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IMPLEMENTATION OF A 1550-nm LASER SYSTEM FOR BEAM CHARACTERIZATION AT THE ARGONNE WAKEFIELD ACCELERATOR*

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Abstract

Accurately capturing the longitudinal profile of electron bunches is a critical diagnostic for wakefield accelerators, particularly those employing shaped bunches to enhance transformer ratios. Electro-optic sampling of terahertz fields produced by ps-duration electron bunches offers a non-destructive approach for this purpose. To enable future characterization experiments, the Argonne Wakefield Accelerator (AWA) test facility has recently installed a 1550-nm laser system, along with the necessary support infrastructure to synchronize it with the photoinjector nominal laser system operating at 81.25 MHz. This paper reports on the successful installation and initial synchronization demonstrations, paving the way for advanced diagnostics R&D at AWA.

INTRODUCTION

Over the past two decades, electro-optic (EO) sampling of transient electric fields associated with relativistic electron bunches has proven to be a reliable and effective approach for measuring ultrashort bunches in linacs [1–3] and characterizing instabilities in electron storage rings [4]. The development of stable, synchronized lasers has further extended EO-based methods to serve as beam-arrival monitors with unprecedented sub-10-fs resolution. Recent advancements in EO techniques, such as the phase-diversity approach [5], have enabled precise measurements of beam current profiles with femtosecond resolution.

Given these developments and the Argonne Wakefield Accelerator Test Facility (AWA)'s research focus on beam manipulation—particularly the current profile—to enhance the performance and efficiency of beam-driven wakefield acceleration, AWA is actively considering the adoption of these techniques in its beamline [6]. Additionally, a recent collaborator-driven experiment, supported by the BeamNetUS consortium [7], focused on testing a fiber-coupled thin-film lithium-niobate (TFLN) EO electron beam sensor [8–10]. The current TFLN EO sensor design is optimized to operate with a 1550-nm laser pulse.

In light of these research interests, we recently deployed a fiber-laser system, on loan from collaborators at Fermilab, at the AWA facility. The system is an erbium-doped fiber laser, C-FIBER MENLOSYSTEMS, operating at 81.25 MHz and providing two fiber-coupled outputs with ~ 100 mW average power and ~ 70-fs pulses at λ = 1550 nm.

SYNCHRONIZATION & CONTROL

The C-FIBER laser operates at the 16th subharmonic of the AWA master clock and linac system (f_0 = 1300 MHz), matching the repetition rate of the nominal photocathode seed laser (VITARA-T system from COHERENT) used to generate electron bunches via photoemission from a photocathode located in a 1.5-cell 1.3-GHz RF gun. The laser needs to be phase-locked to the $f_0/16$ = 81.25-MHz reference signal derived from the master clock and used to synchronize the VITARA-T system. In addition the C-FIBER laser needs to have a programmable delay (ie, a phase shift) with respect to the VITARA-T laser. In its nominal implementation, the VITARA-T laser phase is controlled by shifting the phase of its 81.25-MHz reference signal. Due to limitations in the electronics, the phase shift is restricted to $\delta\phi \in [0°, 90°]$ at 81.25 MHz, which is sufficient for nominal operation as it corresponds to a 1.3-GHz phase shift of $\delta\phi_0 = 16\delta\phi$. However, to enable EO-sampling diagnostics, it is necessary

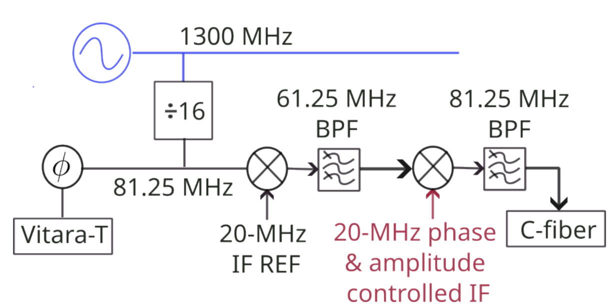

Figure 1: Block diagram of the LLRF system to control the C-FIBER laser phase. Note that both laser are phase-locked using their respective synchronization boxes.

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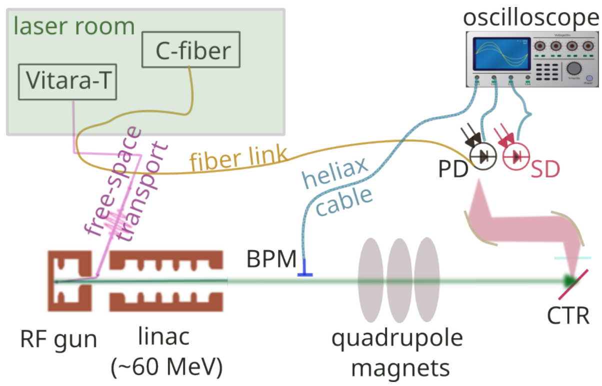

Figure 2: Block diagram of the experimental setup. The labels "CTR," "PD," "SD," and "BPM" represent "coherent transition radiation" station, the "photodiode," "Schottky diode," and the "beam position monitor," respectively.

to scan the delay of the fiber laser over a full 81.25-MHz period. This requirement necessitated the development and implementation of a new laser phase shifter, designed according to the block diagram shown in Fig. 1. Specifically, the 81.25 MHz signal is down-converted to 61.25 MHz and mixed with a phase- and amplitude-controlled 20-MHz intermediate frequency (IF) signal. By controlling the phase of the 20-MHz IF signal (shown in red), we achieve precise control of the up-converted 81.25-MHz signal, which serves as the reference for the C-FIBER synchronization electronics. Additionally, the C-FIBER laser is phase-locked to the 81.25-MHz reference using a commercial RRE-SYNCHRO locking module (MENLOSYSTEMS). To automate phase-delay scans, the control for the new phase shifter was integrated into the AWA EPICS system. The delay minimum step size is currently limited by the performance of the implemented electronic phase shifter to approximately ~ 750 fs. Future improvements will include the addition of an optical fiber-based delay system to enhance precision by enabling fs-scale time steps albeit limited to a window of ~ 500 ps.

The C-FIBER laser was installed in the AWA laser room and connected to a 25-meter fiber link, which consists of two 10-meter polarization-maintaining (PM) fibers interspaced with two 2.5-meter dispersion-compensation fibers. The endpoint of the fiber link is mounted on a breadboard positioned near a coherent-transition-radiation (CTR) station as shown in Fig. 2. Due to transmission losses and reduced output power compared to the original laser performances, the transported laser output power measured at the fiber-link exit is approximately 24 mW.

TIMING & TEMPORAL OVERLAP WITH ELECTRON BUNCH

An essential aspect of laser-based diagnostics is the precise temporal overlap between the electron bunch and the laser pulse. At AWA, electron bunches are produced at a 2 Hz repetition rate, while the C-FIBER laser generates pulses at 81.25 MHz; see Fig. 3(a). By leveraging the ability to

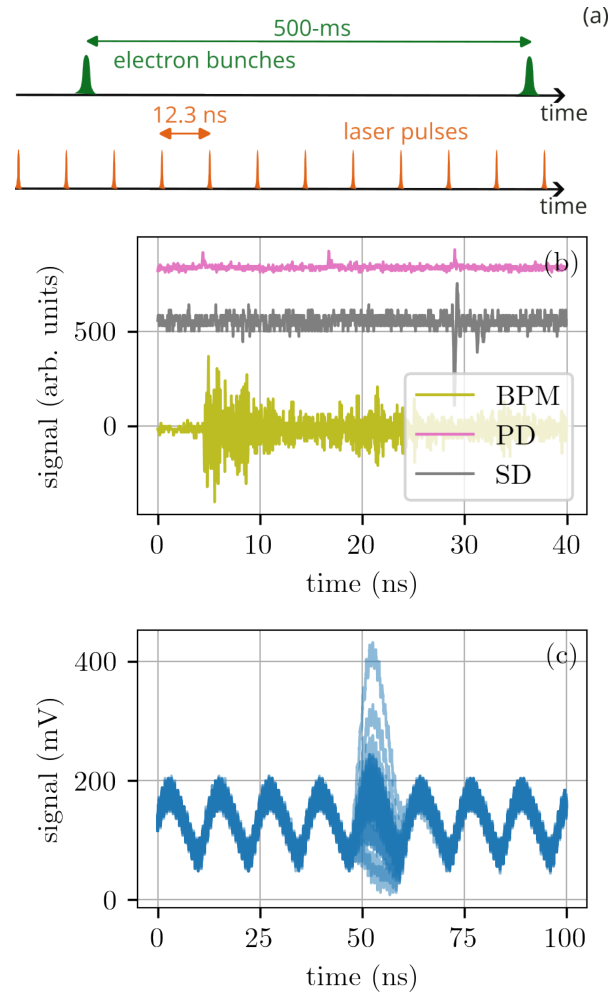

Figure 3: Electron-bunch and C-FIBER laser-pulse temporal structure (not to scale, a), measured PD, SD, and BPM signals on a 40-ns window using the fast oscilloscope, and (c) evolution of the output of the EO detector during a coarse scan showing that only laser pulse #5 located at $t = 52$ ns is modulated by the THz pulse during the scan.

scan the 81.25-MHz laser pulses over a full period of 12.3 ns, we can align one of the laser pulses with the electron bunch. For the current series of experiments where the acquisition of the modulated pulse produced after interaction with THz CTR is detected by a balanced-diode system, the acquisition system can be triggered on a beam-induced signal [e.g., from a beam position monitor (BPM)] and the correct (modulated) 81.25-MHz can be selected. For future experiment where the detection system include the acquisition of the spectrum with a CCD camera, a Pockel's cell will have to be added to select the modulated pulse given the slow integration time of CCD cameras.

To assist with timing alignment, the CTR signal is detected using a Schottky diode (VIRGINIA DIODES model WR5.1ZBD) connected to a fast oscilloscope. The laser pulse is similarly detected by a fast optical photodiode, and both signals are displayed on the oscilloscope for coarse timing adjustments.

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Additionally, the oscilloscope is triggered by the signal from the upstream BPM. Figure 3(b) shows the various signal detector for the coarse timing alignment while Fig. 3(c) shows the evolution of ten 81.25-MHz modulated pulses downstream of the TFLN EO electron beam sensor as the C-FIBER laser is delayed. The delay scan confirms pulse #5 is the one overlapping with the electron beam and providing information on the cross-correlation between the beam-induced THz pulse and the 1550-nm laser pulse. The slower PD signal shown in Fig. 3(c) compared to (b) is due to the detection system of the modulater laser pulse which includes processing electronics with amplification.

EXPERIMENTAL RESULTS

The TFLN EO electron beam sensor described in Ref. [8] was successfully tested using the C-FIBER laser, and its detailed performance will be reported in a future publication. In this study, the detector was employed to directly assess the synchronization performance and shot-to-shot jitter between the C-FIBER laser and the electron bunch. The technique involves scanning the laser to identify a "zero-crossing" of the transient electric field generated by the electron bunch. A linear fit of the signal variation near the zero-crossing (here corresponding to the rising edge of the highest peak [shown as a red dash line in Fig. 4(a)] provides a direct calibration of the output signal versus laser delay. The phase delay of the C-FIBER laser is adjusted to sample the CTR electric field precisely at the zero-crossing point, and the output voltage is recorded over 1,000 shots, corresponding to a total duration of 500 s; see Fig. 4(b).

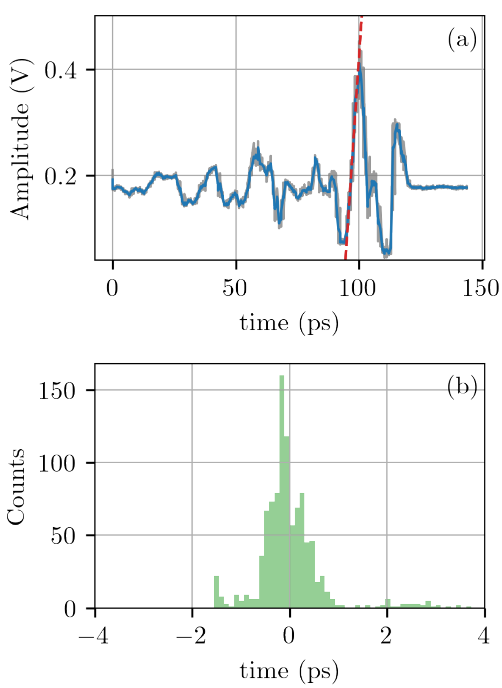

Figure 4: Modulated laser signal as function of C-FIBER laser delay fine scan (a) and resulting temporal jitter between the C-FIBER laser and electron bunch; see text for details (b). The blue trace in (a) represents the average amplitude (10 shots are taken for each time-delay setpoint), and the red dash line shows the linear fit around the rising edge of the peak.

The data indicates that the temporal jitter between the C-FIBER laser and the electron bunch is approximately 700 fs (RMS) over short periods of time. However, a gradual drift is observed over longer durations, manifesting as a tail developing at positive time in Fig. 4(b). This result aligns with expectations, given the aging RF and LLRF systems currently in operation. Significant improvements are anticipated following the planned acquisition of new klystrons and the completion of the AWA LLRF control system upgrade [11], which leverages the open-source MARBLE platform developed at LBNL [12].

CONCLUSION

We successfully installed and synchronized a new femtosecond pulsed 1550-nm fiber laser system at AWA. Initial tests demonstrated that the system achieves an RMS jitter with the electron beam below 1 ps (rms) over short periods but is prone to slow drift in time. This system successfully supported a BEAMNETUS-funded experiment. With planned enhancements, including finer delay scans enabled by an optical fiber-based delay system and the deployment of an upgraded LLRF control system, we anticipate that this setup will enable precise and reliable characterization of the electron current profile with sub ~ 100-fs resolution.

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