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SIMULATIONS OF SEEDING OPTIONS FOR THz FEL AT PITZ

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Abstract

A THz FEL is under commissioning at PITZ as a proof-of-principle experiment for a high power and high repetition rate THz source and as an option for THz-driven experiments at the European XFEL. Some of these experiments require excellent coherence and CEP stable THz pulses. In SASE regime, the coherent properties of the FEL radiation are limited. A seeding scheme can be used instead of SASE to improve the coherent properties and shot-to-shot stability. Several options for seeding are considered in simulation for the THz FEL at PITZ: external laser pulse, pre-bunched electron beam, energy modulated electron beam and additional short spike on top of a smooth beam profile. The improvements over SASE in energy, spectral and temporal stability of the THz pulse are presented.

INTRODUCTION

The scientific opportunities of using terahertz (THz) radiation in modern x-ray free electron lasers (FELs) are recognized by the user community of the European XFEL [1]. Intense THz pulses are required for research of non-linear physics in THz-driven pump-probe experiments. The desired THz source is high-power, tunable and operates at a high repetition rate. An accelerator-driven source is a promising option. One concept of accelerator-driven source that matches the requirements is a THz FEL. At present, a proof-of-principle experiment of THz FEL source has achieved first lasing at the Photo Injector Test Facility at DESY in Zeuthen (PITZ) [2]. For this experiment, a LCLS-I undulator was installed in a second tunnel as an extension to the already existing PITZ accelerator.

In addition to high intensity, the ideal THz source should deliver identical and carrier-envelope phase stable pulses with good synchronization (low arrival time jitter). Typically in SASE regime FELs demonstrate significant shot-to-shot fluctuation due to the stochastic nature of the SASE process. This fluctuation manifests itself as final intensity, arrival time and spectral profile differences between shots of the FEL. To achieve more stable shot-to-shot performance, a seeding method is applied to the FEL. Several seeding options are studied in simulation for the THz FEL at PITZ and a summary of the results is given in this text.

SEEDING OPTIONS

The simulations are performed for four seeding options:

- External laser pulse,
- Pre-bunched electron beam [3],
- Energy modulated electron beam, and
- Short electron beam spike on top of main beam current profile.

A common FEL seeding method is the inclusion of a laser pulse along the electron beam in the undulator. In this setup, the FEL acts as an amplifier and inherits the coherent properties of the initial seeding radiation. The main simulation parameter of this seeding option is the seeding pulse power - it has to dominate over the beam noise.

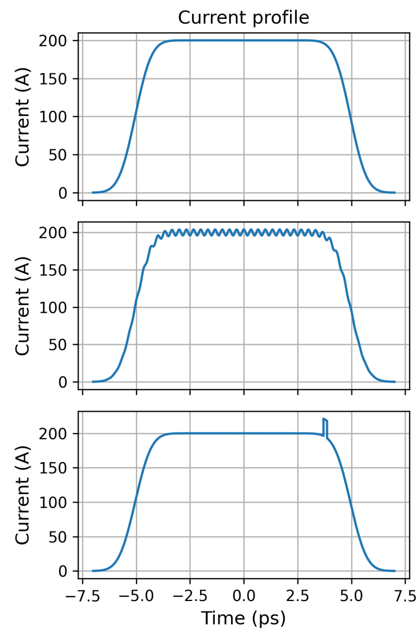

Figure 1: Electron beam current profile for SASE (top), pre-bunched beam with $b = 10^{-2}$ (center) and short 25 A spike (bottom).

Another technique is to deliver longitudinally density-modulated electron beam with the same periodicity as the FEL radiation, also called pre-bunched electron beam, to the undulator. An example is shown in the middle plot of Fig. 1, note the relatively small modulation amplitude. The main parameter of the simulation is the initial bunching factor b [4] given by:

$$b = \frac{1}{N_e}\left|\sum_{k=1}^{N_e} e^{-i\omega t_k}\right|, \quad (1)$$

where ω is the FEL resonant frequency, N_e is the number of electrons/macroparticles in the beam and t_k is the time coordinate of the kth particle. Sufficient pre-bunching will drive the FEL process and define the properties of the radiation pulse. The density-modulations generated in the simulation code Genesis 1.3 [5] for different bunching values are shown in Fig. 2.

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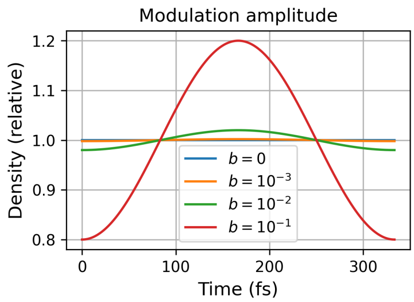

Figure 2: Electron beam current modulation along the duration of one period for different bunching values.

An alternative to pre-bunched beams is sending into the undulator a beam with periodic energy modulation along the beam at the resonant FEL frequency. As the beam travels through the undulator, the energy modulation drives the microbunching process. The main simulation parameter is the amplitude of the energy modulation.

Finally, a seeding option is to introduce a short spike on top of smooth beam current profile that is shorter than the radiation wavelength. Such a spike will radiate coherently from the start of the undulator. The spike radiation acts as a seeding signal that is amplified by the main electron beam in the FEL. A proper position of the spike for this model beam is at the tail of the main electron beam as shown in Fig. 1 bottom plot. Because of the slippage between the radiation and the electron beam inside the undulator, the radiation pulse will move forward relative to the electron beam. Therefore the emission from a seeding spike at the tail of the beam will move towards the head of the beam and the seeding signal will eventually cover the entire beam.

SIMULATION SETUP

The simulations are performed for model electron beams using Genesis 1.3 [6] version 2. While this version is not the most recent, it applies space-charge effects during simulation, which are relevant for the PITZ FEL parameter space. The parameters of the simulated lattice with LCLS-I undulator are given at the top of Table 1. Key beam parameters are given at the bottom of Table 1. The beam emittance and energy spread are assumed to be similar to experiments for few nC-charge beams [7]. The beam current profile is a flat-top with 10 ps FWHM and 2 ps rise time, shown in Fig. 1 top plot, however it may differ depending on the seeding method applied. The current profile is a model for the simulations and not a beam profile measured in experiments. The particle coordinates are generated in a quasi-random fashion to ensure that the macro-particle shot-noise is suppressed at the resonance frequency [5].

SIMULATION RESULTS

The simulation results are presented in Figs. 3 to 6 and for SASE in Table 2. The results for each method are based on 100 shots statistics with different seed number given to

Table 1: Simulation parameters

Parameter	Value
Undulator parameter	3.49
Period length	30 mm
Number of periods	113
Start/end drift	105 mm
Resonant frequency	3 THz
Peak current	200 A
Duration, FWHM	10 ps
Emittance (x, y)	4 mm mrad
Mean energy	17.06 MeV
Energy spread	85.3 keV

the particle generator in the simulation code. The final pulse energy is the average over all shots and the energy fluctuation is calculated as one standard deviation of the energy at the undulator exit. The arrival time for each shot is the time of the centroid of the radiation pulse. Then the arrival time jitter is one standard deviation of the arrival times of all shots. The spectrum fluctuation Δ_s is estimated with the formula:

$$\Delta_s = \frac{\sum \sigma_i}{\sum a_j}, \quad (2)$$

where a_j is the average spectral power of all shots at jth wavelength of the discrete simulation spectum and σ_i is the standard deviation of the spectral power at ith wavelength. The above formula can be derived from

$$\Delta_s = \frac{\sum (\sigma_i/a_i)w_i}{\sum w_j}, \quad (3)$$

where σ_i/a_i is the relative deviation of the spectral power at ith wavelength and $w_i = a_i$ are weights for each wavelength point.

Table 2: SASE FEL performance

Parameter	Value
Final energy	35 µJ
Energy fluctuation	27 µJ
Arrival time jitter	667 fs
Spectrum fluctuation	0.826

The results of the simulation with external seeding laser pulse are shown in Fig. 3. At the lowest laser power, there is a relatively small improvement to SASE. When the external pulse power is increased, all studied FEL-pulse parameters continuously improve. At 1 kW laser power the FEL performance is significantly improved compared to SASE.

The bunching factor of pre-bunched beam simulations is scanned from 10^{-6} to 10^{-2} and shown in Fig. 4. Up to bunching factor of 10^{-5}, there is no significant seeding effect and between bunching of 10^{-5} and 10^{-4} there is an improvement of the FEL efficiency. Passing that point, all four parameters are improved with increased bunching factor.

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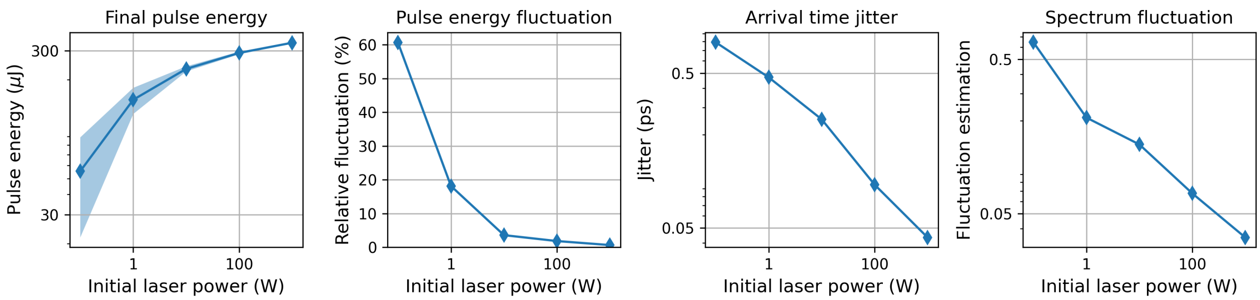

Figure 3: Summary of simulation results with external laser seeding. The laser power varies from 100 mW to 1 kW.

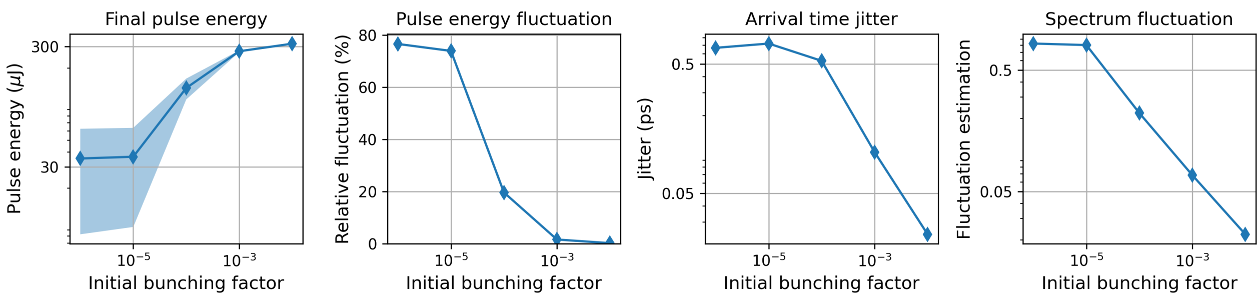

Figure 4: Summary of simulation results with pre-bunched electron beam. The bunching factor varies from 10^{-6} to 10^{-2}.

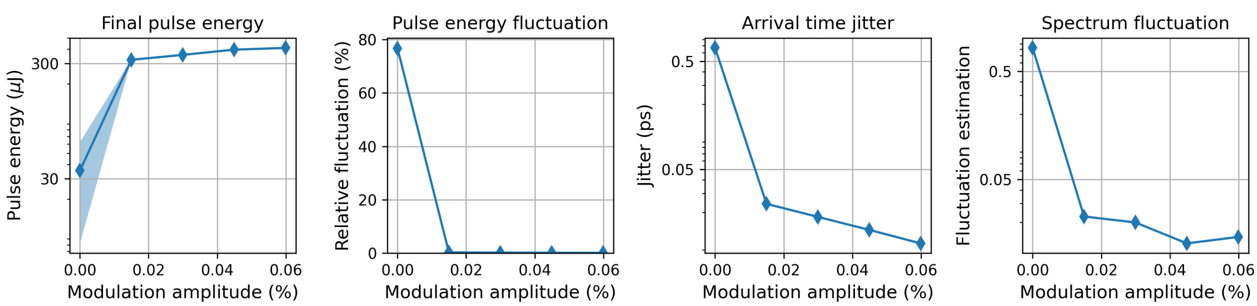

Figure 5: Summary of simulation results with energy modulated electron beam. The modulation amplitude spans from 0 to 10.2 keV.

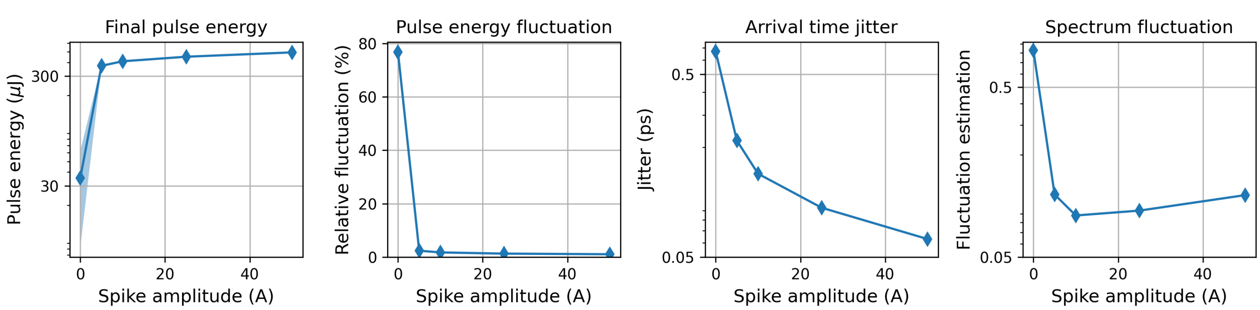

Figure 6: Summary of simulation results with additional short spike for spike currents 0, 5, 10, 25, 50 A.

With an energy modulation amplitude of 2.56 keV (0.015 % of the average electron energy) there is strong seeding effect. Such amplitude of the modulation is difficult to observe, since it is much smaller than the uncorrelated energy spread of 0.5 %. Nevertheless at that point, the FEL is clearly not in SASE regime as indicated by the plots in Fig. 5. One possible explanation is the quick evolution of the energy modulation into bunching with a factor above 10^{-4} in the drift before the undulator. Further increase of

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the energy modulation amplitude in the shown range does not change the FEL performance significantly.

Finally, results with a short spike added near the tail of the electron beam are shown in Fig. 6. The spike is created by rearranging macroparticles and increasing the current accordingly. The spike is a flattop with a duration half of that of the radiation period. Adding a 5 A spike to the main electron beam is enough to apply seeding in this simulation. Further increase in the spike current decreases the arrival time jitter and there is minimum of spectral fluctuation at 10 A point.

Overall, significant gains in the FEL performance and stability are achieved in all of the simulated seeding options. For any of them with strong seeding applied, the final FEL pulse energy exceeds 300 µJ while the energy fluctuation is 1 % or lower. Also, the arrival time jitter is below 67 fs (1/5th of the radiation period). Finally, the spectral fluctuation estimation falls under 0.1 (for a short spike, it is 0.088 at 10 A). In comparison to the SASE performance in Table 2, there is a clear improvement.

OUTLOOK

The simulation results thus far are a showcase for the four seeding methods with flattop model beam with 200 A current, but they may not be a complete and fair comparison. The actual choice of seeding method for PITZ also depends on the availability of the method and the electron beam preparation in an experiment. It is challenging to find a suitable and affordable THz source for a seeding pulse in the present. Delivering a pre-bunched beam in the undulator is a promising method for seeding and sub-THz current modulations were observed experimentally at PITZ [8]. The main difficulties of the method are beam transport with space-charge forces and higher modulation frequencies. A solution to the latter is a development of modulation harmonics by non-linear space-charge oscillations during beam transport [9]. Energy modulation can be achieved with a dielectric lined waveguide in the beam path [10], but it is not easy to achieve modulation frequency as high as 3 THz. Finally, a short spike may be generated by hitting the photocathode with two laser pulses simultaneously. One laser pulse is high intensity and smooth over time while the other laser pulse has short duration. The optical beamline and electron transport are left as concerns for this two laser setup.

CONCLUSION

In simulation with model flattop 200 A electron beam, all studied seeding options bring significant improvements to the FEL efficiency and shot-to-shot stability. The necessary seeding strength for each method is also indicated in the presented simulation results. Since overall the seeding effect is comparable in all options, there is a free choice of the most appropriate seeding method to be implemented in PITZ, with most to date research performed for pre-bunched beams.

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