Review of experimental results from high brightness dc guns: Highlights in FEL applications
Outline

• Introduction
• The DC gun-based Cornell photoinjector
• High voltage DC gun at JAEA
• High gradient and high voltage DC guns at KEK and Cornell
• Summary
High repetition rate FEL

https://portal.slac.stanford.edu/sites/lcls_public/lcls_ii/Pages/design.aspx

10 kW FEL for EUV lithography

# LCLS-II injector specifications

<table>
<thead>
<tr>
<th>bunch charge</th>
<th>$95 % \varepsilon_n$ ($\mu$m)</th>
<th>peak current (A)</th>
<th>average current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 pC</td>
<td>0.25</td>
<td>5</td>
<td>0.02</td>
</tr>
<tr>
<td>100 pC</td>
<td>0.40</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>300 pC</td>
<td>0.60</td>
<td>30</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- The Cornell photoinjector demonstrated cathode thermal emittance dominated beam satisfying LCLS-II specifications in 2015.


- The Cornell photoinjector demonstrated average beam current of 75 mA much higher than LCLS-II specifications in 2013.

  L. Cultrera et al., Appl. Phys. Lett. 103, 103504 (2013);

- Reliability (long-term operational experience) is important especially for industrial application such as 10 kW EUV FEL for lithography.
Cathode thermal emittance

\[
\varepsilon_{n,th} = \sigma_x \sqrt{\frac{MTE}{mc^2}} \geq \frac{1}{2} \sqrt{\frac{q}{\pi \varepsilon_0 E}} \sqrt{\frac{MTE}{mc^2}}
\]

- **MTE**: cathode mean transverse energy
- **\(\sigma_x\)**: initial rms beam size
- **q**: bunch charge
- **E**: applied cathode field

The applied cathode field \(E\) should be greater than image charge field \(q/\varepsilon_0 \pi (2\sigma_x)^2\).

\(MTE = 140\text{meV}\) (corresponds to 0.5 mrad): NaKsB cathode

\(E = 4.3\text{MV/m}\): 400 kV DC gun

<table>
<thead>
<tr>
<th>bunch charge</th>
<th>(\varepsilon_{n,th} (\mu\text{m}))</th>
<th>95 % (\varepsilon_n (\mu\text{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 pC</td>
<td>0.11</td>
<td>0.25</td>
</tr>
<tr>
<td>100 pC</td>
<td>0.24</td>
<td>0.40</td>
</tr>
<tr>
<td>300 pC</td>
<td>0.41</td>
<td>0.60</td>
</tr>
</tbody>
</table>

D. Nguyen et al., “RF Linac for High-Gain FEL Photoinjectors”, LA-UR 14-23995

Cornell photoinjector
Cornell photoinjector

400 kV DC Gun + Bunching/Focusing

400 kV DC Gun

Inner stock and electrode assembly
Vacuum chamber
High Voltage Gap
50 MHz
520 nm
Laser pulses
Electron bunches

Courtesy of Adam Bartnik
Cornell photoinjector

NaKSB: $\text{MTE} = 140 \text{ meV}$, $\text{QE} \text{ roughly 5\%}$

400 kV DC Gun

Short SRF Linac
5 – 15 MeV

400 kV DC Gun + Bunching/Focusing

400 kV DC Gun

Inner stock and electrode assembly
Vacuum chamber
High Voltage Gap
Laser pulses
Electron bunches

Courtesy of Adam Bartnik
Cornell photoinjector

Superconducting RF Cavities (niobium)

400 kV DC Gun

Short SRF Linac
5 – 15 MeV
Bunching/Focusing

400 kV DC Gun +

50 MHz
520 nm

Inner stock and electrode assembly
Vacuum chamber
High Voltage Gap
Laser pulses
Electron bunches

Courtesy of Adam Bartnik
Cornell photoinjector

Short SRF Linac
5 - 15 MeV
400 kV DC Gun +
Bunching/Focusing

Superconducting
RF Cavities (niobium)

400 kV DC Gun

Inner stock and
electrode assembly
Vacuum
chamber
Cathode
High Voltage Gap
Insulator
50 MHz
520 nm
Laser pulses
Electron bunches

Courtesy of Adam Bartnik
Cornell photoinjector
6 Dimensional Phase Space Diagnostics + High Power Beam Dump

Emittance Measurement System

400 kV DC Gun

50 MHz
520 nm

Viewscreen Deflecting Cavity 2nd Slit 1st Slit

Faraday Cup + Viewscreen

Inner stock and electrode assembly

Vacuum chamber

Cathode

High Voltage Gap

Laser pulses

Electron bunches

Courtesy of Adam Bartnik
Beam based alignment with near-zero bunch charge

- Measured beam response of each injector component.
- Performed beam based alignment of gun, buncher, SRF cavities, and solenoids within 50 μm accuracy.
- Confirmed the emittance and beam sizes are reproduced by GPT simulations.
- Loaded optimum parameter set for each bunch charge and measured emittance and longitudinal profile.

<table>
<thead>
<tr>
<th>Bunch charge</th>
<th>ε_{n,x}(100%)</th>
<th>ε_{n,y}(100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 pC</td>
<td>0.33 μm</td>
<td>0.20 μm</td>
</tr>
<tr>
<td>77 pC</td>
<td>0.69 μm</td>
<td>0.40 μm</td>
</tr>
<tr>
<td>300 pC</td>
<td>1.36 μm</td>
<td>0.79 μm</td>
</tr>
</tbody>
</table>

Courtesy of Adam Bartnik
Origin of asymmetry

- Found a beam asymmetry after the first solenoid.
- Likely culprit: stray quad field in the solenoid.
- Mitigated with a correcting quadrupole coil.
Emittance and longitudinal profile measurements


<table>
<thead>
<tr>
<th>Q (pC)</th>
<th>(I_{\text{peak}}) Target (A)</th>
<th>(I_{\text{peak}}) (A)</th>
<th>(\varepsilon_n) Target (95%, (\mu m))</th>
<th>(\varepsilon_n) (95%, (\mu m))</th>
<th>(\varepsilon_{n,\text{th}}/\varepsilon_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5</td>
<td>5</td>
<td>0.25</td>
<td>H: 0.18, V: 0.19</td>
<td>60%</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>11.5</td>
<td>0.40</td>
<td>H: 0.32, V: 0.30</td>
<td>80%</td>
</tr>
<tr>
<td>300</td>
<td>30</td>
<td>32</td>
<td>0.60</td>
<td>H: 0.62, V: 0.60</td>
<td>70%</td>
</tr>
</tbody>
</table>

Courtesy of Adam Bartnik
Effects of the laser shape


Courtesy of Adam Bartnik
Effects of the laser shape


Courtesy of Adam Bartnik
Effects of the laser shape


Courtesy of Adam Bartnik
Effects of the laser shape


Courtesy of Adam Bartnik
Development of a 500 kV gun at JAEA

- a segmented insulator
- 160 mm acceleration gap

Field emission

R. Nagai et al., RSI 81, 033304 (2010).
N. Nishimori et al., PRSTAB 17, 053401 (2014).

![Graph showing voltage over time](image-url)
500keV beam generation

N. Nishimori et al., APL 102, 234103 (2013)
compact ERL (cERL) at KEK

- Oct. 2012  Transport of gun from JAEA to cERL at KEK
- Jun. 2013  Injector commissioning 5MeV-0.3μA
- Mar. 2014  ERL loop commissioning 20MeV-4.5μA
- Mar. 2015  Laser Compton Scattering (LCS) 20MeV-80μA

Gun voltage is limited to 390kV at cERL.
cERL
prototype for future ERL light sources: LCS, THz, and EUV FEL


10 kW EUV FEL injector specifications after merger

<table>
<thead>
<tr>
<th>bunch charge</th>
<th>$\varepsilon_n$ ($\mu$m)</th>
<th>peak current (A)</th>
<th>average current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 pC</td>
<td>0.60</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

Reliability and high average current are important as well as brightness.
Gun operational status for two weeks

Stable operation

Pressure rise caused by gate valve open and close

Interruption to enter the acceleration hall
Gun operational status during LCS experiment

![Graph showing beam current and QE (%) over time]

- Beam current (μA)
  - Aug. 24, 2015
  - Time (hours)
  - QE (%) GaAs @530nm

N. Nishimori    FEL15 at Daejeon
Quantum efficiency (%)

1/e life=6,000 hours

GaAs @ 530nm

laser position

Quantum efficiency (%) vs. Charge extracted (C)

QE during the cERL operation
A Plan to 500kV operation at the cERL
A Plan to 500kV operation at the cERL
A Plan to 500kV operation at the cERL

- Installed an additional ceramics in July 2015
- Performed HV test up to 550 kV without stalk
- Install a stalk in Sep. 2015
- Perform HV test with cathode electrode
- Perform beam generation in Nov. 2015
HV test with the additional insulator without stalk

550kV for > 3 hours
MOGA optimization for EUV FEL photoinjector

EUV FEL injector (merger not included)

N. Nakamura et al., Proc. of ERL2015, MOPCTH010

10 kW EUV FEL injector specifications after merger

<table>
<thead>
<tr>
<th>bunch charge</th>
<th>$\varepsilon_n$ ($\mu$m)</th>
<th>peak current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 pC</td>
<td>0.60</td>
<td>30</td>
</tr>
</tbody>
</table>

$\varepsilon_n = 0.30 \mu$m, 30A before merger

N. Nishimori – FEL15 at Daejeon

Aug. 24, 2015

Courtesy of Tsukasa Miyajima
70 mm gap 500 kV gun at KEK

\[ \epsilon_{n,th} \geq \frac{1}{2} \sqrt{\frac{q}{\pi \varepsilon_0 E}} \sqrt{\frac{MTE}{mc^2}} \]

✓ 6.9 MV/m @ photocathode center (=E)
✓ 11.0 MV/m @ cathode ball surface

Courtesy of Masahiro Yamamoto
HV conditioning test

Reached 550kV in 48 trips / a short time (~7 hs.)

Vacuum pressure: ~4x10^{-10} Pa

Courtesy of Masahiro Yamamoto
No breakdown happened during totally 50 hours of 500 kV-holding test.
Variable gap segmented insulator gun at Cornell

J. Maxson et al., RSI 85, 093306 (2014)

Stability test with various gaps:


\[ V(kV) = 58 \times s(mm)^{0.58} \]

\[ V(kV) = 123 \times s(mm)^{0.34} \]

Courtesy of Jared Maxson
Variable gap segmented insulator gun at Cornell

J. Maxson et al., RSI 85, 093306 (2014)

Stability test with various gaps:


- Surprisingly good agreement between different HV systems.
- But what configuration is best for the beam emittance? – Turn to simulations.

Courtesy of Jared Maxson
MOGA optimizations with various gaps

- Choose 3 Cornell style guns as the injector source → use MOGA
  - 500 kV: 70 mm
  - 450 kV: 50 mm
  - 400 kV: 30 mm

![Graph showing electric field and breakdown voltage](image)


**Larger field...**

**...smaller V**

Z position within gun (mm)

**Courtesy of Jared Maxson**
Emittance vs. bunch charge with various gaps

Approaching thermal emittance!

\[ \epsilon_{cnx} = \frac{1}{4 \pi \rho_{max}} \]

100% emittance (\(\mu m\))

Core emittance (\(\mu m\))

Courtesy of Jared Maxson

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)
Summary

- The DC gun-based Cornell photoinjector demonstrated cathode emittance dominated beam satisfying LCLS-II specifications with a 400 kV gun.
- Higher voltage and higher gradient gun developments with segmented insulators are in progress at JAEA/KEK and Cornell University to go beyond the Cornell photoinjector.
  - 500 keV beam generation from JAEA gun with 160 mm gap
  - 50 hours holding at 500kV with 70 mm gap at KEK gun
  - Experimental and numerical studies with 20-50 mm gaps at Cornell gun
- Gun operational experience for users is accumulated at the cERL.
Acknowledgements

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 JAEEA for helpful discussion on KEK/JAEA gun developments.

This work is partially supported by JSPS Grants-in-Aid for Scientific Research in Japan (15H03594).