OPTIMUM ELECTRON BUNCH CREATION IN A PHOTOINJECTOR USING SPACE-CHARGE EXPANSION

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Abstract

Recent studies have shown that by illuminating a photocathode with an ultra-short laser pulse of appropriate transverse profile, a uniform density, ellipsoidally shaped electron bunch can be dynamically formed. Linear space-charge fields then exist in all dimensions inside of the bunch, which minimizes emittance growth. Here we study this process, and its marriage to the standard emittance compensation scenario that is implemented in most modern photoinjectors. We show that the two processes are compatible, with simulations indicating that a very high brightness beam can be obtained. An initial time-resolved experiment has been performed at the SPARC injector in Frascati, involving Cerenkov radiation produced at an aerogel. We discuss the results of this preliminary experiment, as well as plans for future experiments at the UCLA Pegasus laboratory 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 high brightness electron beams from photoinjectors, it is most common to rely on the process of *emittance compensation* [1]. Optimization of this process demands that the transverse fields be as uniform, and as linear (in radius r) as possible. The existing studies of emittance compensation have, to that end, assumed use of a uniform density electron bunch, having a cylindrical shape. However, this shape produces nonlinear fields near the bunch head and tail that result in emittance growth.

It is now known 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 bunch, 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 [4]. Thus such laser pulses are a natural, and technically achievable way of producing an ellipsoidally shaped, nearly uniform density bunch.

As the beam dynamics just after photoemission are qualitatively different in the traditional emittance compensation scenario than 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 is indeed possible; further, the combination of emittance compensation and dynamic creation of the ellipsoidally shaped bunch 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 bunch profile expands and deforms longitudinally to produce, in the final state, a uniformly filled ellipsoid of charge. In order to understand this process, the dynamics of space-charge-dominated bunch expansion have been studied [5] and may be summarized in a few points:

- 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 bunch profile. This is quantified by the condition $\alpha \equiv 4\pi\sigma_b/E_0 \ << 1$.

- The laser pulse length must be much shorter than the electron bunch length after expansion, in order to be able to ignore the details of the initial laser pulse profile. The bunch length after expansion is estimated as

$L_b \approx 2\pi\sigma_b m_e c^2/E_0^2$.

- To achieve the desired ellipsoidal bunch shape, one must choose the correct initial surface current density distribution: $\sigma_b(r) = (3Q_b/2\pi a^2)\sqrt{1-(r/a)^2}$.

While the analysis of the beam dynamics is useful, the central issue of joining this regime—now commonly known as the "blowout regime"—with emittance compensation must be explored with simulations and experiments.

BLOWOUT REGIME WITH EMITTANCE COMPENSATION: GENERAL STUDY

Initial UCLA `parmela` [6] simulations have been performed to explore joining the Serafini-Luiten scheme with the optimized emittance compensation working point of the SPARC injector at LNF. 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, and a radial Gaussian with $\sigma_x = 0.77$ mm (cutoff at 1.8σ). The gun (1.6 cell, 2856 MHz) 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. It is noted that the peak value of α in the present case is 0.11, as opposed to 0.42 in the LCLS design.

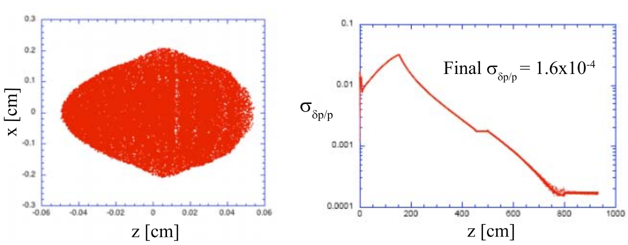

Figure 1: (left) `parmela` simulation results of electron bunch (x, z) distribution showing ellipsoidal bunch boundary, and (right) evolution of $\sigma_{\delta p/p}$ in z for emittance compensation case.

The formation of the quasi-ellipsoidal bunch is clearly 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 bunch 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.

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.

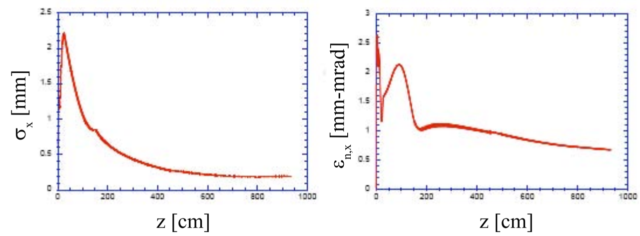

Figure 2: (left) Evolution of RMS transverse beam size σ_x and (right) evolution of RMS normalized emittance $\epsilon_{n,x}$ for emittance compensation case, from `parmela` simulation.

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, the emittance behavior is not as familiar. Details can be found in Ref. [7]. This scheme 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.

After acceleration to higher energy (84.5 MeV), the beam is not space-charge dominated, and the (x, z) profile no longer ellipsoidal. Nonetheless, the beam has excellent emittance. With a high initial current, and low intrinsic energy spread, this beam may be compressed further, with very high final peak current achievable [9].

INITIAL SPARC AND PEGASUS EXPERIMENTS

Experimental Signatures and Measurements

In the initial experiments, the electron bunch is imaged (time-integrated) at low energy (5-7 MeV) in the region after the gun, using a YAG detector. For time resolved measurements the beam spatial information will be converted to photons with a Cerenkov emitter. In order to have a manageably small angle of emission we use aerogel as the emitter, which has a small index of refraction ($n = 1.005$-1.02). The aerogels have been custom fabricated at the Jet Propulsion Laboratory. Simulations consist of providing electrons (typically 40,000) from `parmela` to `geant4` [10], which simulates the scattering of the electrons in the entrance foil and generates a collection of Cerenkov photons produced in the aerogel. The photon distributions that result are then passed to a *Mathematica* based, optical ray-tracing program, *Rayica*.

FIRST RESULTS

The first stage of experimentation on the blowout regime took place at INFN-LNF beginning at the end of March 2006 and has been reported on previously [7, 8]. 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; nevertheless, impressive first data was obtained.

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

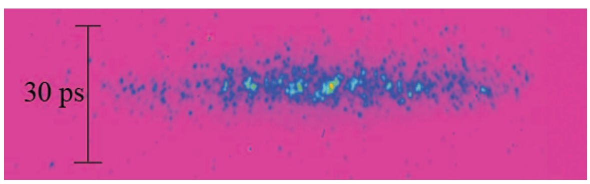

Figure 3: Streak image from initial SPARC experiment.

The image displays the profile obtained from a bunch with charge of 700 pC. In order to extract information from single shots concerning the streak image—which should represent the bunch density distribution in an (x, z) slice in the midplane of the bunch—a maximum likelihood analysis has been chosen to test for different assumed types of bunch distributions. The (x, z) slice distributions tested for consistency with the experimental 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 one looks 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.

The data from the streak images was fit to these functions to determine which of the assumed three profiles gives the best fit. Such an exercise has been performed for the streak given in Fig. 3, with the results shown in Fig. 4. It is noted that the 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. Further experiments, including further

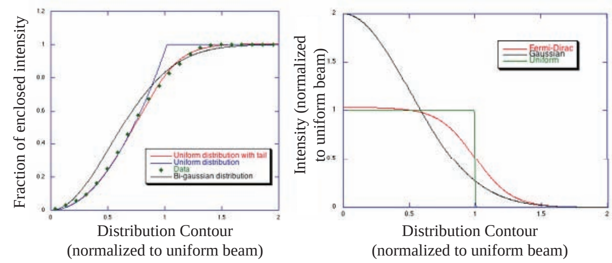

Figure 4: Analysis of streak data, with fraction of integrated intensity of data inside of elliptical contour shown. Best fit of data points to three models are shown: bi-gaussian distribution, uniform elliptical distribution, and Fermi-Dirac (uniform with tails) distribution.

exploration of low energy, time-resolved imaging of electron bunch profiles will be performed at the UCLA Pegasus laboratory in 2007-2008. 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.

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