1 | BC2 |
|---|---|---|
| Beam energy (MeV) | 269 | 2156 |
| Compression ratio | 7 | 15 |
| $R_{56}$ (mm) | -60.8 | -34.6 |
| Total length (m) | 12.2 | 24 |

The microbunching is modelled with the simulation code ELEGANT [1], which is commonly considered as a high-fidelity code in accelerator and beam physics. Due to the computing power, 20 million macro-particles are used to simulate 100 pC charge in the simulation. However, referring to [2], this number of macro-particle are nearly enough for this amount of charge.

To study the microbunching effects, equation (1) [3] is used to estimate the wavelength of the microbunching at the peak. Or in other words, the smearing of microbunching from the uncorrelated energy spread across the chicane is not effective until

$$\lambda_0 \leq \left|\frac{2\pi R_{56}}{1+hR_{56}}\right| \sigma_\delta \equiv \lambda_c, \quad (1)$$

Where $h$ is the energy chirp, $R_{56}$ is the momentum compaction of the chicane, and $\sigma_\delta$ is the uncorrelated energy spread of the beam before compression. With the magnetic chicane parameters in Table 1 and the corresponding beam parameters, we have $\lambda_c = 70.9$ μm for BC1, and $\lambda_c = 15.1$ μm for BC2 which corresponds to the initial density modulation of $\lambda_c \approx 106$ μm before BC1. Therefore, one

* Work supported by National Natural Science Foundation of China, Grant No. 1675248
† email address: huangdazhang@zjlab.org.cn

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may conclude that the peak of the overall microbunching gain shall locate in the vicinity of 72.7 μm and 106 μm in wavelength.

The analytical estimation above is reasonably consisted with the numerical simulation. Figure 2 and Figure 3 shows the final gain curve which peaks around110 μm, and the longitudinal phase spaces of the beam with various initial density modulations, respectively. The gain curve in Figure 1 is computed from the Fast Fourier Transform (FFT) of the residual current amplitude obtained through the polynomial fit to the current profile in the middle part of the beam [3] at the linac exit.

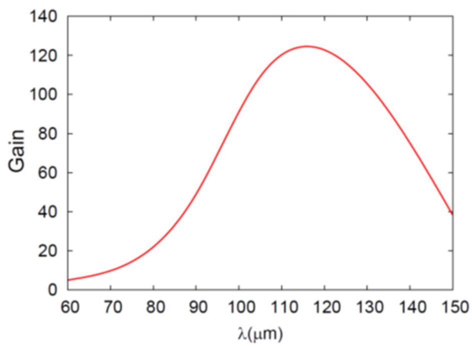
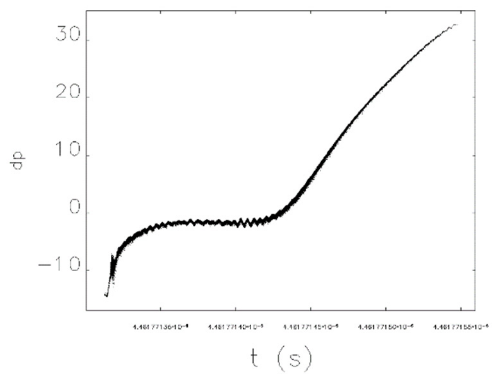
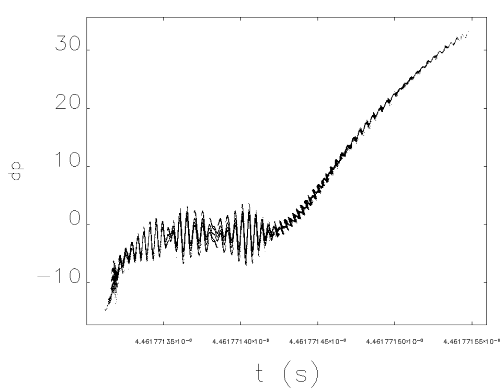


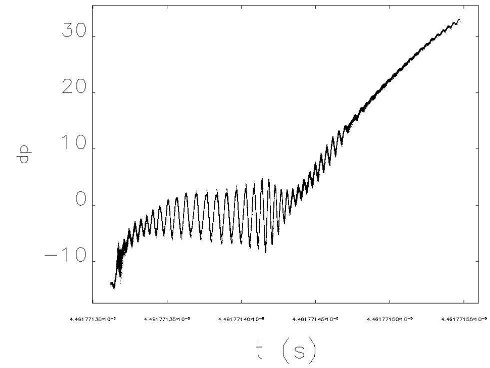

Figure 2: Final gain curve computed from the residual current of FFT of beam current obtained by ELEGANT.



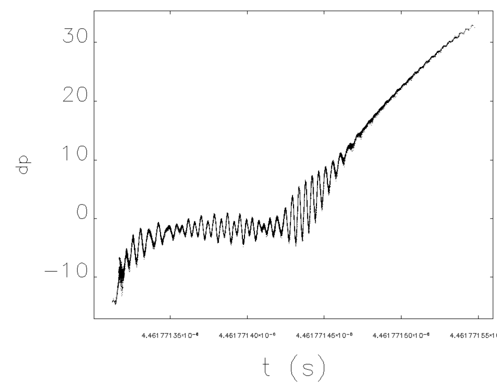

(a)




(b)




(c)




(d)

Figure 3: Longitudinal phase space of the beam at the exit of SHINE linac, with (a) 60 μm, (b) 90 μm, (c) 120 μm, (d) 150 μm initial density modulation.

## LASER HEATER

The gain (growth rate) of the microbunching instability for the case of linear compression has been discussed by Saldin et al. [4] phenomenologically by comparing the energy distributions before and after the compression. Consider a density modulation at wavenumber *k,* without higher harmonic of beam current taken into account, the gain of the instability driven by the wakefields upstream of the compressor reads (2) [4]

$$G = Ck|R_{56}|\frac{I_0}{\gamma I_A}\frac{|Z_{tot}(k)|}{Z_0}exp\left(-\frac{1}{2}C^2k^2R_{56}^2\frac{\sigma_\gamma^2}{\gamma^2}\right), \qquad (2)$$

where $\gamma$ is the nominal relativistic factor of the electron beam with rms local energy spread $\sigma_\gamma$in front of the bunch compressor,$C = 1/(1 + hR_{56})$ is the compression ratio, $h$ is the linear energy chirp, $R_{56}$ is the 5-6 element of the transport matrix, $I_0$ is the initial peak current of the beam, $Z_0 = 377\ \Omega$ is the free-space impedance, $Z_{tot}$ is the overall impedance upstream of the compressor including those of the LSC, linac wake, etc., and $I_A = 17\ kA$is the Alfven current.

From equation (2) one can see that the most effective way to suppress the microbunching instability is to increase the uncorrelated energy spread $\sigma_\gamma$. For the purpose of that, the device called laser heater has been designed.

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The layout of a typical laser heater is shown in Figure 4, which consists of an injection laser, an undulator and a chicane-type bunch compressor.

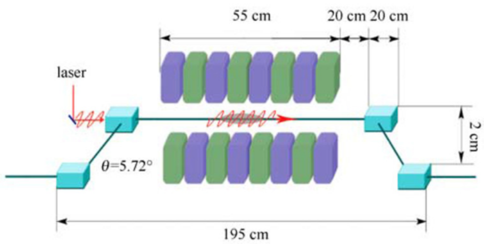


Figure 4: Layout of a typical laser heater.

A laser heater increases the uncorrelated energy spread of the beam by introducing the interaction between beam and laser. The detailed study of the laser heater can be found in [4]. Besides introducing the extra uncorrelated energy spread, there is also focusing effect on the vertical plane in the undulator, therefore we also have to rematch the beam twiss parameters to recover the optics.

Figure 5 shows the longitudinal phase space of the beam at the exit of SHINE linac with the laser heater on and off. In the figure one can see that microbunching is significantly suppressed by the laser heater.

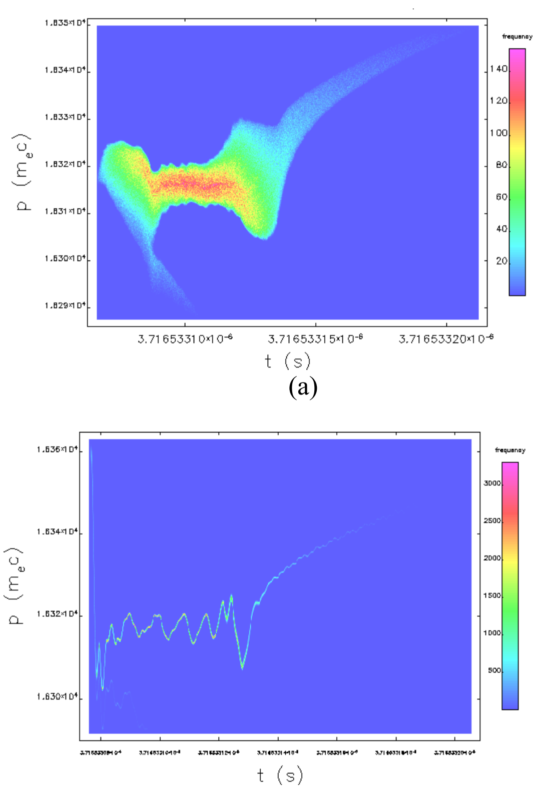


Figure 5: Longitudinal phase space of the beam at the linac exit, with laser heater on (a) and off (b)

The $\beta$ function in the laser heater and throughout the whole linac are also illustrated in Figure 6. In the figure we can see that the variations of the $\beta$ functions on both horizontal and vertical plane along the undulator in the laser heater are very small, which is requested by the interaction condition of the beam and laser in the undulator, whereas the $\beta$ functions still need to be optimized throughout the linac globally.

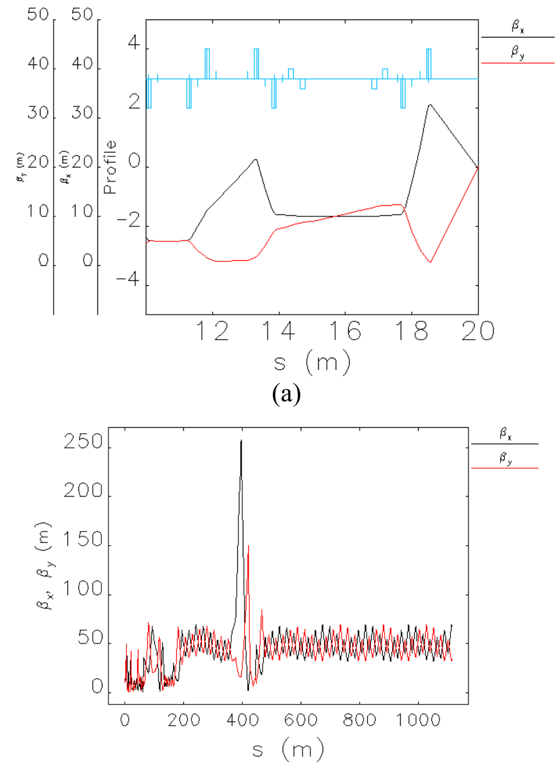


Figure 6: $\beta$ function in the laser heater and throughout the whole linac.

## CONCLUSIONS

The study of microbunching instability of SHINE linac has been carried out with the lattice design up-to-date. The results show that the analytical estimation is reasonably consisted with the numerical simulation, which provides us the information about the range of the initial modulation wavelength that should be avoided when operating the machine. The preliminary study of the laser heater for the suppression of the instability is done, and further investigations of the laser heater is needed to reveal the suppression effects for various modulation wavelength.

## REFERENCES

[1] Y. Wang and M. Borland, "Pelegant: A Parallel Accelerator Simulation Code for Electron Generation and Tracking", *AIP Conf. Proc.*, vol. 877, p. 241, 2006. doi:10.1063/1.2409141

[2] M. Borland, "Modeling of the microbunching instability", *Phys. Rev. ST Accel. Beams*, vol. 11, p. 030701, 2008. doi: 10.1103/PhysRevSTAB.11.030701

[3] Z. Huang, M. Borland, P. Emma *et al.*, "Suppression of microbunching instability in the linac coherent light source", *Phys. Rev. ST Accel. Beams*, vol. 7, p. 074401, 2004. doi:10.1103/PhysRevSTAB.7.074401

[4] Z. Huang *et al.*, "Insightful D-branes", SLAC, USA, Rep. SLAC-PUB-13584, 2009.