SOURCE OF MICROBUNCHING AT BNL NSLS SOURCE DEVELOPMENT LABORATORY*

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Abstract

We report experimental studies of the origins of electron beam microbunching instability at BNL Source Development Laboratory (SDL). We eliminated laser-induced microbunching by utilizing an ultra-short photocathode laser. The measurements of the resulting electron beam led us to conclude that, at SDL, microbunching arising from shot noise is not amplified to any significant level. Our results demonstrated that the only source of microbunching instability at SDL is the longitudinal modulation of the photocathode laser pulse. Our work shows that assuring a longitudinally smoothed photocathode laser pulse allows mitigating microbunching instability at a typical FEL injector with a moderate microbunching gain.

INTRODUCTION

A linear accelerator with bunch compressor can amplify the initial small modulation in electron beam longitudinal density, leading to microbunching instability [1-4].

The microbunching instability was observed and experimentally characterized [5] at the SDL [6] and other facilities, and mitigation of microbunching instability with so-called laser heater [7] was demonstrated at SLAC Linac Coherent Light Source [8]. Yet, the solid experiment characterizing the source of initial microbunching is missing. We explored the source of initial microbunching at SDL by separating the shot-noise-induced microbunching from laser-induced one. To do this, we used an ultra-short photocathode laser pulse. Both cross-correlation and spectral measurements indicate that such laser pulse is clean, pedestal-free, and contains no satellite pulses. This excludes the possibility of laser-induced modulation of the longitudinal beam density.

In SDL the electron beam generated in photocathode RF gun is accelerated to 70MeV, and compressed in the bunch compressor (BC) consisting of the linac section, which introduces correlated energy spread, and the four-bend chicane. The BC is followed by three linac sections capable of accelerating electron beam up to 300MeV. Fully accelerated beam is fed to the 10m long undulator to produce coherent radiation from IR to XUV. The SDL beamline is equipped with a spectrometer magnet located downstream of the BC, followed by a beam profile monitor (BPM). The SDL layout is schematically shown in Figure 1.

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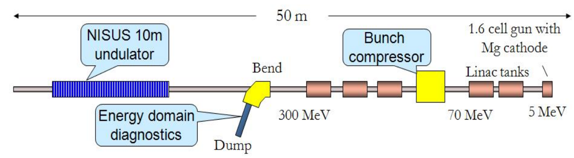

Figure 1: The SDL layout.

MICROBUNCHING GAIN AT SDL

The wakefield upstream of the bunch compressor converts small beam density modulation at the beginning of a FEL injector into energy modulation. The energy modulation of amplitude Δγ prior to BC is converted into additional density modulation due to nonzero dispersion in the BC, thus giving a rise to microbunching instability. The microbunching gain factor is [3]:

$$G = \left| CkR_{56} \frac{\Delta\gamma}{\gamma b(k)} \right| \exp\left(-\frac{(CkR_{56}\sigma_\gamma / \gamma)^2}{2} \right) \quad (1)$$

where C is compression ratio, k is modulation wavenumber, R_{56} is momentum compaction, $b(k)$ is bunching factor characterizing beam density modulation, γ is relativistic gamma factor and σ_γ is the rms energy spread.

The change in the energy modulation along the linac due to the longitudinal space charge (LSC) wake $Z(k,z)$ is:

$$\Delta\gamma(k,s) = -\frac{4\pi I}{Z_0 I_A} \int_0^s Z(k,z) b(k,z) dz \quad (2)$$

Here I is beam current, Z_0=377Ω is the free-space impedance and I_A=17kA is Alfven current. At a sufficiently high energy the current modulation is frozen and the energy modulation induced through wakefields can be calculated as:

$$\Delta\gamma(k,s) = -\frac{4\pi I b(k,0)}{Z_0 I_A} \int_0^s Z(k,z) dz \quad (3)$$

Applying this model to the SDL injector we compute energy modulation driven by LSC by numerically solving (2) upstream the exit of the first accelerating section and using (3) downstream of it down to the chicane. Substituting obtained net amplitude of energy modulation in (1) we find the LSC-driven microbunching instability gain. Figure 2 shows the microbunching gain calculated for beam parameters discussed in next section.

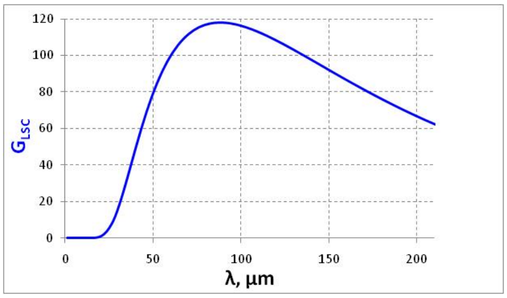

Figure 2: LSC-driven microbunching gain at SDL.

Coherent synchrotron radiation (CSR) and linac wakefields also can drive microbunching instability. Our analysis shown that both CSR and linac wakes-driven microbunching gains at SDL are negligible in comparison to the gain driven by LSC.

From the above considerations one can expect to see microbunching amplification at wavelengths > 20µm. The substructures of these sizes can be easily detected by SDL longitudinal diagnostics since its resolution [9] is ≈2 µm. At the given gain of microbunching instability we expect to be able to detect the amplification of initial modulations of as low amplitude as 0.03%.

EXPERIMENTAL RESULTS

In our experiments we used beam charges in the range of 10-100pC. The observed behaviour for all charges was very similar. Below we will consider dynamics of 40pC beam created by Gaussian 100fs (FWHM) photocathode laser. Such beam is about 0.8ps FWHM at the exit of the gun.

While the spectrum of the uncompressed beam shows no signs of longitudinal fragmentation, the compressed beam spectrum exhibits distinct spikes (Figure 3) with the most pronounced modulation at C=4.

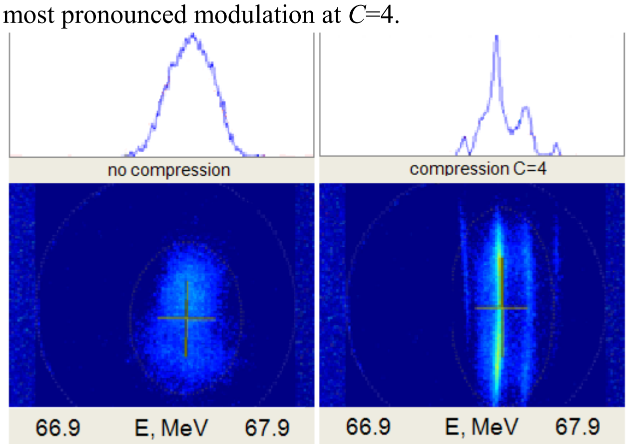

Figure 3: Spectra of uncompressed (left plot) and compressed (right plot) beams.

We evaluated the period of modulation and the characteristic width of the spikes by removing the chirp remaining after compression by the third linac section, and performing the zero phasing measurement [9] with the fourth section; Figure 4 shows the respective pictures at the spectrometer. Interpreting observed substructures as density modulations, we estimate their width as $\arcsin(\Delta E/E_{RF})/k_{RF} \approx 15$µm, where the characteristic size of substructures is $\Delta E \approx 30$keV, E_{RF} in tank 4 is 32MeV, and $k_{RF} \approx 60\text{m}^{-1}$. Similarly, the period of modulation is ≈60µm.

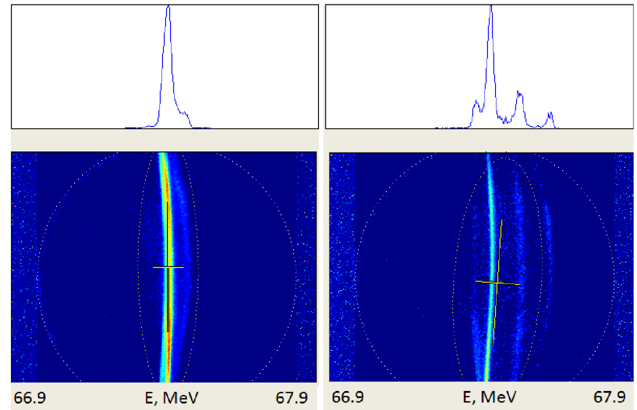

Figure 4: Compressed beam with the chirp removed by tank 3 at spectrometer (left plot) and zero phasing measurement performed with tank 4 (right plot).

The described observations might be interpreted as shot-noise-induced microbunching with an initial modulation of ~0.5%, amplified through LSC-driven instability. However, careful analysis of the beam dynamics shows that dramatic fragmentation of the longitudinal phase space is not a result of microbunching but rather is the net modulation of the beam with initially smooth longitudinal profile by different self-fields.

Indeed, at low energies, space charge field can modulate the beam energy significantly. Both simulations (performed with PARMELA [10]) and tomographic reconstruction of the longitudinal phase space of uncompressed beam show that from photocathode to the entrance of second linac section the beam acquires substantial energy modulation at the wavelength comparable to the bunch length. As the beam passes through the bunch compressor, considered macro-modulation in energy becomes density modulation at compressed wavenumber $k_{macro} \approx C\pi/(2\sigma_z)$, where σ_z is the rms beam length. Downstream of the BC space charge effect is small and linac wakefield plays the main part in both chirping the compressed beam and modulating its energy. Finally, the resulting energy spectrum has higher number of peaks than just the two present in the time domain, and interpreted as a result of beam density modulation, such spectrum gives modulation period $\approx \pi/k_{macro} \approx 50$µm.

Simulating the beam dynamics at SDL with ELEGANT [11] confirmed above assumptions. The simulated energy spectrum of the compressed beam agrees with the experimentally observed one in both the depth of modulation and the periodicity (Figure 5). Good qualitative correspondence between the simulations and the experimental results suggest that the observed fragmentation of longitudinal phase space of compressed beam is not caused by spontaneous microbunching enhanced through LSC, but is explained by the mechanism detailed above.

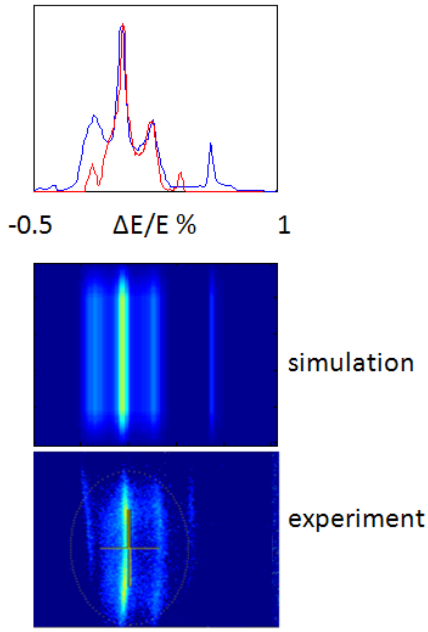

Figure 5: A comparison of the simulated (blue) and the measured (red) spectra of compressed beam.

It is important to note that obtained strong beam fragmentation is due to the very short initial bunch length chosen for these studies. It does not occur during normal SDL operations.

Our experiments prove that the only significant source of microbunching at the SDL is the laser-induced modulation of initial beam density. The initial modulation depth of spontaneous microbunching at the SDL is too small (<0.03%) to affect the quality of the SDL beam. Therefore, a longitudinally smooth photocathode laser pulse eliminates the possibility of microbunching instability at the SDL developing to any significant level.

CONCLUSION

In this paper we investigated the source of microbunching instability at the SDL.

To distinguish microbunching induced by shot noise from that arising from the longitudinal modulation of the photocathode laser, we studied the beam created by a very short laser pulse, thus eliminating the possibility of laser-induced microbunching. While the measured energy spectra of compressed beam did reveal severe longitudinal fragmentation, an analysis of the beam dynamics proved this to be due to self-fields acting on a beam with an initially smooth longitudinal profile, and not due to microbunching instability. Such fragmentation only was possible with the very short bunch chosen for these studies, and is absent in routine SDL operations.

Our experiment shows that in the absence of the initial laser-induced beam modulation, microbunching instability at the SDL is not observed, and must be well below the levels that would limit the FEL performance. This result agrees with assumption of previous SDL studies that (when present under different machine conditions) microbunching instability at the SDL was laser-induced.

Microbunching instability gain at the SDL is moderate. This is mainly because the SDL utilizes a single stage bunch compressor as well as due to the small compression ratio. Since the design of the SDL injector is typical of the majority of FEL injectors, our experiment proves that one possible way to control microbunching instability in such machines (that by design have a moderate microbunching gain) is to maintain a sufficiently smooth longitudinal profile of the photo-cathode laser. We note that the general principles for designing a machine with a moderate microbunching instability gain are presented in [12].

In conclusion, our experiment demonstrates that microbunching instability can be eliminated from a typical FEL injector with single stage bunch compressor (and operating without a laser heater) as long as the photocathode laser is longitudinally smooth. For machines with multi-stage bunch compressors, our results offer an important benchmark to establish a minimal laser heater power for instability-free operation.

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