ELECTRON BEAM LOSS IN THE LCLS

<table>
<thead>
<tr>
<th>Authors</th>
<th>Date</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>

**Brief Summary:**
This specification summarizes various electron beam loss mechanisms, locations, and nominal as well as worst-case power levels. Maximum credible beam power is estimated at various locations and allowable beam power loss thresholds are documented, based on shielding limitations. A convenient summary table is listed on the first page with supporting details in the text sections to follow.
Change History Log:

<table>
<thead>
<tr>
<th>Rev Number</th>
<th>Revision Date</th>
<th>Sections Affected</th>
<th>Description of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Jan. 17, 2006</td>
<td>All</td>
<td>Initial Version</td>
</tr>
<tr>
<td>1</td>
<td>June 7, 2006</td>
<td>All</td>
<td>Add forward power limit at dump/FEE wall; add Fig. 1 and update Fig. 2; add MCP at FCG1; add <em>Losses in the Injector</em> - Section 2. Finally, add undulator damage loss estimates.</td>
</tr>
<tr>
<td>2</td>
<td>June 22, 2006</td>
<td>Section 2</td>
<td>Eliminate BC2 insertable stopper (TD21)</td>
</tr>
<tr>
<td>3</td>
<td>Oct. 18, 2006</td>
<td>Section 4</td>
<td>Correct error in end-of-linac max. credible beam power, from 60 kW to 100 kW and in dump power from 18 kW to 100 kW.</td>
</tr>
<tr>
<td>4</td>
<td>Oct. 27, 2006</td>
<td>Table 2</td>
<td>Correct error in dark current entries of Table 2. The text above Table 2 was always correct, but the table entries had a few errors.</td>
</tr>
<tr>
<td>5</td>
<td>July 23, 2007</td>
<td>Section 3</td>
<td>Refine section on beam loss in the BYD dump magnets (add last two paragraphs).</td>
</tr>
<tr>
<td>6</td>
<td>Aug. 14, 2007</td>
<td>Section 3</td>
<td>Refine section on beam loss in the BC2 (added first paragraph in section 3 and entry to Table 4).</td>
</tr>
<tr>
<td>7</td>
<td>Sep. 7, 2007</td>
<td>Add Section 5</td>
<td>Add new section 5 which describes usage estimates for Tune-up Dumps, Wires, and Screens in the LTU/undulator.</td>
</tr>
<tr>
<td>8</td>
<td>Nov. 17, 2008</td>
<td>Modify BFW text in Section 5</td>
<td>Alter usage estimates for BFWs.</td>
</tr>
</tbody>
</table>

Check the LCLS Project website to verify that this is the correct version prior to use.
Electron Beam Loss in the LCLS

Although the LCLS accelerator generates and transports a high-brightness electron beam, there are still various mechanisms and locations which will produce beam loss in nominal operating conditions, special tune-up configurations, and rare worst-case accident scenarios. Such situations include normal beam collimation, insertable beam stoppers and kickers, and worst-case transport of the maximum credible beam power from the RF photocathode gun. This note lists recognized sources of beam loss and documents several average power threshold levels where a beam shut-off or machine rate-limit is required.

1 Summary of Results

For convenience, the beam power levels described in this document are summarized here. The supporting details are given in the text to follow under the indicate document section number.

Table 1. Beam power level summary (see text in sections below for details).

<table>
<thead>
<tr>
<th>Description</th>
<th>machine location</th>
<th>$P$ [kW]</th>
<th>document section</th>
</tr>
</thead>
<tbody>
<tr>
<td>'design-to’ spec.</td>
<td>main dump (120 Hz) [3]</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>'design-to’ spec.</td>
<td>abort dump (120 Hz)</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>'design-to’ spec.</td>
<td>undulator tune-up dump (10 Hz)</td>
<td>0.42</td>
<td>2</td>
</tr>
<tr>
<td>allowable continuous loss</td>
<td>one undulator segment</td>
<td>$10^{-5}$</td>
<td>2</td>
</tr>
<tr>
<td>allowable continuous loss</td>
<td>full undulator channel</td>
<td>$10^{-4}$</td>
<td>2</td>
</tr>
<tr>
<td>Max. avg. beam power loss</td>
<td>BTH enclosure and Und. Hall (lateral shielding)</td>
<td>0.005</td>
<td>3</td>
</tr>
<tr>
<td>Max. avg. beam power loss</td>
<td>collimation section of BTH (locally shielded)</td>
<td>0.020</td>
<td>3</td>
</tr>
<tr>
<td>Max. avg. beam power loss</td>
<td>main dump line (lateral shielding)</td>
<td>0.005</td>
<td>3</td>
</tr>
<tr>
<td>Max. avg. beam power loss</td>
<td>forward power at dump-FEE wall</td>
<td>0.020</td>
<td>3</td>
</tr>
<tr>
<td>Max. credible beam power</td>
<td>entrance to L1 linac</td>
<td>0.9</td>
<td>4</td>
</tr>
<tr>
<td>Max. credible beam power</td>
<td>135-MeV spectrometer</td>
<td>5.0</td>
<td>4</td>
</tr>
<tr>
<td>Max. credible beam power</td>
<td>end of linac through DL2 bends</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>Max. credible beam power</td>
<td>main dump</td>
<td>100</td>
<td>4</td>
</tr>
</tbody>
</table>

2 Nominal Beam Loss and Losses in Special Machine Configurations

Losses in the Injector
The LCLS Injector is located in the off-axis housing at Sector 20, consisting of a photocathode RF gun followed by two 3-m long accelerating RF sections, L0-a and L0-b. Figure 1 gives the locations of the radiation sources in the gun-to-linac region, due to nominal beam stopped by various intercepting diagnostics. These levels are due to the nominal 1-nC photocurrent beam at 120 Hz.

**Nominal operation**
120 Hz., 1 nC, 6.2 MeV
0.744 watts Stopped in
Either FC01/YAG01, FCG1 or YAG02

**Figure 1.** Nominal beam loss locations in the gun-to-linac region, not including dark current.

In addition to the 1-nC photocurrent beam, there is also a charge contribution from dark current (field emission) both in the gun (up to 3 nC [1]) and the accelerator sections. Nearly all the gun dark current is lost in the gun-to-linac region. The dark current produced in the accelerating sections is 0.019 $\mu$A for each structure, and for the worse case it is assumed this beam is accelerated through both structures. The dark current beam power produced in the L0-a structure is estimated at: $(0.019 \mu$A)$ \times (62 \text{ MeV} - 6 \text{ MeV}) = 1.1 \text{ W}$. Similarly L0-b can produce another $(0.019 \mu$A)$ \times (135 \text{ MeV} - 62 \text{ MeV}) = 1.4 \text{ W}$, due to its dark current plus $(0.019 \mu$A)$ \times (135 \text{ MeV} - 6 \text{ MeV}) = 2.5 \text{ W}$, due to acceleration of the dark current from L0-a. Thus if there is no loss of the L0-a dark current, there will be two-components to the dark current energy spectrum after L0-b. Table 1 summarizes the dark current parameters for the injector.

**Table 2.** Dark current energy sources and power estimates for the LCLS injector at 120 Hz.

<table>
<thead>
<tr>
<th>where dark current is generated</th>
<th>where dark current is observed</th>
<th>dark current energy (MeV)</th>
<th>dark current charge/pulse (nC)</th>
<th>current at 120 Hz ($\mu$A)</th>
<th>average beam power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in gun</td>
<td>after gun</td>
<td>6.2</td>
<td>3</td>
<td>0.36</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Table 3 lists beamline locations where electron beam loss is likely to occur during normal operations or special beam tune-up conditions. While losses at insertable beam stoppers and Farady cups are listed, not all insertable screens are listed (except the one off-axis screen in sector 25). Accident scenarios are not included in this section. Average beam power loss is based on a single bunch charge of 1 nC, a 120-Hz repetition rate (except where MPS rate limits apply), and a final electron acceleration to 14 GeV. Dark current losses are also included based on a worst case of 3 nC from the cathode [1] integrated over the RF pulse duration, and the losses calculated along the accelerator through computer tracking. The linac $z$-coordinate is measured along the main linac axis ($z = 2032$ m at sector-21 start), while the LCLS $z'$-coordinate is measured from station-100 and parallel to the undulator axis as described in Ref. [2].

Table 3. Estimated average beam power loss and location along the LCLS in nominal and special tune-up conditions. Power levels set in bold type occur in normal operating conditions. Non-bold entries are special configurations as described in the “note” column.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Area</th>
<th>Linac z [m]</th>
<th>LCLS $z'$ [m]†</th>
<th>Energy [GeV]</th>
<th>Power [W]</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC01</td>
<td>Gun Faraday cup</td>
<td>gun</td>
<td>2018.42</td>
<td>-</td>
<td>0.006</td>
<td>3</td>
<td>$aa$</td>
</tr>
<tr>
<td>FCG1</td>
<td>Spec. Faraday cup</td>
<td>gun</td>
<td>2018.47</td>
<td>-</td>
<td>0.006</td>
<td>0.7</td>
<td>$aa$</td>
</tr>
<tr>
<td>GSDMP</td>
<td>gun-spec. dump</td>
<td>gun</td>
<td>2018.44</td>
<td>-</td>
<td>0.006</td>
<td>0.7</td>
<td>$a$</td>
</tr>
<tr>
<td>SDMP</td>
<td>inj.-spec. dump</td>
<td>SAB</td>
<td>2036.08</td>
<td>-</td>
<td>0.135</td>
<td>16</td>
<td>$b$</td>
</tr>
<tr>
<td>BX01</td>
<td>DL1 bend chamber</td>
<td>DL1</td>
<td>2032.07</td>
<td>-</td>
<td>0.135</td>
<td>2</td>
<td>$c$</td>
</tr>
<tr>
<td>L1X</td>
<td>X-band struc. iris</td>
<td>BC1</td>
<td>2044.76</td>
<td>-</td>
<td>0.260</td>
<td>$0.5$</td>
<td>$c$</td>
</tr>
<tr>
<td>CE11</td>
<td>energy collimator</td>
<td>BC1</td>
<td>2049.34</td>
<td>-</td>
<td>0.250</td>
<td>$&lt; 0.1$</td>
<td>$c$</td>
</tr>
<tr>
<td>TD11</td>
<td>tune-up dump</td>
<td>BC1</td>
<td>2058.57</td>
<td>-</td>
<td>0.250</td>
<td>30</td>
<td>$d$</td>
</tr>
<tr>
<td>CE21</td>
<td>energy collimator</td>
<td>BC2</td>
<td>2424.97</td>
<td>-</td>
<td>4.3</td>
<td>$0.3$</td>
<td>$c$</td>
</tr>
<tr>
<td>OTR_TCAV</td>
<td>OTR screen</td>
<td>Sec-25</td>
<td>2537.86</td>
<td>-</td>
<td>5.8</td>
<td>60</td>
<td>$e$</td>
</tr>
<tr>
<td>C29096</td>
<td>$y$-collimator</td>
<td>Sec-29</td>
<td>2842.50</td>
<td>-</td>
<td>11</td>
<td>3</td>
<td>$c$</td>
</tr>
<tr>
<td>C29146</td>
<td>$x$-collimator</td>
<td>Sec-29</td>
<td>2856.74</td>
<td>-</td>
<td>11</td>
<td>1</td>
<td>$c$</td>
</tr>
<tr>
<td>C29446</td>
<td>$y$-collimator</td>
<td>Sec-29</td>
<td>2893.78</td>
<td>-</td>
<td>11</td>
<td>4</td>
<td>$c$</td>
</tr>
<tr>
<td>C29546</td>
<td>$x$-collimator</td>
<td>Sec-29</td>
<td>2906.12</td>
<td>-</td>
<td>11</td>
<td>3</td>
<td>$c$</td>
</tr>
<tr>
<td>C30096</td>
<td>$y$-collimator</td>
<td>Sec-30</td>
<td>2945.21</td>
<td>-</td>
<td>12</td>
<td>$&lt; 0.1$</td>
<td>$c$</td>
</tr>
<tr>
<td>C30146</td>
<td>$x$-collimator</td>
<td>Sec-30</td>
<td>2958.25</td>
<td>-</td>
<td>12</td>
<td>$&lt; 0.1$</td>
<td>$c$</td>
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<tr>
<td>C30446</td>
<td>$y$-collimator</td>
<td>Sec-30</td>
<td>2995.27</td>
<td>-</td>
<td>13</td>
<td>$&lt; 0.1$</td>
<td>$c$</td>
</tr>
<tr>
<td>C30546</td>
<td>$x$-collimator</td>
<td>Sec-30</td>
<td>3007.63</td>
<td>-</td>
<td>13</td>
<td>$&lt; 0.1$</td>
<td>$c$</td>
</tr>
<tr>
<td>B50B1</td>
<td>SL2 stopper*</td>
<td>BSY</td>
<td>3070.00</td>
<td>22.00</td>
<td>14</td>
<td>1650</td>
<td>$f$</td>
</tr>
</tbody>
</table>
Table 3 Notes:

aa. This loss occurs only when this Faraday cup is inserted (6 MeV, 120 Hz).

a. This loss occurs only with beam on the gun spectrometer (6 MeV, 120 Hz).

b. This loss occurs only with beam on the injector spectrometer (135 MeV, 120 Hz).

c. This is a normal loss due primarily to dark current from gun and injector.

d. This loss occurs only with beam on this tune-up dump (120 Hz).

e. This loss occurs only with beam on the sector-25 off-axis transverse RF deflector screen during bunch length measurements (6 GeV, ~10 Hz).

f. This loss occurs only with beam on the BSY SL2 stoppers (14 GeV, 120 Hz).

g. This loss occurs only with beam kicked into the abort dump (14 GeV, 120 Hz).

h. This loss occurs only with beam on this tune-up dump (14 GeV, 10-Hz rate limit).

i. This is the main beam dump where the full beam power is deposited (14 GeV, 120 Hz).

These losses are the expected nominal levels, not the upper-limit design values. As stated in the Global Requirements Document [3] the main dump will be designed for a 5-kW power, as will the abort dump, TDKIK. The insertable stopper just upstream of the undulator, TDUND, will be designed for a 10-Hz maximum machine rate with a maximum average beam power of 420 W.

The nominal beam loss in the undulator channel will be controlled to very low levels using beam collimators in both the linac and the LTU beamlines to clean up beam halo and dark current. Primary betatron collimation is included in the main linac, some 600 meters upbeam of the undulator, and secondary betatron collimation is located in the LTU, within 50 meters of the undulator. Primary and secondary energy collimation is accomplished in the LTU, about 200 meters upbeam of the undulator, and a final fixed aperture, 1-m long protection collimator is located 1 meter before the undulator completely shadowing the undulator.
These collimators and apertures, together with radiation monitors distributed throughout the undulator, must protect the undulator magnets by limiting continuous beam power loss to a roughly estimated level of 10 mW in any segment, and 100 mW ($6\times10^{-5}$ relative loss) in the entire undulator line (channel). At 10-mW of power loss continuously deposited into one undulator segment, the permanent magnet undulator fields will be degraded by about 0.01% in roughly 1 year. One year is the approximate planned period of time between undulator segment validations when the segment is removed, retuned, and replaced.

3 Beam Loss Assumptions for Shielding Calculations

Although no significant beam loss is expected under normal operation, the first and second bunch compressor chicanes (BC1 and BC2) jog the beam over 0.3-0.5 meters horizontally in normal operation. These chicanes are moveable with a motorized translation stage and also include a remotely controlled pair of horizontal collimator jaws. It is therefore possible to set the bend fields or beam energy inconsistently with the motorized stage position, or close the collimators, therefore intercepting the full beam power. For this reason a toroid comparator machine protection system (MPS) is used to rate limit the beam to 10 Hz when more than about 15% of the beam is lost across the chicanes. For BC1 the total beam power (1 nC, 250 MeV, 120 Hz) is only 30 W, so a 4.5-W loss (15%) is not an issue, but for BC2 (4.3 GeV) the total beam power is 520 W, so a 77-W loss has some impact on the local shielding design. Therefore, the operational loss limit is set at 100 W in BC2, but should typically be <1 W in normal conditions (see Table 3 above).

In the main dump line, for the purpose of lateral shielding calculations, the maximum allowable average beam power loss at any point from exit of FEL undulator to dump ($z' = 650$ m to 718 m), is set at **5 W**.

Similarly, for the purpose of shielding calculations, the maximum allowable average beam power loss at the collimators in the BTH where local shielding is possible ($z' = 386$ m to 514 m) is **20 W**. At locations where only the BTH enclosure wall provides shielding, including the undulator hall, the limit is **5 W**, again based on lateral shielding limitations.

To estimate shielding requirements in the forward direction at the Beam Dump-FEE wall, we start with a scenario where a few beamline locations each simultaneously produce a 5 W electron loss. Specifically, we require shielding at the BD/FEE wall against simultaneous 5-W losses at the four most likely loss points: 1) CEDL1 ($z' = 224$ m), CX35 ($z' = 456$ m), PCMUON ($z' = 514$ m), and the first dump bend, BYD1 ($z' = 647$ m). Due to their longitudinal separation such simultaneous losses will not affect lateral shielding required. However, radiation from such losses can, to some extent, add up in the forward direction resulting in up to a 20-W beam loss.
In the worst case, where the full 20-W electron beam loss is at a single point at the start of the BYD1 magnet, and horizontally offset by about 18 mm (hitting the chamber wall there), this will be considered a “mis-steering” event and will trip off the LCLS beam.

For the less severe case, where the 20-W beam loss is uniformly distributed over the entire length of the BYD1 dipole (and horizontally offset by 18 mm), this distributed 20-W loss is an acceptable (nominal) level for LCLS operation.

**Table 4.** Maximum beam power loss assumptions used for shielding calculations.

<table>
<thead>
<tr>
<th>Description</th>
<th>shielding</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. loss across BC2 chicane</td>
<td>locally shielded</td>
<td>100</td>
</tr>
<tr>
<td>Abort dump (TDKIK)</td>
<td>locally shielded</td>
<td>5000</td>
</tr>
<tr>
<td>electron transport line in BTH &amp; Undulator Hall</td>
<td>housing provides shielding</td>
<td>5</td>
</tr>
<tr>
<td>collimation section in BTH</td>
<td>locally shielded</td>
<td>20</td>
</tr>
<tr>
<td>TDUND tune-up dump</td>
<td>locally shielded</td>
<td>420</td>
</tr>
<tr>
<td>main dump transport line</td>
<td>housing provides shielding</td>
<td>5</td>
</tr>
<tr>
<td>max. total beam power in the forward direction</td>
<td>housing provides shielding</td>
<td>20</td>
</tr>
<tr>
<td>main electron dump</td>
<td>locally shielded</td>
<td>5000</td>
</tr>
</tbody>
</table>

### 4 Maximum Credible Beam Power

This section describes the maximum credible beam power the LCLS injector can produce and lose at various locations along the beamline. The estimation procedure is based upon three previous reports [4, 5, 6].

The source of maximum credible beam results from explosive electron emission in the photocathode if the drive laser intensity exceeds the threshold for plasma production. In this event, the gun’s RF field can extract a large number of electrons which are accelerated out of the gun and into the beamline. This emission persists until it has depleted the gun of all its energy. Hence the number of electrons emitted per pulse is limited by the amount of stored RF energy in the gun. This type of emission is highly undesirable, as it causes permanent damage to the cathode. A drawing of the injector beamline is shown in the Fig. 1 for reference.

The maximum stored energy in the gun is \( 10 \text{ J} \) for operation at 140 MV/m [7]. Due to beam loading the average electron energy will be reduced from 7 to 4 MeV, therefore the maximum charge per pulse the gun can produce is \( (10 \text{ J})/(4 \text{ MeV}) = 2.5 \mu \text{C} \), which, for a repetition rate of 120 Hz,
gives an average current of 0.30 mA. Previous studies [4, 5] showed that 85% of this beam is lost between the gun and first linac section (L0-a), therefore the average beam power deposited in this region is $(4 \text{ MeV}) \times (0.30 \text{ mA}) \times (85\%) \approx 1.0 \text{ kW}$.

With the gun spectrometer bend magnet ($BXG$, see Fig. 1) switched on and set for the maximum charge transmission at 4 MeV, the maximum credible beam power incident on the gun-spectrometer Faraday cup ($FCG1$, see Fig. 1) can be estimated by still assuming that 85% of the beam power is lost prior to this point (conservatively includes beam losses up to and including the $BXG$ dipole). This sets the maximum credible beam power on $FCG1$ at $(4 \text{ MeV}) \times (0.30 \text{ mA}) \times (15\%) = 180 \text{ W}$.

The time to deplete the gun of its 10 Joules is approximately 300 ns [6], giving a macro-pulse beam current of $(2.5 \mu\text{C})/(300 \text{ ns}) \approx 8.3 \text{ A}$. With 85% lost in the gun region, 1.2 A (0.38 $\mu$C) are left to enter the L0-a section.

Figure 2. A drawing of the injector beamline from gun to main linac injection.

The beam-loaded energy gain in one 3-m SLAC RF structure is given by [8]

$$\Delta E[\text{MeV}] \approx 10.6 \sqrt{P[\text{MW}]} - 38.3 \cdot I_b[\text{A}],$$
where $P$ is the structure power and $I_b$ is the average beam current over the macro pulse (bunch train). The maximum RF power that the L0-a structure can operate at is 42 MW [9], resulting in $I_b \approx 1.8$ A as the maximum current the structure can accelerate. The available current of 1.2 A is less than this limit and will therefore be accelerated through L0-a, but due to beam loading it will have a large energy spread, 21 to 76 MeV, with an average energy of 48 MeV. The average beam power at the exit of L0-a is computed using this average energy: $(48 \text{ MeV}) \times (0.38 \mu\text{C}) \times (120 \text{ Hz}) \approx 2.2$ kW.

The quadrupole magnets between L0-a and L0-b are set to transport 64 MeV electrons and will therefore over-focus the electrons causing many to be lost in the L0-b structure. Thus the maximum power deposited in L0-b is approximately the full beam power of 2.2 kW.

In the event the quadrupoles are turned OFF, this beam can also be accelerated through L0-b. In this case, the beam will exit L0-b with a range of energies between 56 to 160 MeV, based upon the maximum available RF power of 62 MW [9] and beam loading, producing an average beam energy of $(160 \text{ MeV} + 56 \text{ MeV})/2 \approx 110$ MeV and an average power of $(110 \text{ MeV}) \times (0.38 \mu\text{C}) \times (120 \text{ Hz}) \approx 5.0$ kW after L0-b.

The beam now has one of two possible fates. If the DL1 bend dipoles are switched off, it will drift into the straight ahead spectrometer and be lost in and after the spectrometer dipole. If the DL1 dipoles are turned on, then most of the beam will be lost in and immediately after the first dipole. However, electrons with energies within the energy acceptance of the DL1 bend will be transported to the main linac. The DL1 energy acceptance is ±5% (1-inch ID) and for nominal operation is centered at 135 MeV, thus the energy spread is $(\pm 5\%) \times (135 \text{ MeV}) \approx \pm 6.8$ MeV, or about 14 MeV total width. This width represents $(14 \text{ MeV})/(110 \text{ MeV}) \approx 13\%$ of the charge, which will be transported through the bends and onto the axis of the main linac. Therefore the power in this transported beam will be $(13\%) \times (0.38 \mu\text{C}) \times (110 \text{ MeV}) \times (120 \text{ Hz}) \approx 0.6$ kW.

The DL1 magnets are able to transport a beam energy up to at least 180 MeV [10]. Since the maximum electron energy in this case is 160 MeV, and the energy acceptance is ±5%, the highest energy with maximum charge transmission is $(1 - 5\%) \times (160 \text{ MeV}) \approx 150$ MeV. In this worst case scenario, the beam which is transported to the main linac will be centered on 150 MeV and have an average power of $(13\%) \times (0.38 \mu\text{C}) \times (150 \text{ MeV}) \times (120 \text{ Hz}) \approx 0.9$ kW.

With the DL1 magnet settings at 150 MeV (worst case), this 0.9-kW beam with energy up to 160 MeV will be accelerated in the main linac. The DL1 beam loss will reduce the current in the macro pulse from 1.2 A down to 0.16 A (13% transmission). In the worst (unusual) case, with both bunch compressor chicanes switched off, some of this charge will be accelerated. It is difficult to predict the charge loss in the linac based on over- or under-focusing through the many quadrupole magnets, since there are many possible quadrupole settings that can impact beam transmission. Ignoring this potentially large charge loss in the linac, with all klystrons switched on allowing a 17-GeV maximum energy at crest phase, and including the beam loading of 850 meters of SLAC RF structures at a
current of 0.16 A, the full energy range is 15 to 17 GeV \((i.e., \pm 6\%\) energy spread) with an average energy of 16 GeV. This gives a maximum (over-estimated) power of \((0.9\ kW) \times (16\ GeV)/(0.15\ GeV) \approx 100\ kW\) at the end of the linac, ignoring all linac losses.

If the dog-leg bend system (DL2), after the linac and prior to the undulator, is switched off, this 100-kW power will be deposited in the DL2 bends (in the BSY enclosure). If the bends are switched on, the system has an energy acceptance of about \(\pm 10\%\) (1-inch ID), which passes the full bunch charge through the DL2 bends. The maximum dump line power is then the same as the end-of-linac power, at 100 kW. The actual power will be less than this due to beam loss in the linac with large energy spread, which is difficult to estimate with high confidence and not taken credit for here.

As a simple sensitivity test, if the beam transmission across the gun is improved from 85\% to 75\%, the final end-of-linac and main dump power levels increase by less than a factor of two, while the L0-b exit power increases from 5 kW to 6.5 kW, the relative insensitivity due to increased beam loading when transmission improves.

### Table 5. Summary of maximum credible beam power levels along the injector.

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Energy (GeV)</th>
<th>Charge per pulse (μC)</th>
<th>Current at 120 Hz (μA)</th>
<th>Beam Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun exit</td>
<td>0.004</td>
<td>2.5</td>
<td>300</td>
<td>1.2</td>
</tr>
<tr>
<td>Beam loss in gun region</td>
<td>0.004</td>
<td>2.1</td>
<td>260</td>
<td>1.0</td>
</tr>
<tr>
<td>Beam on FCG1 Faraday cup in gun spectrometer</td>
<td>0.004</td>
<td>0.38</td>
<td>45</td>
<td>0.18</td>
</tr>
<tr>
<td>L0-a exit</td>
<td>0.048</td>
<td>0.38</td>
<td>45</td>
<td>2.2</td>
</tr>
<tr>
<td>Max. beam loss in L0-b</td>
<td>0.048</td>
<td>0.38</td>
<td>45</td>
<td>2.2</td>
</tr>
<tr>
<td>L0-b exit</td>
<td>0.110</td>
<td>0.38</td>
<td>45</td>
<td>5.0</td>
</tr>
<tr>
<td>Beam loss at straight ahead spectrometer</td>
<td>0.110</td>
<td>0.38</td>
<td>45</td>
<td>5.0</td>
</tr>
<tr>
<td>Beam transported to main linac (nom. DL1 setting)</td>
<td>0.110</td>
<td>0.050</td>
<td>6.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Beam transported to main linac (max. DL1 setting)</td>
<td>0.150</td>
<td>0.050</td>
<td>6.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Beam transported to end of linac (over-estimate)</td>
<td>16</td>
<td>0.050</td>
<td>6.0</td>
<td>100</td>
</tr>
<tr>
<td>Beam transported to main dump (over-estimate)</td>
<td>16</td>
<td>0.050</td>
<td>6.0</td>
<td>100</td>
</tr>
</tbody>
</table>

5 Usage Estimates for Tune-up Dumps, Wires, and Screens in the LTU/undulator

The following are the usage-time estimates for the several components which generate beam loss in the LTU and undulator sections. We also differentiate the first commissioning year from the later operating stages. These numbers are difficult to estimate with a high confidence level, so we stress
that there is a significant margin of error in these values. The various component estimates are as follows:

**Single-Beam Dumper (SBD):**

This is a pulsed vertical dipole (BYKIK) which kicks the unwanted electron pulses downward into a local dump (TDKIK), which is just 2 cm below the beam axis and located between the first two LTU dipoles, BX31 and BX32. The SBD is capable of dumping a 120-Hz beam at full power (see PRD 1.3-014).

We estimate that the first year of LTU commissioning (early spring of 2008 at ≤30 Hz) will require an average of 1 hour per day of 30-Hz beam on the SBD, or about 4% of the beam pulses. This should drop by perhaps a factor of 10 after commissioning, to 0.4% of the pulses (but the beam rate may then increase to 120 Hz). These tuning-time estimates are in addition to the continuous beam aborts which may occur at a rate of about 1 abort/sec, or another 3% of all beam pulses aborted into the SBD, for a total of 7% of all beam pulses aborted into the SBD in the first year (at 30 Hz or less). After commissioning, and at an increased beam rate of 120 Hz, the continuous rate of 1 abort/sec will likely continue and produce 0.8% of all beam pulses aborted into the SBD. Therefore, a total of about 1% of all beam pulses will be aborted into the SBD after commissioning.

**Insertable Tune-up Dump (TDUND):**

This is an insertable beam stopper which is located a few meters upstream of the undulator. This device will rate limit the LCLS beam to 10 Hz when inserted (see PRD 1.3-021). This will be the main tune-up dump used to stop beam before the undulator.

We estimate the TDUND stopper may be inserted for 2 hrs per day in the first year of commissioning, or about 8% of all 10-Hz beam pulses (<8% if beam rate with TDUND OUT is >10 Hz). This may drop to below 1% after commissioning.

**LTU Wire Scanners (WS31-34):**

The LTU wire-scanners (see PRD 1.1-323) are located within about 100 meters of the undulator and are used to measure electron beam emittance.

There are four 40-micron diameter carbon wire scanner units, each with 2 wires (x & y) per scanner. Estimating 10 full scans in x and y over all scanners per day at a 30-Hz beam rate (assuming 50 beam shots per scan), we find that 0.2% of all beam pulses will interact with a wire. This number may be 2-3 times larger during initial commissioning, but should diminish to this 0.2% level, or lower, after commissioning.

**Beam Finder Wires (BFW01 – BFW33):**

The beam finder wires (BFW) are insertable 40-micron diameter carbon wires (x and y) at the entrance to every 3.4-m long undulator section (PRD 1.4-004). These are used to align the undulator sections to the beam in x and y.
There are 33 BFW's in the undulator, each with 2 wires/BFW. When a single BFW is inserted (only one at a time) the beam rate will be set to 'one-shot' mode (zero-rate) by the MPS system by firing the BYKIK abort, meaning no beam is transported through the undulator until the user or the controls software sends a one-shot request. The one-shot request will send only $N_{\text{avg}} = 1$ to 10 beam pulses immediately, at whatever beam rate is present. The number of beam shots is a user option, and will not exceed 10 per one-shot request. The undulator, and therefore the BFW, will then be moved in position ($x$ or $y$) by about 10 µm and another one-shot will be sent. This sequence will continue until the undulator is scanned over a range of about ±400 µm. With a nominal 36-µm rms beam size ($x$ and $y$), only about 10 consecutive girder positions will intercept any significant beam intensity, meaning only $10 \times N_{\text{avg}} \leq 100$ beam pulses will intercept the wire per BFW scan. With one full scan per day, multiplied by 33 BFWs, and 2 wires per BFW, there will be $\leq 100 \times 33 \times 2 = 6600$ beam pulses intercepting BFW wires per day. At a 30-Hz nominal beam rate the usage fraction then becomes $6600/(24 \times 60 \times 60 \times 30) = 0.25\%$ of all beam pulses interact with a BFW. The number of BFW scans per day will drop by at least a factor of ten after initial commissioning and at 120 Hz the usage rate then becomes just 0.006\%.

**OTR Screens (OTR30, OTR33, and OTRDMP):**

The OTR screens are thin (1-micron) aluminum foils which insert into the beam and are used to measure the transverse beam size using a CCD camera (see PRD 1.3-020). These screens rate limit the machine to 10 Hz when inserted. They also generate almost no beam loss and simply blow up the beam size by a factor of 3-4. There are two OTR screens in the LTU and one in the dump-line. (Most likely the SBD or TDUND will be used to stop the beam prior to the undulator when OTR30 or OTR33 are inserted, while OTRDMP is located well after the undulator, near the main dump).

We assume that just one, or any combination, of these screens is inserted for a total of up to 1 hour each day during initial commissioning (i.e., 36000 beam pulses on any combination of these 3 screens per day at 10 Hz). Using a nominal beam rate of 30 Hz with screen out, this will mean that 1% of all beam pulses interact with a screen. This number will drop by at least a factor of 10 after commissioning.

**Table 6.** Summary of usage estimates.

<table>
<thead>
<tr>
<th>Source</th>
<th>1st year commissioning</th>
<th>After commissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>beam rate [Hz]</td>
<td>fractional loss [%]</td>
</tr>
<tr>
<td>SBD</td>
<td>30</td>
<td>7</td>
</tr>
<tr>
<td>TDUND</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>LTU wires</td>
<td>30</td>
<td>0.4</td>
</tr>
<tr>
<td>BFW's</td>
<td>30</td>
<td>0.25</td>
</tr>
<tr>
<td>OTR screens</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

**References**

Check the LCLS Project website to verify that this is the correct version prior to use.