SLAC MEMORANDUM-E163

DATE: November 16, 2005

TO: Heinz Vincke

FROM: Eric Colby, Robert Noble

SUBJECT: **Maximum Credible Beam Power: revisiting the Explosive Electron Emission (EEE) Loss Calculations for E163**

This memo describes a calculation of the maximum credible beam power that can be delivered to the Experimental Hall. "Explosive Electron Emission" (EEE) from the photocathode of the E163 rf gun was described in a earlier memo[1]. The prior memo calculated transmission of the EEE current with magnets and rf structures set to an otherwise nominal configuration.

This document carries those calculations further, under the following, more conservative assumptions:

1) RF devices are set to the maximum gradient possible with the available klystron power
2) The magnet lattice is reoptimized for best transmission of the EEE current to the Experimental Hall

These are conditions that would arise if a skilled operator deliberately operates the machine in a manner that is destructive to the components (both through frequent rf breakdown and large beam losses) and quite difficult to optimize (since several key groups of diagnostics will be saturated by the high charge). Such operation goes well beyond the scope of accidents that could occur with an unskilled operator, and is possible only with a malicious accelerator operator.

One can immediately bound the maximum beam power possible from the electron gun by observing that (1) the laser pulse (hence the onset of EEE) is always very near the end of the rf pulse, and (2) the total stored EM energy is 6.8J for 115 MV/m, the demonstrated maximum field in the gun. At the highest gun PRF of 10 Hz, this limits the output beam power to 68 Watts, assuming perfect conversion to beam power. (This is the number listed in Table 1 of the memo titled "Installation of New Electron Source" to Sayed Rokni).

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[1] E. Colby, memo to Heinz Vincke/RP, "EEE Loss Calculations for E163", SLAC Memorandum, (2004).

A similar argument may be applied to the stored energy in the x-band accelerator sections. With a $Q_o = 7005$[2], and a peak accelerating field of 70 MeV/m for 100 MW forward power[3], the available stored energy is 9.75J per structure. Adding this to the gun energy gives a maximum possible beam power of 263 Watts, assuming again that all the stored energy becomes usable beam power.

When one properly accounts for beam loading effects and beam transmission losses, this number becomes significantly lower. We will now more carefully evaluate this number.

Explosive Electron Emission Model and Beam Loading in the Gun

The explosive emission process results from the formation of plasma on the cathode surface with approximately the same dimensions as the laser pulse that ignited it. The current which may be extracted is presumed to be fully space-charge-limited, that is, the Child-Langmuir law may be applied to estimate the current as a function of field strength and time. The total charge extracted in an rf bucket may be estimated as:

$$Q_i = (\pi r^2)\frac{4}{9}\varepsilon_o\sqrt{\frac{2e}{m_e}}E_{cath}^{3/2}d^{1/2}\int_0^{\tau/2}\sin^{3/2}(\omega t)dt$$

Where the result of the half-cycle integral is $2\int_0^{\pi/2}\sin^{3/2}(\omega t)dt = \frac{1}{3\omega\sqrt{2\pi}}\Gamma(\frac{1}{4})^2$.

Energy balance in the gun cavity provides:

$$\frac{dU(t)}{dt} = P_F(1-\rho^2) - P_{beam} - P_{wall} - P_{rad}$$

With the reflection coefficient ρ included to properly account for the cavity mismatch induced when heavy beam loading modifies the cavity impedance. For a maximum gun gradient of 115 MV/m (on the cathode, corresponding to $P_F = 10\ MW$), and a 5 mm radius laser spot, and the laser timed to arrive 50 nsec before the end of the rf flat-top (when maximum stored energy is available to make EEE beam), the emitted charge per rf bucket, gun gradient, beam exit energy, and cavity stored energy are shown in figure 1. This small time offset before the end of the rf pulse is typical of normal operation, and does little to change to total stored energy (since 50 nsec is short compared to the fill-time, 307 nsec.)

Note that the RF forward power (i.e. power entering the cavity) drops abruptly from 10 MW to 5.5 MW when EEE commences, and recovers only slightly as the EEE current drops. RF power is terminated at t=0.5x10^{-7} seconds.

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[2] NLC ZDR, SLAC-474, page. 486.

[3] C. Adolphsen, private communication, 11/11/2005.

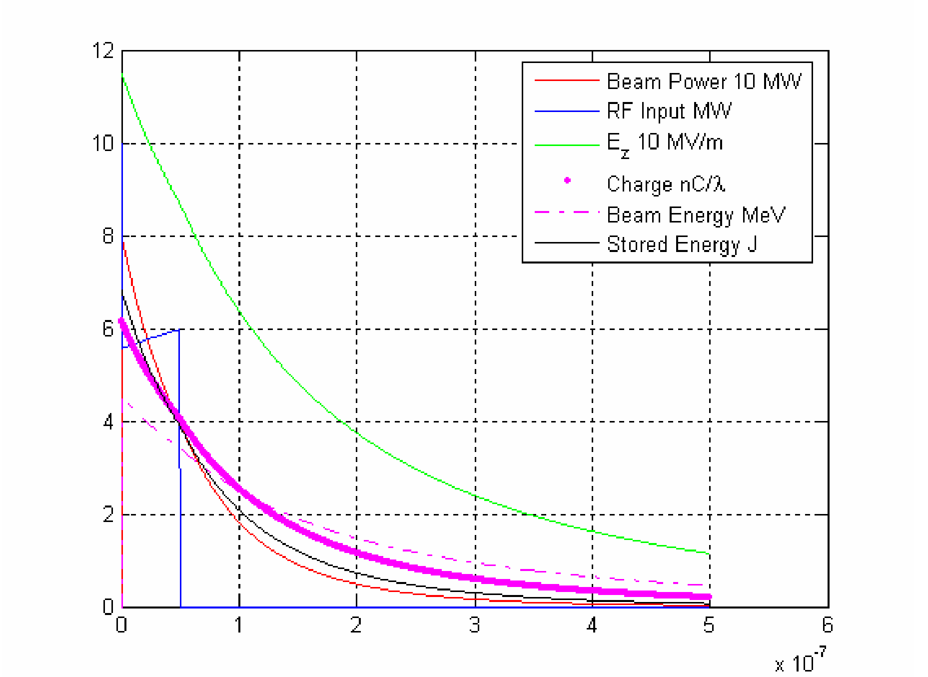

FIGURE 1. Gun fields (green), stored energy (black), forward power (blue), emitted charge per rf bucket (pink dots), emitted bunch energy (pink dot-dash), and beam loading power (red), as a function of time. Note scaling factors of x10 in some units. The total emitted charge and beam power are 2.1 μC and 56 Watts, respectively.

Beam Loading in the Injector X-band Accelerator

The model is implemented in a manner analogous to the gun model, but without correction for cavity mismatch due to increased beam loading. As before, the laser pulse is presumed to be timed within 50 nsec of the end of the x-band power pulse, at the time when the stored energy in the accelerator is maximum, and additional power from the klystron can help sustain the fields during the EEE beam passage.

Figure 2 shows the evolution of the linac accelerating voltage, forward rf power, final EEE beam energy, beam loading power, and bunch charge (Calculated transmission losses of 80%, evaluated with Parmela, are included) , zoomed in to cover the initial 75 nsec period when the cavity fields are dropping rapidly. Note the scale is magnified compared with figure 1. Blue dot-dash lines indicate the momentum bandwidth and temporal extent accepted by the magnet lattice for highest EEE beam power which can be transported to the Experimental Hall.

It is clear from Figures 2 that within the first 5 nsec after onset of EEE, the accelerating gradient in the linac has been depleted significantly, causing the exiting EEE beam energy to drop more than 10%. This rapid decline is a direct result of the very large current represented by the first EEE bunches emitted—in this case corresponding to an initial current of over 3.5 Amperes—well above the design loaded value.

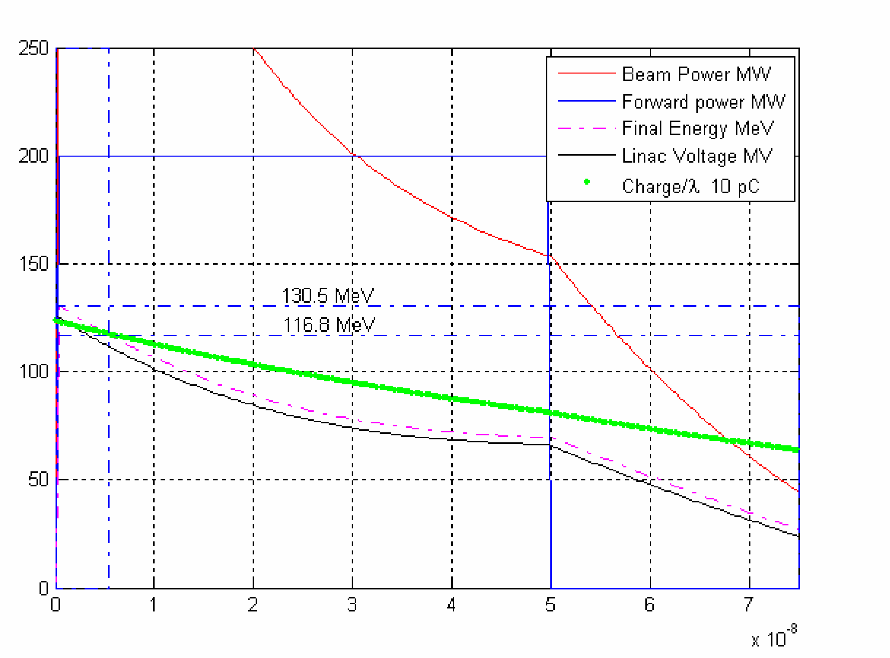

FIGURE 2. Injector Linac total voltage (black), RF total forward power (blue), bunch charge (green), final bunch energy (pink dot-dash), and beam power (red) for the first 75 nsec after onset of EEE. Note scaling factor of x0.1 in charge units. Horizontal blue dot-dash lines indicate the momentum range that actually survives transport through the NLCTA chicane. The vertical blue dot-dash line indicates the last EEE bunch that survives transport, the remaining bunches are lost in the NLCTA chicane.

EEE Beam Transmission to the Experimental Hall

Transmission losses of the EEE beam are calculated and included in the credible beam power estimate as follows. A Parmela simulation from the gun to the exit of the x-band accelerator sections was made to establish the accelerated EEE beam properties. This beam phase space was loaded into Elegant and transported into the experimental hall. The Elegant simulation was repeated for the first 33 bunches (viz. until transmission dropped below 0.5% per bunch) and the transmission fraction for each was evaluated. Figure 3 shows the transmitted fraction and mean energy for the first 33 bunches. The beam phase spaces for each of the subsequent bunches was assumed identical to the highest energy (first) bunch, but with the beam momenta scaled to match the declining bunch energy calculated and displayed in figure 2. The bunch charge is taken directly from the calculated values shown in figure 2.

We note that transmission losses were included in calculating the maximum credible beam power deliverable to End Station A[4].

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[4] S. Ecklund, SLAC Memo, “Maximum Credible Power to End Station A”, 28 November 2000.

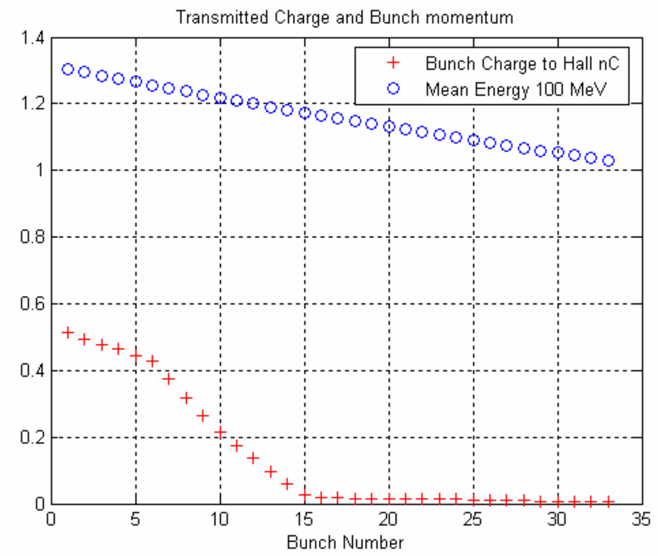

Figure 3. Bunch-by-bunch mean energy in units of 100 MeV (blue circles) and transmitted charge in units of nC reaching the Experimental Hall (red plus signs).

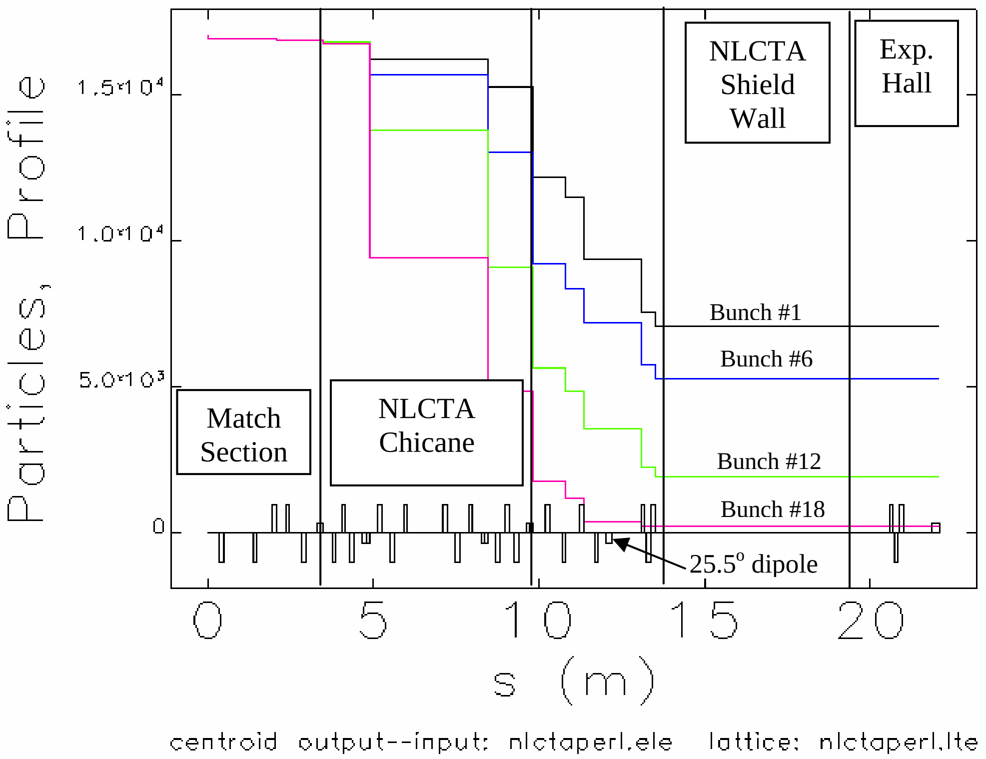

Figure 4. Transmission of charge from the exit of the x-band injector accelerators through to the Experimental Hall. The four traces show the number of particles surviving (out of 17,019 initial macroparticles) for the 1st, 6th, 12th, and 18th bunches. The lattice magnet positions are indicated at the bottom of the graph.

The limited momentum bandwidth significantly reduces the beam power that can be transmitted to the Experimental Hall, with much of the beam power being lost in the NLCTA chicane. Figure 4 shows the scraping losses for four representative bunches. As the energy rapidly slews downward, the lower energy bunches are lost earlier in the NLCTA chicane.

If one sums the beam power transmitted in the first 33 bunches (beyond which bunch transmission is less than 0.5% per bunch and the energy is ever decreasing) the maximum credible beam power is:

$$P_{ave} = PRF \cdot \sum_{0<i<34} Q_i V_i = (10Hz) * 0.524 C \cdot V = 5.24 \text{ Watts}$$

And the total transmitted charge per beam pulse is:

$$Q_{tot} = \sum_{0<i<34} Q_i = 4.68 \text{ nC}$$

which is distributed into ~33 rf buckets.

Conclusion

Although deliberate tuning of the beamline to pass a significant fraction of the EEE current is possible, the combined beam loading effects and poor transmission result in the maximum credible beam power which can be delivered to the Experimental Hall of just 5.2 Watts at 130 MeV peak energy.

If one also includes the possibility that an astute operator could (1) modify or bypass the BCS rep-rate limiter and (2) provide new hardware or make appropriate SCP modifications to produce a 30 Hz gun trigger (slightly above the maximum rep rate possible with the present s-band HV charging supply), then the maximum credible beam power is 15.7 Watts at 130 MeV.

This stands in marked contrast to the prior calculations[5] which showed that EEE beam power of ~1 Watt would survive transport to the Experimental Hall if the NLCTA chicane collimator was fully open, and that “tens of mW” would survive transport if the chicane collimator was set to the position used for conducting E163’s low-charge experiments. The significant gain in power is traceable to two sources: (1) a doubling of the beam energy, and (2) significantly improved transmission (10% vs. <1%) possible if the magnet lattice is reoptimized to pass the EEE beam. The former case is the most probable accident scenario during otherwise normal operation. The case presented here requires skill and malice (or at least willful neglect of obvious signs the machine is

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[5] E. Colby, memo to Heinz Vincke/RP, “EEE Loss Calculations for E163”, SLAC Memorandum, (2004).

operating abnormally, such as frequent rf breakdown and saturated diagnostics) on the part of the operator.

It should be noted that EEE results in substantial degassing (since the cathode is being aggressively eroded by the emitting plasma), which would result in both the MPS vacuum interlock tripping off the gun (resulting in a significantly lowered repetition rate), and in such poor vacuum conditions that the gun would breakdown on most rf pulses. Long-term operation in EEE mode (hours) would result in substantial physical damage to the cathode, and would be very likely to make the gun prone to voltage breakdown even in the absence of EEE.

It should also be noted that the EEE beam will comprise ~4.7 nC of total charge, almost a factor of 5 above the maximum design charge (1 nC), and roughly two orders of magnitude above the nominal E163 bunch charge (50 pC). This beam will drive many of the beam diagnostics (e.g. profile screens and BPMS) to saturation, providing a readily recognized indication of a problem to the operator, and making the tuning of magnets to optimize EEE beam problematic.