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Maximum Beam Power and Nominal Beam Losses at S-20

J. Clendenin

1. **Maximum credible beam**.

The maximum credible beam power values for electrons shown in **Table 1** for e^- beams are based on a beam power of 1.8 MW (1.875×10^{12} e^- at 120 Hz) for an energy of 50 GeV at S-30. Positrons are limited by the positron source damage threshold to an average current of ~2 μA, i.e., ~10^{11} e^- per pulse at 120 Hz on the target [1]. The ratio of e^+ at S-1 per e^- on the conversion target is ≤2. At S-20 the maximum linac energy is 33 GeV, while the HER and LER Bypass beams are limited to 12 and 4 GeV respectively by the BCS.

Table 1. Maximum credible beam power at Sector 20.

Beam Line	Power (MW)	Comments
Linac	1.2 MW	For 1.8 MW beam at S-30
HER Bypass	430 kW	For 1.8 MW beam at S-30
LER Bypass	16 kW	For maximum current (10^{11} e^- at 120 Hz incident on the positron target, yield of 2)

2. **Nominal beam losses**.

2.1. *Estimate of upper limit of losses in linac*.

2.1.1. A *gedanken* experiment. The long pulse (up to 400 ns) beams in the linac represent the maximum power for normal operations. Normally there are no visible signs of beam loss in S-2 through 20 of the linac (no PLIC signal, no loss on the toroids) except at the DRIP (S-1 and -2), the PEP extraction points (S-4 and -10), and the Lambertson at S-19. The nominal beam losses shown in **Table 5** are consistent with a *gedanken* experiment as follows. A 1.5-mm orbit (largest orbits normally encountered are 1-mm) is assumed in the S-20 region of the linac, where the smallest beam-stay-clear radius is 9.5 mm (smallest iris of a standard SLAC accelerator section). If a 2-mm misalignment is also assumed, the radial clearance for the beam may be as small as 6 mm. See **Table 2**.

Table 2. Beam-stay-clear assumptions.

	Linac	HER Bypass	LER Bypass
Beam-stay-clr radius (mm)	9.5 (last iris)	24 (2” OD, 0.065” wall)	24
Assumed orbit (mm)	1.5	1.5	1.5
Assumed misalignment	2	2	2
Net clear radius (mm)	6	20.5	20.5

[1] The SLC operated with positron currents (<10^{11} e^-) that at 120 Hz were near the threshold for destroying the positron target.

The methodology adopted here is to choose a beam size that is realistic, then calculate the expected beam loss based on a simple model of the charge distribution in the beam.

The lattice is designed for β=50 m, and the projected, measured, normalized rms emittance for the long pulse beam is ε_n=20×10^{-5} m. This yields $\sigma \equiv \sqrt{\beta\,\varepsilon/\gamma} = 0.4$ mm at S-20 (γ=6×10^4). There are at least two ways a larger σ could occur. If there is a factor of f β-mismatch, or if ε_n grows by f (which might be due to large tails), or if there is the appropriate combination of these two, then σ will be larger. A value of f=8 is chosen, resulting in a value of σ=1.2 mm.

If the spatial distribution of particles in the beam is assumed to be Gaussian with an rms radius of σ, then the fraction, F, of beam outside nσ can be approximated by

$$F = 1 - \left(1 - e^{-\frac{n^2}{2}}\right)^{\frac{1}{2}}. \qquad (1)$$

Values of F for various values of n are compiled in **Table 3** using Eq. (1).

Table 3. Interpretation of Eq. (1).

n	0	1	2	3	4	5	6	∞
F	1	3.7×10^{-1}	7×10^{-2}	5.6×10^{-3}	1.7×10^{-4}	1.9×10^{-6}	7.6×10^{-9}	0

For a σ of 1.2 mm and radial clearance of 6 mm, n~5.2, which by Eq. (1) implies F~6.7×10^{-7}. Thus for a 600 kW beam [2], a loss of 0.4 W is expected.

The upper limit on the nominal loss for high-intensity long-pulse beams at section 20-8C (at 33 GeV) is estimated to be 6×10^5 e$^-$ per pulse (0.4 W at 120 Hz).

2.1.2. <u>Comparison with PLIC</u>. At 33 GeV, a loss of 0.4 W at 120 Hz corresponds to ~6×10^5 e$^-$ per pulse. If one assumes that this loss is the type described by the *gedanken* experiment above and that it repeats itself at the output coupler of each 3-m section, then the loss in the S-20 area should be no more than ~2×10^5 e$^-$ per m, 6×10^5 e$^-$ per 3-m section, or 2×10^7 e$^-$ per pulse for all of S-20. Can such a loss be detected by the PLIC?

For a high-intensity long-pulse beam, no PLIC signal above noise can be seen at Sector 20. In **Fig. 1**, the only discrete losses that can be seen are a 20 mV peak at the S-1

[2] For a beam of 1×10^{12} e$^-$ at 120 Hz, the beam power at 33 GeV is ~600 kW.

chicane (early in S-1) and also at the DRIP (end of S-1, beginning of S-2), a 3 mV peak at S-4, 2 mV at S-10, and 8 mV at the S-19 Lambertson, and then a small loss at about S-25. (There is evidence on the S-19 pulse of a shoulder at ~2.5 mV that is located very close to S-20.) The discrete losses are characterized by a relatively fast risetime followed by a slower tail. The FWHM of a discrete PLIC pulse for the long-pulse beam is about 600 ns, which also corresponds to about 1 sector or 100 m. The height of the PLIC noise is no more than 2 mV. A 2 mV discrete pulse every 100 m will appear to be a fairly uniform 2 mV signal. Thus the noise can be considered equivalent to a maximum uniform loss of 0.02 mV per m.

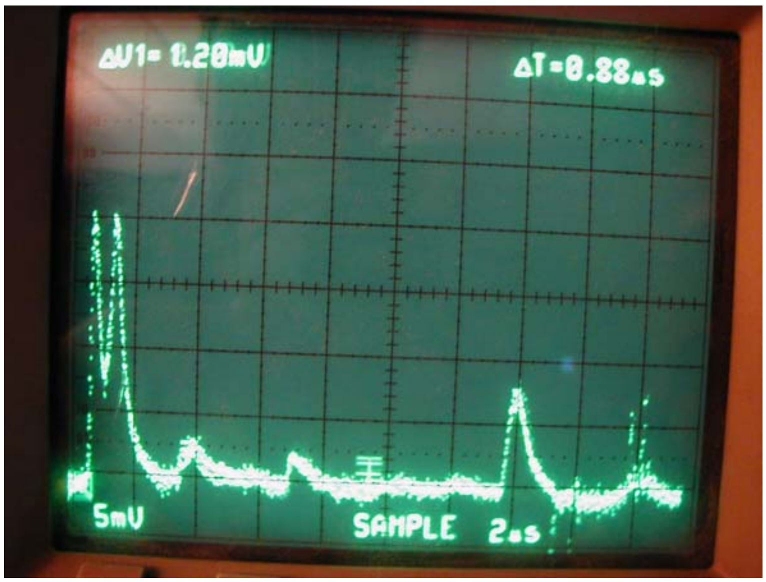

Fig. 1. Linac PLIC signal on Jan. 16, 2002, at 11:36 for a bunch of 6×10^{11} e^- with a bunch length of 320 ns. (eoicdesk pc: P1161136.jpg). The units are 5 mV/cm and 2 µs/cm for the vertical and horizontal axes respectively. Photo by Paul Miller.

Recently the PLIC signal for a 28 GeV beam was variously calibrated to be 4.7×10^6 e^- per mV (Paul Miller directed a known beam intensity into the ST960 stopper [3]) or 5×10^7 e^- per mV (Mike Stanek scrapped the tails of the beam by a known amount using the moveable collimator at 29-1 [4]). Thus the PLIC noise corresponds to an upper limit on a uniform loss of 10^5 to 10^6 e^- per m or 3×10^5 to 3×10^6 e^- per 3-m section (0.19 to 1.9 W per section at 120 Hz and 33 GeV).

At the suggestion of Marc Ross, the raw PLIC signal was examined. This increases the PLIC sensitivity by about an order of magnitude. The results are shown in **Fig. 2**. Due to the change in the scope scale, the S-19 signal now appears just to the right of the scope center and is 108 mV, a factor of 13.5 greater than in **Fig. 1**. The noise is ~10 mV or only a factor of ~5 greater than in **Fig. 1**. The noise in **Fig. 2** implies the upper limit on a uniform loss derived from **Fig. 1** should be a factor of 2 lower, corresponding to a loss of

[3] M. Saleski email to J. Clendenin, Jan. 23, 2002, 4:34 PM.
[4] M. Stanek email to R. Nelson, Oct. 22, 2001, 12:18:54.

0.1 to 1 W per 3-m section at 120 Hz and 33 GeV. The shoulder at S-20, if it represents real beam loss, would add another 0.1 to 1 W for the entire sector.
Thus the upper limit on the loss predicted in section 2.1.1 (6×10^5 e^- in a 3-m section) is consistent with the observed PLIC signal for a high-intensity long-pulse linac beam.

Fig. 2. Raw linac PLIC signal on Feb. 25, 2002, at about 09:55 for a bunch of 5.9×10^{11} e^-. The units are 50 mV/cm and 4 µs/cm. Photo by Paul Miller.

2.1.3. Comparison with the "1% rule." The loss per section derived from the *gedanken* experiment is less than 4% of the 10-W loss per section assumed by the traditional "1% rule" for losses in the linac [5]. The 1% rule assumes uniform losses along the linac, whereas most of the losses should occur at the low-energy end when the beam size is larger.

2.2. *Nominal losses in HER and LER Bypass lines*.

There are likewise no visible signs of beam loss in the HER/LER Bypass lines. The linac beam is monitored fairly carefully, so the losses due to large orbits, mismatch, and emittance growth are minimal. However, the HER/LER Bypass lines are not so closely monitored. To account for this situation, the beta mismatch factor in the Bypass lines is assumed to be 50% larger than in the linac, i.e., f=12 is assumed. This leads to σ=3.2 mm in the HER Bypass. See **Table 4**. The beam pipe has an inner radius of 24 mm. Again assuming a 1.5 mm orbit and 2 mm misalignment, the radial clearance for the beam may

[5] For a beam of 1×10^{12} e^- at 120 Hz, the beam power at 50 GeV is ~1 MW, 1% of which is 10 kW. Assuming a uniform loss along the linac, this corresponds to 10 W per 3-m section.

be as low as 20.5 mm. See **Table 2**. Consequently, n=6.4 and the expected losses are 10^{-6} W.

On the other hand, in the LER Bypass the positron beam size for the same conditions as in HER, because of the lower energy, is significantly larger, i.e., σ=5.9 mm. Then the vacuum pipe is only 3.5 σ away, thus F~10^{-3}. For a nominal beam power of 1.5 kW, this is a loss of 1.5 W.

Table 4. Comparison of Linac and HER /LER Bypass beams.

	Design β (m)	***f***	**ε_n (m)**	**γ**	**σ (mm)**	**n**	**Nominal S-20 beam power**	**Nominal S-20 beam loss**
Linac	50	8	20×10^{-5}	6×10^{4}	1.15	5.2	600 kW [2] (120 Hz)	0.4 W
HER Bypass	350	12	5×10^{-5}	2×10^{4}	3.2	6.4	5 kW (60 Hz)	1 μW
LER Bypass	350	12	5×10^{-5}	6×10^{3}	5.9	3.5	1.5 kW (60 Hz)	1.5 W

2.3. *Summary*.

The upper limit for the nominal beam losses expected at Sector 20 are summarized in **Table 5**.

Table 5. Summary of beam losses at Sector 20 for corresponding nominal beam power.

Beam Line	**Beam loss (W)**	**Corresponding nominal beam power**
Linac	0.4	1×10^{12} e^- at 33 GeV and 120 Hz→600 kW
HER Bypass	10^{-6}	4×10^{10} e^- at 12 GeV and 60 Hz→5 kW
LER Bypass	1.5	4×10^{10} e^- at 4 GeV and 60 Hz→1.5 kW

Acknowledgements: F.-J. Decker suggested many of the scenarios discussed here. Paul Miller organized the PLIC measurements for the high power linac beam. Mike Saleski contributed many useful comments.

From: Saleski, E. Michael
Sent: Wednesday, January 23, 2002 4:34 PM
To: Clendenin, James
Cc: Miller, Paul; Stanek, Michael; Nelson, W. Ralph; Prinz, Alyssa A.
Subject: Loss Estimate using PLIC

Jim,

Unfortunately, I don't think that PLIC has enough resolution for your needs. You want to claim/verify that the average loss from the main linac is 0.4W in the vicinity of the LCLS injector. This is average power, and PLIC looks at power/pulse; in other words, it is repetition rate independent. So, assuming 120Hz rep rate for the 0.4W loss, that gives us 7.3e5 particles/pulse that we are trying to verify is the normal loss for the beam in that region.

Paul's December ST950 and ST960 calibrations also gave us fiducials for the PLIC. He ran 2e10 electrons/pulse at 28.5 GeV into the stoppers (90W at 1Hz) and the PLIC signal achieved 3.0V and 4.25V for stoppers 950 and 960, respectively. Let's consider ST960's 4.25V, as it turns out that sensitive PLIC would be favorable for this measurement. Also, let's forget about scaling the PLIC readings with energy and assume that the Linac beam will be at 28.5 GeV as it passes the LCLS injector; it's a close enough approximation. So the ST960 PLIC signal corresponds to 4.7e6 electrons/mV of PLIC signal. Also, I spoke with Mike Stanek, and he told me that he found a 10 mV PLIC reading with 5e8 electrons as best estimated with torroids for beam loss with the sector 30 collimators (also at 28.5 GeV); this is 5e7 electrons/mV of PLIC signal.

Now, to find 7.3e5 particles on the PLIC scope, I need to look for 0.11mV signal (Paul's calibration) or a 0.015mV signal (Stanek's calibration). When I go look at the PLIC scope, I observe that there is 1mV or more of noise! We can't measure better than 1e7 electrons (plus or minus, depending which calibration you believe), which is unfortunate.

However, I do remember some years ago when I was a new OP at MCC and Marc Ross actually found a kimwipe left in the beampipe using PLIC (we knew that something was blowing up the emittance). It seems to me that a kimwipe would cause less than 1e7 electrons/pulse loss. I would talk to Marc Ross on this one. Regardless, he would be an excellent source of estimating the losses along the linac, and he's a member of the RSC, so he'll certainly carefully scrutinize your estimation eventually, anyway.

As far as the old OPS at most 1% is lost, the '1% rule,' goes... If we assume that normal beam loss occurs on the smallest aperture on each accelerating structure, as designed, we find that just over 1e-3 of the loss occurs at each structure (about 950 structures), or 1e-5 of the beam is lost at each structure (an order of magnitude larger than you assertion). This 1e-5 agrees with the PLIC limit: If we consider a 6.5e11 p/p beam (the 550kW E158 beam), then 1e-5 loss at each accelerator structure is 6.5e6 p/p. This is just at the limit of the sensitivity of the PLIC system; we may or may not be able to see this. That's probably where the 1% rule came from. Nonetheless, I will only be able to confirm that normal beam loss does not exceed 1% with PLIC. For LCLS, you really need to demonstrate that you meet the 0.1% rule, it seems.

Mike Saleski

Date: Mon, 22 Oct 2001 12:18:54 -0700
From: "Stanek, Michael" <stanek@SLAC.Stanford.EDU>
To: "Nelson, W. Ralph" <wrnrp@SLAC.Stanford.EDU>
Subject: Possible beam power loss at 20-9

Ralph,

I did some experiments with the present beam in the Linac on Friday, and came up with the estimate below.

I tried to mis-steer a ~28 GeV beam at 20-9, and was not able to generate any PLIC signal or noticeble beam loss with dipoles in that viscinity. I was able to make some loss further downstream, probably at ~25-9, with a several mm oscillation starting in Sector 20. If I were to interrupt the PEP beams, I could probably generate loss at 20-9 by steering upstream of the Scavenger line. I was not able to do that last week.

So to get a more controlled estimate, I used the moveable collimator at 29-1, and scraped the beam tails until I measured a PLIC signal ~10% of the trip threshold (10 mV, and rate limit starts at 100 mV). This should replicate an E158 "possible" beam loss at 20-9 that might persist for some time. I doubt if normal beam tuning would result in this condition, but it is possible.

The measured beam loss for this 10 mV PLIC signal at 28 GeV is ~5e8 e-/pulse. Projecting this to 120 pulses/sec gives a beam power loss of ~270 Watts.

I hope this is what you are looking for. If you have any questions, let me know.

Michael Stanek
stanek@slac.stanford.edu
SLAC - phone (650)926-4340
home - (408)255-2311