MICROBUNCHING INSTABILITY STUDIES IN SWISSFEL

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Abstract

Shot noise or an initial intensity modulation in the beam pulse may have a strong effect in the FEL linacs and also severely degrade the machine performances in terms of FEL performances. In this paper we present the simulations done to study this effect in SwissFEL, the future free electron laser under design at Paul Scherrer Institute. In particular we calculated the gain of the microbunching instability in the low and high energy part and we performed start-to-end simulations using as initial distribution something as close as possible to the laser profile measured at the SwissFEL injector test facility. We finally present the preliminary calculations to estimate the effect of the laser heater to mitigate this effect.

THE MICROBUNCHING IN SWISSFEL

SwissFEL [1] will produce 0.1 nm to 7 nm coherent x-ray radiation compressing an initial ~20 A bunch to 2.7 kA in two stages in the most recent design, as sketched in Fig. 1.

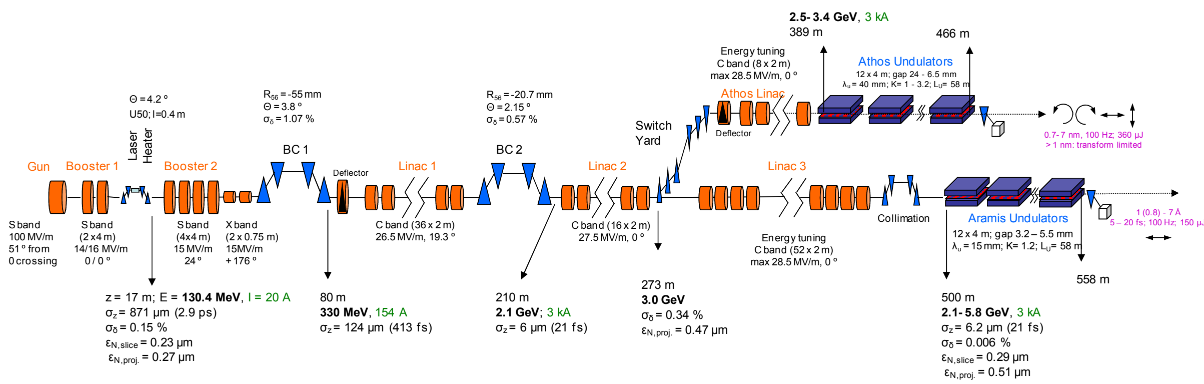

Figure 1: SwissFEL schematic layout.

Due to the long distance of the two bunch compressors from the cathode, where the momentum modulation can be accumulated, and a very small uncorrelated energy spread expected according to the simulations, the microbunching instability may have a strong impact on the machine. To simulate the effect of the instability on a realistic beam we generated a distribution accordingly to the longitudinal laser profile measured at the SwissFEL Injector Test Facility (SITF), as shown in Fig. 2. We finally performed start-to-end simulation tracking this distribution with Astra [2] up to the end of booster 2 and with Elegant till the entrance of the Aramis undulator†. In Fig. 3 the residual momentum* at two locations along the machine is shown.

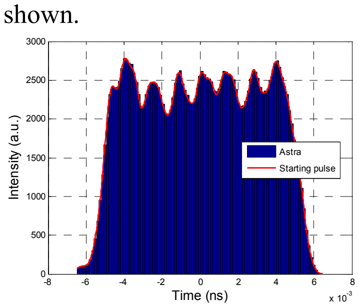

Figure 2: Temporal bunch profile at the cathode.

† The simulation refers to the 3.7 kA final current lattice.
*More details will be given in the section "Two stages model".

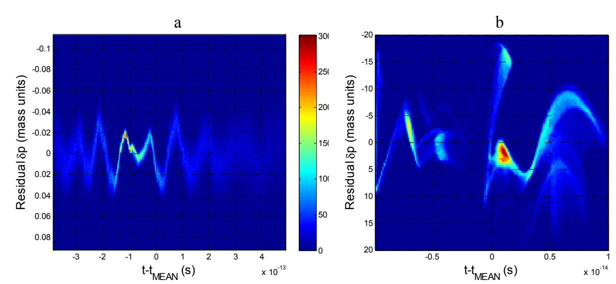

Figure 3: Start to end simulation. Residual momentum of the real shape bunch tracked to (a) the entrance of BC1 and (b) the Aramis undulators.

The generated momentum modulation translates into such a strong current modulation along the bunch at the entrance of the Aramis undulator that the FEL performances may be strongly degraded.

TWO STAGES MODEL

The microbunching instability is commonly studied in two regimes distinguished by the beam energy. First the low energy part, from the gun to ~130 MeV, where the current modulation for wavelengths smaller than the bunch length is reduced and a momentum modulation is generated, the high energy region, where the current modulation is increased basically only in the bunch compressors (the beam is too rigid to increase the current modulation in drifts and cavities) and more momentum modulation is cumulated.

In the past years several analytical models have been developed to study the microbunching instability in the high energy part [3], but for the low energy regime, due to the complicated dynamics, no model has been elaborated and only numerical simulations are used to study the problem in this region. To have the amplification to any initial beam the spectral gain curve at each critical location of the machine is commonly computed to have the amplification at each frequency of the Fourier decomposed of any initial beam. This curve at a given z gives the amplification factor at each wavelength, so that the gain for any bunch shape at the gun can be calculated from the gain of each its Fourier component.

We studied first the microbunching in the high energy part by means of numerical simulations and analytical model as well, neglecting the effect of the low energy part. As a second step we computed the influence of the low energy part to the gain.

High Energy Part

We considered modulations at different wavelengths, but also amplitudes, but also scan over amplitudes to identify the non-linear region. To study the microbunching in the high energy part we imposed the modulations on the initial distribution at the end of booster 2 and we tracked it by using Elegant [4]. As a preliminary step we tracked a bunch without any modulation from the cathode to the end of the low energy region (using Astra) with different number of particles to define the distribution at the end of booster 2. The results are shown in Fig. 4.

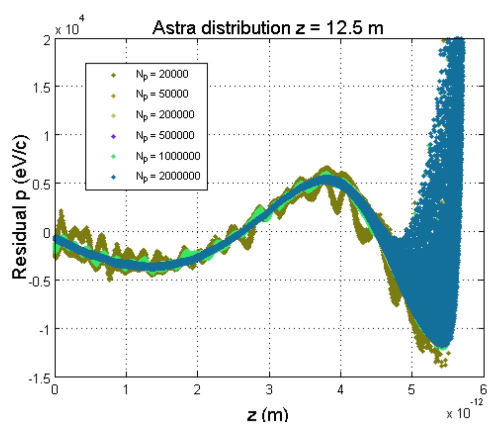

Figure 4: Astra output distributions at the end of the low energy region for different number of particles.

We converted the Astra output to an Elegant distribution and we super-imposed on it for each run one modulation at one amplitude on top using the smoothDist6s function, one of the specialized functions for Elegant, which super-imposes an intensity modulation while smoothing the longitudinal phase space (momentum). All the simulations are performed automatically in "bunches" using a Matlab script developed at this scope. The post-processing is done by a Matlab code, which analyses bunches of results like proposed in [5].

The spectral gain at the entrance of BC1 is shown in Fig. 5.

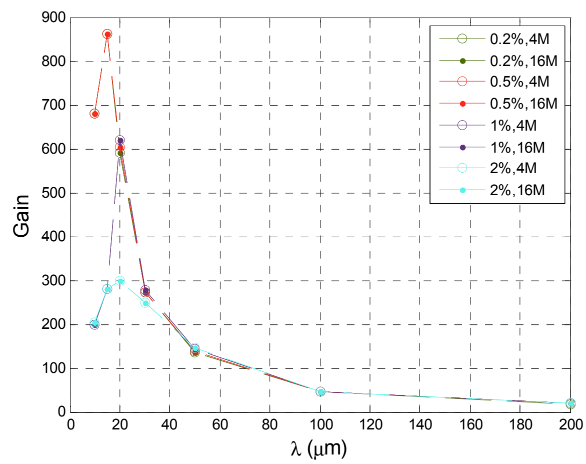

Figure 5: Spectral gain at the entrance of BC1 obtained by numerical simulations.

The fact that the results agree between the 4 and the 16 millions particles distributions is an indication that the noise is well under control. We notice also that the simulations for initial amplitudes smaller than 0.5% agree. This indicates that for these values we are out of the non-linear region.

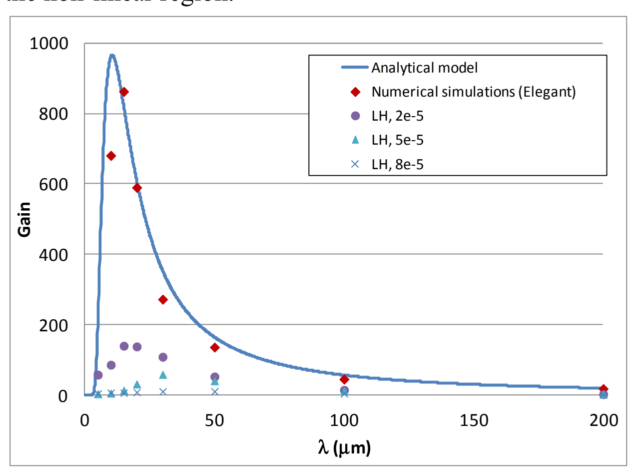

Figure 6: Comparison between the numerical simulation results and the analytical model at the exit of BC1. The results of the numerical simulations for several induced uncorrelated energy spread (laser heater) are also shown.

The gain at the entrance of the first bunch compressor is larger than the one compared to other machines. This can be caused by the small uncorrelated energy spread resulting from the Astra tracking.

Once the analytical model, based on [3], has been validated by the numerical simulations, as it can be seen

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in Fig. 6, we used it to compute the gain at the exit of the second bunch compressor, where especially for the smallest initial amplitudes it would be necessary to further increase the number of particles to control the noise level (the same sub-functions are re-used and the model has been checked versus the LCLS calculations). The gain after BC2 has a peak of about 45000, which is about the double of the LCLS case.

Low Energy Part

After the analysis of the high energy part we calculated the effect of the low energy section. There are several codes to study this part of the machine. We did the majority of the studies with Astra. We produced a nominal un-modulated distribution using the Astra routine "generator" and we shifted each particle at position z_0 as indicated in Eq. (1):

$$\begin{cases} z = z_0 - m \cdot \sin\left(\frac{2\pi}{\lambda} z_0\right). \\ m = \frac{\lambda \cdot A}{2\pi} \end{cases} \qquad (1)$$

where A is the target amplitude and λ is the modulation wavelength. In Fig. 7 we show the amplitude of the Fourier transform of the residual momentum calculated as described in the previous subsection as a function of z along the injector. Consistently with other machines [6, 7], the contribution of the low energy part to the amplification in the wavelength range relevant for the high energy region is almost negligible, as it can be seen in Fig. 7 for the momentum modulation.

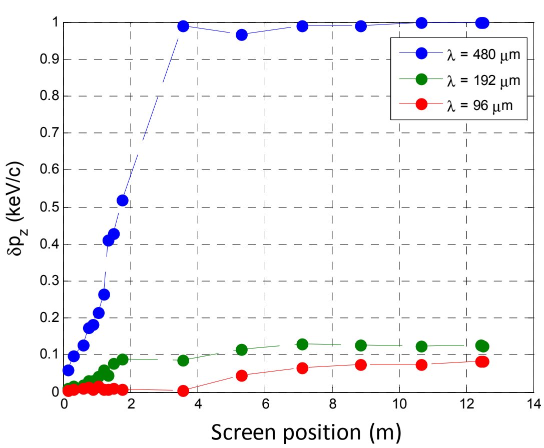

Figure 7: Amplitude of the momentum modulation along the low energy part.

During the generation of the momentum oscillation the current modulation is strongly reduced (at 96 μm is reduced by about a factor 10), but, due to the large gain in the high energy part this is not sufficient to eliminate the instability.

MITIGATION OF THE INSTABILITY

Several techniques are under study to minimize this effect, but the most common one is the laser heater [8], which introduces controlled uncorrelated energy spread. As a preliminary study of this device we artificially imposed a Gaussian noise on top of the modulated distribution at the beginning of the high energy part at several amplitudes and we repeated the simulations. The results are shown in Fig. 6.

LCLS experimentally demonstrated that an increase of the FEL performances is achieved with a reasonable increase of the uncorrelated energy spread [8], the threshold being defined by the negative contribution of the energy spread to the FEL efficiency. Other possible solutions are presently under investigation and among them a very interesting concept is the reversible laser heater [9], which allows removing the energy spread after the compression stage.

This solution can be considered for SwissFEL especially if the large gain coming out from the simulations will be confirmed by the measurements in the test facility.

CONCLUSIONS

We carried out a campaign of simulations to calculate the spectral microbunching gain. We split the problem in the low energy and high energy region. The simulations indicate that the microbunching gain may have a strong impact on the SwissFEL performances. We also presented a preliminary study of the mitigation effect using a laser heater, already previewed in the SwissFEL lattice.

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