In simulations of the Wisconsin superconducting radiofrequency (SRF) electron gun, 100-pC bunches with normalized transverse emittance of 0.37 mm-mrad and peak current of 10 A are produced when the laser pulse on the Cu or Cs$_2$Te photocathode is much longer than that used for blowout mode. The emittance and peak current are one-half of those observed in blowout-mode 100-pC bunch simulations.

With the use of a lower emittance cathode, normalized transverse emittance of 0.23 mm-mrad and peak current of 10 A are obtained. With either photocathode, the low-emittance bunches have slice energy spread of 1.4 keV, suitable for a free-electron laser with output at MHz repetition rates.
The Wisconsin superconducting radiofrequency (SRF) electron gun was designed to operate in blowout mode, where the initial bunch length on the photocathode is short compared to that of the accelerated bunch. The use of blowout mode provides a short bunch with a large peak current, while smoothing out the effects of non-uniform laser pulses.

Simulations of the production of 200-pC bunches by the Wisconsin SRF electron gun have been described in Ref. [1–6]. The simulations of blowout mode [7] include the emittance compensation [8] from focusing the bunches in a high-temperature superconducting (HTS) solenoid, and then accelerating them to 85 MeV in a TESLA 1.3-GHz cryomodule.

For several initial bunch lengths, we study the production of 100-pC bunches when the peak field in the 200-MHz cavity equals the design value of 41 MV/m and the cathode is flush with the cavity surface. The ASTRA [9] code is used to perform 100,000-particle simulations of realistic bunches that initially have truncated Gaussian radial and longitudinal profiles, truncated at 0.8 \( \sigma \).

For a truncated Gaussian radial profile with radial \( \sigma \) of \( \sigma \), \( \sigma_{x,y} = 0.4 \sigma \).

Figure 1 shows the results of simulations for initial longitudinal \( \sigma \) values of 187.5, 562.5, 1687.5, 5062.5, and 6250 fs; the corresponding initial full bunch lengths are 0.3, 0.9, 2.7, 8.1, and 10 ps. For each value of the initial bunch length, we optimized the initial bunch radius and the strength of the emittance-compensation solenoid in order to minimize the projected emittance of the accelerated bunch that exits the TESLA module. For the optimized solenoid strength, the image of the photocathode is near the upstream end of the second rf cavity in the 8-cavity TESLA module. Because the first rf cavity is used as a buncher, the image is near the upstream end of the first rf cavity that is utilized for bunch acceleration [6]. This is consistent with the emittance compensation process in which a beam waist is formed near to the entrance of the first acceleration cavity [1, 8].

Figure 1(a) shows the projected emittance of the accelerated bunch, and the slice emittance and slice energy spread in the longitudinal center of the bunch. To evaluate the slice properties, 200 slices—each containing 500 particles—were considered. Since the slice emittance is largest near the bunch center, it is possible to obtain a projected emittance that is lower than the slice emittance of the center slice. The optimal initial bunch radius and the accelerated bunch peak current are plotted in figs. 1(b) and 1(c).

By using a short laser pulse on the photocathode to obtain blowout mode, accelerated bunches are produced with normalized projected and slice emittances of 0.8 mm-mrad, slice energy spread of 0.4 keV, and peak current of 21 A. With a longer laser pulse, accelerated bunches can be produced with normalized projected and slice emittances of 0.37 mm-mrad, slice energy spread of 1.4 keV, and peak current of 10 A.

We then consider a lower emittance photocathode that produces electrons with initial transverse emittance that obeys \( \varepsilon_{x,y} \) [mm-mrad]= 0.5 \( \sigma_{x,y} \) [mm], corresponding to initial transverse energy of 0.128 eV [12, 13]. This case corresponds to theoretical photocathode behavior for several materials with perfectly smooth, flat surfaces. Figure 2 shows the simulated bunch properties when the initial bunch radius and the emittance-compensation solenoid strength are optimized to minimize the projected emittance. By using a sufficiently short laser pulse to obtain blowout mode, accelerated bunches can be produced with normalized projected and slice emittances of 0.5 mm-mrad, slice energy spread of 0.35 keV, and peak current of 21 A. With a longer laser pulse, accelerated bunches can be produced with
normalized projected and slice emittances of 0.23 mm-mrad, slice energy spread of 1.4 keV, and peak current of 10 A.

For both photocathodes, the use of a 10-ps laser pulse gives simulated 100-pC bunches with transverse emittance < 0.4 mm-mrad, slice energy spread of 1.4 keV and peak current of 10 A. Such bunches are suitable for a free-electron laser with output at MHz repetition rates.

References
Figure 1. Bunch properties vs. initial bunch length for a photocathode that produces electrons with initial transverse energy of 0.511 eV. The initial bunch radius and the solenoidal field are optimized for each value of the initial bunch length, in order to minimize the projected emittance. (a) The projected and slice emittances and slice energy spread at the exit of the TESLA module. (b) The optimal value of the initial bunch truncated-Gaussian radial $\sigma_r$. (c) Peak current at the exit of the TESLA module.
Figure 2. Bunch properties vs. initial bunch length for a photocathode that produces electrons with initial transverse energy of 0.128 eV. The initial bunch radius and the solenoidal field are optimized for each value of the initial bunch length, in order to minimize the projected emittance. (a) The projected and slice emittances and slice energy spread at the exit of the TESLA module. (b) The optimal value of the initial bunch truncated-Gaussian radial $\sigma_r$. (c) Peak current at the exit of the TESLA module.