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INDUCING MICROBUNCHING IN THE CLARA FEL TEST FACILITY

A. D. Brynes*
STFC Daresbury Laboratory & Cockcroft Institute, Warrington, UK

Abstract

We present simulation studies of the laser heater interaction in the CLARA FEL test facility using a non-uniform laser pulse. The microbunching instability, which manifests itself as correlated energy or density modulations in an electron bunch, can degrade the performance of an FEL. Most x-ray free electron lasers (FELs) utilise a so-called laser heater system to impose a small increase in the uncorrelated energy spread of the bunch at low energy to damp the instability – this technique involves imposing a laser pulse on the bunch while it is propagating through an undulator in a dispersive region. However, if the instability can be controlled, the electron bunch profile can be manipulated, yielding novel applications for the FEL, or for generation of THz radiation. Control of the microbunching instability can be achieved by modulating the intensity profile of the laser heater pulse to impose a non-uniform kick along the electron bunch. We have simulated this interaction for various laser intensity profiles and bunch compression factors.

INTRODUCTION

The quality of a photon beam produced by an FEL, in terms of spatial and temporal coherence, is strongly dependent on the electron bunch parameters. One important factor which can degrade the quality of an electron bunch in an FEL is the influence of collective effects, such as coherent synchrotron radiation (CSR) [1], or the microbunching instability [2]. This instability arises from density or energy variations in the bunch at low energies (due to factors such as shot noise [3], or longitudinal space charge [4]), and can become amplified due to CSR in dispersive regions, for example in bunch compressors [5]. Upon reaching the FEL undulator section, the electron beam can develop a correlated energy spread, which can limit the performance of x-ray FELs. The most commonly implemented solution to this is the laser heater [6].

Laser heater systems have proven to be crucial in improving the performance of x-ray FELs [7–9]. Recent results have also shown that, through modulating the temporal profile of the laser pulse used in the laser heater, it is possible to achieve a greater degree of control over the longitudinal profile of the electron bunch, yielding novel applications in the production of multi-colour FEL beams, or the production of THz radiation via a bunch with induced microbunching [10]. This technique is similar to the echo-enabled harmonic generation scheme [11], but it can achieve similar results in a shorter space, as it does not require multiple modulators before the FEL radiator section. In this paper we investigate the possibility of providing a tunable longitudinal profile of the electron beam in the CLARA FEL test facility [12], which is currently under construction at Daresbury Laboratory.

* alexander.brynes@stfc.ac.uk

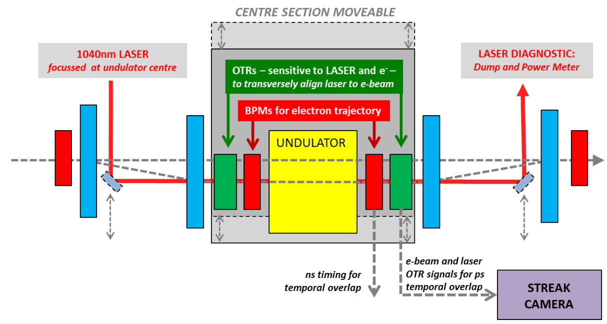

Figure 1: Schematic of laser heater system. Dipoles are shown in blue.

THE CLARA LASER HEATER

In a typical laser heater system, an unmodulated Gaussian laser pulse is propagated with the bunch in the undulator, and any small-scale modulation is removed through the uncorrelated energy spread increase and the R_{52} parameter of the second half of the chicane. A schematic of the CLARA laser heater system is shown in Fig. 1, and the laser heater system parameters are given in Table 1; further details can be found in [13]. Simulations have shown that, while the microbunching instability is not expected to have a large impact on the nominal CLARA modes of operation, it would still be useful to install a laser heater in order to investigate potential methods of utilising the laser heater in novel configurations in order to achieve flexible control of the electron bunch properties. Current profiles and longitudinal distributions up to the exit of the CLARA accelerating section, at 240 MeV, have been simulated using the Elegant code [14] (with CSR and longitudinal space charge included) for the nominal laser heater operating mode, and with the laser heater off are shown in Fig. 2. In the nominal laser heating operating mode, sufficient power will be available to damp any small-scale structure in the electron bunch. Simulations have shown that a small increase in the RMS energy spread of 25 keV, or 0.1 % of the final beam energy, should be sufficient to heat the beam without greatly degrading the quality of the FEL – for this nominal operating mode of the laser heater, a pulse energy of around 48 μJ is required.

CHIRPED-PULSE BEATING

There are various ways of using modified laser pulses to modulate the longitudinal profile of an electron bunch. One method for achieving this is through chirped-pulse beating [15] of the laser heater pulse. The pulse is stretched

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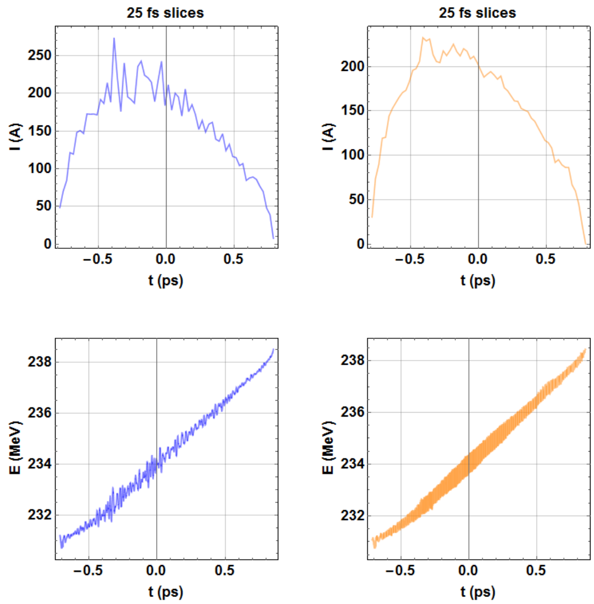

Figure 2: Current profiles at full energy for: Left: laser heater off; Right: laser heater at nominal settings.

Table 1: Laser Heater System Parameters

BEAM TRANSPORT	
Chicane magnet length	10 cm
Chicane magnet bend angle	0 – 5 °
Beam energy	100 – 200 MeV
Emittance	0.5 mm–mrad
UNDULATOR	
Period	60 mm
Number of full periods	8
Total length inc. end terminations	585 mm
Minimum undulator gap	24 mm
Undulator parameter	0.8 – 3.0
LASER	
Wavelength	1040 nm
Spot size σ_{rad} at undulator centre	≤ 500 µm
Pulse energy	80 µJ

temporally (or chirped), then split in a Michelson interferometer, one arm of which has a variable length. The two laser pulses are recombined, and they overlap in the temporal domain. By varying the length of the interferometer arm, a delay between the two pulses can be created, giving rise to a laser pulse with a beat frequency that is directly related to the delay parameter τ. The intensity profile of such a laser pulse is given by:

$$I_{tot}(t) = I^{+}(t) + I^{-}(t) + E_0{}^2\left(\frac{\sigma}{\sigma_n}\right) \times \exp\left(\frac{-2t^2}{\sigma_n{}^2}\frac{-\tau^2}{2\sigma_n{}^2}\right)\cos\left(\frac{2t\tau}{\sigma_n\sigma} + \omega_0\tau\right), \tag{1}$$

with E_0 the field strength of the initial pulse, σ the Gaussian half-width of the initial pulse, σ_n the stretched pulse half-width, ω_0 the centre of the optical pulse spectrum, and $I^{\pm} = E_0{}^2\frac{\sigma}{2\sigma_n}\exp\left(-2(t \pm \frac{\tau}{2})^2/\sigma_n{}^2\right)$. For a frequency chirp rate of μ, the beat frequency of the modulated laser is given by $f(\tau,\mu) \approx \mu\tau/2\pi$ [15]. We can take the parameters for the CLARA photoinjector laser pulse stretcher as an example: the initial laser pulse, with an rms duration of 76 fs will be stretched to a length of 1 − 8 ps. The longer laser pulse should provide consistent overlap with the electron bunch, which has a FWHM duration of 4 ps in the laser heater section.

The interaction of such a modulated laser pulse with an electron bunch undergoing periodic motion can cause the bunch to develop longitudinal structure, thus inducing the microbunching instability. Taking the parameters for the CLARA laser heater and applying the chirped-pulse beating technique, we can obtain a range of longitudinal intensity profiles, as shown in Fig. 3. The flexibility of laser intensity modulations provided by this technique could lead to the generation of a range of customisable longitudinal electron beam profiles.

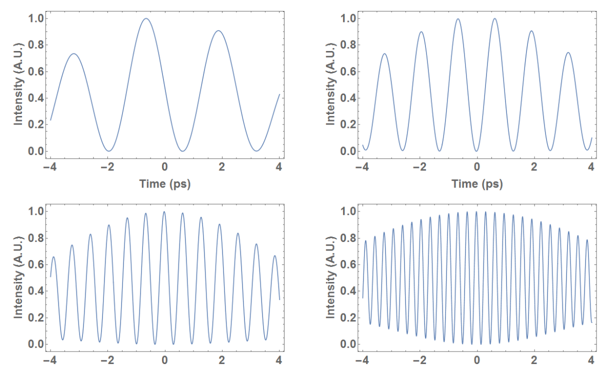

Figure 3: Calculated intensity profiles of modulated laser pulses for: Top left: 1 ps; top right: 2ps delay; bottom left: 4ps delay; bottom right: 8ps delay.

LASER HEATER SIMULATIONS

The interaction of a modulated laser pulse with the electron bunch in the CLARA laser heater chicane has been modelled using the Elegant simulation code [14], which allows the user to implement custom laser fields in a laser-electron interaction. Scans of a number of laser heater parameters have been performed in order to determine the optimal settings for inducing the largest density/energy variations in the bunch. After the laser heater interaction, which occurs at around 130 MeV, the bunch is shortened in a magnetic compression chicane and accelerated to its full energy of 240 MeV. As shown in [5], any perturbations in the bunch density or energy can be amplified in a bunch compressor, and so we should expect to observe a more pronounced microbunching effect after compression.

A number of operating modes have been specified for CLARA, depending on the electron bunch length and the energy [16]; here we simulate the chirped-pulse beating interaction for the Short bunch mode at 240 MeV. Parameter scans over modulation wavelength and bunch compressor

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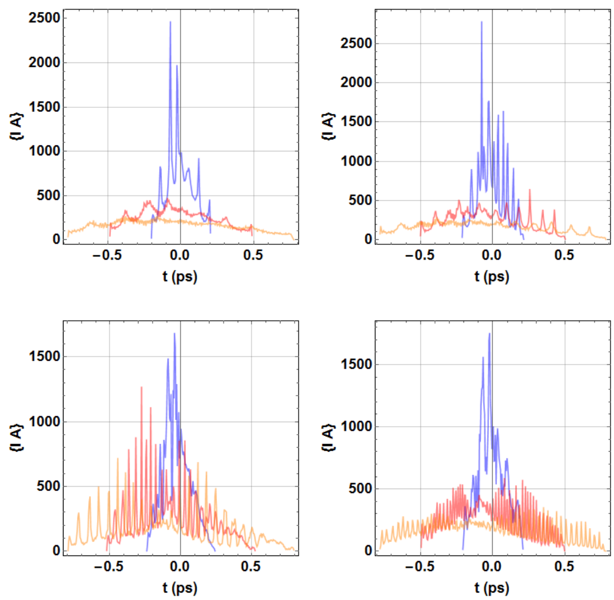

Figure 4: Current profiles for scans of bunch compression factor for the laser intensity profiles given in Fig. 3: Blue: 1.4; Red: 3.0; Orange: 4.6.

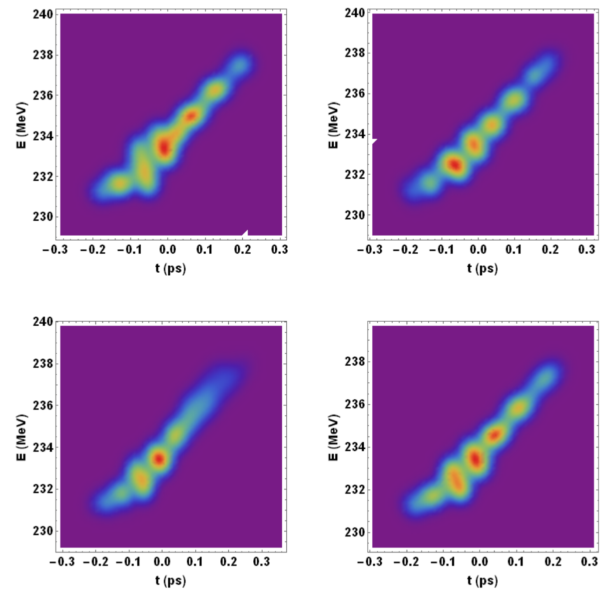

Figure 5: Energy profiles for the laser intensity profiles given in Fig. 3 near maximal bunch compression factor.

angle have been performed in simulations in order to determine the effects of varying these parameters on the energy and longitudinal profile of the bunch. The laser intensity profiles shown in Fig. 3 correspond to modulation wavelengths of 376 µm, 188 µm, 94 µm and 47 µm. The bunch compressor angle was set to 104 mrad, 104.5 mrad and 105 mrad (the nominal setting for the short bunch operating mode), corresponding to compression factors of 1.4, 3.0, and 4.6, respectively. Current profiles for various bunch compression factors and modulation wavelengths are shown in Fig. 4. We see that, as the modulation wavelength decreases, the electrons become more tightly (micro-)bunched. As the compression factor increases, we see much larger peaks in the current profile as the bunch becomes maximally compressed, but with fewer peaks due to the shorter bunch length. In Fig. 5 we show the bunch energy profiles only for the maximally compressed bunch at the wavelengths given above, as this is where the energy modulations are most pronounced; at most other bunch compression factors, the R_{52} parameter of the laser heater chicane was sufficient to remove longitudinal energy variations along the bunch. These energy profiles show that it may be possible to use this method to produce multi-colour FEL light in CLARA (similar to [10]), but further simulations are needed to confirm this.

From these simulations we can see that, by varying the modulation wavelength of the laser heater, we can induce a variation in the current profile of the electron bunch. The flexibility that the chirped-pulse beating technique affords in terms of the laser pulse beating frequency, in addition to the variable bunch compression factor, could increase the range of FEL pulse characteristics that CLARA can provide.

SUMMARY

We have proposed a method of inducing small-scale structure on bunches in the CLARA FEL test facility via the interaction with a frequency-modulated laser. The flexibility of the frequency modulations offered by the chirped-pulse beating method, along with the variation of the laser heater parameters and the bunch compression schemes, may provide a range of new modes of operation for the FEL. Further work will include simulations of these modulated electron bunches in the CLARA undulator section, to investigate the applicability of this technique to novel FEL schemes, and the potential for the generation of THz radiation.

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