ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP069

OBSERVATIONS ON MICROBUNCHING OF ELECTRONS IN LASER-DRIVEN PLASMA ACCELERATORS AND FREE-ELECTRON LASERS*

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Abstract

We provide observations on the visible-wavelength microbunching of relativistic electrons at beam energies >200 MeV in both laser-driven plasma accelerators (LPAs) and a self-amplified spontaneous emission (SASE) free-electron laser (FEL). An analytical model for coherent optical transition radiation interferometry (COTRI) addresses both cases. It is noted that the COTR/OTR gain observed in the LPA rivals that of the SASE FEL at saturation, although the few micron transverse sizes of the microbunched beamlets are much smaller than in the FEL. The broadband microbunching observed in the LPA case could act as a seed for a SASE FEL experiment with tunability over the visible regime, in principle.

INTRODUCTION

The periodic longitudinal density modulation of relativistic electrons at the resonant wavelength (microbunching) is a well-known, fundamental aspect of free-electron lasers (FELs) [1]. In one classic case, microbunching fractions reached 20% at saturation of a self-amplified spontaneous emission (SASE) FEL resulting in gains of 10^6 at 530 nm [2]. In that experiment the concomitant z-dependent gain of coherent optical transition radiation (COTR) was also measured at the $>10^5$ level. Microbunching at visible wavelengths in laser-driven plasma accelerators (LPAs) had been reported previously [3,4], but it has only recently been measured in near-field and far-field images on a single shot for the first time with significant COTR enhancements involved [5-7].

We reintroduce an analytical model for COTR interferometry (COTRI) first developed for the SASE-FEL-induced microbunching case [8] to evaluate the LPA case. The coherence function was treated in this analytical model that addresses both cases and the expected fringe patterns. In the FEL, one identified microbunched transverse cores of 25-100 microns in extent while in the LPA the recently reported transverse sizes at the exit of the LPA were a few microns [5-7]. In the latter case, signal enhancements $>10^5$ and extensive fringes out to 30 mrad in angle space were recorded. We suggest the broadband microbunching observed in the LPA case could act as a seed for a SASE FEL experiment with tunability in principle over the visible regime.

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

EXPERIMENTAL ASPECTS

The APS Linac and Previous SASE FEL Setup

The APS linac is based on an S-band rf photocathode (PC) gun which injects beam into an S-band linear accelerator with acceleration capability currently up to 450 MeV as shown in Fig. 1 [9]. The drive laser is a Nd:Glass-based chirped pulse amplifier (CPA) operating at an IR wavelength of 1053 nm, twice frequency doubled to obtain UV output at 100 μJ per pulse which irradiated the Cu photocathode of the gun [10]. Beam diagnostics in the linac include imaging screens, rf BPMs, and coherent transition radiation (CTR) autocorrelators located before and after the chicane at the 150-MeV point.

The previous SASE FEL configuration is also seen in Fig. 1 and included up to 9 undulators (~21 m of magnetic structure) with a period of 3.3 cm and appropriate undulator parameter, *K*, of value 3.1 resulting in lasing at 530-540 nm at a beam energy of 217 MeV The FEL gain saturated at about z=15 m, or ~20 gain lengths. Diagnostic imaging stations were located before the first undulator and after each undulator to provide assessment of both the optical gain and uniquely the COTR gain. These are described in more detail in Ref. [11]. This experiment motivated the development of the COTRI model which is now being applied to the recent LPA results.

The LPA at HZDR

The LPA is based on the DRACO laser with a peak power of 150 TW at a central wavelength 800 nm interacting with a He gas jet (with 3% Nitrogen) at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) facility [12]. The LPA was operated with a plasma electron density ne ~3 x 1018 cm-3 in the self-truncated ionization-injection mode. Beam energies of ~215 MeV in a quasi-monoenergetic peak were observed in a downstream spectrometer. After the LPA, a 75-μm thin Al foil blocked the laser pulse and was followed by an Al-coated Kapton foil as shown in Fig. 2. The latter's back surface provided the source point of the near field (NF) COTR imaging, and a polished Si mirror at 45° to the beam direction redirected this light to the microscope objective. The configuration provided a magnification factor of 42 at the camera and a calibration factor of 0.09 μm/pixel. This mirror was located 18.5 mm downstream of the Al-coated Kapton and also generated backward COTR that combined with the first source to provide COTRI in the far-field (FF) imaging

39th Free Electron Laser Conf. FEL2019, Hamburg, Germany JACoW Publishing
ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP069

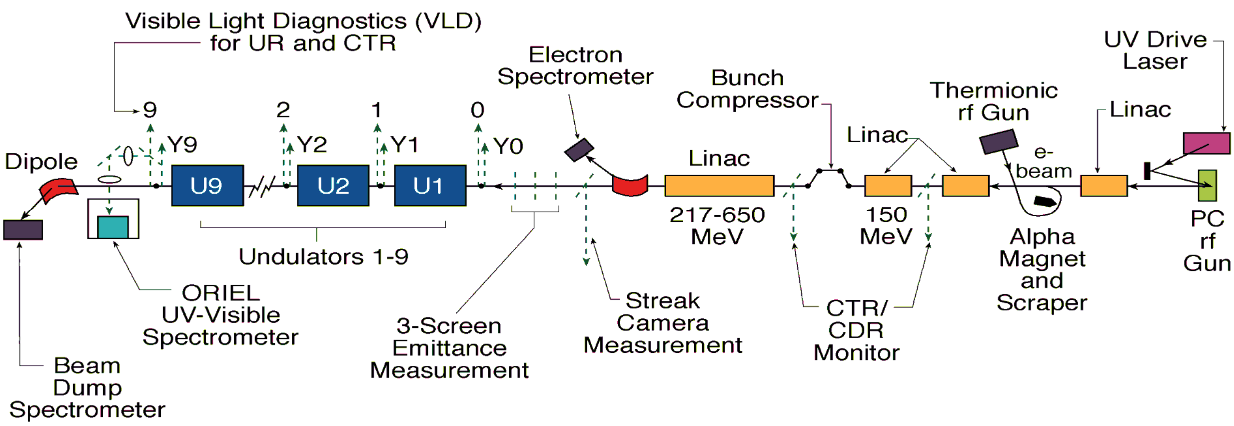

Figure 1: Schematic of the APS linac and SASE FEL beamline layout showing the UV drive laser, PC rf gun, linac, and SASE FEL undulators with diagnostic station locations circa 2002 [2].

camera. The significantly enhanced signal allowed the splitting of the signal into two NF cameras as well as a FF camera with a 633±5 nm bandpass filter (BPF) as in Fig. 3.

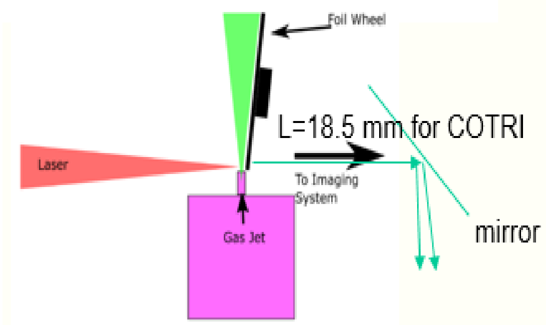

Figure 2: Schematic of the LPA showing the laser, gas jet, and foil geometry at HZDR with a foil separation L= 18.5 mm for COTRI [5,6].

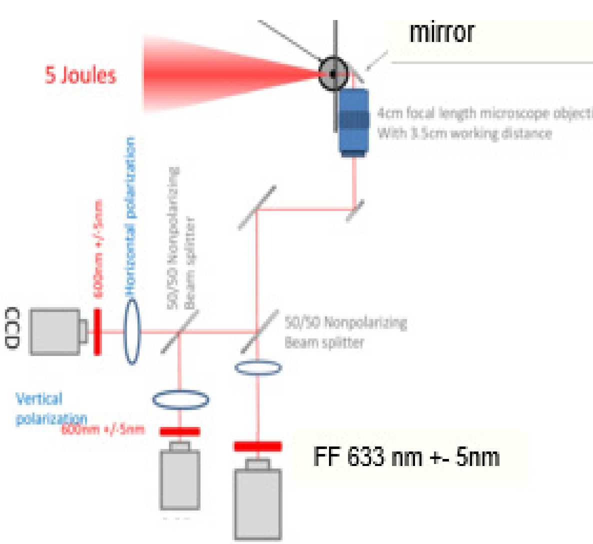

Figure 3: Schematic of the LPA and an early version of the NF and FF imaging setup using the beam splitters to redirect the optical signals to the different cameras [5,6].

ANALYTICAL MODEL RESULTS

Space precludes a full description of the COTRI analytical model which is being applied to the LPA case. The base equation includes the reflection coefficients, single electron spectral angular distribution $d^2W_1/d\omega d\Omega$, the interference term $\boldsymbol{I(k)}$, and the coherence function $\boldsymbol{J(k)}$.

$$\frac{d^2W}{d\omega d\Omega} = \left|r_{\parallel,\perp}\right|^2 \frac{d^2W_1}{d\omega d\Omega}\, \boldsymbol{I(k)J(k)} \qquad (1)$$

This has been presented in detail in Ref. [8] and more recently in [7]. However, relevant model results are shown in Fig. 4 illustrating the divergence effect on fringe visibility (negative angles) and the beam size effect on the enhancement of fringes (positive angles). One can see the fringe visibility is reduced for the 1.0 mrad case vs the 0.5 mrad case at the left. On the right, the coherence function is shown to be dramatically reduced at larger angles for the larger beam sizes. This means the FEL data only had a few visible fringes while the LPA fringe data extend out to 30 mrad. The foil separation was 18.5 mm and λ= 633±5 nm.

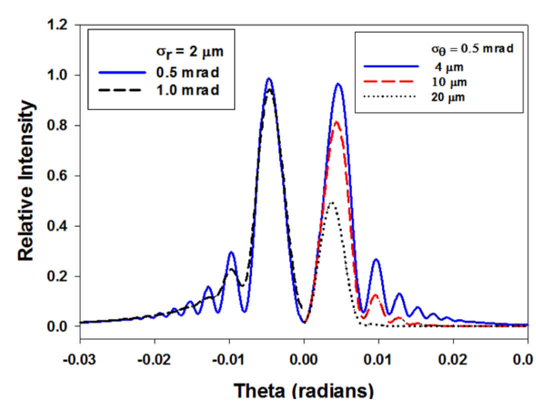

Figure 4: COTRI calculations for the effects of beam divergence in negative angles for a fixed beam size and the effects of microbunched beam size on fringe intensity for a fixed beam divergence of 0.5 mrad for the positive angles.

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EXPERIMENTAL RESULTS

Previous SASE FEL Data

Fig. 4 illustrated how the transverse charge form factors determine the COTR gain as a function of angle. Previously the effect was evaluated for 0.2% microbunched beams of 25-, 50-, and 100-µm radius as shown in Fig. 5a [13]. This figure compares the COTR fringes to the incoherent OTRI pattern. Three fringes are enhanced for the 25-µm beam, but only one for the 100-µm case. Former COTRI results from a SASE FEL operating at 537 nm as shown in Fig. 5b graphically illustrate this principle [2]. Here, azimuthally asymmetric fringes (one x-fringe spanning $0 < \theta_x < 2$ mrad, 3 y-fringes spanning $0 < \theta_y < 6$ mrad) from post saturated gain regions of the FEL pointed to a microbunched core of radii σ_x=100 µm and σ_y =25 µm, embedded within a total electron beam of radii σ_x=200 µm and σ_y=100 µm. However, at saturation both fringe patterns were single fringes indicating more extensive microbunching transversely in the core and with a ~20 % microbunching fraction.

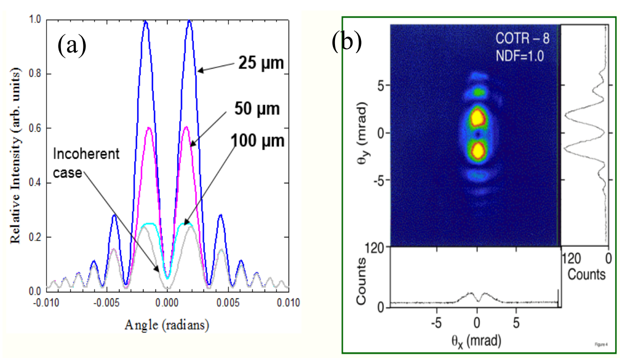

Figure 5: a) COTRI calculations for three beam sizes of 25, 50, and 100 µm indicating the effects on fringe intensity for a fixed divergence of 0.2 mrad [13]. b) Example COTRI image obtained post saturation after undulator 8 in the SASE FEL showing the results of the spatially asymmetric microbunched distribution at that z location [2].

Recent LPA Data

Examples of the NF and FF images from the same LPA shot at 215 MeV are shown in Figs. 6 and 7, respectively. In Fig. 6a we see the vertically polarized COTR point spread function (PSF) lobes for two beamlets separated on the x axis (laser polarization axis) by about 6 µm. A sample of the analysis technique which used the measured PSF lobe separation of 5.0 µm in y to determine the vertical beam size of about σ = 2.0 µm is shown in Fig. 6b. In Fig. 7a, the FF COTRI pattern is shown whose fringe number and visibility are compared to Fig. 4 model results as well as nearby model results to obtain a sub-mrad divergence of 0.5 ± 0.2 mrad and a beam size less than 4 µm. In addition, the analysis of the intensity of the FF image referenced to a calibrated laser source at 633 nm led to an estimated COTR gain >10^5 [7]. This is surprisingly similar to the SASE FEL COTR result at saturation, although the number of microbunched electrons in the LPA case is 30-50 times smaller, as is the beam distribution.

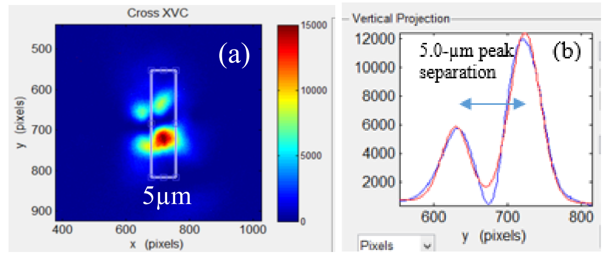

Figure 6: a) Vertically polarized NF image showing two pairs of coherent PSF lobes for two beamlets separated by about 6 µm. b) vertical profile of right hand beamlet with a 5-µm lobe separation which is mapped to 4.6 µm (FWHM) or 2.0 µm (σ).

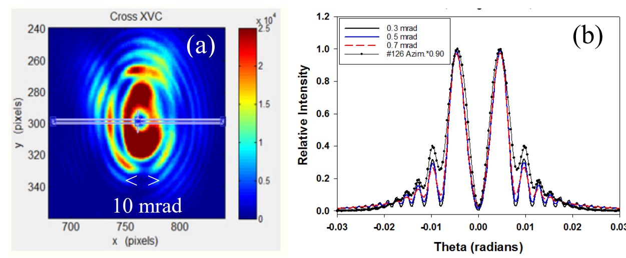

Figure 7: (a) Example of a FF COTRI image at 633±5 nm from the same shot as Fig. 5. (b) Comparison of the azimuthally averaged fringe data and the COTRI model for 0.3,0.5, and 0.7 mrad divergence. The fringe peak positions are well matched, but the relative intensities of some outer fringes are higher in the data. The best match is 0.5 mrad.

SUMMARY

In summary, we have revisited a classic SASE FEL case where the electron microbunching was tracked as a function of z, and a COTRI model was applied. We have compared that observed COTR gain seen at saturation to a recent LPA experiment that obtained single shot NF and FF images to determine beam size and divergence. We have noted the similar COTR gain in the two experiments, although there is a marked difference in the transverse size of the microbunched portion. In the case of the LPA, this microbunching appears to be a fundamental aspect of the LPA process and merits further investigation. We also suggest that the LPA microbunching at the 1% level in a narrow band might be used to seed a visible light SASE FEL experiment by adding an undulator(s) downstream of the LPA.

ACKNOWLEDGMENTS

The first author acknowledges the support of C. Drennan and M. Lindgren of the Accelerator Division at Fermilab. The University of Texas authors acknowledge support from DoE grant DE-SC0011617, and M.C.D. from the Alexander von Humboldt Foundation.

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP069

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