Experimental Demonstration of Emittance Compensation with Velocity Bunching

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In this Letter we report the first experiments aimed at the simultaneous demonstration of the emittance compensation process and velocity bunching in a high brightness electron source, the SPARC photoinjector in INFN-LNF. While a maximum compression ratio up to a factor 14 has been observed, in a particular case of interest a compression factor of 3, yielding a slice current of 120 A with less than 2 μm slice emittance, has been measured. This technique may be crucial in achieving high brightness beams in photoinjectors aiming at optimized performance of short wavelength single-pass free electron lasers or other advanced applications in laser-plasma accelerators.

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Ultrashort electron bunch production is a subject of investigation that has attracted increasing attention in recent years, spurred by a large number of applications, spanning short wavelength free electron lasers (FEL), THz radiation production, linear colliders, and plasma wake field accelerators. Space charge effects at low energy prevent the generation of short electron bunches (<1 ps) with a significant amount of charge (>10 pC) directly from the electron source, leading to emittance degradation and bunch elongation within a few centimeters downstream the cathode. As such, bunch compression is always necessary to shorten the electron pulse to the required length thus achieving a high peak current. The most popular and effective device used thus far is the magnetic compressor in which a bunch with a time-energy correlation (or chirp) is driven along an energy-dependent path length by a dispersive, nonisochronous beam transport section, consisting, in its simplest form, of four dipoles placed in a chicane configuration. The process of magnetic compression may often unacceptably degrade the beam quality, however, due to significant emittance growth caused by coherent synchrotron radiation effects in bends [1].

On the other hand, a new method termed velocity bunching, able to compress the bunch using rectilinear trajectories at relatively low energy [2], which must thus be integrated into the emittance compensation process [3], has been proposed in [4]. The longitudinal phase space rotation in the velocity bunching process is based on a correlated time-velocity chirp in the electron bunch, in such a way that electrons on the tail of the bunch are faster than electrons in the bunch head. This rotation occurs inside the longitudinal potential of a traveling rf wave (longitudinal focusing) which accelerates the beam inside a long multicell rf structure and simultaneously applies an off crest energy chirp to the injected beam. This is possible if the injected beam is slightly slower than the phase velocity of the rf wave so that when injected at the zero crossing field phase it slips back to phases where the field is accelerating, but is simultaneously chirped and compressed. The key point is that compression and acceleration take place at the same time within the same accelerator section, the initial one following the gun.

In order to prevent irreversible emittance growth during bunch compression the key issue is to preserve the laminarity of the beam with an envelope propagated as close as possible to a Brillouin-like flow, represented by an invariant envelope [5] as generalized to the context of beam compression and thus increasing I during acceleration. For these kind of beams, mismatches between the space charge correlated forces and the external focusing gradient produce slice envelope oscillations that cause normalized emittance oscillations. It has been shown that to keep such oscillations under control during the velocity bunching, the beam has to be injected into the rf structure with a laminar envelope waist ($\sigma' = 0$) and the envelope has to be matched to the accelerating and focusing gradients in such a way to stay close to an equilibrium mode [5,6]. Ponderomotive rf focusing force are actually too weak in a travelling wave structure [7] to provide sufficient beam focusing. A long solenoid around the accelerating structure is a convenient replacement to provide the necessary focusing.

In this configuration the matching condition for the transverse rms envelope σ is given by

$$\sigma = \frac{1}{k}\sqrt{\frac{I_0}{4\gamma_0 I_A}\left(1+\sqrt{1+\left(4\frac{\varepsilon_n\gamma_0 k I_A}{I_0}\right)^2}\right)}, \qquad (1)$$

where $k = \frac{eB_{\rm sol}}{mc}$, $B_{\rm sol}$ is the solenoid field, $I_A = 17$ kA the Alfvén current, ε_n the normalized emittance, γ_0 and I_0 are the values for the current and the energy, respectively, at injection into the compressor. The previous relation represents a new exact equilibrium solution (including the emittance contribution which in practical cases of velocity bunching is small but not negligible; previously derived approximate solutions are discussed in Ref. [8]) of the beam envelope equation:

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \left(\frac{k}{\gamma}\right)^2\sigma = \frac{I}{2I_A\gamma^3\sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma^3}, \qquad (2)$$

where $\gamma' \approx 2E_{\rm acc}$, $E_{\rm acc}$[MV/m] being the accelerating field. The main approximation leading to solution (1) consists on the assumption that the beam current grows linearly in the compressor as $I = I_0\gamma/\gamma_0$. Nevertheless this result is confirmed by observations performed in several simulations of the rf compressor [6], indicating that best performances in terms of final beam brightness are achieved near the condition of beam flow at constant envelope. The matching conditions (1) guarantee beam laminarity preservation during acceleration and compression, but the final value of the emittance is strongly affected by the phase of the emittance oscillation in the velocity bunching, that cannot be easily predicted by the theory. The fine-tuning of the emittance compensation process can be performed by varying the injection spot size via a parametric scan of the gun solenoid field [9], as will be shown later.

In this Letter we report the first experimental observation of effective emittance compensation in a velocity bunching device. The experiment described here was performed at the SPARC photoinjector, during the final commissioning stage of the SPARC project [10]. Experiments aiming at the demonstration of the velocity bunching principle have been previously performed in other laboratories [11–16] in photoinjector configurations not specifically designed for emittance compensation, thus limiting the achieved beam brightness. This simultaneous demonstration of emittance compensation with significant beam compression obtained using the velocity bunching technique, has indeed been one of the central goals at the beam physics program at SPARC. For this reason, the first two S-band traveling wave accelerating structures downstream the 1.6 cells S-band rf gun, are embedded in long solenoids, consisting of 13 coils each with a maximum field of 1.8 kG, in order to keep the space charge induced emittance oscillations under control as the bunch is compressed.

The SPARC beam diagnostics allow rms beam envelope measurements on four screens: three screens are located at the entrance of each rf structure while the fourth is located at the linac exit. Downstream the linac exit the rms normalized emittance ε_n is measured using the quadrupole scan technique, while an rf deflecting cavity allows horizontal slice emittance measurements [17] as well as bunch length measurements with a resolution of 60 fs [18].

During the experiments the drive laser was operated with a 7.3 ps FWHM long pulse, having a rms spot radius of 350 μm. The bunch charge was 280 pC giving a maximum slice current of about 30 A without compression. At the gun exit the beam energy was 4.4 MeV corresponding to a peak field on the cathode of about 100 MV/m, limited by rf breakdown. This field limit is the central reason our rf photoinjector does not achieve emittance performances similar the one obtained with the new rf gun design at the Linac Coherent Light Source [19]. When the beam was accelerated on crest, using an accelerating field amplitude of 20 MV/m in the first two sections and 10 MV/m in the final section, the final energy was 148 MeV with an energy spread of 0.1% and an rms energy stability better than 0.1%. The rms bunch length measured at the linac exit was 3 ps, with a measured minimum rms projected emittance of 1.5 μm in both planes with the gun solenoid set to 2.46 kG (long solenoids off).

For linac-driven FEL applications, the bunch slice parameters are most relevant to the amplification process. The SPARC FEL operating at 530 nm has a typical slippage length of the order of 250 μm; we have thus taken this value as the bunch slice length in our analysis. In Fig. 1 the beam current profile and the slice emittance is plotted vs the longitudinal bunch coordinate.

The first measurements made at SPARC in the velocity bunching mode were devoted to study the longitudinal focusing effects as a function of the injection phase, with-

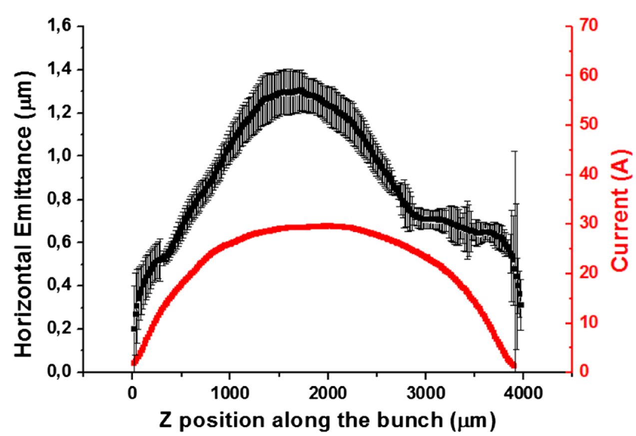

FIG. 1 (color online). Horizontal slice emittance and corresponding current profile (continuous lines), for the noncompressed beam. Gun solenoid set to 2.46 kG, long solenoids off.

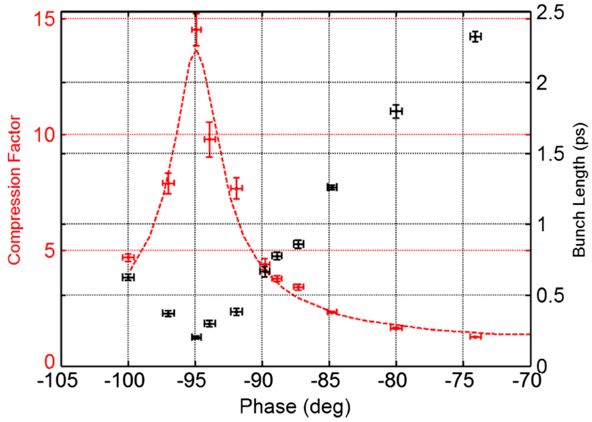

FIG. 2 (color online). Measured rms bunch length (black) and corresponding compression factor (red) of a 280 pC beam versus the phase of the first traveling wave structure. PARMELA simulations are also shown with dashed red line.

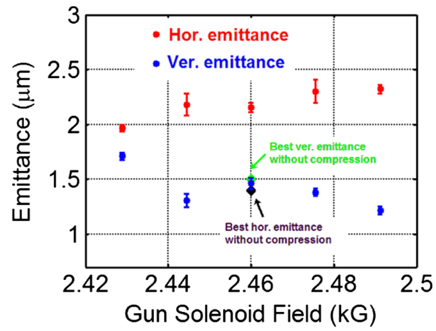

FIG. 3 (color online). Measured rms normalized emittance at $C = 3$ as a function of the gun solenoid field, long solenoid set to 450 G. For comparison black and green dots represent best results without compression, long solenoid off.

out any additional external focusing (long solenoids off). Figure 2 shows the measured rms bunch length σ_t versus the injection phase φ of the first traveling wave structure. The corresponding measured rms compression factor $C = \sigma_t(0)/\sigma_t(\varphi)$, the bunch length after on crest acceleration divided by the bunch length after compression, is also shown. Significant bunch compression occurs only at a phase shift of 85° forward of crest. At this injection phase the beam energy reduces to 100 MeV and the energy spread grows up to 1%.

The strong compression regime occurs when the phase shifts from −85° to −95°, as expected, with almost constant final energy and energy spread observed. The shortest measured rms bunch length is 210 fs (63 μm), limited by the longitudinal beam emittance. The final two measurements also illustrate the effect of overcompression when the phase setting exceeds −95°. In Fig. 2 the results of PARMELA [20] simulations are also shown. The agreement is quite satisfactory even in the over-compression regime.

A systematic study of the emittance compensation process has been carried out using the moderate compression ratio of 3, as that one foreseen for the SPARX FEL project [21]. The SPARX linac has been in fact designed to produce a 1 kA beam at 1.5 GeV in two compression stages: a low energy velocity bunching with a compression factor 3 followed by a magnetic compressor at higher energy. We have considered this quite conservative choice for the compression factor the most suitable for a proof of principle experiment with the emphasis on the emittance compensation process, whose effectiveness in this regime has not been demonstrated so far. The final rms normalized emittance has been optimized as a function of the gun solenoid field for a given value of the long solenoids of 450 G, as shown in Fig. 3. The observed asymmetry in x and y planes is likely due to an offset of the solenoid magnetic axis with respect to the linac rf axis [22]. In Table I the measured beam parameters and related experimental conditions are summarized. The second column contains the measured data of the uncompressed beam (on crest acceleration) for comparison. To estimate the chromatic effects induced by the solenoids we have measured the emittance with solenoids on and off also for the uncompressed beam. We expect a significant reduction of chromatic effect with a careful beam based alignment of the long solenoids.

The lowest achieved emittances in the velocity bunching mode are $\varepsilon_{nx} = 2.12$ μm and $\varepsilon_{ny} = 1.45$ μm (to be compared with $\varepsilon_{nx} = 6.2$ μm and $\varepsilon_{ny} = 4.0$ μm with long solenoids off, marked with * in the table). Comparing the geometric mean of the emittances with and without compression (long solenoids turned on in both cases) the results are even more remarkable. With a slice peak current of 120 A this bunch exhibits the highest beam brightness ($\sim 10^{14}$ A/m^2) so far obtained by the SPARC injector. In Fig. 4 (left plot) the measured envelopes are shown in comparison with simulations for three different conditions:

TABLE I. Measured beam parameters.

	No compression	Compression ratio 3
Charge (pC)	280	280
Gun solenoid field (kG)	2.460	2.460
Long solenoid field (G)	660	450
	0*	0*
Injection phase (deg)	0	−88
Energy (MeV)	148	100
Energy spread (%)	0.1	1.0
Rms bunch length (ps)	3.0	0.97
ε_{nx} (μm)	1.85	2.12
	1.4*	6.2*
ε_{ny} (μm)	1.65	1.45
	1.5*	4.0*
Geometric mean $\sqrt{\varepsilon_{nx}\varepsilon_{ny}}$ (μm)	1.75	1.75
	1.45*	5.0*

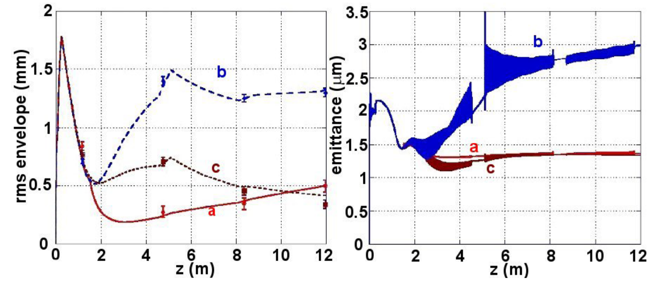

FIG. 4 (color online). Measured envelopes and PARMELA simulations (left plot). Emittance evolution along the linac, PARMELA simulations (right plot). No compression (curves *a*), compression with long solenoids off (curves *b*), same compression with long solenoids set to 450 G (curves *c*).

no compression (beam on crest), compression factor 3 with long solenoids off, same compression with long solenoids set to 450 G. The corresponding evolution of the emittances as simulated by PARMELA are shown in Fig. 4 (right plot). The effect on emittance compensation produced by the solenoids is clearly visible in the simulation and it is in good agreement with our measurements. Note that the matching condition prescribed by the condition (1) would indicate with the actual parameter a spot size of 390 μm at injection in the velocity bunching (at $z \sim 170$ cm), a 22% smaller spot size compared to Fig. 4. The beam envelope results in fact partially mismatched, as expected, after the gun solenoid fine-tuning, providing the lowest measured emittance at the exit of the velocity bunching.

In Fig. 5 the slice emittance and the current profiles are shown for different values of the gun solenoid field. As one can see by comparison with Fig. 1 the slice emittance degradation in the slice with the highest current is quite

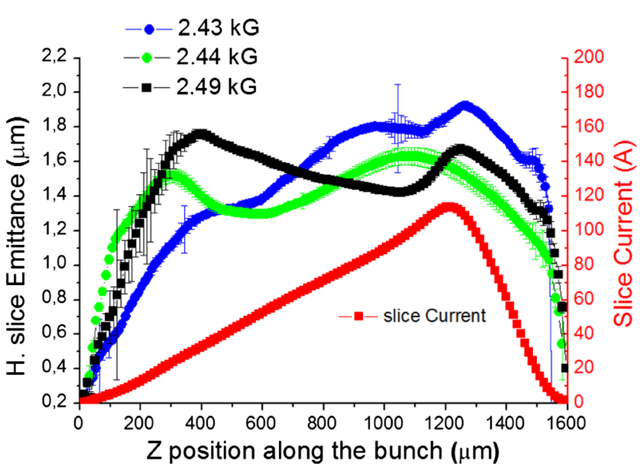

FIG. 5 (color online). Horizontal slice emittance profiles for three levels of the gun solenoid field together with beam current profile ($C = 3$). Long solenoids set to 450 G.

limited: 1.6 μm at 120 A to be compared with 1.2 μm at 30 A (250 μm long slice in both cases).

In this Letter we have experimentally shown for the first time that a successful mitigation of the emittance degradation during compression with the velocity bunching is possible with optimized compensation applied. This goal has been achieved with the long solenoids installed around the accelerating sections, as predicted by the theory [4]. We are confident that velocity bunching will open new interesting opportunities in the design of future compact short wavelength FELs and for advanced accelerator applications.

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