OPTIMUM BEAM CREATION IN PHOTOINJECTORS USING SPACE-CHARGE EXPANSION*

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Abstract

It has recently been shown that by illuminating a photocathode with an ultra-short laser pulse of appropriate transverse profile, a uniform density, ellipsoidally shaped bunch is dynamically formed, which then has linear space-charge fields in all dimensions inside of the bunch. We study here this process, and its marriage to the standard emittance compensation scenario that is implemented in most modern photoinjectors. It is seen that the two processes are compatible, with simulations indicating that a very high brightness beam can be obtained. The scheme has produced stimulus for a series of experiments at the SPARC injector at Frascati in 2006-2007. An initial time-resolved experiment has been performed involving Cerenkov radiation produced at an aerogel. We discuss the results of this preliminary experiment, as well as plans for future experiments to resolve the ellipsoidal bunch shape at low energy. Future measurements at high energy based on fs resolution RF sweepers are discussed.

INTRODUCTION

In order to obtain the highest brightness electron beams from photoinjectors, it is most common to rely on the emittance compensation process [1]. Optimization of this process demands that the transverse fields be as uniform, and linear (in radius r) as possible. The existing studies of emittance compensation have, to that end, assumed use of a uniform density electron beam, having a cylindrical shape. However, this shape produces space-charge fields near the beam head and tail that have pronounced nonlinear dependencies on the spatial coordinates. These nonlinearities result in both transverse and longitudinal emittance growth.

It has been known for some time, however, that a uniform ellipsoidal density distribution yields space-charge fields that are linear in all dimensions [2]. Under such conditions, it is conceivable that one may obtain essentially emittance growth-free dynamics. How to produce such a distribution has, until recently, remained an unanswered question.

In 1997, Serafini proposed the dynamic creation of an ellipsoidal bunch by launching an ultra-short, radially shaped beam, which then evolves to achieve the desired longitudinal shape [3]. On the other had, it has recently been shown by Luiten, et al., that in obtaining the correct final ellipsoidal distribution, there is essentially no requirement on the shape of the initial laser pulse other than it be ultra-short (length τ_l much shorter than eventual beam length after space charge expansion) [4]. Thus such laser pulses are a natural, and technically achievable way of producing an ellipsoidally shaped, nearly uniform density beam.

As the beam dynamics just after photoemission are qualitatively different in the traditional emittance compensation scenario and in the Luiten-Serafini scheme, it is not immediately apparent that one may successfully combine the two. The UCLA-SPARC collaboration has recently shown [5] that this marriage is indeed possible; further, the combination of emittance compensation and dynamic creation of the ellipsoidal shaped beam produces results that in many ways are superior to those obtained in state-of-the-art designs. As the bunches that are produced are shorter than in standard cases, very high brightness beam creation is possible.

The basic idea behind the Luiten-Serafini scheme is simple: the beam profile expands and deforms longitudinally to produce, in the final state, a uniformly filled ellipsoid of charge. In the process, phase space rearrangements occur which degrade the emittances– especially in the longitudinal dimension. In order to understand this process, to specify experimental requirements, and to identify experimental signatures associated with the process, we have analyzed the dynamics of space-charge-dominated beam ex-

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pansion [5].

This analysis may be summarized in a few points:

First, the injected bunch surface charge density $\sigma_b = dQ_b/dA$ must not be too high, or image charge effects at the cathode distort the final pulse profile so that it is not ellipsoidal. This is quantified by the condition $\alpha \equiv 4\pi\sigma_b/E_0 \ << 1$.

Second, the beam must be much shorter than its eventual size in order to be able to ignore the details of the initial pulse profile. In practice, 300 fs laser pulses (typical of the limitations of the SPARC photocathode drive laser after conversion to UV) excite roughly the same length electron bunch, which expands to around 4 psec in our example cases. The pulse length after expansion is estimated as $L_b \approx 2\pi\sigma_b m_e c^2/E_0^2$.

The current density that is achieved after expansion is $J_z = eE_0^2/4\pi m_e c$, a constant dependent only on the applied electric field E_0. All beams become uniform in density. To achieve the desired ellipsoidal beam shape, one must choose the initial surface current density distribution correctly, which implies that $\sigma_b(r) = (3Q_b/2\pi a^2)\sqrt{1-(r/a)^2}$.

While the analysis of the beam dynamics is useful, the central issue of joining this regime with emittance compensation must be explored with simulations. The initial simulations begun in Ref. [5] that we have performed are in the context of the SPARC scenario, so that we may proceed directly to discussing the experimental tests of this new regime– now commonly known as the "blowout regime"– of the photoinjector there.

BLOWOUT REGIME WITH EMITTANCE COMPENSATION: GENERAL STUDY

We have performed initial UCLA PARMELA [6] simulations to explore joining the Serafini-Luiten scheme with the optimized emittance compensation working point of the SPARC injector at LNF. We assume that the gun (1.6 cell, 2856 MHz) and solenoid are the same, and run near to the standard conditions. Through trials, we have optimized the launch conditions of the beam. In order to have values of α which do not give excessive image charge effects, the beam charge is lowered and the beam radius is slightly enlarged. In the preliminary optimization, we launch a 0.33 nC beam with an initial longitudinal Gaussian distribution having $\sigma_t = 33$ fs beam, and a radial Gaussian with $\sigma_x = 0.77$ mm (cutoff at 1.8σ). The gun is run with a peak on-axis gradient of 120 MV/m; the beam is launched at 33 degrees forward of crest. This is a bit advanced in comparison to the nominal launch phase for a standard bunch, and serves to control the excessive beam energy spread after the gun. The emittance compensation solenoid is run with peak field $B_z = 2700$ G, which is slightly below the standard scenario, as the beam has slightly lower energy exiting the gun. We note that the peak value of α in our case is 0.11, as opposed to 0.42 in the LCLS design.

The formation of the quasi-ellipsoidal bunch is clearly

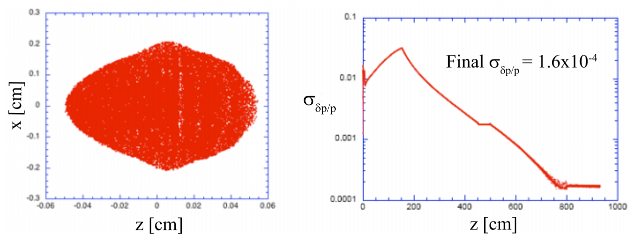

Figure 1: (left) PARMELA simulation results of electron bunch (x, z) distribution 133 cm from cathode (6.3 MeV energy), showing ellipsoidal beam boundary. (right) Evolution of $\sigma_{\delta p/p}$ in z for emittance compensation case, from PARMELA simulation.

shown in Fig. 1, which displays the bunch (x, z) distribution at a point 133 cm from the cathode, in the drift space after the gun and just preceding initial traveling wave linac section. Here the beam has 6.3 MeV mean energy, and its transverse dynamics are space charge-dominated. Thus one sees clearly the "inflated" ellipsoidal beam shape. The final bunch length is 1.3 mm full width, corresponding to a peak current of 105 A. Thus even with one-third of the charge, this scheme should produce a higher current than obtained in simulations of the standard design.

Two notable defects are seen in the beam shape in Fig. 1. The first is the extension of the half-ellipsoid in the trailing part of the bunch as compared with the initial half– an asymmetry caused by image charge effects. This non-ideal behavior in fact gives the limit on σ; when one attempts to launch a higher surface charge density, the bunch deformation from the desired symmetric ellipsoid produces poor emittance performance. The second notable feature is the existence of an anomalous ring at the outer radial edge of the beam. This part of the beam has low surface charge density and experiences radially fringing fields due to its edge location. Because of these effects, it does not experience enough longitudinal expansion to keep pace with the rest of the bunch, but instead has a moderate amount of radial expansion.

As the longitudinal space-charge during much of the acceleration is also linear, and total pulse length T is short, the longitudinal phase space is very compact. The evolution of the relative momentum spread $\sigma_{\delta p/p}$ in z is shown in Fig. 1. The final achieved RMS value is $\sigma_{\delta p/p} = 1.6 \cdot 10^{-4}$, which is an order of magnitude smaller than that obtained in the standard LCLS type (or SPARC type) design.

The evolution of the RMS transverse beam size σ_x , and the RMS normalized emittance $\epsilon_{n,x}$ are shown in Fig. 2. While the behavior of σ_x is similar in most respects to the standard design, with the beam approximately matched at linac entrance to the invariant envelope, the emittance behavior is not as familiar. In the standard LCLS design, $\epsilon_{n,x}$ achieves a minimum value in the post-gun drift, rising to a local maximum at injection into the linac. The focusing and adiabatic damping of the motion in the linac then produce a

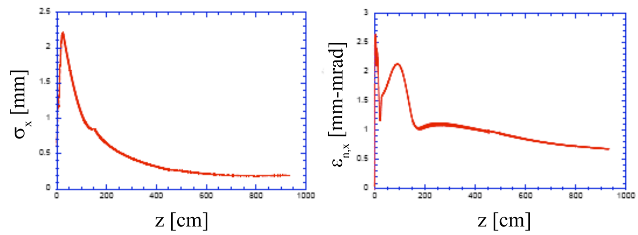

Figure 2: (left) The evolution of RMS transverse beam size σ_x for emittance compensation case, from PARMELA simulation. (right) Evolution of RMS normalized emittance $\epsilon_{n,x}$ for emittance compensation case.

monotonic decrease of $\epsilon_{n,x}$ in z. In our case, the transverse space-charge and thus the plasma/emittance oscillations do not "turn on" until after the longitudinal expansion is well underway, thus delaying the emittance minimum in Fig. 2 to occur inside of the linac. In order to produce faster emittance oscillations in the linac to strongly diminish $\epsilon_{n,x}$ before acceleration removes the plasma-dominated beam behavior, the solenoid field in the first linac section has been raised by 40% relative to the standard scenario. This ploy works well, as the final value (still slightly decreasing) of $\epsilon_{n,x}$ at the end of the second linac (84.5 MeV energy) is 0.68 mm-mrad. The thermal emittance at the cathode is 0.4 mm-mrad, and so the space-charge induced emittance is well compensated.

After acceleration to higher energy (84.5 MeV), the beam is not spacecharge dominated, and the (x, z) profile no longer ellipsoidal. Nonetheless, the beam has excellent emittance, and maintains a current profile with shape $I(t) \propto \sqrt{1-(2t/T)^2}$. With a high initial current, and low intrinsic energy spread, this beam may be compressed further, with very high final peak current achievable [7].

CONSIDERATIONS FOR SPARC EXPERIMENT

Laser and photocathode issues

Before discussing the planned electron beam measurements, we first review some experimental considerations specific to the use of such short lasers. First, we note that the laser pulse should be tailored, either by collimating and relay imaging, and that it must be quite short. In first measurements at SPARC, we have found, through cross-correlation measurements, that the UV pulse is difficult to make shorter than 300 fs using 3rd harmonic generation with noncollinear mixing in the conversion crystals. In order to obtain even this result, we must give up UV energy, going from 1.5 mJ to 0.2 mJ. While this energy is still adequate for obtaining 0.33 nC of charge using a metal cathode (Cu or Mg), to go shorter may be difficult. In order to check the effect of this extra pulse length on the scheme, we have performed simulations analogous to the original exploratory, indications are that the added length in the laser pulse does not affect the final electron beam configuration at this level.

The laser intensity needed for this scenario is a factor of 30-100 higher than in the LCLS case. The issue of laser damage at the cathode surface has been examined, and found based on previous experience at UCLA and at the BNL ATF to not be worrisome [7].

Experimental signatures and measurements

In the SPARC experiment, we plan first to image the beam (time-integrated) at low energy (5-7 MeV) in the region after the gun, using a YAG detector. For time resolved measurements we will first convert the beam spatial information to photons with a Cerenkov convertor. In order to have a manageably small angle of emission we use aerogel, which has a small index of refraction (n = 1.005-1.02). At 5 MeV the Cerenkov emission threshold is reached for $n = 1.005$; we may choose angles of emission from near zero at this threshold to up to 9 degrees with the aerogels that are presently in hand. The aerogels have been custom fabricated at the Jet Propulsion Laboratory.

Simulations consist of providing electrons (typically 40,000) from PARMELA to GEANT [8], which simulates the scattering of the electrons in the entrance foil and generates a collection of Cerenkov photons in the aerogel. The photon distributions that result are then passed to a *Mathematica* based, optical ray-tracing program, *Rayica*.

The streak camera at SPARC has 2 ps FWHM time resolution, which is on the border of resolution for the bunch length of interest. This will be handled in initial measurements by use of higher charges (above 1 nC), and thus longer beams, to test the longitudinal expansion dynamics of the beam. We thus must consider alternative schemes based on ultra-fast gating [7].

FIRST RESULTS

The first stage of experimentation on the blowout regime took place at INFN-LNF beginning at the end of March 2006. During commissioning of the SPARC RF photocathode gun, the UCLA-produced gun was conditioned quickly up to 11 MW, which produces 110 MV/m peak electric field, and a 5.7 MeV electron beam.

The laser was reconfigured for short pulses (less than 0.5 psec FWHM) and up to 1.6 nC of charge. The conditions for observing the dynamic creation of nearly uniformly filled ellipsoidal charge distributions were not quite present; in fact, the emittance was not of equivalent quality to that obtained in standard operation. Nevertheless, impressive first data was obtained.

Initial measurements of the longitudinal-transverse profile of the beam were made with aerogel with index $n = 1.008$, with the Cerenkov radiator placed 2.4 m away from the cathode, downstream of the slit-based emittance measurement system. Streak camera images were obtained using the transport system described in the previous section. Such a streak, after correction, is shown in Fig. 3.

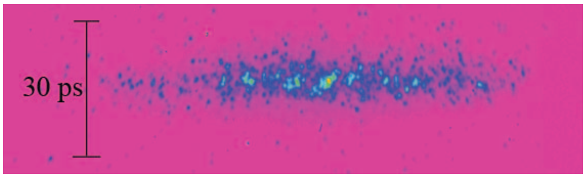

Figure 3: Streak image from SPARC experiment, after correction.

This image displays the profile obtained from a bunch with charge of 700 pC. A large charge is preferred in this case in order to discern information at a time scale longer over the streak camera resolution; the 700 pC case is expected to have expansion of approximately 7 psec FWHM, well in excess of this 2 psec FHWM resolution.

Streak images obtained in the highest temporal resolution mode are inherently noisy; this condition is required in order to avoid space-charge induced pulse distortion inside of the streak tube. Thus in order to extract information from single shots concerning the streak image– which should represent the beam density distribution in an (x, z) slice in the midplane of the bunch– we have adopted a maximum likelihood analysis to test for different assumed types of beam distributions.

The (x, z) slice distributions we have tested for consistency with the data include: (1) a bi-Gaussian (thermal-type) distribution; (2) a uniformly filled ellipse (assumed arising from a parent uniformly filled ellipsoid); and (3) a nearly uniformly filled ellipse with a tail, which we choose to represent as a Fermi-Dirac distribution.

As all of the distributions assumed have contours of constant density that are elliptical, a systematic statistical approach is possible, in which we look at the total integrated intensity inside of ellipses of size varying from zero area to an area covering the entire streak image. These ellipses are all required to have the same aspect ratio, which is given by the intensity profile itself, $R = \sigma_x/v_s\sigma_t$, where v_s is the streak velocity, and σ_t=3.45 psec for the streak in Fig. 3.

With these functions in hand, we can fit to the data given in the streak images to determine the likelihood that one of the assumed three profiles is more likely than the others. Such an exercise has been performed for the streak given in Fig. 3, with the results shown in Fig. 4. It can be seen the bi-Gaussian hypothesis can be rejected as the least likely model. While the uniformly filled ellipsoid gives a good fit near the distribution center, it is not very accurate at the edge, where one expects strong deviations in any case from this model. Finally, we note that the best fit obtained from the Fermi-Dirac model gives an excellent match to the data.

CONCLUSIONS

While the first measurements have established the soundness of the basic experimental approach, much more remains to be done. As of now, the SPARC injector is being modified to allow for near-axis (as opposed to 70 degree) injection. Additional improvements should also result from use of laser cleaning of the cathode. The SPARC injector will soon be completed with the addition of post-acceleration linacs and beam diagnostics (e.g. RF sweeper). In this fully mature experimental scheme, a complete test of the consistency of the Luiten-Serafini scheme with emittance compensation should be possible, using the large array of techniques described here. Further experiments will also emphasize the demonstration of high quality longitudinal phase space and concomitant low energy spread, as well as high compressibility.

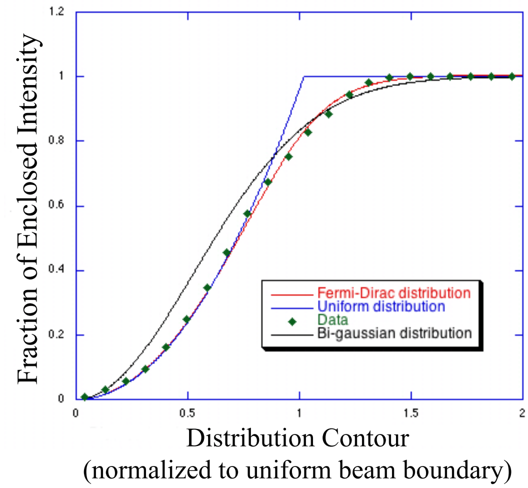

Figure 4: Analysis of streak data, with fraction of integrated intensity of data inside of elliptical contour shown. Best fit of data points to three models are shown: bi-gaussian distribution, uniform elliptical distribution, and Fermi-Dirac (uniform with tails) distribution.

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