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# LSC ASSISTED EEHG SEEDING WITH LASER-SPOILER SASE BACKGROUND SUPPRESSION

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*Abstract*

External seed lasers can be used to manipulate the longitudinal charge density of particle bunches traveling in particle accelerators, yielding a longitudinally microbunched structure with a periodicity proportional to the seed wavelength. As the seeded beam propagates through a drift, such microbunches experience longitudinal space charge wakes which increase the energy spread of the microbunches. Depending on the strength of the wakes, the energy spread of a microbunch can be increased to the point that it will no longer lase in an FEL of a reasonable length. To use this effect to advantage, producing a short, seeded pulse of FEL radiation with a suppressed SASE background, this requires a new concept in which the second stage modulation of a form of Echo-Enabled Harmonic Generation (EEHG) seeding is generated through a longitudinal space charge (LSC) wake while the background particles experience an energy spread increase which suppresses their contribution to SASE background radiation.


## INTRODUCTION

External seed lasers can be used to manipulate the energy of particle bunches traveling in particle accelerators. When an energy modulated particle bunch travels through a dispersive section, the high energy particles travel a longer path than the low energy particles, facilitating a longitudinally microbunched structure with a periodicity equal to the seed wavelength for a given relationship between energy and dispersion,

$$\Delta z = R_{56}\frac{\Delta E}{E} \qquad (1)$$

where z is the longitudinal position of the electron, $R_{56}$ is the transfer matrix element describing the dispersion, and $E$ is the energy of the particle. A dispersive section which will bunch a small energy modulation will over-fold a larger energy modulation. As a seeded beam propagates through a drift, such microbunches experience longitudinal space charge (LSC) wakes which increase the energy spread of the microbunches according to [1]

$$\Delta\gamma = \frac{|Z(k)|}{Z_0}\frac{I_0}{I_A}\rho_i \qquad (2)$$

where $Z_0$ = 377 Ω is the impedance of free-space, $I_A$ = 17 kA is the Alfen current, and $\rho_i$ is a small current perturbation at some wavenumber $k$, and $\gamma$ is the Lorentz factor. Depending on the strength of the wakes and the length of the drift, the energy spread of a microbunch can be increased to the point that it will no longer saturate in an FEL undulator of a reasonable length.

By using a seed laser pulse made up of a picoseconds long, low-intensity background pulse superimposed on a femtoseconds long, high-intensity pulse, different growth rates of the longitudinal space charge wake are facilitated for the background and central spike. While a strongly bunched portion seeded by the low-intensity background will experience energy spread growth in the drift akin to the seeded microbunching instability which has been observed during sFLASH experiments [2] (Fig. 1a), the more strongly modulated central spike will have smeared out microbunches in the drift which will more slowly develop an additional energy modulation provided by the longitudinal space charge wake (Fig. 1b). The overfolded and modulated structure shown in Fig 1b can be bunched in a small chicane prior to a radiator undulator in order to make a seeded electron beam with bunching at a high harmonic of the seed laser. This bunched beam will radiate coherently at a given harmonic while the noisy SASE background will be suppressed.

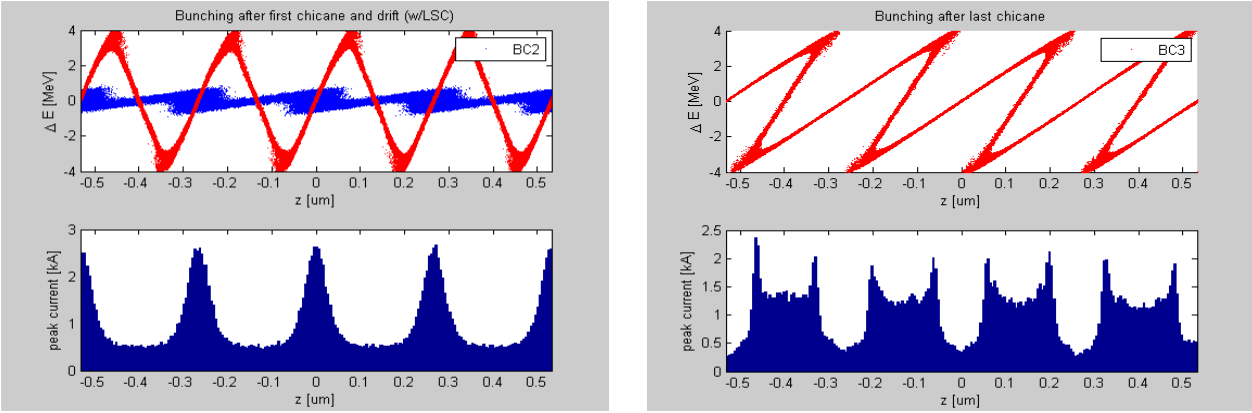
Simulation results backing up this idea were produced with a 1-D particle tracking code written in Matlab with the LSC wakes given by:

$$Z_{LSC}(k) = \frac{iZ_0}{\pi k r_b^2}\left[1 - \frac{k r_b}{\gamma}K\left(\frac{k r_b}{\gamma}\right)\right] \qquad (3)$$

where $r_b$=0.85($\sigma_x$+$\sigma_y$) is the radius of a uniform, round beam, K is a modified Bessel function, γ is the Lorentz factor, and $kr_b<\gamma/2$ [3] . These wakes are applied at ~0.5 meter intervals and particle motion is produced at each step according to $L/\gamma^2$, where L is the 0.5 meter interval. The initial energy modulation produced by the seed is calculated for a given seed waist, peak power and number of modulator undulator periods. Changes in the longitudinal positions of particles in chicanes are calculated with Eq. 1. Half of a million particles are used in a 5 μm long, 1-D electron bunch. An estimate of the impact of the transverse inhomogeneity of the LSC wake is made in the section on tolerances.

This seeding method is unique in that it offers a combination of laser-based SASE suppression of the background particles together with a short, seeded pulse which will radiate strongly and coherently in the FEL undulators, providing improved contrast compared to other types of seeding. The idea combines concepts from Longitudinal Space Charge Amplification (LSCA) [4] with Echo-Enabled Harmonic Generation (EEHG) [5]. It constitutes a unique form of EEHG in that an LSC wake in a drift provides the energy modulation which, in standard EEHG, is provided by an additional external seed laser and an additional modulator undulator magnet. The overfolding in conventional EEHG is also typically much stronger than what is used in this scheme.

(a.) Initial bunching (blue) and result of LSC wake (red) on SASE suppressed portion of bunch




(b.) Initial overfolding (blue) and result of LSC wake (red) on LSC-EEHG seeded portion of bunch

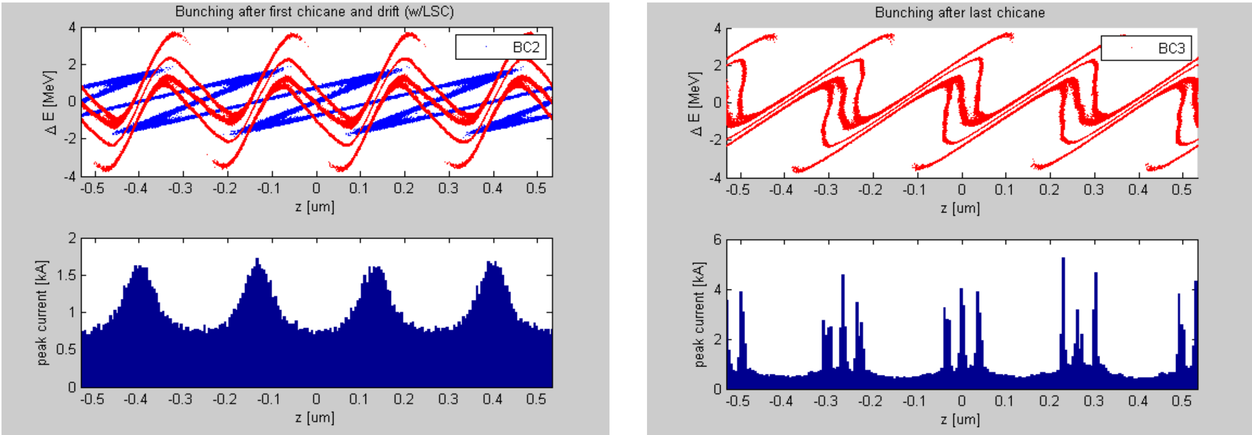



Figure 1: The portion of the bunch seeded with a picosecond, low-intensity laser pulse (a.) will experience a more rapid LSC induced energy spread growth than the portion of the bunch seeded with a femtosecond, high-intensity laser pulse (b.) due to the higher peak current after the first chicane ($R_{56}$=140µm). When these particle distributions are sent through a final chicane with a small, 30 µm $R_{56}$, the SASE suppressed current density will be smeared out, while the LSC-EEHG seeded portion will be bunched. The seed wavelength was 266 nm, the average beam radius in the drift was 70 µm, the beam energy was 0.7 GeV, and the initial peak current was 1 kA with a 150 keV initial slice energy spread.

## LSC-EEHG CONCEPT

The layout of this seeding scheme starts with a 6 period modulator undulator followed by a few-hundred micron dispersion magnetic chicane and a 20 m drift section in which, on average, $\sigma_x = \sigma_y$ = 70-150 µm. A shorter drift could be used with a smaller average beam radius or for operation with lower harmonics. After the drift section, there would be an additional, small chicane directly prior to the FEL radiator (Fig. 2). This provides the final bunching with an $R_{56}$=20-50 µm.

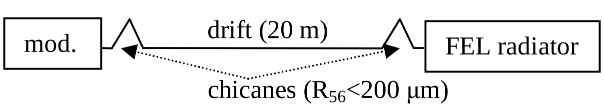



Figure 2: Layout of seeding scheme. A modulator undulator is followed by a bunch compressor chicane and a 20 meter long drift section. After the drift section, there is an additional bunch compressor chicane directly prior to the FEL radiator.

The seed laser consists of a few picoseconds long, low power (0.1 GW) background pulse with a short, high-power (1 GW) pulse in the middle (Fig. 3).

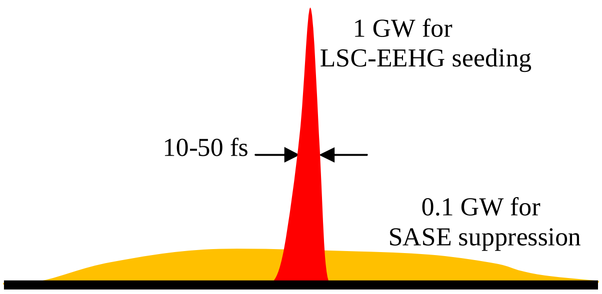



Figure 3: Seed laser profile for LSC-EEHG with SASE background suppression. The central spike is responsible for seeding, while the longer, background pulse is responsible for SASE suppression.

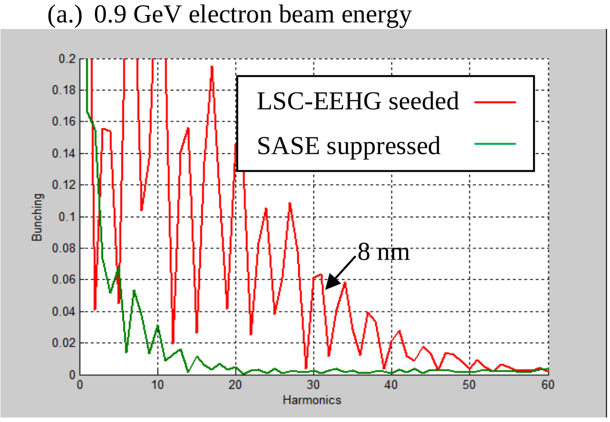
This seed beam with an ~800 µm (FWHM) waist would overlap with the electron beam in the 6 period modulator undulator and create an energy modulation of 0.6 MeV in the background portion and 2 MeV in the middle.

After the final chicane, the SASE suppressed part of the beam has a smeared out charge density in the energy band which is capable of contributing to SASE (Fig 1a) while the LSC-EEHG seeded part will have a microbunched structure at a high harmonic of 266 nm (Fig. 1b). When one takes the Fourier transform of a single cycle of the peak current distribution shown in Fig. 1, one can then plot the bunching factor as a function of harmonic number as shown below in Fig. 4a where at high harmonics of the seed wavelength, the LSC-EEHG seeded portion of the bunch has strong harmonic content, while the SASE suppressed portion does not.

In order to seed shorter wavelengths with this method in the fixed gap SASE undulators at FLASH, the beam energy needs to be increased from 0.73 GeV to 0.9 GeV and a slight adjustment of chicane settings ($R_{56}$=140µm→130µm in the first chicane and $R_{56}$=35µm→50µm in the last chicane) is required to produce the harmonic content shown in Fig. 4b.

The energy spread of the seeded microbunches shown in Fig. 1 is a bit larger than ideal and this can be reduced by either reducing the $R_{56}$ in the first chicane by 10 - 30 µm, by increasing the average beam radius in the drift, or by reducing the length of the drift. This reduces the harmonic content, but since the SASE undulators are so long, decreasing the bunching factor as a trade-off for a smaller energy spread would be a valuable tuning parameter for optimization of FEL operation. An alternative operation point with a smaller net microbunch energy spread would utilize the particle distribution shown in Fig. 5.

(a.) 0.9 GeV electron beam energy




(b.) 0.73 GeV electron beam energy

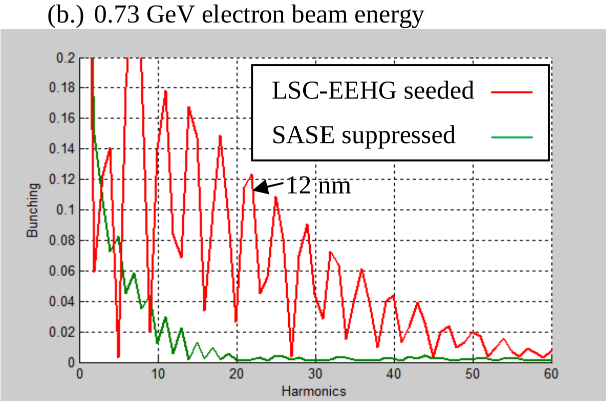
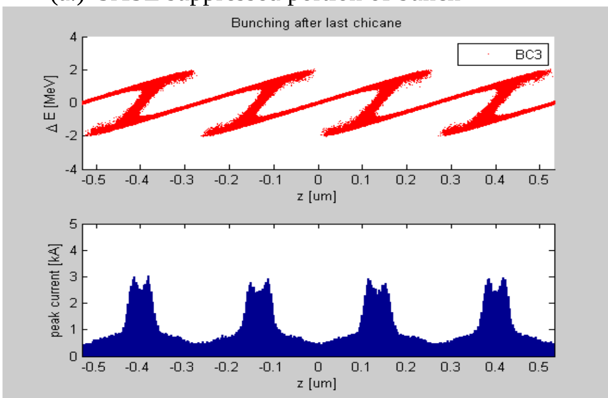
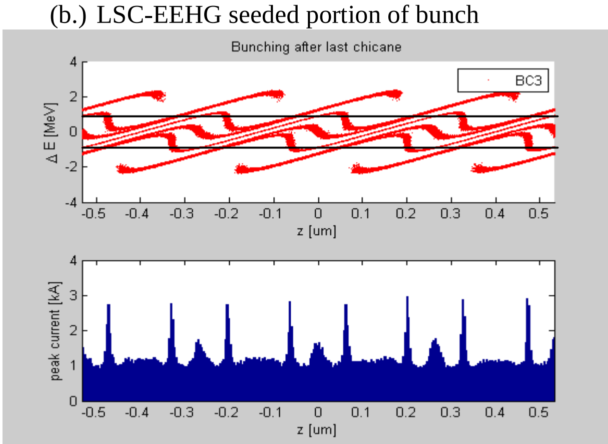



Figure 4: Harmonic content after last chicane for seeded and suppressed portions of the beam at different electron beam energies. Seeding was done with 266 nm in both the background and in the central spike.

(a.) SASE suppressed portion of bunch




(b.) LSC-EEHG seeded portion of bunch




(c.) Harmonic content of bunch portions

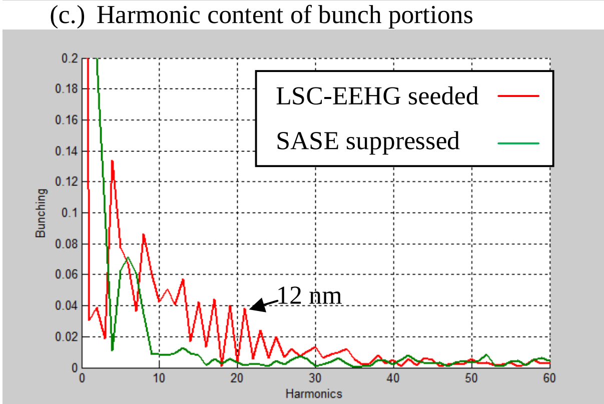
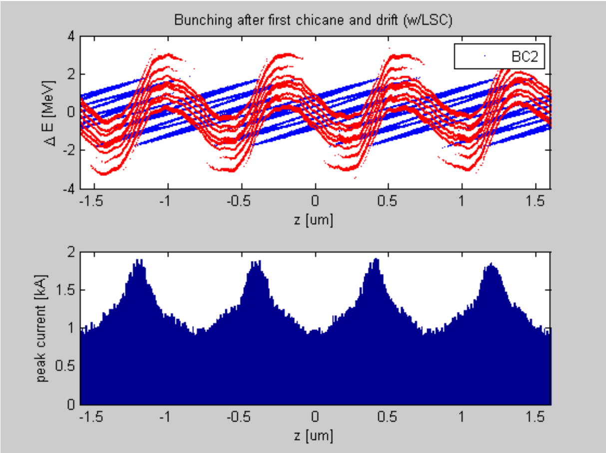


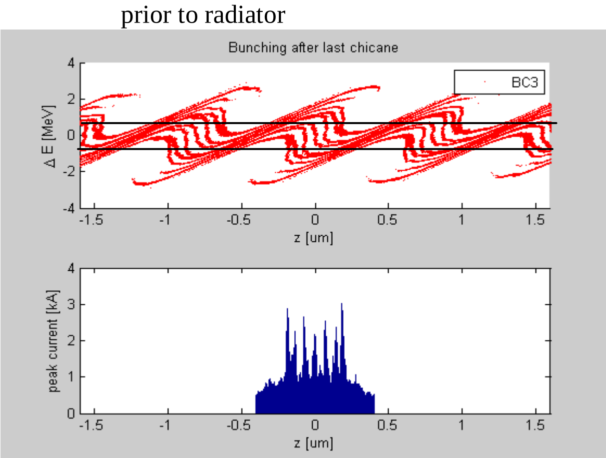

Figure 5: Microbunches with a reduced net energy spread compared to those in Fig. 4a. The beam energy is 0.73 GeV. The black horizontal lines represent the energy range for which the FEL gain is high.

Variations on this technique involve making the low-intensity background pulse a sub-harmonic of the high-intensity seed and using stronger dispersion to fold the beam. This is shown below in Fig. 6 for the case of an 800 nm background and a 266 nm seed.

(a.) Initial bunching pattern (blue) induces LSC wake modulation of particles (red)




(b.) Bunching pattern of seeded portion of beam prior to radiator




(c.) High harmonic content of seeded portion.

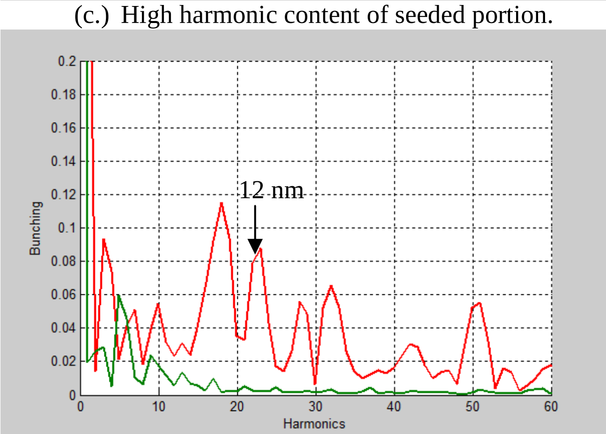



Figure 6: EEHG-LSC seeding with 800 nm background and 266 nm in seeding spike. The beam energy is 0.73 GeV and the average beam radius in the drift is 70 μm (rms). The black horizontal lines in (b.) represent the energy range for which the FEL gain is high.

The short-wavelength oscillations shown in Fig. 6 come from numerical noise. However this raises concerns about the influence of shot noise on the cold, narrow energy bands in the folded beam. If the wake develops short-wavelength oscillations due to shot-noise amplification in the low uncorrelated energy spread of the stripes of charge in longitudinal phase space, then this will limit the method. If the charge density remains smooth, as in Fig. 1b, the technique offers SASE background suppression together with easier implementation compared to conventional EEHG in terms of lower laser power and chicane strength and fewer modulator undulators required. As an upgrade for an existing SASE installation, the scheme's lack of compactness is not disadvantageous.

## LSC WAKE PROPERTIES

In conventional EEHG, the tolerance of the wavefront flatness of the seed laser in the second stage is on the order of a few nanometers (rms) [6]. The synchronization and overlap tolerances for the seed laser are also challenging, whereas in this LSC-EEHG method, the second stage seeding is done through the perfectly synchronized and overlapped LSC wake instead of through an external seed laser. The quality of this wake determines the limits of the method and not the quality of the seed laser.

A quick, 1-D estimate of the tolerance of different charge densities within the beam can be made by varying the peak current of the beam and checking the impact on the bunching factor at a given harmonic. Since the charge density varies transversely and longitudinally in the bunch, it gives an estimate of the changes in the bunching factor as a function of transverse or longitudinal position in the electron bunch. This was done for the case shown in Fig. 3 and it is plotted below in Fig 7.

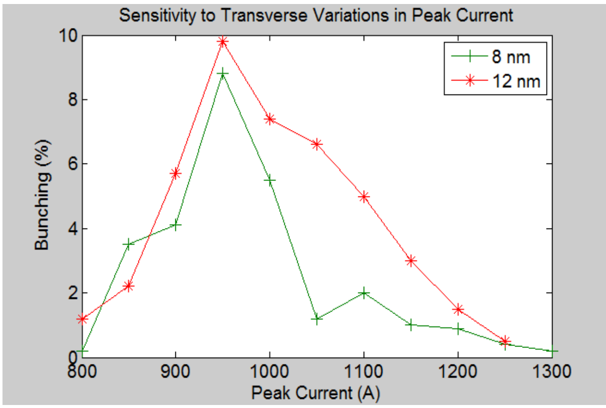



Figure 7: Taking 2% as a lower bound for an acceptable bunching factor, LSC-EEHG at 12 nm in the SASE undulators at FLASH would tolerate transverse variations in the peak current of $\pm$15-20%, providing seeded bunching for a majority of the charge in the bunch. For shorter wavelengths, the tolerance is tighter.

In general, the laser wavefront is a parameter which it is possible to control in conventional EEHG while the transverse properties of the LSC wake are determined by the shape of the electron bunch. For that reason, conventional EEHG could potentially seed shorter wavelengths than the LSC assisted EEHG presented here. The LSC-EEHG concept does, however, have advantages in terms of SASE background suppression and reduced chicane, modulator, and laser requirements compared to conventional EEHG. For the energy spreads available at FLASH, it can seed significantly shorter wavelengths than single-stage HGHG is capable of, for which SASE background suppression is not possible.

## OPERATION

The Free Electron LASer in Hamburg provides infrastructure which is adequate for implementing this concept if one uses the ORS section to seed the bunch and the sFLASH undulator section as a drift space prior to the 27 meter long SASE undulators with a K parameter of 0.87 and a period of 27.3 mm. The sFLASH extraction chicane would act as the final bunching chicane in this design. In order to commission this type of seeding parasitically with a user experiment operating with the SASE undulators, the user would need to tolerate small adjustments of the extraction chicane in order to facilitate the search for optimal bunching. The goal would be to see a difference in the gain length for SASE, SASE suppression, and LSC-EEHG conditions as plotted below in Fig. 8.

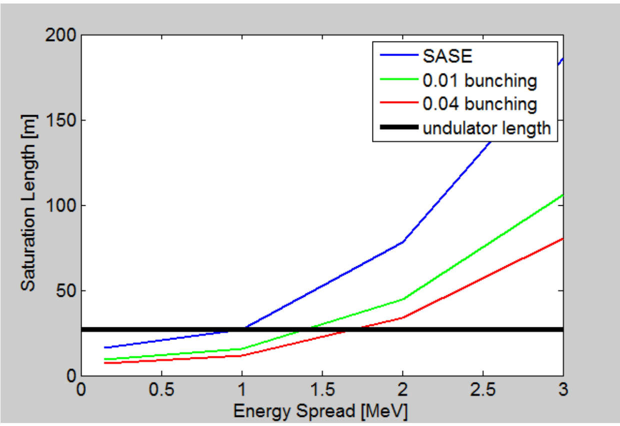



Figure 8: Saturation length as a function of rms slice energy spread for different initial bunching factors generated by the Xie 3D model [7] and Eq. 4 [8]. A 1 kA peak current was used at a beam energy of 0.73 GeV.

This plot was produced through the Xie 3-D model for SASE [7] with modifications for initial bunching factors given by [8]

$$L_{sat} = L_g \cdot \log(1/\alpha * b_n) \qquad (4)$$

Where $L_g$ is the gain length without seeding, $\alpha$ is the 1/9 fraction of noise power coupled into the dominant mode and $b_n$ is the bunching factor at the $n^{th}$ harmonic. Here, the $21^{st}$ harmonic (12 nm) was used.

For SASE conditions, saturation would be achieved after 16 meters with a slice energy spread of 150 keV (rms). For the SASE suppressed conditions from Fig. 5, with an rms energy spread of 3 MeV, the saturation length would be 360 meters; it would be 150 meters if one has a bunching factor of 0.01 at the resonance wavelength. For LSC-EEHG seeded conditions from Fig. 5, with a bunching factor of 0.04 and an rms energy spread of 1 MeV in the bunched core region, saturation would be achieved within the 27 m length of the undulator. Without the SASE background suppression, the seeded beam pulse energy would be smaller than the SASE pulse energy for short seed pulses and long SASE pulses. The alternative method to suppress the SASE background of a short, seeded pulse is to make the seedable portion of the bunch very short, but this puts difficult constraints on the synchronization of the seed laser.

Diagnosing overlap and seeding with this technique would be facilitated through already commissioned sFLASH diagnostics, including a parasitic streak camera installed in the first chicane, COTR, and an RF transverse deflecting structure (TDS). These are largely redundant methods, but each has unique advantages in terms of determining the overlap and energy modulation of the electrons. The final bunching after the last chicane would be observed in terms of enhanced or suppressed FEL radiation at the expected wavelength. Changing the amplitudes of the long and short pulse seed lasers would turn on and off the individual LSC-EEHG seeding and SASE suppression effects.

## CONCLUSION

This is a new seeding technique with a built in mechanism for suppressing the SASE background. The SASE suppression aspect is optional in this concept, although it is constitutes the prime advantage compared to other seeding techniques which cannot exploit this option. Without the SASE suppression, it offers advantages over traditional EEHG in that a second modulator and seed laser is not required for the second stage of EEHG, removing the synchronization and overlap difficulties inherent within. It also removes the difficulties associated with laser wavefront quality tolerances for the second EEHG stage, trading this for tolerances of the transverse curvature of the LSC wake.

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