LCLS Maximum Credible Beam Power

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1. Introduction.

The *maximum credible beam power* is defined as the highest credible average beam power that the accelerator can deliver to the point in question, given the laws of physics, the beam line design, and assuming all protection devices have failed.

For a new accelerator project, the official *maximum credible beam power* is determined by project staff in consultation with the Radiation Physics Department, after examining the arguments and evidence presented by the appropriate accelerator physicist(s) and beam line engineers. The definitive parameter becomes part of the project's safety envelope.

This technical note will first review the studies that were done for the Gun Test Facility (GTF) at SSRL, where a photoinjector similar to the one proposed for the LCLS is being tested. In Section 3 the maximum charge out of the gun for a single rf pulse is calculated. In Section 4, PARMELA simulations are used to track the beam from the gun to the end of the photoinjector. Finally in Section 5 the beam through the matching section and injected into Linac-1 is discussed.

2. Review of GTF Studies.

The GTF consists of a 1.6-cell S-band rf gun illuminated by a 10-ps 266-nm laser pulse. The approximately 6-MeV beam out of the gun is then boosted to 30 MeV in a single S-band 3-m accelerator section. There are 2 XK5 klystrons each capable of producing up to about 20 MW peak power, one for the gun, the second for the booster.

The GTF shares the radiation-shielded vault with the SPEAR injector linac. The rf can operate at up to 10 Hz.

Normally the maximum photoelectron beam that can be produced at the gun is about 1 nC per macropulse, while another 2 nC can be present as dark current. However, a mode known as enhanced electron emission (EEE) is possible [1]. When the laser energy density at the cathode exceeds a threshold that depends on the rf field, a high-density plasma is formed near the photocathode from which electrons are extracted in each rf bucket until the rf energy in the gun is depleted [2]. The maximum charge in the

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[1] X.J. Wang et al., J. Appl. Phys. 72 (1992) 888.
[2] RF breakdown that occurs in the absence of a laser pulse can also be described using a plasma source. See, for example, P.B. Wilson, "A Plasma Model for RF Breakdown in Accelerator Structures," presented at the 20th Int. Linac Conf. (Linac 2000), Aug. 21-25, 2000, Monterey, CA, SLAC-PUB-8653 (Oct. 2000).

macropulse was measured during cathode cleaning with rf on and found to be 1 μC with a maximum pulse length of 50 ns and 70% energy spread, and with an average energy of 4 MeV [3]. Due to the large emittance and energy spread, only about 30% of this beam is expected to make it through the booster linac.

It was noted that the normal laser beam hitting the cathode is several hundred microjoules in a 1-mm radius spot. Experience indicates that this charge density is only a factor of 2 or 3 from the EEE threshold. Thus an accidental focusing of the laser beam to a radius at the cathode of <0.7 mm could initiate the enhanced electron emission mode.

As a result of these considerations, the *maximum credible beam power* assumed for the GTF at the exit of the booster linac is 100 W [4].

3. Maximum charge out of gun.

The quality factor, Q_L, of an rf cavity is given by

$$Q_L = \omega_0 \frac{U}{P_L},$$
(1)

where $\omega_o / 2\pi = 2856 MHz$, U is the stored energy, and P_L is the power loss. Since Q_L is ~6000 [5], and at steady state P_L is equal to the nominal forward energy, ~13 MW [6], the stored energy is U~4 J.

In the EEE mode, each rf bucket is filled to the space-charge limit until the stored energy is depleted. The energies of the first and last microbunches for nominal forward rf energy are 6 and 2 MeV respectively, where 2 MeV is the minimum energy necessary to exit the gun before phase reversal and subsequent acceleration back toward the cathode. Since the accelerating field is reduced by beam loading in proportion to the extracted charge, the maximum total charge that can be extracted in one macropulse can be determined from the ratio of U to the average energy per unit charge, $\bar{V}$. Since $\bar{V}$ =4 MV, the maximum charge in 1 macrobunch is

$$q = \frac{U}{\bar{V}} = 1.0 \mu C.$$
(2)

[3] D.A. Reis, Ph.D. Dissertation, Section 6.1.1, U. of Rochester (1999).
[4] J. Schmerge, "Radiation Safety for the Gun Test Facility at SSRL," internal technical document (June 17, 1997).
[5] D.T. Palmer, Ph.D. Dissertation, Table 3.8, Stanford University (1998).
[6] The LCLS rf gun is likely to be powered by a 5045 klystron (~60 MW peak power). However, the gun will normally be processed to only ~13 MW, which provides the optimum field in the gun for producing low emittance beams. Processing to >15 MW is physically unlikely because of severe rf breakdown problems.

The maximum charge that can be extracted in a single microbunch is governed by the space-charge limit of the gun. The space-charge limit can be calculated from Gauss' law for the charge that produces a self-field that just cancels the rf field at the cathode, i.e.,

$$q_{sc} = E_{ext}(\pi r^2 \varepsilon_0).$$

(3)

The maximum peak extraction field to be expected at the cathode is E_{ext}=140 MV/m. Although the nominal laser spot size at the cathode will be ~1 mm, once the EEE mode is initiated the effective beam radius can be larger.

If the macrobunch is 50 ns long (see Section 2), i.e., if there are n=140 microbunches, then the average charge per microbunch is 7 nC. According to Eq. (3), the space-charge limit per microbunch decreases linearly with the rf field at the cathode. The maximum (minimum) energy of the electrons exiting the gun is 6 (2) MeV respectively. Thus the charge in the first microbunch should be ~10 nC, decreasing to ~4 nC at bunch #140. For q_{sc}=10 nC and E_{ext}=140 MV/m, Eq. (3) gives r~1.6 mm. This is not an unreasonable value for the average radius of the first EEE bunch traversing the gun half cell. For comparison, at the CLIC Test Facility (CTF), 35 nC has been extracted from an S-band gun (~110 MV/m) in a single microbunch [7]. In that case (not EEE emission), the laser spot size was r~5 mm, which is about what Eq. (3) would predict. The limiting effects of space charge were noted in reference 7.

4.   Beam through Linac-0.

The LCLS photoinjector will consist of a symmetrized 1.6-cell rf gun followed by two 3-m accelerating sections (the booster). The entrance (exit) to the booster is 1.5 (8) m from the cathode respectively. The nominal energy out of the gun (booster) is 6 (150) MeV. A matching section separates the injector from the entrance to Linac-1. The overall layout of the LCLS photoinjector and linac is shown in Fig. 1.

The analysis in Section 3 above does not take into account beam losses in the gun itself due to the rapidly diverging beam and the effect of these losses on the energy distribution. PARMELA simulations show that only ~15% of the EEE charge survives to the end of the booster (8 m), with most of the loss taking place in the gun itself (first few cm). When beam loading is taken into account, only 10% of the charge survives. See Fig. 2. These simulations are for a nominal beam energy of 180 MeV. At 150 MeV the losses will be slightly larger.

Thus for a nominal energy of 150 MeV at the booster exit, the *maximum credible beam power* is 1.8 kW based on 100 nC of charge per macropulse at a maximum rate of 120 Hz.

[7] R. Bossart et al., Proc. Part. Accl. Conf. (1995) 719.

5. Beam into Linac-1.

The energy acceptance of the quadrupole aperture between the pair of bends just before Linac-1 is ±6.5%. The energy distribution of the surviving beam at the exit of the booster is shown in Fig. 3. Approximately 80% of the particles exiting the booster are within an energy spread of 8.4% [8].Thus the *maximum credible beam power* at the entrance to Linac-1 is 1.5 kW, while at the end of the linac, at 15 GeV, the *maximum credible beam power* is ~150 kW.

6. Conclusions.

The rf gun can produce up to 1 µC of charge in a 50-ns pulse in the explosive electron emission mode. However, in this mode, the beam losses due to the rapidly diverging beam are very high, while additional losses due to the large energy spread are encountered at the limiting energy aperture in the matching section.

The *maximum credible beam power* at the entrance to Linac-1 at 150 MeV and at the exit of the linac at 15 GeV [9] are 1.5 and 150 kW respectively.

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[8] Given the long low-energy tail of the beam, it is clear that increasing the energy window of Fig. 3 to equal the total 13% acceptance of the matching section would not significantly increase the transmission.
[9] The nominal maximum energy of the LCLS linac is 15 GeV. With all spare klystrons accidentally added to the beam, the maximum energy could conceivably be ~10% higher. However, before a result of this precision can be claimed, additional simulations should be run for Linac-1 using the beam out of the booster corresponding to enhanced electron emission as illustrated in Figs. (2) and (3).
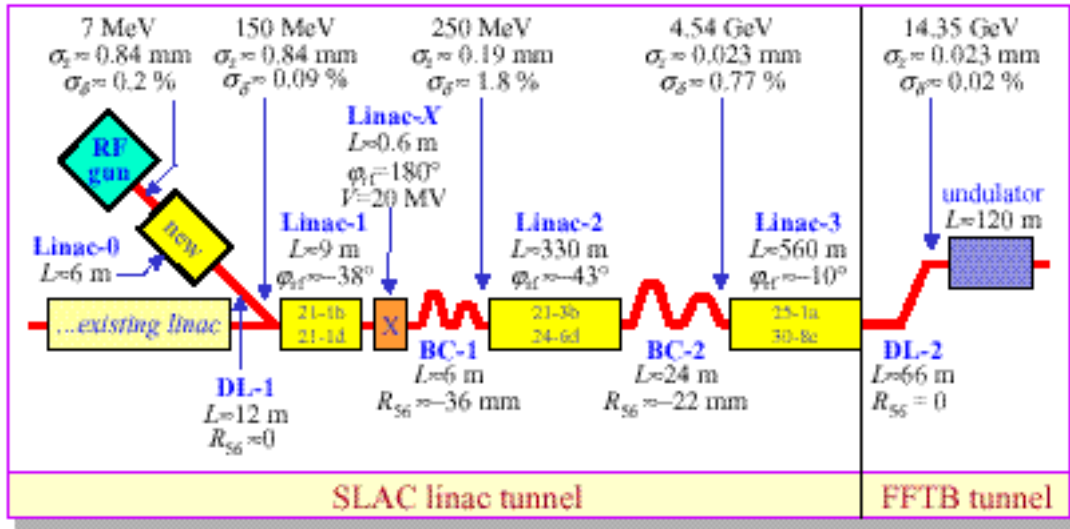
Fig. 1. Overall layout of LCLS photoinjector and linac. (See Fig. 7.1-1 in the Draft CDR.) Linac-0 consists of 2 3-m accelerating sections. Between Linac-0 and Linac-1 is a matching section consisting of a series of quadrupoles. The 45° bend is accomplished with two identical 22.5° bends between which is one of these quadrupoles.
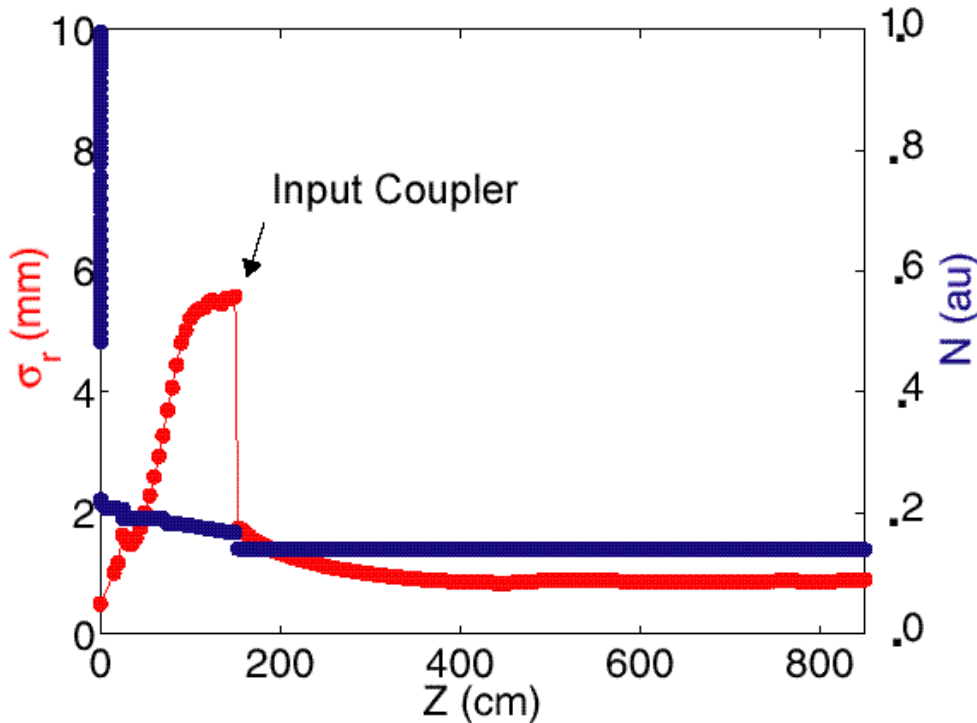

Fig. 2. RMS beam radius, σ_r (red), and number of surviving particles, N (blue), as a function of axial distance, z, from the photocathode, simulated for a total charge of 1 µC using PARMELA (version 3) with beam loading included. The beam size is seen to increases almost linearly up to the input coupler of the booster, while N decreases to the 20% level within the gun itself, and to the 15% level after entering the booster, after which there are no additional significant losses.
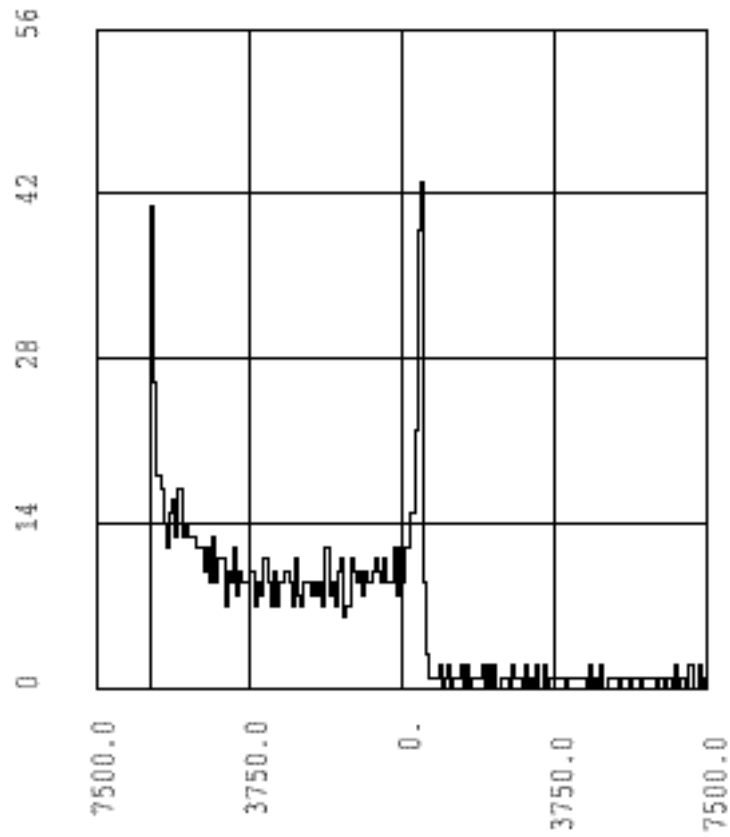
Fig. 3. Energy distribution of the beam exiting the booster, simulated for a total charge of 1 μC using PARMELA (version 3) with beam loading included. The PARMELA simulation is for a total charge of 1 μC and includes beam loading. The energy scale is in keV relative to the 180 MeV central energy of the simulation. An energy window of 8.4% is shown with the edge of the beam positioned about 1.3 MeV from the high-energy edge.