Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the Sparc High-Brightness Photoinjector

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(Received 1 August 2007; published 6 December 2007)

In this Letter we report the first experimental observation of the double emittance minimum effect in the beam dynamics of high-brightness electron beam generation by photoinjectors; this effect, as predicted by the theory, is crucial in achieving minimum emittance in photoinjectors aiming at producing electron beams for short wavelength single-pass free electron lasers. The experiment described in this Letter was performed at the SPARC photoinjector site, during the first stage of commissioning of the SPARC project. The experiment was made possible by a newly conceived device, called an emittance meter, which allows a detailed and unprecedented study of the emittance compensation process as the beam propagates along the beam pipe.

DOI: 10.1103/PhysRevLett.99.234801 PACS numbers: 29.27.Bd, 07.77.Ka, 41.75.Ht

Future light sources based on high gain free electron lasers require the production, acceleration and transport up to the undulator entrance of high brightness (low emittance, high peak current) electron bunches [1]. In this Letter we report the experience recently done at the SPARC photoinjector [2] in order to better understand the emittance compensation process downstream the gun exit and the first experimental observation of the double emittance minimum effect on which is based the optimized emittance compensation process in the SPARC photoinjector.

In a photoinjector electrons are emitted by a photocathode, located inside an rf cavity, illuminated by a laser pulse so that the bunch length and shape can be controlled on a picosecond time scale via the laser pulse. The emitted electrons are rapidly accelerated to relativistic energies thus partially mitigating the emittance growth due to space charge force effects. Since the early 1980s was clear that the space charge induced emittance growth in an rf gun is partially correlated and can be reduced in the downstream drift by a simple focusing scheme invented by Carlsten [3], with a solenoid located at the exit of the rf gun. In order to prevent additional space charge emittance growth in the subsequent accelerating sections (booster), the final emittance minimum has to be reached at high beam energy so that space charge forces are sufficiently damped. To this end the beam has to be properly matched to the following accelerating sections in order to keep under control emittance oscillations and obtain the required emittance minimum at the booster exit. A theoretical description of the emittance compensation process made by Serafini and Rosenzweig [4] has demonstrated that in the space charge dominated regime, i.e., when the space charge collective force is largely dominant over the emittance pressure, mismatches between the space charge correlated forces and the external rf focusing gradient produce slice envelope oscillations that cause normalized emittance oscillations, also referred as plasma oscillations. It has been shown that to conveniently damp emittance oscillations the beam has to be injected into the booster with a laminar envelope waist ($\sigma' = 0$) and the booster accelerating gradient has to be properly matched to the beam size σ, energy γ and peak current $\hat{I}$, according to the following condition $\gamma' = \frac{2}{\sigma}\sqrt{\frac{\hat{I}}{2I_0\gamma}}$ where $I_0 = 17$ kA is the Alfvén current and $\gamma' \approx 2E_{\mathrm{acc}}$, E_{acc} being the accelerating field. The matching conditions presented above guarantee emittance oscillations damping, preserving beam laminarity during acceleration, but the final value of the emittance is strongly dependent on the phase of the plasma oscillation at the entrance of the booster, that cannot be easily predicted by the theory. Typical behaviors of emittance oscillations in the drift downstream the rf gun are reported in Fig. 1 as

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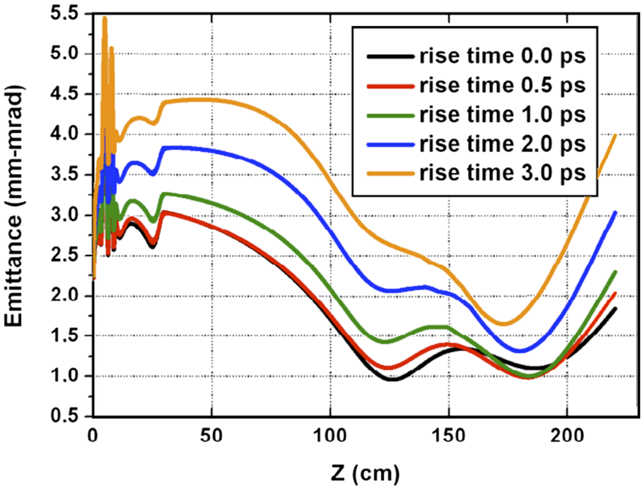

FIG. 1 (color online). Normalized rms emittance oscillations in the drift downstream the rf gun as computed by PARMELA, for different initial electron pulse rise times. Gun length 15 cm, solenoid length 20 cm centered at $z = 20$ cm.

computed by PARMELA [5], for different initial electron pulse shapes.

The pulse shaping considered in these simulations is a quasi flat top distribution in which a 1 nC charge is uniformly distributed in a 10 ps FWHM pulse length with increasing rise time: from a pure cylindrical bunch (0 ps rise time) to a quasi-Gaussian distribution (3 ps rise time). As one can notice the emittance minimum decreases with shorter rise time because of the reduced nonlinear transverse space charge effects in cylindrical like bunch charge distributions [6]. In addition an unexpected emittance oscillation appears in the drift downstream the rf gun showing a double emittance minimum [7]. The relative emittance maximum disappears with longer rise time and becomes a knee in a quai-gaussian distribution. Emittance oscillations of this kind have been explained as produced by a beating between head and tail plasma frequencies caused by correlated chromatic effects in the solenoid [8,9]. In the Gaussian pulse case [10] this effect is weaker since the slice current at the bunch "ends" is vanishing. In particular, the bunch tails actually go through a crossover, which prevents them from correctly undergoing the emittance correction process: this bifurcation is irreversible, leaving a part of the beam propagating as a split beam.

Following the previously discussed matching conditions and after the observation of the peculiar behavior of a flat top bunch shape, a new effective working point very suitable to damp emittance oscillations was found [7] in the context of the LCLS FEL project, and later adopted also by the X-FEL collaboration at DESY [11] and by the SPARC photoinjector [2]. The basic idea of this working point is to place the booster entrance where the relative emittance maximum occurs and at the same time fulfill the envelope and gradient matching conditions. By doing so the second emittance minimum could be shifted at higher energy and frozen at the lowest value, taking advantage of the additional emittance compensation occurring in the booster. Figure 2 shows the optimized matching with the booster in which damping of the emittance oscillations is obtained by accelerating the beam up to 150 MeV, for different pulse rise times. As one can see the additional emittance compensation is relatively poor for a Gaussian-like distribution, even in this optimized case, while for a flat top like distribution case the final emittance is lower than the minimum obtained at the booster entrance.

Measurements of emittance evolution along the drift downstream the rf gun and validation of our theoretical prediction with a direct measurement of double emittance minimum were the main goal of the first SPARC commissioning phase, as will be discussed hereafter.

The SPARC project comprises an R&D photoinjector facility devoted to the production of high-brightness electron beams to drive a SASE-FEL experiment in the visible light. The first phase of the SPARC project, that is now concluded, consists in characterizing the electron beam out of the photoinjector, a 1.6 cell S-band rf gun, at low energy ($\sim$5.6 MeV with 120 MV/m peak field on the cathode), before the installation of the 3 S-band accelerating sections, located after a drift downstream the rf gun (the so called split configuration), which will boost the beam energy up to 150–200 MeV. In order to study the first few meters of beam propagation a new sophisticated diagnostic tool has been installed and commissioned: the movable emittance meter described in [12]. This device has allowed measuring the evolution of beam sizes, energy spread, rms transverse emittances and transverse phase space at different locations along the beam line, the so called Z scan, in the range 1 m to 2.1 m from the cathode location. The SPARC laser is composed by a Ti:Sa oscillator generating 100 fs long pulses with a repetition rate of

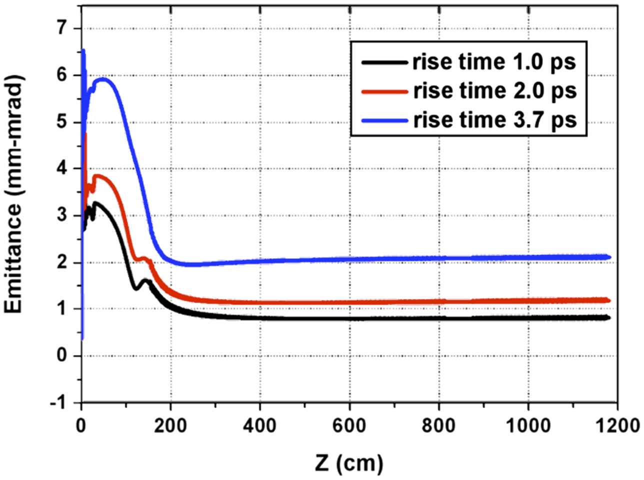

FIG. 2 (color online). Normalized rms emittance damping in the booster downstream the rf gun as computed by PARMELA, for different initial electron pulse rise times. Booster entrance at $z = 150$ cm.

79.3 MHz and an energy of 10 nJ, as described in [13]. An acousto-optic programmable dispersive filter called "DAZZLER" [14] used to modify the spectral amplitude and phase function, is placed between the oscillator and the amplifier to obtain the target temporal profile, thus allowing us to study beam dynamics with different pulse shapes. A quasi flat top laser pulse, retrieved from the spectral measurement is shown in Fig. 3.

Several runs have been dedicated to study the beam dynamics under different conditions: moving the injection phase, changing the solenoid strength, and varying the longitudinal profile of the laser [15]. The design goal in terms of peak current (92 A with 0.8 nC) and emittance (1.6 μm), corresponding to a peak brightness of 7×10^{13} A/m^2, has been successfully overcome with a UV "flat top" laser pulse illuminating the cathode, as reported in [15].

Despite the encouraging results obtained from the beginning of the experiments, obtaining a clear evidence of the double emittance minimum was not an easy task. In order to enhance the oscillation we decided to increase the energy spread across the pulse. A 3% of energy spread was obtained by shifting the gun phase φ toward the maximum energy gain phase $\varphi_{\max}$, $(\varphi - \varphi_{\max} = +12^\circ)$, the expected price to pay was a higher final emittance. The laser pulse rise time was also reduced in this case to 1.5 ps, another important prerequisite to observe emittance oscillations, with a ripple in the longitudinal distribution of 15%; see Fig. 3.

In addition, to be sure to observe the relative maximum at the designed position (1.5 m from the cathode) where the booster will be placed, we decided to measure the emittance at a fixed position ($z = 1.5$ m) and to perform a scan of the solenoid field around the optimal value. By increasing the solenoid field in fact the emittance oscillation tends to occur closer to the cathode as predicted by simulation. Thus, exploring the emittance at a fixed location by varying the B field, is practically equivalent to a continuous shift from different Z-scan curves, as is shown in Fig. 4. The same figure shows that for a coil current of 199 A the emittance relative maximum should occur exactly at $z = 1.5$ m.

In Fig. 5 the results of emittance versus solenoid magnetic field measurements at a fixed position ($z = 1.5$ m) are shown. The bunch charge was 0.5 nC in a 5 ps FWHM long bunch, corresponding to a 100 A peak current and energy was 5.5 MeV. The laser temporal profile during all measurements and in simulations was the one reported in Fig. 3. All emittance measurements reported in this paper have been made with single-slit multishot method, keeping constant the number of sampling across the beam, 13 beamlets per measurement with variable distance per step across the beam, in order to prevent undersampling when the beam size is too small or too large compared to the multislit spacing. Because of the multishot nature of the measurements, the primary source of uncertainty are the beam fluctuations like charge, phase, and accelerating gradient [15]. Therefore we have taken the average over 30 bunches in every slit position and we have calculated the measurement uncertainty as the standard deviation from the average [16]. The error bars in the following plots correspond to the 95% Gaussian confidence level, according to Type A evaluation of uncertainty reported in [17]. The emittance behavior in Fig. 5 is mainly sensitive to charge fluctuations and the continuous lines represent the results of simulations done with charge variations of ±6% with respect to the nominal value (0.5 nC). Nevertheless a reasonable agreement between the experimental data and the simulations has been observed [18].

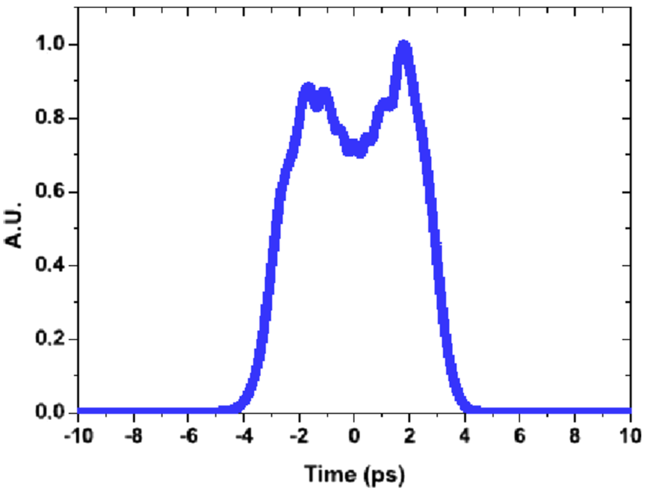

FIG. 3 (color online). Flat top temporal laser pulse shape with 5 ps FWHM and 1.5 ps rise time, retrieved from the spectral measurement.

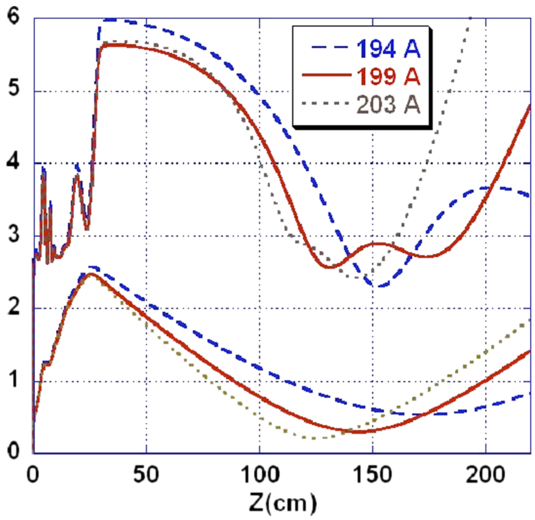

FIG. 4 (color online). Envelope (lower lines) and rms norm. emittance (upper lines) evolution along z for different solenoid coil currents. PARMELA simulations.

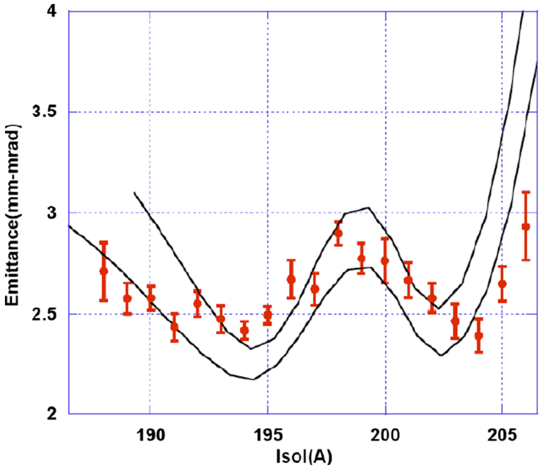

FIG. 5 (color online). Emittance measurements versus solenoid magnetic field (coils current) at a fixed position ($z = 150$ cm). Simulations with charge fluctuations of ±6% are also shown (continuous lines).

We then repeated an emittance measurement along the drift in the same operating conditions, setting the solenoid field where we observed the relative maximum where it was expected in the optimal matching conditions, i.e., 199 A. The results of the Z-scan are reported in the Figs. 6 and 7. Again the agreement with PARMELA simulations [18], performed with the same beam parameters, is very good, confirming also that in the emittance meter wake fields effects are negligible [19] compared to direct space charge effects. As expected the emittance minima were not optimized with respect to the one obtained with correct injection phase, nevertheless this measurements represents the first direct evidence of the double emittance minimum. The amplitude of the observed oscillation is about 0.3 μm which is above the resolution of our measurement system [16]. With the optimized injection phase ($\varphi - \varphi_{\max} = -8^\circ$) this effect was hardly visible because the two emittance minima (expected to be below 1.5 μm in this case) were hidden by the nonlinear space charge effects caused by not uniform transverse charge distribution and thermal emittance contributions that limited our best results to 1.5 μm [15].

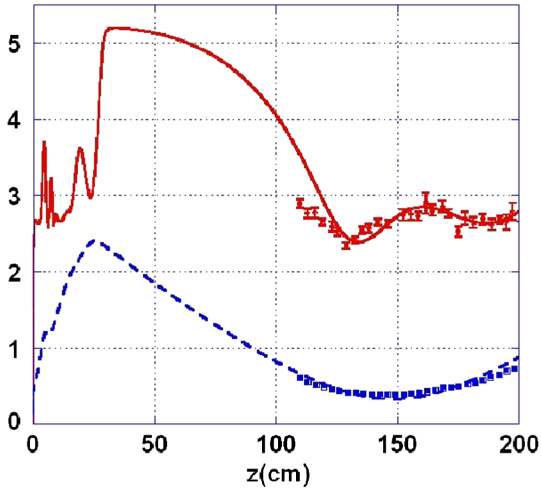

FIG. 6 (color online). rms envelope and rms norm. emittance evolution from the cathode up to the beam line end as computed by PARMELA, compared to measurements taken in the emittance-meter range.

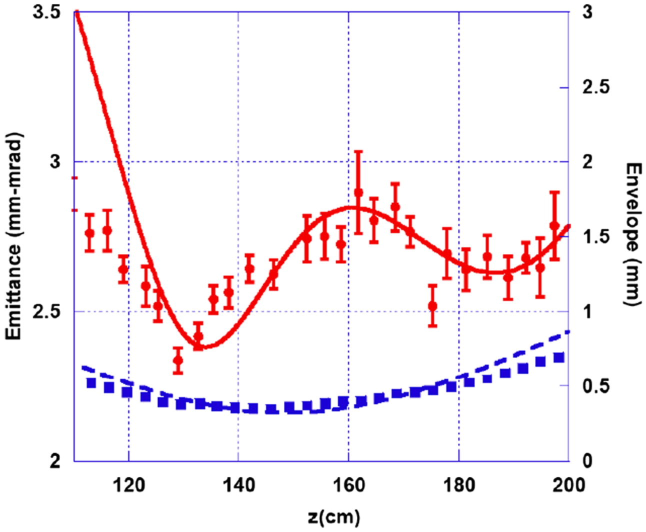

FIG. 7 (color online). Blow up of the previous figure in the emittance-meter range.

In this regime simulations show a cross shape in the transverse phase space of a flat top distribution at its relative emittance maximum. A comparison of the transverse phase space as reconstructed from beam measurements and as produced by simulation for the same beam is reported in Fig. 8. This result proves that under laminar conditions, i.e., when the solenoid field is not too high to cause crossover, the space charge dominated waist is reached at different positions by the head and the tail slices of the bunch, so that when the bunch tail is already diverging the bunch head is still converging, thus resulting in the observed cross shaped transverse phase space.

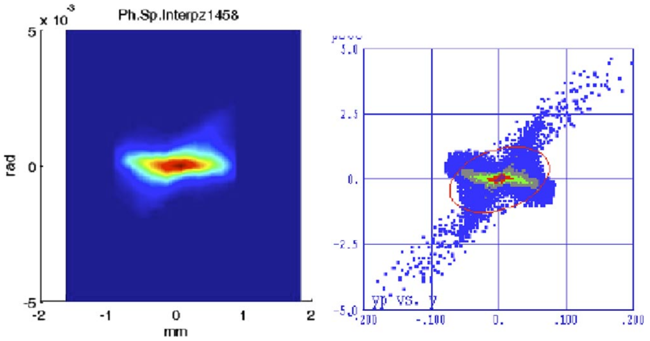

FIG. 8 (color online). Transverse phase space at $z = 150$ cm. Measurements left plot and simulation right plot. Same beam of Fig. 7.

We have reported in this Letter the first experimental evidence of emittance oscillation in the drift of a split photoinjector that we expect to be the optimal prerequisite for an optimized design of a photoinjector operating in the flat top laser pulse mode. We have observed the double emittance minimum in Z-scan measurements allowed by a new dedicated movable emittance measurement and we have studied the relations with the standard solenoid scan (B-scan) performed at a fixed position. The latter will be the only technique available in the future runs of SPARC, as in any other photoinjector, because the emittance meter has been now removed and the booster linac has been mounted on its place. The agreement with simulation was very good in all cases including the transverse phase space comparison.

This work has been partially supported by the EU Commission in the sixth framework programme, Contract No. 011935 EUROFEL and from the MIUR Progetti Strategici No. DD1834.

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