

## COMMISSIONING OF THE X-BAND TEST AREA AT SLAC<sup>#</sup>

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### Abstract

The X-Band Test Area (XTA) was installed in the NLCTA tunnel at SLAC over the spring and summer of 2012. The first gun to be tested is an upgraded version of a 5.5 cell, 200 MV/m peak field X-band gun designed at SLAC in 2003 for a Compton scattering experiment run in ASTA [1]. The first photo-electron beam was generated at the end of July. We report on the results of the first eleven days of commissioning.

### X-BAND TEST AREA

The X-Band Test Area (XTA) is a gun test facility located in the SLAC NLCTA tunnel that uses exclusively X-Band technology. In its initial configuration, a 5.5 cell photo-rf gun is followed by a 1-m long accelerator structure (denoted T105) that had been built for NLC rf breakdown studies. Both are driven by a single klystron whose power is compressed (x4 in magnitude) with a SLED-II system. A combination of high power phase shifters and 3 dB hybrids allows the phase and amplitude of the gun and accelerator to be controlled independently.

Simulations [2] have shown that such a photoinjector has great potential to be a compact driver for X-ray FELs [3], for a compact Compton-generated photon source [4] and for Ultra-Fast Electron Diffraction. The main challenges of this technology were expected to be alignment and high dark current levels. Early operation of the facility indicates that these issues are manageable. Detailed tuning and full beam characterization will continue this year.

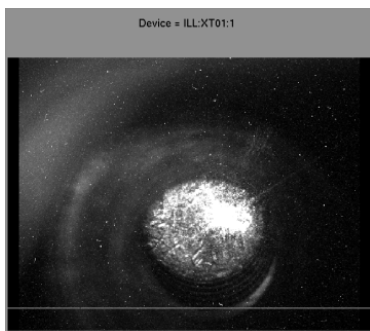


Figure 1: Green alignment laser striking the cathode.

### LASER SYSTEM

#### Photo-Injector Laser

A Spectra Physics Tsunami oscillator locked at 79.3 MHz to the rf master clock provides a 305 mW, 65 nm

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bandwidth seed to a Coherent Elite regenerative Ti:Sapphire amplifier. The regenerative amplifier produces 600Hz, 3.5 mJ pulses of IR. This amplifier is shared with another experiment so pulses are sent to the XTA line at 300 Hz. The stretched IR pulses are transported through 26 m of vacuum pipe via relay imaging, yielding 2.6 mJ of IR at the XTA laser table. The IR is then compressed to 70 fs pulses of 1.7 mJ each. A non-linear tripling of the frequency with two 0.3 mm thick BBO crystals yields 120 uJ UV pulses. Finer tuning should provide a higher conversion efficiency, up to 10%, which this is not required initially.

#### Alignment Laser

A green laser was used to align the optics to the cathode – the image of this laser on the cathode is shown in Fig. 1. This procedure had to be implemented for two reasons: the rf gun does not have a removable cathode and the laser injection chamber was installed after the gun had already been positioned. The UV pulse follows the path defined by the green laser. A leakage of 10% before entering the injection chamber is sent to a virtual cathode camera as shown in Fig. 2.



Figure 2: Virtual cathode image (4x6 mm): the main spot is the non-attenuated UV and the upper left spot is the green laser attenuated with filters.

#### Injection Chamber

The gun irises are 4 mm in radius which translates into a laser half-opening angular aperture of 45 mrad from the last adjustable mirror. Optimum emittance compensation requires having the first accelerator positioned as close as possible to the gun exit. However the injection mirror, which is located in between, has to be far enough away from the cathode to allow a reasonable beam stay-clear. As a compromise, the ~ 45 degree injection mirror was located 53 cm from the cathode plane. It is a 12.7 mm diameter Al substrate mirror with a UV protected Al coating. An extraction mirror for viewing the cathode is located symmetrically opposite of the injection mirror with a 7 mm gap between them. The injection chamber also accommodates a YAG screen combined with a

Faraday cup. A shadow of the two mirrors is visible on the dark current imaged on the YAG screen as shown in Fig. 3.

### X-BAND GUN

After transport to the XTA area from the SLED II compression system, the rf is split via a 6 dB H-plane hybrid. A quarter of the power feeds the gun and three quarters feeds the T105 accelerator. The gun power is split, sent through the two phase shifters and recombined. Each phase shifter has a 110-deg range and the relative phase can be adjusted remotely to vary the combined power from zero to 100% of the input power. The linac line is also equipped with a 110-deg phase shifter to adjust the relative gun-to-linac phase (although this can also be done by changing the gun shifters in common). With 76 MW from the SLED II system and the 20% attenuation that occurs during transport, the gun input power is 15.2 MW, which should produce a cathode peak field of 186 MV/m after 200 ns.

#### Gun Exit Energy

The bunch energy was measured by recording the beam excursion on a YAG screen as a function of corrector strength (see Fig. 3). A bunch energy of 6.85 MeV +/- 0.15 MeV was observed with 76 MW from SLED II. Both vertical and horizontal measurements are consistent. This beam energy corresponds to a cathode peak voltage of at least 180 MV/m and depends on the rf-to-beam phase at the cathode (see Fig. 4), which was not known for this experiment.

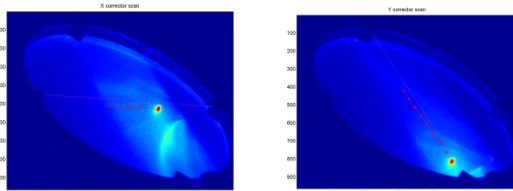


Figure 3: Beam centroid displacement as a function of (left) horizontal corrector and (right) vertical corrector settings.

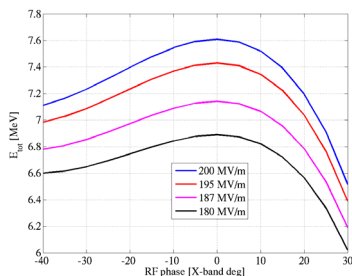


Figure 4: ASTRA-calculated energy at the gun exit for four cathode voltages:

#### Gun Tuning

To maximize the field in the gun, the reflected power was minimized by adjusting the gun temperature (the rf frequency is kept constant at 11.424 GHz). The gun operating temperature had been anticipated to be around 53 degC from design and cold test tuning. The

minimization of reflected power indeed occurs at 53 degC as can be seen from the waveforms in Fig. 5. Systematic beam energy measurements as a function of temperature will be performed during the next run.

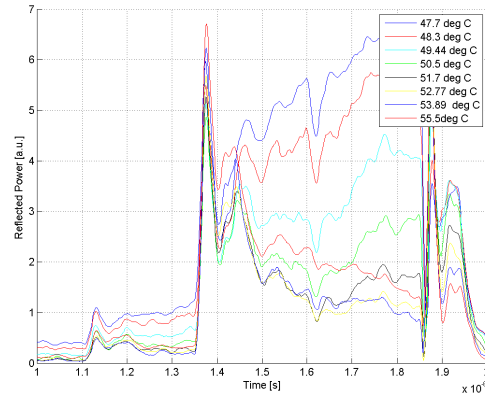


Figure 5: Reflected power waveforms from the gun for cathode temperatures between 47.7 degC and 55.5 degC.

#### Dark Current

The integrated dark current per pulse was measured as a function of the cathode temperature for 76 MW, 200 ns rf pulses from SLED II. The dark current was observed to increase as the temperature was lowered from the value that gives minimum reflected power (see Fig. 6). At the operating temperature of 53 degC, the dark current is about 150 pC, which should be manageable. The fluctuations in the dark current were of the order of 13%, and since the dark current increases as a high power ( $n > 10$ ) of the peak voltage ( $I \sim V^n$ ), the field stability appears to be at the 1% level or smaller.

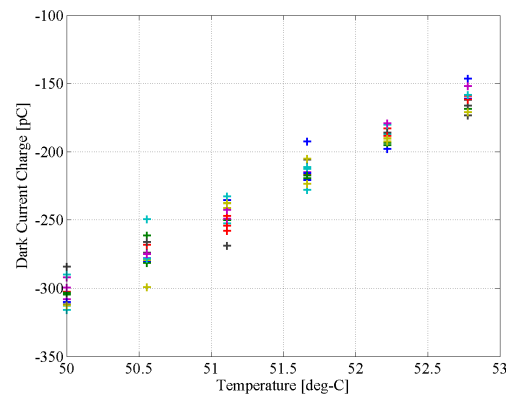


Figure 6: Gun dark current versus cathode temperature.

#### Beam Based Alignment

The laser should strike the cathode at the electromagnetic center of the rf gun and the electromagnetic axis of the gun should coincide with the magnetic axis of the solenoid. Preliminary measurements were made to establish a procedure to optimize the centering of the laser on the cathode. An rf phase scan was performed and the centroid of the photo-electron beam recorded on the first YAG screen. For the data shown in Fig. 7, the laser center is estimated to be offset from the gun center by 200 μm horizontally and 2.2 mm vertically.

## Quantum Efficiency

Low energy ( $\sim 7 \mu\text{J}$ ) laser pulses were used initially to avoid damage during laser alignment. This produced bunch charges of up to 15 pC. The quantum efficiency was thus around  $10^{-5}$ .

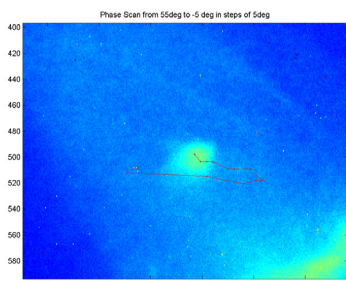


Figure 7: Electron beam centroid position on first YAG screen for various rf-to-beam phases.

## HIGH ENERGY

### Energy Measurement

The beam was accelerated in the linac and transported to the spectrometer at the end of the beamline. The gun-to-linac distance was not set precisely, and with the limited range of the phase shifters with full gun power operation, on-crest operation could not be achieved, although the phase offset was probably about 15 deg. The electron beam energy was measured to be 50 MeV. An appropriate positioning of the gun phase shifters should allow us to reach crest and 70 MeV. The T105 structure presently installed cannot be conditioned above about 65 MV/m due to pulse heating limits in the couplers. A new T105 structure with racetrack couplers will be installed next year and should allow up to 100 MV/m acceleration.

### Energy Jitter and Energy Spread

Large bunch energy jitter was measured at the spectrometer, about 2% at 50 MeV beam energy as shown in Fig. 8. This corresponds to excursions of  $\pm 3$  deg X-band. Jitter levels of 3 deg could be traced back to the Low Level RF system. A new LLRF electronics system with higher initial power levels [5] will be installed and should lower this jitter. The additional jitter comes from the laser oscillator phase locking. The Tsunami oscillator is rated for 500 fs timing jitter, i.e., 2 deg X-band. However, we suspect that a larger oscillator phase jitter was present at the time of our experiment which would explain the  $\pm 3$  deg total excursion. Acquiring a lower timing jitter ( $< 60$  fs rms) oscillator is presently being considered.

Correlated energy spreads smaller than 50 keV were observed on the YAG screen of the spectrometer line. The YAG thickness and blurring effects hide the true beam size values. An OTR screen will be available for the next run.

### Transverse Beam Characterization

The beam emittance was measured on a YAG screen as the OTR station was not equipped with appropriate lenses

for capturing large cones of light. Small and intense spots were nevertheless observed on the OTR screen.

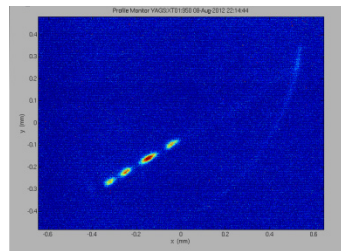


Figure 8: Five, 50 MeV pulses on the spectrometer YAG screen.

## CONCLUSION

First photo-electron beam was successfully produced at the XTA facility after only 18 months of design, construction and installation. The rapid turn-on of this facility owes a lot to the expertise of various SLAC departments and the many years of X-band technology development. The results reported here cover only 11 days of commissioning and thus more work will be needed to fully optimize and understand the beam characteristics. However the early results look promising. In particular, the dark current levels and cathode QE are acceptable.

For the next run, an X-Band transverse deflector will be installed that will allow bunch length and slice emittance measurements. Many tools developed for optimizing the LCLS injector will be reused here. The OTR modules will be equipped with appropriate imaging systems for high resolution beam size determination. A peak brightness three to four times higher than that achieved at LCLS is expected with bunch lengths three times shorter than those obtained from S-Band guns.

## ACKNOWLEDGMENT

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