# THE LCLS-II INJECTOR DESIGN*

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*Abstract*

The new LCLS-II project will construct a 4 GeV continuous wave (CW) superconducting linear accelerator to simultaneously feed two undulators which will cover the spectral ranges 0.2-1.2 keV and 1-5 keV, respectively. The injector must provide up to 300 pC/bunch with a normalized emittance < 0.6 μm and peak current > 30 A at up to 1 MHz repetition rate. An electron gun with the required brightness at such high repetition rate has not yet been demonstrated. However, several different options have been explored with results that meet or exceed the performance requirements of LCLS-II.

The available technologies for high repetition-rate guns, and the need to keep dark current within acceptable values, limit the accelerating gradient in the electron gun. We propose a CW normal conducting low frequency RF gun for the electron source due to a combination of the simplicity of operation and the highest achieved gradient in a CW gun, potentially allowing for lower beam emittances. The high gradient is especially significant at the 300 pC/bunch charge where beam quality can suffer due to space charge. This paper describes the design challenges and presents our solutions for the LCLS-II injector.

## INTRODUCTION

LCLS-II [1] is a proposed FEL user facility driven by a 4 GeV CW superconducting linac under construction at SLAC. The injector must simultaneously deliver high repetition rate up to 1 MHz and high beam brightness with normalized emittance of < 0.6 μm at 300 pC/bunch and peak current > 30 A. An injector capable of delivering the desired parameters has not yet been demonstrated. This paper describes one possible design for the LCLS-II injector.

The preferred LCLS-II electron gun is a normal conducting, CW, rf gun operating at 186 MHz (7$^{th}$ sub-harmonic of 1.3 GHz) like the APEX gun at LBNL [2]. Multiple gun technologies with different advantages and disadvantages were considered and the APEX gun was ultimately adopted for LCLS-II largely due to the high achieved gradient of 20 MV/m and the demonstrated reliable CW operation. The gradient is especially important at 300 pC/bunch where beam quality can suffer due to space charge. The nominal values as well as the range of all the injector parameters are listed in Table 1. Parameters are specified at the injector exit unless otherwise indicated. The layout of the full injector is shown in Figure 1 including the gun, buncher, superconducting accelerator, laser heater for microbunching instability suppression and diagnostics. The accelerator is comprised of a single standard TESLA cryo-module with eight 9-cell SRF cavities which accelerates the beam from < 1 to approximately 100 MeV.

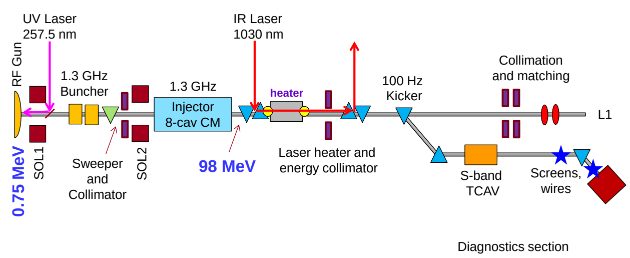


Figure 1: Injector layout

## GUN TECHNOLOGY

Three gun technologies, each with distinct advantages and disadvantages, were considered for LCLS-II.

1. DC guns
2. VHF rf gun at linac sub-harmonic
3. Superconducting high gradient multi-cell gun

The DC gun at Cornell has nearly demonstrated the nominal LCLS-II parameters as shown in Figure 2 [3]. These results were obtained with the DC gun operating at 350 kV corresponding to about 4 MV/m at the cathode but the gun will need to be operated at closer to 500 kV to meet the LCLS-II emittance requirements at 300 pC. The Cornell DC gun has recently been operated at 400 kV but no DC gun has yet demonstrated reliable e-beam operation at 500 kV including guns with segmented insulators. One advantage of the DC gun is to allow for arbitrary pulse separation which can fill adjacent linac buckets and is desired for multi-bunch operation.

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However, LCLS-II is currently designed to operate with only a single bunch.

Table 1: LCLS-II Injector Specifications

| Parameter | Nominal | Range | Units |
|---|---|---|---|
| **Electron energy at gun exit** | 750 | 500-800 | keV |
| **Electron energy** | 98 | 95-120 | MeV |
| **Bunch charge** | 100 | 10-300 | pC |
| **Bunch repetition rate** | 620 | 0-929 | kHz |
| **Dark current** | | 0-400 | nA |
| **Peak current** | 10 | 5-30 | A |
| **Average current** | 0.062 | 0-0.3 | mA |
| **Average beam power** | 6.1 | 0-36 | kW |
| **Normalized slice emittance (rms)** | 0.4 | 0.2-0.6 | μm |
| **Bunch length (rms)** | 1 | 0.3-10 | mm |
| **Slice energy spread (rms)** | 1 | 1-5 | keV |
| **Vacuum pressure in gun** | 1 | 0.1-1 | nTorr |
| **Cathode quantum efficiency** | 2 | 0.5-10 | % |
| **Laser (UV) energy at cathode** | 0.02 | 0-0.3 | μJ |
| **Laser (IR) energy at laser heater** | 1 | 0-15 | μJ |
| **Average CW RF gradient** | 16 | 15-18 | MV/m |

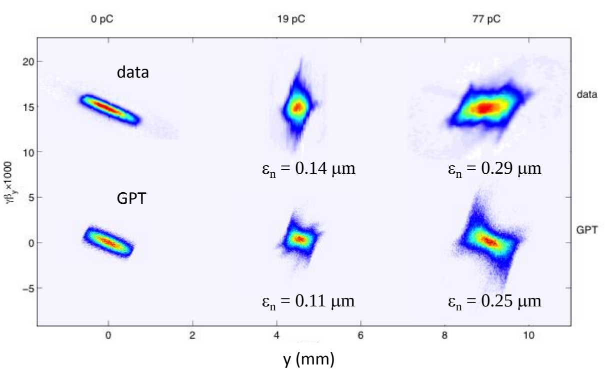


Figure 2: Cornell DC gun phase space measurements and comparison with GPT simulations at three charges. Emittances listed are for 90% of the particles.

The low frequency rf guns can reach high gradients including 20 MV/m for normal conducting and over 30 MV/m for superconducting [4]. While neither technology has demonstrated the desired brightness it is expected that they will perform similar to the DC guns because these guns operate near crest and the transit time plus laser pulse length is much shorter than the rf period. While the superconducting guns can produce higher gradient they have not yet demonstrated reliable operation and thus were not yet considered suitable for a user facility.

The multi-cell superconducting rf guns operate similar to the existing LCLS rf gun at GHz frequencies and high gradient. This combination produces shorter pulses requiring less compression downstream. Like the DC guns they permit multi-bunch FEL operation because they can fill every linac bucket. However, problems such as optimizing emittance compensation due to magnetic field locations, multi-pacting and cathode exchanges still exist and require additional R&D. While we believe the superconducting guns (both low and high frequency) have the greatest potential to deliver the brightest beams due to the high gradients achievable, they are not yet ready for operation in a user facility requiring > 99% injector reliability. A SRF gun is considered an upgrade path in the future.

Based on the technology reliability and potential for high charge operation, we concluded the best candidate for the LCLS-II injector was the low frequency normal conducting rf gun. The gun cross-section is shown in Figure 3 and the basic parameters are listed in Table 2.

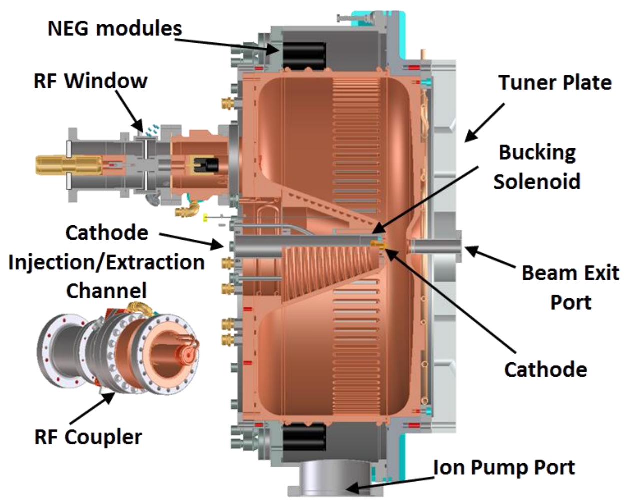


Figure 3: Cross section of the APEX CW rf gun.

Table 2: Measured APEX Gun Parameters

| Parameter | Value |
|---|---|
| **Frequency** | 186 MHz |
| **Gap Voltage** | 750 kV |
| **Field at Cathode** | 19.5 MV/m |
| **$Q_0$** | 26500 |
| **Shunt Impedance** | 6.5 MΩ |
| **RF Power** | 100 kW |
| **Peak Surface Field** | 24 MV/m |
| **Peak Wall Power Density** | 25 W/cm$^2$ |
| **Accelerating Gap** | 4 cm |
| **Diameter** | 69.4 cm |
| **Length** | 35 cm |
| **Operating Pressure** | 0.1-1 nTorr |

## CHALLENGES

The primary challenge for the LCLS-II injector is the demonstration of the desired brightness at MHz repetition rate. Other challenges include the laser and cathode performance, dark current generation and preservation of the high brightness beam as the beam is accelerated to higher energies. Each of these challenges and our proposed mitigation is briefly described below.

### *High Brightness Demonstration*

SLAC is collaborating with both Cornell and LBNL to demonstrate high repetition, high brightness beams with up to 300 pC/bunch charges at up to 1 MHz rate in 2015. The Cornell gun will be operated at a maximum energy of 400 keV and the APEX gun will operate at a maximum of 800 keV. Beam characterization will be performed at 10 and 30 MeV respectively. Layouts of the two machines are similar but not identical. Details on the optimization of various layouts and performance over a range of gun energies are reported elsewhere [5].

### *Laser and Cathode*

The laser and cathode are extremely important components of the injector. We have adopted the conservative approach using a $Cs_2Te$ cathode operating in the UV with QE > 0.5%. This leads to the spec of 0.3 µJ of laser energy at the cathode assuming the maximum charge of 300 pC. The measured lifetime as a function of QE is shown in Figure 4. The lifetime is especially important for user facilities and this measurement shows cathodes can easily deliver QE > 0.5% for more than the required 7 days. Alternative cathodes operating in the visible such as K2CsSb and NaKSb will be considered in the future as they are further characterized and developed.

At 1 MHz rate and assuming 10% IR to UV conversion plus 90% losses in the transport and conditioning components leads to a 30 W IR laser power specification. The best candidate for the required laser system is a fiber oscillator/amplifier. They have the combination of average power scalability, beam quality, power and timing stability. Fiber-based laser systems with >10 W output power, MHz repetition rate, and high transverse and longitudinal beam quality are commercially available [6]. We anticipate improvements in commercially available systems in the next few years prior to ordering the LCLS-II laser. However, some R&D may be necessary to simultaneously deliver temporal and transverse shaping with the desired power and pointing stability.

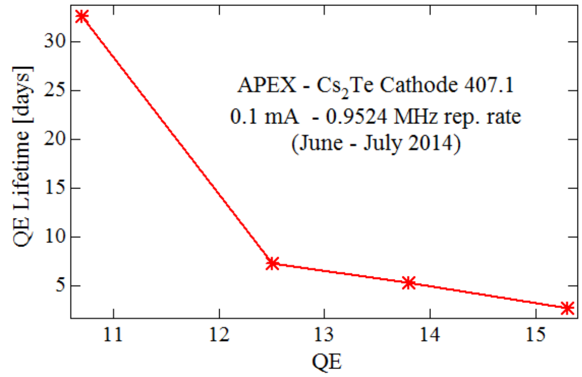


Figure 4: Measured $Cs_2Te$ lifetime versus QE.

The laser also needs the capability to switch continuously between single shot and 1 MHz in order to allow different machine operation modes. A pulse picker system such as an Electro-Optic Modulator or Acousto-Optic Modulator will be used to vary the rate.

### *Dark Current*

Dark current can be detrimental to the performance of a SRF based FEL due to possible quench of SRF cavities and radiation damaging of permanent magnet undulators. The dark current from the APEX gun has been characterized [7] with roughly 350 nA measured at the location of the first LCLS-II SRF cavity as shown in Figure 5. The dark current is dominated by field emission around the cathode plug outer diameter where the plug meets the gun "nose". The "nose" has a small radius which enhances the field and generates the majority of the dark current. Figure 6 shows an image of the cathode on a downstream screen clearly showing the dark current dominated at the plug to gun boundary.

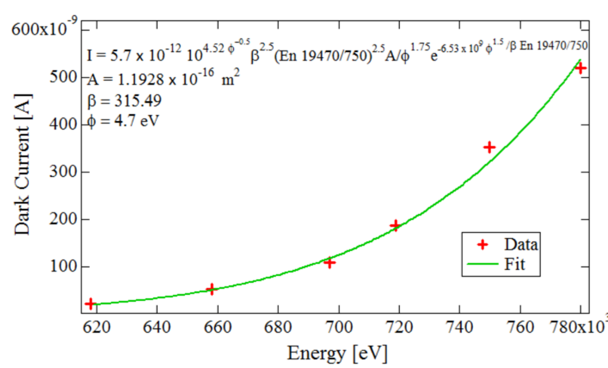


Figure 5: Measured Dark Current at location of first LCLS-II superconducting accelerator cavity.

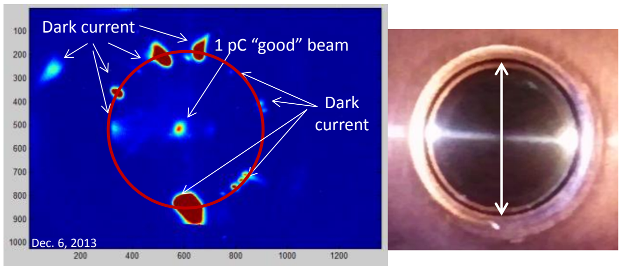


Figure 6: Measured dark current imaged onto a screen at left and the cathode plug on the right. The diameter of the ring of dark current matches the diameter of the plug.

Although the measurements shown already meet the LCLS-II spec we realize the dark current can increase with time and cathode exchanges so we have developed several methods for mitigation. An obvious method to reduce dark current is to reduce the gradient at the cathode. Figure 5 shows nearly an order of magnitude reduction is possible by operating at 650 keV instead of 750 keV. This method will clearly work but at the expense of beam quality so other methods are preferred. One method will be to clean the cathode and gun surface with $CO_2$ snow as demonstrated on the PITZ L-band gun [8] which resulted in an order of magnitude reduction in dark current. This method is effective at removing particulates and will be tested shortly on the APEX gun. Another possibility is to use a collimator to scrape the dark current electrons emitted from the gun "nose" since they originate at a much larger diameter than the photo-electrons. This method can potentially decrease the dark current an order of magnitude without scraping photo-electrons. A collimator will be tested soon and is described in more detail in reference 7.

## *Emittance Preservation*

The standard TESLA SRF cavities include one Higher Order Mode (HOM) coupler at the upstream and downstream ends to damp higher order mode power plus the rf power feed coupler at the downstream end. These couplers produce field perturbations that break the field symmetry and cause beam deflection and emittance growth. The perturbation strength is largest at large radius and thus predominantly impacts the high charge cases. Figure 7 shows the emittance for both transverse planes at 300 pC with perfectly symmetric fields (no couplers), the standard TESLA cavity case with 2 HOMs and a single power coupler and a TESLA cavity modified to eliminate only the upstream HOM. The emittance for the standard TESLA cavity is approximately 30% larger than the symmetric case but most of the emittance is recovered by eliminating the upstream HOM. The difference between x and y plane emittances in the figure are due to a small quadrupole term that can be corrected. Additional information and discussion is included elsewhere [9].

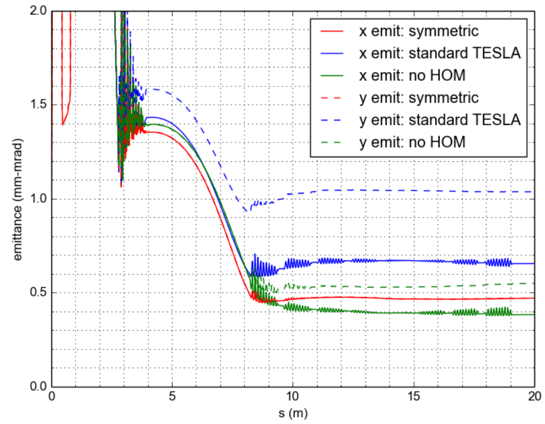


Figure 7: Horizontal and vertical emittance for 300 pC as a function of distance from the cathode for three cases; 1) ideal case with perfectly symmetric cavity fields, 2) 3-D fields from standard TESLA cavity including HOM couplers and 3) 3-D fields from standard TESLA cavity with upstream HOM coupler removed.

While it would be desirable to minimize the perturbations from all the couplers in the injector, the simulations show that only the first SRF cavity requires modification to the upstream HOM coupler to preserve the emittance since the beam energy increases an order of magnitude in the first cavity. Modification of the couplers existing design requires significant effort and expense so we are planning to modify only the first cavity.

We have considered three methods for eliminating the upstream HOM. The first method moves the upstream HOM to the downstream end so there are two HOMs and one power feed downstream. The couplers are arranged to minimize dipole and quadrupole perturbation terms. A second method is to add a second HOM at the upstream end approximately 180 degrees apart to minimize the dipole term. A third method completely eliminates the HOM and instead uses a coaxially symmetric beam absorber as described in reference 3. Simulations indicate that all three methods are equally effective. We are currently evaluating the engineering implications and other potential risks and benefits for the three options and will adopt a final choice in the near future.

Optimizing the brightness will require diagnostics to characterize the full 6-D phase space. Thus we plan to include transverse rf deflectors as shown in Figure 1 to measure the time dependent transverse phase space as well as longitudinal phase space. A pulsed kicker will operate up to 100 Hz to divert single pulses onto the diagnostic beamline. Continuous monitoring of the injector beam quality will allow implementation of feedbacks as necessary. Diagnostics will be critical to deliver the emittance values described here and in reference 5.

## CONCLUSION

Simulations show the APEX gun, a normal conducting, 186 MHz rf gun, can deliver the desired LCLS-II electron beam parameters including <0.6 μm normalized emittance with 300 pC/bunch at 1 MHz repetition rate. Demonstrations of high repetition, high brightness beams with up to 300 pC/bunch charges are expected at both APEX and Cornell in 2015. In addition the APEX gun with $Cs_2Te$ cathode has demonstrated reliable CW operation, with the required dark current, QE, thermal emittance and lifetime. Additional R&D may be needed for the laser to simultaneously deliver the desired temporal and transverse pulse shapes with the required pulse energy and stability. In order to preserve the emittance downstream of the gun, modification of the rf HOM coupler in the first superconducting rf cavity will be necessary.

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