LCLS-II Technical Note

LCLS-II MPS Beam Class Definition

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Y. Ding, J. Welch, J. Mock, W. Schlotter

(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, ΔT;
3. the maximum beam charge Q integrated in ΔT.

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, $\leq$ 120 Hz when inserted, unlimited beam when retracted.
- TDUNDB, at the entrance of the SXR undulator, 40 W [3] 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 a **master** beam class 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 a master beam class that administratively limits 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 ≥ 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**: Beam with 10 Hz limit (minimum bunch separation is limited to ≥ 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 higher rates. The maximum beam charge is based on limiting 350 pC per shot.

- **Beam Class 4**: Diagnostic beam class ($\Delta T = 0.5\ s,\ Q \leq 5000\ pC$, equivalent maximum average current is 10 nA). This is a power/current that is generally safe for diagnostic purpose. The power would be 40 W at 4 GeV. This is also the maximum Beam Class for TDUNDB.

- **Beam Class 5**: 120 Hz maximum beam rate. This class will be assigned to the DIAG0 line with limiting the beam rate and maximum allowed power. This 120-Hz rate beam class can also be used for future profile screen monitors when the cameras are ready for taking data at 120 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 12 for the 100% MAP definition.

- **Beam Class 8, 9, 10**: 5%, 10% and 25% of Maximum Allowed Power (MAP). These are three additional administrative beam classes that are defined for photon system. They can be used as a master beam class that administratively controls the beam power to be below one class. Some of the classes would also be assigned to photon system components through PMPS during early commissioning period, e.g., at a specific cooling condition or before the damage limits are fully studied.

- **Beam Class 11**: 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 μA). 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 12**: 100% Maximum Allowed Power (MAP) (120 kW at 4 GeV). ($\Delta T = 200\ \mu s$, $Q \leq 6000\ pC$, equivalent maximum average current is 30 μA). 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 13**: Unlimited beam power. 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 undulator section we can set BPM position tolerance of ± 1 mm and other (non-dispersive) areas to be ± 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 relax 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 tolerance 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 (chicanes, 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 probably only consider that requirement when the actual beam power in the linac is at or above the Beam Class 7.

5 Version history

- Version 1.0: original release
- Version 1.1: changed Beam Class 5 from 100 Hz to 120 Hz. Added Beam Class 2 with Charge limit 350 pC.
- Version 1.2: Added 3 new Beam Classes 5%, 10% and 25% MAP per photon side request. Added Bill Schlotter as coauthor.
- Version 1.3: Revised Beam Class 5 by reducing the integrated charge to be 6000 pC (previous was 8400 pC).

Table 1: LCLS-II MPS Beam Class definition

Index	Display Name	ΔT	dt	Q	Rate max	Current	Power @ 4 GeV	Int.Energy @ 4 GeV	Notes -
		s	s	pC	Hz	nA	W	J	-
0	Beam Off	0.5	-	0	0	0	0	0	Beam off, Kickers off
1	Kicker STBY	0.5	-	0	0	0	0	0	Beam off, Kickers standby
2	BC1Hz	1	1	350	1	0.35	1.4	1.4	350 pC $\times$ **1** Hz
3	BC10Hz	1	0.1	3500	10	3.5	14	14	350 pC $\times$ **10** Hz
4	Diagnostic	0.5	-	5000	-	10	40	20	50 pC $\times$ 200 Hz
5	BC120Hz	0.2	0.0083	6000	120	30	120	24	250 pC $\times$ **120** Hz
6	Tuning	0.2	-	7000	-	35	140	28	100 pC $\times$ 350 Hz
7	1% MAP	0.01	-	3000	-	300	1200	12	100 pC $\times$ 3 kHz
8	5% MAP	0.003	-	4500	-	1500	6000	18	100 pC $\times$ 15 kHz
9	10% MAP	0.001	-	3000	-	3000	12000	12	100 pC $\times$ 30 kHz
10	25% MAP	4×10^{-4}	-	3000	-	7500	30000	12	100 pC $\times$ 75 kHz
11	50% MAP	2×10^{-4}	-	3000	-	15000	60000	12	100 pC $\times$ 150 kHz
12	100% MAP	2×10^{-4}	-	6000	-	30000	120000	24	100 pC $\times$ 300 kHz
13	Unlimited	-	-	-	-	-	-	-	-

- Version 1.4: Temporally revised Beam Class 4 by adding minimum spacing in order to limit maximum rate 120 Hz. This will be used for early injector commissioning phase where limiting beam rate to 120 Hz is required before BCS certification.
- Version 1.5: Removed the 120Hz limit in Beam Class 4 Diagnostic Class which was used temporally for injector commissioning.

References

[1] MPS PRD LCLSII-2.7.PR-0078-R1.

[2] MPS ESD LCLSII-2.7-ES-0347-R0.

[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.