Beam power ratings for cooled LCLS-II Stoppers*

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Contents

1 Introduction

LCLS-II will repurpose various stoppers to also act as tune-up dumps to absorb low power beams. In this note I examine the behavior of these devices as a function of beam power and provide a beam power rating such that, if the devices are water cooled within the stated range, they should safely absorb the rated beam power indefinitely.

This rating on stopper performance is based on the onset of pressure and flow fluctuations in cooling water which can cause water flow interlocks to issue a fault. If the beam power is too high, local heating in part of the cooling coil will generate a film of water next to the copper coil surface of such high temperature that it is thermodynamically possible for the water to convert to vapor.

The rating given in this document is made to avoid trips due to pressure fluctuations generated by excessive heat flux. Such trips would not damage the stoppers. As explain in Section 4.2, for beam power around the rated power the peak slug core temperature is quite modest and is not at risk of thermal damage.

Conversion of liquid water to vapor actually increases the heat transfer coefficient and improves the cooling efficiency as long as the power is below a critical value. When the power exceeds the critical value the heat removed by the vapor can no longer keep up and runaway heating occurs leading to burnout and damage to the stopper. This burnout power is many times higher than that required to cause localized bubbles.

In making the rating I assume the instantaneous temperature rise from a single pulse can be neglected for operational parameters used at LCLS-II. The bunch charge that is useful for an FEL is about an order of magnitude less than those used for high energy physics and produces only a few degrees centigrade instantaneous rise in temperature when it is absorbed [1].

2 Stoppers/tune-dumps

The stoppers that double as tune-up dumps in LCLS-II are identified by the MAD element names: STCLTS, TDUND, TDUNDB and D2. These de-

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vices differ from one another in detail but are of the same general design. Beam is absorbed in a cylindrical copper slug that is water cooled on the cylindrical surface.

STCLTS will use a ‘Large PEP-II’ stopper with a coil based on drawing PF-344-606-20 and shown in Figure 1.

TDUND will continue to use the stopper with coil based on drawing PF-380-545-41 and shown in Figure 2.

TDUNDB will use at stopper sometimes referred to as the Small PEP-II stopper, with a coil based on drawing PF-344-660-69 and shown in Figure 3.

D2 has a stopper of a somewhat different design and is considerably larger than the other stoppers. Rather than a coil of tubing, it has a channel cut in the slug with the shape of a coil and a stainless steel sleeve brazed around it to seal the circuit. It is based on drawing SA-405-002-01-R1 and is shown in Figure 4.

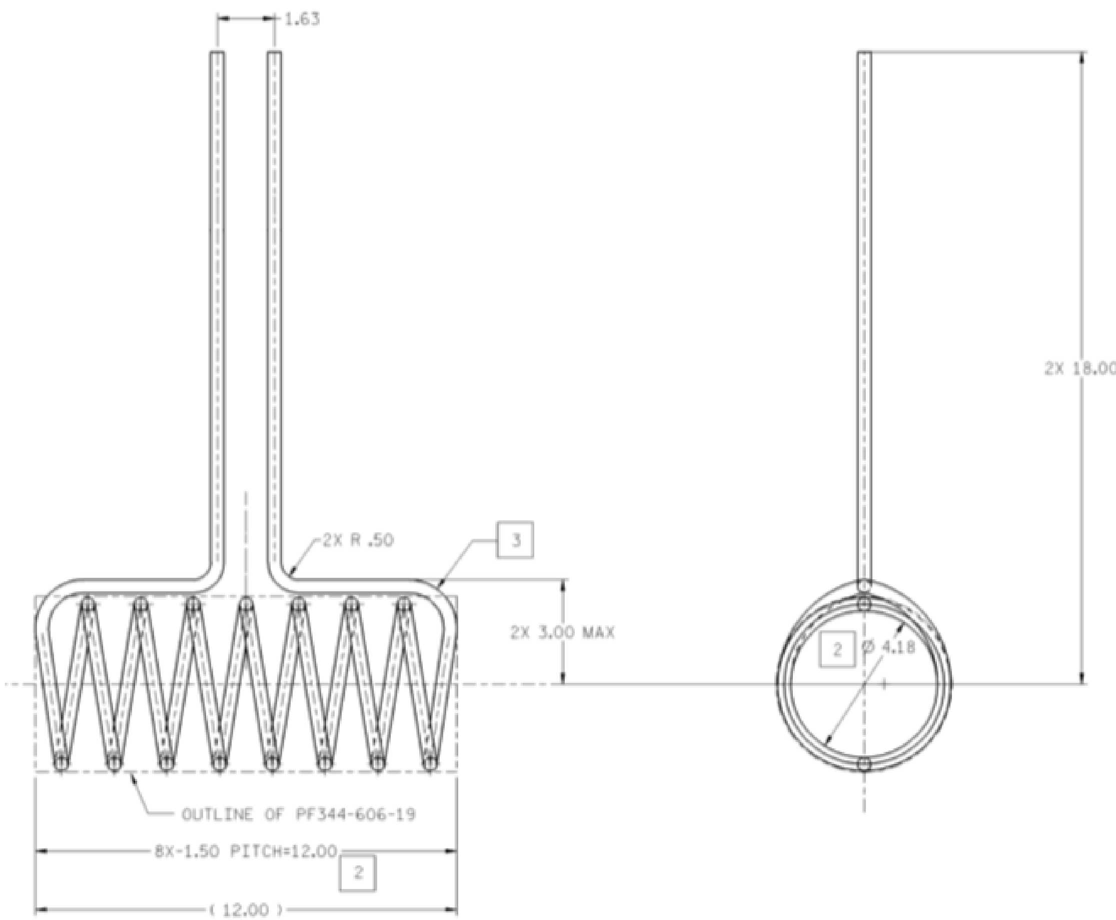

Figure 1: Coil used in the stopper at STCLTS (PF-344-606-20)

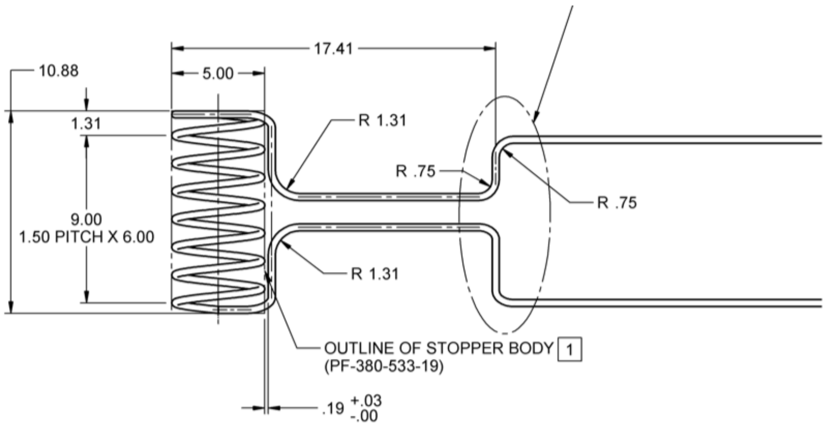

Figure 2: Coil used in the stopper at TDUND (PF-380-545-41)

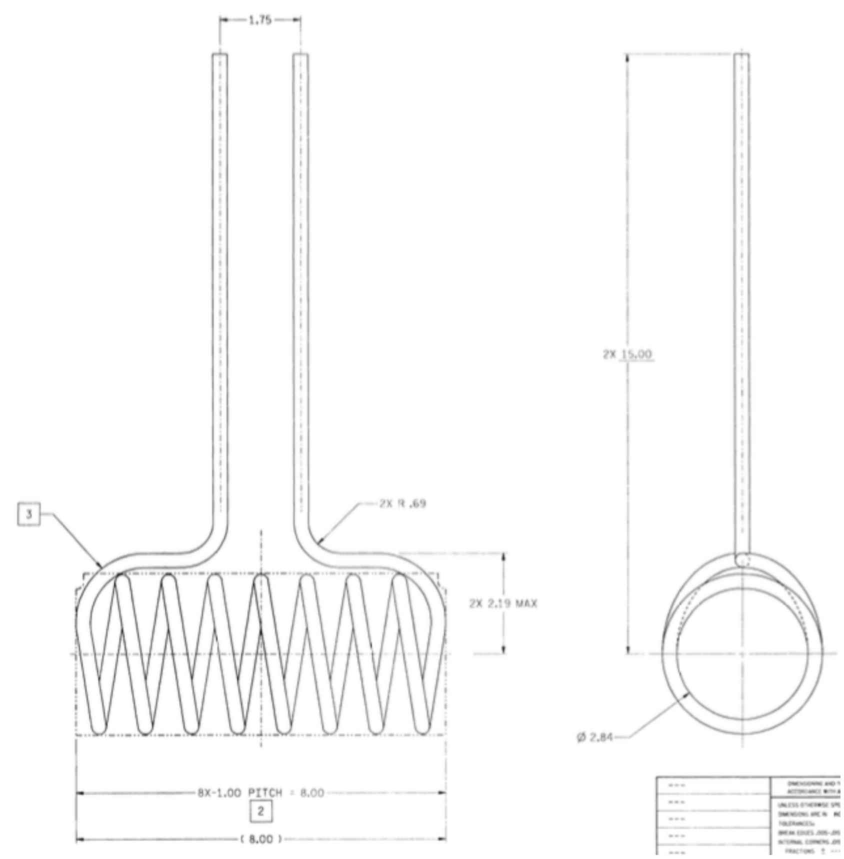

Figure 3: Coil used in the stopper at TDUND (PF-344-660-69)

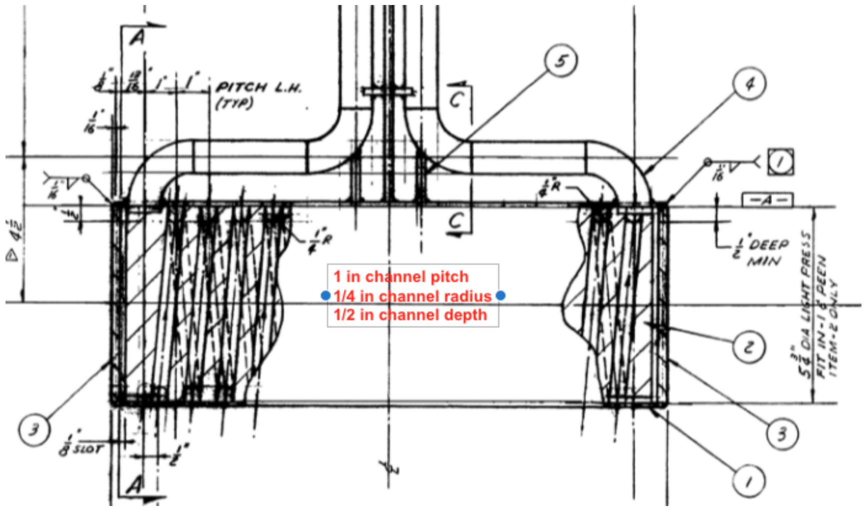

Figure 4: Coil and core used in the stopper at D2 (SA-405-002-01-R1)

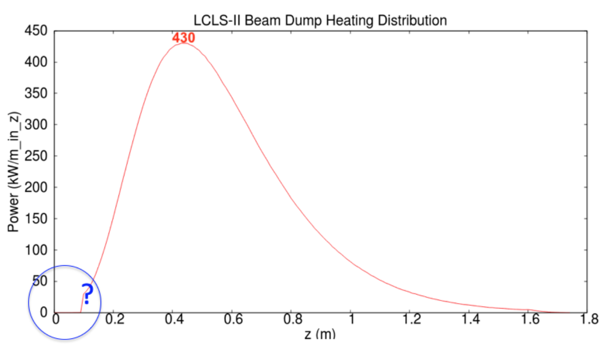

Figure 5: Deposited power per unit length for a 250 kW, 4 GeV electron beam striking an aluminum cylinder - from Z. Li talk February 2, 2016

3 Ratings

Beam power ratings are given in Tables 2-5 for a range of cooling flows. If a stopper is operated at flow within the given range for rating, there should not be flow interlock trips generated generated by excessive heat flux. If beam power exceeds the rating, such trips are possible, but stopper damage would not result unless the beam power is many times higher than the rating.

If a stopper is operated at flow below the lower limit of the given range for the rating, the Tables can be used to establish a limit. No rating is given for flow rates that are higher than about 10 fps. High flow rates are associated with excessive erosion rate of the coil material. Thermally the stoppers work better for higher flows, but operating them in the high flow velocity regime is likely to lead to either short coil lifetime, excessive corrosion/erosion radioactive byproducts, or both.

The ratings are conservative in the sense they are based on limiting the temperature of the copper at the copper/water interface to 100 $^{\circ}C$. This limit was chosen because vapor could form if the water pressure is at or below 15 psia. In practice water pressure is higher and has a saturation temperature higher than

100 $°C$. Furthermore, even if it is thermodynamically possible to make vapor, vapor may not form. A nucleation point as well as additional energy to overcome the latent heat of vaporization are required. See chapter 10 of [2] for a in-depth discussion of heat transfer involving a change of phase.

The three newer stoppers have virtually the same power ratings (7000 or 8000 W), but the flow requirements are somewhat different. The Small PEP-II stopper, because of its smaller coil tubing requires less flow to obtain good heat transfer compared with the Large PEP-II stopper or the Photon/electron stopper. The large stopper for D2, on the other hand, requires much more flow and can also handle considerably more power. Somewhat ironically, at 1 gpm, because of the large channel size and slow flow velocity, it cannot handle as much power as the Small PEP-II stopper.

4 Details

Details of some of the assumptions and methods used to determine the numbers given in Tables 2-5 are explained in this section.

4.1 Heat flux

To simplify the analysis for the stoppers I assume all the energy is deposited in a cylinder of radius R_m. I also assume that the heat flow is only radial, so the depth from the front face of maximum heat flux must be the same as the that of the peak fractional energy loss per cm.

Beam energy is absorbed along the axis of the slug cylinder over a radial region of roughly the Moliere radius R_m which for copper is 1.568 cm. The highest absorbed energy density occurs a few radiation lengths from the front face. See Figure 5. For a 250 kW beam the peak loss rate of is 430 kW/m and occurs about 40 cm from the front face of an aluminum cylinder, which is about 4.5 radiation lengths ($X_L = 8.897\ cm$). The peak fractional energy loss per unit length of the copper slug is then $P'_{n,Al} = 430/250 = 1.72\ m^{-1} = 0.0172\ cm^{-1}$.

Table 1: Temperature drop due to conduction for a 10 kW beam.

		$\Delta T[C°]$
TDUNDB	Small PEP-II stopper	40
STCLTS	big PEP-II stopper	56
D2	swing arm stopper	62
TDUND	Photon/electron stopper	53

The peak fractional loss per cm for copper can be scaled from the aluminum result by the radiation length; that is,

$$\begin{aligned} P'_{n,Cu} &= P'_{n,Al} \times X_{0,Al}/X_{0,Cu} && (1)\\ &= 0.0172 \times 8.897/1.436 && (2)\\ &= 0.107\ cm^{-1}. && (3) \end{aligned}$$

The peak power deposited per unit length is therefore equal to the total beam power P divided by an effective length $\Delta z_{eff} = 1/0.107 \approx 9.4\ cm$.

4.2 Conduction

Even though the core of the slug will reach the highest temperature, it turns out that the limitation on these stoppers is not due to excessive temperature at the core, but is due to the heat flux transferred to the water. The temperature drop due to thermal conduction in the copper slug from the core to the water cooling interface can be estimated approximately using

$$\Delta T = \frac{P}{2\pi \Delta z_{eff} K} ln \frac{R_{coil}}{R_m}$$

where $K \approx 4\ Wm^{-1}\ °C^{-1}$ is the thermal conductivity of copper, and R_{coil} is the radius of the water interface. Values of the temperature drop are given in Table 4.2 for a beam power of 10 kW. Even for a 10 kW beam the temperature drop due to conduction, when added to the maximum allowed temperature of the coil at the water surface of 100 $°C$, is well within normal use for copper.

4.3 Film drop

Cooling water passing in the coil around the stopper absorbs heat from the copper slug and carries it away. The rate at which heat is transferred from the copper to the water depends on the difference between the copper temperature at the water/copper interface and the bulk temperature of the coiling water at that point. The difference between the bulk water temperature and the surface temperature of the adjacent copper surface is called the 'Film drop'. The temperature of the copper is the sum of the bulk temperature and the Film drop. When it becomes high enough, bubbles of water vapor may start to form. The bulk temperature rise is calculated from the specific heat of the water and the total power absorbed in the stream. The Film drop is calculated from heat transfer coefficient based on a dimensionless formula that was derived from measurements [2].

4.4 Pressure drop

The pressure drops listed in the Tables refer only to the pressured drop in the coil and don't include pressure drop in ancillary plumbing. The pressure drop in the tables goes up to roughly 10 psi, corresponding to the highest useful flow rates.

4.5 Bulk water temperature rise

Given the relatively low power levels and the fact that the film drop is the dominate limiting mechanism, the bulk temperature rise of the cooling water is unimportant. Typically at the rated power the bulk temperature rise is only around 10 $^\circ C$.

References

[1] J. Welch, J. Blaha, P. Cutino, D. Hanquist, A. Ibrahimov, M. Kosovsky, Z. Li, and M. Santana-Leitner, "LCLS-II beam dumps," Tech Note LCLS-II TN-17-12, SLAC, October 2017.

[2] F. Kreith, *Principles of Heat Transfer*. Int. Textbook Co, 1967.

Table 2: Flow, pressure, power limits and rating for the Small PEP-II stopper at TDUNDB

flow gpm	velocity fps	ΔP psi	P limit ($T_{wall} = 100\ C^{\circ}$) W
1	6.6	4.1	7000
1.5	9.9	8.4	10000
gpm range:	1 - 1.5	Rating: 7000 W	

Table 3: Flow, pressure, power limits and rating for the Large PEP-II stopper at STCLTS

flow gpm	velocity fps	ΔP psi	P limit ($T_{wall} = 100\ C^{\circ}$) W
1	4.2	2	6100
1.5	6.3	4	8700
2	8.5	6.7	11200
2.5	10.6	9.9	13700
gpm range:	1.5 - 2.5	Rating: 8000 W	

Table 4: Flow, pressure, power limits and rating for the Photon/electron stopper at TDUND

flow gpm	velocity fps	ΔP psi	P limit ($T_{wall} = 100\ C^{\circ}$) W
1	4.2	1.8	5900
1.5	6.3	3.6	8500
2	8.5	6	11000
2.5	10.6	8.9	13300
gpm range	1.5 - 2.5	Rating: 8000 W	

Table 5: Flow, pressure, power limits and rating for the swing arm stopper at D2

flow gpm	velocity fps	ΔP psi	P limit ($T_{wall} = 100\ C^{\circ}$) W
1	1.6	0.4	4600
1.5	2.5	0.8	6500
2	3.3	1.3	8400
2.5	4.1	1.9	10200
3	4.9	2.6	11900
5	8.2	6.2	18500
7	11.4	11.4	25000
gpm range	3 - 5	Rating: 11000 W	