

Fundamental and Harmonic Microbunching Measurements in a High-Gain, Self-amplified, Spontaneous Emission Free-Electron Laser

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Abstract

The self-amplified, spontaneous emission free-electron laser (SASE FEL) gain process is a collective instability which induces microbunching in the electron beam. Microbunching approaching unity at the fundamental FEL wavelength (845 nm), and its second harmonic, have been measured at the VISA FEL, at or near saturation. These measurements, which use the beam's coherent transition radiation (CTR) spectrum, are compared to the predictions of FEL simulations. Comparison of shot-by-shot SASE and CTR signals firmly establishes the role of SASE in the development of microbunching harmonics.

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Significant progress has been recently achieved in the worldwide effort of Self Amplified Spontaneous Emission Free Electron Laser (SASE FEL) R&D; saturation [1-3] and nonlinear harmonic radiation [4-5] have been observed from the near infrared to UV wavelengths. A signature of the FEL is the microbunching of the longitudinal electron beam distribution with a periodicity of the FEL's fundamental wavelength. For current SASE FEL's, the microbunch spacing can now be below 100 nm [3], which is the shortest structure yet imparted to laboratory electron beams. By measuring the degree to which the electron beam is microbunched, important microscopic properties of the SASE radiation system can be determined. In the current measurements, we have a tightly microbunched system, a characteristic of the FEL saturation, in which case the microbunching structure contains rich harmonics.

Observations were first made on fundamental SASE FEL microbunching using coherent transition radiation (CTR) [6-7] and later on an FEL oscillator using other methods [8]. In this letter, the first direct experimental observation of the correlation between the SASE FEL output and electron beam longitudinal microbunching (determined by CTR) is presented. We will also discuss the first measurement of harmonic microbunching in a SASE FEL. Bunching factors for both the fundamental, b_1 , and second harmonic, b_2 , are experimentally characterized and compared with computer simulation. The technique presented in this letter provides another independent verification that the fundamental microbunching drives both the SASE FEL gain mechanism and nonlinear harmonic generation.

We begin by reviewing the basic physics of the SASE FEL. An intense relativistic electron beam propagating through a periodic magnetic undulator may undergo a radiation-producing interaction termed the SASE FEL instability [9]. This instability proceeds by generating light at the FEL's resonant wavelength, $\lambda_{r,n=1}$ (the fundamental given by Eq. 1 below), and allows the beam to microbunch at the same wavelength. This process has positive feedback, as microbunching stimulates more *coherent* radiation production. As this process evolves and the electron beam continues to microbunch further, the coherence of the radiated field increases, and the SASE power grows exponentially through the undulator, $P \propto P_0 \exp(z / L_g)$. Here, P_0 is usually taken as the coherent fraction of the spontaneous radiation in the first field gain length, z is the

distance along the undulator, and L_g is the power gain length. When the exponential growth in radiated power ends (levels off), the FEL is in a state termed saturation [10]. At saturation, the beam is most strongly microbunched, and further coherent power generation is mitigated. As saturation is approached, the modulation of the beam current becomes deep and non-sinusoidal, with significant higher harmonic content. Thus the onset of saturation should be accompanied by the generation of harmonics, both in the FEL light that is generated [9-12], and the microbunching of the electron beam distribution.

The wavelengths at which the electron beam is microbunched, λ_{mb} , are given by

$$\lambda_{mb,n} = \lambda_{r,n} = \frac{\lambda_u}{2\gamma^2 n} \left(1 + \frac{K^2}{2} \right) \quad (1)$$

where λ_u is the undulator period, γ is the electron beam energy, K is the undulator parameter, and $n=1,2,3\dots$ is the harmonic number with $n=1$ as the fundamental mode. Near saturation, most of the electrons in the beam are densely packed in a narrow region, much shorter than the fundamental period, $\lambda_{mb,1} = \lambda_{r,1}$. This dense packing implies the existence of harmonics in the longitudinal distribution [10]. Further, this harmonic microbunching will generate radiation at the same wavelength, $\lambda_{r,n}$, although because of the nature of the radiative process in a planar undulator FEL, odd harmonic radiation production is favored [12]. Because the higher harmonic SASE process is driven by the fundamental microbunching, it is termed nonlinear harmonic radiation. The growth of the nonlinear harmonic radiation starts later in the undulator compared to that of the fundamental, as the fundamental must have considerable gain before the harmonic microbunching can develop. Experimental observation of nonlinear harmonic radiation on the VISA FEL has been reported in an earlier publication [4]

The theory of CTR and its use for longitudinal microbunching measurements of electron beams has been extensively studied [6-7,13-14]. The most common model of this process describes transition radiation (TR) approximately as an annihilation (or creation) of an electron with its image charge at the conductor/vacuum interface. A more physical picture of the process, known as the virtual photon, or Weizsacker-Williams

method [15] can also be used to give the same predictions concerning CTR microbunching [14]. In addition, this theory has been bench-marked with experiment [6-7].

We now quantify our model for measuring the microbunching. A useful form of the electron beam charge distribution at the exit of a SASE FEL is

$$\rho(x, y, z) = \frac{eN \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right)}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \left[1 + \sum_{n=1}^{\infty} b_n \cos(nk_r z) \right], \quad (2)$$

where N is the number of electrons in the bunch, $\sigma_{x,y,z}$ are the transverse (x,y) and longitudinal (z) beams sizes, respectively, k_r is the fundamental wavenumber from Eq. 1, n is the harmonic number, and b_n is the microbunching factor for the n th harmonic.

Assuming the microbunching period in the beam's rest frame is small compared to the transverse beam size, $k_r \sigma_{x,y} / \gamma \gg 1$, the CTR energy emitted at a given harmonic may be calculated using both annihilation [6,13] and virtual photon models [14],

$$U_n = \frac{N^2 e^2 b_n^2}{8\sqrt{\pi} \sigma_x \sigma_y \sigma_z} \left(\frac{\gamma}{nk_r}\right)^4 \left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right). \quad (3)$$

The predictions of Eq. 3 will be compared to our experimental results, along with microscopic predictions of the microbunching given by simulations of the experiments. CTR energy is quite dependent on nk_r , and Eq. 3 shows that CTR from harmonic microbunching is reduced significantly from that of the fundamental.

The SASE FEL microbunching experiments reported here were performed using the VISA (Visible to Infrared SASE Amplifier) FEL, located at Brookhaven National Laboratory's Accelerator Test Facility (ATF). In this ultra-high gain experiment, saturation was achieved, for the typical running conditions, near the end of a 4-m undulator. The undulator has a period of 1.8 cm with built in strong focusing, and an undulator strength $K=1.26$ [16]. The characteristics of the fundamental [2] and

nonlinear harmonic [4] SASE radiation, as well as the photoinjector operation [17] and beam transport [2] in this experiment have been described elsewhere. The high brightness beam used for VISA is generated from a 1.6 cell S-band photoinjector. A beam energy of 71 MeV is obtained after acceleration through two SLAC-type traveling wave accelerator sections. The beam is then delivered to the VISA undulator through matching quadrupoles after propagating through two dipole bends, which along with a slight retuning of the linac serve to compress the beam strongly [2]. The beam is compressed from 60 A peak current at injection, to over 275 A at the experiment, with a spike formed in the current distribution that has an equivalent Gaussian width of 54 μm .

A microbunching diagnostic station consisting of a thin aluminum foil and half-inch laser quality mirror was installed 30 cm downstream of the undulator exit. The light-tight 6 μm foil is used to separate the SASE radiation from the CTR, as shown in the schematic given in Fig. 1. The SASE radiation is reflected downward from the front surface of the foil. Back-emitted CTR from the front surface of the foil is also emitted downward, but has at least three orders of magnitude less energy than the SASE, and its contribution to the SASE signal is negligible. Forward CTR (from the back surface of the foil) combines with the back-emitted CTR (from the mirror) and both are directed into the microbunching detector. The diagnostic station described here makes it possible for simultaneous measurement of both the SASE and CTR (microbunching) signals shot-to-shot. The beam and relevant FEL parameters at the foil are given in Table 1.

Calibrated joulemeters were used for measuring both the SASE and CTR signals. To select a desired microbunching signal, bandpass filters of known spectral responses (centered at 850 and 415 nm) were situated in front of the CTR detector. For each measurement, two filters were used, and an attenuation of at least six orders of magnitude outside the bandpass was obtained; no contamination was possible from the n values.

Three factors must be considered when analyzing the measured microbunching bunching factors, b_n ; electron beam de-bunching after the undulator, scattering inside the foil, and interference between foil and mirror emitted CTR (see Fig. 1). Each effect is discussed subsequently. First, the electron beam propagates 30 cm after the undulator exit before reaching the foil. At saturation, the electron beam is optimally microbunched and has a large energy spread. The energy spread causes the electrons to de-bunch in the drift

space after the undulator, lowering the bunching factor and thus degrading the CTR. In addition, the beam expands transversely after exiting the strong-focusing undulator; Eq. 3 indicates that this transverse expansion can significantly degrade the CTR energy. The computer code GENESIS [18] was used to simulate the VISA FEL interaction and electron beam dynamics during the post-undulator drift space. Second, the electron beam propagates through the foil before creating the measured CTR. Thin-target scattering effects in the foil induce transverse motion in the electrons that can greatly reduce the amount of CTR emitted [6]. For the 6 μm foil used, presented at a 45 degree angle, and the parameters given in Table 1, the CTR energy is reduced by about 35% for both the fundamental and 2nd harmonic. And finally, we note the interference between the forward and back emitted CTR (see Fig. 1). The effects of TR interference between two parallel foils are examined in Ref. 19. When the fields from the two sources combine, those emitted from the mirror will have an additional spatially dependent phase. As this phase varies strongly over the emission at the mirror, due the use of non-parallel emitters, the interference between the two CTR sources is diminished. Furthermore, the foil used here has significant surface roughness, and CTR emission is more specular from the foil than from the mirror, and the overlap of the two CTR signals necessary for interference is again significantly reduced. The lack of CTR interference was confirmed when a CCD camera focused onto the far field onto a similar microbunching monitor (using a 6 μm foil) observed no interference pattern, but a strong CTR signal. For these reasons, the CTR collected from the foil and mirror add independently, with no interference effects.

Before we make a comparison between the measured and predicted CTR energy, we first examine the qualitative nature of the CTR energy, U_n , as a function of the SASE energy, U_{SASE} . The fundamental CTR energy, U_1 , vs. U_{SASE} was measured, and the results are shown in Fig. 2. This is a shot-to-shot measurement; no averaging or statistical interpretation is needed. During exponential gain, we expect both U_1 and U_{SASE} to be proportional to b_1^2 and observe that they are indeed proportional to each other before saturation (lower SASE energies in Fig. 2). This confirms that the microbunching is integral to the SASE gain process and that the fundamental microbunching and SASE radiation have the same exponential dependence (growth rate) [9],

$$b_1^2 \propto E_{SASE} \propto \exp\left(\frac{z}{L_{g,1}}\right), \quad (4)$$

where $L_{g,1}$ is the gain length for the fundamental SASE radiation. The exponential growth of the fundamental SASE radiation for these conditions at VISA has been reported elsewhere [2] with a gain length, $L_{g,1} = 18.7$ cm, and a total gain of over 10^8 .

Simultaneous measurement of the CTR and SASE energy provides another technique by which FEL saturation can be verified. At high U_{SASE} and above saturation in Fig. 2, the proportionality described by Eq. 4 is missing. Even though marginally more SASE radiation is produced in the undulator, by the time the beam strikes the CTR foil, it is partially debunched and b_1 decreases. The lack of increase in the CTR signal is further evidence that the FEL is in saturation. To compare these results to a microscopic model of the beam, GENESIS was used to simulate the FEL, where the particle input used comes from previous simulations of the injector and beam transport to the undulator [2]. Fig. 3 plots the microbunching factor b_1 as a function of z , as calculated from GENESIS, for the case with near-optimal gain. When the FEL begins to enter saturation towards the undulator end, no further microbunching occurs, as expected from the CTR measurements. These simulations predict that b_1 is reduced to 0.52 at the CTR diagnostic station from its optimum value, $b_1=0.6$, immediately preceding the undulator exit. Using this result in Eq. 3 and applying the foil scattering factor described above, a peak CTR energy of $U_1=510$ pJ is predicted, in good agreement with the measured value of 490 pJ.

To study the 2nd harmonic microbunching at 422 nm, two bandpass filters (centered at 415 nm) were placed before the CTR detector. Figure 4 shows the 2nd harmonic longitudinal microbunching, U_2 , vs. U_{SASE} . The unfiltered SASE energy is dominated by the fundamental since higher harmonics account only for about 1% of the fundamental [4]. Again at high U_{SASE} , the 2nd harmonic microbunching stops growing, an indication that the beam is not microbunching further. GENESIS simulations in Fig. 3 show the 2nd harmonic microbunching, b_2 , as a function of z . Once again at saturation, the harmonic microbunching stops growing, and de-bunching becomes a significant effect even before the undulator exit, confirming the trend shown in Fig. 4.

We can approximately relate the microbunching on the 2nd harmonic to that on the fundamental using the theoretical prediction [10] $b_2^2 \propto \exp(z/L_{g,2}) \propto \exp(2z/L_{g,1}) \propto b_1^4$, where $L_{g,2}$, the gain length for the 2nd nonlinear harmonic, is related to that of the fundamental by $L_{g,2} \cong L_{g,1}/2$. This relationship, which was verified experimentally at VISA [4], states that U_2 should be quadratic with U_{SASE} . The data show that U_2 is a stronger function of U_{SASE} than is the fundamental CTR signal, U_1 , but it is difficult to establish a quadratic dependence from the small portion of the data that does not display saturation of U_2 .

The peak energy observed in U_2 is approximately 1.9 pJ. To generate a prediction for the expected CTR signal, we refer to the results GENESIS as displayed in Fig. 3. The bunching factor at the foil is approximately, $b_2 = .20$, reduced from $b_2 = .40$ at the undulator exit, yielding a predicted CTR energy of 4.4 pJ. The discrepancy between predicted and measured microbunching may be due to a variety of factors, including uncertainty in the de-bunching, to which higher harmonics are much more sensitive. Perhaps more importantly the microbunching calculation assumes a Gaussian longitudinal envelope to the beam, whereas the bunch shape displays non-Gaussian structure [2].

The difficulty of obtaining information about higher harmonic microbunching is further demonstrated by the search for the 3rd harmonic (280 nm) CTR signal, inspired by previous observation of 3rd nonlinear harmonic SASE signal [4]. Bandpass filters for the 3rd harmonic were situated in front of the CTR detector, but no conclusive signal was measured. Equation 3 predicts a detectable signal (albeit down from the fundamental by a factor of 81), but GENESIS predicts that the effect of the de-bunching on b_3 reduces the amount of CTR by a factor of almost 10 on the 3rd harmonic, rendering the signal undetectable.

In conclusion, for the first time, the dependence of the longitudinal microbunching up to the second harmonic on the observed SASE FEL gain into saturation has been directly measured using CTR. The linear proportionality of U_1 on SASE gain up to saturation is clearly established, as is the lack of further CTR growth after saturation. The 2nd harmonic CTR appears strongly in this SASE FEL near

saturation, as expected. The results of the experiments were compared to the predictions of CTR theory and a detailed simulation model and were in excellent agreement with the fundamental microbunching measurements. Less impressive agreement was obtained for the 2nd harmonic CTR case due to uncertainties in de-bunching, transverse beam expansion, and a need to generalize the theory to include non-Gaussian macrobunch pulse shapes. Two parameters have been simultaneously measured and the linear relationship between the microbunching and SASE growth is evidence that the electron beam microbunching grows exponentially like that for the FEL radiation. In addition, the two lowest microbunching factors (b_1 and b_2) were characterized; the electrons in the beam are strongly bunched at 845 and at 422 nm. These results show the dependence of SASE gain and nonlinear harmonic radiation on the longitudinal structure of the electron beam, the driving mechanism of an FEL.

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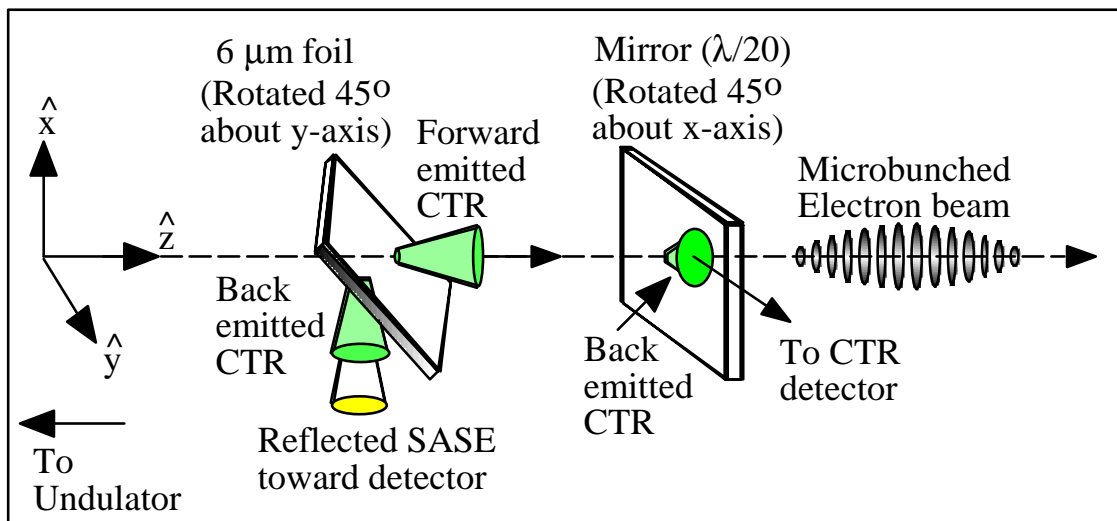


Figure 1. CTR microbunch monitor. System simultaneously captures CTR (microbunching) and SASE.

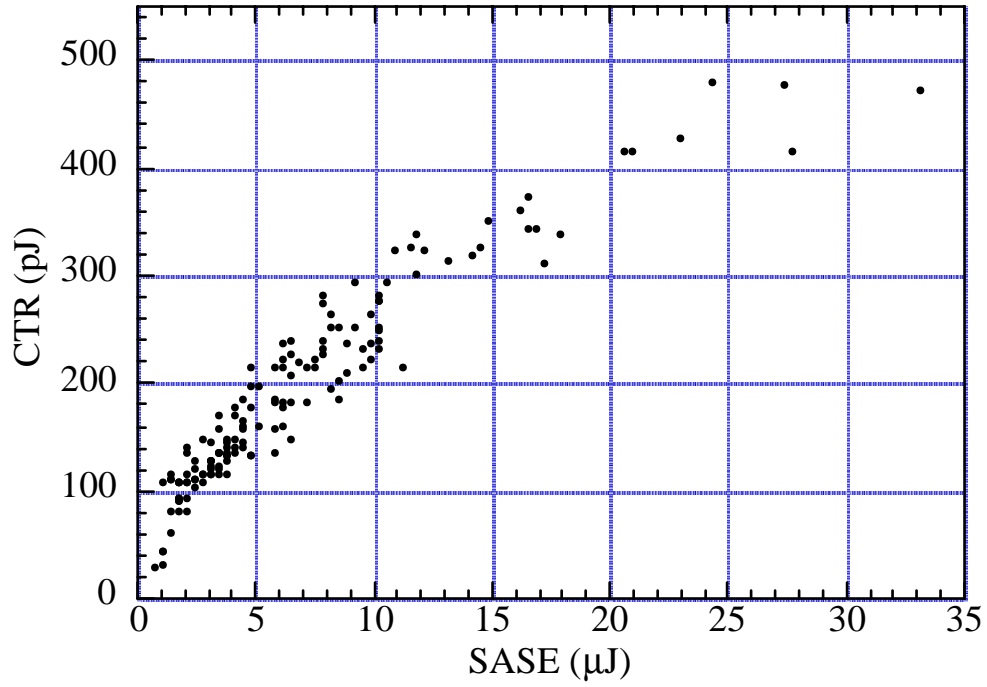


Figure 2. Measured Fundamental Microbunching vs. SASE. Beam is longitudinally microbunched at a period of 845 nm.

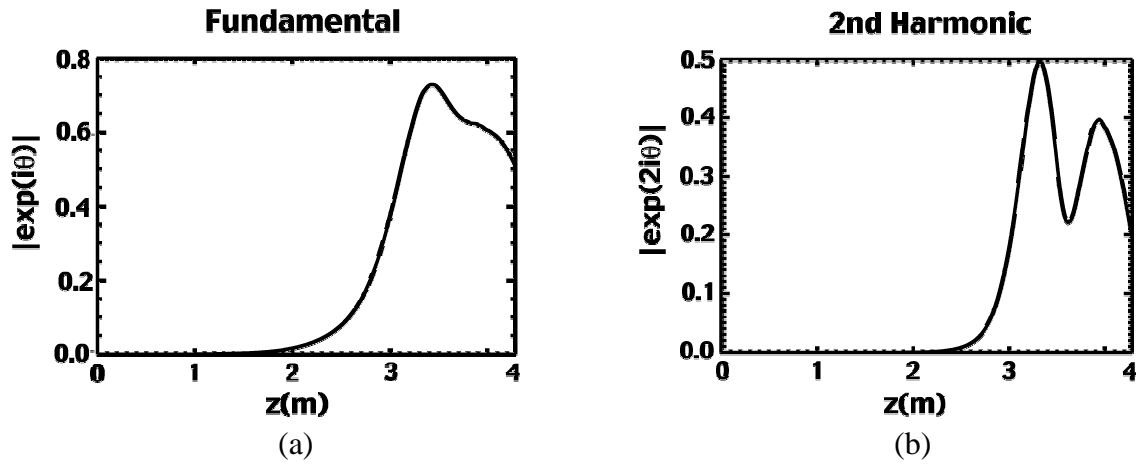


Figure 3. GENESIS simulations. (a) Fundamental bunching, b_1 vs. z at peak FEL gain. De-bunching observed during the 30 cm drift after the undulator. (b) Second harmonic bunching, b_2 vs. z at peak FEL gain. De-bunching observed during the 30 cm drift after the undulator.

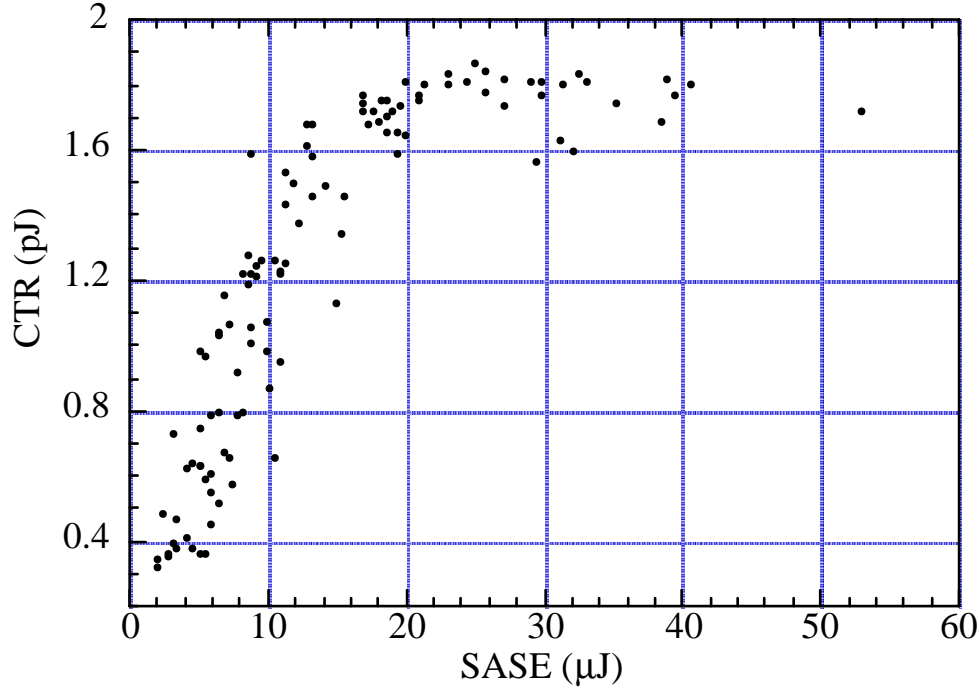


Figure 4. Measured 2nd Harmonic Microbunching vs. SASE. The beam is longitudinally microbunched at a period of 422 nm.

Beam Energy γ	139
Fundamental Wavelength $\lambda_{r,l}$	845 nm
Spot size σ_x, σ_y	60 μm , 120 μm
Pulse length, σ_z	54 μm
Charge Q	145 pC

Table 1. Electron beam and FEL parameters at CTR foil, 30 cm after undulator

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