LCLS INJECTOR LASER SHAPING AND APPLICATIONS

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Abstract

In the Linear Coherent Light Source (LCLS) at SLAC, the injector laser plays an important role as the source of the electron beam for the Free Electron Laser (FEL). The beam emittance and FEL performance are highly related to the transverse shape of the injector laser. When the injector laser has hot spots and non-uniformities that can carry over to the electron beam and degrade electron emittance and FEL performance, it requires long hours of manual adjustment by laser engineers and strenuous machine tuneup. The injector laser shaping project at LCLS aims to have precise control of the driver laser transverse profile in order to produce arbitrary electron beam profiles, which will enable us to study effects of laser shape on beam emittance and FEL performances. We use a digital micromirror device (DMD) to manipulate the drive laser profile. In this paper, we briefly discuss the implementations of laser shaping at LCLS. We demonstrate two applications of laser shaping. We present results of using laser shaping to control the X-ray laser output via an online optimizer. We also show the photocathode quantum efficiency measurements across cathode surface using the DMD.

INTRODUCTION

X-ray free electron laser (FEL) is the fourth generation light source that produces high power, tunable and coherent x-rays. Relativistic electrons traveling in alternating magnets, or undulators, radiate coherent x-rays via resonant interaction with emitted photons [1]. Current state of the art FEL facilities utilize photocathode RF guns to produce high brightness electron beams [2–4]. The drive laser strikes the photocathode surface to emit electrons. The transverse profile of the injector laser and the quantum efficiency (QE) variation across the photocathode surface determine the electron distribution in the emitted beam. Non-uniformities in the drive laser and photocathode surface can carry over to the electron beam and can degrade beam brightness and FEL performance. Past studies have shown that certain laser profiles lead to lower electron beam emittance [5, 6]. It is therefore of great significance to be able to control the transverse profile of the drive laser, and to study its influence on electron beam properties.

Recent studies have used liquid crystal based spatial light modulators (SLMs) to achieve drive laser shaping for Cornell's high voltage dc gun at 532 nm [7, 8] and for PITZ drive laser at 1030 nm [9]. However, current X-ray FEL facilities rely on an ultraviolet (UV) photocathode to emit electrons, which eliminates the use of liquid crystal SLMs directly in UV. We resort to a different type of adaptive optics, digital micromirror device (DMD), that can work in UV with some hardware manipulation. In this paper, we briefly discuss experimental implementations of injector laser shaping at LCLS using DMD. Next, we will focus on two specific applications of the laser shaping technique. First, we show that by varying the drive laser transverse profile we can control the final x-ray pulse energy with an online FEL optimizer, Ocelot [10]. Secondly, we present the cathode QE measurement with DMD.

EXPERIMENTAL IMPLEMENTATION

The injector laser at LCLS consists of a Ti:Sapphire laser system, producing a 2 ps pulsed laser at 760 nm with a repetition rate of 120 Hz. The infrared laser is then converted to ultraviolet wavelength (253 nm) via nonlinear process in a frequency tripler. The UV laser then strikes a copper photocathode which emits photoelectrons [11]. In order to find an adaptive optic that works with our UV drive laser, we have done extensive damage tests with various materials such as liquid crystal based SLM and deformable mirrors. Considering the damage threshold, shaping resolution, and the convenience of installation, we choose to work with digital micromirror device (DMD) from Texas Instruments [12]. Unfortunately, there is no DMD available to work in deep UV as our laser wavelength, so we resort to a third-party company for replacing the window on the chip in order to transmit UV. Damage tests have shown that a converted UV DMD can sustain up to 90 μJ laser power with beam size 1 cm (damage threshold varies with beam size), when the laser pulse is placed after the micromirrors have just stabilized into a new state for each period. The DMD consists of 768×1024 micromirrors with size 13.68 μm. The micromirrors can flip into two states, ON or OFF corresponding to +/-12 °, given an input voltage. The geometry of the micromirrors introduce a pulse front tilt in the laser pulse, which effectively results in a pulse lengthening in the electron bunch length. The effect is compensated by adding in an optical grating with the opposite pulse front tilt to cancel that introduced by the DMD. Details can be found at [13, 14].

To achieve correct and fine adjustments of the transverse laser profile, we need to obtain a mapping relation between the target plane and DMD plane. This is done by turning on small sections of micromirrors and record signal locations on the target plane. Solving a system of linear equations using least square fitting gives us the linear transformation [8, 14]. To achieve shaping while minimizing shaping error and light loss, we developed an iterative algorithm given a user-provided shape choice and minimum efficiency requirement. The algorithm searches for specific shape parameters by minimizing a cost function that considers the shaping

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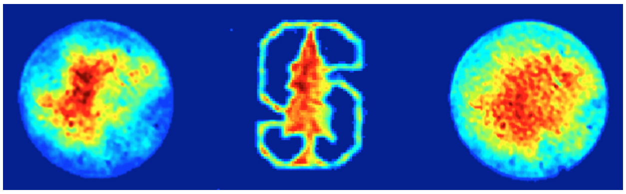

Figure 1: Laser shaping results using DMD. Left: original beam profile. Middle: Stanford tree. Right: cut-Gaussian profile. Note that the color scale of the middle and right images is adjusted to be 60% of the original beam image to show better contrast.

error and efficiency. Figure 1 shows the result of laser shaping. The upright direction of the Stanford tree logo also indicates correct mapping relation. Detailed implementation of mapping and shaping can be found at [14] and in a future publication.

FEL OPTIMIZATION

We apply the laser shaping technique to optimize the FEL performance at LCLS, with the help of a Bayesian optimizer, Ocelot [10]. Ocelot can handle a few machine parameters and aim to maximize an objective function. In the case of laser shaping, we limit the scanning variables to those only relevant to the drive laser profile, while keeping all other machine parameters fixed. For this study, we focus on a cut-Gaussian type shaping. We use the following three parameters to characterize the drive laser profile: x offset, y offset, and the cut ratio. The x and y offsets describe the beam center offset relative to the aperture center in units of DMD pixels. The cut ratio is defined as the ratio of the intensity at the cut radius to the center intensity. According to [5], the optimal cut ratio is empirically found to be 0.5, corresponding to a half-maximum truncation.

We conducted a scan of 40 iterations, targeting to optimize FEL power. The scan starts with an intentionally off-centered, widely cut beam profile, and Ocelot eventually brings the beam center close to the aperture center and cuts around half maximum. With an intentionally distorted drive laser profile, the x-ray pulse energy is initially below 200μJ. Together with real time drive laser shaping, the Ocelot scan improves the FEL gas detector reading by more than a factor of 2. The evolution of the beam shape and FEL pulse energy are shown in Fig. 2 and Fig. 3. These plots clearly show a convergence towards an optimum where the beam center is close to aperture center (x and y offset close to 0), and the beam is cut at half maximum (cut ratio close to 0.5). More details will be published in the future.

PHOTOCATHODE QUANTUM EFFICIENCY SCAN

Traditionally the photocathode QE has been measured by steering a small laser spot (usually on the order of tens of microns) across the cathode[15, 16]. Without automatic control of the steering, this process requires careful monitoring and stabilization of the laser power, steering mirrors, and various machine parameters. Spatial light modulators, such as DMDs, become the perfect candidate for this purpose. In order to obtain a QE profile, we need to know the charge counts corresponding to a localized laser illumination on the photocathode. We capture the electron emission on a YAG screen downstream of the cathode. We turn on a small square of pixels on the DMD and move it across the laser profile. For each square, we obtain the charge counts, laser intensity, and laser spot location from the YAG screen and cathode laser camera. The details of the measurement procedure can be found at [14], and here we simply present the result. Figure 4 shows the results from two scans with calibrated QE. From the overlapped region of the two scans we obtain a 10% relative difference between the two independent measurements.

Using spatial modulators such as DMD to measure QE across the photocathode has many potential applications. Specifically, this measurement prepares us for electron beam shaping. Compared to shaping the laser, the complication of shaping the electron beam comes in from mapping the target plane to the DMD plane. To avoid the non-linear imaging process of electron beams, we can choose the target plane immediately after cathode, where the electron emission profile is calculated as the product of the laser profile and the QE profile of the cathode. Knowing the localized QE across the cathode surface, we can feed the measured electron emission profile into the shaping algorithm described above. In this way, we can produce arbitrary electron shapes.

CONCLUSION

In this paper, we show that we can use a digital micromirror device to produce arbitrary laser profiles at the LCLS injector. We describe two specific applications of drive laser shaping - FEL optimization and photocathode QE measurement. We optimize the X-ray laser output by varying the drive laser profile through an online optimizer while keeping all other machine parameters fixed. The increase in FEL pulse energy shows that indeed laser shaping provides appreciable improvement and convenience in operation. The photocathode QE measurement using the DMD demonstrates a procedure that provides an easy access to the photocathode condition for daily operation. The most direct benefit of QE measurement is to prepare for electron beam shaping. Given a detailed QE map, the electron emission can be shaped into any arbitrary profiles using the same shaping algorithm as in the drive laser shaping case. This opens up enormous potential for studying electron beam accelerators.

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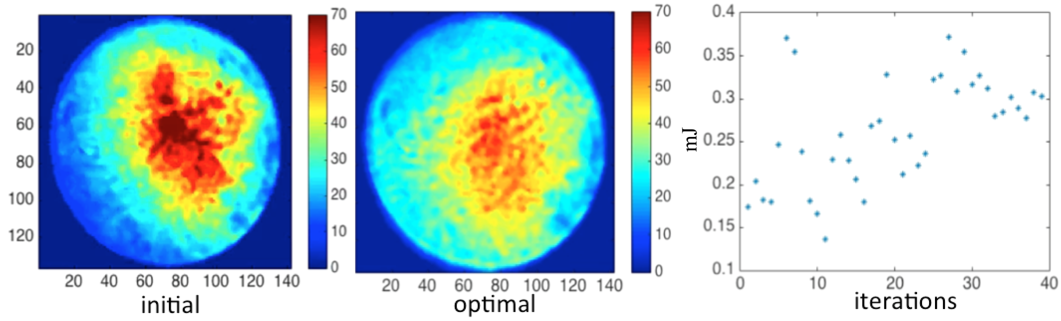

Figure 2: Left: initial beam profile corresponding to 175μJ. Middle: optimal beam profile corresponding to 372μJ. Right: gas detector reading evolution through 40 iterations.

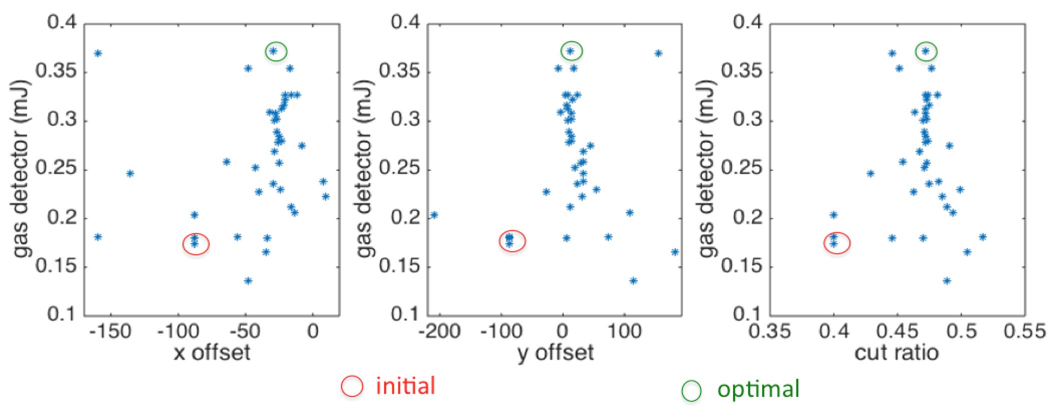

Figure 3: The evolution of the FEL gas detector reading as a function of each of the variables.

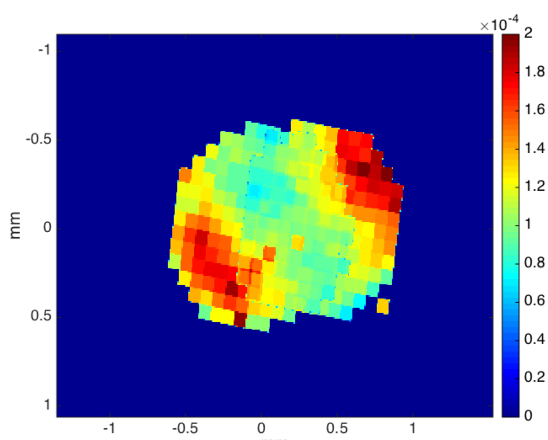

Figure 4: Combined two raster scan results of the QE map.

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