LCLS-II MPS Beam Class Definition

LCLS-II-TN-20-12

(Dec. 2020, R1.0)

Y. Ding, J. Welch, J. Mock

(SLAC)
1 Introduction

Based on the LCLS-II machine protection PRD [1] and the ESD [2], a “Beam Class” (or sometime also called “beam power class”) concept has been adopted in the Machine Protection System (MPS). In this note we define various Beam Classes and provide a rationale for the choices.

Beam Classes are used to define limits on the beam when devices are inserted into the beam and to classify the operating limits under certain conditions. Each Beam Class is defined by three input parameters:

1. the minimum bunch spacing (including non-periodic bunch patterns), $dt$;
2. the integration time window, $\Delta T$;
3. the maximum beam charge $Q$ integrated in $\Delta T$.

Based on the ESD, each Beam Class is assigned a number, including 0 for “no beam”, with higher numbers for beams that are “more powerful”. Note that Beam Class definitions do not directly depend on beam power. If a device operating limit is set by beam power (where energy is needed together with charge and integration time to calculate the beam power), then to determine the Beam Classes allowed for that device, we also need to know or assume a beam energy at that device location.

In the next section we list most of the known LCLS-II SC-linac beamline device operating limits. We then define and discuss 11 Beam Classes. In the last section we discuss how the MPS response to faults depends on Beam Classes.

2 Device operating limits and Beam Classes

By design some devices intercept the electron beam, such as profile monitors, wire scanners, tuneup dumps, etc. The device operating limits are typically defined by the maximum sustainable absorbed beam power, and depends on thermal and mechanical properties, cooling system limitations, and the shielding design around the device. In some cases operating limits are estimated only by previous experience where only the maximum safe repetition rate is known.

Here is a list of the most common insertable devices and the fixed dumps in LCLS-II design and the assumed operating limits.

- Vacuum valves, no beam allowed when vacuum valves are closed, unlimited beam when open.
- Profile monitor YAG/OTR screen in the gun area, $\leq 10$ Hz when inserted, unlimited beam when retracted.
- Profile monitor YAG/OTR screen in downstream of the gun area, $\leq 100$ Hz when inserted, unlimited beam when retracted.
• TDUND, at the entrance of the HXR undulator, 140 W \[4\], when inserted, unlimited beam when retracted.

• Three fixed final dumps (without rastering), 120 kW;

• Three fixed final dumps (with future rastering magnets to be added by LCLS-II-HE project), 240 kW.

• PPS stoppers, no-beam allowed when inserted, unlimited beam when retracted.

• D2 insertable dump, no SC beam allowed when inserted, unlimited beam when retracted.

• TDKIK and TDKIKS, no SC beam allowed when when kicker is operating, unlimited SC beam when kicker is not operating.

All fixed dumps will have a single maximum allowed Beam Class which corresponds to the assumed operating limit. All insertable devices (and devices that depend on kickers for beam) will have a maximum allowed Beam Class when inserted (or when the kicker is active) and a different beam class when retracted (usually unlimited).

During commissioning and early stage operation, additional Beam Classes can be useful that are administrative and not based on the device limits. This administrative control provides an MPS controlled limit on beam that is independent of the beam classes allowed by the devices. For example, during initial commissioning of the SC linac we really want to avoid accidentally losing more than about 10 W in a cryomodule. We may want to set the administrative limit to Beam Class 3 (12 W at 4 GeV) until we are sufficiently confident to proceed to higher beam classes.

3 Beam Class definitions

Considering the above discussed device limits and administrative control needs, we define 11 Beam Classes (listed in Table 1) and discuss the possible use cases for each class.

• Beam Class 0: beam off and kicker off. There will be no photo-electrons at this beam class (The UV laser is blocked to avoid illuminating the gun cathode). However the gun/linac RF can still be on and the dark current will be produced and going as far as the BSY dump and the spreader kicker. The spreader kicker is off. Downstream of the spreader kicker there is no photo-electron or dark current. This is an administrative Beam Class.

• Beam Class 1: beam is off and the spreader kicker is on standby. The “standby” mode of the kickers is set by the timing system when they are not timed to kick photo-electron bunches. With this standby mode, no
photo-electron bunch will be kicked to the post-spreader beamline areas, but it is still possible for dark current to go past the kickers. This class differs from Beam Class 0 only for beam paths downstream of the spreader kicker.

- Beam Class 2: Pilot beam with 1-Hz rate limit (minimum bunch separation is limited to $\geq 1$ second). This class can be used to recover the beam when there is MPS fault from BPM orbit deviation or from a beam loss monitor.

- Beam Class 3: Diagnostic-I with 10 Hz (minimum bunch separation is limited to $\geq 0.1$ second). This class will be assigned to the injector area profile screens and other profile screen monitors if the cameras are not ready for taking data at 100 Hz. The only input parameter for this beam class is the minimum bunch spacing, and there is no limit on the charge or time window.

- Beam Class 4: Diagnostic-II ($\Delta T = 0.5 \, s, \, Q \leq 5000 \, pC$, equivalent maximum average current is 10 nA). This is a power/current that is generally safe even for diagnostic purpose, without a beam rate limit. The power would be 40 W at 4 GeV. This is also the maximum Beam Class for TDUNDB.

- Beam Class 5: 100 Hz maximum beam rate. This class will be assigned to the DIAG0 line with limiting the beam rate and maximum allowed power. This 100-Hz rate beam class can also be used for future profile screen monitors when the cameras are ready for taking data at 100 Hz.

- Beam Class 6: General tuning ($\Delta T = 0.2 \, s, \, Q \leq 7000 \, pC$, equivalent maximum average current is 35 nA, any beam rate). This is also the maximum beam class for TDUND (at 4 GeV the maximum power is 140 W at this class).

- Beam Class 7: 1% of Maximum Allowed Power (MAP) (1.2 kW at 4 GeV). This is an administrative beam class with the maximum beam power at this class is 1.2 kW at 4 GeV, which is at the lower end of the high power operating range (1% of the full power). This is about the similar power level for the present Cu-linac operation (for example, for beam with 15 GeV, 120 Hz and 0.3 nC, the average power is 540 W). See Beam Class 9 for the 100% MAP definition.

- Beam Class 8: 50% of Maximum Allowed Power (MAP) (60 kW at 4 GeV). ($\Delta T = 200 \, \mu s, \, Q \leq 3000 \, pC$, equivalent maximum average current is 15 $\mu A$). The maximum beam power at this class is 60kW at 4 GeV or 120 kW at 8 GeV. This is an administrative class for LCLS-II, and can also be used for LCLS-II-HE dumps when the rastering magnets are not in operating status.
• Beam Class 9: 100% Maximum Allowed Power (MAP) (120 kW at 4 GeV). 
\( \Delta T = 200 \mu s, \quad Q \leq 6000 \, \mu C \), equivalent maximum average current is 
30 \( \mu A \). This is the operating limit of the maximum beam power at the 
designed facility. For LCLS-II (with no rastering magnets before the 
dumps in the project baseline scope), the 100% MAP is 120 kW; for LCLS-
II-HE, with the rastering magnets to be added and the 100% MAP will 
be 240 kW. This class is assigned to BSY dump and the two undulator 
dumps.

• Beam Class 10: Unlimited. This can be used for burst mode, BCS tests, etc. No mitigation methods will be needed for this class.

4 MPS trip thresholds and fault recovery

During normal operation, in most cases, when an MPS fault happens the beam 
should be reduced to a 1-Hz pilot beam. The operators should be notified and 
then attempt to fix the problem with the 1-Hz beam before restoring the beam 
to the previous operating power. In the early stage of operation, the MPS fault 
recovery process should be handled manually. Auto-recovery can be developed 
later after gaining experiences from early operation.

For some particular MPS faults, we could consider more complex actions 
where MPS trip thresholds may depend on the beam class of the operating 
beam. Note the analog devices (BPMs, loss monitors, etc.) can support 8 
threshold pairs. So, one could set increasingly strict thresholds as the beam 
classes are increased. Here are a few examples.

• BPM position tolerance in non-dispersive areas: In general in the undu-
lator section we can set BPM position tolerance of \( \pm 1 \) mm and other 
(non-dispersive) areas to be \( \pm 2 \) mm. If the beam power is high this 
tight tolerance is important to avoid beam hitting on the wall due to 
mis-steering. But when we run the machine with a lower beam power 
such as at the diagnostic classes (Beam Class 4 and below), we could re-
lax or remove this threshold. One application is to take oscillation data 
for model measurement, where we need to use correctors to make an orbit 
oscillation and record the BPM readings. When the actual beam power 
is at or below the diagnostic class level, the BPM position trip threshold 
can be set bypassed entirely. For the BPM TMIT threshold, we can apply 
the similar concept. At higher beam power, the BPM TMIT variation tol-
erance should tighter than at lower beam power. Also we could consider 
evaluating a few more downstream BPM TMIT readings when one BPM 
TMIT reading is lower than the threshold before tripping the machine.

• BPM position tolerance in dispersive areas: In the dispersive area (chi-
canes, dogleg, etc.), energy variation from RF jitter or cavity trips will 
cause changes in the measured beam position in the bending plane. For 
example, BPM position readings in BC2 and the Dogleg areas could be
used to diagnose such a cavity trip, and depending on beam class, a BPM position trip threshold could be set. In general, the BPM position trip threshold can be set at the similar range of the energy collimator gap in that area. A cavity trip could be allowed when the actual beam power is at or below the diagnostics beam classes. The energy vernier should only be applied after careful test at lower power. At the downstream beamline of the spreader kicker, the trip threshold of the BPM position in the dispersive areas can be set tighter.

- **LBLM trip threshold.** The MPS LBLM trip thresholds are set to prevent thermal damage to components if the beam should accidentally strike something, except in a few cases where BCS trip thresholds are particularly low and the trip threshold is set to prevent a BCS trip. Component damage requires beam loss of at least roughly 50 J of beam energy in less than 0.5 s. Normally it would be possible to run with beam class 4 (40 W at 4 GeV) and still lose the entire beam somewhere (other than the BTH) without causing an MPS trip. But even with no photo-electron beam present there may be as much as 1 or 2 kW of beam power in dark current. So when an MPS LBLM trip occurs, the maximum allowable beam class should be set to 1 (Beam off, kicker on standby). The operators can then try to restore a pilot beam and work up from there. If the dark current is low enough they should be successful even if the mis-steering condition is still present. But if the dark current is too high, to measure and correct the orbit the operators will have to use the kicker to create single bunches.

- **For the “stay-alive” beam requirement in the BSY dump beamline,** we should only consider that requirement when the actual beam power is at or above the Beam Class 7.
Table 1: LCLS-II MPS Beam Class definition

<table>
<thead>
<tr>
<th>Index</th>
<th>Name</th>
<th>$\Delta T$</th>
<th>$dt$</th>
<th>$Q$</th>
<th>Rate @ 4 GeV</th>
<th>Current @ 4 GeV</th>
<th>Power @ 4 GeV</th>
<th>Bunch energy</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Beam and kicker off</td>
<td>0.5</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>dark current stopped</td>
</tr>
<tr>
<td>1</td>
<td>Beam off, kicker standby</td>
<td>0.5</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>dark current kicked</td>
</tr>
<tr>
<td>2</td>
<td>Pilot beam</td>
<td>1</td>
<td>1</td>
<td>330</td>
<td>1</td>
<td>0.33</td>
<td>1.32</td>
<td>1.32</td>
<td>$330 \text{ pC} \times 1 \text{ Hz}$</td>
</tr>
<tr>
<td>3</td>
<td>Diagnostic-I (10 Hz)</td>
<td>-</td>
<td>0.1</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$10 \text{ Hz}$</td>
</tr>
<tr>
<td>4</td>
<td>Diagnostic-II (10 nA)</td>
<td>0.5</td>
<td>-</td>
<td>5000</td>
<td>-</td>
<td>10</td>
<td>40</td>
<td>20</td>
<td>$50 \text{ pC} \times 200 \text{ Hz}$</td>
</tr>
<tr>
<td>5</td>
<td>100 Hz</td>
<td>0.2</td>
<td>0.01</td>
<td>6600</td>
<td>100</td>
<td>33</td>
<td>132</td>
<td>26.4</td>
<td>$330 \text{ pC} \times 100 \text{ Hz}$</td>
</tr>
<tr>
<td>6</td>
<td>Tuning</td>
<td>0.2</td>
<td>-</td>
<td>7000</td>
<td>-</td>
<td>35</td>
<td>140</td>
<td>28</td>
<td>$100 \text{ pC} \times 350 \text{ Hz}$</td>
</tr>
<tr>
<td>7</td>
<td>1% MAP</td>
<td>0.01</td>
<td>-</td>
<td>3000</td>
<td>-</td>
<td>300</td>
<td>1200</td>
<td>12</td>
<td>$100 \text{ pC} \times 3 \text{ kHz}$</td>
</tr>
<tr>
<td>8</td>
<td>50% MAP</td>
<td>$2 \times 10^{-4}$</td>
<td></td>
<td>3000</td>
<td>-</td>
<td>15000</td>
<td>60000</td>
<td>12</td>
<td>$100 \text{ pC} \times 150 \text{ kHz}$</td>
</tr>
<tr>
<td>9</td>
<td>100% MAP</td>
<td>$2 \times 10^{-4}$</td>
<td></td>
<td>6000</td>
<td>-</td>
<td>30000</td>
<td>120000</td>
<td>24</td>
<td>$100 \text{ pC} \times 300 \text{ kHz}$</td>
</tr>
<tr>
<td>10</td>
<td>Unlimited</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

References

[3] for TDUNDB, PRD defines TDUNDB 40 W; BCS limit RP-18-18-R2 defines 100W. Could evaluate later for LCLS-II-HE case to see if 8 GeV can stay at this class.
[4] for TDUND, PRD defines 140 W; radiation shielding limit 420 W, RP-RPG-111003-MEM-03 and 060-103-066-00, LCLS-II prelim rad shielding specs, and RP-17-05-R1 and RP-11-08. Could evaluate later for LCLS-II-HE case to see if 8 GeV can stay at this class.