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BEAM PREPARATION WITH TEMPORALLY MODULATED PHOTOCATHODE LASER PULSES FOR A SEEDED THz FEL*

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Abstract

The need for carrier-envelope-phase (CEP) stable THz pump pulses is recognized at many pump-probe experiments at the European XFEL. At the Photo Injector Test Facility at DESY in Zeuthen (PITZ), a proof-of-principle experiment of an accelerator-based THz FEL source is in preparation. Since the CEP stability of FEL pulses is not guaranteed in the SASE regime, a seeding scheme is needed. A common scheme for seeding is to drive the microbunching process with external laser pulses, which are power-limited in the THz range. Alternatively, a pre-bunched beam, generated for example by applying a temporally modulated photocathode laser pulse, can be used to drive the FEL. The beam dynamics with such a seeding method are studied with ASTRA tracking code simulations with space-charge forces as well as experimentally. The results of these studies are shown and discussed.

INTRODUCTION

Intense THz radiation has a broad set of applications for the European XFEL user community [1]. The research capabilities of the European XFEL can be extended with THz pump-probe experiments, which utilize an intense THz pulse to drive states or effects in matter. A current challenge for such a setup is the availability of THz sources with appropriate parameters for the pump-probe experiment requirements. The ideal THz source must have a tunable frequency, a high field strength, carrier-envelope-phase (CEP) stable pulses and high repetition rate up to the European XFEL repetition rate of 4.5 MHz, among other requirements.

Optical laser-based THz sources, such as optical rectification or difference frequency generation [2, 3], have limited pulse energy at high repetition rate and often are not widely tunable, therefore an accelerator-based THz source is also considered [1]. A THz SASE FEL source is expected to deliver high energy THz pulses at MHz repetition rates with high tunability, but the CEP stability is not ensured due to the FEL process starting from shot noise [4]. A proof-of-principle experiment for an accelerator-based THz FEL source is prepared at the Photo Injector Test Facility at DESY in Zeuthen (PITZ) [5]. The effort includes improvement of the CEP stability by a seeded THz FEL scheme. A common seeding scheme is to send external laser together with the beam into the FEL to drive the formation of coherent microbunches [6], but as mentioned before, powerful high-repetition rate THz lasers are not easily available.

This paper focuses on an alternative method to seed a THz FEL. Using a photocathode laser pulse with temporal intensity modulations, an electron beam with corresponding current modulations is generated. The beam current modulations act as an initial coherent signal that is amplified in the FEL [7].

SIMULATION

By special tuning of the Lyot filter in the regenerative amplifier of the photocathode laser system [8] strongly temporally modulated laser pulses can be generated. The temporal intensity profile of the generated infrared (IR) pulses can be modeled as:

$$I_{\mathrm{IR}}(t) = G(t,\sigma)\Big(1 + \sin(2\pi f t)\Big), \tag{1}$$

where I_{IR} is the IR pulse intensity at time t, f is the beating frequency, $G(t,\sigma)$ is a Gaussian envelope with RMS duration σ. The intensity profile after conversion into UV is $I_{\mathrm{UV}}(t) \propto I_{\mathrm{IR}}^4(t)$.

The particle tracking simulations with space-charge forces are performed with ASTRA code [9] for the PITZ linac. The accelerating field of the RF gun is set to give the maximum mean beam momentum of 6.7 MeV/c on crest phase. The beam is accelerated further in a booster to mean beam momentum of 20.5 MeV/c on crest phase. The beam is then drifted to 13 m from the photocathode, where a screen station is used for experiments. The RF gun is surrounded by an emittance compensating solenoid magnet which is also used to focus the beam. Different beam charges were simulated and 500 pC is discussed in detail in the paper.

A challenge in using temporally modulated photocathode laser pulses for modulated current profiles is the longitudinal shape degradation driven by space-charge forces of the electron beam. Starting with a modulated photocathode laser pulse, the beam current profile of electron beam at 13 m from the photocathode is shown in Fig. 1. The initial clear modulation is lost, instead much broader and merging peaks take place. As a consequence of the beam shape smearing, the spectral content of the modulation frequency is significantly reduced.

While the longitudinal modulations are mostly lost in the beam current profile, they are still present in the longitudinal

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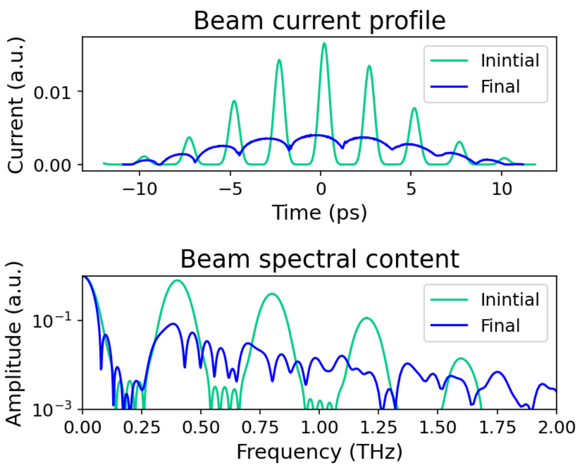

Figure 1: Beam current of initial and final simulated beams (top) and corresponding beam spectral content (bottom).

phase space (LPS) of the simulated beam. The LPS is plotted for 500 pC on Fig. 2. The beam modulations are clearly visible in LPS coordinates. Each peak from the initial modulated particle distribution is stretched in time and energy with positive chirp. The preserved modulations in LPS can be utilised in combination with a suitable device, such as a bunch compressor, to restore the beam current modulations for the purpose of FEL seeding.

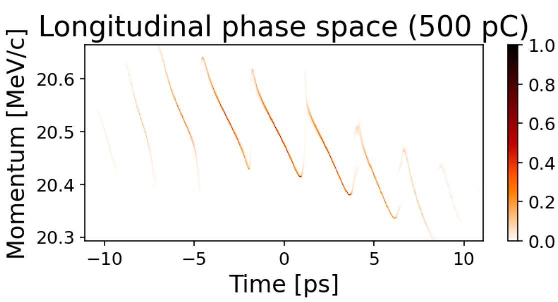

Figure 2: Longitudinal phase space of simulated 500 pC beam from temporally modulated photocathode laser.

Non-Linear Longitudinal Oscillations

Non-linear longitudinal space-charge driven oscillations are found in scans of gun solenoid field strength. For sufficiently large amplitude of an initial modulation of the beam, harmonics of the modulation appear. This effect is described and was observed in electron beams in the past [10]. After half-period of the beam plasma oscillation the modulation harmonics add constructively and form sharp peaks in the beam current.

In the simulation with modulated photocathode laser for PITZ, non-linear plasma oscillations develop for stronger gun solenoid field, that increases the space-charge forces driving the plasma oscillations. In addition, higher harmonics are already present in the initial beam current because of the non-linear UV conversion as shown in Fig. 1. The beam current profile of a 500 pC beam with 370 A gun solenoid current is presented in Fig. 3. Sharp current spikes are present at the locations between the initial modulation peaks. It should be noted that the duration of some spikes approaches the slice size of the given simulation setup.

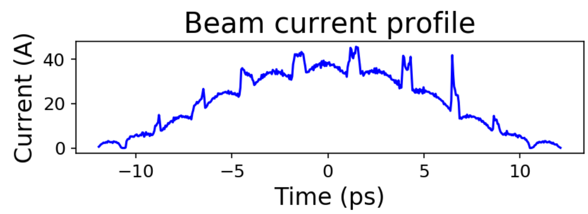

Figure 3: Beam current profile of simulated 500 pC beam from temporally modulated photocathode laser. Sharp spikes from non-linear plasma oscillations are visible.

The sharp beam current peaks formed by non-linear plasma oscillations carry high frequency content. These formations have a potential for seeding a FEL with resonant wavelength at higher harmonics of the initial beam modulation. Such scheme would ease the requirement on the photocathode laser to deliver pulses modulated for the THz FEL frequency.

EXPERIMENT

The experimental setup is close to the simulation setup. A temporally modulated photocathode UV laser pulse is delivered to the photocathode and the emitted electrons are accelerated in the RF gun to 6.7 MeV/c and then in the booster to 20.9 MeV/c. The gun solenoid field is applied for emittance compensation and beam focusing.

About 13 m downstream from the photocathode a screen station is equipped with a foil generating coherent transition radiation (CTR) which is measured in the THz range. PITZ also includes a transversely deflecting structure (TDS) and dispersive arm to image the beam longitudinal phase space (LPS) [11].

The temporally modulated photocathode laser pulse profile is estimated from the beam current profile at low beam charges and is presented in Fig. 4. While the peak separation is not as good as in the theoretical model, shown before in Fig. 1, there is a clear peak at roughly 0.4 THz in the spectrum in Fig. 4. The second harmonic at 0.8 THz is also present above background.

The beam current profile for 500 pC beam charge measured with TDS streaking is shown in Fig. 5. The modulation structure has degraded due to the space-charge stretching of the peaks, but it is still present in the beam current. Simulation prediction (Fig. 1) is in good agreement with the measured profile.

The 500 pC beam is focused at an aluminium foil and CTR is generated and then transported to the Michelson

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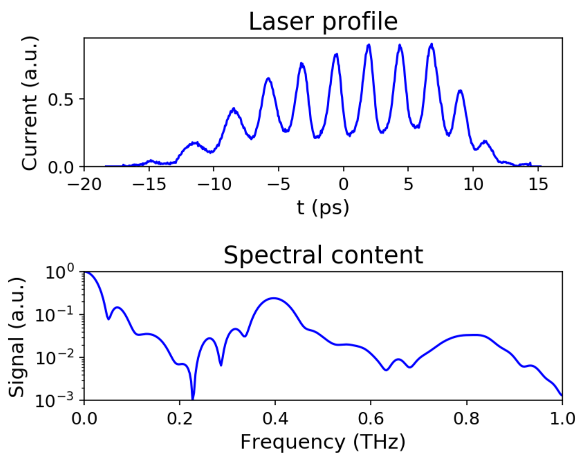

Figure 4: Measured laser intensity profile from a 10 pC electron beam (top) and its spectral content (bottom).

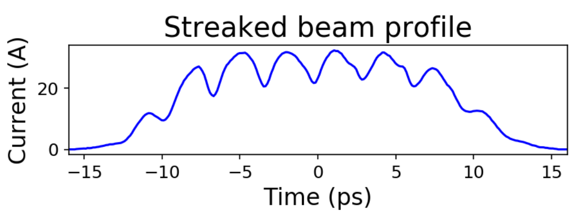

Figure 5: Measured current profile of a 500 pC electron beam after streaking with TDS.

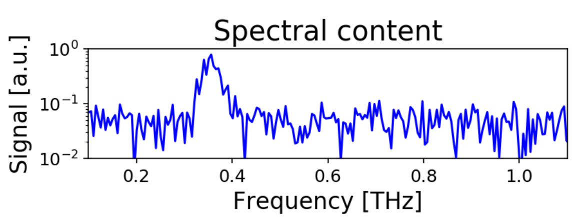

Figure 6: Spectrum analysis of CTR interferogram from the Michelson interferometer.

interferometer. The CTR intensity is proportional to the form factor of the beam current profile [12] and spectral information is obtained from the Fourier transform of the interferogram, as presented in Fig. 6. The spectral peak is at 0.36 THz, the shift to lower frequency is explained by beam stretching from the space-charge effect.

Non-linear space-charge dynamic is confirmed experimentally. By applying stronger gun solenoid field resulting in a stronger beam focusing, sharp current spikes form in the modulated 500 pC electron beam. They are presented in Fig. 7 together with a streaked beam image. While the spikes are not significantly developed, their presence confirms the observations in simulation. It is also possible that the spikes are not completely resolved due to the limited measurement resolution.

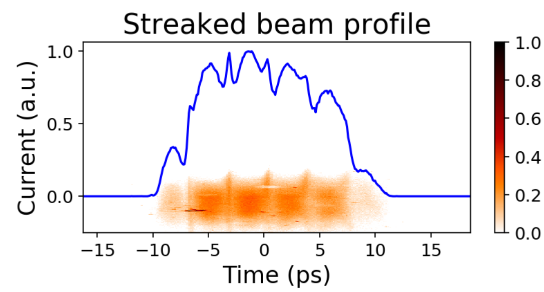

Figure 7: Measured current profile (blue curve) and time-horizontal image of a streaked 500 pC electron beam. Sharp modulation peaks are formed from non-linear plasma oscillations.

Finally, a measurement of the LPS for 500 pC beam is presented in Fig. 8. It must be noted that the booster phase is off-crest by -30 deg to stretch the beam. The need for this change in the machine settings comes from the low resolution of the measurement, the beam modulations in LPS are more clearly visible at an off-crest phase. These results confirm that strong modulation is preserved in LPS and it should be possible to recover beam current modulations with e.g. a bunch compressor.

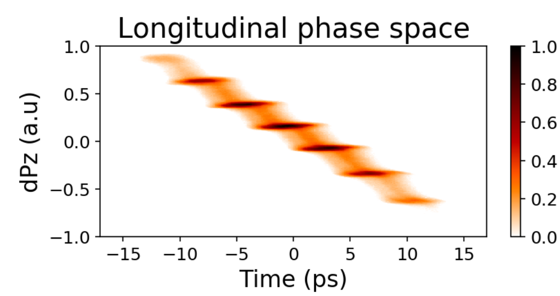

Figure 8: Longitudinal phase space of the 500 pC electron beam at -30 deg off-crest booster phase. Due to the far off-crest phase the modulation chirps are not visible as in Figure 2.

CONCLUSION

This paper presented simulation and experimental studies on THz temporally modulated electron beams by using temporally modulated photocathode laser pulses. The space-charge effect was found to play a significant role for generating modulated electron bunches with high charge. On the one hand, it leads to broading and smearing of the initial peaks in the photocathode laser pulse. On the other hand a special tuning of the focusing gun solenoid could cause non-linear space-charge driven oscillations resulting in more efficient high harmonic generation. This is considered as possible mechanism for THz FEL seeding. The topic will be studied further via simulations, e.g. FEL simulation and bunch compressor simulation.

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