LCLS-II Halo Collimator Beam Related Failure Modes *

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Summary

This note describes two possible beam-related failure modes of the Halo Collimators for LCLS-II. It was prompted by remarks that a failure mode analysis could be important to the decision in an ongoing discussion of whether or not to implement cooling flow switch interlocks on each jaw. Although this note only deals with beam related failure modes, several other failure modes and risks were identified at the 'LCLS-II Halo Collimator Review, Readiness for Manufacturing' held in March 2019 [1], and the combined set of modes is reasonbly complete.

Normally there is very little interaction between the beam and the Halo Collimators because the beam halo is very weak, especially compared to the core beam, and the core beam has an extremely small size compared with the gap between the jaws.

In this note I consider hypothetical circumstances where a beam could in principle damage Halo Collimators. In particular I discuss what would happen if:

- a powerful beam strikes a jaw, or
- a weak beam hits a jaw, but there is a complete absence of jaw cooling.

In the first failure mode, powerful beam strikes, I found that MPS, implemented as assumed in this note, would provide adequate protection to complete avoid damage for any possible beam power. In the second failure mode, total absence of cooling, there would not be any permanent damage resulting to the jaw, provided the absorbed beam power is kept below 500 W, though the jaw may move slightly out of position tolerance due to thermal expansion. MPS should be able to keep the absorbed beam power well below that level.

Interlocked flow switches on the cooling circuit would prevent an out of position tolerance condition when there is a total absence of cooling. However such mitigation would have negative operational effect and is not recommended. If the flow switches merely alarmed on insufficient flow, the alarm could serve as a maintenance notice and possibly lead to earlier repair. But the net value of such an alarm would be negligible given the MPS protection from beam strikes of greater than about 100 W.

Beam Strike

A powerful beam can accidentally strike a collimator jaw either by mis-steering the beam or by putting the jaw in wrong position. LCLS-II beams can easily damage or destroy any component they strike in the entire beam line except for beam dumps. Halo Collimators are somewhat more at risk than other components because the jaws are operated relatively close to the beam.

Hazard

The Halo Collimator jaws are made of Tungsten. Tungsten has remarkable high temperature perfor-

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mance. It is extremely hard to melt because it radiates so much power well before the melting point. The most likely thing to happen when a powerful beam strikes a jaw is that the jaw shatters due to thermal shock. Pieces of the jaw may fall off and the collimator would no longer collimate the halo. A collimator edge check would show either the edge has moved a great deal or that edge cannot be detected.

The combination of high Young's modulus and low thermal conductivity lead to high internal stress from the thermal gradient generated by the narrow distribution of absorbed beam power. This failure was demonstrated in an experiment done at SLAC [2] in which a high power beam was suddenly applied to a large block of tungsten. The block completely shattered instantly. This failure mode for the Halo Collimators is discussed in [1].

Mitigation

Extensive use of radiation detectors is part of the LCLS-II upgrade. LBLMs (Line or Long Beam Loss Monitors) detect radiation from beam strikes throughout the nearly 4000 m of the accelerator housing. At critical locations PBLMs (Point Beam Loss Monitors) are deployed, including one PBLM attached to each Halo Collimator. All these detectors are connected to the MPS.

MPS can protect Halo Collimators against beam strikes using any and all of the following methods:

1. monitoring the beam position at nearby BPMs and reducing or turning off the beam if too large a deviation takes place.

2. monitoring PBLMs and reducing or turning off the beam when the beam power striking the jaw is more than 100 W.

3. monitoring LBLMs in the vicinity of the Halo Collimators and turning off or reducing the beam when the beam power is more than that allowed for area.

4. monitoring RTDs on the supply and return of each collimator for excessive ΔT, corresponding to excess absorbed power and alarming, or reducing or turning off the beam.

The first three of these methods are fast enough that very little energy can be absorbed by the jaw before the beam is rendered safe, even for the highest power beams. Using the signals from radiation detectors, MPS should be able to turn the beam within about 200 μs. In that time a 250 kW will deposit only 50 joules of energy, which is just enough to raise the average temperature the jaw by only 0.6 $^\circ C$. Simulations of thermal deposition of beam energy were done in [3].

None of these methods is expected to be completely effective. Beam position monitoring does not protect against jaw mis-positioning. LBLMs might be blind to radiation from shielded collimators or required to have a trip level for the region that is higher than that needed for the Halo Collimators. PBLMs should work but have not been employed in this application before. RTDs are too slow for protection against all but the lowest power beams. For these reason I recommend that all methods be employed by MPS.

Cooling Failure

Halo Collimators normally absorb only up to a few watts of power from the halo of the beam — often less. But on occasion it is desirable to have low power beam directly hit the collimator jaws. For example to accurately find the position of the edge of the jaw relative to a position of a low power beam, the jaw is gradually moved toward the beam until significant beam loss or beam generated radiation is observed. Nevertheless because the jaws are supported by a long 'stalk' in a vacuum vessel, even a few watts of power can eventually cause high temperature to build up, so water cooling is provided in the design. Even a trace amount of water flow would be adequate to avoid high temperatures [4].

Complete absence of cooling could occur if a valve is inadvertently closed, there is a complete obstruction in the cooling lines, or for some reason the cooling system is empty.

Hazard

We first assume the beam power absorbed by a jaw is a steady 100 W. This is the upper limit on the power allowed by MPS and is well above the expected normal values. We also assume the total absence of cooling condition goes on indefinitely and that the beam power is not high enough to shatter the jaw, as that case has been covered.

The long stainless steel stalk almost totally prevents heat flow by conduction to the outside, so the jaw gradually gets hotter until radiative heat loss balances the beam power absorbed. Given the mass and specific heat of the jaw, 100 W of power translates to about $1^\circ\ C/s$ rate of temperature rise. [1]

The tungsten jaws are mechanically attached to the stainless steel components which are brazed together in two places. Once the temperature of the jaw gets to the point where the braze material starts to flow the jaw assembly may fall apart and the device is ruined — but this cannot happen with only 100 W of beam power. It takes about 550 W of beam power to melt the braze filler. Driven by 100 W of beam power the jaw reaches a temperature of around 600° C in roughly 10 minutes, and the stalk develops a thermal gradient along its length going from the jaw temperature to room temperature.

While no permanent damage occurs, the stalk is thermally elongated by about 0.7 mm and the position of the jaw is displaced slightly more than the tolerance expected. (Here I assume the average temperature change of the stalk is one-half the jaw temperature rise.) A typical jaw-to-jaw gap is 6 mm or more. The effect on the beam of the jaw position shift, if there is one, might not be noticed by operators but may cause slight wakefield induced degradation of beam quality (energy spread) as well as slight blurring of the edge of the halo. The effects would go away when the beam strike ends and the stalk cools down (~ 1 hour). It is important to realize that the 100 W figure is the upper limit and might only occur whenever we do edge scans. It does not represent a realistic beam power on the jaw for normal operations. For normal operation the typical beam power on a jaw is expected to be a few watts or less — more than an order of magnitude less than 100 W. For a 10 W beam the jaw will eventually heat up to about 170 $^\circ C$ and the expansion is only 0.2 mm. This small change will not have a measurable affect on the beam.

If absence of coolant does not cause a failure or significant performance degradation, one has to ask why we have coolant at all. Here are some reasons:

- Some of the halo collimators are in regions where vacuum requirements are demanding. Running jaws at high temperatures would cause higher outgassing rates and higher background pressure.
- Beam depending shifts in jaw position, even if they are at the few tenths of millimeter level are at best annoying.
- I don't think anyone really trusts the braze and weld joints for multiple thermal cycles, though they have survived at least two high temperature brazes.

Mitigation

An interlocked flow control panel with flow switches that fault whenever the flow is less than a preset value would in turn cause MPS to reduce or turn off the beam whenever there is insufficiency or absence of coolant. The negative effect on the beam would obviously be more than the effect of the thermal expansion by itself. If the action was only to alarm and not to reduce the beam, it would serve as a maintenance notice and presumably lead to earlier repair.

Other possible mitigations:

- A single RTD could be mounted on the exposed portion of the stalk. It will heat up eventually (< 1 hour).
- If there is a total absence cooling there would be a discrepancy in the beam power as calculated

[1] Calculations are based on a rectangular parallelepiped version of the jaw attached to the stalk as shown in Figures 1, 2 and drawings PF375-303-23, -25, -29, -40, -43, - 49, -51, and SA-375-303-23. The parallelepiped dimensions are given in Table 1. Radiation assumption are given in Table 2. An emissivity value is conservatively low for high temperatures [5]. Thermal diffusion time is defined as the relevant length squared divided by the thermal diffusivity.

from the ΔT across the RTDs and the nominal flow rate, and the beam power lost as calculated from the BPM signals before and after the Halo Collimator. This discrepancy would be evident only for cases where there is a good fraction of the beam lost so that BPMs came measure it.

References

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[2] D. Walz, "Instant catastrophe." SLAC High Power Productions movie, January 1971.

[3] M. Santana-Leitner, "Accidental steering of LCLS-II beam onto the halo collimators. Estimated temperature rise before beam shut-off," RP Memo RP-RPG-150612, SLAC, June 2015.

[4] P. Cutino and J. Welch, "Halo collimator minimum/maximum LCW flow," Engineering Note LCLSII-2.4-EN-1596-R0, SLAC, December 2019.

[5] R. Shurtz, "Total hemispherical emissivity of metals applicable to radiant heat testing," Report SAND2018-13271, Sandia National Laboratories, 2018.

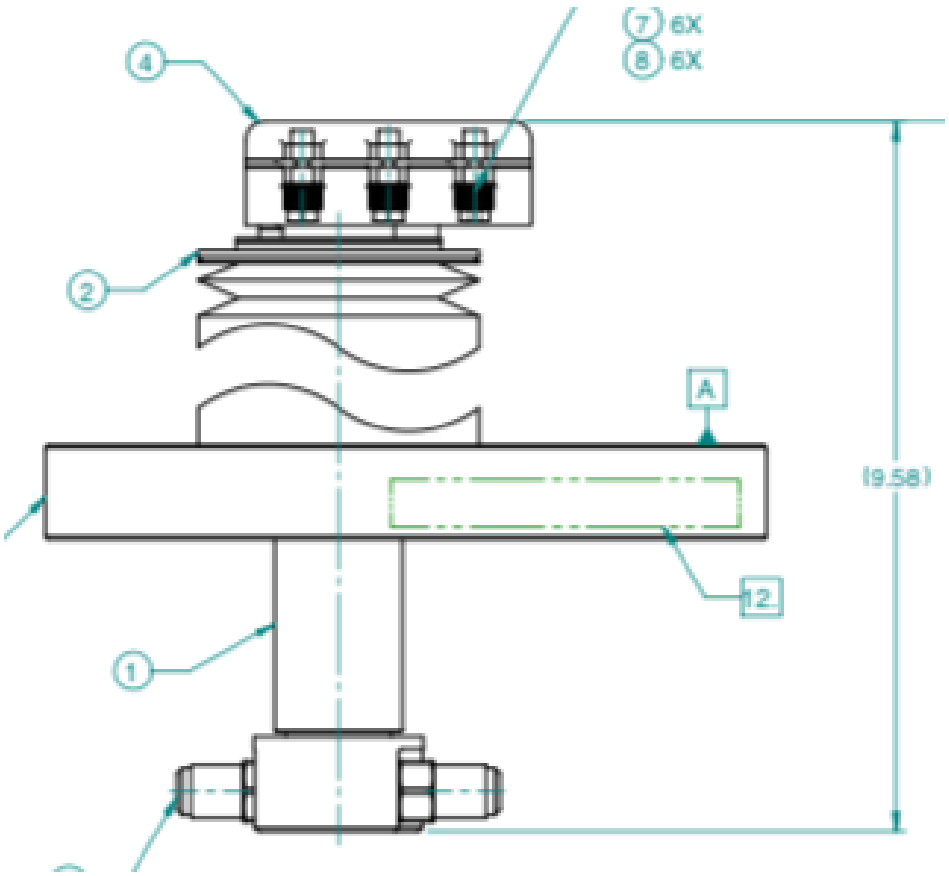

Figure 1: Halo Collimator jaw and stalk assembly.

Table 1: Parallelepiped approximation of a radiating jaw.

length	6.0	cm
width	4.1	cm
depth	1.4	cm

Table 2: Assumption made in the calculation of radiative power.

emissivity	0.5	$Wm^{-2}K^{-1}$
temperature	990	$^{\circ}C$
emitted power	561	W

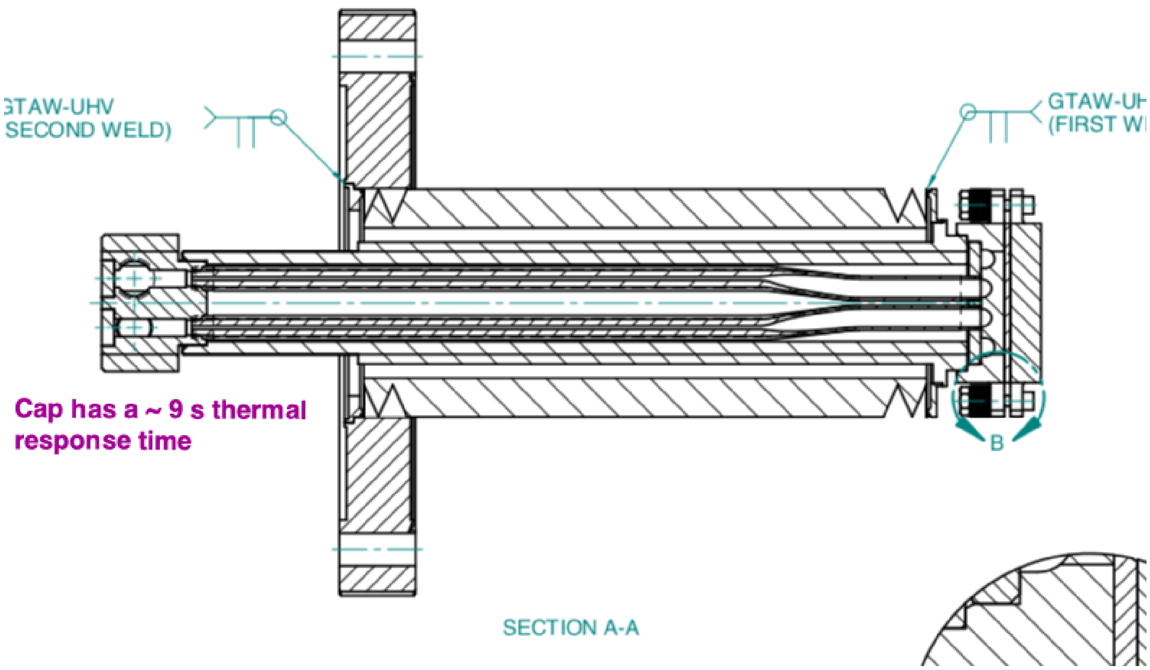

Figure 2: Halo Collimator jaw and stalk section.