Lecture 12:
Architecture of An Injector for 4th Generation Light Sources

D. H. Dowell, SLAC

• The objective of this lecture is to describe the components and their functions of a high-brightness injector for SASE light source.

• The student will learn what is required to meet the stringent beam requirements for 4th generation light sources operating in the x-ray region. The LCLS facility is used as the archetypal light source.
### LCLS Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental FEL Wavelength</td>
<td>1.5</td>
<td>15</td>
<td>Å</td>
</tr>
<tr>
<td>Electron Beam Energy</td>
<td>13.6</td>
<td>4.3</td>
<td>GeV</td>
</tr>
<tr>
<td>Normalized Slice Emittance (rms)</td>
<td>1.2</td>
<td>1.2</td>
<td>mm-mrad</td>
</tr>
<tr>
<td>Peak Current</td>
<td>3.4</td>
<td>3.4</td>
<td>kA</td>
</tr>
<tr>
<td>Energy Spread (slice rms)</td>
<td>0.01</td>
<td>0.03</td>
<td>%</td>
</tr>
<tr>
<td>Bunch/Pulse Length (FWHM)</td>
<td>≤ 200</td>
<td>≤ 200</td>
<td>fs</td>
</tr>
<tr>
<td>Saturation Length</td>
<td>87</td>
<td>25</td>
<td>m</td>
</tr>
<tr>
<td>FEL Fundamental Power @ Saturation</td>
<td>8</td>
<td>17</td>
<td>GW</td>
</tr>
<tr>
<td>FEL Photons per Pulse</td>
<td>1</td>
<td>29</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Peak Brightness @ Undulator Exit</td>
<td>0.8</td>
<td>0.06</td>
<td>$10^{33}$ *</td>
</tr>
</tbody>
</table>

* photons/sec/mm²/mrad²/0.1%-BW
Linac Coherent Light Source at SLAC

X-FEL based on last 1-km of existing linac

1.5-15 Å

Existing 1/3 Linac (1 km) (with modifications)

New e− Transfer Line (340 m)

Undulator (130 m)

Near Experiment Hall

Far Experiment Hall
LCLS Accelerator Schematic

- **6 MeV**
  - $\sigma_z \approx 0.83$ mm
  - $\sigma_\delta \approx 0.05$ %

- **135 MeV**
  - $\sigma_z \approx 0.83$ mm
  - $\sigma_\delta \approx 0.10$ %

- **250 MeV**
  - $\sigma_z \approx 0.19$ mm
  - $\sigma_\delta \approx 1.6$ %

- **4.30 GeV**
  - $\sigma_z \approx 0.022$ mm
  - $\sigma_\delta \approx 0.71$ %

- **13.6 GeV**
  - $\sigma_z \approx 0.022$ mm
  - $\sigma_\delta \approx 0.01$ %

**Linac-0**
- $L = 6$ m
- $\varphi_{rf} = -160^\circ$

**Linac-1**
- $L \approx 9$ m
- $\varphi_{rf} \approx -25^\circ$

**Linac-2**
- $L \approx 330$ m
- $\varphi_{rf} \approx -41^\circ$

**Linac-3**
- $L \approx 550$ m
- $\varphi_{rf} \approx 0^\circ$

**Linac-X**
- $L = 0.6$ m
- $\varphi_{rf} = -160^\circ$

**DL1**
- $L \approx 12$ m
- $R_{56} \approx 0$

**BC1**
- $L \approx 6$ m
- $R_{56} \approx 39$ mm

**BC2**
- $L \approx 22$ m
- $R_{56} \approx 25$ mm

**25-1a 30-8c**

**undulator**
- $L = 130$ m

**DL2**
- $L = 275$ m

**undulator**

- **X-rays in spring 2009**

---

High Brightness Electron Injectors for Light Sources - January 14-18 2007

Lecture 12

D.H. Dowell, S. Lidia, J.F. Schmerge
Gun-To-Linac (GTL) Section

- RF gun
- Cathode
- Bucking solenoid
- Main solenoid
- Spectrometer dipole
- UV Drive Laser
- YAG screens
- 6 MeV
Laser Room and Injector Vault

Laser room (recent construction)

Linac gallery

RF hut

Linac enclosure

cables run down through penetration enclosed by RF Hut

Lecture 12
D.H. Dowell, S. Lidia, J.F. Schmerge
Thales Drive Laser System

Measuring 150-200fs phase stability from osc.

Femtolasers Synergy Oscillator

Spectra Physics MILLENNIA Vs

UV-diagnostics: Streak camera Spectrometer Cross-correlator TG-Frog...

~12m to cathode

UV Transport to Cathode

>0.4mJ, 120Hz 255 nm

1.0mx1.5m breadboard

119MHz >600mW

Stretcher

>300ps 5 nm

DAZZLER

Regen Amp

>1.5mJ, 120Hz 15mJ 120 Hz

Pulse Picker

>1mJ, 120Hz

Pre-Amp 4-pass Bowtie

>22mJ, 120Hz 75mJ 120 Hz

Amplifier 2-pass Bowtie

>40mJ 120Hz

JEDI #1 100 mJ, 120 Hz

>3mJ 120Hz

THG

Compressor

>3mJ 120Hz

>30mJ 120Hz

>40mJ 120Hz

80mJ 120 Hz

JEDI #2 100 mJ, 120 Hz

>1mJ 120Hz

1.0mx1.5m breadboard

Updated figure compliments Ph. Hering

>2mJ 120Hz

UV Transport to Cathode

>3mJ 120Hz

>30mJ 120Hz

>40mJ 120Hz

80mJ 120 Hz

JEDI #2 100 mJ, 120 Hz

>1mJ 120Hz

1.0mx1.5m breadboard

Updated figure compliments Ph. Hering

High Brightness Electron Injectors for Light Sources - January 14-18 2007

Lecture 12

D.H. Dowell, S. Lidia, J.F. Schmerge
RF Photo-Cathode Gun

- **1.6-cell S-band** (2856 MHz - BNL/SLAC/UCLA)
- Copper cathode
- **120-Hz repetition rate**
- **140-MV/m cathode field (max)**
- Axially symmetric RF fields
- Dual RF-feed

ANSYS model of thermal profile
Details of the RF Gun and GTL

- Focusing solenoid
- Cathode flange
- Dual rf power feed

Graph showing rf phase and mm deviation for different cavity designs:
- Cylindrical cavity
- Various racetrack cavity designs with different dimensions

Images of the RF Gun and GTL system components.
Drive Laser Performance

- Laser reliability is very good: Up-time > 90%
- Excellent support from Thales & Femtolasers
- Delivering > 400 microJoules to cathode (250 is spec)
- Shaping needs work, but still producing good emittances
- Excellent energy stability (1.1%)
- Position stability on cathode, ~10-20 microns.

1.1% charge stability at 1nC, 2% is spec

Laser reliability

Laser reliability is very good: Up-time > 90%

- Excellent support from Thales & Femtolasers
- Delivering > 400 microJoules to cathode (250 is spec)
- Shaping needs work, but still producing good emittances
- Excellent energy stability (1.1%)
- Position stability on cathode, ~10-20 microns.

Image of Laser Profile on Virtual Cathode Camera

Laser stability vs. time

1.1% charge stability at 1nC, 2% is spec

X-Correlator Measurement of Laser Pulse

High Brightness Electron Injectors for Light Sources - January 14-18 2007

Lecture 12
D.H. Dowell, S. Lidia, J.F. Schmerge
RF Phase & Amplitude Stability

Gun:
rms amplitude error = 0.018%
rms phase error = 0.032 degS

Linac:
rms amplitude error = 0.056%
rms phase error = 0.108 degS
Viewing the Cathode and Laser Mirror Surfaces

- Changing the zoom allows imaging of the mirrors and cathode surfaces
Imaging Cathode Emission on YAG at 5-10 pC

\[ \begin{pmatrix} 1 & L_3 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} C^2 & \frac{SC}{K} & \frac{S^2}{K} & L_2 \\ \frac{S^2}{C} & -KSC & -KS^2 & 0 \\ -SC & \frac{SC}{C^2} & -S^2 & 0 \\ \frac{KS^2}{C} & \frac{SC}{K} & -KS & 0 \end{pmatrix} \begin{pmatrix} 1 & L_2 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{E_0 \sin \phi_{exit}}{mc^2} & 0 & 0 \\ 0 & 0 & 1 & \frac{E_0 \sin \phi_{exit}}{mc^2} \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & L_1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \]

\[ K(B_{\text{solenoid}} \cdot p_{\text{beam}}) = \frac{B_{\text{solenoid}}(\text{kG})}{2 \cdot 0.033356 \text{ p}_{\text{beam}}(\text{MeV} / \text{c})}(\text{m}^{-1}) \]

\[ S = \sin(KL_{\text{solenoid}}) \quad C = \cos(KL_{\text{solenoid}}) \]

Cathode Uniformity:
Comparison of White Light & Electron Emission Images

June 2, 2007
Electron beam image of cathode @ ~9pC

June 6, 2007
White light cathode image

Grain boundaries

Feature produced by high-power conditioning in Klystron Lab

- Emission is very non-uniform on the 10-micron scale
- Perform ~weekly inspection of the cathode surface
RF Gun (20-6)
6 MV, 115 MV/m
Laser 30° from zero-crossing

L0A (20-7)
57 MV, 19 MV/m
on crest

L0B (20-8)
72 MV, 24 MV/m
3° off crest

L1S (21-1)
147 MV, 20 MV/m
25° nominal chirp

L1X (21-2)
X-band
20 MV, 33 MV/m
160° nominal

RF Gun (20-6) 6 MV, 115 MV/m Laser 30° from zero-crossing

L0A (20-7) 57 MV, 19 MV/m on crest

L0B (20-8) 72 MV, 24 MV/m 3° off crest

L1S (21-1) 147 MV, 20 MV/m 25° nominal chirp

L1X (21-2) X-band 20 MV, 33 MV/m 160° nominal

T-Cavity (20-5)
1.4 MV, ~4 MV/m
180° transverse
Bunch length diag.

Bunch Compressor #1

PH01
Beam phase Monitor cavity

PH02
Beam phase Monitor cavity

SLED
**Bunch Length Measured with Transverse RF Deflectors:**

**One at 135 MeV & Another at 14 GeV**

---

**Deflector used to measure:**

1. *absolute bunch length,*
2. *time-sliced x-emittance,* and
3. *time-sliced energy spread*
Transverse RF Deflector in Injector (135 MeV)
(55 cm long, ~1 MV)
BC1 Chicane in Linac Enclosure

Chicane length 6.3 m, 250 MeV, 5° bends
Coherent Edge Radiation used for Compressor Diagnostics

L1S-linac RF phase: used to drive bunch length feedback

(J. Wu, D. Fairley)
Find the X-band RF Structure in the Linac

Length 60 cm, 20 MV, −160°

Compliments
P. Emma
BC1 Chicane Emittance Growth

Best $\gamma x$ after BC1 with nom. (& more) compression is 1.6 $\mu$m (& larger)

Poor bend field quality (grad. + sext.) – $\Delta E/E$ scan shows 1st & 2nd-order $\eta$

Screen image biased by COTR – wires vibrate – variable results (& in $y$)

Bends will be upgraded in fall ’07 + proper chirp set (now >2% $\rightarrow$ 1.6%)

Light Sources - January 14-18 2007

D.H. Dowell, S. Lidia, J.F. Schmerge
Transverse Cavity (RF-Deflector) Measurements of Bunch Length

Deflector OFF  Deflector ON  Deflector ON in Dispersion Region

RF Gun
Gun Solenoid
Gun Spectrometer
RF Deflector

2-km point in 3-km SLAC linac ↑

L0a, L0b, L1S, BC1, X-band RF acc. section
Linearization of Longitudinal Phase Space Measured Using the RF Deflector & OTR Screen in Center of BC1

X-band OFF

X-band ON
Bunch Length Measurements at 135 MeV & 15 GeV

Beam Energy 135 MeV
1.10 mm rms

Beam Energy 15 GeV
BC1 Design Compression
0.058 mm rms bunch length
L1S phase = 25 degS
L1X phase = -30 degX
Klystron drive at 60%.

Max Compression
10.3 ps
1.7 ps
0.89 ps

97 A
520 A
950 A

135 MeV
15 GeV
15 GeV
### Design and Demonstrated Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>sym</th>
<th>dsgn</th>
<th>meas.</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final injector $e^-$ energy</td>
<td>$\gamma mc^2$</td>
<td>14</td>
<td>16</td>
<td>GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>$Q$</td>
<td>1</td>
<td>1</td>
<td>nC</td>
</tr>
<tr>
<td>Init. bunch length (fwhm)</td>
<td>$\Delta t_0$</td>
<td>9</td>
<td>11</td>
<td>ps</td>
</tr>
<tr>
<td>Fin. bunch length (fwhm)</td>
<td>$\Delta t_f$</td>
<td>2.3</td>
<td>0.4-10</td>
<td>ps</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>$I_{pk0}$</td>
<td>100</td>
<td>100</td>
<td>A</td>
</tr>
<tr>
<td>Projected norm emittance</td>
<td>$\gamma e_{x,y}$</td>
<td>1.2</td>
<td>1.2</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>Slice norm. emittance</td>
<td>$\gamma e_{x,y}^s$</td>
<td>1.0</td>
<td>0.9</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>Slice energy spread (rms)</td>
<td>$\gamma e_{x,y}^s$</td>
<td>&lt;5</td>
<td>&lt;6</td>
<td>keV</td>
</tr>
<tr>
<td>Single bunch rep. rate</td>
<td>$f$</td>
<td>120</td>
<td>10-30</td>
<td>Hz</td>
</tr>
<tr>
<td>RF gun field at cathode</td>
<td>$E_g$</td>
<td>120</td>
<td>110</td>
<td>MV/m</td>
</tr>
<tr>
<td>Laser energy on cathode</td>
<td>$u_l$</td>
<td>250</td>
<td>300</td>
<td>$\mu J$</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>$\lambda_l$</td>
<td>255</td>
<td>255</td>
<td>nm</td>
</tr>
<tr>
<td>Laser diameter on cath.</td>
<td>$2R$</td>
<td>1.5</td>
<td>1.7</td>
<td>mm</td>
</tr>
<tr>
<td>Cathode material</td>
<td>-</td>
<td>Cu</td>
<td>Cu</td>
<td></td>
</tr>
<tr>
<td>Cathode quantum eff.</td>
<td>$QE$</td>
<td>6</td>
<td>2</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Commissioning duration</td>
<td>-</td>
<td>8</td>
<td>5</td>
<td>mo</td>
</tr>
</tbody>
</table>