Comprehensive Single-shot Diagnostics for Quantifying LWFA Beam Quality

Alex H. Lumpkin[1], Max LaBerge[2], Jeroen van Tilborg[3], A. Debus[4], Arie Irman[4], and Michael C. Downer[2]

[1]Accelerator Division (GSR), Fermi National Accelerator Laboratory, Batavia IL 60510 USA

[2] Physics Department, University of Texas-Austin, Austin TX 78712 USA

[3]Lawrence Berkeley National Laboratory, Berkeley CA 94720 USA

[4]Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

INTRODUCTION

The continuing challenge to the laser-driven wakefield accelerator (LWFA) community is to demonstrate beam quality using a compact configuration that is comparable to that of the rf-linac-driven accelerators in regard to electron beam size, divergence, energy, energy spread, and pointing stability. The much higher gradients (GV/m) of the LWFA process [1] and ultrashort bunch lengths make it a very tantalizing endeavor for advanced accelerator research in category AF6 of the Snowmass21 process. Beam quality on a single shot and shot-to-shot stability are prime areas for investigation according to the HEPAP 2015 guidance [2]. Previously, it has been shown that in the laser-electron interactions within the plasma, a subset of the ensemble of electrons was microbunched at blue-shifted wavelengths of the high-power driving laser [3-5]. Most recently and importantly, a 10-nm-bandwidth sampling of coherent optical transition radiation (COTR) images determined that this subset's beam size, divergence, and estimated emittance were few-micron, sub-mrad, and sub-mm mrad, respectively with the latter ~10 times lower than that of the ensemble [5]. In addition, the microbunching fraction was ~1% of the 200-pC charge. This was determined from the measured COTR intensity which indicated a COTR/OTR gain of over 100,000. Lin et al. [4] deduced the energy spread of microbunched electrons was at the ~1% level in their tests, noticeably below the ensemble energy spread of an LWFA. A diagnostic configuration is proposed that potentially could provide the multi-parameter assessment of the microbunched electrons that are correlated with the quasi-monoenergetic peak (QMEP) in the electron spectrum. These techniques could provide the characterizations of the electron beam quality in various injection schemes from gas jets to a discharge-capillary structure and for single-stage, two-stage, and perhaps multi-stage LWFAs. The overarching objective is to develop a comprehensive, single-shot diagnostic package that will support efforts to measure the transverse and longitudinal charge distributions and to increase the microbunching fraction while maintaining the localized beam quality.

DIAGNOSTIC TECHNIQUES

The LWFA electron beam could have multi-parameter characterizations on a *single shot* using the COTR techniques that are uniquely applicable to the microbunched electrons. By using thin Al or Ti foils for both foil locations of the interferometer of reference [5] and a metal foil or coating for COTR generation at the downstream spectrometer focal plane, we expect microbunching would be preserved and the beam size, divergence, estimated emittance, angular trajectory, microbunching fraction, energy, and energy spread data would all be obtained on a single shot for few-hundred MeV electron beams with narrow-band COTR. Near-field imaging would be used for the beam size, energy, and energy spread data, and far-field imaging would provide the divergence, pointing information, and microbunching fraction. A model for the COTR point-spread function to determine few-micron beam sizes and a model for COTR interferometric (COTRI) fringe visibility to determine sub-mrad beam divergence would be utilized [5]. If the LANEX screen view in the spectrometer were preserved, the ensemble electrons' energy, energy spread, divergence, and charge would also be obtained on the same shot with optical imaging. In addition, the forward CTR/COTR from the second thin foil should be available for broadband optical spectroscopy for temporal profile reconstructions [6]. Any concerns about the possible emittance growth in the drift between the interferometer foils were addressed by a modified COTRI code described in reference [5]. Initial results at the 1.0-GeV level using the interferometer at an early stage of development suggest the techniques scale to that energy regime and this is supported by COTRI modeling [7].

EVALUATION OF INJECTION SCHEMES AND STAGING

A preliminary evaluation of the presence of microbunching in LWFA beams based on the COTR strength has been summarized in Section 4 of the Supplemental Material of Ref. [5]. We present COTR energy and energy spectra in Fig. 1 for the four different operating regimes or injection scenarios: no QMEP in a shot, self-truncated ionization injection with 3-mm long (STII 3 mm) He gas jet with N_2 doping, STII 5 mm with N_2 doping, shock-front injection, and no doping of the He gas jet. The strength of COTR for an operating regime within the wavelength band $\lambda = 600 \pm 5$ nm remains stable from shot to shot (typically few tens-of-percent RMS variations). The COTR energy from electrons in the QMEP is deduced to go with microbunching fraction, not total integrated charge. Figure 1a shows the phenomenon is present in all LWFA conditions tested, but COTR energies can vary by orders of magnitude across injection scenarios. The phenomenon was also reported in the capillary-based injection scheme at LBNL [4]. Extensive studies of the beam quality parameters' variances would be the next phase of studies, including variation of the conditions to increase the COTR gain and therefore microbunching fraction.

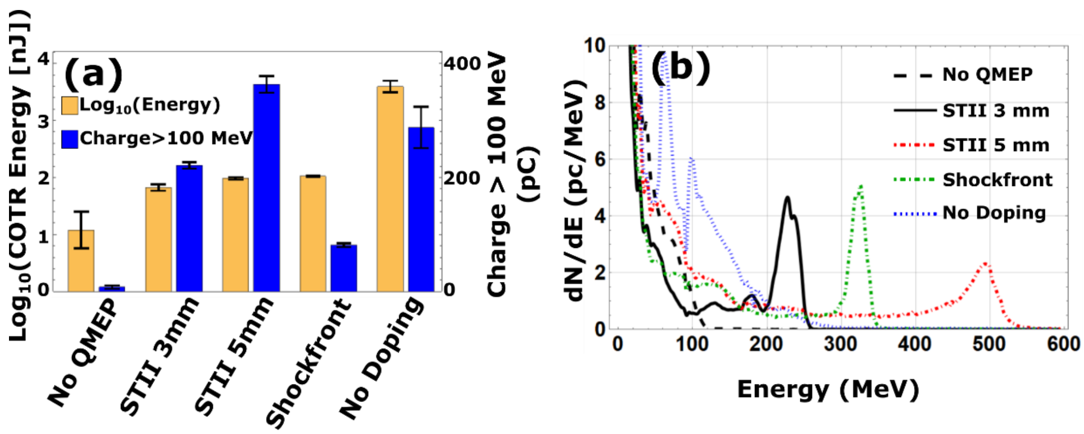

Fig. 1: Correlation of COTR energy with LWFA operating regime. **(a)** COTR energy per shot at 600 ± 5 nm (yellow bars, left vertical axis) and total charge above 100 MeV per shot (blue bars, right vertical axis) for five regimes listed along horizontal axis. The data set for each regime included: 3 no QMEP shots, 41 STII 3 mm shots, 46 STII 5 mm shots, 60 shock-front shots, and 7 no doping shots. Bar heights represent mean, error bars standard error, for each data set. **(b)** Representative electron energy distribution curves for each regime [5, Supplemental Material].

The other aspect is two-stage experiments such as S. Steinke et al. [8] which initially focused on energy gain and charge. Full characterization of the beam parameters would be fundamental [9], and there may be fine timing/synchronization adjustments needed between the two stages that would affect the microbunching fraction and beam quality. Such tests might prepare one for multi-stage acceleration beam tests.

SIMULATIONS

These experiments should be supported by simulations such as done before that show longitudinal microbunching into the UV [10]. For directly comparing with experimental data, the simulations should also compute synthetic diagnostics, i.e. provide simulated diagnostics signal output based on the simulation data. Additionally, simulations of LPA-driven undulator radiation experiments would be appropriate where the microbunching provides a pre-bunched beam at the resonant wavelength.

SUMMARY

In summary, an opportunity to examine the heart of the LWFA process and the critical laser-electron interactions in the plasma by means of COTR-based imaging techniques has been identified. The initial findings that the microbunched electrons have superior beam quality to the ensemble of electrons in the QMEP is a clue we should follow with comprehensive investigations across injection schemes and staging. The configurations proposed enable measurements of the key properties of the ensemble of the electrons as well as comprehensive, single-shot evaluations of the microbunched electrons' properties.

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