FEMTOSECOND RF TIMING IN LOW CHARGE PHOTOINJECTORS

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Abstract

Photoelectron gun rf parameter mapping is explored as an extension to electro-optic sampling to monitor bunch vs. laser relative time-of-arrival. The method is evaluated for timestamping sub-picocoulomb femtosecond laser-pumped dynamics in graphite via electron diffraction where the required timing resolution is < 10 fs.

INTRODUCTION

Due to its high bunch brightness and low emittance, the electron photoinjector readily provides a platform for ultrafast dynamics material studies. A sample is pumped by a fraction of the fs drive laser. As the ultrashort bunch diffracts from the atoms in the material, changes in atomic position can be resolved directly at the time scale of the bunch length. Using a relativistic rf photoinjector gun we have shown sub-ps laser pumped melting dynamics in thin single-crystal gold foils [1].

Currently the highest temporal resolution in pump-probe style electron diffraction experiments has been achieved with electron bunches created by injecting an ultrashort laser onto a photocathode in a DC electric field. These so called DC photoguns have been used to study laser ablation dynamics in thin graphite films with timing resolution < 250 fs [2]. Rf compression schemes to overcome space charge driven expansion have lowered the resolution to sub-100 fs [3]. DC guns have the advantage that the relative time-of-arrival (TOA) between pump and probe at the diffraction target can be set with an opto-mechanical delay. In rf photoguns the bunch accelerates to relativistic energies in a very short distance. The space charge forces are suppressed and the injected bunch remains short. However, the rf jitter makes optical synchronization impossible using only mechanical delays and necessitates an external TOA measurement.

In rf gun pump-probe diffraction, the time resolution is given by the convolution of the laser and bunch time profiles, and the pump-probe velocity mismatch in the sample. If we are unable to determine the relative TOA there is an rf jitter term that dominates the resolution. The two ways we can improve resolution past the DC gun limits are to make the electron bunches shorter (using higher fields and less charge per bunch) and to make a nondestructive time-of-arrival measurement. The final goal is to obtain resolution of < 10 fs rms.

In order to shorten the bunch, we have significantly lowered the charge. This has forced us to increase our detection efficiency. In order to use the shortest possible bunches, we need to resolve diffraction peaks into which only a few electrons have scattered. To this end we have explored: 1. more efficient light collection (optical coupling), 2. increased camera dynamic range and decreased noise [4], and 3. higher yield phosphor screens. Although effective for preserving a short bunch length, switching to lower charge beams presents difficulties for optical timing schemes in our laser-pump, electron-probe experiment.

We originally proposed to use single-shot spatially-encoded electro-optic sampling (EOS) to measure pump-prove timing differences and then timestamp the diffraction images. With our novel EOS setup, we have measured bunches with charge as low as a few pC [5]. While our setup is sensitive enough to detect these fields when the beam is focused under the crystal, the imaging condition required to make the diffraction pattern downstream (~ 1 m) requires a change in the solenoid. As a result, we may not be able to satisfy the tight focus required at the EOS crystal to measure very low charge.

In this paper, we propose developing a time-of-flight map based on single-shot measurements of two photoinjector parameters (the gun electric field amplitude and rf phase relative to the drive laser injection) to extend our timing capabilities to these low charge bunches. In order to measure the laser synchronization error with respect to the master rf oscillator we employ a separate DC photocathode gun with an rf-driven deflector. We further explore the gun diagnostics required to achieve dynamic diffraction timestamping with a resolution better than 10 fs rms.

THEORY

Modeling Longitudinal Dynamics in the Rf Gun

To understand the source of the fluctuations in cathode to target time-of-flight, we explore the expected longitudinal dynamics particles in the rf photoinjector gun. We limit ourselves to a 1-d single particle solution to the longitudinal equations of motion [6].

$$\frac{d\phi}{dz} = k\left(\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right) \tag{1}$$

$$\frac{d\gamma}{dz} = \frac{eE(z)}{2mc^2}\sin(\phi + kz) \tag{2}$$

To solve the equations, we use a simulated electric field map $M(z)$ which we scale so that $E(z) = E_0 M(z)$. We choose E_0 so that the solution for γ agrees with the measured average beam energy.

Rf Gun Fluctuations

According to the gun model, the parameters that most strongly affect the acceleration of the bunch through the gun are the gun electric field amplitude E_0 and the rf phase at which the charge is injected at the cathode ϕ_0. Both parameters pick up uncorrelated random fluctuations from the electronics used to amplify the low level rf.

We want to determine how the random fluctuations affect the time required for the electrons to travel from the cathode to the diffraction target. This time is the rf gun time-of-flight (TOF), τ_{rf}. Based on the solution for ϕ and γ from the initial conditions $(\phi_0, \gamma_0 = 1)$, we can calculate the time it takes for a particle to traverse the gun as the first term of Eqn. 3. The addition of a drift term allows us to calculate the total TOF as

$$\tau_{\mathrm{rf}}(\phi_0) = \frac{(\phi - \phi_0)}{\omega} + \frac{L}{c}\frac{\gamma}{\sqrt{\gamma^2 - 1}} \tag{3}$$

To validate the model over a large usable range we performed a sweep of the input phase ϕ_0 over the entire range of acceleration while the EOS setup measured the TOF. The data is plotted in Fig. 1 along with the numerical solution of Eqn. 3. Over this sweep, we assume the fluctuations in gun electric field amplitude are small compared to the change in phase. For each phase point we average the EOS TOF centroid over 100 consecutive shots. The error bars are the TOF jitter at each point and are consistent with measured values of the small phase and electric field amplitude fluctuations.

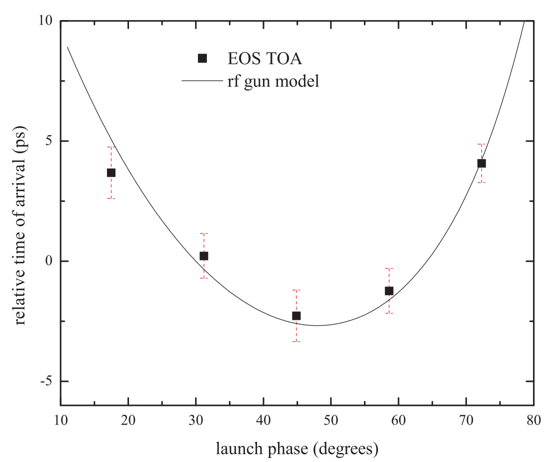

Figure 1: Time-of-flight measurement during a phase scan around the maximum-energy setting. Each point is averaged over 100 shots.

Focusing now on random fluctuations near the normal operating gun phase and electric field amplitude, we solve Eqns. 1 - 3 for a sample set falling within one standard deviation of the mean phase and amplitude. Fig. 2 shows the result of mapping those solutions onto a surface. By approximating this surface with a power series we can quickly calculate τ_{rf} based on measurements of ϕ_0 and E_0.

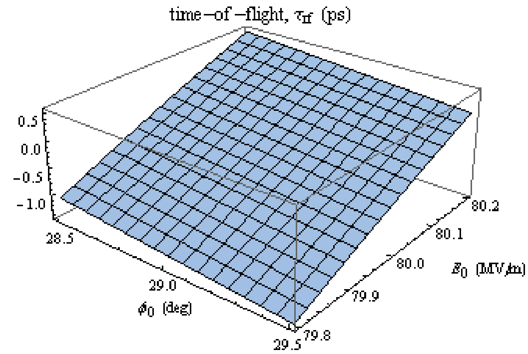

Figure 2: Map of the relative time-of-flight of a bunch transiting the gun, calculated from small variations around the typical Pegasus rf gun parameters.

Limits to Laser-rf Phase Locking

There is a contribution to the total jitter that we cannot determine through rf measurements because the gun phase is mixed with and measured relative to the output of the kW preamplified signal. The kW signal already has been delayed τ_ℓ which is the synchronization error between the rf master oscillator and the Ti:Sapphire laser oscillator. In our system, the rf phase is actively synchronized to the laser pulse train with the Coherent Synchrolock-AP as shown in Fig. 3. The stability of our laser-rf synchronization at this level is limited to $\sim$ 300 fs rms.

The total laser-bunch relative time-of-arrival at the diffraction target τ must include the laser synchronization term τ_ℓ in addition to the rf gun TOF τ_{rf} which we have already discussed how to calculate. The total TOA timestamp is simply the sum of the two timing differences:

$$\tau = \tau_{\mathrm{rf}} + \tau_\ell \tag{4}$$

The specific task is to measure the laser pulse delay relative to the kW amplified rf signal that serves as the reference to the gun phase measurement. This way we fully close the timing loop in a single shot. We propose to run a DC photoinjector gun and use the resultant ultrashort bunch to measure the phase of the preamp rf signal. In this scheme, we send the DC gun bunch into an rf deflecting cavity. The kW preamplifier powers the cavity and sets up a transverse deflecting magnetic field, mapping the longitudinal profile of the bunch onto the transverse dimension.

If we drive the DC gun with a laser pulse split from the diffraction target pump pulse, the acceleration stage of the DC gun adds no additional temporal jitter to the deflector measurement. Therefore, fluctuations in the centroid of the deflected beam correlate exactly with the laser-kW rf synchronization error, τ_ℓ. With this additional measurement, we can fully determine the relative time of arrival of the diffraction probe and the laser pump, τ.

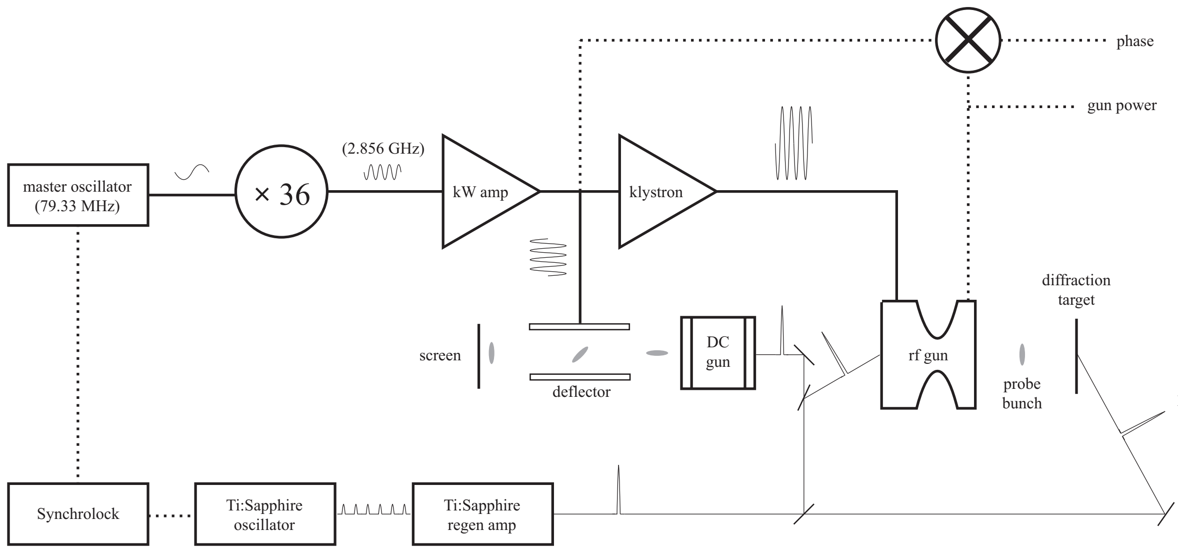

Figure 3: rf system timing schematic. Measuring the total delay between the pump laser and the probe electron bunch at the diffraction target requires a two step measurement, and the use of a DC photoelectron gun. The output of the deflector provides the relative timing measurement between the laser pulse and the kW rf signal (τ_ℓ) . Using the 1-D model we can calculate the additional timing delay introduced by the klystron (τ_{rf}) by measuring the gun power and phase relative to the kW amplifier signal.

EXPERIMENT

The UCLA rf gun and the deflector are both designed to run at $f_{\mathrm{rf}} = \omega/2\pi = 2.856$ GHz. The measured rf signals are attenuated as needed and then digitized with an NI PCI-5105. The resolution of the digitizer is sufficient to measure fluctuations in rf gun phase down to 0.001 degrees, or about 1 fs at this frequency.

The DC gun is expected to operate at 30 kV. We seek to minimize non-rf related TOF fluctuations in the DC gun to $<$ 1 fs rms. To this end we need a very stable power supply so that fluctuations in the accelerating gradient do not exceed $\delta V/V \sim 10^{-6}$.

The timing resolution of this method is expected to be limited by the streaking resolution of the S-band magnetic deflector when applied to the DC gun bunch. Powering the deflector with the rf from the kW preamplifier is integral to the timing scheme. However, the low power available from the preamplifier puts an upper bound on the deflecting gradient. According to simulations of the DC gun and the deflector, we expect to determine timing fluctuations to 10 fs rms or better[1].

CONCLUSION

A novel method for mapping time of flight of an ultrashort electron bunch through an rf photocathode gun has been explored. We characterize the time-of-flight jitter between the bunch and the photocathode drive laser pulse in terms of the rf gun phase and electric field magnitude. The additional jitter contribution of the laser to the low level rf phaselocking system is evaluated in a single shot through the use of a DC photogun and kW rf deflector. This allows us to determine the relative pump-probe time-of-arrival completely in a single shot with an expected resolution better than 10 fs rms for electron bunches of arbitrarily low charge.

[1] Special thanks to Peter van Abswoude visiting from the University of Groningen for his continuing work on the DC gun simulations.

ACKNOWLEDGMENTS

We would like to acknowledge our funding sources, US Office of Naval Research Grant No. N000140711174 and US Department of Energy Grant No. DE-FG02-92ER40693.

Additionally, C.M. Scoby wishes to thank the PAC eleven organizers for their generous student support.

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