# REVIEW OF EXPERIMENTAL RESULTS FROM HIGH BRIGHTNESS DC GUNS: HIGHLIGHTS IN FEL APPLICATIONS

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*Abstract*

Future energy recovery linac light sources and high repetition rate X-ray FELs require high-brightness and high-current electron guns. A DC photoemission gun is one of the most promising candidates for such guns, because a record high current of 75 mA and generation of high brightness beam satisfying LCLS-II injector specifications were recently demonstrated at the Cornell photoinjector with a 400 kV photoemission gun. Further increases of gun high voltage and cathode gradient are desirable to reduce space charge induced emittance growth especially for higher bunch charge applications. Employment of a segmented insulator is a key to reach higher voltage. This technique led to generation of a 500 keV beam from the JAEA gun with 160 mm acceleration gap, conditioning voltage more than 500 kV at the Cornell gun with gap < 50 mm, and demonstration of 500 kV holding for 10 hours at the KEK gun with 70 mm gap. In this paper, recent experimental results of high brightness DC guns are presented.

## INTRODUCTION

High repetition rate FELs such as LCLS-II and high power FEL for EUV lithography require a high-brightness and high-current electron gun [1,2]. A normal conducting RF gun operating at 186 MHz has been developed for the next generation FELs and recent experimental results are described in the FEL2014 [3]. In this paper we focus on experimental results from high brightness DC guns as another candidates for the high repetition rate FELs. Those DC gun-based photoinjectors are designed and constructed being inspired by the great success of Jefferson laboratory energy recovery linac (ERL) FEL [4].

The recent highlight in FEL applications is the first demonstration of cathode thermal emittance dominated high bunch charge beams satisfying LCLS-II injector specifications at the Cornell photoinjector [5]. The cathode thermal emittance is given by [6]

$$\varepsilon_{n,th} = \sigma_x \sqrt{\frac{MTE}{mc^2}},$$

where $MTE$ is cathode mean transverse energy, $\sigma_x$ is the initial rms size of the beam and $mc^2$ is the electron rest energy. The charge $q$ can be generated from cathode as long as the external cathode gradient $E$ is greater than the image charge field given by $q/\varepsilon_0 \pi (2\sigma_x)^2$ [7]. The thermal emittance for charge $q$ and cathode gradient $E$ is thus given by [6]

$$\varepsilon_{n,th} \geq \frac{1}{2}\sqrt{\frac{q}{\pi\varepsilon_0 E}}\sqrt{\frac{MTE}{mc^2}}.$$

Substitution of cathode gradient $E$ = 4.3 MV/m, and $MTE$ = 140 meV of NaKSb cathode used for the Cornell experiment yields minimum thermal emittance of $\varepsilon_{n,th}$ = 0.11 μm for 20 pC, 0.24 μm for 100 pC, and 0.41 μm for 300 pC. Although those emittance values are within the LCLS-II specifications summarized in Table 1, it had been considered to be difficult to preserve the thermal emittance through a DC gun-based photoinjector. Recently the Cornell photoinjector demonstrated that the emittance at the injector exit increases only by 50% or less from the cathode thermal emittance, satisfying the LCLS-II specifications [5]. The sophisticated injector design, excellent injector components including the 400 kV photoemission gun and advanced beam transport techniques relying on space charge simulation codes led to preservation of the high brightness performance from the cathode through the injector accelerator with bunch compression required for LCLS-II specifications.

Generation of a record high average current of 75 mA demonstrated at the Cornell photoinjector is also a highlight in FEL applications [8,9]. The average current is three orders of magnitudes greater than LCLS-II specification and high enough for high power EUV FEL. Generation of both cathode emittance dominated high bunch charge and high current beams was achieved with the same NaKSb cathode.

Table 1: LCLS-II Injector Specifications [5]

| Bunch charge | 95% $\varepsilon_n$ (μm) | Peak current (A) |
|---|---|---|
| 20 pC | 0.25 | 5 |
| 100 pC | 0.40 | 10 |
| 300 pC | 0.60 | 30 |

Further increase of the gun high voltage is desirable to reduce space charge induced emittance growth especially for FELs driven by high bunch charge. Employment of a segmented insulator is a key to reach higher voltage [10]. This technique led to the first demonstration of 500 keV beam from a photoemission DC gun with 160 mm acceleration gap at Japan Atomic Energy Agency (JAEA) [11]. The cathode gradient is 5.8 MV/m without Pierce-type focusing electrode. The gun has been used for commissioning of the compact ERL (cERL) at KEK for more than two years [12]. The gun operational voltage at the cERL is however limited to 390 kV, because the insulator is operated with eight segments due to the failures of two segments out of the full ten. Recently a new two segmented insulator was installed on the top of

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ISBN 978-3-95450-134-2

the existing insulator. The insulator with 2+8 segments was successfully conditioned up to 550 kV without the central stalk. Beam generation from the gun with the additional insulator will be performed at the cERL in the near future.

Higher cathode gradient along with high voltage has been pursued at KEK and Cornell. The 70 mm gap photogun at KEK demonstrated holding at 500 kV for 50 hours [13]. The cathode gradient is 6.9 MV/m without Pierce-type focusing electrode. The HV conditioning up to 550 kV was achieved with small number of HV trip events about 50. The trip number is much fewer than the JAEA and other DC guns. Although there are a few differences such as the insulator material used at KEK and the HV chamber design, it is still unclear what mainly contributes to the much better HV performance of the KEK gun, compared with the JAEA gun. The beam generation test will be performed soon.

A photogun with a segmented insulator has been also developed at Cornell University [14]. The unique feature is a movable anode, allowing the cathode-anode gap to be adjusted. The measured breakdown voltage as a function of the gap length was found to agree well with the empirical equation given by $V(kV) = 123 \times g^{0.34}(mm)$ [15]. They pointed out that the KEK result at 500 kV with 70 mm gap is consistent with the equation and that the normalized emittance for bunch charges higher than 150 pC approaches thermal emittance as the voltage approaches 500 kV [16].

In this paper, we describe recent experimental results of high brightness DC guns. In Sec. 2, the results from the Cornell photoinjector are described. As already mentioned, various developments of the photoinjector components and advanced beam transport techniques based on space charge simulation codes contribute to the unprecedentedly high brightness and high current beam generation. In Sec. 3, the results from the JAEA 500 kV gun are described. In Sec. 4, high gradient 500 kV gun at KEK and Cornell are described.

## CORNELL PHOTOINJECTOR

Generation of high brightness electron beam satisfying LCLS-II specifications has been demonstrated at the Cornell photoinjector. Their success relies on various developments in the whole injector system.

The Multi Objective Genetic Algorithm (MOGA) optimization developed for design of the Cornell ERL injector [17,18] has been used to find optimum parameter sets for the high brightness beam satisfying LCLS-II injector specifications. Three dimensional space charge simulation codes such as GPT [19] along with realistic models of gun acceleration field, injector cavity fields, and magnetic fields have been used in the MOGA optimizations. The 3D space charge code is shown to agree well with phase space measurements of space charge dominated beams at the Cornell photoinjector [5,20-22]. The MOGA optimization is now widely used for injector designs at other facilities [23,24].

Before the measurements of space charge dominated bunches, the GPT model for the Cornell photoinjecotor was verified with sophisticated measurements at near-zero bunch [22], as briefly described in the following. The transverse beam position change was measured with downstream BPMs by changing the initial position of the beam on cathode or kicking the beam with a corrector magnet. This was repeated for each element in the injector. The measured responses were found to agree well with the GPT model for all the elements including the 3D rf field maps used to model the cavities and fields due to the input power couplers. The alignment of the beam through the whole injector is also found to be very important to generate the low emittance beam. An element by element alignment procedure was developed for the gun, the buncher cavity, and the SRF cavities with corrector coils within accuracy of 50 μm. The solenoids were physically moved to align their magnet centers with beam trajectory within accuracies of 50 μm and 0.2 mrad. As the final check, the injector was set up with parameters for 20 pC/bunch and the emittance at the injector exit was measured with a two slit Emittance Measurement System (EMS). The emittance was verified to agree well with thermal emittance at the cathode measured with a solenoid scan technique. The beam sizes at several locations along the injector are also verified to agree well with the GPT model.

After all the injector components were verified to have responses predicted by the GPT model for near-zero bunch, an optimum parameter set for each bunch charge was loaded to the injector. The measured emittance and longitudinal current profile at the EMS location are shown to agree well with the GPT model and to satisfy the LCLS-II specifications [5]. Small discrepancy between the simulation and the measurement seen in a graph of optimized emittance vs. rms bunch length is attributed to the difference between ideal and measured transverse laser distributions. This suggests that further improvement of emittance is anticipated with an improved laser shaping technique [25].

Recently a beam asymmetry after the first emittance compensation solenoid was discovered and attributed to the stray quadrupole fields in the solenoid. The asymmetry was mitigated with a correcting quadrupole coil. This greatly contributed to demonstration of the cathode emittance dominated beams [26].

The gun at the Cornell photoinjector is operated at 400 kV with a non-segmented insulator and the cathode-anode gap length of 50 mm [27]. The cathode gradient is 4.3 MV/m with Pierce-type focusing electrode. They developed various types of photocathodes [6,28,29] and used a NaKSb with a 140 meV cathode mean transverse energy to demonstrate both high brightness and high current performance. The gun has a high voltage power supply capable of delivering 100 mA beam.

## HGH VOLTAGE GUN AT JAEA

As demonstrated at the Cornell photoinjecotor, it is feasible to generate cathode emittance dominated beam



ISBN 978-3-95450-134-2

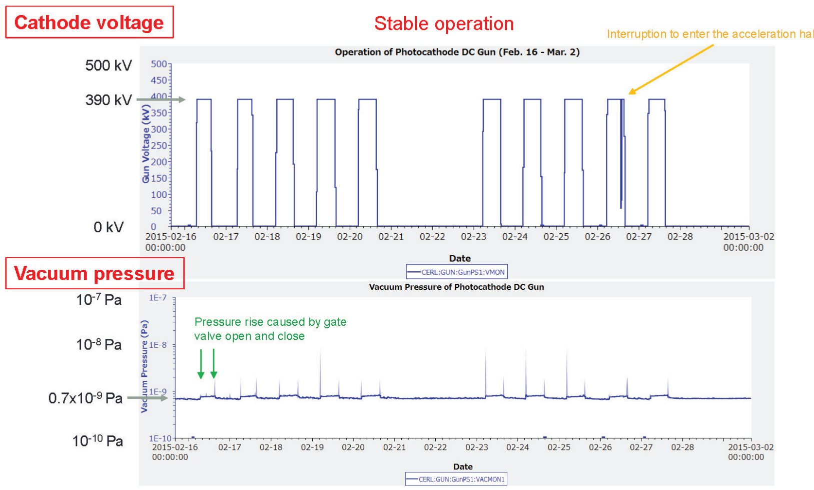


Figure 1: Typical gun cathode voltage and vacuum pressure during two weeks of the cERL operation.

when the whole injector system is carefully set up and the beam response is well reproduced by space charge simulation codes. Development of higher voltage and higher gradient gun will help further improve the performance of the DC gun-based photoinjector. In this section, development of a high voltage photoemission gun at JAEA is described.

The details of the gun system are described in Refs. [10,11,30]. A segmented insulator with guard rings employed to protect the ceramics from field emission is a key to reach high voltage without giving fatal damage to the insulator. The high voltage conditioning up to 550 kV with the stalk was achieved in 2009 [10], and 500 keV beam with current up to 1.8 mA from a photoemission DC gun was demonstrated in 2012 [11]. The cathode-anode gap length was changed from the original design of 100 mm to 160 mm to demonstrate 500 keV beam [30]. This is because field emitters that could not be pacified were created repeatedly at 100 mm gap, preventing the stable gun operation at 500 kV.

The gun was installed at the cERL at KEK and stably delivered beam for more than two years since April 2013. The gun operational voltage has been limited to 390 kV. This is because failures of two out of ten segments of the insulator were found at KEK after the gun shipment from JAEA. Short bars have been connected between the electrodes of the failed segments. The gun insulator has been operated with eight segments during the commissioning instead of full ten segments.

Figure 1 shows a typical operational status of the gun voltage and vacuum pressure during two weeks. The gun is operated from 12:00 to 23:00 on a week day. The stability of the gun voltage is excellent and no HV breakdown event was observed in the past two years. This is very good for such a future industrial application as EUV lithography [2]. The gun vacuum pressure during the operation is $8\times10^{-10}$ Pa. The average beam current at the cERL is increased 10 times every year starting from 1 μA, as they monitor the radiation level outside the accelerator hall. The maximum average current generated so far is 100 μA and will be increased up to 1 mA by the end of FY 2015 [12]. The ERL beam has been used for laser Compton scattering (LCS) X-ray generation [31]. The cathode material is GaAs. The quantum efficiency at 530 nm laser measured during the LCS experiment from January to July in 2015 is plotted in Fig. 2. The 1/e life time is 6000 hours long enough for the LCS commissioning, although the charge extracted is only 6 C. The cathode lifetime study at the cERL will be continued with elevated beam current. This would provide an estimation of the cathode life time of a DC gun-based photoinjector for high repetition rate FELs.

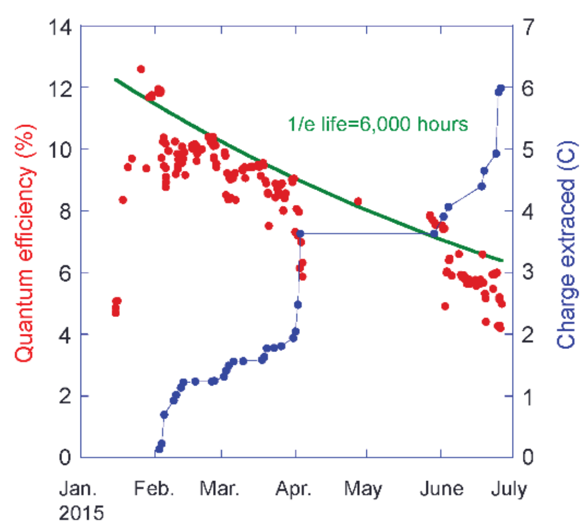


Figure 2: Quantum efficiency of GaAs photocathode and charge extracted during the cERL commissioning from January to July in 2015.

Recently a newly manufactured two segmented insulator was installed on the top of the existing insulator to recover 500 kV operation, as shown in Fig. 3. The insulator with 2+8 segments was successfully conditioned

ISBN 978-3-95450-134-2

up to 550 kV without the central stalk (see Fig. 4). Beam generation from the gun with the additional insulator will be performed in the near future.

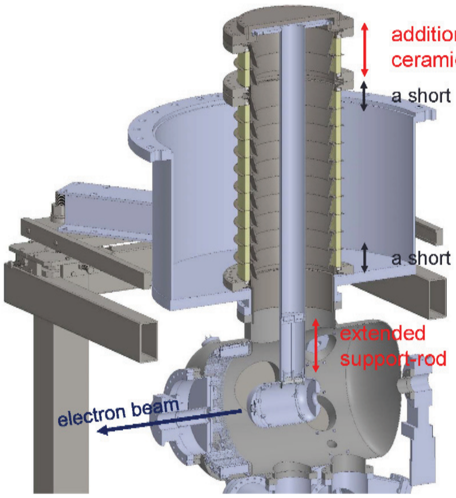


Figure 3: Gun configuration with additional two segmented ceramics at the cERL.

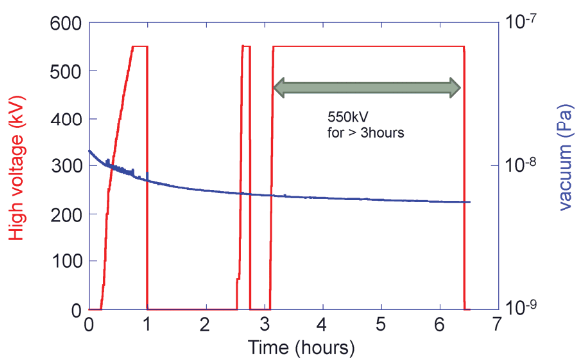


Figure 4: HV test without central stalk with additional ceramics at the cERL. Red is high voltage and blue is gun vacuum.

A simulation study of the cERL photoinjector for FEL applications is presented in Ref. [24]. Although there are many differences between the cERL and Cornell pohtoinjectors, the simulation suggests that LCLS-II specifications could be satisfied at the cERL photoinjector if higher acceleration gradient becomes available at the injector cavity. At the moment, we try to reproduce the cERL beam generated with presently available injector parameters by space charge simulation codes [32]. This will eventually lead to generation of cathode emittance dominated beam at the cERL.

## HIGH VOLTAGE GUNS WITH NARROW GAPS AT KEK AND CORNELL

The photoemission gun developed at KEK is similar to that at JAEA. The most significant difference is the short cathode-anode gap of 70 mm [13]. The cathode gradient is 6.9 MV/m at 500 kV and the maximum gradient of the cathode electrode surface is 11.0 MV/m. Although the short-gap is believed to yield difficulty in HV application [30], the gun was successfully conditioned up to 550 kV with the HV trip number less than 50, which is much fewer than the JAEA gun. Holding test at 500 kV for 50 hours without any breakdown event nor any vacuum activity was also demonstrated. The gun vacuum is $4 \times 10^{-10}$ Pa good enough to avoid photocathode damage due to ion back-bombardment created by residual gas in the cathode-anode gap. The structure of the segmented insulator with guard ring is almost the same as that of the JAEA gun. The insulator material is high voltage resistant $Al_2O_3$ based ceramic called TA010 fabricated by Kyocera. It is different from 99.8 % $Al_2O_3$ used at JAEA [33]. The material used for both KEK and JAEA guns is titanium. The design of the chamber is different from each other. It is under investigation what mainly contributes to much better HV performance at the KEK gun, compared with the JAEA gun. The downstream beam line including radiation shield is under construction at KEK. The beam generation test will be performed soon.

A segmented gun has also been developed at Cornell University [14]. Although the design of the insulator is similar to the JAEA/KEK gun, the insulator diameter and the number of the segments are greater than those of the JAEA/KEK gun. This would be better for operation at such high voltage as 750 kV. The gun was successfully conditioned up to > 500 kV with 50 mm gap using combination of UHV and noble gas conditioning. The helium gas processing was found to be effective in suppressing field emitters observed at voltages above 400 kV. This is different from JAEA experience that the gas conditioning is not effective once the field emitter appeared [34]. The most unique feature is a movable anode, allowing the cathode-anode gap to be adjusted from 20 to 50 mm. The measured breakdown voltage as a function of the gap length is found to agree well with the empirical equation given by $V(kV) = 123 \times g^{0.34}(mm)$ in a textbook [15]. Those measured data are 400 kV for 30 mm gap and 450 kV for 50 mm gap. The optimum set of gun voltage, transverse focusing fields by Pierce-type electrode, and field strength at the photocathode are studied numerically [14,35]. The simulation suggests that a 30 mm gap at 400 kV has smaller emittance than a 50 mm gap at 450 kV for charges up to 100 pC, when the segmented gun is placed in the Cornell photoinjector [14]. They pointed out that the result of 70 mm gap KEK gun is consistent with the empirical breakdown voltage equation and that the normalized emittance for bunch charges higher than 150 pC approaches thermal emittance as the voltage approaches 500 kV [16].

## SUMMARY

Recent experimental results from high brightness DC guns are presented. The DC gun-based Cornell photoinjector successfully demonstrated both cathode emittance dominated and high current beam satisfying the LCLS-II specifications with a 400 kV non-segmented insulator gun with 50 mm gap and Pierce-type focusing



ISBN 978-3-95450-134-2

electrode. The success relies on various developments in the whole injector system and further improvement is anticipated with improved laser shaping. Efforts to increase the gun high voltage and cathode gradient are in progress with employment of segmented insulators. A 500-keV electron beam was demonstrated at JAEA and gun operational experience at the cERL is accumulated. Gun operation at 500 kV with 70 mm gap was demonstrated at KEK indicating further improvement of the DC gun-based photoinjector is feasible. The experimental and numerical studies at the Cornell segmented insulator gun with variable cathode-anode gap suggest that there is an optimum set of gun voltage, electrode shape and cathode field strength depending on the application.

## ACKNOWLEDGMENTS

We acknowledge Adam Bartnik, Colwyn Gulliford, Jared Maxson, Bruce Dunham, and Ivan Bazarov at Cornell University for useful discussion on the Cornell photoinjector developments. We thank Masahiro Yamamoto, Tsukasa Miyajima, Yosuke Honda at KEK, Masao Kuriki at Hiroshima University, Ryoji Nagai and Ryoichi Hajima at JAEA for helpful discussion on KEK/JAEA gun developments. This work is partially supported by JSPS Grants-in-Aid for Scientific Research in Japan (15H03594).

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ISBN 978-3-95450-134-2