

COMPRESSION AND SYNCHRONIZATION OF MEV SCALE SUBPICOSECOND ELECTRON BEAMS IN A THz IFEL INTERACTION

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Abstract

Recent development of MW peak power THz sources from efficient optical rectification of broadband IR pulses by pulse front tilting has made available laser locked single cycle THz pulses suitable for compression and laser-synchronization of photoinjector generated subpicosecond electron beams. Three dimensional simulations have shown that a waveguided 8 pulse THz train can be used to interact with a sub picoseconds electron beam in an undulator to achieve compression and laser synchronization. We present a THz pulse train source currently under development at UCLA PBPL as well as detailed 3 dimensional simulations including the effect of the interaction on transverse beam quality.

INTRODUCTION

Advanced accelerators such as laser wakefield accelerators (LWFA) [1] with plasma densities on the order of 10^{16} cm^{-3} have pushed acceleration buckets down to the picosecond timescale. These high gradient structures typically use self injection methods that have a wide phase acceptance, resulting in beams with large energy spread.

Photoinjectors can produce well characterized high brightness beams but suffer from rf phase jitter on the scale of hundreds of fs. This jitter makes reliable injection into short timescale accelerating structures impossible. To make direct injection into high frequency structures possible, the photoinjector beam must be both synchronized to an optimal accelerating phase and occupy a small region near that optimal phase. This demands a longitudinal phase space control that reduces the time of arrival (TOA) jitter relative to the drive laser and compresses the beam before injection. A THz inverse free electron (IFEL) interaction can be used as such a control.

Previous work [2] has focused on the overview of a compression / synchronization scheme as well as the integration of 1-D equations of motion without space charge effects. In this paper the concept is further examined, focusing on experimental efforts to increase the power of the laser locked THz source through cooling of the lithium niobate crystal as well as extending the model into 3 dimensions to examine the effects of matching. The paper is organized as follows: A brief description of the compression scheme is given, followed by a detailed description of the THz source driving the interaction, a description of the 3D modelling in Genesis [10], and finally the future direction of experimental and simulation efforts.

OVERVIEW OF COMPRESSION AND SYNCHRONIZATION SCHEME

The scheme to compress and synchronize the electron beam to a laser accelerator is shown in Fig. 1. The drive laser is split into three parts. One part goes to the photocathode to produce the electron beam, one part goes to make a THz pulse train, and the remaining laser goes to drive the accelerating structure with a controllable delay. The electrons acquire jitter due to the rf acceleration process in the photogun, while the synchronized THz pulse remain locked to the laser with a few fs rms. The THz pulse train and electron beam interact through the undulator, imprinting the temporal information of the THz pulse train back onto the electron bunch, reducing the jitter as well as compressing it.

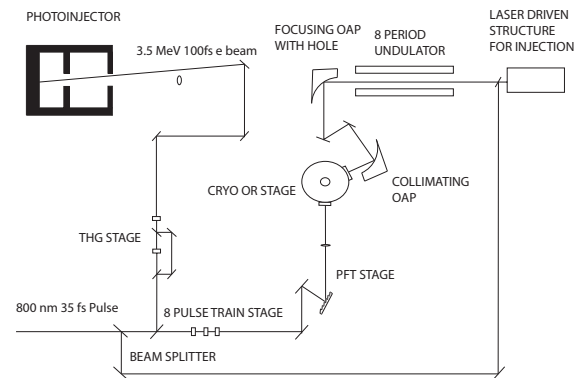


Figure 1: Diagram of the Compression and Synchronization Scheme.

The electron beam is modeled using the particle tracing code, General Particle Tracer (GPT) [3]. The electron beamline consists of a SLAC/UCLA/BNL 1.6 Cell S-Band photogun, a solenoid which acts as a lens, a quadrupole section for matching, and a drift up to the undulator. The beam has a bunch length of 100 fs, a well defined chirp that is insensitive to charge fluctuations and has a small slice energy spread, making the beam highly compressible [5]. The beam is matched into the undulator's focusing channel using a quadrupole triplet section.

CRYO-COOLED THZ SOURCE

The THz pulse train is generated using the process of pulse front tilt optical rectification (PFT OR) [6]. In OR, a broadband intense laser pulse impulsively drives a nonlinear crystal. Difference frequency mixing within the bandwidth of the laser pulse results in generation of low frequency radiation ranging from DC to several THz. At Pegasus, stoichiometric lithium niobate (sLN) is chosen due to its high effective nonlinear coefficient of 169 pm/V [7]. OR is strongly dependent on the phase matching condition, where the difference between the phase velocities of the laser and the generated THz radiation must be close to zero. While the efficiency of OR scales as the square of the nonlinear coefficient, sLN suffers from a strong velocity mismatch between the 800 nm laser and the generated THz, which have respective indices of refraction of 2.25 and 4.96. Phase matching is achieved by pulse front tilting (PFT) the drive laser to the Cerenkov angle in the crystal using a diffraction grating to acquire angular dispersion and an achromatic lens images the pulse.

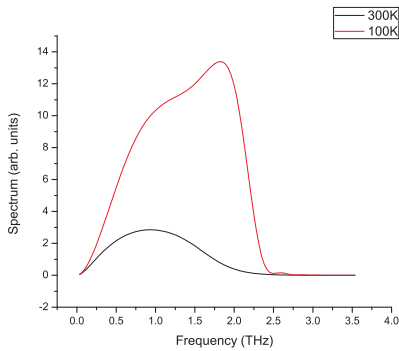


Figure 2: Modeled Spectra of THz resulting from 300K and 77K.

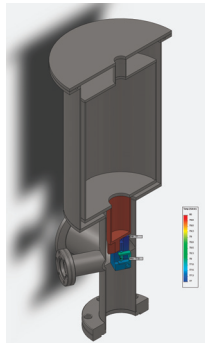


Figure 3: CAD drawing and thermal simulation of the cryo-cooled optical rectification setup.

Single cycle pulses are insufficient to drive the undulator interaction efficiently because the electron beam stops interacting with the resonant spectral component of the THz radiation after one undulator period due to slippage between the laser pulse and the electron beam. Thus a series

of α -BBO crystals is utilized to create a pulse train with alternating polarizations. Upon interacting with the grating to acquire angular dispersion only the vertical component of the electric field is transmitted, resulting in a pulse train with reduced energy which undergoes OR and a THz pulse train is generated. Generation of the THz pulse train elongates the pulse so that the temporal overlap of the electron beam and THz pulse is extended and the number of undulator periods is likewise extended to the number of single cycle pulses in the train, as the resonant condition, demands that the electron slip one radiation wavelength in one undulator period.

This method of generating a pulse train is inefficient thus the optical rectification process must be made more efficient to achieve sufficient power to obtain the desired interaction. Work with lithium niobate [8] has shown that the absorption of THz is strongly temperature dependent. By cooling the crystal to 77K using liquid nitrogen in a custom thermal jacket, the energy of THz produced can be increased by at least a factor of 3. The spectra resulting from a model comparison between OR at 300K and 77K are shown in Fig. 2. A cooling chamber designed to hold the lithium niobate crystal and cool it down to 77K can be seen in Fig. 3.

Table 1: Compression Scheme Parameters

Beam Parameters	
Average γ	7
Normalized Emittance	.1 mm-mrad
Charge	1 pC
Undulator Parameters	
K	1.656
K_L	$4.21 \cdot 10^{-4}$
λ_w	1.77 cm
λ	430 μ m
L_u	14.2 cm

THE INTERACTION

Previous work has simply examined interaction by numerically integrating the IFEL 1-D equations of motions for the particles [9].

$$\frac{d\gamma}{dz} = \frac{1}{2\gamma} k K_L K J J \sin\Psi \tag{1}$$

$$\frac{d\Psi}{dz} = k_w - \frac{k}{2\gamma^2} \left(1 + \frac{K^2}{2}\right) \tag{2}$$

Here k is $2\pi/\lambda$, K_L is the radiation parameter equal to $eE_0\lambda/2\pi mc^2$ and E_0 is the peak radiation electric field, m is the electron mass, and c is the speed of light. K is the undulator strength parameter and is equal to $eB_w\lambda_w/2\pi mc^2$ and B_w is the peak undulator magnetic field. JJ is the coupling factor of the planar undulator γ is electron beam en-

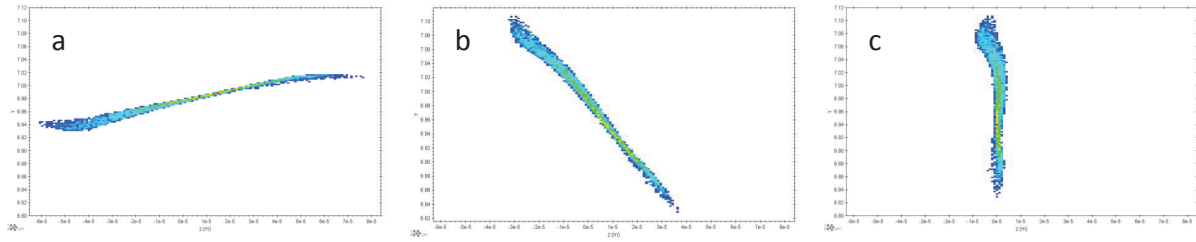


Figure 4: Longitudinal phase spaces of the beam at (a) the entrance of the undulator (b) the exit of the undulator (c) a 9 cm drift after the undulator exit.

energy scaled by its rest mass, and Ψ is the pondermotive phase, defined by $(k + k_w)z - \omega t$.

The undulator parameters values can be seen in Table 1. These parameters were selected to match the IFEL resonant condition, in which the pondermotive phase remains constant along the undulator:

To extend the model to include transverse effects one had to consider the beam interacting with a diffraction dominated THz pulse train. Unfortunately with the available amount of power in the pulse train (estimated to be $10 \mu\text{J}$ when using the cryo-cooled OR setup) a diffraction dominated beam has insufficient field to drive the interaction effectively over the 8 periods of the undulator. Thus a waveguide can be utilized to maintain higher peak field on the beam. Utilization of a waveguide, however, changes the resonant condition, as the radiation will now setup modes that cause the phase velocity of the propagating THz to increase. As a result with the same undulator parameters the resonant wavelength increased as more phase slippage will occur in within a single undulator period.

To model this interaction a beam distribution was generated using General Particle Tracer (GPT) [3]. This distribution was then inserted into the FEL code Genesis [10] to model the interaction. Genesis can model the period averaged behavior of the electron beam in a rectangular waveguide. After the modeling the interaction the distribution is placed back into GPT to investigate space charge effects on the beam as the beam reaches full compression. The results of the simulation can be seen in Fig. 4. The initial blowout beam, positively chirped from its expansion's longitudinal phase space is rotated by the interaction resulting in a negative chirp at the end of the undulator. It is allowed to drift with space charge and reaches a full compression with a reduction rms bunch length from 100 fs to 6 fs 9 cm after the exit of the undulator. Thus the laser accelerator should be placed 9 cm after the exit of the undulator to take advantage of the compression. The beam is better synchronized by approximately an order of magnitude reduction in time of arrival at the laser accelerator as long as the initial beam displacement is less than 200 fs from the ideal phase.

While Genesis models the interaction fairly well, it does not fully model the space charge during the interaction and is period averaged, using the pondermotive phase as a canonical longitudinal coordinate. For a more complete

picture, current simulation efforts are directed at modeling the interaction fully in a particle tracking code with space charge included at every point in the interaction.

CONCLUSION AND OUTLOOK

With the Cryo-cooled THz pulse train source developed and the 3D simulations performed in genesis confirming the interaction to be viable, the experimental efforts will now be focused on further increasing THz power and design of the undulator. The simulation effort will be directed in modeling the interaction with space charge throughout and tracking the particles in time rather than as a function of period averaged pondermotive phase.

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