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INITIAL OPERATION OF THE LCLS-II ELECTRON SOURCE*

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Abstract

The Early Injector Commissioning program for LCLS-II aims to demonstrate CW electron beam production this year in the first two meters of the injector that includes the room-temperature 185.7 MHz single-cell gun and the 1.3 GHz two-cell buncher cavity. These cavities were designed and built by LBNL based on their experience with similar ones for their Advanced Photo-injector Experiment (APEX) program. With the 258 nm laser system and Cs_2Te cathodes, bunches of up to 300 pC are expected at rates as high as 1 MHz. The paper presents results from this program including the vacuum levels achieved, RF processing and field control experience, dark current measurements and laser and beam characterization.

INTRODUCTION

A 4 GeV linac based on 1.3 GHz SRF technology is being constructed at SLAC as part of the LCLS-II project [1]. The photo-electron based source for this linac has been installed in the SLAC Linac Tunnel and has been undergoing commissioning during the past year. As shown in Fig's. 1 and 2, this short beamline includes a room-temperature gun and buncher cavity together with focusing and bending magnets and various beam instrumentation (two BPMs, a toroid and a YAG profile monitor). The endcap for the first cryomodule is located about 2 m after the gun cathode, but currently this cryomodule is not installed and the beamline extends about 1 m past this structure, terminating at a Faraday Cup. A cathode load-lock system extends upstream of the gun that allows cathode plugs to be exchanged, and a mirror box is located 1.1 m downstream of the cathode to inject the laser pulses.

This beamline and associated RF system were acquired or built by a group at LBNL and are similar to that developed for their APEX project [2]. Modifications to the APEX design were made based on lessons learned (e.g., improved anode plate cooling) and specific requirements for LCLS-II. The gun and downstream beamline were shipped to SLAC as separate assemblies without having been vacuum baked.

At SLAC, the Early Injector Commissioning program was started last June to demonstrate the injector performance to the extent possible given the low energy beam and limited diagnostics. The ultimate goals for the EIC program include generating 750 keV, 300 pC, > 20 ps long bunches from the gun at a rate up to 929 kHz. This paper reviews the injector design and the commissioning progress to date.

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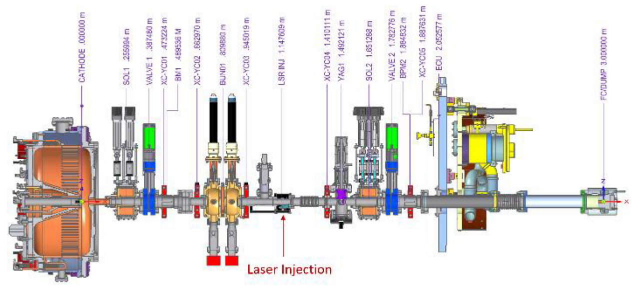

Figure 1: Injector source beamline.

Figure 2: Layout upstream of the gun showing the waveguide connections and cathode load-lock system.

GUN DESIGN

The single-cell gun cavity is designed for CW operation at 185.7 MHz, the seventh sub-harmonic of the 1.3 GHz linac frequency. The cavity has an R/Q of 221 Ohm, a Qo of 31200, and two RF power ports with net beta = 1 coupling. The design beam energy is 750 keV, which requires a combined input power of 81.5 kW. The resulting cathode gradient is about 20 MV/m.

The gun is largely vacuum pumped by 12 NEGs that are located around the outer cavity radius in a volume that is cutoff to the RF. A pressure below about 1e-9 Torr is required to achieve a reasonable lifetime for the Cs_2Te cathodes planed for LCLS-II. Thus far, only a molybdenum cathode has been used as it is more robust for the commissioning conditions. The gun is water cooled through five separate circuits that connect to the 30 °C SLAC LCW system – the combined flow is around 40 gpm. The coupler vacuum widows are air cooled (~ 10 CFM each) and are located about 1 m from the coupler loop antennas, after a 90° bend in the vacuum coax waveguide that connects to

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the gun (see Fig. 2). Solenoidal permanent magnets are installed around these sections to suppress multipacting.

With the large cavity size, there is significant detuning of its frequency from RF heating and a system of four mechanical tuners as shown in Fig. 3 are used to push or pull the anode plate to adjust the cavity frequency. For each tuner a DC motor plus a 30-to-1 gear box rotates a shuttle that screws onto a bolt connected to the anode plate. When bowing the anode outward from the cavity, for example, the reactive force on the shuttle disk is transferred through a piezo actuator and load cell to a thick plate that is attached to the outer rim of the anode. The load cells provide a measure of the applied force, which is adjusted as part of a feedback loop that regulates the cavity frequency (a 32 N change in force at all four tuners moves the anode plate by about 1 micron and changes the cavity frequency by about 1 kHz). However, there is no readback of the actual motion. Thus far only pull motion has been needed and the piezo actuators, which are meant to provide fine frequency control, have not been required.

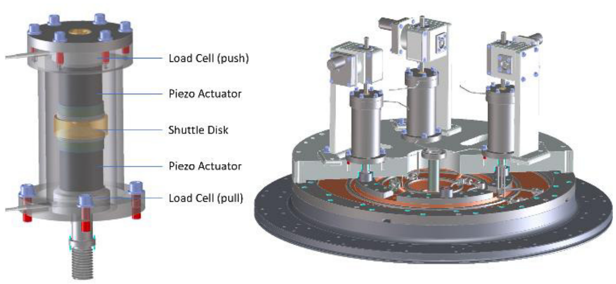

Figure 3: Details of the tuners used to push or pull the gun anode plate.

GUN RF SYSTEM

Each of the two gun-ports are powered via a 60 kW, CW, 186 MHz Solid State Amplifier (SSA) that sums power from 60, 1 kW push-pull LDMOS transistors (NXP model MRF1K50N). The power from pairs of transistors are first combined locally and then summed in a 30-to-1 coaxial combiner (see Fig. 4). For reliability, the DC power supplies are distributed, that is, three 2.5 kW, 50 V supplies power modules containing four transistors. If one power supply or the entire module fails, the SSA can still provide more than 50 kW of power. At 60 kW, the overall AC to RF efficiency is 54%, and at 40 kW, the gain compression is < 1 dB. The SSA output power is very stable without feedback, about 0.01% rms in amplitude and 0.1 deg rms in phase on a one second time scale. To date, the two SSAs have run at about 40 kW for more than 100 hours without major issues.

The SSAs are located in the SLAC Linac Gallery and 6 1/8 inch rigid coaxial waveguide (WG) is used to transport the RF power down to the beamline 7 m below. Although the SSAs are back-terminated, high power isolators are included in the transport lines in the Gallery. For non-ionizing radiation safety, most of the WG is pressurized at a few psi, which requires the use of coaxial air barriers. One of these failed (burned through) due to a gap between the inner bullets that capture the Teflon barrier. This led to an inspection of the full WG system, which found other issues, mostly related to the way it had been assembled. When reassembling the system, care was taken to ensure that the initial transverse offset before joining WG pieces was < 1 cm per meter of unconstrained WG as recommended by the manufacturer. Also 16 temperature sensors were added along each of the two transport lines to monitor for hot spots - none have been found.

The WG and gun are well matched RF-wise in that the fractional power measured at the isolator loads are 0.4% and 0.8% after optimizing the relative drive phase of the SSAs. The larger value can likely be reduced by adjusting the isolator magnetic trim current. The gun has run for more than a day without the need to reoptimize the relative phase.

The LLRF system used to drive the SSAs is based on previous systems designed by LBNL but uses the architecture developed for the LCLS-II SRF cavities. The system regulates one of the gun probe signals using a P-I feedback loop, and has stabilized it over hours to much better than the 1e-4 rms amplitude and 0.01 deg rms phase requirement. However, the other gun probe had failed early on so there is no out-of-loop signal for verification.

The gun has mostly been run with the field unregulated as it is not needed to process the gun, and turning the loop on requires some finesse. However, the LLRF system is essential for 'SEL mode' operation where the drive frequency tracks the gun frequency as measured either in pulsed mode, where the frequency is determined by the phase variation during the field decay period, or in CW mode, where the frequency is determined from the forward minus probe RF phase difference. Most running thus far as has been in SEL mode with high duty (> 99%) pulses as it is robust and effective for long term processing.

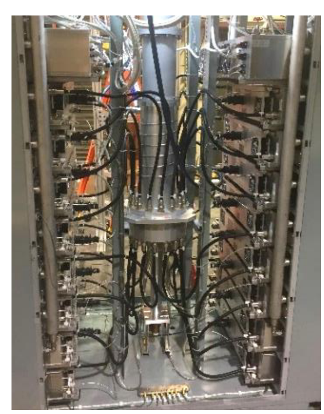

Figure 4: Photo of the inside of one of the 60 kW SSAs showing the 30-to-1 coaxial RF combiner.

GUN OPERATION

Getting to the point where a beam could be generated required overcoming a myriad of issues, most of which have been fixed or mitigated [3]. The biggest obstacles was that the NEG pumps in the gun, beamline and load-lock

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were contaminated with hydrocarbons (likely oil), which became apparent from RGA scans of the vacuum system while under bake. The initial plan to bake the gun by using RF to heat it had to be abandoned as the vacuum pumping (3 l/s) was insufficient and strong multipacting (MP) in the gun and coupler WG limited the power below about 600 W. A larger turbo pump (30 l/s) was installed and the gun was heat-tape baked at up to 190 °C for more than 10 days (although the window temperatures were kept below 80 °C). This reduced the pressure some but MP still limited the RF power, so the NEGs were activated after conditioning them during the bake. This made it relatively easy to burn through the low power MP barriers and achieve nominal 80 kW CW operation.

The goal then was to continue to run at full power to reduce the vacuum to the 1e-9 Torr level, and to learn how to efficiently bring the gun to full power at the nominal frequency. Turning-on the gun is done in SEL mode with full peak power pulses but the duty factor in increased in steps from about 10% to near 100%. This takes about 10 minutes during which the cavity frequency increases about 400 kHz as the anode plate bows outward. The frequency then decreases by 50 kHz over a roughly 30-minute period as the outer cavity wall expands radially, pulling in the anode plate. Throughout this warm-up process, the load cell forces are held constant by a feedback loop that controls the voltage applied to the tuner motors.

Increasing the duty factor in steps is necessary as the frequency tracking as currently implemented cannot keep up with changes faster than roughly 1 kHz/sec, and when the frequency lag exceeds around 30% of 6 kHz cavity half bandwidth, the resulting 10% level of reflected power likely causes MP in the coupler WG that increases the vacuum above the trip threshold (1e-7 Torr). This is an issue with the tuners as well, which can change the frequency at a rate up to 2 kHz/sec.

Once the gun frequency is reasonably stable, the tuners are used to bring it close (< 300 Hz) to the nominal value. Although the motor + gear box torque is rated high enough (1500 in-lb at ~ 1 rpm) to easily deflect the anode plate, frictional forces in the shuttle coupling mechanism limit what they can achieve. In particular, the tuners sometime get stuck above about 3500 N when operating at around 10% of their torque rating. For this reason, the anode water cooling flow rate was adjusted so the load cell forces are around 2 kN at nominal frequency. Even at low load, the tuners do not always respond to small requested changes (< 1 % of their rating) so a high proportion gain is used when regulating the load force.

With the cavity frequency near nominal, SEL mode is turned off and a two-tiered control loop is turned on in which a high-level feedback loop adjusts the load cell setpoints based on the detuning relative to the nominal frequency, and four low-level feedback loops regulate the tuner loads to the setpoint values. Initially, the pulse mode detuning values are used, but after this is seen to operate stably, the duty is increased to 100% and the CW mode detuning values are used. This control method has worked well, regulating the frequency to within about 2% of the cavity half bandwidth. Temporal changes are largely driven by slow, 0.5 °C variations the facility water temperature, which cause frequency changes of about 30% of the cavity half bandwidth. The main issue has been errant detuning values during debugging that generate large enough reflected power to trip the system on the vacuum pressure rise it causes, after which the whole turn-on procedure has to be repeated.

With continued operation, the gun vacuum has lowered significantly. Currently when switching from 100 Hz pulsed operation at 99% duty to CW, the vacuum level immediately decreases by a factor three, indicting a large contribution from MP during the pulse rise and fall periods. When operating CW with the gun temperatures in steady state, the vacuum pressure is 1.6e-9 Torr. The dark current as measured with the Faraday Cap started out low (< 1 nA) but at one point increased to around 100 nA and stayed at this level, which still meets the < 400 nA spec.

INITIAL BEAM OPERATION

The gun laser system uses an oscillator, chirped-pulse amplifier and acousto-optic pulse picker to generate 1030 nm IR light at a rate up to 929 kHz with an average power up to 50 W. Using two non-linear crystals, this light is converted to UV (257.5 nm) at 10 times lower power, and another factor of 10 reduction occurs during transport of the UV light from the laser room to the gun cathode, leaving at maximum about 0.5 uJ per pulse. Ideally, the longitudinal profile would be essentially flat with a ~ 30 ps width but so far only a ~ 20 ps FWHM Gaussian shape has been achieved. A pulse stretcher has been added in the UV region to improve the shape.

The first beam was generated on May 29, 2019 with 10 kHz, 0.28 uJ laser pulses impinging on the Mo gun cathode with a roughly 0.5 mm FWHM Gaussian transverse profile in X and Y. Figure 5 shows the beam as imaged on the YAG screen. With the Faraday Cup, the bunch charge was measured to be 0.3 pC, which corresponds to a cathode QE of 5e-6. The laser and beam have since been run at 92.8 kHz at this pulse energy, and earlier the laser was operated at 926 kHz at a lower pulse energy. The beam energy was computed based on its deflection as measured on the YAG screen when an upstream dipole corrector was varied. The resulting calibration with respect to the gun input power agrees with that expected to within 1%.

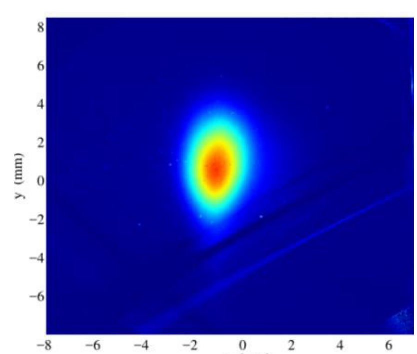

Figure 5: First photocurrent beam from the gun.

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BUNCHER

The buncher is a two-cell, pi-mode, 1.3 GHz cavity with R/Q = 386 Ohm, Qo = 25700 and beta = 1 coupling. It is powered through four couplers (two per cell) by four, 4.2 kW SSAs of the design that will be used to power the SRF cavities. For the nominal combined input of power of 7.8 kW, the integrated field is expected to be 247 keV. The buncher LLRF system capabilities are similar to that for the gun, but instead of tuners, the temperature of the cooling water is adjusted to keep it on frequency. The cavity detunes about -600 kHz with the RF on, which is much larger than the 50 kHz cavity half bandwidth.

Although the cavity processed up to full power fairly quickly in SEL mode, one of 20 cm long coupler arms heats up about twice as much as the others, and the chiller used to regulate the cooling water has not been stable. This has restricted the average power at which the buncher can be run, and has limited the ability to achieve stable operation at nominal frequency.

SUMMARY

Much progress has been made during the last year to demonstrate the LCLS-II electron source performance. With the gun vacuum now in the low 1e-9 Torr scale during CW operation, the current effort is to install a Cs_2Te cathode and to characterize the resulting beam performance. Also, many efforts are underway to improve the system, in particular to increase the speed and robustness of the gun turn-on.

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