LCLS-TN-02-7
December 2002

Reducing the heat load on the LCLS 120 Hz RF gun with RF pulse shaping

John F. Schmerge
Stanford Linear Accelerator Center, Stanford University,
Stanford, CA 94309

Abstract

The LCLS injector must operate at 120 Hz repetition frequency but to date the maximum operating frequency of an S-band rf gun has been 50 Hz. The high fields desired for the LCLS gun operation limit the repetition frequency due to thermal expansion causing rf detuning and field redistribution. One method of addressing the thermal loading problem is too reduce the power lost on the cavity walls by properly shaping the rf pulse incident on the gun. The idea is to reach the steady state field value in the gun faster than the time constant of the gun would allow when using a flat incident rf pulse. By increasing the incident power by about a factor of three and then decreasing the incident power when the field reaches the desired value in the gun, the field build up time can be decreased by more than a factor of three. Using this technique the heat load is also decreased by more than a factor of three. In addition the rf coupling coefficient can be increased from the typical critically coupled designs to an overcoupled design which also helps reduce the field build up time. Increasing the coupling coefficient from 1 to 2 reduces the heat load by another 25% and still limits the reflected power and coupling hole size to manageable levels.

At this time the highest operational repetition rate for a 1.6 cell LCLS prototype RF gun has been 50 Hz [1] at 100 MV/m at the University of Tokyo. At higher repetition rates and fields, the gun field distribution may be significantly perturbed due to thermal expansion. The thermal expansion is not uniform in all dimensions due to the position of the cooling channels which leads to a small but different frequency shift in each cell of the gun. In addition the LCLS gun will utilize a load-lock system for installing new cathode plates and may limit the amount of cooling available at the cathode plate creating strong thermal gradients. The LCLS gun will exhibit a small field redistribution as the cell resonant frequencies change due to the thermal distortions. The most noticeable change in the fields is the ratio of the on axis fields in each cell. The field perturbations may lead to an electron beam exiting the gun with lower than optimal beam brightness since the frequency and field distribution tuning is necessarily done at low power with a network analyzer or similar measurement set up. The effect is especially noticeable in the beam longitudinal emittance where the correlated energy spread depends on the cell field ratio [2].

There are several known methods to solving or mitigating this problem. The ideal method is to first study the energy deposition in the rf gun and provide appropriate cooling at the necessary locations without compromising structural integrity to eliminate frequency shifts and the associated field redistributions. Preliminary analysis of this type has been conducted on the LCLS prototype at BNL [3] as well as SLAC [4] indicating there will be a significant heat load and temperature gradient leading to substantial frequency shifts and a modified cell field ratio. Optimizing the cooling channel location has not been completed but the preliminary analysis indicates it will be difficult to design the cooling channels to eliminate the frequency shift at the required input power level. A second method involves measuring the fields in each cell as a function of time and tuning the gun such that the desired field ratio is achieved at high power when the laser is fired instead of low power on the bench. Measurements can be performed utilizing capacitive probes located outside the coupling or laser ports on the full cell and half cell respectively. This method requires retuning the gun each time the field level, rf pulse shape, or repetition rate is changed. The author expects that the field measurements will be a good diagnostic to indicate the field ratio has been altered, but should not be relied on as the sole method of maintaining the cell field ratio. Instead the gun design should include a method to reduce the frequency shifts as much as possible to reduce the amount of high power tuning necessary.

Thus the desired method to reduce the resonant frequency shifts of the gun cells is to reduce the heat dissipated in the gun. The dominant heating mechanism of the gun is resistive heating due to the finite conductivity of the cavity walls. Other energy deposition (such as the photocathode drive laser) and extraction (such as the electron beam) mechanisms are negligible compared to the rf power heating since they involve considerably less energy. The stored energy in the cavity fields is 6.7 J for the LCLS design of 120 MV/m and assuming a Q_0 of 12000 and a critically coupled cavity as are typically obtained with the LCLS prototype RF photocathode gun. However a 6.2 MeV, 1 nC beam only extracts 5.7 mJ of energy and the drive laser supplies around 0.5 mJ of UV energy. Thus both of these effects have a negligible effect on the energy lost to the cavity walls and can be ignored in this calculation.

In order to reduce the amount of energy lost on the cavity walls, one must either reduce the resistivity of the walls or reduce the amount of energy incident on the gun. Since the LCLS prototype gun is already constructed out of Cu specifically because of the high conductivity, the only additional benefit is to operate the gun at 30 C instead of the traditional 45 C for SLAC accelerators to reduce the resistivity by about 10% [3]. However, this only reduces the energy lost in the walls by 10% and the benefit is reduced if temperature tuning the gun frequency is required after a cathode replacement. Alternatively one can drive the gun to its operating voltage in a shorter period of time and thereby reducing the energy lost to the walls.

Since the cavity is designed to operate as an efficient accelerator, the cavity losses are kept low to maximize the accelerating voltage in the gun for a given klystron power input. In other words the gun is designed to have high shunt impedance. However, because the gun cavity is operated as a standing wave structure, the filling time becomes large as the losses decrease. Thus, when one uses the minimum necessary klystron power to drive the cavity, one must wait several time constants before the cavity voltage builds up to the required field level for normal operation. A typical filling time constant for the LCLS prototype gun is 670 ns. Since the field builds up exponentially, there is a relatively long time spent at field levels just below the desired operating field level and therefore a large amount of energy is dissipated as heat in the cavity walls. However, if a higher power klystron were used, the cavity could be filled to the desired field level in a much shorter time period. In fact a sufficiently high power klystron could fill the gun in an arbitrarily short time regardless of the filling time constant. Once the cavity is filled, the klystron power can be quickly reduced to the steady state value necessary to maintain the cavity at the desired field level. The rapid change in klystron power can be achieved using a fast attenuator (100 ns or faster) at the klystron drive input line. The attenuator should be as fast as possible but need not be faster than the rise time of the klystron (roughly 100 ns [5]) since this will ultimately limit the output response. Alternatively, a fast phase shifter could be used to achieve the same effect but due to the stringent timing jitter requirements of the injector it would be preferably to avoid modifying the rf phase.

The amount of energy lost on the walls of the gun can be calculated from the cavity voltage and the shunt impedance. The shunt impedance is defined for a standing wave structure as $R = 1/2\ V^2/P_{wall}$ where R is the shunt impedance, V is the cavity voltage and P_{wall} is the power lost on the cavity walls. The total energy lost to the walls is given by $\int P_{wall}\, dt$. While it is difficult to measure the shunt impedance directly, the cavity quality factor, Q_0, can be measured either by time or frequency domain techniques and the shunt impedance is directly proportional to Q_0. The proportionality factor is simply a function of cavity geometry and can easily be computed by field solver programs such as SUPERFISH. Q_0 is defined as $Q_0 = \omega_0 U/P_{wall}$ where ω_0 is the resonant frequency and U is the stored energy in the cavity. The measured value of Q_0 for the 1.6 cell RF gun installed at the Gun Test Facility is roughly 12,000. The expected shunt impedance using the measured Q_0 and the proportionality constant from SUPERFISH calculations is 1.7 MΩ/m. Finally the cavity voltage is calculated from the equation below where β is the rf coupling coefficient and P_k is the incident rf power delivered from the klystron. The equation assumes that there is no beam loading and the gun is operated on resonance.

$$\tau \frac{dV}{dt} + V = \frac{\sqrt{8\beta R P_k(t)}}{\beta + 1}$$

$$V(t) = \frac{\sqrt{8\beta R P_k(t)}}{\beta + 1}\left(1 - e^{-\frac{t}{\tau}}\right)$$

The solution to the equation for a step function klystron drive pulse 3 μs wide is plotted in figure 1 for a critically coupled gun (β=1). In order to achieve the desired 5.7 MV accelerating voltage (120 MV/m peak field at the cathode), only 10 MW of RF power is required. The voltage builds up exponentially with a time constant of 670 ns for 3 μs before the end of the rf pulse and then exponentially decays. Assuming 120 Hz repetition rate, the average power dissipated by the gun cavity under these conditions is 2.8 kW. However, if a 30 MW klystron were used for the first 800 ns and then the output power dropped to the 10 MW level for 200 ns before the end of the pulse, only 0.9 kW of power would be dissipated. The cavity voltage as a function of time for this case is also plotted in figure 1.

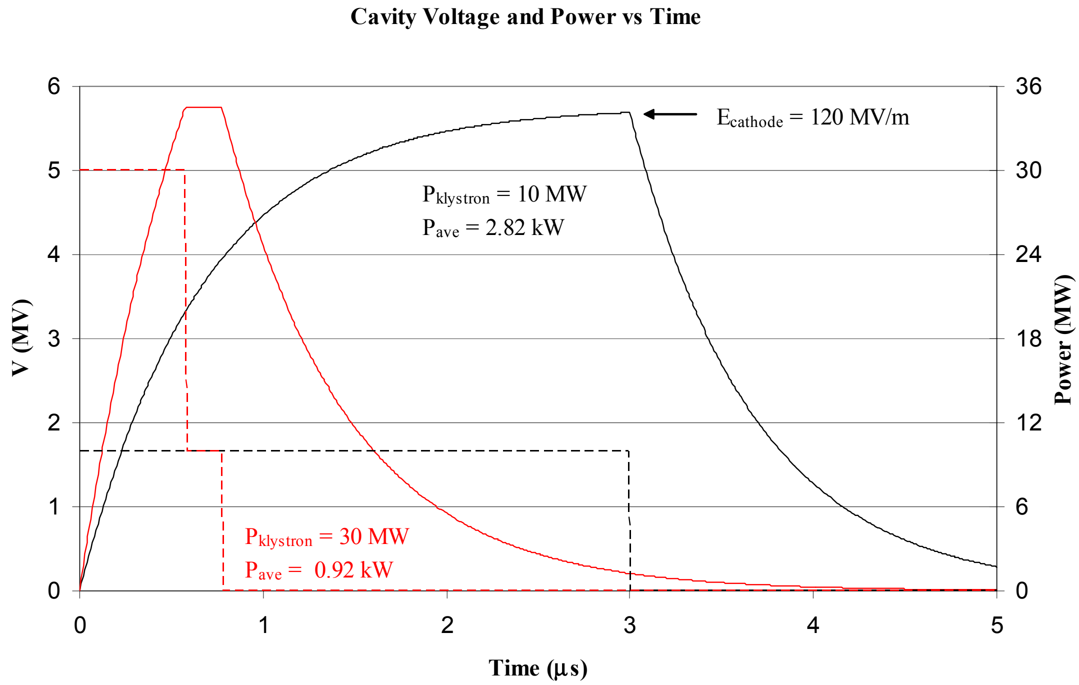

Figure 1 – Cavity voltage and klystron power as a function of time for a 10 MW, 3 µs wide klystron pulse and a 30 MW, 800 ns pulse which is then decreased to 10 MW for 200 ns. The power lost to the cavity walls is proportional to the integral of the square of the voltage. The peak field at the cathode for this case is the LCLS design specification of 120 MV/m.

Since there is more rf power available than is needed, there is no benefit for the LCLS gun to be designed with a coupling coefficient of unity. The consequences of a larger coupling coefficient are shorter filling times and a slightly larger reflected power. Since a substantial amount of the rf power is already reflected, a modest increase in reflected power will not be noticed while the shorter filling time will decrease the heat load. For example, increasing β from 1 to 1.5 will reduce the average power at 120 Hz repetition rate to 0.8 kW and a β of 2 will reduce the power to 0.7 kW. Further increases have even smaller effects because the heat load will be dominated by the 200 ns flat-top assumed in the calculation. Increasing β in the low power klystron case will also decrease the heat load. However, the klystron power must be increased above 10 MW to compensate for the small amount of reflected power due to the mismatch and the pulse length must be decreased or no benefit will be achieved. To limit the reflected power from the gun to about 10% at steady state and minimize the necessary field perturbations due to the coupling holes, the maximum coupling coefficient considered is 2 which only reduces the heat load to 2 kW and requires a 12 MW klystron with 2 µs duration. Thus even without rf pulse shaping, increasing the coupling coefficient would be useful to reduce the necessary pulse width of the klystron. The author considers a coupling coefficient of 2 a reasonable compromise between heat load, filling time, reflected power and field perturbations due to the coupling holes.

All the calculations reported above assume a peak field at the cathode of 120 MV/m or a 5.7 MV cavity voltage which is the LCLS design specification. However, according to simulation the LCLS gun would produce a lower emittance if the field at the cathode were increased to 140 MV/m. The heat load would increase to 3.9 kW with 14 MW of RF power and 1.3 kW with 40 MW of rf power for the constant klystron output and the shaped klystron pulse respectively. Increasing the coupling coefficient to 2 reduces the load to only 1.0 kW. The LCLS gun should be designed to meet these heat load requirements so that the thermal properties of the gun will not limit the peak field at the cathode.

All the above calculations assume a klystron pulse with zero rise time. Of course no klystron produces a perfect step function output but the additional heat loading due to the rise time of the klystron is small since the gun cavity voltage is relatively small during the klystron rise time. Thus for a 100 ns rise time, the additional power dissipation is less than 0.1 kW. Likewise there is no significant benefit from reducing the heat load due to the trailing edge of the rf pulse because most of the trailing edge is spent at low field levels where there is minimal power dissipation.

For comparison the heat load on the 50 Hz gun [1] at 100 MV/m would be 0.8 kW and for the GTF gun [6] operated at 140 MV/m and 10 Hz is 0.3 kW. However, since the field ratio is not currently measured on these guns as a function of time but rather only at low power during bench tests, it is not clear that the cooling channels on these guns is sufficient to prevent frequency shifts and cell field ratio changes. The combination of cooling channels, rf pulse shaping and field measurement will allow the LCLS gun to operate at the desired cell field ratio at 120 Hz independent of cathode field value.

Of course the main problem with implementing this technique is to limit the reflected power at the klystron. The reflected power can cause klystron window damage and a time varying output power. This can be addressed with a high power circulator as used at the GTF or some other sort of device to limit the reflected power at the klystron such as a directional coupler which would then require more power out of the klystron. The author wishes to thank J. Clendenin, D. Dowell and S. Gierman for interesting discussions and comments on this topic.

References

[1] M. Uesaka (U. Tokyo) and M. Kando (JAERI Advanced Photon Research Center), private communication, Nov, 2000.

[2] M. Borland, “A high brightness thermionic microwave electron gun”, SLAC-Report-402, February, 1991, p. 76.

[3] X.J. Wang, M. Babzien, I. Ben-Zvi, X.Y. Chang, S. Pjerov, and M. Woodle, "High-rep rate photocathode injector for LCLS", Proceedings of the 19th Particle Accelerator Conference, Chicago, 2001, p. 2233.

[4] D. Dowell and I. Nzeadibe, SLAC, private communication, Mar, 2002.

[5] R. Akre, SLAC, private communication, Sep, 2002.

[6] J.F. Schmerge et al, Photocathode rf gun emittance measurements using variable length laser pulses, SLAC PUB 8065