INITIAL PERFORMANCE MEASUREMENTS OF MULTI-GHz ELECTRON BUNCH TRAINS*

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Abstract

LLNL's compact laser-Compton based x-ray source is currently producing up to 35 keV photons, with the capability to upgrade to 250 keV. Increasing the average brightness of such sources requires increasing the electron beam current. To avoid degradation of the narrow-bandwidth performance of the source, the per-bunch charge shouldn't increase; the effective repetition rate of the electron beams must be raised. It has been proposed [1] to generate bunch trains of several hundred pulses spaced by the period of X-band RF (~87 ps), which raises questions about beam-loading effects on the energy uniformity of the bunches and wakefield effects degrading the emittance of later bunches, compromising the x-ray quality. As a first test of this concept, we have installed into the electron-generating laser of our system optical pulse-stacking hardware to allow generation of 16-electron-bunch trains. Here we present the current status of our x-ray source, along with initial results using this new multi-bunch train. This includes characterization of collective electron-beam energy spread and emittance growth.

INTRODUCTION

LLNL has a successful history utilizing gamma-rays generated by a linac-driven, laser-based Compton scattering gamma-ray source [2–5]. Increasing the average flux of x-rays or gamma-rays at a specific energy (that is, $Number/eV/sec$ at the energy of interest) enables many applications such as medical imaging [6]. One way to accomplish this is to increase the effective repetition rate by operating the RF photoinjector in a multi-bunch mode, accelerating multiple electron bunches per RF macro-pulse, while maintaining the single electron bunch emittance and energy spread [7]. An X-band test station has been built and commissioned at LLNL to develop multi-bunch electron beams and generate x-rays, and serve as a platform for future R&D on laser-Compton x-ray sources. This paper summarizes first electron beam results from the initial multi-bunch operation of the X-band RF photoinjector. The current test station parameters are summarized in Table 1. Recent achievements of the test station efforts include: first x-ray demonstration, initial x-ray application experiments, electron beam optimization, demonstration of multiple electron bunches spaced as close as every RF bucket, and upgraded controls systems [8–11]. Electron beam brightness is quite good, with an emittance of 0.3 mm mrad at 88 pC representing a significant improvement on similar results [12] and showing the viability of high gradient compact X-band RF technology as a source for high brightness short electron bunches for UED and light sources. In the burgeoning field of Nuclear Photonics, precision accelerator technology achieves the stable electron beams required for x-ray and gamma-ray applications. More x-ray results are underway [13], and up to 16 electron bunches have been produced, as reported in this paper. X-ray production with the 16 bunches is straightforward, however at the time of this paper not yet demonstrated.

Table 1: LLNL Test Station Parameters

Charge	10–400 pC
Bunch duration	2 ps
Bunch rise/fall	<250 fs
Normalized emittance	0.1–1.3 mm mrad
Gun energy	7 MeV
Cathode field	160–185 MV/m
Section gradient	~50 MV/m
Final energy	30 MeV

TEST STATION

The accelerator is built around a state-of-the-art X-band RF photoinjector [14]. RF power is provided by a 50 MW 11.424 GHz SLAC built XL4 klystron powered by a solid-state Scandinova modulator [15]. A manifold divides the power between the RF gun and the accelerating sections [16]. The RF power is very high quality with a 0.1% pulse flatness, 0.01% shot-to-shot stability, and phase stability of <0.5°, providing excellent electron beam consistency. The Photocathode Drive Laser, which generates the electron beam is a chirped pulse amplification system based on Ti:Sapphire that provides up to 20 mJ of uncompressed 780 nm laser light. This is transported to the accelerator, where a dedicated compressor and frequency tripler compresses the pulse to 200 fs.Typically, 5 µJ of UV light is used to illuminate the cathode, but up to 150 µJ is currently available. A 5.59 cell RF gun incorporates LCLS S-band gun improvements [14], producing 7 MeV submicron emittance bunches in excess of 100 pC. A SLAC-designed T53 traveling wave accelerating section is used to boost the energy from 7 MeV to a maximum of up to 31 MeV. A second T53 accelerating section has been installed and aligned to further increase the energy reach of the test station, and can be commissioned once the final RF distribution hardware is installed. A quadrupole triplet is used for quad-scan emittance measurement [17]. The electron beam energy is measured with a dipole magnet

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that has been calibrated to serve as a spectrometer. The X-band accelerator is shown in Figure 1.

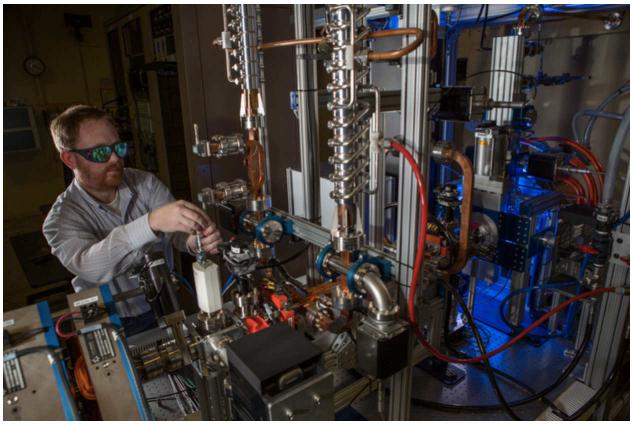

Figure 1: Photograph of X-band test station at LLNL.

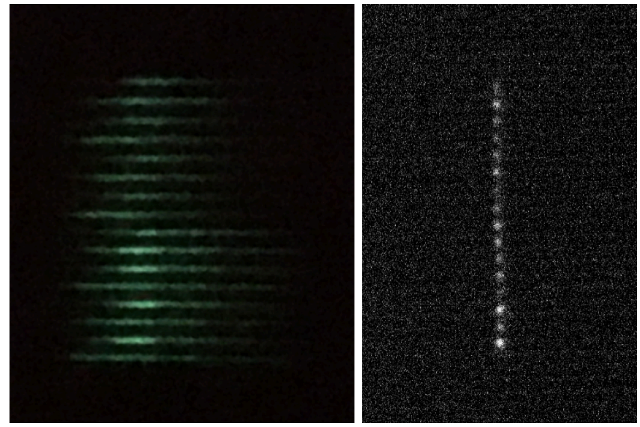

Figure 2: Streak camera images of UV laser (left) and electron beam OTR (right) showing an evenly spaced 16 bunches.

RESULTS

One goal of producing multiple bunches is to increase the average x-ray flux; a natural limit for an RF accelerator is filling every RF bucket, or a bunch every ~87 ps at 11.424 GHz. For the multi-bunch x-rays to remain bright, the electron beam quality must remain the same, leading to an experimental validation of the laser architecture [8, 10, 18] and electron bunch trains. A multi-bunch laser architecture was developed as an alternative photocathode driver [8, 18] in order to produce a higher average flux of narrow-bandwidth x-rays, and this first demonstration of 16 bunches begins to validate the scaling of the initial single bunch x-ray brightness to pulse trains of 100's of bunches [10]. The electron bunches are made by repurposing the UV hyper-Michelson pulse stacker [4, 19] for a bunch spacing of 87 ps, and adding an additional splitter and translation stage for time and phase tuning in the uncompressed IR of the photocathode laser. A streak camera was used to verify the spacing of the 16 UV bunches, as shown in Figure 2. Once the rough spacing of the laser bunches was verified, the delay arms were blocked to produce a single bunch, for which the RF gun operating parameters were optimized. Then the various arms of the hyper-Michelson were blocked to isolate pairs of pulses and the delays adjusted to bring the phase of each arm to within one RF degree of each other. A streak image of optical transition radiation (OTR) from all 16 electron bunches is also shown in Figure 2.

The electron beam energy is measured by a spectrometer; single bunch energy spread has been consistent on the order of 0.03%, and an observed energy jitter of order 0.07%. The second bunch produced in the IR can be very finely tuned because the translation stage used for phase tuning is accessible while the linac is running: the energy spread is the same as that of a single bunch. The full 16 bunch energy measurement shows an increase in energy spread, and distinct bunches can be seen on most spectrometer images. Spectrometer images of 1, 2, and 16 bunches with histograms of the position and width of the beam on the spectrometer screen are shown in Figure 3. With motorized stages on all arms of the hyper-Michelson the single bunch energy spread should be achievable with all 16 bunches. The multi-bunch laser architecture referred to above would be intrinsically synchronized and not susceptible to these timing issues [1, 18].

The electron beam emittance is measured using the standard quadrupole scan technique [17] with the quadrupole triplet upstream of the final focus and a YAG screen with a meter drift. The electron beam has been tuned for minimal emittance by varying the gun emittance compensation solenoid field, cathode gradient, laser position on the cathode, laser transverse profile, laser timing, RF phase, accelerator section phase, and steering. The current data is taken with a lower peak electric surface field on the cathode (~160 MV/m) to minimize the probability breakdown while operating: an RMS normalized emittance of 0.3 mm mrad at 40 pC is typical. To demonstrate 16 bunches a larger aperture was used to make the individual bunches as bright as possible, which resulted in a higher single bunch emittance measurement of 0.6 mm mrad at a bunch charge of 18 pC. An integrated emittance of 1.3 mm mrad was measured with a quadscan of all 16 bunches, assuming the same space charge effect from an 18 pC charge per bunch, and a measured total charge of 290 pC. In addition to the lower beam quality expected from the increased energy spread, the tune for all 16 bunches was a compromise with respect to the single bunch case and could be improved for a lower-than-typical single bunch charge (a result of splitting the single bunch UV energy).

In summary, the LLNL X-band laser-Compton source has demonstrated a route to increasing the average flux by multi-bunch operation, and has utilized this increase for experimental campaigns.

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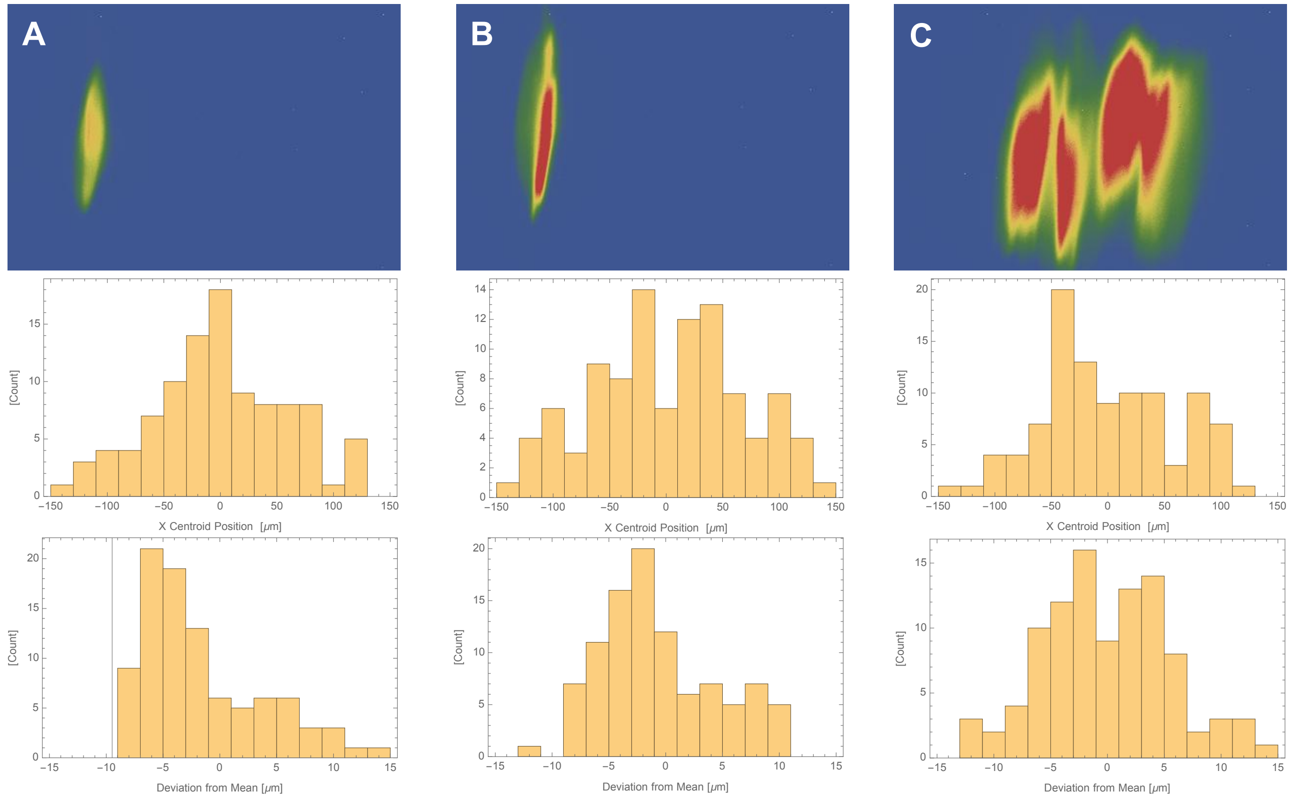

Figure 3: Spectrometer screen images and histograms of the calculated centroid position and width for a single bunch in A; 2 bunches in B; and 16 bunches in C. Energy jitter is uniformly 0.07%; energy spread is 0.04% for 1 and 2 bunches, and 0.16% for 16 bunches.

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